P2P Systems and Blockchains

Spring 2018,

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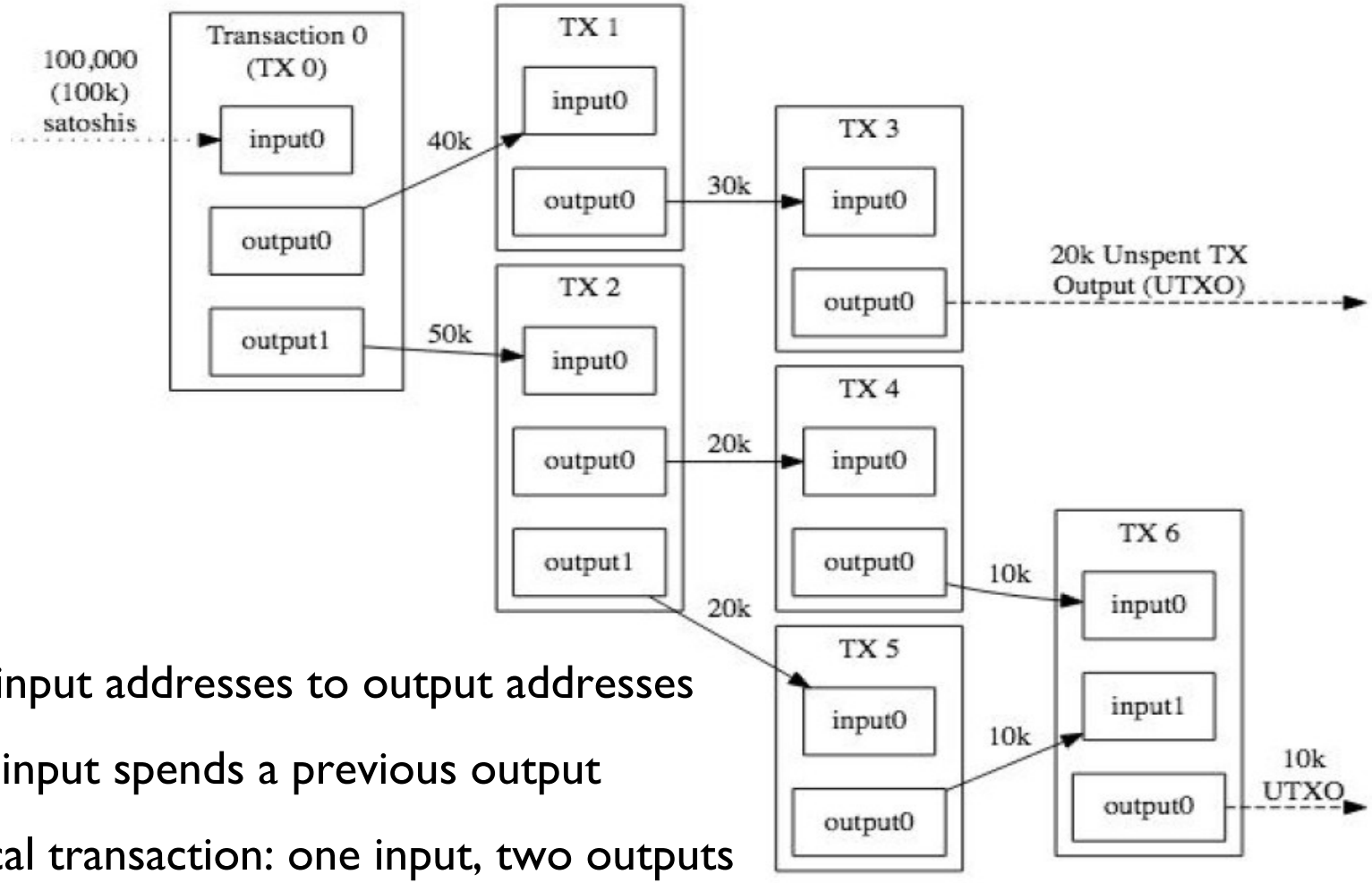
Lesson 14:
BITCOIN:
THE NAKAMOTO CONSENSUS

20/4/2018

TRANSACTIONS: RECAP



- Map input addresses to output addresses
- Each input spends a previous output
- Typical transaction: one input, two outputs
- Contains signature of the owner of the funds

BITCOIN SCRIPTING LANGUAGE: DESIGN GOALS

- Input and output contain scripts
- Bitcoin has its own scripting language for transactions
  - inputs and outputs are scripts written in a **stack based, non-Turing complete** language
  - built for Bitcoin, **FORTH-LIKE**
- not Turing complete: no looping
  - no possibility to create "infinite loops"
  - all Bitocoin "full nodes" (miners and full nodes, notmobiles for instance) have to validate these scripts and they do not have to fall in a loop
  - preventing the transaction validation mechanism from being used as a vulnerability.
  - executable on a range of hardware,

BITCOIN SCRIPTING LANGUAGE: DESIGN GOALS

- stateless: there is no state prior to execution of the script, or state saved after execution of the script.
  - all the information needed to execute a script is contained within the script.
  - deterministic: a script will predictably execute the same way on any system.

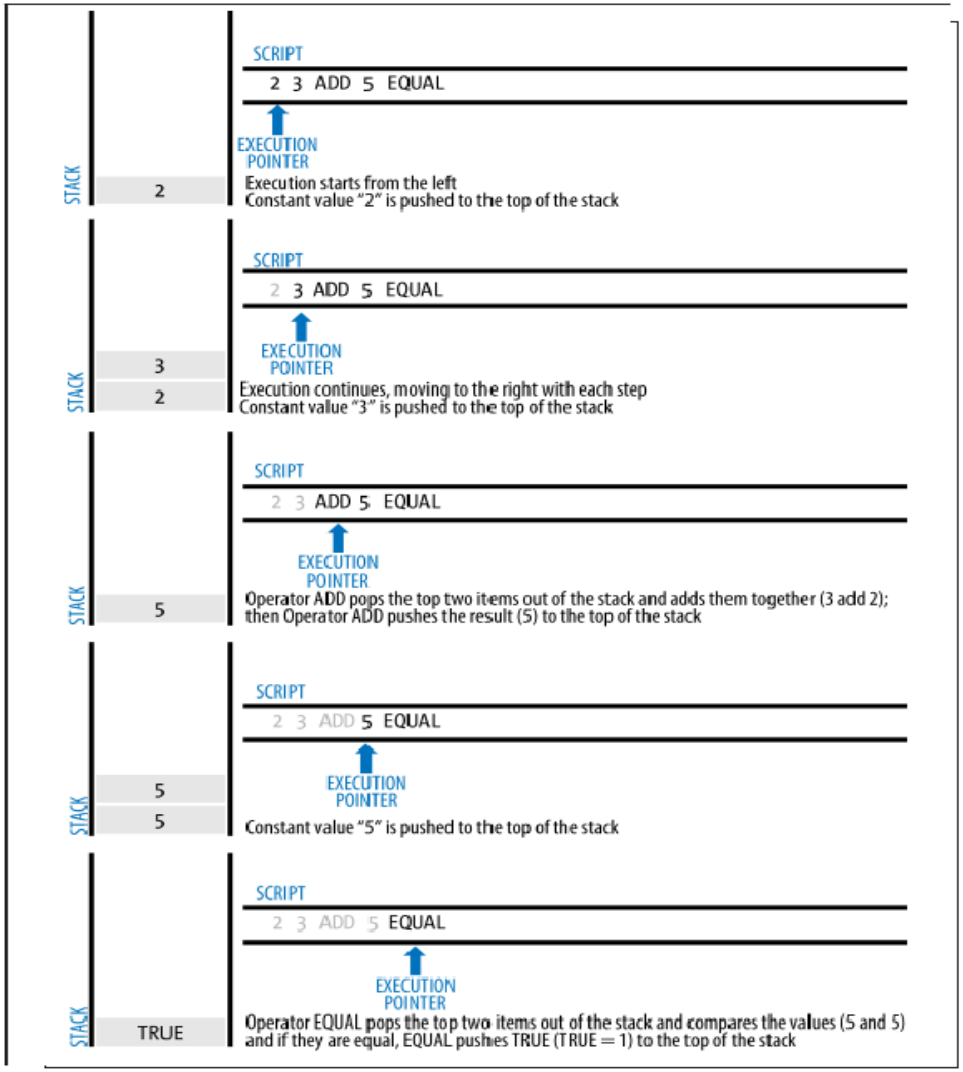
- simple, compact: one byte OPCODE, 256 instructions
  - basic arithmetic, basic logic (IF...THEN...ELSE), special purpose instructions to support cryptography
    - hashes
    - signature verification
    - multisignature verification

BITCOIN SCRIPTING LANGUAGE: DESIGN GOALS

There are 256 opcodes in total: 15 disabled, 75 working; they can be categorised as follows:

- Arithmetic, e.g. OP_ABS, OP_ADD
- Stack, e.g. OP_DROP, OP_SWAP
- Flow control, e.g. OP_IF, OP_ELSE (not while!)
- Bitwise logic, e.g. OP_EQUAL, OP_EQUALVERIFY
- Crypto for:
  - Hashing, e.g. OP_SHA1, OP_SHA256
  - (Multiple) Signature Verification, e.g. OP_CHECKSIG, OP_CHECKMULTISIG
  - Locktime, e.g. OP_CHECKLOCKTIMEVERIFY, OP_CHECKSEQUENCEVERIFY

STACK BASED EVALUATION



Pay-to-Public-Key-Hash (P2PKH)

- for example, Alice's pays 0.00015 bitcoin for a beer to Bob's Bar. Alice makes a payment to the Pub's bitcoin address.

- that transaction output contains a locking script of the form:

  OP_DUP OP_HASH160 <Bar Key Hash> OP_EQUAL OP_CHECKSIG

  where the Bar Key Hash is the bitcoin address of the Bar, the others are FORTH instructions

- The locking script can be satisfied with an unlocking script of the form:

  <Bar Signature> <Bar Public Key>

- The two scripts together would form a combines validation script, which must be executed by all nodes receiving the transaction:

<Bar Signature> <Bar Public Key> OP_DUP OP_HASH160
<Bar Public Key Hash> OP_EQUAL OP_CHECKSIG

P2PKH: SCRIPT EVALUATION

script_to_PubKey_hash (locks output):

```
OP_DUP OP_HASH160 <pubKeyHash> OP_EQUALVERIFY OP_CHECKSIG
```

scriptSig (unlocks output i.e. in input):

```
<sig> <pubKey>
```

script concatenation

```
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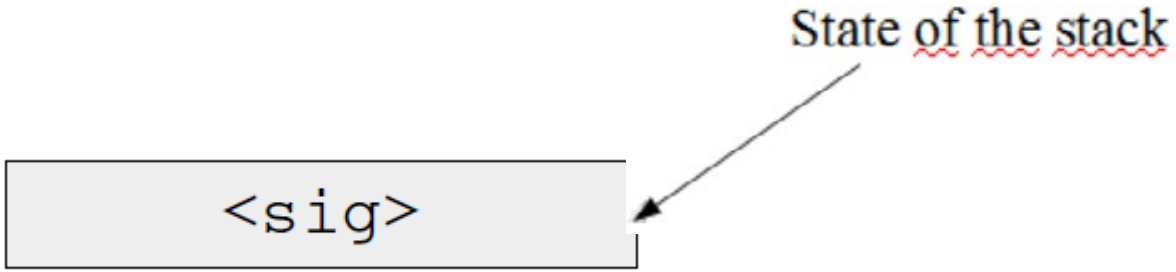

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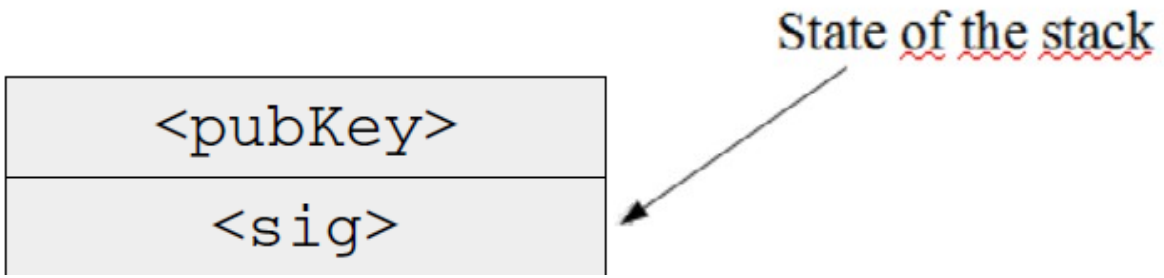

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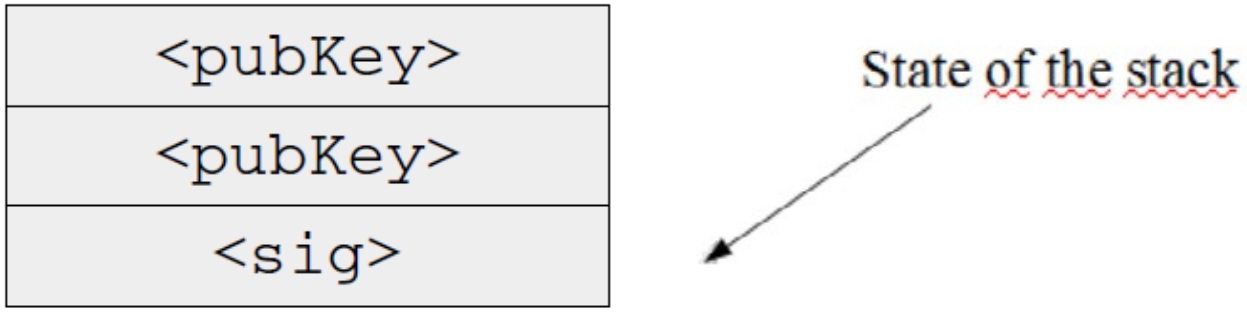

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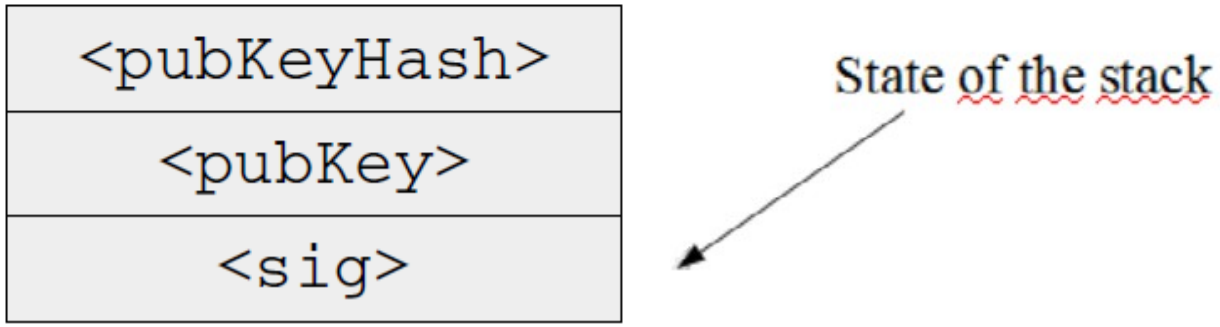

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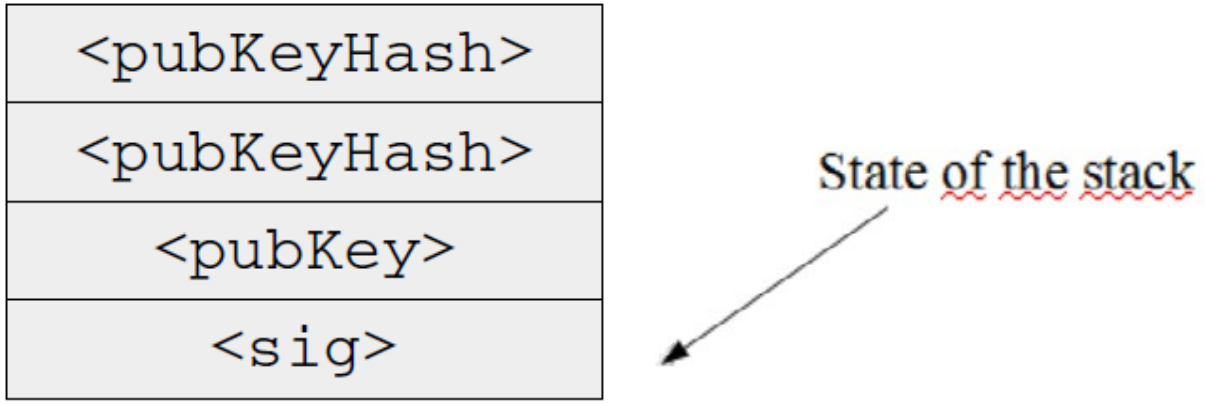

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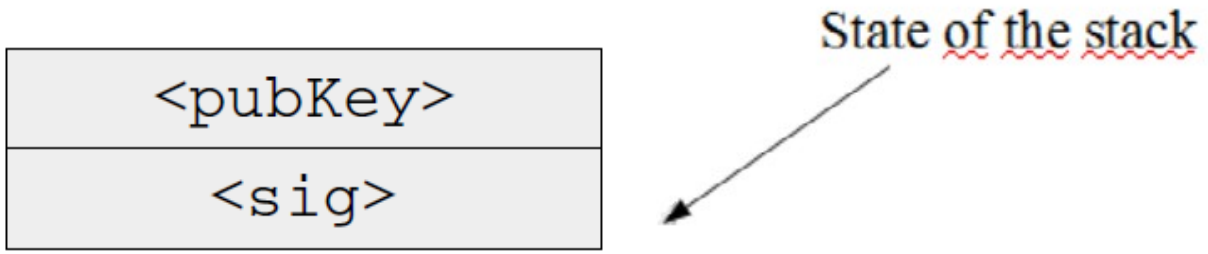

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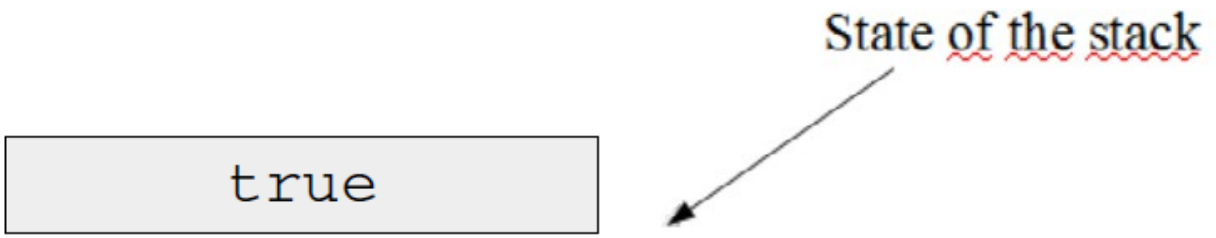
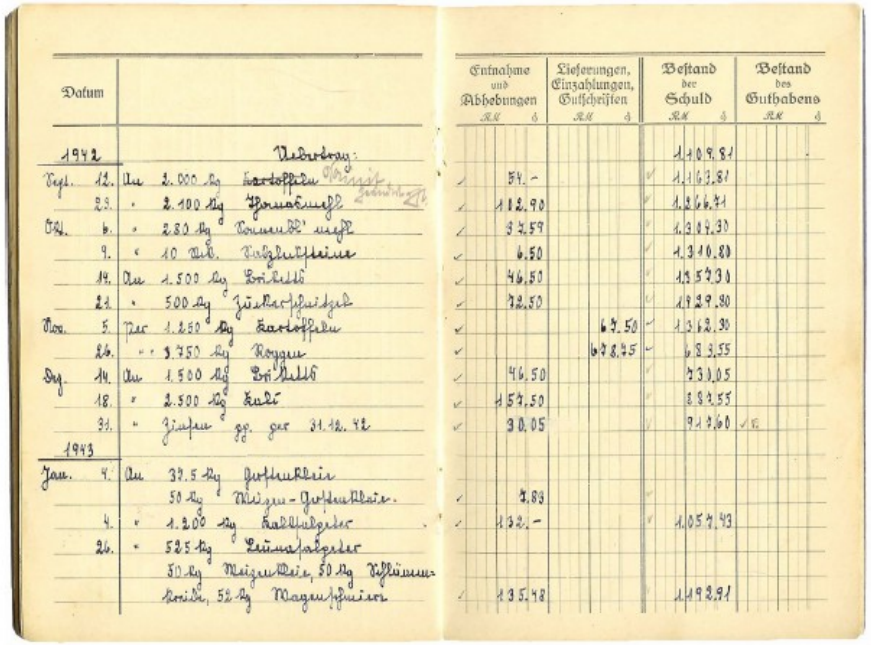


DATA OUTPUT (OP RETURN)

OP_RETURN <data>

- allows developers to add a certain amount bytes (40/80) of nonpayment data to a transaction output
- register the transaction output on the blockchain
- creates an explicitly provably unspendable output, which does not need to be stored in the UTXO set.
- OP_RETURN outputs are recorded on the blockchain, so they consume disk space and contribute to the increase in the blockchain's size
- they are not stored in the UTXO set, therefore do not increase the the RAM cost of full Bitcoin nodes

A DISTRIBUTED LEDGER OF TRANSACTIONS



- Bitcoin goal:
  - Maintain a ledger of transactions, like a bank, but.....
  - making everyone (collectively) the bank
- Define a shared public ledger recording all Bitcoin transactions.
  - everyone using Bitcoin keeps a complete record of which bitcoin belong to which person.
  - replicated on each Bitcoin user
  - eventually all the users have the same, consistent copy of the ledger
- this ledger is stored as a blockchain

A CONSISTENT LEDGER

- A simple (not working!) approach:
  - send each transaction to all the other peer of the P2P network
  - each peer register the transaction in its own ledger.
- Alice sends some bitcoins to Bob, she signs her transaction with her private key and broadcasts it on the P2P network. Bob
  - can use his copy of the ledger to check that, indeed, the bitcoin belongs to Alice and the public key of Alice to verify that the transaction comes from Alice
  - if all checks are ok, Bob will broadcast the transaction on the network
  - every peer updates its copy of the ledger with the new incoming transaction
- Alice can easily cheat by using this protocol
  - double spending her bitcoin
  - this naive protocol does not work!!

YOU CAN NOT DO IT BY YOURSELF!

- A double spending attack:
  - Alice sends a signed transaction to Bob
  - right afterwards sends the same bitcoins to Charlie
  - Bob's and Charlie's ledgers proves that the coin belongs to Alice
  - after checking the validity of the transations they both accept the transaction and broadcast it

- Double spending is detected if Charlie receives the notification from Bob before that the transaction from Alice, but.....
  - network does not maintain message ordering: transaction from Alice may arrive before notification from Bob
  - Alice may
    - use network traffic analysis and find times when there is a lot of latency in communications between Bob and Charlie
    - implement a DOS attack on the channel between Bob and Charlie

NEED OF DISTRIBUTED CONSENSUS

- take another approach: don't try to verify the transaction only by yourself, rather ask help to the network !

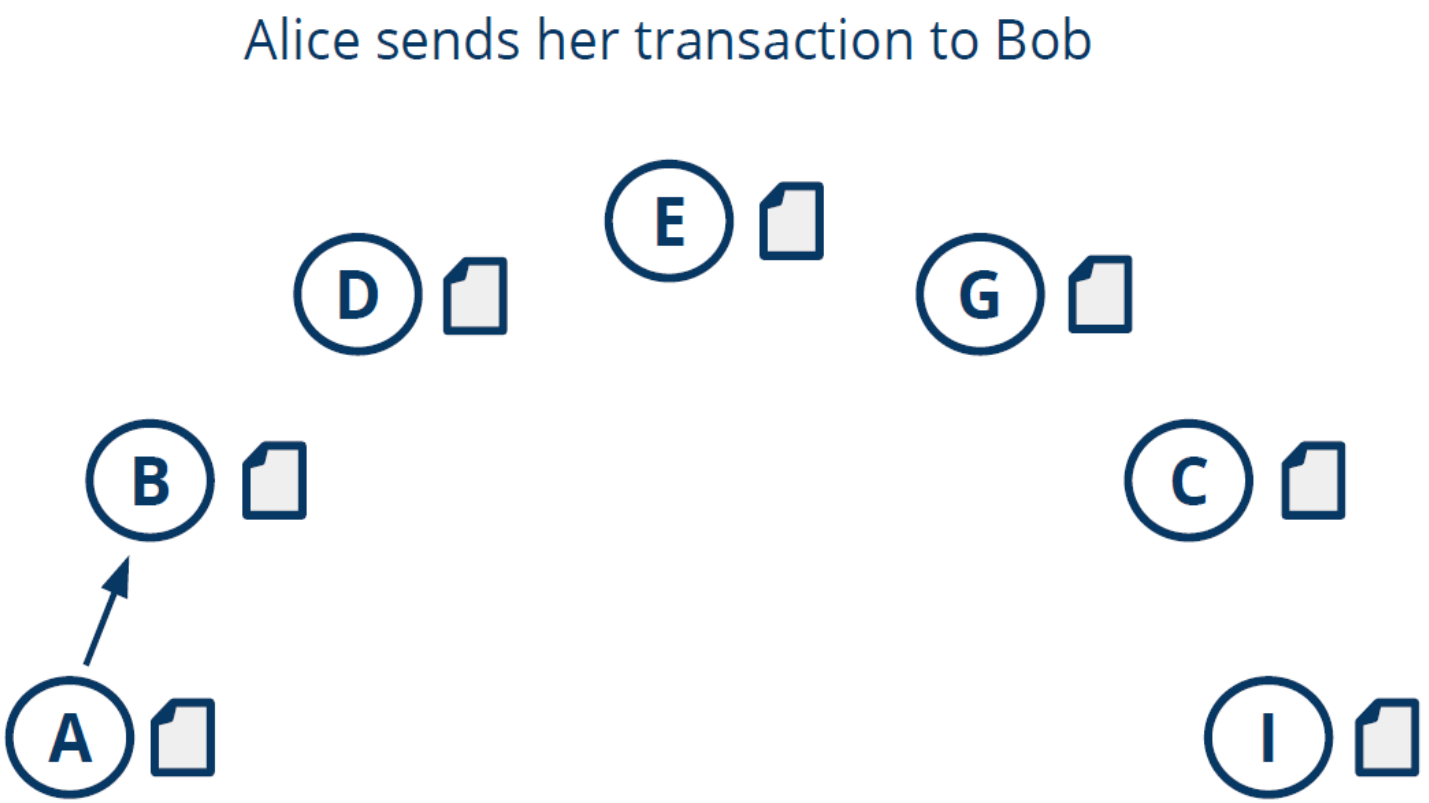
- requires an consensus algorithm, for instance:
  - all the nodes maintain
    - a ledger containing the transactions they have reached consensus on
    - a pool of transactions they have been received but not yet confirmed (not included in the ledger)
  - periodically, each node chooses a block of transactions to be included in the ledger
  - nodes collectively execute a consensus algorithm to decide
    - which block will be included in the ledger or to choose the one that will insert a block in the ledger
    - nodes may be malicious
    - what does majority mean in presence of malicious nodes?

NEED OF DISTRIBUTED CONSENSUS

Making everyone the bank.

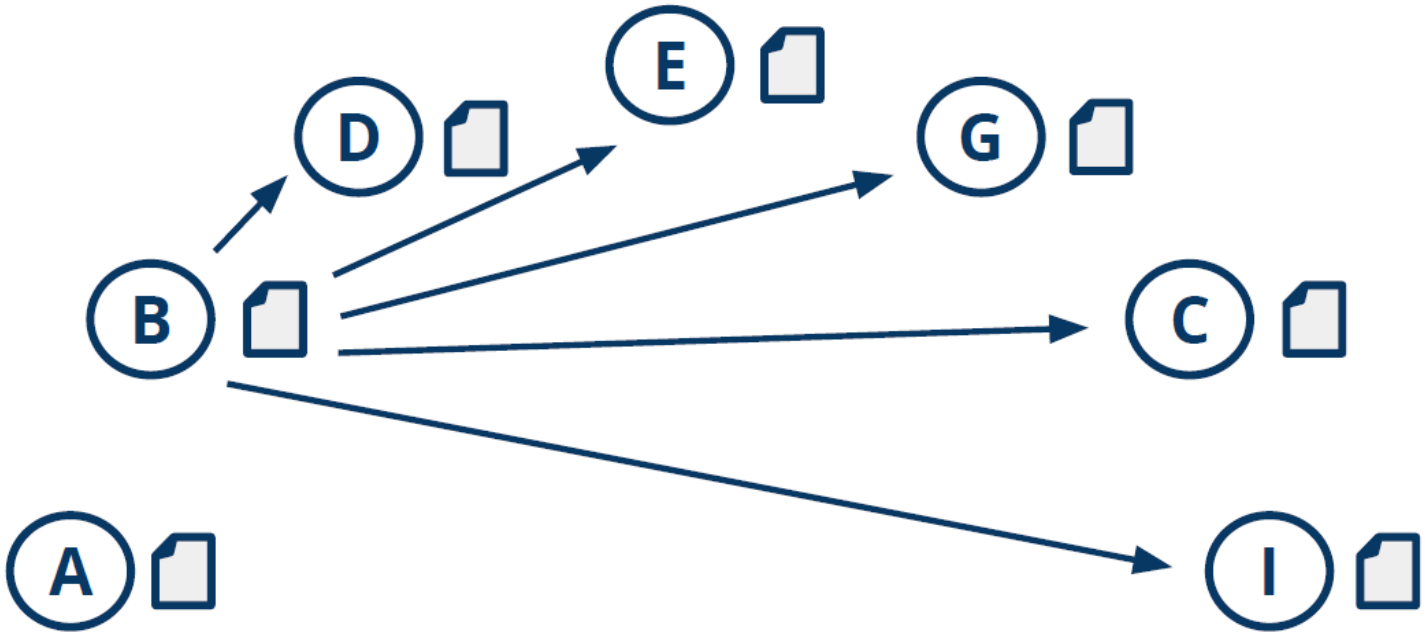
Everyone has a complete record of transactions

NEED OF DISTRIBUTED CONSENSUS



NEED OF DISTRIBUTED CONSENSUS

Bob announces the transaction to the world



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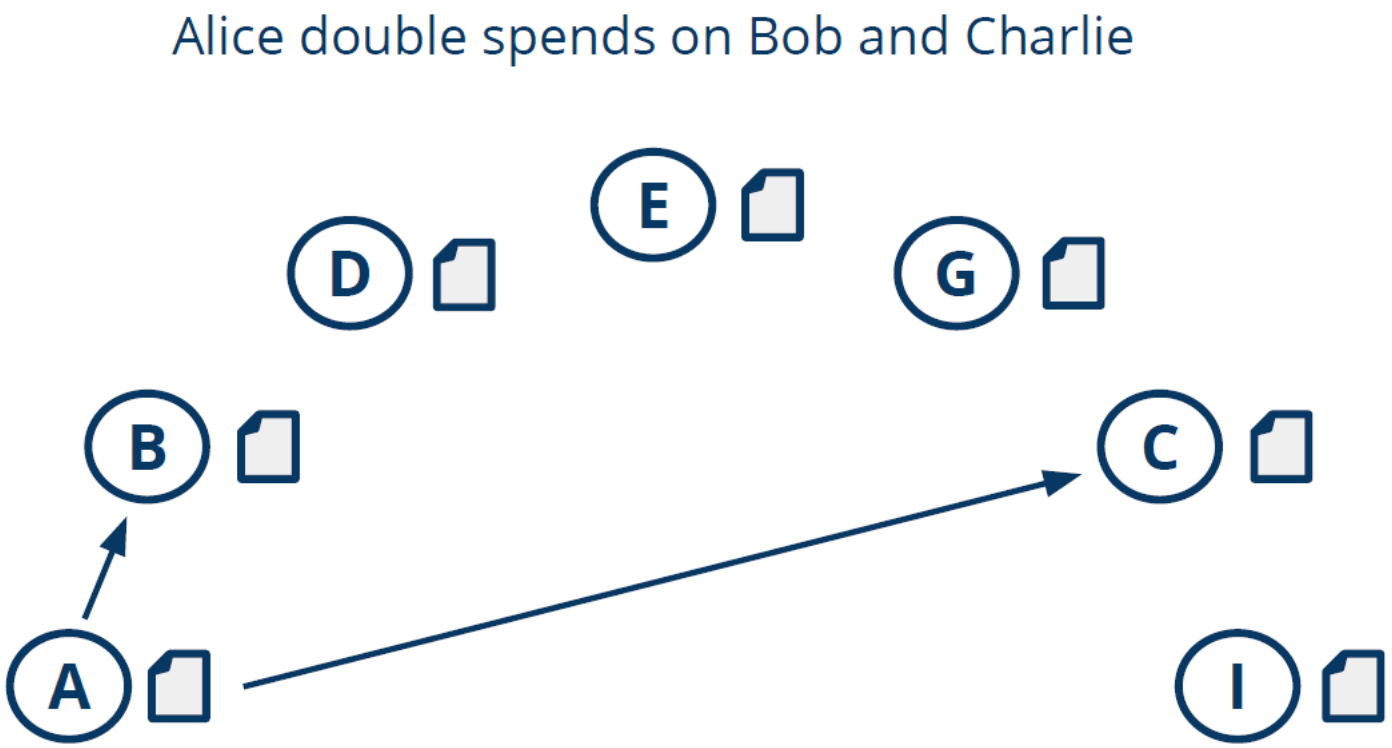

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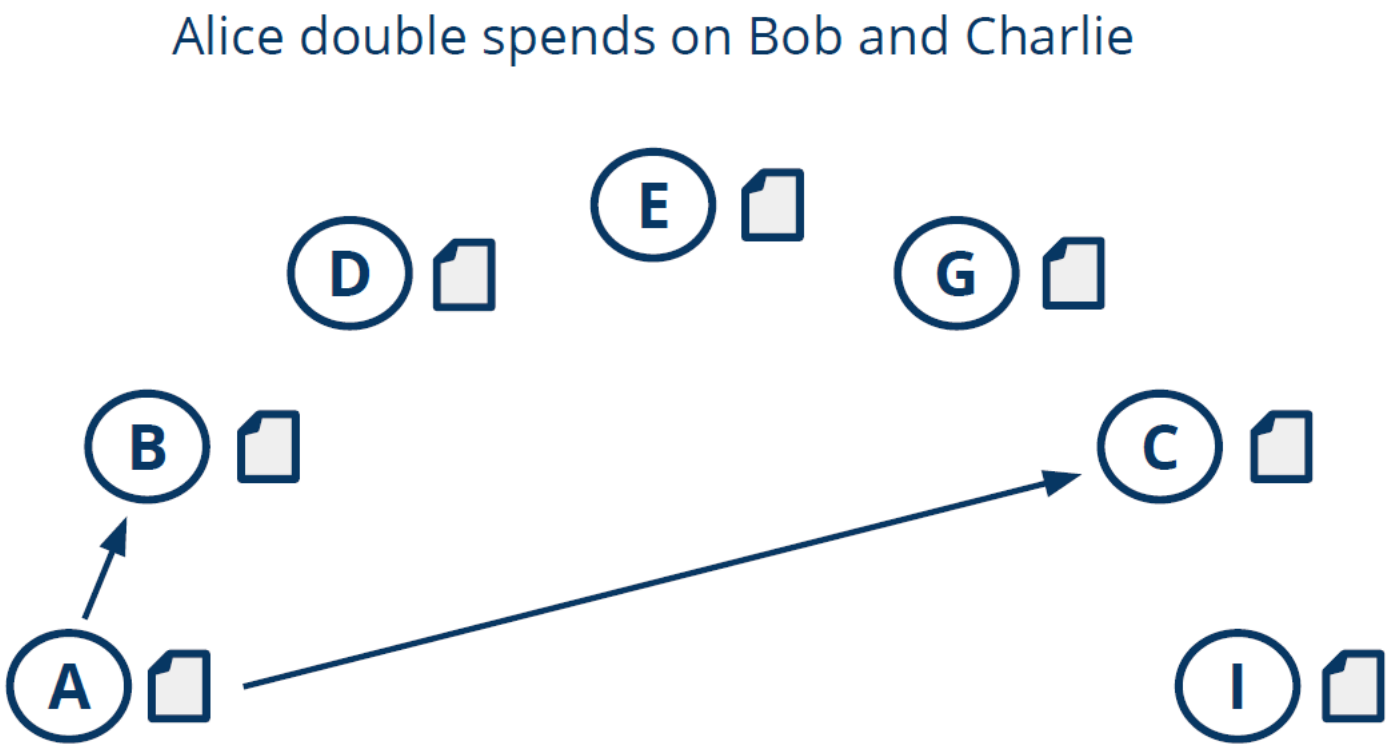

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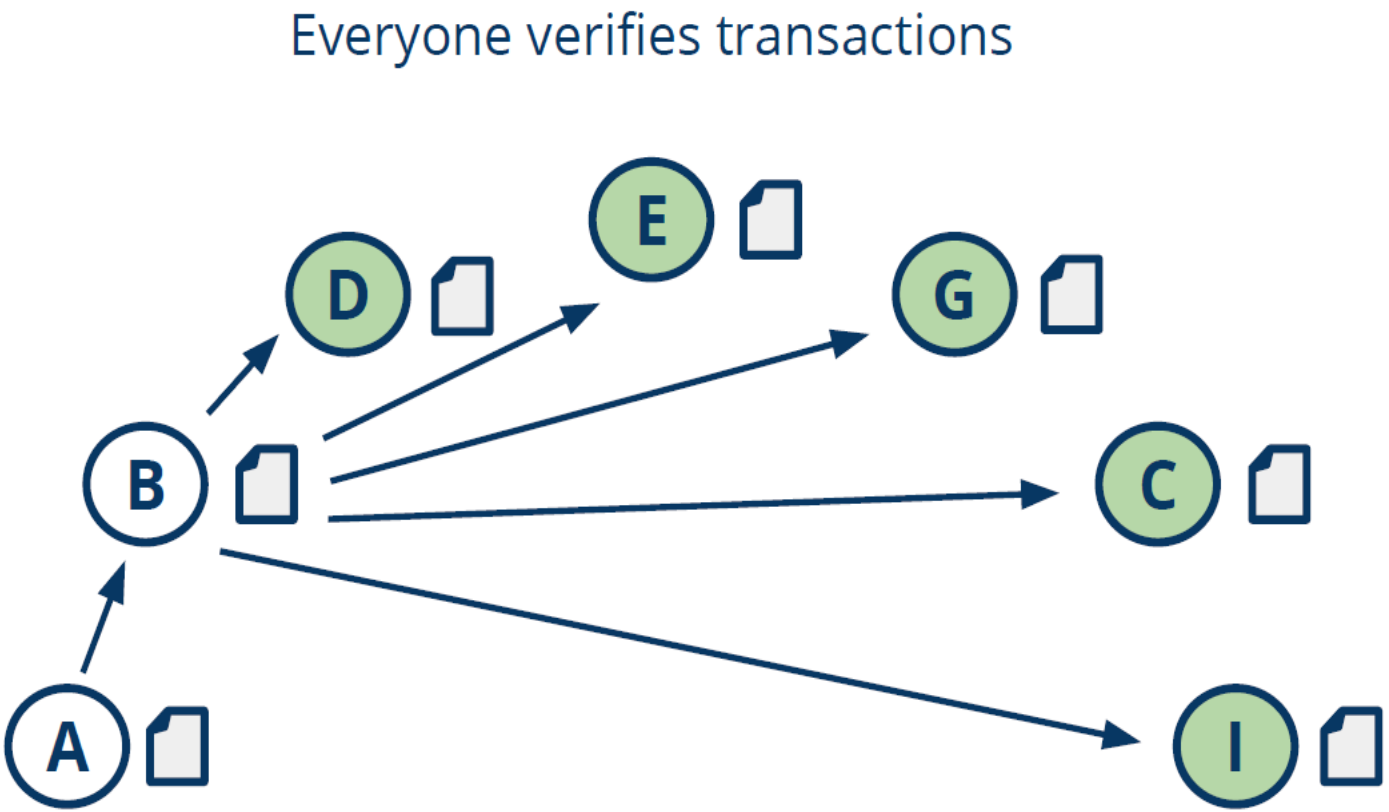
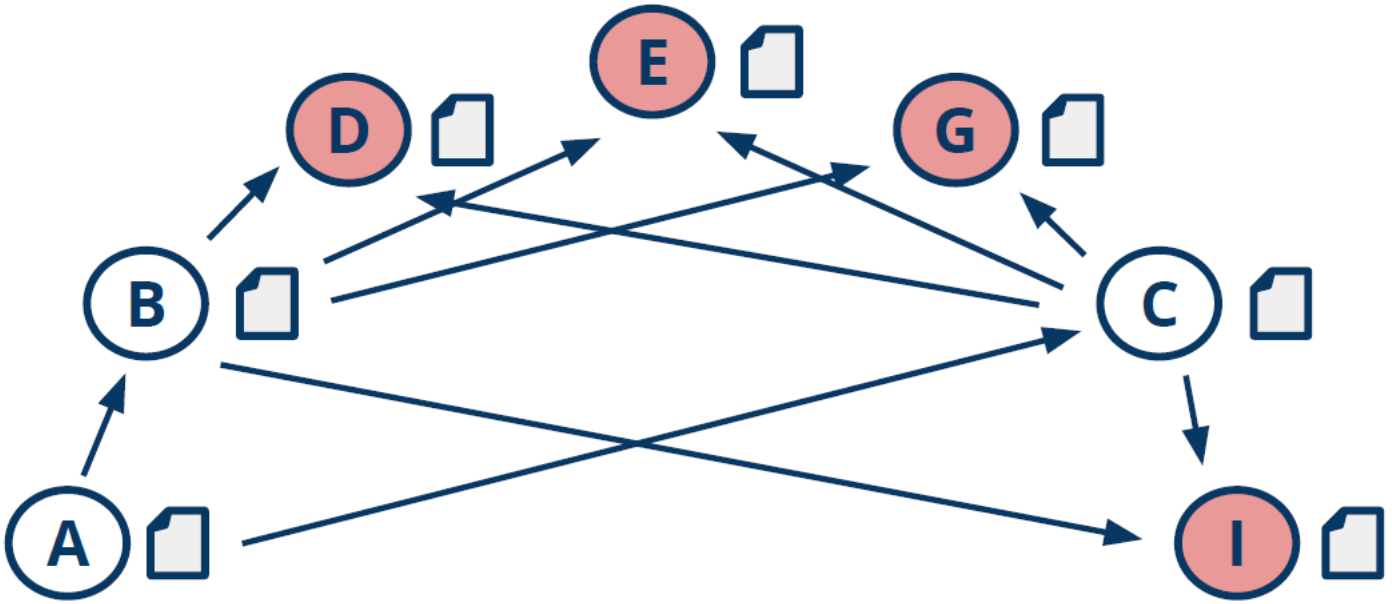


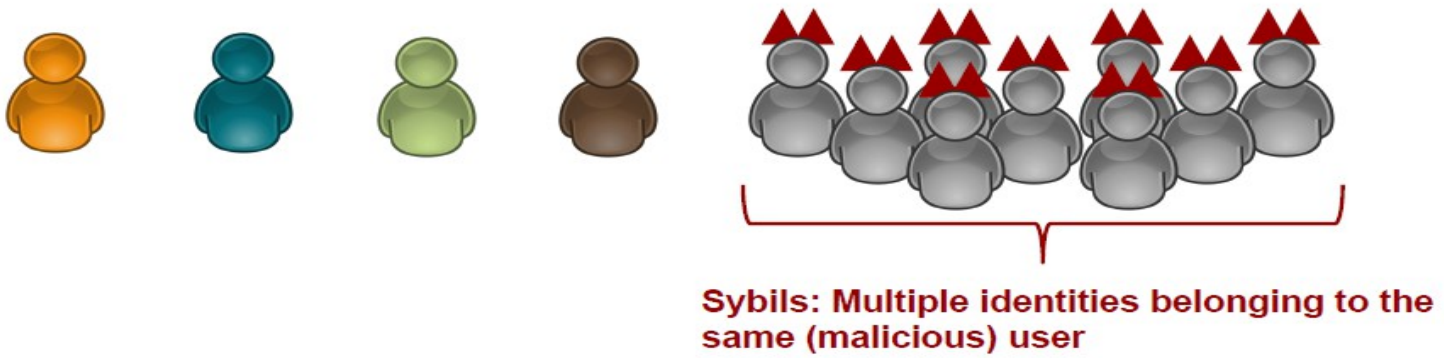
NEED OF DISTRIBUTED CONSENSUS

Alice is prevented from double spending



SYBIL ATTACK

- Sybil attack: in this attack a node in a P2P network claims multiple identities
- is avoided in systems where a central authority assigns identities to partecipants

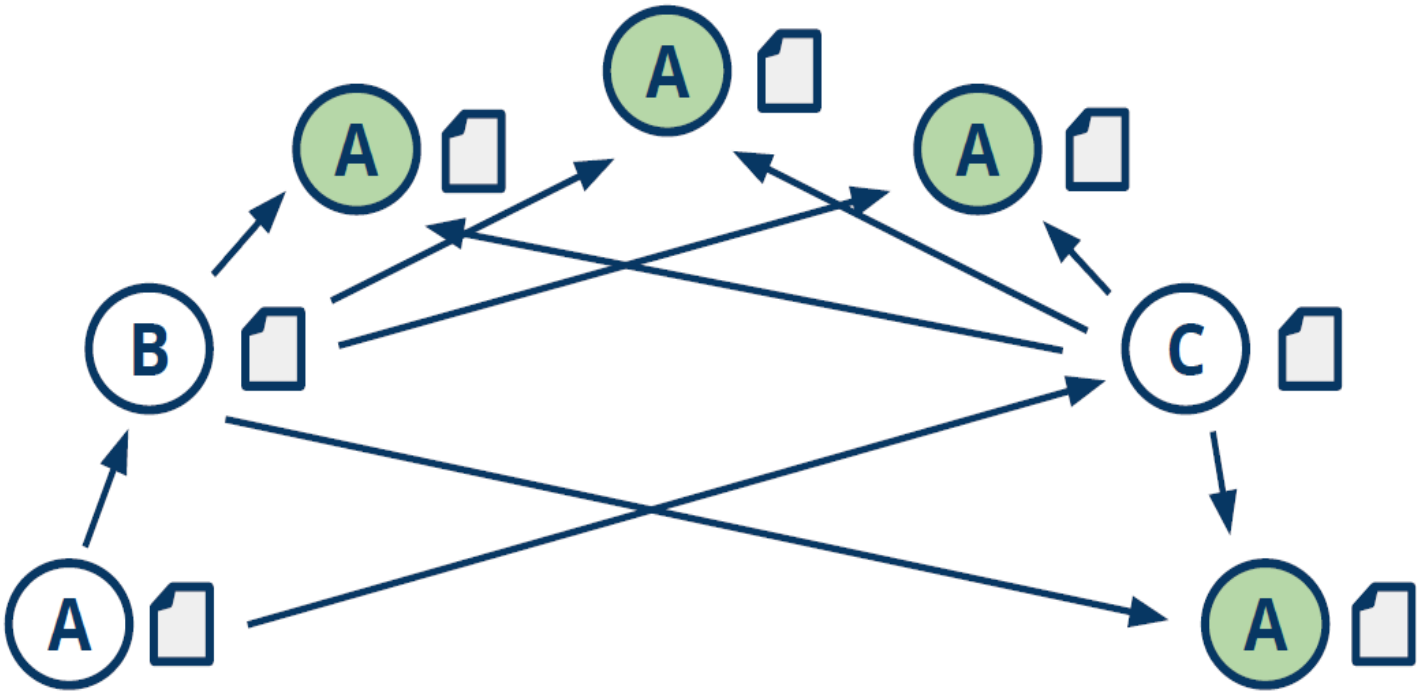


- consensus is even more hard in Bitcoin:
  - everyone is free to participate
  - because of pseudo-anonimity, nodes do not have persistent, long term identities,
  - a node can autonomously generate as many addresses as he/she wants

NEED OF DISTRIBUTED CONSENSUS

Alice double spends with her multiple identities

Sybil Attack: Creating many fake identities to subvert a system



CONSENSUS APPROACHES

Distributed consenus has been widely studied in the last 30 years

- Byzantine agreement
- Paxos
- Zab
- Raft
- Viewstamped Replication
- ……

EXPLICIT CONSENSUS AND BITCOIN

- The approaches in the previous slide exploit forms of explicit consensus: nodes execute a distributed algoritm to reach consensus
  - ...but they do not work for Bitcoin, why?

- in peer to peer networks, due to the high churn
  - nodes do not know each other a-priori
    - nodes come and go
    - anyone can join
  - no authenticated channels
  - no network synchronization

- even if we consensus has been studied for more than 30 years, relative little knowledge about this new model
  - classical algorithms, like Paxos, do not work.

A NEW SOLUTION: NAKAMOTO CONSENSUS

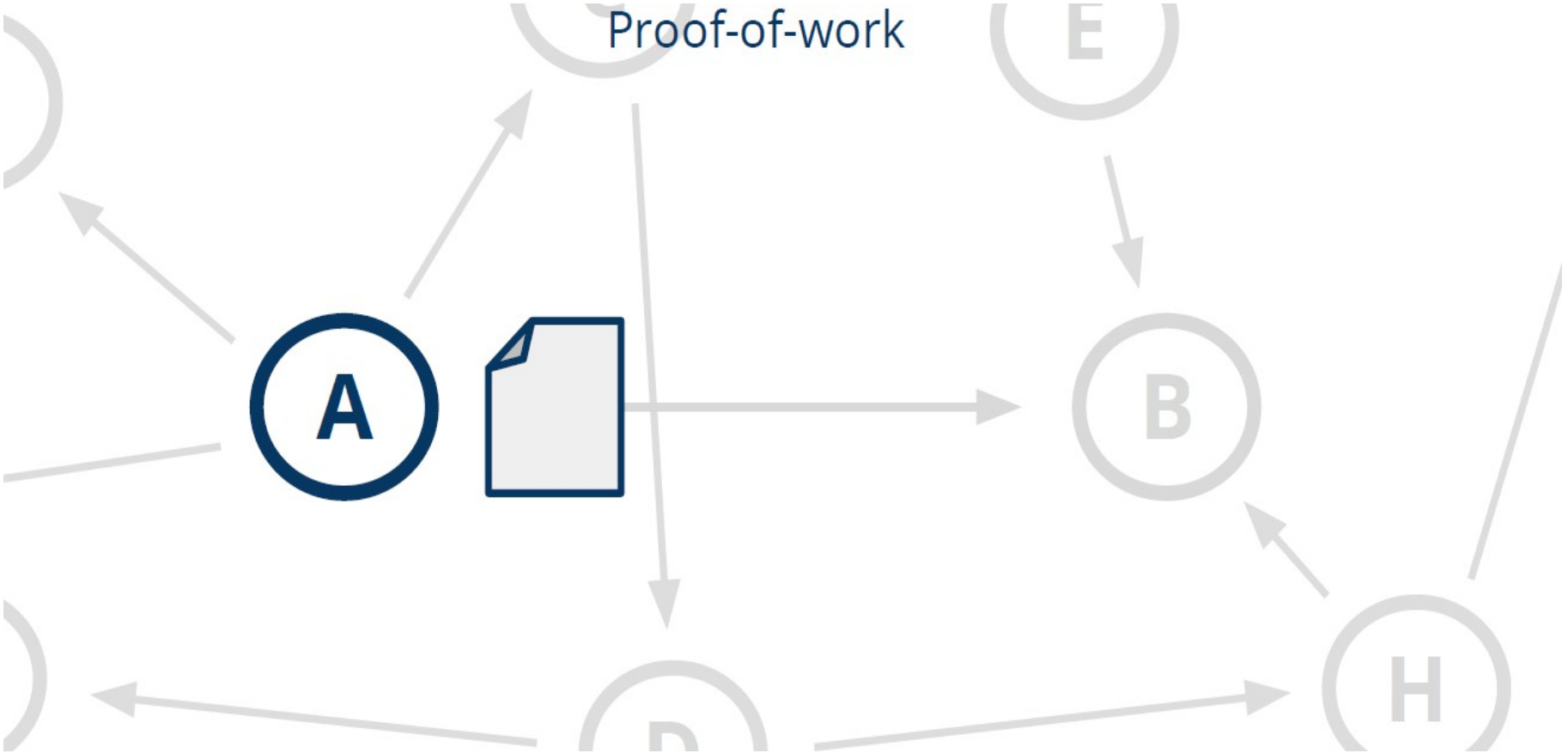
- prevents Sybil attacks with Proof-of-Work Puzzles
- claims blockchain mantains "public ledger" assuming "a particular notion of majority of honest nondes":
  - consistency: eventually everyone sees the same history
  - everyone can add new transactions
- it works in practice, difficult to make theoretical proofs (even if some work have been recently presented).
  - overcomes several impossibility result for unathenticated model

"*...the mechanism through which Bitcoin achieves decentralization is* ***not purely technical,*** *but it's a combination of technical methods and* ***clever incentive engineering***."

NAKAMOTO CONSENSUS

- let us suppose, for the moment, that:
  - it is possible to pick a random node in the network
    - like picking a random token in a lottery
  - at least 51% of the time, this process will pick an honest node.
- the consensus protocol:
  - at each round: select a node n at random
  - n unilaterally proposes, without contacting other nodes, the next block of transactions to be inserted in the ledger (from the unconfimed transactions)
    - can be viewed as a random leader election on every block
  - n broadcasts it in the network
  - all nodes check the validity of the block and update their blockchains with the new chosen block

NAKAMOTO CONSENSUS



The next transaction (block of transaction) is chosen by a single node, which should be, with high probability, a honest node

NAKAMOTO CONSENSUS

- An implicit consensus approach:
  - no collective distributed algorithm executed by the nodes
  - no voting
  - selection of malicious nodes is also implicitily handled by the system
- even if the nodes may have occasionally an inconsistent view of the ledger (blockchain forks) consensus will eventually occur
  - the consistent ledger will eventually be the longest chain
  - This is true if the majority of the nodes are honest

RANDOM NODE SELECTION

- how to select a random node at each round?
- the key idea: node are selected in proportion to a resource that it is hard to monopolize
- in Bitcoin this resource is computational power and selection is done on the basis of the Proof of work

Proof of work

- nodes which try to solve the proof of work are called miners and the whole validation process is called mining

PROOF OF WORK

- A proof of work (PoW) is a mechanism that allows a party to prove to another party that a certain amount of computational resources has been utilized for a period of time.
- Based on puzzles that can be solved, but require a considerable effort which cannot be short-circuited
- it must be possible to verify the effort made to solve a PoW in a easy way
  - verification requires less time with respect to the time needed to conduct the PoW
- many applications of the this technique:
  - deterring DOS attacks
  - deterring e-mail SPAM
  - Bitcoin mining

PROOF OF WORK AND DOS ATTACKS

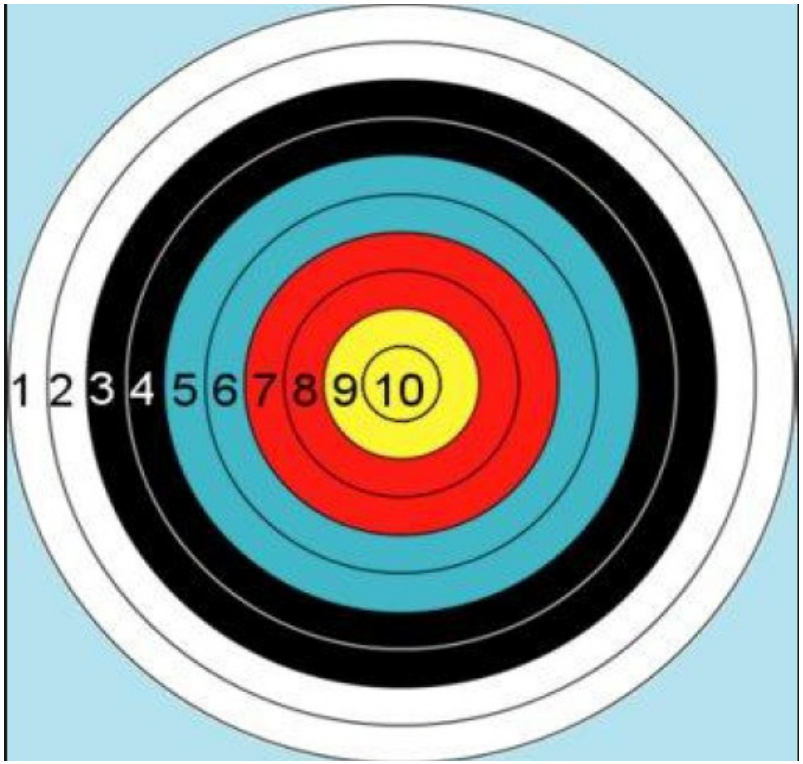
deterring of denial-of-service attacks:

- allow users access to a particular service only if they solve a highly computationally expensive problem
- the computational effort required is effectively a way to throttle the requesters
- it must be easy for the service provider to check if the requester carried out the required work
  - only if that work was carried out the service is given.

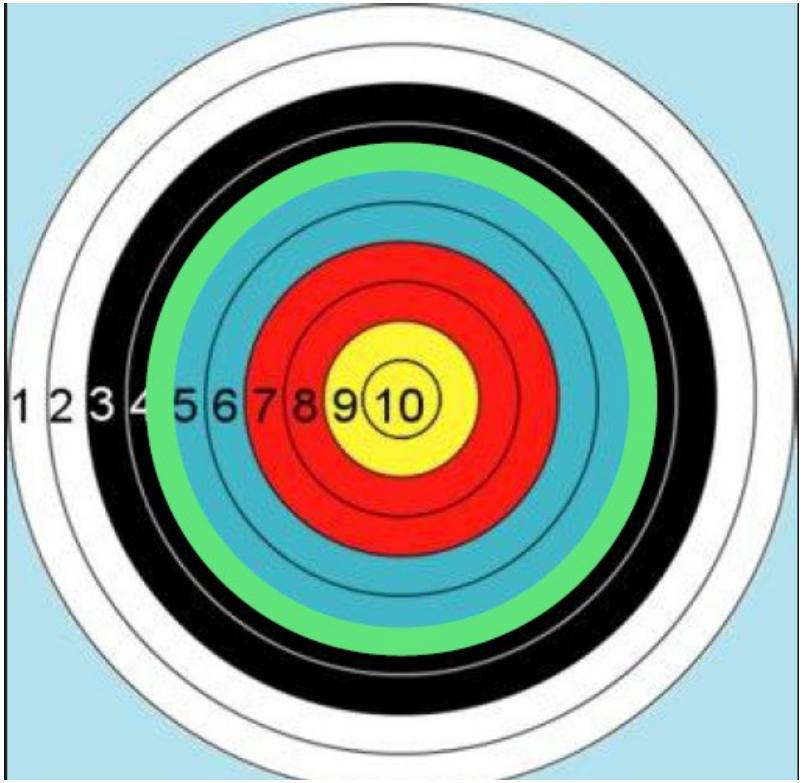
PROOF OF WORK AND EMAIL SPAMS

- a proof of work protocol may be tied to an email message
- like affixing a post stamp to a message
  - rather than paying for that stamp using money, pay for the stamp through CPU cycles
- if someone is sending out a small number of messages
  - the proof of work will not amount to a huge amount of work, because it is only executed a very small number of times
- for a spammer, who might be sending hundreds of thousands or millions of messages
  - it might be prohibitively expensive to use so many CPU cycles for each message it sends

PROOF OF WORK: A METAPHOR



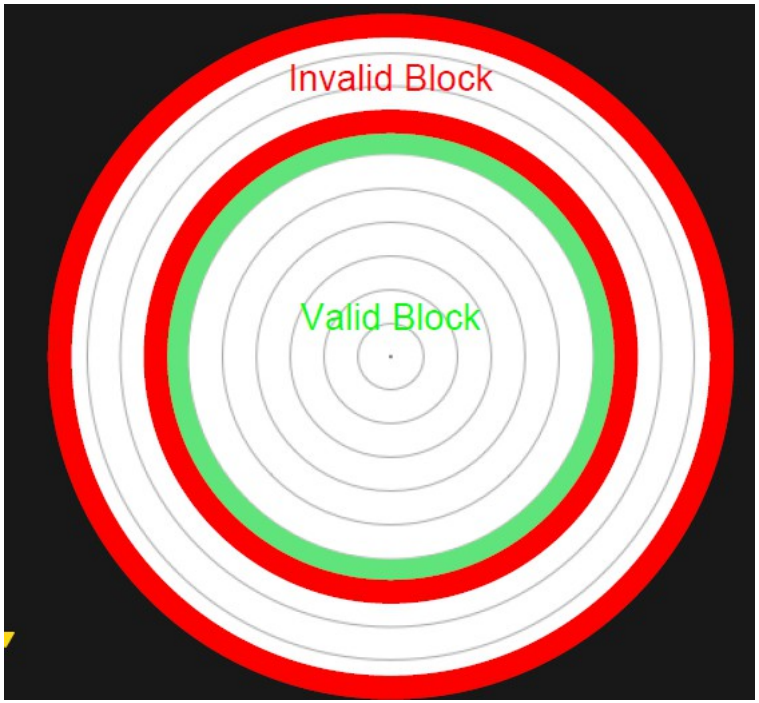
POW: TUNING THE DIFFICULTY



PROOF OF WORK: A METAPHOR

Proof of work is like throwing darts at a target while blindfolded:

- equal likelihood of hitting any ring
- faster throwers: more hit per seconds
- target: within the green ring
- difficulty: inversional proportional to green ring size
  - green ring adjuts depending on average time to produce valid results
  - If people get better at throwing darts, green circle needs to get smaller
  - It can be tuned to obtain the desired difficulty.



POW: A FORMAL DEFINITION

- Consider following notation:
  - d: difficulty, is a positive number which is used to adjust the time to execute the proof
  - c: challange is a string
  - x: nonce is a string

- a Proof-of-Work is a function:

$$F_d(c,x) \rightarrow \{true,false\}$$

which satisfies the following properties:

  - d and c are fixed
  - find x such that $F_d(c,x)$ = true is computationally difficult, but feasible.
  - $F_d(c,x)$ is fast to compute, if d, c, and x are fixed

PROOF OF WORK: HOW DOES IT WORK?

- given challenge string, c, define a proof which is tied to this string
- the challange string may be:
  - for spams, the whole message.
  - for Bitcoin: the header of a block containing a set of transactions
- the prover must find and return a proof nonce string
  - the prover must give a response that has a specific mathematical property in relations to the challenge
- for instance: given the challange c find a nonce p such that

  the output of a cryptographic hash (HASH-256) applied to the concatenation of c and p satisfies some property
- example of property: the output must have a prefix of 0 of predefined length

BITCOIN PROOF OF WORK

$$\mathcal{F}_d(c, x) \rightarrow \mathrm{SHA256}(\mathrm{SHA256}(c|x)) < \frac{2^{224}}{d}.$$

- double hash of the concatenation of the challenge c and the nonce x, using SHA256
- find the nounce such that the hash of the entire block (including the nonce) starts with a given number of zero bits.
  - by incresing d the number of zeros in 2^{224}/d decreaeses
- the output of SHA256 is a cryptographic hash with a numeric value in {0.. 2^{256-1}} which is compared to a target value 2^{224}/d , which gets smaller, when increasing the difficulty.
- In Bitcoin

SHA256(SHA256(prev_hash || BlockHeader || nonce))<target

PROOF OF WORK: HOW DOES IT WORK?

- In a good cryptographic hash function the only known way to find the response string is to try a huge number of distinct alternatives.
  - brute force: trying a lot different proposed strings until you find one that works
  - If we require that the output has a prefix of x consecutive zeros this would require, on the average, to try 2^x possibuilities
    - but if you are lucky, you will resolve it faster
  - a lot of computational power !

- But... it is easy to be verified: if someone proposes a nounce, it is very easy to validate it is a correct proof of work
  - take the challange and the nounce and hash them together
  - if the output produced by the PoW has the required number of leading zeros, the PoW is valid

PROOF OF WORK: HOW DOES IT WORK?

Why brute force is the only possible approach?

- what makes proof of work hard to solve?
  - the output from a cryptographic hash function behaves like a random number
  - each output bit looks like coin flips (0/1)
  - change the input a bit and the output from the hash function changes completely
- so no better way of finding the correct output than trying by brute force
  - the probability to find out the right output is very small!

PROOF OF WORK: HOW TO SOLVE IT?

An example of a simplified PoW

- c = "Hello, world!" and nonce x = 0 then (output is in hexadecimal)

h("Hello, world! 0") = 1312Af178c253f84028d480a6adc1e25e81caa44c749ec81976192e2ec934c64

- first with x = 0 is a failure, since the output does not begin with any zeroes at all, try nounce x = 1

h("Hello, world! 1") = e9afc424b79e4f6ab42d99c81156d3a17228d6e1eef4139be78e948a9332a7d8

- keep trying different values for the nonce, x = 2, 3,.... finally, at x = 4250 obtain:

h("Hello, world! 4250") = 0000c3af42fc31103f1fdc0151fa747ff87349a4714df7cc52ea464e12dcd4e9

success if the proof of work requires 4 leading zeros !

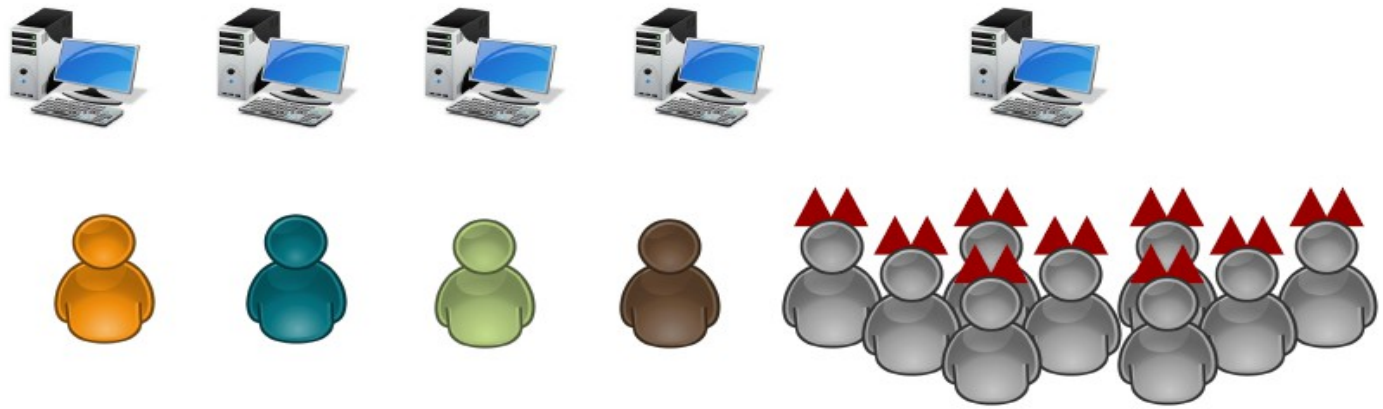
MINING A BLOCK

- But who is solving the PoW?
- Bitcoin miner must:
  - verify incoming transactions by checking signatures
  - create a block of transactions collected valid transactions
  - find the nounce, starting from the block header (the core mining process)
  - hope that your block is accepted by other nodes and not defeated by competitor nodes
  - if its is accepted, reward is yours!

NAKAMOTO CONSENSUS AND SYBIL ATTACKS

- Benefit of making it costly to propose new blocs of validated transactions: validation
  - is no longer be influenced by the number of network identities the attacker controls
  - influenced instead by the total computational power the attacker brings to bear on validation.
- a cheater would need enormous computational resources to cheat, making it impractical
  - sybil attack becomes difficult to implement
- reformulate the initial hypothesis:
  - require that the majority of miners, weighted by hash power, are honest, i.e. follow the protocol
  - further, give incentives to miners for being honest!

NAKAMATO CONSENSUS AND SYBIL ATTACKS



- majority of honest nodes refer to majority of miners
- majority defined as the majority of computational power
- note that Sybil creation does not increase attackers computational power !

MINING PROCESS: RECAP

A simplified proof of work algorithm

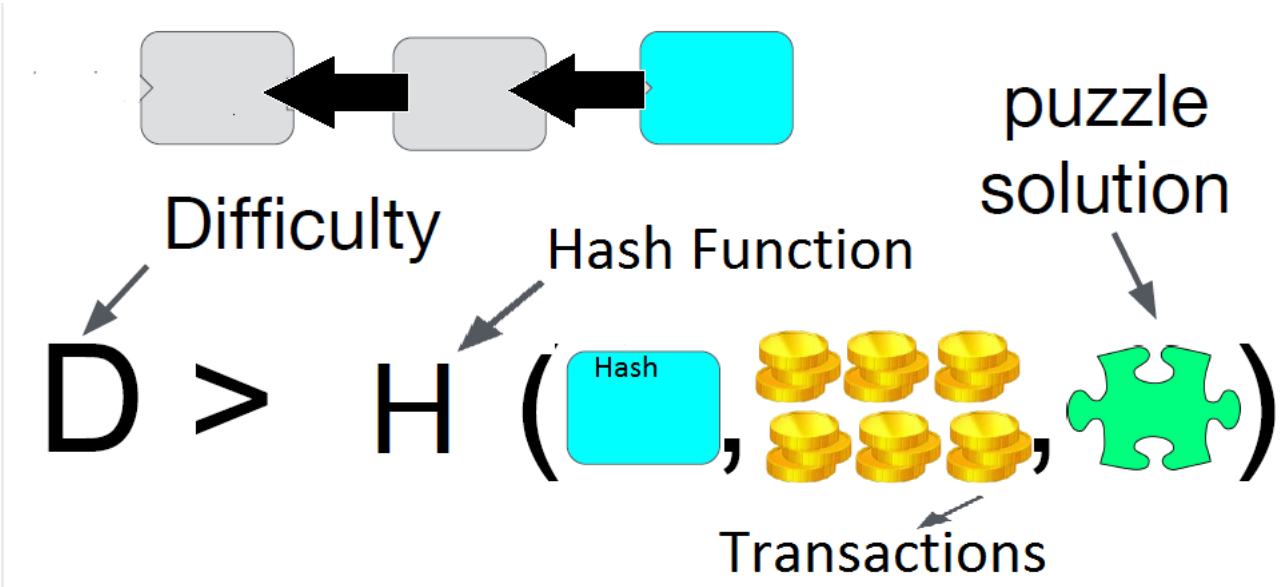
Nonce x = 0, challenge c, difficulty d, previous block b_{t-1}

repeat

x = x + 1

until $F_d(c, x)$ = true

broadcast block b_t = (memory-pool, b_{t-1}, x)



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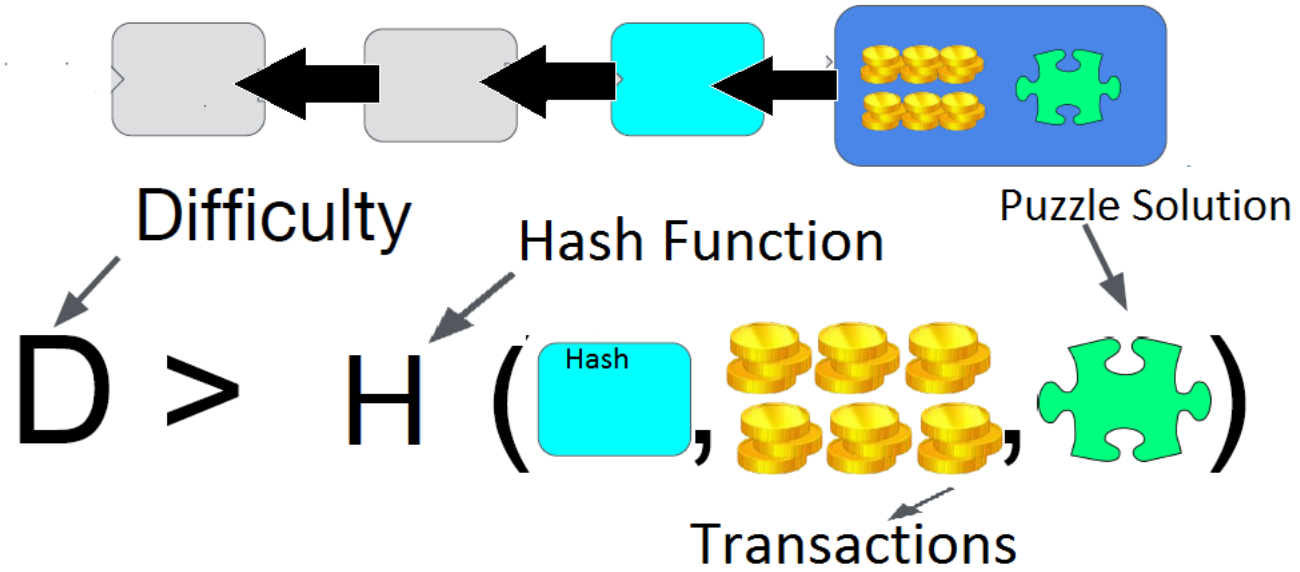
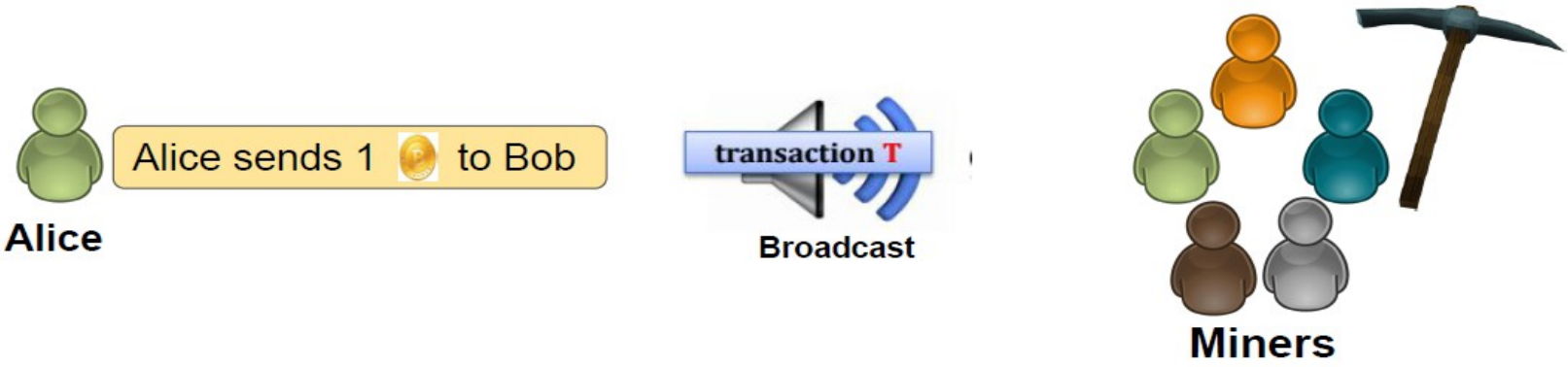
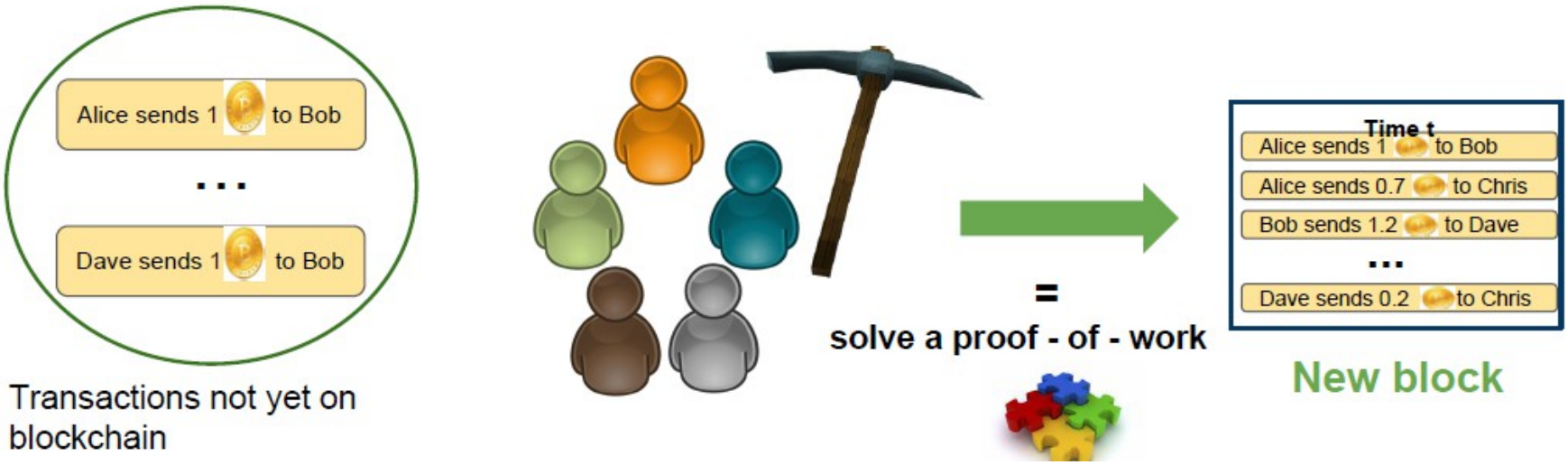


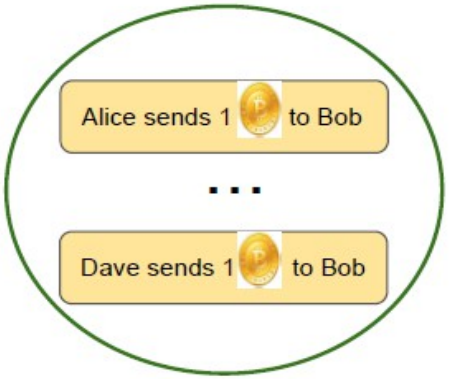
MINING PROCESS: RECAP



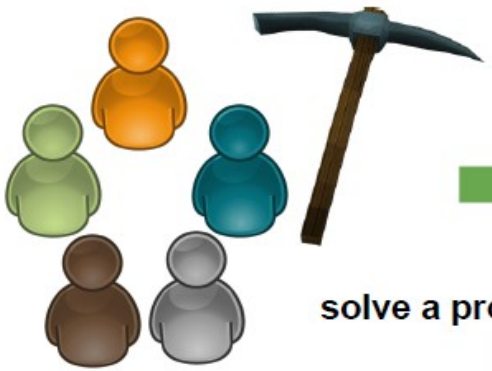
Miners compete on who will be able to propose the next block.



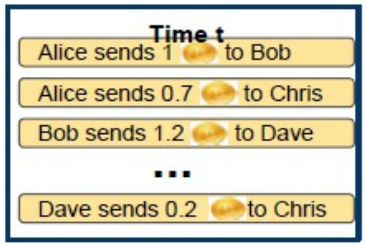
MINING PROCESS: RECAP



Transactions not yet on blockchain

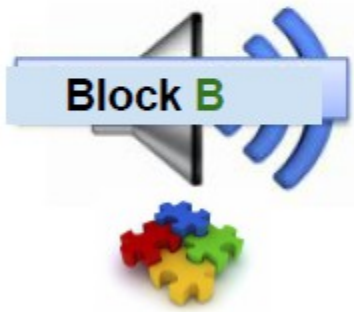


= solve a proof - of - work



New block

I found a new block!

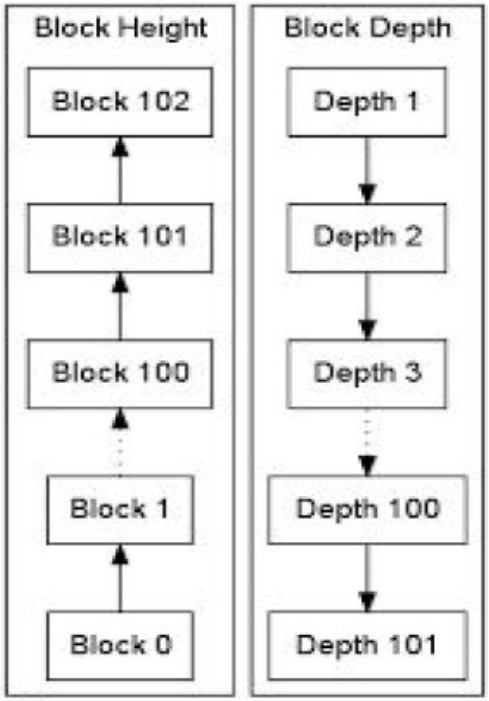


And to other nodes

CREATINGA BLOCKCHAIN

- A miner which can to solve the PoW, for a block, links the block to the previous one
  - The block contains the hash of the previous one

- The result is a chain of blocks, the blockchain
  - block: contains a bunch of transactions
  - the entire set of blocks chained together

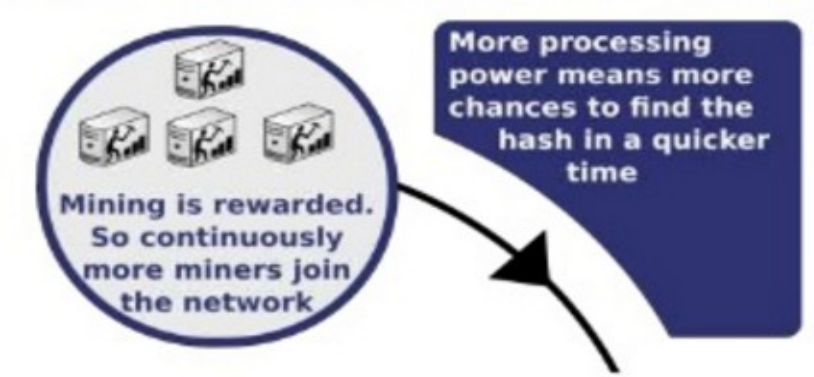


ADJUSTING THE POW DIFFICULTY

- one of the goals of the Bitcoin protocol is to have a block mined every 10 minutes
- mining frequency depends on the difficulty of the PoW and on the number of miners power n the network
- mining power is continously added to the network
  - miners can enter the network whenever they want
  - miners are incentivates to enter, becuse of
    - the fees they receive
    - a reward for having mined a block
  - no centralized control
  - the more miner, the more computational power, the more it is easy to find a block
- the time to find a new block decreases

ADJUSTING THE POW DIFFICULTY

ADJUSTING THE POW DIFFICULTY



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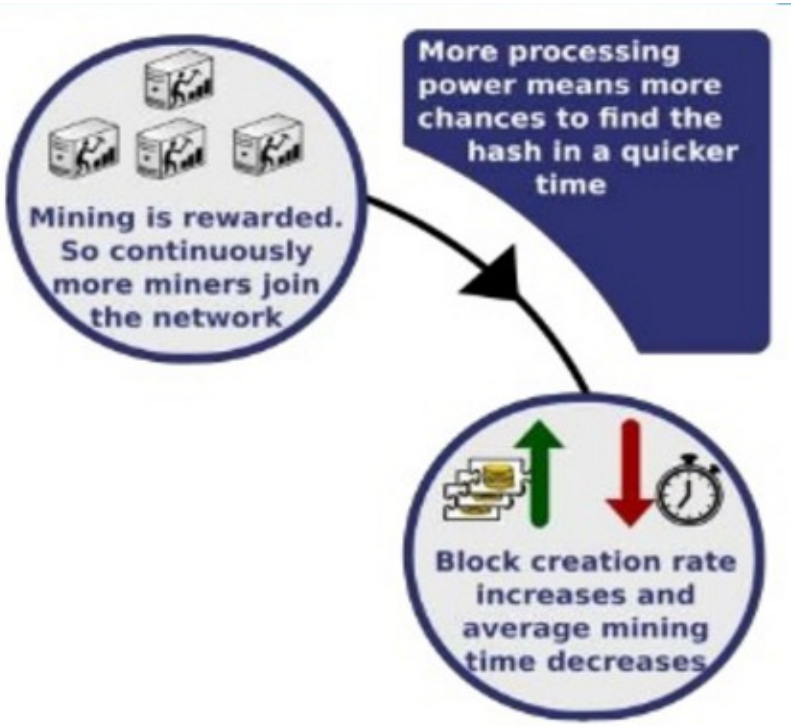

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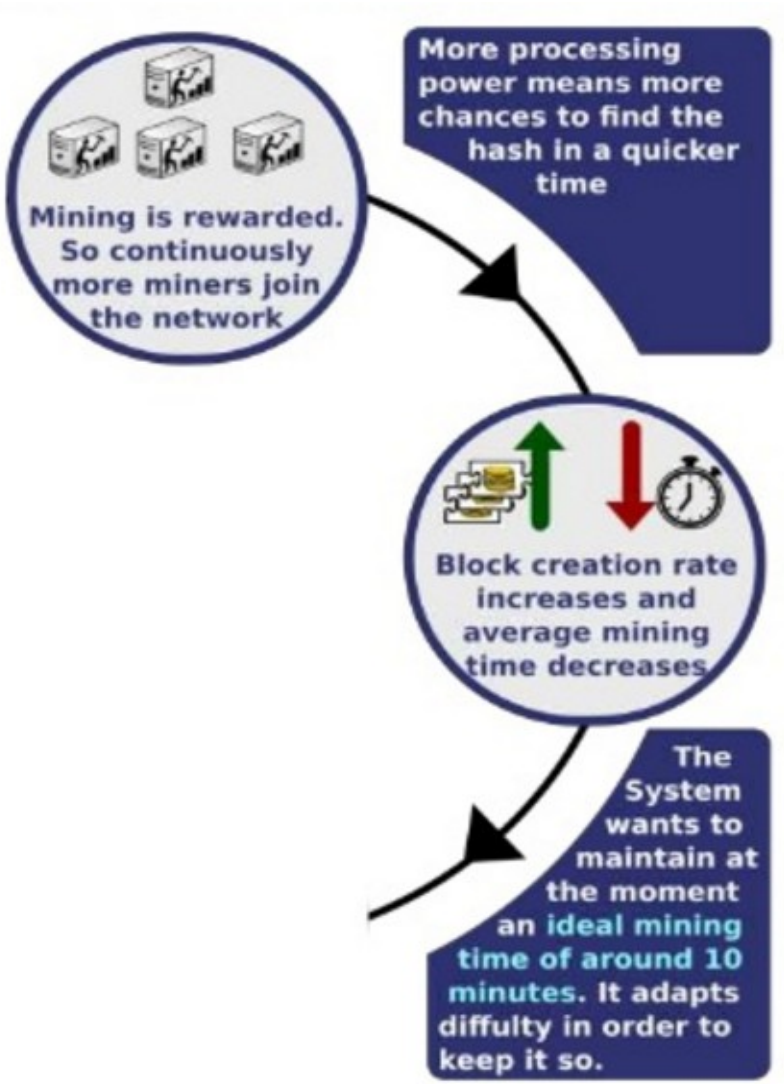

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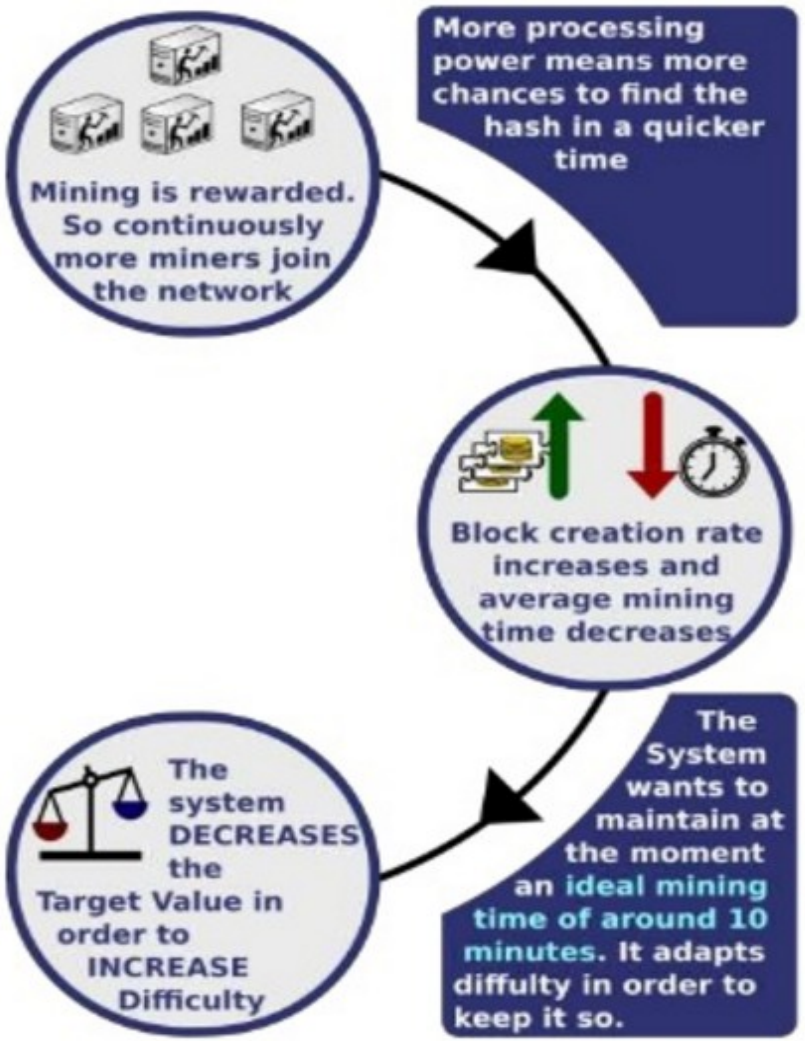

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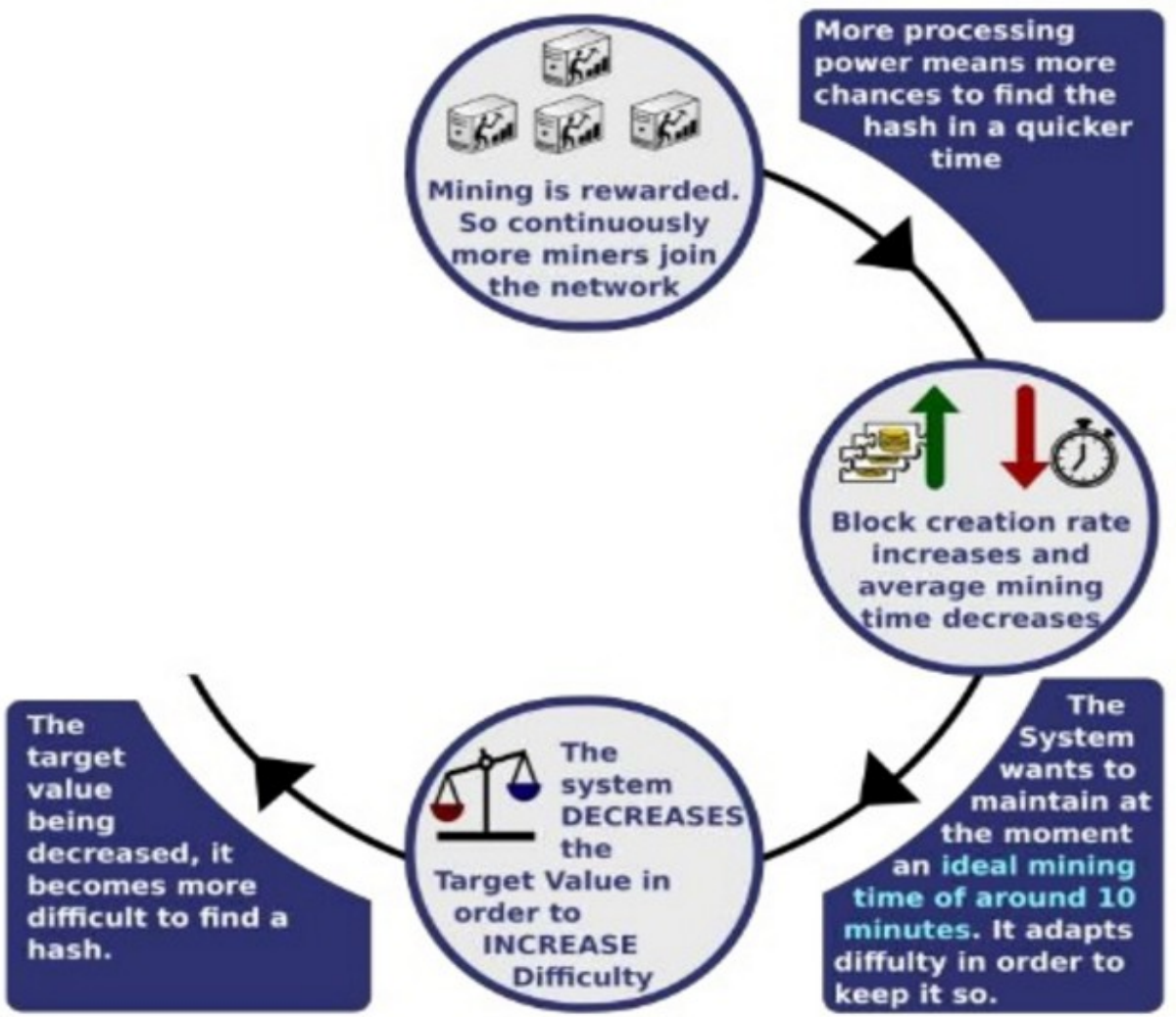

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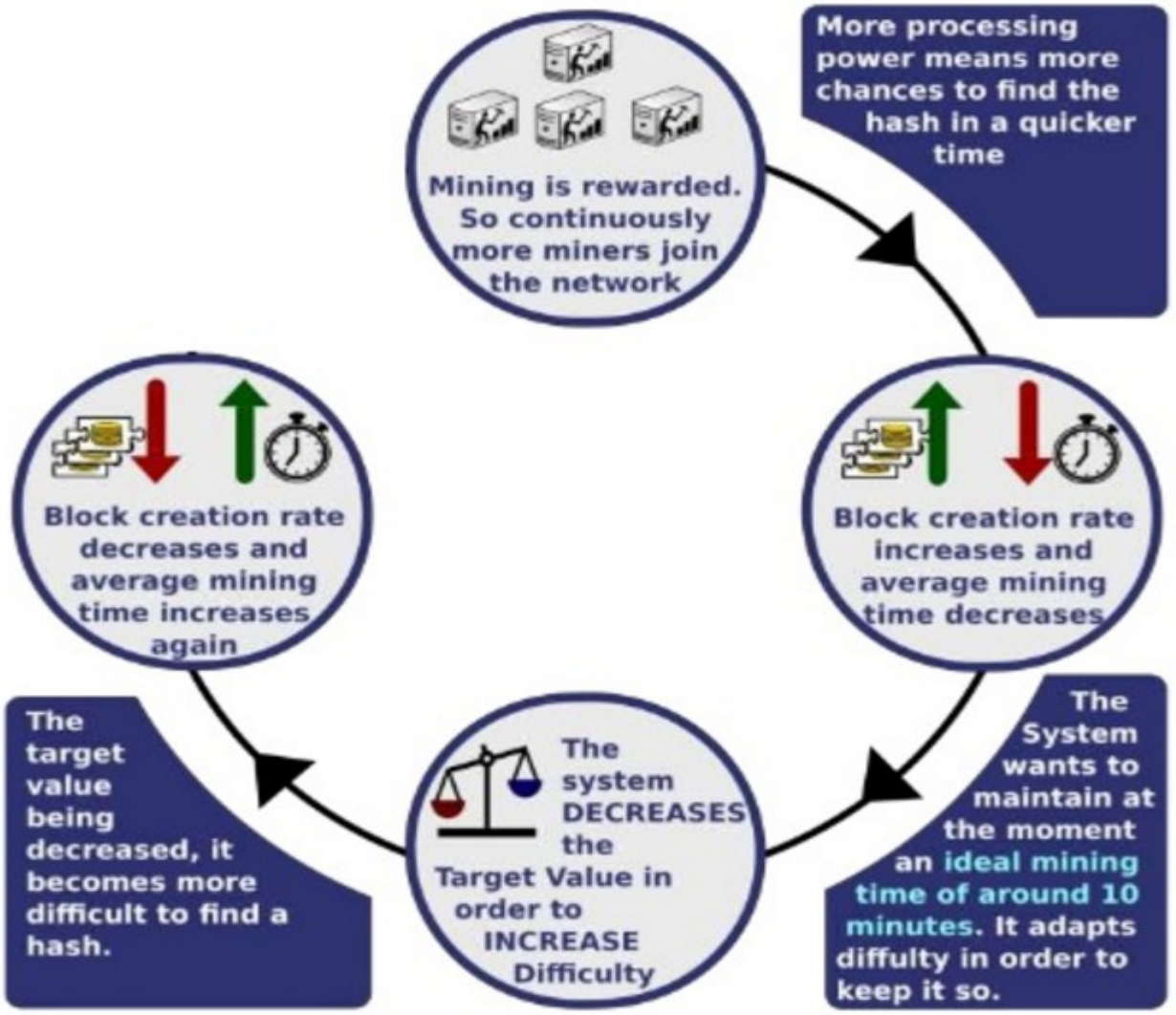

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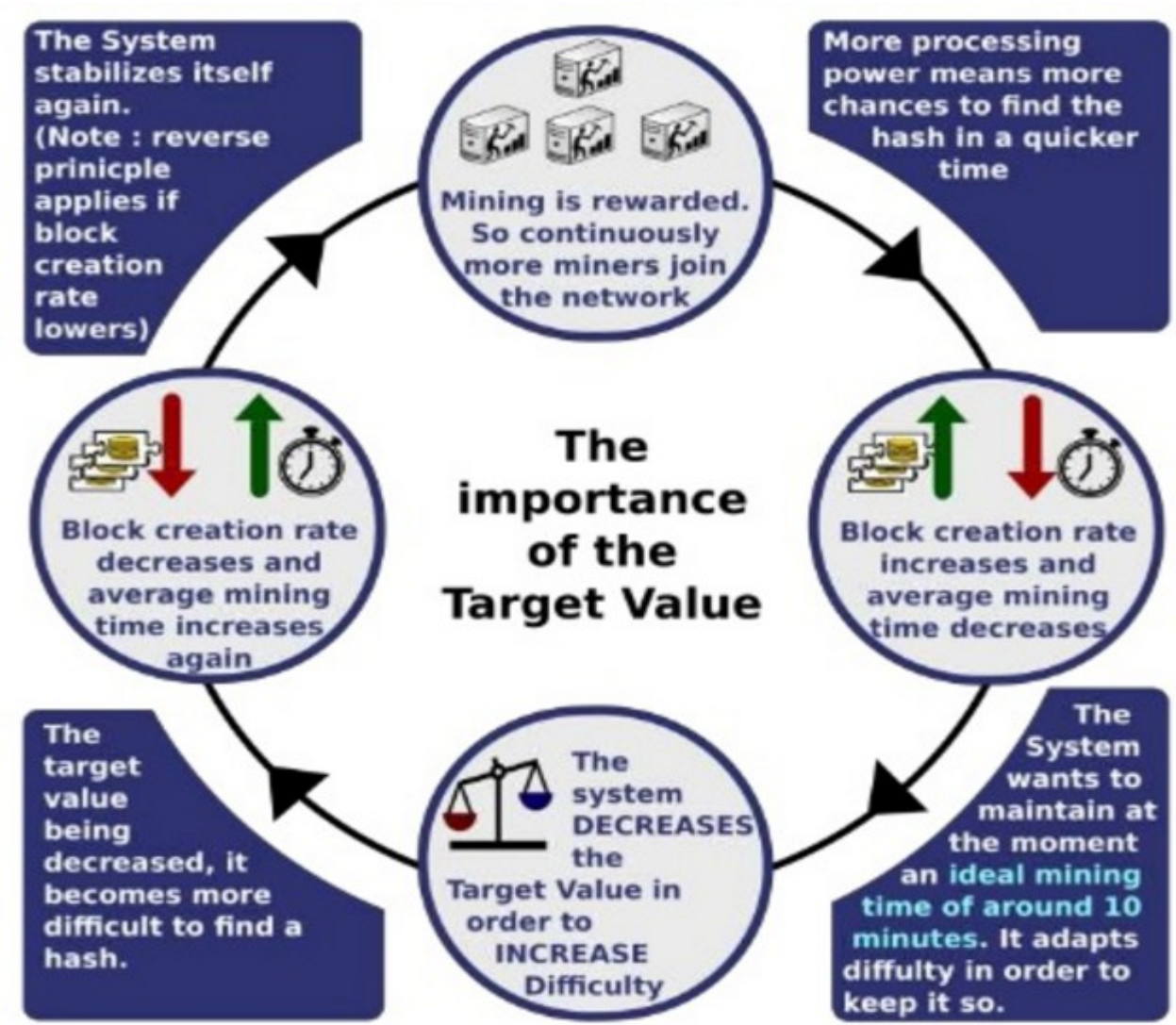


ADJUSTING THE POW DIFFICULTY

- to maintain the 10 minutes frequency: adjust block difficulty !
  - less leading zeros correspond to less difficulty
  - difficulty adjusted every 2,016 blocks or roughly every 2 weeks
- the adjustment takes into account the change in the computational power of the whole network since the last adjustment
  - compare the time-stamps of two blocks 2,016 positions apart
  - increase the number of starting zero bits in the target
- difficulty adjustment is part of the rules of Bitcoin protocol and it is coded into every Bitcoin client.

VERIFYING THE POW

- it takes, a lot of tries to find a nonce that makes the block hash fall below the target
- instead, verifying the Pow must be easy
- nonce is published as part of the block to allow PoW verification by the other nodes
- any node which receives the mined block may:
  - hash all the block contents together, and verify that the PoW has been carried on, i.e. the output is less than the target.
- another property allowing to get rid of centralization:
  - no centralized authority to verify that miners are doing their work properly

INCENTIVES: BLOCK REWARDS

- Why I should be a miner?
- Incentive miners to be honest: further prevents sybil attacks
- There are two kind of incentive:
- Block reward:
  - the miner is rewarded for confirming transactions by allowing it to mint new coins.
  - like a payment to the miner in exchange for the service of creating a block on the consensus chain.
  - the only way in which new bitcoins are allowed to be created in Bitcoin !

INCENTIVES: BLOCK REWARDS

- a miner solving the PoW can include in the block a special transaction:
  - reward transaction: the first transaction in a block:
    - a dummy input
    - sum of output values:

      fixed subsidy + sum of the fees of transactions confirmed in the block
    - reward dynamically varies in time
  - the recipients of the reward are typically one or more addresses of the miner

INCENTIVES: TRANSACTION FEES

- Transaction fee:
  - difference between the total value of the transaction inputs and the outputs
  - voluntarily inserted to obtain a certain degree of quality of service from the miners
- the miner that first puts that transaction into the blockchain
  - collects the fee for all the transactions in the block

ADJUSTING BLOCK REWARD

- 1 BTC = 10^8 Satoshi
- rule: half the mining reward after all 210.000 blocks (roughly every 4 years)

  Era 1: 50/1 50 BTC

  Era 2: 50/2 = 25 BTC

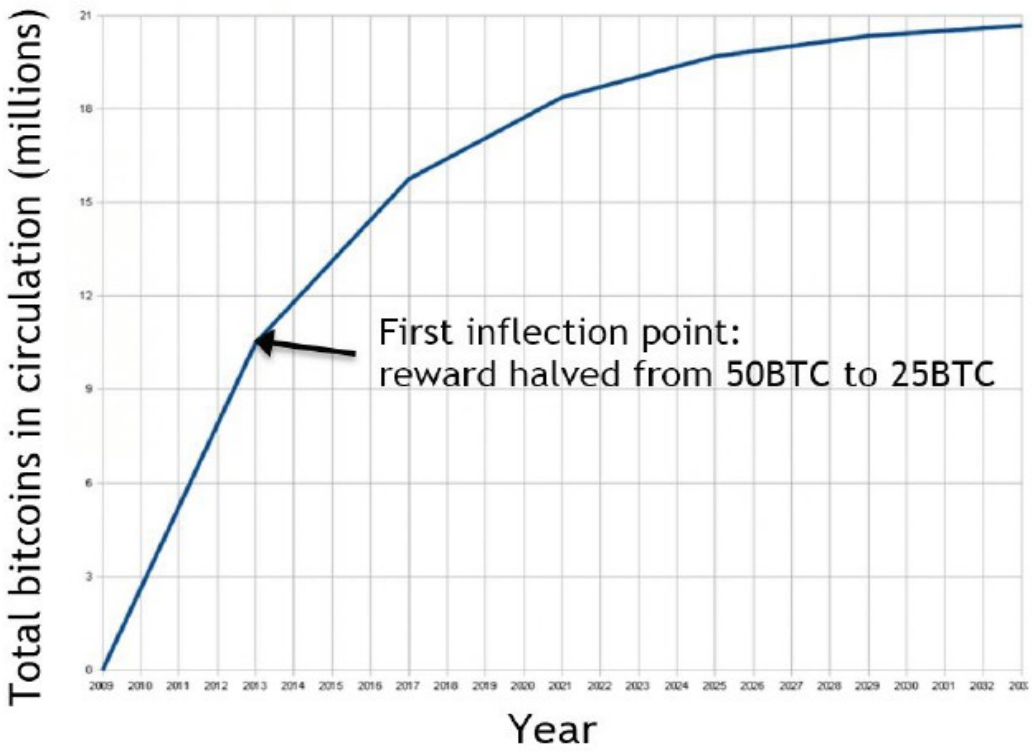
  Era 3: 25/2 = 12.5 BTC

  ...

  Era 33: 0.00000001 "Satoshis" (smallest unit)

- currently, the value of the block reward is fixed at 12.5 Bitcoins
  - last split in July 2016
  - we are in the third period of the "bitcoin era"
- based on the rate of block creation

ADJUSTING BLOCK REWARD



ADJUSTING BLOCK REWARD

- Historically, most of the compensation of miners has come from the block reward, and only a small percentage of their retribution from transaction fees
- it is expected that over time a larger percentage of the retribution will be due to transaction fees.
- new entrances try to capture block rewards, lowering the reward of all miners already in the network.
- so miners have to keep increasing their hashing rate in order to obtain the same reward.

NAKAMOTO CONSENSUS: CONCLUSIONS

Differences between the Bitcoin model of consensus and the others:

- randomized or probabilistic consensus (also called stabilizing consensus) i.e. the probability to disagree, decreases over time
- it uses a non-deterministic consensus protocol
- it uses a network of unknown size, i.e. supports anonymity
- users can join and leave the network (also called permission-less). This actually makes the problem harder
- it relies on some form of synchrony (bounded delay)
- it introduces the idea of incentives