# Binocular: A Decentralized Bitcoin Oracle on Cardano

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## Abstract

Binocular is a Bitcoin oracle for Cardano that enables smart contracts to access and verify Bitcoin blockchain state. The protocol allows anyone to submit Bitcoin block headers to a single on-chain Oracle UTxO without registration or bonding requirements. All blocks are validated against Bitcoin consensus rules (proof-of-work, difficulty adjustment, timestamp constraints) enforced by a Plutus smart contract. The Oracle maintains a tree of competing forks and automatically selects the canonical chain using Bitcoin's chainwork calculation. Blocks achieving 100+ confirmations and 200+ minutes of on-chain aging are promoted to the confirmed state, providing a Merkle tree root that enables transaction inclusion proofs. Security relies on a 1-honest-party assumption and Bitcoin's proof-of-work security, with economic analysis showing that mining 100 Bitcoin blocks costs significantly more than any potential oracle manipulation reward.

## Introduction

Cross-chain interoperability requires reliable access to external blockchain state. Cardano smart contracts currently cannot directly observe or verify Bitcoin transactions, limiting potential applications like cross-chain bridges, Bitcoin-backed stablecoins, and decentralized exchanges. Binocular addresses this by implementing a Bitcoin oracle that validates block headers on-chain using Cardano's extended UTxO model.

### Problem

Existing cross-chain oracles typically rely on trusted intermediaries, multi-signature committees, or external validators. These approaches introduce additional trust assumptions beyond the security of the underlying blockchains. A Bitcoin oracle should ideally inherit Bitcoin's security properties while operating within Cardano's smart contract environment.

### Contribution

Binocular makes the following contributions:

1. **On-chain Bitcoin Validation**: Complete implementation of Bitcoin consensus validation ( proof-of-work, difficulty adjustment, median-time-past, timestamp validation) in Plutus using Scalus, enabling Cardano smart contracts to verify Bitcoin block headers without external trust.
2. **Permissionless Participation**: Anyone can submit Bitcoin blocks to the Oracle without registration, bonding, or special privileges. The validator contract

enforces all validation rules, rejecting invalid blocks automatically.

3. **Simplified Single-UTxO Architecture**: A single Oracle UTxO contains both the confirmed state ( Merkle tree of blocks with 100+ confirmations) and a tree of competing unconfirmed forks. Updates atomically select the canonical chain and promote qualified blocks.
4. **Challenge Period Mechanism**: Blocks must exist on-chain for 200 minutes before promotion to confirmed state, providing time for honest parties to counter pre-computed attacks while maintaining liveness.
5. **Security Analysis**: Formal proofs of safety and liveness properties, along with quantitative economic analysis demonstrating attack infeasibility.

The protocol operates under a 1-honest-party assumption: at least one participant monitors the Bitcoin network and submits valid blocks to the Oracle. This assumption is minimal - requiring only that someone, somewhere, runs the freely available software.

## Overview

### Key Concepts

- **Oracle UTxO**: A single on-chain UTxO containing the complete Oracle state (confirmed blocks and forks tree).
- **Confirmed State**: Bitcoin blocks that have achieved 100+ confirmations and 200+ minutes of on-chain aging, stored as a Merkle tree root.
- **Forks Tree**: A tree data structure holding competing unconfirmed Bitcoin block chains, indexed by block hash.
- **Canonical Chain Selection**: Automatic selection of the highest chainwork fork following Bitcoin's longest chain rule.
- **Block Promotion**: Blocks meeting confirmation and aging criteria are automatically moved from the forks tree to confirmed state.
- **Challenge Period**: 200-minute on-chain aging requirement before blocks can be promoted, preventing pre-computed attacks.
- **Chainwork**: Cumulative proof-of-work calculation used to determine the canonical chain.

### Architecture

The Binocular Oracle uses a simplified single-UTxO design:

**Oracle UTxO State**:

```
ChainState {
  // Confirmed state (blocks with 100+ confirmations, 200+ min old)
  blockHeight, blockHash, currentTarget, blockTimestamp,
  recentTimestamps[11], previousDifficultyAdjustmentTimestamp,
  confirmedBlocksRoot,  // Merkle tree of confirmed blocks

  // Forks tree (competing unconfirmed chains)
  forksTree  // Tree of BlockNodes indexed by block hash
}
```

### Protocol Operation

#### 1. Submitting Blocks

Anyone can submit an update transaction containing:

- New Bitcoin block header(s)
- Fork point specification (which block the new blocks extend)

The on-chain validator performs atomic operations:

- Validates each block against Bitcoin consensus rules (PoW, difficulty, timestamps)
- Adds valid blocks to the forks tree
- Selects the canonical chain (highest chainwork)
- Promotes blocks meeting criteria (100+ confirmations AND 200+ min old) to confirmed state
- Updates the confirmed blocks Merkle tree root

#### 2. Fork Competition

Multiple competing forks coexist in the forks tree. The canonical chain is determined by:

- Cumulative chainwork calculation (sum of difficulty targets)
- Follows Bitcoin's longest chain rule
- Selection happens automatically on every update

#### 3. Block Promotion (Maturation)

Blocks are promoted when they satisfy both criteria:

- **Confirmation Depth**: 100+ blocks deep in the canonical chain
- **On-chain Aging**: 200+ minutes since the block was added to the forks tree

The 200-minute requirement prevents pre-computed attacks: an attacker cannot mine 100+ blocks offline and immediately promote them, as they must first exist on-chain for the challenge period.

## Protocol Specification

This section provides complete technical specifications for all data structures and algorithms implemented in the Binocular Oracle.

### Data Structures

#### Type Aliases:

For semantic clarity and type safety, the implementation uses the following type aliases:

```scala
type BlockHash = ByteString      // 32-byte SHA256d hash of block header
type TxHash = ByteString          // 32-byte SHA256d hash of transaction
type MerkleRoot = ByteString      // 32-byte Merkle tree root hash
type CompactBits = ByteString     // 4-byte compact difficulty target representation
type BlockHeaderBytes = ByteString // 80-byte raw Bitcoin block header
```

The Oracle maintains a single UTxO with the following datum structure:

```scala
case class ChainState(
   // Confirmed state
   blockHeight: BigInt, // Current confirmed block height
   blockHash: BlockHash, // Hash of current confirmed block
   currentTarget: CompactBits, // Difficulty target (compact bits format)
   blockTimestamp: BigInt, // Timestamp of current confirmed block
   recentTimestamps: List[BigInt], // Last 11 timestamps (newest first) for median time
   previousDifficultyAdjustmentTimestamp: BigInt, // For difficulty retarget calculatio
   confirmedBlocksRoot: MerkleRoot, // Merkle tree root of confirmed block hashes

   // Forks tree
   forksTree: Map[BlockHash, BlockNode] // Block hash → BlockNode mapping
)

case class BlockNode(
    prevBlockHash: BlockHash, // 32-byte hash of previous block (for chain walking)
    chainwork: BigInt, // Cumulative proof-of-work from genesis
    addedTimestamp: BigInt, // When this block was added on-chain (for 200-min rule)
    children: List[BlockHash] // Hashes of child blocks (for tree navigation)
)

case class BlockHeader(
    bytes: BlockHeaderBytes // Raw 80-byte header
)
```

**BlockHeader Fields** (extracted from bytes):

- `version` (bytes 0-3): Block version
- `prevBlockHash` (bytes 4-35): BlockHash - Hash of previous block
- `merkleRoot` (bytes 36-67): MerkleRoot - Merkle root of transactions
- `timestamp` (bytes 68-71): Block timestamp (Unix epoch seconds)
- `bits` (bytes 72-75): CompactBits - Difficulty target (compact format)
- `nonce` (bytes 76-79): Proof-of-work nonce

### Bitcoin Consensus Constants

The following constants match Bitcoin Core's `chainparams.cpp` and `validation.cpp`:

```scala
UnixEpoch: BigInt = 1231006505 // Bitcoin genesis block timestamp
TargetBlockTime: BigInt = 600 // 10 minutes (nPowTargetSpacing)
DifficultyAdjustmentInterval: BigInt = 2016 // Retarget every 2016 blocks
```

```
MaxFutureBlockTime: BigInt = 7200 // 2 hours (MAX_FUTURE_BLOCK_TIME)
MedianTimeSpan: BigInt = 11 // For median-time-past (CBlockIndex::nMedianTimeSpan)
PowLimit: BigInt = 0x00000000ffffffffffffffffffffffffffffffffffffffffffffffffffffffff
MaturationConfirmations: BigInt = 100 // Blocks needed for promotion
ChallengeAging: BigInt = 200 * 60 // 200 minutes in seconds
```

### Core Algorithms

This section documents all validation and state transition algorithms implemented in the on-chain validator (BitcoinValidator.scala).

**Algorithm 1: Compact Bits to Target Conversion** Converts Bitcoin's 4-byte compact "bits" representation to a 256-bit target value. Matches `arith_uint256::SetCompact()` in Bitcoin Core's `arith_uint256.cpp`.

**Mathematical Specification:**

Given compact bits $c$ as 4 bytes $[c_0, c_1, c_2, c_3]$ (little-endian):

- Exponent: $e = c_3$
- Coefficient: $m = c_0 + c_1 \cdot 256 + c_2 \cdot 256^2$

Target value:

$$T = \begin{cases} m/256^{3-e} & \text{if } e < 3 \\ m \cdot 256^{e-3} & \text{if } e \geq 3 \end{cases}$$

With overflow checks: $m \leq 0x007fffff$ and $T \leq \text{PowLimit}$.

**Pseudocode:**

```
Function compactBitsToTarget(compact: CompactBits) → BigInt:
  Input: 4-byte compact bits (little-endian)
  Output: 256-bit target value

  exponent ← compact[3]
  coefficient ← LE_to_int(compact[0:3])

  require coefficient ≤ 0x007fffff, "Negative bits"

  if exponent < 3 then
    target ← coefficient / 256^(3 - exponent)
  else
    // Check overflow: exponent too large for coefficient size
    if coefficient ≠ 0 and (
       exponent > 34 or
       (coefficient > 0xff and exponent > 33) or
       (coefficient > 0xffff and exponent > 32)
    ) then
      fail "Bits overflow"
    target ← coefficient × 256^(exponent - 3)

  require target ≤ PowLimit, "Bits over PowLimit"
  return target
```

**Implementation Reference:** BitcoinValidator.scala:120-137

**Algorithm 2: Target to Compact Bits Conversion** Inverse operation: converts 256-bit target to 4-byte compact representation. Matches `arith_uint256::GetCompact()` in `arith_uint256.cpp`.

**Mathematical Specification:**

Given target $T$, find exponent $e$ and coefficient $m$ such that:

$$T \approx m \cdot 256^{e-3}$$

where $m$ fits in 3 bytes and the most significant bit of $m$ is 0 (positive number encoding).

**Pseudocode:**

```
Function targetToCompactBits(target: BigInt) → CompactBits:
  Input: 256-bit target value
  Output: 4-byte compact bits

  if target = 0 then return 0

  // Convert to 32-byte array to find significant bytes
  targetBytes ← toBigEndianBytes(target, 32)

  // Find number of significant bytes (from MSB)
  nSize ← findMostSignificantByteIndex(targetBytes) + 1

  // Extract compact representation
  if nSize ≤ 3 then
    nCompact ← target × 256^(3 - nSize)
  else
    nCompact ← target / 256^(nSize - 3)

  // Ensure positive encoding (MSB = 0)
  if nCompact ≥ 0x800000 then
    nCompact ← nCompact / 256
    nSize ← nSize + 1

  // Pack: [3-byte coefficient][1-byte exponent]
  return intToBytes(nCompact + nSize × 0x1000000, 4)
```

**Implementation Reference:** BitcoinValidator.scala:145-186

**Algorithm 3: Block Header Hash** Computes double SHA-256 hash of block header. Matches `CBlockHeader::GetHash()` in Bitcoin Core's `primitives/block.h`.

**Mathematical Specification:**

$$H = \text{SHA256}(\text{SHA256}(\text{header\_bytes}))$$

**Pseudocode:**

```
Function blockHeaderHash(header: BlockHeader) → BlockHash:
  return SHA256(SHA256(header.bytes))
```

**Implementation Reference:** BitcoinValidator.scala:89-90

**Algorithm 4: Proof-of-Work Validation** Validates that block header hash meets the difficulty target. Matches `CheckProofOfWork()` in `pow.cpp:140-163`.

**Mathematical Specification:**

Given block header $h$ with difficulty bits $d$:

$$\text{PoW is valid} \iff \text{Hash}(h) \leq \text{compactBitsToTarget}(d)$$

where hash is interpreted as a little-endian 256-bit integer.

**Pseudocode:**

```
Function validateProofOfWork(header: BlockHeader, targetBits: CompactBits) → Bool:
  hash ← blockHeaderHash(header)
  hashInt ← LE_to_BigInt(hash)
  target ← compactBitsToTarget(targetBits)
  return hashInt ≤ target
```

**Implementation Reference:** BitcoinValidator.scala:357-361

**Algorithm 5: Median Time Past** Computes median of last 11 block timestamps for timestamp validation. Matches `CBlockIndex::GetMedianTimePast()` in `chain.h:278-290`.

**Mathematical Specification:**

Given timestamp list $[t_1, t_2, \dots, t_n]$ sorted newest-first:

$$\text{MedianTimePast}(T) = T[\lfloor n/2 \rfloor]$$

**Pseudocode:**

```
Function getMedianTimePast(timestamps: List[BigInt]) → BigInt:
  Input: List of up to 11 timestamps (reverse sorted, newest first)
  Output: Median timestamp

  if timestamps.isEmpty then return UnixEpoch
  n ← timestamps.length
  medianIndex ← n / 2
  return timestamps[medianIndex]
```

**Implementation Reference:** BitcoinValidator.scala:192-198

**Algorithm 6: Difficulty Adjustment** Calculates new difficulty target every 2016 blocks. Matches `GetNextWorkRequired()` and `CalculateNextWorkRequired()` in `pow.cpp:14-84`.

**Mathematical Specification:**

Difficulty retargets every 2016 blocks. Given:

- $T_{\text{current}}$: current target
- $t_{\text{last}}$: timestamp of last block in period
- $t_{\text{first}}$: timestamp of first block in period

Calculate actual timespan:

$$\Delta t_{\text{actual}} = t_{\text{last}} - t_{\text{first}}$$

Clamp to prevent extreme adjustments:

$$\Delta t_{\text{clamped}} = \min\left(\max\left(\Delta t_{\text{actual}}, \frac{\Delta t_{\text{target}}}{4}\right), \Delta t_{\text{target}} \times 4\right)$$

where $\Delta t_{\text{target}} = 2016 \times 600 = 1209600$ seconds (2 weeks).

New target:

$$T_{\text{new}} = \min\left(\frac{T_{\text{current}} \times \Delta t_{\text{clamped}}}{\Delta t_{\text{target}}}, \text{PowLimit}\right)$$

**Pseudocode:**

```
Function getNextWorkRequired(
  height: BigInt,
  currentTarget: CompactBits,
  blockTime: BigInt,
  firstBlockTime: BigInt
) → CompactBits:

  // Only adjust every 2016 blocks
  if (height + 1) mod 2016 ≠ 0 then
    return currentTarget

  // Calculate actual timespan
  PowTargetTimespan ← 2016 × 600  // 2 weeks
  actualTimespan ← blockTime - firstBlockTime
  // Clamp adjustment (Bitcoin Core pow.cpp:55-60)
  clampedTimespan ← min(
    max(actualTimespan, PowTargetTimespan / 4),
    PowTargetTimespan × 4
  )

  // Adjust target
  currentTargetInt ← compactBitsToTarget(currentTarget)
  newTarget ← (currentTargetInt × clampedTimespan) / PowTargetTimespan
  newTarget ← min(newTarget, PowLimit)

  return targetToCompactBits(newTarget)
```

**Implementation Reference:** BitcoinValidator.scala:315-343

**Algorithm 7: Timestamp Validation** Validates block timestamp against median-time-past and future time limits. Matches `ContextualCheckBlockHeader()` in `validation.cpp:4180-4182`.

**Validation Rules:**

$$\begin{aligned}\text{MedianTimePast}(T_{\text{recent}}) &< t_{\text{block}} \\ t_{\text{block}} &\leq t_{\text{current}} + 7200\end{aligned}$$

Where $T_{\text{recent}}$ are the last 11 block timestamps and $t_{\text{current}}$ is the current Cardano slot time.

**Implementation Reference:** BitcoinValidator.scala:373-378

**Algorithm 8: State Transition (Block Validation)** Complete validation and state update for adding a new block. Matches validation logic across Bitcoin Core's `validation.cpp`.

**Pseudocode:**

```
Function updateTip(
  prevState: ChainState,
  blockHeader: BlockHeader,
  currentTime: BigInt
) → ChainState:

  // 1. Extract block data
  blockTime ← blockHeader.timestamp
  blockBits ← blockHeader.bits
  hash ← blockHeaderHash(blockHeader)

  // 2. Validate previous block hash
  require blockHeader.prevBlockHash = prevState.blockHash,
    "Previous block hash mismatch"

  // 3. Validate proof-of-work
  require validateProofOfWork(blockHeader, blockBits),
    "Invalid proof-of-work"

  // 4. Validate difficulty adjustment
  nextDifficulty ← getNextWorkRequired(
    prevState.blockHeight,
    prevState.currentTarget,
    prevState.blockTimestamp,
    prevState.previousDifficultyAdjustmentTimestamp
  )
  require blockBits = nextDifficulty,
    "Incorrect difficulty"

  // 5. Validate timestamp
  medianTimePast ← getMedianTimePast(prevState.recentTimestamps)
  require blockTime > medianTimePast,
    "Timestamp not greater than median"
  require blockTime ≤ currentTime + MaxFutureBlockTime,
    "Timestamp too far in future"

  // 6. Validate version
  require blockHeader.version ≥ 4,
    "Outdated block version"

  // 7. Update difficulty adjustment timestamp
  newAdjustmentTime ← if (prevState.blockHeight + 1) mod 2016 = 0
    then blockTime
    else prevState.previousDifficultyAdjustmentTimestamp

  // 8. Update recent timestamps (maintain last 11, newest first)
  newTimestamps ← insertReverseSorted(blockTime, prevState.recentTimestamps)
  newTimestamps ← newTimestamps.take(11)

  // 9. Return new state
  return ChainState(
    blockHeight = prevState.blockHeight + 1,
    blockHash = hash,
    currentTarget = nextDifficulty,
    blockTimestamp = blockTime,
    recentTimestamps = newTimestamps,
    previousDifficultyAdjustmentTimestamp = newAdjustmentTime,
    confirmedBlocksRoot = prevState.confirmedBlocksRoot  // Updated separately
  )
```

**Implementation Reference:** BitcoinValidator.scala:345-405

**Algorithm 9: Canonical Chain Selection** Selects the fork with highest cumulative chainwork. Follows Bitcoin's longest chain rule.

**Mathematical Specification:**

Given forks tree $F$, find canonical tip:

$$h^* = \arg\max_{h \in \text{Tips}(F)} \text{chainwork}(h)$$

where $\text{Tips}(F)$ are all blocks with no children (leaf nodes).

**Pseudocode:**

```
Function selectCanonicalChain(forksTree: Map[BlockHash, BlockNode]) → BlockHash:
  Input: Tree of competing forks
  Output: Hash of canonical tip (highest chainwork)

  // Find all tips (blocks with no children)
  tips ← {hash | hash ∈ forksTree.keys and forksTree[hash].children.isEmpty}

  // Select tip with maximum chainwork
  canonicalTip ← argmax(tips, key = λh. forksTree[h].chainwork)

  return canonicalTip
```

**Algorithm 10: Block Promotion (Maturation)** Identifies blocks eligible for promotion to confirmed state and moves them from forks tree.

**Promotion Criteria:**

Block $b$ on canonical chain can be promoted if:

$$\text{depth}(b) \geq 100$$
$$t_{\text{current}} - t_{\text{added}}(b) \geq 200 \times 60$$

**Pseudocode:**

```
Function promoteConfirmedBlocks(
  forksTree: Map[BlockHash, BlockNode],
  confirmedTip: BlockHash,
  currentTime: BigInt
) → List[BlockHash]:

  // Find canonical chain
  canonicalTip ← selectCanonicalChain(forksTree)

  // Walk back from canonical tip to confirmed tip
  chain ← []
```

```
currentHash ← canonicalTip
while currentHash ≠ confirmedTip:
  chain.prepend((currentHash, forksTree[currentHash]))
  currentHash ← forksTree[currentHash].prevBlockHash

// Identify promotable blocks (from oldest)
blockHashesToPromote ← []
for i ← 0 to chain.length - 1:
  (blockHash, blockNode) ← chain[i]
  depth ← chain.length - i
  age ← currentTime - blockNode.addedTimestamp

  if depth ≥ 100 and age ≥ 200 × 60 then
    blockHashesToPromote.append(blockHash)
  else
    break  // Stop at first non-qualified block

return blockHashesToPromote
```

### Validation Rules Summary

The on-chain validator enforces all Bitcoin consensus rules:

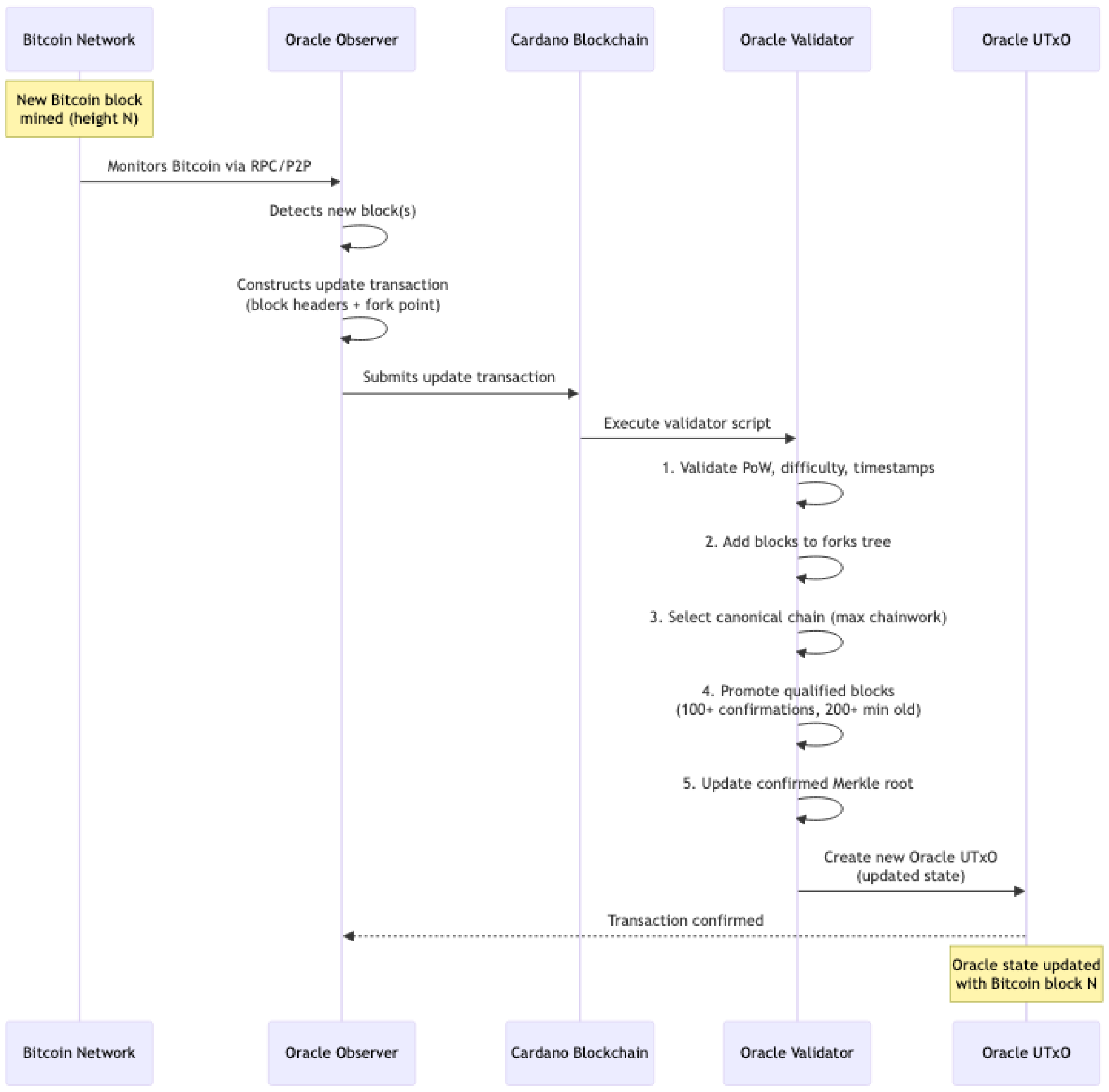
1. **Proof-of-Work**: Block hash ≤ target derived from bits field
2. **Difficulty**: Bits field matches expected difficulty (retarget every 2016 blocks)
3. **Timestamps**: Block time > median of last 11 blocks, < current time + 2 hours
4. **Version**: Block version ≥ 4 (reject outdated versions)
5. **Chain Continuity**: Previous block hash matches parent in tree
6. **Promotion Criteria**: 100+ confirmations AND 200+ minutes on-chain aging

## Communication Protocols

This section describes the key interaction flows and system architecture through sequence and architecture diagrams.

### Diagram 1: Oracle Update Flow

This sequence diagram shows how anyone can submit Bitcoin blocks to update the Oracle state.

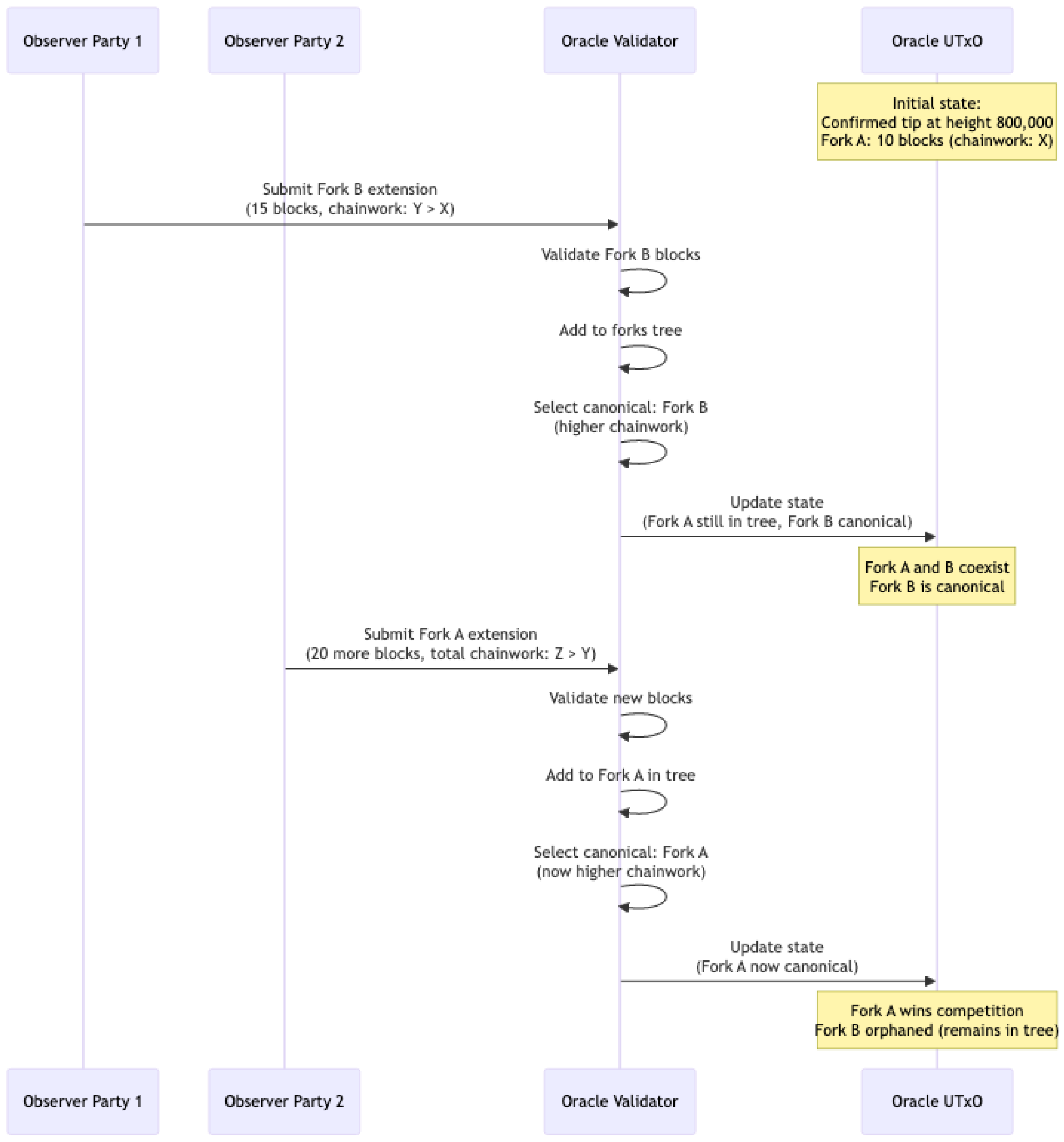

Bitcoin Network
Oracle Observer
Cardano Blockchain
Oracle Validator
Oracle UTxO
New Bitcoin block mined (height N)
Monitors Bitcoin via RPC/P2P
Detects new block(s)
Constructs update transaction (block headers + fork point)
Submits update transaction
Execute validator script
1. Validate PoW, difficulty, timestamps
2. Add blocks to forks tree
3. Select canonical chain (max chainwork)
4. Promote qualified blocks (100+ confirmations, 200+ min old)
5. Update confirmed Merkle root
Create new Oracle UTxO (updated state)
Transaction confirmed
Oracle state updated with Bitcoin block N
Bitcoin Network
Oracle Observer
Cardano Blockchain
Oracle Validator
Oracle UTxO

**Key Points:**

- Permissionless: Any observer can submit updates
- Atomic: All validation and state updates happen in one transaction
- Automatic: Canonical selection and block promotion are deterministic

### Diagram 2: Fork Competition Resolution

Shows how multiple competing forks coexist and resolve through chainwork comparison.

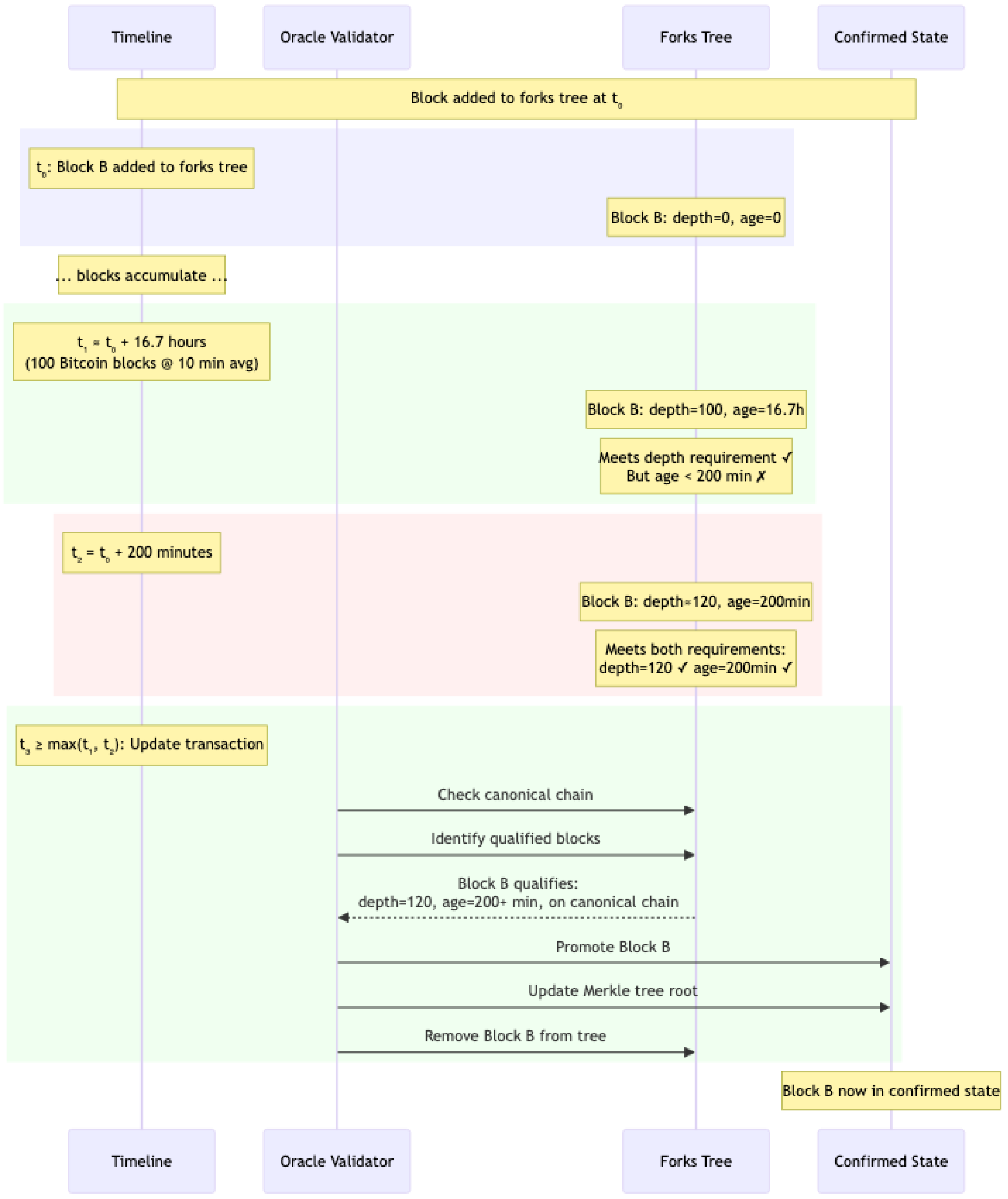


**Key Points:**

- Multiple forks coexist in the tree
- Canonical selection happens automatically on each update
- Orphaned forks remain until pruned (space permitting)
- Follows Bitcoin's longest chain (most chainwork) rule

### Diagram 3: Block Promotion Process

Detailed timeline showing how blocks move from forks tree to confirmed state.



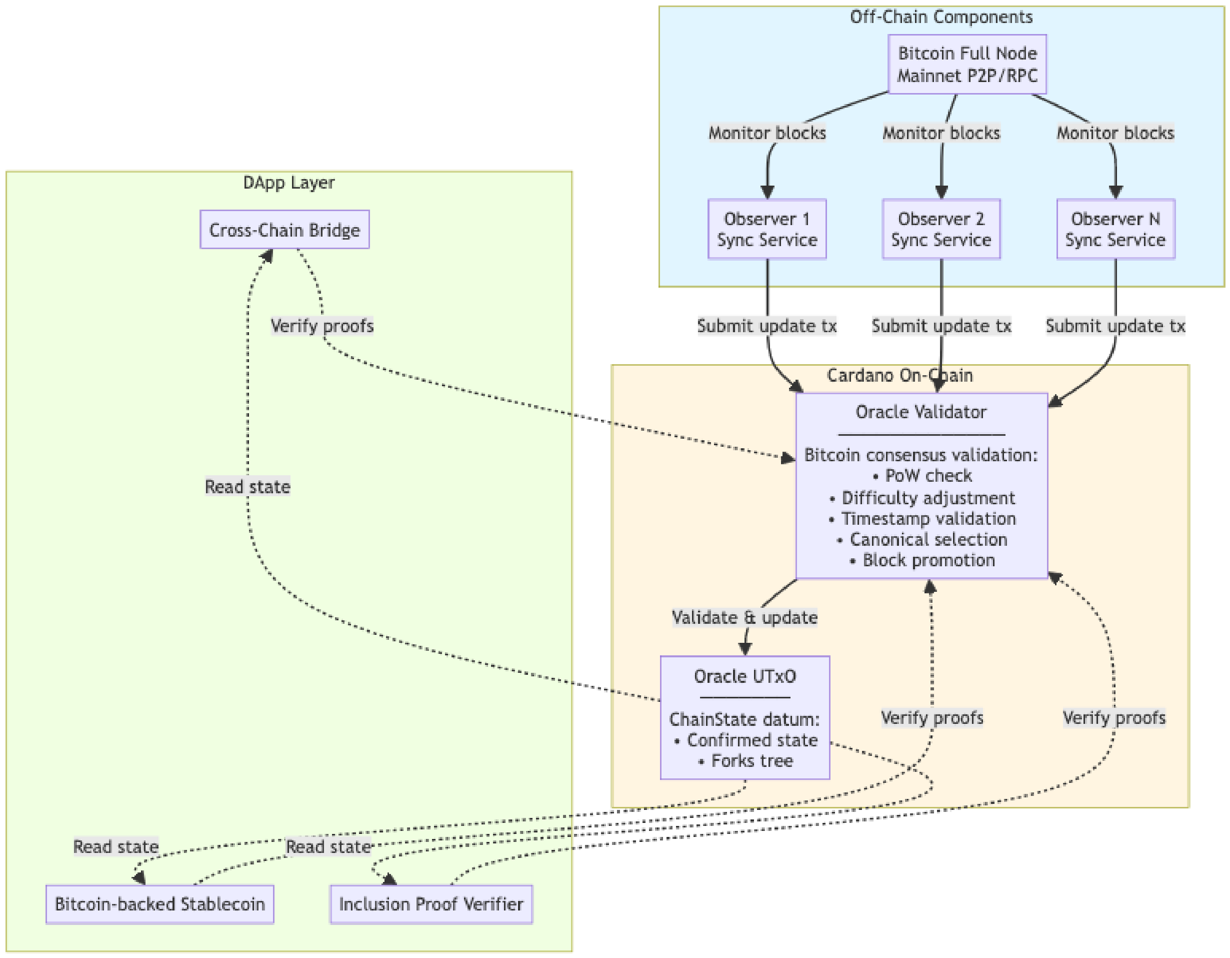
Timeline
Oracle Validator
Forks Tree
Confirmed State
Block added to forks tree at t₀
t₀: Block B added to forks tree
Block B: depth=0, age=0
... blocks accumulate ...
t₁ ≈ t₀ + 16.7 hours (100 Bitcoin blocks @ 10 min avg)
Block B: depth=100, age=16.7h
Meets depth requirement ✓ But age < 200 min ✗
t₂ = t₀ + 200 minutes
Block B: depth≈120, age=200min
Meets both requirements: depth=120 ✓ age=200min ✓
t₃ ≥ max(t₁, t₂): Update transaction
Check canonical chain
Identify qualified blocks
Block B qualifies: depth=120, age=200+ min, on canonical chain
Promote Block B
Update Merkle tree root
Remove Block B from tree
Block B now in confirmed state

**Key Points:**

- Both criteria must be met: 100+ confirmations AND 200+ minutes on-chain
- 200-minute requirement prevents pre-computed attacks
- Promotion happens atomically during any update transaction
- Multiple blocks can be promoted in one transaction

**Diagram 4: System Architecture**

Overall system architecture showing on-chain and off-chain components.



**Key Points:**

- **Off-chain**: Multiple independent observers monitor Bitcoin
- **On-chain**: Single Oracle UTxO + Validator enforcing all rules
- **Permissionless**: Anyone can run an observer and submit updates
- **Applications**: Use Oracle UTxO as reference input for proofs

## Formal State Machine

This section formally specifies the states and transitions of blocks within the Oracle system.

### State Definitions

The Oracle system has two levels of state:

**1. Oracle-Level State:**

```
OracleState = OPERATIONAL
```

The Oracle UTxO is always operational, accepting update transactions from any party. There is no registration, initialization beyond genesis, or shutdown state.

**2. Block-Level States (within forks tree):**

A block in the forks tree can be in one of the following states:

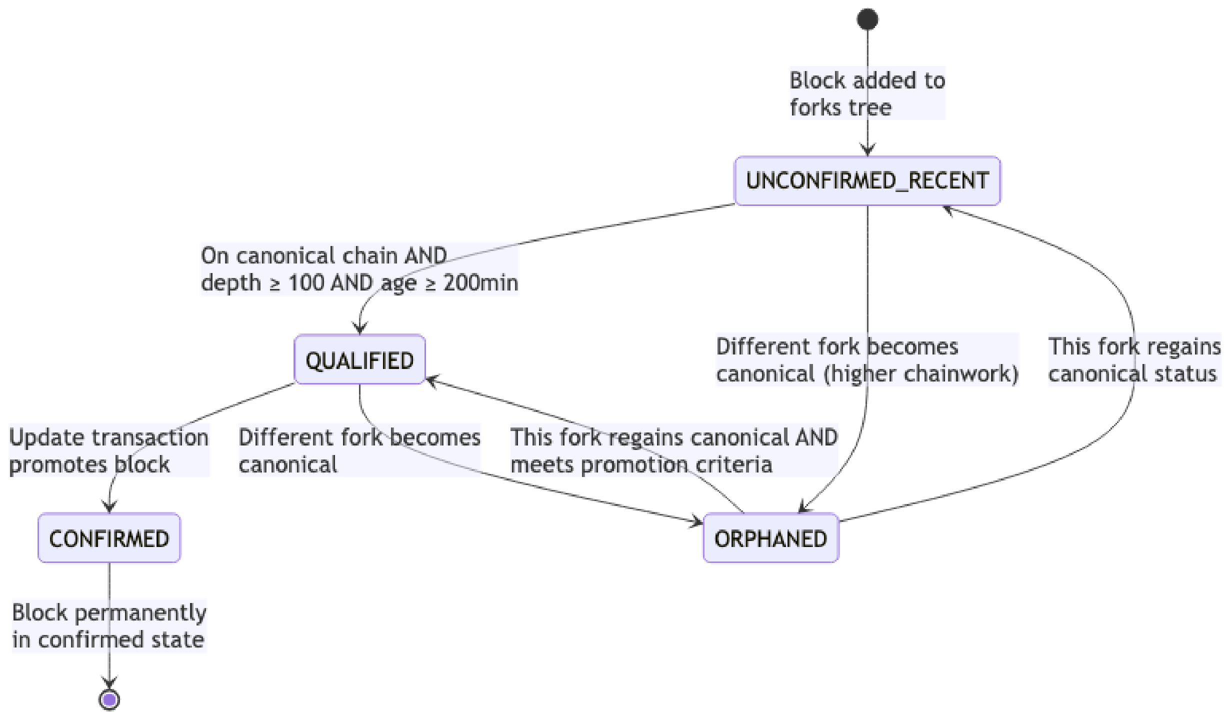
```
BlockState ∈ {
  UNCONFIRMED_RECENT,    // Recent, not yet qualified for promotion
  QUALIFIED,             // Meets promotion criteria, awaiting transaction
  CONFIRMED,             // Promoted to confirmed Merkle tree
  ORPHANED               // Not on canonical chain
}
```

**State Descriptions:**

- **UNCONFIRMED_RECENT**: Block has been added to forks tree but does not yet meet both promotion criteria (100+ confirmations depth AND 200+ minutes on-chain age).
- **QUALIFIED**: Block is on the canonical chain (highest chainwork) and satisfies both:
  - Depth ≥ 100 blocks from canonical tip
  - Age ≥ 200 minutes since added to forks tree

  Block is eligible for promotion in the next update transaction.
- **CONFIRMED**: Block has been promoted to the confirmed state. Its hash is now part of the confirmed blocks Merkle tree and it has been removed from the forks tree.
- **ORPHANED**: Block is not on the current canonical chain. It remains in the forks tree but will not be promoted unless it becomes part of the canonical chain through fork competition.

### State Transition Diagram


Block added to forks tree
UNCONFIRMED_RECENT
On canonical chain AND depth ≥ 100 AND age ≥ 200min
QUALIFIED
Different fork becomes canonical (higher chainwork)
This fork regains canonical status
Update transaction promotes block
Different fork becomes canonical
This fork regains canonical AND meets promotion criteria
CONFIRMED
ORPHANED
Block permanently in confirmed state

### Transition Rules

### Transition 1: Add Block

```
Precondition: Valid block header with valid PoW, difficulty, timestamps
Trigger: Update transaction includes new block(s)
Guard:
  - blockHeader.prevBlockHash exists in forks tree OR equals confirmed tip
  - validateProofOfWork(blockHeader) = true
  - Difficulty matches expected value
  - Timestamp > median-time-past, ≤ current time + 2 hours
Actions:
  - Validate full block header (PoW, difficulty, timestamps, version)
  - Extract prevBlockHash from header
  - Create BlockNode with prevBlockHash, chainwork, addedTimestamp
  - Insert into forksTree[blockHeaderHash(blockHeader)]
  - Update parent's children list
Next State: UNCONFIRMED_RECENT
```

### Transition 2: Qualify for Promotion

```
Precondition: Block in UNCONFIRMED_RECENT state
Trigger: Sufficient time/depth accumulated, or canonical chain changes
Guard:
  - Block is on canonical chain (highest chainwork path)
  - depth(block) ≥ 100 (from canonical tip)
  - currentTime - block.addedTimestamp ≥ 200 × 60
Actions:
  - Mark block as promotable (implicit in qualification check)
Next State: QUALIFIED
```

**Transition 3: Promote to Confirmed**

```
Precondition: Block in QUALIFIED state
Trigger: Any update transaction (automatic check)
Guard:
  - Block still on canonical chain
  - Block still meets promotion criteria
Actions:
  - Add block hash to confirmed blocks Merkle tree
  - Update confirmed state (height, hash, timestamps, etc.)
  - Remove block from forksTree
Next State: CONFIRMED (permanent)
```

**Transition 4: Become Orphaned**

```
Precondition: Block in UNCONFIRMED_RECENT or QUALIFIED state
Trigger: Fork competition - different fork achieves higher chainwork
Guard:
  - selectCanonicalChain(forksTree) ≠ path containing this block
Actions:
  - Block remains in forksTree
  - No longer eligible for promotion
Next State: ORPHANED
```

**Transition 5: Regain Canonical Status**

```
Precondition: Block in ORPHANED state
Trigger: Fork competition - this block's fork regains highest chainwork
Guard:
  - selectCanonicalChain(forksTree) = path containing this block
Actions:
  - Block becomes eligible again
Next State: UNCONFIRMED_RECENT or QUALIFIED (depending on depth/age)
```

### Invariants

The following properties hold at all times:

1. **Confirmed Validity**: All blocks in CONFIRMED state have been validated against Bitcoin consensus rules.
2. **Canonical Uniqueness**: At any time, exactly one chain in the forks tree has the highest chainwork (the canonical chain).
3. **Promotion Monotonicity**: Confirmed block height is monotonically increasing. Once a block is CONFIRMED, it never returns to any other state.

4. **Aging Monotonicity**: A block's `addedTimestamp` never changes once set. Age only increases.
5. **Depth Consistency**: Depth calculation matches the canonical chain at time of evaluation.
6. **Challenge Period**: No block transitions UNCONFIRMED_RECENT → QUALIFIED → CONFIRMED in less than 200 minutes from initial addition.

## Security Analysis

This section provides formal security analysis including threat model, security theorems with proofs, and attack scenario analysis.

### Threat Model

**Adversary Capabilities:**

- Computational: Attacker may control significant Bitcoin mining hashrate (up to <51%)
- Financial: Attacker has access to Cardano ADA for transaction fees
- Network: Attacker can submit transactions to Cardano blockchain
- Information: Attacker observes all on-chain state

**Adversary Limitations:**

- Cannot forge Bitcoin proof-of-work (computational hardness)
- Cannot censor Cardano transactions (Cardano's censorship resistance)
- Cannot modify on-chain validator logic
- Limited by Bitcoin's 51% attack economics

**Honest Party Assumptions:**

- At least one honest party monitors the Bitcoin network
- Honest parties have access to canonical Bitcoin blockchain data
- Honest parties can submit transactions to Cardano within 200 minutes
- Honest party monitoring frequency: reasonable (e.g., hourly checks)

**Network Model:**

- Partial synchrony: Messages delivered within bounded time
- Cardano finality: Transactions final after confirmation
- Bitcoin confirmation: Standard 10-minute average block time

### Security Theorems

**Theorem 1: Safety (Confirmed State Validity)** **Statement**: The confirmed state never contains a block that violates Bitcoin consensus rules.

**Formal**:

$$\forall b \in \text{ConfirmedState} : \text{ValidBitcoinBlock}(b) = \text{true}$$

**Proof**:

By induction on confirmed state transitions:

*Base case*: Genesis block is valid by definition.

*Inductive step*: Assume all blocks in confirmed state up to height $n$ are valid. Consider block $b_{n+1}$ being promoted.

For $b_{n+1}$ to be promoted:

1. Must exist in forks tree → passed initial validation
2. Initial validation (Algorithm 8) checks:
    - PoW: Hash$(b_{n+1}) \leq$ target □
    - Difficulty: Matches expected retarget □
    - Timestamps: > median-time-past, < current + 2h □
    - Version: ≥ 4 □
    - Previous block: Links to valid chain □
3. Must be on canonical chain (highest chainwork)
4. Canonical chain contains only validated blocks

Therefore $b_{n+1}$ is valid.

By induction, all confirmed blocks are valid. □

**Theorem 2: Liveness (Progress)** **Statement**: Under the 1-honest-party assumption, the confirmed state eventually includes all Bitcoin blocks (with at most 100-block lag plus 200-minute delay).

**Formal**:

$$\exists \Delta t : \forall b \in \text{BitcoinChain}, \quad b \in \text{ConfirmedState after time } \Delta t(b)$$

where $\Delta t(b) = t_{\text{Bitcoin}}(b) + 1000 \text{ min} + 200 \text{ min} + \delta$

**Proof**:

Given: At least one honest party $H$ monitors Bitcoin.

1. **Block Detection**: Honest party $H$ observes Bitcoin block $b$ within monitoring interval $\tau$ (assume $\tau \leq 20$ minutes).

2. **Submission**: $H$ constructs and submits update transaction to Cardano. Transaction confirmed within Cardano finality period (≈ 5 minutes).

3. **Validation**: On-chain validator validates $b$ against Bitcoin rules. Since $b$ is from canonical Bitcoin chain, validation succeeds.

4. **Addition to Forks Tree**: Block $b$ added to forks tree at time $t_0$ with:

    - `addedTimestamp = t_0`
    - On canonical chain (honest $H$ submits real Bitcoin blocks)

5. **Accumulation**: After 100 more Bitcoin blocks, $b$ has depth ≥ 100.

    - Time for 100 blocks: $\approx 1000$ minutes (16.7 hours)

6. **Aging**: At $t_0 + 200$ minutes, aging requirement satisfied.

7. **Qualification**: Block $b$ qualifies when:
    - $\max(100 \text{ Bitcoin blocks time}, 200 \text{ min})$
    - $\approx 1000$ minutes (100 blocks takes longer)
8. **Promotion**: On next update transaction (submitted by anyone, including $H$), block $b$ automatically promoted.

**Total latency**: $\Delta t \leq \tau + 1000 + \max(200 - 1000, 0) + 5 \approx 1025$ minutes

Therefore, confirmed state progresses within bounded time. ∎

**Theorem 3: Economic Security (Attack Infeasibility)** **Statement**: The cost of successfully attacking the Oracle (causing it to confirm invalid Bitcoin blocks) exceeds any realistic financial benefit.

**Quantitative Analysis**:

To attack the Oracle, adversary must:

1. Mine 100+ Bitcoin blocks forming alternative history
2. Have these blocks promoted to confirmed state

**Attack Cost Calculation**:

Current Bitcoin parameters (2025 estimates):

- Network hashrate: $H \approx 600$ EH/s
- Block reward: $R = 3.125$ BTC (post-2024 halving)
- Bitcoin price: $P \approx \$100,000$ USD/BTC
- Electricity cost: $E \approx \$0.05$ USD/kWh
- Mining efficiency: $\approx 30$ J/TH (modern ASICs)

**Scenario 1: 51% Attack (Rent Hashrate)**

Required hashrate for >50%: $H_{attack} > 600$ EH/s

Time to mine 100 blocks: $t \approx 100 \times 10 \text{ min} = 1000 \text{ min}$

Energy consumption:

$$\text{Energy} = 600 \times 10^{18} \times 30 \times 10^{-12} \times \frac{1000}{60} \text{ kWh} = 300,000,000 \text{ kWh}$$

Cost: $300M kWh × $0.05 = $15,000,000 USD

Opportunity cost (lost block rewards from honest mining):

$$100 \text{ blocks} \times 3.125 \text{ BTC} \times \$100,000 \approx \$31,250,000 \text{ USD}$$

**Total direct cost**: $15M + $31M = **$46 million USD**

**Scenario 2: Pre-compute Attack (Buy Hardware)**

ASIC cost: $\approx \$30$/TH

Required hashrate: 600 EH/s = 600,000,000 TH/s

Hardware cost: \$600M TH × \$30 = **\$18 billion USD**

Plus energy cost (\$15M) and opportunity cost (can't resell ASICs after attack).

**Realistic Attack Rewards**:

- Oracle manipulation for DApp exploit: < \$10M realistic
- Market manipulation: Hard to monetize, likely < \$100M
- Attacks destroy Bitcoin value, making reward worthless

**Conclusion**: Attack cost (\$46M - \$18B) » Attack reward (< \$100M)

Therefore, economic attack is infeasible. ▯

**Theorem 4: Challenge Period Sufficiency** **Statement**: The 200-minute on-chain aging requirement provides sufficient time for honest parties to detect and counter pre-computed attacks.

**Formal**:

Given:

- Adversary $A$ pre-computes 100-block Bitcoin fork offline
- $A$ publishes fork to forks tree at time $t_0$
- Fork cannot be promoted until $t_0 + 200$ minutes

Honest party $H$ monitoring interval: $\tau$ minutes

**Proof**:

1. **Attack Timeline**:
    - $t_0$: Attacker publishes pre-computed fork on-chain
    - $t_0 + 200$ min: Earliest fork can be promoted
2. **Detection Window**:
    - Honest party $H$ checks Oracle state every $\tau$ minutes
    - $H$ detects attack fork at latest by $t_0 + \tau$
3. **Response Time**:
    - $H$ observes attack fork is not canonical Bitcoin chain
    - $H$ submits correct Bitcoin blocks to forks tree
    - Cardano transaction finality: $\approx 5$ minutes
    - Correct fork added to tree by: $t_0 + \tau + 5$
4. **Canonical Selection**:
    - Correct Bitcoin fork has higher chainwork (real PoW vs pre-computed)
    - Oracle automatically selects correct fork as canonical
    - Attack fork becomes ORPHANED state
5. **Required Condition**: For attack to succeed: $\tau + 5 > 200$ (honest party responds after aging period)

This requires: $\tau > 195$ minutes (check less than once per 3.25 hours)

**Realistic Monitoring**:

- Automated systems: $\tau \approx 5 - 15$ minutes

- Manual monitoring: $\tau \approx 60$ minutes
- Conservative estimate: $\tau \leq 60$ minutes

**Response Window**: $200 - 60 - 5 = 135$ minutes to spare

Therefore, 200-minute challenge period is sufficient for honest parties to respond. ▯

**Attack Scenarios**

**Attack 1: Pre-computed Fork Attack** **Scenario**: Attacker mines 100+ block Bitcoin fork offline (taking weeks/months), then publishes to Oracle hoping to immediately promote malicious blocks.

**Mitigation**:

- 200-minute on-chain aging prevents immediate promotion
- Honest parties have 200 minutes to submit real Bitcoin chain
- Canonical selection prefers real chain (higher chainwork continuing from real Bitcoin)

**Outcome**: Attack fails. Attacker wastes mining resources.

**Attack 2: 51% Bitcoin Hashrate Attack** **Scenario**: Attacker controls >50% of Bitcoin hashrate, mines alternative Bitcoin history, attempts to get Oracle to confirm it.

**Mitigation**:

- Economic infeasibility (Theorem 3): Cost $46M+ exceeds rewards
- Attack affects Bitcoin itself, not just Oracle
- Honest parties would create social recovery if Bitcoin is compromised

**Outcome**: Economically irrational. Would destroy Bitcoin value, making attack self-defeating.

**Attack 3: Spam Forks Tree** **Scenario**: Attacker floods Oracle with many fake fork branches to bloat datum size, hoping to cause denial-of-service or prevent legitimate updates.

**Mitigation**:

- All blocks must pass validation (PoW, difficulty, timestamps)
- Invalid blocks rejected by validator
- Creating many valid forks requires mining many blocks (expensive)
- Datum size naturally limits tree size

**Outcome**: Attack fails. Cannot spam with invalid blocks, and creating valid blocks is expensive.

**Attack 4: Censor Oracle Updates** **Scenario**: Attacker tries to prevent honest parties from submitting updates to Oracle.

**Mitigation**:

- Cardano's censorship resistance: No single party can censor transactions
- Multiple honest parties can submit updates
- Permissionless participation: Anyone can submit

**Outcome**: Attack fails due to Cardano's decentralization.

**Attack 5: Oracle State Staleness** **Scenario**: No honest party submits updates, Oracle state becomes stale.

**Impact**: Oracle stops progressing, but does not confirm invalid state.

**Mitigation**:

- 1-honest-party assumption: Requires only one participant
- Economic incentive: Applications depending on Oracle incentivize updates
- Low barrier: Any party can run observer software

**Likelihood**: Low. Multiple parties likely interested in Oracle freshness.

## Design Decisions

This section explains key design choices and parameter selections.

### Single UTxO vs Multiple Fork UTxOs

**Decision**: Use a single Oracle UTxO containing both confirmed state and forks tree, rather than separate UTxOs for each fork.

**Rationale**:

*Advantages*:

1. **Simpler State Management**: One UTxO to track instead of potentially unbounded fork UTxOs
2. **Atomic Updates**: All operations (validation, canonical selection, promotion) happen in single transaction
3. **Automatic Resolution**: Fork competition resolves through chainwork comparison in same validator execution
4. **No Coordination**: Don't need to coordinate between multiple UTxOs or manage UTxO lifecycle
5. **Predictable Costs**: Transaction costs more predictable with single UTxO

*Trade-offs*:

1. **Datum Size**: Forks tree limited by Cardano datum size constraints
2. **Contention**: Multiple parties updating same UTxO may cause occasional transaction conflicts ( resolved by retry)

**Analysis**: The benefits of simplicity and atomic operations outweigh the trade-offs. Datum size limits naturally bound the forks tree, preventing spam. Transaction contention is rare in practice and easily handled by retry logic.

**NIPoPoW Approach**

**Background**: Non-Interactive Proofs of Proof-of-Work (NIPoPoWs) [3] enable efficient proofs that a block is part of a blockchain without providing all intermediate blocks. Instead of storing all block hashes, NIPoPoWs use a "superblock" structure containing blocks that achieve higher-than-required difficulty, forming a compressed chain representation.

**Decision**: Use simple Merkle tree accumulator for confirmed blocks rather than NIPoPoW structure.

**Rationale**:

*Why NIPoPoWs Were Considered*:

- Enables light clients to verify proofs with logarithmic communication
- Reduces storage for applications needing historical proof verification
- Elegant cryptographic construction

*Why Simple Merkle Tree Was Chosen*:

1. **Implementation Simplicity**: Merkle tree operations well-understood and already implemented in Plutus
2. **Script Size Constraints**: NIPoPoW verification requires complex on-chain logic
    - Superblock validation
    - Interlink pointer verification
    - Variable-length proof handling
3. **Current Use Cases**: Transaction inclusion proofs need block header presence, not compressed history
4. **Sufficient Efficiency**: Applications can query confirmed block hashes via off-chain Oracle state query
5. **Future Compatibility**: Architecture allows adding NIPoPoW later without breaking changes

*Implementation Comparison*:

| Aspect | Merkle Tree | NIPoPoW |
|---|---|---|
| On-chain complexity | Simple (hash operations) | Complex (superblock validation) |
| Script size | Small (~1-2 KB) | Large (~5-10 KB estimated) |
| Proof size (client) | O(log n) | O(log n) (similar) |
| Light client support | Requires confirmed list query | Native |
| Current tool support | Excellent (Plutus, Scalus) | Limited |

**Decision**: NIPoPoWs are not planned for integration. Direct block validation was chosen as the final approach.

**Header Storage Optimization**

**Decision**: Store only `prevBlockHash` from block headers in the forks tree, rather than full 80-byte Bitcoin block headers.

**Rationale**:

*Why Headers Were Considered*:

- Convenient access to all block metadata (timestamps, merkle roots, nonces)
- Simpler API for chain walking operations
- Direct Bitcoin Core data structure analogy

*Why Minimal Storage Was Chosen*:

1. **Validation Timing**: Block headers are only needed during initial validation when adding blocks to the tree. After validation passes, the header data is never accessed again on-chain.

2. **Datum Size Efficiency**: Storing only `prevBlockHash` (32 bytes) instead of the full header (80 bytes) keeps per-block storage minimal at ~88 bytes versus ~152 bytes, enabling forks tree capacity of ~172-210 blocks instead of ~98 blocks.

3. **Chain Walking Requirements**: Walking the fork tree backwards only requires `prevBlockHash` (32 bytes), not the full header. The map key provides the current block hash.

4. **Promotion Process**: Block promotion only requires:

   - Block hash (already the map key)
   - Chainwork comparison (stored separately)
   - Depth and age checks (stored as `addedTimestamp`)
   - The full header is not needed

5. **Application Use**: Applications verifying Bitcoin transaction inclusion proofs provide their own block headers off-chain. They only need to verify:

   - Block hash exists in Oracle's confirmed Merkle tree
   - Transaction Merkle proof against header's merkle root
   - Header validation happens client-side

*Storage Comparison*:

| Approach | Per-Block Storage | Capacity (16 KB tx) | Use Case Coverage |
|---|---|---|---|
| Full headers | ~152 bytes | ~98 blocks | All fields available |
| **Optimized** | **~88 bytes** | **~172 blocks** | **All operations supported** |

*Operations Supported*:

- Chain walking: □ (uses `prevBlockHash`)
- Canonical selection: □ (uses `chainwork`)

- Block promotion: □ (uses depth + `addedTimestamp`)
- Fork competition: □ (uses `chainwork` + tree structure)
- Tree navigation: □ (uses `children` list)

**Implementation Notes**:

The validation workflow becomes: 1. Receive full block header in update transaction 2. Validate header completely (PoW, difficulty, timestamps, version) 3. Extract only essential data: `prevBlockHash`, compute `chainwork` 4. Store minimal `BlockNode(prevBlockHash, chainwork, addedTimestamp, children)` 5. Discard full header after validation

This optimization maximizes forks tree capacity while maintaining all required protocol operations.

## Parameter Justification

**100-Block Confirmation Requirement** **Decision**: Blocks must have 100+ confirmations before promotion to confirmed state.

**Rationale**:

1. **Bitcoin Standard**: Matches Bitcoin's coinbase maturity rule (100 confirmations)
2. **Economic Security**: Mining 100 blocks costs $46M+ (Theorem 3)
3. **Reorganization Depth**: Bitcoin reorganizations >100 blocks have never occurred in mainnet history
4. **Application Safety**: Provides high confidence blocks won't be reversed

*Alternative Considered*:

- 6 confirmations (Bitcoin "standard"): Too shallow, reorg possible
- 50 confirmations: Half the security, not standard
- 144 confirmations (1 day): Higher latency without significant security benefit

**Trade-off Analysis**:

| Confirmations | Reorg Cost | Latency | Historical Safety |
|---|---|---|---|
| 6 | ~$2.8M | ~1 hour | Reorgs occurred |
| 50 | ~$23M | ~8.3 hours | Very rare |
| **100** | **~$46M** | **~16.7 hours** | **Never occurred** |
| 144 | ~$66M | ~24 hours | Never occurred |

**Selection**: 100 blocks provides optimal balance of security and latency.

**200-Minute Challenge Period** **Decision**: Blocks must exist on-chain for 200 minutes before promotion.

**Rationale**:

1. **Pre-computed Attack Prevention** (Theorem 4): Provides challenge window for honest parties
2. **Response Time**: Sufficient for automated systems to detect and counter (135+ minute buffer)
3. **Faster Than Bitcoin**: 200 min < 1000 min (100 blocks), doesn't add latency
4. **Cardano Slot Duration**: Well-aligned with Cardano's ~20-second slots

*Alternative Considered*:

- No aging requirement: Vulnerable to pre-computed attacks
- 60 minutes: Insufficient buffer for reliable response
- 500 minutes: Adds unnecessary latency (longer than 100-block wait)

**Trade-off Analysis**:

| Aging Period | Attack Window | Honest Response | Latency Impact |
|---|---|---|---|
| None | Immediate | No defense | None |
| 60 min | 60 min | Tight (risky) | None |
| **200 min** | **200 min** | **Comfortable** | **None** |
| 500 min | 500 min | Excessive | +5 hours |

**Selection**: 200 minutes is minimum period providing robust defense without adding latency (100 blocks takes ~1000 minutes, » 200 minutes).

**Parameter Summary Table**

| Parameter | Value | Primary Rationale | Security Benefit |
|---|---|---|---|
| Confirmation depth | 100 blocks | Bitcoin standard, historical safety | $46M attack cost |
| Challenge period | 200 minutes | Pre-computed attack defense | 135+ min response window |
| Median timespan | 11 blocks | Bitcoin consensus rule | Timestamp manipulation resistance |
| Future block time | 2 hours | Bitcoin validation rule | Clock skew tolerance |
| Difficulty interval | 2016 blocks | Bitcoin consensus rule | Predictable retarget |

## Limitations & Future Work

### Current Limitations

#### 1. Participation Incentives

The current design relies on honest parties voluntarily submitting updates without explicit economic rewards. While applications depending on the Oracle have natural incentives to ensure its freshness, and transaction fees are minimal, explicit incentivization mechanisms could strengthen participation guarantees.

### 2. Datum Size Constraints

The forks tree is limited by Cardano's maximum datum size. While this naturally prevents spam and should accommodate typical Bitcoin fork scenarios (multiple competing forks of reasonable depth), extreme cases with many simultaneous deep forks could require pruning strategies.

**Capacity Analysis:**

Cardano imposes a maximum transaction size of 16,384 bytes (16 KB) according to current protocol parameters. This limit applies to the **entire transaction**, not just the datum.

*Transaction Overhead:*

An Oracle update transaction consists of:

- **Transaction structure**: ~50-100 bytes (inputs count, outputs count, fee, validity interval)
- **Input (Oracle UTxO)**: ~40 bytes (transaction hash + output index)
- **Output (new Oracle UTxO)**: ~60-80 bytes (address + value + datum hash/inline marker)
- **Redeemer**: Variable size, contains Bitcoin block headers being submitted
  - Per block header: 80 bytes (raw Bitcoin header)
  - Typical update (1-10 blocks): 80-800 bytes
  - Large batch (20 blocks): ~1,600 bytes
- **Script reference**: 0 bytes (using reference script stored elsewhere) or ~10-20 KB (inline script)
- **Witnesses/signatures**: ~100-150 bytes

**Assuming reference script usage** (best practice for large validators):

Total transaction overhead (excluding datum): ~250-650 bytes (typical), up to ~2,700 bytes (large batch)

Conservative estimate: **~500-1,000 bytes transaction overhead**

*Datum Storage Breakdown:*

Confirmed state (fixed overhead): - blockHeight, blockHash, currentTarget, blockTimestamp: ~72 bytes - recentTimestamps (11 × 8 bytes): ~88 bytes - previousDifficultyAdjustmentTimestamp: ~8 bytes - confirmedBlocksRoot (Merkle root): 32 bytes - Map overhead: ~8 bytes - **Total confirmed state**: ~208 bytes

Forks tree (per-block storage): - Map key (block hash): 32 bytes - BlockNode.prevBlockHash: 32 bytes - BlockNode.chainwork: ~8 bytes (typical BigInt encoding) - BlockNode.addedTimestamp: ~8 bytes - BlockNode.children (list overhead + 32 bytes per child): ~8 bytes base - **Total per block**: ~88 bytes (base) + 32 bytes per child

For blocks without children (leaf nodes) or with one child (typical case): ~88-120 bytes per block

*Capacity Calculation:*

Total transaction size budget: 16,384 bytes

Transaction overhead (conservative): 1,000 bytes

Available for datum: 16,384 - 1,000 = 15,384 bytes

Datum overhead (confirmed state): 208 bytes

Available for forks tree: 15,384 - 208 = 15,176 bytes

Maximum blocks (worst case with minimal children): 15,176 / 88 ≈ **172 blocks**

Maximum blocks (optimistic with no children lists): 15,176 / 72 ≈ **210 blocks**

Note: Using reference scripts (storing validator script separately and referencing it) minimizes transaction overhead. Typical updates with 1-10 block headers use ~350-900 bytes of transaction overhead, leaving more space for the forks tree.

*Historical Analysis:*

Bitcoin fork scenarios provide context for capacity requirements:

- **Typical forks**: 1-6 blocks deep, resolve within ~1 hour
- **Deep forks**: Rarely exceed 10 blocks (e.g., 2013 fork: 24 blocks, 2015 BIP66: 6 blocks)
- **Multiple simultaneous forks**: Extremely rare; typically one active fork at a time
- **100-block confirmation requirement**: Acts as natural pruning—blocks promote and free space

With 172-210 block capacity, the Oracle can accommodate: - One deep fork of 100+ blocks (pending promotion) - Multiple smaller competing forks simultaneously - All historical Bitcoin fork scenarios with substantial margin

**Conclusion**: The datum size naturally bounds the forks tree while providing adequate capacity for all realistic Bitcoin fork scenarios. The 100-block confirmation requirement ensures regular pruning as blocks promote to confirmed state, maintaining available capacity.

### 3. Historical Query Efficiency

Applications needing to verify historical Bitcoin transactions must query the confirmed blocks Merkle tree. While the tree structure enables efficient inclusion proofs, applications without Oracle state access need additional infrastructure.

## Future Enhancements

### Incentive Layer

Design explicit economic incentives for Oracle maintenance:

- **Update Rewards**: Small ADA rewards for submitting valid updates
- **Liveness Bonds**: Optional bonding mechanism where participants stake ADA and earn rewards for consistent updates
- **Treasury Funding**: Potential integration with Cardano Treasury for sustainable funding

- **Application Fees**: DApps using the Oracle could contribute to maintenance fund

**Tree Pruning Strategies**

Develop sophisticated pruning algorithms for the forks tree:

- Automatic removal of deeply orphaned forks
- Configurable depth limits based on datum size
- Optimal balance between fork preservation and size constraints

**Enhanced Monitoring Infrastructure**

Build open-source Oracle observer infrastructure:

- Reference implementation for running Oracle observers
- Monitoring dashboards showing Oracle state and health
- Alert systems for detecting Oracle staleness or potential attacks
- Multi-platform support (Docker, cloud services, etc.)

### BiFROST Protocol Integration

**Binocular will be further developed and integrated into the BiFROST cross-chain bridge protocol**. BiFROST aims to provide secure, decentralized asset bridges between Bitcoin and Cardano, leveraging Binocular's trustless Bitcoin state verification as a foundational component.

Potential BiFROST enhancements to Binocular:

- Optimized for high-frequency bridge operations
- Enhanced transaction inclusion proof capabilities
- Integration with Bitcoin Script verification for complex bridge contracts
- Coordination with Cardano-side bridge contracts

The current Binocular design provides a solid foundation for BiFROST while being useful as a standalone Oracle for various applications.

## Conclusion

Binocular provides a Bitcoin oracle for Cardano that validates block headers on-chain using Bitcoin consensus rules. The protocol's key contributions include:

1. **Complete On-chain Validation**: Implementation of Bitcoin proof-of-work, difficulty adjustment, and timestamp validation in Plutus using Scalus, enabling Cardano smart contracts to verify Bitcoin blocks without external trust.

2. **Simplified Architecture**: Single Oracle UTxO containing both confirmed state and forks tree, with automatic canonical chain selection and block promotion through chainwork comparison.

3. **Permissionless Participation**: Anyone can submit updates without registration or bonding requirements, with all validation enforced by the on-chain validator.

4. **Security Guarantees**: Formal proofs of safety and liveness properties, combined with quantitative economic analysis demonstrating that attack costs (\$46M - \$18B) far exceed realistic rewards.
5. **Challenge Period Defense**: 200-minute on-chain aging requirement prevents pre-computed attacks while maintaining liveness under minimal 1-honest-party assumption.

The protocol enables applications to verify Bitcoin transaction inclusion proofs, supporting use cases including cross-chain bridges, Bitcoin-backed stablecoins, and decentralized exchanges. By inheriting Bitcoin's proof-of-work security and operating within Cardano's smart contract environment, Binocular provides a foundation for secure cross-chain interoperability.

Future development will focus on explicit participation incentives, enhanced tooling, and integration into the BiFROST cross-chain bridge protocol.

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