Fundamentals of Blockchain

Introductory Lecture Series

Rhys Bidder
rhys.m.bidder@kcl.ac.uk

KBS, QCGBF

September 2023

Disclaimer: Any opinions expressed, errors or omissions should be regarded as those of the author and not necessarily those of KCL, KBS, QCGBF, QCB or BoE.

Outline

Cryptoasset transactions are illegal in many jurisdictions. Do not violate these or any other laws. I am not promoting the use of crypto in countries where it is illegal in any form and these slides are not a promotion of crypto or an invitation to participate in crypto-related activities in such countries. They are purely for educational purposes.

Introduction to blockchain

Introduction to blockchain

- **Q:** What is a ledger?

Introduction to blockchain

- **Q:** What is a ledger?
  - A database recording current ‘account’ balances and the history of transactions between ‘accounts’
  - E.g. 1: Set of accounts handwritten in a physical book
  - E.g. 2: Set of accounts entered in an Excel spreadsheet

Introduction to blockchain

- People often use the terms ‘distributed ledger technology’ and ‘blockchain’ interchangeably
- But blockchain is only a *particular type* of DLT
- Not all examples of DLT are blockchains (see here or here)
- One can create a **distributed ledger** by putting an excel spreadsheet in a shared passwordless Google drive
  - See discussion in Voshmgir - Token Economy, 2nd ed.
- Shared ledger that anyone can inspect, store and change
- **DLT, but not a blockchain**

Introduction to blockchain

$$\begin{aligned} \textit{Blockchain} &\Rightarrow \textit{DLT} \\ \textit{DLT} &\nRightarrow \textit{Blockchain} \end{aligned}$$

Introduction to blockchain

We will be discussing blockchains

Introduction to blockchain

- Imagine we want to store pieces of data - or *'transactions'* - that arrive as time passes
  - For now, we will not specify the precise form of a transaction
- A **block** is made up of...
  - A header
  - Transactions data
  - Perhaps other objects, depending on the blockchain protocol
- Header contains several components - the most vital being:
  - Hash of the previous block (the genesis block has no previous block in which case hash is set trivially to zero)
  - Merkle root of tree of hashed transactions

Introduction to blockchain

Q: Why is the hash of the previous block so vital?

Introduction to blockchain

Q: Why is the hash of the previous block so vital?

- Because it links the block to the previous block
- Iterate on this logic: **this is what yields a blockchain**
- All blocks are linked together *via* repeated pairwise inclusion of the previous block's hash in the current block's header

Introduction to blockchain

Q: Why is the hash of the previous block so vital?

- Because it links the block to the previous block
- Iterate on this logic: **this is what yields a blockchain**
- All blocks are linked together *via* repeated pairwise inclusion of the previous block's hash in the current block's header

Q: Why is the Merkle root of transactions so vital?

Introduction to blockchain

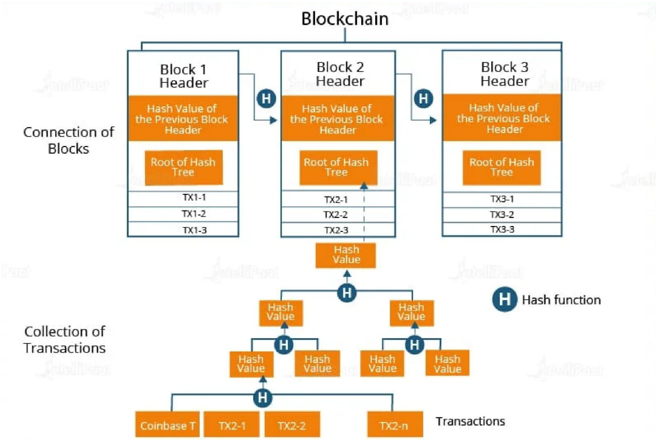
Q: Why is the hash of the previous block so vital?

- Because it links the block to the previous block
- Iterate on this logic: **this is what yields a blockchain**
- All blocks are linked together *via* repeated pairwise inclusion of the previous block's hash in the current block's header

Q: Why is the Merkle root of transactions so vital?

- Because it allows rapid comparison of transactions data

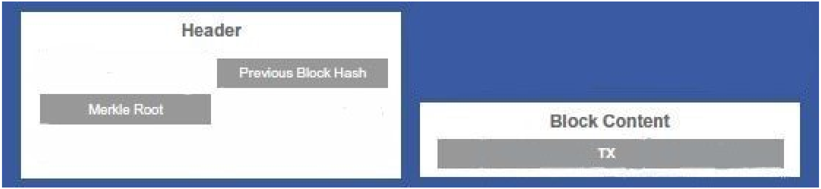
Introduction to blockchain



Source: IntelliPaat

Blocks

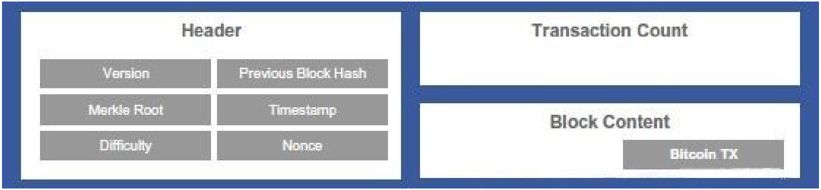
Consider a (simplified) block structure:



Source: Hellwig *et al* - *Build Your Own Blockchain* (amended)

Blocks

Block structure in the **Bitcoin** blockchain...



Source: Hellwig *et al* - *Build Your Own Blockchain*

- We will discuss 'difficulty' and the 'nonce' shortly
- Permitted 'size' of the transactions set varies across protocols

Blocks

Let us consider an actual Bitcoin block:

- **Note:** the TX list here is actually the list of transaction IDs (TXIDs) - hashes of the transactions data


```
{
  "hash": "0000000000000001b6b9a13b095e96db41c4a928b97ef2d944a9b31b2cc7bdc4",
  "confirmations": 37371,
  "size": 218629,
  "height": 277316,
  "version": 2,
  "merkleroot":
"c91c008c26e50763e9f548bb8b2fc323735f73577effbc55502c51eb4cc7cf2e",
  "tx": [
    "d5ada064c6417ca25c4308bd158c34b77e1c0eca2a73cda16c737e7424afba2f",
    "b268b45c59b39d759614757718b9918caf0ba9d97c56f3b91956ff877c503fbe",
    "04905ff987ddd4cfe603b03cfb7ca50ee81d89d1f8f5f265c38f763eea4a21fd",
    "32467aab5d04f51940075055c2f20bbd1195727c961431bf0aff8443f9710f81",
    "561c5216944e21fa29dd12aaa1a45e3397f9c0d888359cb05e1f79fe73da37bd",
[... hundreds of transactions ...]
    "78b300b2a1d2d9449b58db7bc71c3884d6e0579617e0da4991b9734cef7ab23a",
    "6c87130ec283ab4c2c493b190c20de4b28ff3caf72d16ffa1ce3e96f2069aca9",
    "6f423dbc3636ef193fd8898dfdf7621dcade1bbe509e963ffbff91f696d81a62",
    "802ba8b2adabc5796a9471f25b02ae6aeee2439c679a5c33c4bbcee97e081196",
    "eaaf6a048588d9ad4d1c092539bd571dd8af30635c152a3b0e8b611e67d1a1af",
    "e67abc6bd5e2cac169821afc51b207127f42b92a841e976f9b752157879ba8bd",
    "d38985a6a1bfd35037cb7776b2dc86797abbb7a06630f5d03df2785d50d5a2ac",
    "45ea0a3f6016d2bb90ab92c34a7aac9767671a8a84b9bcce6c019e60197c134b",
    "c098445d748ced5f178ef2ff96f2758cbec9eb32cb0fc65db313bcac1d3bc98f"
  ],
  "time": 1388185914,
  "mediantime": 1388183675,
  "nonce": 924591752,
  "bits": "1903a30c",
  "difficulty": 1180923195.258026,
  "chainwork":
"000000000000000000000000000000000000000000000934695e92aaf53afa1a",
  "previousblockhash":
"0000000000000002a7bbd25a417c0374cc55261021e8a9ca74442b01284f0569",
  "nextblockhash":
"000000000000000010236c269dd6ed714dd5db39d36b33959079d78dfd431ba7"
}
```


Output from bitcoin-cli getblock. Source: Antonopoulos - *Mastering Bitcoin*

Blocks

Let us consider an actual Bitcoin block:

- **Note:** the TX list here is actually the list of transaction IDs (TXIDs) - hashes of the transactions data


```
{
  [redacted]
  "confirmations": 37371,
  "size": 218629,
  "height": 277316,
  "version": 2,
  "merkleroot":
"c91c008c26e50763e9f548bb8b2fc323735f73577effbc55502c51eb4cc7cf2e",
  "tx": [
    "d5ada064c6417ca25c4308bd158c34b77e1c0eca2a73cda16c737e7424afba2f",
    "b268b45c59b39d759614757718b9918caf0ba9d97c56f3b91956ff877c503fbe",
    "04905ff987ddd4cfe603b03cfb7ca50ee81d89d1f8f5f265c38f763eea4a21fd",
    "32467aab5d04f51940075055c2f20bbd1195727c961431bf0aff8443f9710f81",
    "561c5216944e21fa29dd12aaa1a45e3397f9c0d888359cb05e1f79fe73da37bd",
[... hundreds of transactions ...]
    "78b300b2a1d2d9449b58db7bc71c3884d6e0579617e0da4991b9734cef7ab23a",
    "6c87130ec283ab4c2c493b190c20de4b28ff3caf72d16ffa1ce3e96f2069aca9",
    "6f423dbc3636ef193fd8898dfdf7621dcade1bbe509e963ffbff91f696d81a62",
    "802ba8b2adabc5796a9471f25b02ae6aeee2439c679a5c33c4bbcee97e081196",
    "eaaf6a048588d9ad4d1c092539bd571dd8af30635c152a3b0e8b611e67d1a1af",
    "e67abc6bd5e2cac169821afc51b207127f42b92a841e976f9b752157879ba8bd",
    "d38985a6a1bfd35037cb7776b2dc86797abbb7a06630f5d03df2785d50d5a2ac",
    "45ea0a3f6016d2bb90ab92c34a7aac9767671a8a84b9bcce6c019e60197c134b",
    "c098445d748ced5f178ef2ff96f2758cbec9eb32cb0fc65db313bcac1d3bc98f"
  ],
  "time": 1388185914,
  "mediantime": 1388183675,
  "nonce": 924591752,
  "bits": "1903a30c",
  "difficulty": 1180923195.258026,
  "chainwork":
"000000000000000000000000000000000000000000000934695e92aaf53afa1a",
  "previousblockhash":
"0000000000000002a7bbd25a417c0374cc55261021e8a9ca74442b01284f0569",
  "nextblockhash":
"000000000000000010236c269dd6ed714dd5db39d36b33959079d78dfd431ba7"
}
```


Output from bitcoin-cli getblock. Source: Antonopoulos - *Mastering Bitcoin*

Strictly, *current block's* hash is not part of this block

Blocks

Let us consider an actual Bitcoin block:

- **Note:** the TX list here is actually the list of transaction IDs (TXIDs) - hashes of the transactions data


```
{
  "hash": "0000000000000001b6b9a13b095e96db41c4a928b97ef2d944a9b31b2cc7bdc4",


  "height": 277316,
  "version": 2,
  "merkleroot":
"c91c008c26e50763e9f548bb8b2fc323735f73577effbc55502c51eb4cc7cf2e",
  "tx": [
    "d5ada064c6417ca25c4308bd158c34b77e1c0eca2a73cda16c737e7424afba2f",
    "b268b45c59b39d759614757718b9918caf0ba9d97c56f3b91956ff877c503fbe",
    "04905ff987ddd4cfe603b03cfb7ca50ee81d89d1f8f5f265c38f763eea4a21fd",
    "32467aab5d04f51940075055c2f20bbd1195727c961431bf0aff8443f9710f81",
    "561c5216944e21fa29dd12aaa1a45e3397f9c0d888359cb05e1f79fe73da37bd",
[... hundreds of transactions ...]
    "78b300b2a1d2d9449b58db7bc71c3884d6e0579617e0da4991b9734cef7ab23a",
    "6c87130ec283ab4c2c493b190c20de4b28ff3caf72d16ffa1ce3e96f2069aca9",
    "6f423dbc3636ef193fd8898dfdf7621dcade1bbe509e963ffbff91f696d81a62",
    "802ba8b2adabc5796a9471f25b02ae6aeee2439c679a5c33c4bbcee97e081196",
    "eaaf6a048588d9ad4d1c092539bd571dd8af30635c152a3b0e8b611e67d1a1af",
    "e67abc6bd5e2cac169821afc51b207127f42b92a841e976f9b752157879ba8bd",
    "d38985a6a1bfd35037cb7776b2dc86797abbb7a06630f5d03df2785d50d5a2ac",
    "45ea0a3f6016d2bb90ab92c34a7aac9767671a8a84b9bcce6c019e60197c134b",
    "c098445d748ced5f178ef2ff96f2758cbec9eb32cb0fc65db313bcac1d3bc98f"
  ],
  "time": 1388185914,

  "nonce": 924591752,

  "difficulty": 1180923195.258026,


  "previousblockhash":
"0000000000000002a7bbd25a417c0374cc55261021e8a9ca74442b01284f0569"


}
```


Output from bitcoin-cli getblock. Source: Antonopoulos - *Mastering Bitcoin*

Blocks

- Block is at 'block height' 277316 with hash...
  0000000000000001b6b9a13b095e96db41c4a928b97ef2d944a9b31b2cc7bdc4
- Blocks are being stacked 'on top' of eachother (another way of looking at the chain)

Blocks

- Block is at 'block height' 277316 with hash...
  0000000000000001b6b9a13b095e96db41c4a928b97ef2d944a9b31b2cc7bdc4
- Blocks are being stacked 'on top' of eachother (another way of looking at the chain)
- **Remember for later:** Note the run of zeros at the start of the hash

Blocks


```
{
  "hash": "000000000000001b6b9a13b095e96db41c4a928b97ef2d944a9b31b2cc7bdc4",

  "height": 277316,
  "version": 2,
  "merkleroot":
"c91c008c26e50763e9f548bb8b2fc323735f73577effbc55502c51eb4cc7cf2e",
  "tx": [
    "d5ada064c6417ca25c4308bd158c34b77e1c0eca2a73cda16c737e7424afba2f",
    "b268b45c59b39d759614757718b9918caf0ba9d97c56f3b91956ff877c503fbe",
    "04905ff987ddd4cfe603b03cfb7ca50ee81d89d1f8f5f265c38f763eea4a21fd",
    "32467aab5d04f51940075055c2f20bbd1195727c961431bf0aff8443f9710f81",
    "561c5216944e21fa29dd12aaa1a45e3397f9c0d888359cb05e1f79fe73da37bd",
[... hundreds of transactions ...]
    "78b300b2a1d2d9449b58db7bc71c3884d6e0579617e0da4991b9734cef7ab23a",
    "6c87130ec283ab4c2c493b190c20de4b28ff3caf72d16ffa1ce3e96f2069aca9",
    "6f423dbc3636ef193fd8898dfdf7621dcade1bbe509e963ffbff91f696d81a62",
    "802ba8b2adabc5796a9471f25b02ae6aeee2439c679a5c33c4bbcee97e081196",
    "eaaf6a048588d9ad4d1c092539bd571dd8af30635c152a3b0e8b611e67d1a1af",
    "e67abc6bd5e2cac169821afc51b207127f42b92a841e976f9b752157879ba8bd",
    "d38985a6a1bfd35037cb7776b2dc86797abbb7a06630f5d03df2785d50d5a2ac",
    "45ea0a3f6016d2bb90ab92c34a7aac9767671a8a84b9bcce6c019e60197c134b",
    "c098445d748ced5f178ef2ff96f2758cbec9eb32cb0fc65db313bcac1d3bc98f"
  ],
  "time": 1388185914,

  "nonce": 924591752,

  "difficulty": 1180923195.258026,


  "previousblockhash":
"000000000000002a7bbd25a417c0374cc55261021e8a9ca74442b01284f0569"


}
```


Output from bitcoin-cli getblock. Source: Antonopoulos - *Mastering Bitcoin*

▸ Mining

Blocks

Let's find that transaction in the Bitcoin ledger!

- Many ways to do this - e.g. programmatically, using command line and API
- Here we will use Blockchain.com's explorer
- The block is found here
- The first entry in the transaction list is found here and the second is found here
- **Q:** Look at the urls of these links - what are they?

Blocks

Let's find that transaction in the Bitcoin ledger!

- Many ways to do this - e.g. programmatically, using command line and API
- Here we will use Blockchain.com's explorer
- The block is found here
- The first entry in the transaction list is found here and the second is found here
- **Q:** Look at the urls of these links - what are they?
  - For block, the height is used, and for transactions, the TXID

Blocks

Pause. Breathe. Take a step back.

Blocks

Pause. Breathe. Take a step back.

Our discussion $\Rightarrow$ 'just' a database with particular structure:

- Data arrives
- It gets bundled up in a block that points to the previous block
- Repeat (over and over)

What is in the data might be very simple. . .

- In simplest Bitcoin case, just value transfers

. . . or it may be more complex

- In Ethereum, the transactions may encode *elaborate* smart contracts and other data (in fact, the Bitcoin transactions involve simple smart contracts too. . .)

Blocks

Pause. Breathe. Take a step back.

Our discussion $\Rightarrow$ 'just' a database with particular structure:

- Data arrives
- It gets bundled up in a block that points to the previous block
- Repeat (over and over)

What is in the data might be very simple...

- In simplest Bitcoin case, just value transfers

...or it may be more complex

- In Ethereum, the transactions may encode *elaborate* smart contracts and other data (in fact, the Bitcoin transactions involve simple smart contracts too...)

But it's still just bits of data

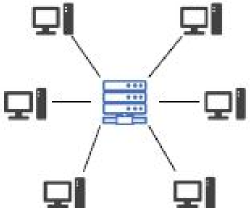
Network structure

- We have discussed data being bundled into blocks, and added to the blockchain
- But how? Who does it? Who stores the ledger?
- I could make a blockchain on my computer just for me
  - That would be pretty stupid (and sad/lonely)
- Blockchain comes into its own in a particular **network** context

Network structure

- Many systems we are familiar with operate under a **centralized** network structure
- Ledger stored on a ‘server’ run by a centralized authority
- Other nodes - using ‘client’ software - access ledger only through the server
- Changes to ledger only possible by interfacing with, and with the approval of, the server
- Central authority *could* unilaterally change data, reform system, or limit user access

Network structure



Server model. Source: Hellwig *et al* - *Build Your Own Blockchain* (amended)

Network structure

Another centralized system central bankers will be familiar with...

- Settling transactions between commercial banks' reserve accounts, *via* the central bank's balance sheet
- Very common for transactions between financial institutions (typically banks) to settle in this way
- CB maintains a single copy of the ledger, reflecting past transactions and current account balances (see here for further discussion)

Network structure

Consider another framework, with less centralization:

- Network participants interact through ‘transactions’ but. . .
- Suppose:
  - each participant maintains own ledger of *their* transactions
  - messages with transaction details are sent bilaterally by phone, email, or some system *separate from the ledgers*
  - each participant updates their ledger by converting the message data into their own *idiosyncratic* format
  - conversion possibly subject to error, using techniques/software unknown to other participants
- In many (even advanced) countries, this is how much financial trading occurs

Network structure

- It is only after **checking and reconciliation** occurs that trades (implied by the 'messages') are actually **settled**
  - **T + K delays:** T is transaction day, K might be as long as 3
  - Many markets now achieve $T + 2$
  - Some examples (not Blockchain-based) of $T + 0$ but *rare*
  - These processes are expensive (direct and time costs)

- Settlement may fail or be delayed due to disagreements
  - Adds to the K of $T + K$
  - Expensive reversion of trades/litigation

Trades and ledger(s) of settled transactions are distinct

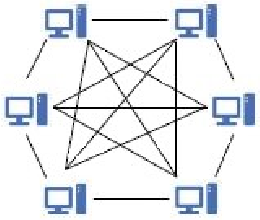
Various ad hoc coordination systems required to agree on accepted common truth

Network structure

A peer to peer network differs from a client-server model in that:

- **Client-Server:** Clients request data and services from server
- **P2P:** *All* nodes can request data **and** provide services

Network structure



P2P model. Source: Hellwig *et al* - *Build Your Own Blockchain* (amended)

Network structure

In the extreme case, a fully decentralized p2p network:

> *consist(s) of individual nodes, which make their computational resources directly available to all other members of the network without having any central point of coordination. The nodes in the network are equal concerning their rights and roles in the system. Furthermore, all of them are both suppliers and consumers of resources.*

In the context of blockchain this means that *any* node has the same rights and responsibilities in administering, accessing, storing, and updating the ledger

- This is the Bitcoin/Ethereum setup

Network structure

Blockchains differ in their precise network structure

- Roles and capabilities of different nodes
- Extent of decentralization (we will return to this topic)

Important distinction: Is the blockchain **'public'** or **'private'**?

- Often referred to as **'permissionless'** or **'permissioned'**

Network structure

Public/permissionless blockchain:

- **Open participation**
  - Anyone with relevant hardware + client software can join
  - No credentials required
  - Pseudonymous (and in some cases anonymous)
- Explicitly **decentralized** across (often enormous) number of participants
  - No central authority
  - Though some centralization may be latent/unintentional
- Designed to operate in **'trustless'** contexts
  - Mechanism design/incentives ensure robustness to (some) nefarious behavior
  - **Arguably the most spectacular achievement of blockchain (starting with Bitcoin)**

Network structure

Private/permissioned blockchain:

- **Limits participation**
  - Typically through some sort of certificate authority
  - Significant credentialing requirement (AML/KYC)
- More likely to entail (explicit) **centralization** (e.g CA, monitoring/regulator nodes, validating/notary nodes, block-building nodes)
  - There may even be a 'natural' central authority
  - Nevertheless, still significant decentralization in most cases
- Significant **'trust'** often can be assumed among participants
  - Perhaps familiarity through business network / activities
  - Threat of reputation loss/punishment (CA $\Rightarrow$ identifiable)
- Several companies / consortia now help set these up
  - Hyperledger (Fabric)
  - R3 (Corda)

Addresses, wallets, keys. . .

Recall our earlier discussions of asymmetric key cryptography

- Let us assume we have (carefully) obtained a private key (a *very* large random integer) and its public counterpart

Blockchain addresses are derived from the public key

- Basically involves a load of hashing of the public key

$\Rightarrow$ Results in a shorter and more easily usable representation

Addresses, wallets, keys...

Knowing the private key $\Leftrightarrow$ ownership of cryptoassets associated with public address

- **The private key should be kept safe and never revealed**
- Loosely: 'Not your keys, not your coins'

Transactions will be sent to (public) addresses

- Only the person with the private key can use assets associated with that address
- **Why?** They have the private key to sign (and thus authorize) any transactions

Addresses, wallets, keys...

A wallet stores private keys

- Typically also provides other functionality, such as signing transactions, analytics, a nice user interface etc.
- It may hold many private keys and help administer many associated addresses

In some blockchains (e.g. Bitcoin) there isn't a native concept of an 'account' distinct from an address

- Some wallets may allow an account abstraction by collecting information on transactions to and from addresses associated with a given user
- **Note:** A user can (and typically will) have several (or even a vast number of) addresses

Addresses, wallets, keys. . .

Many crypto wallets are now available (see here)

- Wallets offer security-convenience tradeoffs
  - Cold wallets: Disconnected from the internet (keys stored offline - inconvenient but relatively secure)
  - Hot wallets: Connected to the internet (keys stored online - convenient but relatively vulnerable to theft/hacks)

- In the UK, I legally use (without endorsement!)

Cold Ledger Nano X
Hot Metamask (app and browser extension)
Hot Wallet (app from Coinbase)

Terminology warning: Many people (including me) will often talk about *'sending BTC to an address, or wallet'* but transactions simply transfer **ownership claims** among addresses and only **keys** are stored in a wallet (not BTC).

Addresses, wallets, keys. . .

I hold (very) limited amounts of cryptoassets for research and education purposes

- **For me** there is limited downside to losing my crypto, so (while being careful) I don't adopt a super secure approach
- If I were to get nervous or hold significant amounts, I would use my Nano X much more and generally take greater care!

Transactions

So far, we have discussed:

- **Addresses**, between which transactions are sent and the cryptographic techniques underpinning them
- How **private key** knowledge allows the use (and effectively defines ownership) of cryptoassets, by signing transactions with **digital signatures**
- How **blocks** bundle up transactions and are **linked together into a chain**

But what are transactions?

Transactions

Taking a technical (rather than legal) perspective, a 'transaction' is a *signed message*

- Messages are constantly being sent and received among the nodes in the P2P network
- Client software used by nodes execute certain actions on the basis of the messages and their current view of the chain
- These actions update the 'state' of a blockchain when they are included in blocks (if they are ever included) and consensus is achieved

The format of the message, the actions they induce, and the nature of the 'state' will (obviously) depend on the specific protocol

Concept of ‘state’

Digression on concept of a ‘state’ and its ‘evolution’

- Most economists encounter the concept of the ‘state’ in first year PhD macro or econometrics!
- Our models talk about how an economy evolves from time t to time $t+1$
- By iterating on this logic, we can talk about how the economy evolves over many periods
- We talk about how the world ‘is’ today, how it ‘will be’ tomorrow, and how it gets there

Concept of 'state'

How can we describe how the world 'is' today?

- Do we need to list 'everything'?
- No - we can describe a smaller set of variables *from which everything else that 'is' can be derived?*
- **That set of variables is the state**

Tell me the state today and I can tell you 'everything' about today

- Similarly, tell me what the state will be tomorrow and I can tell you 'everything' about tomorrow

The state (and knowledge of the model) tells me 'everything I need to know'

The model tells how the state evolves (or transitions) from the value it holds today, to the value it holds tomorrow

Concept of 'state'

There may be various ways of choosing state variables, or representing it

- Maybe there is some reason to represent it differently
- Possibly for clarity, computational load, compatibility. . .

Examples

Concept of ‘state’

For a blockchain, **transactions are what evolve the state**

- They are the only source of randomness
- Blockchain nodes running clients will come to the same answer if they execute with the same knowledge of the state
- The blockchain protocols and the actions of nodes collectively constitute a ‘replicated deterministic state machine’

Concept of ‘state’

Essentially **a blockchain and its protocols define a type of computer** that continually calculates updates to the state and records the state’s evolution (see here)

- This interpretation is *heavily* emphasized in Ethereum
- In Bitcoin, ‘transactions’ have a similar meaning to our daily use of the word
- In Ethereum (and other blockchains) a ‘transaction’ means something far more general

This is why so many people think blockchain is such a transformative computing technology for decentralized and trustless environments

Concept of ‘state’

Digression over!

- Let’s get back to discussing what a transaction is in practice

Bitcoin transactions

Bitcoin adopts the Unspent Transaction Output (UTXO) model

- UTXOs are unspent chunks of value, denominated in bitcoin, leftover from transactions, which can then be used in later transactions.
- **Note:** Other important blockchains use UTXO, including some private chains (e.g Corda)

Very readable discussions can be found here and here

- The intuition of UTXOs is *a bit like* using different coins/notes in our pockets to execute transactions
- Those coins/notes were 'unspent outputs' from previous transactions and we combine them to make future transactions
- **Warning:** The parallels are not complete between UTXOs and coins/notes

Bitcoin transactions

The state in Bitcoin is represented by many chains of transactions, each traceable back to a 'coinbase transaction(s)'

- As we will discuss later, bitcoin is created through **'mining'**
- New bitcoin emerges from rewards paid to 'miners' in the **coinbase transaction** (the 'money supply' in Bitcoin)
- **Chains arise from outputs (UTXOs) from earlier transactions being used up as inputs to new transactions**

Terminology warning: These chains are distinct from the overall *block*chain

- They capture the conceptual book-keeping of *payments*
- The blockchain and its protocols provide the technology implementing and recording this

Bitcoin transactions

- Every transaction must spend **all** of each UTXO associated with a transaction
  - The UTXOs from sending address(es) become **inputs**
  - Once they are 'consumed', they no longer exist
- Every transaction must have at least one output
  - **Outputs** are new UTXOs associated with receiving address(es)
- Reiterate: **All** of a UTXO used as an input must be spent
  - We need to allow for **'change'** when paying someone else
  - Typically a transaction *also* sends residual to *sender's* address!
  - So, unlike change in the real world, this isn't *'given back'*

Bitcoin transactions

- A typical (non-coinbase) Bitcoin transaction is a message containing various 'fields' of information
- We will highlight the most important (see here and here for richer detail)
  - Transaction ID (TXID)
  - SignatureScript
  - Input information
  - Output information

Bitcoin transactions

- Transaction ID (TXID)
  - Hash of all of the other information in the transaction
- SignatureScript
  - Reflects the signing of the transaction by authorized parties
  - **Relies on careful protection of private keys**
  - In simplest case, only sender signs, but additional signers can be used for extra security

Bitcoin transactions

Input information

- TXIDs of previous transactions whose UTXOs are being used as inputs for payment in *this* transaction
- The indices of the UTXOs in the previous transactions
  - **Q:** Why do we need 'OutIndices'?
  - A transaction may have many UTXOs as outputs
- PubKeyScript
  - Checks if signatures match authorizers' public keys
- Total input value (in BTC)
  - Adds up value of all UTXOs being sent

Each transaction is linked to a previous transaction(s)

⇒ **Chains of TXID-OutIndices**

Bitcoin transactions

Output information

- Total output value (in BTC)
  - This must be $\leq$ total input value
  - Residual is optional, but advisable, TX fee payment to miner
  - Fee used to incentivise inclusion in a block

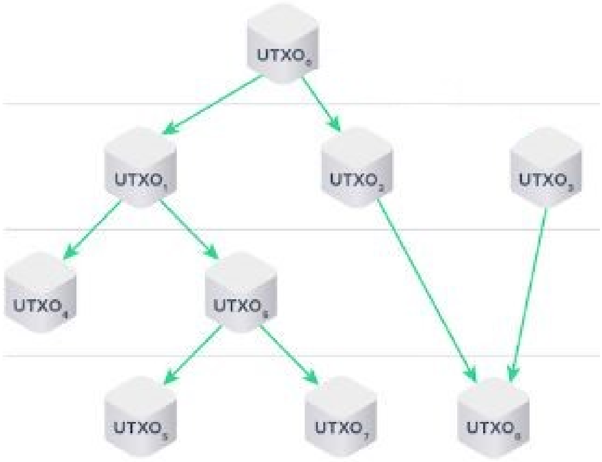
- Output addresses, values and indices
  - To whom the outputs are sent (can be one or multiple)
  - How much in BTC in each UTXO
  - Indices referencing particular UTXOs (previously mentioned in inputs discussion)

- PubKeyScript
  - Specifies **requirements** for UTXOs to be spent (when used as inputs in future transaction)
  - **Note:** Distinct from the PubKeyScript mentioned in the *inputs*

Bitcoin transactions

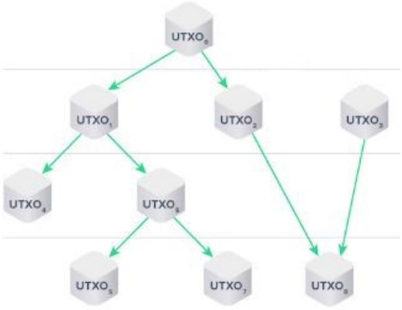
- Each transaction is linked to a previous transaction(s)
  - By iterating on that link, the transaction is connected to all transactions back to the coinbase transaction(s)...
  - ...**and** to any transactions that succeed it, using inputs derived from the outputs of this transaction
- So transactions are chained via the creation/use of UTXOs
  - In particular, *via TXID-OutIndices* pairs
- As we will discuss later this has implications for privacy
  - Esp. when combined with tools to de-pseudonymize addresses

Bitcoin transactions



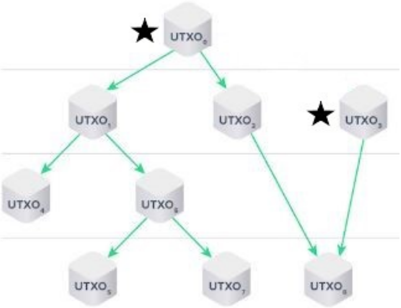
Connecting UTXOs - Directed Acyclic Graph (DAG). Source: Horizen Academy

Bitcoin transactions



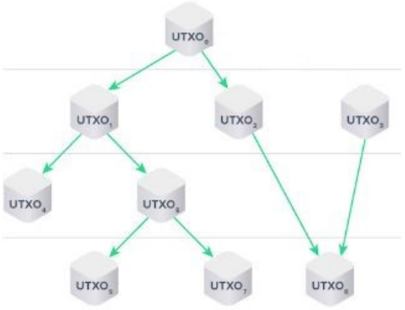
- Each transaction represented by arrows coming out of a node

Bitcoin transactions



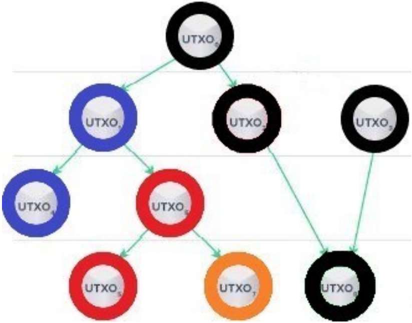
- Two UTXOs assumed to arise from mining

Bitcoin transactions



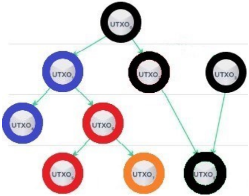
- UTXOs destroyed and created in every transaction

Bitcoin transactions



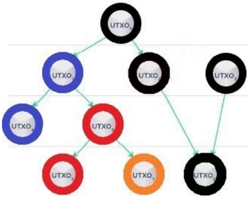
- Let each color correspond to an address

Bitcoin transactions



- **Black** address transacts with blue
  - Sends some of its UTXO balance to them
  - Sends 'change' to itself
- Blue transacts with red
  - Uses UTXO from **black** as input
  - But not all of it - so sends some 'change' to itself
- Red transacts with orange
  - Uses UTXO from blue as input
  - But not all of it - so sends some 'change' to itself

Bitcoin transactions



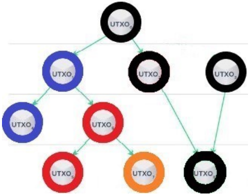
Consider the right hand side - why is the miner using two UTXOs to send a single UTXO to herself?

- Common practice called ‘consolidation’
- Using multiple small UTXOs for a large payment makes transaction computationally expensive for miners

⇒ Less likely transaction will be added to block quickly

Note that transactions to ‘yourself’ and the use of multiple addresses makes it very hard to assess (naively) the true amount of activity in such blockchains

Bitcoin transactions



Note: More than one color may correspond to a user

- For example, several of these addresses might be the miner's
- Blue could be an address stored in a cold wallet
- Red might be a transactional address managed by a hot wallet

Bitcoin transactions

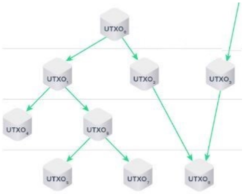
How does (this part) of the blockchain state evolve in our example

- I say 'this part' because there will be many such DAGs recorded in the blockchain - and they generally will interact
- Indeed, I *could* have drawn an arrow coming from off-screen
  - **Q:** What would that represent?

Bitcoin transactions

How does (this part) of the blockchain state evolve in our example

- I say 'this part' because there will be many such DAGs recorded in the blockchain - and they generally will interact
- Indeed, I *could* have drawn an arrow coming from off-screen
  - **Q:** What would that represent?
  - **A:** Transaction using as input a UTXO from a DAG emerging from a *different* coinbase transaction

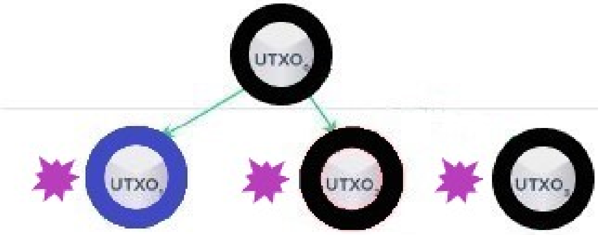


But for the next few slides, set that aside and assume our original DAG is the full set of UTXOs. . .

Bitcoin transactions

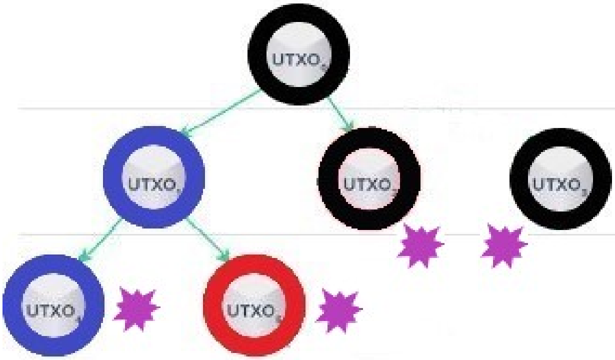
Evolution of state (purple splodge). Source: Horizen Academy

Bitcoin transactions



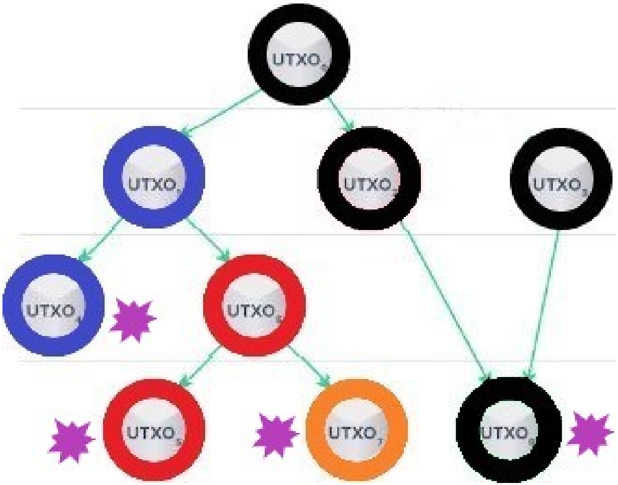
Evolution of state (purple splodge). Source: Horizen Academy

Bitcoin transactions



Evolution of state (purple splodge). Source: Horizen Academy

Bitcoin transactions



Evolution of state (purple splodge). Source: Horizen Academy

Bitcoin transactions

The purple splodges were highlighting the currently unspent outputs (the **UTXOs**) and the **addresses** that have ownership of them

- These are the state of the Bitcoin system
- Nevertheless, the blockchain records the entire history of transactions, implicit in the entire history of blocks

Bitcoin transactions

The resources an *address* can draw upon comprise the aggregation of all the unspent outputs sent to that address

- The resources that a *user* can draw on is an aggregation over the resources of her addresses
- Let's proceed by assuming each user has just one address

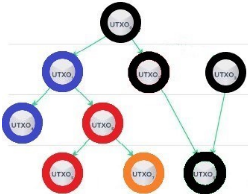
Why not represent state as the aggregation - an **account** balance?

- Why track a load of transaction chains when all I care about is whether someone has enough resources to pay?
- Ethereum adopts the account representation

Both representations can work (pros and cons)

- See here and Ch. 5-6 of Lipton and Treccani's *Blockchain and Distributed Ledgers*

Bitcoin transactions



Evolution of state. Source: Horizen Academy

Suppose we want to think of this not in UTXO, but more intuitively in terms of what the different addresses are sending/receiving:

- **Q:** What would that look like?
- **Q:** How are their BTC balances evolving?

Bitcoin transactions

Period	Transfers	# Transactions	Balances				Total BTC
			Bk	B	R	O	
1	(Coinbase; {Bk100})	1	100	0	0	0	
2	(Bk; {B70, Bk30}), (Coinbase; {Bk100})	2					
3	(B; {R5, B65})	1					
4	(R; {O4, R1}),(Bk30,Bk100; {Bk130})	2					

Assume:

- Addresses receiving coinbase previously controlled no UTXO
- Other addresses also initially controlled no UTXO
- No other TX associated with these addresses in the blockchain
- We are also ignoring (optional but advisable) transaction fees

Note: Numbers are arbitrary/illustrative

Bitcoin transactions

Period	Transfers	# Transactions	Balances				Total BTC
			Bk	B	R	O	
1	(Coinbase; {Bk100})	1	100	0	0	0	
2	(Bk; {B70, Bk30}), (Coinbase; {Bk100})	2	130	?	?	0	
3	(B; {R5, B65})	1	130	65	?	0	
4	(R; {O4, R1}),(Bk30,Bk100; {Bk130})	2	130	?	1	4	

Assume:

- Addresses receiving coinbase previously controlled no UTXO
- Other addresses also initially controlled no UTXO
- No other TX associated with these addresses in the blockchain
- We are also ignoring (optional but advisable) transaction fees

Note: Numbers are arbitrary/illustrative

Bitcoin transactions

Period	Transfers	# Transactions	Balances				Total BTC
			Bk	B	R	O	
1	(Coinbase; {Bk100})	1	100	0	0	0	100
2	(Bk; {B70, Bk30}), (Coinbase; {Bk100})	2	130	70	0	0	200
3	(B; {R5, B65})	1	130	65	5	0	200
4	(R; {O4, R1}),(Bk30,Bk100; {Bk130})	2	130	65	1	4	200

Assume:

- Addresses receiving coinbase previously controlled no UTXO
- Other addresses also initially controlled no UTXO
- No other TX associated with these addresses in the blockchain
- We are also ignoring (optional but advisable) transaction fees

Note: Numbers are arbitrary/illustrative

Bitcoin transactions

Period	Transfers	# Transactions	Balances				Total BTC
			Bk	B	R	O	
1	(Coinbase; {Bk100})	1	100	0	0	0	100
2	(Bk; {B70, Bk30}), (Coinbase; {Bk100})	2	130	70	0	0	200
3	(B; {R5, B65})	1	130	65	5	0	200
4	(R; {O4, R1}),(Bk30,Bk100; {Bk130})	2	130	65	1	4	200

Comments:

- **Note:** Total 'money supply' only $\Uparrow$ with coinbase tx
  - Other transactions simply divide up value
- Had we allowed for payment of transaction fees (to miner) we would have had to adjust the numbers
- Second coinbase *could* have been for mining block containing transaction implementing (Bk; {B70, Bk30})

Ethereum transactions

Note: Calling this subsection 'Ethereum transactions' is a bit of a trick because it will contain...

- Discussion of Ethereum's background
- Accounts, Ether, gas and smart contracts

Ethereum transactions

There are many topics we discussed above in the context of Bitcoin that will apply to Ethereum also - so I will try and focus on the particularities of Ethereum

- We have already (in the example of the account balance view of transactions) begun to transition towards Ethereum
- Many of the cryptographic tools are - allowing for implementation differences - very similar
- The abstract concept of a blockchain is also, essentially shared (though see later for discussion of *consensus*)

Ethereum transactions

Ethereum is in many respects an attempt to extend the functionality of Bitcoin

- While it offers a crytocurrency (Ether or ETH), its functionality is designed to be far broader than simply payments
- ETH is used to allow more elaborate computation to be done by the Ethereum system - it is a *utility currency*
- Far more general and powerful smart contracts than is possible in Bitcoin

Ethereum transactions

Far more general and powerful **smart contracts** than is possible in Bitcoin

- **What?** Where were the smart contracts in Bitcoin?
- Remember the PubKeyScript?

Bitcoin has a smart contract programming language: Script

- Script is not 'Turing complete'
- Inherent theoretical limitations to what it can compute

Ethereum transactions

I was going to write a high-level summary of Ethereum but I can't do any better than the following three paragraphs written in the excellent book - Mastering Ethereum - by one of its founders, Gavin Wood (though the person most people associate with it is its other founder, Vitalik Buterin)...

Ethereum transactions

From a computer science perspective, Ethereum is a deterministic but practically unbounded state machine, consisting of a globally accessible singleton state and a virtual machine that applies changes to that state.

From a more practical perspective, Ethereum is an open source, globally decentralized computing infrastructure that executes programs called smart contracts. It uses a blockchain to synchronize and store the system's state changes, along with a crypto currency called ether to meter and constrain execution resource costs.

The Ethereum platform enables developers to build powerful decentralized applications with built-in economic functions. While providing high availability, auditability, transparency, and neutrality, it also reduces or eliminates censorship and reduces certain counterparty risks.

Ethereum transactions

From a computer science perspective, Ethereum is a **deterministic but practically unbounded state machine**, *consisting of a* **globally accessible** *singleton state and a virtual machine that applies changes to that state.*

From a more practical perspective, Ethereum is an **open source, globally decentralized computing infrastructure that executes programs called smart contracts**. *It uses a blockchain to synchronize and store the system's state changes, along with* **a crypto currency called Ether to meter and constrain execution resource costs**.

The Ethereum platform **enables developers to build powerful decentralized applications** *with built-in economic functions. While providing high availability, auditability, transparency, and neutrality, it also reduces or eliminates censorship and reduces certain counterparty risks.*

Ethereum transactions

- Note that the 'computer' he refers to is often termed the 'Ethereum Virtual Machine' or (EVM)

Ethereum transactions

- Note that the ‘computer’ he refers to is often termed the ‘Ethereum Virtual Machine’ or (EVM)
- The EVM acts on ‘bytecode’: a bunch of instructions for the computer that are hard for me and you to understand

Ethereum transactions

- Note that the 'computer' he refers to is often termed the 'Ethereum Virtual Machine' or (EVM)
- The EVM acts on 'bytecode': a bunch of instructions for the computer that are hard for me and you to understand
  - Bytecode is obtained by 'compiling' 'sourcecode' that you or I could write and understand - with some practice. . . ☺
  - We could write the smart contract sourcecode in a few languages, but the dominant one is Solidity
  - Building on smart contracts and adding an interface, one can create 'dApps'

Ethereum transactions

- Note that the ‘computer’ he refers to is often termed the ‘Ethereum Virtual Machine’ or (EVM)
- The EVM acts on ‘bytecode’: a bunch of instructions for the computer that are hard for me and you to understand
  - Bytecode is obtained by ‘compiling’ ‘sourcecode’ that you or I could write and understand - with some practice. . . ☺
  - We could write the smart contract sourcecode in a few languages, but the dominant one is Solidity
  - Building on smart contracts and adding an interface, one can create ‘dApps’
- Transactions (sending ETH and data) instigate evolution of the system’s state

Ethereum transactions

- Note that the 'computer' he refers to is often termed the 'Ethereum Virtual Machine' or (EVM)
- The EVM acts on 'bytecode': a bunch of instructions for the computer that are hard for me and you to understand
  - Bytecode is obtained by 'compiling' 'sourcecode' that you or I could write and understand - with some practice... ☺
  - We could write the smart contract sourcecode in a few languages, but the dominant one is Solidity
  - Building on smart contracts and adding an interface, one can create 'dApps'
- Transactions (sending ETH and data) instigate evolution of the system's state
- Participants in the Ethereum blockchain network must run client software - one implementation of which is geth
- Like Bitcoin, Ethereum is a public/permissionless blockchain

Ethereum transactions

```
PUSH1 0x60 PUSH1 0x40 MSTORE CALLVALUE ISZERO PUSH2 0xF JUMPI PUSH1 0x0 DUP1
REVERT JUMPDEST PUSH1 0xE5 DUP1 PUSH2 0x1D PUSH1 0x0 CODECOPY PUSH1 0x0 RETURN
STOP PUSH1 0x60 PUSH1 0x40 MSTORE PUSH1 0x4 CALLDATASIZE LT PUSH1 0x3F JUMPI
PUSH1 0x0 CALLDATALOAD PUSH29
0x100000000000000000000000000000000000000000000000000000000
SWAP1 DIV PUSH4 0xFFFFFFFF AND DUP1 PUSH4 0x2E1A7D4D EQ PUSH1 0x41 JUMPI
JUMPDEST STOP JUMPDEST CALLVALUE ISZERO PUSH1 0x4B JUMPI PUSH1 0x0 DUP1 REVERT
JUMPDEST PUSH1 0x5F PUSH1 0x4 DUP1 DUP1 CALLDATALOAD SWAP1 PUSH1 0x20 ADD SWAP1
SWAP2 SWAP1 POP POP PUSH1 0x61 JUMP JUMPDEST STOP JUMPDEST PUSH8
0x16345785D8A0000 DUP2 GT ISZERO ISZERO ISZERO PUSH1 0x77 JUMPI PUSH1 0x0 DUP1
REVERT JUMPDEST CALLER PUSH20 0xFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF AND
PUSH2 0x8FC DUP3 SWAP1 DUP2 ISZERO MUL SWAP1 PUSH1 0x40 MLOAD PUSH1 0x0 PUSH1
0x40 MLOAD DUP1 DUP4 SUB DUP2 DUP6 DUP9 DUP9 CALL SWAP4 POP POP POP POP ISZERO
ISZERO PUSH1 0xB6 JUMPI PUSH1 0x0 DUP1 REVERT JUMPDEST POP JUMP STOP LOG1 PUSH6
0x627A7A723058 KECCAK256 PUSH9 0x13D1EA839A4438EF75 GASLIMIT CALLVALUE LOG4 0x5f
PUSH24 0x7541F409787592C988A079407FB28B4AD000290000000000
```

Bytecode for simple ‘faucet’ example. Source: Mastering Ethereum

Ethereum transactions

```
// Our first contract is a faucet!
contract Faucet {

    // Give out ether to anyone who asks
    function withdraw(uint withdraw_amount) public {

        // Limit withdrawal amount
        require(withdraw_amount <= 100000000000000000);

         // Send the amount to the address that requested it
         msg.sender.transfer(withdraw_amount);
     }

     // Accept any incoming amount
     function () public payable {}

}
```

Solidity source code for simple ‘faucet’ example. Source: Mastering Ethereum

Ethereum transactions

Native currency of the Ethereum system is Ether (ETH)

- There are various sub-denominations
- For example: $1ETH = 1 \times 10^{18} wei$

To execute any transaction the sender must pay 'gas'

- The cost of a unit of gas is denominated in ETH
- How much gas is required depends on complexity of computation implied by the transaction
  - If triggers a complicated smart contract, then 'more' gas
  - If simply sending ETH from A to B then 'less' gas

One of the common criticisms of Ethereum is that gas prices are volatile and prohibitively high

Ethereum transactions

Why have gas?

- Gas fees go towards incentivizing network participants (validators) who verify and process TX
  - More on validators later...
- Gas limits are also key in preventing the Ethereum system being overwhelmed by endless computation
  - Turing completeness $\Rightarrow$ 'anything' can be programmed
  - Inadvertently/maliciously, a smart contract might never stop
  - Every TX must set a max amount of gas it can 'spend'
  - Once that runs out, the computation will cease
- *Economist's view:* Presumably helps ration computational resources 'efficiently'
  - Incentivises efficient contracts?

Ethereum transactions

As in Bitcoin, Ethereum has accounts controlled by private key

- Referred to as **‘Externally Owned Accounts’** (EOA)
- Not operated by smart contract code

But it also has a second type of account, controlled by smart contract code assigned to it at its creation

- These are referred to as **‘Contract Accounts’** (CA)
- Not *directly* controlled by an agent with a private key

CA may *respond* if a user sends a transaction to it, or to another CA that in turn sends a transaction to it

- Only EOA can **start** this (perhaps complex sequence of) calls

Ethereum transactions

Here is where the concept of a transaction becomes very broad

- In Bitcoin, value was sent between addresses, with a bit of programmatic (Script) information
- **In Ethereum, TXs can contain ETH and data**
- When the CA receives the ETH and the data, its associated smart contract will operate on both
  - ETH is deposited in the 'contract balance'
  - Data will specify a function (there may be many) in the contract and inputs for it

On running, the CA may send TXs to other EOA or CA to...

- Trigger (or make) other smart contracts
- Make other transfers of value and data

Ethereum transactions

Another key distinction between Ethereum and Bitcoin is that contracts can store info between TXs

- In Bitcoin, a contract would simply receive UTXO, consume it, and output another UTXO
  - Nothing is saved between calls, so it executes the same way for a given input
- Ethereum associates 'storage' with contracts, allowing them to be 'stateful'
  - The value of the (contract) state may determine its response to a given input
- Vital for storing token balances, among other things

Ethereum transactions

Transactions have the following components:

- Nonce (‘number used once’)
- Gas, Maximum Fee per Gas, Maximum Priority Fee per Gas
- Digital signature of sender
- Recipient address
- Value of ETH to be sent
- Data to be sent
- ChainID

Ethereum transactions

The 'nonce' is important because of the **account** rather than **UTXO** approach of Ethereum:

- Ethereum's state is a list of address-**account balance** pairs

$\Rightarrow$ Risk that a transaction could be 'replayed'
  - Could keep sending identical transaction until account drained
  - In UTXO, first transaction consumes a particular UTXO
  - UTXO no longer exists for a 'replay' transaction

- Nonce tracks # transactions from an address
  - Incremented with every transaction from the address

- So it will never be the same in two transactions
  - Trying the 'same' transaction again will be revealed

Sidenote: ChainID also plays a similar role in preventing replays across different chains following forks

Ethereum transactions

Maximum Fee per Gas and Maximum Priority Fee per Gas

- **Max fee:** Limits what sender is prepared to pay for gas
- **Max priority fee:** Controls how much TX fee sender will pay to validator to include in block

Smart contracts

We will now expand a little on the topics of smart contracts:

▸ SC Example

- Owing to the Turing complete nature of Ethereum's supported languages, smart contracts can implement a wide variety of functionality

- While their adoption is still in its early stages, some important uses are:
  - Implementing tokens issued on a blockchain
  - Enabling consensus mechanisms (staking involves locking a native token by sending to a SC)
  - Organizing interactions among collaborators in 'Decentralized Autonomous Organizations' (DAO)
  - Automating business and regulatory logic (such as in supply chains and banking)
  - Underpinning decentralized market activity (such as in AMMs or flash lending)

Smart contracts

Key (perceived) advantages are:

- Immutability of smart contracts, censorship resistance and robust, round the clock operation
  - Inherited from the underlying blockchain
- Transparency and lack of ambiguity in contract operation
  - By default, SC implementation is exposed on the blockchain
- Replacement of error-prone manual operations and expensive intermediaries
  - Advanced business logic - and possibly innovative approaches - likely infeasible without automation
  - Smart contract interaction can eliminate/accelerate administrative steps
- Collocation of data and computation
  - SCs and (some) of the data they use are both 'on chain'

Smart contracts

Smart contract development is still in its relatively early stages and there are some warnings to keep in mind:

- Immutability is a double edged sword - if it's wrong, it can't be updated
  - Rigorous testing, including on 'testnets' is key
  - Importing/reusing SCs produced by reputable parties, such as OpenZeppelin
- Bugs can be catastrophic
  - Barely a day goes by without some bug leading to an exploit
  - Code re-use (though it has its benefits) makes it hard to know exactly what is going on
  - Bug bounties increasingly common, as are SC auditors

Smart contracts

Smart contract development is still in its relatively early stages and there are some warnings to keep in mind:

- Some important blockchains (e.g. Ethereum) may become congested and expensive
  - Volatility in gas fees may interfere with SC operation
- Legal standing of smart contracts, and ambiguity whom to blame in the case of failures
  - Limited regulatory guidance
  - Defi insurers, such as Nexus Mutual, are emerging to insure against SC bugs among other things
- Transparency also has its downsides
  - Makes bugs easily discoverable
  - Also can lead to problems with front running while smart contract transaction is in mempool

Smart contracts

Many smart contracts that one might want to write, will need data that is not ‘native’ to the blockchain

- Eg. a financial contract may need info about a stock price, or temperature in a particular location...

How are they to receive such data?

- This is where ‘oracle’ protocols come in
- Provide connections between blockchains and real-world data
- In fact, oracles also help connect *multiple* blockchains and legacy systems (will discuss later)

Clearly, it is absolutely vital that SC’s receive accurate information

- But, ideally, should be done in a trustless/decentralized way
- Otherwise, why bother with blockchain? **Do you agree?**

Smart contracts

One popular oracle service that also is - to a large degree - decentralized, is Chainlink

- Interestingly, Chainlink is a blockchain built on top of Ethereum in the sense that its LINK token is implemented via an Ethereum smart contract
- Chainlink network operators are compensated with LINK for obtaining, verifying and cleaning off-chain data - and also must 'stake' LINK tokens to participate
  - Poor performance by the operators may see their stakes taxed
  - Chainlink will examine data feeds from multiple operators, discarding those that seem faulty or misleading
  - The average or best feed will then be transmitted back to the SC that requested external data
- It can also provide a 'verifiable random function' which is another key requirement for many blockchain SCs (e.g. related to gambling and games) - **why?** (see here and here)

Consensus

So far, we understand that:

- A blockchain is a database that:
  - enables transactions
  - organizes and records transactions data
- The resulting ledger comprises a chain of linked blocks
  - Transactions (transfers and SC calls) bundled into blocks
  - 'State' of the ledger evolves via transactions
- Communication is based on a distributed network
  - But degree of centralization may differ according to protocol
- Blockchains rely *heavily* on cryptographic techniques
  - Asymmetric key systems for wallets, signing
  - Hashing for predictable and compact data formats

But there is a big gap in our coverage so far...

Consensus

- Blockchain participants must (eventually) agree on what the 'true' ledger is (the history of valid transactions)
  - What transactions should be added to blocks (validation)
  - What sequence of blocks is the accepted 'state' of the system
- How this comes about is referred to as the **'consensus mechanism'** of the blockchain
  - 'Consensus' connotes a **distributed** form of agreement
  - Public blockchains (and many private) do not rely on a single centralized trusted party to impose agreement

Consensus

If the consensus mechanism does not ensure sensible outcomes then everything else we've discussed is pointless

- Why should we expect many pseudonymous participants, unknown to eachother and untrusted by eachother, to reach agreement on a desirable outcome?
- What if incompetent, malfunctioning, or nefarious participants are present?
- Think about the earlier 'shared public Excel spreadsheet' example (that would be a **disaster**)

Consensus

- All nodes must (eventually) accept the current 'state' of the blockchain as a single, shared truth
- This allows deterministic execution/approval of transactions
  - All nodes (eventually) treat the same transaction in same way
- The protocol may achieve this 'consensus' in various ways:
  - **Bitcoin:** Proof of Work (PoW) and Longest Chain Rule
  - **Ethereum:** Was PoW, now Proof of Stake (PoS)
  - **Permissioned systems:** Often use Proof of Authority (PoA)
  - Other protocols exist - see here for example

Consensus

Let us consider what is known as a 'Sybil attack':

- A single entity creates (very) many accounts/addresses that *ostensibly* are different users, but in fact **are all controlled by that entity**
  - Recall, public blockchains are typically pseudonymous
  - It's essentially costless to create an account
  - Thus, they are especially vulnerable to this sort of attack
- Makes it difficult to reach legitimate consensus - certainly with a naive 'voting' protocol
  - Suppose one player controls more than half of all addresses
  - $\Rightarrow$ enough influence to manipulate the blockchain record
  - Replace previously 'confirmed' blocks, manipulate which transactions get added, censor other participants...

Proof of work

We first consider PoW

- Still the most 'famous' consensus mechanism and part of the broader 'Nakamoto' consensus protocol used by Bitcoin

Basic idea:

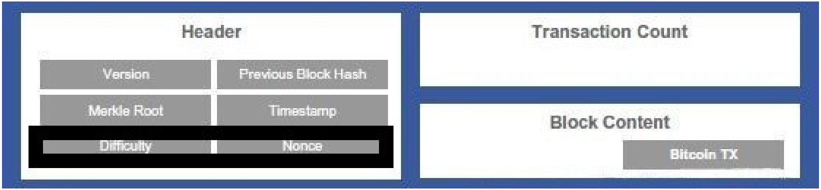
- Provide incentives such that proper behavior is individually rational and bad behavior is individually irrational
- Requires proposal of a valid block to be 'costly'
- On the flip side, if a valid block is proposed by a node, there should be 'rewards'
- Recall 'incentive compatibility' from university economics (?)

'Work': Makes block proposals costly
'Proof': Impossible to propose valid block without work

Proof of work

To understand this we reconsider the contents of a generic block in the chain…

Proof of work



Source: Hellwig *et al* - *Build Your Own Blockchain*

Recall we deferred discussion of 'difficulty' and the 'nonce'

- They are just numbers - it's how they are used that is clever

This is a *Bitcoin* block but similar logic applies to other PoW setups (see others here)

- What constitutes 'work' could differ
- *Something* costly that can be verifiably completed is necessary

Proof of work

Let us summarize the process of proposing a new block:

1. Download 'the' up-to-date chain from network peer(s)
   - Different chains may be regarded as 'the' up to date chain by different nodes (P2P network latency)
   - Eventually this is resolved (will discuss)

2. Check validity of all the blocks/transactions in the chain
   - Hashes, Merkle trees, Merkle roots etc. $\Rightarrow$ quick process

3. Choose a set of *pending* transactions from the 'mempool(s)'
   - A *mempool* is like a waiting area of validated transactions not yet included in a block in the chain
   - Nodes come to be aware of such transactions because of P2P communication across the network

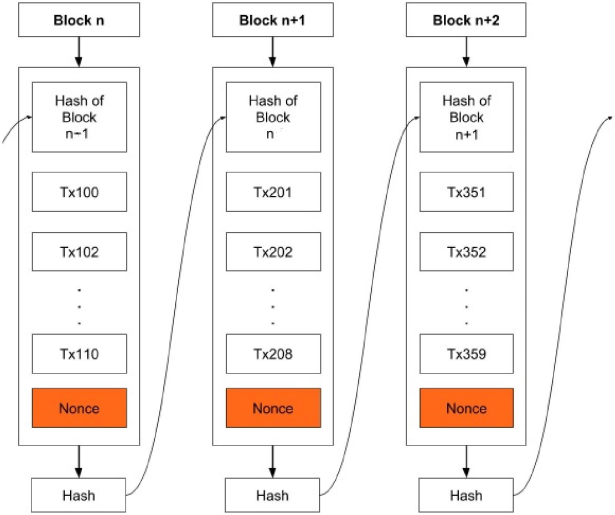
Proof of work

Once the node (the 'block miner') has selected transactions it wishes to add to the proposed block, the miner...

4. Assembles all the elements of a block (*except* the nonce)
5. Guesses a value for the nonce to complete the candidate block
6. Hashes the *candidate* block's header (twice) using SHA-256
7. The hash value will have a certain number of leading zeros
   - If number is 'large enough' then block is valid and the miner broadcasts it to the network
   - If not, then the node tries another nonce (repeat process...)

▸ Zeros

Blockchain



Source: TutorialsPoint

Proof of work

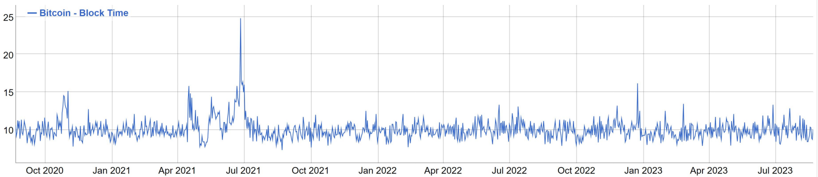
If number is 'large enough' then block is valid and the miner broadcasts it to the network

- **Q:** What is 'large enough'?
- **A:** This is determined by the 'difficulty'

In the Bitcoin protocol, the difficulty is automatically adjusted every two weeks

- **Goal:** Keep the time taken for a new block to be added at approximately 10 minutes
- The more hashing power is devoted to mining, the greater the difficulty must be (see recent discussions)

Proof of work



Source: bitinfocharts.com

Proof of work

Recall, because of the nature of hash functions, it's impossible to know in advance what nonce will work

- Thus - at the cost of enormous computational power, electricity, hardware installation - the only approach is brute force guessing
  - In mid-2022 Bitcoin mining was consuming 150 terawatt-hours of electricity (more than Argentina)
- Miner keeps trying until finds a suitable nonce **or** (often) some other miner succeeds first!
  - Risky business $\Rightarrow$ risk-averse miners often pool together to share risk and rewards

Proof of work

Once a miner finds a valid block, it broadcasts the new block to peers in the network

- Peers that receive it check it and add it to the chain they currently possess
- **Note that it is hard/slow to find the nonce - but very quick to check it**
- They remove any of the transactions included in the new block from their mempools

Proof of work

Three questions:

- Why do miners bother?
  - They aren't charities!
- What happens if two or more miners find legitimate blocks almost simultaneously?
  - Leads to a 'fork' $\Rightarrow$ network isn't fully synchronized across nodes (for a time)
- What prevents (or discourages) bad behavior?
  - Builds on answers to the previous two questions

Why do miners bother?

Why do miners bother?

- Mining is competitive and costly
- Soon after Bitcoin's emergence, mining nodes began to invest in specialized hardware to enhance their hash rate
- Higher hash rate $\Rightarrow$ higher chance of finding legit nonce first

Clearly there must be some incentive to do this:

- **Block rewards** sent to miners in a 'coinbase transaction'
- **Transaction fees** assigned to successful miner by the initiators of transactions
- These rewards are paid in BTC
  - **Common for platforms to use 'native currency' to incentivise**

Why do miners bother?

Block rewards

- This is how newly issued bitcoins enter the system (the ‘monetary policy’) of Bitcoin
- Only a maximum of 21bn bitcoin will ever be issued and the block reward halves approx. every 4 years

Transaction fees

- Optional, but miners less likely to select transactions for inclusion without it
- Up to some point, a higher fee will likely get a transaction added to a block more quickly
- Even if it’s added to the ‘next’ block, that will typically take 10 minutes

These rewards incentivise good behavior

What happens in the case of a fork?

It could be that two or more miners almost simultaneously find legitimate nonces and broadcast their valid block

- Given the difficulty, there is unlikely to be many that do so (one reason why Bitcoin targets 10 min. blocks)
- But it regularly happens and is referred to as a 'fork' (excellent discussion here)

Some nodes will see and accept one block, and others will see and accept another

- Reflects P2P nature of communication and network latency
- Some miners attempt add to one chain, and some to another
- Two (or more) chains emerge from a common block
- Which one grows faster is somewhat random - **but one will become 'longer'** (entailing more hashing 'work')

What happens in the case of a fork?

Knowledge of the chains spreads through the P2P network...

- The 'Longest Chain Rule' (LCR) is respected by nodes
- When they see the longer chain, they discard the alternative
- They switch to the longest chain (called a 'reorganization') and eventually (typically) the entire network will do so
  - Unless shorter chain's miners add to chain quickly enough
  - Requires massive amount of computational effort (+ luck)
  - Especially difficult if longer chain is 'several' blocks ahead
  - Each block added 'on top' of longer chain is a 'confirmation'

Strictly, it is PoW + LCR that constitutes the Bitcoin consensus mechanism

What happens in the case of a fork?

- Transactions included in discarded chain (and not in the longest) return to mempool(s)
  - Can be enormously disruptive
  - **Good practice:** Wait for a 'reasonable' number of confirmations before treating as 'final'
  - What constitutes 'reasonable' depends on cost/benefit of speed vs reorg risk and is problem specific
- There is always some (eventually vanishingly small) probability or a transaction being reverted
  - **Bitcoin transactions are never completely final!**
- Block rewards (coinbase and transaction fees) to miners of 'orphaned' blocks are withdrawn
  - **Note:** While Ethereum used PoW, there was some residual reward kept by miners on 'ommer' or 'uncle' chains

What prevents bad behavior?

Some mechanical checks:

- Client software on nodes can rapidly check the formal correctness of transactions and blocks
- Quickly discard invalid transactions/blocks
- Merkle root $\Rightarrow$ rapid detection of any tampering with previously accepted blocks

Incentives and network structure:

- Waste of computational power and loss of block rewards if fail
- If platform has massive hashing power distributed across many uncoordinated players, it is wildly expensive to manipulate the blockchain
- *Coordinated* nefarious behavior makes attacks more plausible (but still thought highly unlikely in mature systems)

What prevents bad behavior?

Type 1 ‘double spend’ - attempt a transaction that uses currency that has already been spent

- Assume the agent is ‘small’ (not much hashing power)

Response: Time stamps and checking if UTXO is already used

What prevents bad behavior?

Type 2 'double spend' - manipulate blockchain with 51% attack

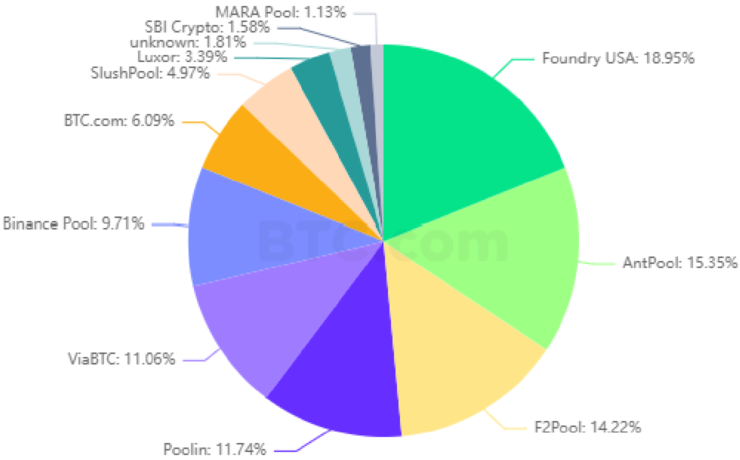
- Assume the agent is 'large' (or coordinated group of agents)
- *Somewhat* more plausible they control enough hash power
- Create fork where new chain omits original payment
- Release chain once long enough to be accepted by network **and after goods purchased are delivered**
- Attacker still has currency to 'spend' a second time

Response: PoW makes attack very expensive and difficult

- Must be extremely costly to acquire 51% hashing power
- Vital the network collectively has massive hashing power relative to any nefarious agent
- Hashing power shouldn't be too concentrated

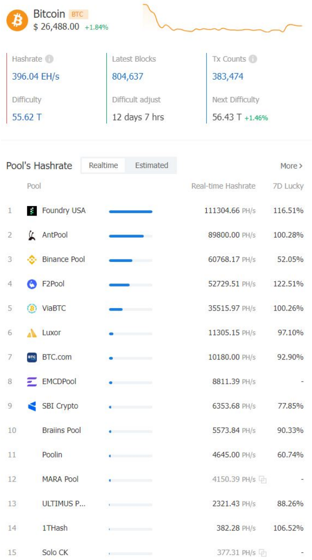
DS Detail

What prevents bad behavior?



Source: Coindesk - March 26, 2022

What prevents bad behavior?



Bitcoin BTC
$ 26,488.00 +1.84%

Hashrate	Latest Blocks	Tx Counts
396.04 EH/s	804,637	383,474
Difficulty	Difficult adjust	Next Difficulty
55.62 T	12 days 7 hrs	56.43 T +1.46%

Pool's Hashrate Realtime Estimated More >

	Pool	Real-time Hashrate	7D Lucky
1	Foundry USA	111304.66 PH/s	116.51%
2	AntPool	89800.00 PH/s	100.28%
3	Binance Pool	60768.17 PH/s	52.05%
4	F2Pool	52729.51 PH/s	122.51%
5	ViaBTC	35515.97 PH/s	100.26%
6	Luxor	11305.15 PH/s	97.10%
7	BTC.com	10180.00 PH/s	92.90%
8	EMCDPool	8811.39 PH/s	-
9	SBI Crypto	6353.68 PH/s	77.85%
10	Braiins Pool	5573.84 PH/s	90.33%
11	Poolin	4645.00 PH/s	60.74%
12	MARA Pool	4150.39 PH/s	-
13	ULTIMUS P...	2321.43 PH/s	88.26%
14	1THash	382.28 PH/s	106.52%
15	Solo CK	377.31 PH/s	-

Source: BTC.com explorer - August 24, 2023

What prevents bad behavior?

How problematic is the concentration?

- Depends - well known mining pools have a lot of 'franchise value' riding on the continued health of PoW blockchains
- The problem with 51% attacks is not so much the spend, but the enormous reputational loss for the platform
- Many of these pools would lose a lot of future revenue (and possibly capital loss on any currency they hold) if they were to abuse the system
- More of a concern for non-economic (e.g. state) actors / terrorists (rich and tooled up terrorists)
- Note the virtuous circle of confidence, high BTC valuation, adoption and **security**

What prevents bad behavior?

Side note 1: People sometimes claim that 'code is law' - the idea that the blockchain and smart contracts does, or will do, away with traditional legal structures

- But clearly if a double spend were achieved, that would be breaking the law
- Need for appropriate legal/regulatory framework (will discuss)

Side note 2: People sometimes (often) claim blockchains are 'immutable'

- In the case of Bitcoin, there is a clear sense in which it is not (orphaning of many blocks under a 51% attack)

What prevents bad behavior?

Side note 3: We referred to agents' economic interest as inducing good behavior - and the possible loss of currency value in the case of bad behavior

- The issue of having a 'stake' in the success of the blockchain platform is formalized in another common consensus mechanism, **Proof of Stake**

Side note 4: Website here *claims* to estimate cost of 1-hour long attack on PoW chains

- Greater risk for smaller blockchains

Proof of stake

- Since 'the merge' Ethereum has been a Proof of Stake blockchain (see here for other PoS chains)
- We will focus on Ethereum's PoS protocol, but the thrust of the logic is quite general

Proof of stake

- Instead of winning the right to add the next block by solving a hard problem, a 'validator' node is chosen randomly
- The more Ether is 'staked' by a validator, the higher the probability of being chosen
  - Stake by locking ETH into the system ('skin in the game')
  - 32 ETH needed per validator ($\approx \$53k$ as of August 24^{th} 2023)
- By staking, the agent helps enhance the validation process and secure the blockchain, in exchange for rewards
  - There are also penalties/punishment if they neglect responsibility or are malicious
- See here (and the next slide) for more detail
  - Also, see here and here for a great low-tech overviews

Proof of stake

Users continually create and sign transactions, before sending them to the network

- Nodes check transactions for validity, broadcast P2P (if valid), and add to mempool(s)

The process below occurs in every ‘slot’ (12 second intervals), with 32 slots (6.4 mins) constituting an ‘epoch’

1. If chosen, a validator may propose and broadcast a block
2. The block is then checked by other validators
3. When a validator ‘attests’ positively, it adds the block to its view of chain

Proof of stake

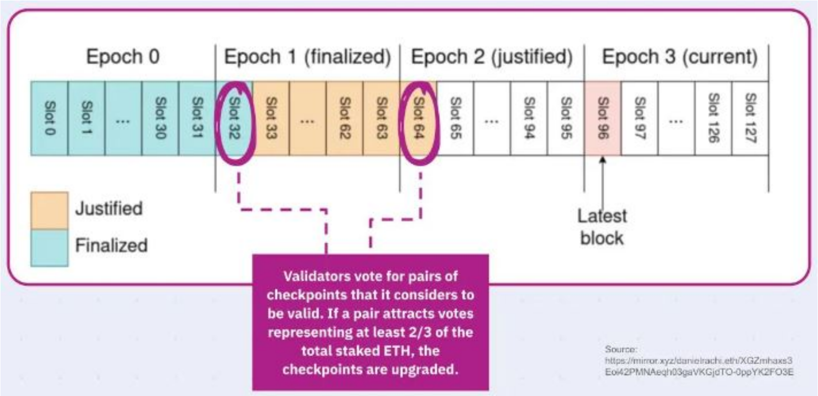
The first block in each *epoch* is called a 'checkpoint'

- If 2/3 of validators - **weighted by staked ETH** - vote in favour of a pair of consecutive checkpoints, the earlier of the pair is regarded as **'finalized'** and the later as **'justified'**

After 2 epochs there is 'no chance' of block reversion

- **Caveat:** Reversion *possible*, but would require expenditure of 1/3 of total stake of ETH (**vast** amount of money)
- More rapid finality than PoW would offer (recall reorgs. . .)
- And timing is regular (finality requires about 12-13 minutes)
- Great discussion of slots/finality here

Proof of stake



Source: Blocknative - August 3, 2023

Proof of stake

WARNING: The precise checkpoint, slot, epoch structure is not necessary for a PoS more generally. It is, however, key to the Ethereum implementation, and thus extremely influential

Proof of stake

In unlikely case of forks, Ethereum validators use ‘heaviest chain’

- Based on number of validators, weighted by ETH staked

More complicated than PoW - and clearly more aspects to be ‘tweaked’

Proof of stake

Validators in Ethereum PoS partly incentivised by rewards paid every epoch...

- Execution
  - Tips/Priority fees
  - Maximal Extractable Value (MEV)
- Issuance
  - Proposal rewards
  - Attestation rewards
  - Sync committee rewards (won't discuss)
  - Reporting violation of slashing rules (won't discuss)

The rewards are adjusted according to 'effective balance' and stakes of all validators (won't discuss)

Proof of stake

Validators in Ethereum PoS partly incentivised by rewards paid every epoch...

- Execution
  - Tips/Priority fees (paid by network users to prioritize transactions for inclusion in block)
  - MEV (complicated bargaining with searchers/builders who optimize the transactions included in block and then have the validator propose it - see also here)
- Issuance
  - Proposal rewards (1/7 of all rewards associated with block)
  - Attestation rewards (must be correct and timely)

These rewards provide the return to staking - though how much you *receive* will depend on how you stake

Proof of stake

- Solo ‘home’ staking
  - If you have tech ability to run node and 32 ETH for validator
  - Most preferred as decentralizes system
  - No intermediary needs to be trusted

- Staking as a service
  - If you have 32 ETH but want someone else to handle admin
  - Possible concerns with centralization of validation
  - Trust SaaS providers they will validate appropriately

- Pooled staking
  - Can contribute fraction of 32 ETH to a pooling service
  - Partly helps decentralization, but large pools account for large fractions of staking amount
  - Must trust pool admin (e.g. Lido)

- Centralized exchanges (CEX)
  - Can do staking for you using the ETH entrusted with them
  - Simple - but massive centralization and incentive for attacks

Proof of stake

We've discussed the carrot, what about the stick?

- **Penalties** (mainly penalizes laziness/incompetence)
  - Failure to vote - or doing it slowly
  - In some cases, literally penalties - in others (e.g. failing to propose when it's your turn) do not receive reward
  - Gradually grinds down the stake - once ≤ 16 ETH, validator status removed

- **Slashing** (mainly penalizes attempt to harm Ethereum)
  - For *more severe offences*, such as 'equivocating' (proposing or signing two blocks in a slot) or double voting
  - Max of 1/32 of staked ETH or 1 ETH is 'burned' daily
  - Process continues for 36 days until validator is removed
  - *Additional* loss of ETH after 16 days, depending on the ETH staked by all validators are being slashed (worse penalties in case of a 'coordinated' attack)

Must reliably keep your system active **and** that you play by rules

Inactivity Leak

PoS vs PoW

- PoW uses **vastly** more energy - with environmental consequences (though much may be from renewable sources)
  - One of the most commonly cited benefits of PoS
  - Regulators definitely paying attention
  - Ethereum's energy consumption $\Downarrow$ 99.99% after 'the merge'
  - ETH simply needs to be locked up - no work done
- PoW has simpler govenance
  - One dimensional and based on simple incentives - may make more accessible
  - But PoS offers simplicity of delegated staking and has limited hardware demands
- PoS regarded as having faster validation of transactions
  - No need to wait for mining and blocks created on a more regular schedule - though there are (much) faster mechanisms
  - May make other scalability improvements easier to implement
  - PoS gives quicker and less ambiguous finality than PoW

PoS vs PoW

- PoS arguably has a tendency to centralize staked ETH
  - Rewards may make the rich richer (and thus more influential)
  - Some people also point to (excessive?) influence of key voices in Ethereum (Vitalik Buterin, for example)
- Early implementations of PoS locked up staked assets
  - Perhaps reduces liquidity
  - Liquid staking now available (tokens issued against stake)
  - But there are centralization risks from pools
- Raging debate over security
  - Neither protocol has ever been successfully attacked (though the DAO hack in 2016 was very disruptive to Ethereum)
  - Relates to how centralization tendencies stack up (of ETH holdings or of computational power)
  - PoW has a long track record of success under Bitcoin

Proof of authority

- Common among permissioned/private blockchains
- **Why?** Depends heavily on reputation and can assume a somewhat higher level of trust
  - Strict joining criteria
  - Valued relationships underpin threat of punishment or removal
  - Dominant or regulatory players may already be in place
- Get unambiguous finality very quickly with low energy use
  - But quite centralized

Proof of authority

PoA can be implemented in various ways (e.g. Clique or Aura)

- A group of N validators is chosen
  - Process can survive a certain number of dishonest validators
  - In Clique that is N/2 - 1
- Authority to choose blocks rotates through the validators
  - Proposed block from 'leader' may be voted on by other validators
  - Votes may also occur to add/remove validators (reputation)
- Amount of messaging/rounds of communication among the validators will affect the speed with which finality is reached
  - **But massively faster than PoW/PoS**

Proof of authority

- PoA is an example of a Byzantine Fault Tolerant protocol
  Generals
- Other examples are Practical BFT and Istanbul BFT
- Such protocols are robust to different fractions of validators being dishonest or faulty
- Other protocols, such as Raft, may only be robust to nodes that crash, rather than being malevolent
- Some comparisons may be found here, here and here

We will revisit these when we discuss pros and cons of Blockchains - and permissioned blockchains in finance and CBDC applications

Escape slides

Concept of 'state'

Consider a stationary ($|\rho| < 1$) Autoregressive Process of order 1:

$$
\begin{aligned}
y_t &= \rho y_{t-1} + \epsilon_t \\
y_0 &= \bar{y} \\
\epsilon_t &\sim \mathcal{N}(\mu, \sigma^2)
\end{aligned}
$$

What is the state at time t in this model?

- y_t
- y_{t-1} and ϵ_t

Concept of 'state'

Consider a stationary ($|\rho| < 1$) Autoregressive Process of order 1:

$$
\begin{aligned}
y_t &= \rho y_{t-1} + \epsilon_t \\
y_0 &= \bar{y} \\
\epsilon_t &\sim \mathcal{N}(\mu, \sigma^2)
\end{aligned}
$$

What is the state at time t in this model?

- y_t
- y_{t-1} and ϵ_t
- $y_0, \epsilon_1, \epsilon_2, \ldots \epsilon_t$

All these are representations of the state. Now consider a more intuitive example. . .

Concept of 'state'

If you are a *banker*, and all you care about is a prospective borrower's net worth, the state might be:

- Just that one number
- The number last period, together with net income this period
- The number two periods ago, together with net income in the last two periods
- The value of her assets today, together with the value of her value of her debts
- The above numbers, but for all the divisions of her company separately
- Net worth of all the divisions of her company in the first period they were operating, and all the in-goings and out-goings since

Back

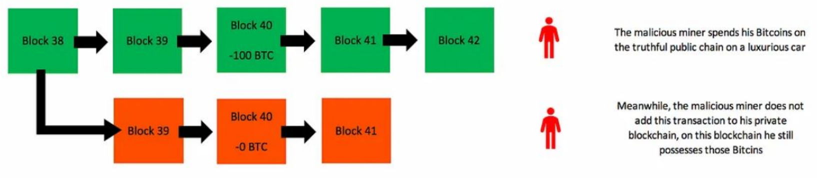
Type 2 double spend / 51% attack

Order of events:

1. Buy a good/service from another agent (a 'supplier')
2. Payment transaction gets added to a block and block is added to chain
3. Supplier provides good or service
4. Attacker quietly (without broadcasting - yet) works very hard to build an alternative chain
5. Alternative chain doesn't include the original transaction
6. Once chain is long enough, attacker broadcasts the fork
7. Reorgs take place and the alternative chain becomes the new accepted blockchain
8. Attacker has good/service and can still spend the same currency

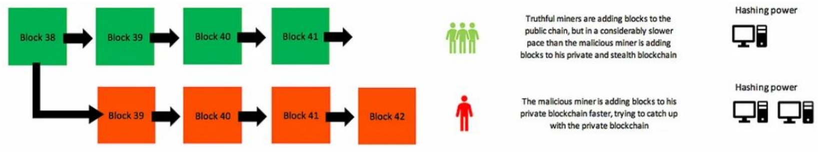
There is an *excellent* discussion here and we use some of its diagrams

Type 2 double spend / 51% attack



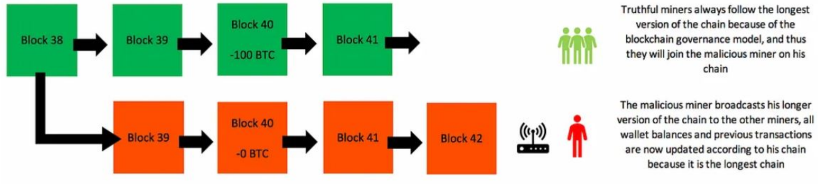
Source: Medium - May 5, 2018

Type 2 double spend / 51% attack



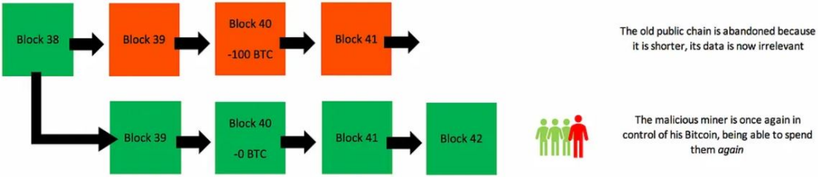
Source: Medium - May 5, 2018

Type 2 double spend / 51% attack



Source: Medium - May 5, 2018

Type 2 double spend / 51% attack



Source: Medium - May 5, 2018

Back

Carrot and stick

Back

Inactivity leak

There are also special penalties for inactivity in the case of difficulties of reaching consensus

- If no finalizations for 4 consecutive epochs (haven't reached 2/3 super majority of staked ETH), an 'inactivity leak' is implemented
- The inactive (at least 1/3 of validators) have their stake reduced gradually, *via* burning - this is the 'leak' of ETH (from the offending validators)
- Eventually they will represent $< 1/3$ of staked ETH and finalization can be re-established
- Happened for the first time in 2023 (here and here)
- Emergency incentive system to ensure robustness of system - big incentive for validators to come (back) online

Back

Byzantine Generals Problem

A decentralized system is Byzantine Fault Tolerant if it can function despite the failure - or malice - of some of its nodes (well discussed here and here)

- Its strange name derives from a famous thought experiment...

  Consider a number of generals who are attacking a fortress. The generals must decide as a group whether to attack or retreat; some may prefer to attack, while others prefer to retreat. The important thing is that all generals agree on a common decision, for a halfhearted attack by a few generals would become a rout, and would be worse than either a coordinated attack or a coordinated retreat.

  The problem is complicated by the presence of treacherous generals who may not only cast a vote for a suboptimal strategy, they may do so selectively. The problem is complicated further by the generals being physically separated and having to send their votes via messengers who may fail to deliver votes or may forge false votes.

▸ Back

Smart contract example: Piggybank

```
pragma solidity ^0.5.1;

contract PiggyBank
{
    address payable public owner;

    constructor() public
    {
        owner = msg.sender;
    }

    function() payable external {}

    function spend() public
    {
        require(msg.sender == owner);
        require(address(this).balance >= 1 ether);
        owner.transfer(address(this).balance);
    }
}
```

Smart contract example: Piggybank

```
pragma solidity ^0.5.1;
```

The first line controls which versions of Solidity should be assumed in compiling the source code

- Necessary since Solidity is a fairly new language that is rapidly changing

We then define the name of our contract, 'Piggybank'

```
contract PiggyBank{}
```

Smart contract example: Piggybank

```
constructor() public {}
```

This is the constructor function of the smart contract

- Will only be executed when the piggbank is deployed

```
owner = msg.sender
```

In the constructor, we set the variable owner to be the address of the sender of this message (the address that deployed the contract)

- We will use this variable to check for conditions later

Smart contract example: Piggybank

```
function() payable external {}
```

This is a default fallback function

- Does not need a name because owner can simply send ETH to the SC without a data component to the payload
- The ‘payable’ keyword $\Rightarrow$ function can be used to accept funds to be deposited in the smart contract’s account

Smart contract example: Piggybank

```
function spend() public {}
```

This defines the function named ‘spend’

- Used to retrieve funds from the SC’s account

```
require(msg.sender == owner);
```

The message sender must be the same address as the one that deployed the SC (set by the constructor function)

Smart contract example: Piggybank

Funds in the smart contract must be more than 1 ether.

```
address(this).balance >= 1 ether);
```

Also we have

```
owner.transfer(address(this).balance);
```

If the above two conditions are met, the smart contracts sends all of its funds to the owner address

- Empties the Piggybank
- Owner gets all the funds he saved back - to spend on whatever...

Back