CSCI 1515 Applied Cryptography

This Lecture:

- Practical Constructions of Block Cipher (Continued)
- Secure Hardware: Intel SGX, HSM
- Blockchain

Block Cipher

$$F: \{0,1\}^{\lambda} \times \{0,1\}^{n} \to \{0,1\}^{n}$$

λ: key length

n: block length

It is assumed to be a pseudorandom permutation (PRP).

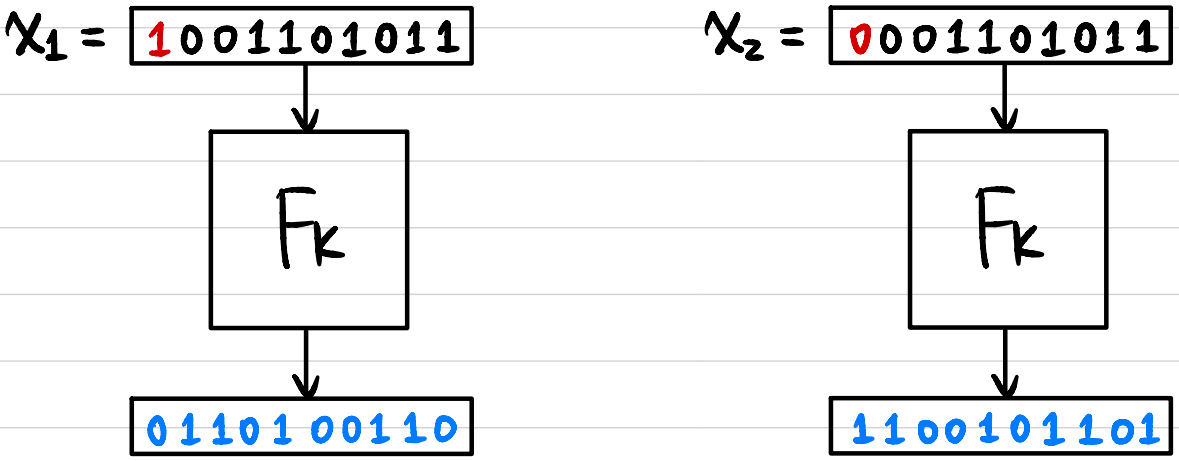
Construction: Advanced Encryption Standard (AES)

- $\lambda = 128/192/256$, $n = 128$
- Standardized by NIST in 2001
- Competition 1997-2000

Before AES: Data Encryption Standard (DES)

- $\lambda = 56$, $n = 64$

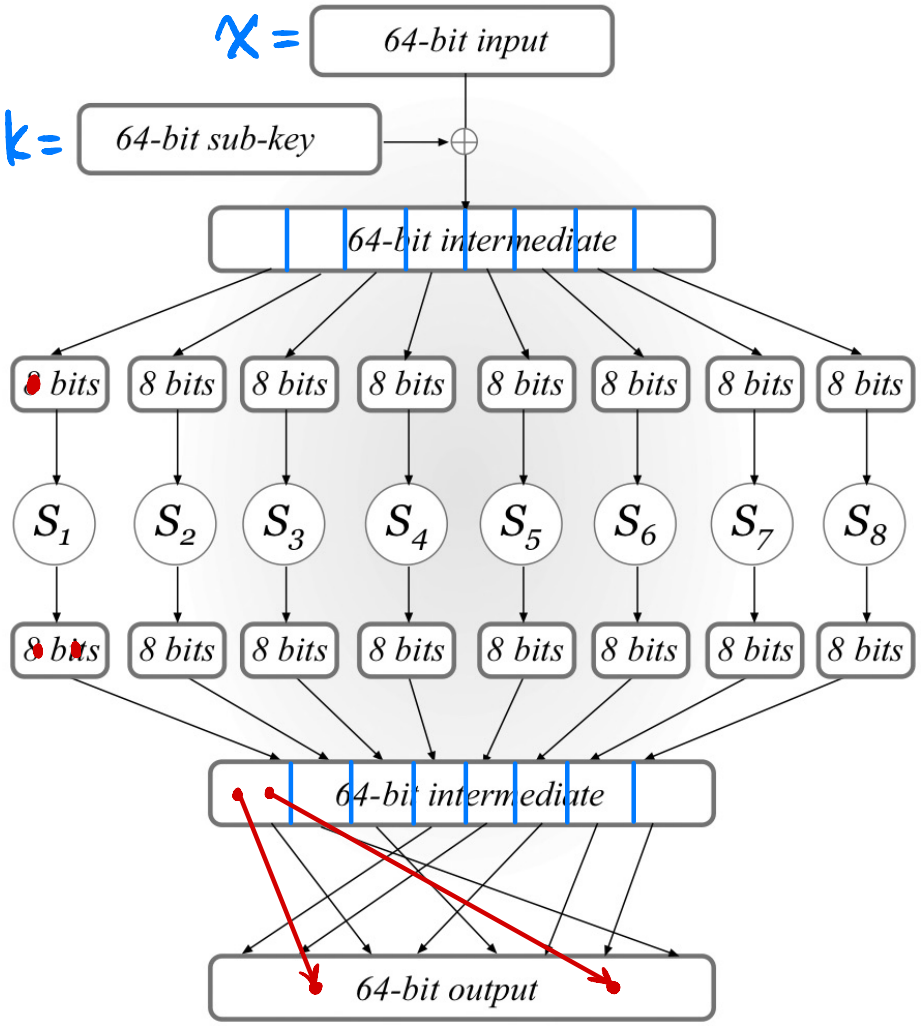
Substitution-Permutation Network (SPN)



Design Principle: "Avalanche Effect"

A one-bit change in the input should "affect" every bit of the output.

Substitution-Permutation Network (SPN)



A single round of SPN

"Confusion-Diffusion Paradigm"

Step 1: Key Mixing

$x := x \oplus k$

Step 2: Substitution (Confusion Step)

$S_i : \{0,1\}^8 \rightarrow \{0,1\}^8$ (S-box)

Public permutation / one-to-one map

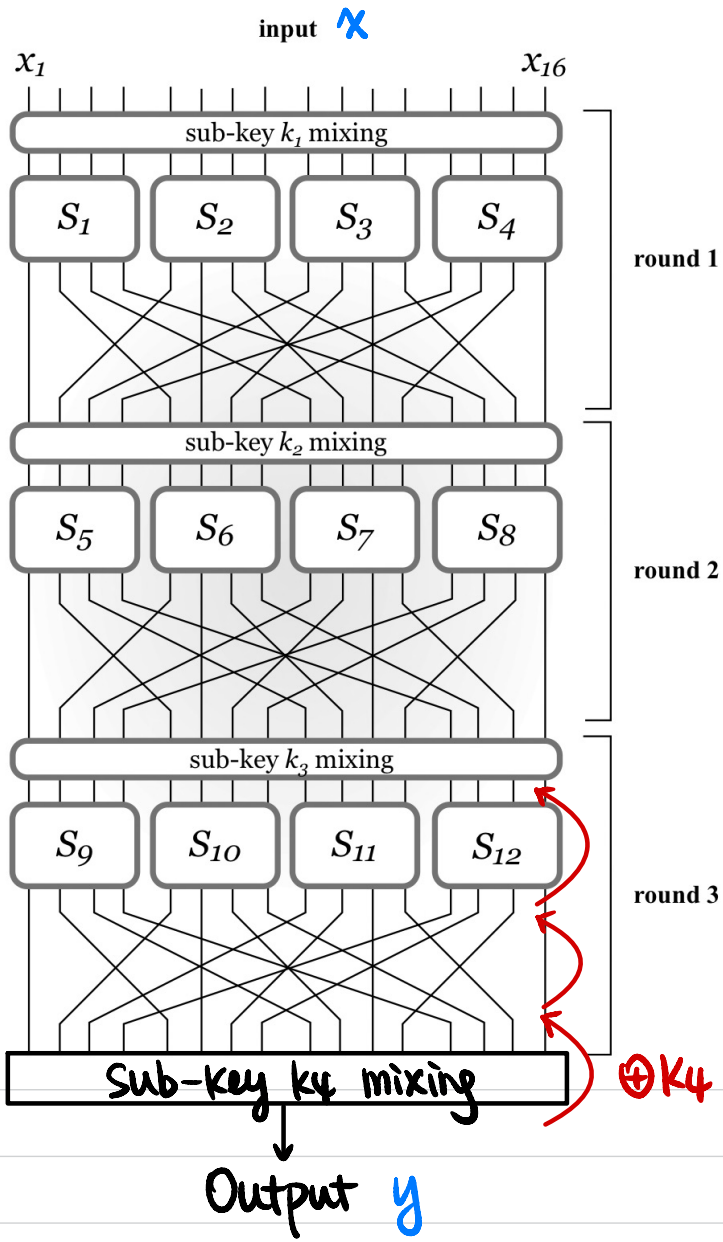
1-bit change of input
→ at least 2-bit change of output

Step 3: Permutation (Diffusion Step)

$P : [64] \rightarrow [64]$

Public mixing permutation
↓
affect input to multiple S-boxes next round

Substitution-Permutation Network (SPN)



An SPN is invertible given the master key.

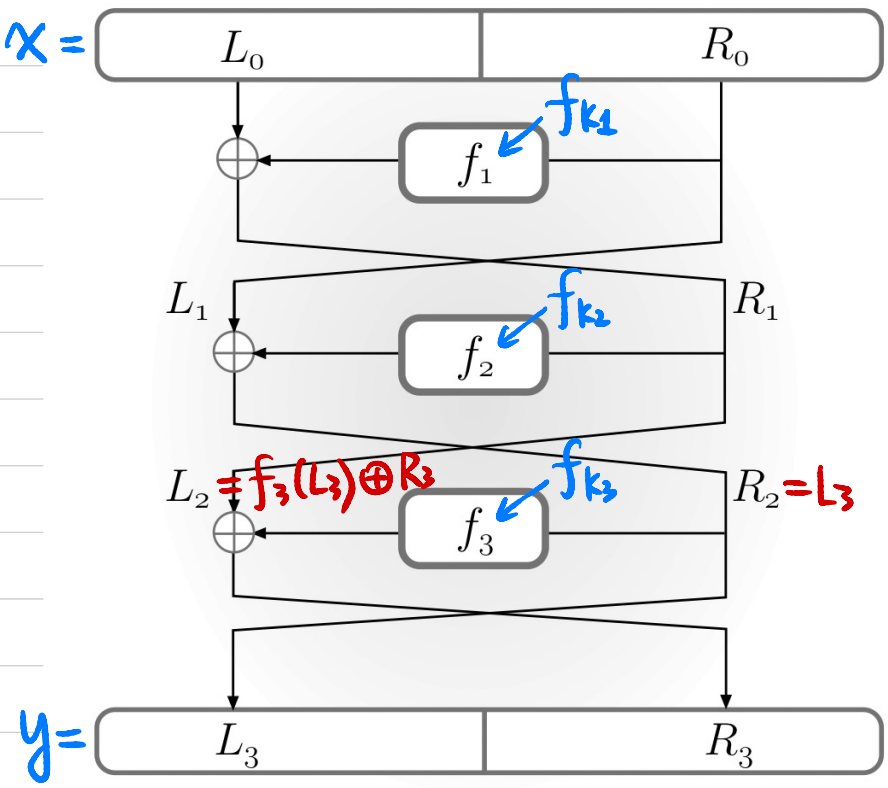
⇓

permutation

How to compute $F_k^{-1}(y)$?

Why do we need a final key mixing step ?

Feistel Network



3-round Feistel Network

$f_{k_i}: \{0,1\}^{n/2} \rightarrow \{0,1\}^{n/2}$

↑ round function

How to compute $F_k^{-1}(y)$?

Attacks on reduced-round Feistel Network

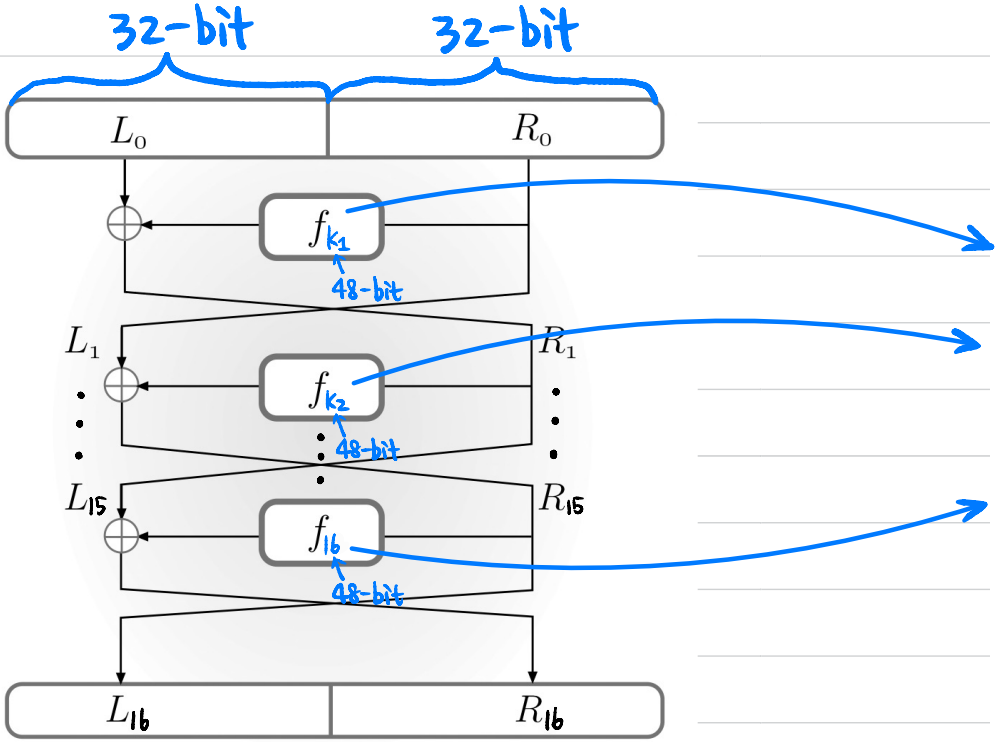
Data Encryption Standard (DES)

$F: \{0,1\}^\lambda \times \{0,1\}^n \to \{0,1\}^n$

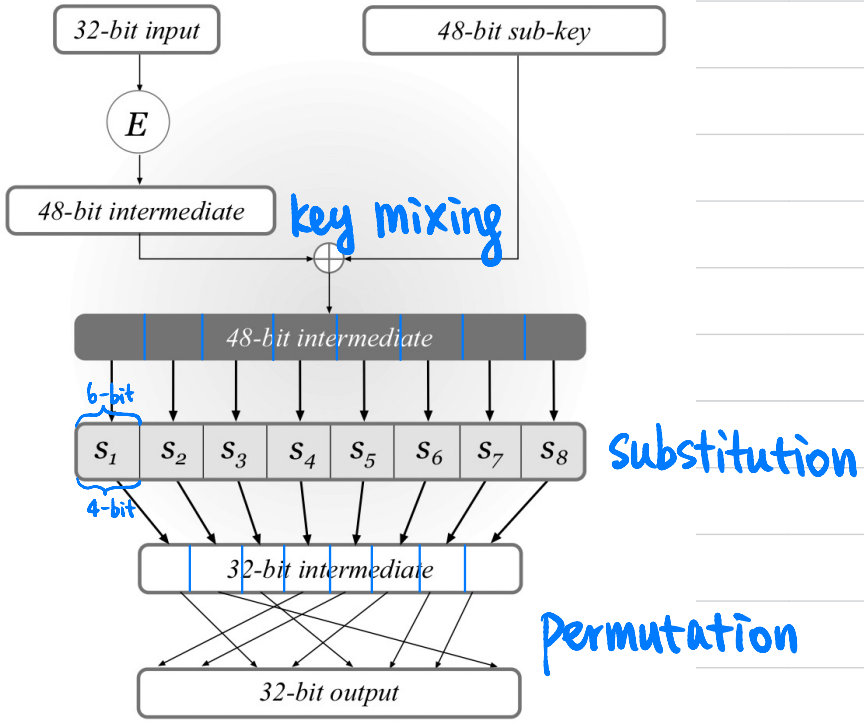
block length $n=64$

master key length $\lambda=56$

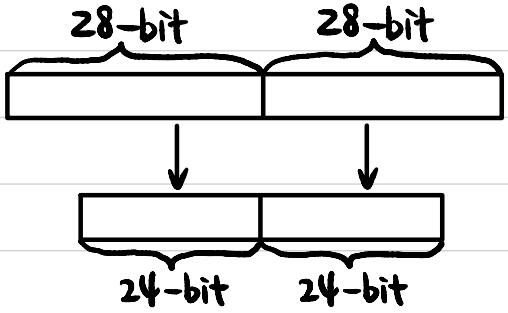
16-round Feistel Network



DES mangler function

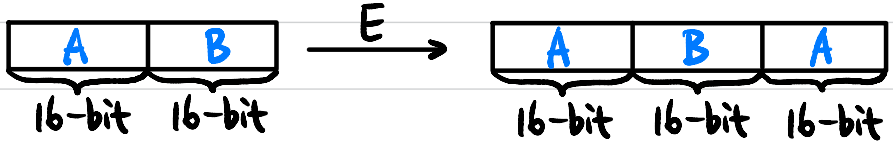


Key Schedule:



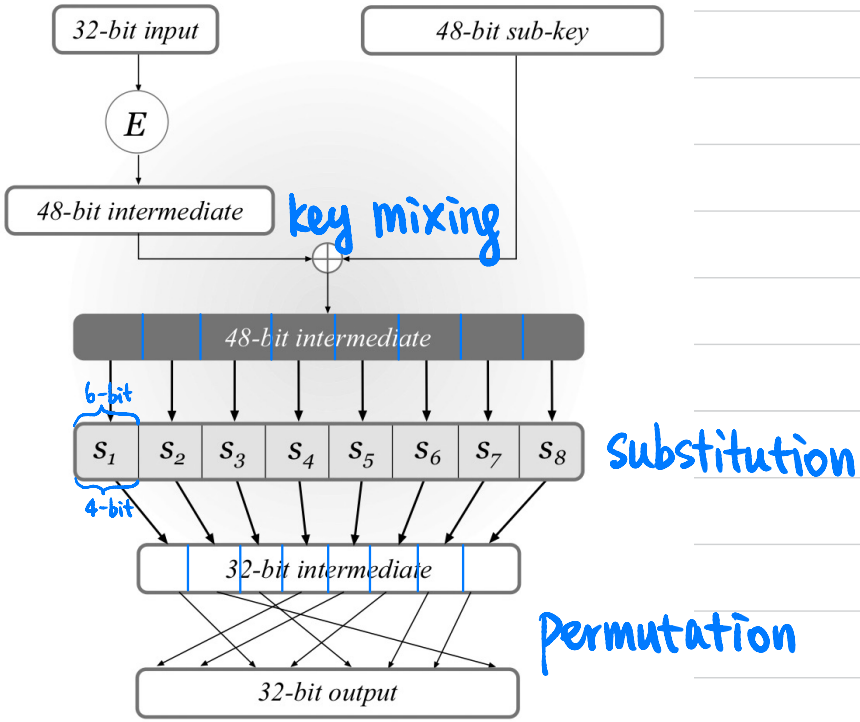
(master key)

E: expansion function



Data Encryption Standard (DES)

DES mangler function



S-box: $\{0,1\}^6 \rightarrow \{0,1\}^4$

① "4-to-1":

Exactly 4 inputs map to same output

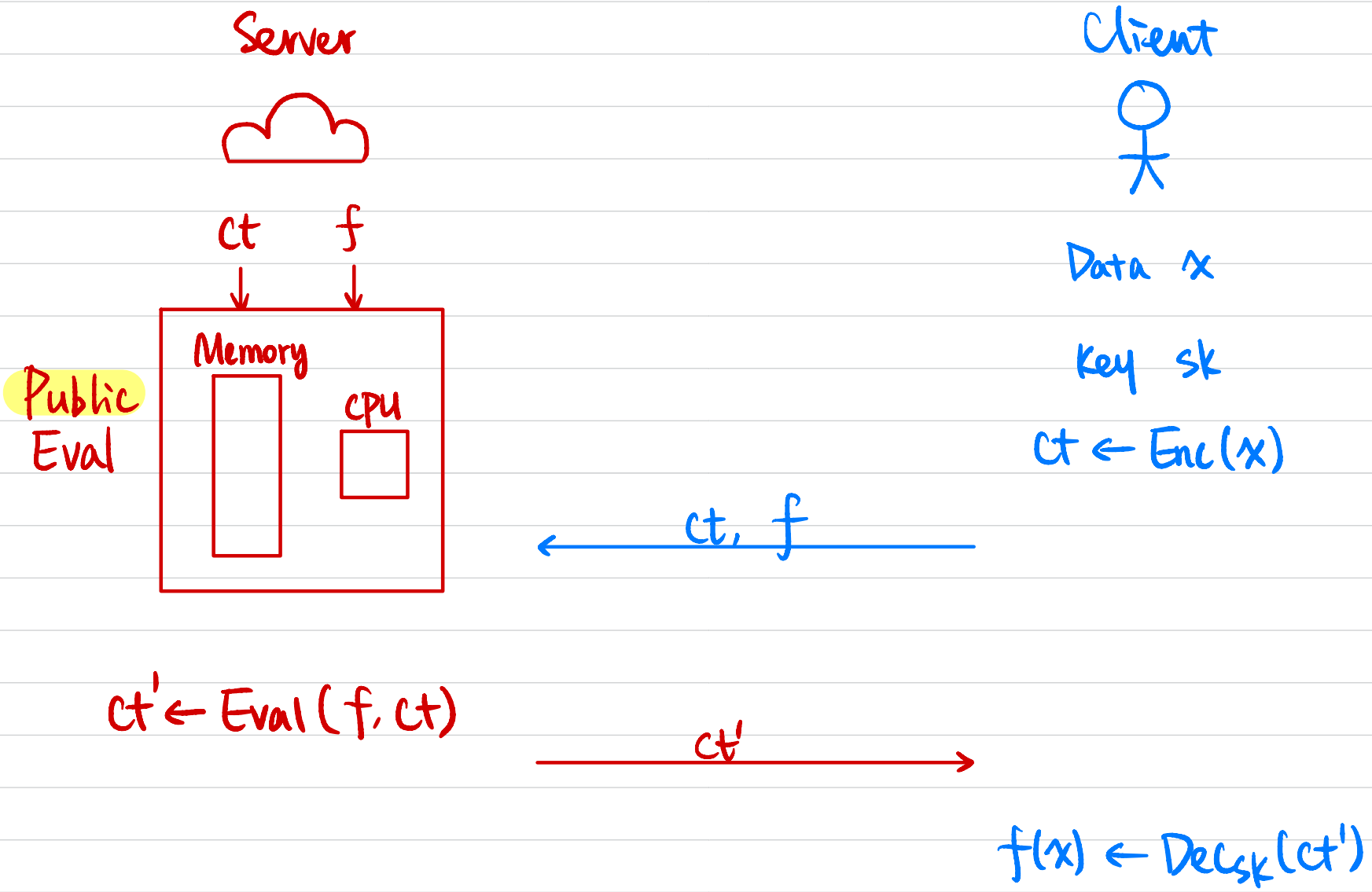
② 1-bit change of input

→ at least 2-bit change of output

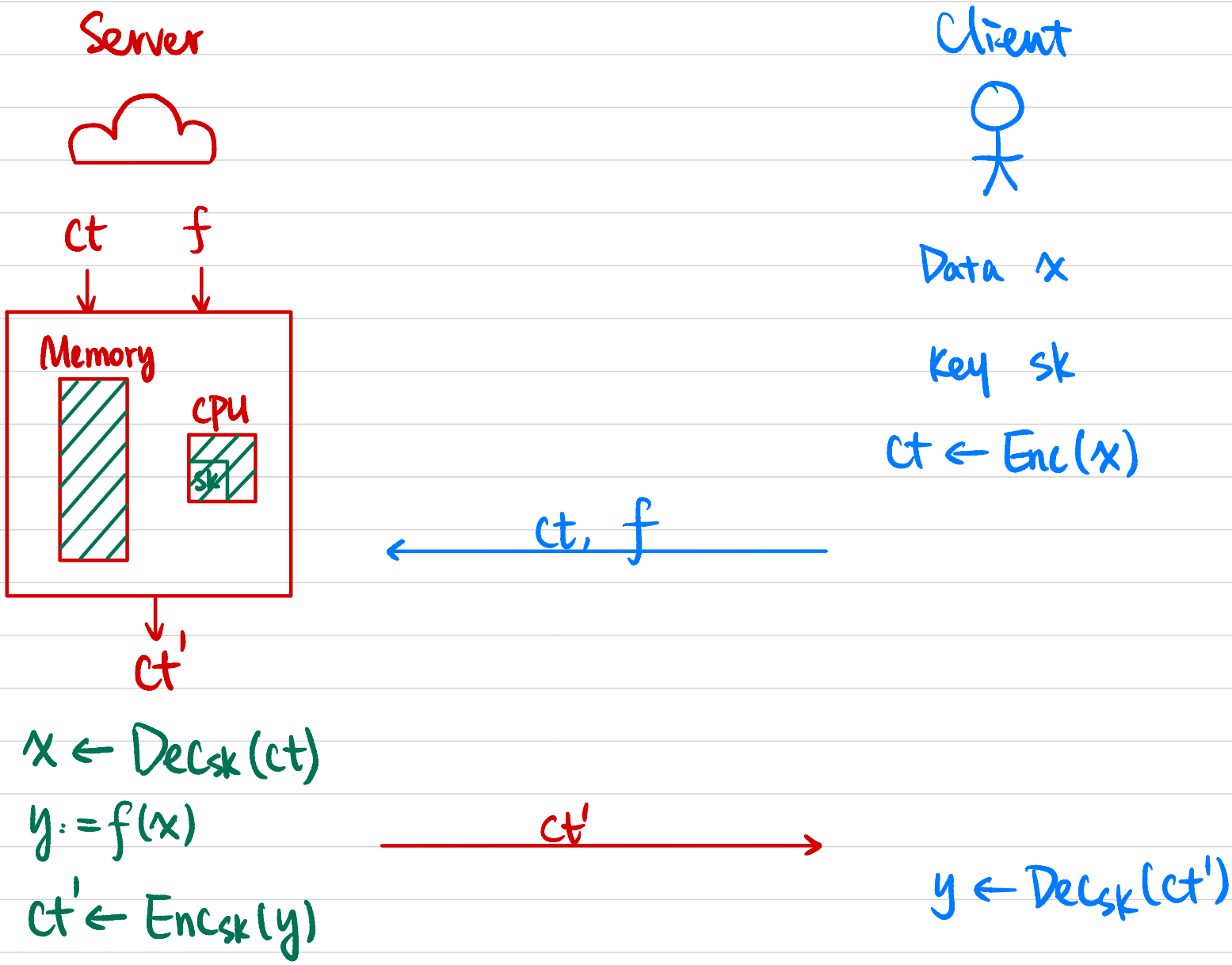
Mixing Permutation: $[32] \rightarrow [32]$

4 bits from each S-box will affect the input to 6 S-boxes in the next round

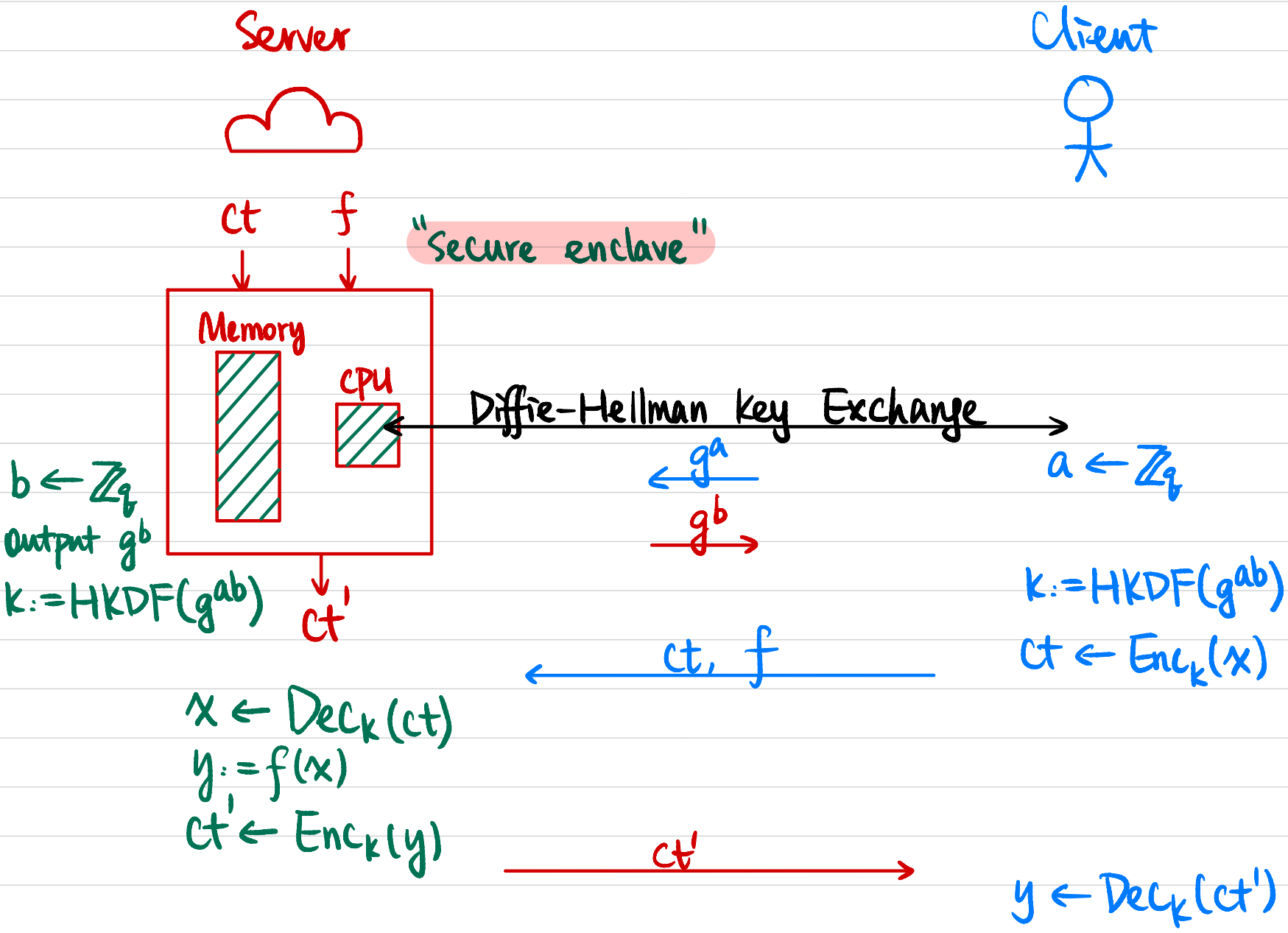
Outsourcing Computation by FHE



Outsourcing Computation by Secure Hardware

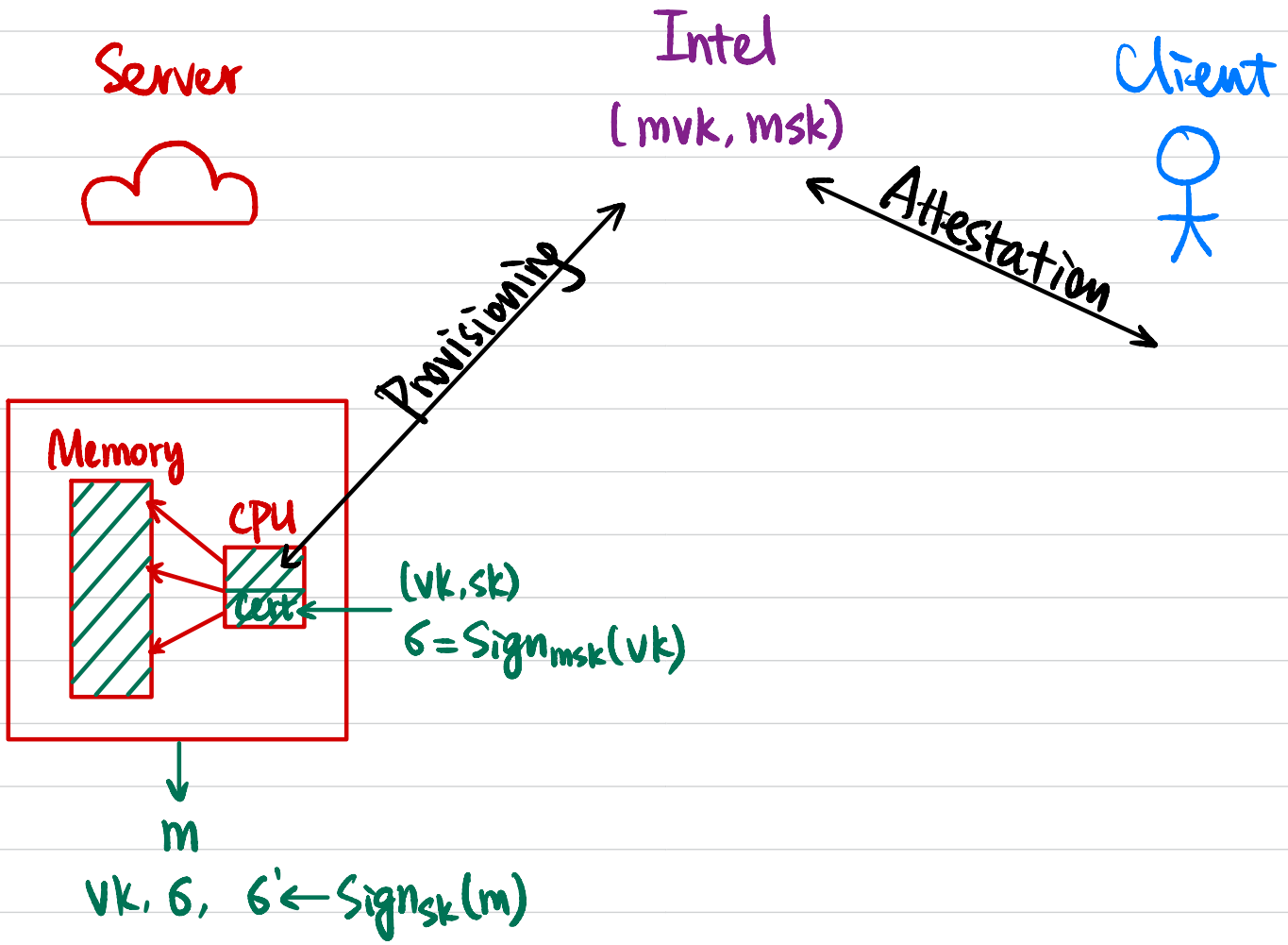


Intel Software Guard Extension (SGX)



What could go wrong?

Intel Software Guard Extension (SGX)



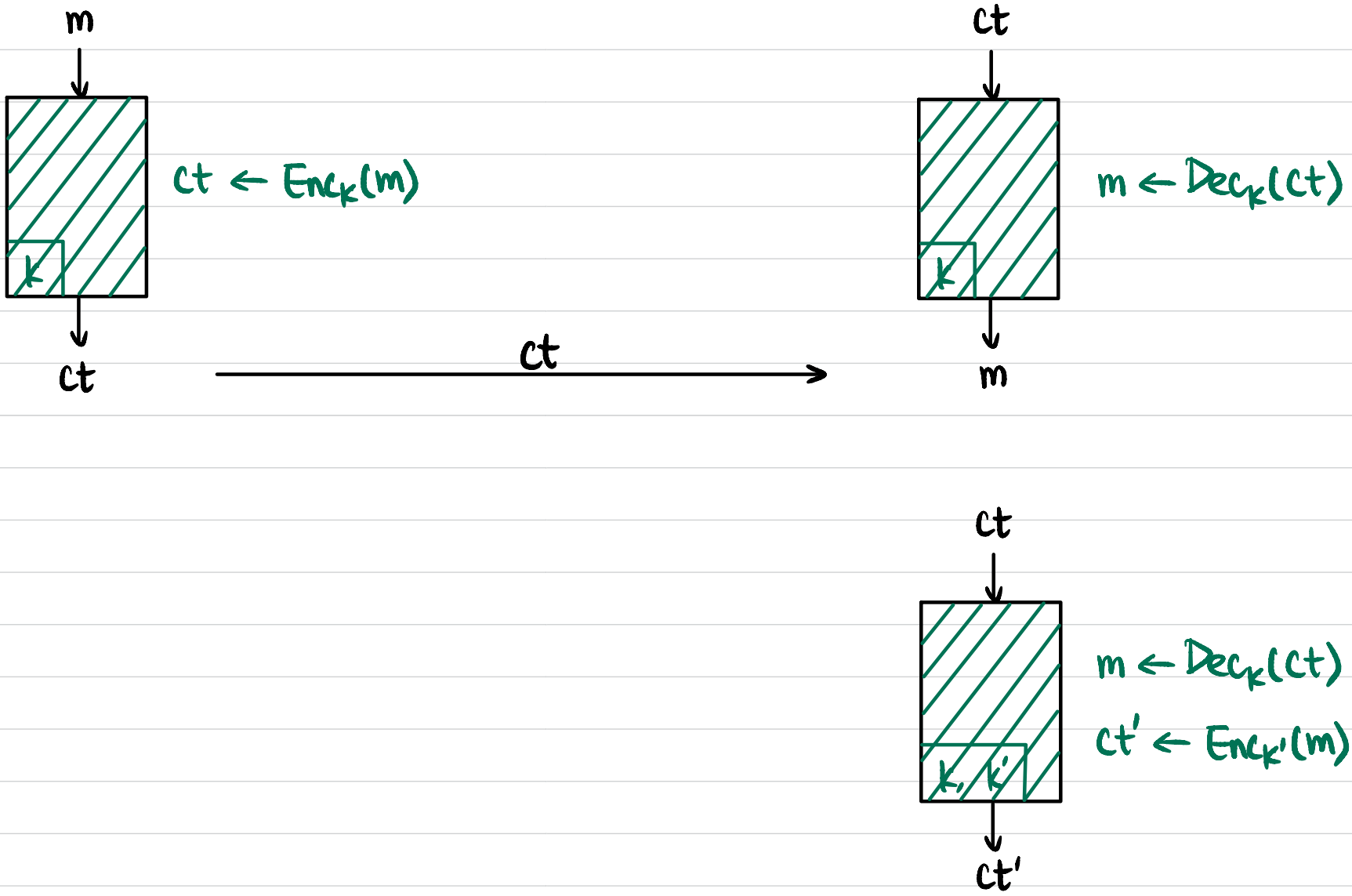
m

vk, σ, σ'

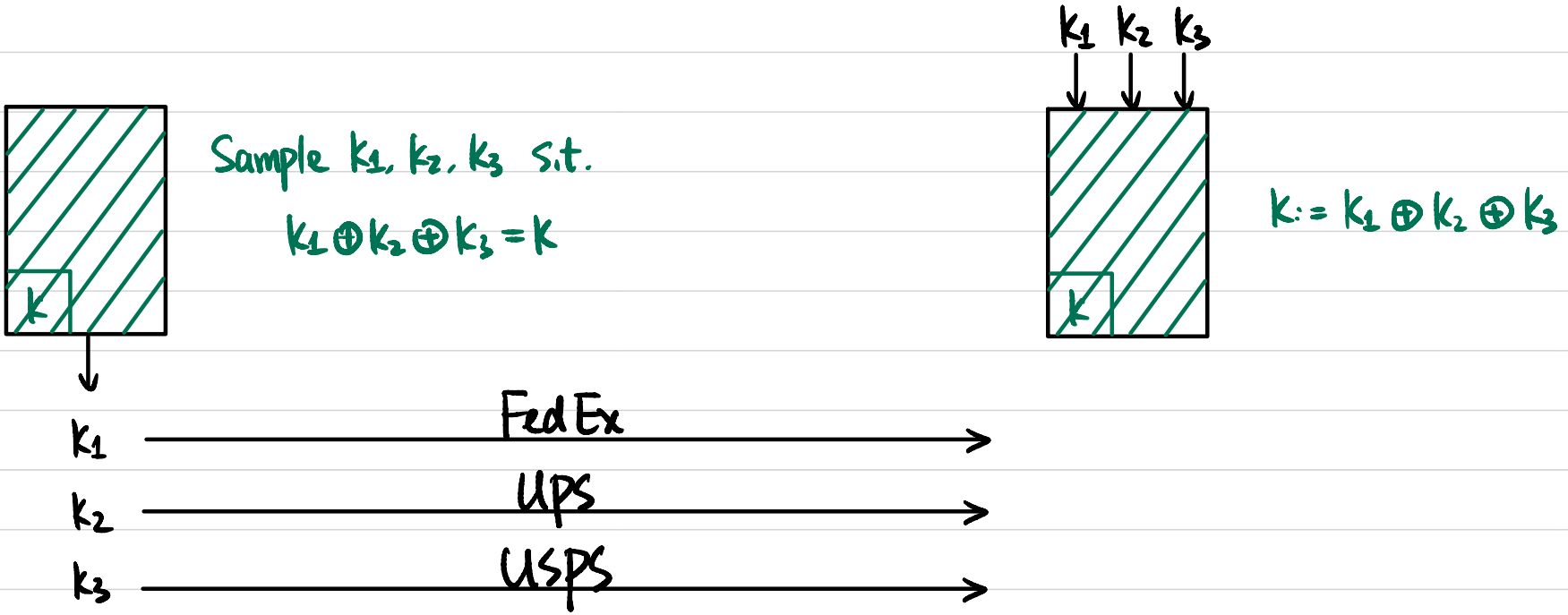
Constraints & Attacks

- Trust in hardware
- Trust in Intel
- Limited memory size: 128 MB
- Replay attacks
- Side-channel attacks: memory access pattern
  - ↳ fix: Oblivious RAM (ORAM)
    overhead $\Theta(\log N)$
    ↑ memory size

Hardware Secure Module (HSM)



Key Agreement



Transactions in Real Life

Alice → Starbucks $3

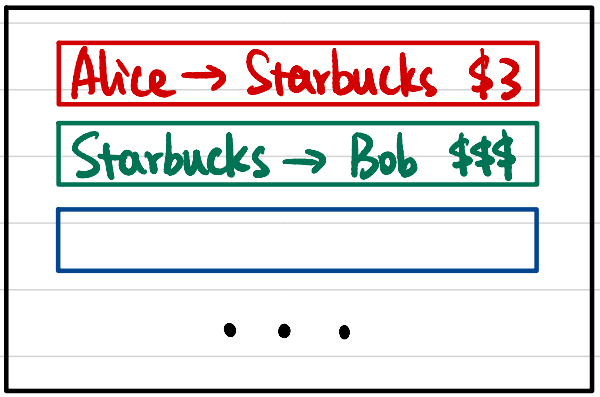
Starbucks → Bob $$$

Bank of America

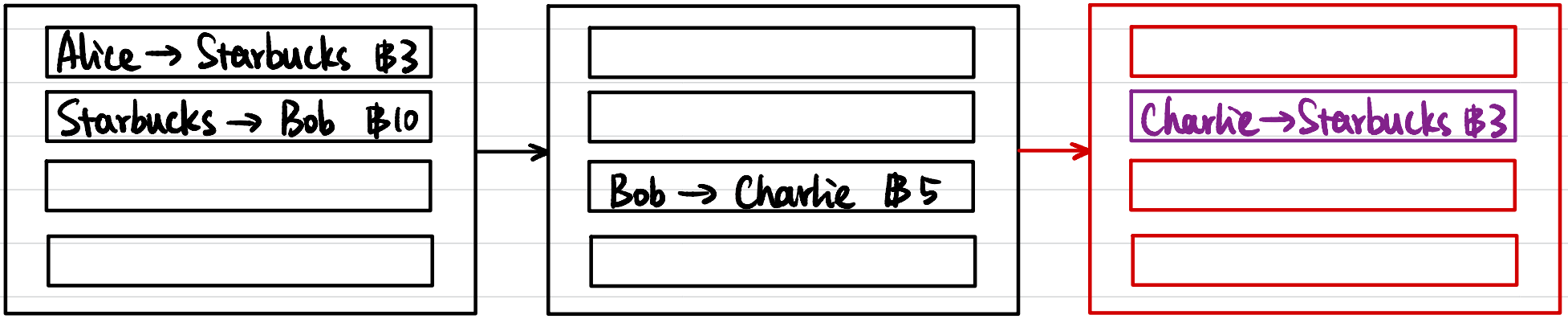
① initiated by sender

② enough balance in sender's account

A trusted party that maintains a private ledger



Blockchain



- Public ledger that everyone can view & verify
- Maintained by "miners" in a distributed way

Step 1: Charlie wants to make a transaction `Charlie → Starbucks ฿3`
↳ broadcasts it to the entire network

Step 2: All miners collect all transactions in the network
- Verify validity
  - ① initiated by sender ← How?
  - ② enough balance in sender's account
- Agree on next block ← How?

Step 3: Repeat

Transaction Authentication

Alice: $(vk_A, sk_A) \leftarrow KeyGen(1^\lambda)$

Bob: $(vk_B, sk_B) \leftarrow KeyGen(1^\lambda)$

Charlie: $(vk_C, sk_C) \leftarrow KeyGen(1^\lambda)$

Starbucks: $(vk_S, sk_S) \leftarrow KeyGen(1^\lambda)$

Bob → Charlie ฿5 :

$m_1 = (vk_B, vk_C, 5) \quad \sigma_1 \leftarrow Sign_{sk_B}(m_1)$

Charlie → Starbucks ฿3 :

$m_2 = (vk_C, vk_S, 3) \quad \sigma_2 \leftarrow Sign_{sk_C}(m_2)$

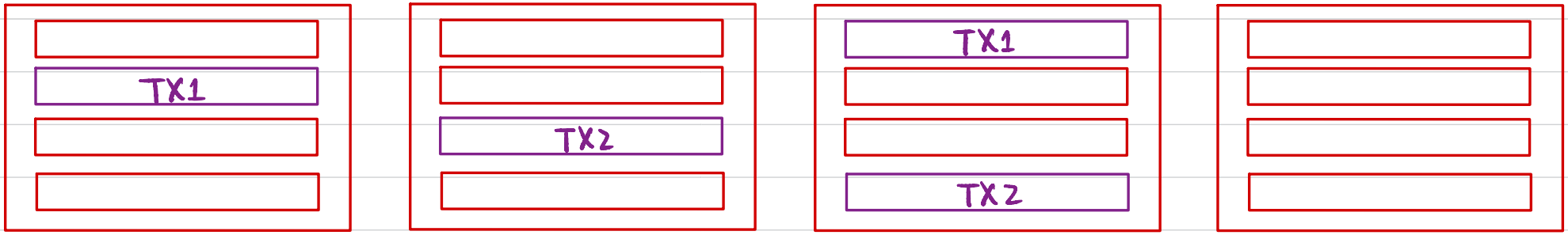
Consensus Protocol

TX1 = Charlie → Starbucks ฿3 :

$m_2 = (vk_C, vk_S, 3)$ $\sigma_2 \leftarrow Sign_{sk_C}(m_2)$

TX2 = Charlie → Alice ฿4 :

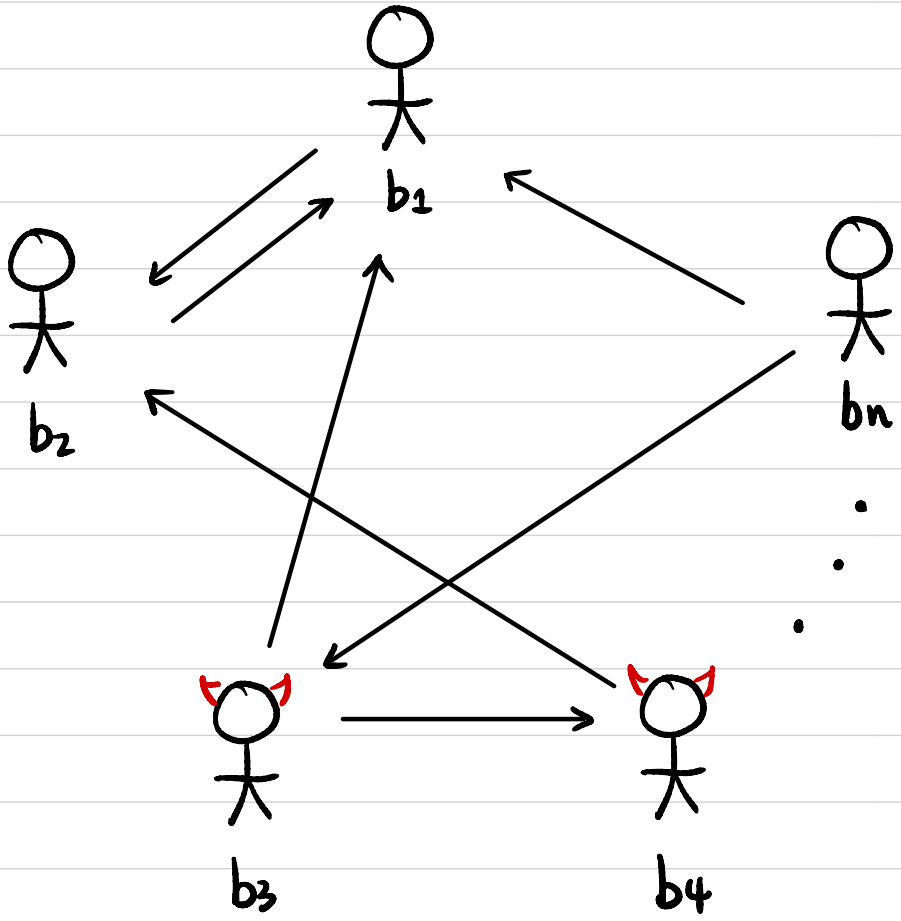
$m_3 = (vk_C, vk_A, 4)$ $\sigma_3 \leftarrow Sign_{sk_C}(m_3)$



WANT: ① All miners agree on the same block

② New block is valid

Byzantine Agreement



Agree on a block

(Guaranteed Output Delivery)

Byzantine Fault Tolerance (BFT) Protocol:

If $n \geq 3t+1$, (necessary)

then it's possible to reach consensus.

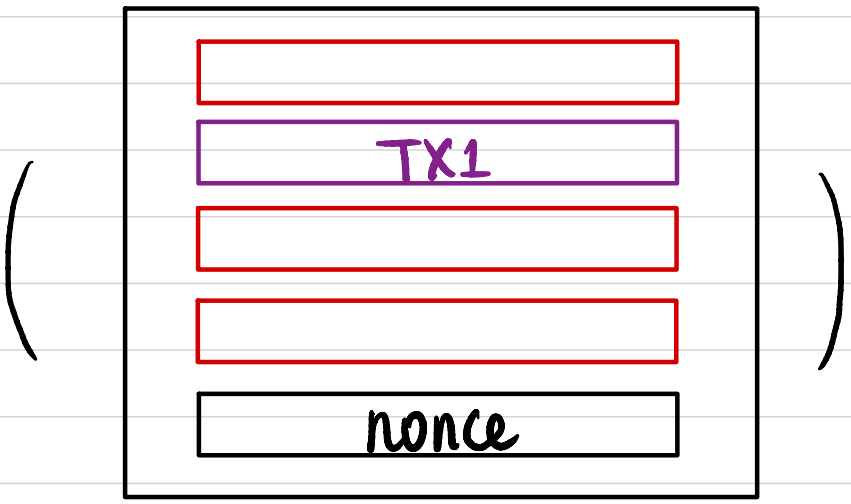
Assume $t < n/3$, then agree on a valid block.

Any problem?

Sybil Attack

Proof of Work (PoW)

Miner 1:

Hash 

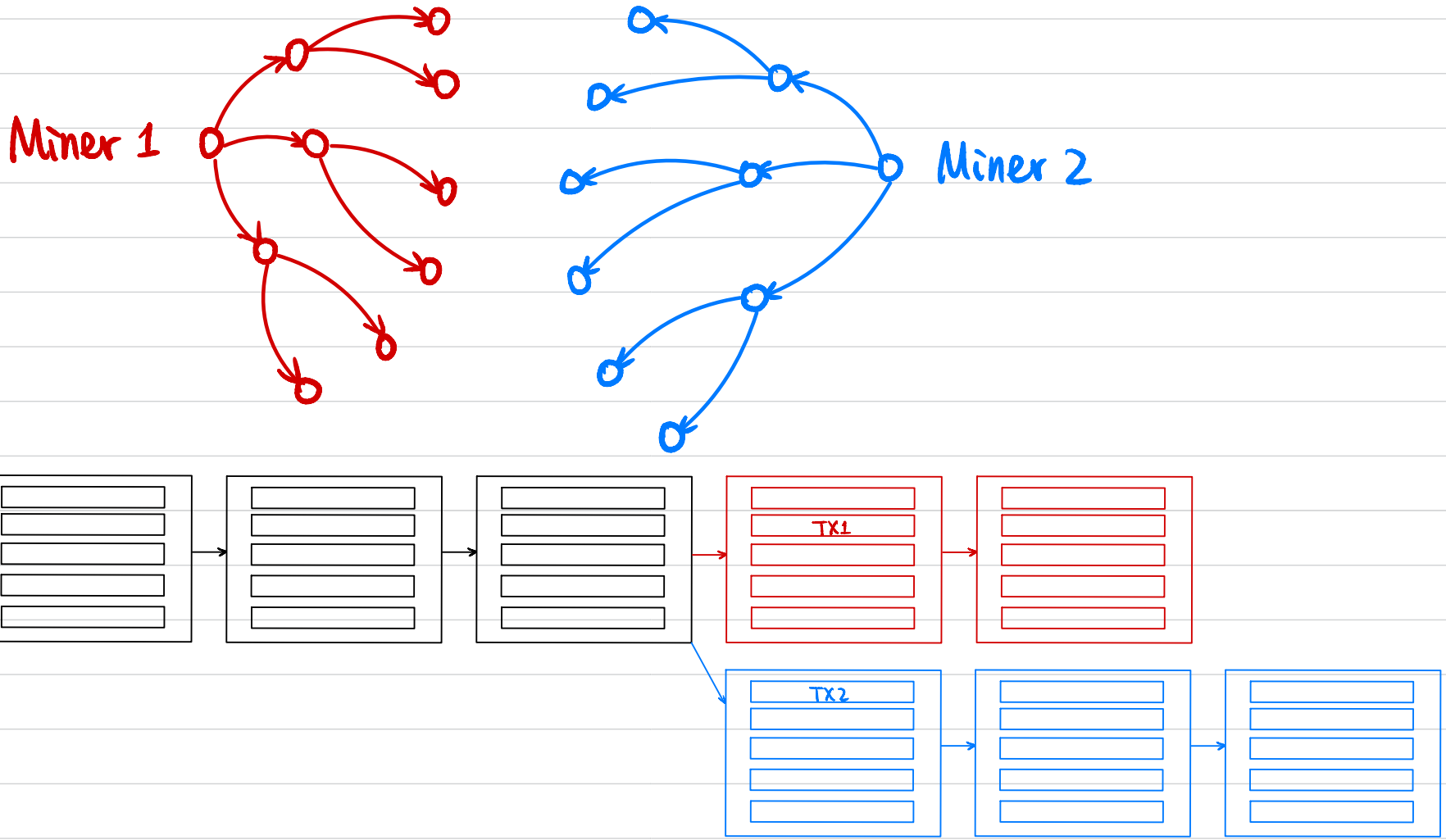
$= \underbrace{00\cdots0}_{30}1011\cdots0$

Find nonce s.t. Hash(block) has $\geq$ 30 leading 0's.

Consensus Protocol:

Whoever first finds a block that hashes to a value w/ $\geq$ 30 leading 0's, that block becomes the next block.

Proof of Work (PoW)



Longest Chain Rule: Always adopt the longest chain.

Assuming honest majority of computation power, the longest chain is always valid.

Blockchain

- Settlement of a transaction:

  Included in a block which is ≥ 6 blocks deep (~ 1 hr)

- Dynamically adjust # leading 0's s.t. each block takes $\sim$ 10min to mine

  Last 1 hr: > 6 blocks: increase # leading 0's

  < 6 blocks: decrease # leading 0's

- Miners' motivation:
  - transaction fee
  - new coin generated in each block goes to miner

- Extensions
  - Proof of Stake (PoS)
  - Anonymous transactions (zk-SNARGs)
  - Smart Contracts
  - Public ledger