The Cost of Security in a Blockchain

Saravanan Vijayakumaran
sarva@ee.iitb.ac.in

Department of Electrical Engineering
Indian Institute of Technology Bombay

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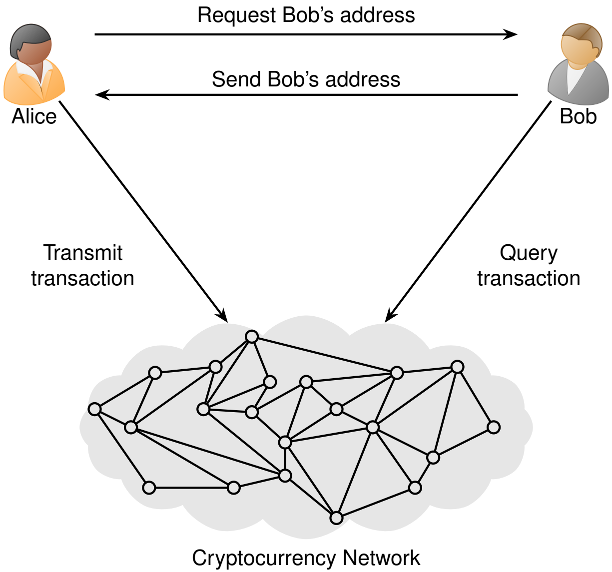
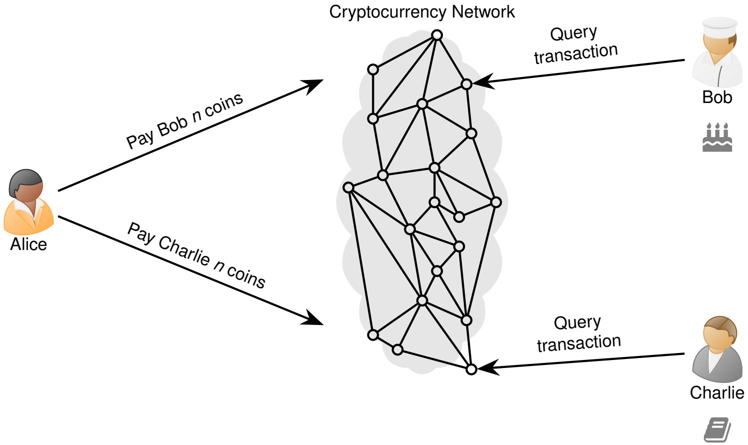
Cryptocurrency Transaction Workflow



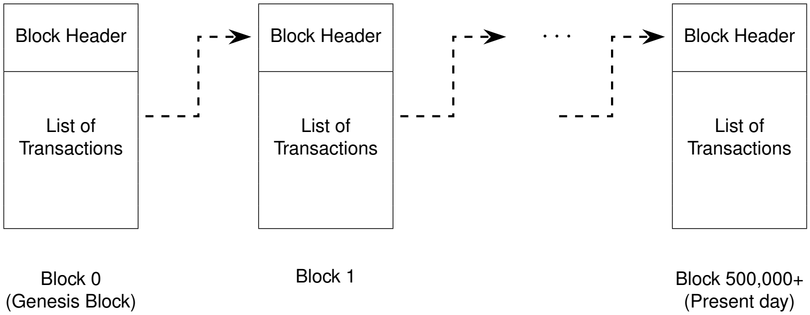
Double Spending Problem



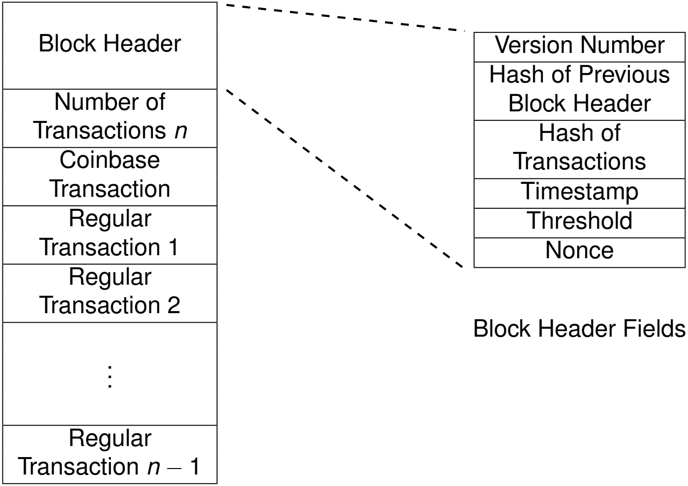
- Alice pays Bob n coins for a cake
- Alice uses the **same** n coins to pay Charlie for a book

The Bitcoin Blockchain

A public database to store all transactions which is replicated by many network nodes



Block and Header Formats



Block Header Fields

- Hash = Output of cryptographic hash function

Cryptographic Hash Functions

- Easy to compute but difficult to invert
- Collision-resistant
- Pseudorandom outputs

Input	SHA-256 Output
`bitcoin0`	`2277efd2e9051a1978682cad7a111876031f7fcdb9a2a06b5fdeee160dd8f34e`
`bitcoin1`	`dbdbac0b3072d7677fc94eebaf8eba9e81e5c3b7de6899dae12c98d6799b065a`
`bitcoin2`	`1ed7259a5243a1e9e33e45d8d2510bc0470032df964956e18b9f56fa65c96e89`
`bitcoin3`	`0c5582329503f93b4b243a986551d9e22e46ee9ba681d687078cbcbad0c7d023`
`bitcoin4`	`0a49508bf91ac4f98e6a01b575e1a3f200a5d9a03d00219aea52b15b064cdf50`
`bitcoin5`	`de6206bd52f4228ebc556c85b26e3582fa141f8839a11d2a2ca761d0f7e24ec3`
`bitcoin6`	`e1abb7b46d14bb2c3e13208ebc9790ab847f6b5265adbf154d4200b513359e22`
`bitcoin7`	`c07bed0fae2067f2ed35cc443d97aeacbaf0b59dcbd619f76c75477690b82d3b`
`bitcoin8`	`8ecc8a5ebc2a99db8e950c29242e7052ae2930cd60258176efe36750a4e33170`
`bitcoin9`	`38ab2bcafbf65eb6204162d28082ad7616f2a66f20b27696262e3842b3712d0b`

- SHA-256 = NIST approved CHF with 256-bit outputs

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`bitcoin4`	`0a49508bf91ac4f98e6a01b575e1a3f200a5d9a03d00219aea52b15b064cdf50`
`bitcoin5`	`de6206bd52f4228ebc556c85b26e3582fa141f8839a11d2a2ca761d0f7e24ec3`
`bitcoin6`	`e1abb7b46d14bb2c3e13208ebc9790ab847f6b5265adbf154d4200b513359e22`
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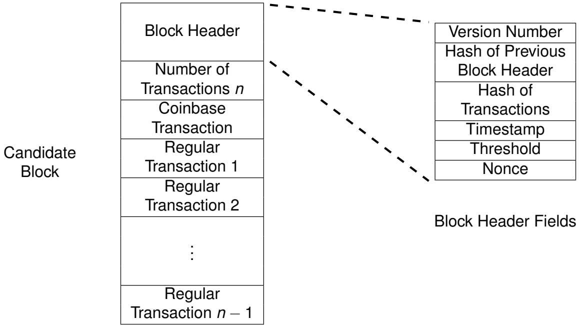
- SHA-256 = NIST approved CHF with 256-bit outputs
- At a billion outputs per second, 78 billion years required to calculate 2^{100} outputs

Who Adds Blocks?

- Mining = Process of adding new blocks to the blockchain
- Nodes which want to perform transactions broadcast them
- Miners collect some of these transactions into a candidate block



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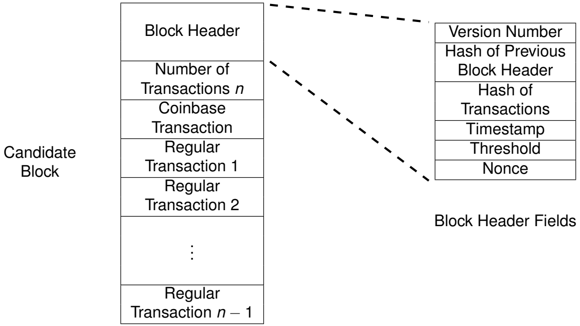

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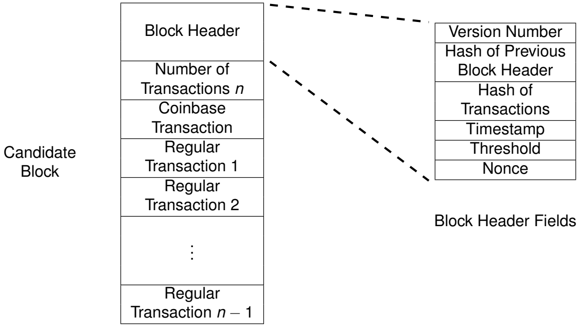

- Threshold encodes a 256-bit value like $0x\underbrace{00\cdots00}_{\text{16 times}}\underbrace{\text{FFFFF}\cdots\text{FFFFF}}_{\text{48 times}}$
- Miner who can find Nonce such that

$$\text{SHA256}(\text{SHA256}(\underbrace{\text{Version Number} \parallel \cdots \parallel \text{Nonce}}_{\text{Candidate Block Header}})) \leq \text{Threshold}.$$

can add a new block

Mining Difficulty and Rewards

- Why is mining hard?
  - Brute-force search is the only way to find suitable nonce
  - Target area is small compared to output space of SHA256

$$\Pr\left[\text{Success in single trial}\right] \approx \frac{\text{Threshold}}{2^{256}}$$

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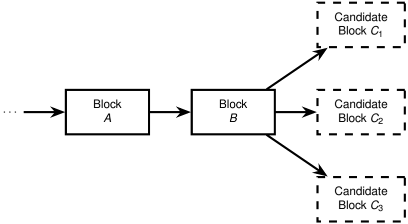
- Why do mining?
  - Successful miner gets rewarded in bitcoins
  - Every block contains a **coinbase transaction** which creates 12.5 bitcoins
  - Miners also collect the transaction fees in the block

Block Addition Workflow

- Nodes broadcast transactions
- Miners accept valid transactions and reject invalid ones (solves double spending)
- Miners try extending the latest block



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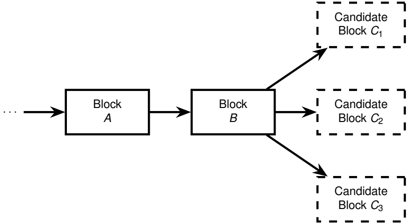
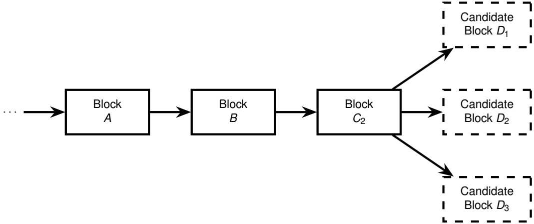
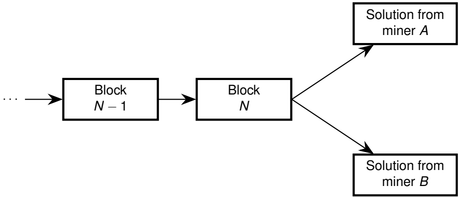


- Successful miners broadcast solutions
- Unsuccessful miners abandon their current candidate blocks and start work on new ones



What if two miners solve the puzzle at the same time?



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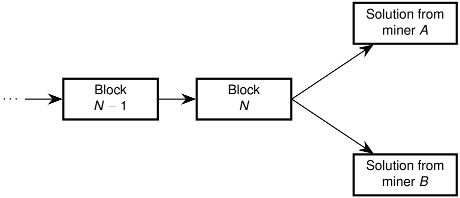

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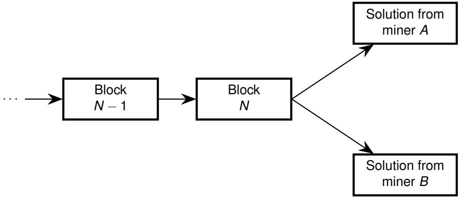

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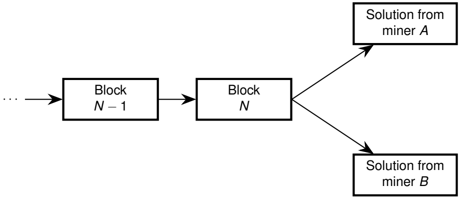

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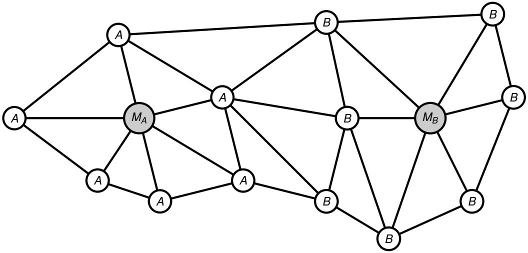

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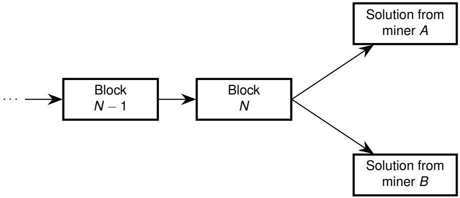

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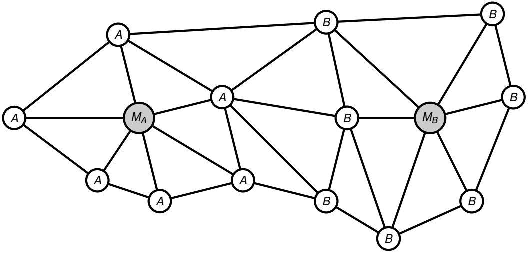

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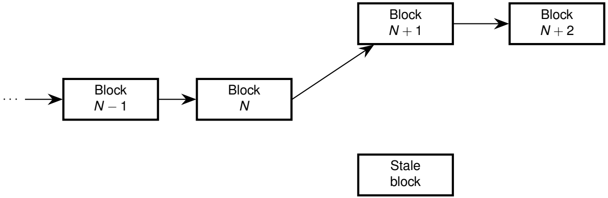

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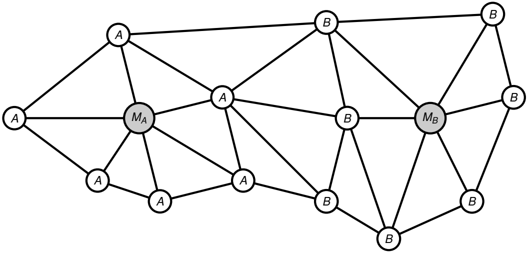

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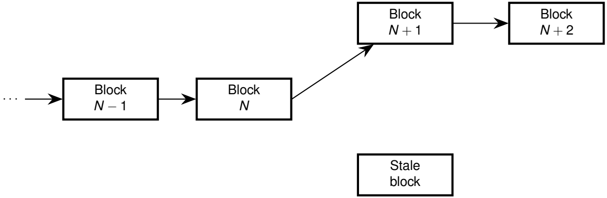

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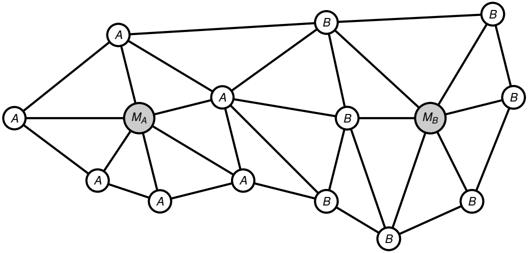

- Nodes always switch to the chain which was more difficult to produce
- Eventually the network will converge and achieve consensus

Tamper Resistance

- Suppose Alice wants to modify block B_N

$$\cdots \longrightarrow \boxed{B_{N-1}} \longrightarrow \boxed{B_N} \longrightarrow \boxed{B_{N+1}} \longrightarrow \cdots \longrightarrow \boxed{B_{N+m-1}}$$

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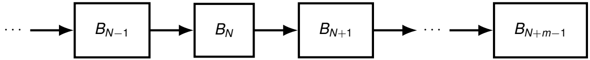
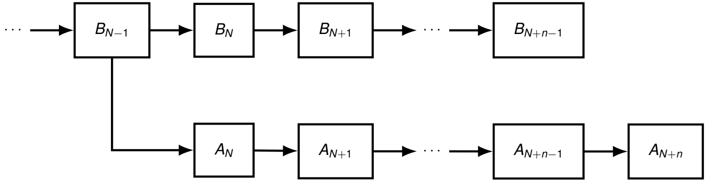


- Alice works on A_N branch; other miners work on B_N branch



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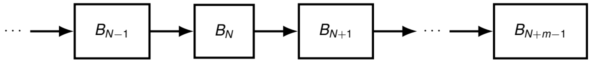

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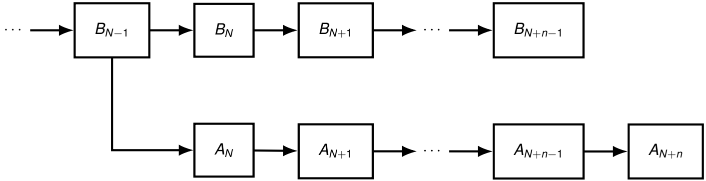

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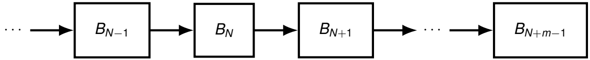

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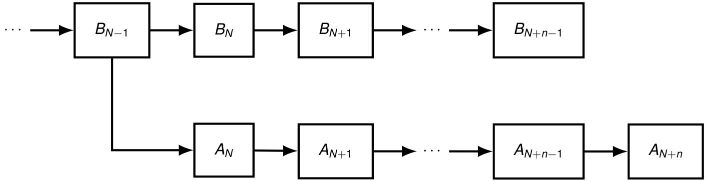

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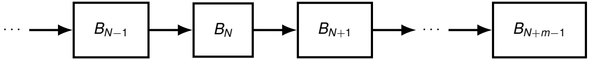

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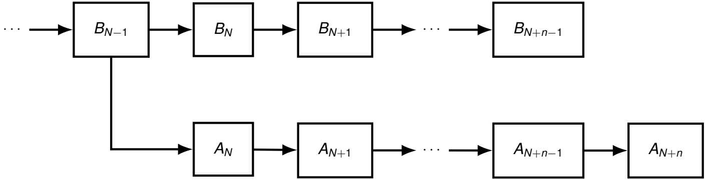

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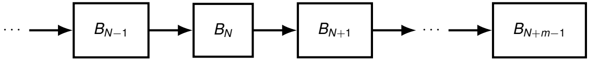

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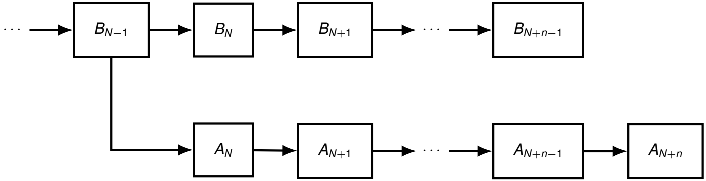

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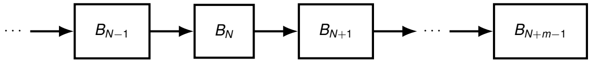

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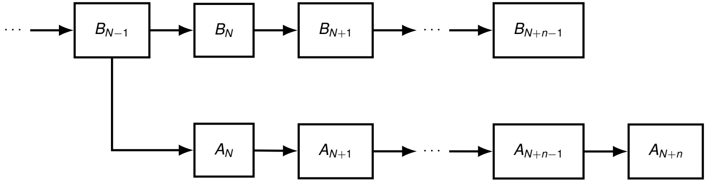

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- Controlling 50% of hashrate = Controlling 775 million USD worth of hardware

Challenges for Enterprise Blockchains

- Proof-of-work consensus is not suitable
- Proof-of-authority is an alternative but insecure
  - A valid block is one with a certain number of approvers
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