BLOCKCHAIN

A confluence of Cryptography, Game Theory and Distributed Computing

by

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Blockchain solves a very hard problem

In this lecture:

- What is the hard problem?
- What is the pleasing solution?

The problem
(High level Overview)

The Big Picture

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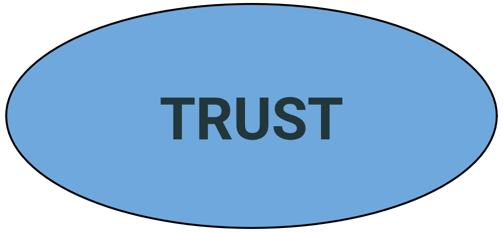

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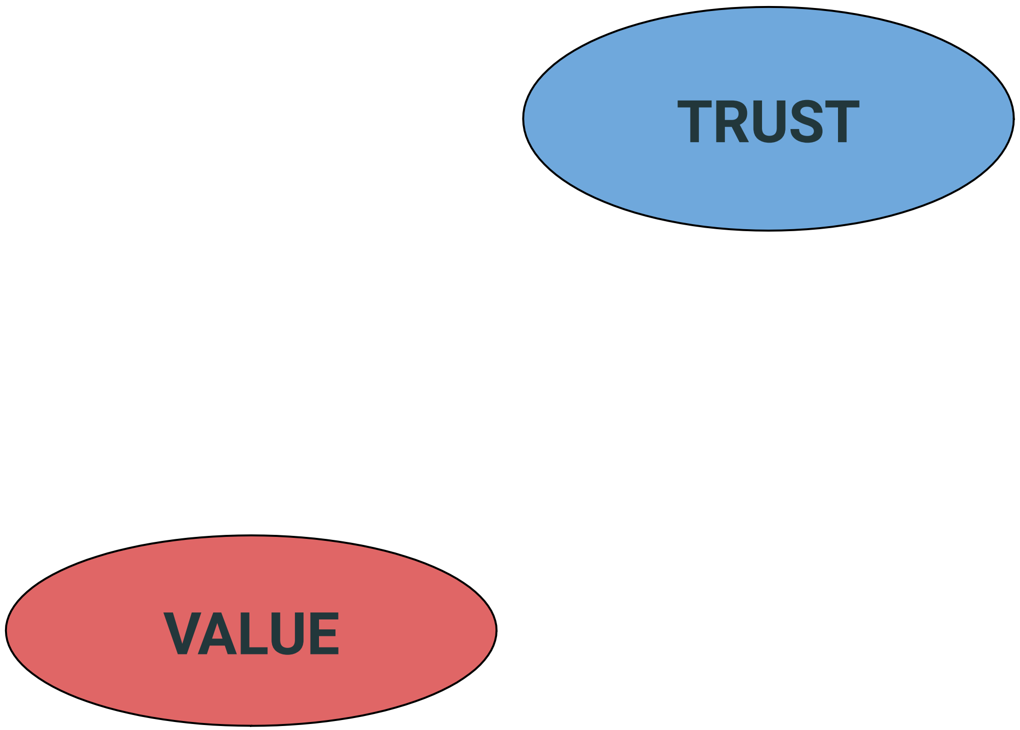

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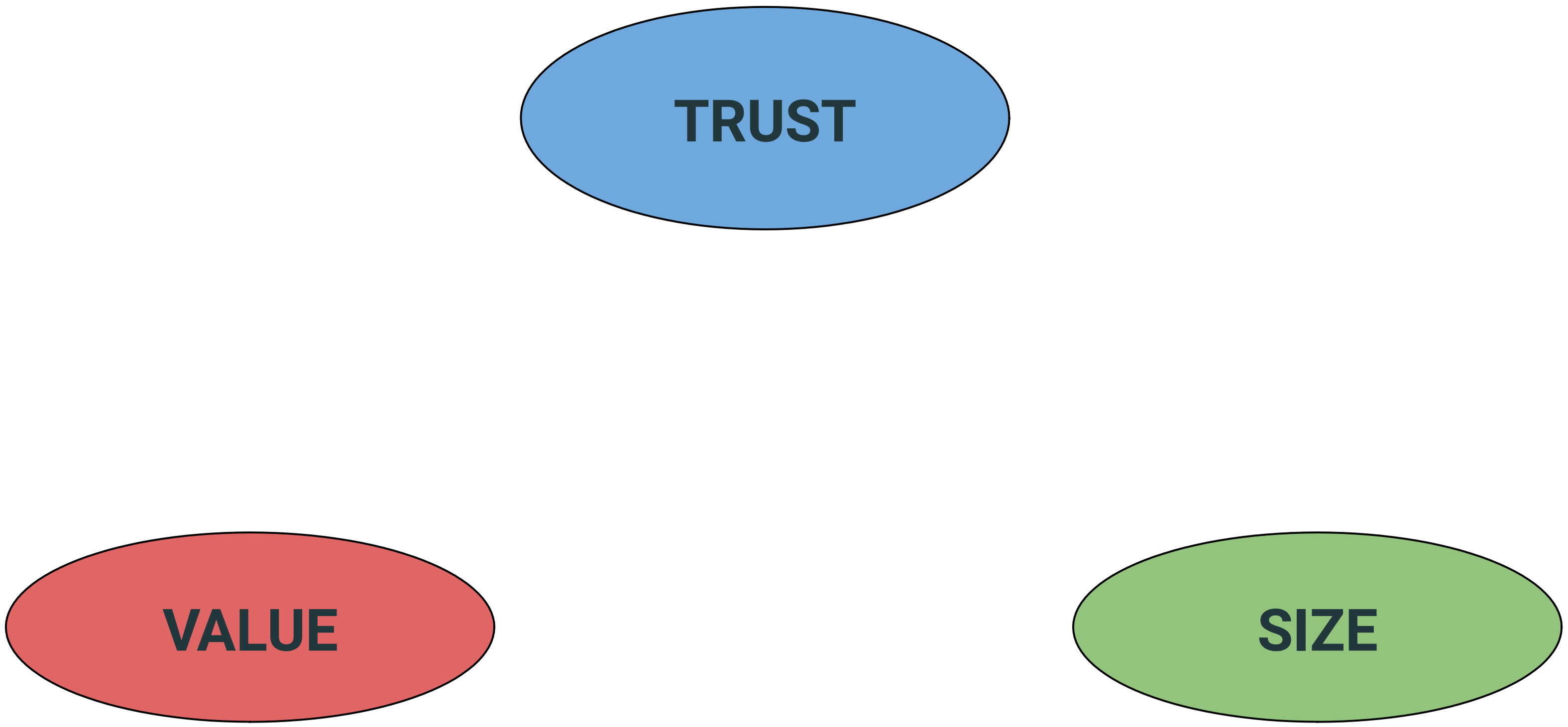

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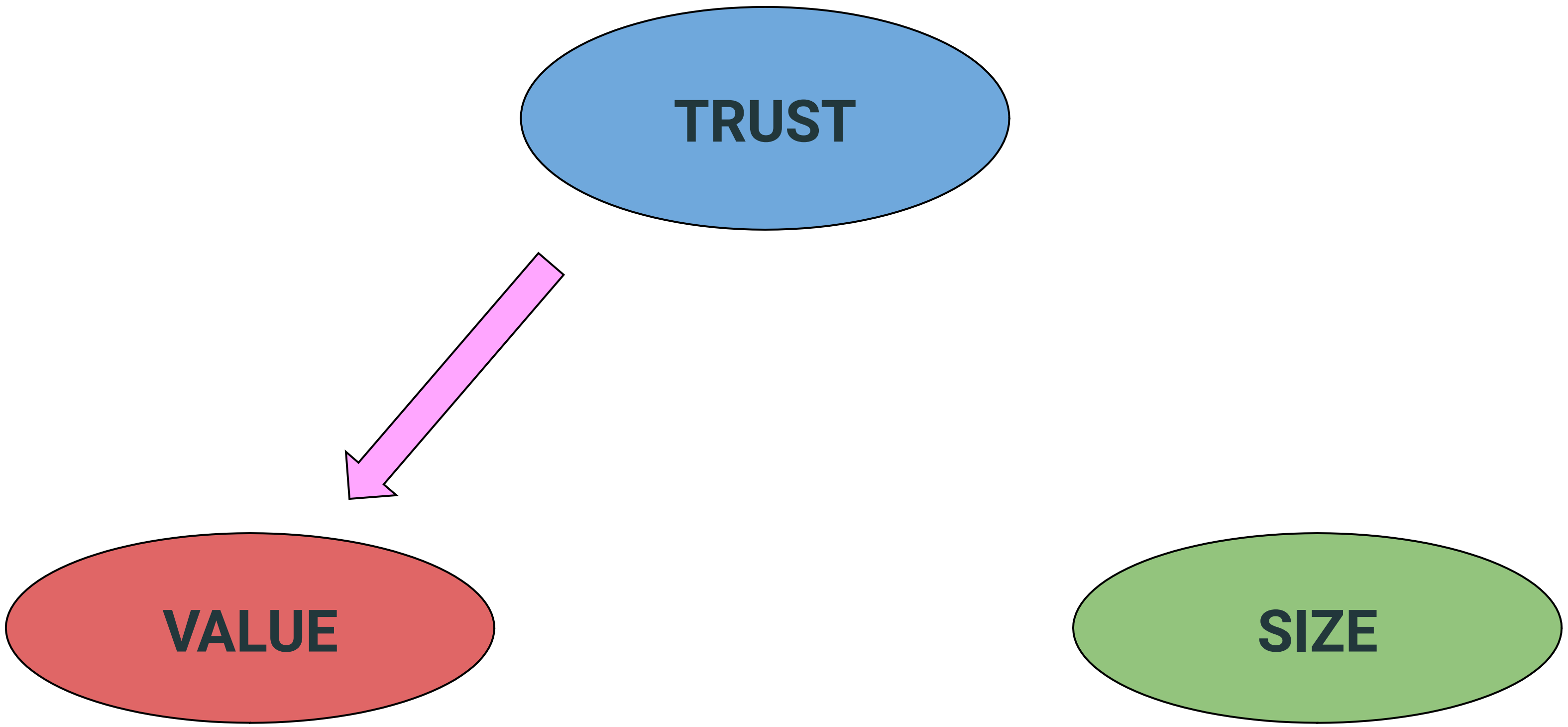

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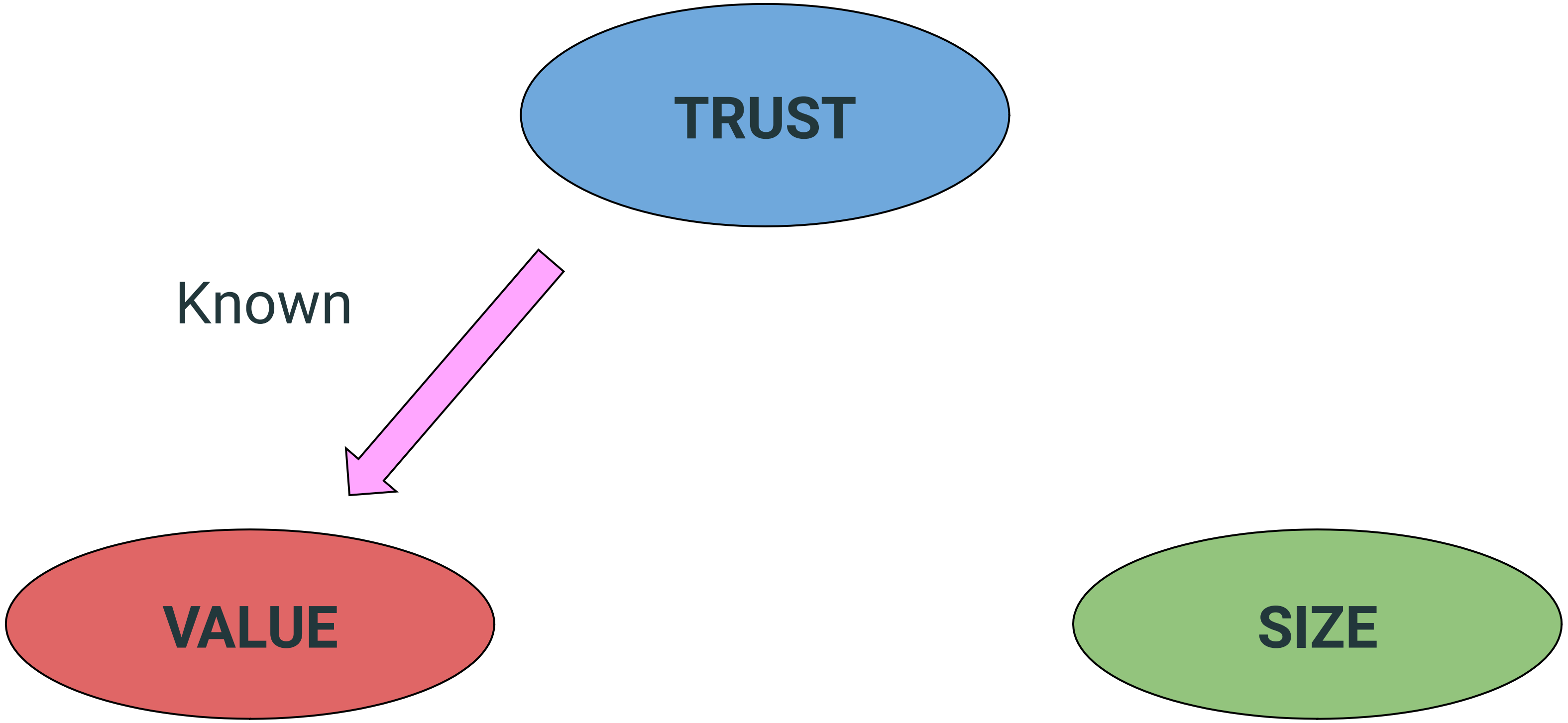

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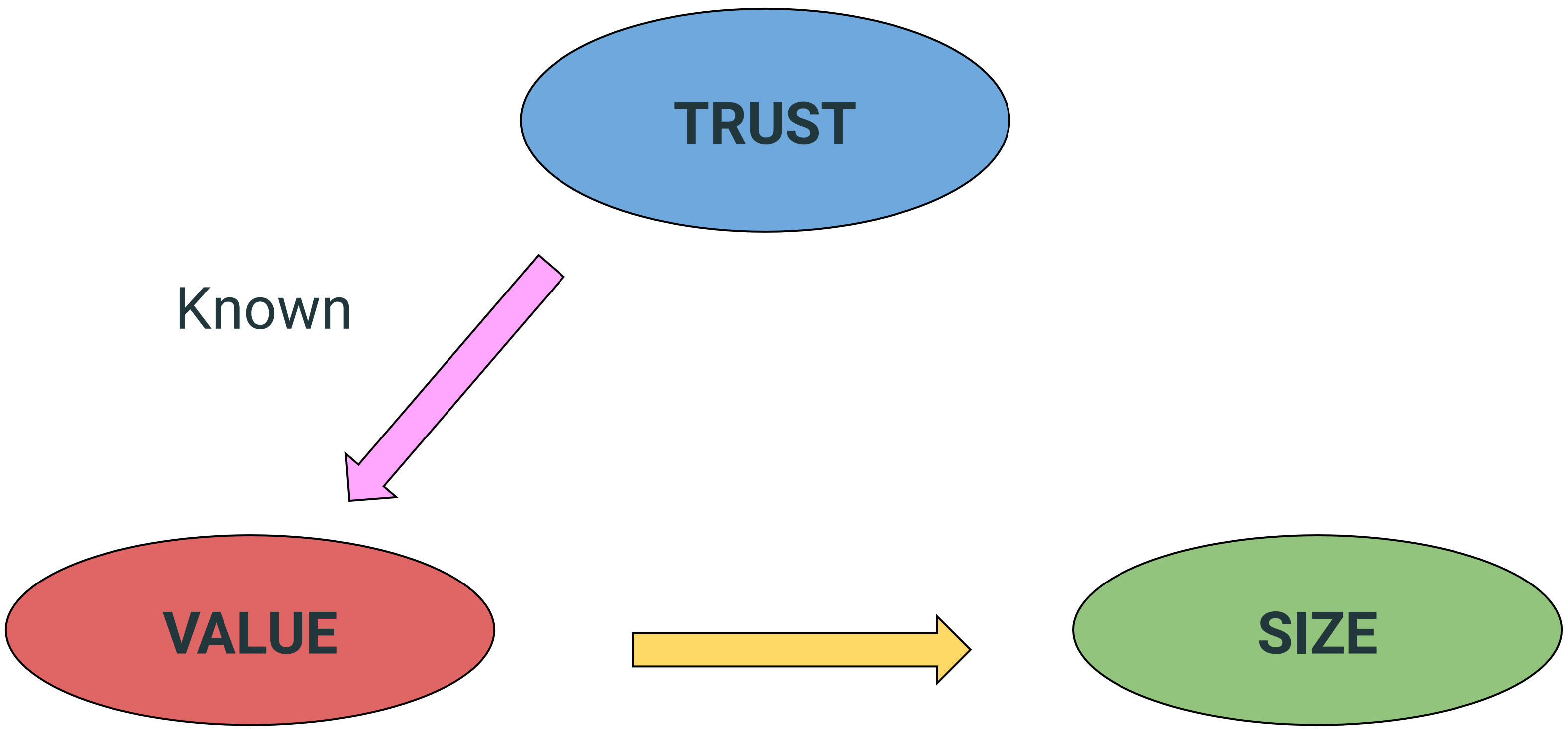

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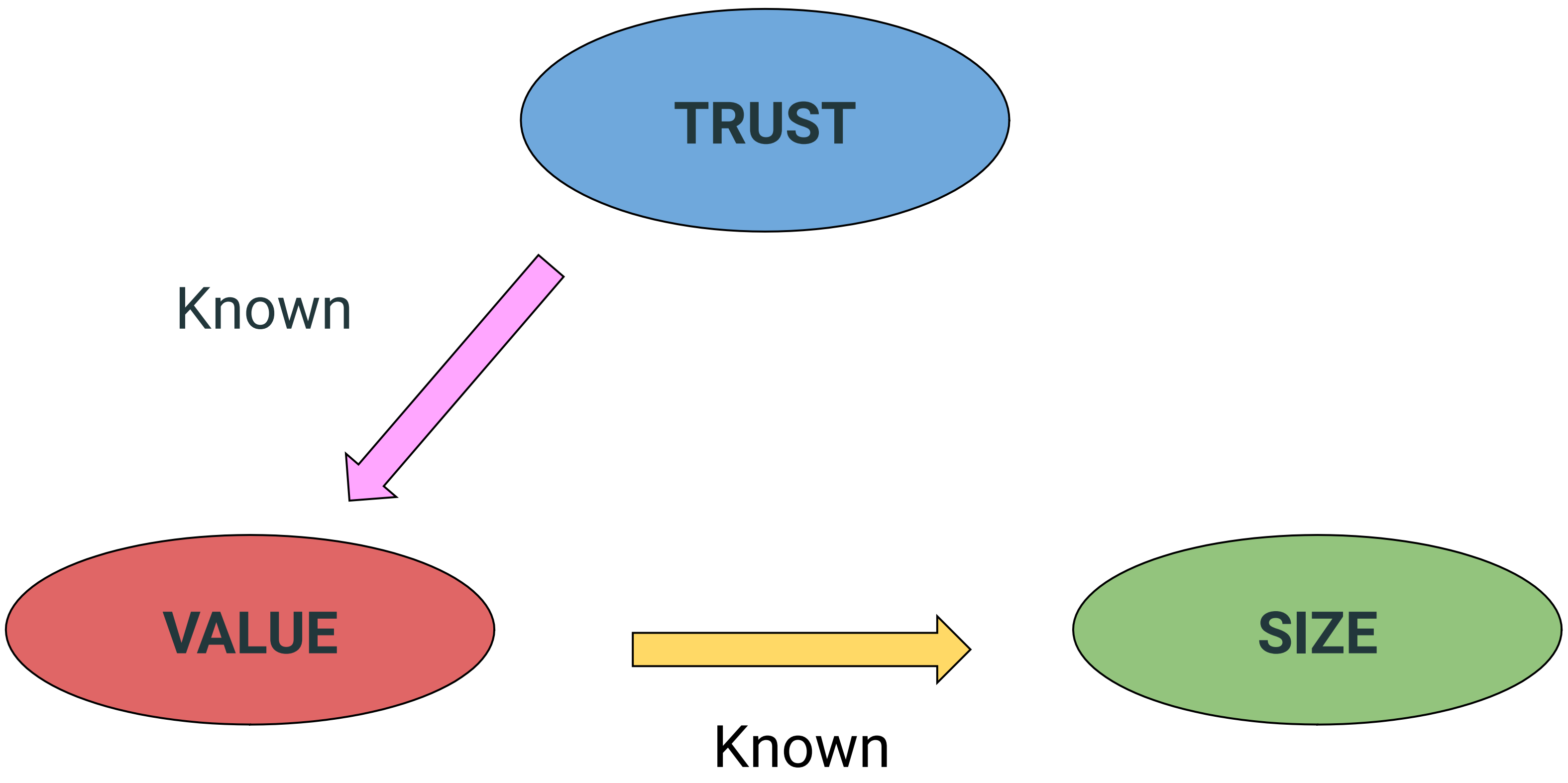

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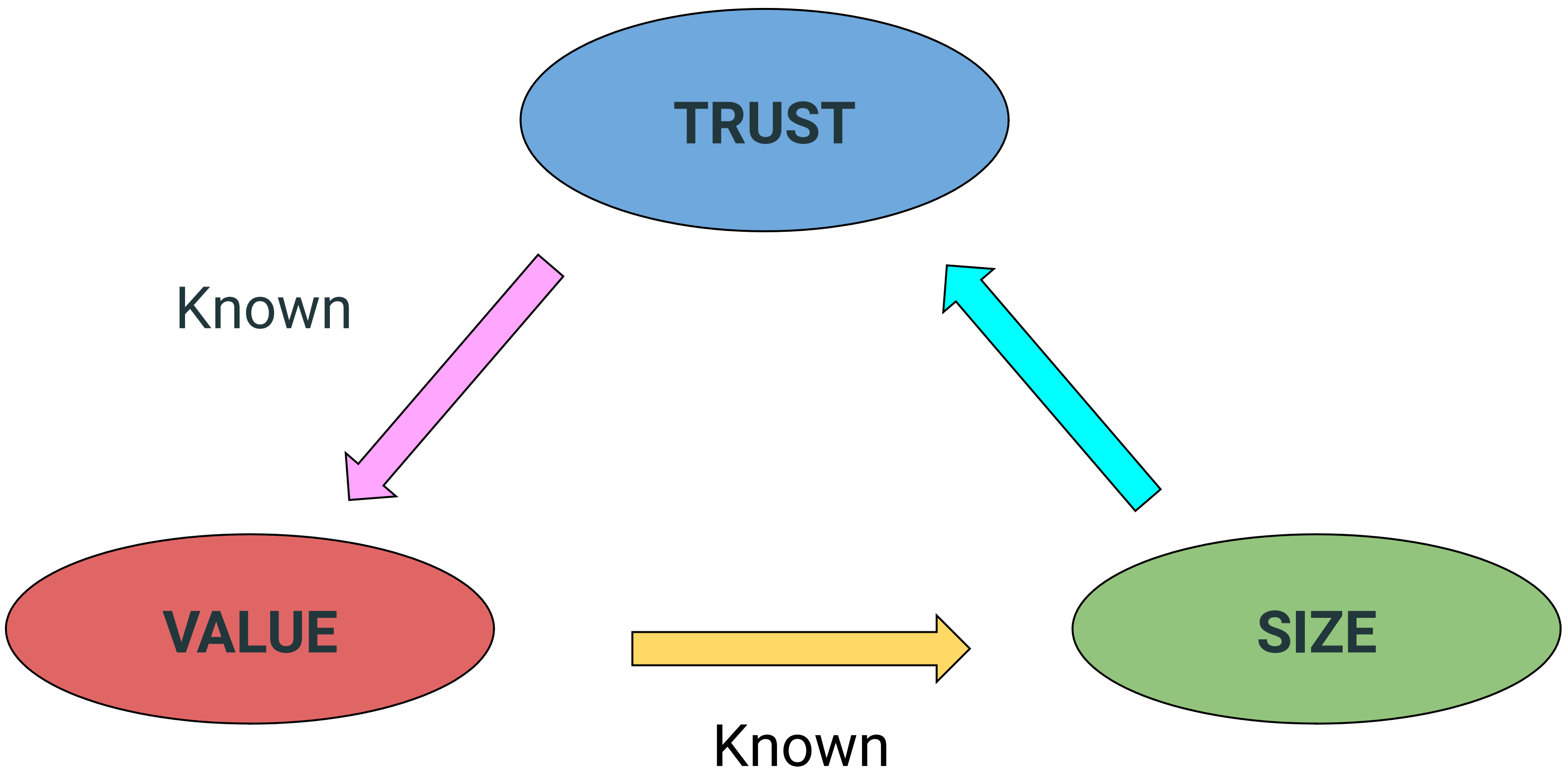

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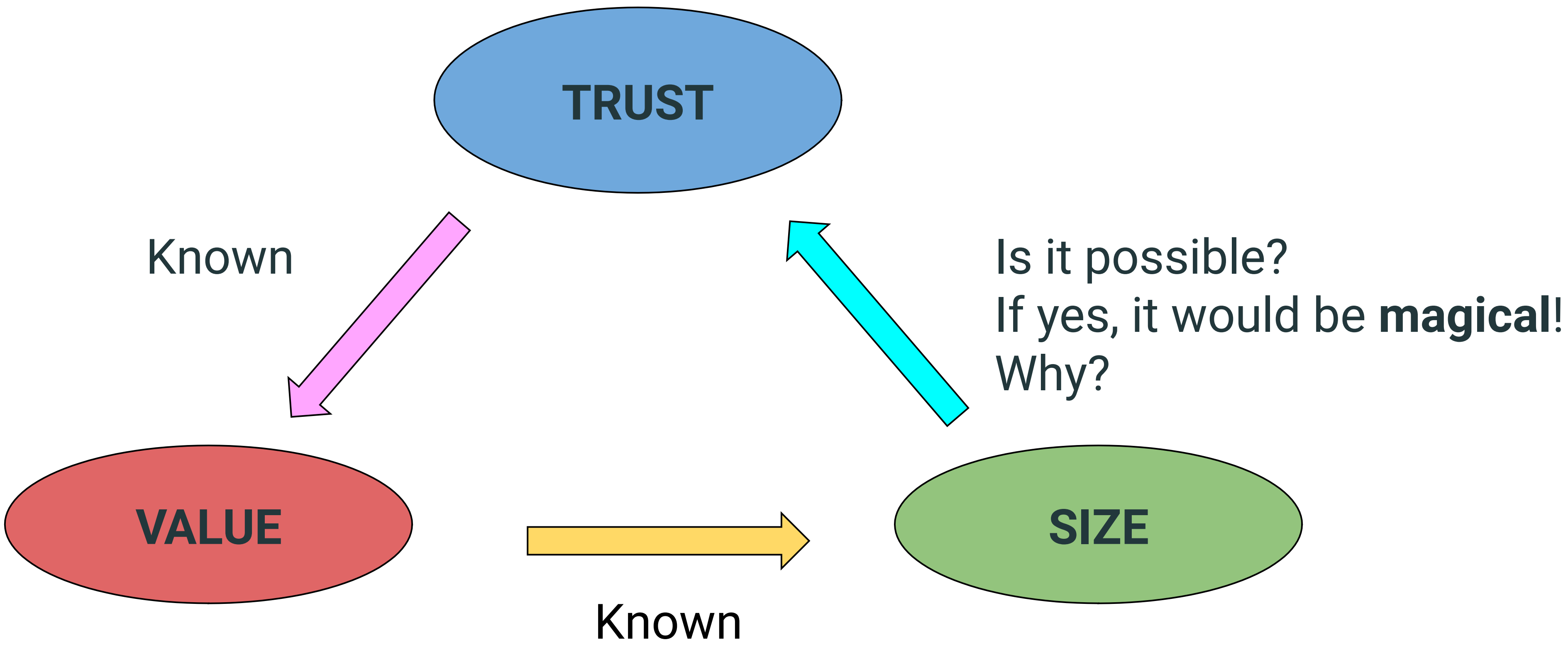

What’s The Challenge?

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Distributing Trust

Can a collection of untrustworthy nodes simulate a trustworthy one?

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Can a collection of untrustworthy nodes simulate a trustworthy one?

Recall: Too many (good) cooks spoil the broth!

(Consensus is not easy)

What to say if some of them are outright malicious?

Byzantine Agreement

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A Fundamental Problem

Simulating Broadcast in P2P Networks

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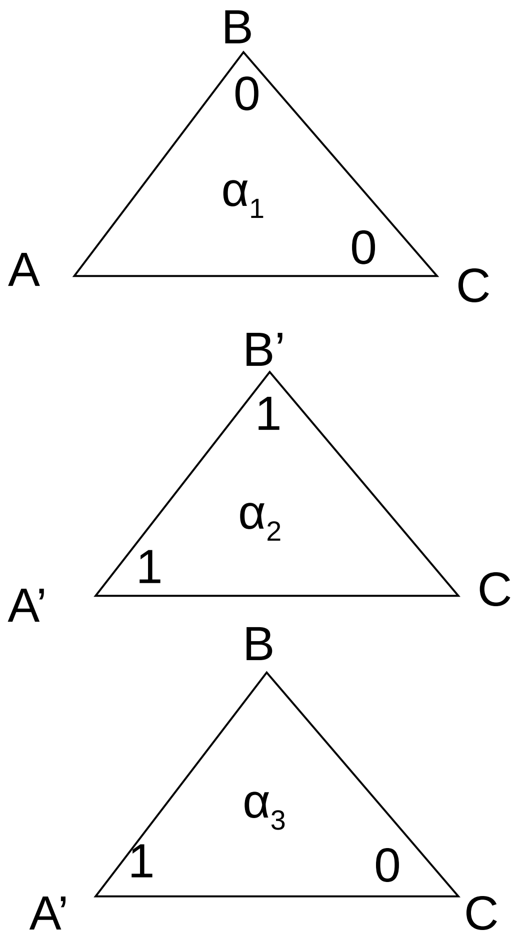
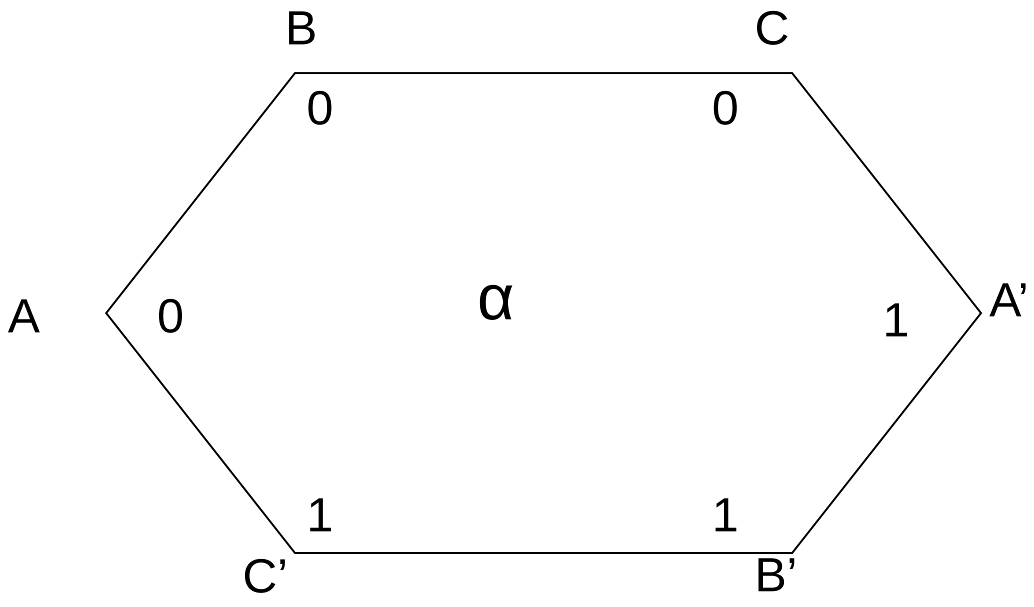
What's the issue?

Atomicity!

Impossibility for 1 out of 3 [2]





[2] Michael J. Fischer, Nancy A. Lynch, Michael Merritt. **Easy impossibility proofs for distributed consensus problems** , PODC '85, 59-70.

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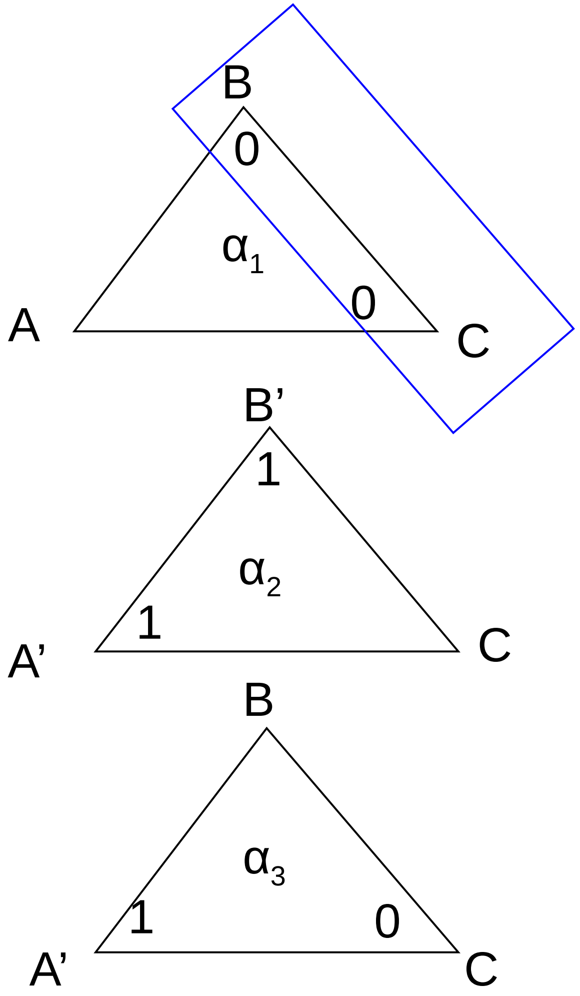

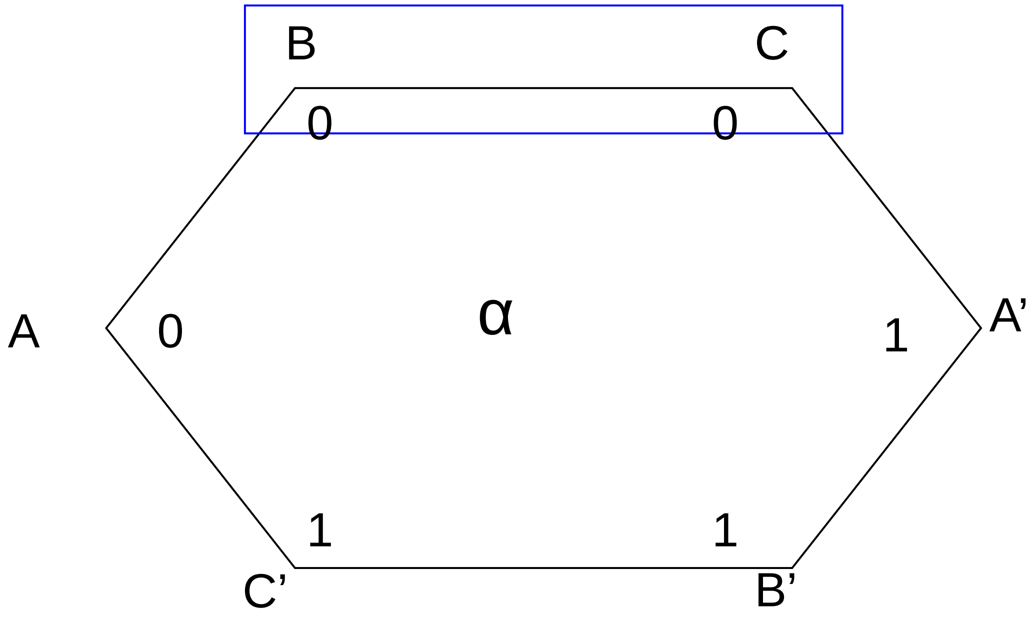

Executions α_1 and α are indistinguishable to processes B and C

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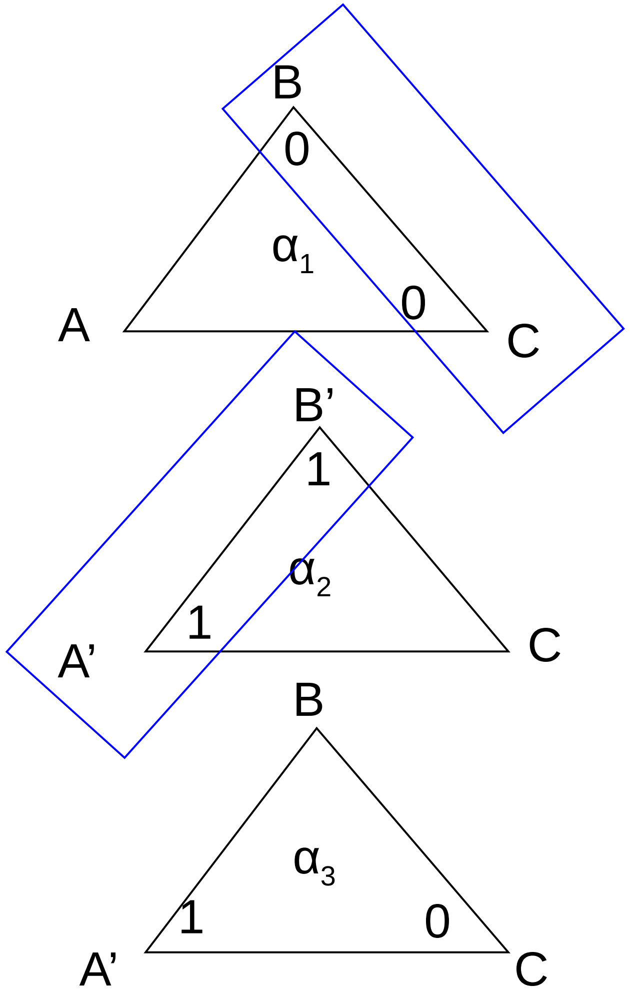

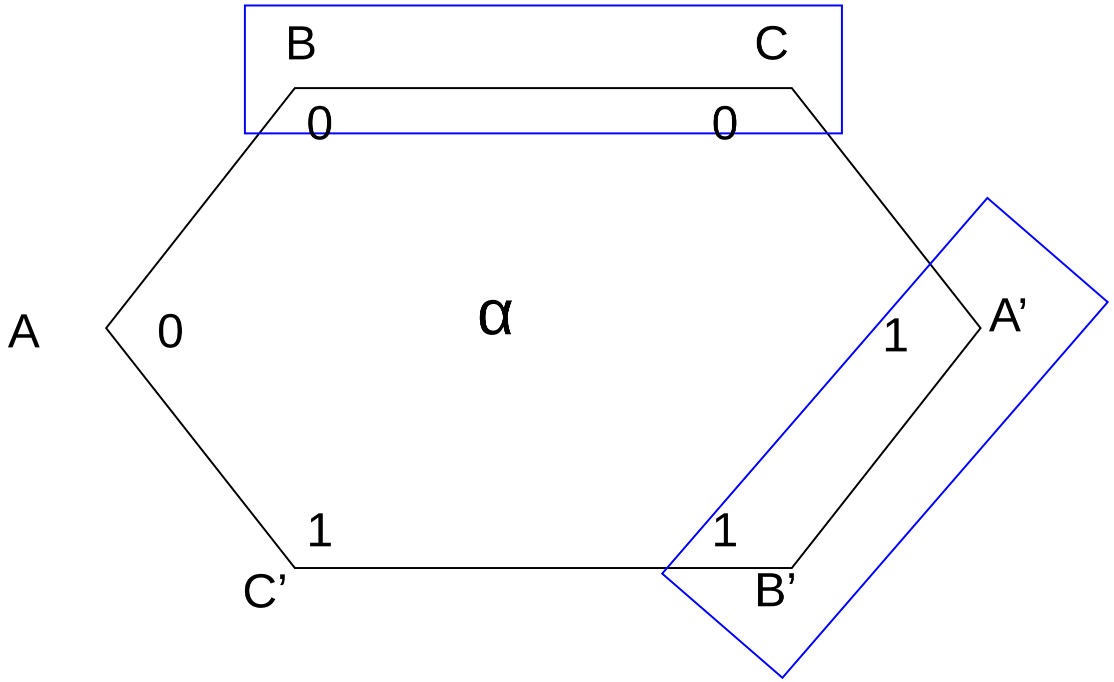

Executions α_2 and α are indistinguishable to processes A’ and B’

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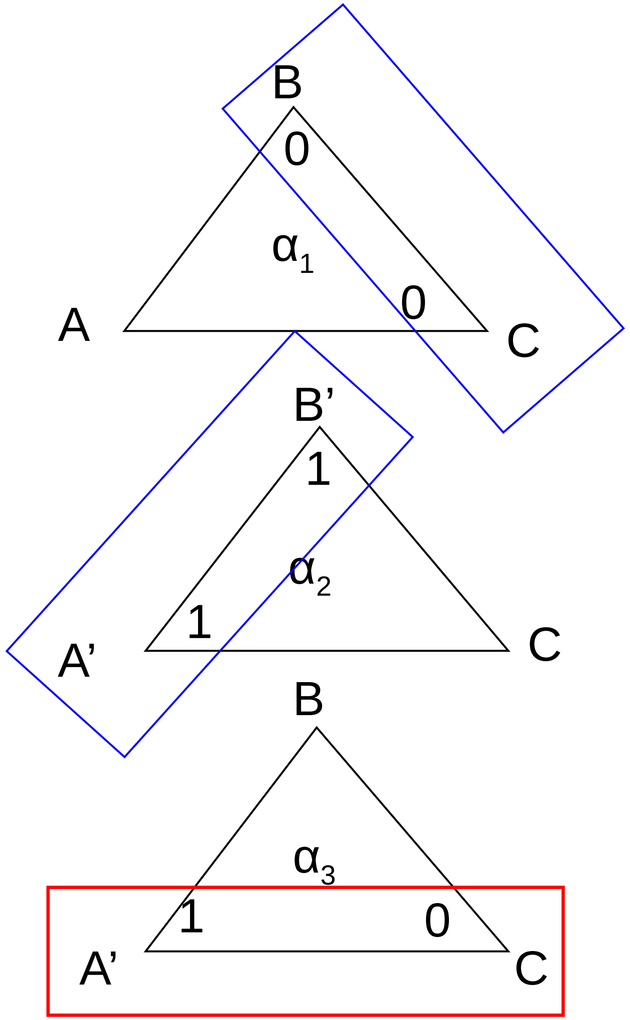

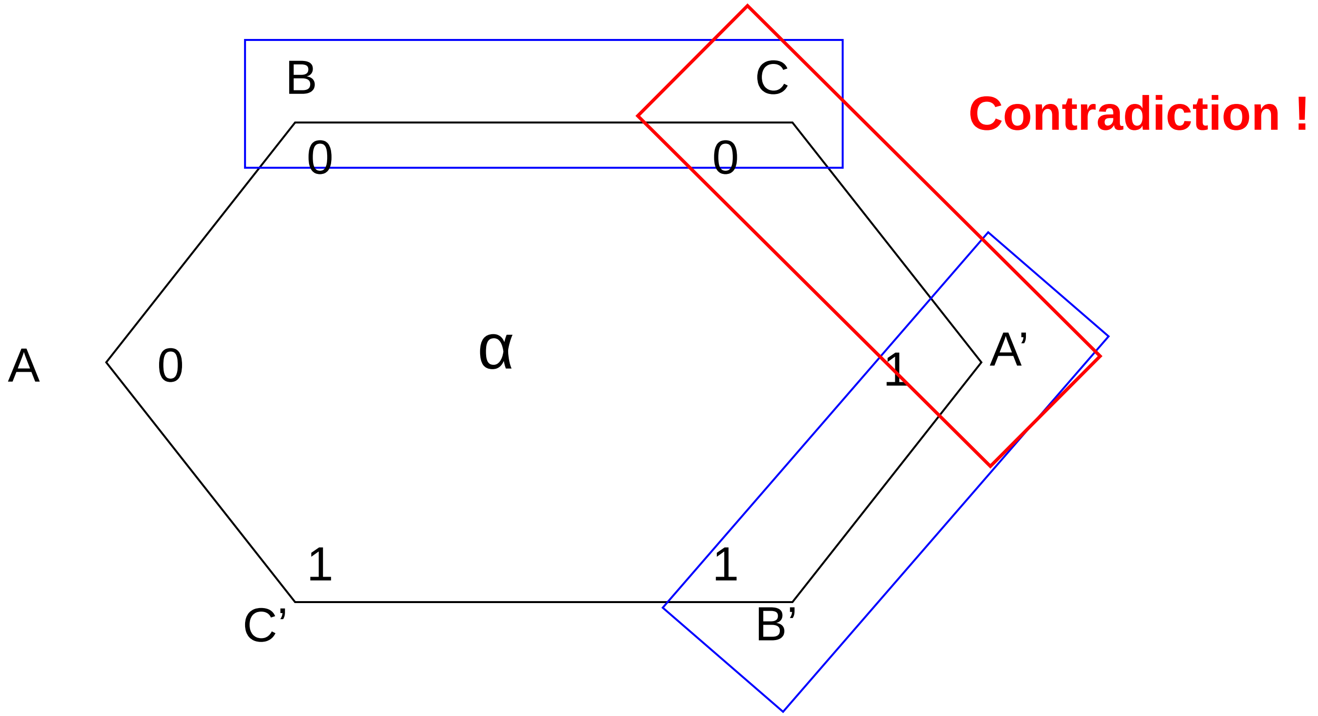

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(Future) **Conscious Computing**: Distributing consciousness/intelligence.

Gearing-Up Our Ammunition

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The “Utopian” Ammunitions:

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- The ability to be anywhere, instantaneously.

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Omniscience

- The ability to access/know any data, instantaneously.

The Three Fields involved

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Non-omniness creates/solves problems:

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- Game theory

The Three Fields *Can Be* Mutually “Complementary”

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Is there a problem, so hard, that it is (best) solved by the combined efforts of all the three fields?

How To Solve It ?

(By Non-Omnipotence of machines?)

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Welcome to **Crypto**!

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… no other field of science has ever had to so brazenly circumvent logical *no-go theorems* …

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- Can you spend your digital cash?
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- Should there be CCTV cameras?
  Ans: Yes (for policing) *and* No (for privacy)

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- Privacy Preserving Personalization!

It is naturally *Fundamental* because …

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… cryptography has *famously* extended its success story by revolutionarily circumventing logical no-go theorems in *other areas* too!

Founding Members of the Association on “Beneficiaries of Cryptography”

[Ironically, they are also the prominent members of the Club that Cryptography Benefits From!]

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- Coding Theory: Detecting 100% adversarial noise is feasible!
- Distributed Computing: Byzantine Agreement
- Algorithms: Derandomization
- Mathematics: IP = PSPACE = ZKP = QIP!

Our first exemplary problem

Is Secure Communication a Logical No-Go?

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Yes!

Why?

Secure Communication is Impossible!

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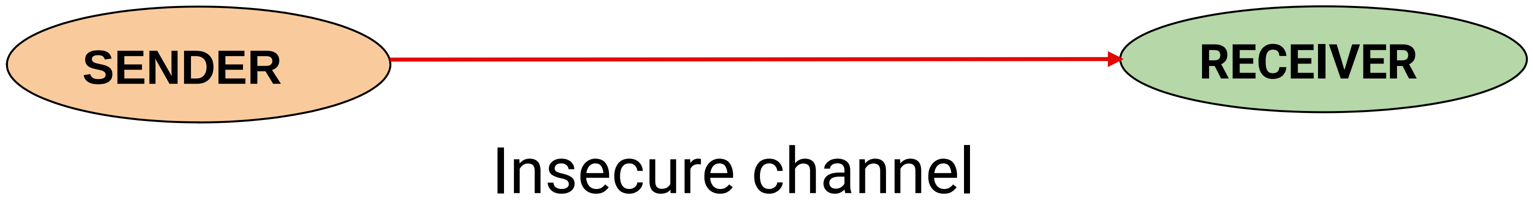

Secure Communication is Impossible!

Adversary

SENDER

RECEIVER

Insecure channel

Secure Communication is Impossible!

At time t_0:

Information@Receiver = Information@Adversary

Recall: Kerckhoff’s Principle

Secure Communication is Impossible!

At time t_0:
Information@Receiver = Information@Adversary
Recall: Kerckhoff's Principle

At every subsequent instant of time:
Information gained by receiver = Information gained by adversary

How to Circumvent the Impossibility?

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Ans: Non-Omnipotence of the eavesdropper!

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Representation matters, indeed.

Natural Numbers, Efficiency of Operations and Modern Cryptography

Ease of Computation Depends on the Representation

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It also depends on the operation!

Ease/Speed of Operation Depends on the Representation

- viii * xvi = cxxviii
- 8 * 16 = 128
- $2^3 * 2^4 = 2^7$

- viii + xvi = xxiv
- 8 + 16 = 24
- $2^3 + 2^4 = 2^3.3$

- viii < ix is true
- 8 < 9 is true
- $2^3 < 3^2$ is true

Is There a Representation Where all Common Operations are FAST?

- Addition (+)
- Comparison (<)
- Multiplication (*)

Is There a Representation Where all Common Operations are FAST?

Not Easy!

- Addition (+)
- Comparison (<)
- Multiplication (*)

Why is the Decimal System Popular?

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	Addition	Multiplication	Comparison
ROMAN	SLOW	SLOW	SLOW
DECIMAL	**FAST**	MEDIUM	**FAST**
PRIME PRODUCT	SLOW	**FAST**	SLOW
RESIDUE SYSTEM	**FAST**	**FAST**	MEDIUM

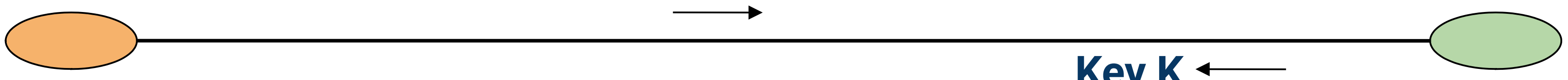
Slowness is advantageous too!

Slowness is <u>advantageous</u> too!

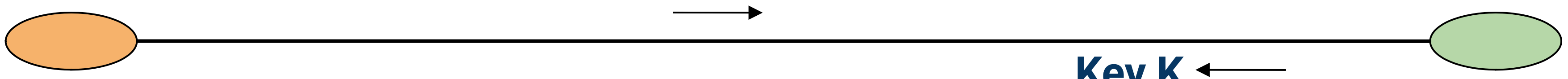
Public Key Cryptography

Secure Communication

Secure Communication



Secure Communication



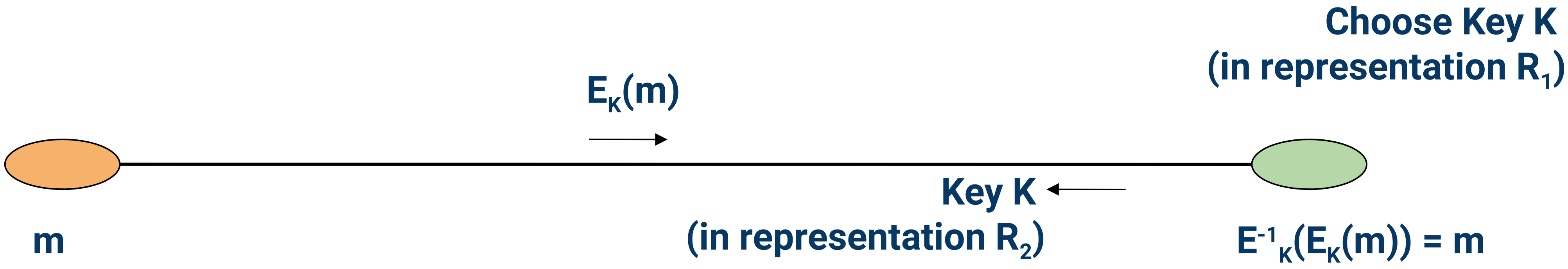
<u>In Representation R_2</u>

- Operation E_K is FAST
- Operation E_K^{-1} is <u>VERY SLOW</u>

<u>In Representation R_1</u>

- Operation E_K^{-1} is FAST

Secure Communication



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<u>EXAMPLE RSA Cryptosystem</u>

R_1 : Product of Primes

R_2 : Decimal

E_K : Modular Exponentiation
$m^e \bmod K$

Our second exemplary problem

Is Collision-Resistant Hashing a Logical No-Go?

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Yes!

Why?

Compression Leads To Collisions!

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Ans: Hash functions take arbitrary length strings and compress them into shorter strings.

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Compression **implies** Collision!

How to Circumvent the Impossibility?

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Ans: Non-Omnipotence of the collision finder!

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Amplifying compression with collision-resistance:

The Merkle-Damgard Transform

Merkle Damgard Transform

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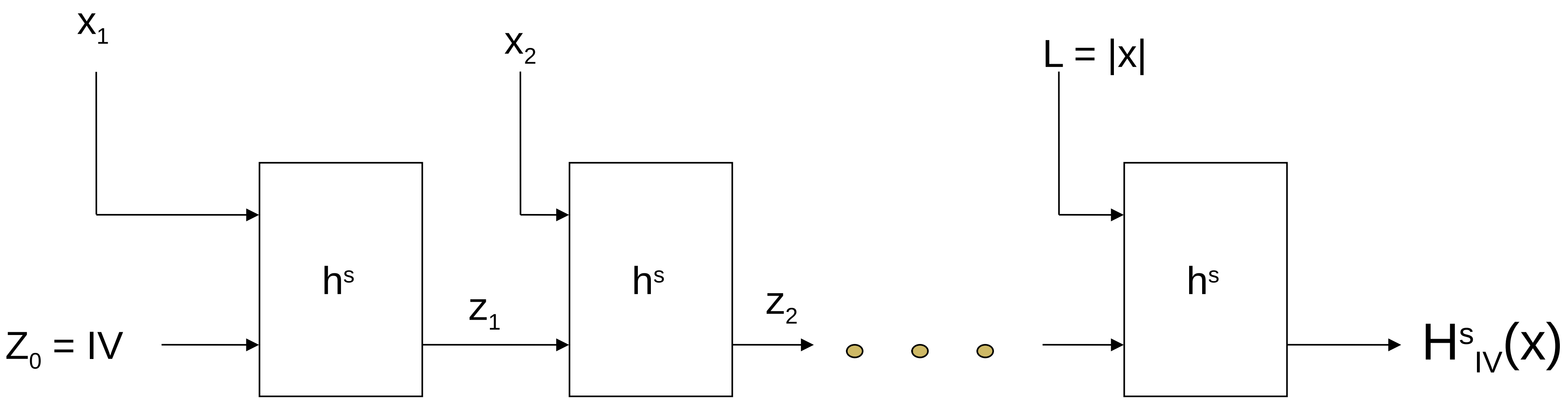
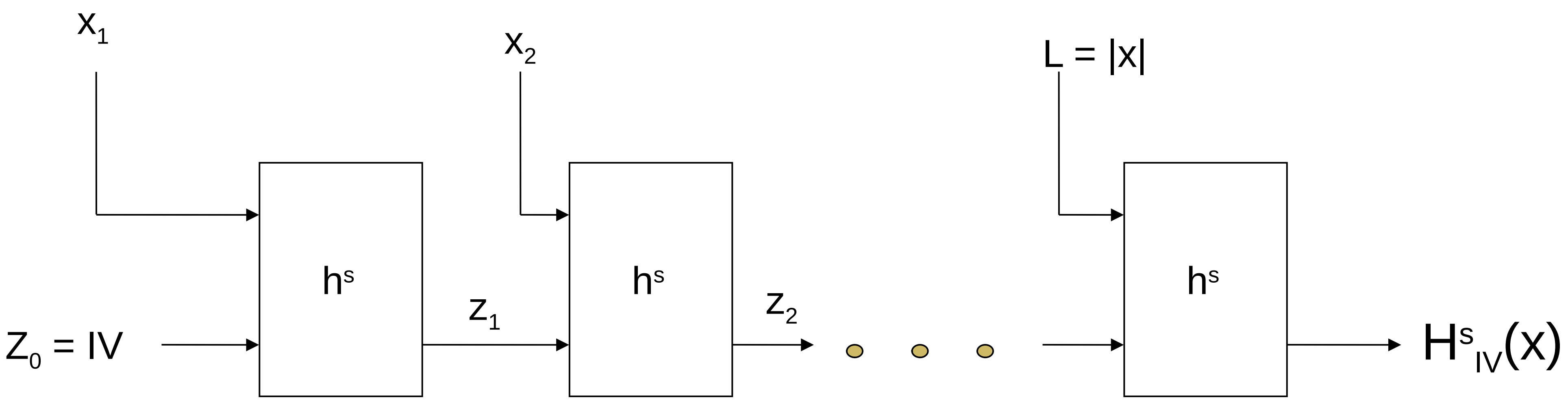


Merkle Damgard Transform



Theorem: If (Gen,h) is a fixed length collision resistant hash function, then (Gen, H) is a collision resistant hash function.

Our third exemplary problem

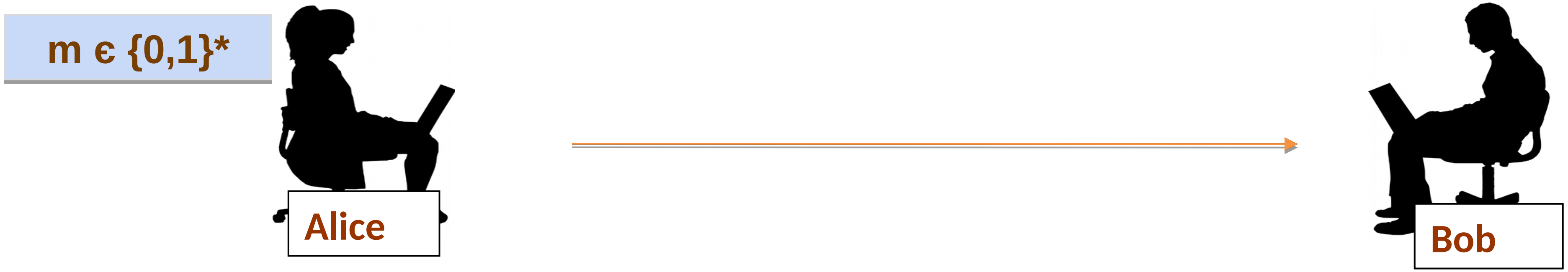
Digital Signatures

Digital Signatures

Perfect Signatures are Impossible!

Why?

Digital Signature Scheme



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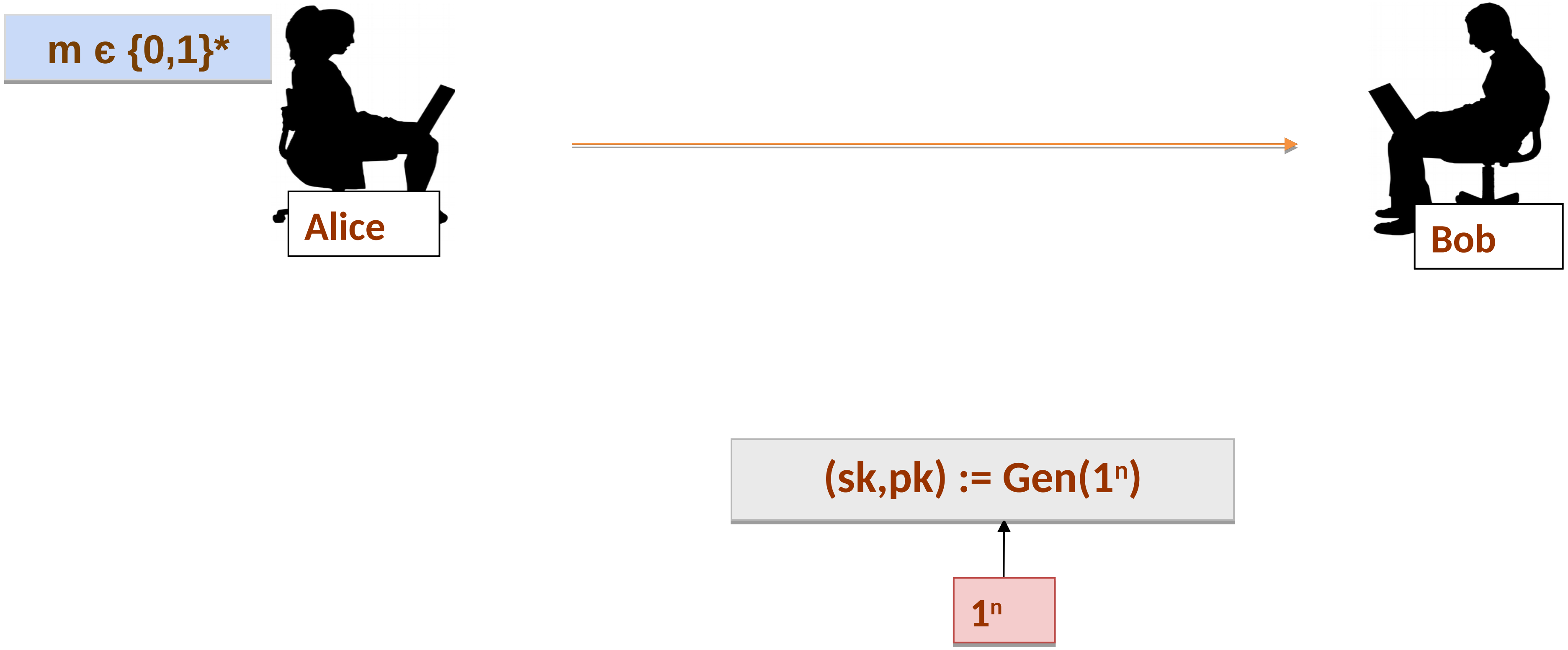

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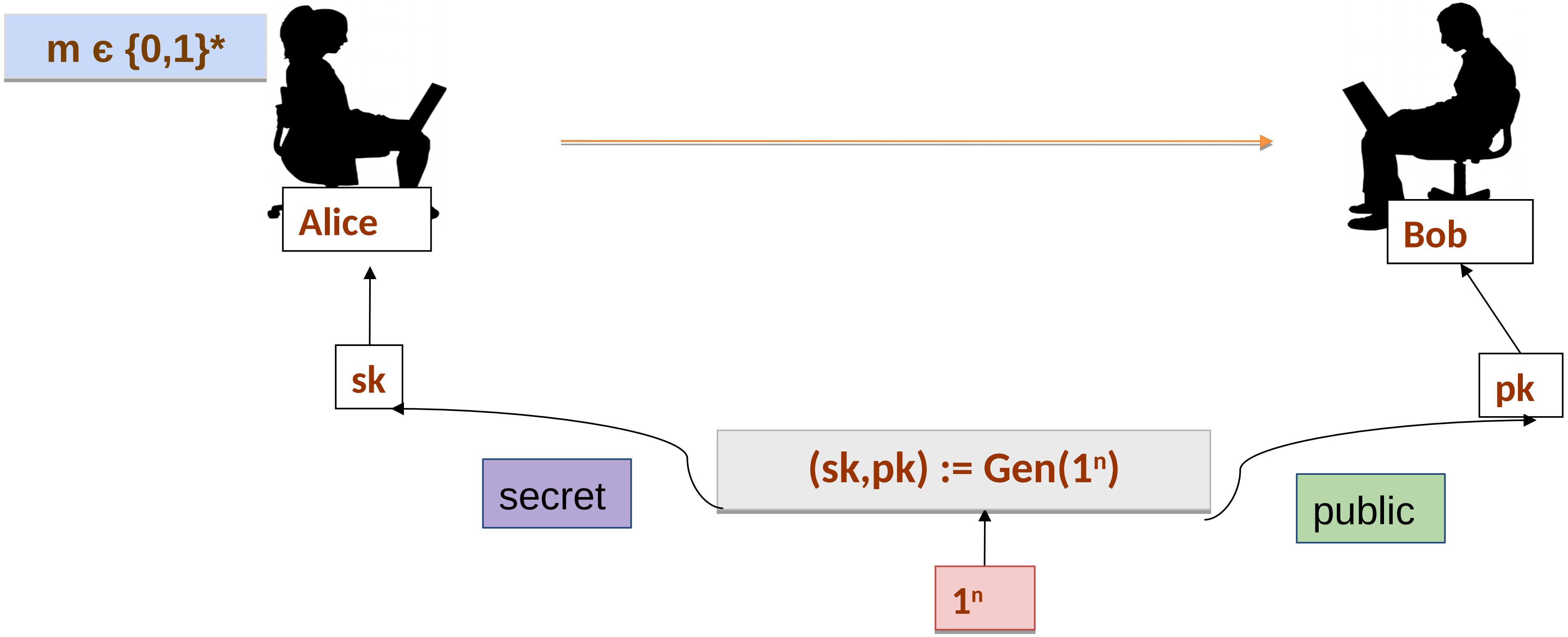

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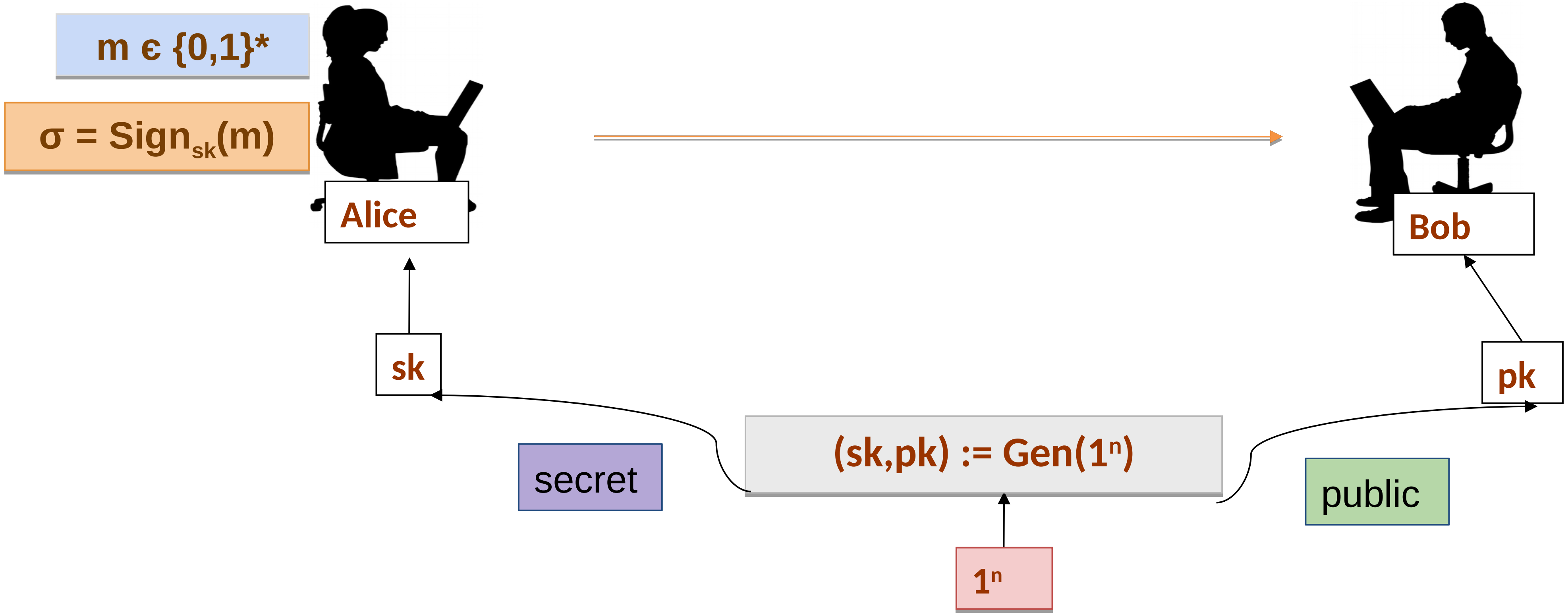

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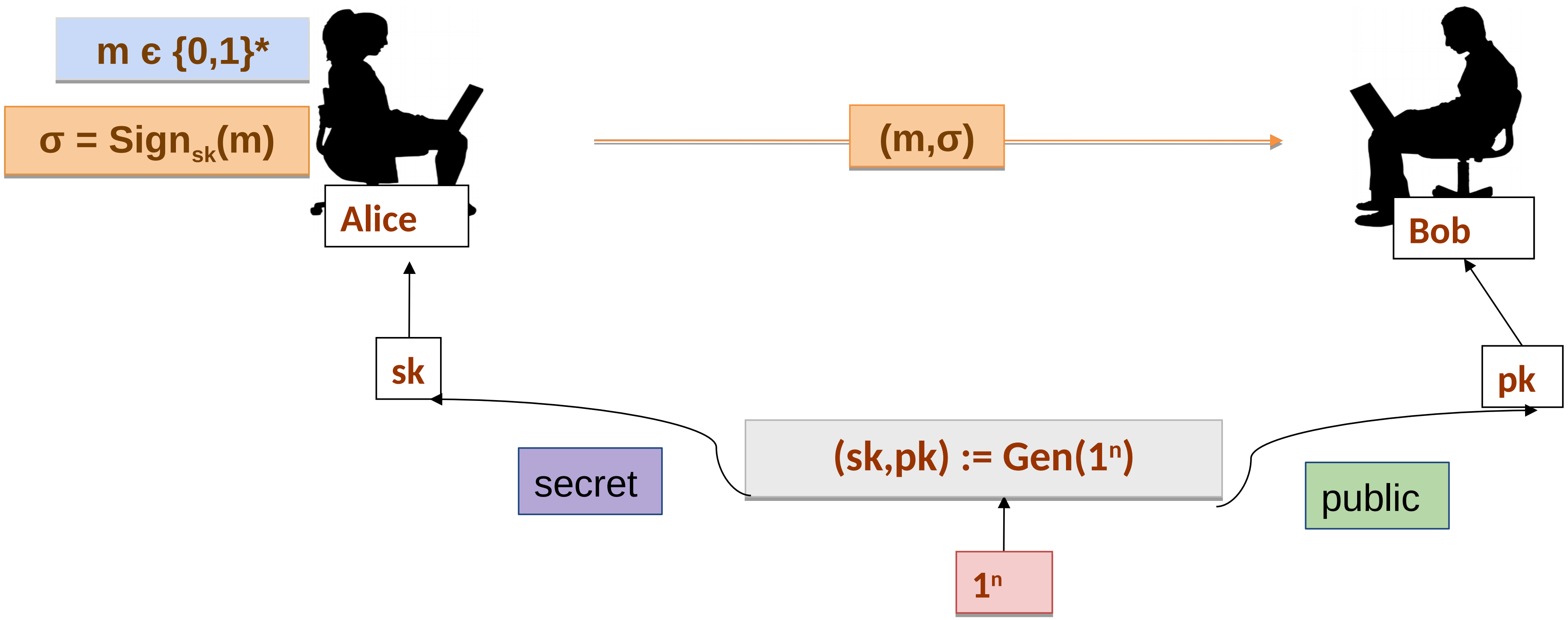

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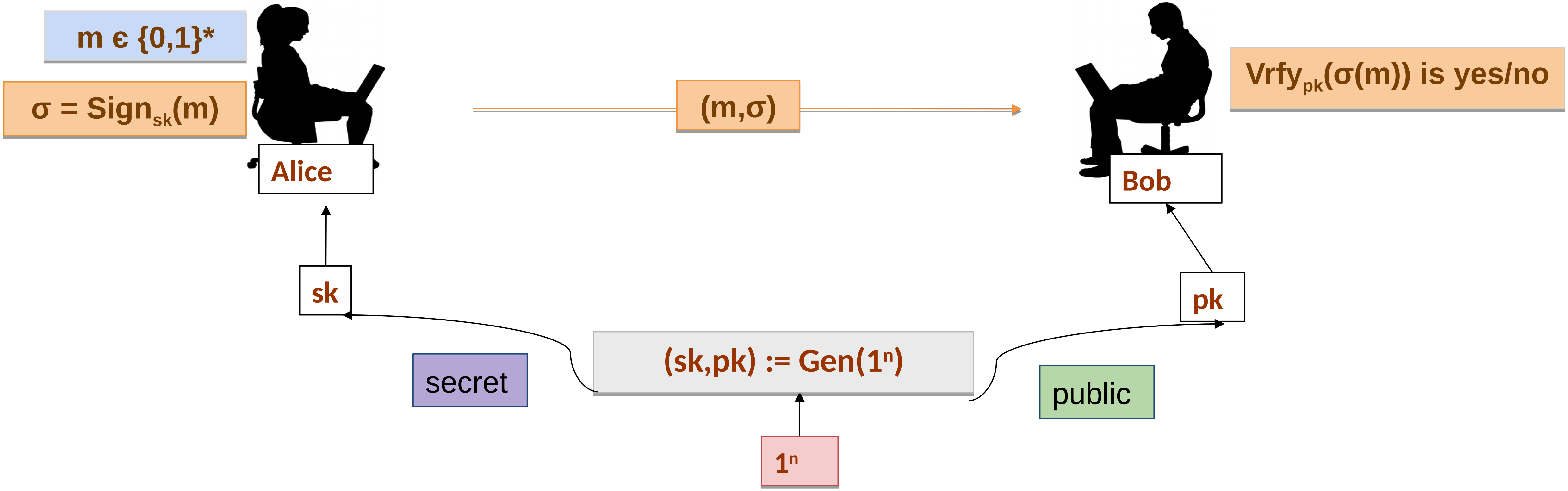

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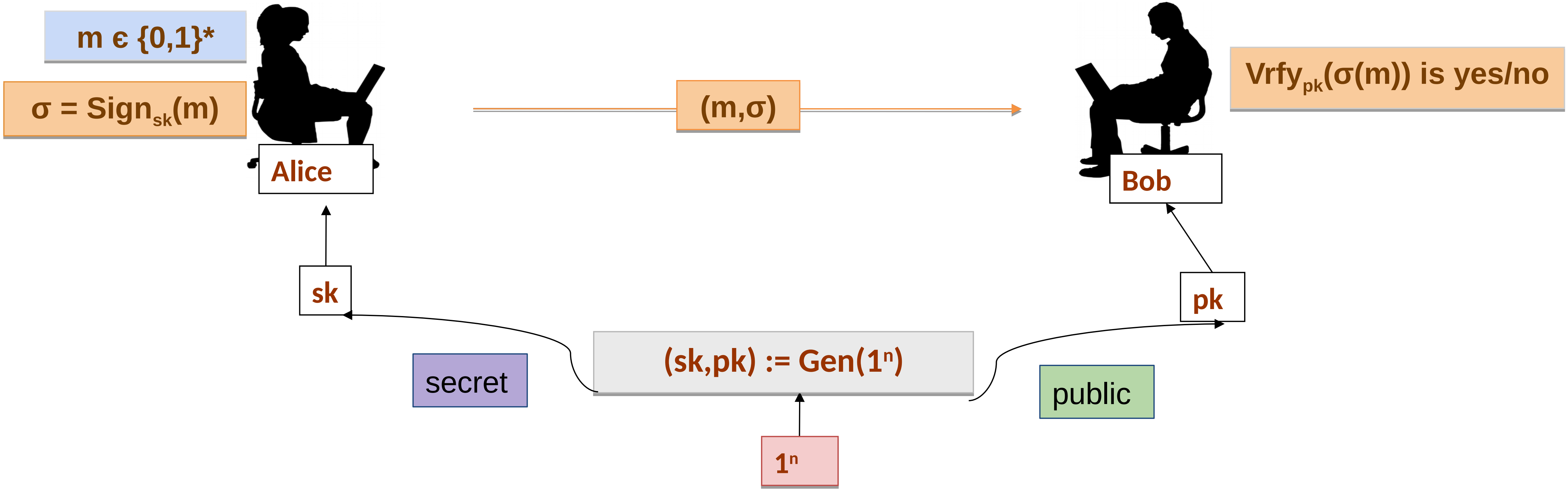

Assuming non-omnipotence:
Forging Alice’s signature without knowing sk is computationally hard

Cryptography requisites

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- Hashing
  - SHA256, RIPEMD
- Signing
  - ECDSA, DSS
- Public-key Schemes
  - RSA, ElGamal

MyCoin: A Use-Case for Public Key Cryptography,Collision-Resistant Hashing and Digital Signatures

MyCoin

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1. a) I should be able to generate MyCoin.
   b) Anyone should be able to verify that MyCoin belongs to me.

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1. a) I should be able to generate MyCoin.
   b) Anyone should be able to verify that MyCoin belongs to me.

2. I, as a owner of the MyCoin, should be able to spend it (and transfer ownership).

MyCoin

The Structure of MyCoin:

CoinID : CreateCoin()

My Publicly verifiable Unique Signature, $Sign_{me}$: Sign($PrivK_{me}$)

MyCoin

Transaction in MyCoin:

$Sign_{me}$: Sign($PrivK_{me}$)

Pay to $PubK_{you}$: H( )

CoinID : CreateCoin()

$Sign_{me}$: Sign($PrivK_{me}$)

MyCoin

Multiple Transaction in MyCoin:

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Multiple Transaction in MyCoin:

CoinID : CreateCoin()

Signed by PrivK_{me}

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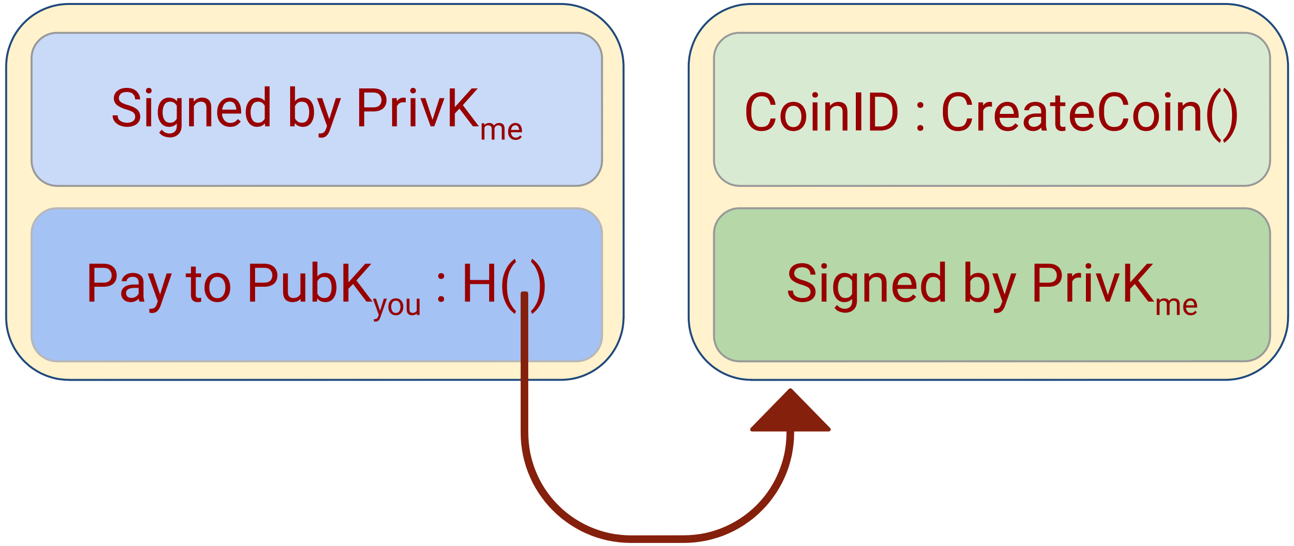

MyCoin

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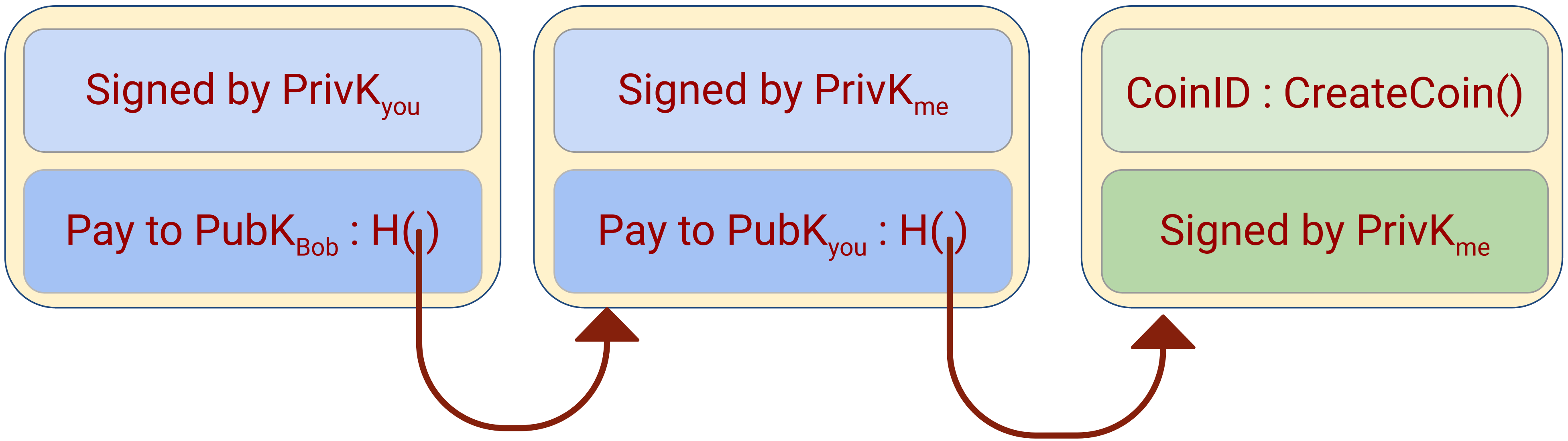

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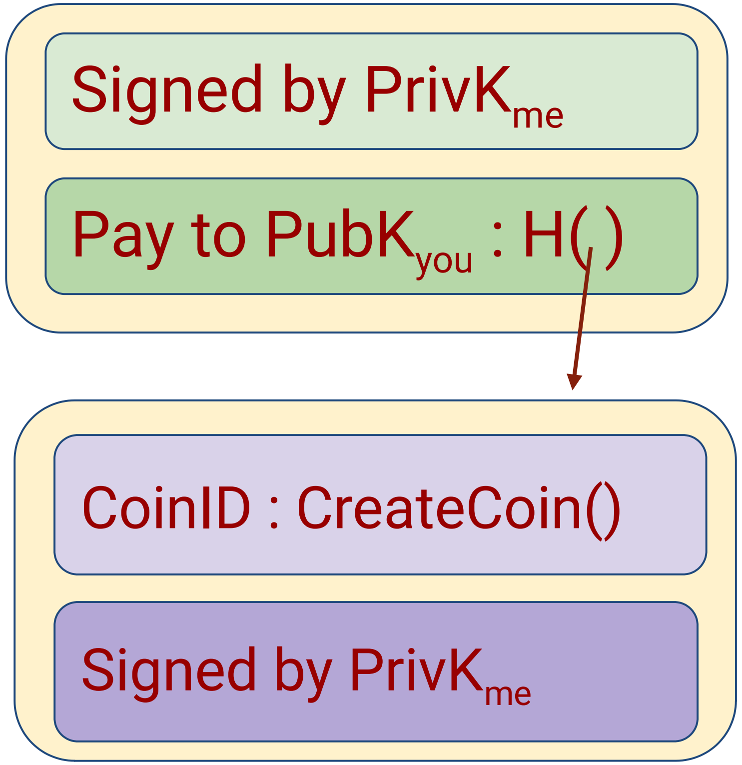

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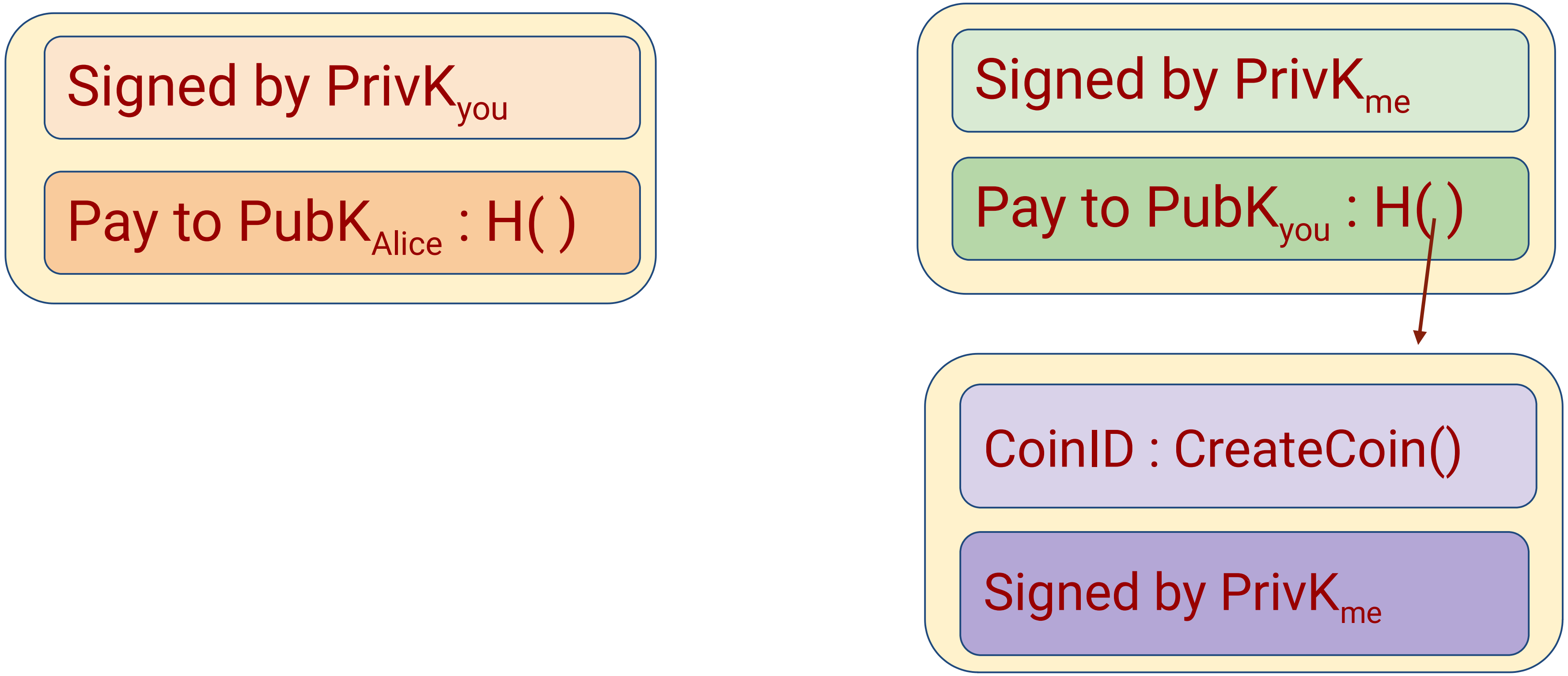

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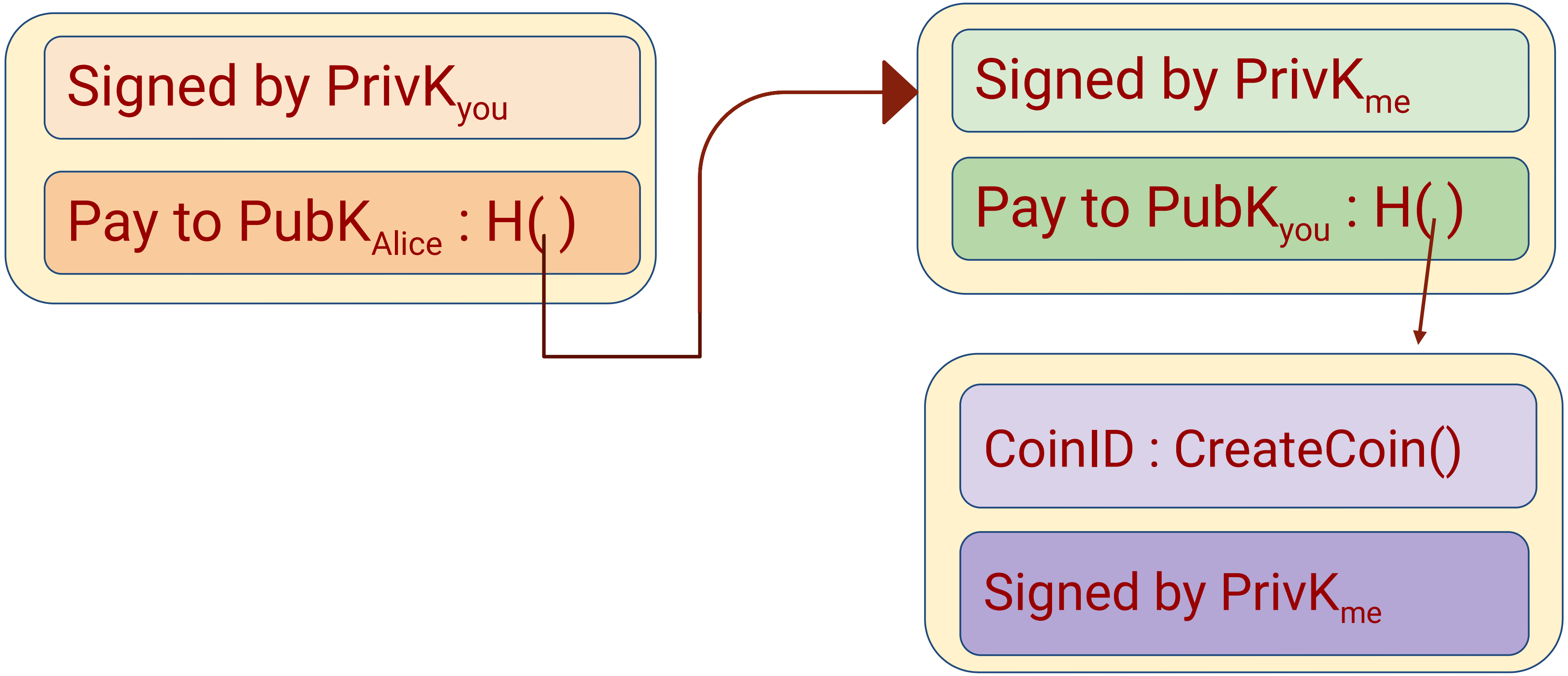

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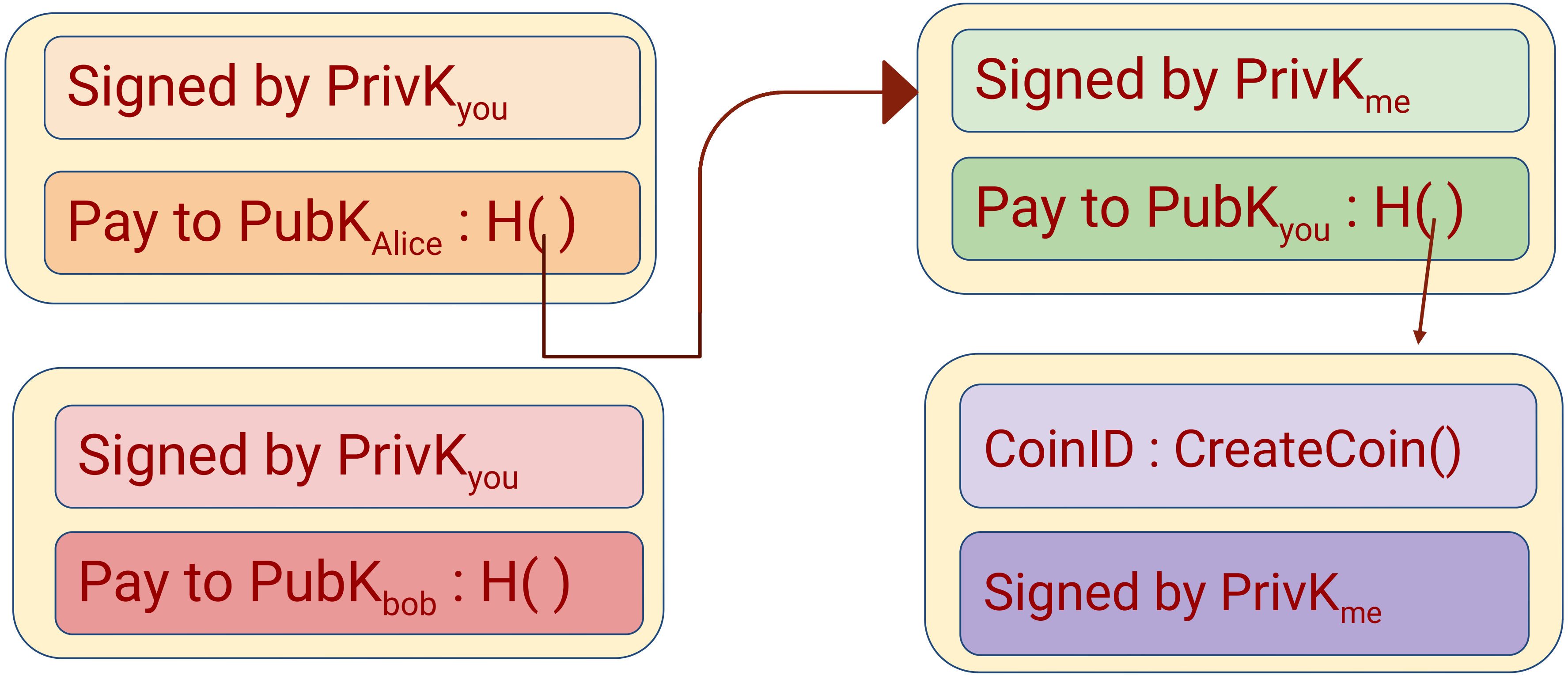

What can go wrong with MyCoin ?

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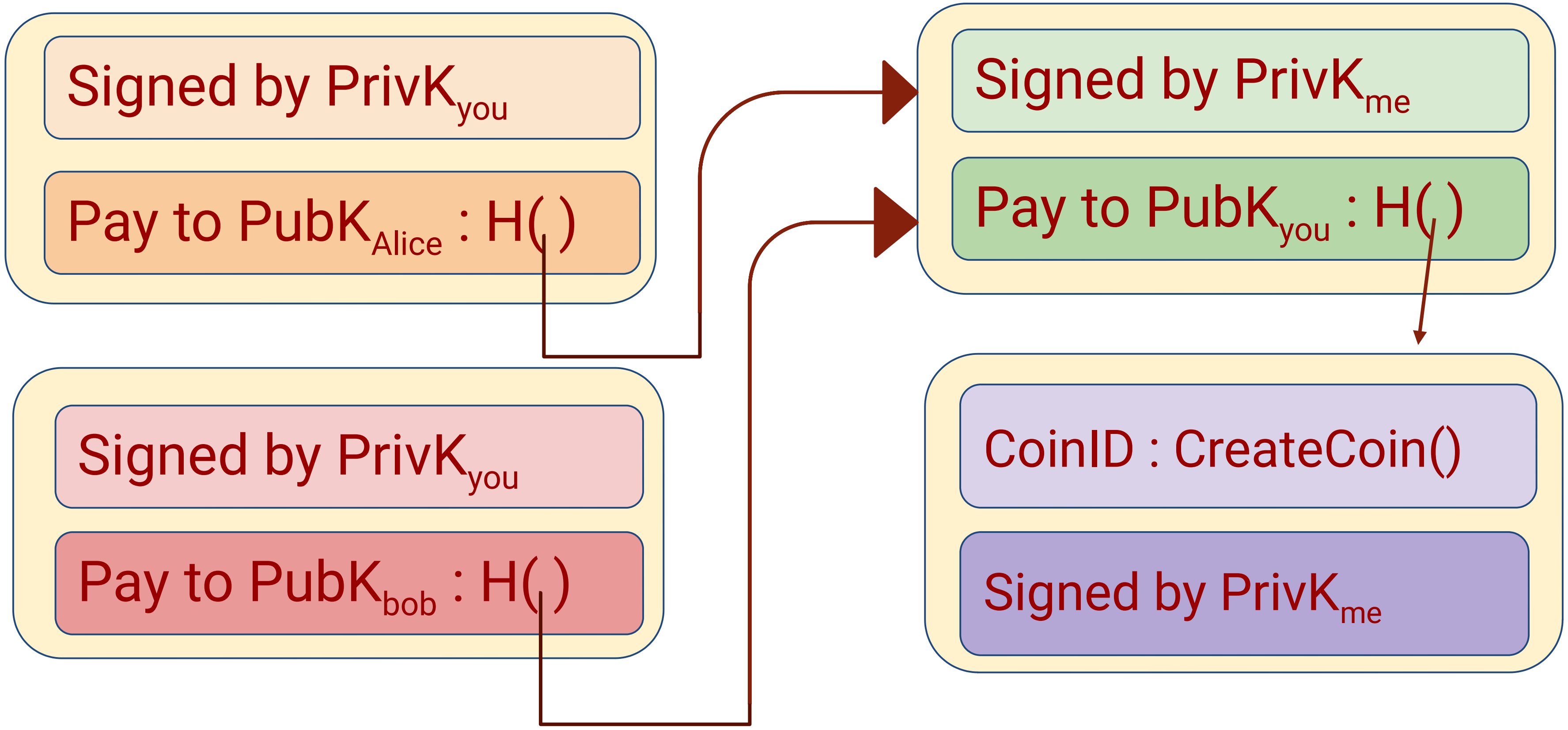

What can go wrong with MyCoin?

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The Problem of **Double Spending**

What can go wrong with MyCoin?

The Problem of **Double Spending**

A tough one!

How to resolve Double Spending Problem?

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Use Distributed Computing (Level I)
(Introducing **TrustMeCoin**)

How to resolve Double Spending Problem?

Use Distributed Computing (Level I)
(Introducing **TrustMeCoin**)

Using Secure DC (Level II)
(Introducing **SimulatedTrustCoin**)

How does **TrustMeCoin** solve Double Spending?

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Publish The Transaction History

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H ( )

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Publish The Transaction History

Hash that is calculated and signed by me

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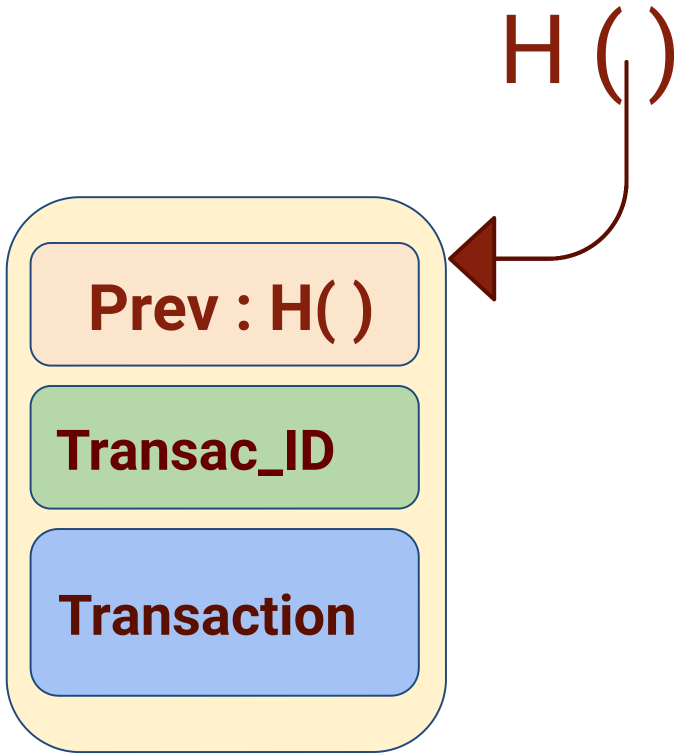

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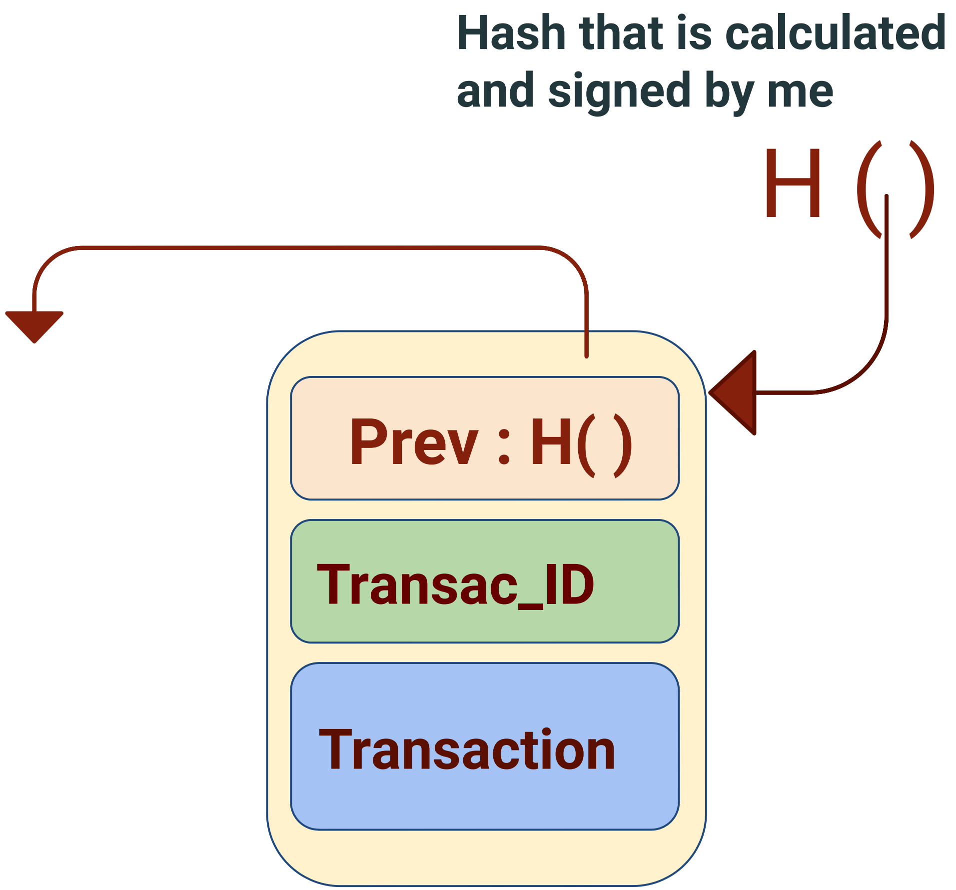

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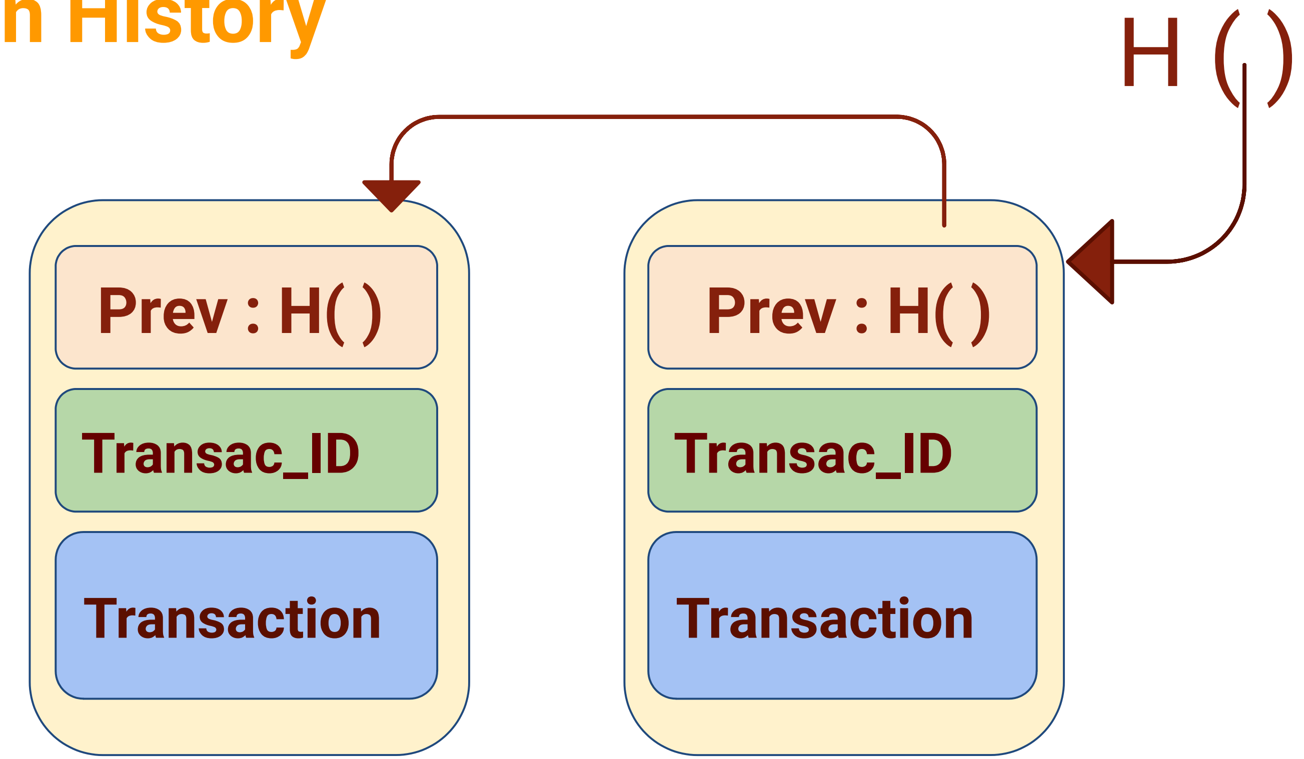

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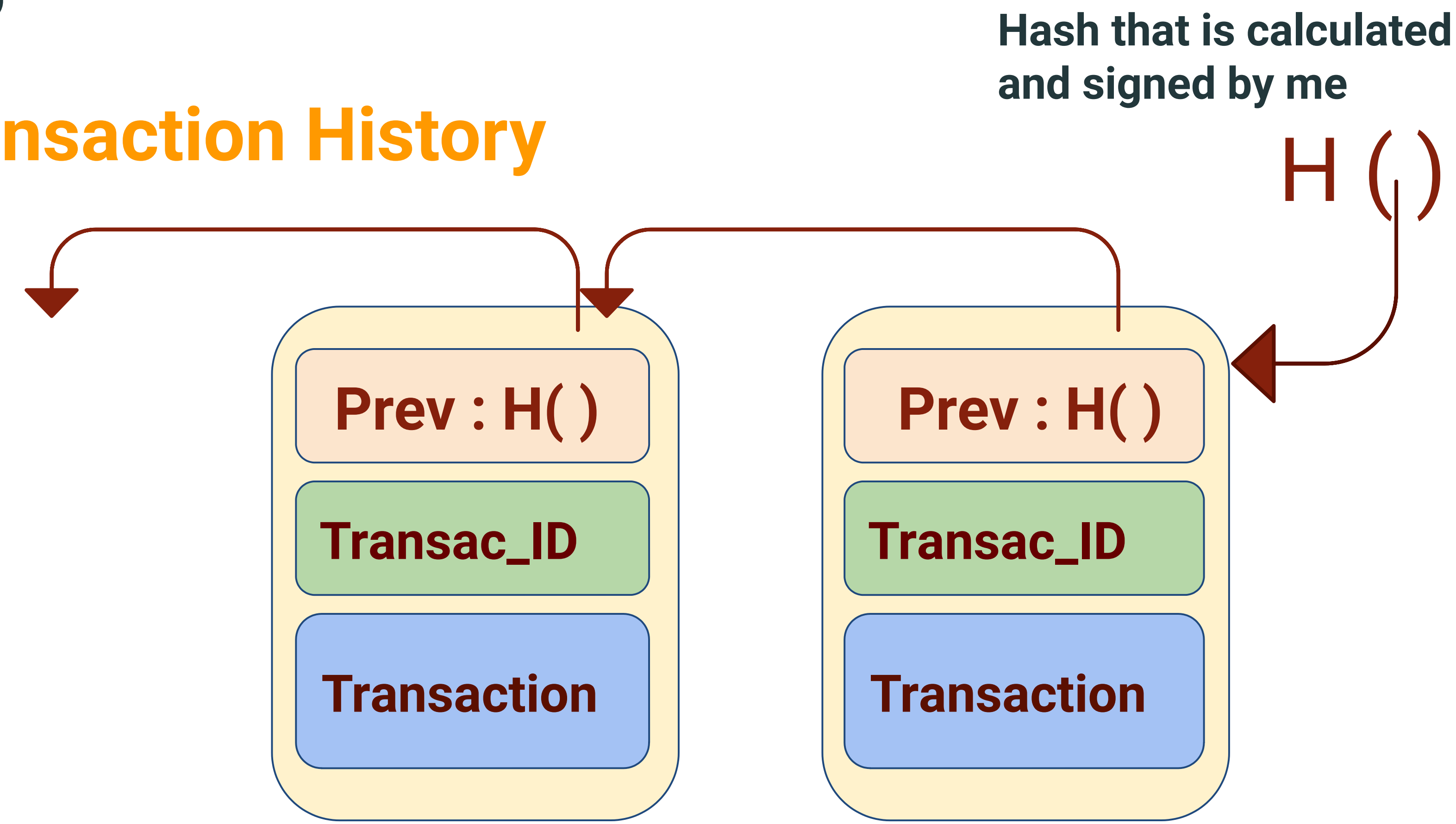

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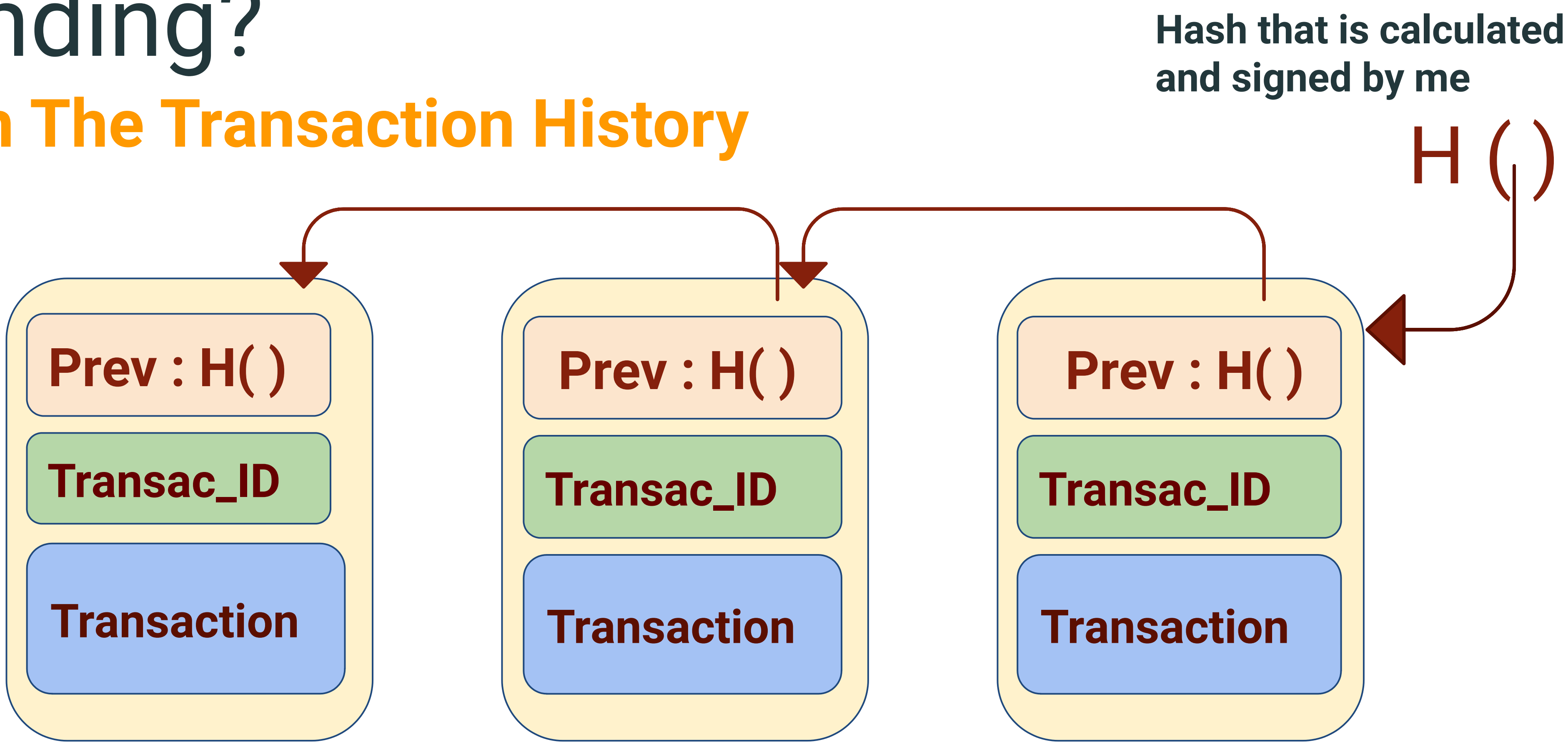

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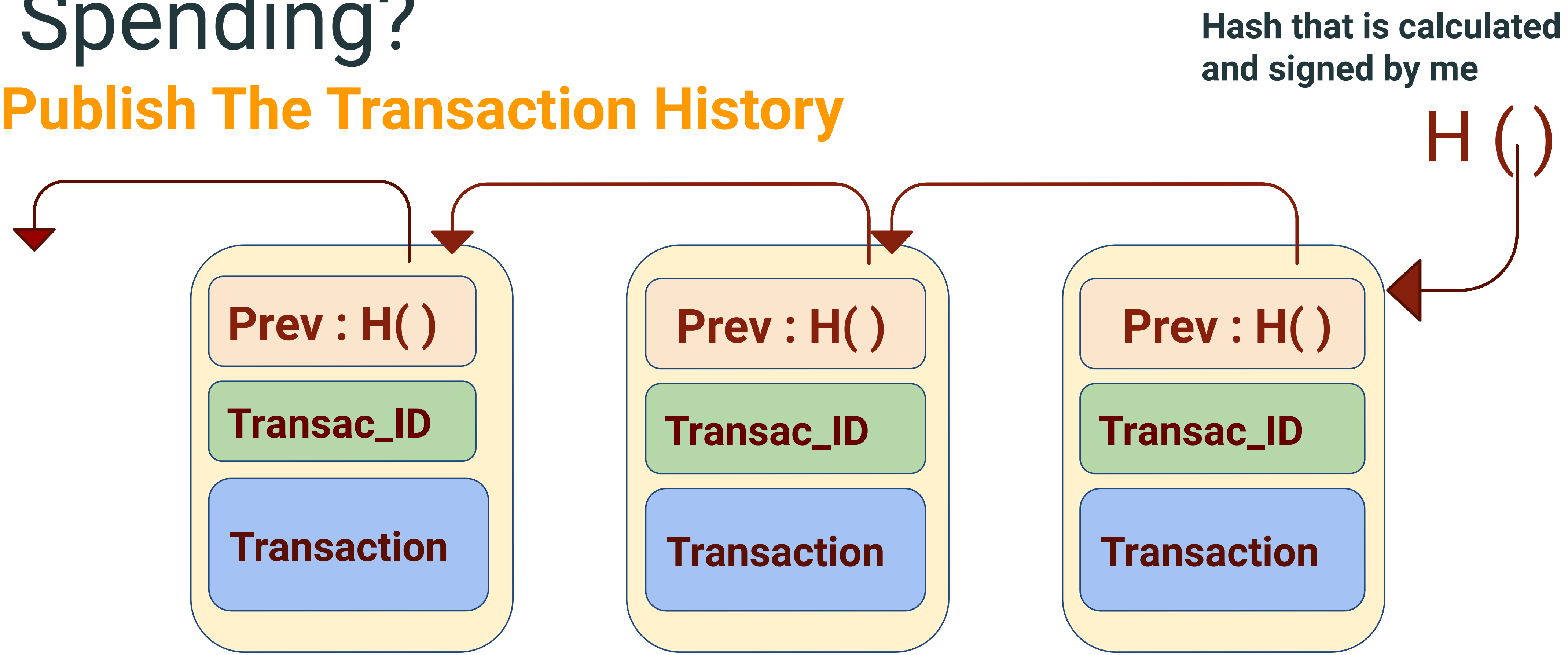

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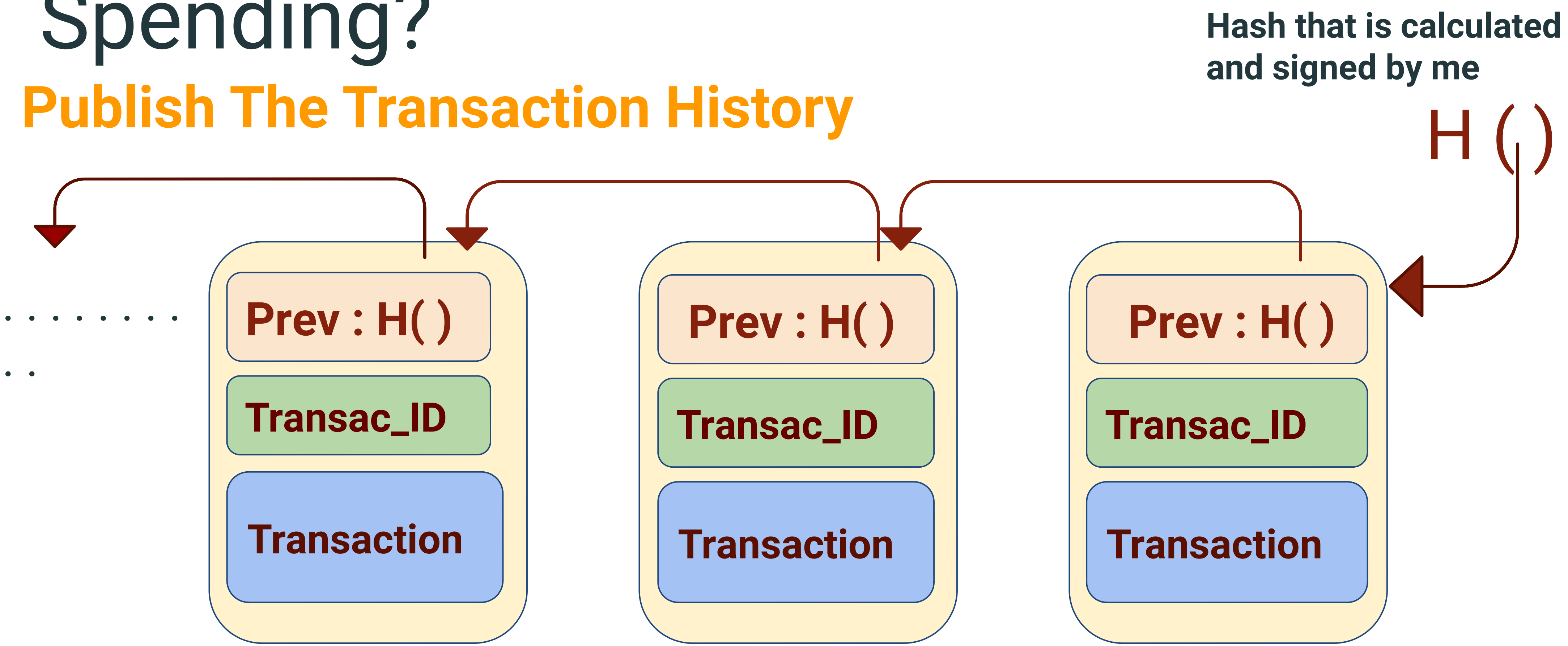

TrustMeCoin : Two types of Transactions

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Transaction Type 1 : CreateCoin, for generating new coins

TrustMeCoin : Two types of Transactions

Transaction Type 1 : CreateCoin, for generating new coins

TransId : 53 Type : CreateCoin

Coin Created

Num	Value	Recipient
1	4.7	0x……...
2	3.7	0x……...
3	2.3	0x……...

Coin Id : 53 (0)

Coin Id : 53 (1)

Coin Id : 53 (2)

TrustMeCoin : Two types of Transactions

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Every created coin is valid , because I have the rule that all coins generated by me are valid.

Coin Id : 53 (0)

Coin Id : 53 (1)

Coin Id : 53 (2)

TrustMeCoin : Two types of Transactions

Some reference taken from free draft of Bitcoin and Cryptocurrency Technologies

TrustMeCoin : Two types of Transactions

Transaction Type 2 : PayCoin, for payment using TrustMeCoin

TrustMeCoin : Two types of Transactions

Transaction Type 2 : PayCoin, for payment using TrustMeCoin

TransId : 67 Type : PayCoin

Input Coin Id(s): 53(0), 53(1), 53(2)

Coin Created

Num	Value	Recipient
1	3.7	0x……...
2	2.3	0x……...
3	4.7	0x……...

Coin Id : 67 (0)

Coin Id : 67 (1)

Coin Id : 67 (2)

Some reference taken from free draft of Bitcoin and Cryptocurrency Technologies

TrustMeCoin : Two types of Transactions

Transaction Type 2 : PayCoin, for payment using TrustMeCoin

TransId : 67 Type : PayCoin

Input Coin Id(s): 53(0), 53(1), 53(2)

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1	3.7	0x……..
2	2.3	0x……..
3	4.7	0x……..

Coin Id : 67 (0)

Coin Id : 67 (1)

Coin Id : 67 (2)

Transaction is Valid if:
- Consumed coins are valid.
- Not Already Consumed.
- Total input = Total Output.
- All consumed coin owners have signed it.

Some reference taken from free draft of Bitcoin and Cryptocurrency Technologies

The problem with **TrustMeCoin**?

The problem with **TrustMeCoin**?

Trust is the Problem.

TrustMeCoin is robust if only you ***trust me***!

Decentralizing the Trust-on-Me

Decentralizing the Trust-on-Me

A Not-So-Simple Distributed Cryptographic Approach

(accentuates the simplicity of blockchains)

How To Solve It ?

(By Non-Omnipotence of machines?)

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(By Non-Omnipotence of machines?)

Welcome to **Distributed (Crypto) Computing**!

Our first exemplary problem (non-omnipresence)

Secret Sharing

t-Secret Sharing

Shamir's Protocol:

- Choose a t-degree polynomial p() over a (large enough) finite field
- Let Secret s = p(0)
- Shares are p(1), p(2), …p(n) for some n

*Ref: **Adi Shamir. How to Share a Secret. CACM, 1979***

Our second exemplary problem

Recall: Secure Communication

Secure Communication: Distributed Algorithmic Solution

- Essentially the distribution helps in improving security. Even perfect security is achievable in some cases.
- Key Ingredient: Secret Sharing

Perfectly Secure Communication

Dolev *et al.* Protocol:

1. Sender shares the message using secret sharing and sends the shares to Receiver along different paths.

2. Receiver collects all the shares, and reconstructs the message.

Ref: ***Danny Dolev, Cynthia Dwork, Orli Waarts, Moti Yung Perfectly secure message transmission, J. ACM 40, 1 (1993), 17-47.***

Recall: Byzantine Agreement

Authenticated Byzantine Agreement (ABA)

- Computationally Bounded Adversary Model
- Processes are supplemented with “magical powers” to a*uthenticate* their communication – *Digital Signatures*.
- Using authentication, fault tolerance can be increased to $t < n$.

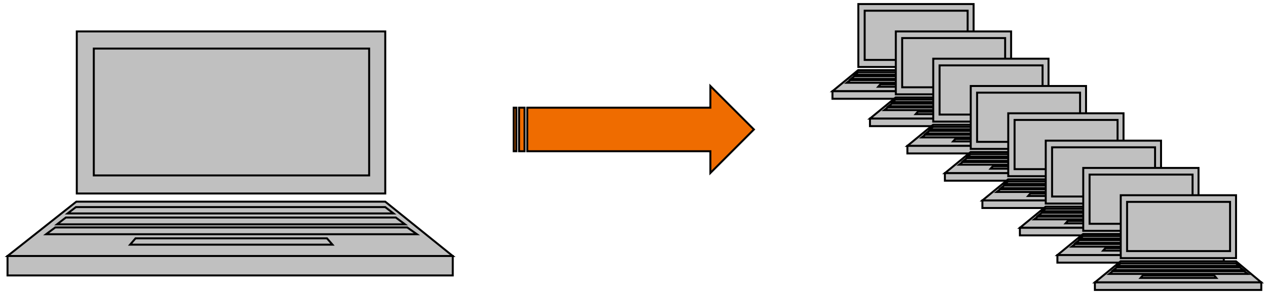
ABA protocol for 1 out of 3

- Player k maintains a set W_{ik}, $\forall\, i \in P$. Initially $W_{kk}=\{\sigma\}$ where σ is player k's input value.
- Repeat the following steps for 2 rounds:
  - Receive values from neighbors and for each received value do:
    - If the message is properly signed, he append its content to the set W_{ik}
    - Sends i, W_{ik} to his neighbors.
- He deletes W_{ik} if $|W_{ik}| \neq 1$.
- Since all remaining W_{ik}'s are singleton, he takes majority over all values. If a majority exists he decides on it, else decides on the default value.

Our last exemplary problem

Secure Multiparty Computation

Simulating Secure Nodes: Basic Idea



- The data in each memory register of the secure virtual server is secret shared and stored across several nodes in the network
- Each CPU instruction of the secure virtual server is simulated via a network protocol
- Our instruction set architecture: XOR, AND, SEND and RECEIVE

Secure Addition Protocol

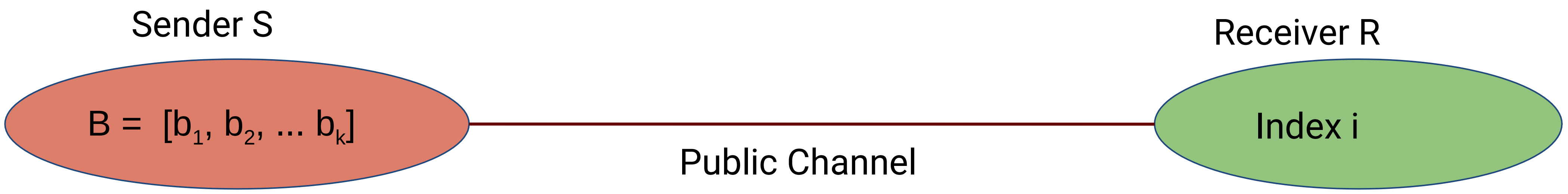
Simple: Local addition entails global addition!

Secure Multiplication Protocol

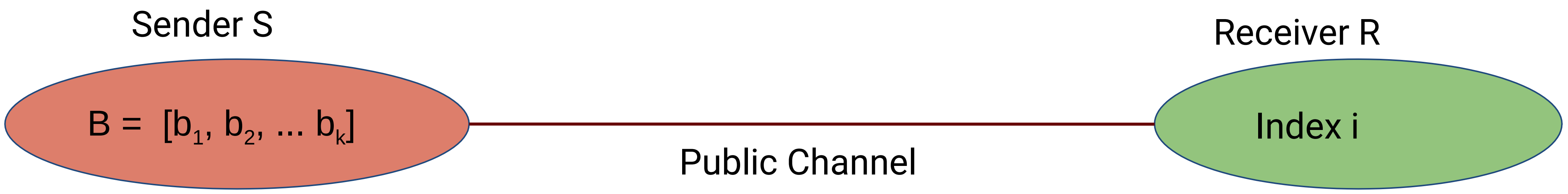
Cryptographic Solution:
Uses Oblivious Transfer

Oblivious Transfer

Oblivious Transfer



Oblivious Transfer



Objective :

- R should be able know b_i without revealing i to S.
- S should be able to send b_i to R without revealing $b_{j \neq i}$

Oblivious Transfer (Contd.)

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- Step 1: R selects uniformly at random k strings $x_1,x_2,\ldots,x_k$ and sets
  $y_i = Enc_{PubKey(S)}(x_i)$ and $y_j = x_j$ for every $j \neq i$; R sends $y_1,y_2,\ldots,y_k$ to S.

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- Step 2: S decrypts y_j's and obtains z_j's. S sets $c_j=b_j$ xor z_j. S sends $c_1,c_2,\ldots,c_k$ to R.

Oblivious Transfer (Contd.)

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- Step 3: R outputs c_i xor x_i

Multiplication in the Shared Domain

- Two-party Passive Adversary Case (all computations are in GF(2)).
- Party P_1 has a_1 and b_1; Party P_2 has a_2 and b_2 ; here $a=a_1+a_2$ and $b=b_1+b_2$
  (that is, a and b are secret shared).
- Objective: P_1 must obtain c_1 and P_2 must obtain c_2 such that:

$$c_1+c_2 = (a_1+a_2).(b_1+b_2).$$

Multiplication in the Shared Domain (Contd.)

- Step 1: P_1 selects c_1 uniformly at random.
- Step 2: An Oblivious Transfer is performed with P_1 as sender and P_2 as receiver, k=4
- P_1's input: $\{c_1+a_1b_1, c_1+a_1b'_1, c_1+a'_1b_1, c_1+a'_1b'_1\}$
- P_2's input: $1+2a_2+b_2$ (from the set {1,2,3,4})

Ref: *Oded Goldreich. Foundations of Cryptography. Cambridge University Press. 2001*

SimulatedTrustCoin

SimulatedTrustCoin

Candidate Solution: Decentralizing the **Trust-on-Me** by simulating a trusted third party

Simplification: Introducing Blockchains

The Blockchain Approach

The Blockchain Approach

Simplify by Game Theory

The Blockchain Approach

Simplify by Game Theory

Incentivising Honesty

The Blockchain Approach

The Blockchain Approach

- Publish the transaction history

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- All the peers *agree* on the correct chain. How?

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    - All double spends are *detected* (like in TrustMeCoin)
    - However no centralized authority exists to correct it!
- All the peers *agree* on the correct chain. How?
    - The longest chain is deemed as *correct*.
    - Appending to the longest chain is rewarded [game theory]
    - Appending elsewhere is penalized [game theory]

Proof-Of-Work

Random Selection, Incentives and Penalties: **All-in-one-Go**!

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Random Selection, Incentives and Penalties: **All-in-one-Go**!

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- If you are compensated for the efforts, there is a reward, *if and only if* your transaction is in the longest chain.
- If the effort is a hash-puzzle, then none can keep winning, entailing random choice.

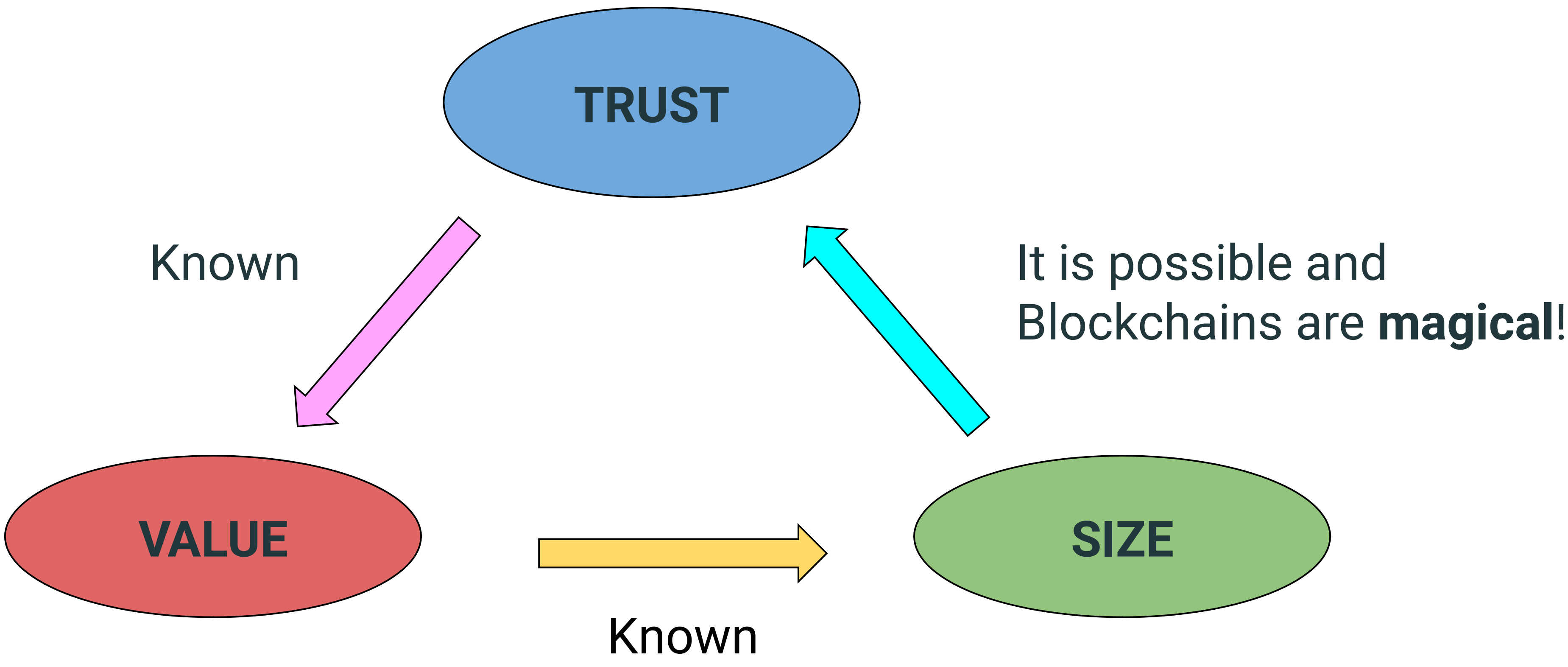
Summary

- Crypto takes us to MyCoin.

  Crypto-and-Distributed Computing takes us to SimulatedTrustCoin.

  Crypto-DC-Game-theory creates **BLOCKCHAIN**.

Conclusion


TRUST
Known
It is possible and
Blockchains are **magical**!
VALUE
SIZE
Known

Thank you.

Any questions?