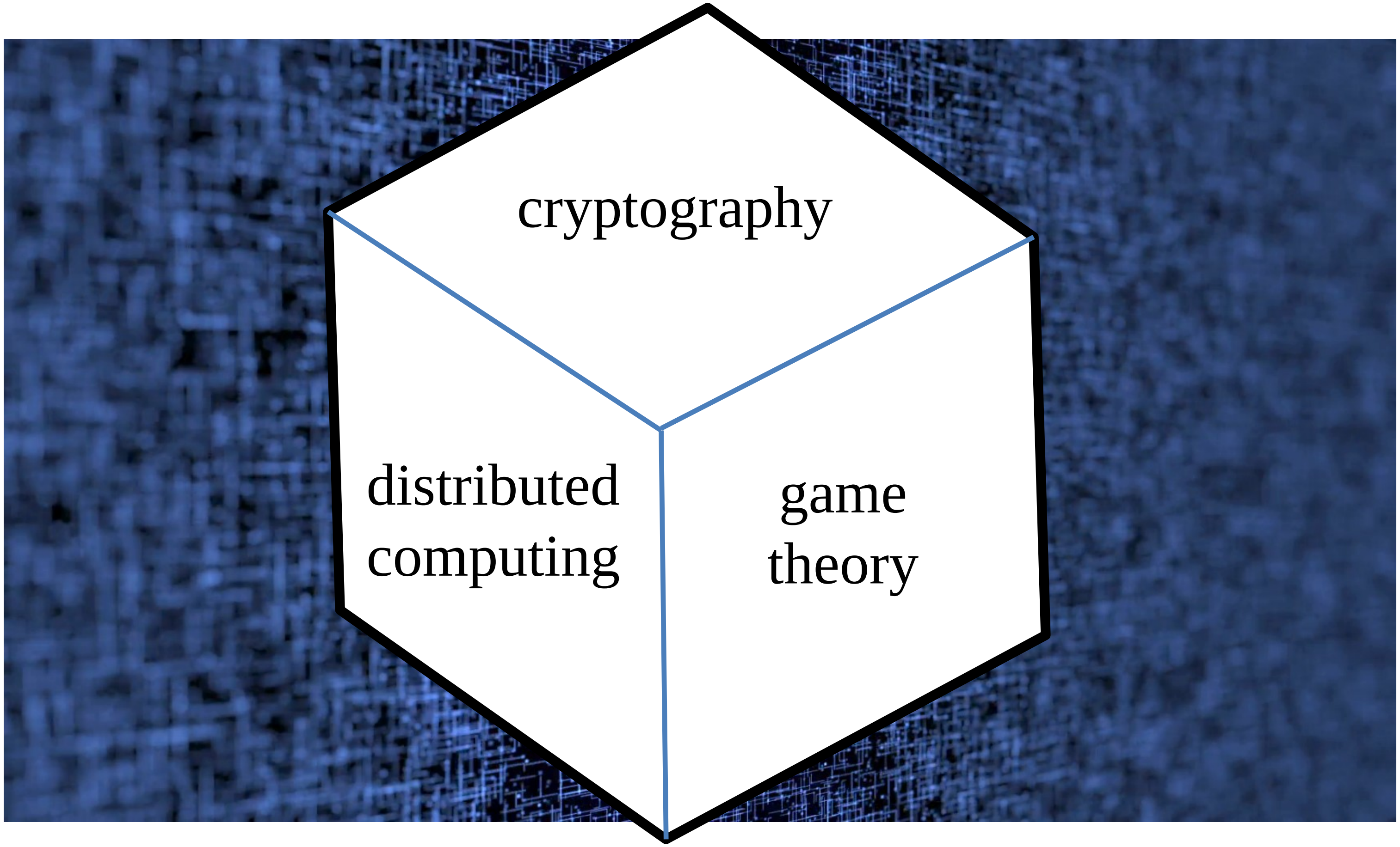
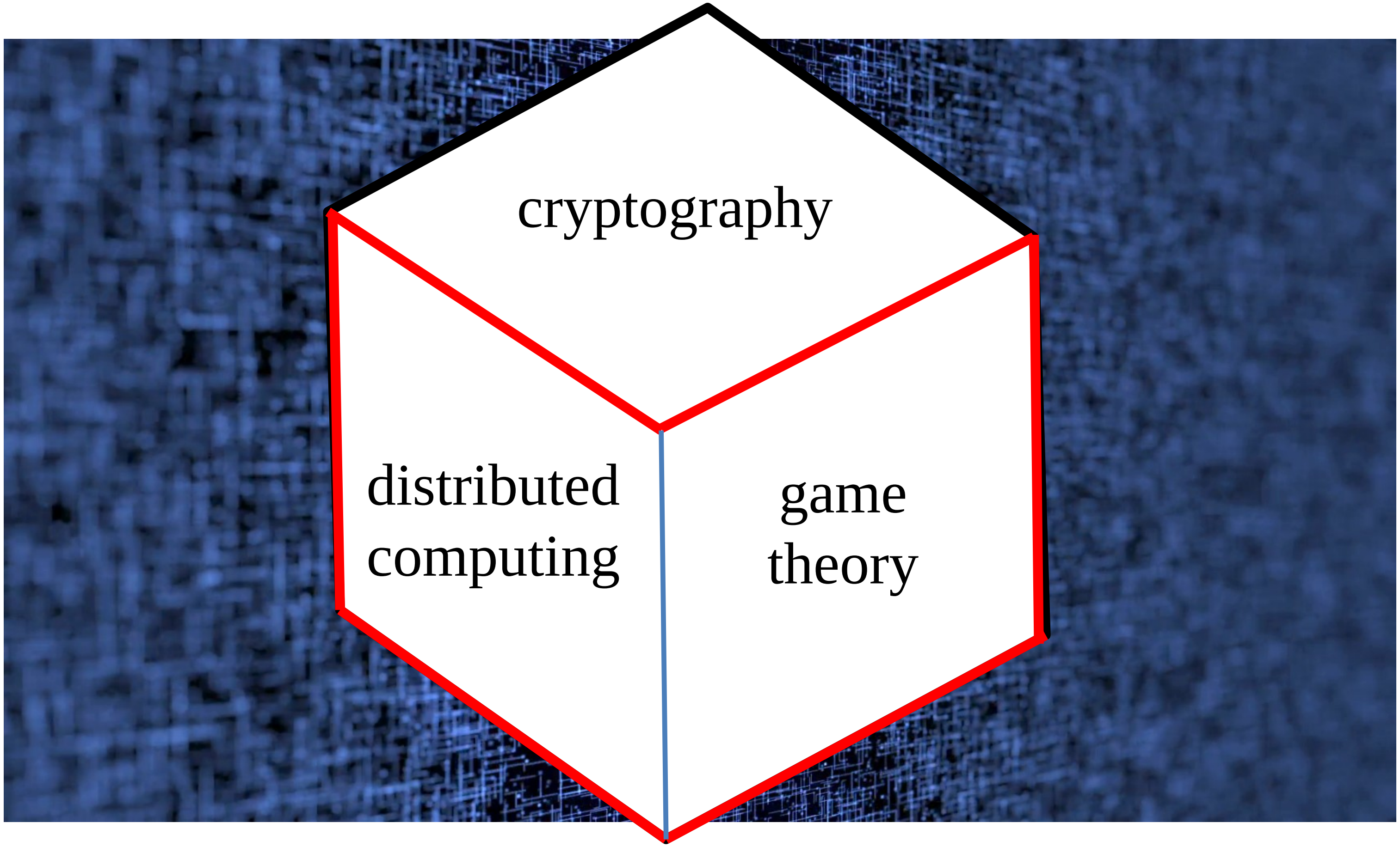
Consensus & fault tolerance: distributed and strategic aspects of the Blockchain technology

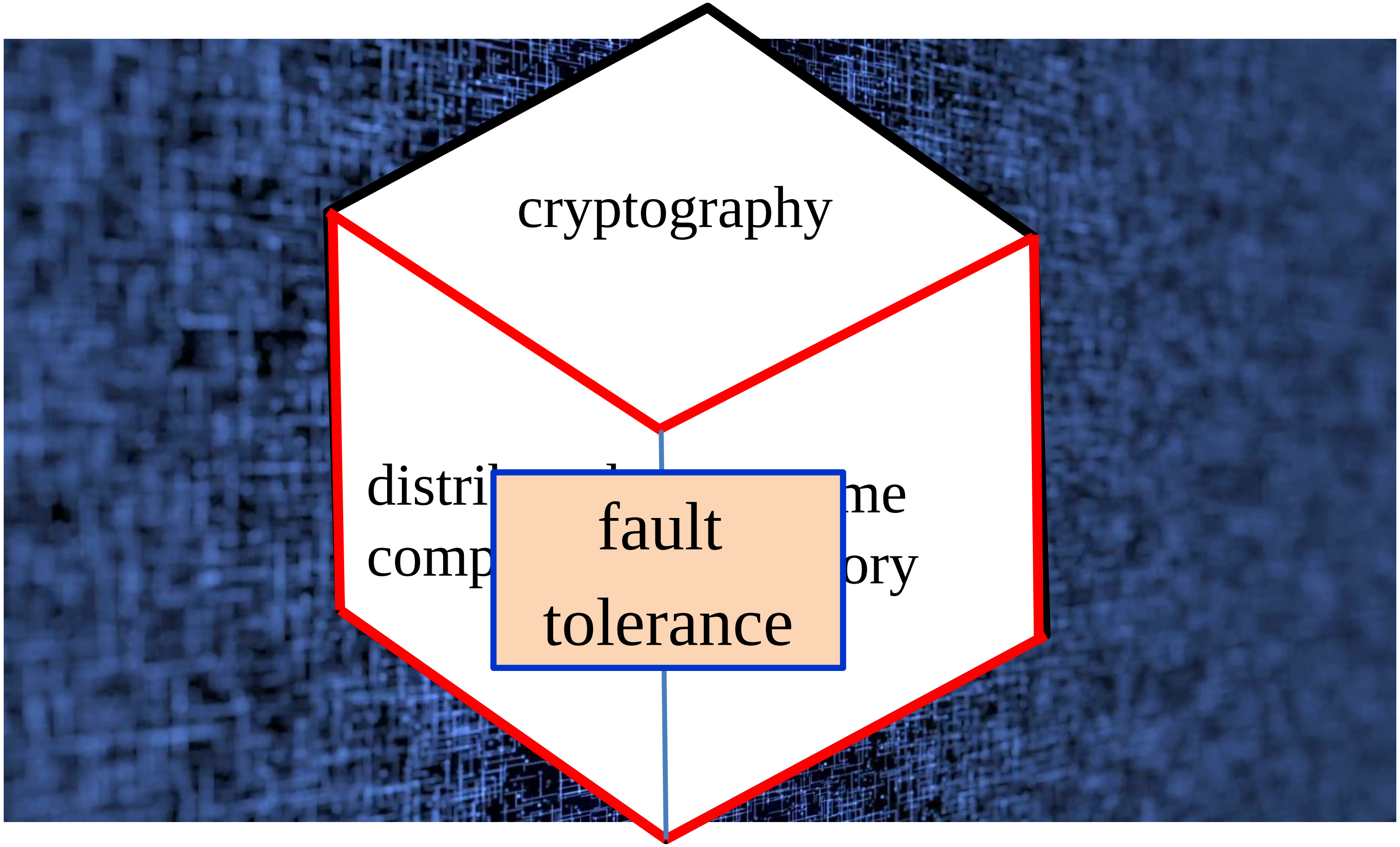
Aspects of the Blockchain technology



Aspects of the Blockchain technology



Aspects of the Blockchain technology

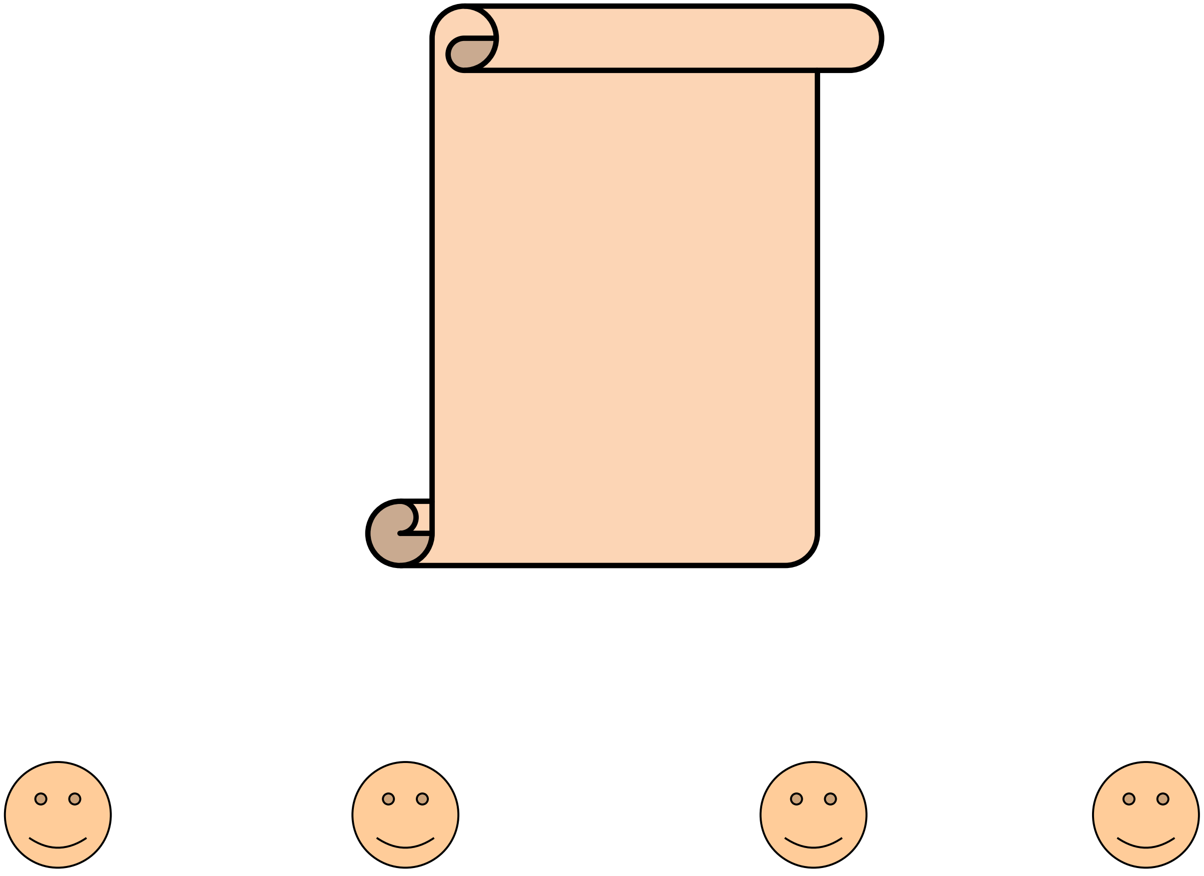


the distributed ledger problem

problem:

maintain a ledger containing a sequence of commands such that:

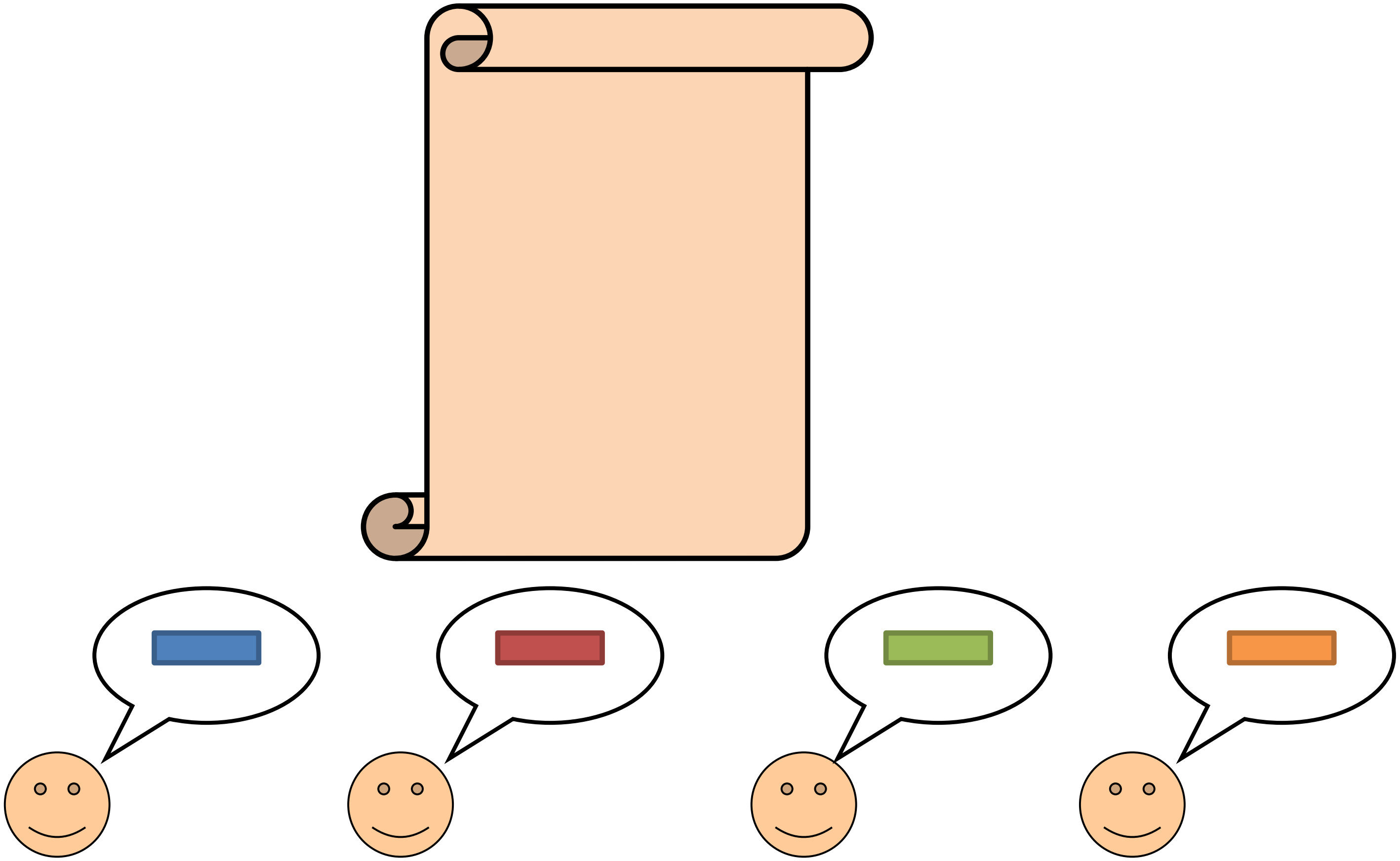
- all agents agree on the content of the ledger
- every agent can fairly write its commands



problem:

maintain a ledger containing a sequence of commands such that:

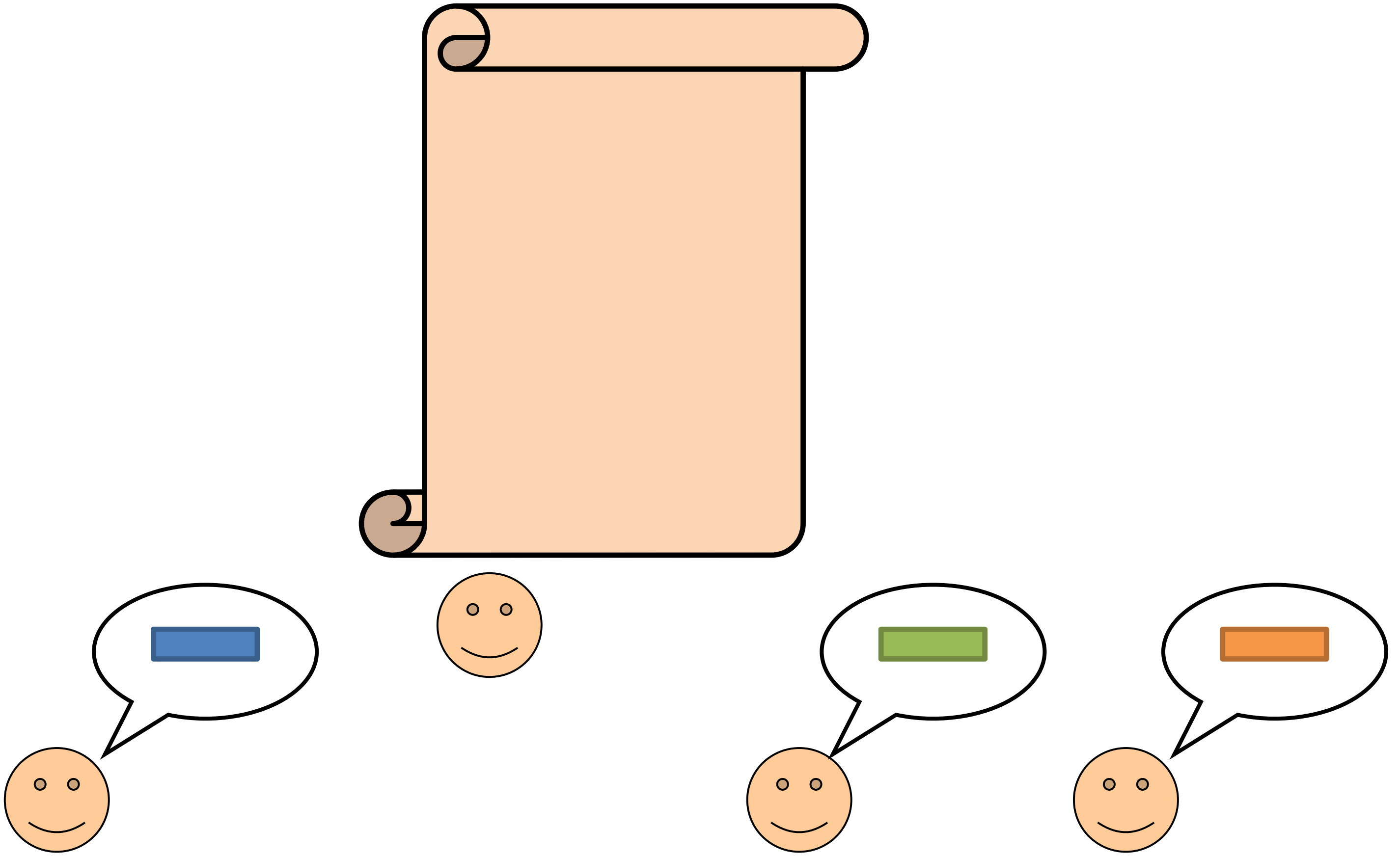
- all agents agree on the content of the ledger
- every agent can fairly write its commands



problem:

maintain a ledger containing a sequence of commands such that:

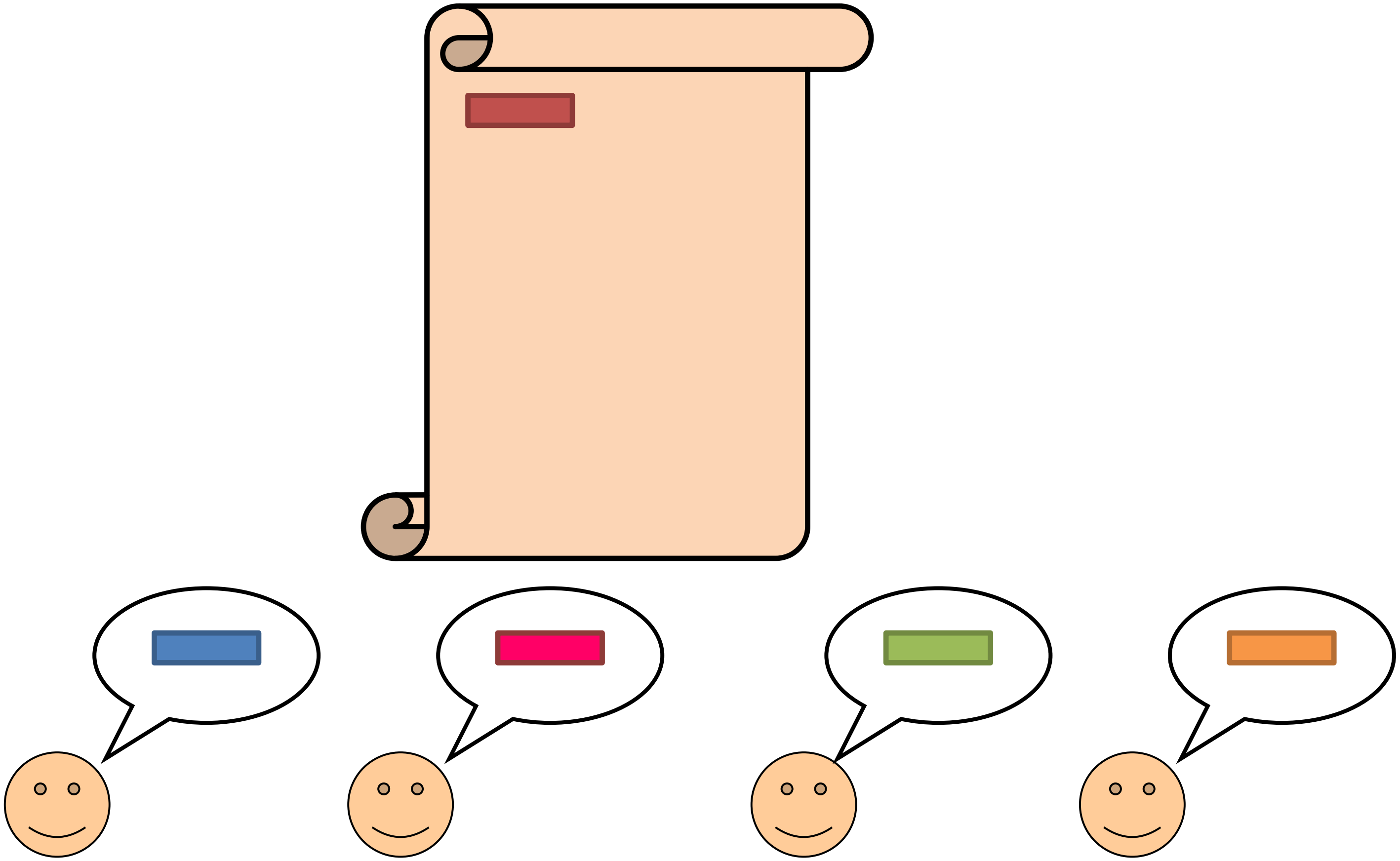
- all agents agree on the content of the ledger
- every agent can fairly write its commands



problem:

maintain a ledger containing a sequence of commands such that:

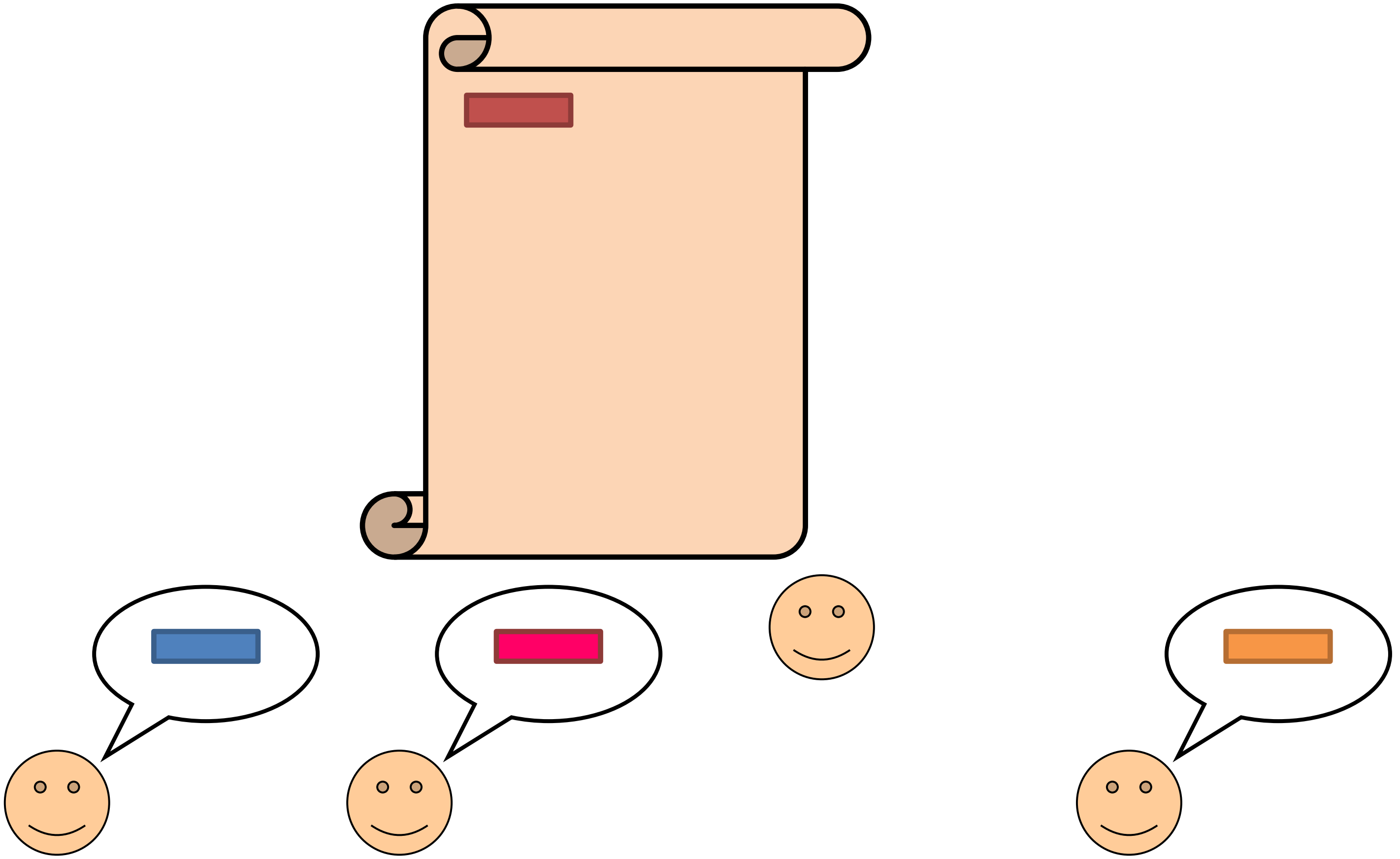
- all agents agree on the content of the ledger
- every agent can fairly write its commands



problem:

maintain a ledger containing a sequence of commands such that:

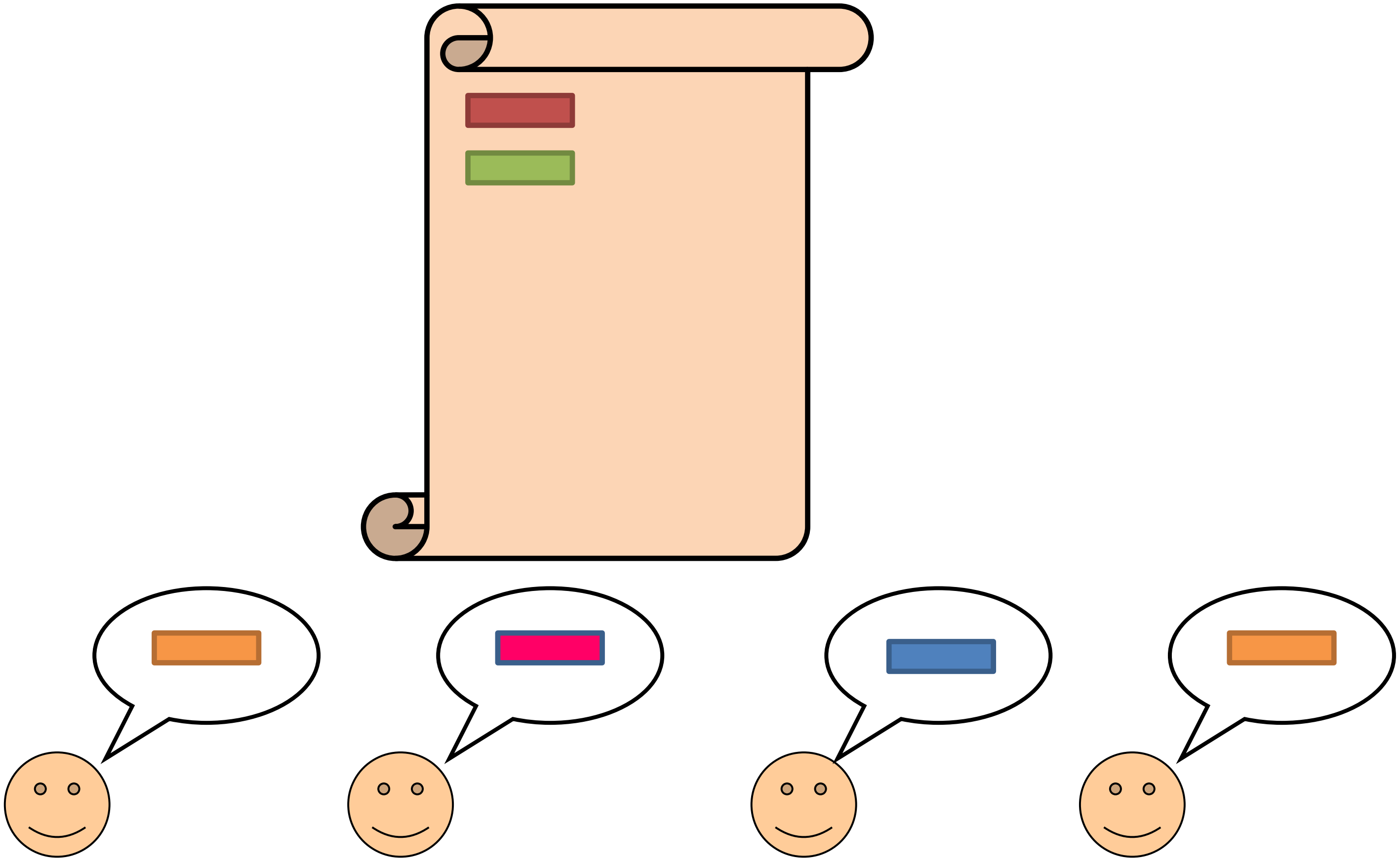
- all agents agree on the content of the ledger
- every agent can fairly write its commands



problem:

maintain a ledger containing a sequence of commands such that:

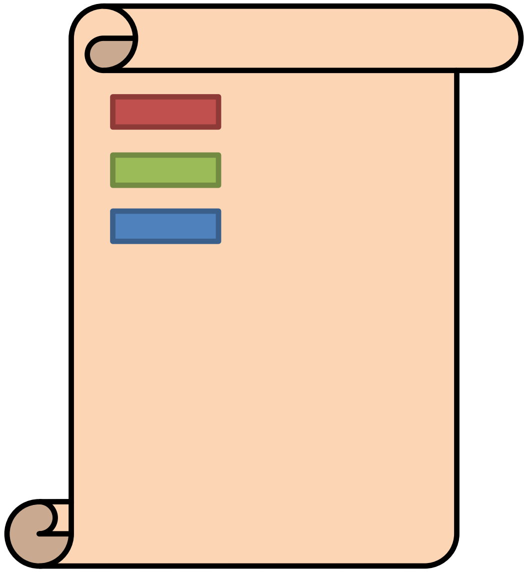
- all agents agree on the content of the ledger
- every agent can fairly write its commands



problem:

maintain a ledger containing a sequence of commands such that:

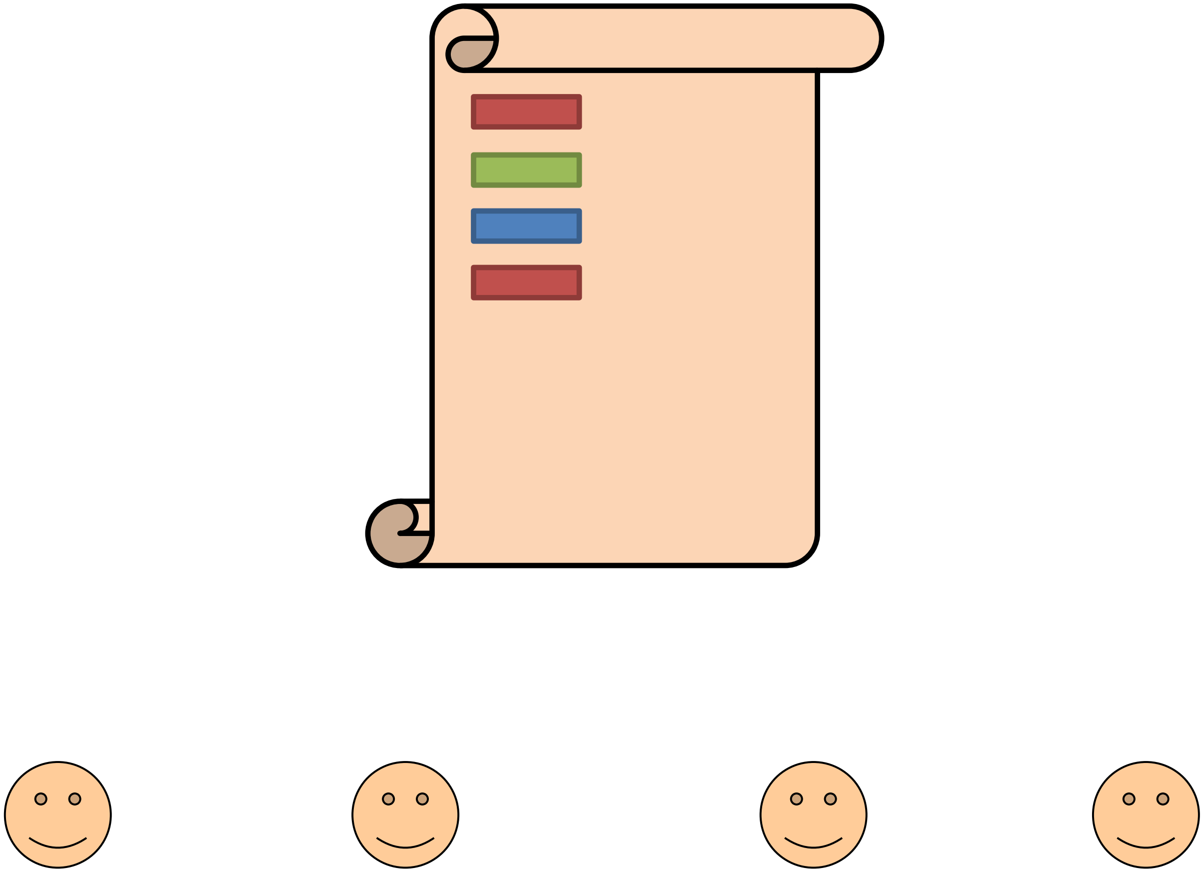
- all agents agree on the content of the ledger
- every agent can fairly write its commands



problem:

maintain a ledger containing a sequence of commands such that:

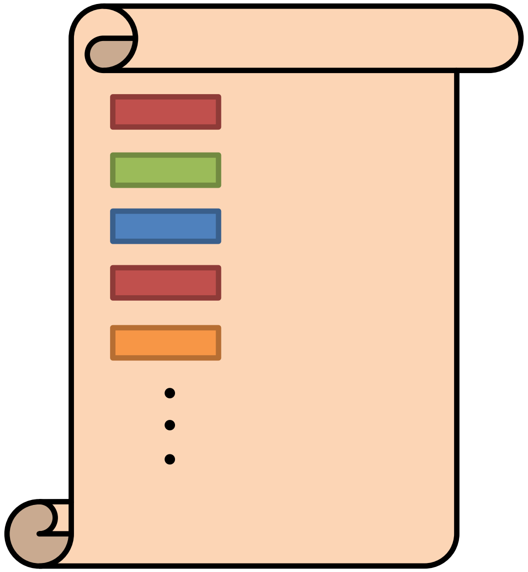
- all agents agree on the content of the ledger
- every agent can fairly write its commands



problem:

maintain a ledger containing a sequence of commands such that:

- all agents agree on the content of the ledger
- every agent can fairly write its commands

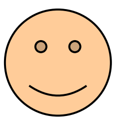


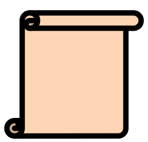
problem:

maintain a ledger containing a sequence of commands such that:

- all agents agree on the content of the ledger
- every agent can fairly write its commands

In Bitcoin System:

 = node of the network

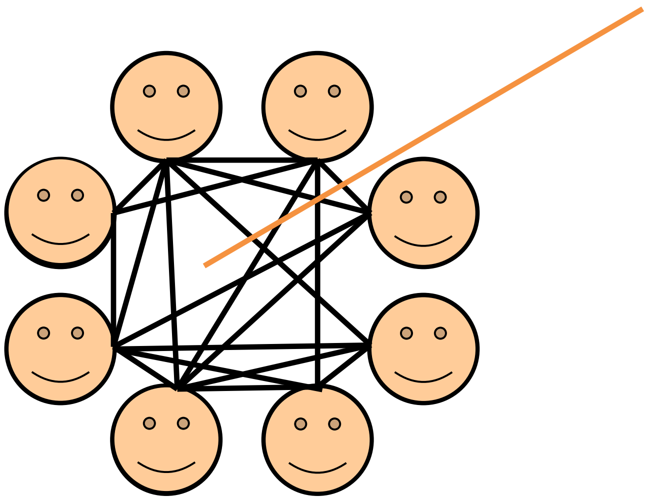
 = blockchain

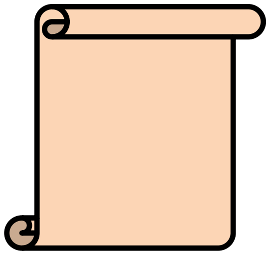
 = block (of transactions)

problem:

maintain a distributed ledger containing a seq. of commands such that:

- all agents agree on the content of the ledger
- every agent can fairly write its commands

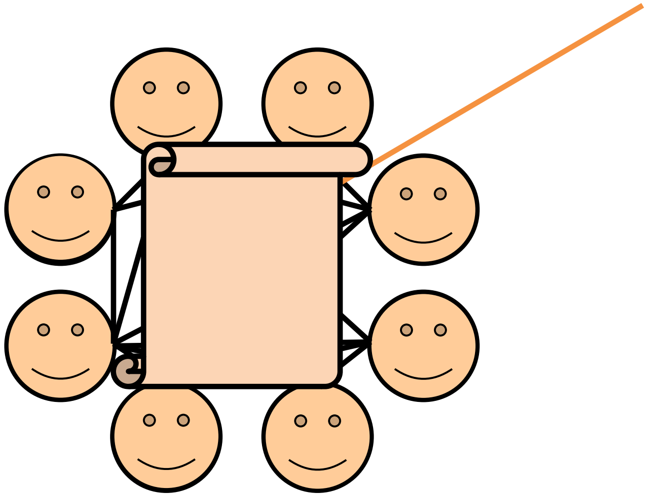




problem:

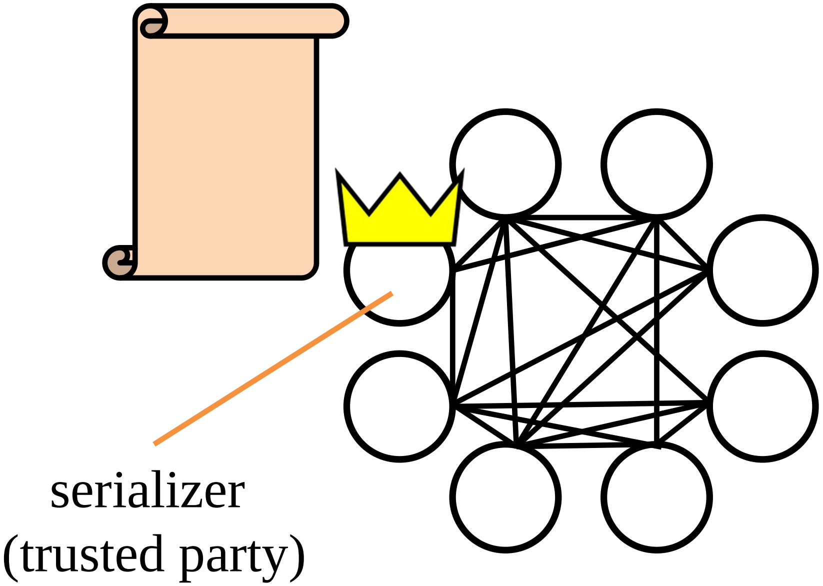
maintain a distributed ledger containing a seq. of commands such that:

- all agents agree on the content of the ledger
- every agent can fairly write its commands

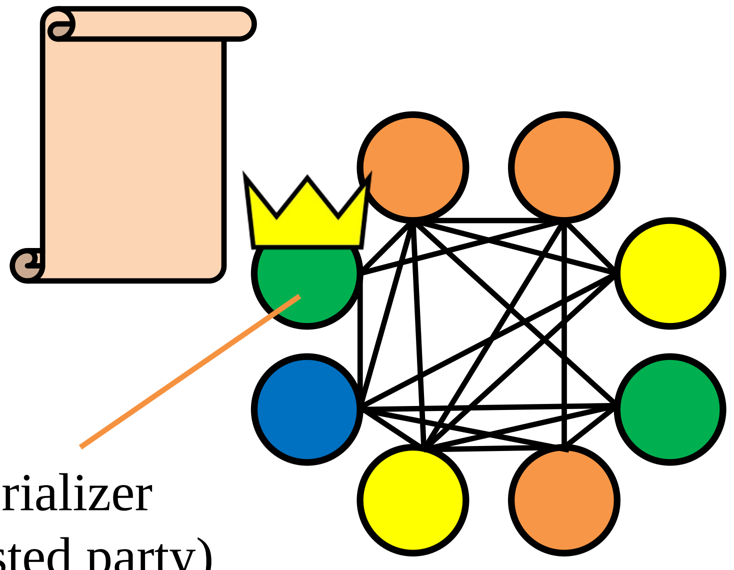


network can be used to exchange messages

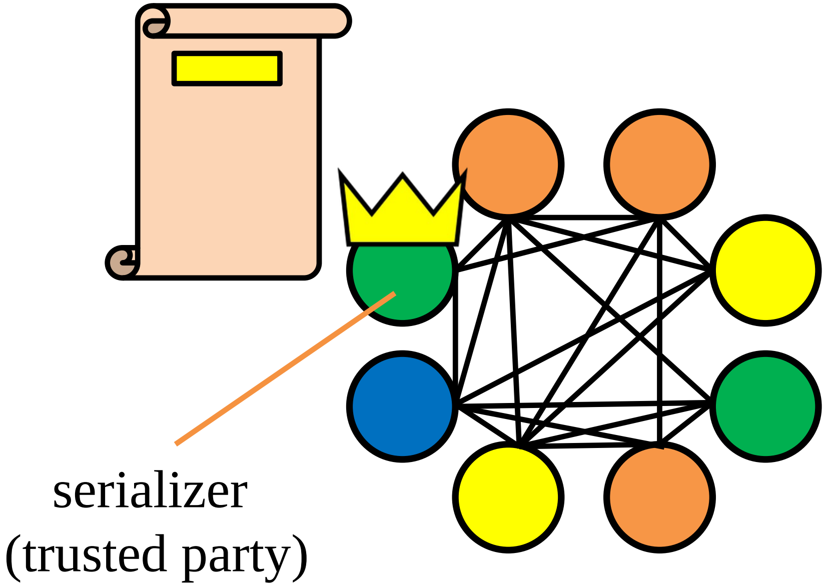
a simple solution



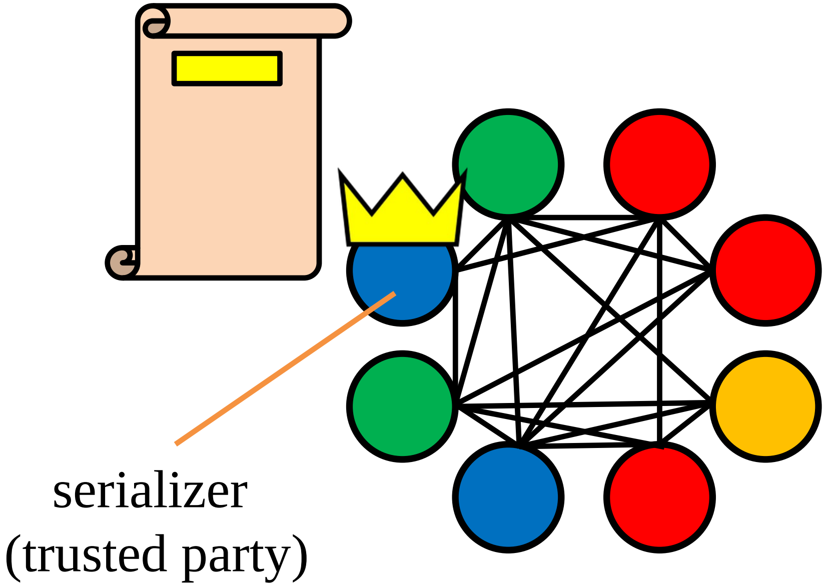
a simple solution



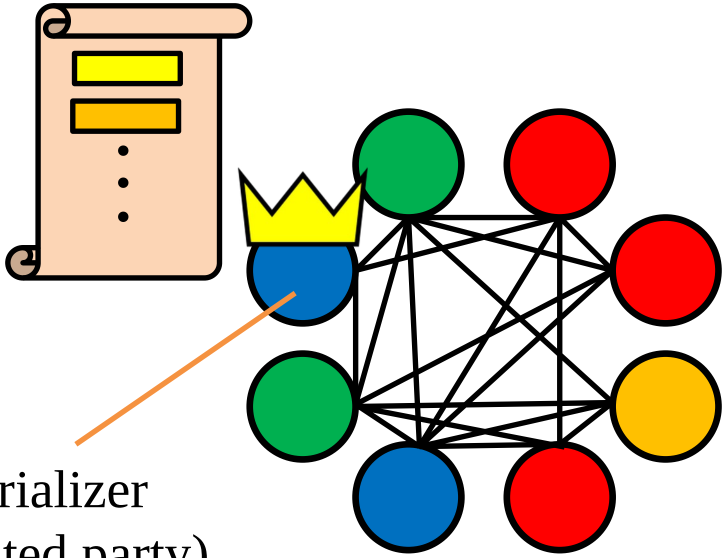
a simple solution



a simple solution

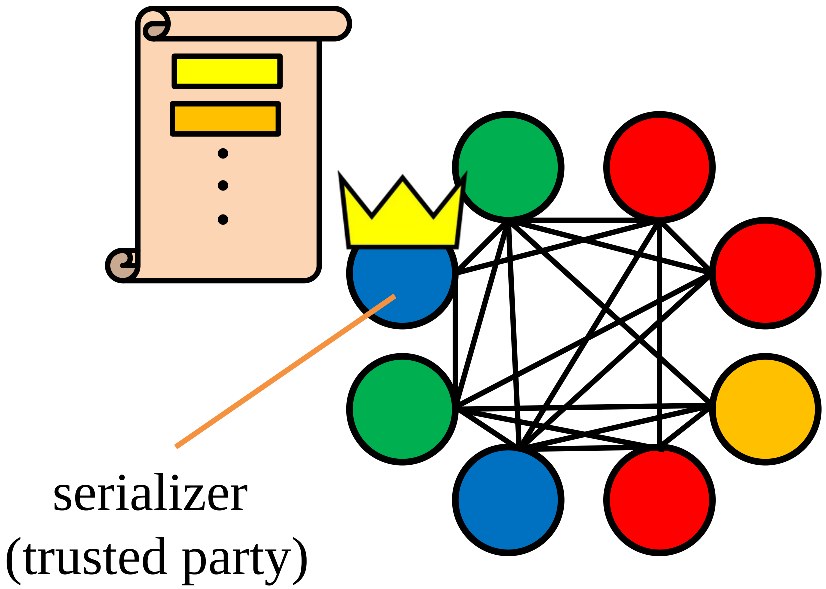


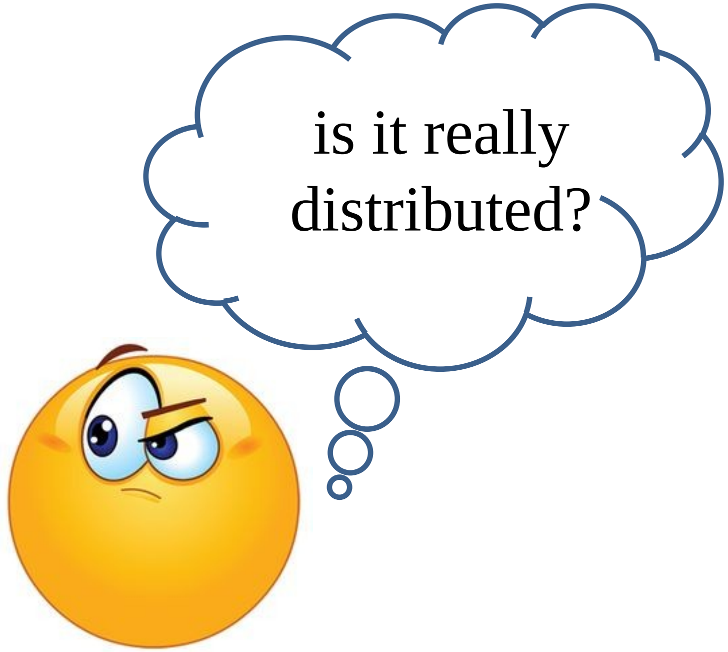
a simple solution



serializer
(trusted party)

a simple solution

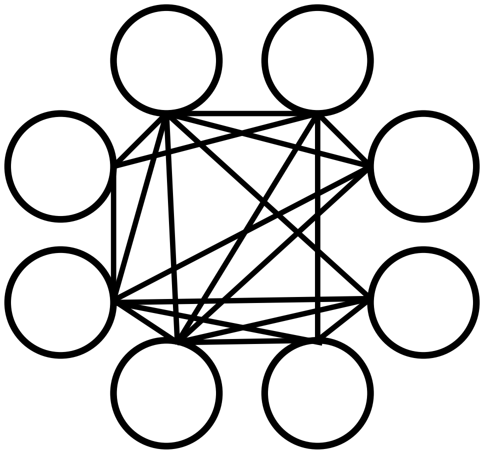




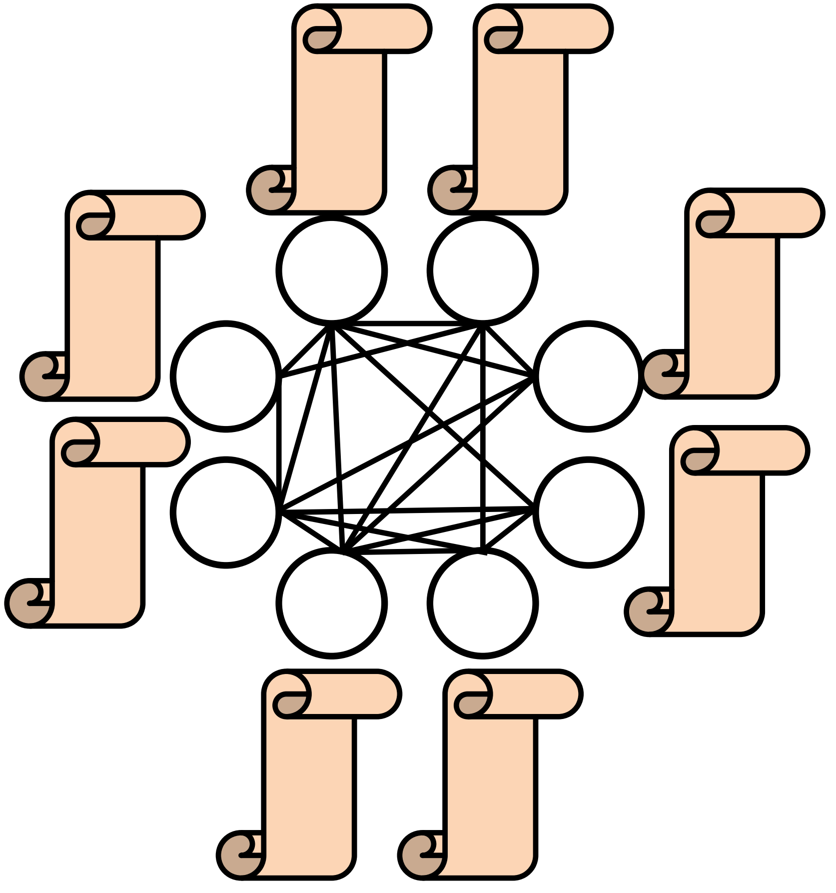
- what if the serializer fails?
- what if the serializer is not honest?

fault tolerance

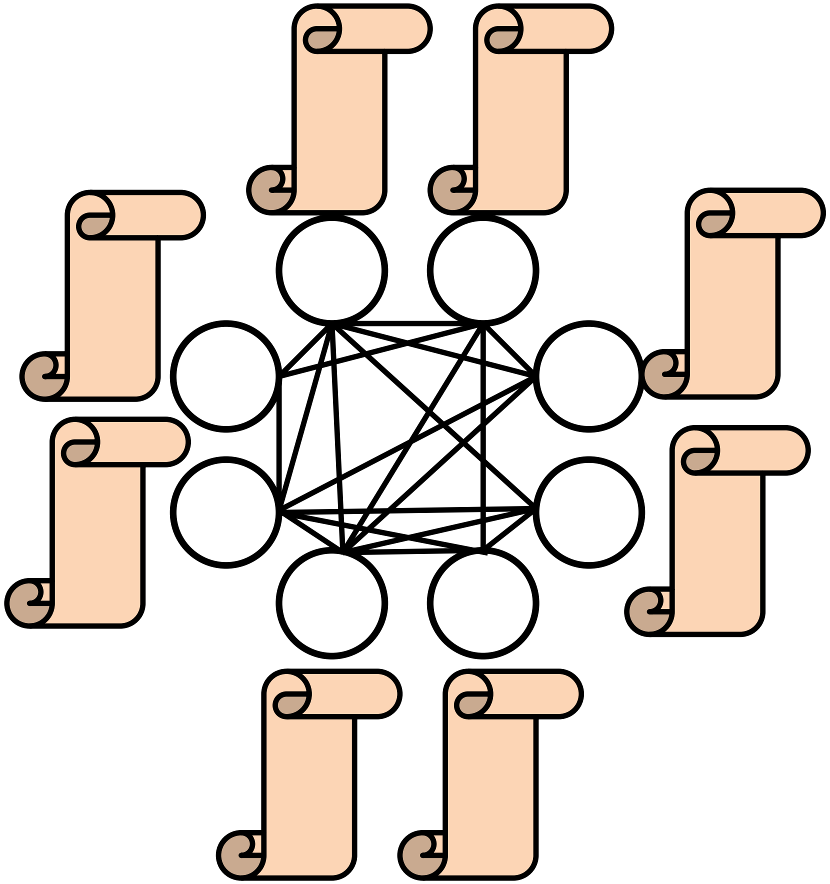
a better solution



a better solution

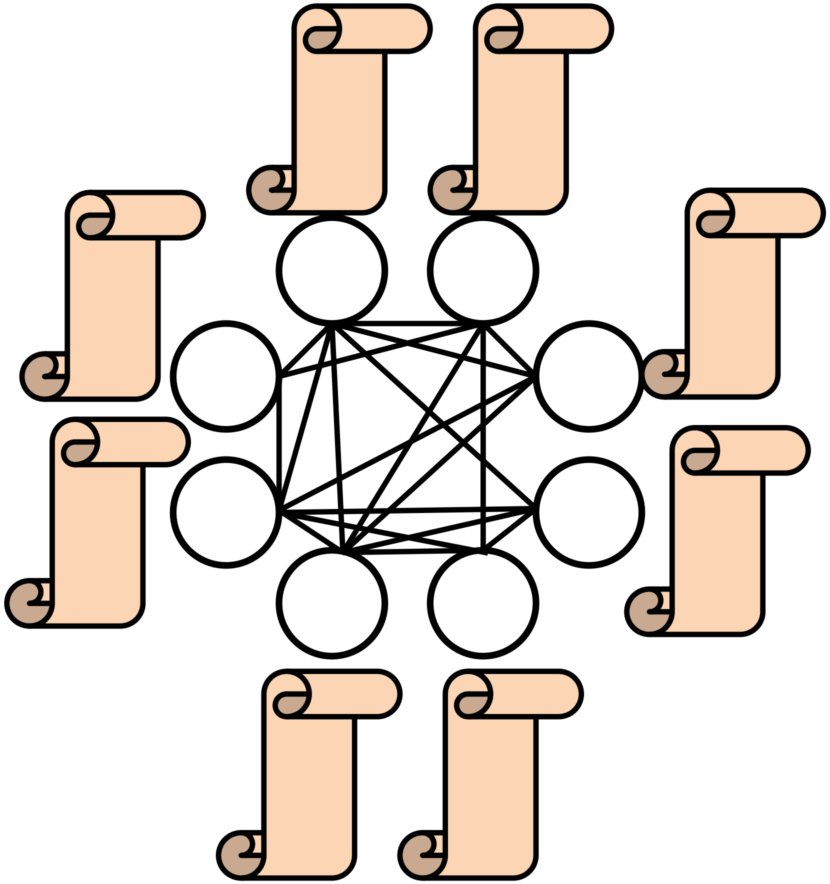


a better solution



Consistency:
all nodes always agree on the current state of the ledger

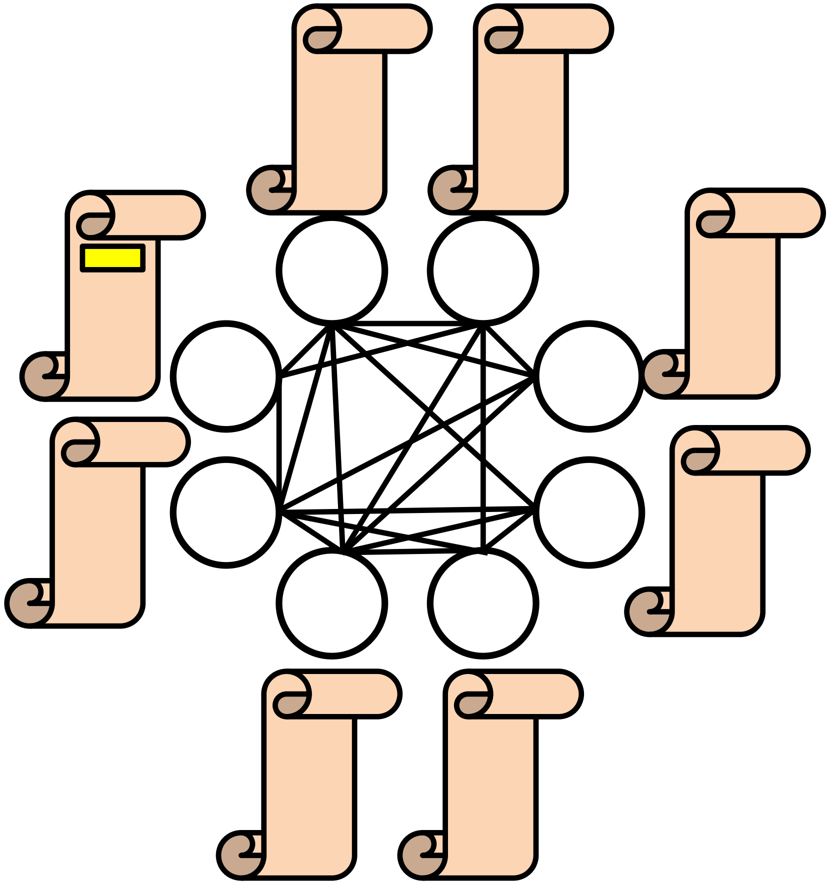
a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

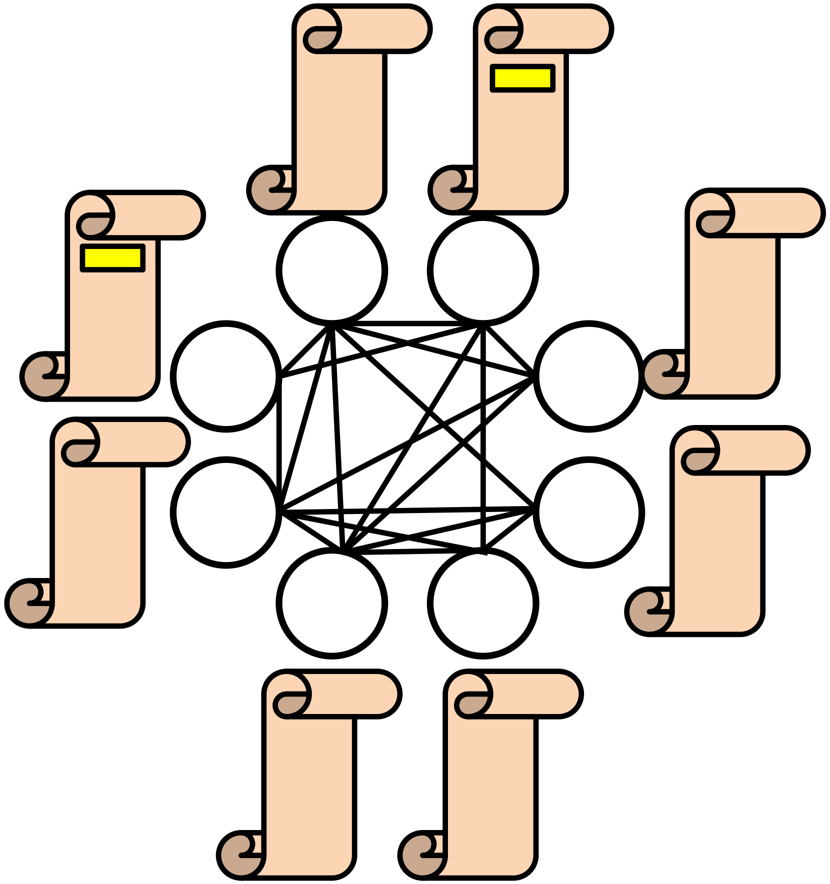
a better solution



Consistency:
all nodes always agree on the current state of the ledger

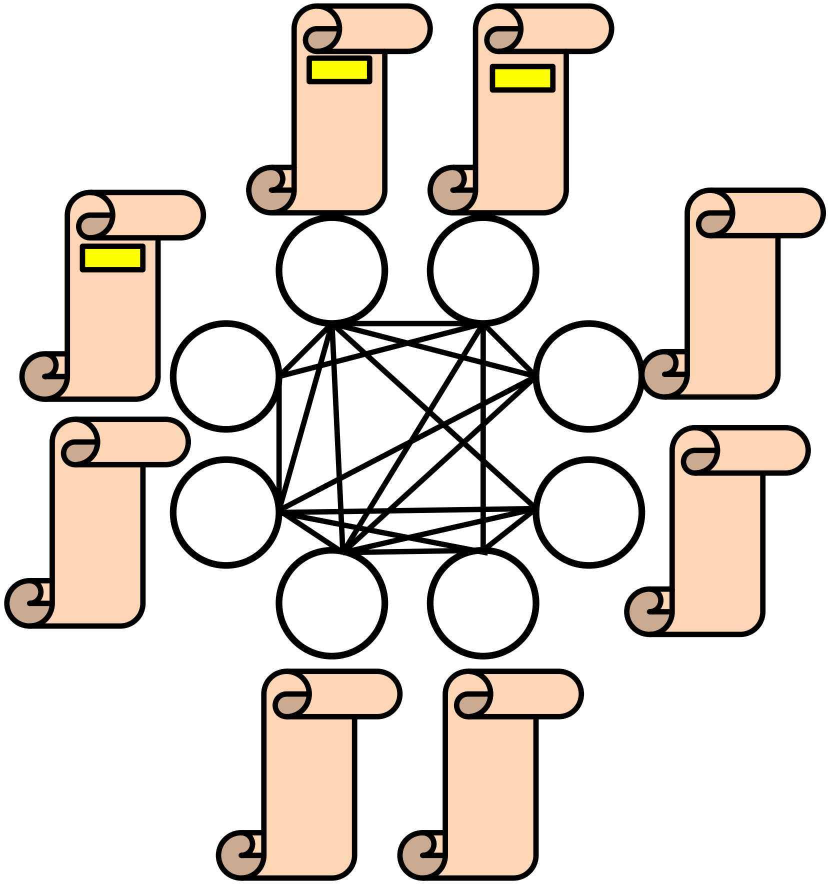
Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

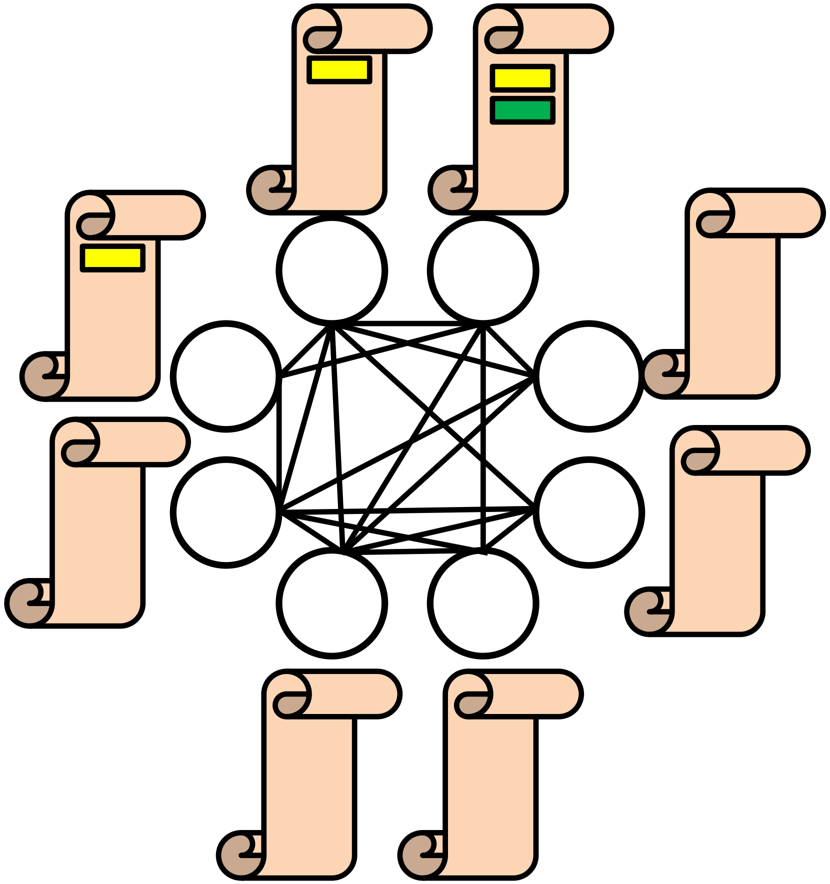


a better solution

Consistency:
all nodes always agree on the current state of the ledger

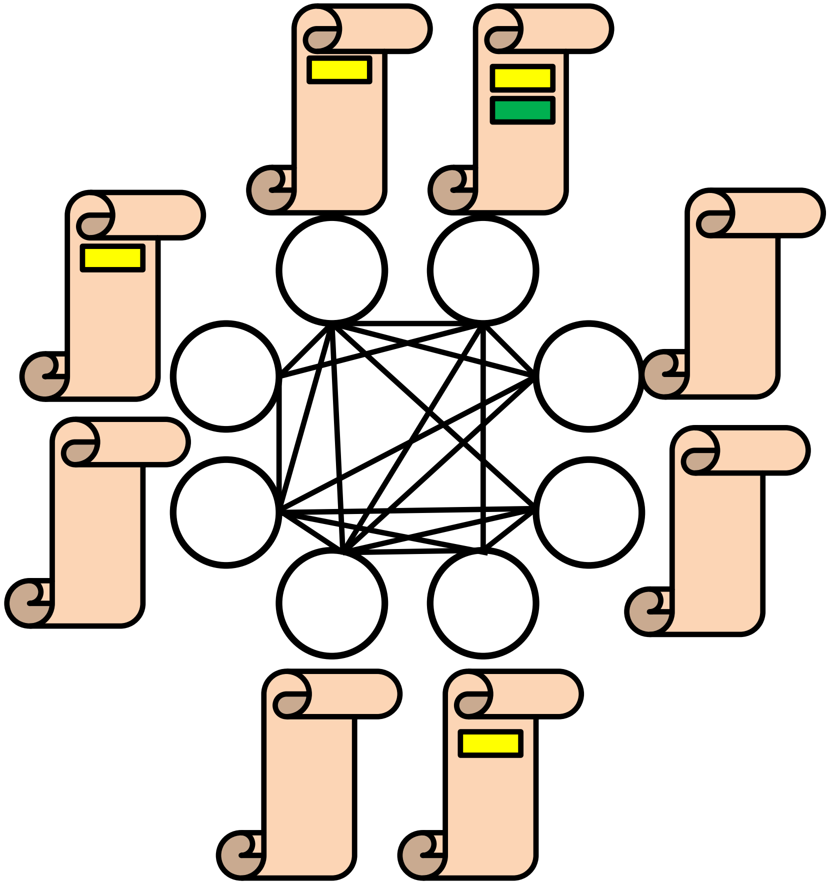
Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

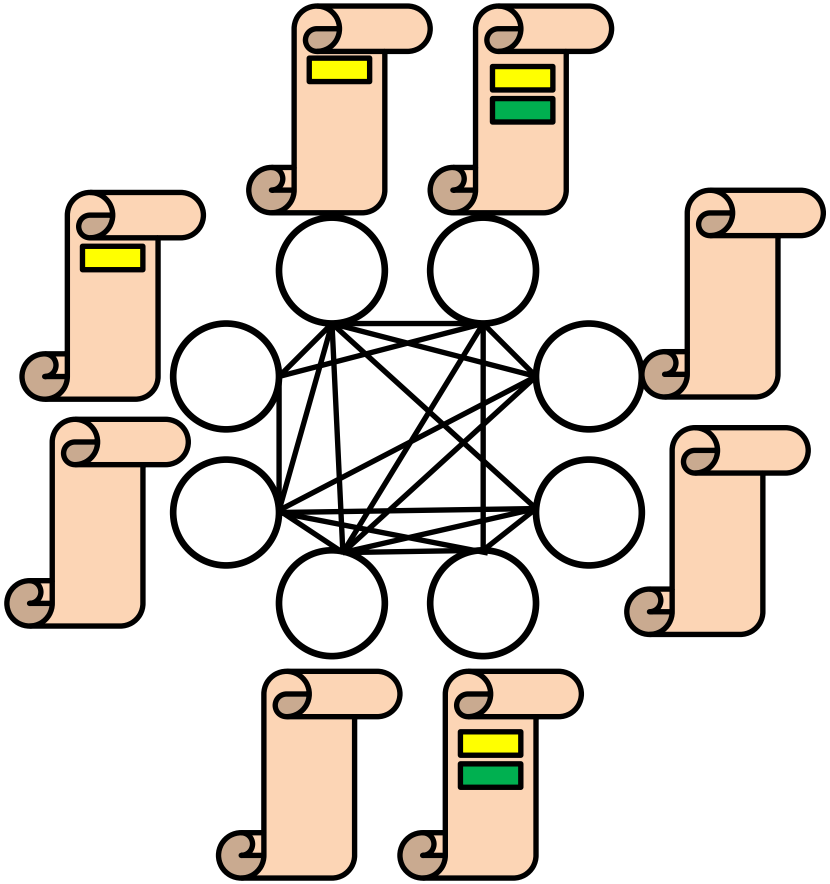


a better solution

Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

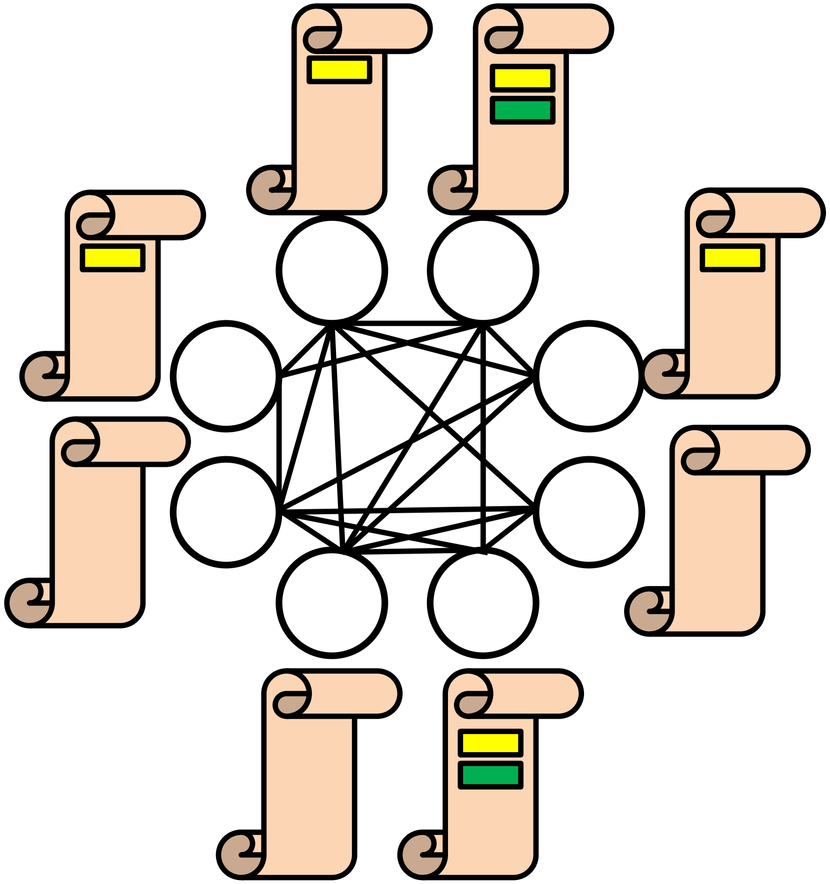
a better solution



Consistency:
all nodes always agree on the current state of the ledger

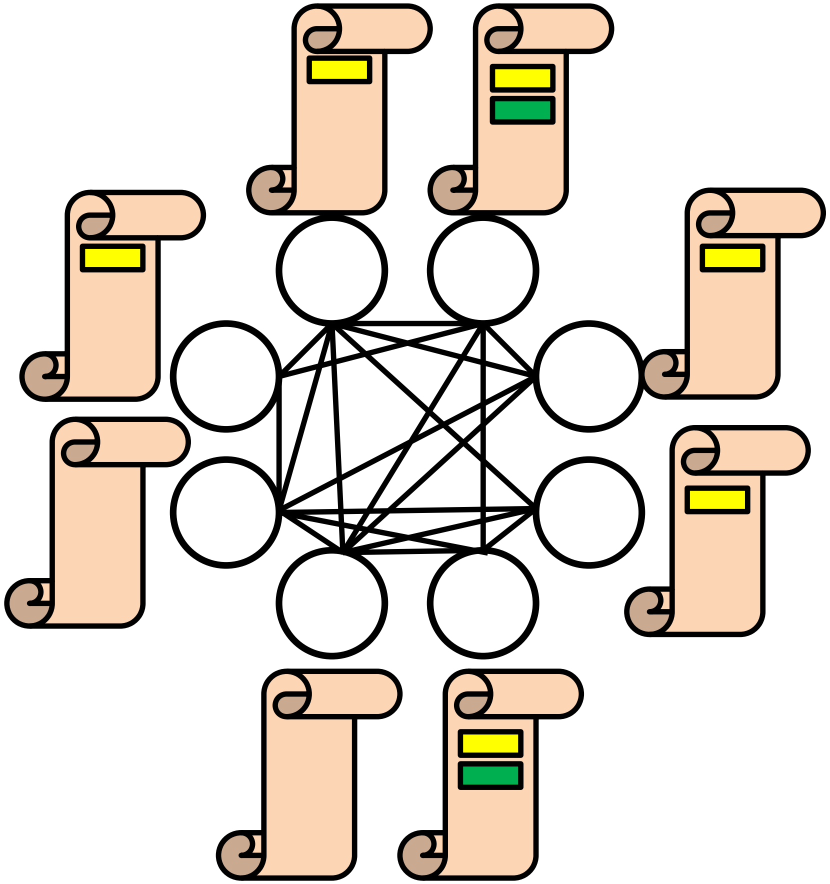
Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

a better solution



Consistency:
all nodes always agree on the current state of the ledger

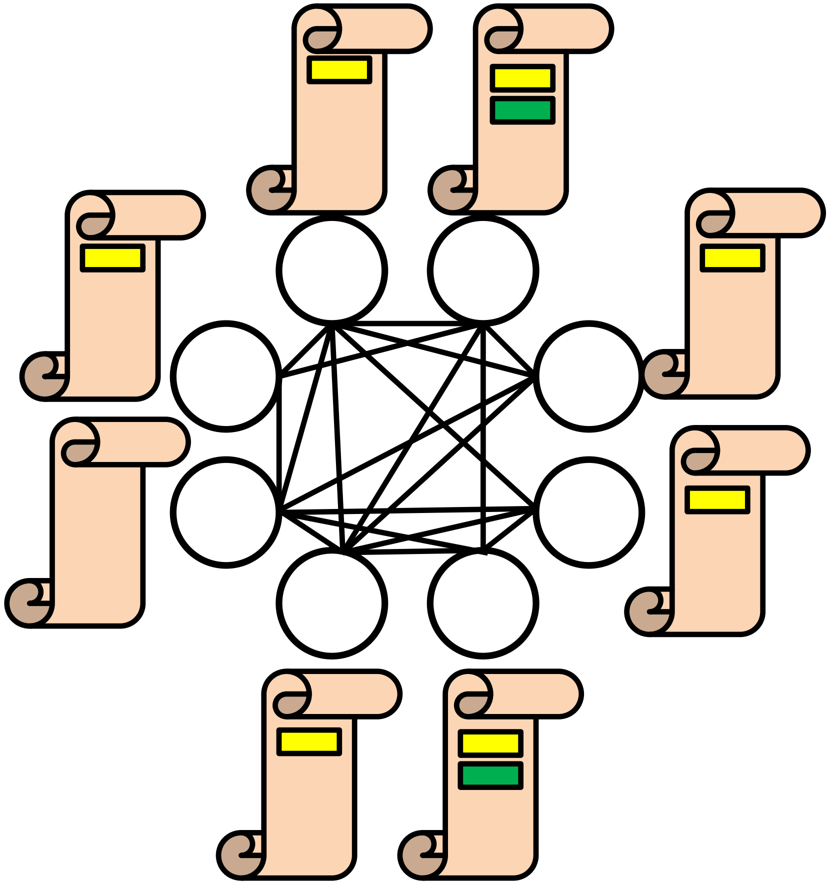
Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)



a better solution

Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

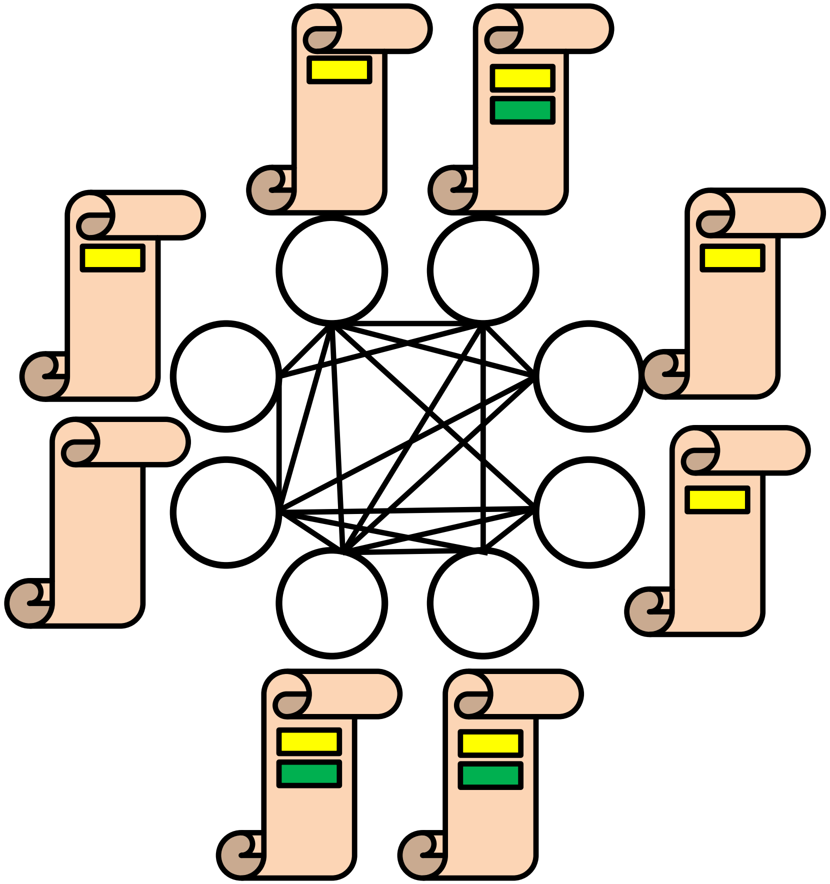


a better solution

Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

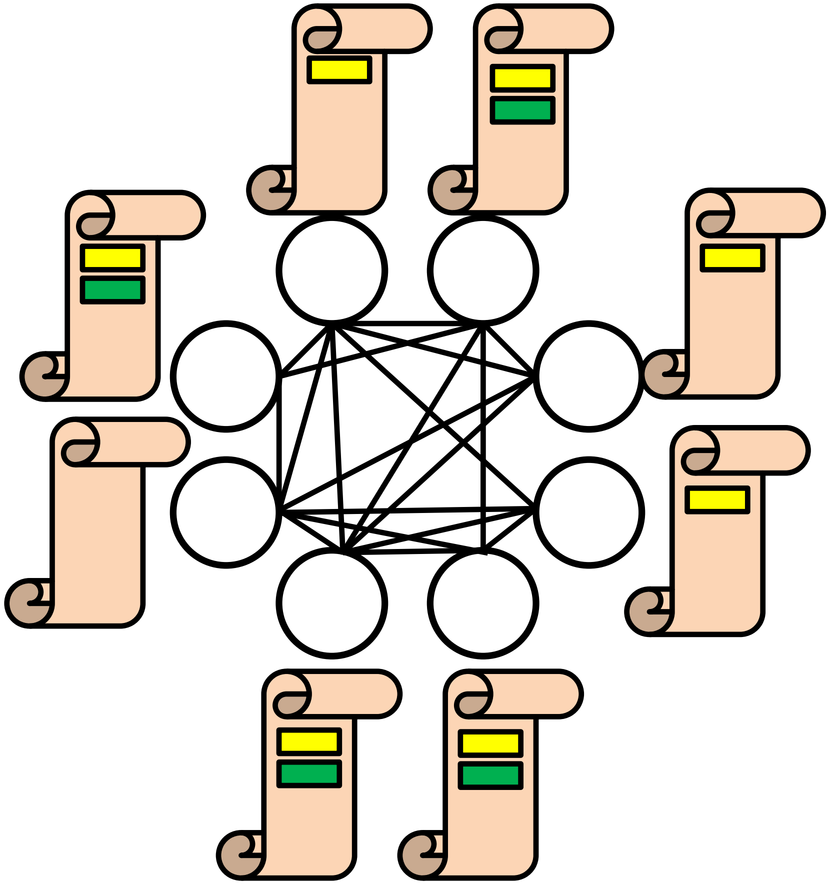
a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

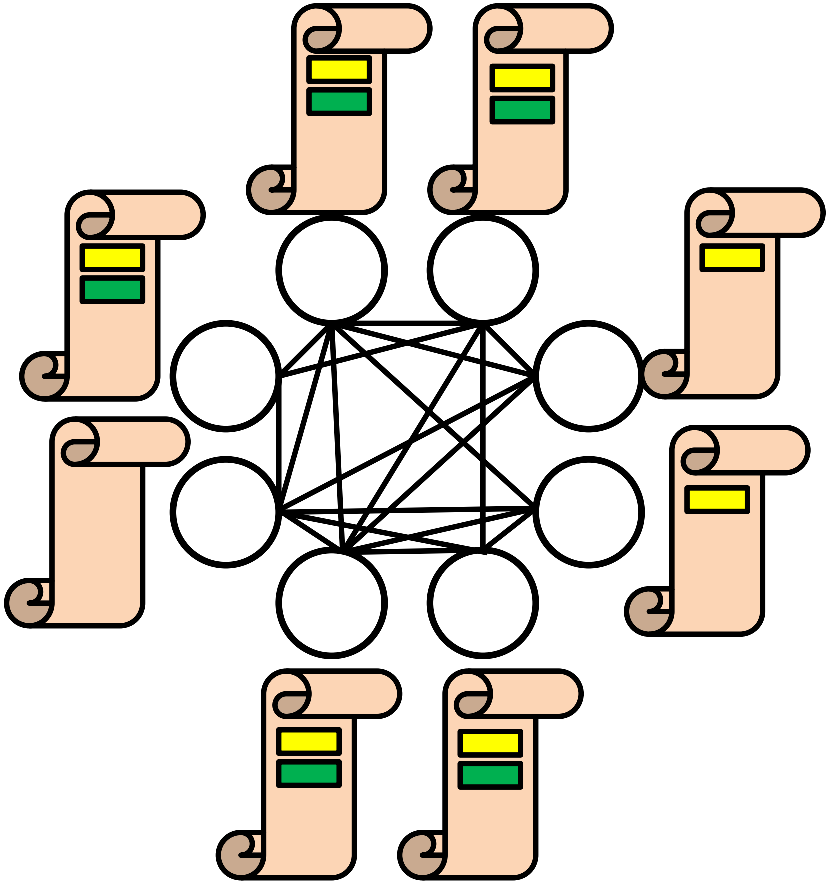
a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

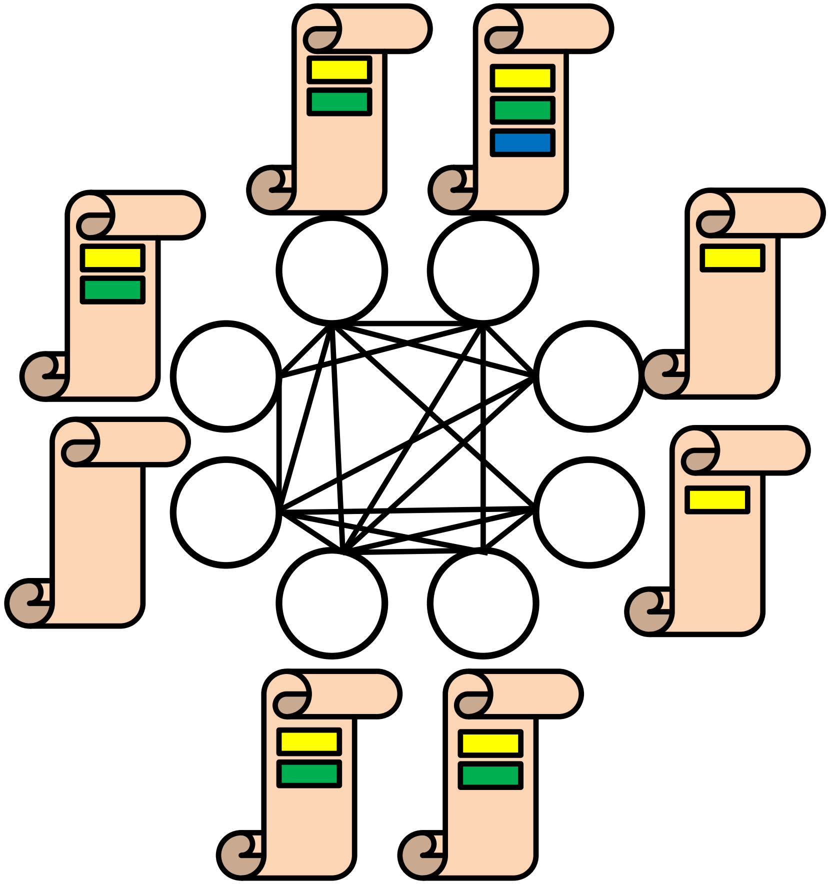
a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

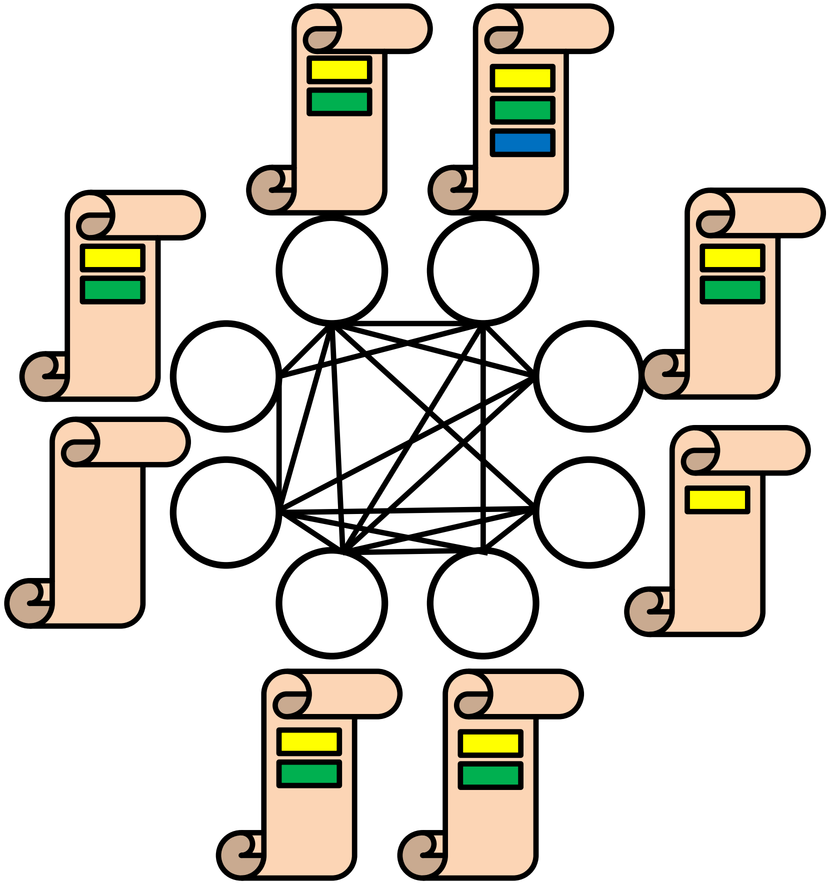
a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

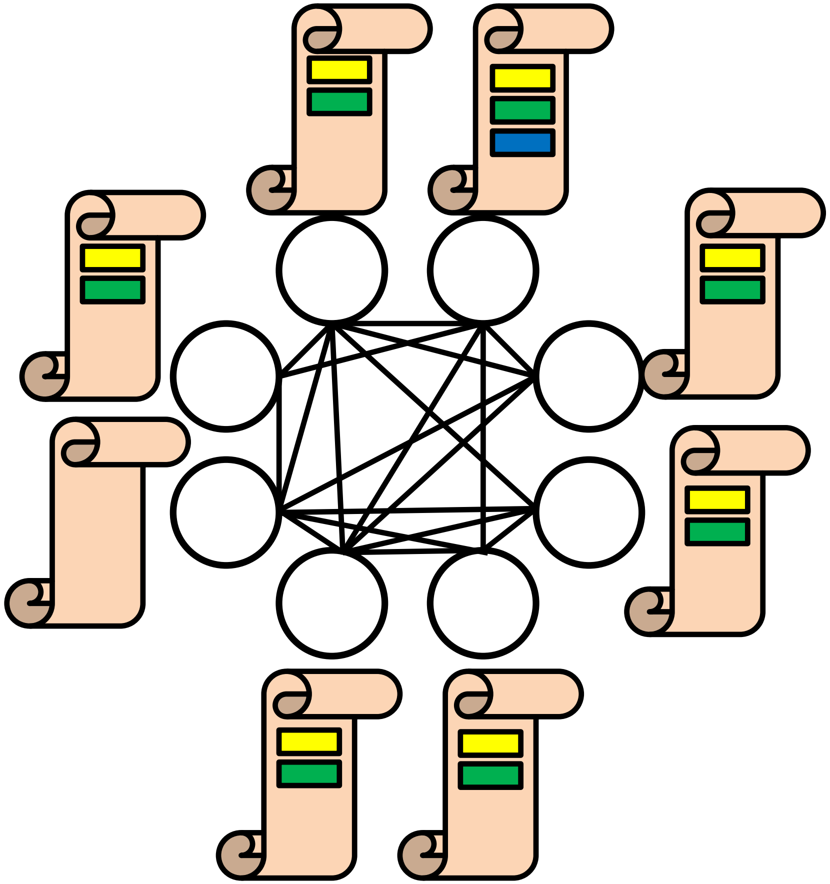
a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

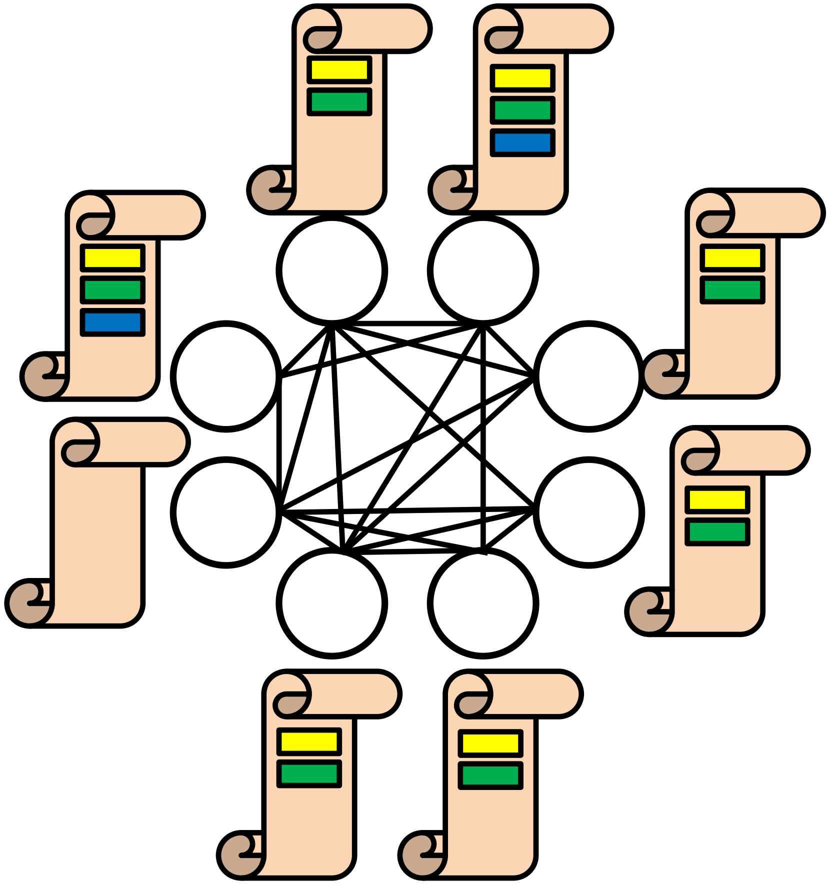
a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

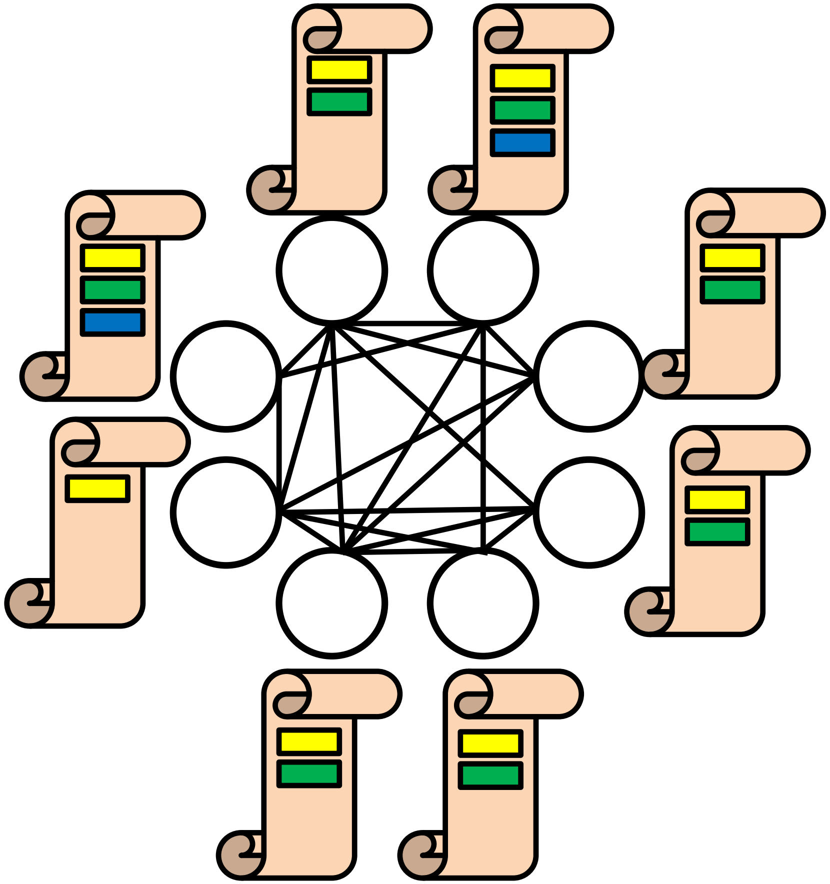
a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

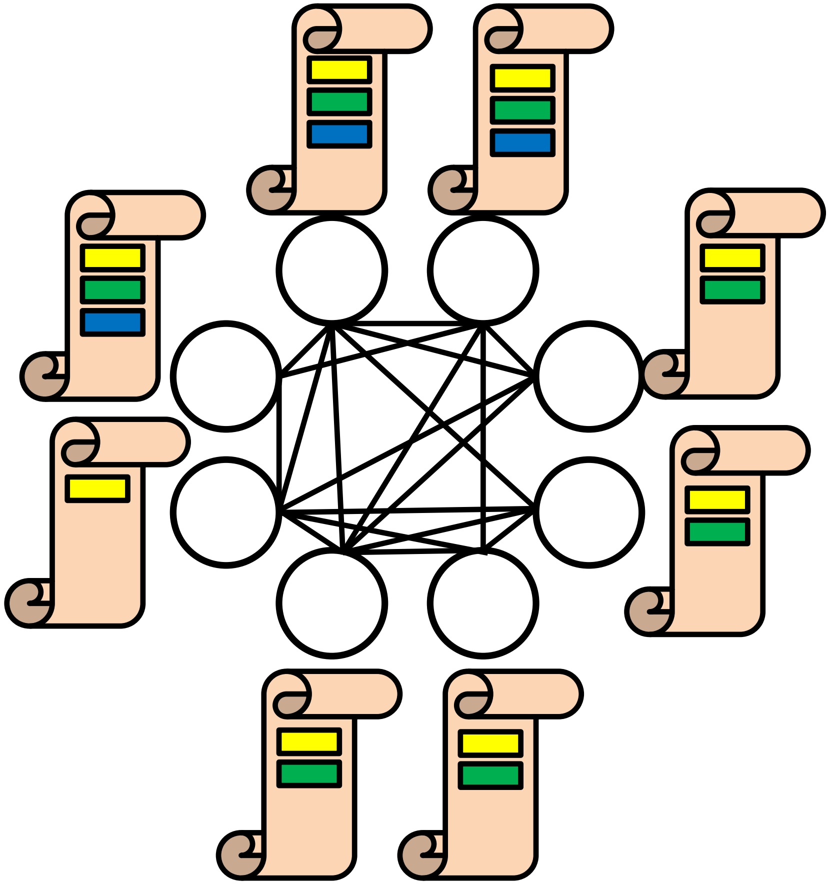
a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

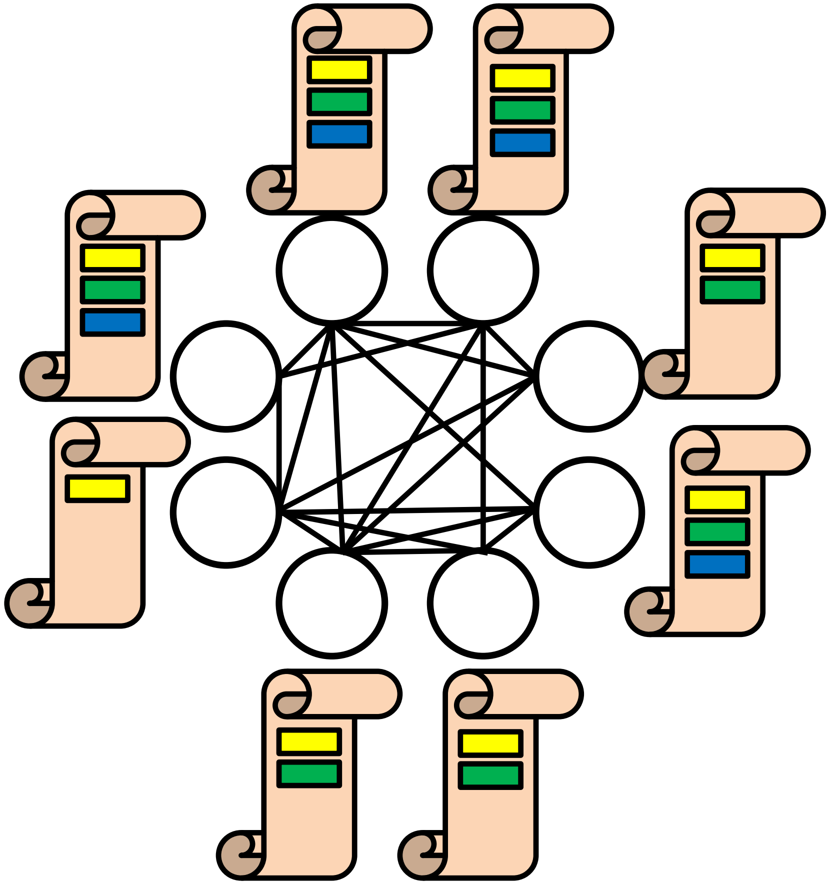
a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

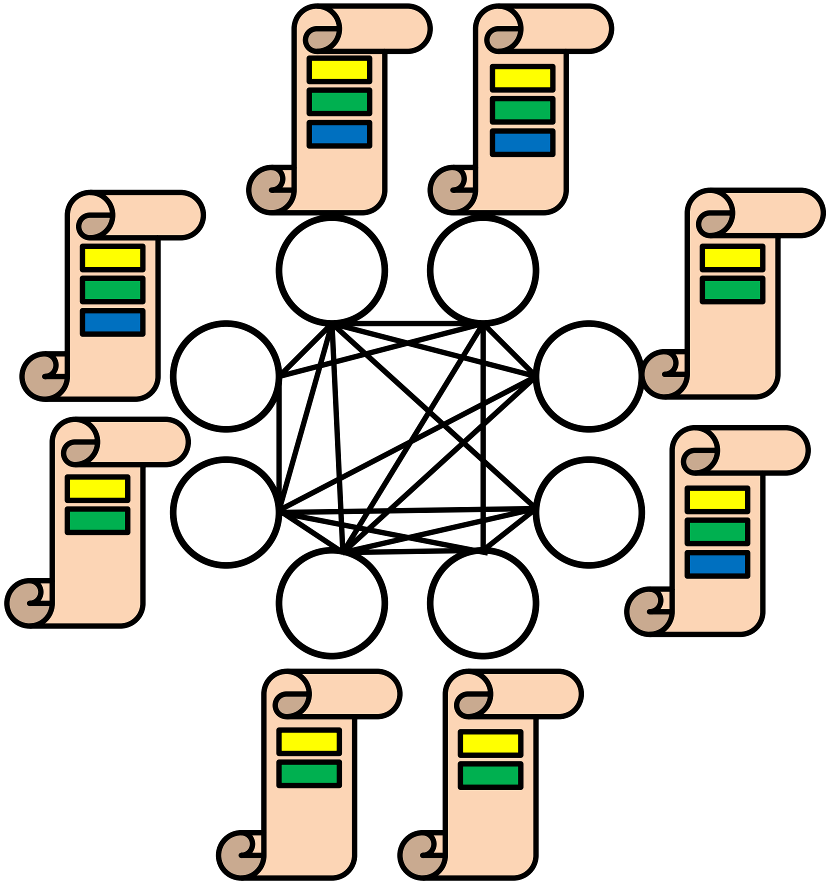
a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

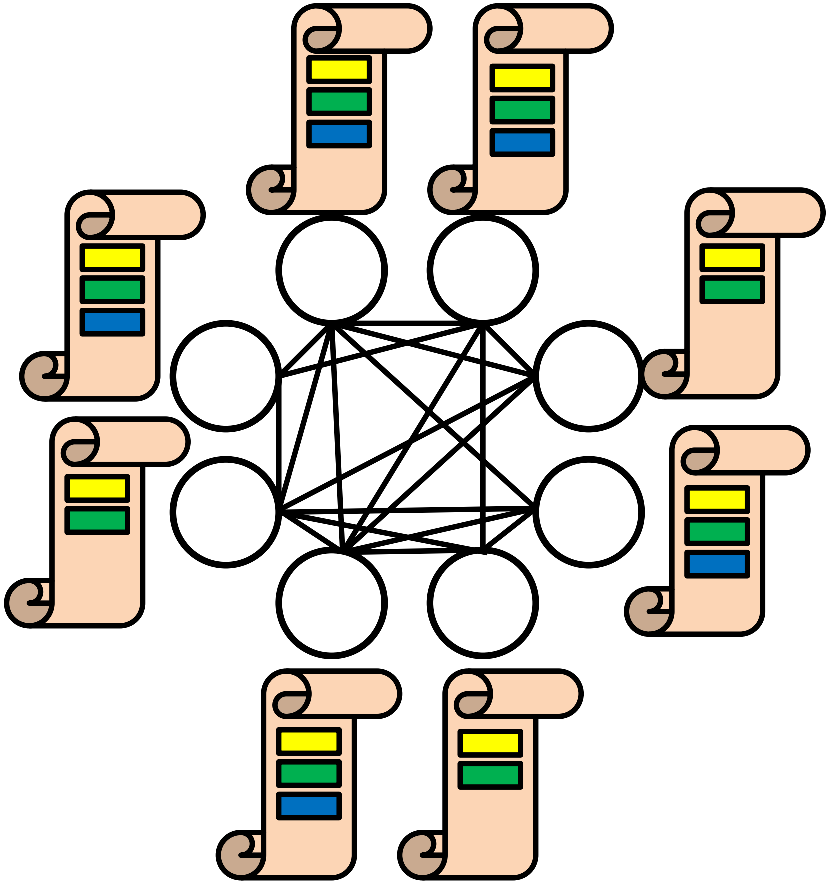
a better solution



Consistency:
all nodes always agree on the current state of the ledger

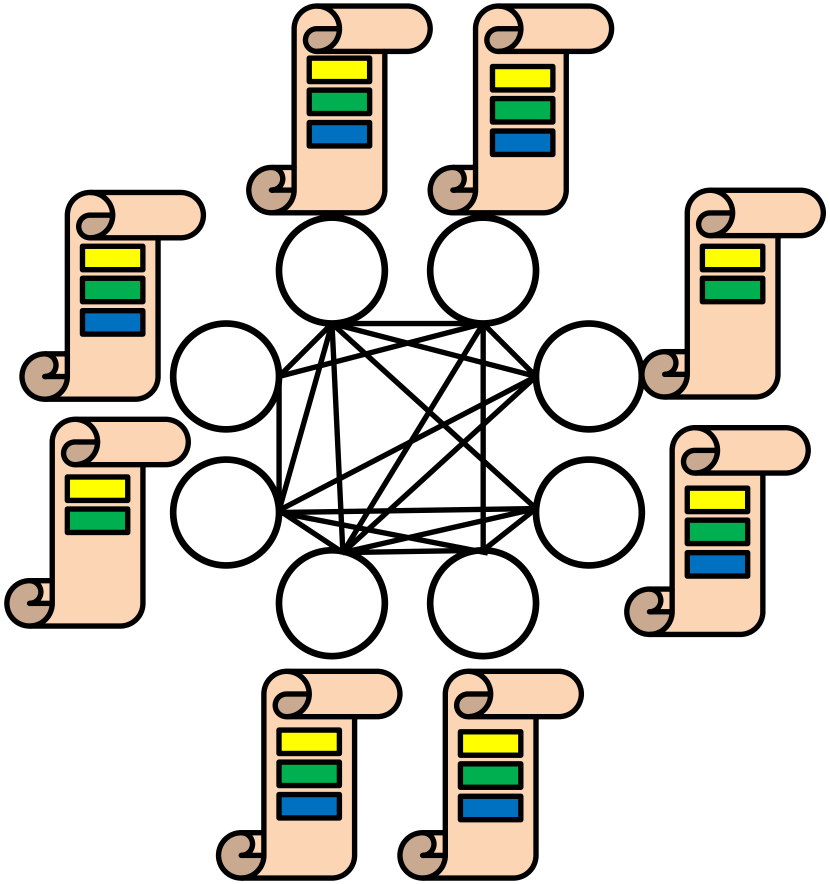
Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

a better solution



Consistency:
all nodes always agree on the current state of the ledger

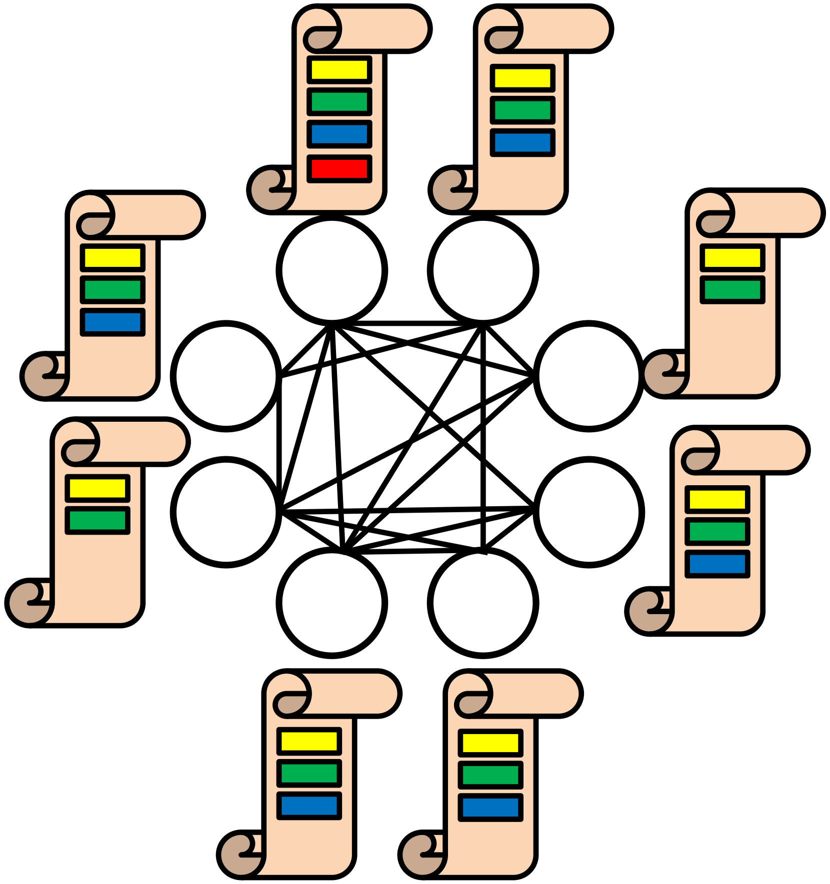
Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)



a better solution

Consistency:
all nodes always agree on the current state of the ledger

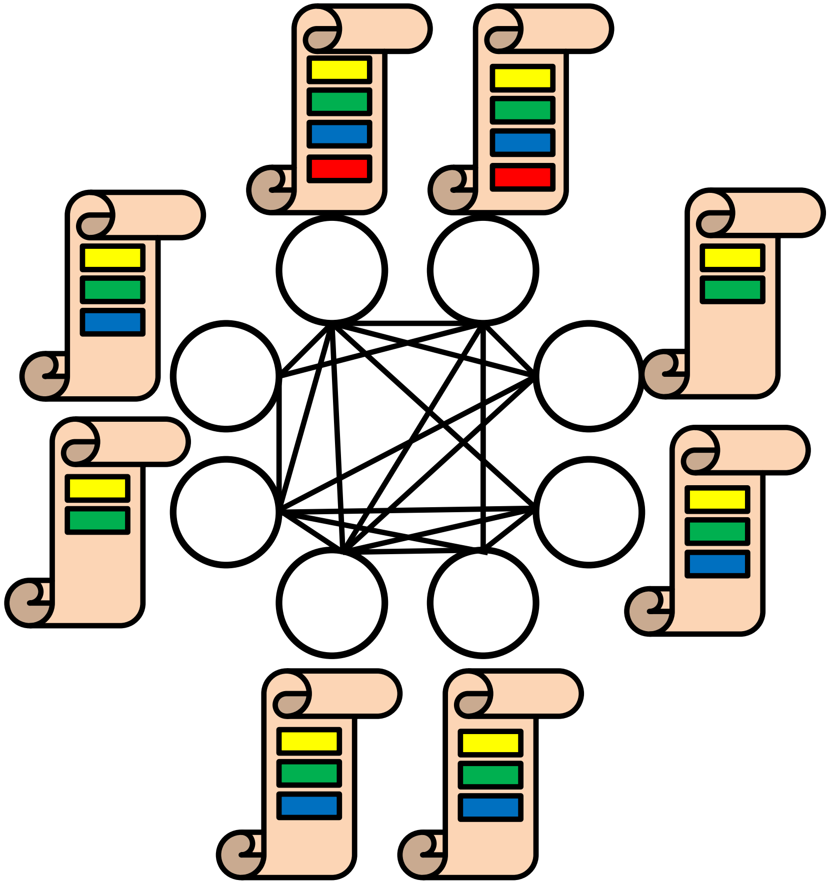
Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)



a better solution

Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

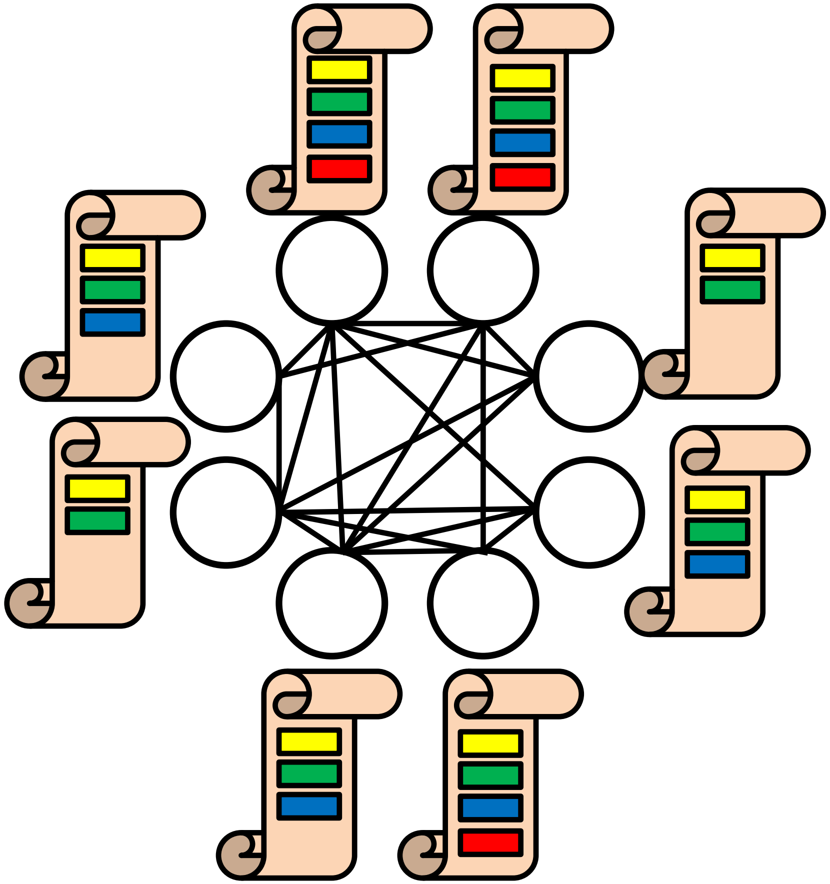


a better solution

Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

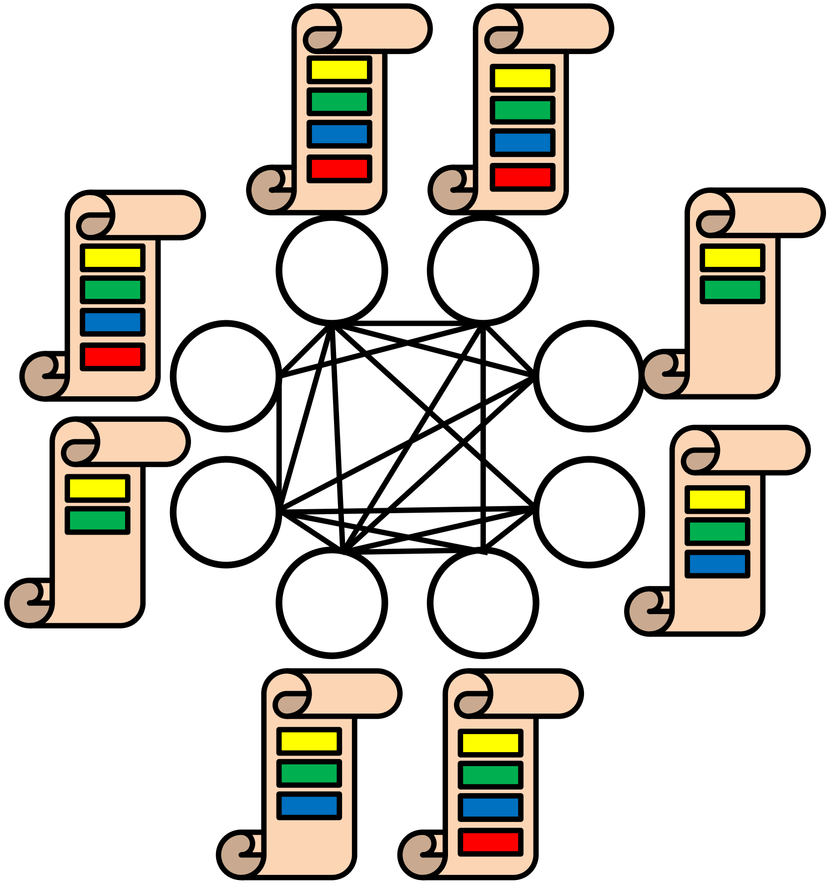
a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

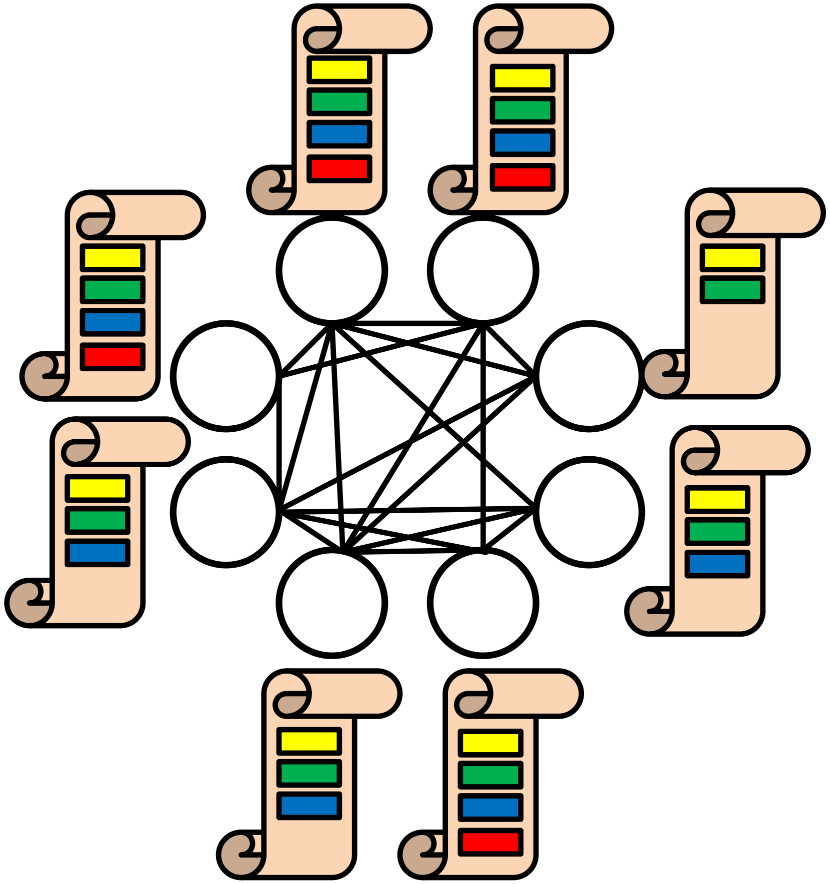
a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

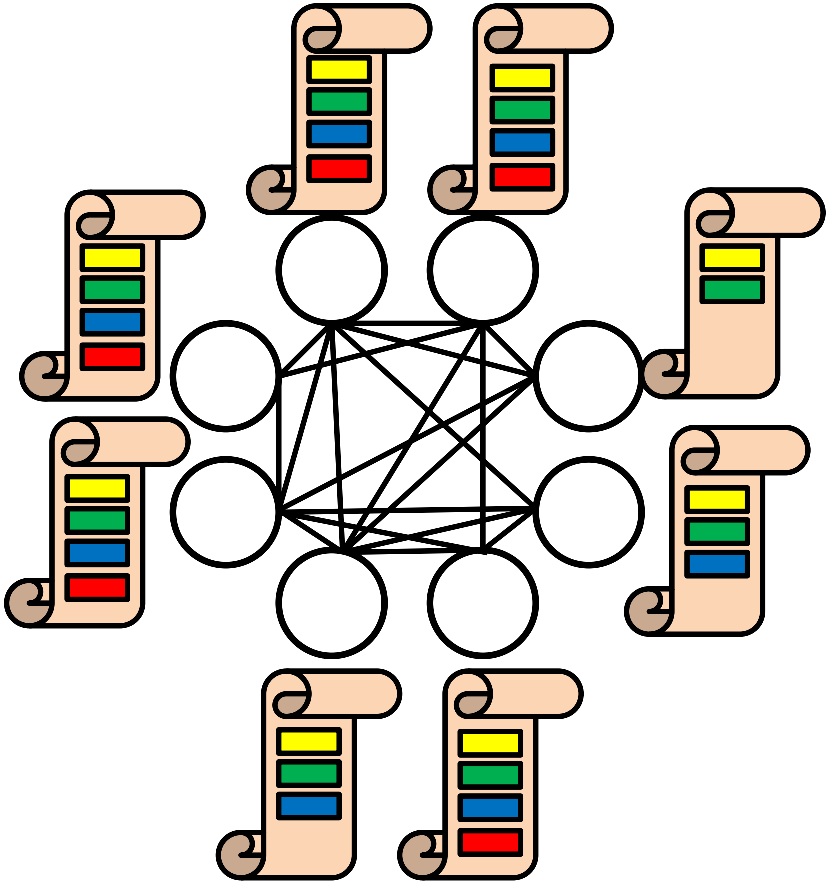
a better solution



Consistency:
all nodes always agree on the current state of the ledger

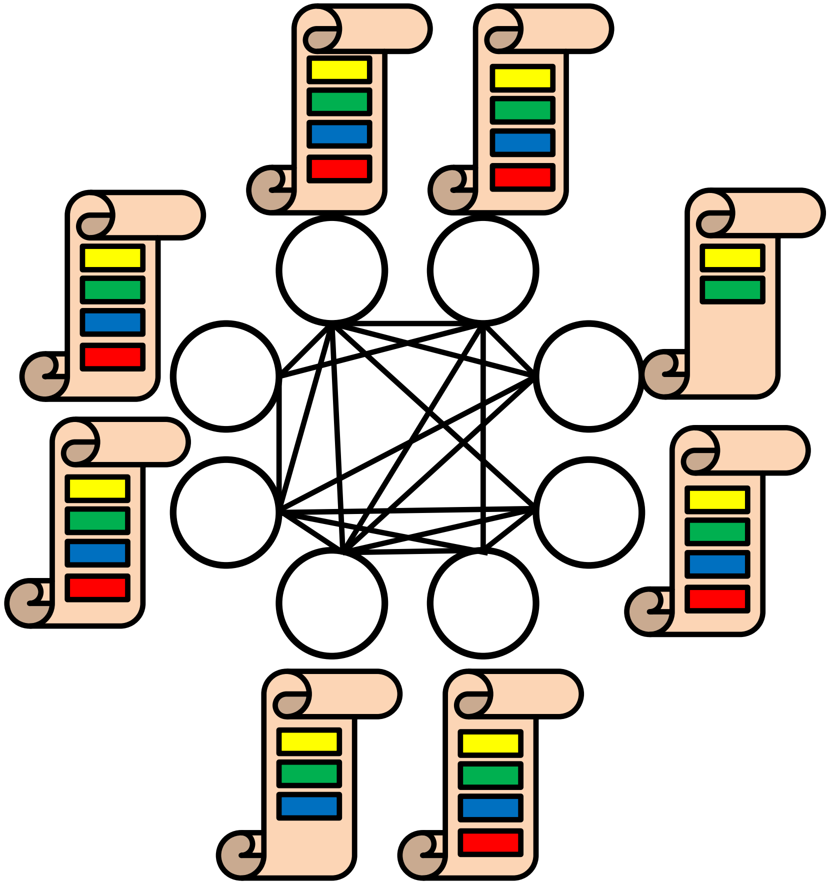
Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

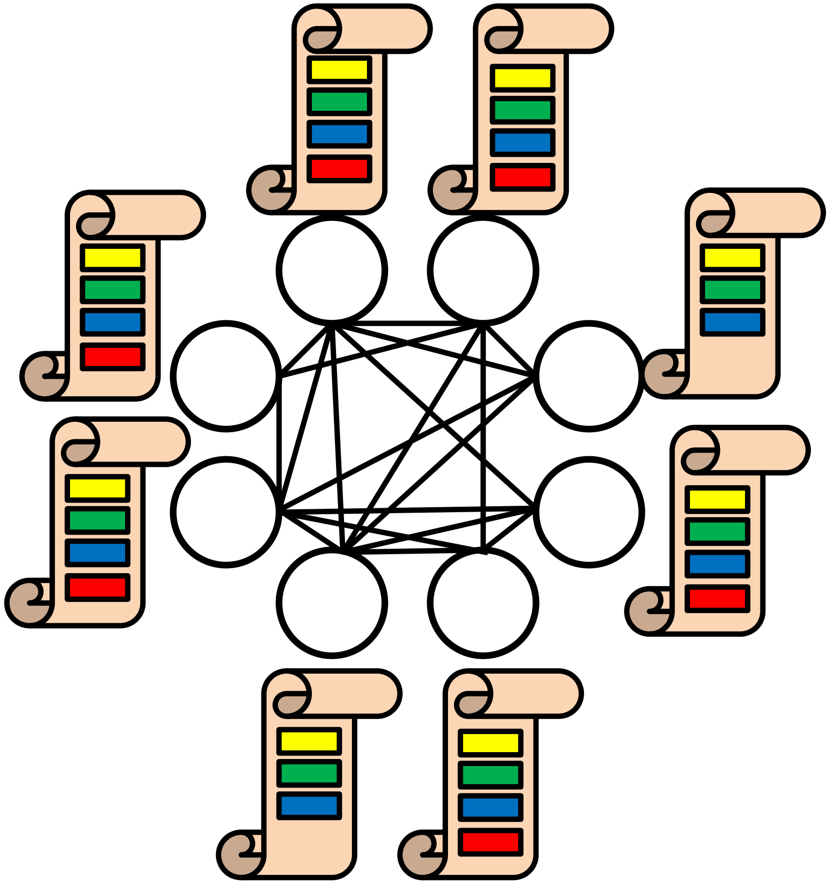


a better solution

Consistency:
all nodes always agree on the current state of the ledger

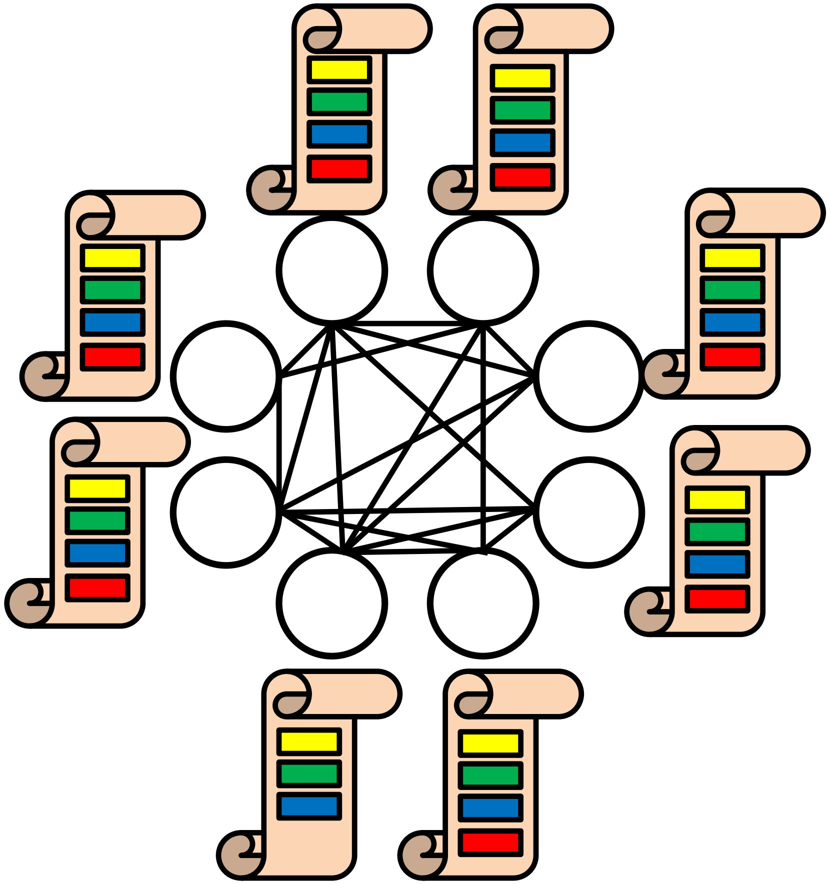
Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

a better solution



Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

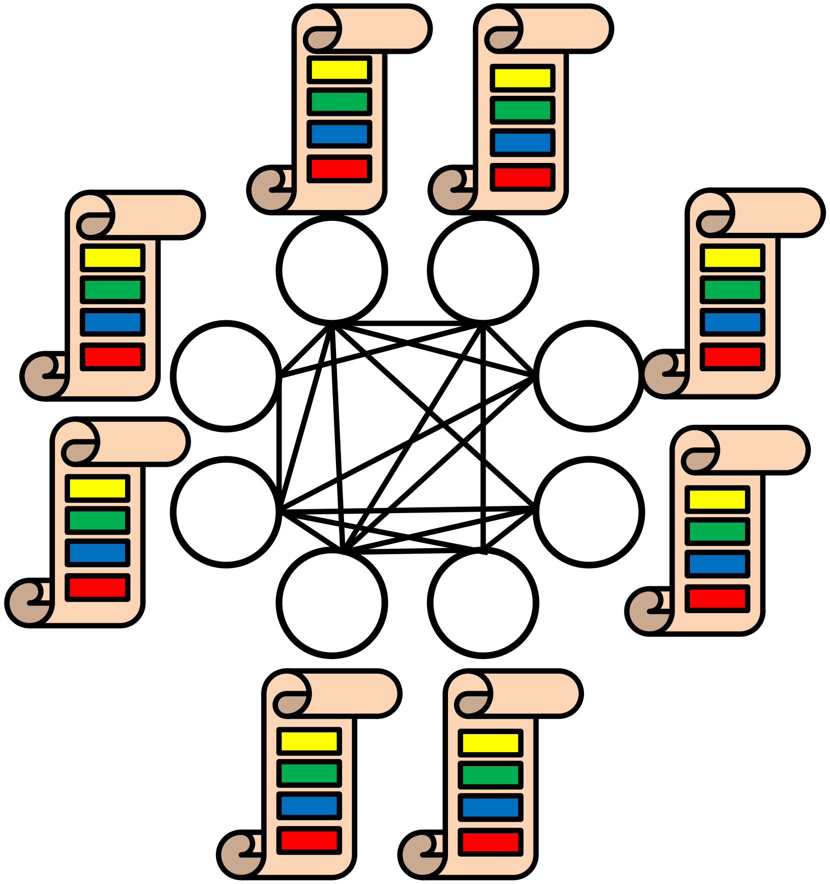


a better solution

Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

a better solution

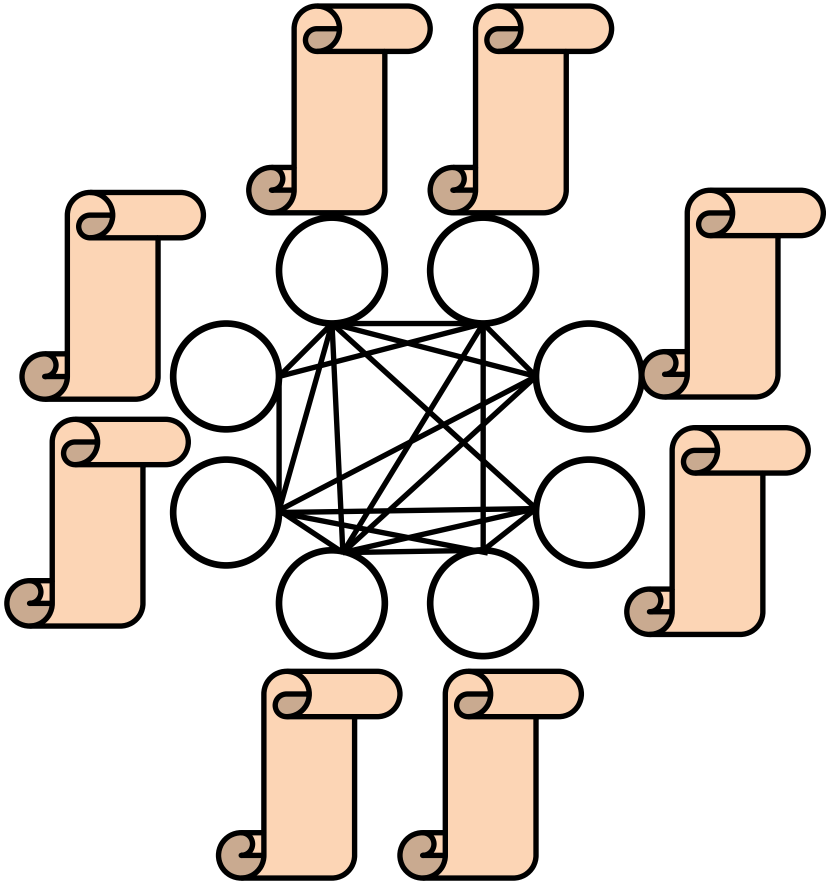


Consistency:
all nodes always agree on the current state of the ledger

Eventual consistency:
all nodes eventually agree on the current state of the ledger (if no new updates are issued)

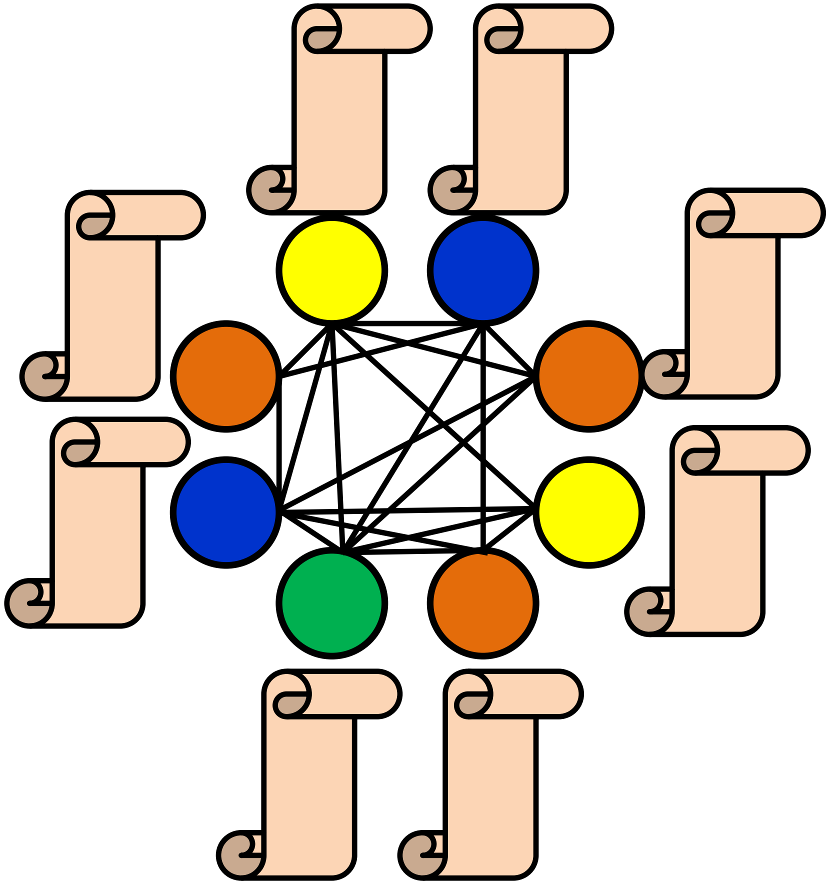
How to solve the distributed ledger problem

distributed ledger via repeated consensus



repeat:

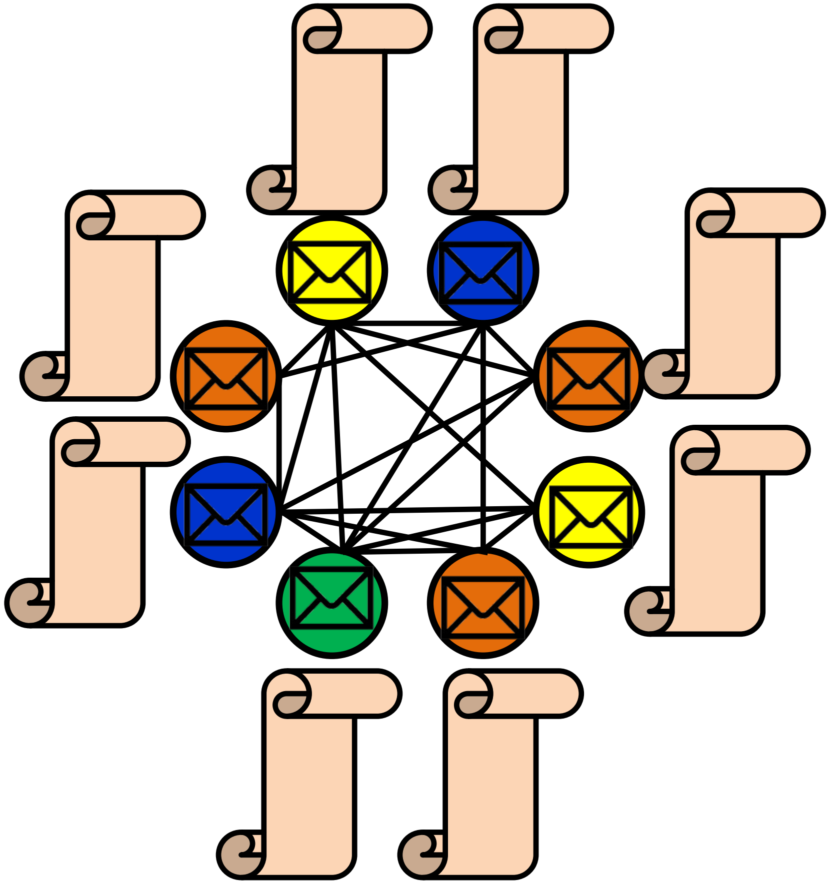
distributed ledger via repeated consensus



repeat:

- each node supports its command

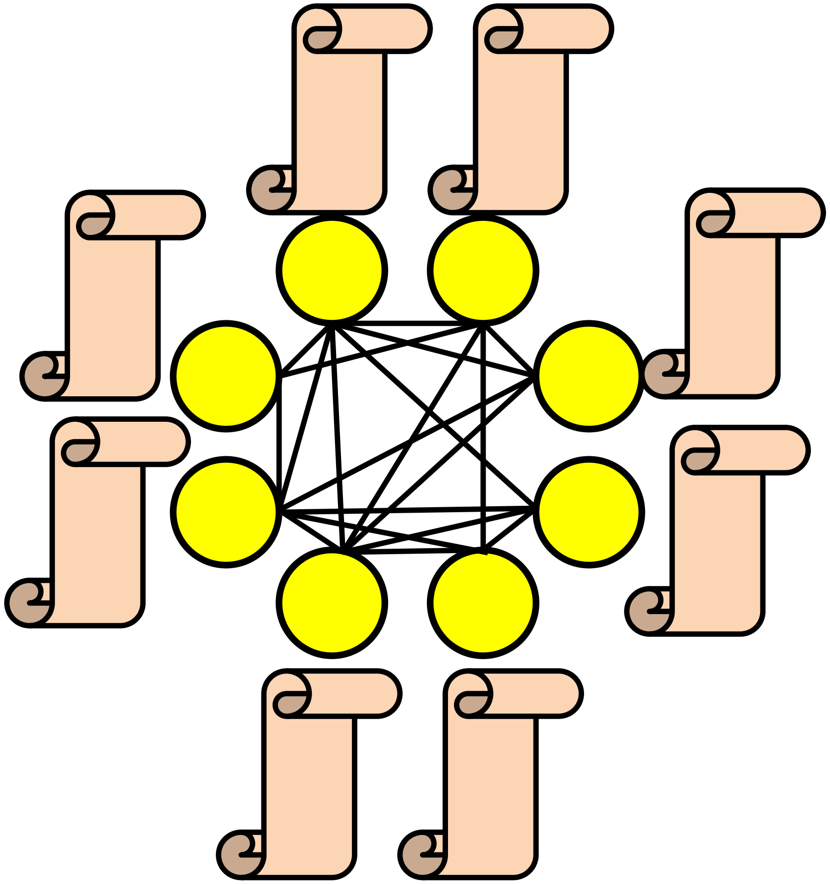
distributed ledger via repeated consensus



repeat:

- each node supports its command
- exchange messages to get an agreement on the winning command

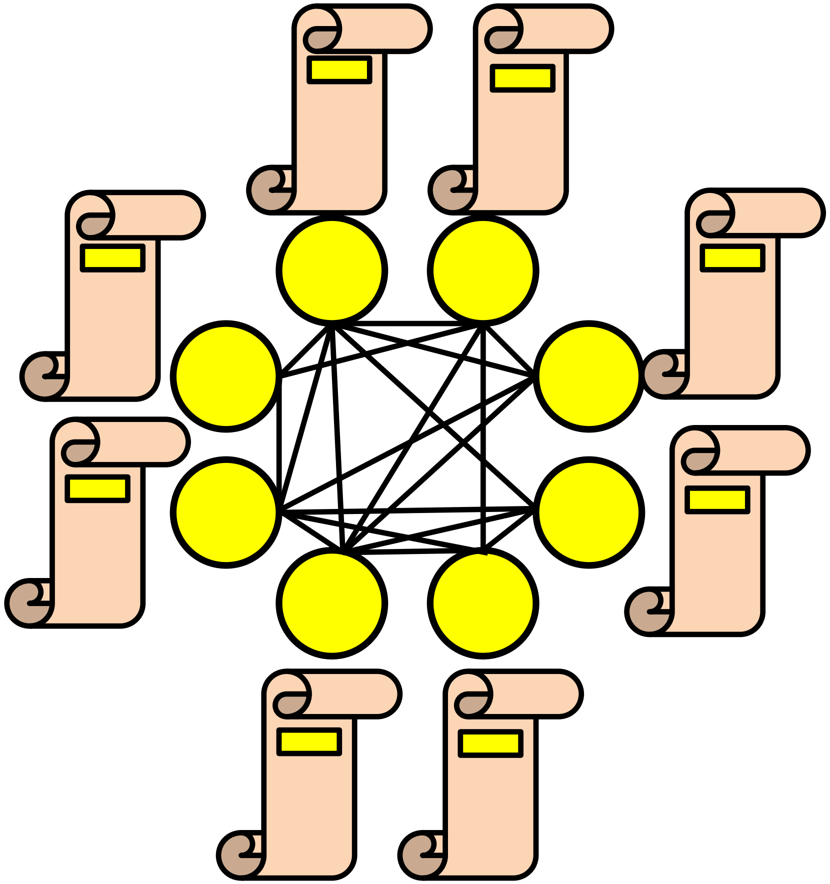
distributed ledger via repeated consensus



repeat:

- each node supports its command
- exchange messages to get an agreement on the winning command

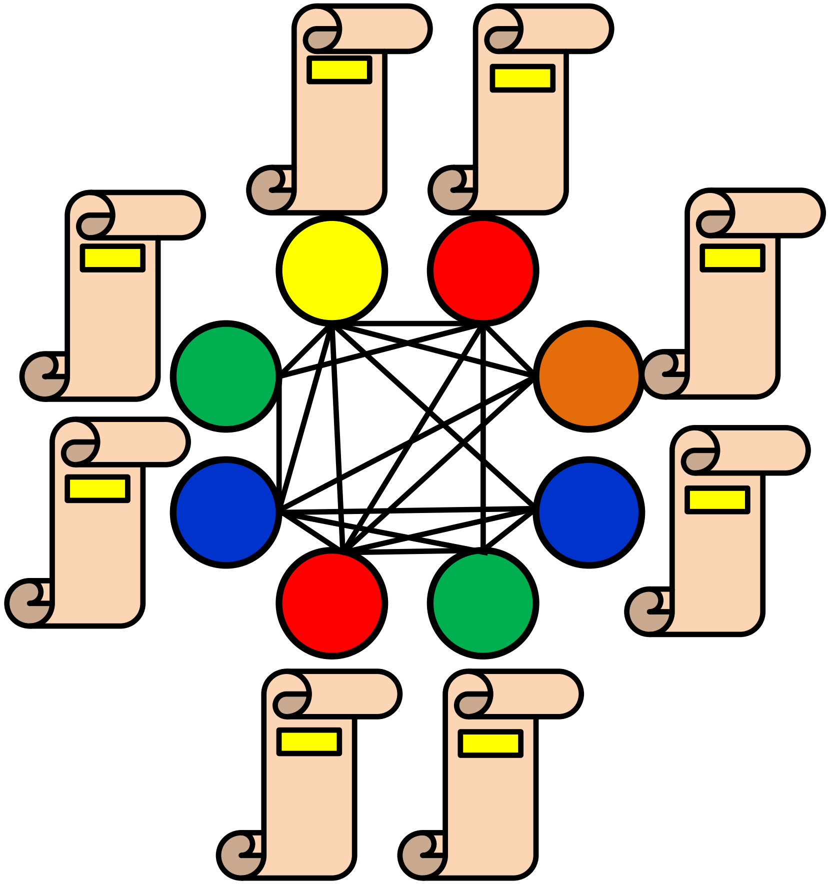
distributed ledger via repeated consensus



repeat:

- each node supports its command
- exchange messages to get an agreement on the winning command
- every node updates its (local) ledger with the winning command

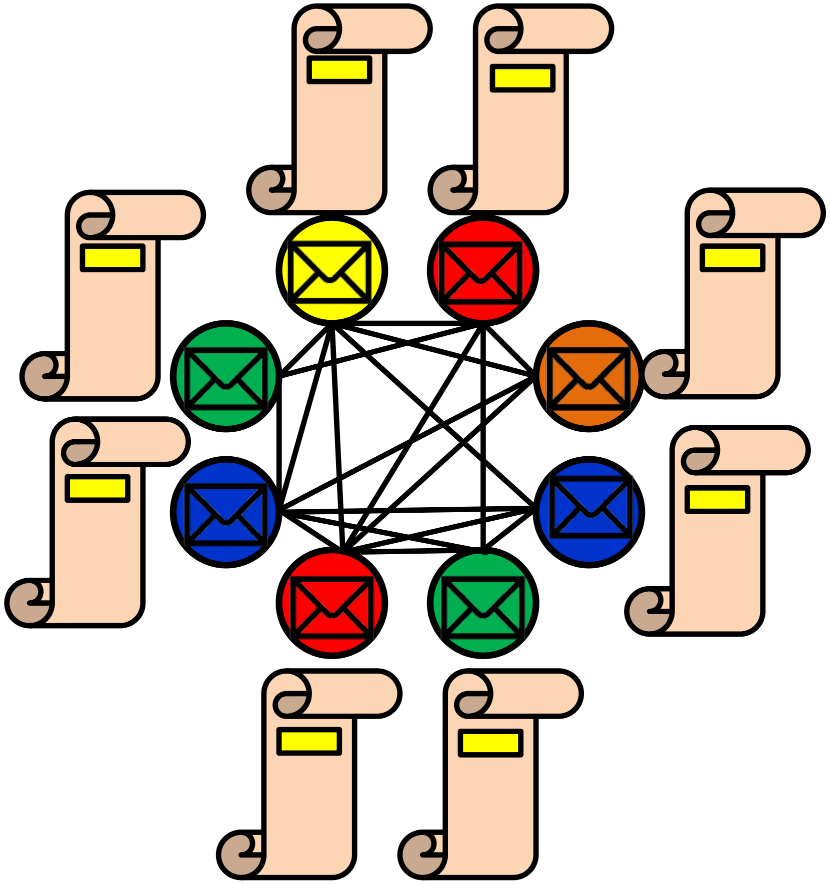
distributed ledger via repeated consensus



repeat:

- each node supports its command
- exchange messages to get an agreement on the winning command
- every node updates its (local) ledger with the winning command

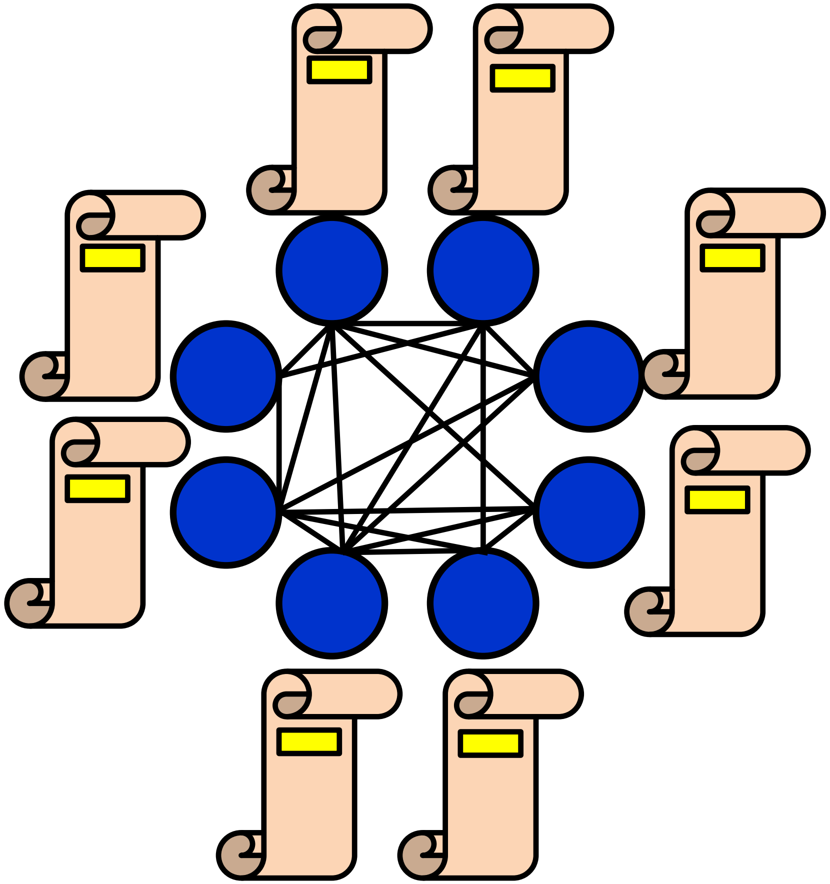
distributed ledger via repeated consensus



repeat:

- each node supports its command
- exchange messages to get an agreement on the winning command
- every node updates its (local) ledger with the winning command

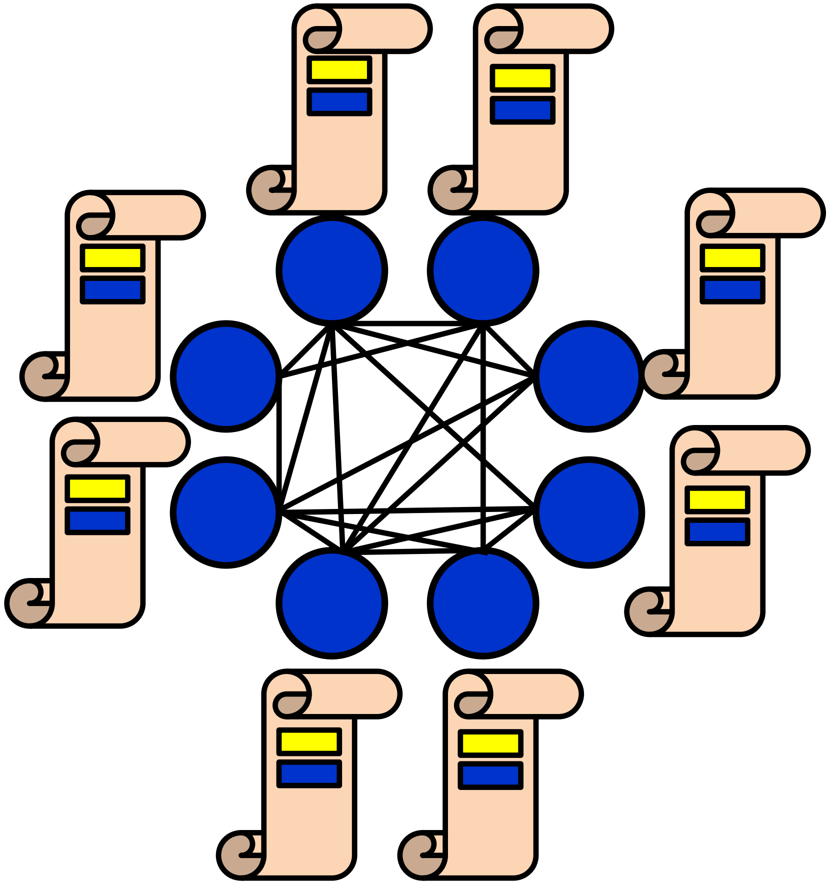
distributed ledger via repeated consensus



repeat:

- each node supports its command
- exchange messages to get an agreement on the winning command
- every node updates its (local) ledger with the winning command

distributed ledger via repeated consensus



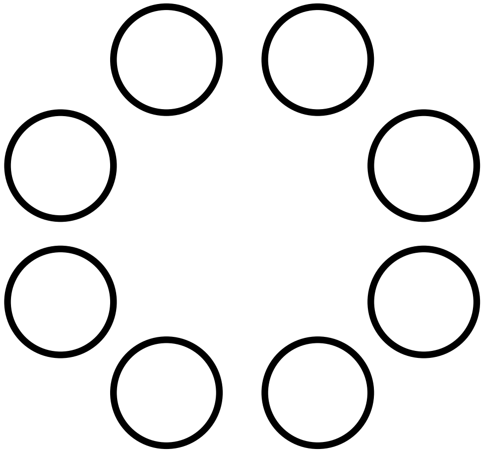
repeat:

- each node supports its command
- exchange messages to get an agreement on the winning command
- every node updates its (local) ledger with the winning command

the consensus problem

Consensus Problem

a set of *n* nodes

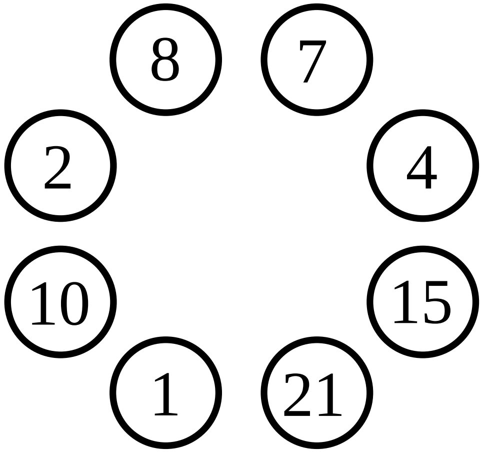


Consensus Problem

a set of *n* nodes

each node has:

unique ID



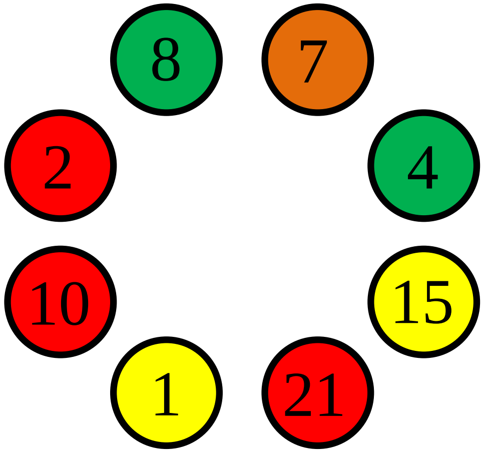
Consensus Problem

a set of *n* nodes

each node has:

unique ID

a color in {  … }



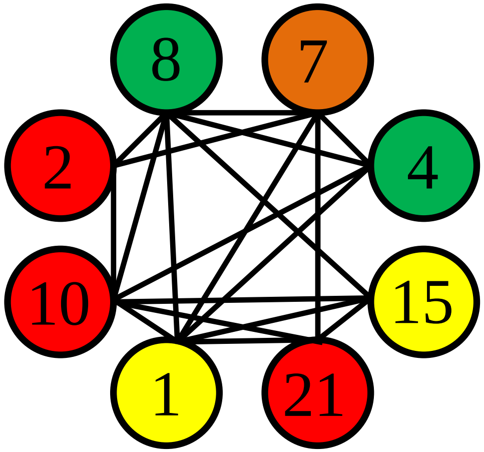
Consensus Problem

a set of n nodes

each node has:

- unique ID
- a color in {  …  }

an underlying communication graph G



Consensus Problem

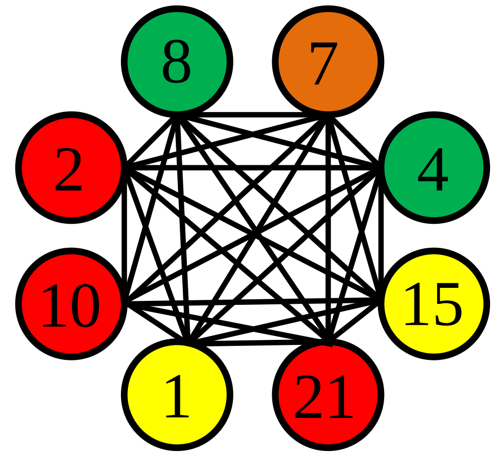
a set of *n* nodes

each node has:

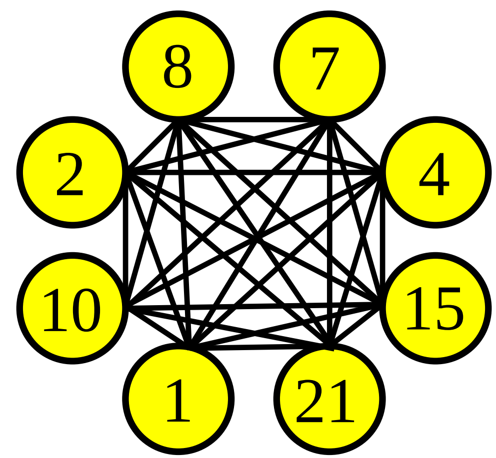
unique ID

a color in { … }

an underlying communication graph *G*



Goal: a *distributed protocol* guaranteeing



Termination (protocol eventually ends)

Consensus Problem

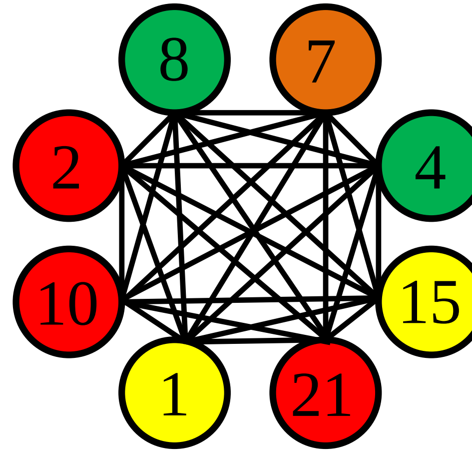
a set of *n* nodes

each node has:

unique ID

a color in {🔴🟡🟢 … 🟠}

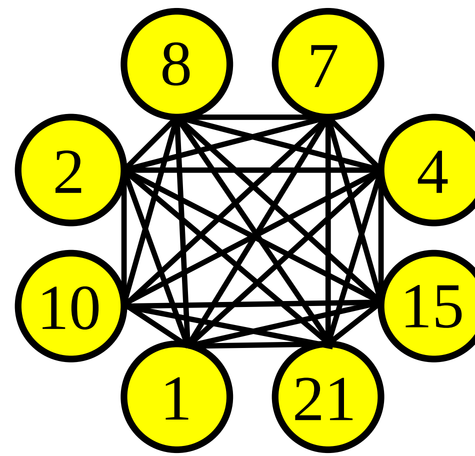
an underlying communication graph *G*



Goal: a *distributed protocol* guaranteeing

Termination (protocol eventually ends)

Agreement (monochromatic final configuration)



Consensus Problem

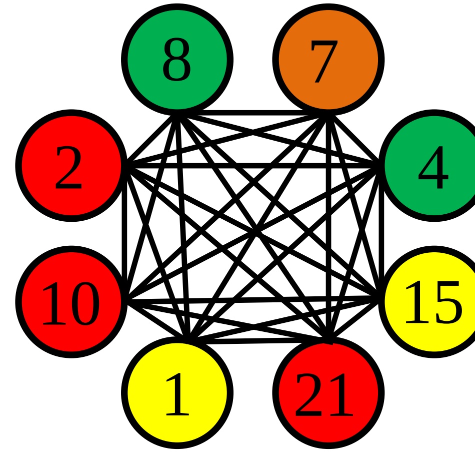
a set of *n* nodes

each node has:

unique ID

a color in {  … }

an underlying communication graph *G*



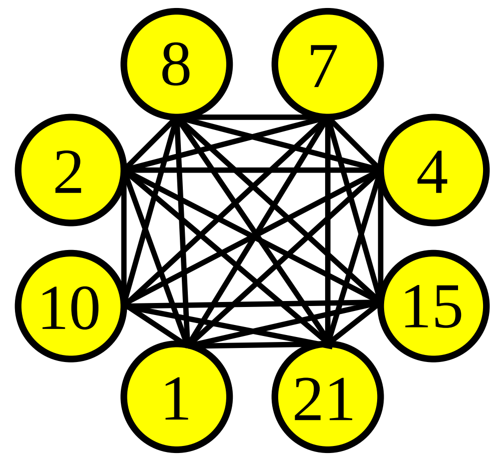
Goal: a *distributed protocol* guaranteeing

Termination (protocol eventually ends)

Agreement (monochromatic final configuration)

Validity

the *winning color* is initially supported by some node

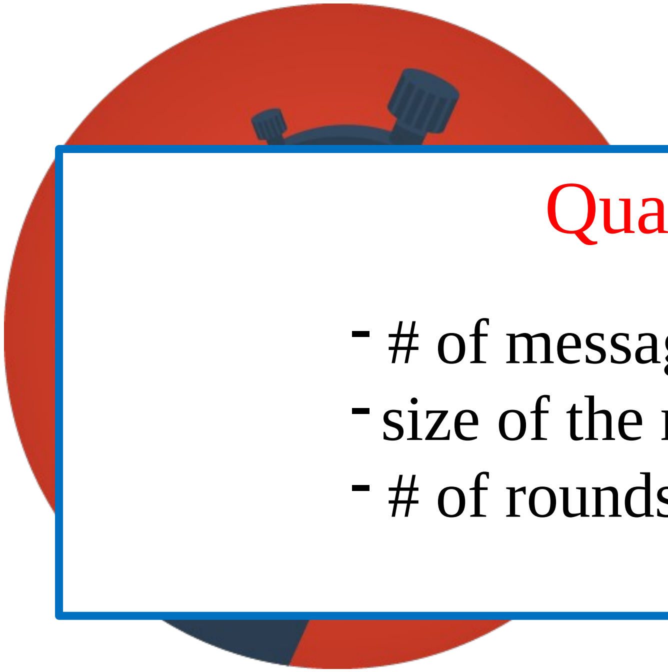


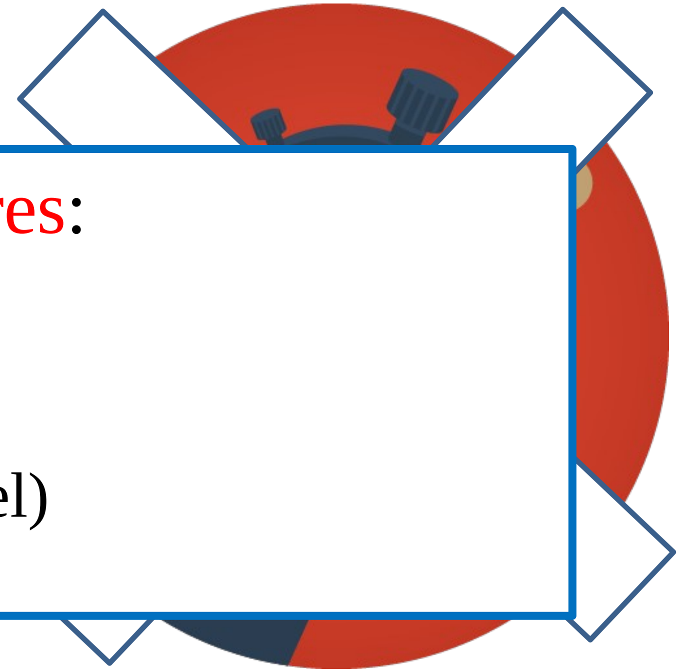
Models of computation

- shared clock
- computation proceeds in *rounds*
- messages sent in a round arrive in the next round
- in a round, a node receives mgs & computes & sends msgs

- no shared clock
- no rounds
- messages arrive in the finite but unbounded time

Models of computation





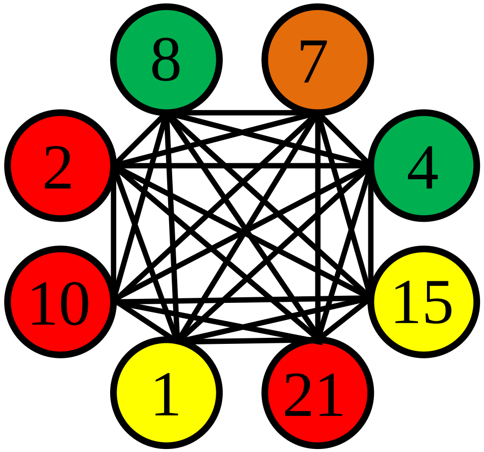
Quality measures:

- # of messages
- size of the messages
- # of rounds (sync. model)

- shared clock
- computation proceeds in *rounds*
- messages sent in a round arrive in the next round
- in a round, a node receives mgs & computes & sends msgs

- no shared clock
- no rounds
- messages arrive in the finite but unbounded time

Consensus Problem



a set of *n* nodes

each node has:

- unique ID
- a color in {  … }

an underlying communication graph *G*

Goal: a *distributed protocol* guaranteeing ...

Simple solution:

Leader Election & convergence to leader’s color

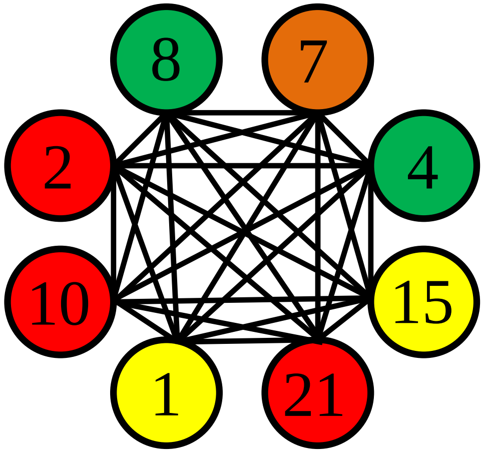
Consensus Problem

a set of *n* nodes

each node has:

- unique ID
- a color in { … }

an underlying communication graph *G*



Goal: a *distributed protocol* guaranteeing ...

Simple solution:

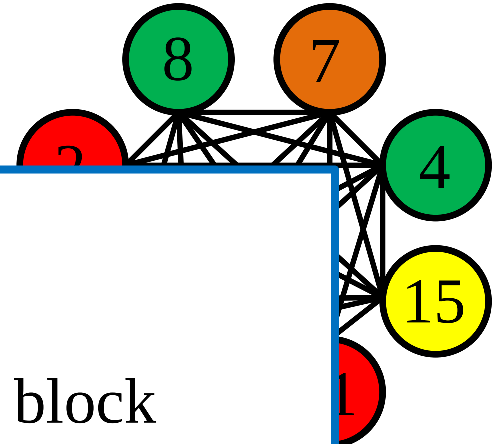
Leader Election & convergence to leader's color

Find-min protocol

Consensus Problem

a set of *n* nodes

each node has:



a

Goa

In the Bitcoin System:

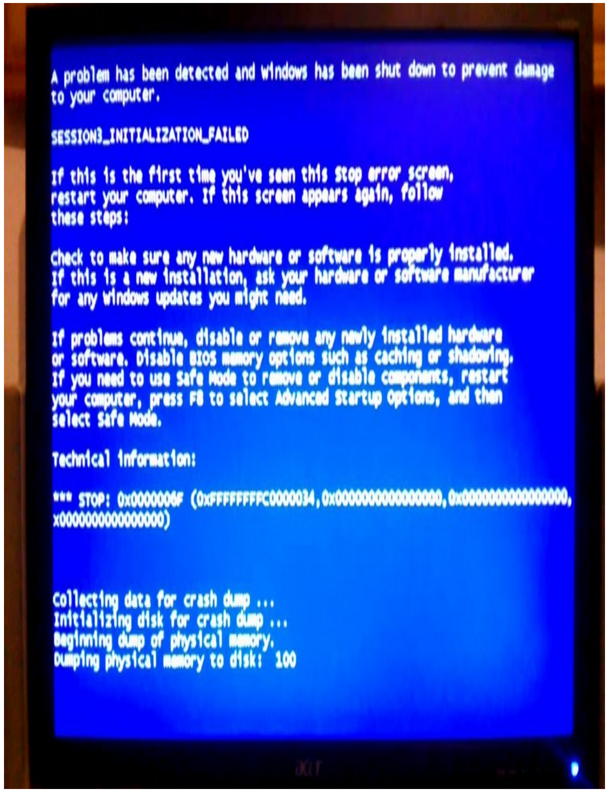
the leader is the node that solves the next block

Leader Election & convergence to leader's color

Find-min protocol

Fault Tolerance

Type of failures

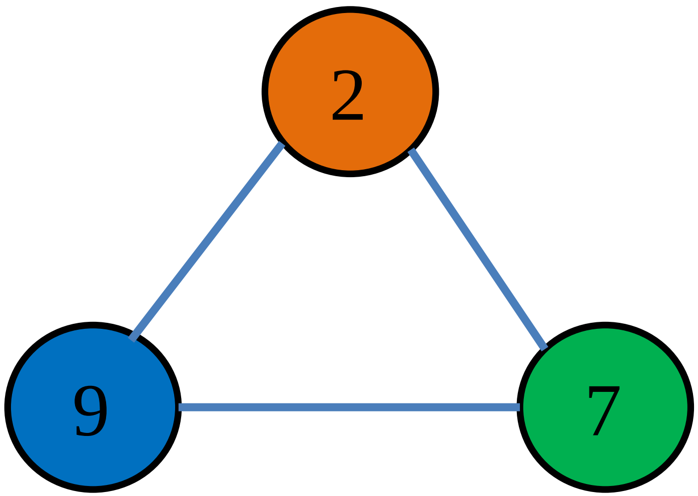


Crash failures

Simple solution:

Leader Election & convergence to leader's color

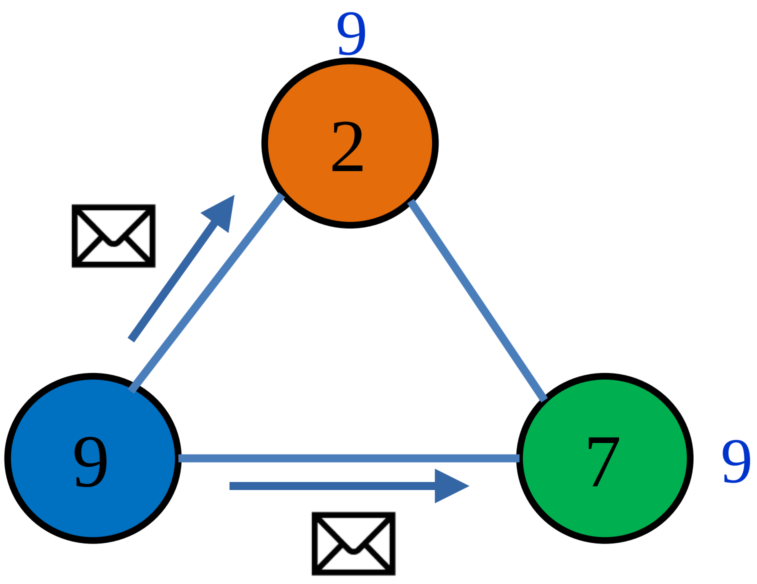
Find-min protocol



Simple solution:

Leader Election & convergence to leader's color

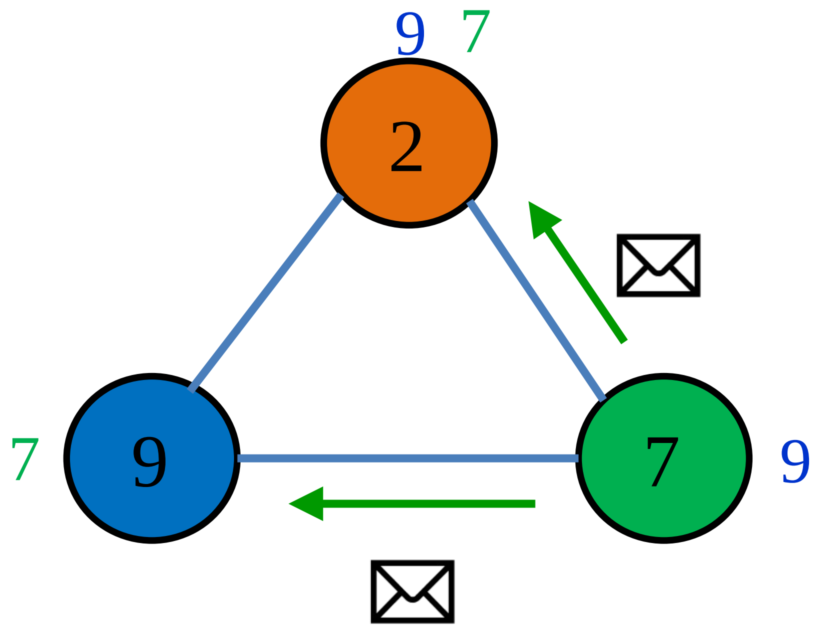
Find-min protocol



Simple solution:

Leader Election & convergence to leader's color

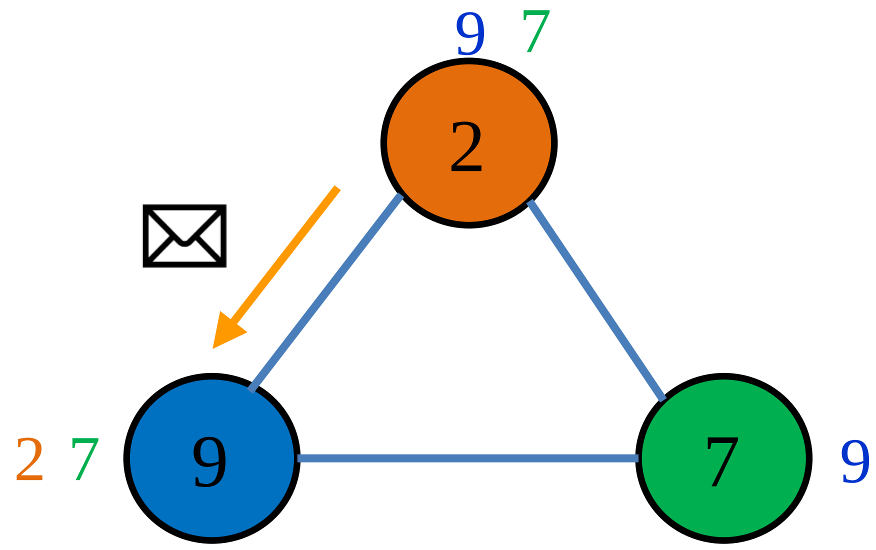
Find-min protocol



Simple solution:

Leader Election & convergence to leader's color

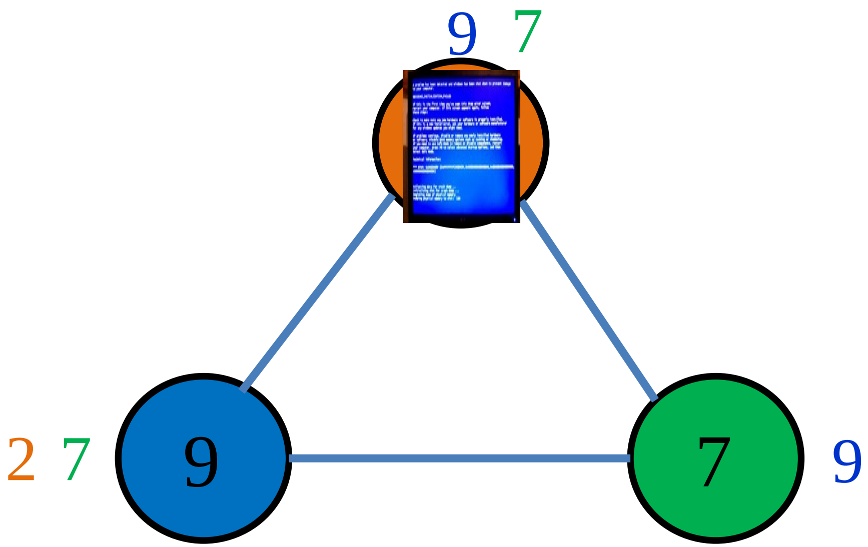
Find-min protocol



Simple solution:

Leader Election & convergence to leader's color

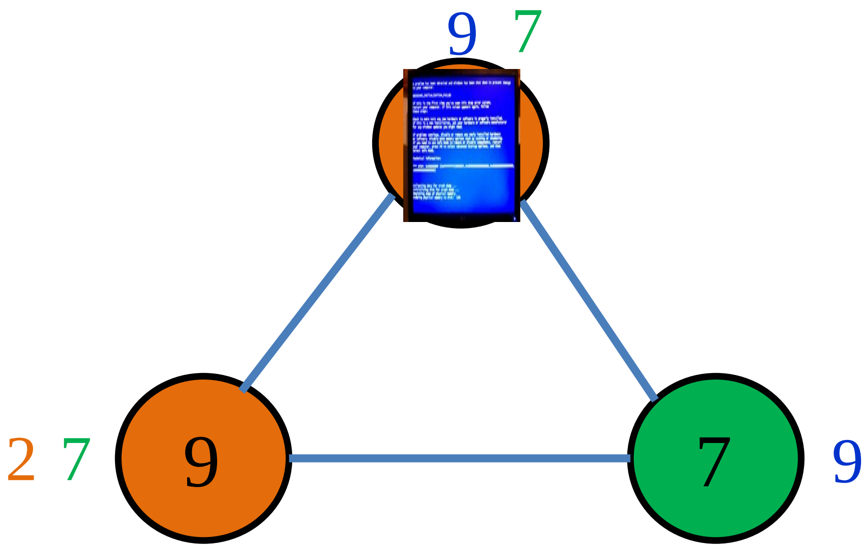
Find-min protocol



Simple solution:

Leader Election & convergence to leader's color

Find-min protocol

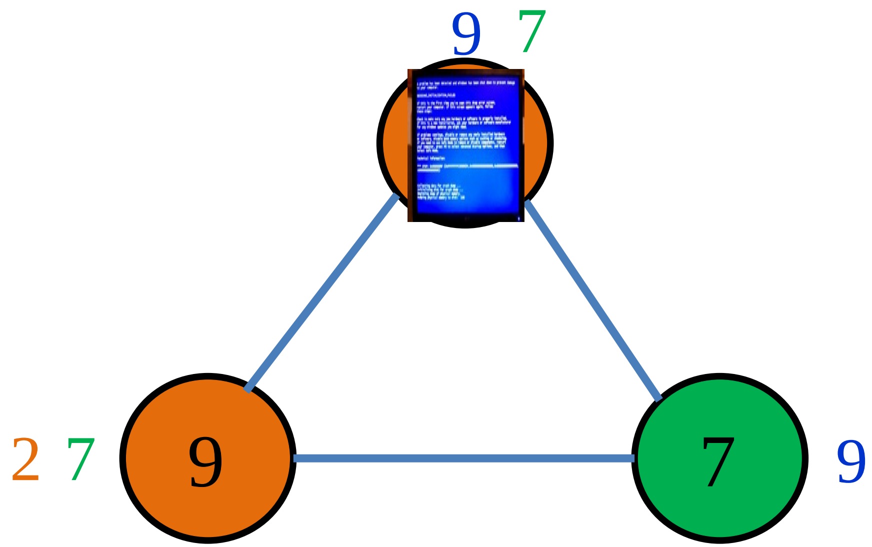


Simple solution:

Leader Election & convergence to leader's color

Find-min protocol

no agreement!



Theorem (1985)

There is no deterministic algorithm which always achieve consensus in the asynchronous model, with $f > 0$ crash failures.

Theorem (1985)

There is no deterministic algorithm which always achieve consensus in the asynchronous model, with $f > 0$ crash failures.

Theorem (1983)

There is a randomized algorithm achieving consensus in the asynchronous model if up to $f < n/2$ nodes crash. No consensus algorithm can tolerate $f \geq n/2$ many crash failures.

Theorem (1985)

There is no deterministic algorithm which always achieve consensus in the asynchronous model, with $f > 0$ crash failures.

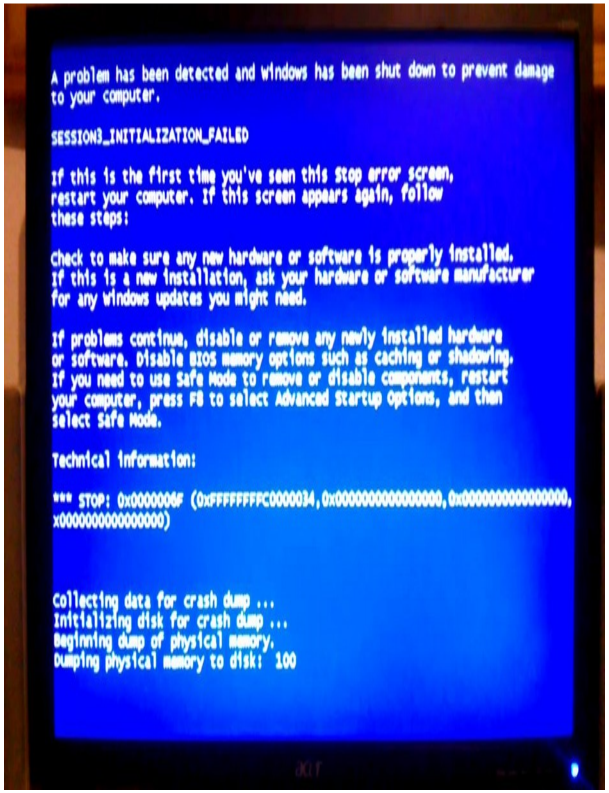
Theorem (1983)

There is a randomized algorithm achieving consensus in the asynchronous model if up to $f < n/2$ nodes crash. No consensus algorithm can tolerate $f \geq n/2$ many crash failures.

Theorem (1983)

There is a consensus algorithm for the synchronous model that tolerates any $f < n$ crash failures.

Type of failures



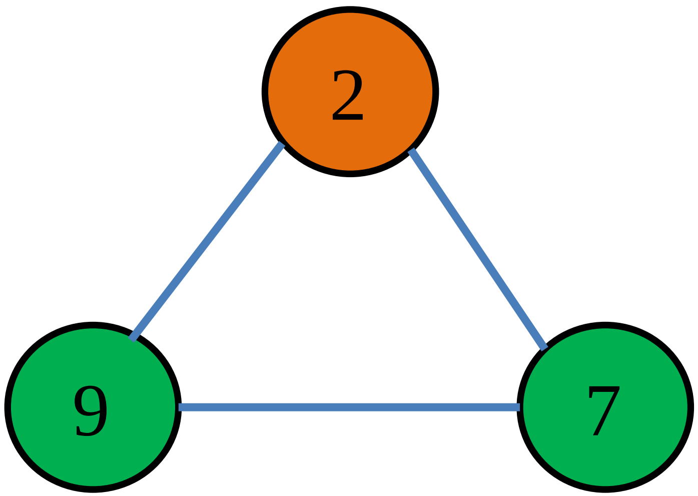
Crash failures

Byzantine failures

Simple solution:

Leader Election & convergence to leader's color

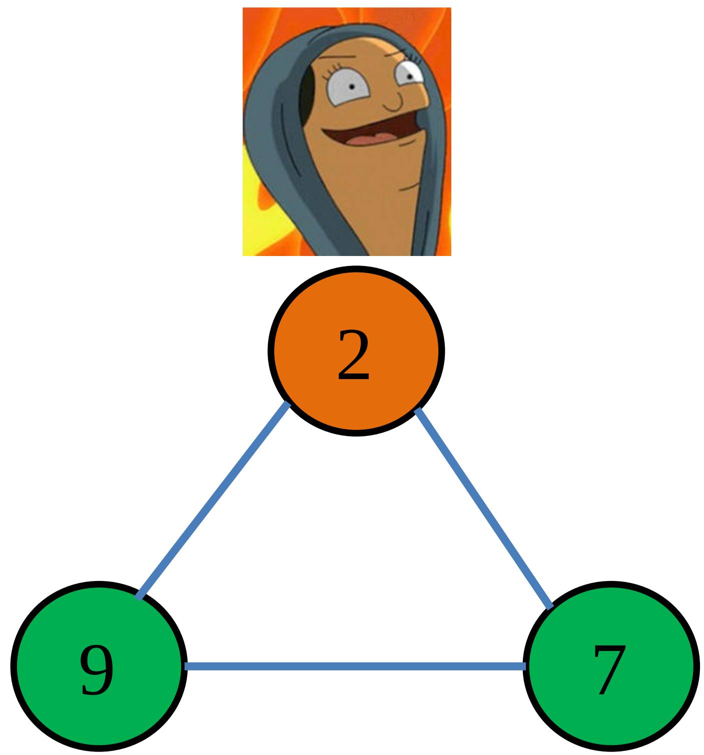
Find-min protocol



Simple solution:

Leader Election & convergence to leader’s color

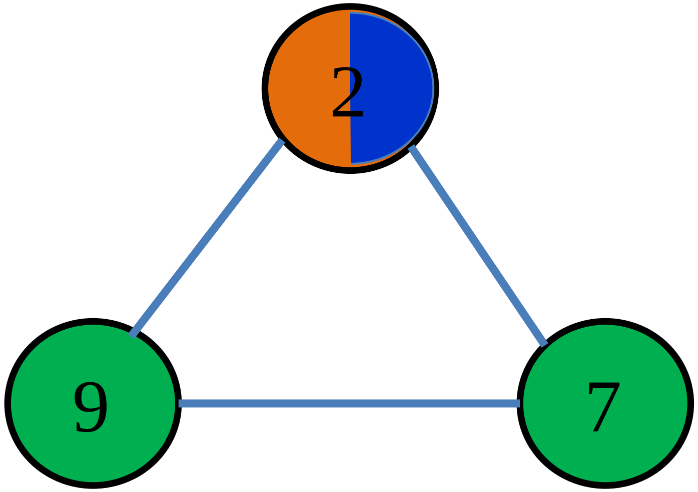
Find-min protocol



Simple solution:

Leader Election & convergence to leader's color

Find-min protocol

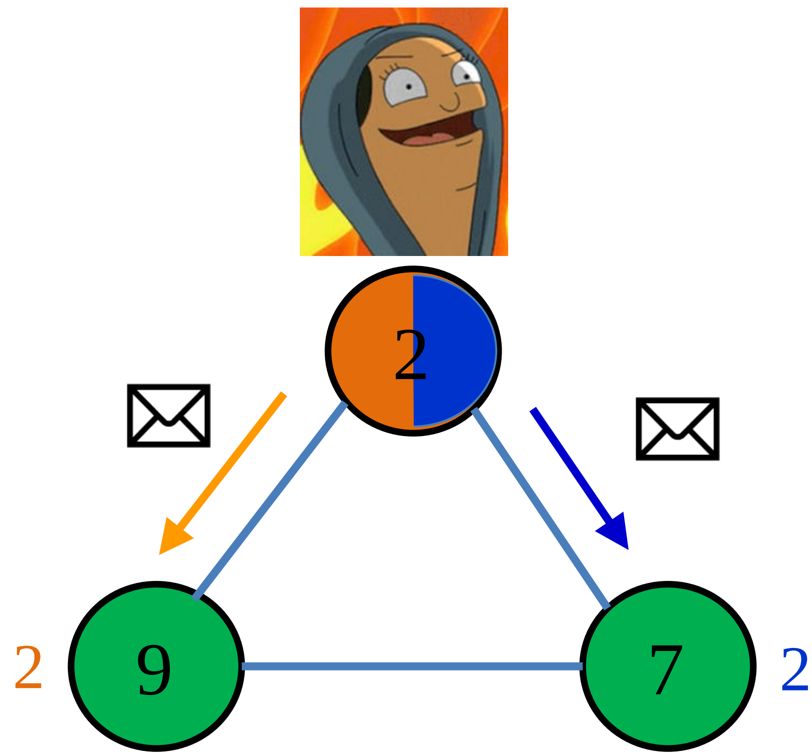


Simple solution:

Leader Election & convergence to leader's color

|

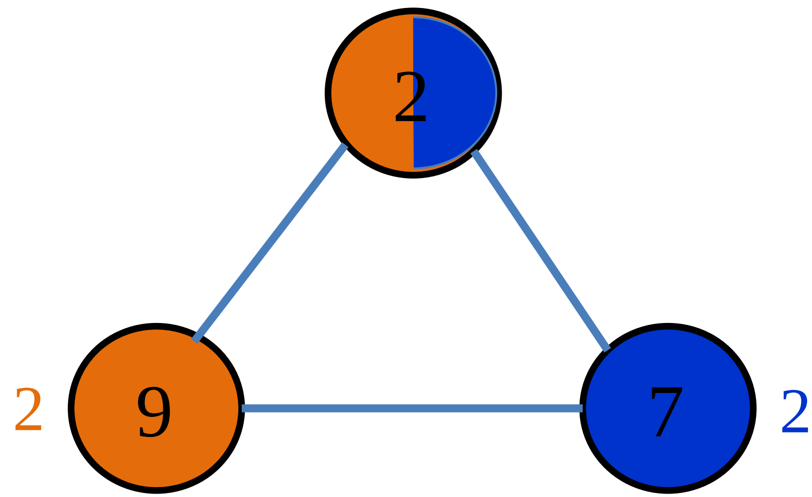
Find-min protocol



Simple solution:

Leader Election & convergence to leader's color

Find-min protocol

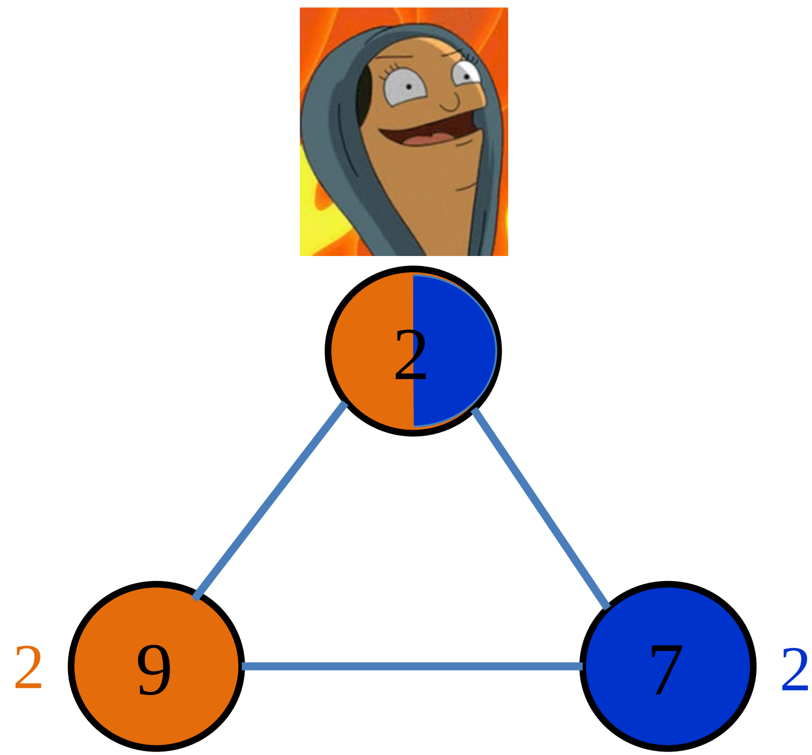


Simple solution:

Leader Election & convergence to leader's color

Find-min protocol

no agreement!



Theorem (1985)

There exists a randomized algorithm achieving consensus in the asynchronous model if up to $f<n/3$ nodes are byzantine.

Theorem (1985)

There exists a randomized algorithm achieving consensus in the asynchronous model if up to $f<n/3$ nodes are byzantine.

Theorem (1989)

There is a deterministic algorithm achieving consensus in the synchronous model if up to $f<n/3$ nodes are byzantine.

Theorem (1985)

There exists a randomized algorithm achieving consensus in the asynchronous model if up to $f<n/3$ nodes are byzantine.

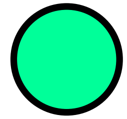
Theorem (1989)

There is a deterministic algorithm achieving consensus in the synchronous model if up to $f<n/3$ nodes are byzantine.

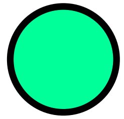
Theorem (1980)

No consensus algorithm can work for $f \geq n/3$ byzantine nodes, even in the synchronous model.

implicit assumption:

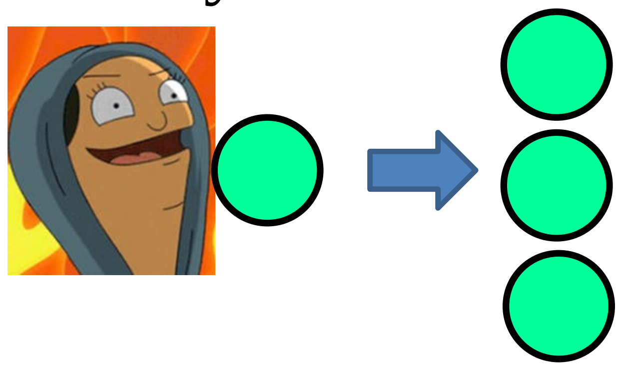
 = 1

implicit assumption:

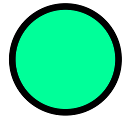


= 1

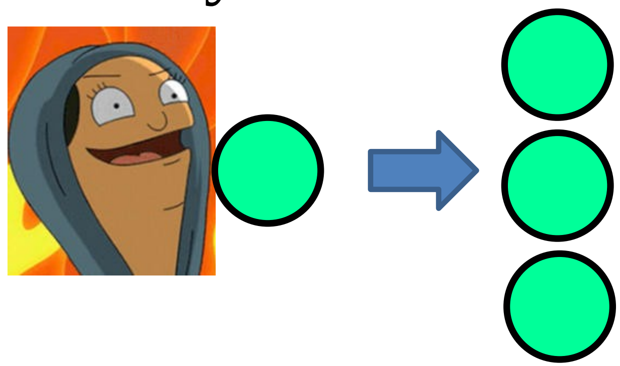
Sybil attack:



implicit assumption:

 = 1

Sybil attack:



Proof of Work idea:

 = 1

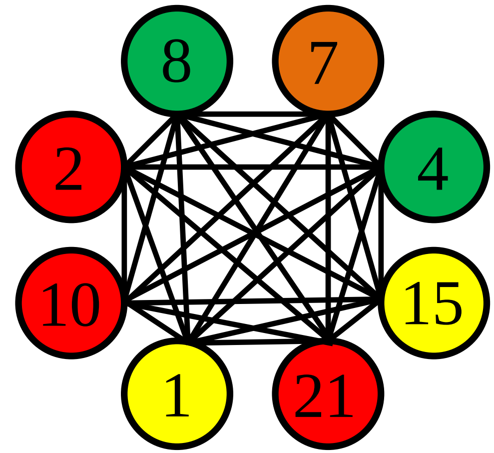
Fair Consensus Problem

a set of *n* nodes

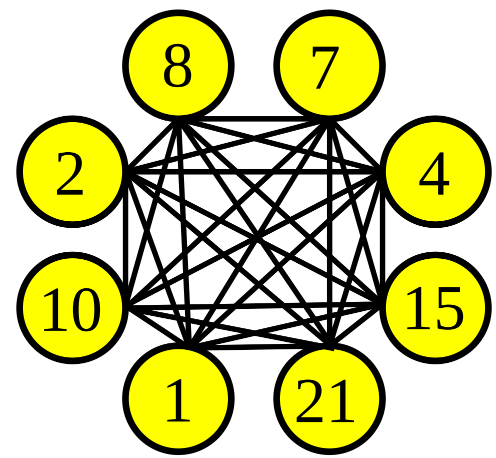
each node has:

- unique ID
- a color in { … }

an underlying communication graph *G*



Goal: a *distributed protocol* guaranteeing



Termination (protocol eventually ends)

Agreement (monochromatic final configuration)

Fair Consensus Problem

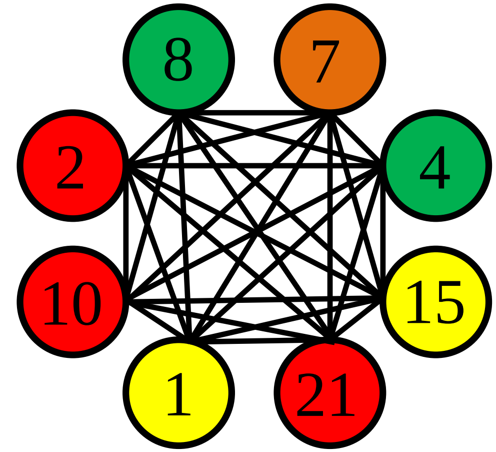
a set of *n* nodes

each node has:

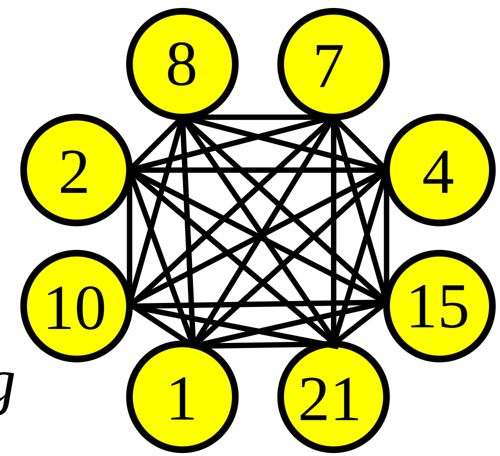
unique ID

a color in {  … }

an underlying communication graph *G*



Goal: a *distributed protocol* guaranteeing



Termination (protocol eventually ends)

Agreement (monochromatic final configuration)

~~Validity~~ ⟶ Fairness

the probability that a color becomes the *winning color* is equal to the fraction of nodes initially supporting it

Fair Consensus Problem

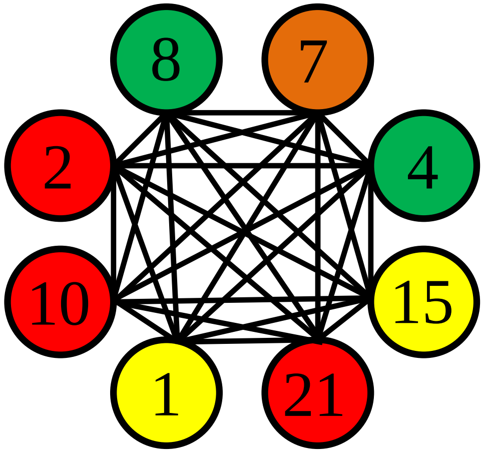
a set of *n* nodes

each node has:

unique ID

a color in {  }

an underlying communication graph *G*



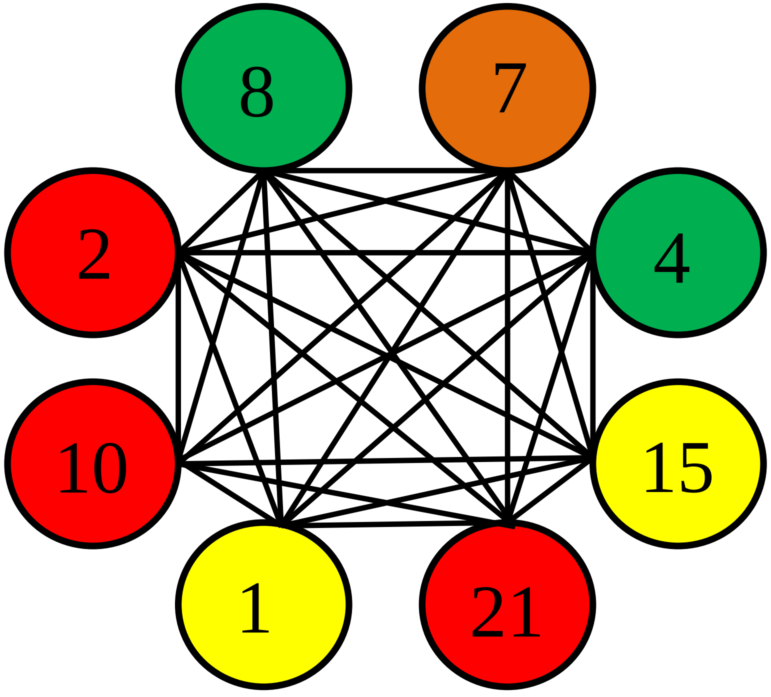
Goal: a *distributed protocol* guaranteeing

Simple solution:

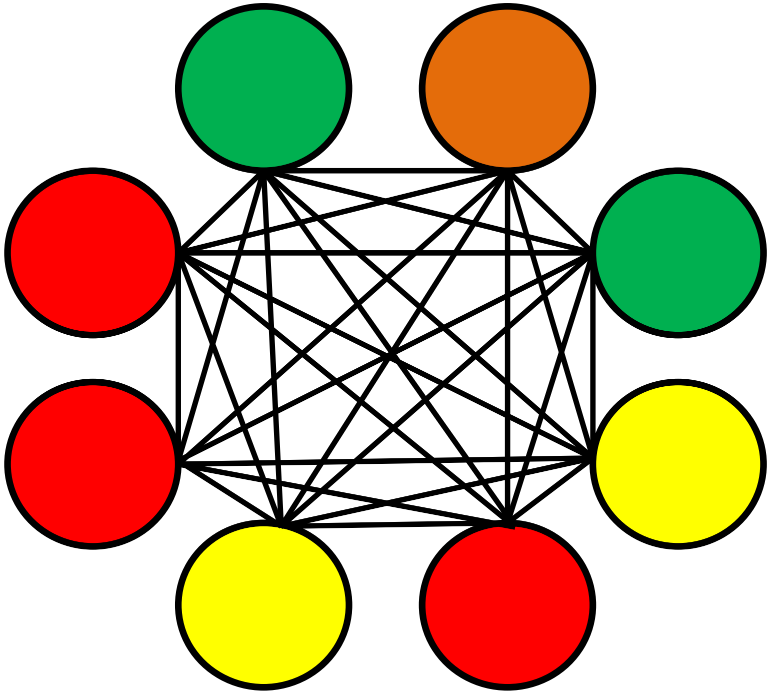
Choose a leader uniformly at random & convergence to leader's color

Randomized Leader Election

Initial configuration:

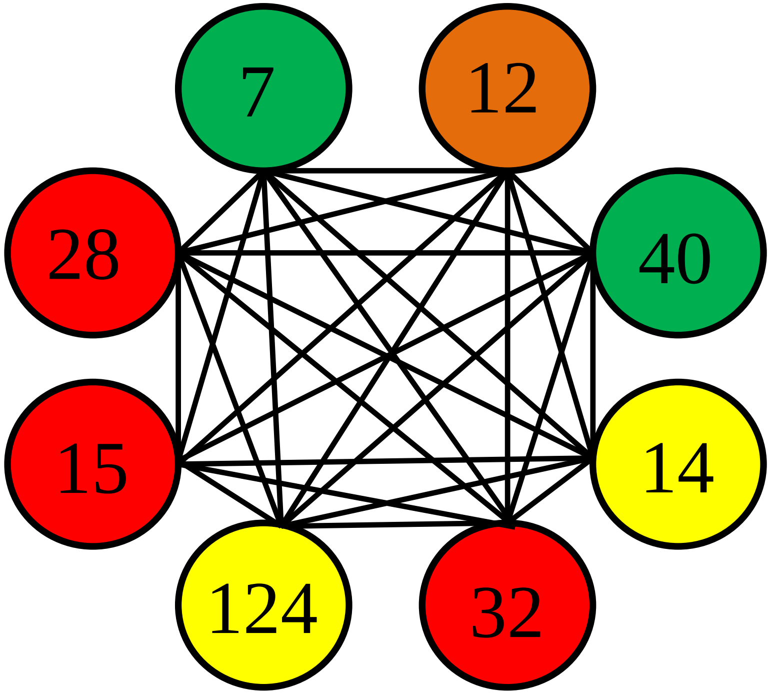


Randomized Leader Election



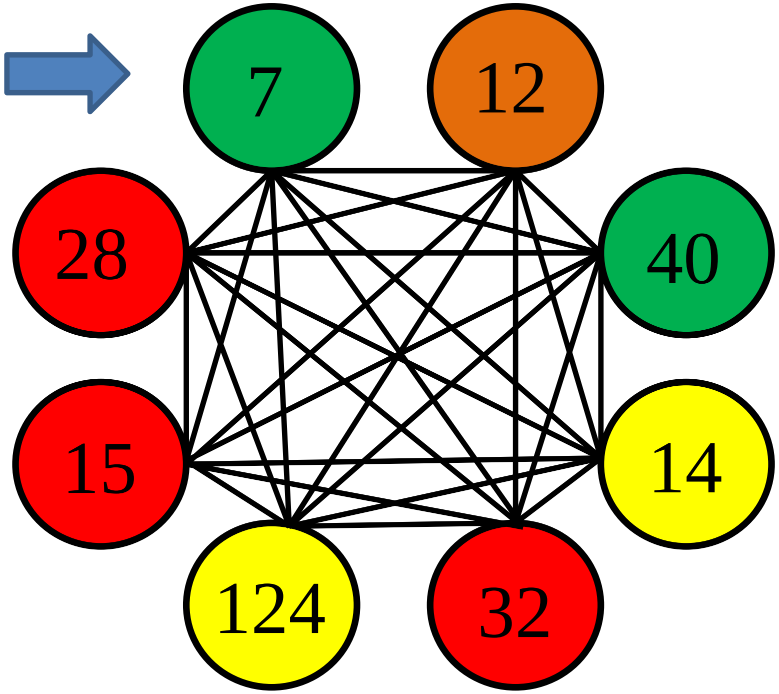
nodes do not use their unique IDs

Randomized Leader Election



each node *u* chooses a value k_u in $[0,n^3]$ u.a.r.

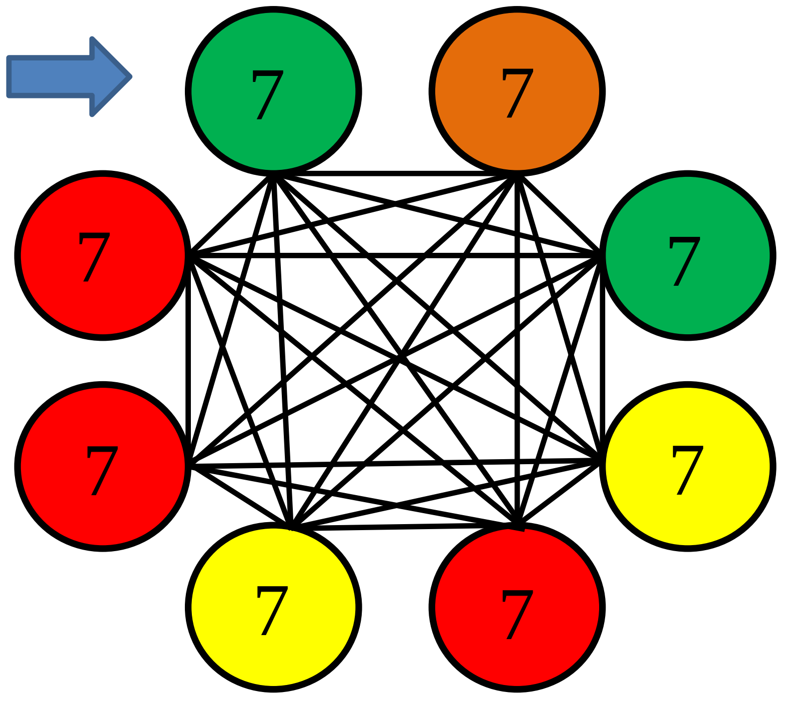
Randomized Leader Election



each node *u* chooses a value k_u in $[0,n^3]$ u.a.r.

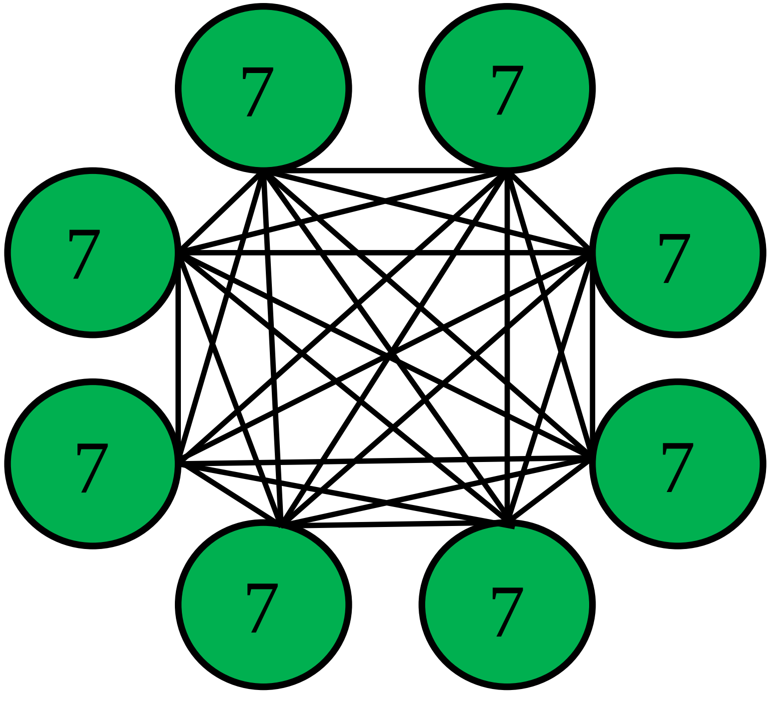
the minimum k value is unique w.h.p.

Randomized Leader Election



Find-min Protocol

Randomized Leader Election



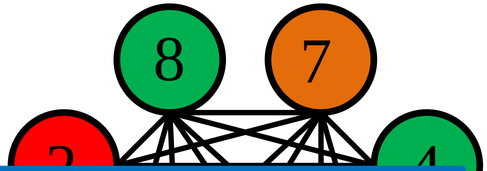
Convergence to leader's color

Fair Consensus Problem

a set of *n* nodes

each node has:

unique ID



ar

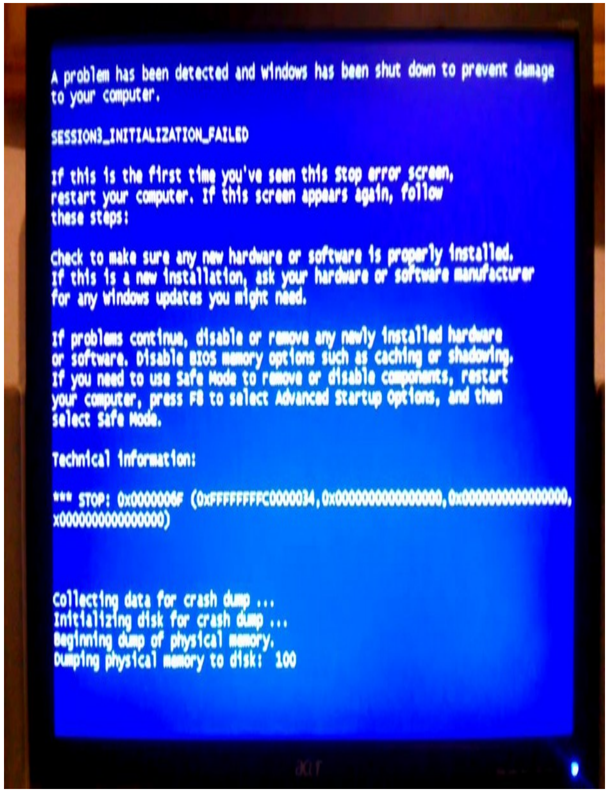
Goa

In the Bitcoin System:

the probability that a node becomes the leader is proportional to its computational power

Choose a leader u.a.r. & convergence to leader's color

Type of failures



Crash failures

Byzantine failures

rational selfish failures

A game-theoretic perspective

Each node is a selfish rational player

for each player/node u:

u's strategy: local algorithm used by u

A game-theoretic perspective

Each node is a selfish rational player

for each player/node *u*:

u's strategy: local algorithm used by *u*

u's payoff:  if the winning color = u's color

A game-theoretic perspective

Each node is a selfish rational player

for each player/node *u*:

u's strategy: local algorithm used by *u*

u's payoff:

-  if the winning color = u's color
-  if the winning color ≠ u's color

A game-theoretic perspective

Each node is a selfish rational player

for each player/node *u*:

u's strategy: local algorithm used by *u*

u's payoff:


if the winning color = u's color


if the winning color ≠ u's color


if the protocol fails

A game-theoretic perspective

Each node is a selfish rational player

for each player/node *u*:

u's strategy: local algorithm used by *u*

u's payoff:


if the winning color = u's color


if the winning color ≠ u's color


if the protocol fails

u's goal: to maximize its expected payoff

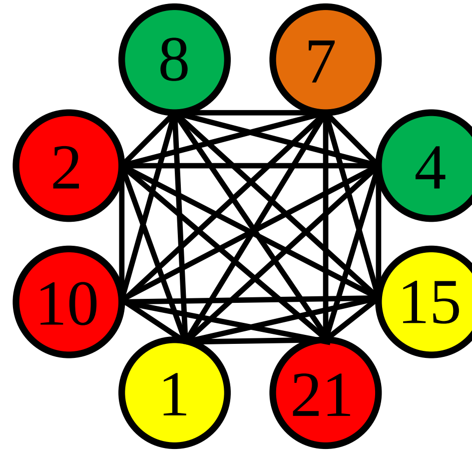
Rational Fair Consensus Problem

a set of *n* nodes

each node has:

- unique ID
- a color in { … }

an underlying communication graph *G*



a protocol solves the Rational Fair Consensus if

it solves the Fair Consensus problem

&

it is resilient to agent deviations

Resiliency to agent deviations

Def. 1. A protocol *P* is a **Nash Equilibrium** if, for any possible deviation of any agent *u*, *u*'s expected payoff in the new protocol *P'* does not increase.

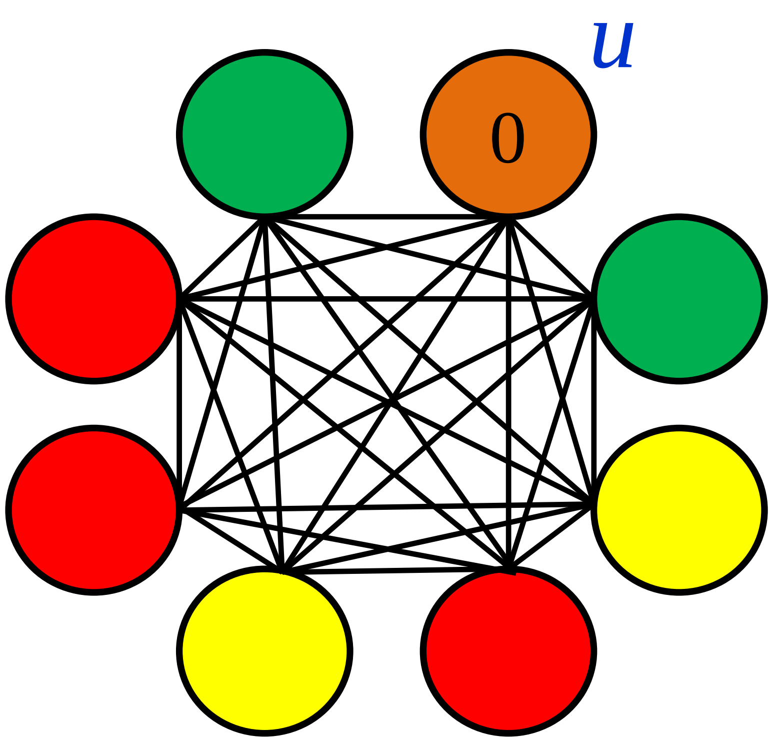
Resiliency to agent deviations

Def. 1. A protocol *P* is a **Nash Equilibrium** if, for any possible deviation of any agent *u*, *u*'s expected payoff in the new protocol *P'* does not increase.

Def. 2. A protocol *P* is a **t-strong Equilibrium** if, for any possible deviation of any coalition *C* of players of size at most *t*, there is a player in *C* whose expected payoff in the new protocol *P'* does not increase.

Rational Fair Consensus Problem

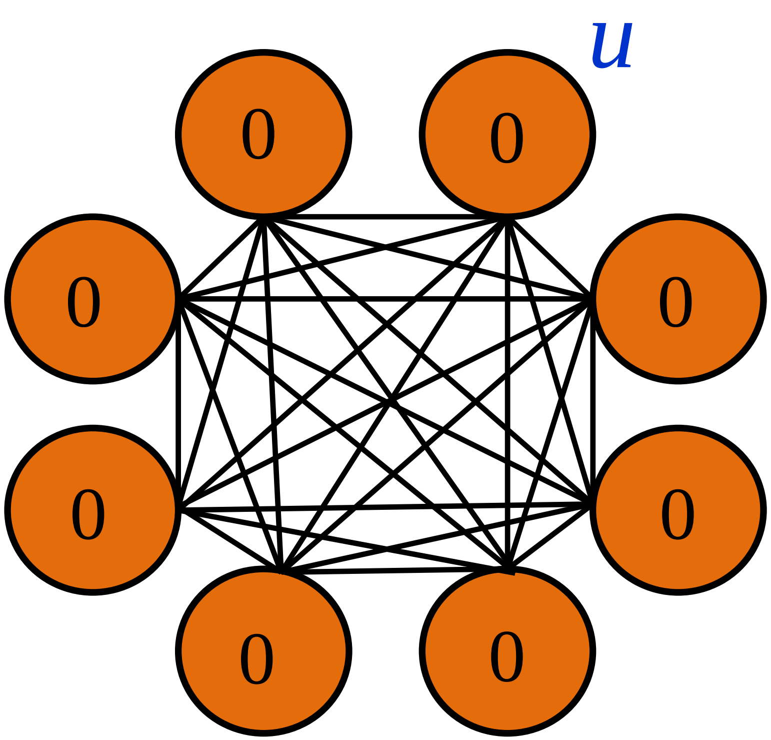
(the simple solution fails)



node u chooses a “random” value k_u =0

Rational Fair Consensus Problem

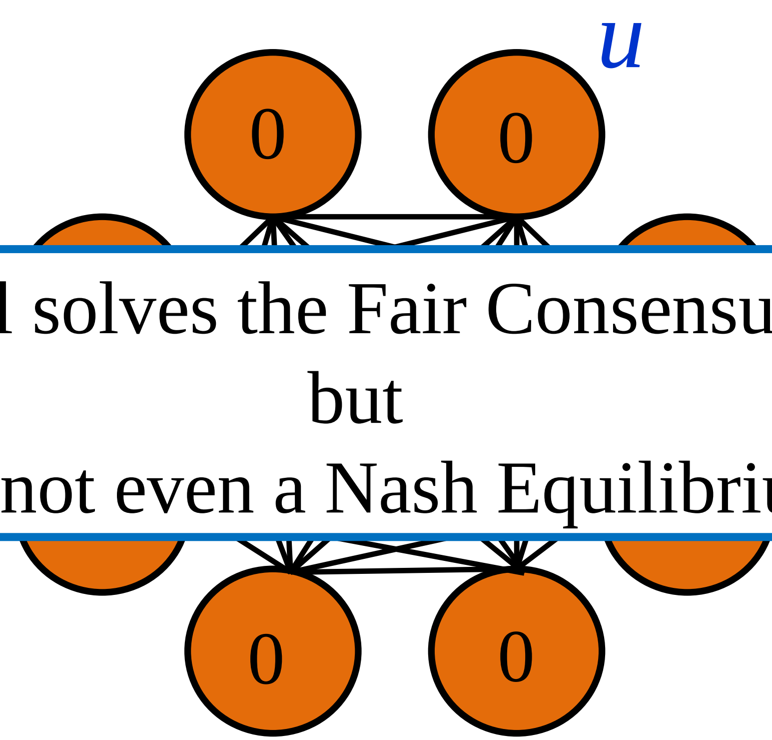
(the simple solution fails)



node *u* chooses a “random” value k_u =0

Rational Fair Consensus Problem

(the simple solution fails)



this protocol solves the Fair Consensus problem
but
it is not even a Nash Equilibrium

node *u* chooses a “random” value k_u =0

Bitcoin Mining Protocol:

- work on the next block to be added to the longest chain
- announce the solved block as soon as you get it

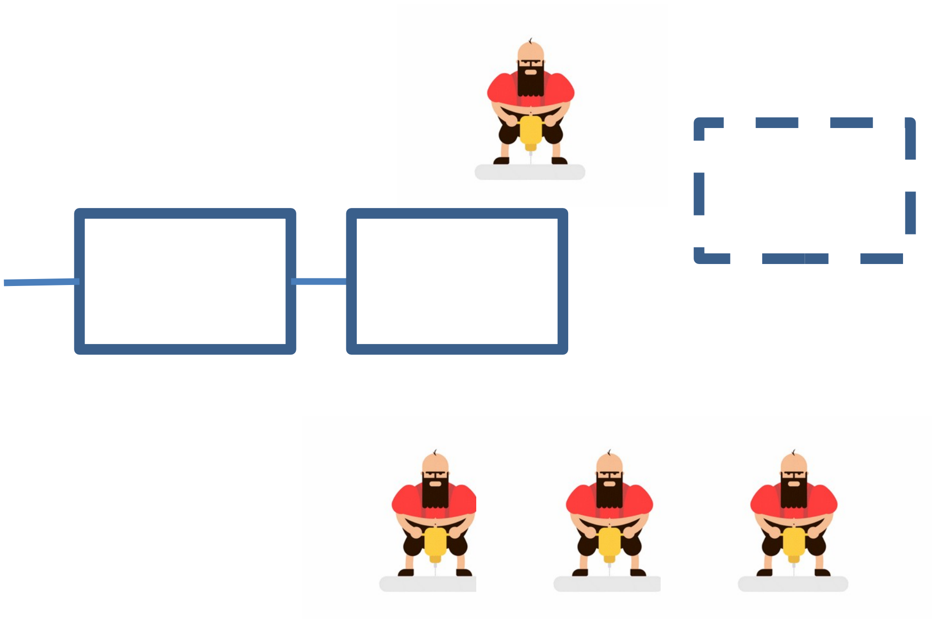
Bitcoin Mining Protocol:

- work on the next block to be added to the longest chain
- announce the solved block as soon as you get it

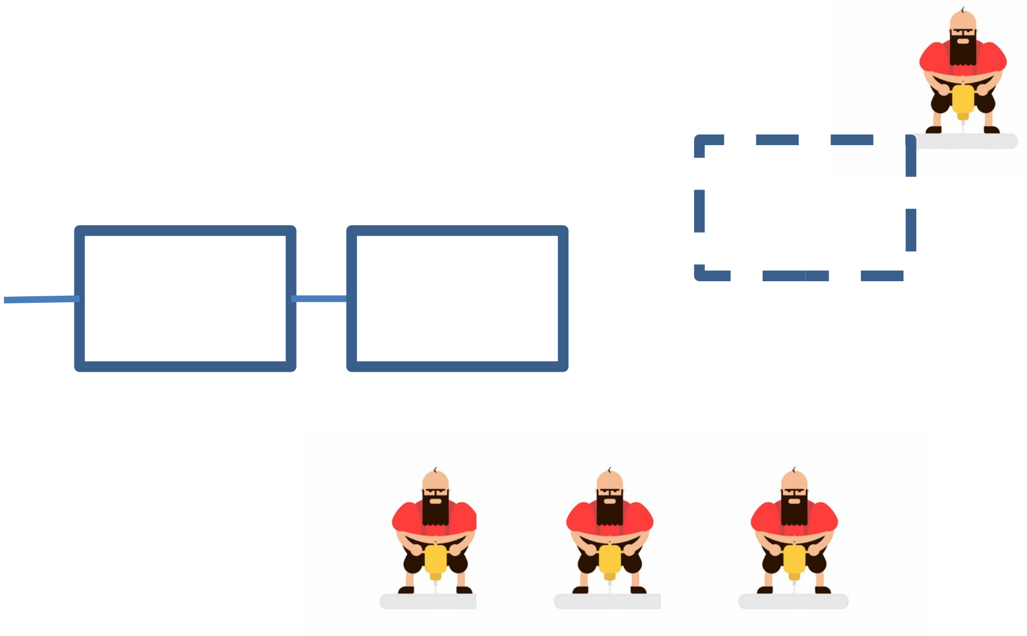
is it an equilibrium?

selfish mining

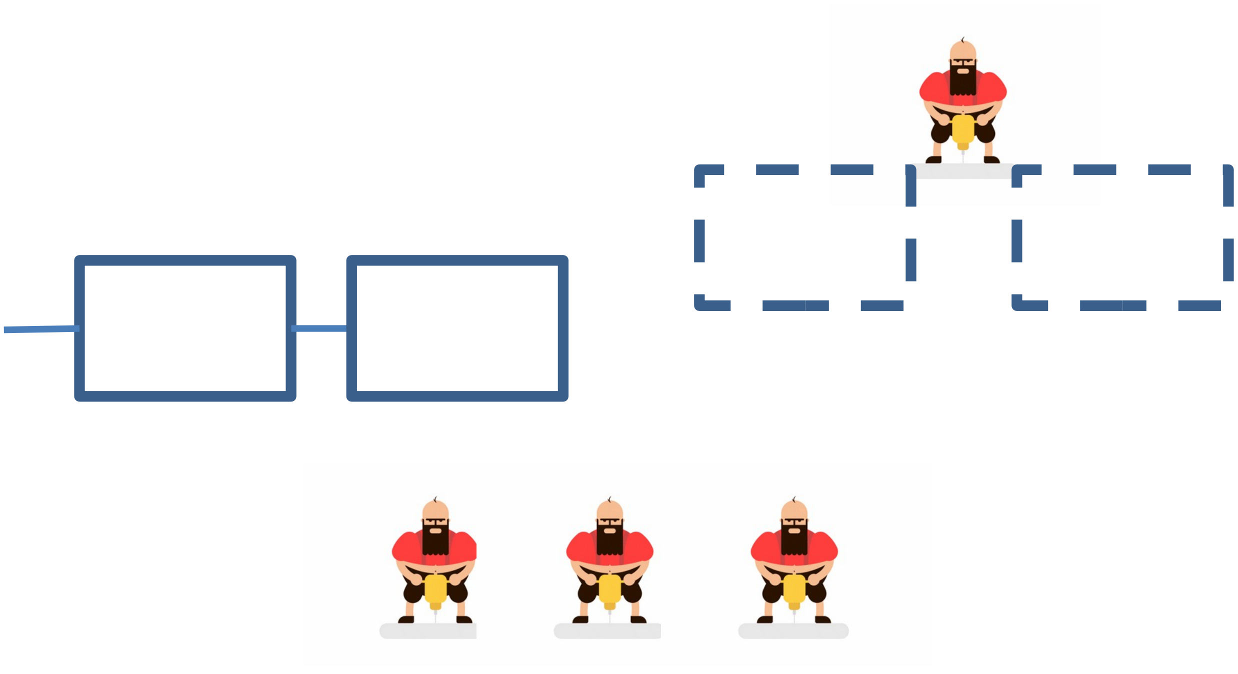
I. Eyal and E. Gun Sirer, Majority is not enough: Bitcoin mining is vulnerable, Financial Cryptography 2014



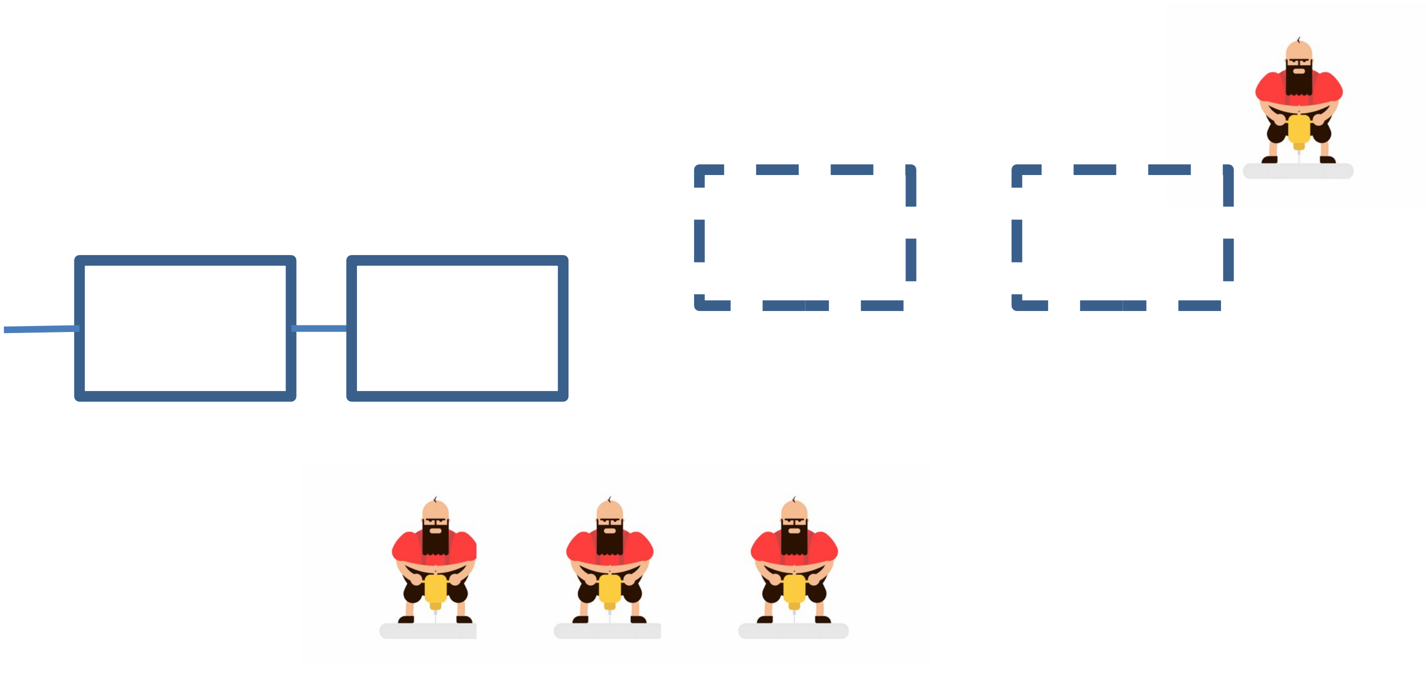
idea: selfishly decide when to announce solved blocks



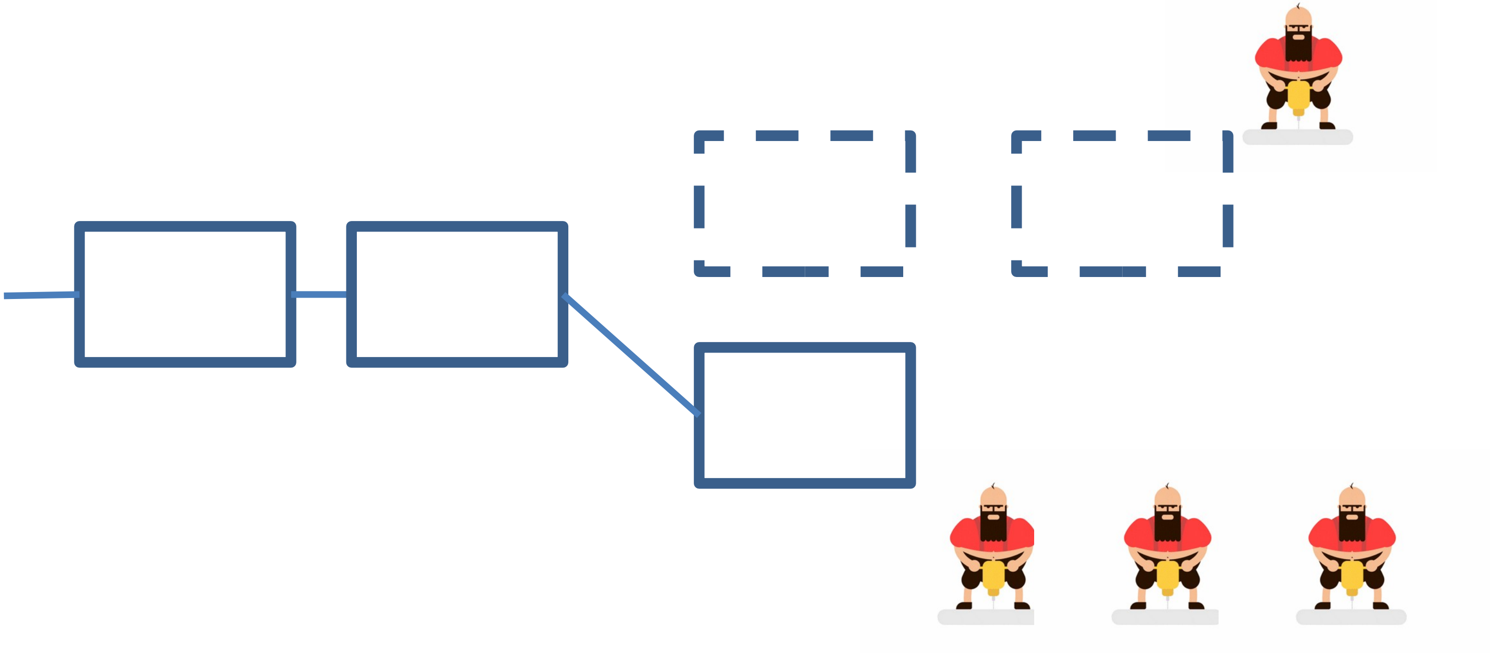
idea: selfishly decide when to announce solved blocks



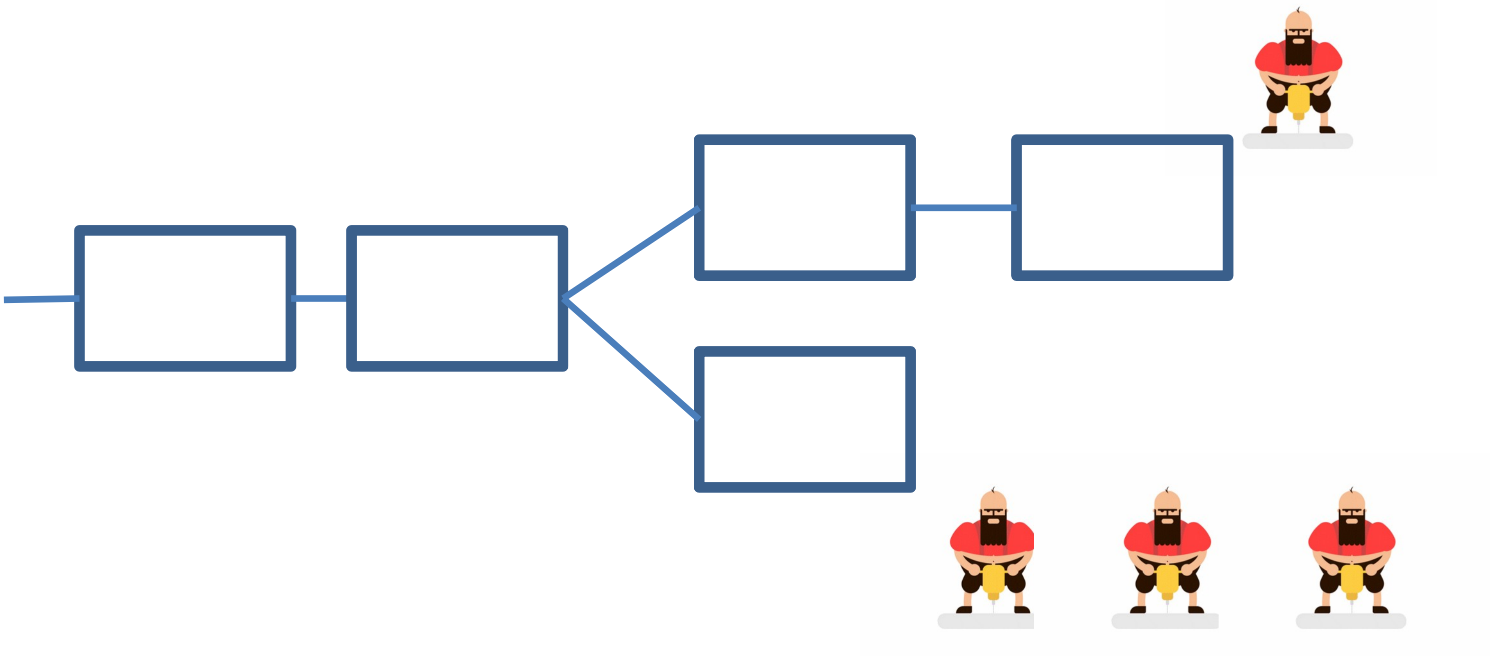
idea: selfishly decide when to announce solved blocks



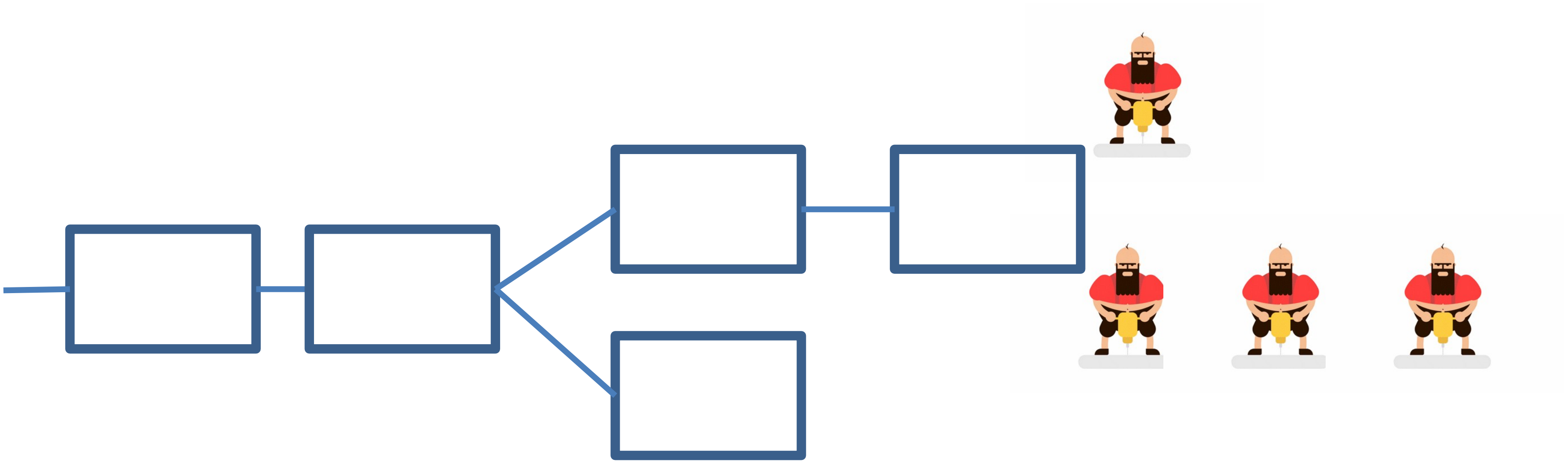
idea: selfishly decide when to announce solved blocks



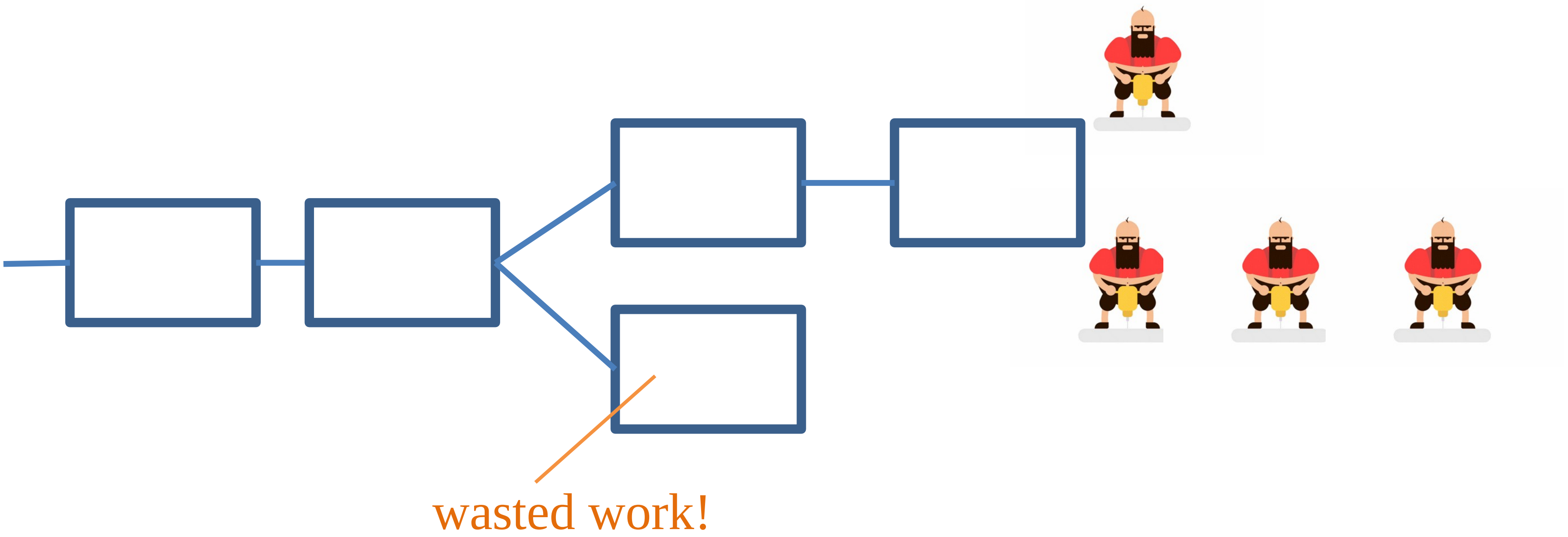
idea: selfishly decide when to announce solved blocks



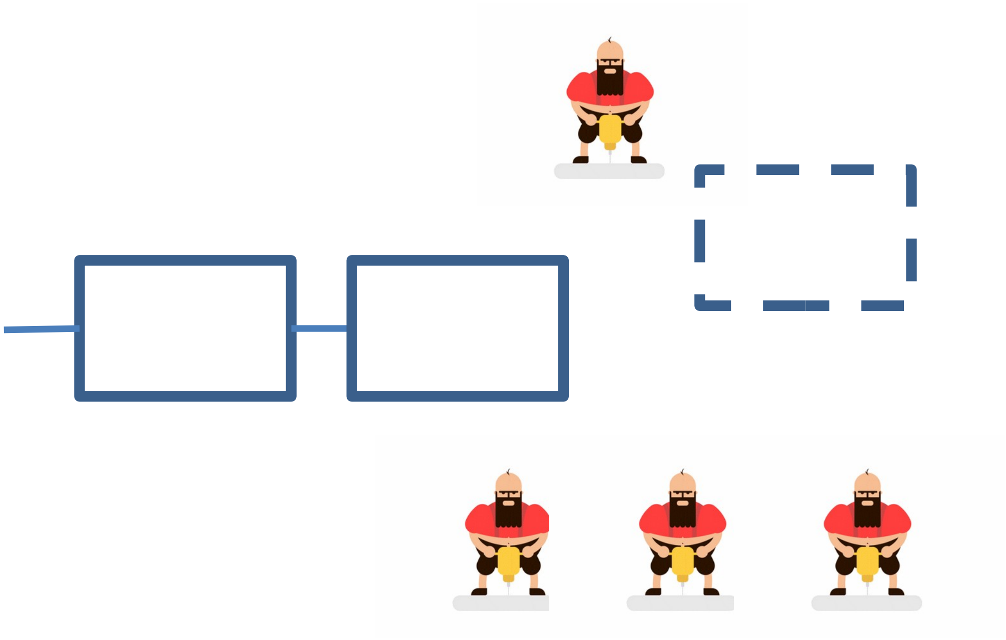
idea: selfishly decide when to announce solved blocks



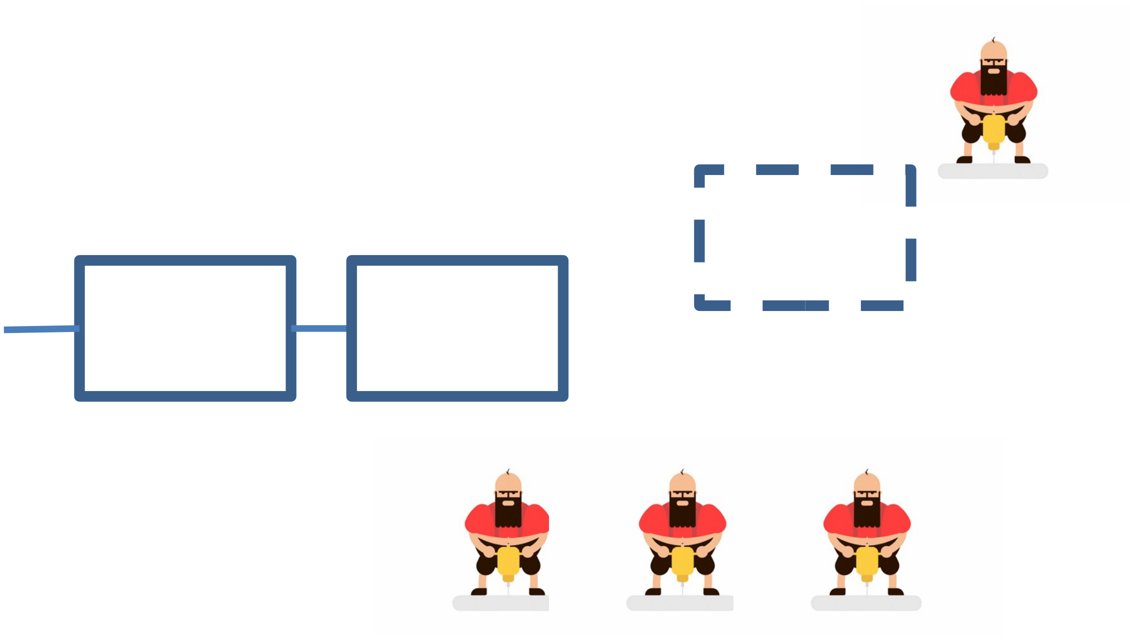
idea: selfishly decide when to announce solved blocks



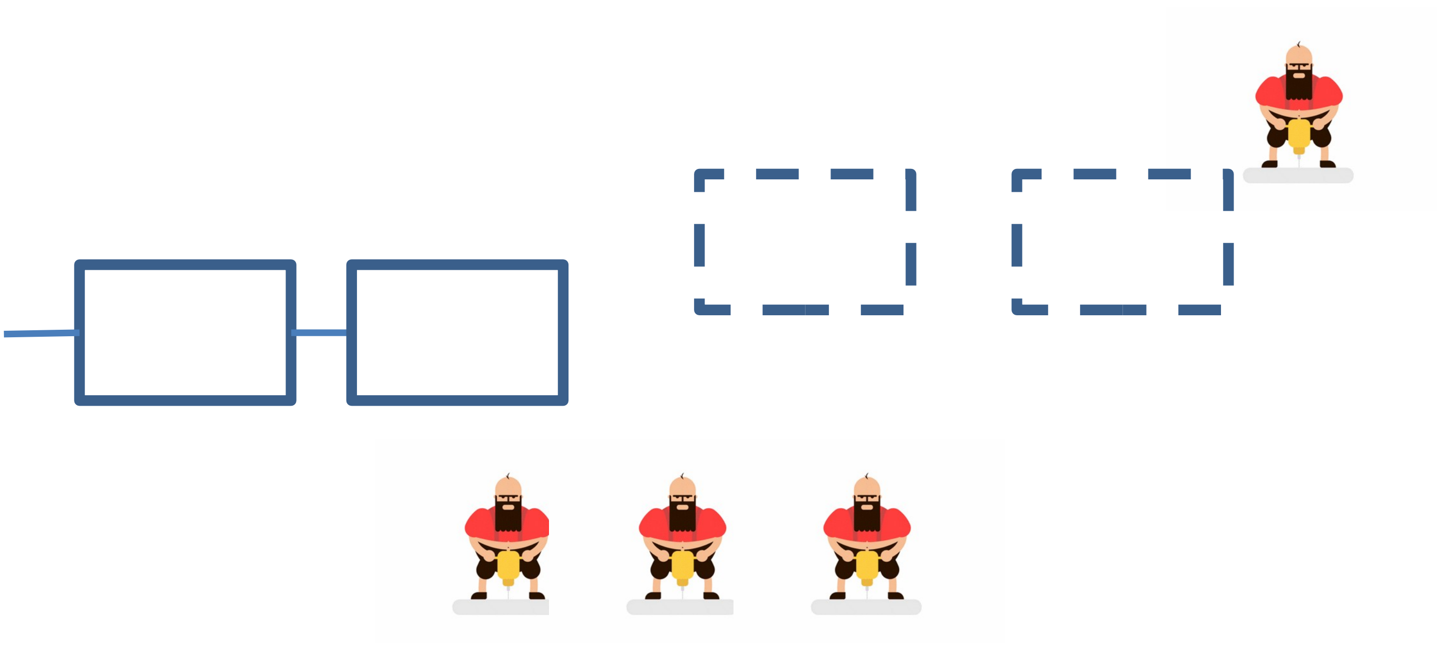
idea: selfishly decide when to announce solved blocks



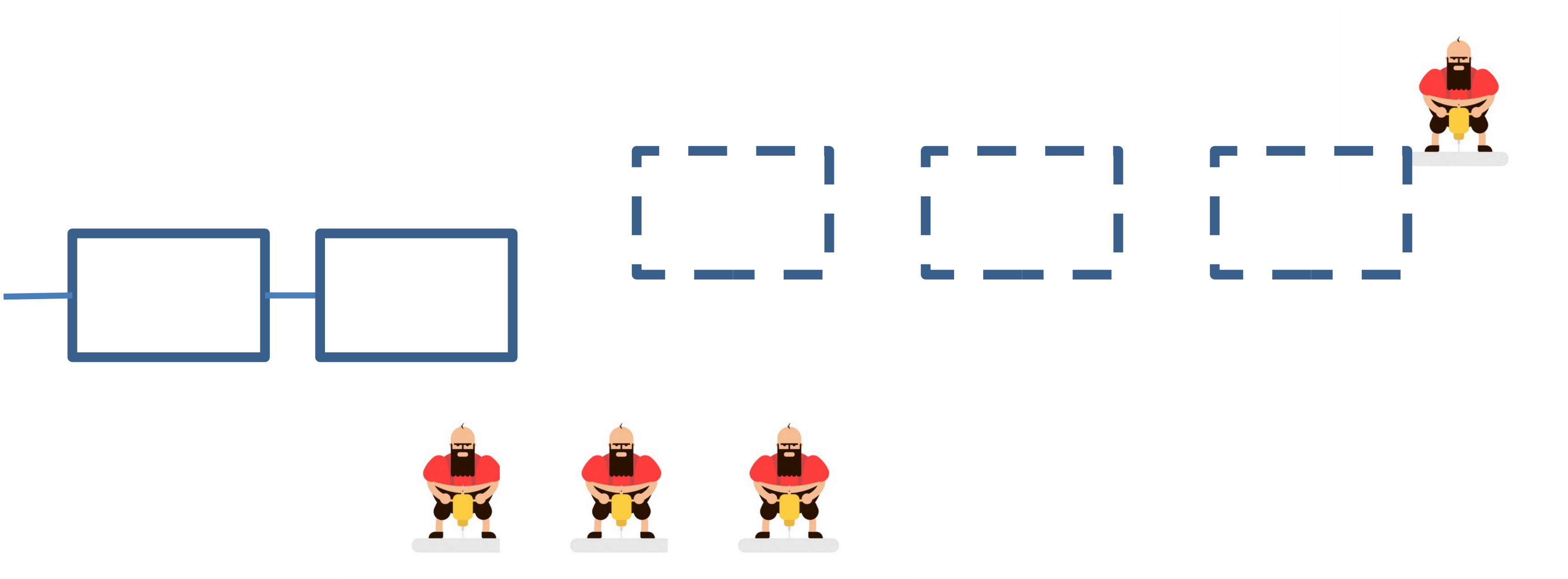
idea: selfishly decide when to announce solved blocks



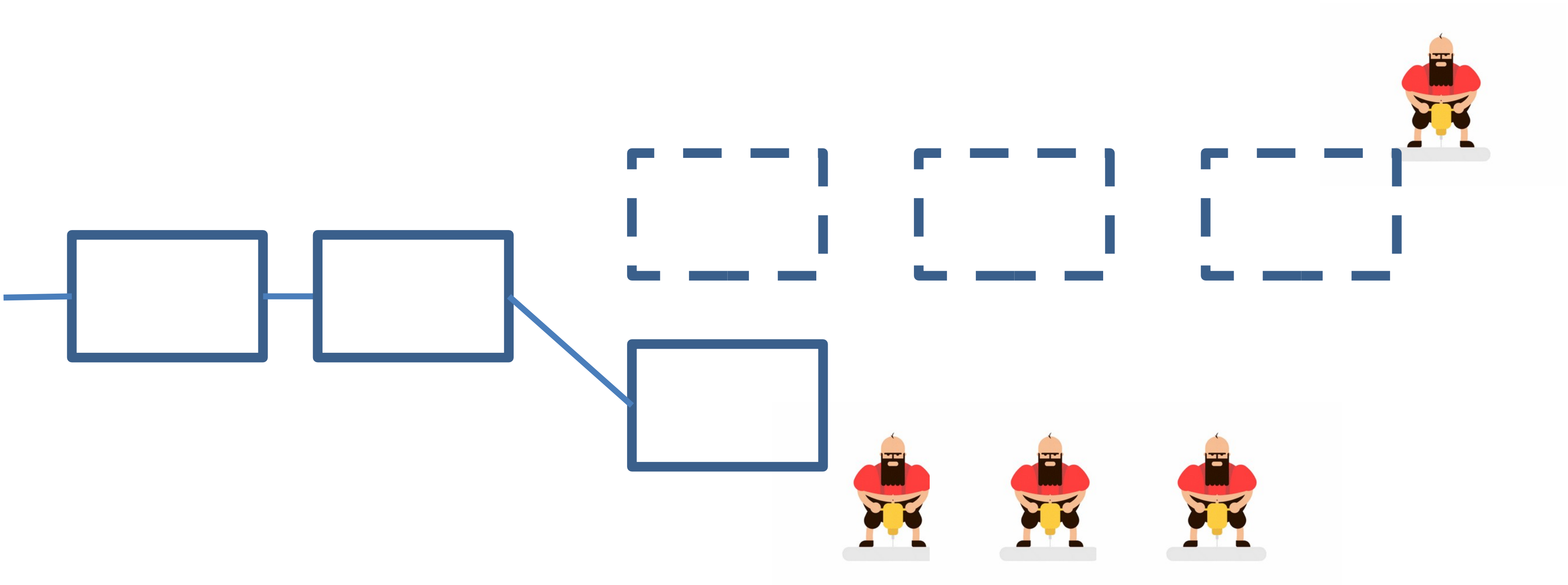
idea: selfishly decide when to announce solved blocks



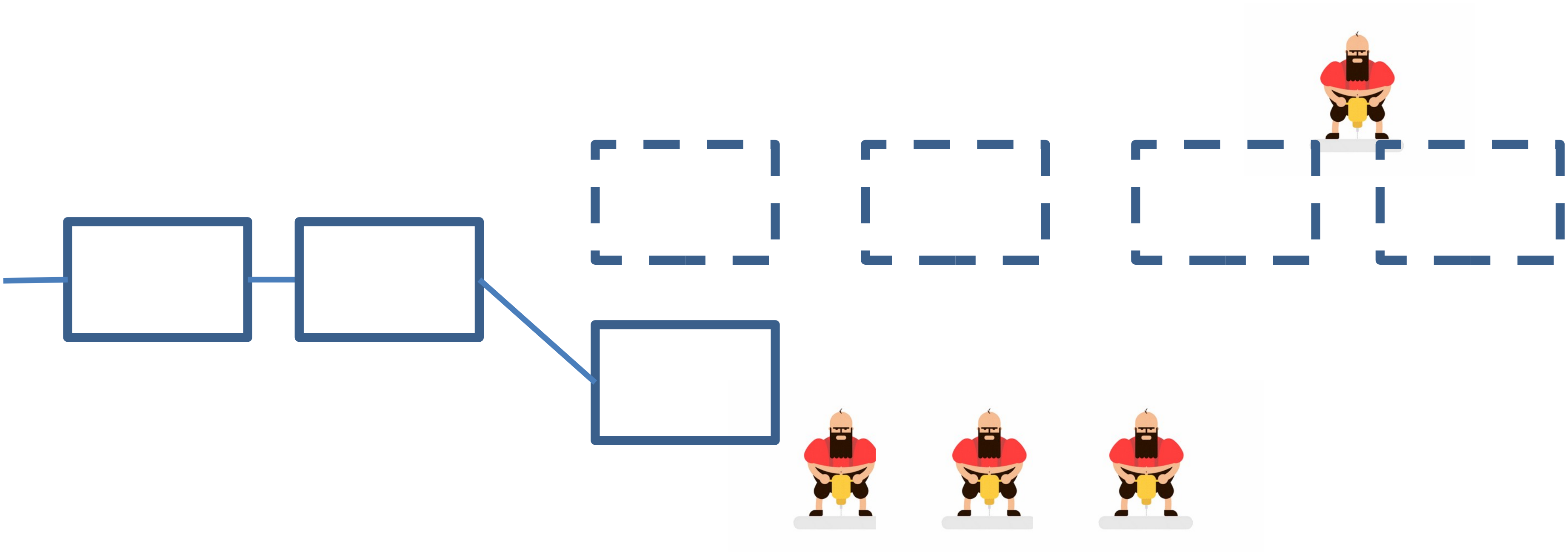
idea: selfishly decide when to announce solved blocks



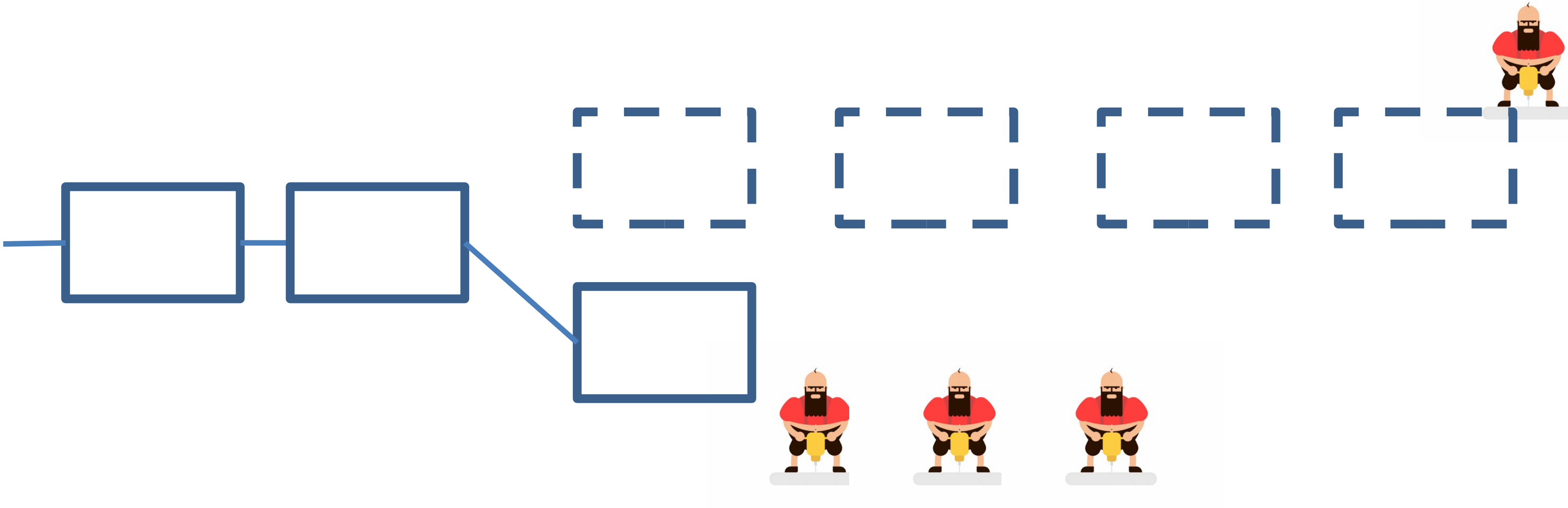
idea: selfishly decide when to announce solved blocks



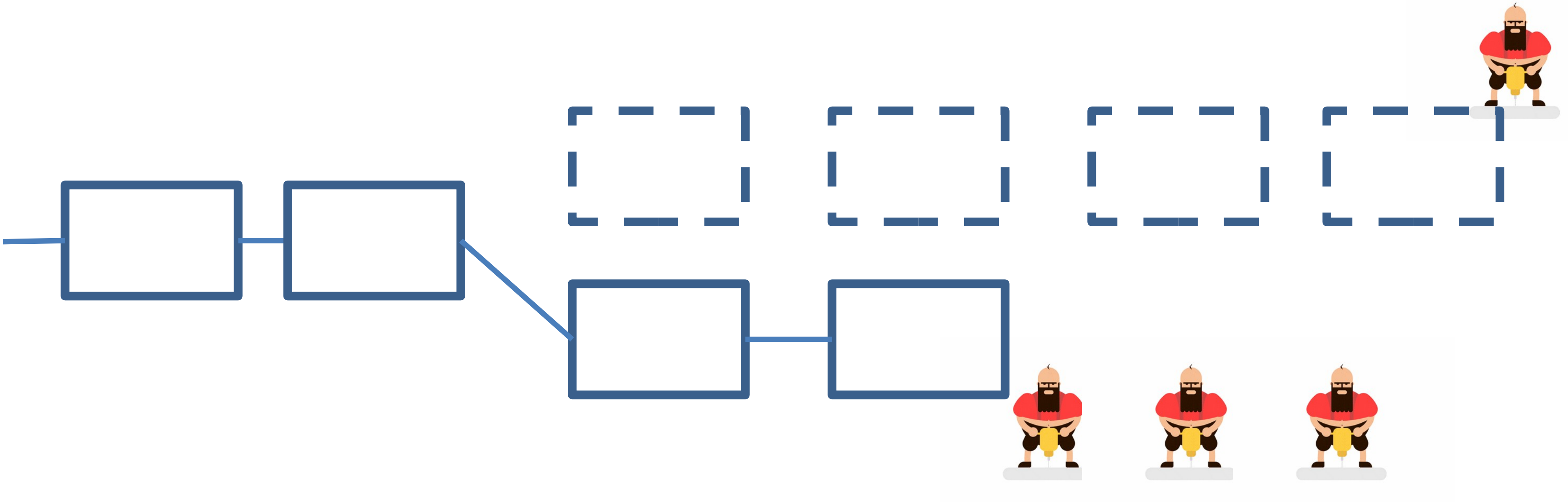
idea: selfishly decide when to announce solved blocks



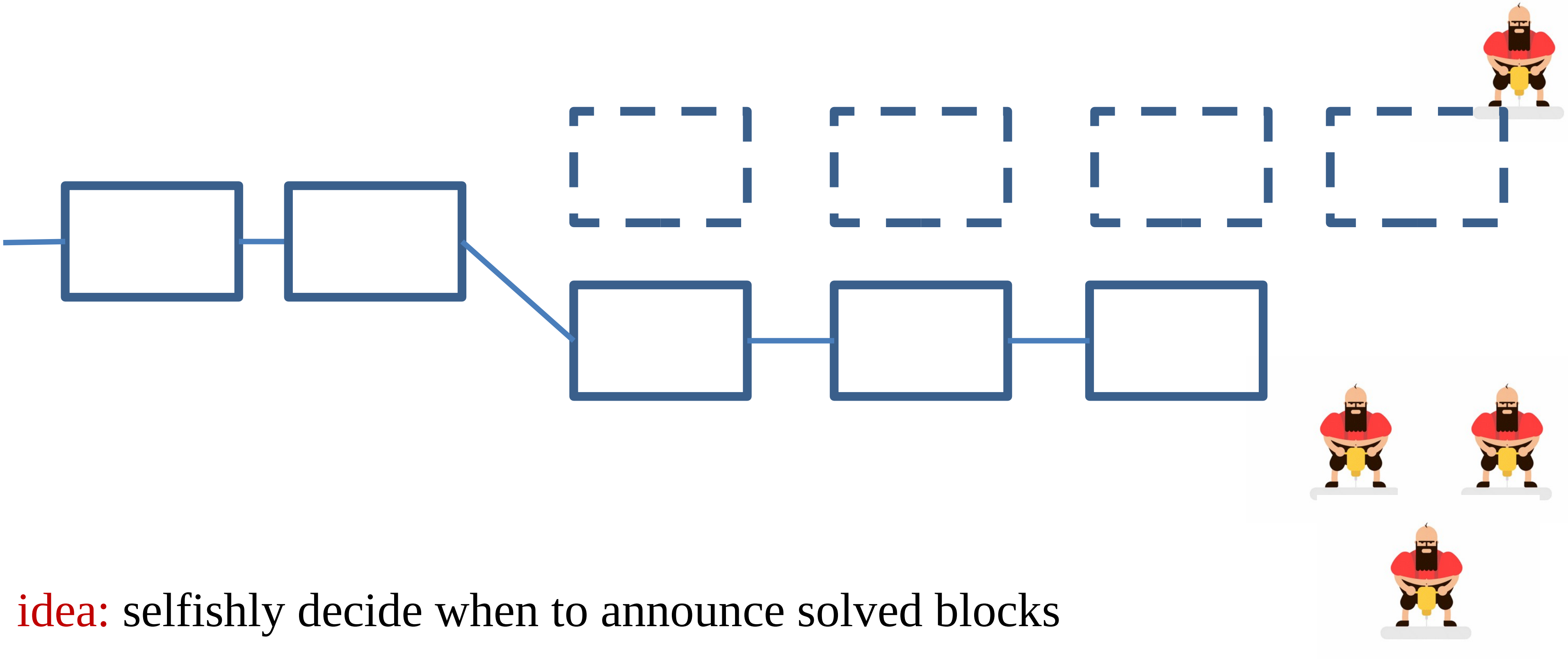
idea: selfishly decide when to announce solved blocks



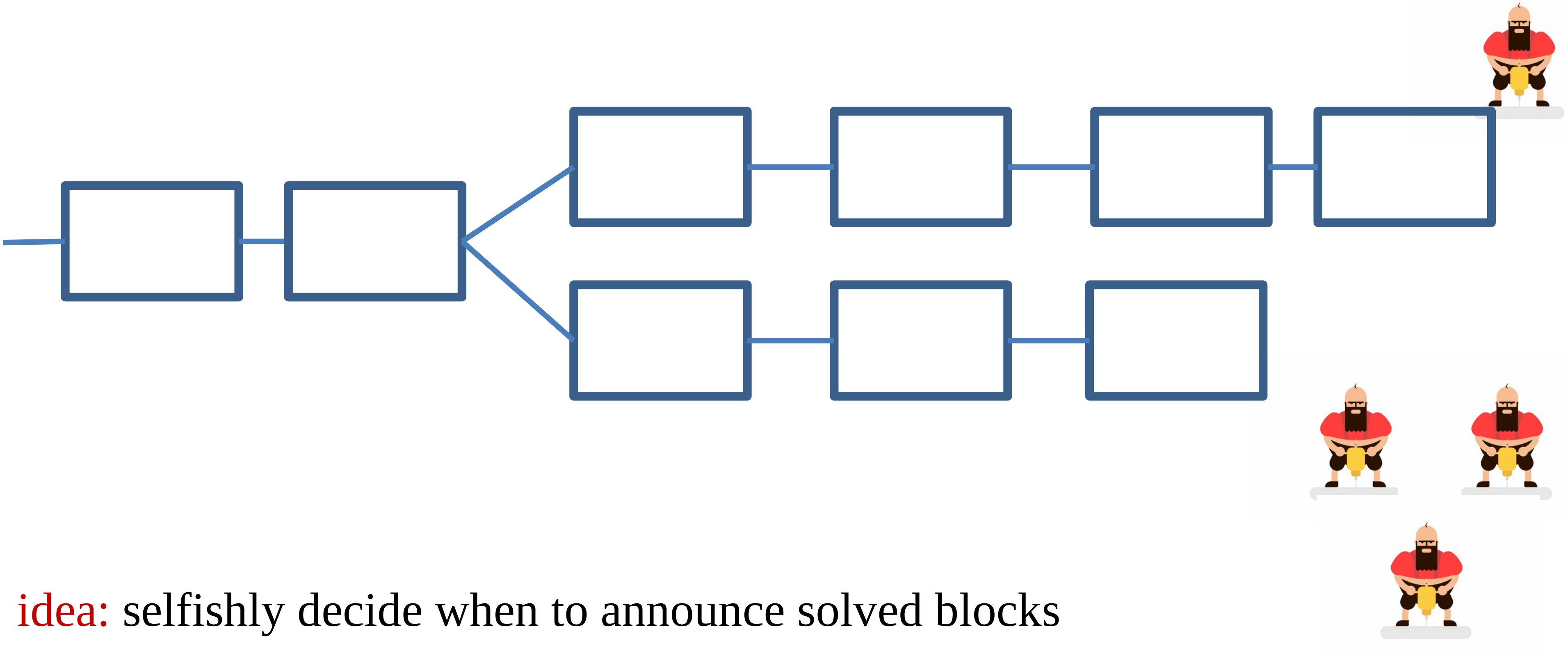
idea: selfishly decide when to announce solved blocks



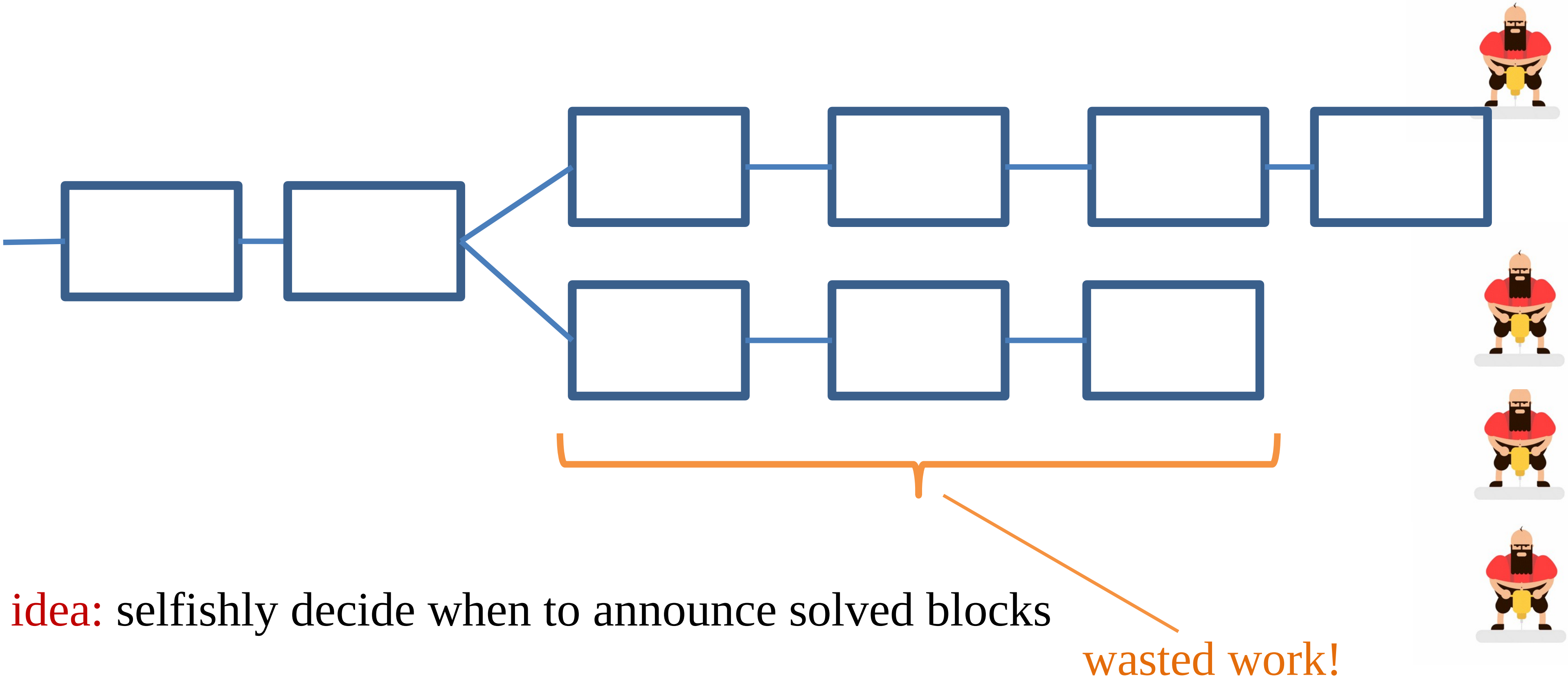
idea: selfishly decide when to announce solved blocks



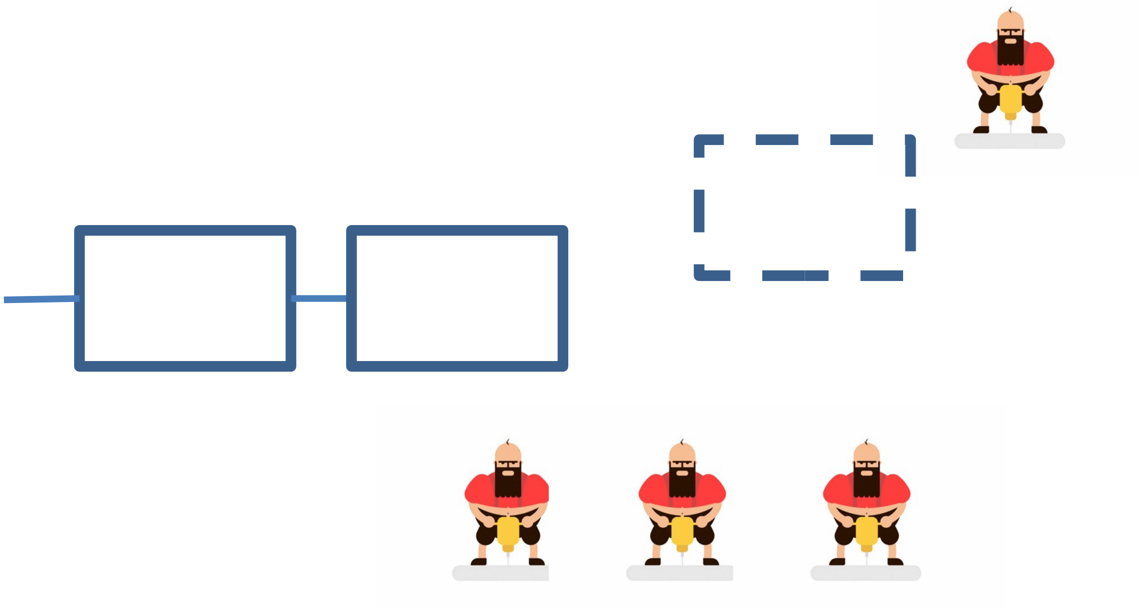
idea: selfishly decide when to announce solved blocks



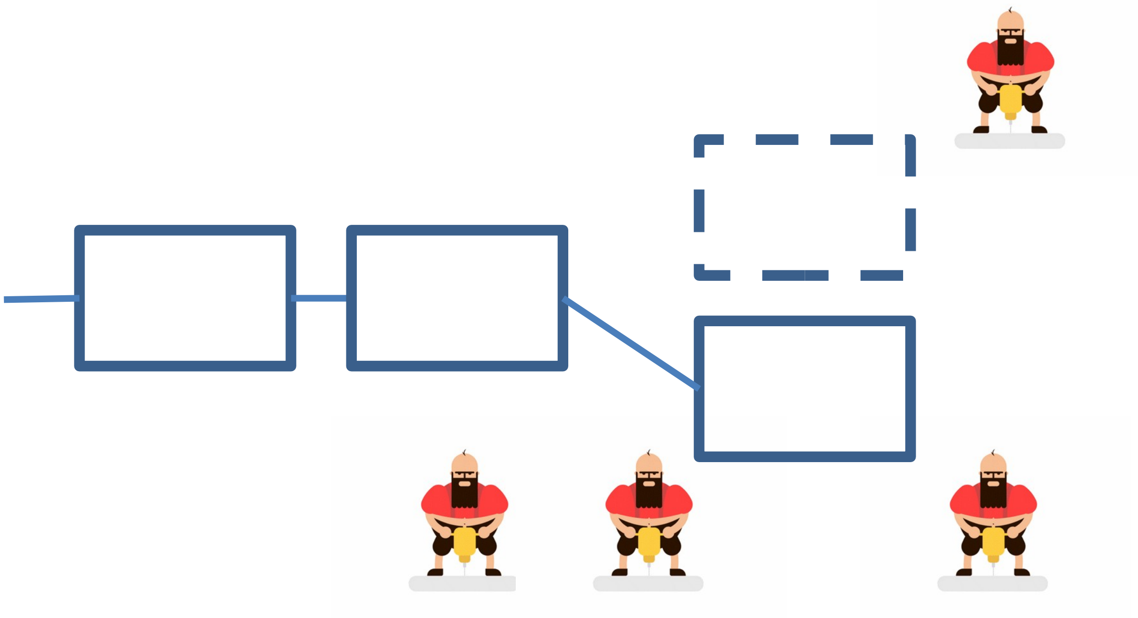
idea: selfishly decide when to announce solved blocks



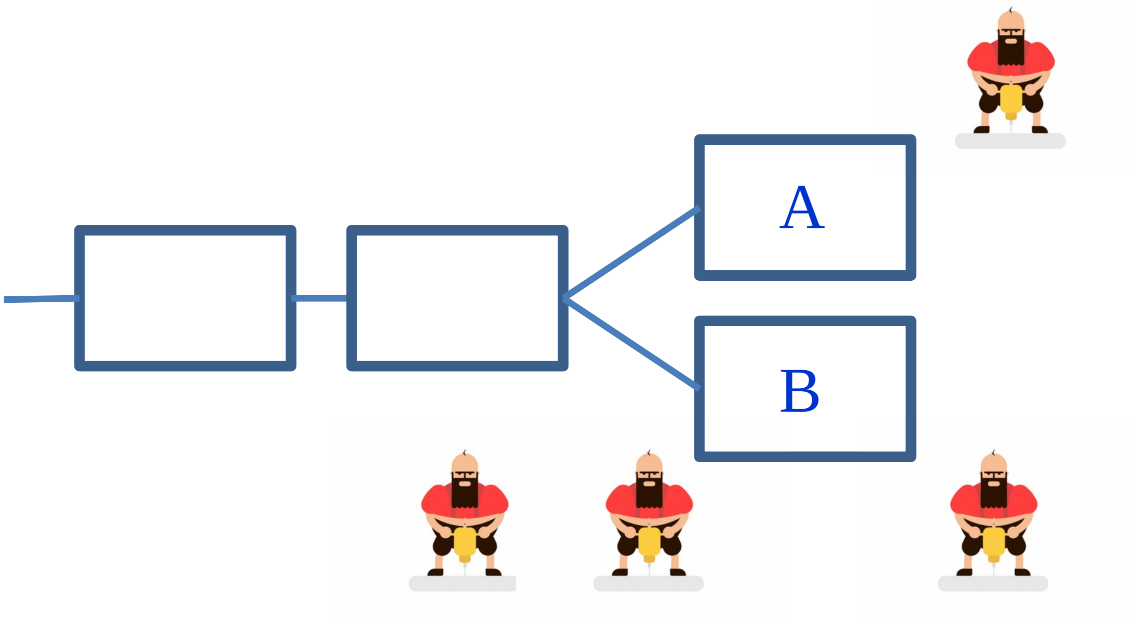
idea: selfishly decide when to announce solved blocks



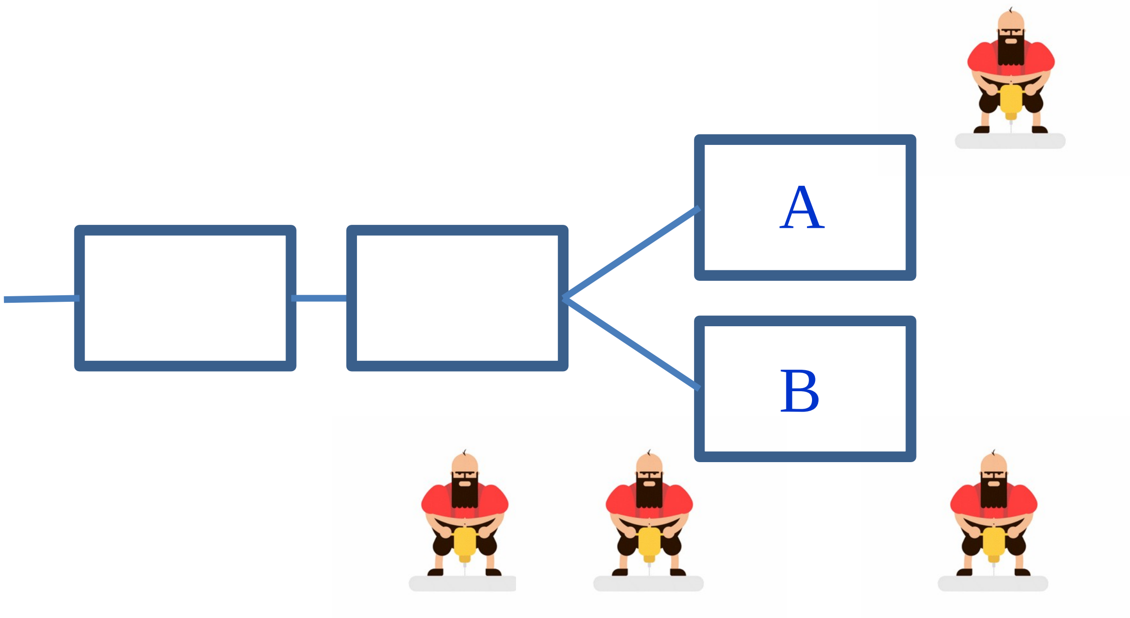
idea: selfishly decide when to announce solved blocks



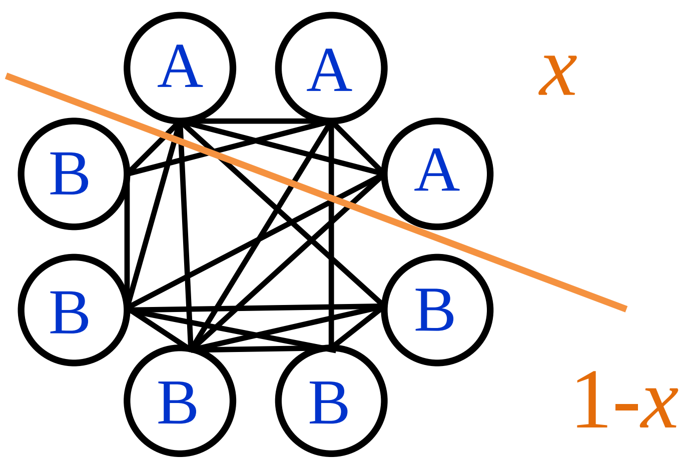
idea: selfishly decide when to announce solved blocks

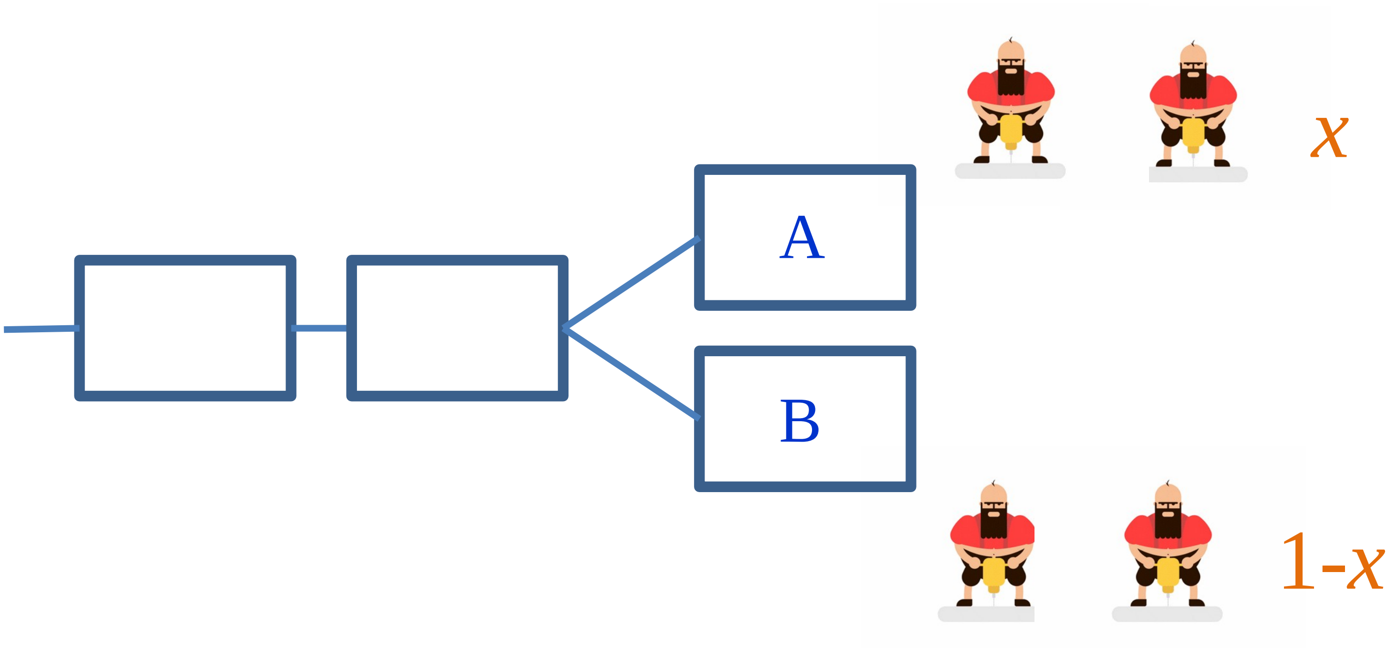


idea: selfishly decide when to announce solved blocks

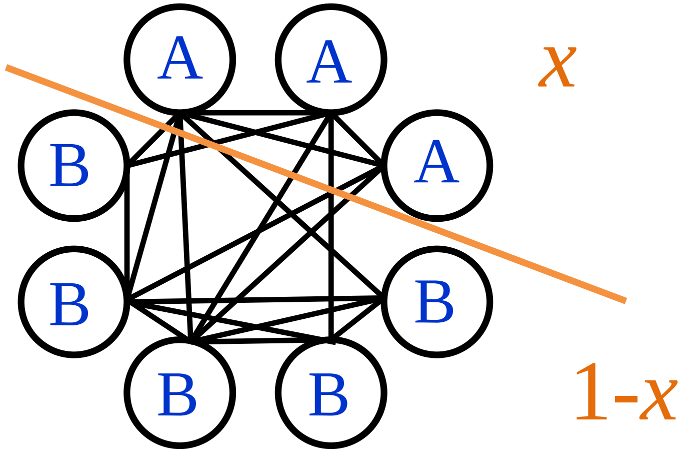


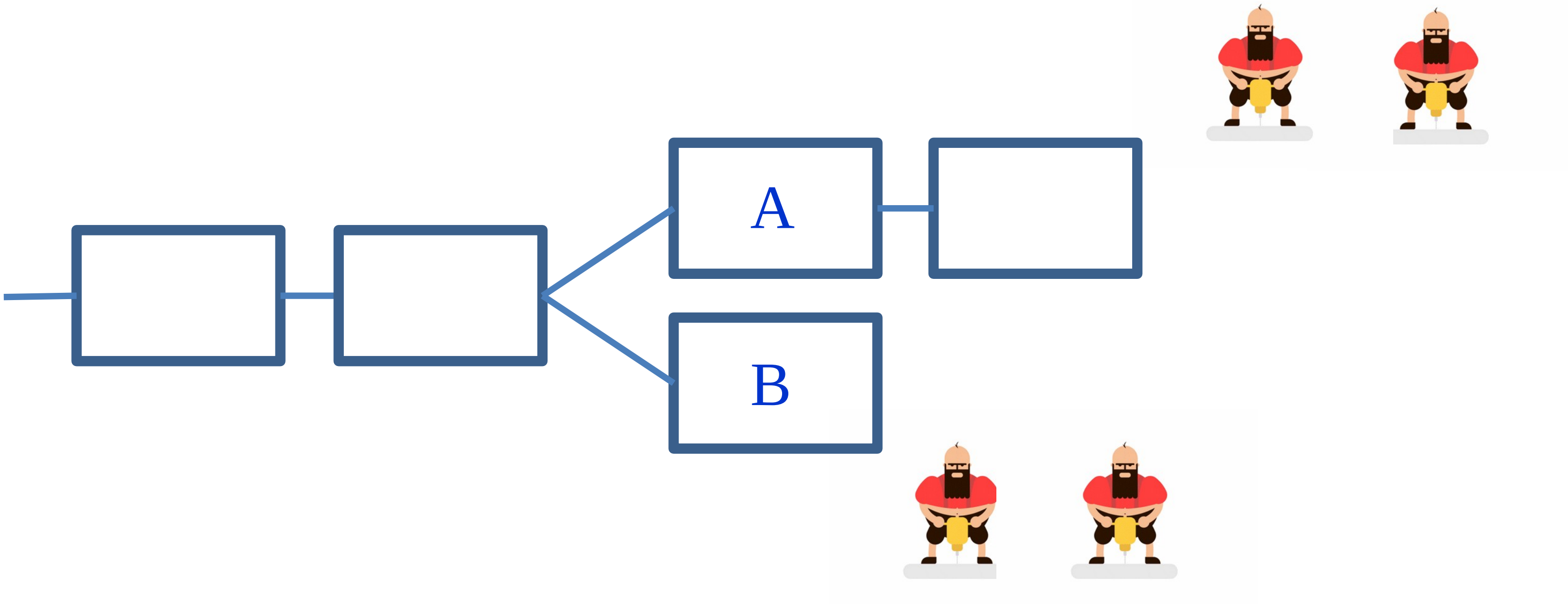
idea: selfishly decide when to announce solved blocks



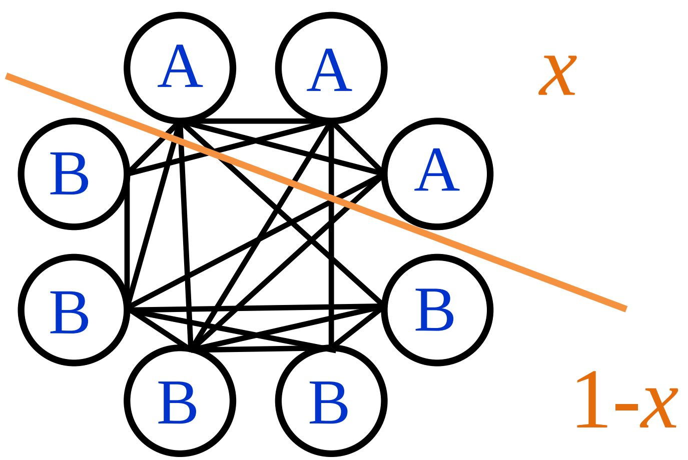


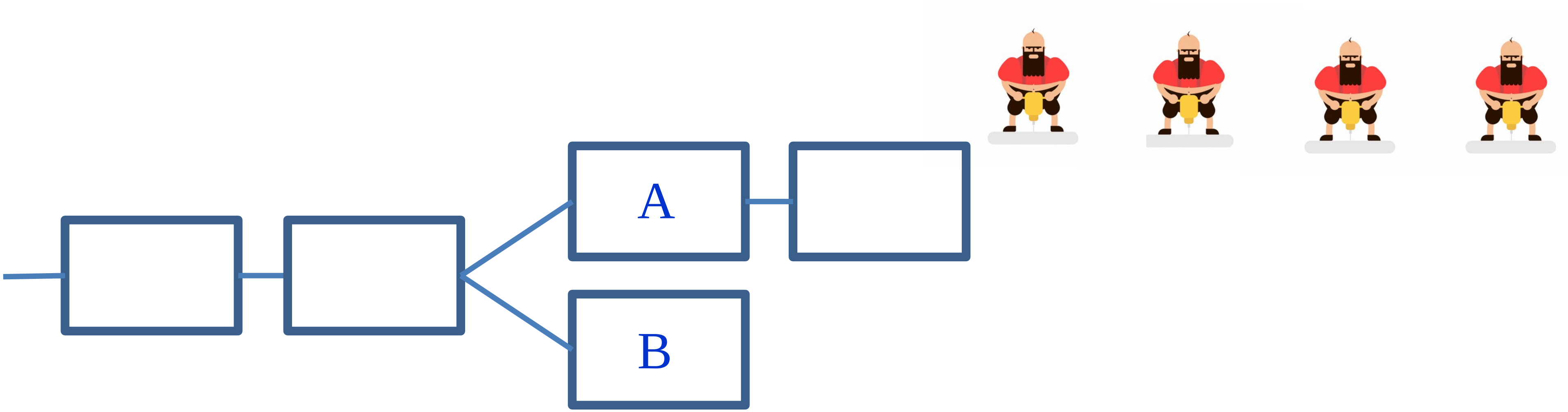
idea: selfishly decide when to announce solved blocks



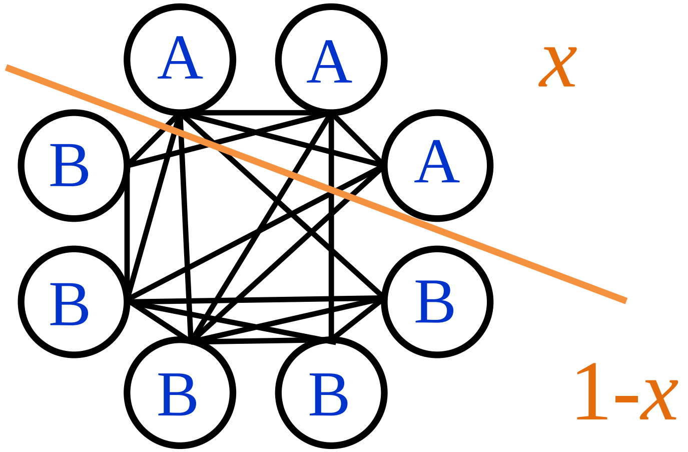


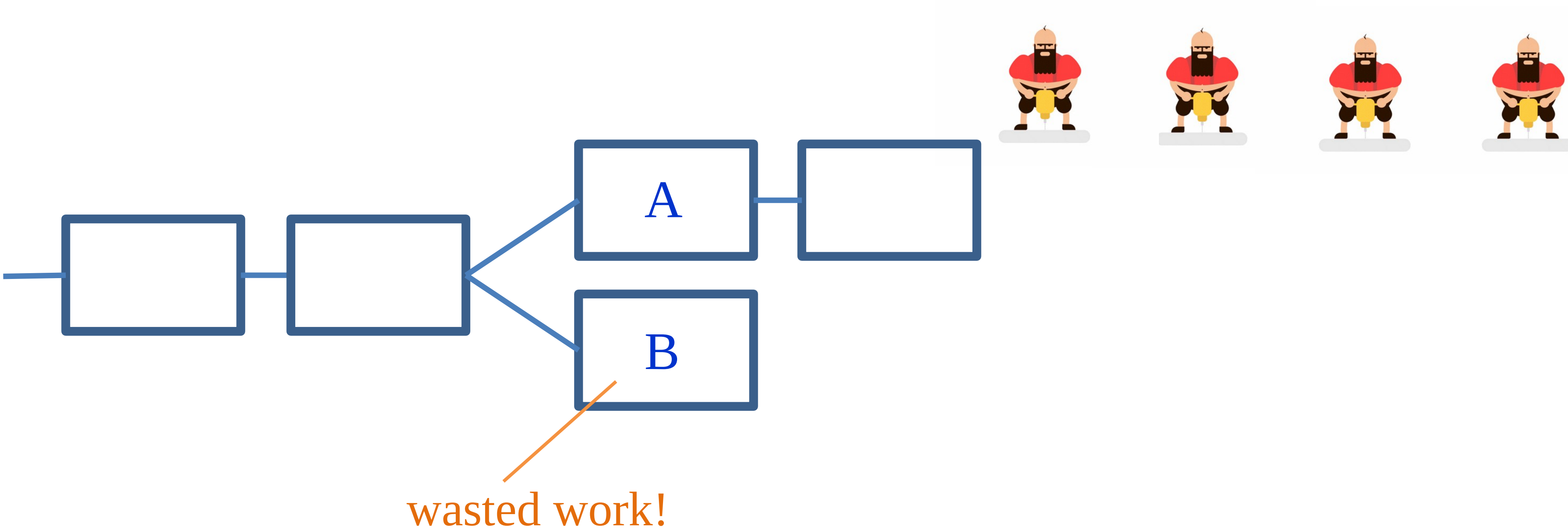
idea: selfishly decide when to announce solved blocks



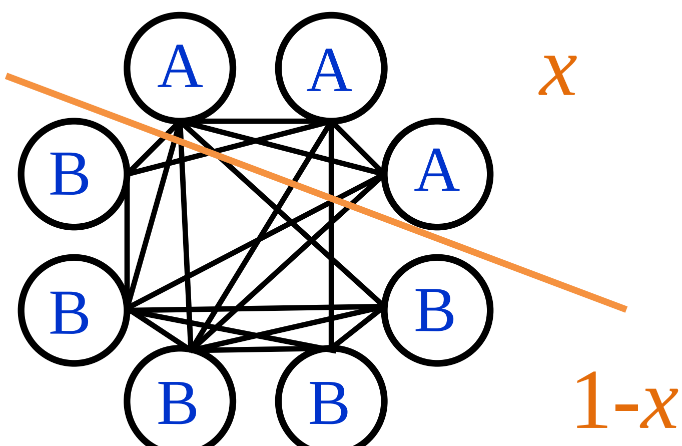


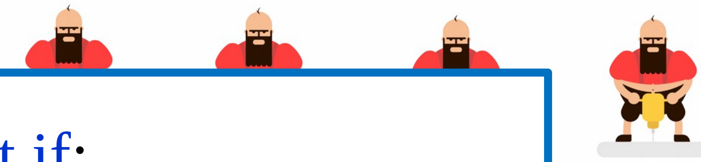
idea: selfishly decide when to announce solved blocks





idea: selfishly decide when to announce solved blocks





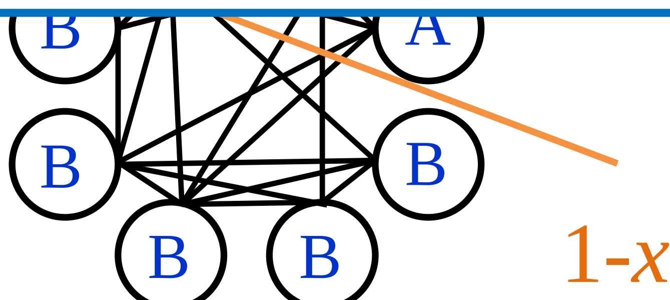
Convenient if:

- > 1/3 of the total computational power of the network

OR

- > 1/4 of the total computational power of the network & x ≥ 1/2

idea:



Bitcoin system (in a nutshell)

Tim Roughgarden, Incentives in Computer Science
Lecture #9: Incentives in Bitcoin Mining,
http://timroughgarden.org/f16/l/l9.pdf

A Bitcoin transaction:

1. One or more senders.
2. One or more recipients.
3. The amount of BTC (Bitcoins) transferred from each sender to each recipient.
4. A proof of ownership of the coins being transferred, in the form of a pointer back to most recent transactions involving the transferred coins.
5. A transaction fee, paid by the sender to the authorizer of the transaction.

Transactions

A transaction is valid if:

1. It has been cryptographically signed by all of the senders.
2. The senders really do own the coins being transferred.

Transactions

A transaction is valid if:

1. It has been cryptographically signed by all of the senders.
2. The senders really do own the coins being transferred.

This can be verified using the senders' public keys.

Transactions

A transaction is valid if:

1. It has been cryptographically signed by all of the senders.
2. The senders really do own the coins being transferred.

This can be verified using the senders' public keys.

This can be verified as follows:

- transactions are broadcast to all other users (through a peer-to-peer network);
- all users keep track of all transactions that have ever been authorized;
- thus, everyone knows everyone's current balance

Transactions

A transaction is valid if:

1. It has been cryptographically signed by all of the senders.
2. The senders really do own the coins being transferred.

This can be verified using the senders' public keys.

This can be verified as follows:

- transactions are broadcast to all other users (through a peer-to-peer network);
- all users keep track of all transactions that have ever been authorized;
- thus, everyone knows everyone's current balance

the ledger: the record of all the authorized transactions.

Transactions

Two important questions:

1. How do transactions get authorized and added to the ledger?
   (Traditionally, this would done by a centralized entity like a bank.)

2. How do Bitcoins get created in the first place?
   (Traditionally, money is printed by the government.)

Blocks

Transactions are added to the ledger in groups, known as blocks.

Blocks

Transactions are added to the ledger in groups, known as blocks.

A block contains:

1. One or more transactions.
2. A hash of the previous block.
3. A nonce. (I.e., a bunch of bits that can be set arbitrarily.)

Blocks

Transactions are added to the ledger in groups, known as blocks.

A block contains:

1. One or more transactions.
2. A hash of the previous block.
3. A nonce. (I.e., a bunch of bits that can be set arbitrarily.)

This imposes a natural linked list-type structure on the ledger:

- the predecessor of a block b_2 is the block b_1 whose hash matches the hash stored in b_2.

Blocks

Transactions are added to the ledger in groups, known as blocks.

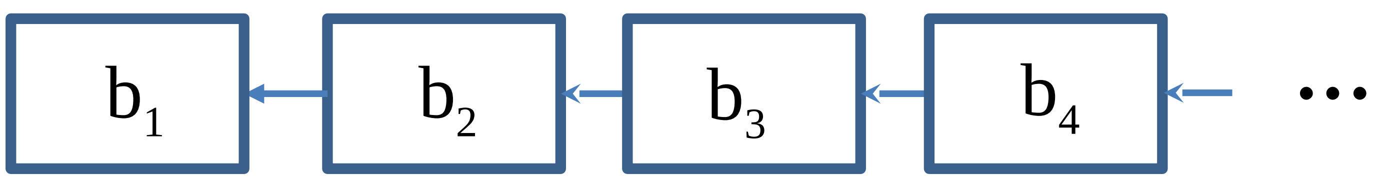
A block contains:

1. One or more transactions.
2. A hash of the previous block.
3. A nonce. (I.e., a bunch of bits that can be set arbitrarily.)

This imposes a natural linked list-type structure on the ledger:

- the predecessor of a block b_2 is the block b_1 whose hash matches the hash stored in b_2.

Blockchain



Blockchain

Some issues:

- How do new blocks get added to the blockchain?
- Who can do it?
- Why should they bother?
- How can we make sure that everybody agrees on the contents of the blockchain?

Blockchain

Some issues:

- How do new blocks get added to the blockchain?
- Who can do it?
- Why should they bother?
- How can we make sure that everybody agrees on the contents of the blockchain?

Two key ingredients:

1. Any user can authorize a block. Bitcoin incentivizes users to do authorizations through explicit monetary rewards (in BTC, naturally).
2. Authorizing a new block of transactions involves a proof of work, meaning that the authorizer has to solve a computationally difficult puzzle.

Computational difficult puzzle

A block b is valid if $h(b)$ is sufficiently close to 0.

h: pre-agreed upon hash function
(currently, SHA-256)

Computational difficult puzzle

A block b is valid if $h(b)$ is sufficiently close to 0.

the leading l bits of $h(b)$ should all be 0, where l is a parameter

h: pre-agreed upon hash function
(currently, SHA-256)

Computational difficult puzzle

A block b is valid if $h(b)$ is sufficiently close to 0.

the leading l bits of $h(b)$ should all be 0, where l is a parameter

h: pre-agreed upon hash function
(currently, SHA-256)

a block contains:
transactions, the hash of the previous block, the nonce

Computational difficult puzzle

A block *b* is valid if *h*(*b*) is sufficiently close to 0.

the leading *l* bits of *h*(*b*) should all be 0, where *l* is a parameter

h: pre-agreed upon hash function
(currently, SHA-256)

a block contains:
transactions, the hash of the previous block, the nonce

has to be set properly set in order to make the block valid

Computational difficult puzzle

A block b is valid if $h(b)$ is sufficiently close to 0.

the leading l bits of $h(b)$ should all be 0, where l is a parameter

h: pre-agreed upon hash function
(currently, SHA-256)

a block contains:
transactions, the hash of the previous block, the nonce

has to be set properly set in order to make the block valid

parameter l chosen to keep the rate of valid block creation roughly every ten minutes

Block Rewards and Bitcoin Mining

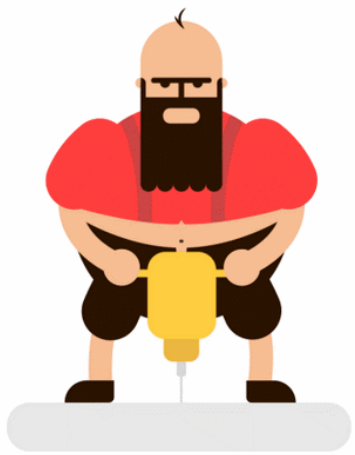
Bitcoin mining: the process of finding new valid blocks.

Block Rewards and Bitcoin Mining

Bitcoin mining: the process of finding new valid blocks.

A *miner*:

- chooses a subset of the transactions;
- inserts the hash of the current last block;
- arbitrarily set the bits in the nonce (and hope that the resulting block is valid).



Block Rewards and Bitcoin Mining

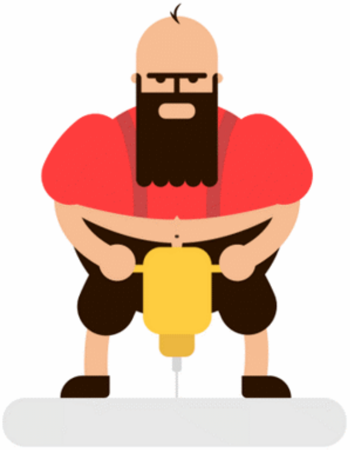
Bitcoin mining: the process of finding new valid blocks.

A *miner*:

- chooses a subset of the transactions;
- inserts the hash of the current last block;
- arbitrarily set the bits in the nonce (and hope that the resulting block is valid).

h is a cryptographic hash function

the accepted belief is that there is no algorithm for finding a valid block that is smarter or faster than random guessing or exhaustive search



Block Rewards and Bitcoin Mining

The reward that a miner gets for adding a new (valid) block to the blockchain has two ingredients:

1. A flat reward that does not depend on the contents of the block
   (When Bitcoin debuted this reward was 50 BTC, but the protocol dictates that this amount gets cut in half every four years. Currently, it is 6.25.)

2. The sum of the transaction fees of the transactions in the block
   (Currently, transaction fees are non-zero but typically constitute only a few percent of the overall reward.)

Block Rewards and Bitcoin Mining

The reward that a miner gets for adding a new (valid) block to the blockchain has two ingredients:

1. A flat reward that does not depend on the contents of the block
   (When Bitcoin debuted this reward was 50 BTC, but the protocol dictates that this amount gets cut in half every four years. Currently, it is 12.5.)

2. The sum of the transaction fees of the transactions in the block
   (Currently, transaction fees are non-zero but typically constitute only a few percent of the overall reward.)

remark: creating a new block is the only way that new money gets printed

Block Rewards and Bitcoin Mining

The reward that a miner gets for adding a new (valid) block to the blockchain has two ingredients:

1. A flat reward that does not depend on the contents of the block
   (When Bitcoin debuted this reward was 50 BTC, but the protocol dictates that this amount gets cut in half every four years. Currently, it is 12.5.)

2. The sum of the transaction fees of the transactions in the block
   (Currently, transaction fees are non-zero but typically constitute only a few percent of the overall reward.)

remark: creating a new block is the only way that new money gets printed

the miner gets the new mined BTCs as special transaction inserted into the mined block

Forks

When a new valid block has been found:

- the miner is supposed to immediately broadcast it across the entire network, so that it gets appended to the blockchain;

- If someone else announces a new valid block first, then the miner restarts this procedure, now using only transactions not already authorized by the new block, and using the hash of the new block.

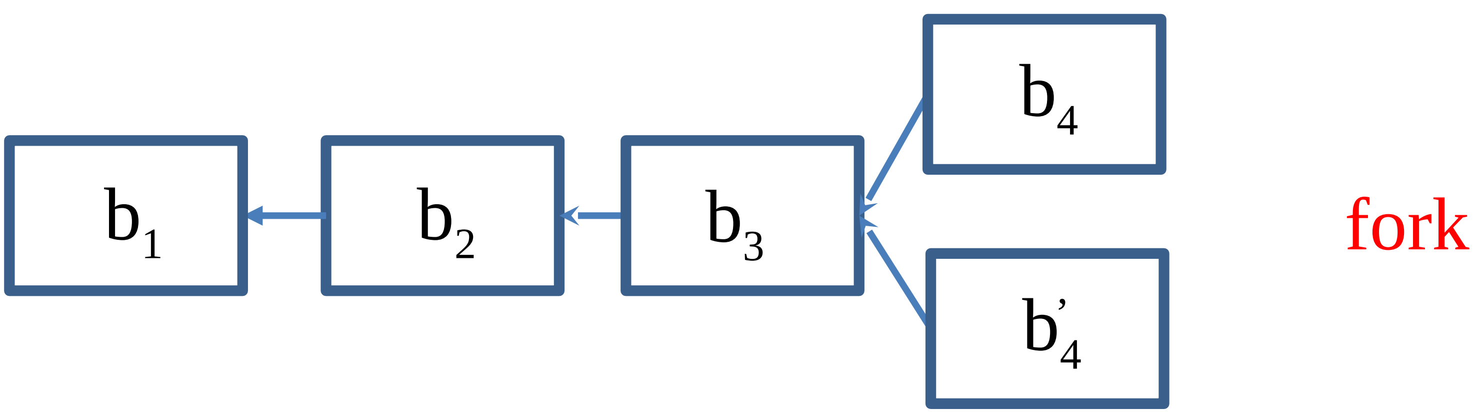
Forks

When a new valid block has been found:

- the miner is supposed to immediately broadcast it across the entire network, so that it gets appended to the blockchain;

- If someone else announces a new valid block first, then the miner restarts this procedure, now using only transactions not already authorized by the new block, and using the hash of the new block.

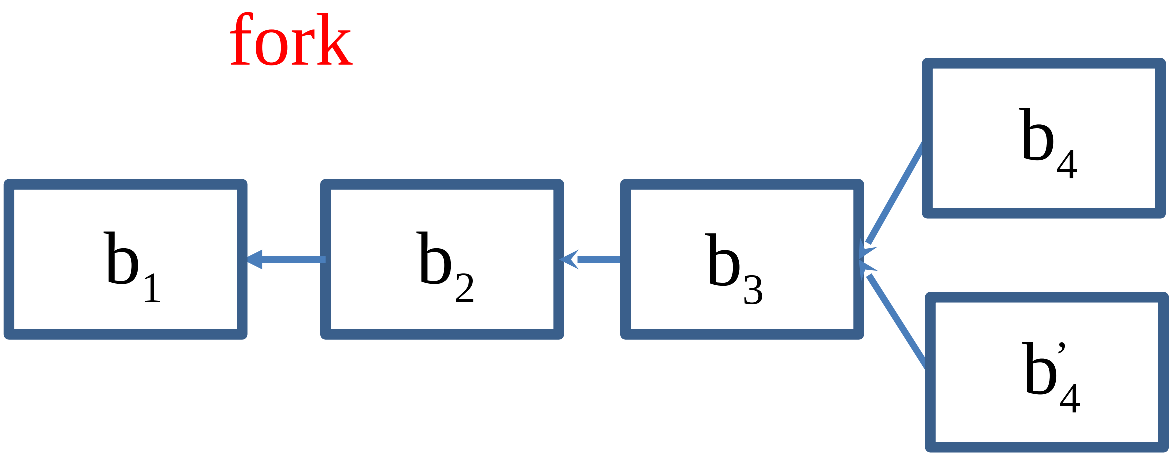
when two miners solve a block at roughly the same time:



Forks

Intended behavior when there is a fork:

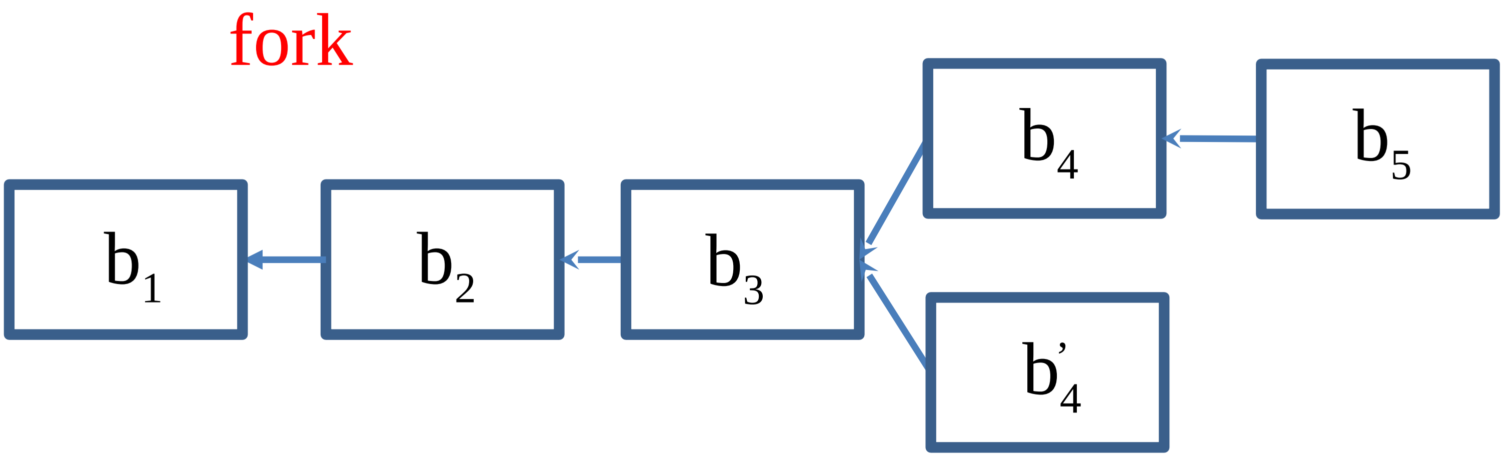
- a user should regard the longest branch as the valid one;
- break ties according to the block that it heard about first.



Forks

Intended behavior when there is a fork:

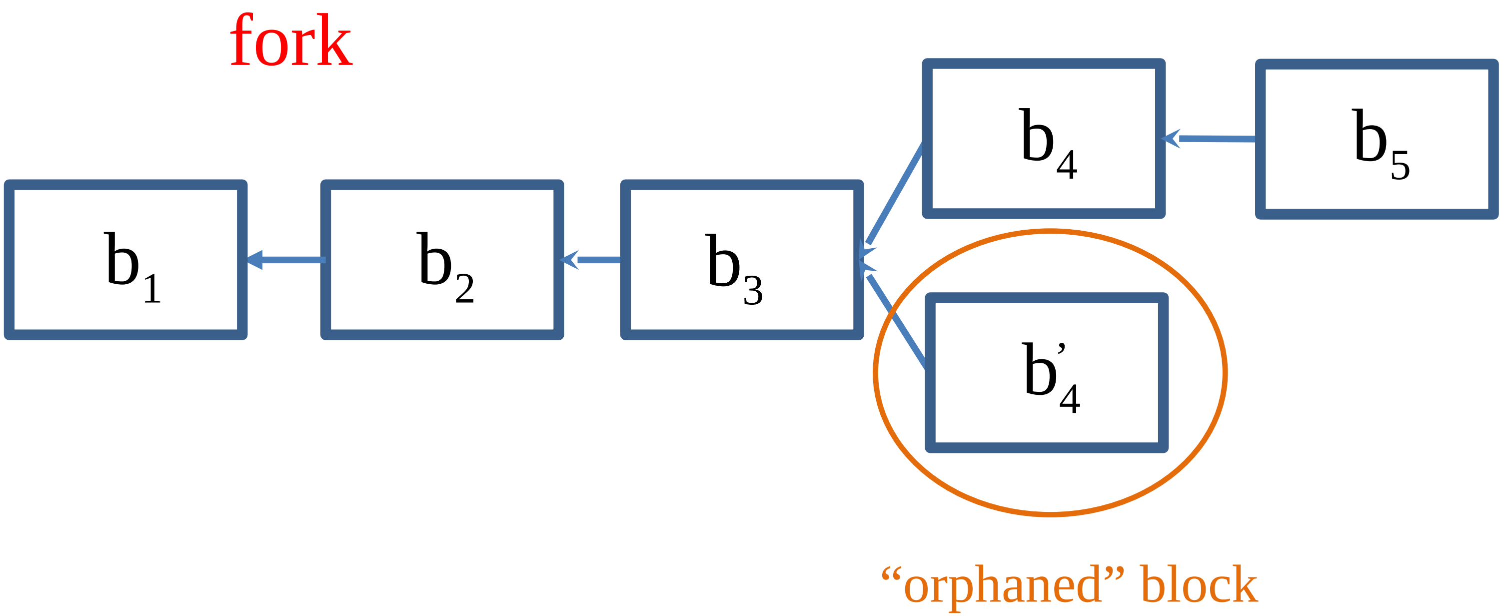
- a user should regard the longest branch as the valid one;
- break ties according to the block that it heard about first.



Forks

Intended behavior when there is a fork:

- a user should regard the longest branch as the valid one;
- break ties according to the block that it heard about first.



Bitcoin Mining Protocol:

- work on the next block to be added to the longest chain
- announce the solved block as soon as you get it

Bitcoin Mining Protocol:

- work on the next block to be added to the longest chain
- announce the solved block as soon as you get it

Does a miner have convenience to follow the protocol?

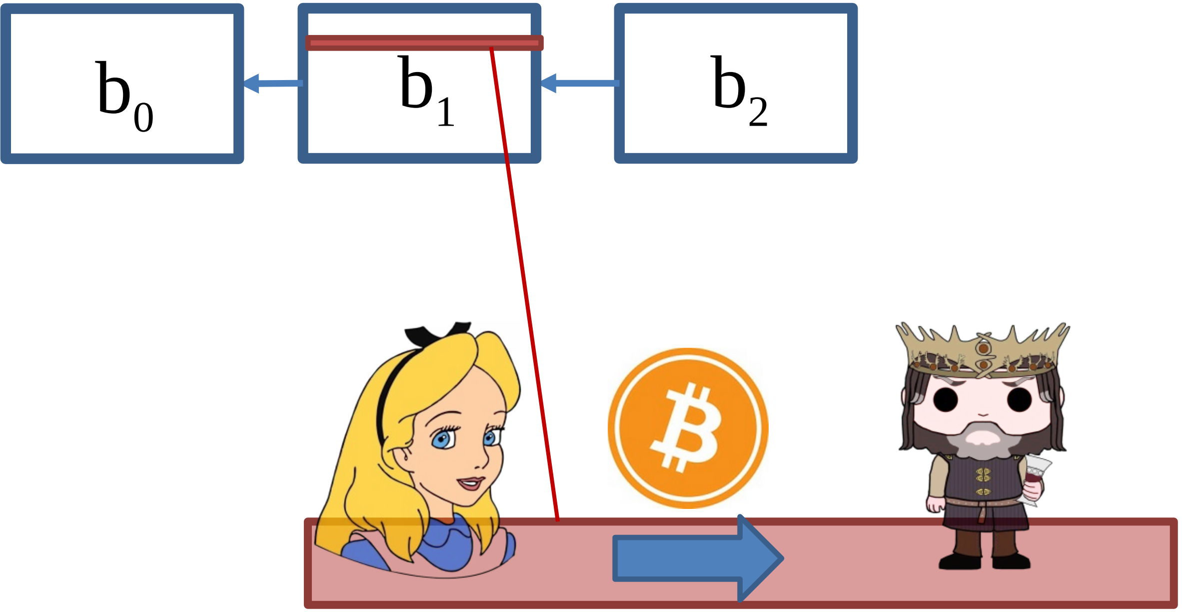
The Double-Spend Attack

Idea: miners deliberately create forks.

The Double-Spend Attack

Idea: miners deliberately create forks.

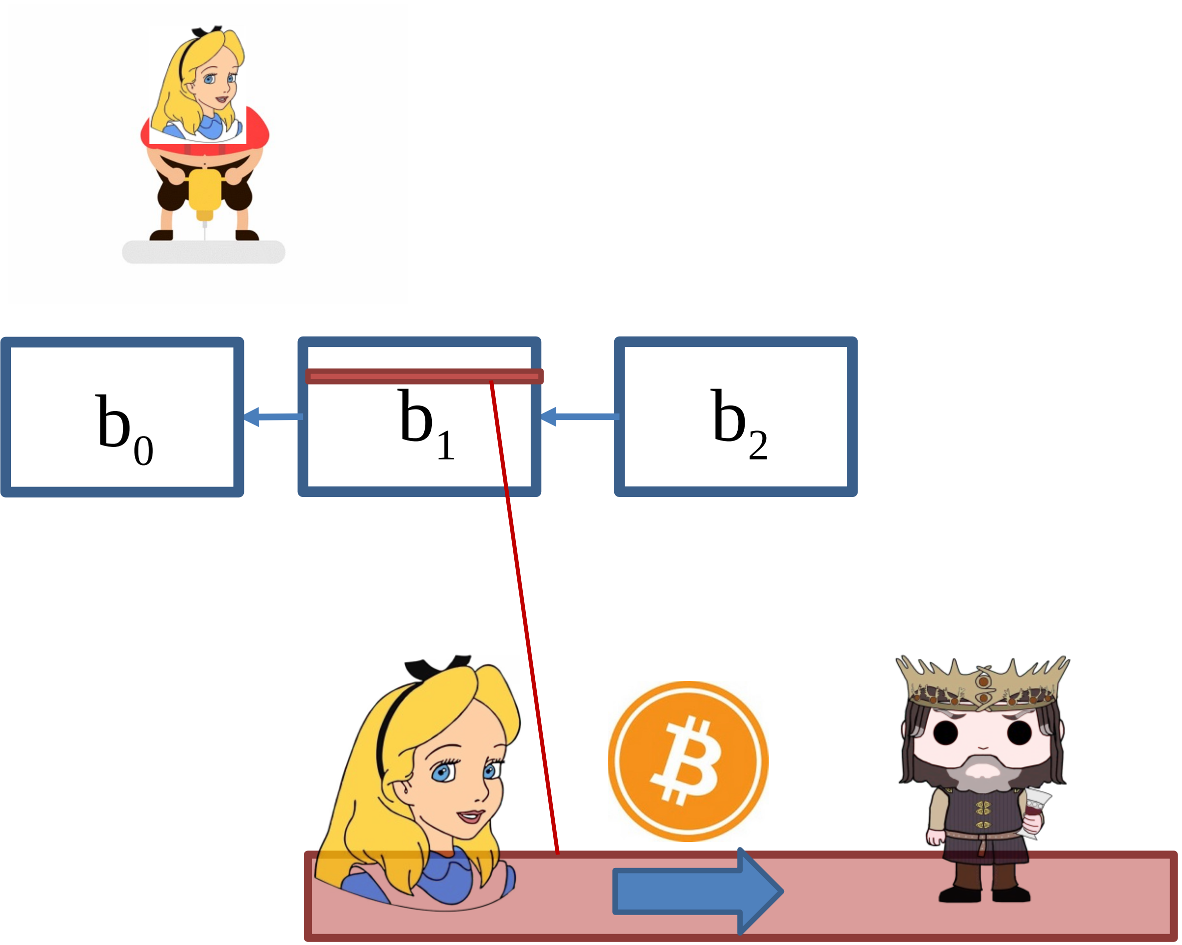
Assumption: Bob only ships the purchased goods to Alice once another block b_2 has been appended to b_1.



The Double-Spend Attack

Idea: miners deliberately create forks.

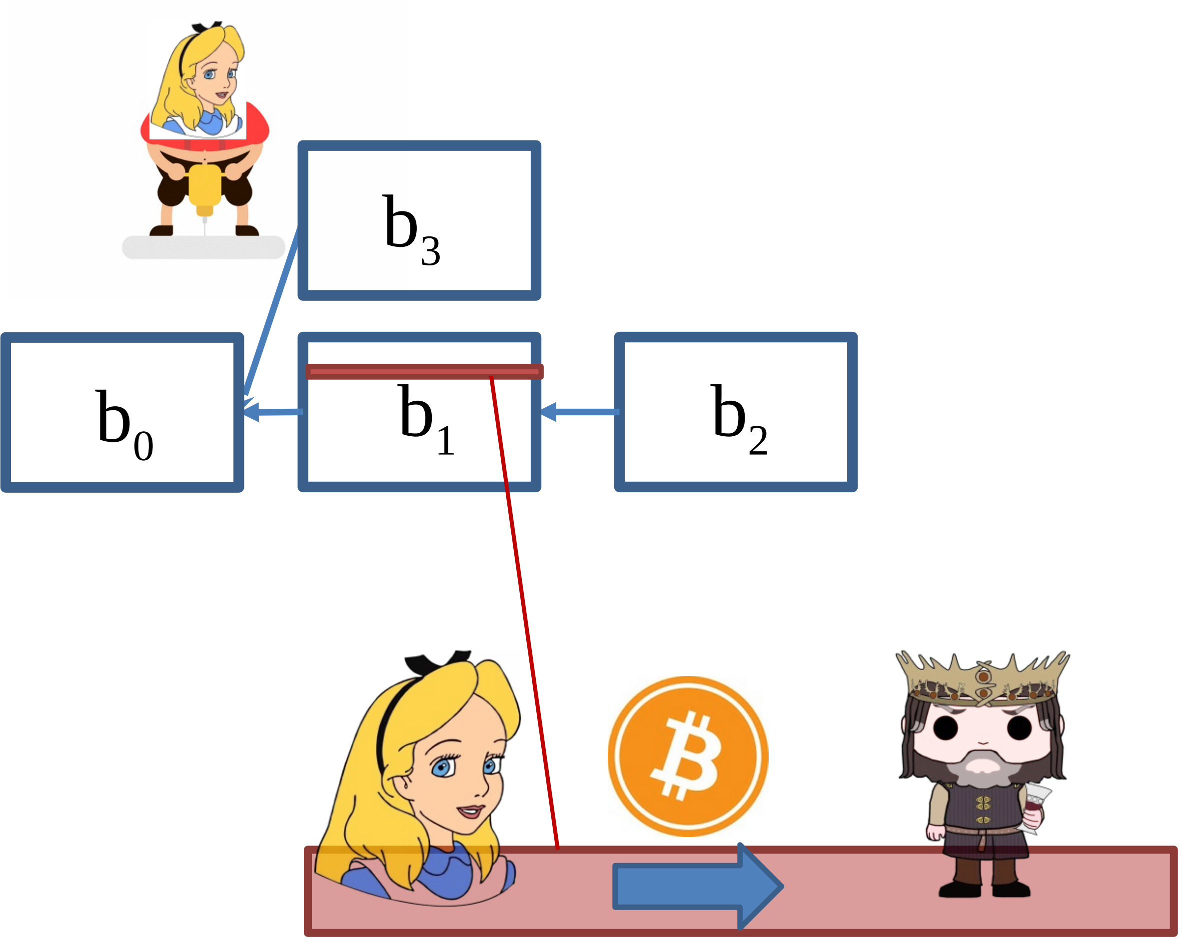
Assumption: Bob only ships the purchased goods to Alice once another block b_2 has been appended to b_1.



The Double-Spend Attack

Idea: miners deliberately create forks.

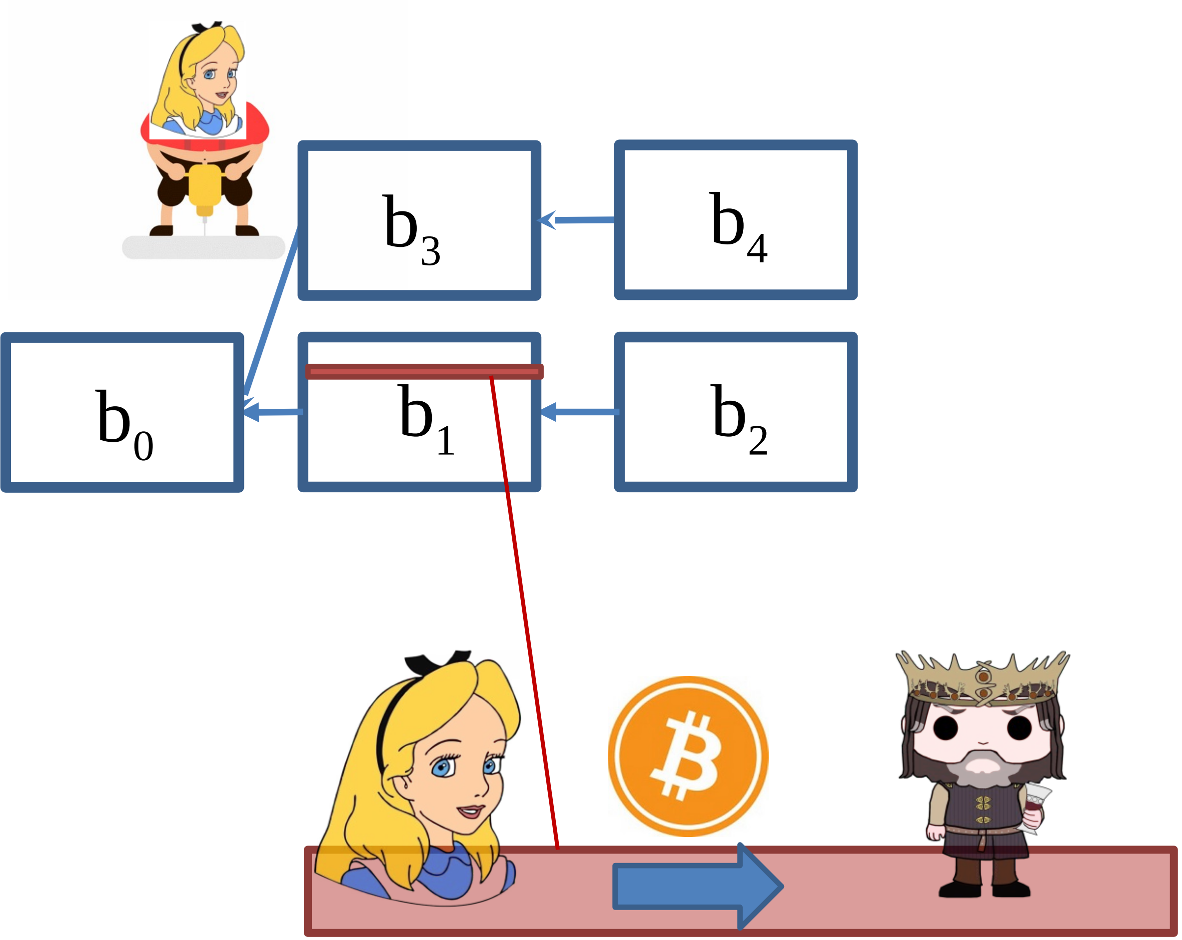
Assumption: Bob only ships the purchased goods to Alice once another block b_2 has been appended to b_1.



The Double-Spend Attack

Idea: miners deliberately create forks.

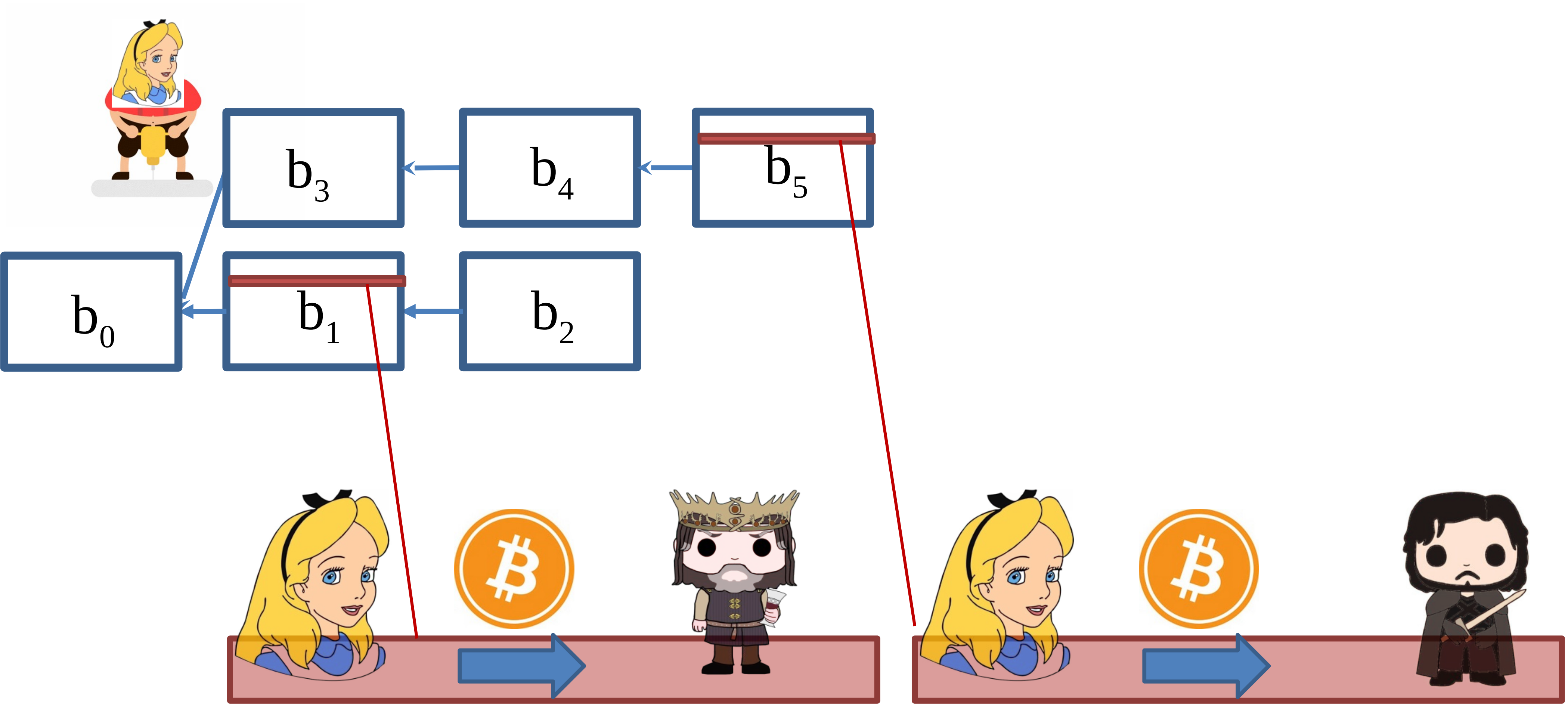
Assumption: Bob only ships the purchased goods to Alice once another block b_2 has been appended to b_1.



The Double-Spend Attack

Idea: miners deliberately create forks.

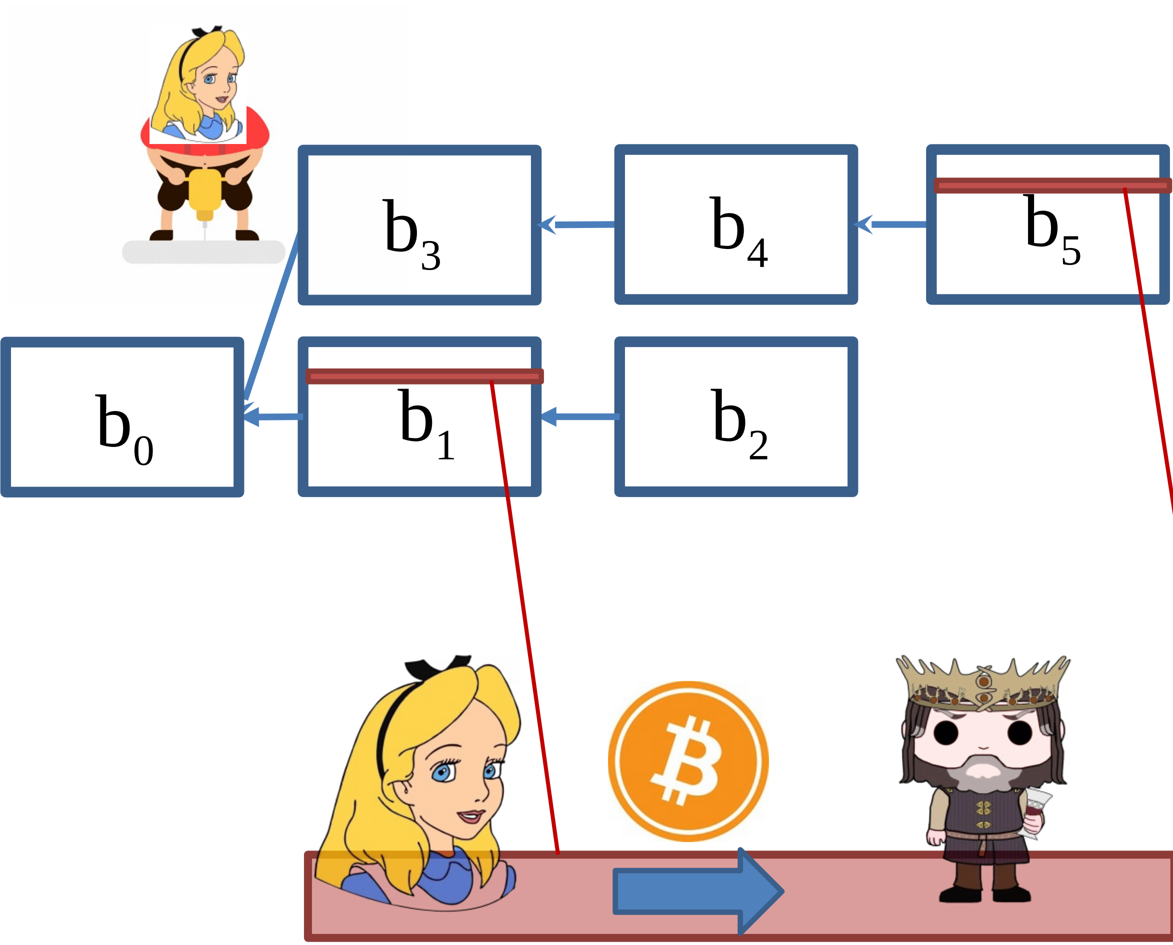
Assumption: Bob only ships the purchased goods to Alice once another block b_2 has been appended to b_1.



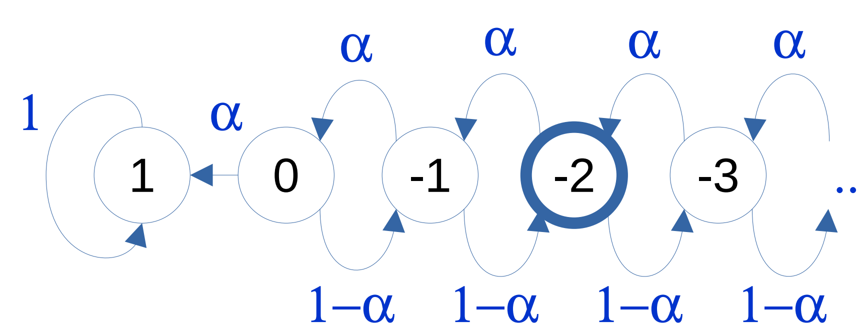
The Double-Spend Attack

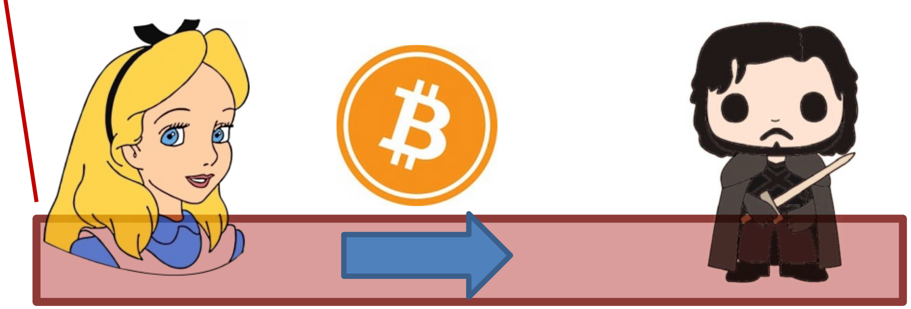
Idea: miners deliberately create forks.

Assumption: Bob only ships the purchased goods to Alice once another block b_2 has been appended to b_1.



α: fraction of the computational power controlled by Alice

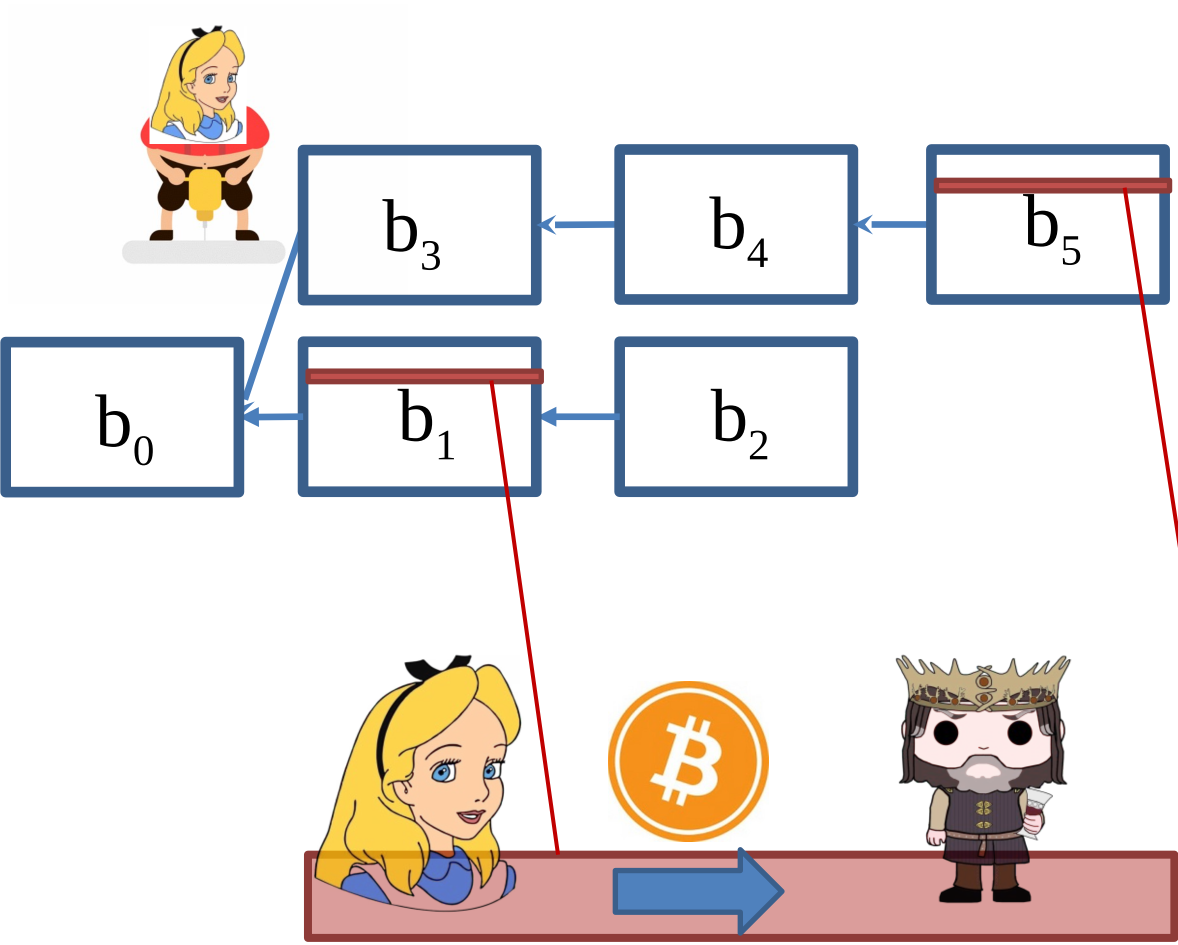




The Double-Spend Attack

Idea: miners deliberately create forks.

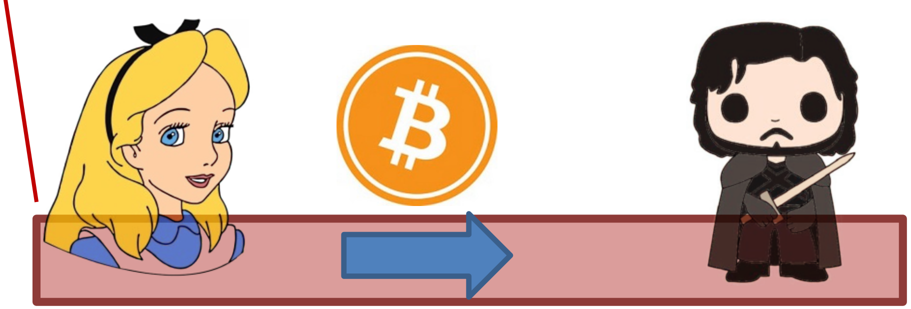
Assumption: Bob only ships the purchased goods to Alice once another block b_2 has been appended to b_1.



α: fraction of the computational power controlled by Alice

probability of success:

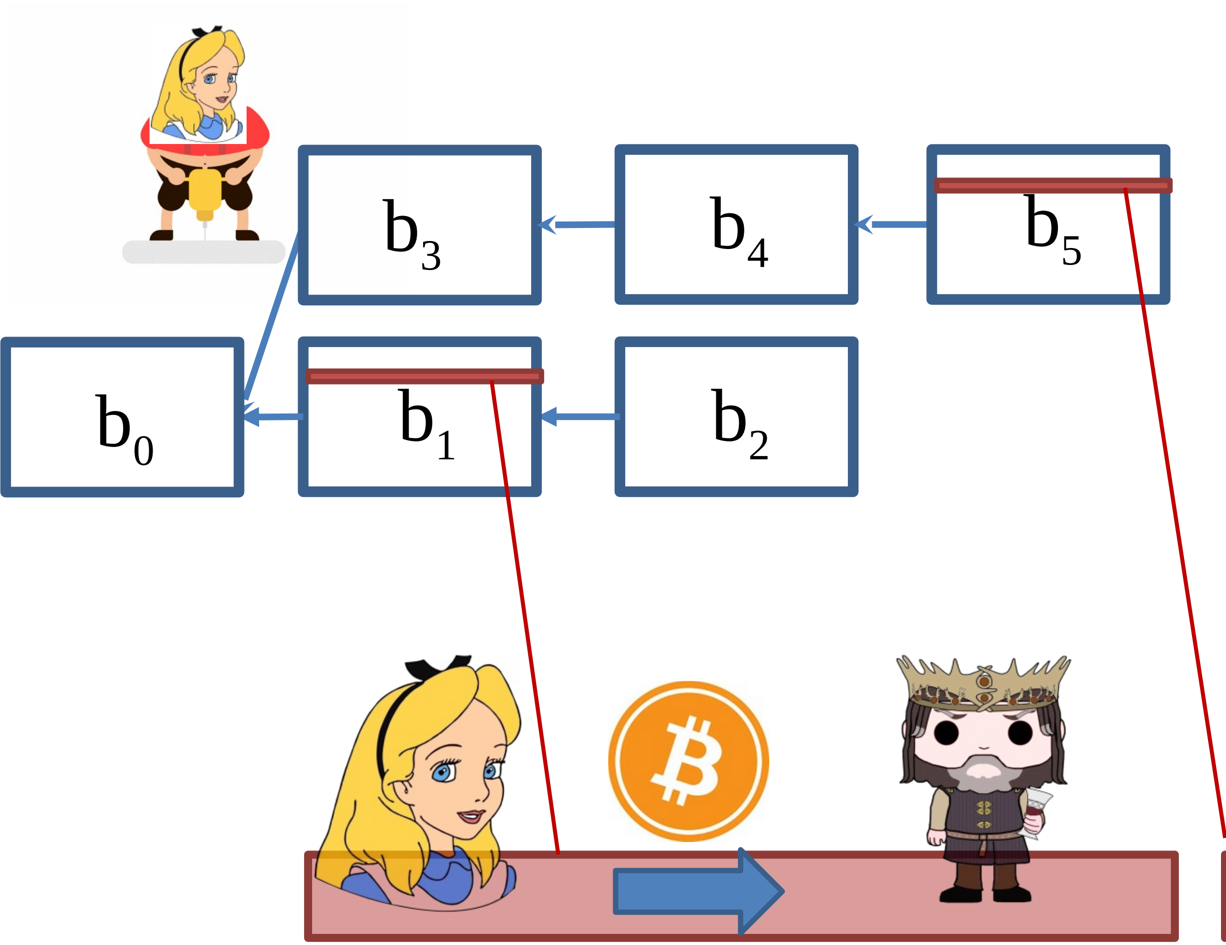
$(\alpha/(1-\alpha))^3$



The Double-Spend Attack

Idea: miners deliberately create forks.

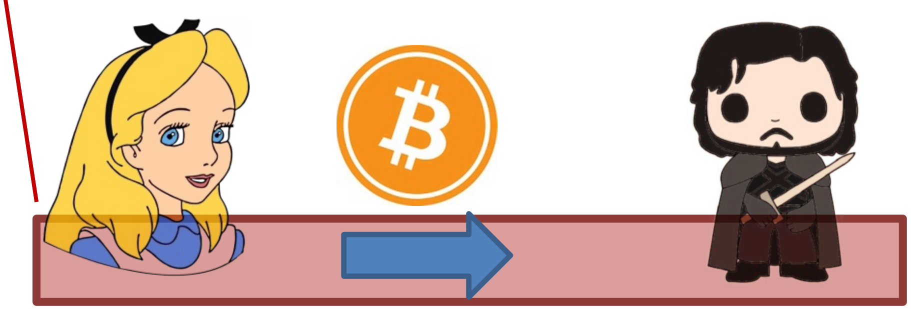
Assumption: Bob only ships the purchased goods to Alice once k other blocks have been appended to b_1.



α: fraction of the computational power controlled by Alice

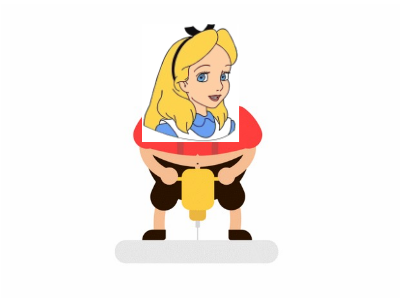
probability of success:

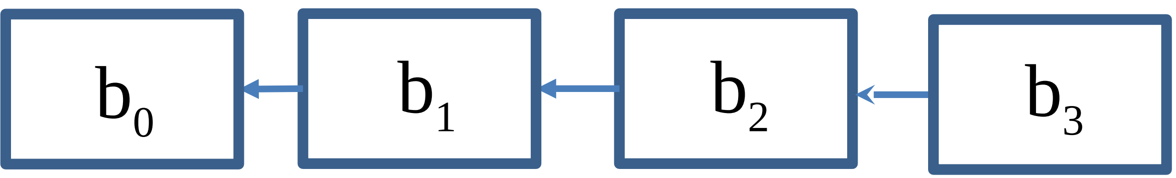
$(\alpha/(1-\alpha))^{k+2}$



The 51% Attack

if Alice controls ≥ 50% of the computational power

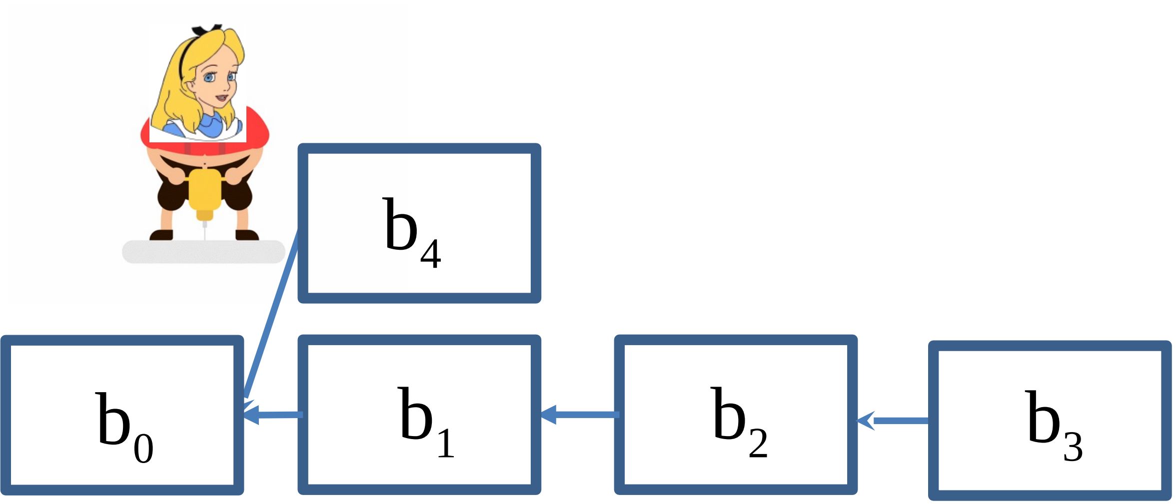




remark:
Bitcoin is not intended to function when a single entity controls more than 50% of the computational power

The 51% Attack

if Alice controls $\geq$ 50% of the computational power

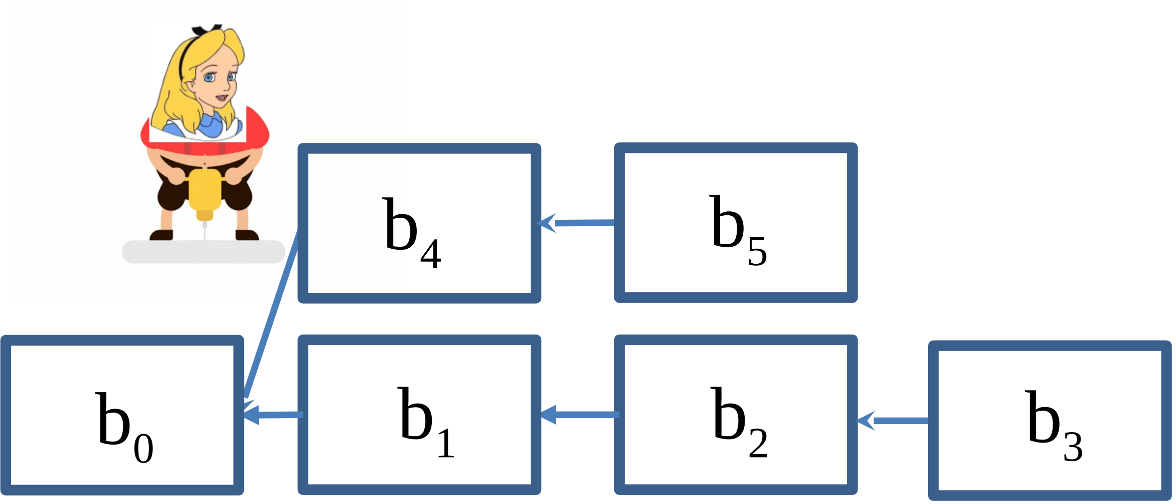


remark:

Bitcoin is not intended to function when a single entity controls more than 50% of the computational power

The 51% Attack

if Alice controls $\geq$ 50% of the computational power

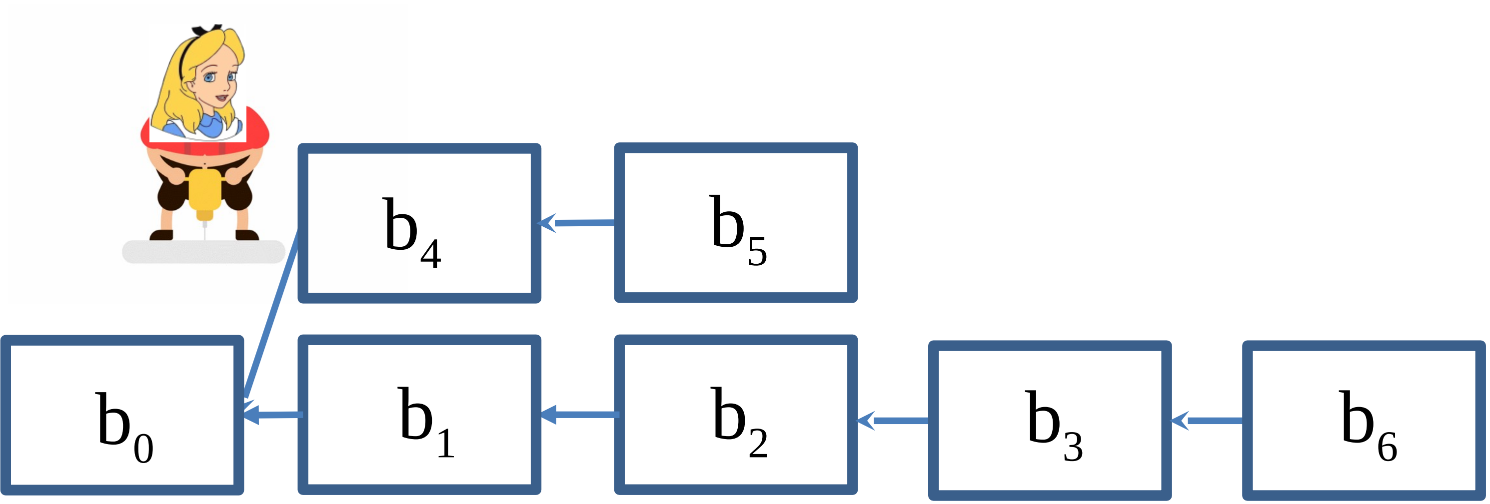


remark:

Bitcoin is not intended to function when a single entity controls more than 50% of the computational power

The 51% Attack

if Alice controls $\geq$ 50% of the computational power

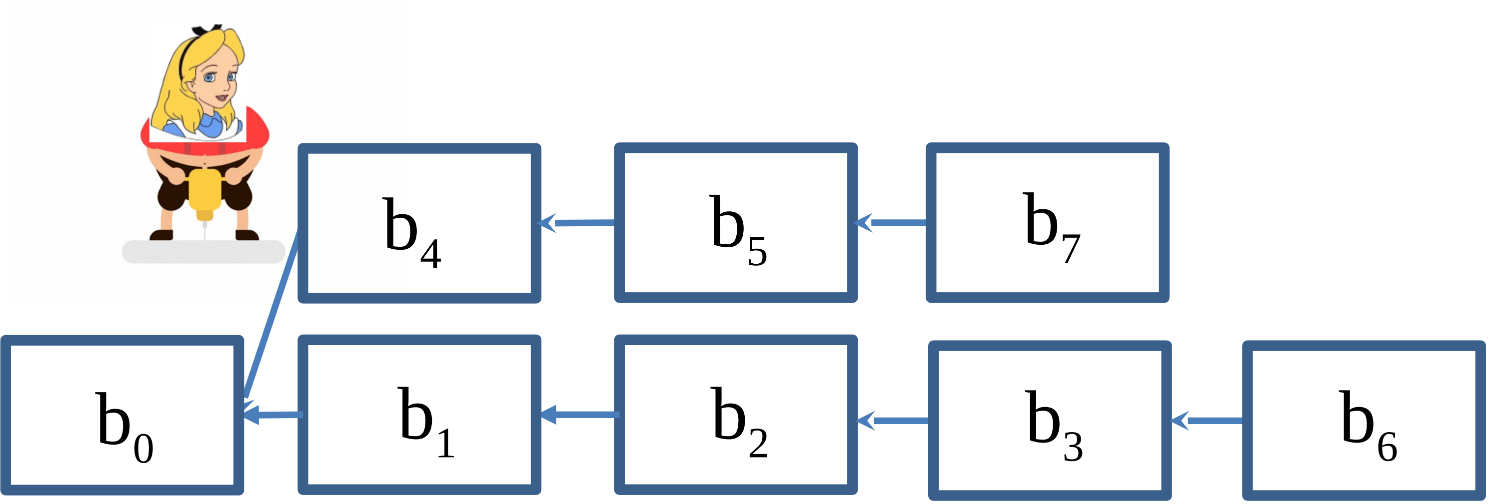


remark:

Bitcoin is not intended to function when a single entity controls more than 50% of the computational power

The 51% Attack

if Alice controls $\geq$ 50% of the computational power

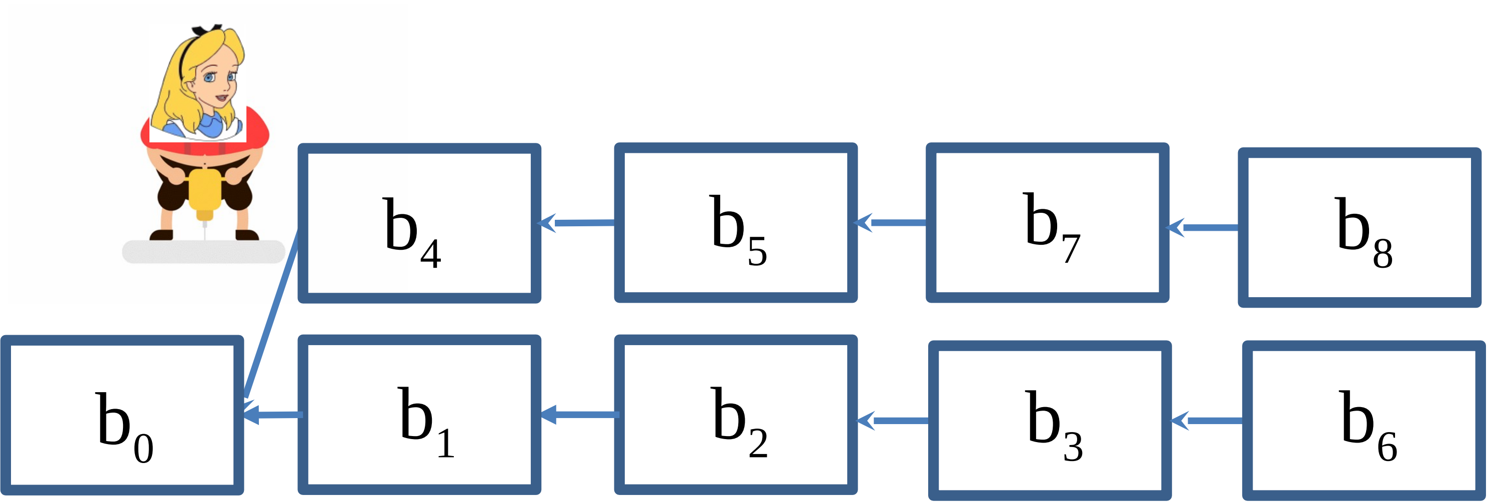


remark:

Bitcoin is not intended to function when a single entity controls more than 50% of the computational power

The 51% Attack

if Alice controls $\geq$ 50% of the computational power

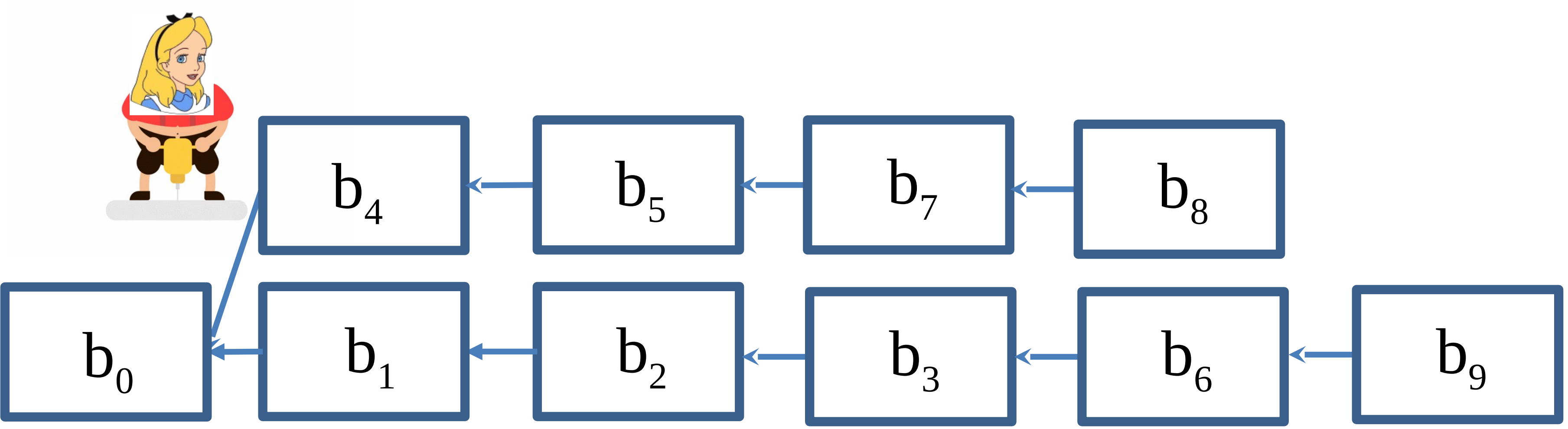


remark:

Bitcoin is not intended to function when a single entity controls more than 50% of the computational power

The 51% Attack

if Alice controls $\geq$ 50% of the computational power

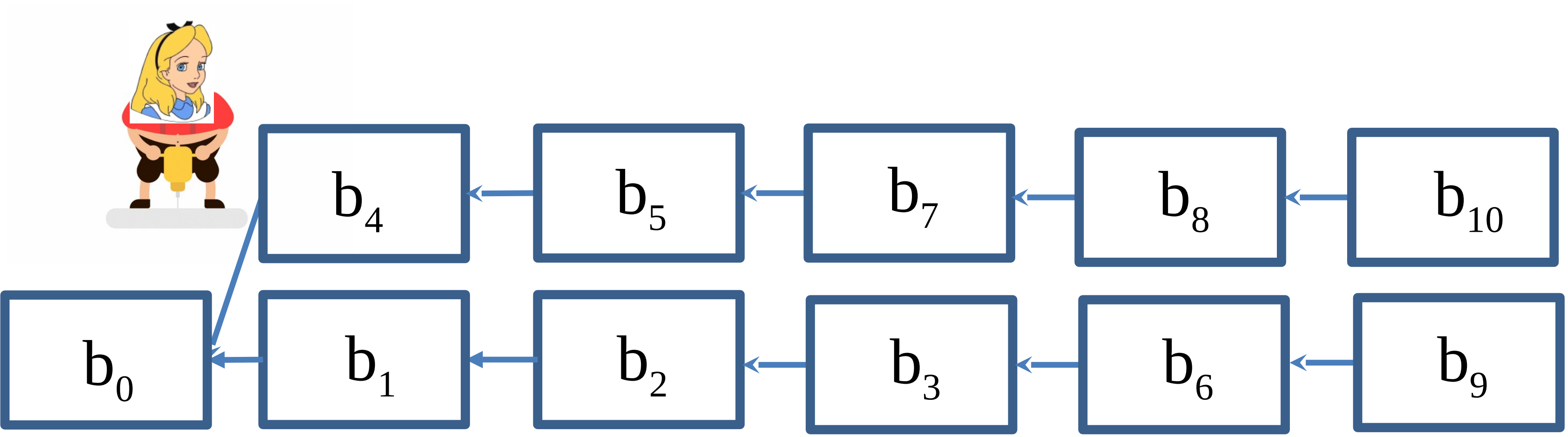


remark:

Bitcoin is not intended to function when a single entity controls more than 50% of the computational power

The 51% Attack

if Alice controls ≥ 50% of the computational power

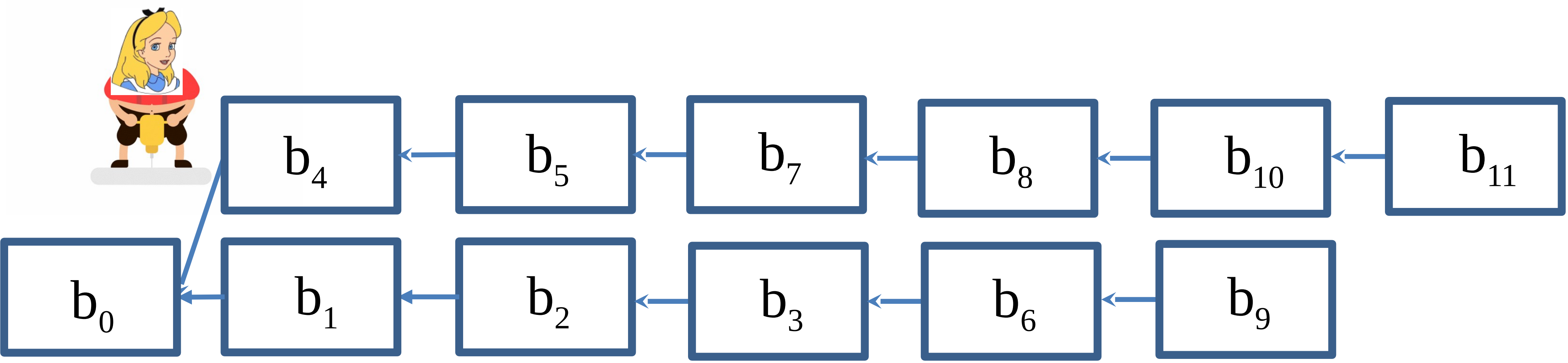


remark:

Bitcoin is not intended to function when a single entity controls more than 50% of the computational power

The 51% Attack

if Alice controls ≥ 50% of the computational power

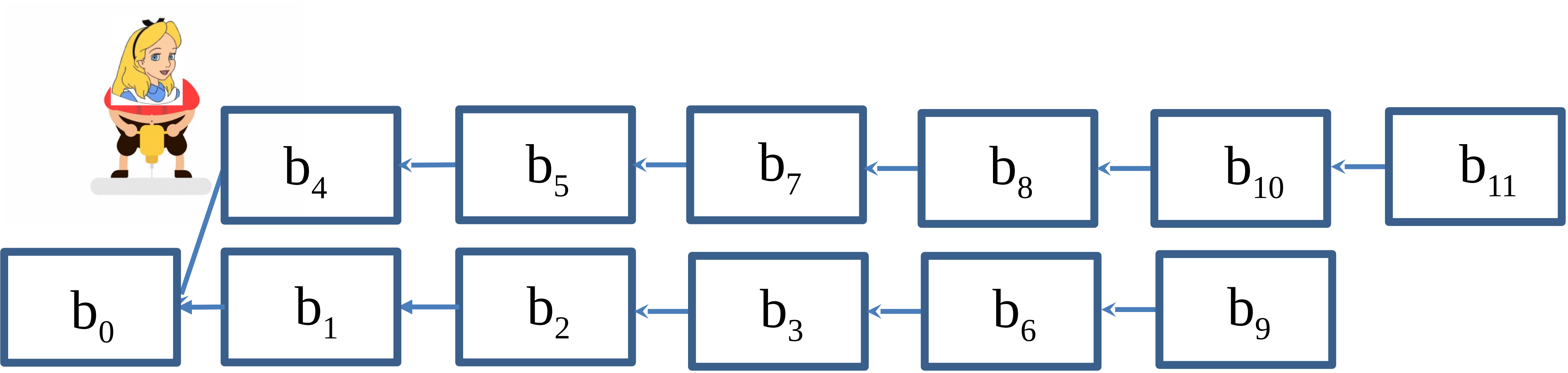


remark:

Bitcoin is not intended to function when a single entity controls more than 50% of the computational power

The 51% Attack

if Alice controls $\geq$ 50% of the computational power



remark:

Bitcoin is not intended to function when a single entity controls more than 50% of the computational power

Alice will eventually build the longest chain (with probability 1)