CS251 Fall 2021

(https://cs251.stanford.edu)

Cryptocurrencies and Blockchain Technologies

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[videos on canvas, discussions on edstem, homework on gradescope]

What is a blockchain?

Abstract answer: a blockchain provides

- coordination between many parties,
- when there is no single trusted party

if trusted party exists ⇒ no need for a blockchain

[financial systems: often no trusted party]

What is all the excitement about?

(1) Basic application: a digital currency (stored value)

- Current largest: Bitcoin (2009), Ethereum (2015)
- Global: accessible to anyone with an Internet connection

Opinion

The New York Times

Bitcoin Has Saved My Family

“Borderless money” is more than a buzzword when you live in a collapsing economy and a collapsing dictatorship.

By Carlos Hernández

Mr. Hernández is a Venezuelan economist.

Feb. 23, 2019

What is all the excitement about?

(2) Beyond stored value: **decentralized applications (DAPPs)**

- **DeFi**: financial instruments managed by public programs
  - examples: stablecoins, lending, exchanges, ...
- **Asset management** (NFTs)**:** art, game assets, domain names.
- **Decentralized organizations** (DAOs): (decentralized governance)
  - DAOs for investment, for donations, for collecting art, etc.

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(3) New programming model: writing decentralized programs

Assets managed by DAPPs

Sep. 2021

Transaction volume

Sep. 2021

	24h volume
Bitcoin • BTC	$30.6B
Ethereum • ETH	$19.2B
Cardano • ADA	$2.3B

Central Bank Digital Currency (CBDC)


China Moves Forward With National Digital Currency

by Sam Klebanov — September 3, 2021

What is a blockchain?

user facing tools (cloud servers)

applications (DAPPs, smart contracts)

compute layer (blockchain computer)

consensus layer

Consensus layer (informal)

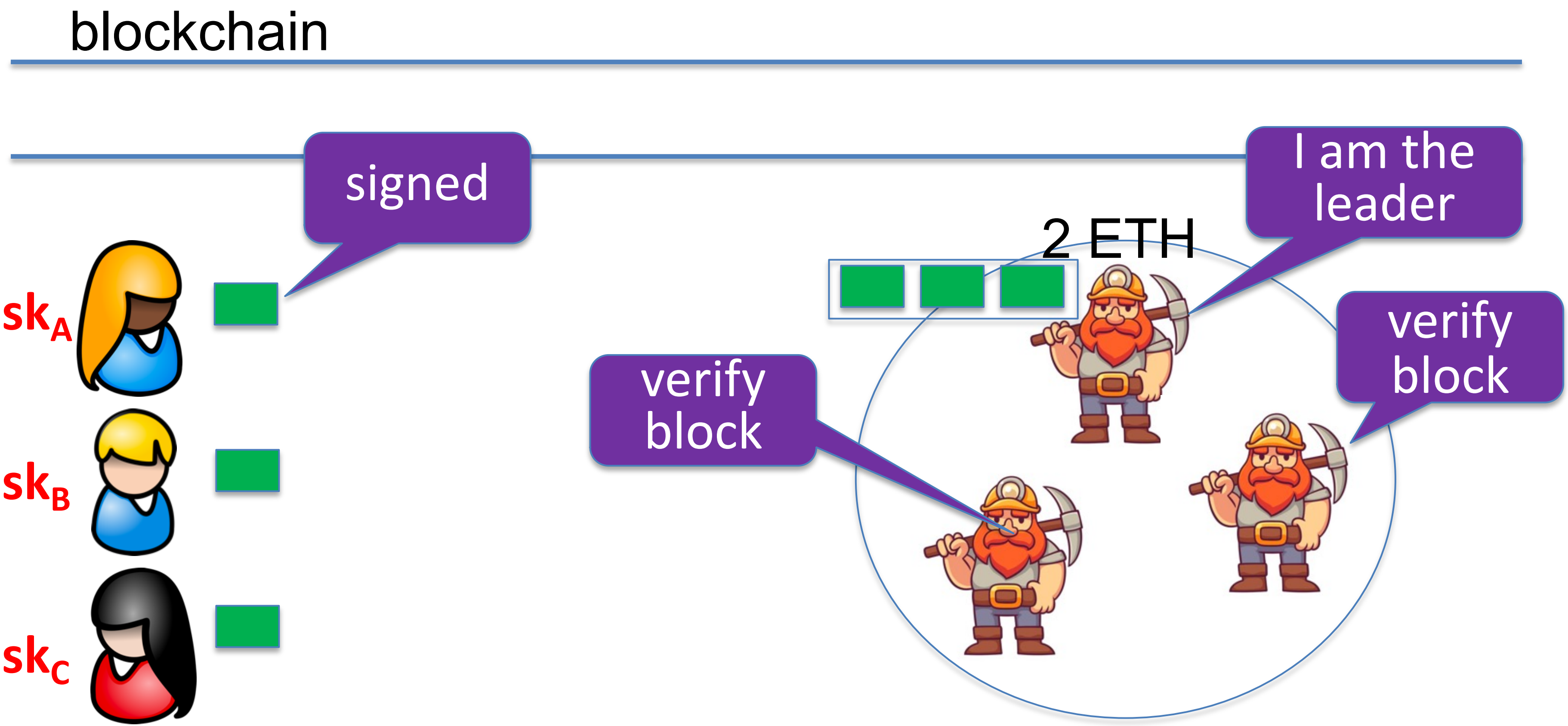
achieved by replication

A **public** append-only data structure:

- **Persistence**: once added, data can never be removed*
- **Safety**: all honest participants have the same data**
- **Liveness:** honest participants can add new transactions
- **Open(?)**: anyone can add data (no authentication)

consensus layer

How are blocks added to chain?



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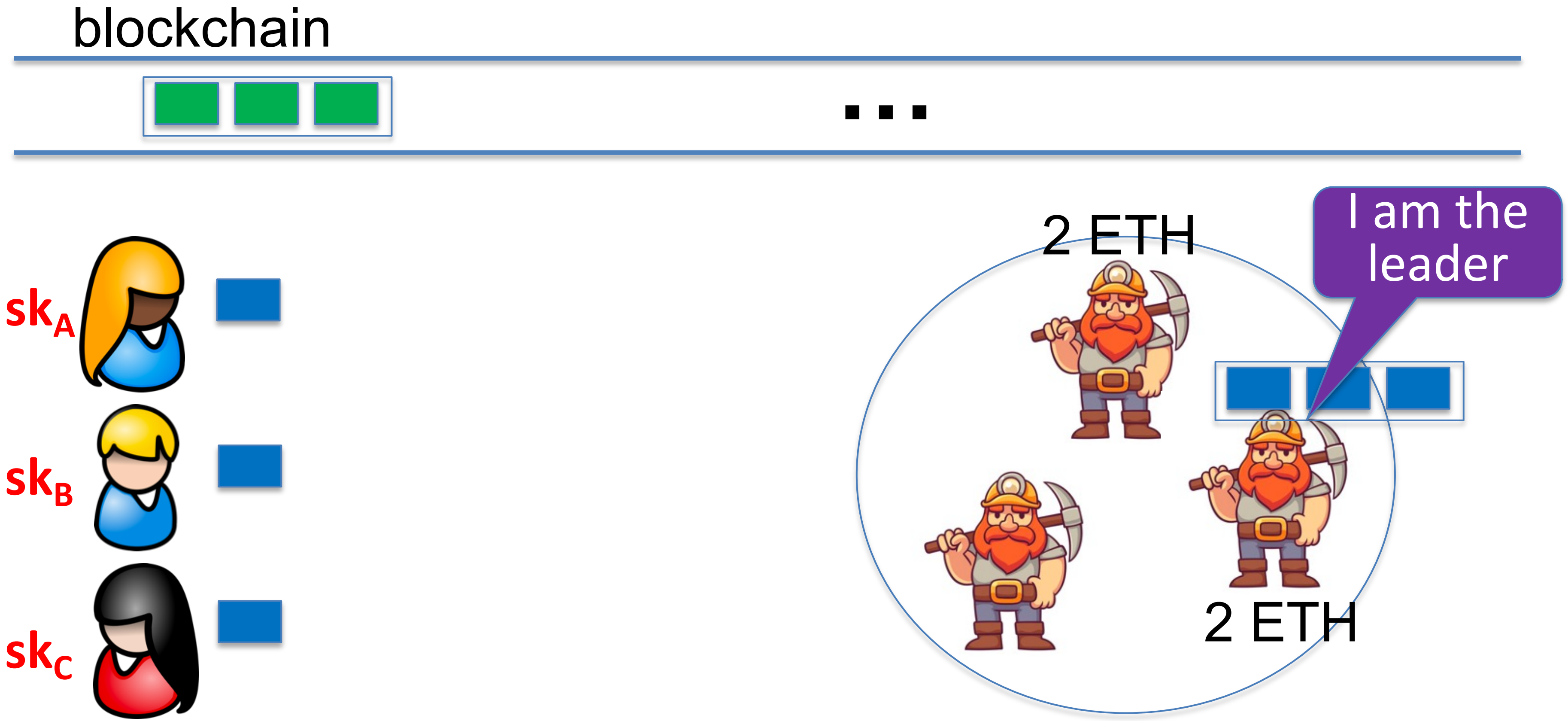
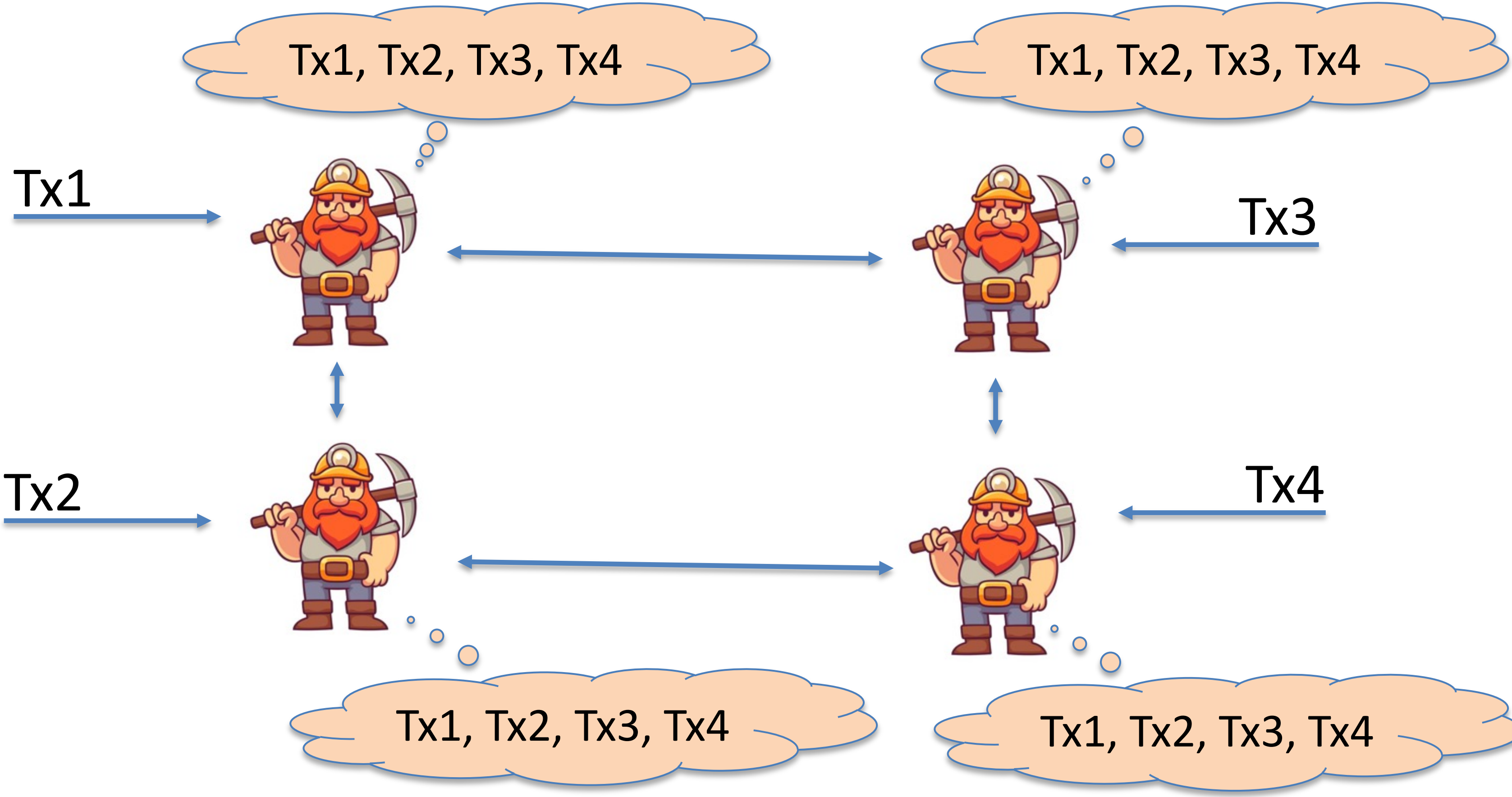
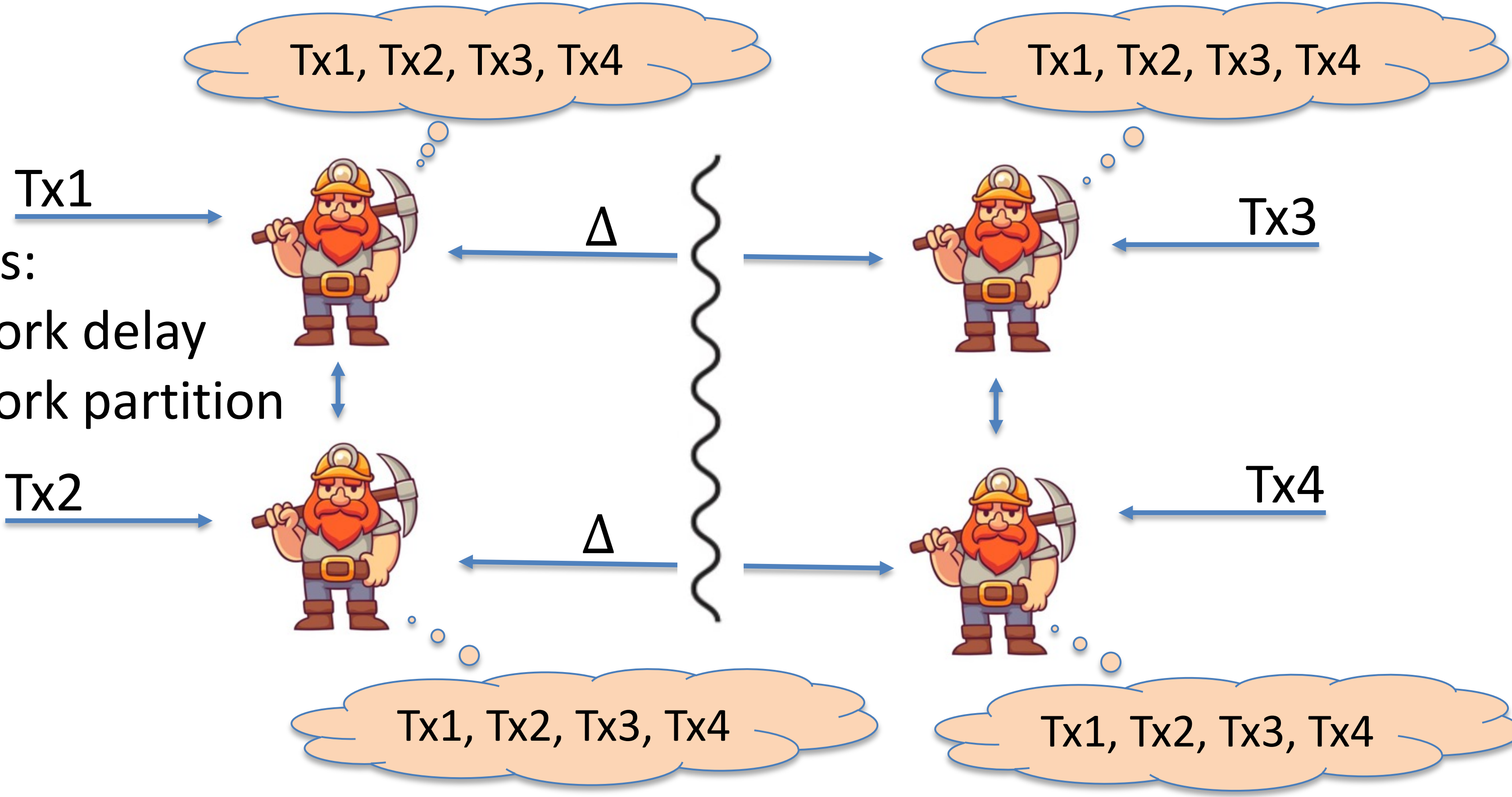


Why is consensus a hard problem?



Why is consensus a hard problem?

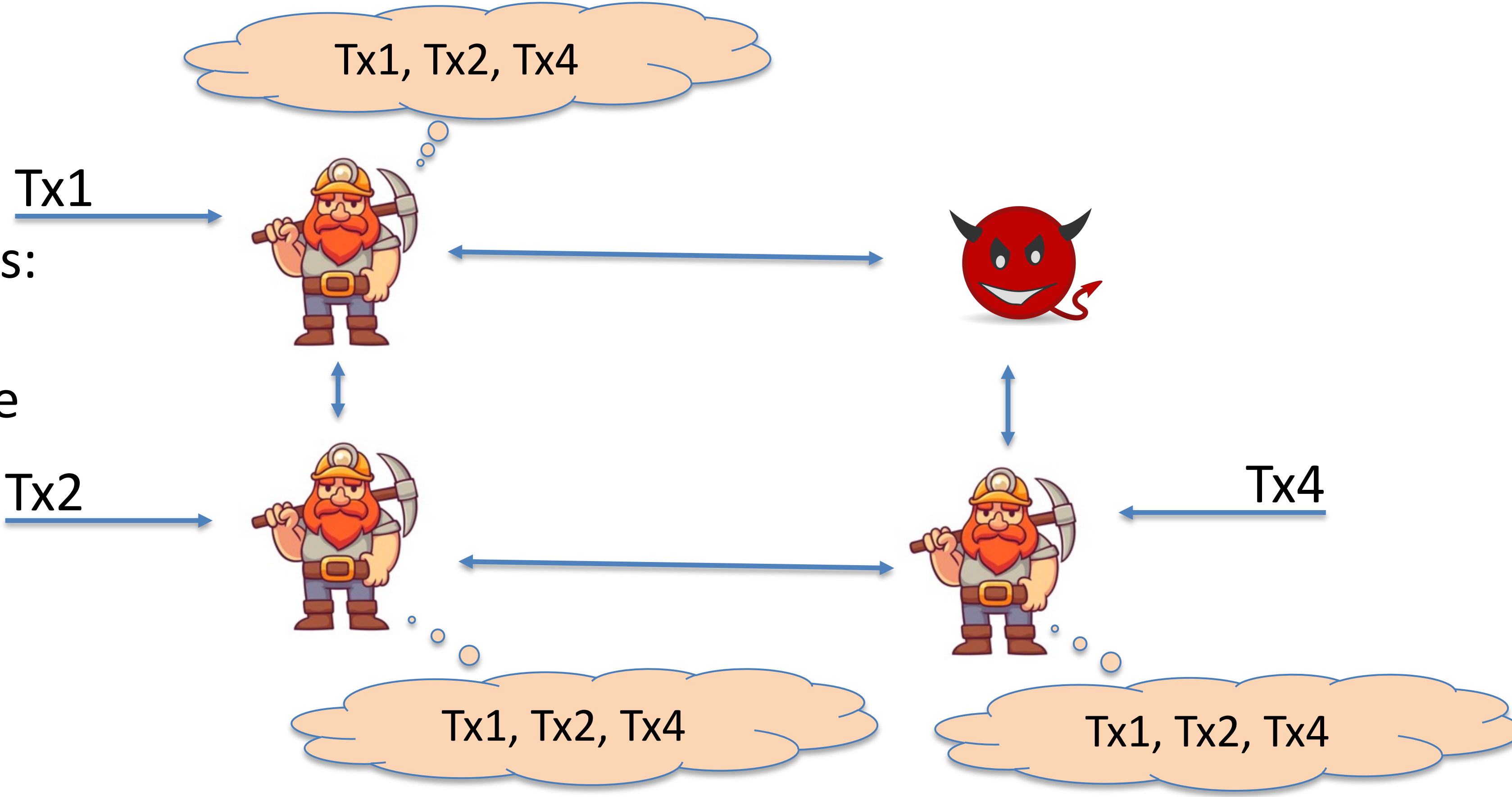
Problems:
- Network delay
- Network partition



Why is consensus a hard problem?

Problems:

- crash
- malice



The blockchain computer

DAPP logic is encoded in a program that runs on blockchain

- Rules are enforced by a public program (public source code)

  ⇒ **transparency**: no single trusted 3^{rd} party

- The DAPP program is executed by parties who create new blocks

  ⇒ **public verifiability**: everyone can verify state transitions

compute layer

consensus layer

Decentralized applications (DAPPS)

Run on blockchain computer

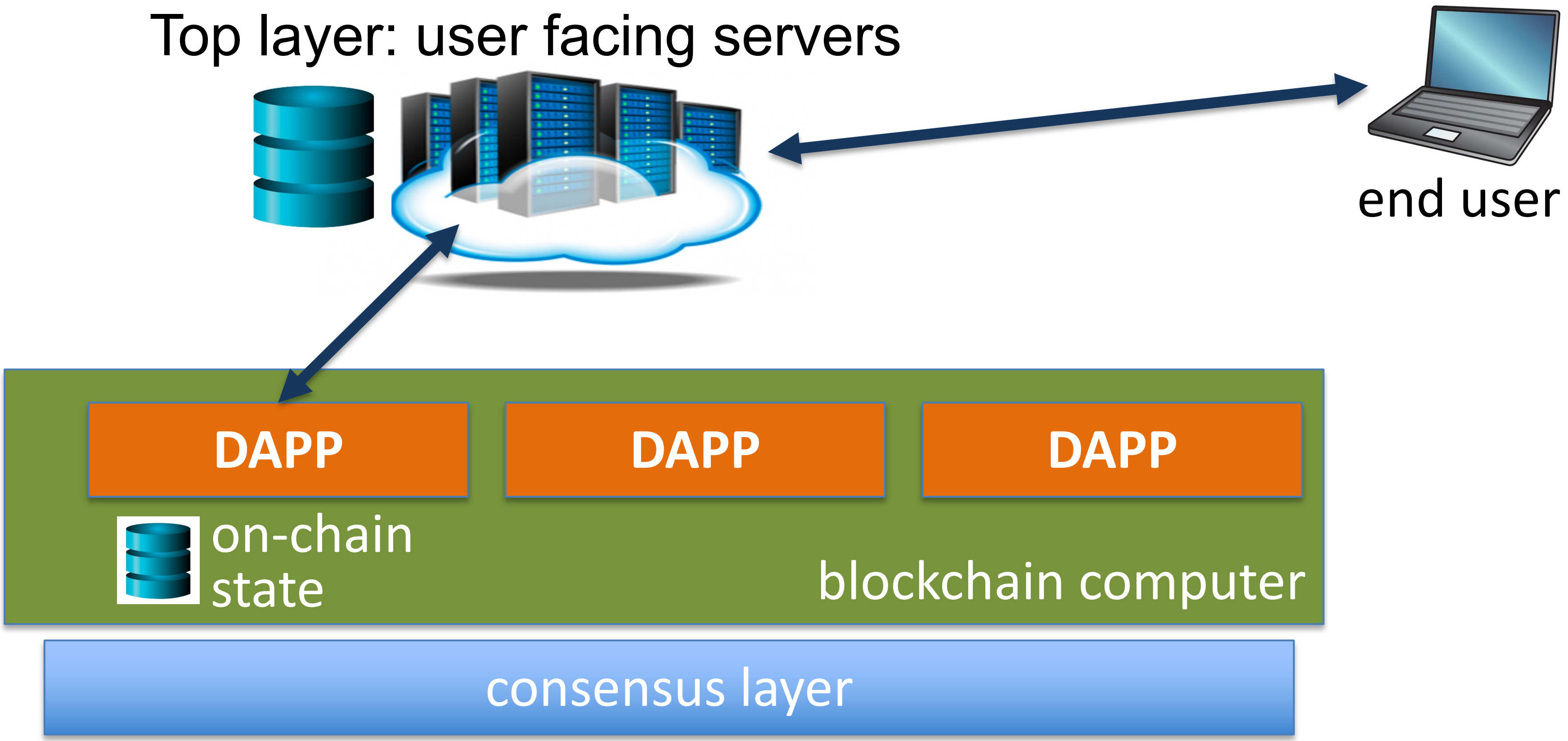
δY/δX

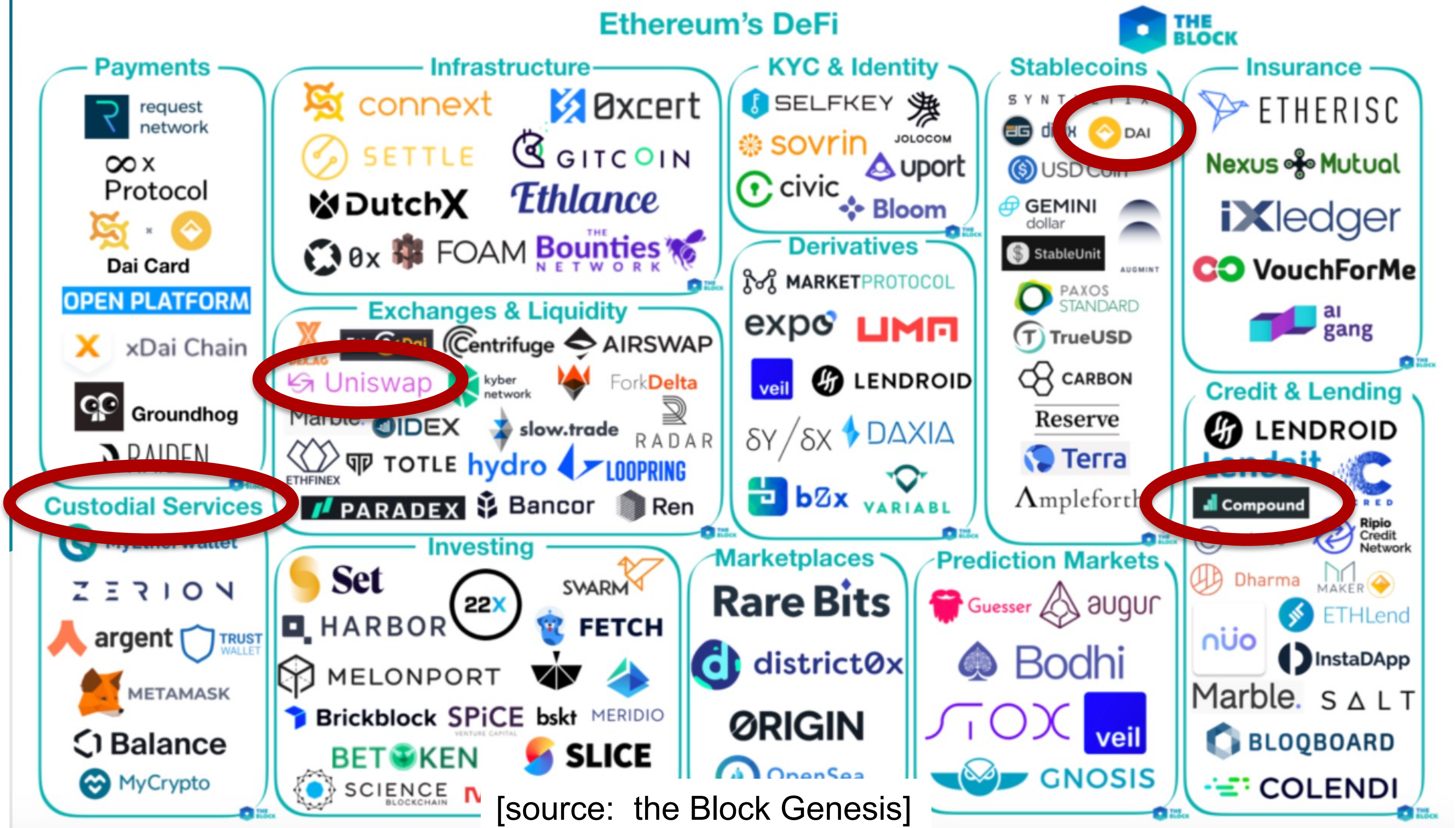
applications (DAPPs, smart contracts)

blockchain computer

consensus layer

Common DAPP architecture



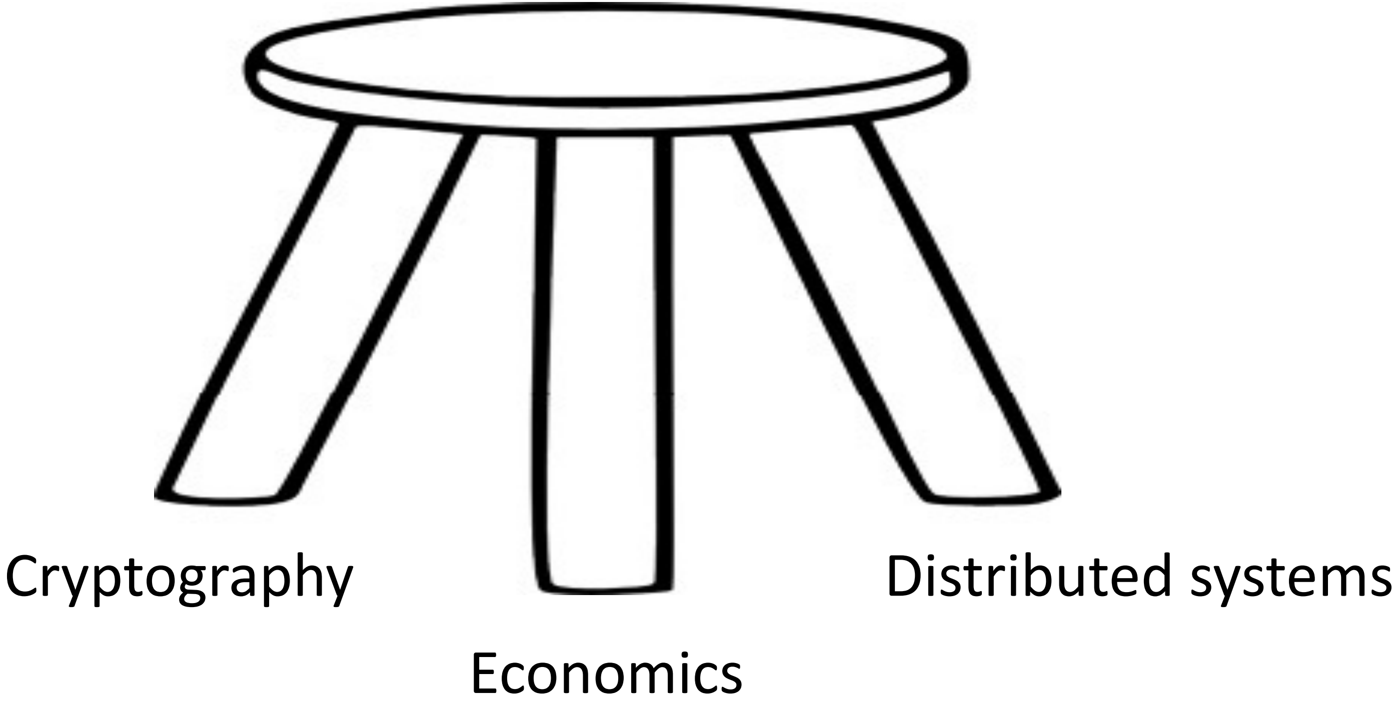


[source: the Block Genesis]

lots of experiments …

				locked
1.	Aave	Multichain	Lending	$16.00B
2.	Maker	Ethereum	Lending	$13.32B
3.	Curve Finance	Multichain	DEXes	$12.73B
4.	InstaDApp	Ethereum	Lending	$12.53B
5.	Compound	Ethereum	Lending	$10.91B
6.	Uniswap	Ethereum	DEXes	$6.54B
7.	Convex Finance	Ethereum	Assets	$6.51B

This course



Course organization

1. The starting point: Bitcoin mechanics
2. Consensus protocols
3. Ethereum and decentralized applications
4. Economics of decentralized applications
5. Scaling the blockchain: 10K Tx/sec
6. Private transactions on a public blockchain
   (SNARKs and zero knowledge proofs)
7. Interoperability among chains: bridges and wrapped coins

Course organization

cs251.stanford.edu

- Three homework problems, four projects, final exam(?)
- Optional weekly sections on Friday

Please tell us how we can improve …
Don’t wait until the end of the quarter

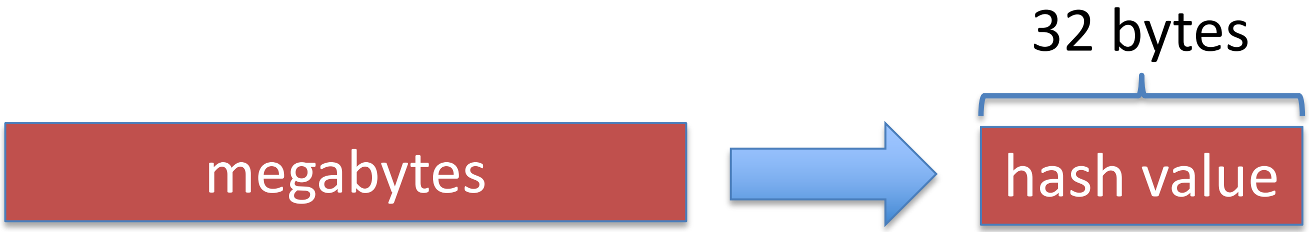
Let’s get started …

Cryptography Background

(1) cryptographic hash functions

An efficiently computable function $H: M \rightarrow T$

where $|M| \gg |T|$



$T = \{0,1\}^{256}$

Collision resistance

<u>Def</u>: a **<u>collision</u>** for $H: M \to T$ is pair $x \neq y \in M$ s.t. $H(x) = H(y)$

$|M| \gg |T|$ implies that <u>many</u> collisions exist

<u>Def</u>: a function $H: M \to T$ is **<u>collision resistant</u>** if it is "hard" to find even a single collision for H (we say H is a CRHF)

Example: **SHA256**: $\{x$: len$(x)<2^{64}$ bytes$\} \to \{0,1\}^{256}$

details in CS255

Application: committing to data on a blockchain

Alice has a large file m. She posts $h = H(m)$ (32 bytes)

Bob reads h. Later he learns m' s.t. $H(m') = h$

H is a CRHF $\Rightarrow$ Bob is convinced that $m' = m$

(otherwise, m and m' are a collision for H)

We say that $h = H(m)$ is a **binding commitment** to m

(note: not hiding, h may leak information about m)

Committing to a list (of transactions)

Alice has $S = (m_1, m_2, \ldots, m_n)$

32 bytes

Goal:

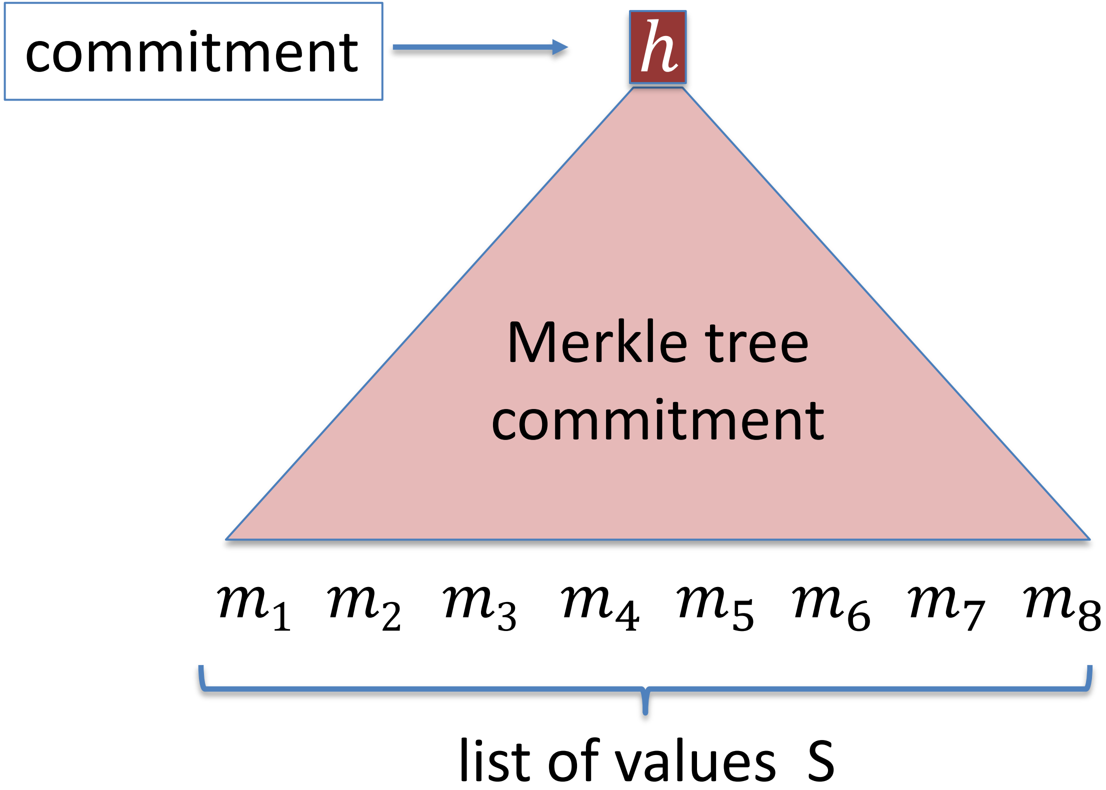
- Alice posts a short binding commitment to S, $h = \text{commit}(S)$
- Bob reads h. Given $(m_i,\ \text{proof}\ \pi_i)$ can check that $S[i] = m_i$

Bob runs $\text{verify}(h, i, m_i, \pi_i) \rightarrow$ accept/reject

security: adv. cannot find (S, i, m, π) s.t. $m \neq S[i]$ and

$\text{verify}(h, i, m, \pi) = \text{accept}$ where $h = \text{commit}(S)$

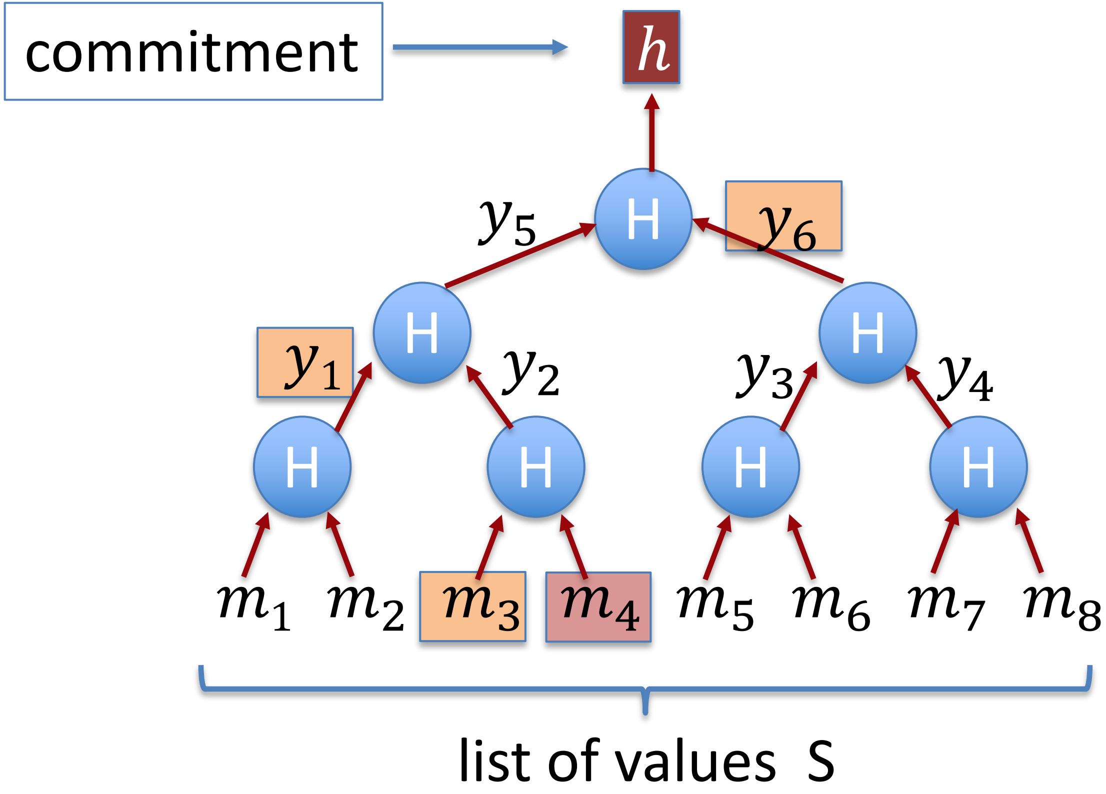
Merkle tree (Merkle 1989)



Goal:

- commit to list S of size n
- Later prove $S[i] = m_i$

Merkle tree (Merkle 1989)



Goal:

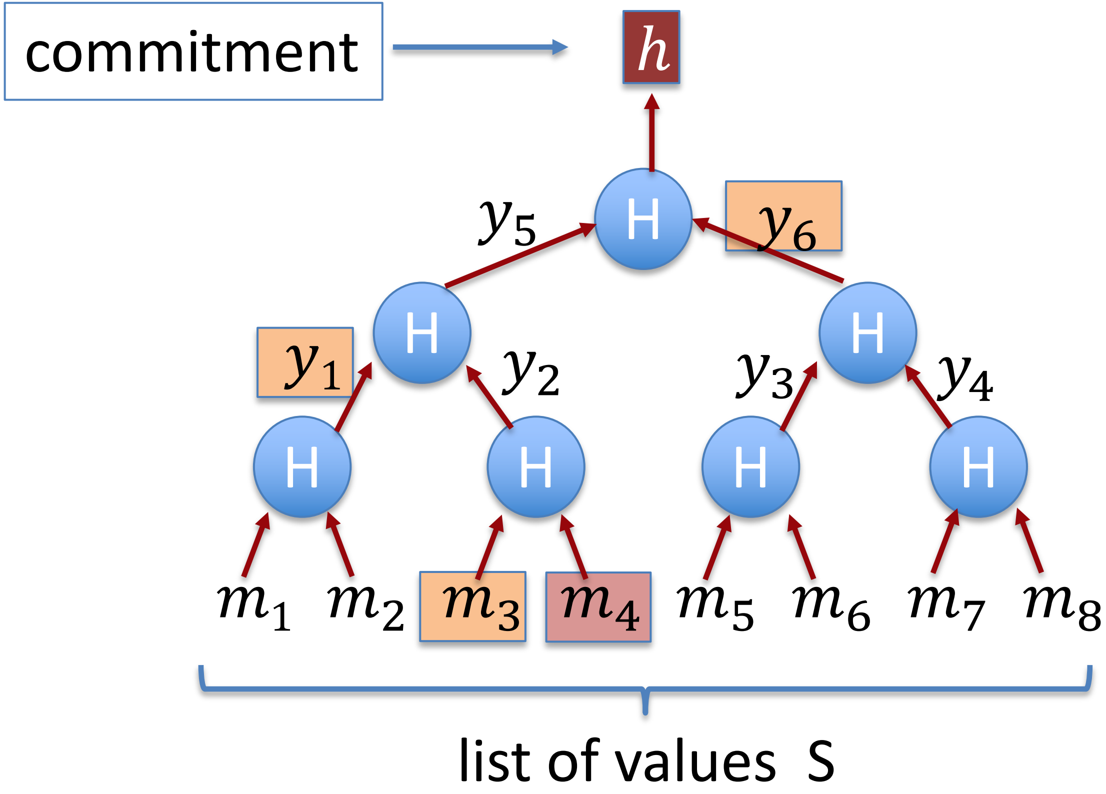
- commit to list S of size n
- Later prove $S[i] = m_i$

To prove $S[4] = m_4$,

proof $\pi = (m_3, y_1, y_6)$

length of proof: $\log_2 n$

Merkle tree (Merkle 1989)



To prove $S[4] = m_4$,

proof $\pi = (m_3, y_1, y_6)$

Bob does:

$y_2 \leftarrow H(m_3, m_4)$

$y_5 \leftarrow H(y_1, y_2)$

$h' \leftarrow H(y_5, y_6)$

accept if $h = h'$

Merkle tree (Merkle 1989)

Thm: H CRHF $\Rightarrow$ adv. cannot find (S, i, m, π) s.t. $m \neq S[i]$ and

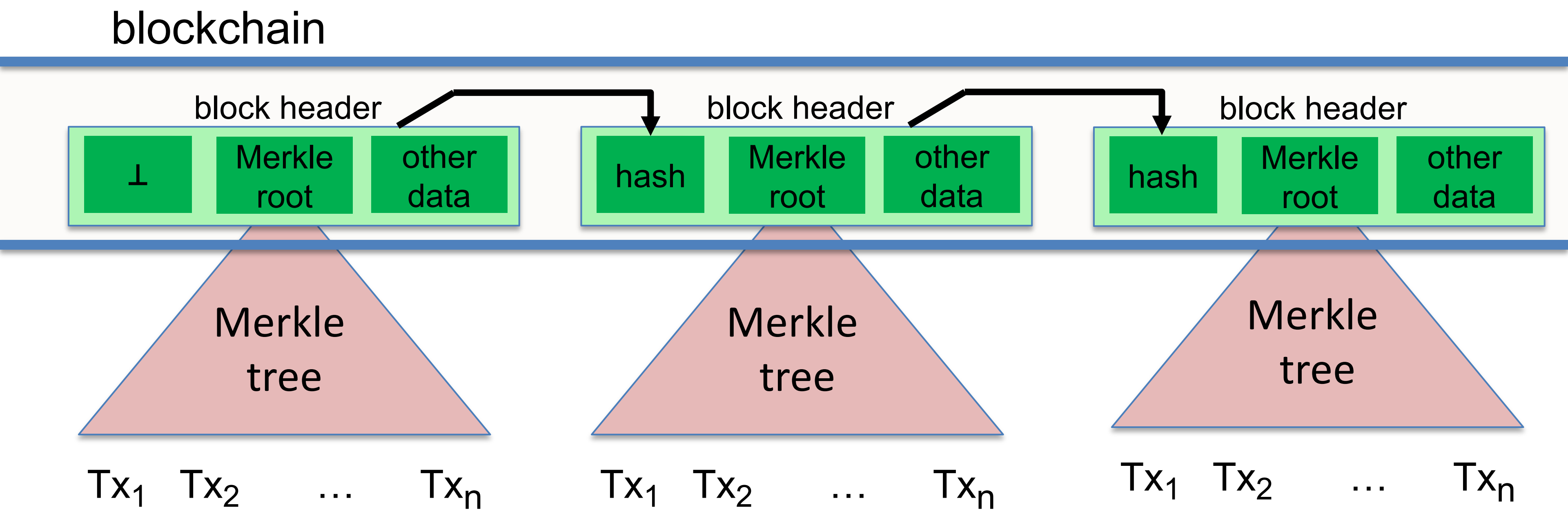
$$\text{verify}(h, i, m, \pi) = \text{accept} \quad \text{where} \quad h = \text{commit}(S)$$

(to prove, prove the contra-positive)

How is this useful? Super useful. Example

- When writing a block of transactions S to the blockchain, suffices to write commit(S) to chain. Keep chain small.
- Later, can prove contents of every Tx.

Abstract block chain



Merkle proofs are used to prove that a Tx is “on the block chain”

Another application: proof of work

<u>Goal</u>: computational problem that

- takes time $\Omega(D)$ to solve, but
- solution takes time O(1) to verify

(D is called the **difficulty**)

How? $H: X \times Y \to \{0,1,2, \ldots, 2^n - 1\}$ e.g. $n = 256$

- puzzle: input $x \in X$, output $y \in Y$ s.t. $H(x, y) < 2^n/D$
- verify(x, y): accept if $H(x, y) < 2^n/D$

Another application: proof of work

Thm: if H is a "random function" then the best algorithm requires D evaluations of H in expectation.

Note: this is a parallel algorithm

$\Rightarrow$ the more machines I have, the faster I solve the puzzle.

Proof of work is used in some consensus protocols (e.g., Bitcoin)

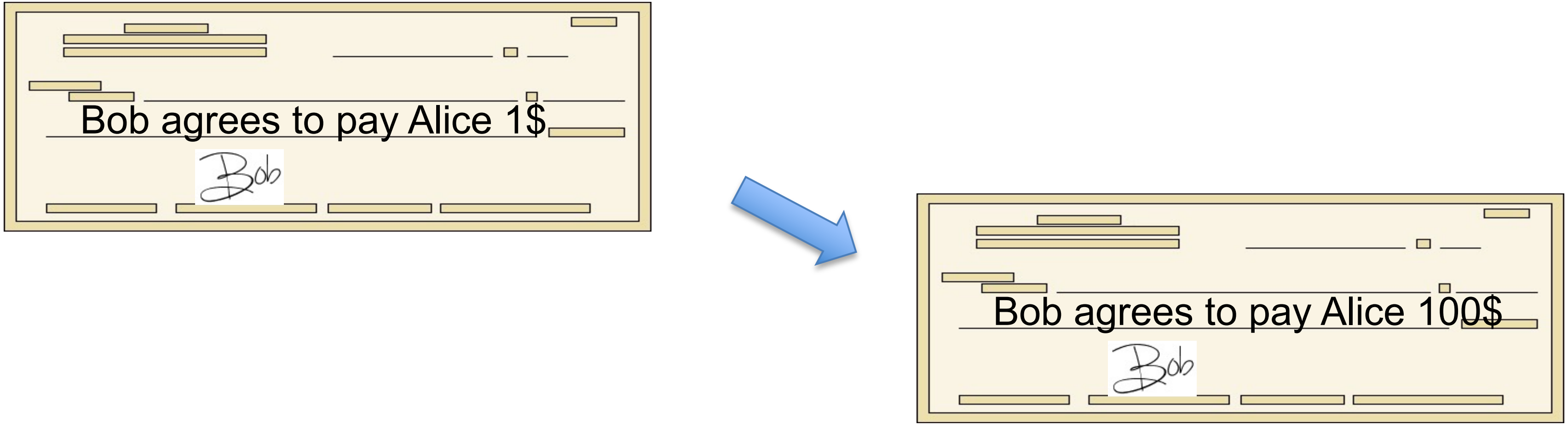
Bitcoin uses $H(x, y) = \mathrm{SHA256}(\mathrm{SHA256}(x.y))$

Cryptography background: Digital Signatures

How to authorize a transaction

Signatures

Physical signatures: bind transaction to author

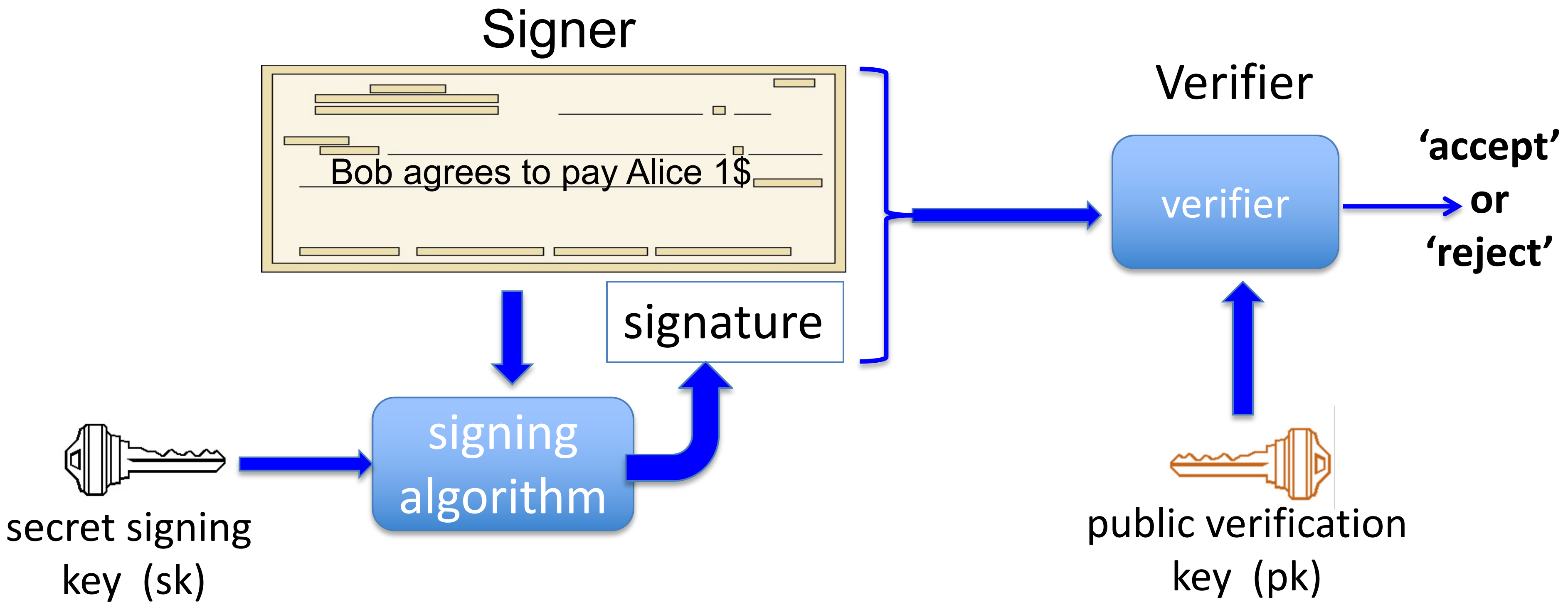


Problem in the digital world:

anyone can copy Bob's signature from one doc to another

Digital signatures

Solution: make signature depend on document



Digital signatures: syntax

Def: a signature scheme is a triple of algorithms:

- **Gen**(): outputs a key pair (pk, sk)
- **Sign**(sk, msg) outputs sig. σ
- **Verify**(pk, msg, σ) outputs 'accept' or 'reject'

Secure signatures: (informal)

Adversary who sees signatures on many messages of his choice, cannot forge a signature on a new message.

Families of signature schemes

1. RSA signatures (old … not used in blockchains):
   - long sigs and public keys (≥256 bytes), fast to verify

2. Discrete-log signatures: Schnorr and ECDSA (Bitcoin, Ethereum)
   - short sigs (48 or 64 bytes) and public key (32 bytes)

3. BLS signatures: 48 bytes, aggregatable, easy threshold

   (Ethereum 2.0, Chia, Dfinity)

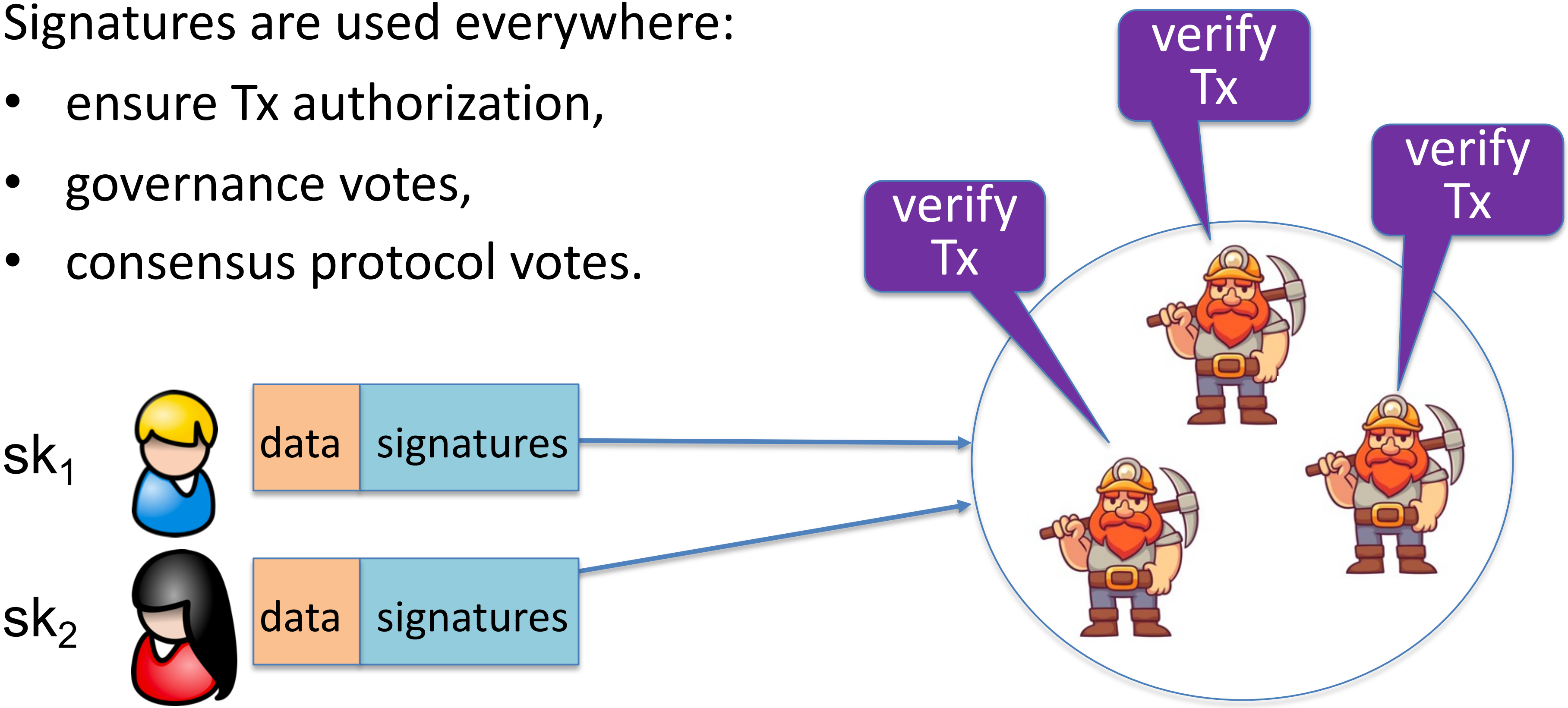
4. Post-quantum signatures: long (≥768 bytes)

details in CS255

Signatures on the blockchain

Signatures are used everywhere:

- ensure Tx authorization,
- governance votes,
- consensus protocol votes.



END OF LECTURE

Next lecture: the Bitcoin blockchain