Blockchains & Distributed Ledgers

Lecture 01

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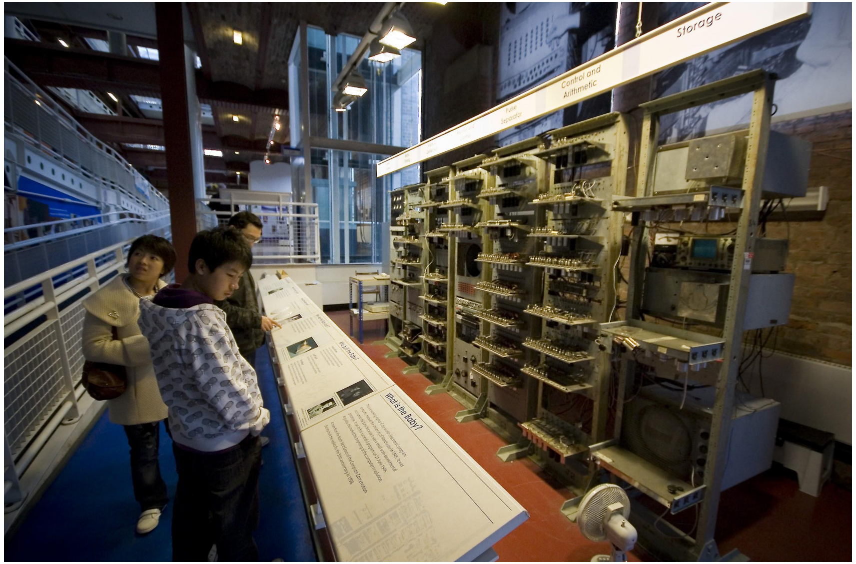
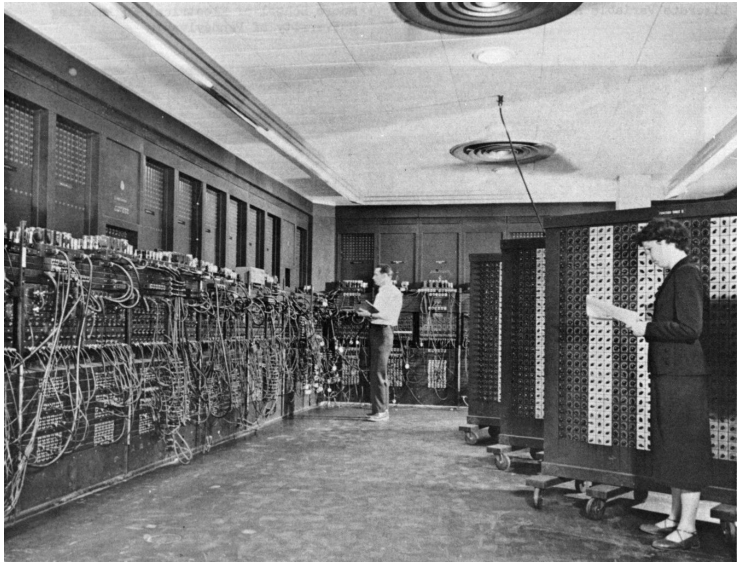
Slide credits: DK, Aggelos Kiayias, Dionysis Zindros, Christos Nasikas

Once upon a time…



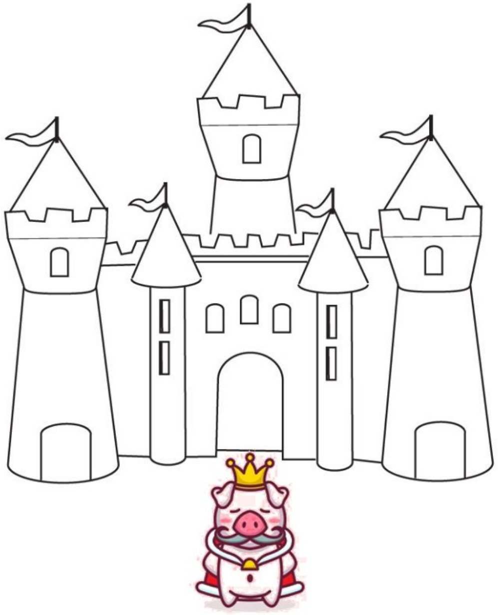
[Manchester baby]



[ENIAC]

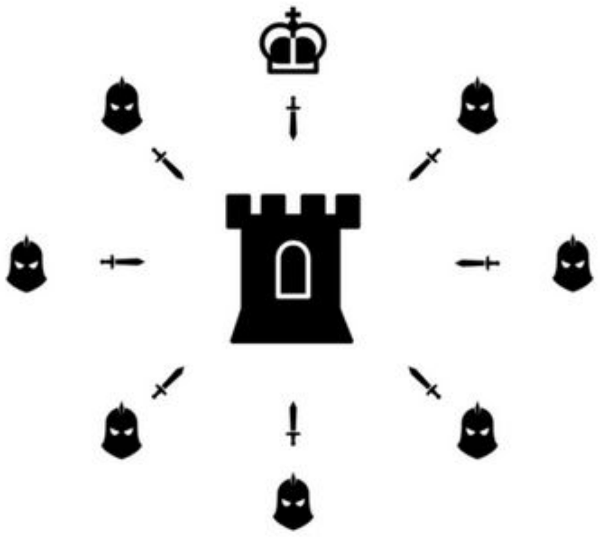
Centrally-controlled systems

- A single person (party/node) controls who can read/write/delete data
- If the person/party/node dies/is dishonest/crashes, the system crashes



Controlled-access distributed systems

- Nodes collectively control the system
- If only few nodes faulty, system remains operational
- Controlled participation - only authorized parties



Open-access distributed systems?

- Nodes collectively control the system
- If only few nodes faulty, system remains operational
- Anyone can participate, join or leave as they please

What is a blockchain ?

- A blockchain is a distributed database that satisfies a unique set of safety and liveness properties
- Distributed ledgers use a blockchain protocol as one means of implementation
- To understand it, we will focus on its first application

Why study blockchains?

Why study blockchains?

- Good foundations for exploring security of information systems in general
- Explore decentralisation, a property of increasing importance in the design of modern information systems
- Solid understanding of many security critical components, including:
  - Key management
  - Software security
  - Privacy preserving technologies
  - Public Key Infrastructure
- Novel opportunities for applications on various aspects of societal organisation
- It's fun!

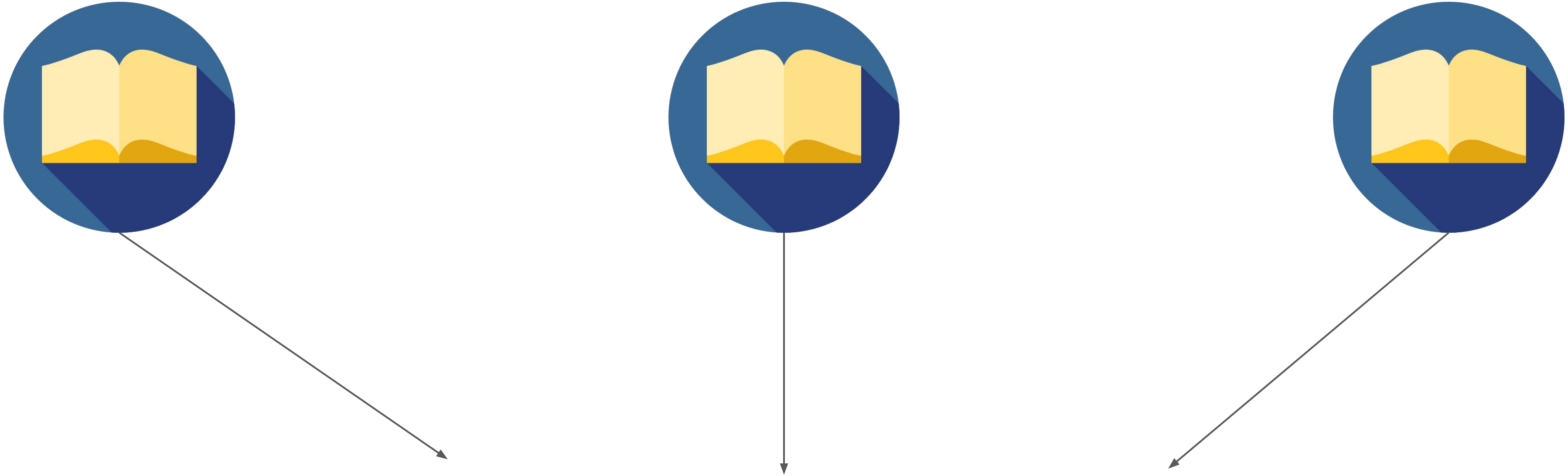
The never-ending book parable

A book of data

- Initially, the book only has a cover
- Anyone can be a scribe and append a page
- New pages are produced indefinitely, as long as scribes are interested in doing so
- Each new page requires some effort to produce

Importance of consensus

If multiple conflicting books exist, which is the "right one" ?



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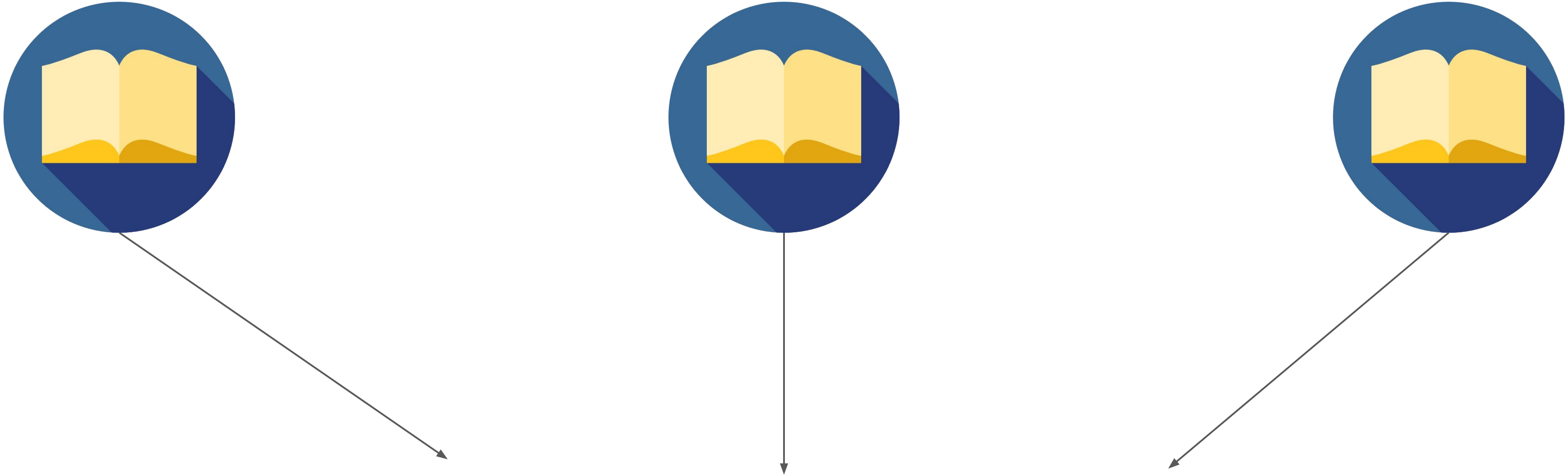
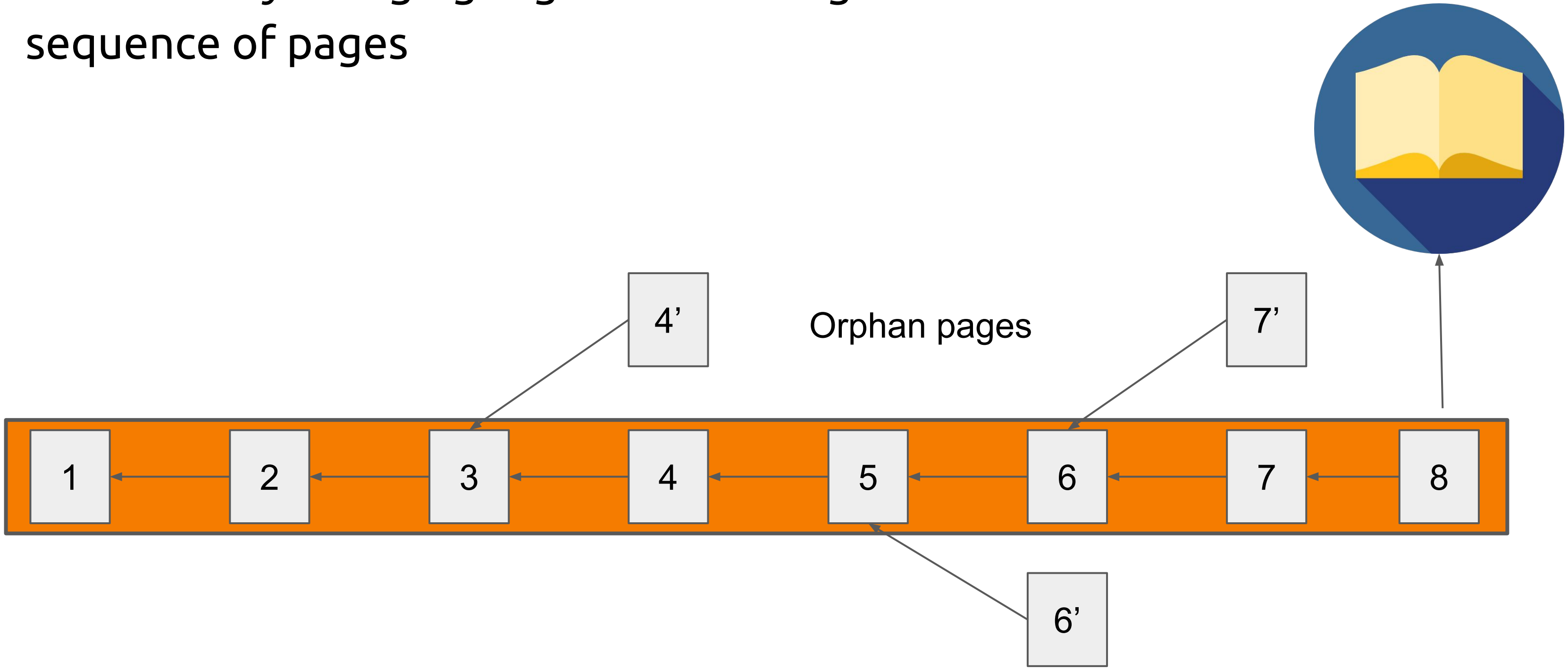


The correct book to work on & refer to is the book with the most pages;
if multiple exist, just pick one at random.

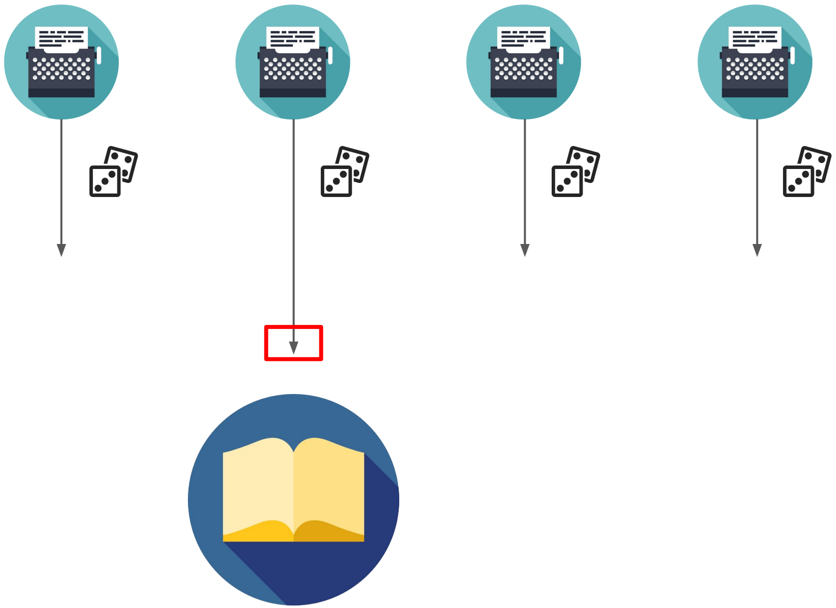
Assembling the book

- Each page is linked to the previous one
- Assemble by stringing together the longest sequence of pages

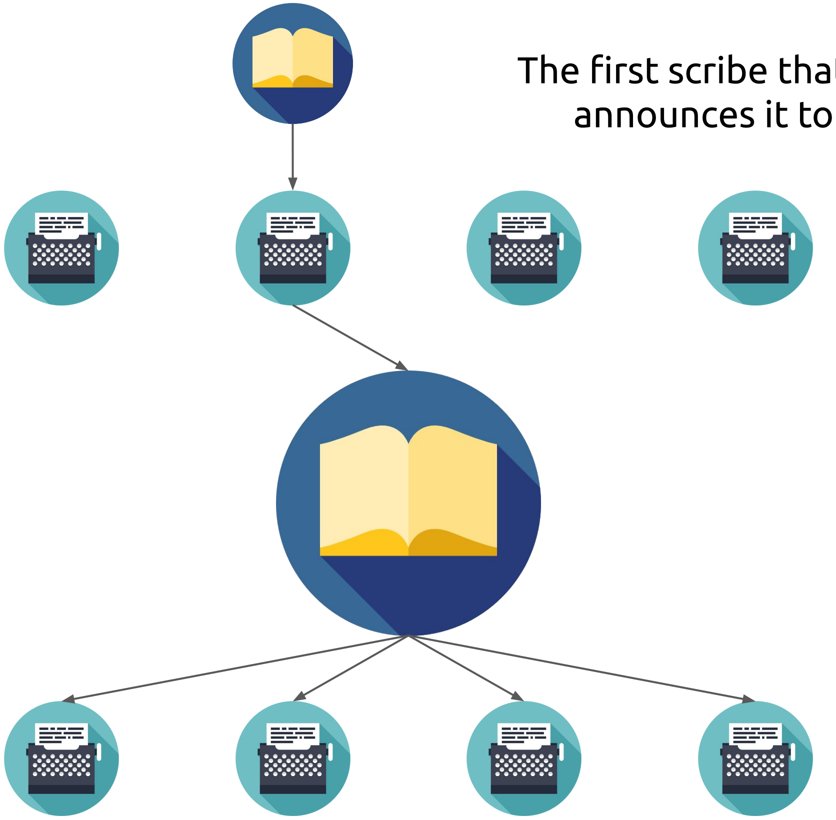


Effort is needed to produce a page

Equivalent: to produce a page, a special combination from a set of dice needs to be rolled.
(the probabilistic nature of the process is paramount to security)

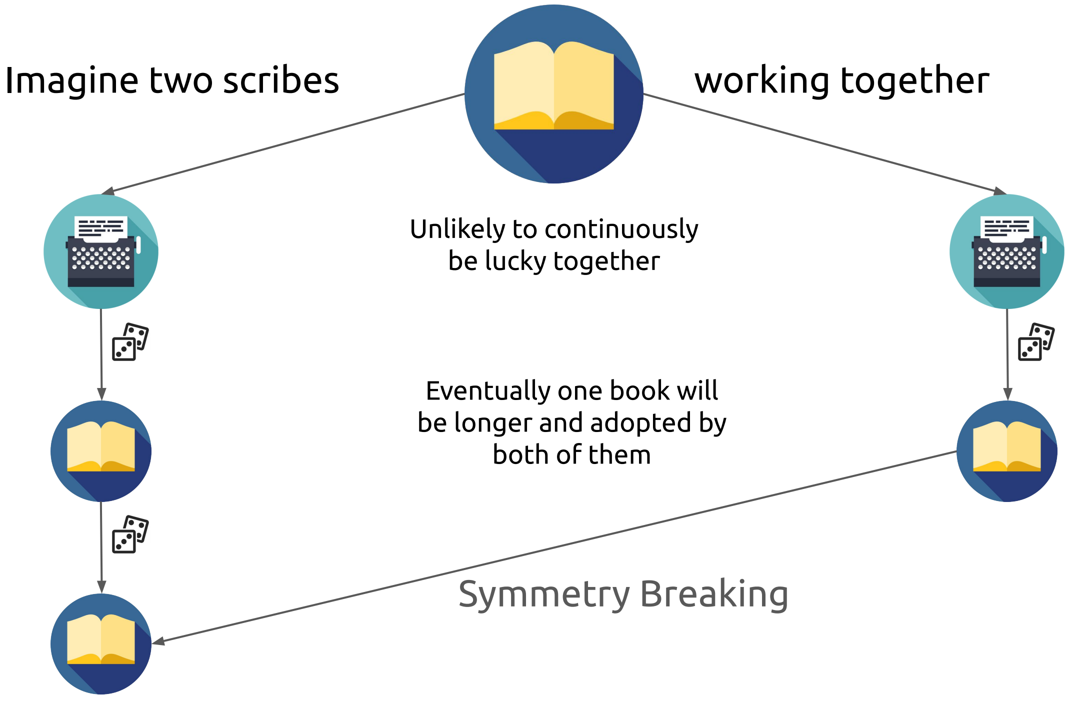


Rules of extending the book



The first scribe that produces a page
announces it to everyone else

The benefits of randomness



Being a scribe

- Anyone can be a scribe for the book…
- … as long as one has a set of dice
- The more dice one has, the higher the likelihood to roll the winning combination to produce a page

Parable & Reality

	The “blockchain”
	“Miners” / Computer systems that organize transactions in blocks
	Solving a moderately hard cryptographic puzzle
	Using a computer to test for a solution from a large space of candidate solutions

Blockchain applications

- Effort is needed to produce a page
  - Why would anyone care to constantly “roll dices” (i.e., spend energy/material)?
- Decentralization is complex
  - What kind of application could benefit from a completely decentralized database?

Bitcoin

Why would people participate?

- Utility: “that property in any object, whereby it tends to produce benefit, advantage, pleasure, good, or happiness” (Jeremy Bentham, 1870)
- Homo Economicus:
  - Constantly acts rationally and optimally
  - Aims to maximize its financial gain

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- Homo Economicus:
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    - Aims to maximize its financial gain
- Bitcoin’s arguments:
    - People would participate, if they are *financially* rewarded
    - Users would pay others to run the system
    - Free market (everywhere)

What is Bitcoin (trying to be)?

- Payment system
  - Competing with cash, bank deposit operation network, Visa, Mastercard, etc
  - High throughput (large volume of transactions/sec)
  - Low latency (fast transaction settlement)
  - Uninterrupted service

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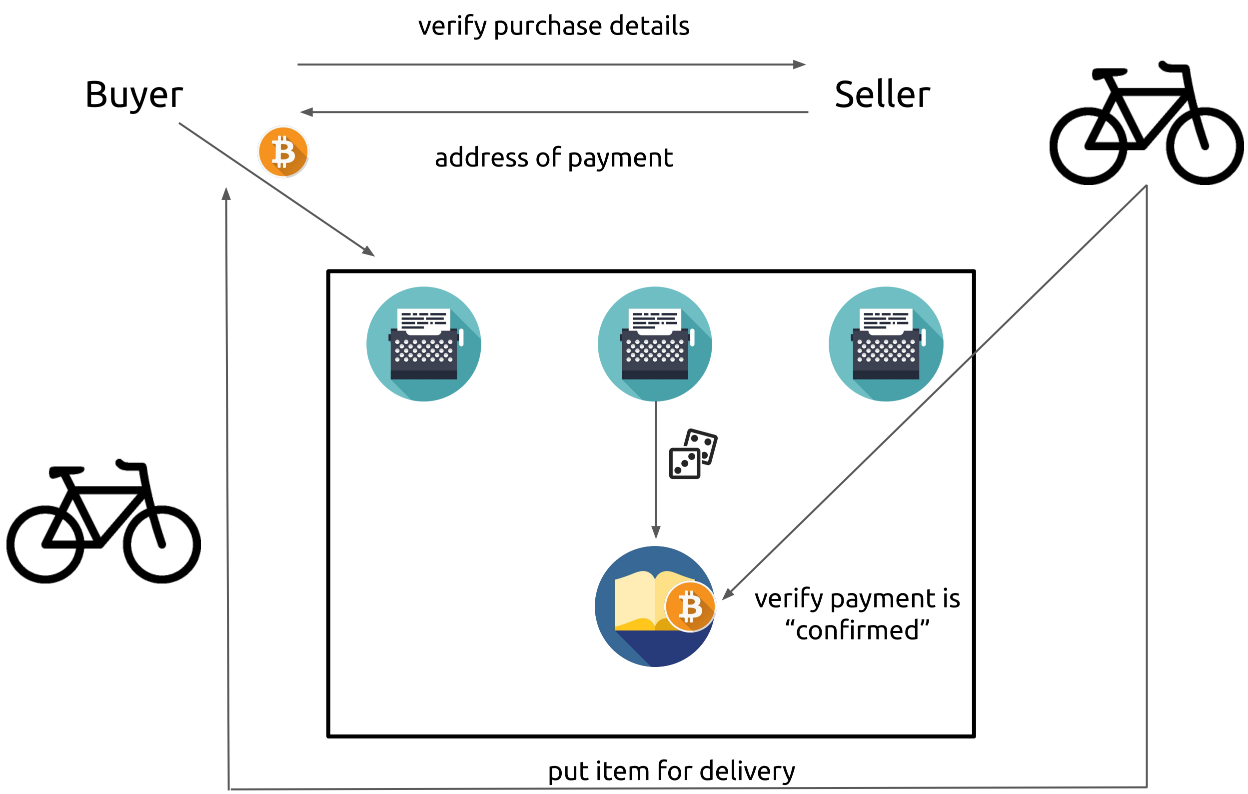
- Digital Asset
  - Money
    - Competing with £, $, €, ¥, etc
    - *Medium of exchange*: give money to get goods and vice versa
    - *Unit of account*: price goods, for accounting/debt purposes
    - *Short/Medium-term store of value*: can be exchanged for the same amount of goods in the (not so distant) future
  - Commodity
    - Competing with gold, silver, oil, etc
    - A (useful) material that can be bought/sold

Using the Bitcoin book



Advantages

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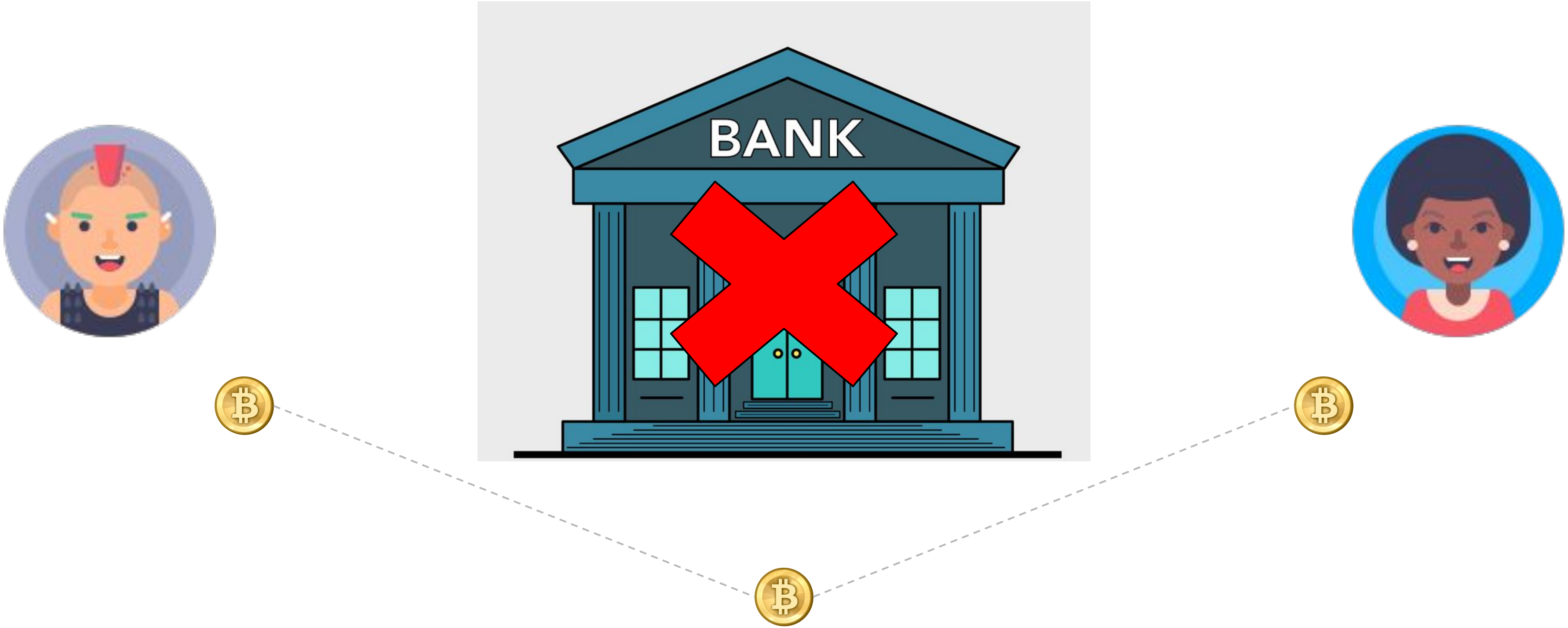
  - Good alternative for borderline (or beyond) legal financial transactions
- Digital and Open
  - New applications can be easily built on top of it
  - Programs can be hosted on the ledger itself (smart contracts)

Person to person



Disadvantages

- Bad as money
  - Price fluctuations and circulation does not follow economic growth (bad store of value)
  - Nothing is priced in Bitcoin (bad unit of account)
  - Slow and expensive (bad medium of exchange)
    - Low throughput (~5 tx/sec)
    - High latency (60 mins)
    - High fees*** (~1$)

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- Environmental inefficiency
  - Bitcoin CO_2 footprint[*]: 71.2 Mt (~Greece)
  - *Single* Bitcoin tx CO_2 footprint[*]: 760.84 kg (~1.7M VISA transactions)
  - Single Bitcoin tx e-waste (2021)[**]: 242g (~1.5 Iphones)

*https://digiconomist.net/bitcoin-energy-consumption

**https://www.sciencedirect.com/science/article/pii/S0921344921005103

***https://bitinfocharts.com/comparison/bitcoin-transactionfees.html

Questions to Consider

- How does a page properly refer to the previous page?
- How are pages created? How can we enforce and verify effort was made and how can we break symmetry?
- How is it possible to prove ownership of digital assets?

Questions to Consider

- How does a page properly refer to the previous page? Hash functions
- How are pages created? How can we enforce and verify effort was made and how can we break symmetry? Proof-of-Work
- How is it possible to prove ownership of digital assets? Digital signatures

Hash Functions

- An algorithm that produces a fingerprint of a file.
- Required properties (traditionally):
    a. Efficiency
    b. A good (ideally uniform) spread for various input distributions

$$\mathcal{H} : \{0,1\}^* \rightarrow \{0,1\}^\lambda$$

One-way functions

$$f : X \to Y$$

easy : given x find $f(x)$

hard : given $f(x)$ sample $f^{-1}(f(x))$

Do one-way functions exist?

Relates to most important open question in computer science right now:

$$P \neq NP$$

Hash Function Cryptographic Considerations

- **Collision attack**: Find x, y: $H(x) = H(y)$
- **Pre-image attack**: Given $H(m)$ for some $m \in \{0, 1\}^t$, find m': $m' = H^{-1}(H(m))$
- **Second pre-image attack**: Given x, find y: $H(x) = H(y)$

<u>Security argument</u>: A hash function should be *resistant* to all these attacks, i.e., it should be infeasible for any (computationally-bounded) attacker to perform any of these attacks (with sizable probability).

Birthday paradox

- How many people should be in a room s.t. two of them share a birthday at 100% probability?

Birthday paradox

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$$n \text{ possible dates, } k \text{ people}$$

$$\mathrm{Pr}[\neg Col] = \frac{n}{n} \cdot \frac{n-1}{n} \cdot \frac{n-2}{n} \cdots \frac{n-k+1}{n} =$$

$$= \prod_{l=1}^{k-1} (1 - \frac{l}{n}) \leq \mathrm{exp}(-\frac{1}{n} \sum_{l=1}^{k-1} l) = \mathrm{exp}(-k(k-1)/2n)$$

$$\mathrm{Pr}[\neg Col] = \frac{1}{2} \Rightarrow k \approx 1.177\sqrt{n}$$

What do we learn about collision finding?

$$\mathcal{H} : \{0,1\}^* \rightarrow \{0,1\}^\lambda$$

Describe an algorithm that finds collisions for H by taking advantage of the Birthday paradox; what is this algorithm's complexity?

Hash function instantiations

- **Retired.** MD5, SHA1.
- **Current.** SHA2, SHA3, available for {224, 256, 384, 512}-bit fingerprints.
- **Bitcoin.** Uses SHA2 with 256 bits output, SHA-256.

Proof-of-Work

- Objective: given some data *d*, ensure that some amount of work has been invested in computations over them
- Example:

```
int w
w ≔ 0
while Hash(d, w) > Target
        increment w
return w
```

Proof-of-Work of *d* is a value *w* such that Hash(*d*, *w*) <= Target

- (Informal) Properties:
  - efficient verification
  - no computational shortcuts (i.e., regardless of algorithm that computes it, complexity is proportional to Target)
  - independence for symmetry-breaking

Proof-of-Work Algorithms

- Hashcash (as in previous slide)
- Memory hardness
  - ASIC resistance (ASIC = Application Specific Integrated Circuit)
  - A number of algorithms proposed: scrypt, argon, progpow

Digital Signatures

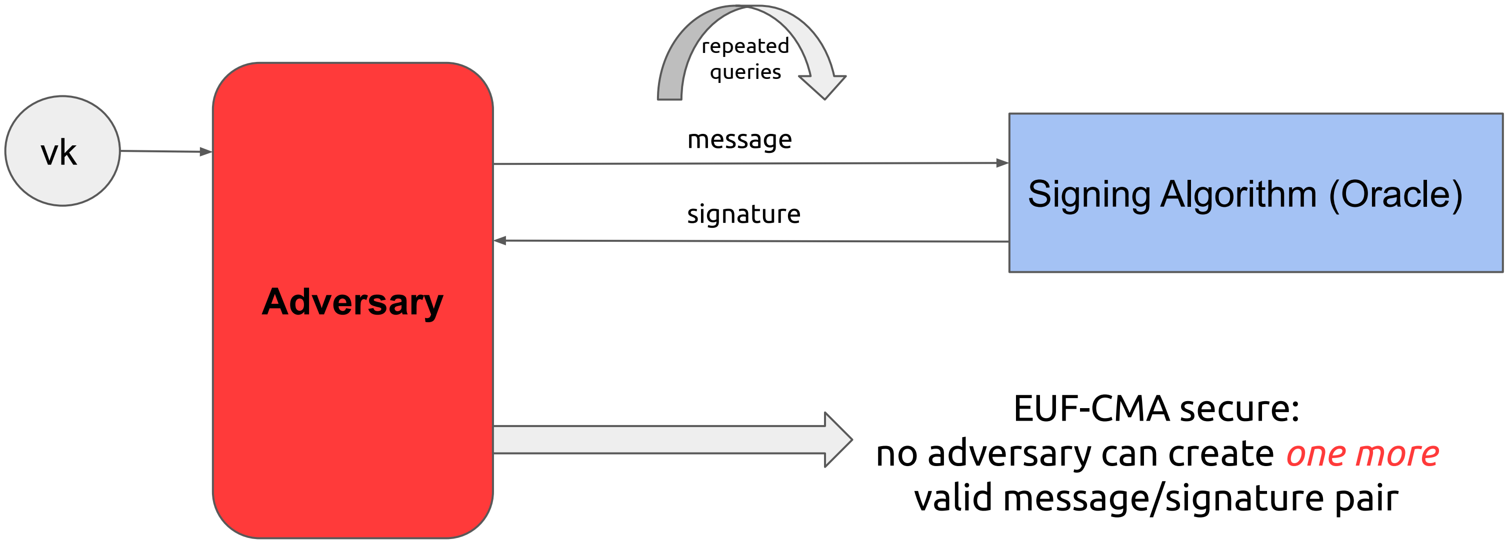
- Can be produced by one specified entity.
- Can be verified by anyone (that is suitably “equipped" and “initialised”).
- Cannot be forged on a new message even if multiple signatures have been transmitted.

Digital Signature Scheme

- Three algorithms: **KeyGen, Sign, Verify**
- **KeyGen**
  - Input: *security parameter* (bits of security)
  - Output: a pair of keys <sk, vk> (sk: signing/private key, vk: verification/ public – key)
- **Sign**
  - Input: <sk, m> (m: message)
  - Output: σ (σ: signature)
- **Verify**
  - Input: <vk, m, σ>
  - Output: {True, False}

Digital Signature Security

Existential Unforgeability under a Chosen Message Attack (EUF-CMA)



Constructing Digital Signatures

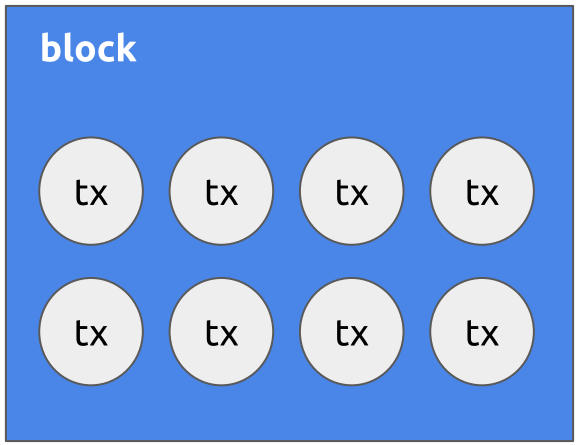
- Major challenge: what prevents the adversary from learning how to *sign* messages by analyzing the *verification key?*

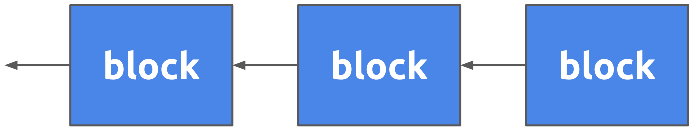
Digital Signature Implementations

- Based on the RSA cryptosystem
    - One way trapdoor function (with hardness that relates to the factoring problem)
    - The RSA algorithm
- Based on the discrete-logarithm problem
    - the DSA algorithm
    - Bitcoin uses ECDSA, a DSA variant over elliptic curve groups

Bitcoin in practice

Blocks





BLOCKS TRANSACTIONS

Height	Age	Transactions	Miner	Size (bytes)
564593	4 minutes	2734	Unknown	1,185,499
564592	9 minutes	2725	AntPool	1,297,232
564591	16 minutes	2537	BTC.com	1,183,625
564590	54 minutes	1757	F2Pool	1,158,256
564589	1 hour	2230	BitClub Network	1,300,144

View More

Blocks

Total transactions

Block ID

Summary	
Number Of Transactions	2973
Output Total	7,994.71534627 BTC
Estimated Transaction Volume	1,428.50299957 BTC
Transaction Fees	0.12706551 BTC
Height	543028 (Main Chain)
Timestamp	2018-09-25 15:56:10
Received Time	2018-09-25 15:56:10
Relayed By	SlushPool
Difficulty	7,152,633,351,906.41
Bits	388454943
Size	1152.48 kB
Weight	3993.111 kWU
Version	0x20000000
Nonce	3705848148
Block Reward	12.5 BTC

Hashes	
Hash	0000000000000000000a318feb2fcf7c2c9dc43c2d1de1606bb5f0cc6dc1d115
Previous Block	00000000000000000003006dab6f32132e7eeda37d2cca4a961339bad35b1e80
Next Block(s)	0000000000000000000868c5eac591d4df331b4c8b4b12c33d40dfddac3feaff
Merkle Root	4dfd79c993bc63e5db09cbda62e9d9df7da1a7d8f1605e97a5ceb1f939509d31

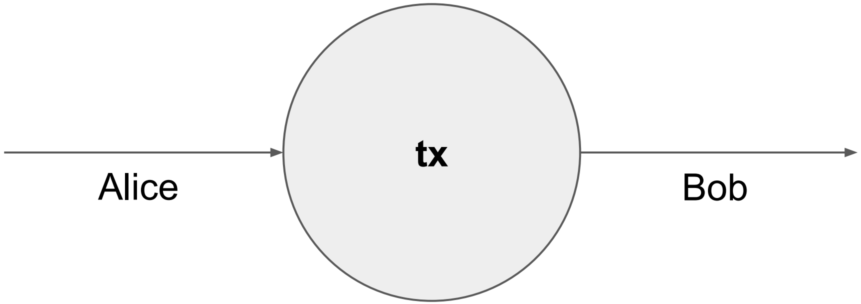
Parent ID

Total fees

Block difficulty

Reward

Transactions



BLOCKS TRANSACTIONS

Transaction Hash	Age	Amount (BTC)	Amount (USD)
7dd6b6e07ea48577ce11fd43cbf20e259d187defc0888eaa698d7...	5 seconds	1.91072766 BTC	$7,304.54
94613360083b2e9bdff659d026021c3df9abad4820c1f2bb6add...	3 seconds	0.02130671 BTC	$81.45
bbda790399d9f44f25d247ea2785b9a687b714665b1fb021cd537...	3 seconds	1.23166111 BTC	$4,708.53
5d96b437de67fc604b025671f4fa199832b60fc21aedcf94b0455...	2 seconds	0.05533534 BTC	$211.54
6e7e9284d3c45111a036dab93aae7f7b057e76935c6186051cf92d...	2 seconds	0.03158347 BTC	$120.74

View More

Transactions

Transaction ID

Receiver

e87f138c9ebf5986151667719825c28458a28cc66f69fed4f1032a93b399fdf8

13hieCEtALdjjZf5hfXEVaqaYitDe9sqQj (0.00013129 BTC - Output)
14L3kyHjMr74ShVweF5CYVVxbQE9gDWdPH (0.0001 BTC - Output)
1JaR2C4y17FW8N4VrwPWTzhrb5xahRFYzV (0.00049266 BTC - Output)
1LgadWMGeGKEKbLAfBcRdMySVNrX9QTmnf (0.0004435 BTC - Output)
156MijasU1ohN22qgFusBiBFUrg4NQG2h3 (0.0000365 BTC - Output)

Sender

1BHUAm4Zb5zz5gDrPmXbvHjETzXAUEecp7 - (Spent) 0.00113384 BTC

Total amount

0.00113384 BTC

Summary	
Size	781 (bytes)
Weight	3124
Received Time	2018-09-25 14:29:54
Included In Blocks	543028 (2018-09-25 15:56:10 + 86 minutes)
Confirmations	21456
Visualize	View Tree Chart

Block number
& timestamp

Confirmations

Inputs and Outputs	
Total Input	0.00120395 BTC
Total Output	0.00113384 BTC
Fees	0.00007011 BTC
Fee per byte	8.977 sat/B
Fee per weight unit	2.244 sat/WU
Estimated BTC Transacted	0.00113384 BTC
Scripts	Hide scripts & coinbase

Addresses

- Like an IBAN (or email)
- You send bitcoins to a person by sending bitcoins to one of their addresses
- You can have as many addresses as you want
- No need to be online to create an address
- Pseudonymous: a unique address used for each transaction
- Wallet: the application that controls a user’s addresses

Development

- Local blockchains:
  - Used for local development
  - Instant mining
  - Very small in size
- You can use a local Ethereum blockchain online with Remix
- Testnets:
  - Used for testing and experimenting
  - Very useful, specifically for smart contract development
  - Different blockchain and different genesis block
  - Coins with no real value, separated and distinct from actual coins
  - Different ports and DNS seeds
  - Ethereum: Goerli, Sepolia (depricated: Ropsten)
- In class we will use our own Ethereum testnet
- Main net (production):
  - Blockchains are immutable and irrevertible
  - You cannot simply update your code once deployed!

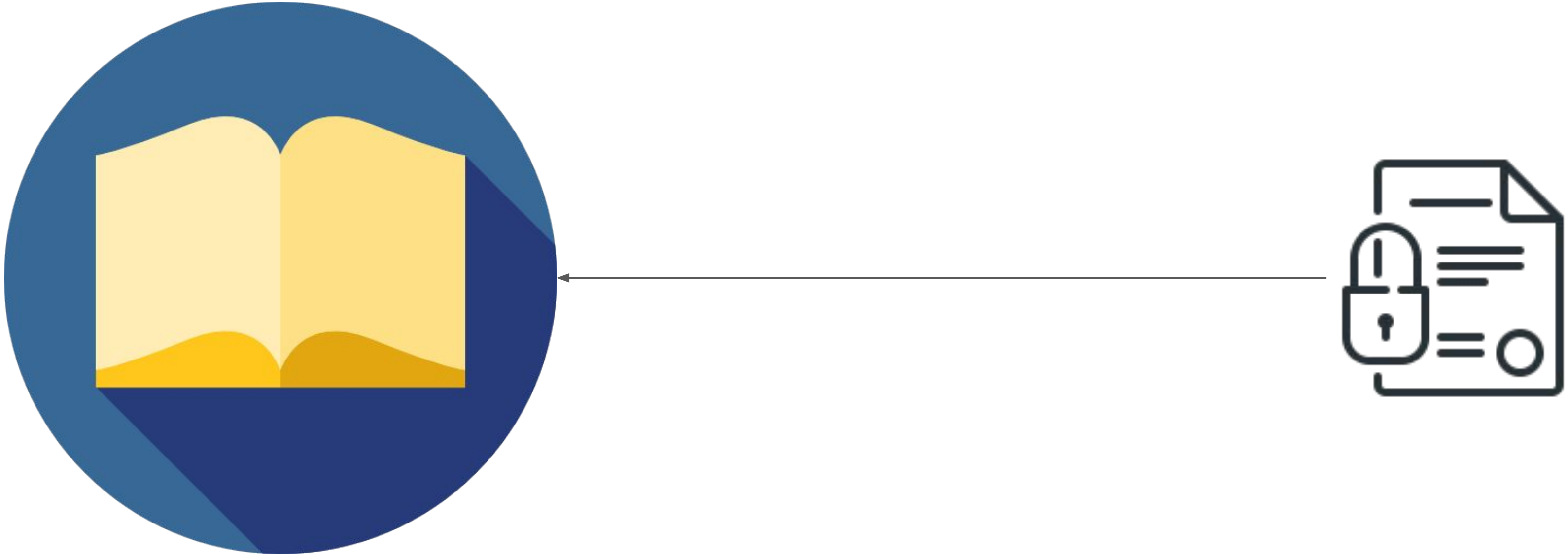
Explorers

- An online blockchain browser
- Displays the contents of individual blocks and transactions
- Displays the transaction histories and balances of addresses
- Quick way to see if your transactions are confirmed
- Bitcoin:
  - https://www.blockchain.com/explorer (Mainnet)
  - https://www.blockchain.com/explorer/assets/btc-testnet (Testnet)
- Ethereum:
  - https://etherscan.io/ (Mainnet)
  - https://goerli.etherscan.io/ (Testnet)
  - https://ropsten.etherscan.io/ (Depricated Testnet)

Faucet

- A way to get test coins, necessary for any testing
- Ethereum:
    - https://goerli-faucet.mudit.blog/
    - https://faucet.metamask.io/
- Bitcoin:
    - https://bitcoinfaucet.uo1.net/
    - https://block.io/ (Online testnet wallet)

Smart contract



From Money to Smart Contracts

- Since we have created the book, why stop at recording monetary transactions?
- We can encode in the book’s pages arbitrary relations between accounts
- Scribes can perform tasks and take action, like verifying that stakeholders comply to contractual obligations