Lesson 3: Cryptographic Hash Functions

Module A: Blockchain Foundations

BSc Blockchain & Cryptocurrency

University Course

2025

Learning Objectives

By the end of this lesson, you will be able to:

1. Define cryptographic hash functions and their key properties
2. Explain the avalanche effect with concrete examples
3. Describe the SHA-256 algorithm and its role in Bitcoin
4. Analyze collision resistance and the birthday paradox
5. Construct and verify Merkle trees step-by-step
6. Identify real-world applications of hash functions beyond blockchain

Prerequisites: L02 - DLT Concepts (Merkle trees introduction)
Building on L02b: DLT Architecture

Fingerprinting Everything

[COMIC: A detective examining a tiny grain of sand with a magnifying glass, and a giant "fingerprint" (hash) floating above it. Caption: "Every piece of data has a unique fingerprint – even this grain of sand."]

[Comic placeholder – to be illustrated]

- Hash functions create unique "fingerprints" for any data – a single byte or an entire database
- Change one bit, and the fingerprint transforms completely

Key point: Fingerprinting Everything

The Problem: How can we prove data integrity without revealing the data?

Part 1/2: Hash Functions (Fundamentals)

The Challenge

How can we compress any data (a single byte or an entire database) to a fixed-size "fingerprint" that uniquely identifies it and proves it hasn't been tampered with?

Why It Matters

- Without hash functions, we cannot detect tampering in blockchain blocks
- Every Bitcoin block must prove integrity of thousands of transactions

What We Need

- Collision resistance (no two inputs produce same output)
- Preimage resistance (cannot reverse the hash)
- Second preimage resistance (cannot forge alternate data)

The Cryptoeconomics Question

How do we create trust in data without a central authority?

Today's lesson: How cryptographic hash functions provide the foundation for blockchain security

Continued

How Do Hash Functions Create Digital Fingerprints?

Hash Function Definition

A **hash function** is a mathematical function that takes an input (message) of arbitrary length and produces a fixed-size output (hash/digest).

Mathematical Notation:

$$H : \{0,1\}^* \rightarrow \{0,1\}^n$$

(takes any binary input $\rightarrow$ outputs fixed-length binary)
Where $\{0,1\}^*$ is any binary string, and $\{0,1\}^n$ is a fixed n-bit output.

Example (SHA-256):

- Input: "Hello World" (any length)
- Output: `a591a6d40bf420404...` (always 256 bits = 64 hex characters)

Hash functions are "digital fingerprints" - unique identifiers for data

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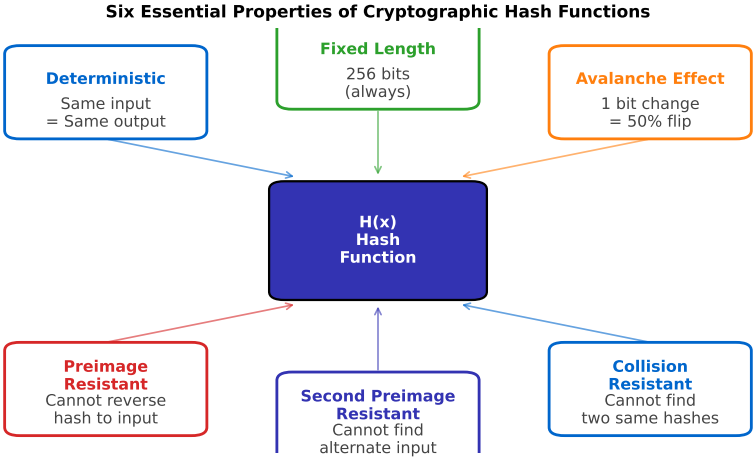
Hash functions create fixed-size fingerprints that prove data integrity without revealing the original data

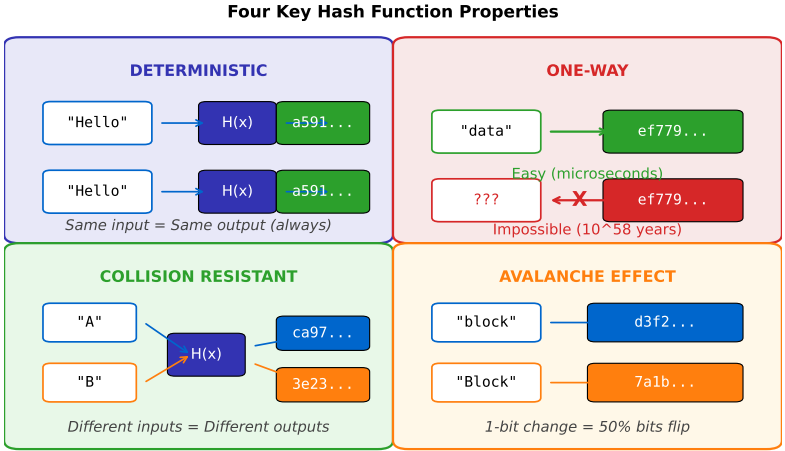
What Are the Six Essential Properties of Cryptographic Hashes?



Key Insight: All six properties are required for cryptographic security.

What Are the Six Essential Properties of Cryptographic Hashes? – visual summary

How Do Hash Properties Work in Practice?



Key Insight: Each property serves a distinct security purpose in blockchain systems.

What's the Difference Between Cryptographic and Non-Cryptographic Hashes?

Non-Cryptographic Hashes

- Fast computation
- Designed for hash tables, checksums
- NOT resistant to adversarial attacks
- Collision attacks are easy

Examples:

- CRC32 (cyclic redundancy check)
- MD5 (broken, not cryptographic anymore)
- MurmurHash (fast, non-crypto)

Cryptographic Hashes

- Slower, but secure
- Collision resistant
- Preimage resistant
- Unpredictable (pseudorandom)

Examples:

- SHA-256 (Bitcoin, SSL/TLS)
- SHA-3 (Keccak, used in Ethereum)
- BLAKE2 (fast, modern)

Key Difference: Cryptographic hashes must withstand deliberate attacks

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Compare the approaches shown above

Why Must Hash Functions Be Deterministic?

Deterministic Property

The same input always produces the same output. No randomness involved.

Example: $H(\text{“blockchain”}) = \texttt{ef7797e1...}$ – computing 1,000 times yields the same result

Why This Matters:

- Enables verification: Anyone can recompute the hash
- Makes auditing possible: Deterministic proofs
- Foundation for digital signatures

Contrast with Random Functions:

- Random: $f(x)$ might return different values each time
- Hash: $H(x)$ is a pure function (functional programming)

Determinism enables trustless verification: anyone can independently recompute and confirm a hash

Why Do Hash Functions Produce Fixed-Length Output?

Fixed-Length Property

Regardless of input size, the hash output is always the same fixed length.

Examples (SHA-256):

- $H(\text{“a”}) = 256$ bits (64 hex characters)
- $H(\text{entire Bitcoin whitepaper}) = 256$ bits (same length)
- $H(\text{1 GB video file}) = 256$ bits (still 64 hex chars)

Common Hash Sizes:

Algorithm	Output Size (bits)	Hex Characters
MD5 (broken)	128	32
SHA-1 (deprecated)	160	40
SHA-256 (Bitcoin)	256	64
SHA-512	512	128

Implication: Infinite inputs map to finite outputs $\Rightarrow$ collisions must exist (pigeonhole principle)

Compare the approaches shown above

What Is the Avalanche Effect?

Avalanche Effect

A tiny change in input (even 1 bit) causes a massive, unpredictable change in the output. Approximately 50% of output bits flip.

Example (SHA-256):

- Input: “blockchain”
  - Hash: `ef7797e13d3a75526946a3bcf00daec9fc9c9c4d51ddc7cc5df888f74dd434d1`
- Input: “Blockchain” (capital B)
  - Hash: `625da44e4eaf58d61cf048d168aa6f5e492dea166d8bb54ec06c30de07db57e1`

Analysis:

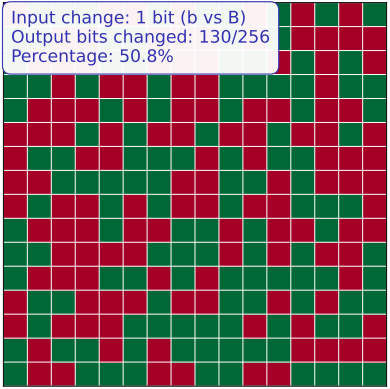
- Only 1 bit changed in input (ASCII: b = 01100010, B = 01000010)
- Output is completely different (no pattern recognizable)
- Approximately 128 out of 256 bits flipped (50%)

Key point: Example (SHA-256)

How Does the Avalanche Effect Prevent Tampering?

Hash 1: ef7797e13d3a7552...
Hash 2: e258d4f4e4e8af58d0...

Avalanche Effect: SHA-256("blockchain") vs SHA-256("Blockchain")



Green = Same bit | Red = Different bit

Observation: 1-bit input change causes approximately 50% of output bits to flip.

The avalanche effect ensures that even minor tampering produces completely different hashes, enabling detection

Why Is Preimage Resistance Critical?

Preimage Resistance

Given a hash output h, it is computationally infeasible to find any input m such that $H(m) = h$.

Analogy: Easy to scramble an egg, impossible to unscramble it

Mathematical Formulation:

- Computing $h = H(m)$ is fast ($\approx$ microseconds)
- Finding m given h requires trying all 2^{256} possibilities
- At 1 trillion hashes/sec: 10^{58} years

Practical Implications:

- Password storage: Store H(password), not password itself
- Blockchain integrity: Cannot reverse-engineer block data from hash
- Commitment schemes: Hash your choice before revealing

One-wayness is the foundation: easy to compute forward, infeasible to reverse

How Does Second Preimage Resistance Prevent Forgery?

Second Preimage Resistance

Given input m_1 and its hash $h = H(m_1)$, it is computationally infeasible to find a different input $m_2 \neq m_1$ such that $H(m_2) = h$.

Scenario:

- You sign a contract: "Pay Alice \$1,000"
- Hash: $H(\text{contract}) = h$
- Attacker tries to find alternate message: "Pay Bob \$1,000,000" with same hash h
- Second preimage resistance prevents this attack

Difference from Preimage Resistance:

- **Preimage**: Given h, find any m where $H(m) = h$
- **Second Preimage**: Given m_1 and $h = H(m_1)$, find different m_2 where $H(m_2) = h$

Key point: Scenario

Why Is Collision Resistance Challenging?

Collision Resistance

It is computationally infeasible to find any two different inputs $m_1 \neq m_2$ such that $H(m_1) = H(m_2)$.

Theoretical Guarantee:

- Pigeonhole principle: Collisions MUST exist (infinite inputs, finite outputs)
- But finding them should be practically impossible

Birthday Paradox Attack:

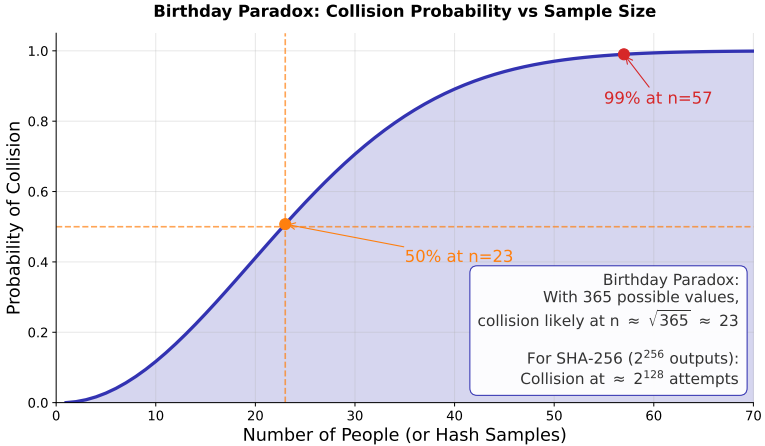
- For n-bit hash, finding collision requires $\approx 2^{n/2}$ attempts (not 2^n) – (Like in a room of just 23 people, there's a 50% chance two share a birthday)
- SHA-256: 2^{128} operations needed ($\approx 10^{38}$ hashes)
- Still infeasible with current technology

Broken Examples:

- MD5 collisions found in 2004 (now insecure)
- SHA-1 collisions demonstrated in 2017 (deprecated for security)

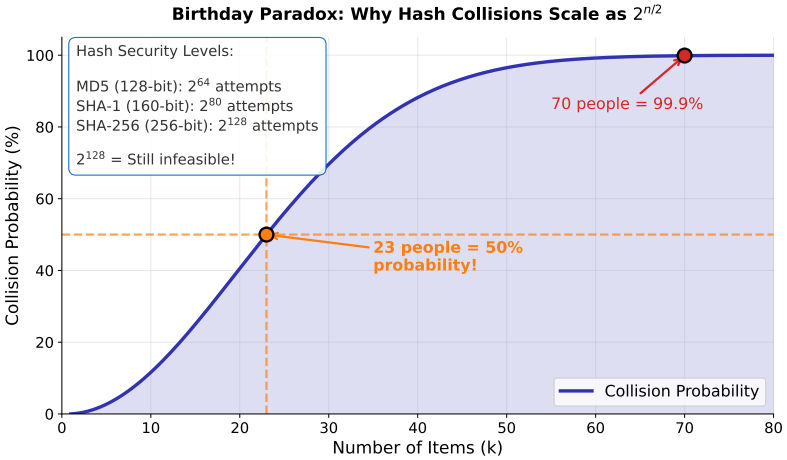
Key point: Theoretical Guarantee

How Does the Birthday Paradox Threaten Hash Functions?



Implication: Collision resistance scales as $2^{n/2}$, not 2^n. This is why we need large hash outputs.

What Is the Collision Probability for SHA-256?



Security Implication: SHA-256 requires 2^{128} operations for birthday attack, still computationally infeasible.

How Does SHA-256 Work?

SHA-256

Secure Hash Algorithm 256-bit is a cryptographic hash function designed by the NSA, published by NIST in 2001 as part of the SHA-2 family.

Specifications:

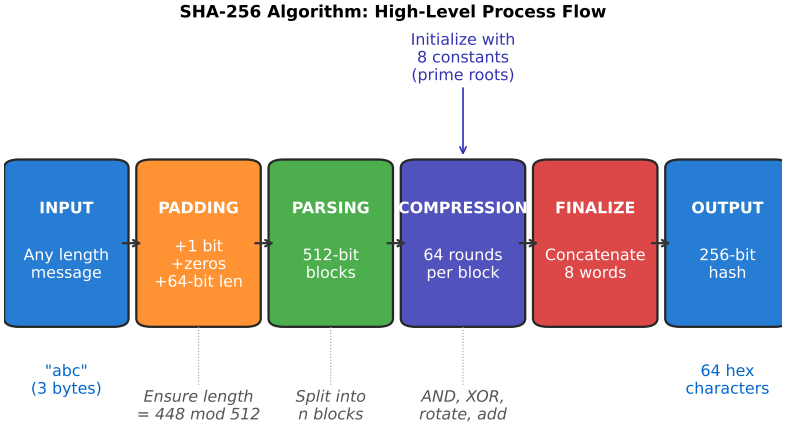
- Output: 256 bits (32 bytes, 64 hex characters)
- Block size: 512 bits (processes data in 512-bit chunks)
- Internal state: Eight 32-bit words (256 bits total)
- Rounds: 64 compression iterations per block

Uses in Bitcoin:

- Block hashing: Double SHA-256 (SHA256(SHA256(header)))
- Transaction IDs: SHA-256 hash of transaction data
- Address generation: SHA-256 + RIPEMD-160
- Merkle tree construction

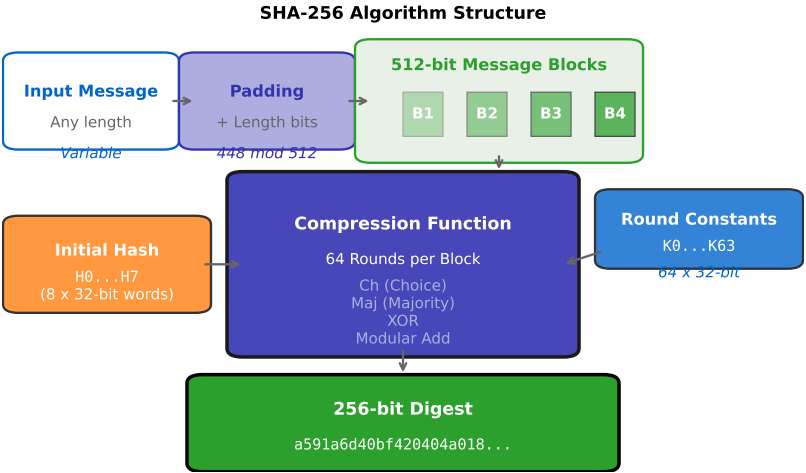
SHA-256 is the cryptographic backbone of Bitcoin – used for blocks, transactions, addresses, and Merkle trees

What Are the Key Steps in SHA-256 Processing?



Key Steps: Padding ensures proper length; compression uses 64 rounds of bitwise operations.

How Is SHA-256's Internal Structure Designed?



Key Insight: The compression function processes 512-bit blocks using 64 rounds of bitwise operations.

Problem Check-In: Hash Functions

Recall Our Problem

How do we prove knowledge without revealing secrets?

What We've Learned So Far

- Six essential properties of cryptographic hash functions
- SHA-256 algorithm and collision resistance guarantees
- Hash properties enable tamper detection and data integrity proofs

Still to Address

- Merkle trees and efficient verification of large datasets
- How do we verify data integrity at scale efficiently?

Think About

- Based on what you've seen, how would *you* solve this problem?
- What trade-offs do you expect?

Pause and reflect: How does what we've learned so far address "How do we prove knowledge without..."?

How Do You Calculate a SHA-256 Hash?

Input: "abc" (3 bytes)

Step 1 – Padding:

- Binary: `01100001 01100010 01100011`
- Add `1` bit, pad zeros until $\equiv 448 \pmod{512}$
- Append 64-bit length

Step 2 – Initialize:

- 8 hash values from first 8 primes
- $H_0 =$ `6a09e667`, ..., $H_7 =$ `5be0cd19`

Step 3 – Compression (64 rounds):

- Bitwise operations (Ch, Maj, Σ_0, Σ_1)
- Each round mixes message schedule with state

Final Output:

$H(\text{"abc"}) =$ `ba7816bf...f20015ad`

Always 256 bits (64 hex chars), regardless of input size.

SHA-256's deterministic computation allows anyone to verify data integrity by recomputing the hash

Why Does Bitcoin Use Double SHA-256?

Why Double Hashing?

Bitcoin uses SHA256(SHA256(x)) instead of single SHA-256 to guard against length-extension attacks (theoretical vulnerability in Merkle-Damgard construction).

Process:

1. Compute $h_1 = \text{SHA256}(\text{data})$
2. Compute $h_2 = \text{SHA256}(h_1)$
3. Use h_2 as final hash

Example - Bitcoin Block Hash:

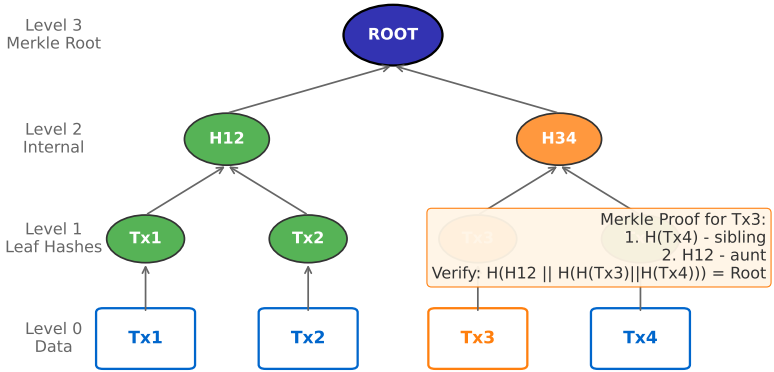
- Input: 80-byte block header
- First hash: $h_1 = \text{SHA256}(\text{header})$
- Second hash: $h_2 = \text{SHA256}(h_1)$
- Result: h_2 must be below difficulty target to be valid

Performance: Modern hardware computes millions of double-SHA256 per second

Key point: Process

How Are Merkle Trees Built?

Merkle Tree: Hierarchical Hash Structure



Key Insight: Merkle proofs enable $O(\log n)$ verification of transaction inclusion.

How Are Merkle Trees Constructed?

Goal: Efficiently verify transaction inclusion without downloading all data

Construction Algorithm:

1. Start with n transactions: $Tx_1, ..., Tx_n$
2. Hash each: $H_i = H(Tx_i)$
3. Pair and hash: $H_{12} = H(H_1||H_2)$
4. If odd, duplicate last hash
5. Repeat until single Merkle Root

Example (4 transactions):

- Level 0: Tx_1, Tx_2, Tx_3, Tx_4
- Level 1: H_1, H_2, H_3, H_4
- Level 2: H_{12}, H_{34}
- Level 3 (Root): $R = H(H_{12}||H_{34})$

Merkle trees compress thousands of transactions into a single 32-byte root hash

How Do You Verify a Merkle Proof?

Scenario: Light client verifies Tx_3 is in block (4 transactions total)

Verifier Has:

- Block header with Merkle Root R
- Transaction Tx_3

Prover Sends (Proof):

- H_4 (sibling of H_3)
- H_{12} (sibling of H_{34})

Verification Steps:

1. Compute $H_3 = H(Tx_3)$
2. Compute $H_{34} = H(H_3 || H_4)$
3. Compute $R' = H(H_{12} || H_{34})$
4. If $R' = R$: Tx_3 is in the block

Only 2 hashes sent instead of 3 other transactions – $O(\log n)$ verification

How Efficient Are Merkle Trees?

Space Complexity:

- For n transactions, tree has $\approx 2n$ nodes
- Merkle proof requires $\log_2(n)$ hashes

Proof Size Comparison:

Transactions in Block	Full Data	Merkle Proof
10	$\approx$ 2.5 KB	4 hashes (128 bytes)
100	$\approx$ 25 KB	7 hashes (224 bytes)
1,000	$\approx$ 250 KB	10 hashes (320 bytes)
10,000	$\approx$ 2.5 MB	14 hashes (448 bytes)

Real-World Impact:

- Bitcoin block: $\approx$ 2,000 transactions $\Rightarrow$ 11-hash proof ($\approx$ 352 bytes)
- Full block: $\approx$ 1 MB
- Savings: $\frac{352}{1{,}000{,}000} = 0.035\%$ of data needed

Compare the approaches shown above

What Are the Different Merkle Tree Variants?

Binary Merkle Tree

- Each node has 2 children
- Used in Bitcoin
- Proof size: $O(\log_2 n)$
- Simple to implement

Merkle Patricia Trie (Ethereum)

- Combines Merkle tree + Patricia trie
- Supports key-value storage
- Enables state root (all accounts)
- More complex, but more powerful

Verkle Trees (Future Ethereum)

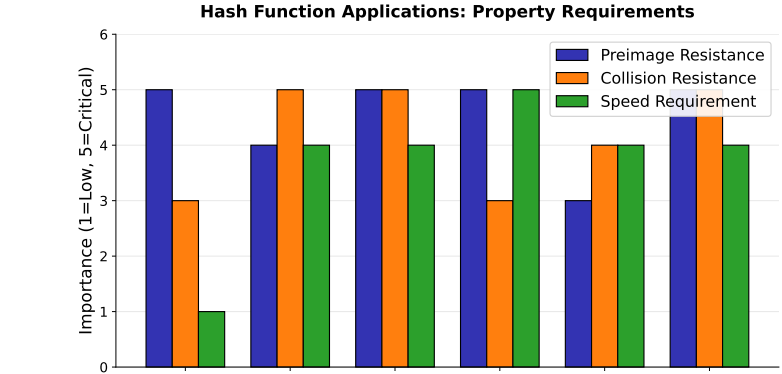
- Uses polynomial commitments
- Constant-size proofs (regardless of tree size)
- Enables stateless clients
- Based on vector commitments

Sparse Merkle Trees

- Fixed depth (e.g., 256 levels)
- Most branches empty (pruned)
- Supports non-membership proofs
- Used in some zero-knowledge systems

Merkle tree variants optimize for different use cases while maintaining the core integrity proof property

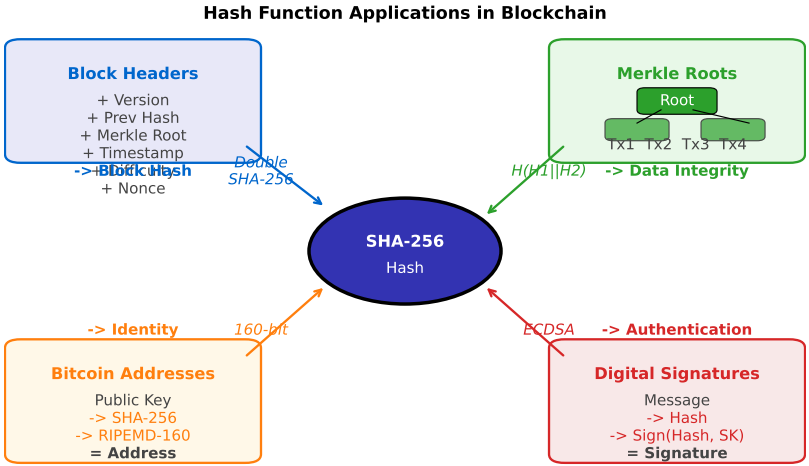
Where Are Hash Functions Used Beyond Blockchain?



Note: Different applications prioritize different hash properties.

Where Are Hash Functions Used Beyond Blockchain? – visual summary

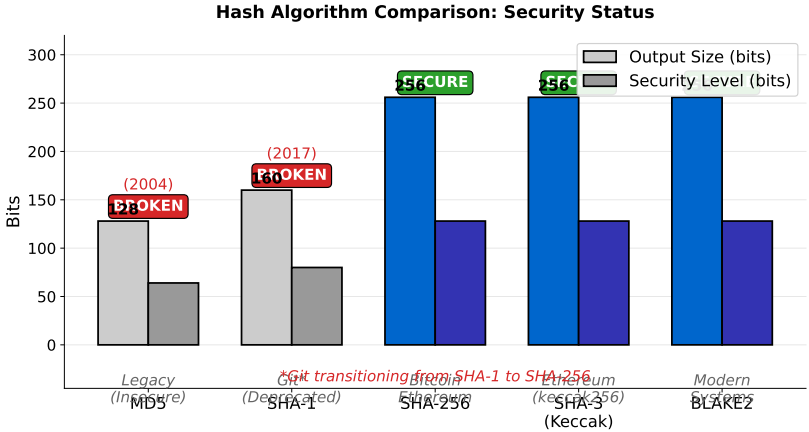
How Do Hash Functions Connect Blockchain Components?



Key Insight: SHA-256 is the cryptographic backbone connecting all blockchain components.

How Do Hash Functions Connect Blockchain Components? – visual summary

Which Hash Algorithms Are Secure?



Warning: MD5 and SHA-1 are broken. Always use SHA-256, SHA-3, or BLAKE2 for security applications.

Which Hash Algorithms Are Secure? – visual summary

How Should Passwords Be Stored Securely?

Problem: Storing passwords in plaintext is insecure (breach exposes all passwords)

Solution: Store $H(\text{password})$ instead

1. User creates password "mypassword123"
2. System computes $h = H(\text{password})$
3. Database stores only h
4. Login: hash input, compare with h
5. Preimage resistance prevents reversal

Enhancements:

- **Salting**: Add random data before hashing to prevent rainbow tables
  - Store $h = H(\text{pwd}||\text{salt})$ and salt
- **Key Stretching**: Slow hash functions (bcrypt, Argon2) resist brute-force

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Hash-based password storage means even database breaches don't reveal user passwords

How Can We Verify File Integrity?

Use Case: Ensure downloaded file hasn't been tampered with

Process:

1. Software developer publishes file hash on official website
   - Example: Ubuntu ISO hash on ubuntu.com
2. User downloads file from mirror site
3. User computes hash of downloaded file locally
4. User compares computed hash with official hash
5. If hashes match, file is authentic and unmodified

Real-World Example:

- Download Ubuntu 24.04 LTS ISO (4 GB)
- Official SHA-256: `c2e6f4dc37ac944e2f8b21de00e9610c79c61d11...`
- Compute: `sha256sum ubuntu-24.04-desktop-amd64.iso`
- Match confirms integrity

Key point: Use Case

How Does Git Use Hash Functions?

Git's Hash-Based Design:

- Every commit has a SHA-1 hash (transitioning to SHA-256)
- Hash computed from: message, author, tree object, parent hash(es)
- Forms a Merkle tree of commits (immutable history)

Example:

- `a3f5c79...` $\rightarrow$ parent `b2e4d31...`
- Changing history requires recomputing all subsequent hashes

Similarity to Blockchain:

- Git is a content-addressed storage system
- Hashes link commits, just like blocks in blockchain
- History tampering is detectable via hash chain breaks

Git and blockchain share the same core principle: hash-linked immutable history

How Do Hash Functions Enable Digital Signatures?

Digital Signatures (more in L05):

- Hash the message: $h = H(m)$
- Sign the hash: $\sigma = \text{Sign}(h, sk)$
- Verify: $\text{Verify}(\sigma, h, pk)$
- Signing 32-byte hash is faster than signing MB+ message

SSL/TLS (HTTPS):

- CAs sign website certificates
- CA computes $h = H(\text{cert})$, signs with private key
- Browser verifies using CA's public key
- Ensures legitimate connection

Algorithms: TLS 1.3 uses SHA-256/384; SHA-1 deprecated

Hashing before signing is both faster and more secure than signing raw data

Continued

How Does Proof-of-Work Mining Use Hash Functions?

Mining Process:

1. Collect transactions into candidate block
2. Construct block header (80 bytes)
3. Compute: $h = \text{SHA256}(\text{SHA256}(\text{header}))$
4. Check if $h < \text{target}$
5. If no: increment nonce, repeat
6. If yes: broadcast block, earn reward

Example (Block 800,000):

- Target: 19 leading zeros
- Success probability: $\frac{1}{2^{76}} \approx 10^{-23}$
- Network: $\sim$500 EH/s (now $>$1 ZH/s)

Why Hashes Enable PoW:

- Unpredictable output (no shortcut)
- Fast verification ($h <$ target? instant)

Hash unpredictability forces brute-force search; hash speed enables instant verification

The Avalanche Effect Butterfly

[COMIC: A butterfly flapping its wings on one side, causing a massive "hash avalanche" on the other side – a tsunami of completely different 1s and 0s. Caption: "One bit flaps, and the entire hash transforms."]

[Comic placeholder – to be illustrated]

- The avalanche effect is cryptography's "butterfly effect" – tiny changes cascade into complete transformation
- This unpredictability is what makes tampering instantly detectable

Key point: The Avalanche Effect Butterfly

Problem Solved? Hash Functions

The Original Problem

How can we prove data integrity without revealing the data?

How Hash Functions Solve It

- SHA-256 provides 256-bit security level (computationally infeasible to break)
- Merkle trees enable efficient verification of large datasets ($O(\log n)$ proofs)
- Collision resistance ensures unique fingerprints for different data

Remaining Limitations

- Quantum computers threaten current hash functions (Grover's algorithm reduces security)
- MD5 and SHA-1 already broken (collision attacks found)

Open Questions

- When should blockchain migrate to post-quantum hash functions?
- Can we develop hash functions resistant to quantum attacks?
- Risk: Coordination challenge in decentralized networks for hash function upgrades

Hash functions solve data integrity verification but face future quantum threats

The Economics of Hash Functions

Incentive Structure

- Miners invest in hash computation; reward = block subsidy + fees
- Mining reward exceeds cost only for valid blocks
- Users pay fees → miners earn rewards for securing the network

Economic Security

- Attack cost = majority of network hash rate
- Cost of 51% attack: billions in hardware + electricity

Key Economic Question

Who Pays, Who Earns?

Users pay transaction fees; miners earn block rewards for hash computation. Security scales with total hash rate investment.

Design Principle

$$\text{Attack Cost} > \text{Potential Gain}$$

Hash functions convert electricity into security: the more energy spent mining, the harder it is to attack

Design Space

Design Space: Hash Functions

Hash Function Choices

1. **SHA-256** (Bitcoin): Battle-tested, ASIC-dominated, 256-bit security
2. **Keccak-256** (Ethereum): ASIC-resistant design (initially), different construction
3. **BLAKE2** (Zcash): Faster computation, smaller output available

Trade-offs Made

- SHA-256: Proven security vs ASIC centralization
- Keccak: ASIC resistance vs less battle-tested

Design Questions

- Should hash functions resist ASICs (fair mining) or embrace them (more security)?
- How large should the output be? 256-bit vs 512-bit?
- When should a blockchain migrate to a new hash function?

Key Insight

Design Is Context-Dependent

Bitcoin chose SHA-256 for proven security; Ethereum chose Keccak for independence from NSA-influenced designs.

Every hash function choice trades off speed, security margin, hardware fairness, and proven track record

Failure Modes: Hash Functions

Critical Failure Modes

- Collision found in the hash function
- Forged blocks, double spends, broken Merkle proofs

Historical Precedents

- **MD5 collision (2004)**: Practical attacks demonstrated
- **SHA-1 collision (2017)**: Google's SHAttered attack (2^{63} operations)
- Pattern: Hash functions weaken over time as attacks improve

Quantum Computing Threat

- Grover's algorithm halves security bits (256 $\rightarrow$ 128 effective)
- SHA-256 remains safe at 128-bit post-quantum security
- ECDSA signatures are more vulnerable than hashes

Early Warning Signs

- ! Reduced collision resistance in academic papers
- ! Practical quantum computers reaching 1000+ qubits
- ! NIST deprecation announcements

Assumption: SHA-256 is computationally infeasible to break. MD5 and SHA-1 show that assumptions can fail.

Key Takeaways

What You Should Remember:

1. **Hash Functions**: Transform arbitrary input to fixed-size output (digital fingerprints)
2. **Core Properties**: Deterministic, fixed-length, avalanche effect, preimage resistance, collision resistance
3. **SHA-256**: 256-bit output, used in Bitcoin (double hashing), computationally infeasible to break
4. **Collision Resistance**: Birthday paradox reduces attack from 2^n to $2^{n/2}$ operations
5. **Merkle Trees**: Binary hash trees enable $O(\log n)$ proofs for transaction inclusion
6. **Applications**: Passwords, file integrity, Git, digital signatures, Proof-of-Work

Critical Insight

Cryptographic hash functions are the foundation of blockchain security. Without collision resistance and preimage resistance, the entire system collapses.

Next Lesson: L04 – Lab: Hash Experiments

Key point: What You Should Remember

What Questions Should We Consider?

Consider and discuss:

1. **Quantum Computing Threat**: Will quantum computers break SHA-256?
   - Research: Grover's algorithm reduces preimage attack to 2^{128} operations
2. **Hash Function Lifespan**: When should we migrate to SHA-3 or BLAKE3?
   - Consider: Coordination challenge in decentralized networks
3. **Environmental Impact**: Can we reduce PoW energy consumption without sacrificing security?
   - Explore: Alternative consensus mechanisms (PoS, PoSpace)

Key point: Consider and discuss

Continued

Where Can You Learn More?

Standards & Specs

- NIST FIPS 180-4 (SHA-2 specification)
- RFC 6234 (SHA and HMAC-SHA)
- Keccak Team (SHA-3 documentation)

Academic Papers

- Merkle (1987): *A Digital Signature Based on a Conventional Encryption Function*
- Wang et al. (2005): *Finding Collisions in SHA-1*

Tools

- `sha256sum` (Linux command-line)
- Online SHA-256 calculator
- Python `hashlib` library

Learning Resources

- Computerphile: "Hashing Algorithms"
- Khan Academy: Cryptography course
- 3Blue1Brown: "But what is a hash function?"

Compare the approaches shown above

What's Next?

L04: Lab - Hash Experiments

Hands-on exercises:

- Generate SHA-256 hashes using Python `hashlib`
- Visualize the avalanche effect (1-bit input change)
- Build a Merkle tree from scratch
- Verify Merkle proofs manually
- Experiment with collision search (limited scale)
- Analyze hash distribution properties

Required Setup: Python 3.8+, Jupyter Notebook or Python IDE

Deliverables: Lab report with code snippets and visualizations

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Key point: L04: Lab - Hash Experiments

Thank you

Questions?

See you in Lab 4: Hash Experiments

Quiz - Part 1

Q1. What is the output size of SHA-256?
A) 128 bits B) 256 bits C) 512 bits D) 1024 bits
Answer: B – SHA-256 produces a fixed 256-bit (32-byte) output, regardless of input size.

Q2. Which property ensures the same input always produces the same hash?
A) Avalanche effect B) Collision resistance C) Deterministic D) Preimage resistance
Answer: C – Deterministic means no randomness; same input = same output always.

Q3. What percentage of output bits typically flip when 1 input bit changes?
A) 10% B) 25% C) 50% D) 100%
Answer: C – The avalanche effect causes approximately 50% of output bits to flip.

Q4. Which hash algorithm is broken and no longer considered secure?
A) SHA-256 B) SHA-3 C) MD5 D) BLAKE2
Answer: C – MD5 collisions were found in 2004; it's not cryptographically secure.

Q5. What does preimage resistance prevent?
A) Finding input from hash B) Finding two inputs with same hash C) Fast computation D) Fixed output length
Answer: A – Preimage resistance means you cannot reverse a hash to find the original input.

Quiz

Quiz - Part 2

Q6. How many rounds of compression does SHA-256 perform per 512-bit block?
A) 16 B) 32 C) 64 D) 128
Answer: C – SHA-256 uses 64 rounds of bitwise operations per block.

Q7. Why does Bitcoin use double SHA-256 instead of single hashing?
A) Faster computation B) Smaller output C) Guard against length-extension attacks D) Easier implementation
Answer: C – Double hashing protects against theoretical length-extension vulnerabilities.

Q8. What is the birthday paradox complexity for finding hash collisions?
A) 2^n B) $2^{n/2}$ C) 2^{2n} D) $\log n$
Answer: B – Birthday attack reduces collision search from 2^n to $2^{n/2}$ operations.

Q9. For SHA-256, approximately how many operations are needed for birthday attack?
A) 2^{64} B) 2^{128} C) 2^{256} D) 2^{512}
Answer: B – $2^{256/2} = 2^{128}$ operations, still computationally infeasible.

Q10. What distinguishes second preimage resistance from preimage resistance?
A) Faster computation B) You're given the original input C) Shorter output D) No difference
Answer: B – Second preimage: find different m_2 for given m_1 where $H(m_1) = H(m_2)$.

Quiz - Part 3

Q11. How many hashes are needed for a Merkle proof with 1,000 transactions?
A) 5 B) 10 C) 100 D) 500
Answer: B – $\log_2(1000) \approx 10$ hashes needed for proof path to root.

Q12. What happens if a Merkle tree has an odd number of leaf nodes?
A) Error occurs B) Last hash is duplicated C) Tree is invalid D) Extra node is discarded
Answer: B – The last hash is duplicated to create a pair for hashing.

Q13. Which Merkle tree variant does Ethereum use?
A) Binary Merkle Tree B) Merkle Patricia Trie C) Verkle Tree D) Sparse Merkle Tree
Answer: B – Ethereum uses Merkle Patricia Trie for state storage with key-value support.

Q14. What is the space complexity of a Merkle proof for n transactions?
A) $O(n)$ B) $O(n^2)$ C) $O(\log n)$ D) $O(1)$
Answer: C – Proof size grows logarithmically with number of transactions.

Q15. In password storage, what is the purpose of salting?
A) Make hash faster B) Prevent rainbow table attacks C) Reduce output size D) Enable reversibility
Answer: B – Salt (random data) prevents precomputed hash tables (rainbow tables).

Quiz - Part 4

Q16. Which hash function is Git transitioning to from SHA-1?
A) MD5 B) SHA-256 C) SHA-3 D) BLAKE2
Answer: B – Git is migrating to SHA-256 due to SHA-1 collision vulnerabilities.

Q17. What makes collision resistance critical for digital signatures?
A) Faster signing B) Prevents forged documents with same hash C) Smaller signatures D) Easier verification
Answer: B – Without collision resistance, attacker could create alternate message with identical hash.

Q18. In Bitcoin mining, what must the hash be less than?
A) Merkle root B) Previous block hash C) Difficulty target D) Nonce value
Answer: C – Hash must be below difficulty target (e.g., certain number of leading zeros).

Q19. What is the block size that SHA-256 processes data in?
A) 128 bits B) 256 bits C) 512 bits D) 1024 bits
Answer: C – SHA-256 processes input in 512-bit (64-byte) blocks.

Q20. Which quantum algorithm threatens preimage resistance of hash functions?
A) Shor's algorithm B) Grover's algorithm C) Deutsch-Jozsa D) Simon's algorithm
Answer: B – Grover's algorithm reduces preimage search from 2^{256} to 2^{128} operations.