# Introduction to Blockchains

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# /me



- IT student at BFH
  - Specialisation in Infosec
  - Been working with Blockchain Technology for 1.5 years
  - Bachelor thesis on the analysis of the Bitcoin Blockchain
- Founding member of the Chaostreff Bern

# Content I

# Content II



Mining

Mining

With this presentation, I want to tell you not only how Blockchains work, but also why they work the way they do and why the ideas and concepts are robust enough.

Section 1

# Systems for representing ownership

# Subsection



## Systems for representing ownership

- State-transition systems
- Double-spend

## Blockchain (without PoW)

## Blockchain

## Bitcoin

## Bonus Slides

# Systems of ownership as state-transition-systems



Systems representing ownership can be modelled as state-transition system.

- Finance
- Estate
- ...

Mapping:

**State** Collection of who owns what

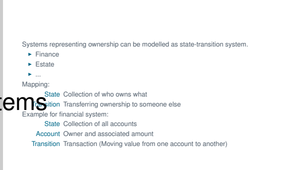
**Transition** Transferring ownership to someone else

Example for financial system:

**State** Collection of all accounts

**Account** Owner and associated amount

**Transition** Transaction (Moving value from one account to another)

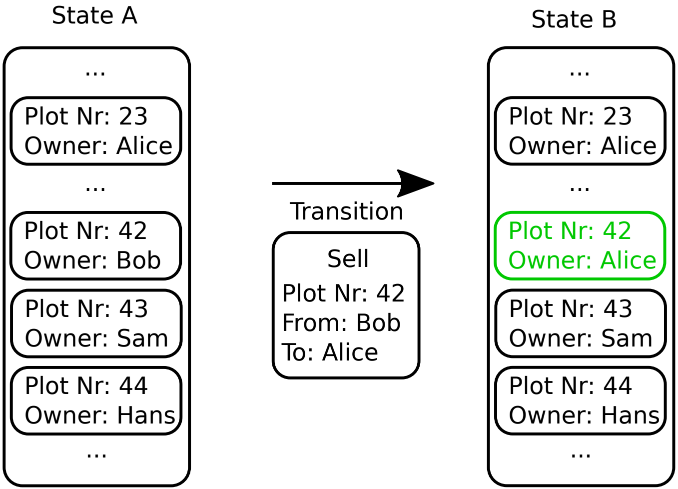



One of the core ideas of this talk is that ownership can be represented as a state-transition system.

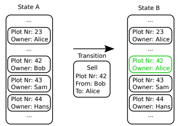
If we represent ownership in a state-transition system, then a state is the information about who owns what at a given point in time. If someone transfers ownership to someone else (for example by selling an object), then that marks a transition which leads to a new state.

We can easily map financial systems to a state-transition-system. All accounts together represent the state. Every time someone makes a transaction, this marks a transition in the system which leads to a new state.

# Showcase



State A
...
Plot Nr: 23
Owner: Alice
...
Plot Nr: 42
Owner: Bob
Plot Nr: 43
Owner: Sam
Plot Nr: 44
Owner: Hans
...
Transition
Sell
Plot Nr: 42
From: Bob
To: Alice
State B
...
Plot Nr: 23
Owner: Alice
...
Plot Nr: 42
Owner: Alice
Plot Nr: 43
Owner: Sam
Plot Nr: 44
Owner: Hans
...




Here we have an example of an estate system expressed as a state-transition system. A state is the collection of all Plots. Each plot has an owner assigned. The state describes by whom each plot is owned. If a plot is sold, such as in the example where Bob sells Plot number 42 to Alice, the system transitions into a new State.

# Subsection

# Consensus



- Consensus is very important
- Before each transaction, all parties need to agree on the current state!
- The reason for this: double-spend

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Consensus means that all parties of the system agree on the state of the system. I will now show how the system can be exploited if the parties can't agree on a state.

# Double-spend



- To spend something twice
  - Spending the same money twice
  - Selling the same plot twice
  - ...
- Obviously malicious
- Well known attack in the Blockchain / Bitcoin world

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Double-spend is the action of spending the same thing twice. This is rather abstract for digital currencies such as the money we have on bank accounts. It's hard to imagine anyone spending the same money twice that way. It's rather simpler to imagine double-spend with estate: Imagine someone selling the same plot twice.

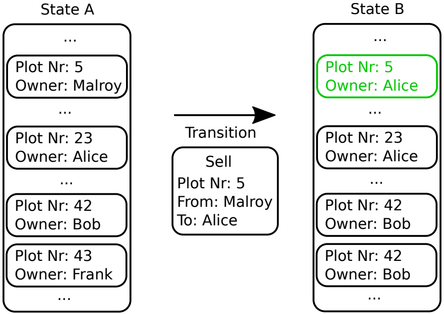
# Double-spend estate example



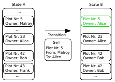
- Malroy has a nice property (Plot number 5)
- Alice is looking to buy a new property
- Bob also wants to buy a new property
- Malroy will attempt to sell the same plot to both of them!

# Example: Alice’s view






Alice has paid for the plot. She thinks it’s now hers.



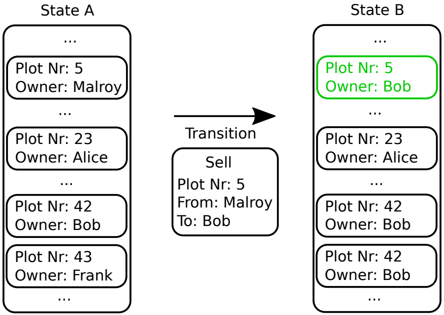

Alice has paid for the plot. She thinks it's now hers.

Alice pays Malroy for the plot and Malroy transfers ownership of the plot to Alice. This results in a new state where Alice is now the owner of plot 42. Both Alice and Bob know about this new state the system is now in.

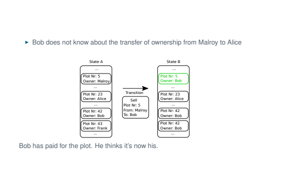
# Example: Bob's view



- Bob does not know about the transfer of ownership from Malroy to Alice




Bob has paid for the plot. He thinks it's now his.




Let's imagine Bob has never learned about the previous transfer of ownership which has led to "State B". Bob is still of the opinion that Malroy is the rightful owner of Plot number 5. So bob will happily "buy" the plot from Malroy who will pretend to transfer ownership over the plot to Bob.

# Example: problem



- Problem: Malroy sold the same plot twice!
- Alice and Bob do not agree on the current state of the system
- Their views on the state are incompatible
- This breaks the system:
  - Possibility to sell plots many times
  - People can't trade with each other

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Bob having sold the plot twice is malicious of course. For him it means profit, but for Alice and Bob it's a big problem. Who owns the plot now? Who can use it and who can sell it to someone else. This is also a problem for other people who might want to buy the plot. Who can they buy it from? Having this situation clearly messes up the system. Some kind of conflict resolution would be needed. It would be even better though, if situations like this didn't occur in the first place.

# Solution



Simple solution in the estate world:

- Registry of deeds (Grundbuchamt)
- Central authority
- Controls the state of the system
- Every time an estate is sold (a transition is made), it has to be done via the registry of deeds
- For each transition, the central authority performs certain checks to make sure the transition is compatible with the current state and either accepts or rejects it

That way, everybody can agree on a certain state and that state is always valid.

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The double-spend problem has been solved in the estate world. The local registry of deeds watches over the state of the system. Each time a plot is sold, the registry of deeds has to be informed. If they notice an inconsistency, they can intervene.

Take the above example: Malroy wants to sell the plot to Alice. So they go to the registry of deeds together. The registry of deeds checks that the plot really belongs to Malroy. When the Malroy transfers ownership to Alice, the registry of deeds updates their records accordingly. Later on, when Malroy comes back with Bob to sell the plot to him, the registry of deeds will see in their records that Malroy does not own the plot any longer and will prevent him from selling it from Bob. The attack has been prevented.

# Solution for monetary systems



Requirements:

- All parties need to agree on the current state
- All parties need to agree on whether a transition is valid

Banks as central authority:

- Banks serve as central authorities
- They control the state and check all transitions
- Always the case for modern day money transfers

This works surprisingly well.

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This works surprisingly well.

The same solution that worked for the estate system, a central authority controlling the state, can also work for monetary systems.

Typically we see this when making monetary transactions via our banks. The bank acts as a central authority that manages the state and ensures the integrity of the system.

# A Solution for the internet



Requirements:

- Decentralized
- Needs to work on the internet

Central authority:

- Possibility of censorship
- Can be attacked
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If we are looking for a system that allows the participants to agree on a state over the internet, it gets a bit more complicated.
Having a central authority manage the state would of course work. Think of Paypal: They are doing just that - allow anyone to make transactions via the internet in a secure manner. Paypal acts as the central authority managing the state and ensuring the integrity of the system.
However, a central authority can censor the system, can be attacked and hacked and it can of course collect all the data of its users. This then is not an adequate solution for a decentralized internet. Paypal should be prove enough that this is not the solution we are looking for.

A new system is required. A system appropriate for the Internet age.

Section 2

# Blockchain (without PoW)

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Blockchain (without PoW)

In this chapter I will introduce the basic ideas of Blockchain systems but without Proof of Work (PoW). I will show how they allow the participants to agree on a state. Without PoW though, the concepts explained here ware insufficient to secure the Blockchain. This is demonstrated by showing a double-spend attack.

The next chapter will introduce PoW and show how it makes the Blockchain secure.

# Another solution



Blockchain is an internet-age solution to the same problem. It provides these (amazing) properties:

- No central authority
- Parties do not need to trust each other
- Parties need no information on who is participating
- ... not even any information on how many others are participating
- And still they can all agree on a state

# Subsection

Let's first talk of the network we use to distribute transactions among all participants.

# The general idea



- We all agree on an initial state
  - Could be an empty state
  - Or something else
- We build a peer to peer network
- Transactions are published / announced to the p2p network
- Network relays transactions

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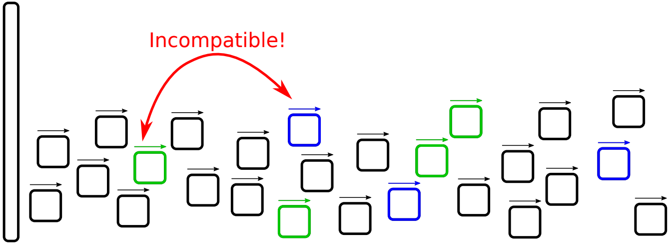
We build a Peer to Peer (p2p) network used to distribute the transactions amongst all participants. Everyone who makes a transaction announced that to the network. The network the relays the transaction until all participants have seen it.

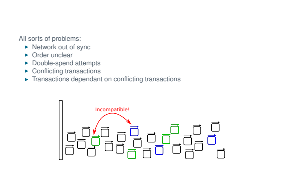
# Distributing transactions



All sorts of problems:

- Network out of sync
- Order unclear
- Double-spend attempts
- Conflicting transactions
- Transactions dependant on conflicting transactions






The transactions on their own are a big mess. Because of delays in the network they don't get consistently spread to all participants, the order in which they arrive may be random, there might even be conflicting transaction. People will attempt double-spends and other attacks.

# Subsection

# Introducing: the Blockchain



A method is needed to establish a consensus, to agree on a state.
We call this method: Blockchain
(For now: Without Proof of Work, PoW)

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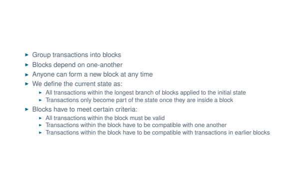
We need a way to assemble the transactions which get distributed through our P2P network. We need a method for agreeing on a state which explicitly defines which transactions are valid.
The system to do that is the Blockchain.

(Again: The Blockchain explained in this chapter is a blockchain without Proof of Work (PoW). Because of that it is incomplete and insecure. The next chapter will introduce POW and explain how it secures the Blockchain.)

# Blocks



- Group transactions into blocks
- Blocks depend on one-another
- Anyone can form a new block at any time
- We define the current state as:
  - All transactions within the longest branch of blocks applied to the initial state
  - Transactions only become part of the state once they are inside a block
- Blocks have to meet certain criteria:
  - All transactions within the block must be valid
  - Transactions within the block have to be compatible with one another
  - Transactions within the block have to be compatible with transactions in earlier blocks



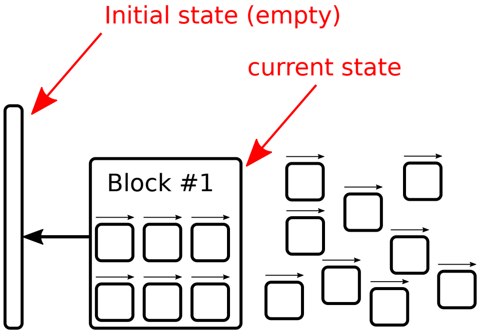

Here is what we do to establish a consensus: We group the transactions into blocks. Anyone can collect a bunch of transactions and turn them into a new block at any time. Whenever a new block is formed, it is then announced by it’s creator to the network which will relay the block to all participants.
The blocks depend one one-another. That is to say, every block has a reference to the block that came before it. That way, the blocks can be connected to a distinct chain of blocks.
All participants agree on a simple rule: The state is the longest chain of blocks. So to form the current state, one takes the initial state and then applies all transactions from block #1, then the transactions from block #2 and so on until all transactions from all blocks have been applied. The result is the current state of the system.
To make sure the resulting state is unambiguous, all blocks have to meet certain criteria.

- They may only contain valid transactions.
  - Transactions which transfer a negative amount of money for example are not allowed
- All the transactions have to be compatible with one another. So if someone attempts to spend the same money twice, only one of the two transactions may be part of the same chain

Blocks which do not meet these criteria are not valid blocks and are to be ignored by the participants of the system.

# Visualization of Blockchain concepts



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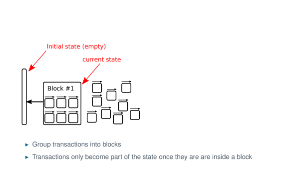
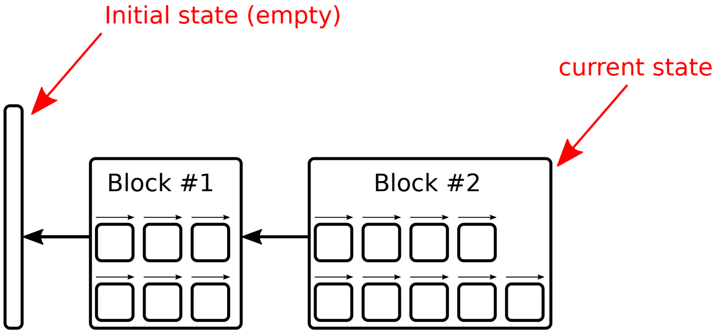



Transactions are grouped into Blocks. Only the transactions which included in a block are part of the state. Transactions that have arrived but not yet included in a block, should be ignored by the client software when calculating the current state.

# Visualization of Blockchain concepts




- Blocks depend on one-another
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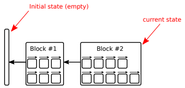
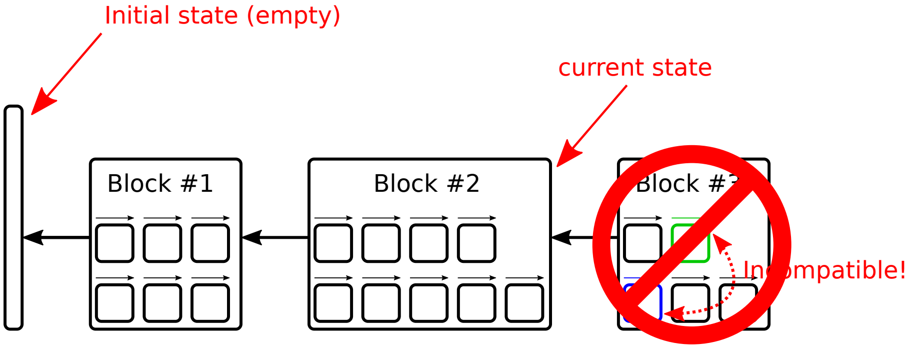



- Blocks depend on one-another
- Anyone can form a new block at any time

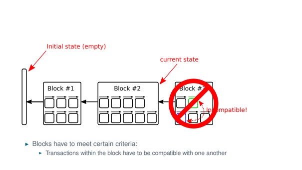
Each block has a reference to its previous block. That way the chain from the latest block to the initial state is unambiguous.

Blocks can be created by anyone at any time. This is important: We want a decentralized network where anyone can participate and noone is able to do censorship. This way a transaction that is ignored by one participant might be included in a new block by another.

# Visualization of Blockchain concepts




- Blocks have to meet certain criteria:
  - Transactions within the block have to be compatible with one another

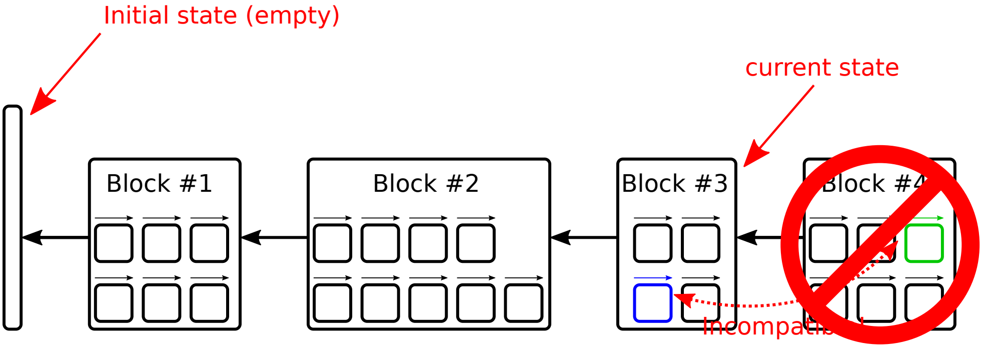



Blocks which do not meet the criteria listed above should be ignored by the participants of the network when calculating the current state.

In this example, the "Block #3" contains two transactions which are not compatible with one another. We do not allow for such blocks and thus this block is dubbed invalid and not part of the state.

# Visualization of Blockchain concepts



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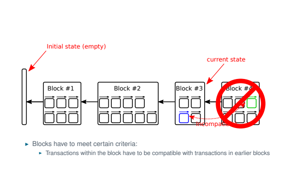
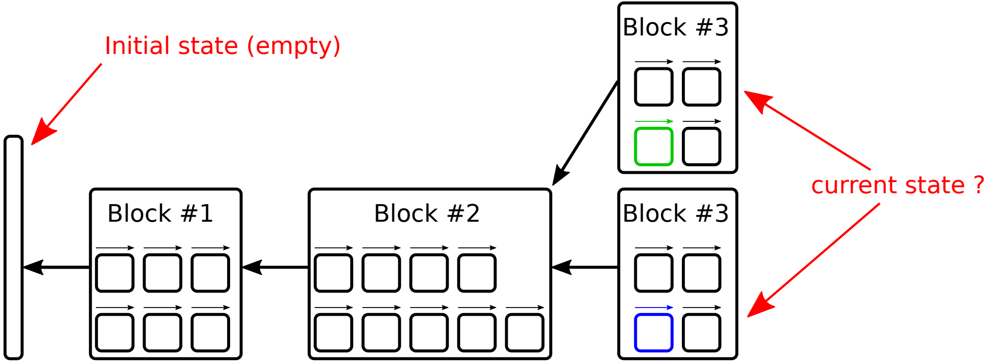


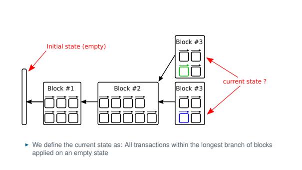

"Block #4" contains a transaction which is not compatible with another transaction which is part of "Block #3". We do not allow this since it would result in the state not being unambiguous. Since the block violates one of our rules, it is not a valid block and does not become part of the state.

# Visualization of Blockchain concepts





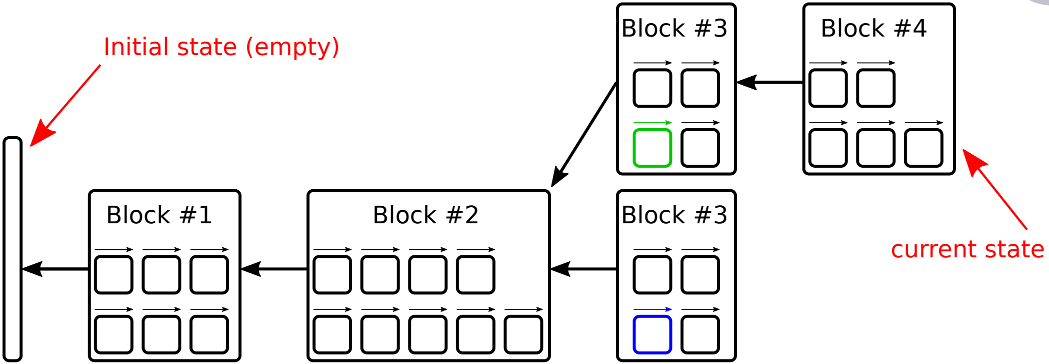

- We define the current state as: All transactions within the longest branch of blocks applied on an empty state




Both of the "Block #3" are valid. They also both form a chain of the same length. This means that the state of the network is no longer unambiguous. Every client might decide for themselves which of the two states they want to accept as the current state.

# Visualization of Blockchain concepts



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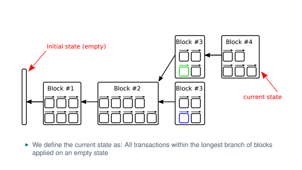



Someone has created a new "Block #4". Because the block has a pointer / reference to the block before it, it is obvious which "Block #3" the new block depends on. One of the two chains has thus become longer than the other and is now accpted by the network as the current state.

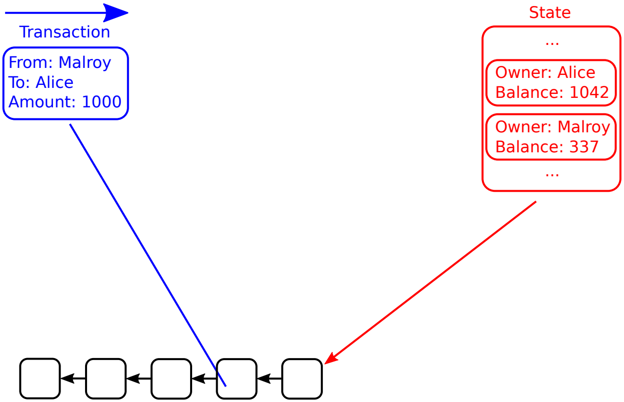
Which previous block the new one should depend on is left to the person who creates the new block. It is their sole decision.

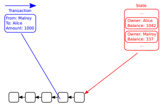
# Subsection

The double-spend attack covered in this chapter is the same one potentially used against real Blockchains. Here it can succeed because we don't use a Proof of Work (PoW). In the next chapter we will discuss how actual Blockchains use PoW to protect against that kind of attack.

# Double-spend on a Blockchain without POW





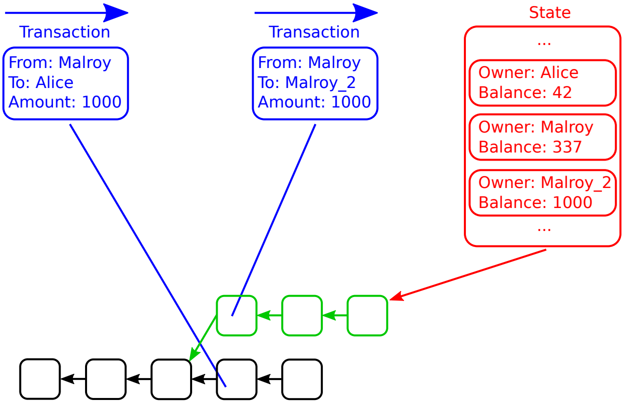


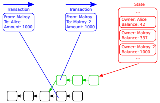

Alice has a shop which sells bicycles. In this example, Malroy will attempt to steal a bicycle. That is to say, he will get Alice to give him the bicycle, but he will keep the money he was supposed to pay for it.

So he goes to Alice and choses a bicycle. This certain bicycle has a price of 1000 Euro. He makes a transaction transferring the 1000 Euro to Alice. A short while later, someone will create a block including this transaction which results in the transationg becoming part of the state. This means that Alice has received the money. She now hands over the bicycle to Malroy who drives off with it. Further blocks are created over time.

# Double-spend on a Blockchain without POW








Malroy who has gotten the bicycle and left to go somewhere save, now starts the attack. He creates a new transaction which transfers the same money he previously sent to Alice to a second account of his instead. This transaction is of course incompatible with his first and won't become part of the chain if he just publishes it.
So Malroy creates a new, alternative block containing this second transaction. Then, he creates a bunch more blocks which all depend on the first one he created. He continues creating more blocks quickly until his chain is longer than the chain currently used on the network. Then he publishes the chain of blocks he has created to the network.

This chain created by Malroy is now the longest chain on the network and thus gets accepted as the state of the system. In this state, Malroy will owns all the money, now distributed over two accounts. The transaction transfering the money to Alice is not part of the state anymore.

# Problems



- Double-spend works
- It is easy and cheap to create blocks
  - Anyone can create any number of blocks at no cost

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  - Anyone can create any number of blocks at no cost

As demonstrated above, the Blockchain described in this chapter is insecure. It is vulnerable to double-spend attacks. This is because the Blockchain described here is incomplete. Let's see how to fix that in the next chapter.

# Section 3

## Blockchain

# Subsection

# The problem



- Problem: Creating blocks is easy
- Solution: Make creating blocks hard

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- Solution: Make creating blocks hard

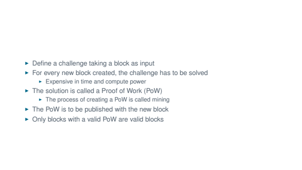
In the previous chapter, Malroy performed a double-spend attack. He did this by creating a large number of blocks quickly to form a branch of the Blockchain that was longer than any other.

The problem is, that it's easy and quick to create new blocks. The solution then is simple: Make creating new blocks hard and time consuming.

# PoW



- Define a challenge taking a block as input
- For every new block created, the challenge has to be solved
  - Expensive in time and compute power
- The solution is called a Proof of Work (PoW)
  - The process of creating a PoW is called mining
- The PoW is to be published with the new block
- Only blocks with a valid PoW are valid blocks

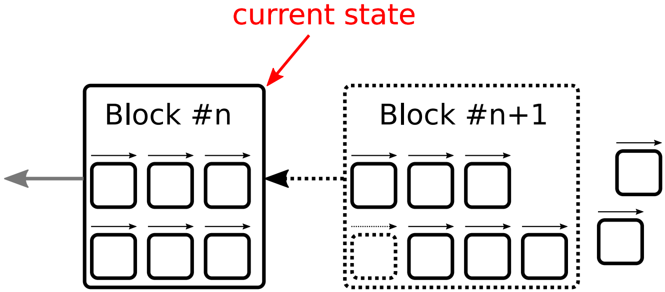



To make creating blocks hard, we define a challenge that has to be solved by anyone who wants to create a new block. The challenge is dependant on the block it is created for and is thus different for each block. The solution to the challenge has to be published together with the block and is called a "Proof of Work" or PoW for short, since it is proof that the person creating the block, called the miner, has performed the work necessary to find this solution.

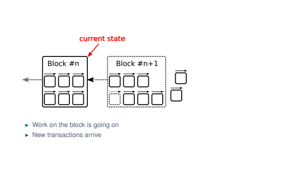
We change the rule for valid blocks so that blocks that do not have a PoW or which's PoW is not valid, are not valid blocks and are to be ignored by the clients on the network.

# Creating PoW protected blocks






- Work on the block is going on
- New transactions arrive




The process of creating blocks changes a bit with the introduction of PoW. They can no longer be created just like that. Miners, which are the people creating new blocks, are constantly working on the next block. In the figure above, the block that is currently being worked on by a miner, is marked by the dotted line. The transactions that will be part of that block are not yet part of the state.

During the time a new block is worked on, new transactions arrive at the miner's machines. The miner stores them in what is called the transaction pools. Transactions in the transaction pool are potential candiates for inclusion in the next block. Each time a new valid block is announced on the network, the miners immediately start work on the next block. Which transactions a miner wants to include in the block they create is their own decision.

# Requirements for PoW



The function / challenge used for the PoW has to meet certain requirements:

- Be hard! Solvable only by brute force
- Validation needs to be fast and easy
- Dependant on the exact block it is produced for
  - To prevent pre-compute attacks
- Variable difficulty

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- Variable difficulty

A client receiving a block and supposedly matching PoW needs to be able to verify the PoW quickly so it can decide whether that block is actually part of the state. So even though creating a PoW needs to be hard, checking it needs to be simple.
The challenge being dependant on the block, that is to say the collection of transactions, it was created for, is very important. If it was not, Malroy could pre-compute a large number of PoWs over a long time and later attach them to some independant blocks to quickly create a long chain of blocks. If however, the PoW is fully dependant on the block it is created for, work on the PoW can only begin once the exact content of the block is known. So in the best case, work on the PoW for a new block, can only start when the block before that is known.

If the system is used for financial transactions, the time it takes for new blocks to appear needs to be stable. For those making transactions, knowing how long it takes for those transactions to become validated is important. But if the network's total compute power increases, the time it takes until a miner successfully creates a new block becomes lower. This is why the difficulty of the problem to be solved should be variable, so it can be changed over time as the network's compute power changes.

# Reward



For mining to be worthwhile, a reward is needed:

- A transaction from nowhere to the miner
  - Transaction fees
  - Coinbase / new money
- Included in the block
- Makes blocks individual
  - Ensures distribution of success amongst all miners

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- Makes blocks individual
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Now that Mining is costly (taking time and using compute power), we need an incentive, otherwise no one is going to do it. The solution used in PoW based Blockchains is called a block-reward. It's a reward going to the person who creates the block.
The easy way to do this is to allow the miner to add a special transaction in the block they create. This transaction transfers money to the miner. It is called a Coinbase transaction. This money can come from various sources:

- The transaction fees of the transactions included in the block
- New money that is introduced into the system

The second option is interesting with the above example where we defined the initial state as an empty state where noone owned any money. This gives us a fair and independent means of bringing money into the initially empty system.
Of course, each miner will transfer the money in the Coinbase transaction to themselves. Because of that, each Coinbase transaction is different. That also means that the exact problem the miner is working on is individual to them, since it depends on the exact input which includes the Coinbase transaction. This ensures another important property:
Imagine if all miners were working on the same exact problem in the same manner. The first miner to find the solution would be the one with the most compute power. Always. That is bad since we want many people to create blocks to prevent censorship. By having all miners on slightly different problems, we give those who have less compute power a chance of finishing first by chance.

In practice, this ensures that the chance of finishing a block first, is roughly equal to the amount of compute power a miner has. That is to say, a miner with 20% of the network's power will generate about a fifth of all blocks.

# Mining I



- Which branch should a miner work on?
- For the reward to be spendable, it needs to be part of the state
- The state is the "longest" branch
- So it only makes sense to work on the "longest" branch
- Works without any coordination!

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- For the reward to be spendable, it needs to be part of the state
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- So it only makes sense to work on the "longest" branch
- Works without any coordination!

We have seen in some of the examples above, that there might be multiple competing branches in a Blockchain. So each miner needs to decide which of those branches they want to work on.
The revard a miner gets, as mentioned above, is a special transactions. If the miner wants to spend the money they get from this transaction, then it needs to be part of the state. It is only part of the sate, if the block it is included in is part of the state. For this reason, it's only interesting for miners to work on the longest branch. This makes sure, that all miners are working on the longest branch without any coordination being necessary.

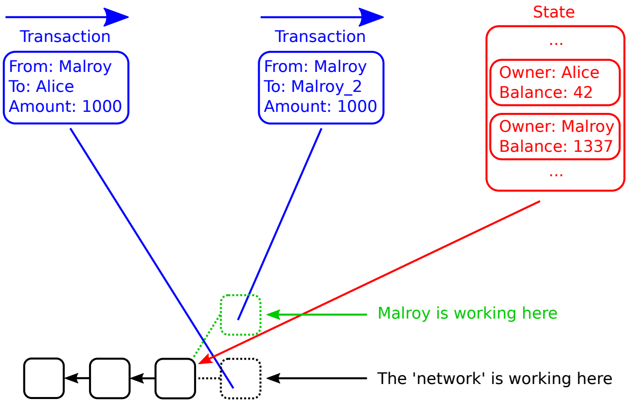
This is important to ensure that the power of the miners gets combined to produce a single branch at the fastest speed possible. Malroy will have to compete against all of them at once when trying to create a separate branch.

# Subsection

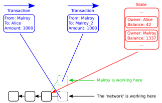
Let’s revisit the double-spend attack from earlier. The attack remains the same, except that we now have PoW enabled on our Blcokchain.

# Double-spend






- Work on the next block starts
- Malroy is the only one working on a different block



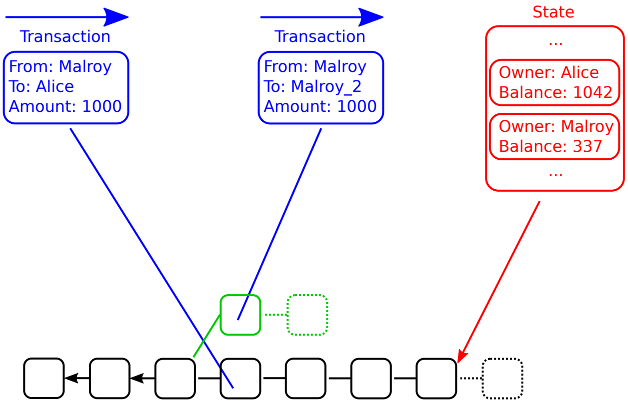

- Work on the next block starts
- Malroy is the only one working on a different block

Note how blocks don't just suddenly appear anymore. Instead the miners are constantly working on new blocks. This is represented by the dotted blocks. The situation is largely the same as it was for the same attack in the last chapter. Malroy starts work on his branch as soon as the previous block has been announced to the network. However, this time, Malroy can't easily create a longer branch. He needs to mine each block. This is a lot of work. Since Malroy's mining power is less than the combined power of all the other miners in the network, Malroy creates new blocks at a slower rate. Thus, his branch never becomes the longest one and never becomes the state of the system.

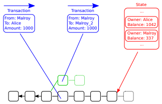
The attack has successfully been prevented!

# Double-spend






- Malroy's chain never becomes the longest

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# 50% attack



- Double-spend is possible
- >50% of network’s power is needed
- With that, Malroy could produce new blocks faster than the rest of the network

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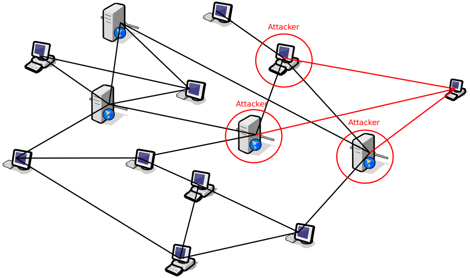
The only way the attack could succeed is if Malroy had more mining power than all the other miners combined. That is to say, Malroy would need more than 50% of the network's mining power. Thus the term 50% attack.

Malroy then would produce more blocks than all the other miners combined.

This would allow him to create his own branches of the chain which would grow faster than any other branch and become the accepted state of the network eventually.

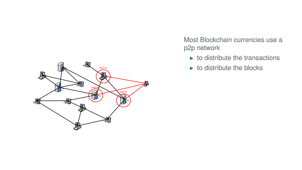
# p2p networking attack setup






Most Blockchain currencies use a p2p network

- to distribute the transactions
- to distribute the blocks




If Malroy controls Alice’s access to the p2p network used to distribute transactions (either by controlling her network connection or by controlling the peers she connects to) he would have a lot of power. He could:

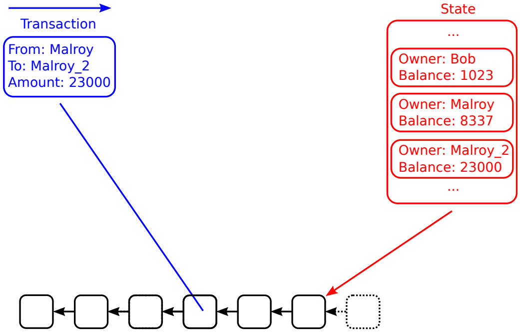
- Control Alice’s view of the network
- Present to her blocks and transactions he does not present to the rest of the network
- Hide from her blocks and transactions the rest of the network sees

This can be used to perform a slightly more complicated and sophisticated form of double-spend attack.

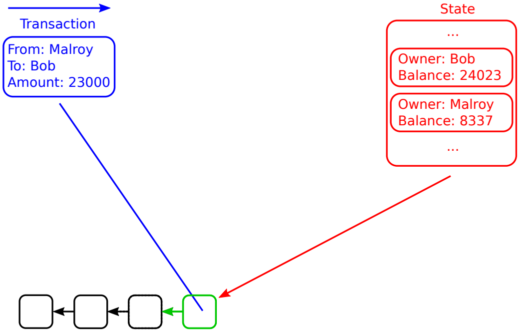
# Network attack



## Public network view:

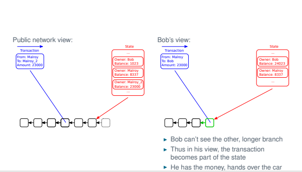



## Bob’s view:




- Bob can’t see the other, longer branch
- Thus in his view, the transaction becomes part of the state

He has the money, hands over the car



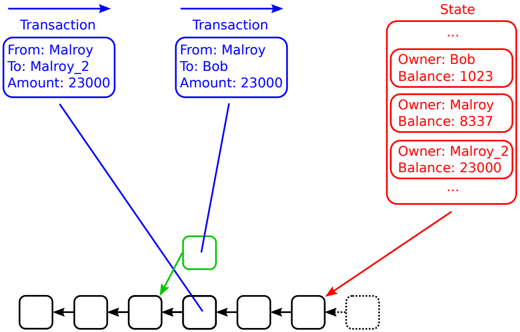

This attack is hard to perform, so Malroy will attempt to steal something more valuable this time. He will steal a car. For that, he goes to Bob who happens to be a car dealer. He will steal a 23000 Euro car.
Malroy control's all the nodes to which Bob is connected on the P2P network. When paying for the car, Malroy creates two different transactions which are not compatible with one-another. The first one is a transaction to Bob. Malroy sends this transaction to Bob only, the rest of the network does not see this transaction. The second transaction cretad by Malroy transfers the same money from his first to his second bank account. This transaction gets published to the network.
As soon as the previous block has been completed by the miners, work on the new block starts. The networ will now create a block which contains the transaction from Malroy to his second account. Malroy alone is working on alternative block which contains the transaction to Bob.

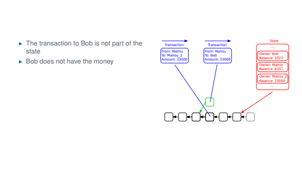
The netowrk as a whole has more compute power than Malroy on his own and thus procudes blocks at a faster pace. Malroy makes sure to block these new blocks so that Bob does not know about their existance. Eventually, Malroy succeeds in creating his block. He sends this blcok to Bob. Bob, who has not received any of the blocks recently created by the network, thinks that the block created by Malroy is in fact the longest branch. In Bob's opinion, the transaction transfering money from Malroy to Bob is now part of the state. He hands over the car to Malroy.

# Network attack



- The transaction to Bob is not part of the state
- Bob does not have the money

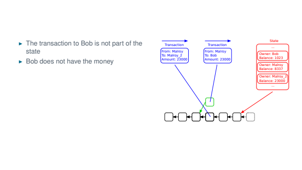





Malroy drives away. After a while he stops the attack. Bob gets unfiltered access to the network again. The two chains get merged. Bob's special chain is shorter than the actual network chain, which is why the transaction from Malroy to Bob is not part of the state.

So this kind of attack still works despite POW.

However, on the following slides, I will explain why such an attack is not worth the effort.




Short discussion: 10 minutes, the block time used by Bitcoin, is a long time. If you buy, say, an ice cream, you don't want to wait 10 minutes for your transaction to be processed. Because of this, some people will accept transactions as soon as they appear on the network - given of course, that the transaction is valid and not in conflict with any other transaction that is already part of the chain.

This will work fine in most cases, and if the ice cream seller gets tricked once or twice a week, he can probably still run his business. However, this practice is NOT SECURE AT ALL. Transactions should only be accepted as valid once they are included in a block.

This very network attack demonstrates why. If the car dealer were to accept transactions that are not yet in any block, all the attacker would have to do was to send a transaction to the car dealer. He would not have to put in the time to mine an extra block and thus the mechanisms described on the following slides would not work.

# What happened



- The attack still worked
- It's now costly though
- Malroy's computer can either:
  - Perform the attack
  - Mine on the network
- For the time of the attack, Malroy has to decide
- This makes using the computer for the attack expensive

Just how expensive exactly?

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- For the time of the attack, Malroy has to decide
- This makes using the computer for the attack expensive

Just how expensive exactly?

The attack of course uses compute power and electricity, both of which have a cost. This cost however, is not what actually makes the attack expensive. Much more expensive than computers or the electricity used, is the time wasted. While the computer is trying to create a fake block for Bob, it can't simultaneously mine on the actual chain. The block rewards Malroy could earn but doesn't due to using the compute power for the attack is what makes the attack so expensive.

# Cost of the attack

- Malroy's compute power: 20% $= \frac{1}{5}$ of the network
- Network average block time: 10min
- Block reward: 1000 Euro

Malroy needs to create one block:

## Time Malroy needs to to create one block

$$100\% Power \Leftrightarrow 10 min \implies 20\% Power \Leftrightarrow 50 min$$

What if Malroy was mining for the same 50 minutes instead?

## Reward in 50min mining

$$100\% Power \Leftrightarrow 5 Blocks \implies 20\% Power \Leftrightarrow 1 Block \implies 1000 Euro$$

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The values in the slide above are example values we are going to use for the calculations. If the produces 1 Block every 10 minutes, then it will take Malroy on his own 50 minutes to create a single block. That means that for 50 minutes, he can't mine on the actual chain.

During 50 minutes, the network produces 5 blocks, one of which, on average, would be produced by Malroy. So by performing the attack, he misses one block reward, worth 1000 Euro.

This does not depend on how much power the attacker has - an attacker with 30% of the network compute power takes less time to perform the attack, but he loses more block rewards per time.

# Protection from the attack



Malroy can chose:

- Do the attack
  - Steal a 23000 Euro car
- Not do the attack
  - Earn 1000 euro mining

## Attacker's power

The power of the attacker does not matter. An attacker with more power needs less time, but he looses more money per time.

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  - Steal a 23000 Euro car
- Not do the attack
  - Earn 1000 euro mining

**Attacker's power**

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In our example, performing the attack makes sense, since the car, at 23000 Euro is worth a lot more than the single block reward. So Bob needs to take additional measures to be secure.

# Waiting

By waiting another block, Bob makes the attack twice as expensive.
So the larger a transaction we protect, the longer we have to wait. You can easily calculate for how long you have to wait to be secure:

## How long to wait?

$$\lceil amount \div Blockreward \rceil + 1$$


To protect himself from an attacker, Bob doesn't hand over the car immediately. Instead, once the transaction has been included in a block, and thus become part of the state, Bob waits until some more blocks have been added to the same branch.

If Bob was under attack, the attacker would have to create those additional blocks as well. It would cost him even more time to do so. All this time the attacker spends on creating the additional blocks he can't spend mining. Thus it costs him money. The longer we wait, the more expensive an attack becomes.

Bob can easily calculate how long exactly he has to wait in order to be secure, based on how expensive the product is he is selling and how high the block reward is.

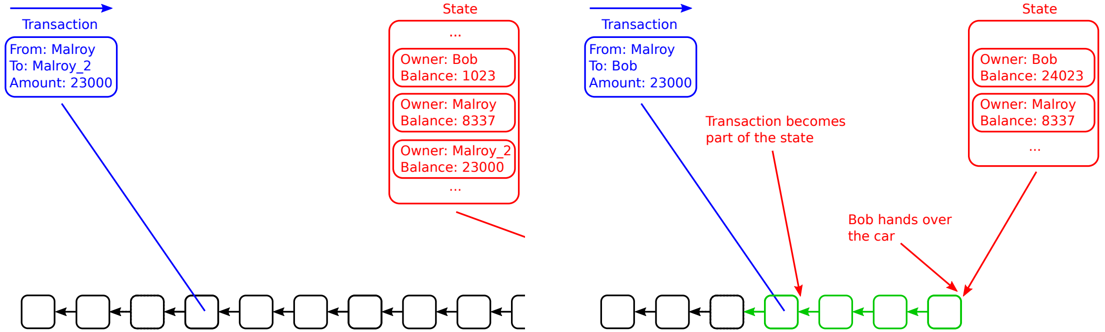
By doing so, Bob makes sure attacking him is never worthwhile. Noone will have an incentive to attack him since doing so makes no sense at all economically speaking.

# Bob's protection

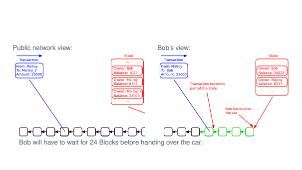


Public network view:

Bob's view:




Bob will have to wait for 24 Blocks before handing over the car.




At 1000 Euro per block, Bob should wait 23, probablly more like 24 blocks before handing the car to Malroy (or any other customer for that). The graphic above is not accurate, since I can’t fit that many blocks onto a single slide ;)

Section 4

# Bitcoin

Section 4

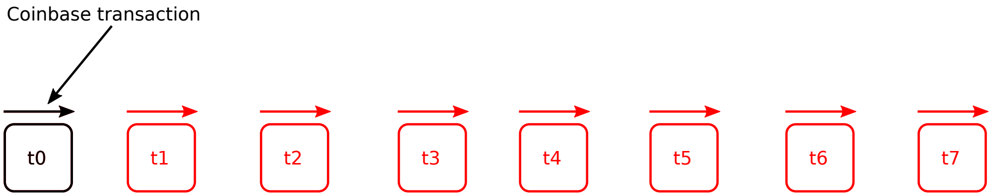
Bitcoin

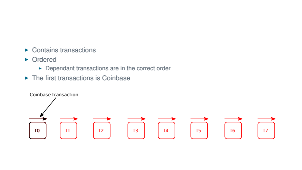
I talked a lot about generic Blockchain designs and concepts. To get a better idea of how these concepts are implemented, we will now take a look at the Bitcoin Blockchain.

# Subsection

# Body

- Contains transactions
- Ordered
  - Dependant transactions are in the correct order
- The first transactions is Coinbase






In IT, we like to separate matadata from data by putting the data in what we call a body and the metadat into a header. We do this for messages, network protocols and file formats. We also do it for Blockchains. In Bitcoin, a block's body is comprised of the blocks it contains. The header contains some metadata.

The transactions inside the block's body are ordered. They get ordered by the miner who creates the block. The miner has to follow few rules for that. If Message "b" depending on message "a" is in the same block as "a", then they have to be in the block in the correct order. Other than that, the miners is basically free to order the transactions whichever way he likes. But once the order has been decided on, it can't be changed anymore.

The leftmost transaction (the first transaction inside the block), is the Coinbase transaction.

# Merkle tree



Bitcoin uses a Merkle tree to secure the transactions. Root of the Merkle tree is part of the Block header.

- Binary tree
- A node is the hash of the two child nodes
- Bitcoin uses sha256 double hashes
  - aka. dhash, double-sha256
  - $sha256(sha256(...))$

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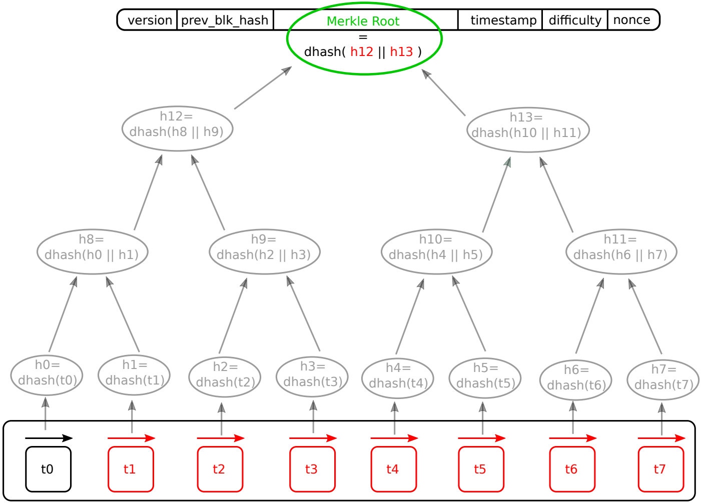
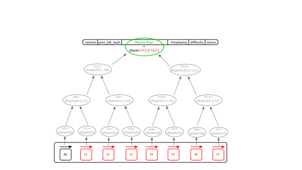
The Merkle tree, as used by Bitcoin, is a binary tree. Every node, except the leave nodes, is formed by creating the doublehash of the concatenation of the two child nodes.

# Merkle tree visualization







The Merkle Root is put into the Block header. The collection of transactions become the block body. The rest of the Merkle tree is then no longer needed. If someone validates the block, they retrieve both the header and the body, then create the Merkle tree from the body they retrieved and compare the Merkle root to the value from the block header. If the two values match, everything is in order

It is important that the order of blocks in the body is preserved, otherwise the result of forming the Merkle tree would be a different one.

All transactions are secure. If one would be changed or replaced, the hash of that transaction would change, which would be reflected in the node above, which in turn would change that node's parent and so on until finally, the Merkle root would be a different one.

# Header



| version | prev_blk_hash | mrkl_root | timestamp | difficulty | nonce |
|---|---|---|---|---|---|
| 32 Bit | 256 Bit | 256 Bit | 32 Bit | 32 Bit | 32 Bit |

**version** Block version. Currently at 4

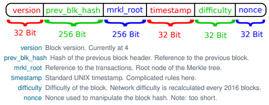
**prev_blk_hash** Hash of the previous block header. Reference to the previous block.

**mrkl_root** Reference to the transactions. Root node of the Merkle tree.

**timestamp** Standard UNIX timestamp. Complicated rules here.

**difficulty** Difficulty of the block. Network difficulty is recalculated every 2016 blocks.

**nonce** Nonce used to manipulate the block hash. Note: too short.




The image above shows the header of a Bitcoin Block.
The prev_blk_hash stands for Previous Block Hash and is just that - the hash of the previous block. In our generic Blockchain construct from the chapters before, we have seen that each block references it's previous block in order to form a chain - this is Bitcoin's way of doing that.
Rules for block Timestamp:
"A timestamp is accepted as valid if it is greater than the median timestamp of previous 11 blocks, and less than the network-adjusted time + 2 hours. 'Network-adjusted time' is the median of the timestamps returned by all nodes connected to you." - The Bitcoin Wiki: `https://en.bitcoin.it/w/index.php?title=Block_timestamp&oldid=51392`
The difficulty is an expression of how hard it was to create the PoW for this block.
The nonce is a field used for mining, see below.
2016 Blocks equals 14 days.

# Bitcoin mining



PoW:

- Bitcoin uses the Block Hash for PoW
  - $dhash(block\_header)$
- PoW: First $n$ Bits of the Block Hash need to be 0
- Mining by incrementing the `nonce` field
  - Too short (32bit nonce for 256bit Hash)
- Secondary nonce
  - tx input / input script of Coinbase transaction
  - Change in transaction changes Merkle root

Difficulty:

- Difficulty is adjusted every 2016 Blocks (14 days)
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Here is how mining in Bitcoin works: The Hash of the block header is used as a PoW. The difficulty in creating it is that the first *n* bits of the header need to be valud 0. A miner can only achieve this by modifying the header, hashing it and testing if the hash meets the criteria. If it does not, the miner has to modify the header again and repeat the process. The way the miner modifies the header, is by incrementing the `nonce` field.

The nonce field is only 32 Bit though and the Hash is 256 bit, so the nonce field might not always be enough to find a matching Hash,

depending on the difficulty target. So the miner modifies another value under their control - the Coinbase transaction. More precisely, the

field used to reference where the money is coming from is not used in the Coinbase transaction and can be filled with arbitrary data.

Modifying the Coinbase transaction changes its hash which eventually changes the Merkle root and thus the header.

# Coinbase: Creating money

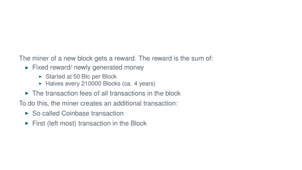


The miner of a new block gets a reward. The reward is the sum of:

- Fixed reward/ newly generated money
  - Started at 50 Btc per Block
  - Halves every 210000 Blocks (ca. 4 years)
- The transaction fees of all transactions in the block

To do this, the miner creates an additional transaction:

- So called Coinbase transaction
- First (left most) transaction in the Block




Adjusting the difficulty target works like this:
Every Bitcoin client compares the actual time it took to generate these blocks with the two week goal and modifies the target by the percentage difference. Each node calculates the network difficulty independently from all other nodes. It is then, important that they all get the same result and thus that they all use the same algorithm.

# Subsection

# Types of Bitcoin clients



- Full node
  - Stores the entire Blockchain
  - Seeds the Blockchain to the network
  - Validates every block
  - Validates every transaction
- Pruning client
  - Validates all blocks
  - Validates all transactions
  - Only stores parts of the Blockchain
  - See the bonus slides
- Light client / SPV client
  - See below

- Full node
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  - Only stores parts of the Blockchain
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- Light client / SPV client
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To my knowledge, there are three types of Bitcoin clients:
Full clients store the entire blockchain and seed the blocks into the network. They validate each transaction and each block.
Pruning clients also check all transactions and all blocks but they don't store the entire blockchain. Instead, they get rid of blocks they no longer need to save storage.
Light clients finally only validate single transactions. They use little bandwidth and storage and are suitable for mobile clients.

# Chain of Block headers



- Download just the headers
- PoW can be checked from just the header
- Previous block can be checked from just the header
- Creating a header is as hard as creating a block!

Advantage:

- 450000 blocks
- Blockchain: >95 GB (>100GB with indexing)
- Block headers: <100 MB

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- Block headers: <100 MB

The first thing a light Client needs to validate a transaction is the list of all block headers. Each block header references the previous' block header by it's hash, thus the correct order of blocks can be determined from the headers alone. The PoW too can be checked from the header alone, since it's the header's hash. Creating a header is as hard as creating an entire block, so re-creating the chain like this is as secure as donloading the entire Blockchain, but much faster.

At the time of writing, there are almost 450000 blocks in the Blockchain which is in total about 95 GB in size. A list of all Block headers can be stored in well under 100 MB.

# Merkle branch

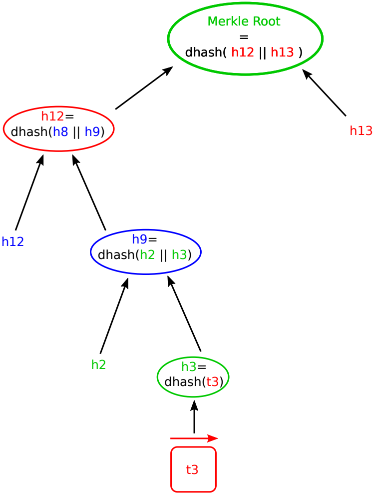


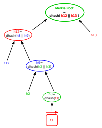
- We have the Merkle root
  - We can get it securely from the Block header
- We do not have the elements it consists of
- We are interested in a single element
  - A single transaction

The Merkle tree allows us to secure all the transactions. Even more interesting though is another feature - the Merkle branch. The Merkle branch allows for a single branch to be extracted and then stored in a space efficient yet safe way. Despite that, it still proves that a transaction is part of a block.

# Merkle branch visualization








For the Merkle branch, instead of downloading all transactions, we only need the one transaction and then one hash from each level of the tree.

In the above example, we can prove that transaction `t3` is part of the block by downloading the transaction itself among with the hashes `h2`, `h12` and `h13`.

From these four values, we can form the Merkle branch and get the Merkle root.

# Merkle branch advantages



Download a Merkle branch instead of all transactions:

- Less elements
- Smaller (hashes instead of transactions)
- The advantages get larger the bigger the tree

Example: Block with 1600 transactions:

- 1600 transactions
- 1 transaction + 11 hashes

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The Merkle branch will, especially for very large blocks, be smaller than the entire body.
Only the specific transaction plus $log_2$(number of transactions in the block) hashes need to be downloaded to form and verify the Merkle branch for a transaction.
Downloading and verifying the Merkle branch is just as secure as downloading the entire Block body.

# SPV



- Simple Payment Verification
- Proof that a transaction is part of the chain
- Avoid downloading the entire chain

1. Retrieve all block headers
2. Rebuild longest branch
3. Retrieve a transaction
4. Retrieve the Merkle branch for the transaction
5. Match the Merkle branch to the chain of block headers

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5. Match the Merkle branch to the chain of block headers

Now we have everything needed to create a light client. This specific type of client is called an SPV client. SPV stands for Simple Payment Verification and was described in Satoshi's Bitcoin Whitepaper.
An SPV client downloads the block headers and forms the Blockchain from them. Then it receives a specific transaction. It requests the Merkle branch for this specific transaction. The Merkle branch connects the transaction to the block headers and thus proves that this transaction is actually part of the Blockchain.

This way, an SPV client can securely receive transactions.

## Questions?

Ask them now or contact me:

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### email

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### XMPP

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# Section 5

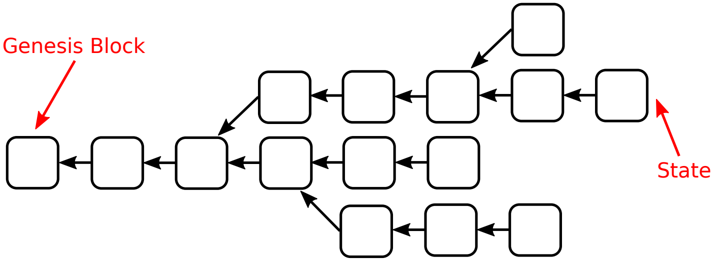
## Bonus Slides

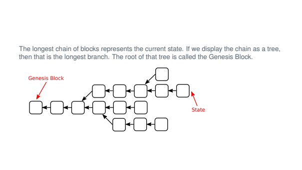
# Subsection

# Status switch between branches



The longest chain of blocks represents the current state. If we display the chain as a tree, then that is the longest branch. The root of that tree is called the Genesis Block.





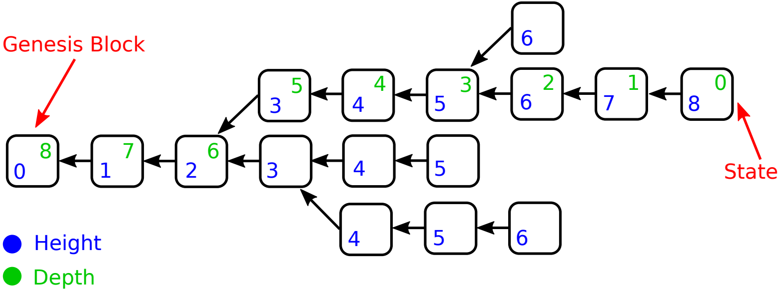

If suddenly, another branch were to become longer, then that branch would then be the state of the system.

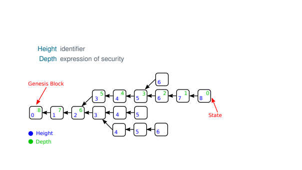
# Block height and depth



**Height** identifier

**Depth** expression of security






Even though we don’t use numbers of blocks anymore to determine their dependencies, numbering them can still be useful. It allows for easy referencing of specific blocks. There are two important ways of doing this:

**Height** The block height expresses the block’s distance from the Genesis Block. The height of a block is always the same and does not change when new blocks are added to the system. Every block in the system has a height.

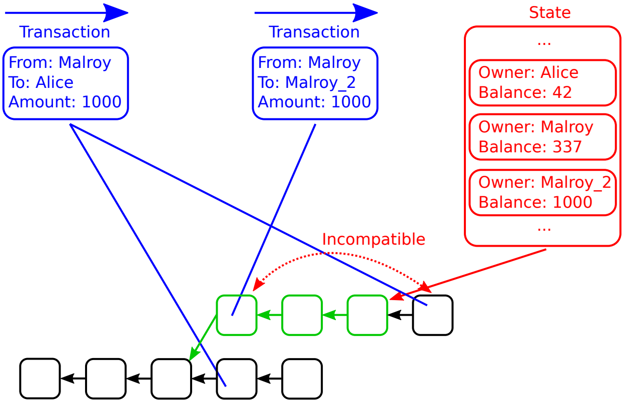
**Depth** The depth of a block expresses the block’s distance from the end of the branch. When a new block is appended to the branch, the depth of every block in the branch is increased by one. The depth is usually only expressed for blocks of the longest branch.

Later on when we introduce POW, the depth will become an important expression of security.

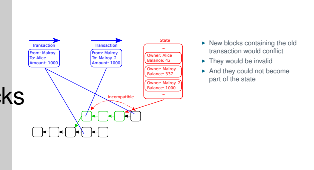
# Subsection

# Conflicting transaction in double-spend attacks






- New blocks containing the old transaction would conflict
- They would be invalid
- And they could not become part of the state

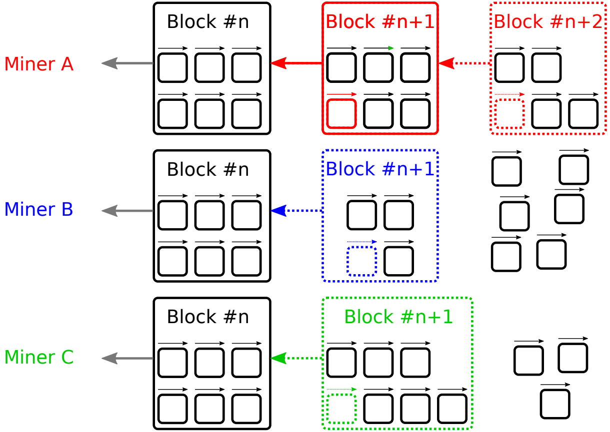



By creating a new transaction (the one transfering the money onto the vimja2 account) that is conflicting with the earlier transaction (the one transfering the money to the car dealer) and putting the new one into my chain/branch, I prevent the first transaction from ever becoming part of the same branch again. A block containing one of them will be in conflict with block containing the other, thus they can't become part of the same branch.

# Subsection

# Example scenario with multiple miners

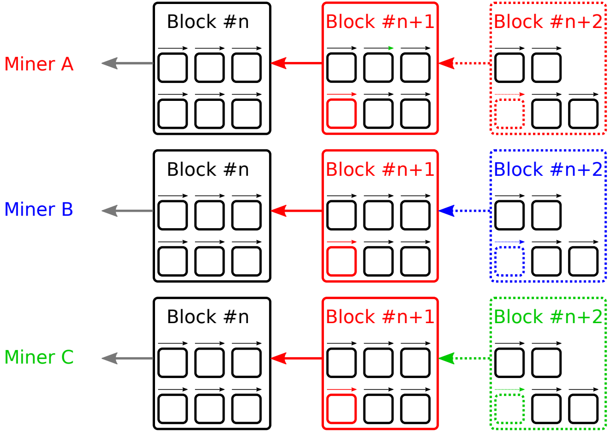





- Miner A finishes Bock #n+1
- Miner A immediately starts work on #n+2
- Miner A broadcasts Block #n+1
- Miners B and C both receive the completed Block #n+1 from miner A
- They change their transaction pools accordingly

# Example scenario with multiple miners






- Miners B and C immediately start work on Block #n+2

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