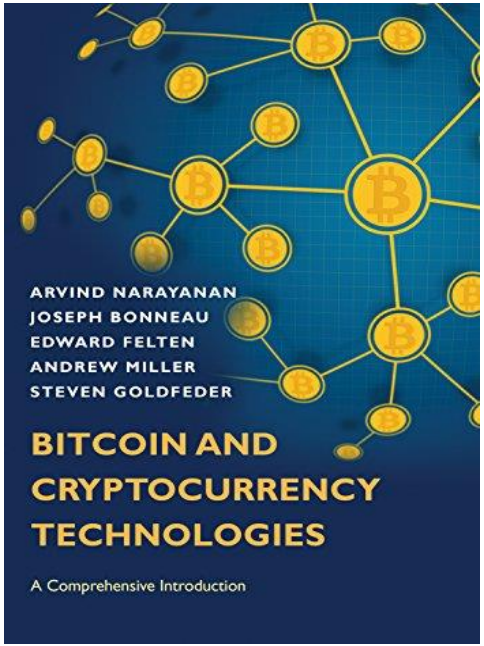
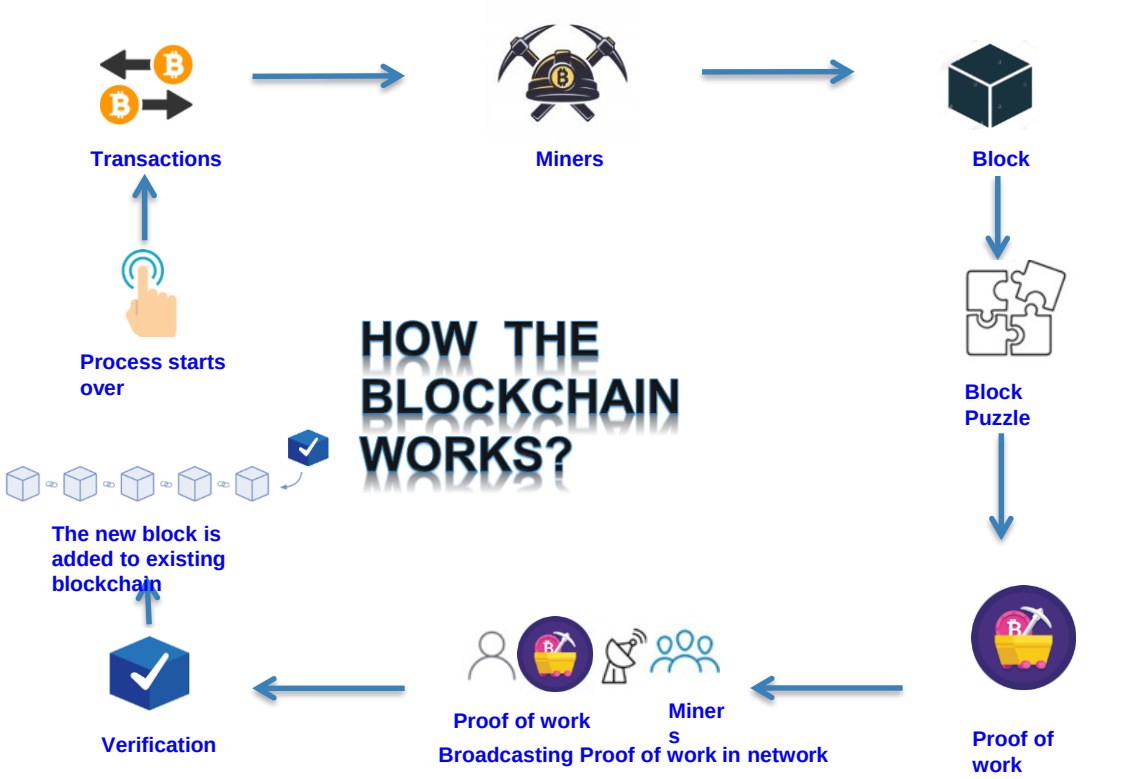
How Bitcoin Achieves Decentralization



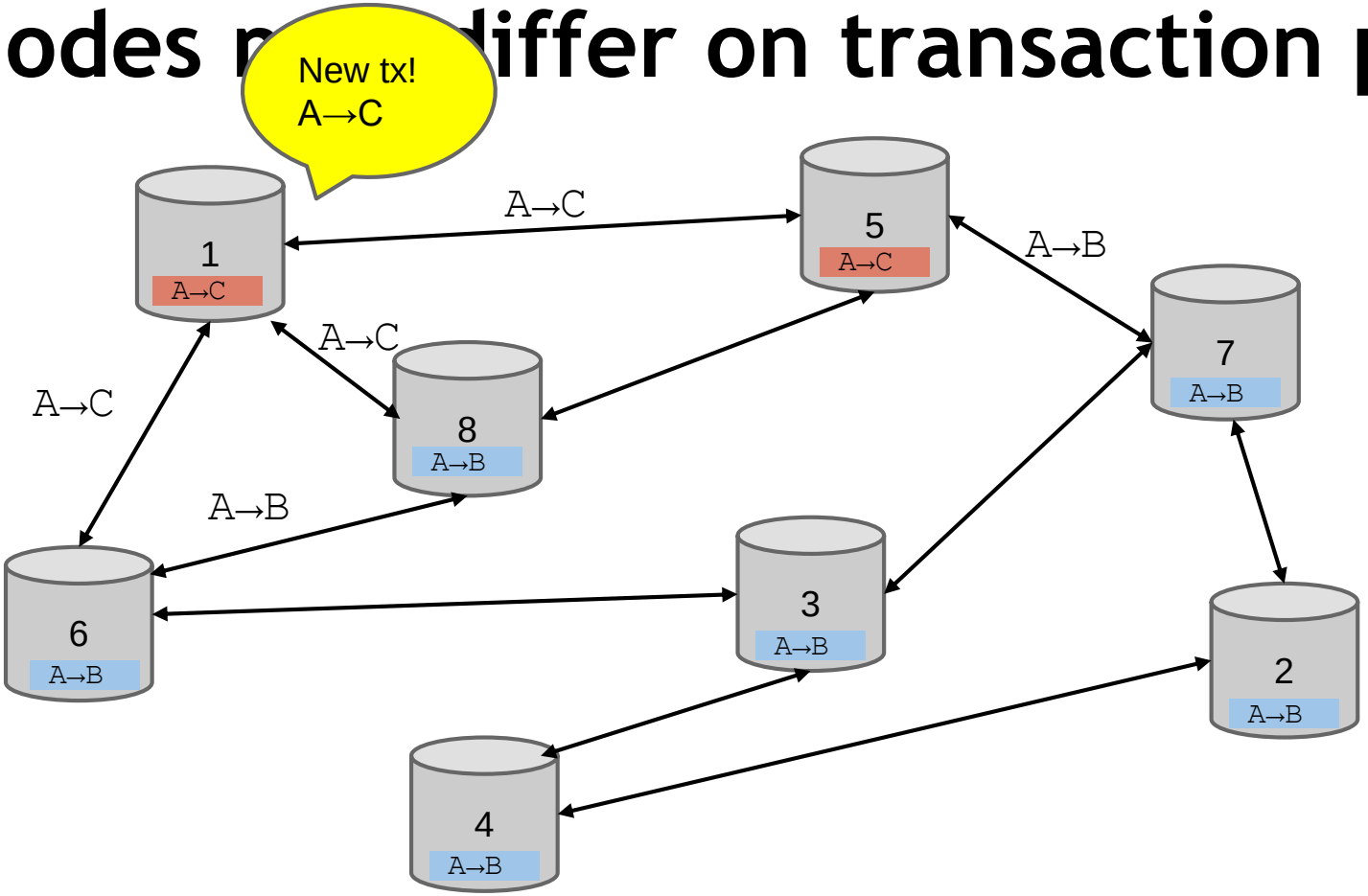
Slides by Arvind Narayanan et al.

BLOCKCHAIN WORKING PRINCIPLE



Bitcoin blocks

Nodes may differ on transaction pool



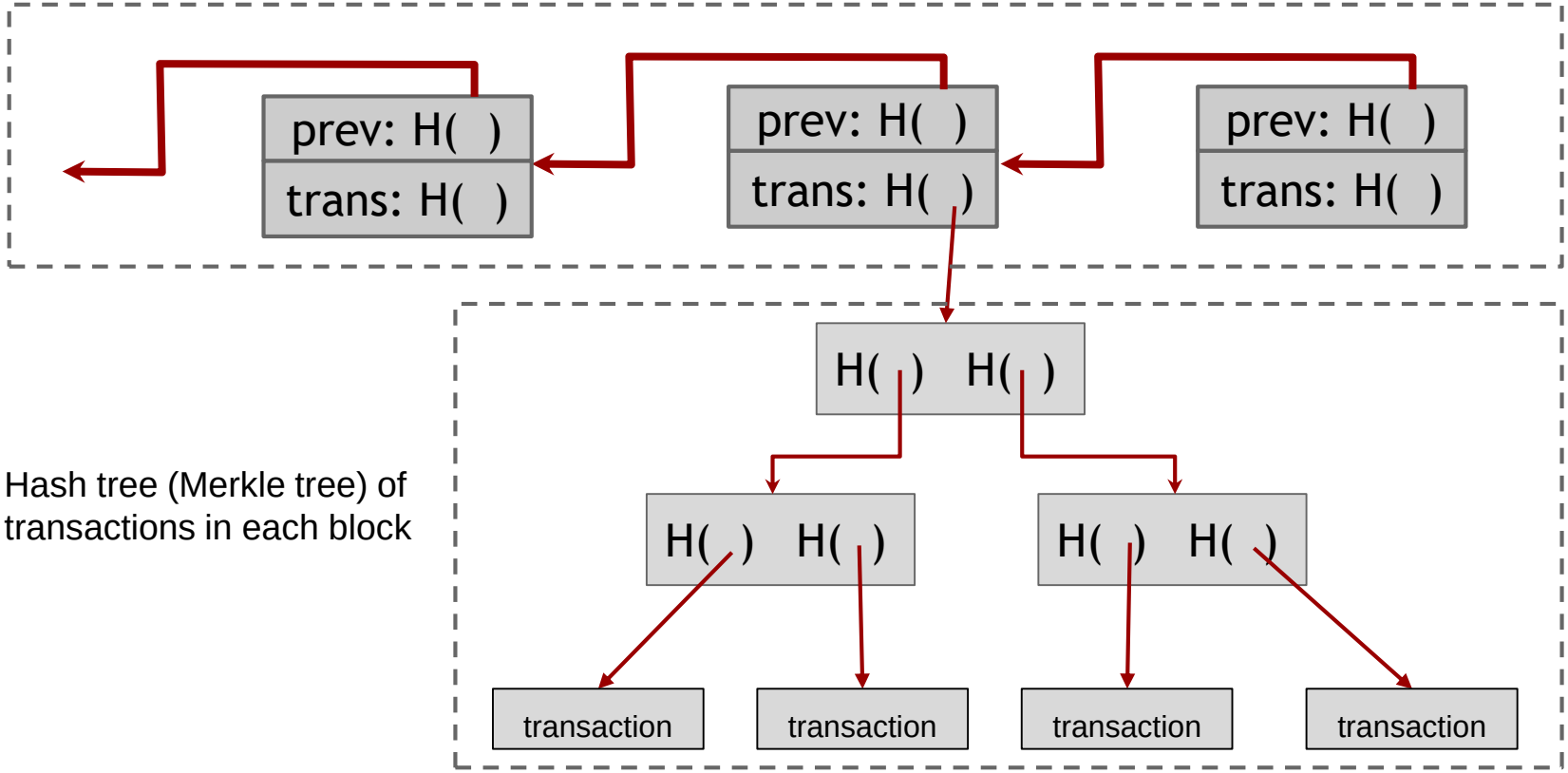
Bitcoin blocks

Why bundle transactions together?

- Single unit of work for miners
- Limit length of hash-chain of blocks
    - Faster to verify history

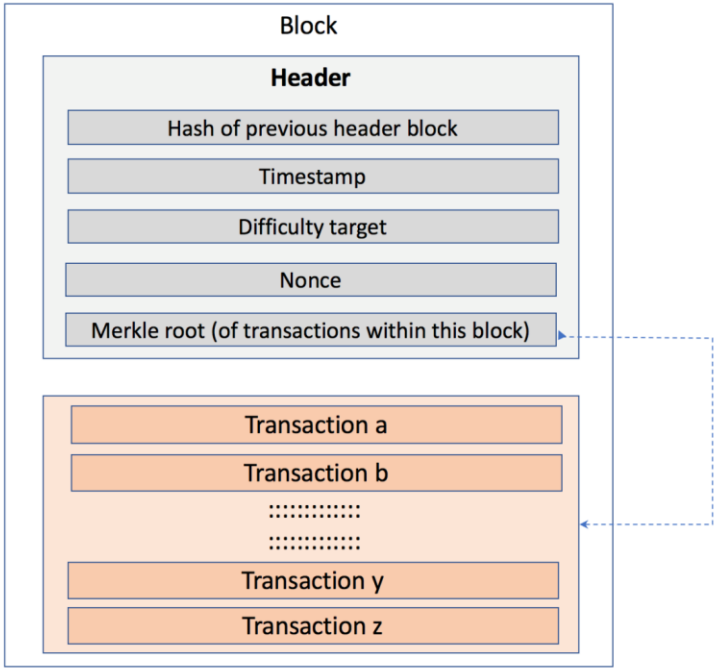
Bitcoin block structure

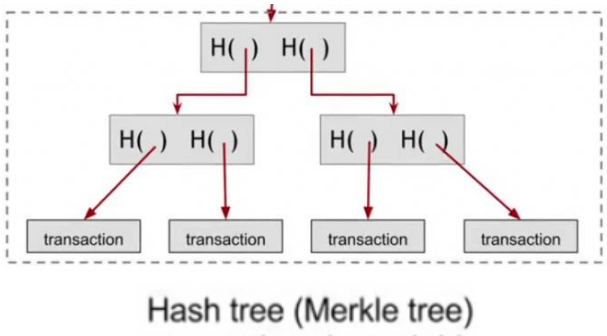
Hash chain of blocks



Hash tree (Merkle tree) of transactions in each block

Bitcoin block structure





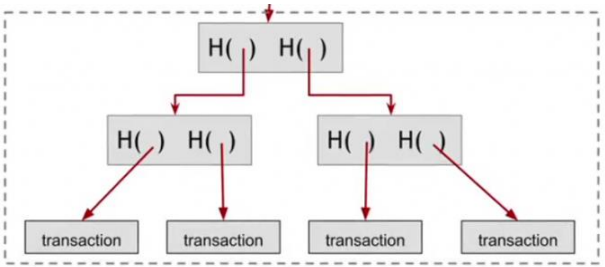
Hash tree (Merkle tree)

The real deal: a Bitcoin block

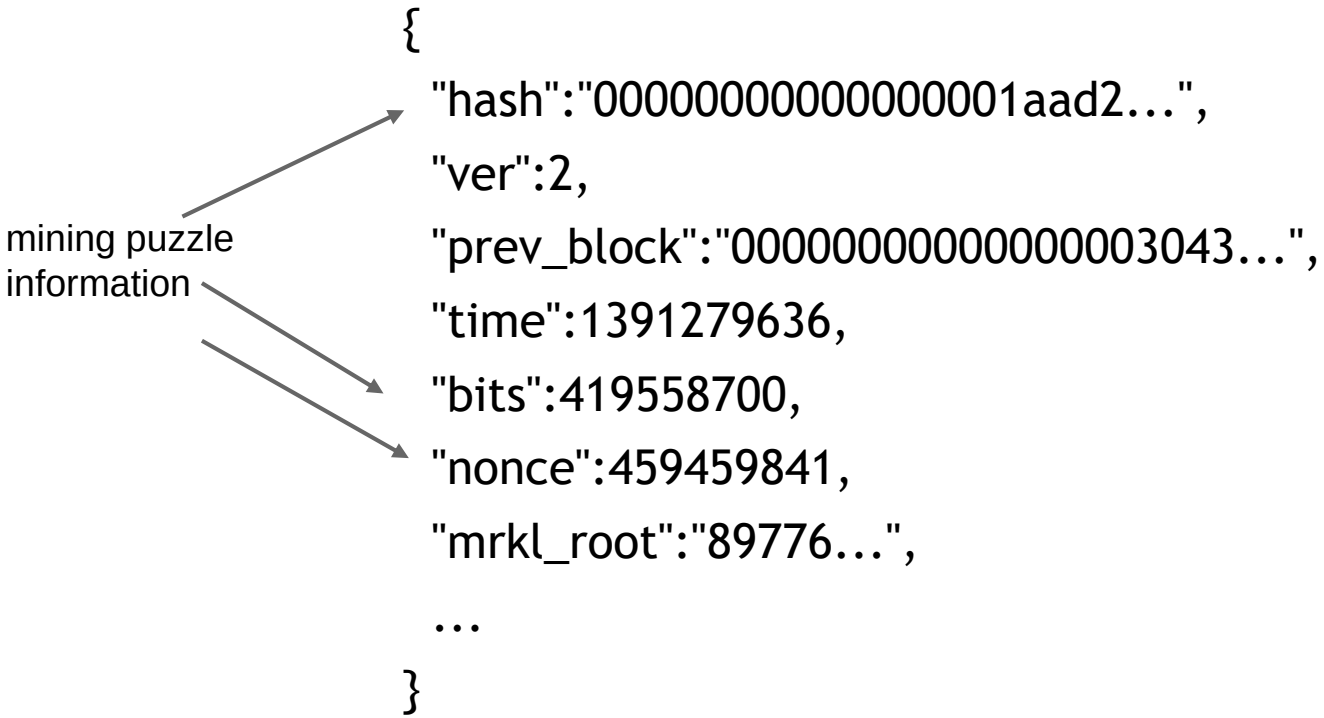
block header

transaction data

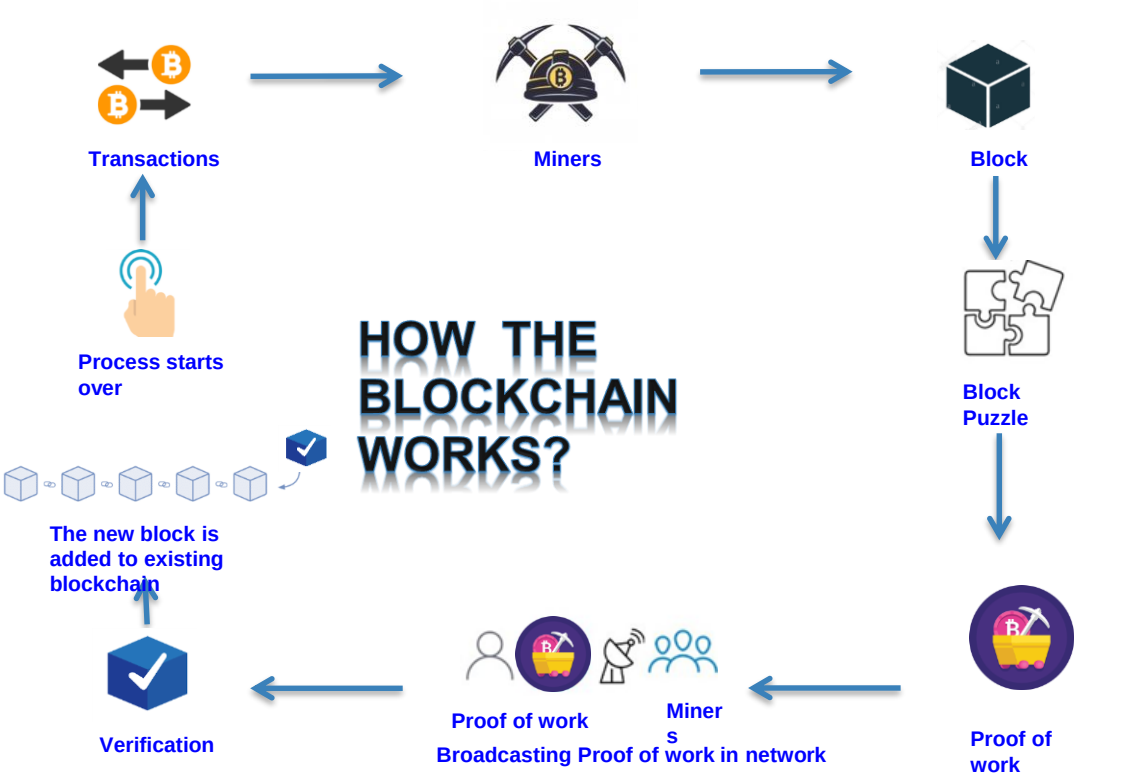
```
{
  "hash":"00000000000000001aad2...",
  "ver":2,
  "prev_block":"0000000000000003043...",
  "time":1391279636,
  "bits":419558700,
  "nonce":459459841,
  "mrkl_root":"89776...",
  "n_tx":354,
  "size":181520,
  "tx":[
    ...
  ],
  "mrkl_tree":[
    "6bd5eb25...",
    ...
    "89776cdb..."
  ]
}
```



The real deal: a Bitcoin block header



BLOCKCHAIN WORKING PRINCIPLE



Bitcoin Consensus

Consensus algorithm (simplified)

1. New transactions are broadcast to all nodes
2. Follow Flooding/Gossip Protocol to broadcast
3. Some nodes collect new transactions into a block
4. In each round a random node gets to broadcast its block
5. Other nodes accept the block only if all transactions in it are valid (unspent, valid signatures)
6. Nodes express their acceptance of the block by including its hash in the next block they create

Mining Process

Consensus Agreement

Hashcash: Proof of work

- Based on the idea of HashCash, a Proof of Work concept invented by Adam Back in 1997 (http://www.hashcash.org/papers/hashcash.pdf)
- Originally proposed as an anti-spam throttling mechanism
- The core idea is that before accepting a transaction, the sender must first demonstrate a “cost” via a computationally “hard” problem that can simultaneously be easily verified.
- This generally referred to as a “Proof of Work”

Hashcash: Proof of work

- HashCash Cost Function: Interactive Vs. Non-interactive
- *s*: service name

$$\begin{cases} \mathcal{T} \leftarrow \mathsf{MINT}(s, w) & \text{mint token} \\ \mathcal{V} \leftarrow \mathsf{VALUE}(\mathcal{T}) & \text{token evaluation function} \end{cases}$$

$$\begin{cases} \mathsf{PUBLIC:} & \text{hash function } \mathcal{H}(\cdot) \text{ with output size } k \text{ bits} \\ \mathcal{T} \leftarrow \mathsf{MINT}(s, w) & \textbf{find } x \in_R \{0,1\}^\star \textbf{ st } \mathcal{H}(s\|x) \overset{\text{left}}{=}_w 0^k \\ & \textbf{return } (s, x) \\ \mathcal{V} \leftarrow \mathsf{VALUE}(\mathcal{T}) & \mathcal{H}(s\|x) \overset{\text{left}}{=}_v 0^k \\ & \textbf{return } v \end{cases}$$

Hashcash: Proof of work

- Hashcash Cost Function: Interactive Vs. Non-interactive

$$\begin{cases} \mathcal{C} \leftarrow \mathsf{CHAL}(s, w) & \text{server challenge function} \\ \mathcal{T} \leftarrow \mathsf{MINT}(\mathcal{C}) & \text{mint token based on challenge} \\ \mathcal{V} \leftarrow \mathsf{VALUE}(\mathcal{T}) & \text{token evaluation function} \end{cases}$$

$$\begin{cases} \mathcal{C} \leftarrow \mathsf{CHAL}(s, w) & \textbf{choose } c \in_R \{0,1\}^k \\ & \textbf{return } (s, w, c) \\ \mathcal{T} \leftarrow \mathsf{MINT}(C) & \textbf{find } x \in_R \{0,1\}^\star \textbf{ st } \mathcal{H}(s||c||x) \overset{\text{left}}{=}_w 0^k \\ & \textbf{return } (s, x) \\ \mathcal{V} \leftarrow \mathsf{VALUE}(T) & \mathcal{H}(s||c||x) \overset{\text{left}}{=}_v 0^k \\ & \textbf{return } v \end{cases}$$

Prevents **DOS motivated attack or** pre-computation attacks

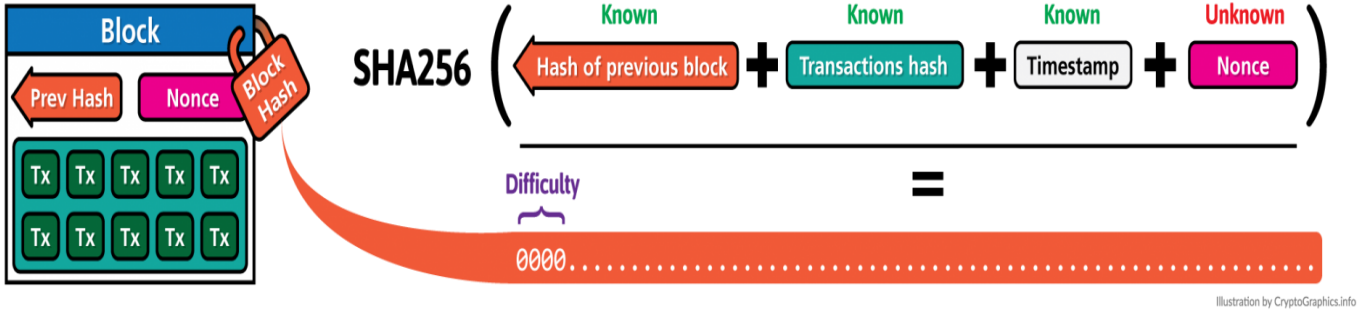
The real deal: a Bitcoin block

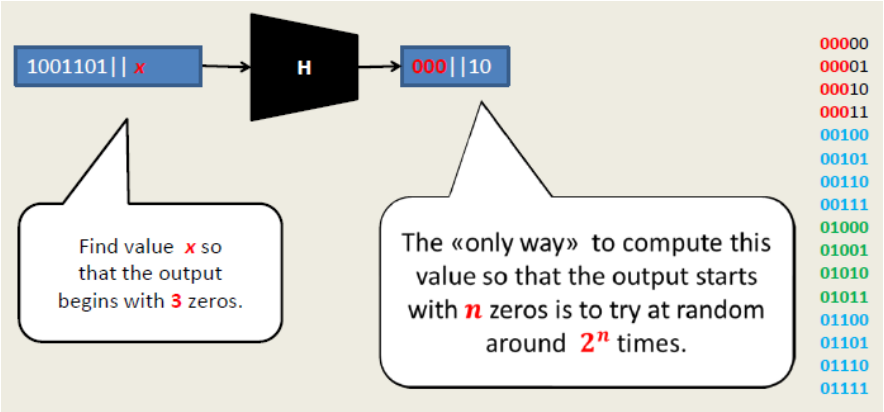
block header

transaction data


```
{
  "hash":"00000000000000001aad2...",
  "ver":2,
  "prev_block":"0000000000000003043...",
  "time":1391279636,
  "bits":419558700,
  "nonce":459459841,
  "mrkl_root":"89776...",
  "n_tx":354,
  "size":181520,
  "tx":[
    ...
  ],
  "mrkl_tree":[
    "6bd5eb25...",
    ...
    "89776cdb..."
  ]
}
```

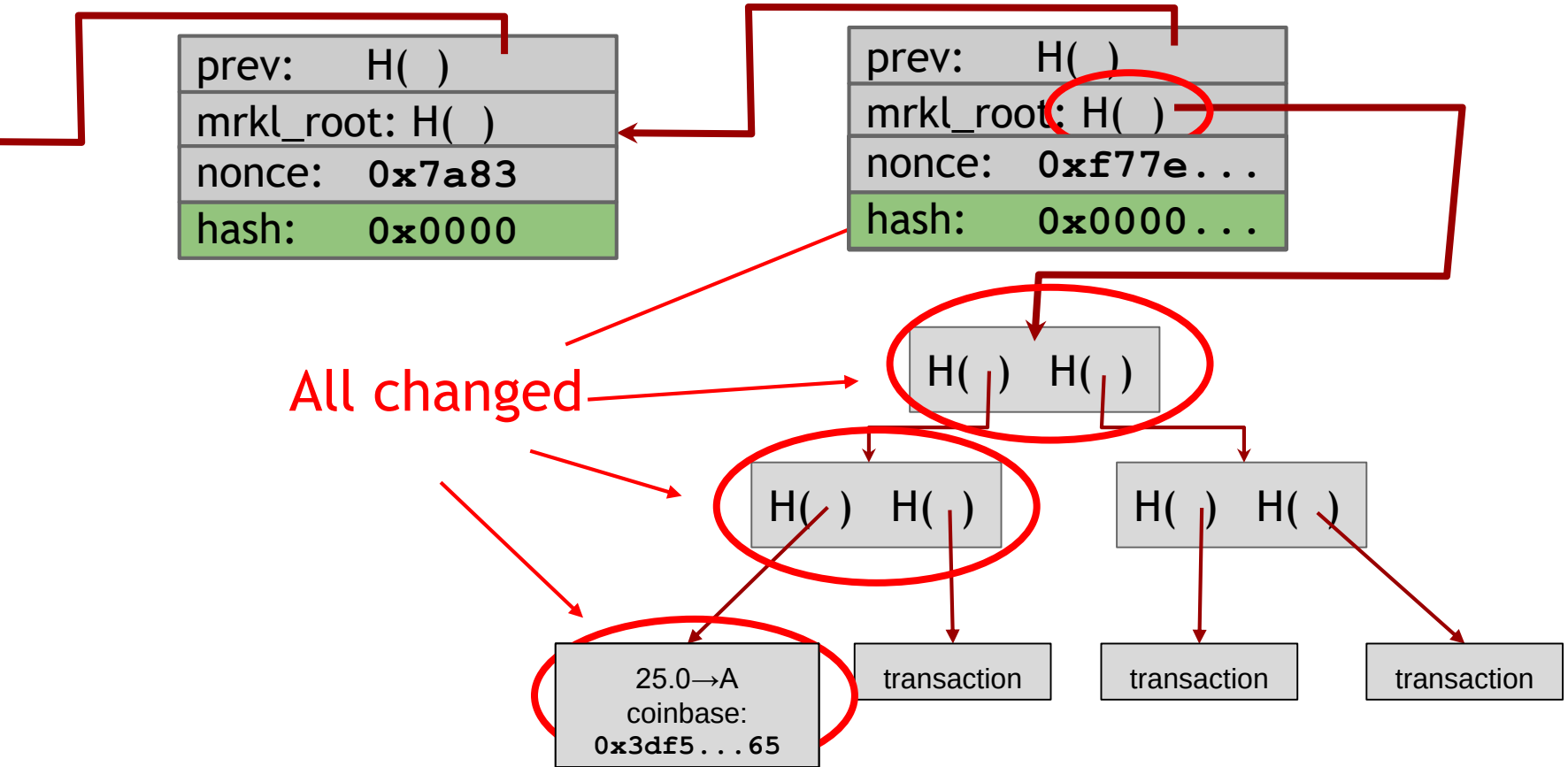
Proof of Work



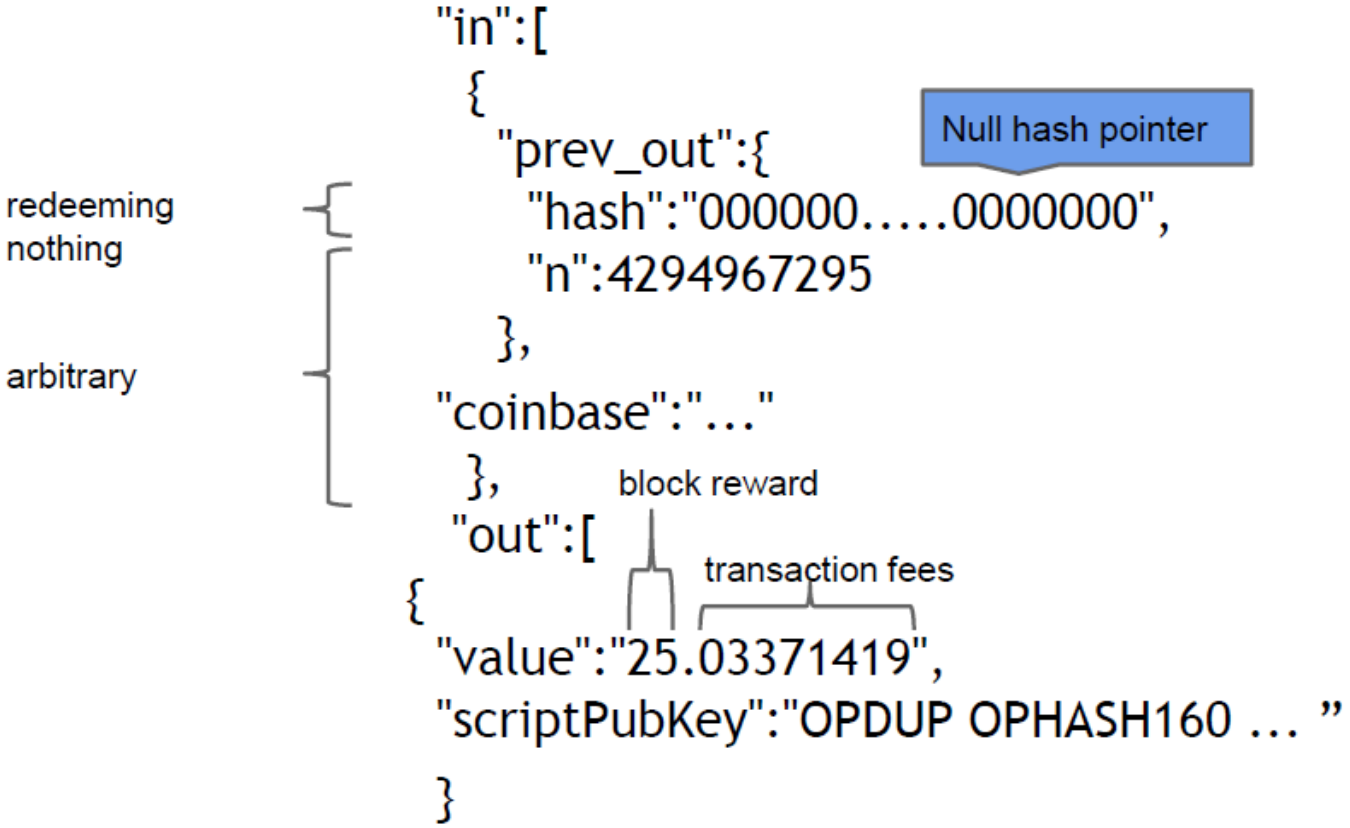


Proof of Work **[Back2002]**

Finding a valid block: Proof-of-Work



Coinbase

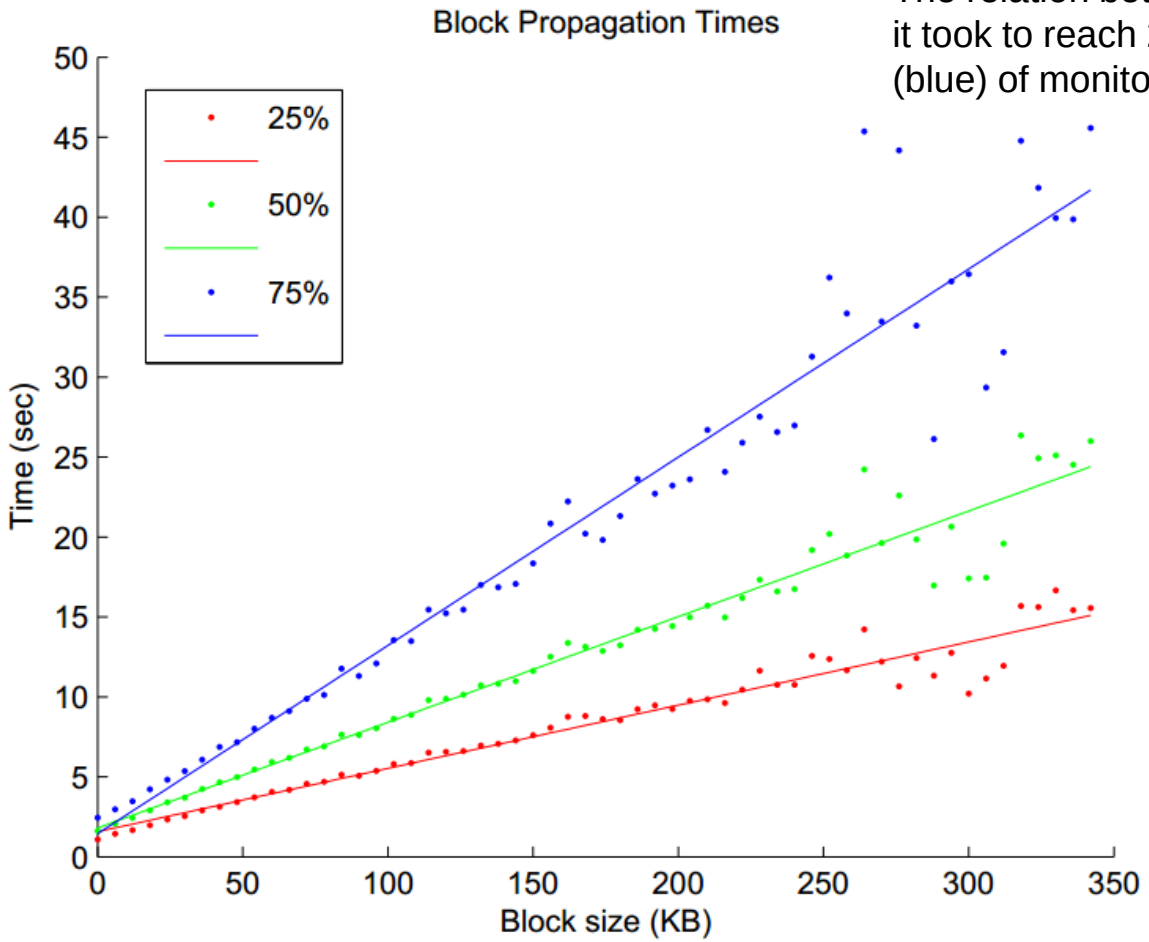

"in":[
{
"prev_out":{
"hash":"000000.....0000000",
"n":4294967295
},
"coinbase":"..."
},
"out":[
{
"value":"25.03371419",
"scriptPubKey":"OPDUP OPHASH160 ... "
}
Null hash pointer
redeeming
nothing
arbitrary
block reward
transaction fees

Block propagation nearly identical

Relay a new block when you hear it if:

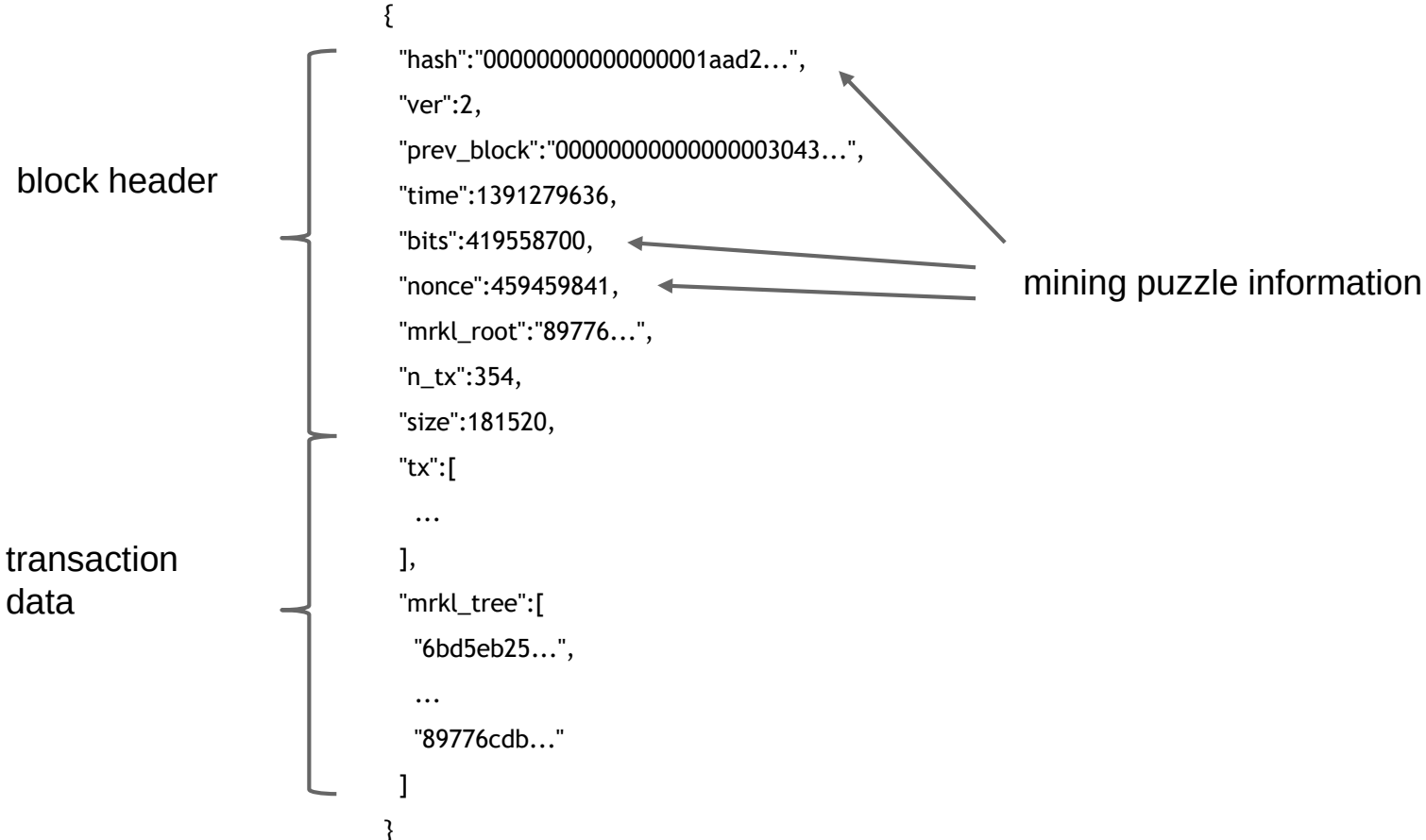
- Block meets the hash target
- Block has all valid transactions
  - Run *all* scripts, even if you wouldn't relay
- Block builds on current longest chain
  - Avoid forks

The relation between the block size and the time it took to reach 25% (red), 50% (green), and 75% (blue) of monitored nodes

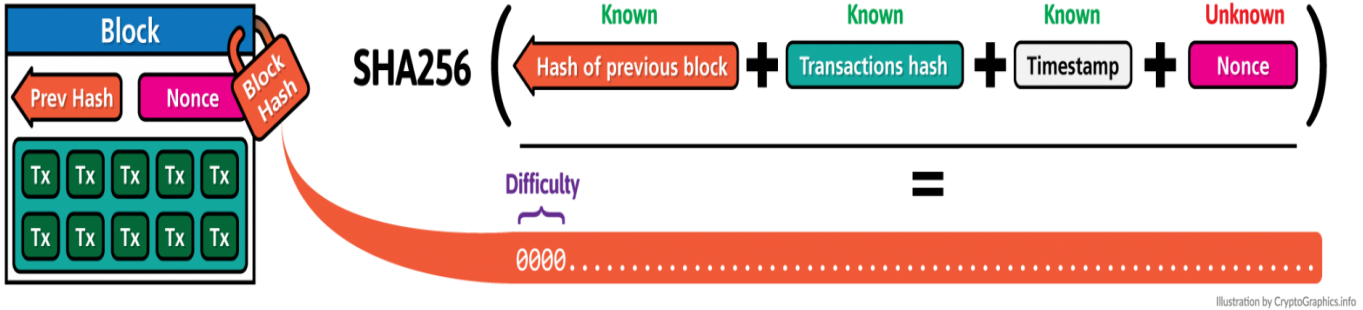


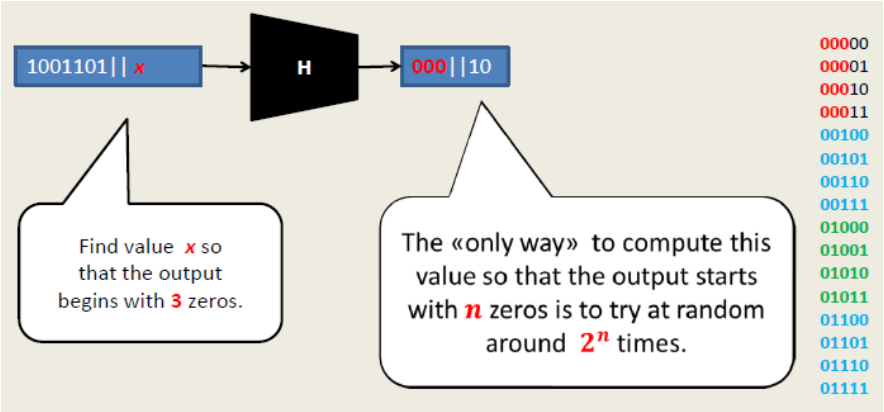
Source: Yonatan Sompolinsky and Aviv Zohar: “Accelerating Bitcoin’s Transaction Processing” 2014

The real deal: a Bitcoin block



Proof of Work





Proof of Work **[Back2002]**

Mining Difficulty (Max Target)

Bits: 486604799 = 1D00FFFF

$$\text{target} = \text{coefficient} * 2^{(8 * (\text{exponent} - 3))}$$

```
target = 00FFFF * 2^(8 * (1D – 3))

target = 00FFFF * 2 ^ (8*1A)

target = 00FFFF * 2 ^ D0
```

Block #0

Summary	
Number Of Transactions	1
Output Total	50 BTC
Estimated Transaction Volume	0 BTC
Transaction Fees	0 BTC
Height	0 (Main Chain)
Timestamp	2009-01-03 18:15:05
Difficulty	1
Bits	486604799
Size	0.285 kB
Weight	0.896 kWU
Version	1
Nonce	2083236893
Block Reward	50 BTC

```
0x00ffff * 2**(8*(0x1d - 3)) = 0x00000000FFFF0000000000000000000000000000000000000000000000000000
```

Mining Pseudocode

More Info: https://en.bitcoin.it/wiki/Difficulty

```
TARGET = (65535 << 208) / DIFFICULTY;
coinbase_nonce = 0;
while (1) {
      header = makeBlockHeader(transactions, coinbase_nonce);
      for (header_nonce = 0; header_nonce < (1 << 32); header_nonce++){
            if (SHA256(SHA256(makeBlock(header, header_nonce))) <
      TARGET)
                  break; //block found!
      }
      coinbase_nonce++;
}
```

Max Target: An application-defined constant, which sets the target hash corresponding to the lowest possible difficulty, 1

CPU mining

```
while (1){
    HDR[kNoncePos]++;
    IF (SHA256(SHA256(HDR)) < (65535 << 208)/ DIFFICULTY)
        return;
}
```

- **Hashes are 256-bit integers. So, TOTAL output size: 2^256.**
- **The current TARGET is "max_target/difficulty", where max_target is (65535 * 2^208).**
- **Therefore, fraction of output space is is TARGET/TOTAL. Therefore, TOTAL/TARGET=(2^256*difficulty/max_target) no. of hashes are needed on average to find a block.**
- **This is done over 600 sec, considering previous 2016 blocks.**
- **Global Hashrate:**

  (2^256 * difficulty/max_target)/600

  = (2^256 * difficulty/65535 * 2^208)/600

  = (2^48 * difficulty/65535)/600

  = difficulty * 7158388.055

Bitcoin Difficulty and Hashrate Ch

https://bitcoinwisdom.com/bitcoin/difficulty

Apps | Mail Login | Finance-1 | Finance-2 | Utility | Travel | Entertainment | Research | Book Online

Bitcoin Difficulty:	6,068,891,541,676
Estimated Next Difficulty:	5,933,343,057,673 (-2.23%)
Adjust time:	After 1529 Blocks, About 11.0 days
Hashrate(?):	40,575,440,550 GH/s
Block Generation Time(?):	1 block: 10.3 minutes 3 blocks: 31.0 minutes 6 blocks: 1.0 hours
Updated:	13:10 (2.6 hours ago)

Bitcoin Hash Rate (2 Months)

Setting the mining difficulty

Nodes automatically re-calculate the target every two weeks

Goal: average time between blocks = 10 minutes

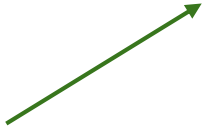
Prob (Alice wins next block) =
fraction of global hash power she controls

Alice with 0.1% of total hash power will find roughly one in every 1000 blocks.

Setting the mining difficulty

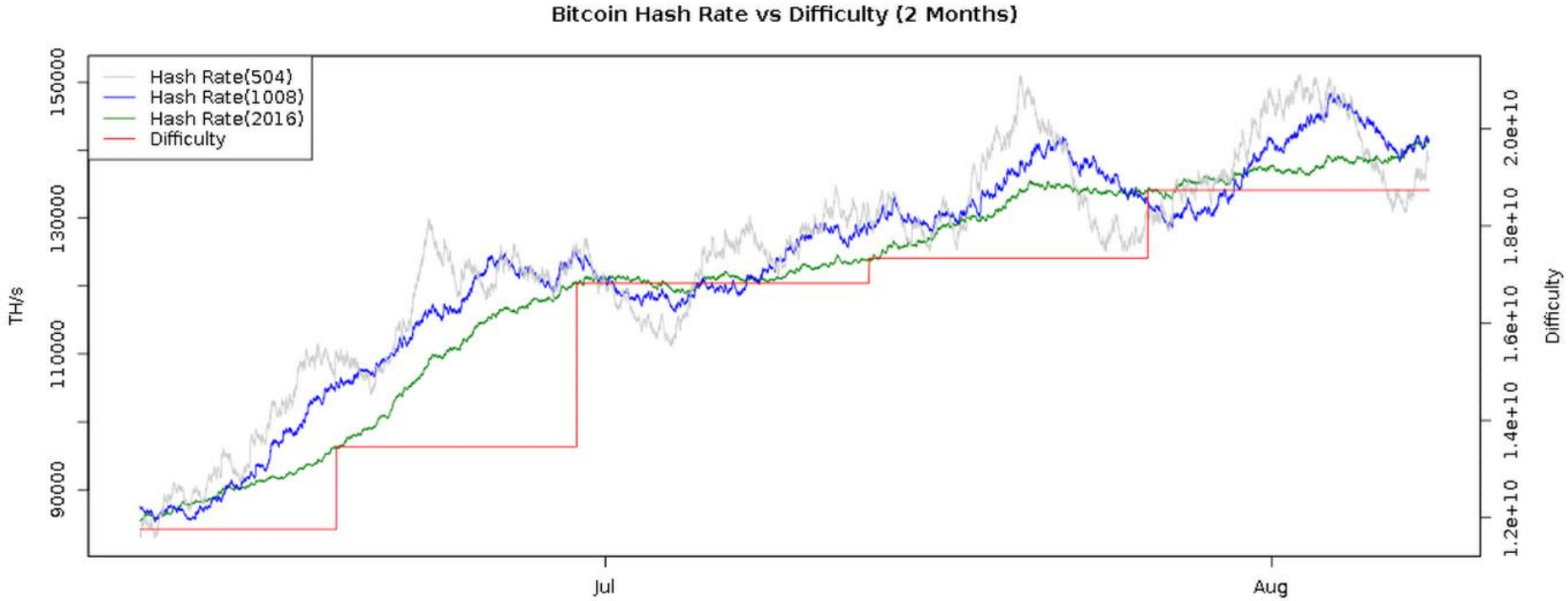
Every two weeks, compute:

```
next_difficulty= currennt_difficulty * (2 weeks)/(time to mine last 2016 blocks)
```



Expected number of blocks in 2 weeks at 10 minutes/block

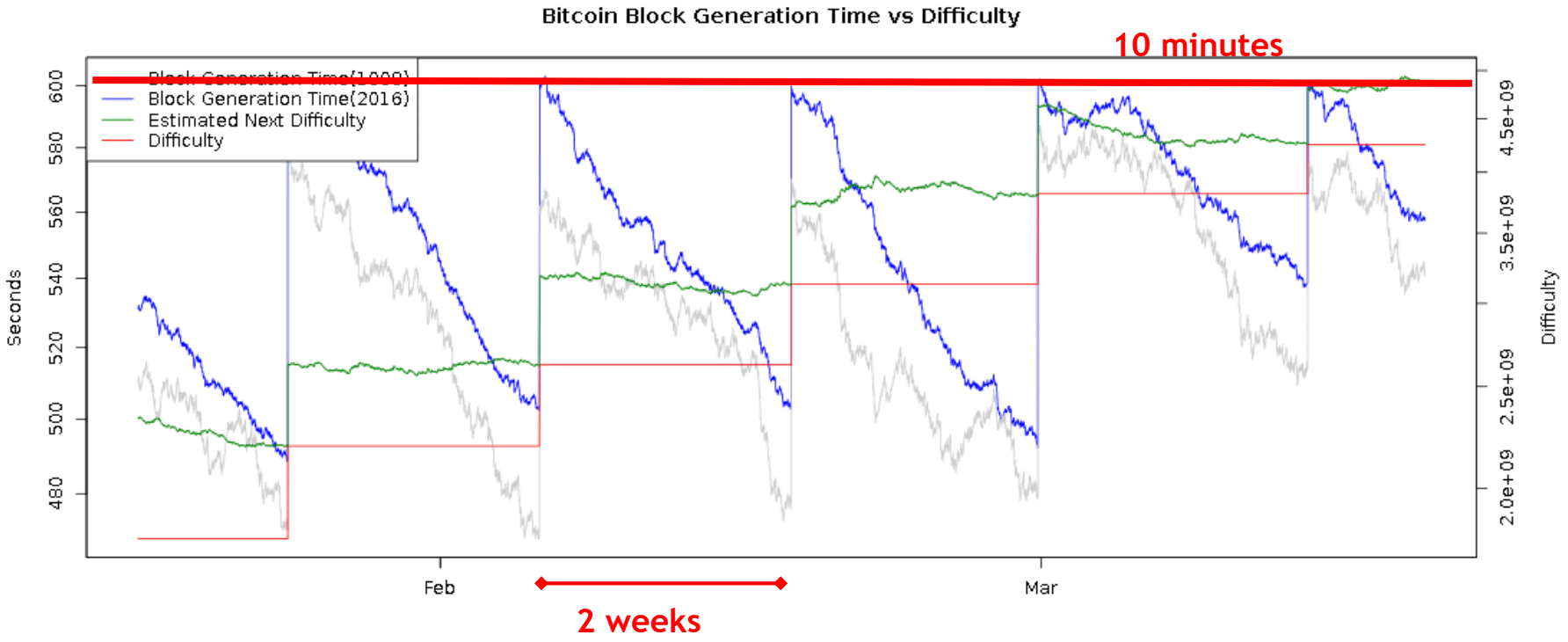
Mining difficulty over time



Note that the y-axis begins at 80,000 TeraHashes/s. The hash rate is averaged over 2016/1008/504 blocks

bitcoinwisdom.com

Time to find a block



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Mining hardware

Evolution of mining

CPU

GPU

FPGA

ASIC

gold pan

sluice box

placer mining

pit mining

CPU mining

```
while (1){
    HDR[kNoncePos]++;
    IF (SHA256(SHA256(HDR)) < (65535 << 208)/ DIFFICULTY)
        return;
}
```

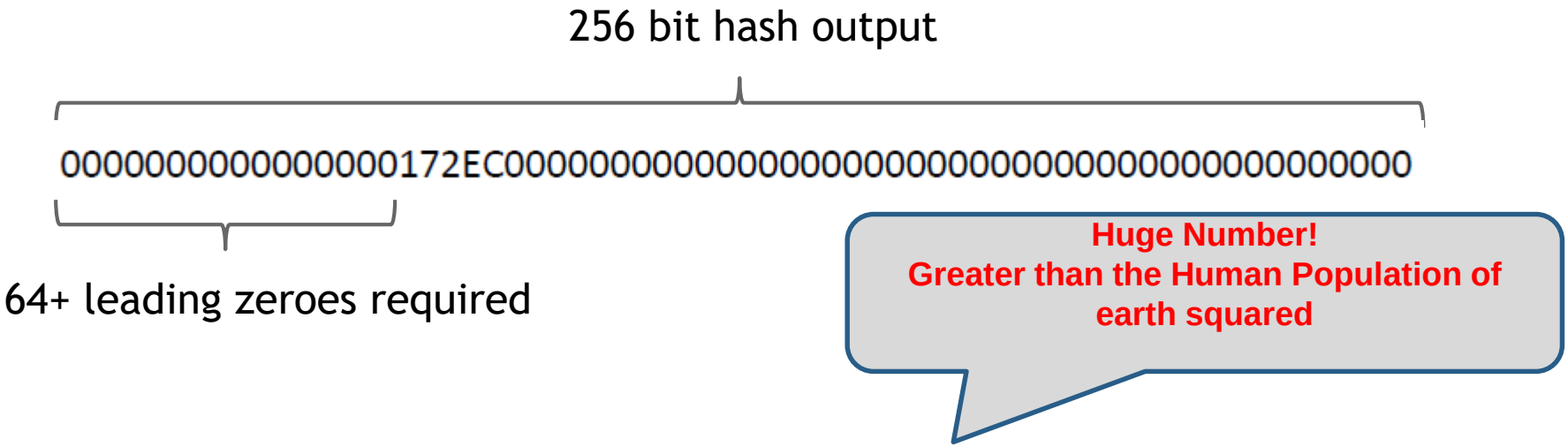
two hashes

Throughput on a high-end PC = 10-**20 MHz** ≈ 2^{24} Hashes/Sec

139,461 years to find a block today!

Mining difficulty “target”

(as of March 2015)



Less than 1 in about 2^{64} nonecs that you try will work

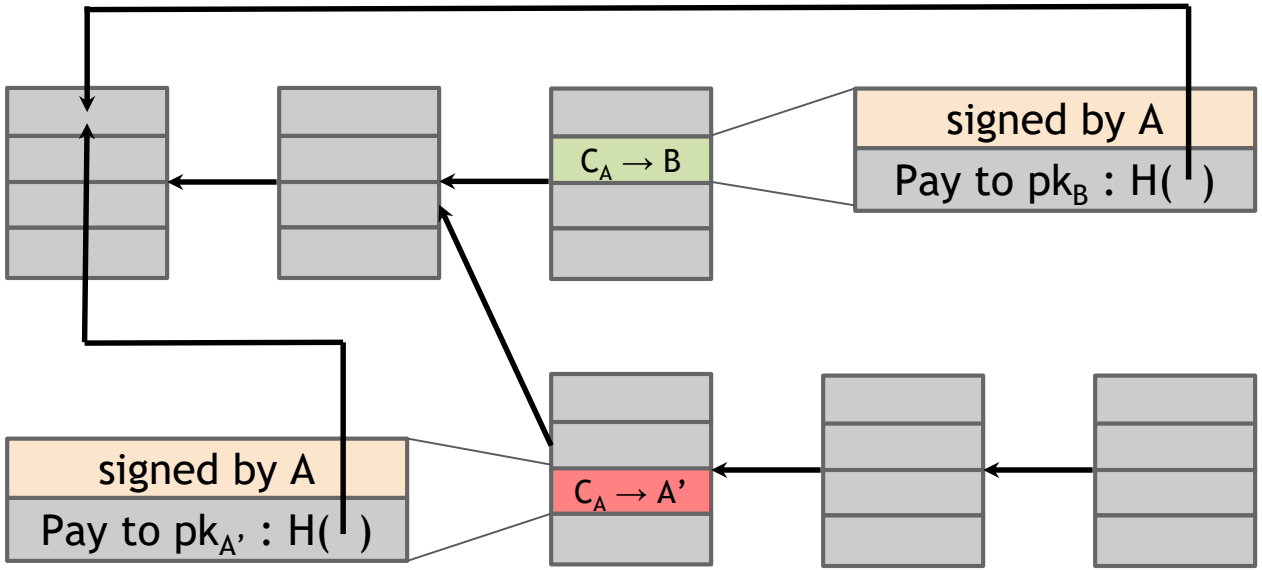
Mining Bitcoins in 6 easy steps

1. Join the network, listen for transactions
    a. Validate all proposed transactions
2. Listen for new blocks, maintain block chain
    a. When a new block is proposed, validate it
3. Assemble a new valid block
4. Find the nonce to make your block valid
5. Hope everybody accepts your new block
6. Profit!

Useful to Bitcoin network

Incentives in proof of work

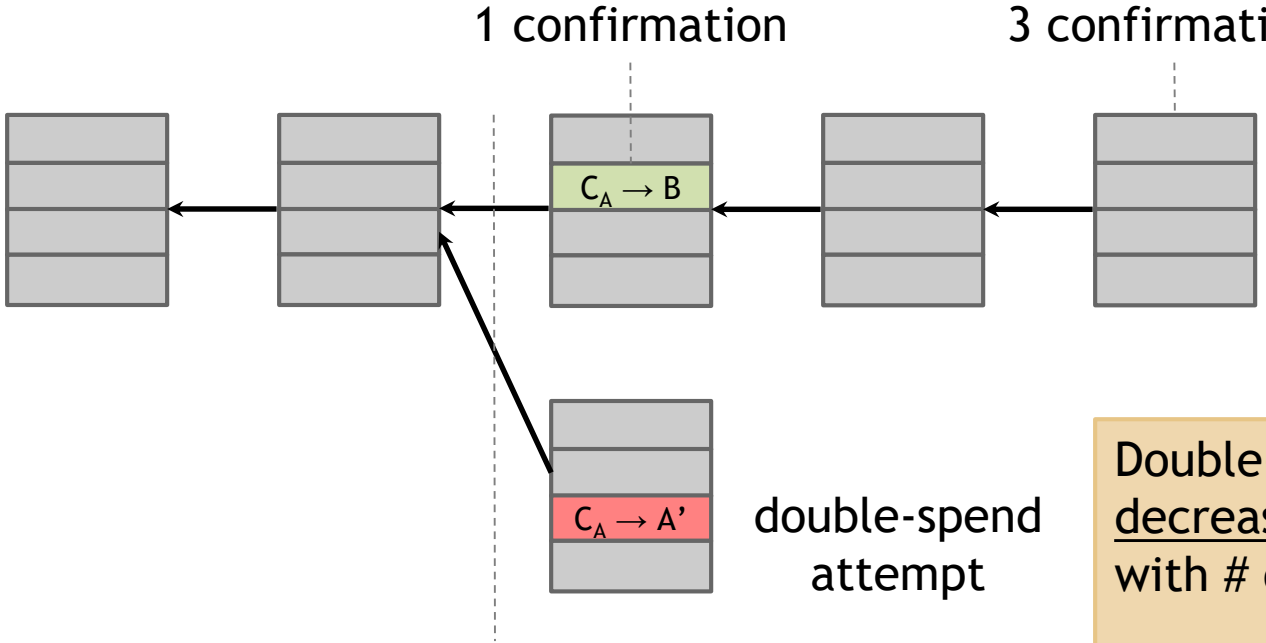
What can a malicious node do?



Double-spending attack

Honest nodes will extend the <u>longest valid branch</u>

From Bob the merchant's point of view



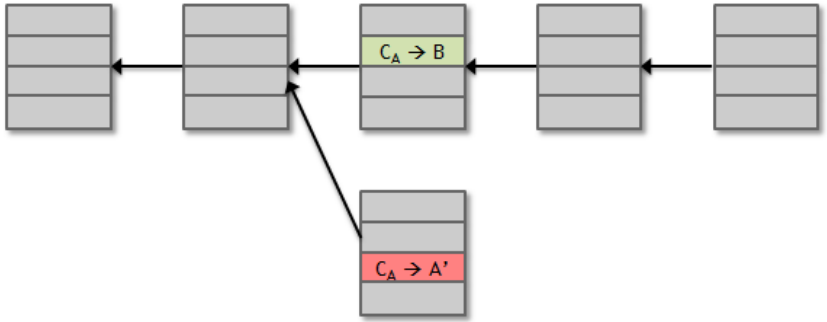
Double-spend probability decreases exponentially with # of confirmations

Most common heuristic:
6 confirmations

Key security assumption

Attacks infeasible if majority of miners weighted by hash power follow the protocol

Security



Protection against invalid transactions is cryptographic, but enforced by consensus

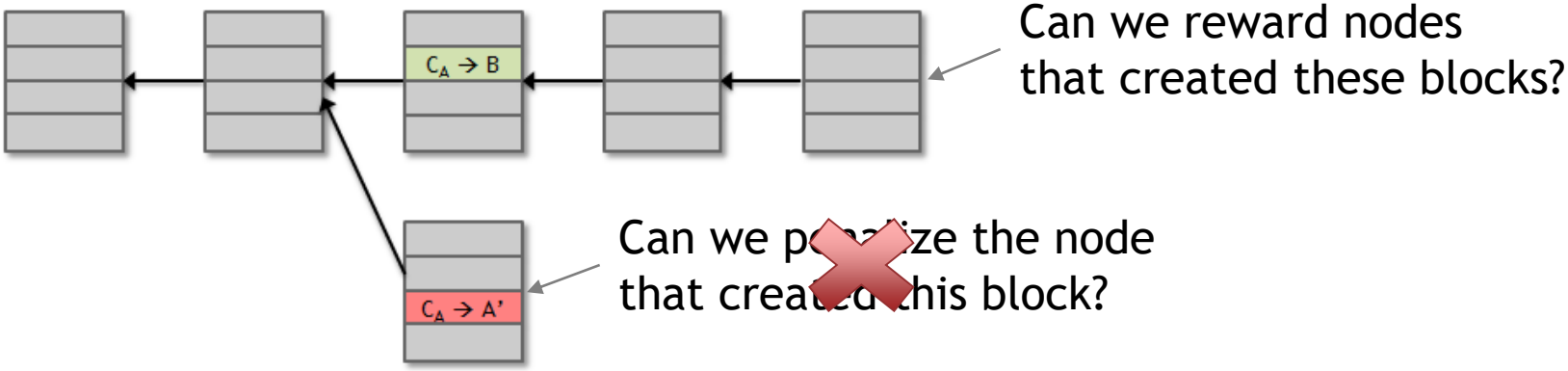
Denial of Service

Protection against double-spending is purely by consensus

You're never 100% sure a transaction is in consensus branch. Guarantee is probabilistic

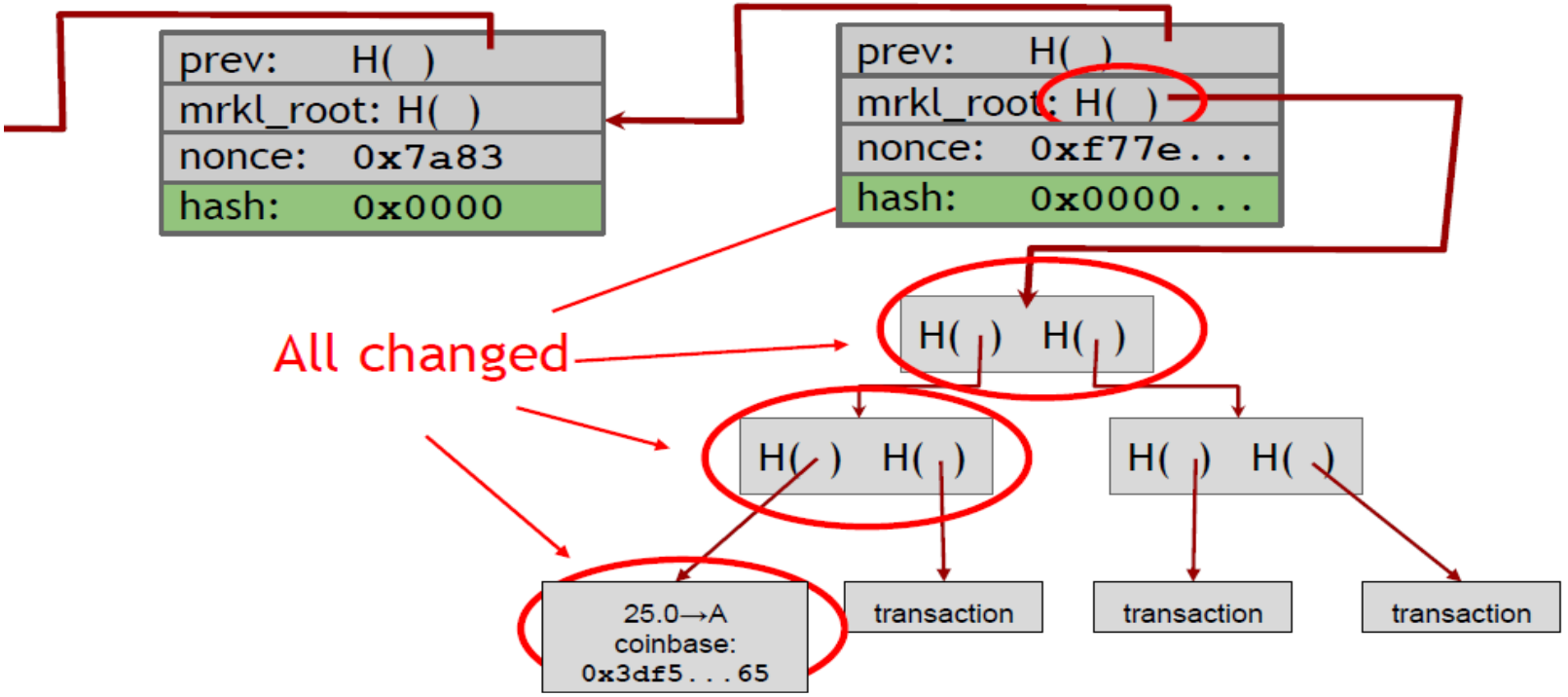
Assumption of honesty is problematic

Can we give nodes incentives for behaving honestly?



Everything so far is just a distributed consensus protocol
But now we utilize the fact that the currency has value

Incentive in Coinbase Transaction



Incentive 1: block reward

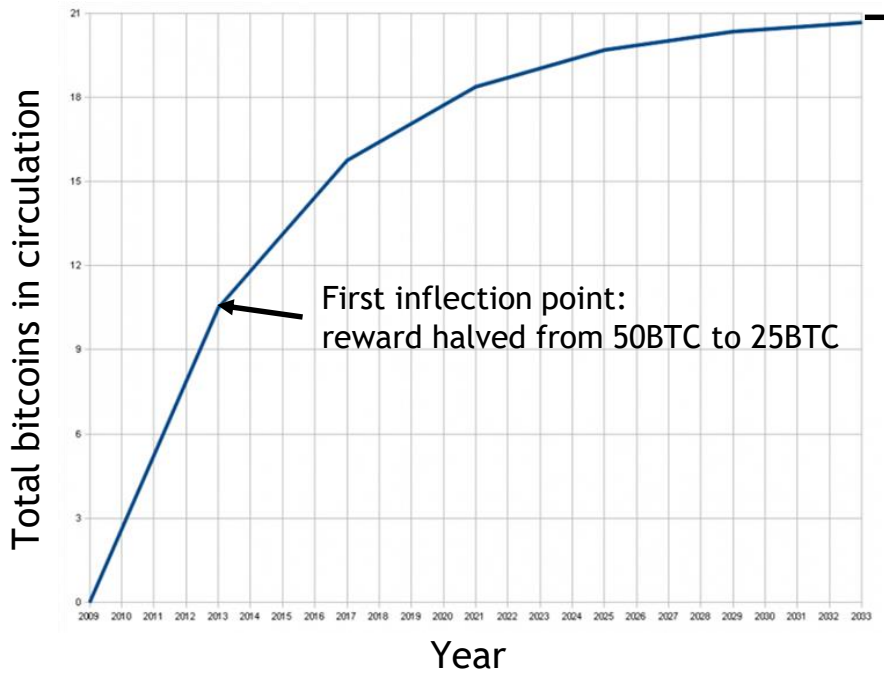
Creator of block gets to

- include special coin-creation transaction in the block
- choose recipient address of this transaction

Value is fixed: currently 12.5 BTC, halves every 4 years

Block creator gets to “collect” the reward only if the block ends up on long-term consensus branch!

There’s a finite supply of bitcoins



Total supply: 21 million

Block reward is how new bitcoins are created

Runs out in 2040. No new bitcoins unless rules change

Incentive 2: transaction fees

Creator of transaction can choose to make output value less than input value

Remainder is a transaction fee and goes to block creator

Purely voluntary, like a tip

Transaction View information about a bitcoin transaction

9cd03f530b83b67eee52bbbd2e9067e79e31513cffb5535c7463d96a8c5d96ae **Transaction ID (TX ID)**

1J29P1ceAfJHpG2jPQN1QxdHgCGEnLHd3u
Input Address

34auLDAG8skCooDAPpWFm69JuDz3rYnaDG	0.1 BTC
16XAfbSNEkkkwshkcusFJS4JxyHs74nudp	0.77 BTC
1AW2YoNvhAwatTjUcnzYWPETb3WSonZUD8	0.58 BTC
1L5a3gfb8FNJQn2MexVEjSzvXkXCp7mEBU	2.87094476 BTC

Output Addresses

1 Confirmations | 4.32094476 BTC

Block Information:

Summary	
Size	292 (bytes)
Weight	1168
Received Time	2018-02-02 07:45:17
Included In Blocks	507234 (2018-02-02 08:12:38 + 27 minutes)
Confirmations	1 Confirmations
Visualize	View Tree Chart

Transaction information:

Inputs and Outputs	
Total Input	4.32123876 BTC
Total Output	4.32094476 BTC
Fees	0.000294 BTC
Fee per byte	100.685 sat/B
Fee per weight unit	25.171 sat/WU
Estimated BTC Transacted	0.1 BTC
Scripts	Show scripts & coinbase

Recall:

transaction fee = value of inputs - value of outputs

fee goes to miner who records the transaction

Costs resources for

peers to relay your transaction

miner to record your transaction

Transaction fee compensates for (some of) these costs

How are transaction fees set today?

No fee if

tx less than 1000 bytes in size,

all outputs are 0.01 BTC or larger, and

priority is large enough

Priority = (sum of inputAge*inputValue) / (trans size)

Otherwise fee is 0.0001 BTC per 1000 bytes

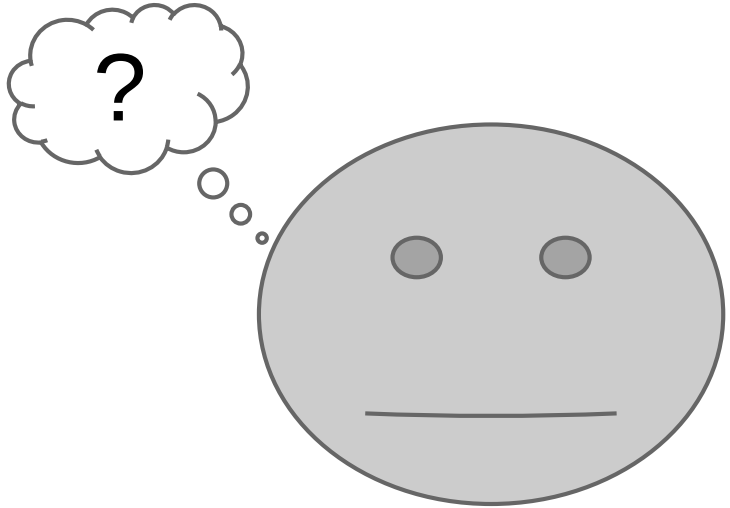
Approx transaction size: 148 N_{inputs} + 34 $N_{outputs}$ + 10

A second look at transaction fees

Default policy:

```
priority = sum(input_value * input_age)/size_in_bytes
```

Accept without fees if:




```
priority > 0.576
```

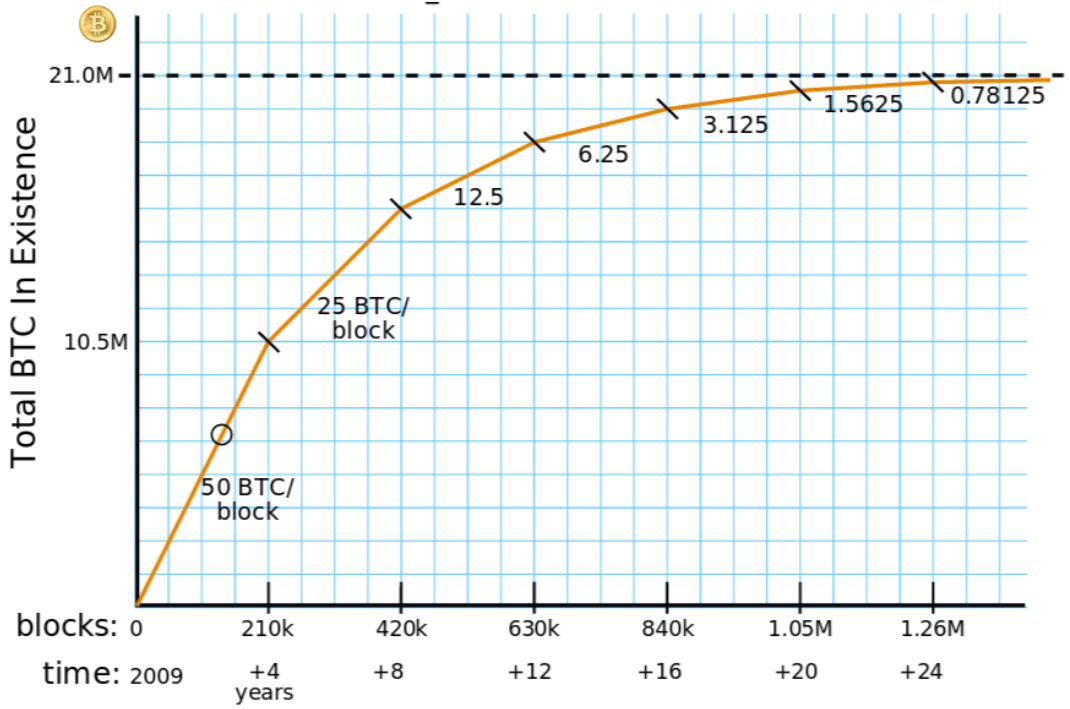
Generally, higher fee means transaction will be forwarded and recorded faster.

If you don’t pay the consensus fee, your transaction will take longer to be recorded.

Miners prioritize transactions based on fees and the priority formula.

Transaction fees will matter more

Currently, block rewards are > 99% of miner revenue. But:

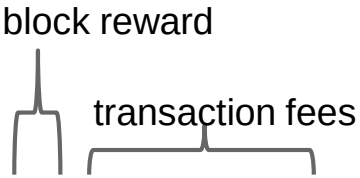


Eventually, transaction fees will dominate

Courtesy:
Brian Warner

The real deal: coinbase transaction


```
"in":[
 {
  "prev_out":{
   "hash":"000000.....0000000",
   "n":4294967295
  },
 "coinbase":"..."
 },
 "out":[
{
 "value":"25.03371419",
 "scriptPubKey":"OPDUP OPHASH160 ... ”
 }
```

Mining economics

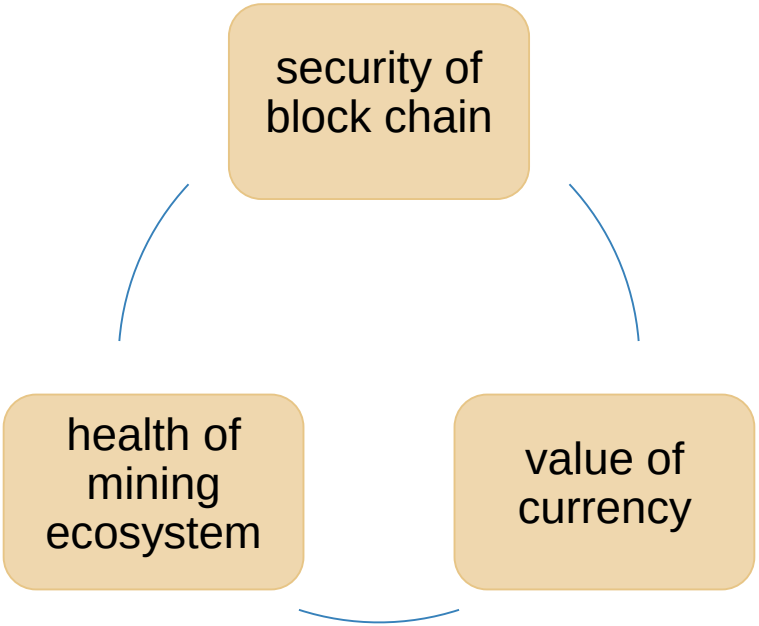
If mining reward (block reward + Tx fees)	>	hardware + electricity cost	→	Profit

Complications:

- fixed vs. variable costs
- reward depends on global hash rate

Putting it all together

Bitcoin is bootstrapped



What can a “51% attacker” do?

Steal coins from existing address? ✗

Suppress some transactions?

- From the block chain ✓
- From the P2P network ✗

Change the block reward? ✗

Destroy confidence in Bitcoin? ✓✓

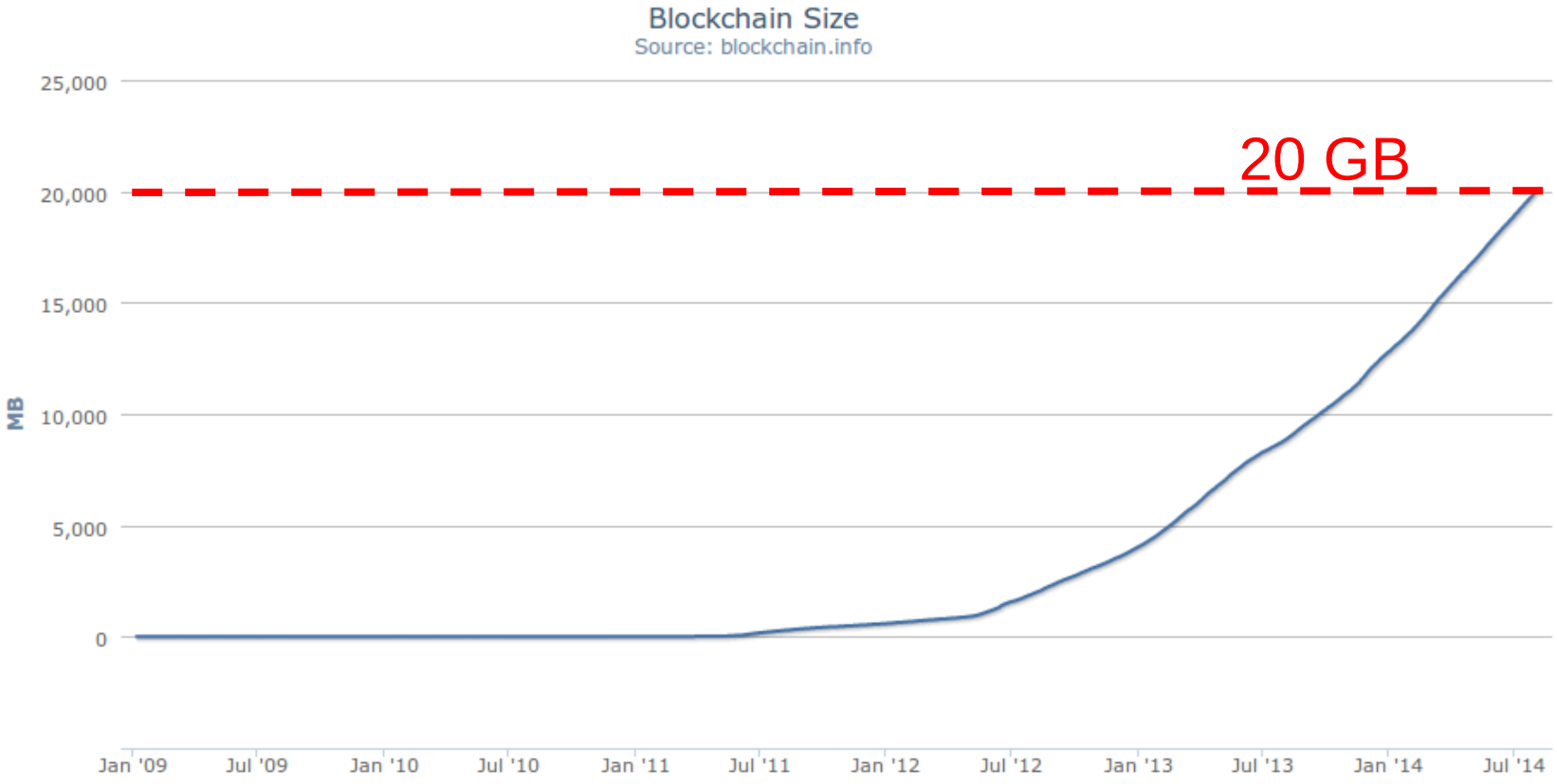
How big is the network?

- Impossible to measure exactly
- Estimates-up to 1M IP addresses/month
- Only about 5-10k “full nodes”
    - Permanently connected
    - Fully-validate
- This number may be dropping!

Fully-validating nodes

- Permanently connected
- Store entire block chain
- Hear and forward every node/transaction

Storage costs (Size of Blckchain)



Tracking the UTXO set

- **U**nspent **T**ransaction **O**utput
  - Everything else can be stored on disk
- Currently ~12 M UTXOs
  - Out of 44 M transactions
- Can easily fit into RAM

Thin/SPV clients (not fully-validating)

Idea: don’t store everything

- Store block headers only
- Request transactions as needed
  - To verify incoming payment
- Trust fully-validating nodes

1000x cost savings! (20 GB -> 23MB)

Limitations & improvements

Hard-coded limits in Bitcoin

- 10 min. average creation time per block
- 1 M bytes in a block
- 20,000 signature operations per block
- 100 M *satoshis* per bitcoin
- 21M total bitcoins maximum
- 50,25,12.5... bitcoin mining reward

These affect economic balance of power too much to change now

Throughput limits in Bitcoin

- 1 M bytes/block (10 min)
- >250 bytes/transaction
- 7 transactions/sec ☹

Compare to:

- VISA: 2,000-10,000 transactions/sec
- PayPal: 50-100 transaction/sec