Information Systems and **Network Security**

Docente: Stefano Leucci

Email: `stefano.leucci@univaq.it`

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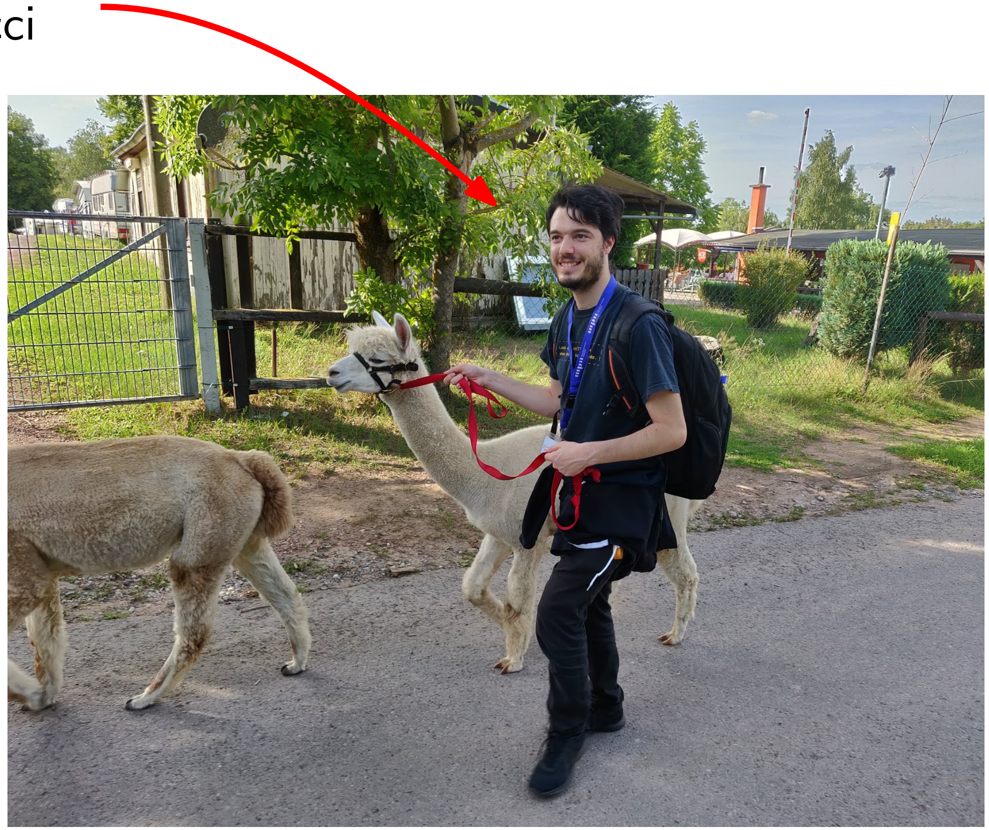

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Basic Info

Course length: 48 hours (6 CFU)

- 24 lectures

When/where:

- Tuesday 9:30 – 11:30 **Room:** A1.2

- Thursday 11:30 – 13:30 **Room:** A1.2

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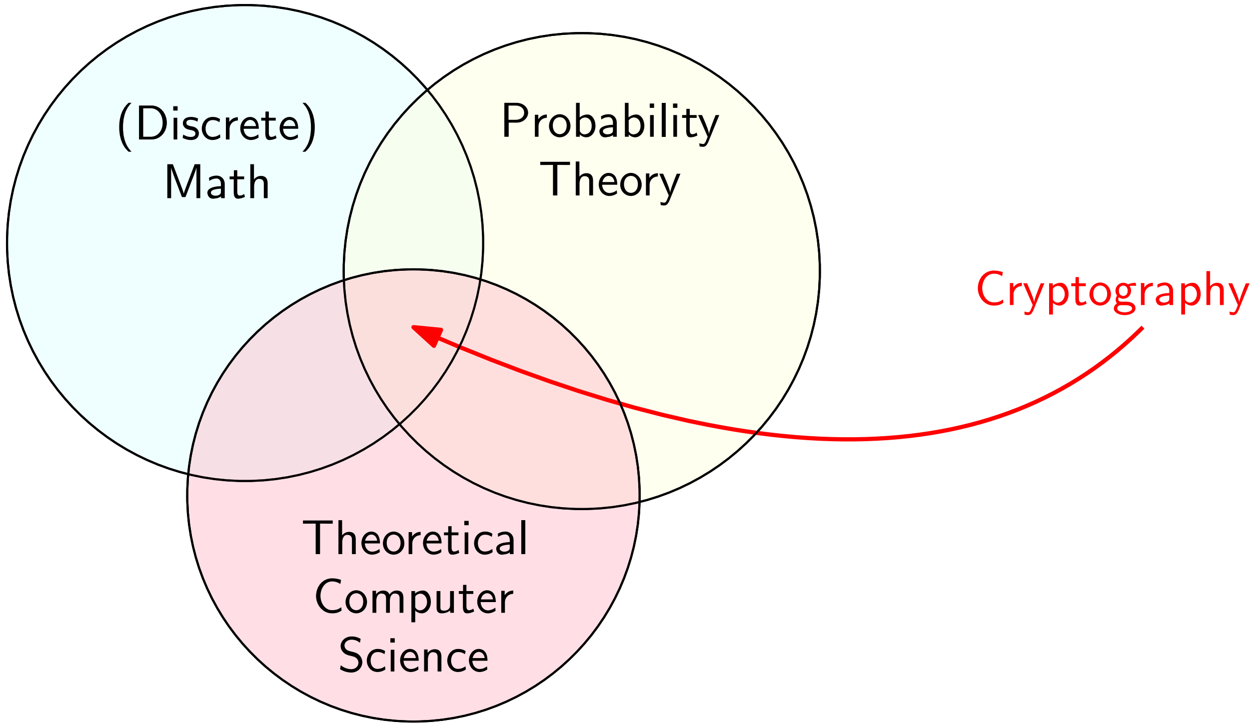
Office hours:

- Thursday 16:30 – 18:30
- Please send an email to `stefano.leucci@gmail.com` or ask before/after class

Course material:

`https://people.disim.univaq.it/~stefanoleucci/isns24/`

Ingredients of Cryptography



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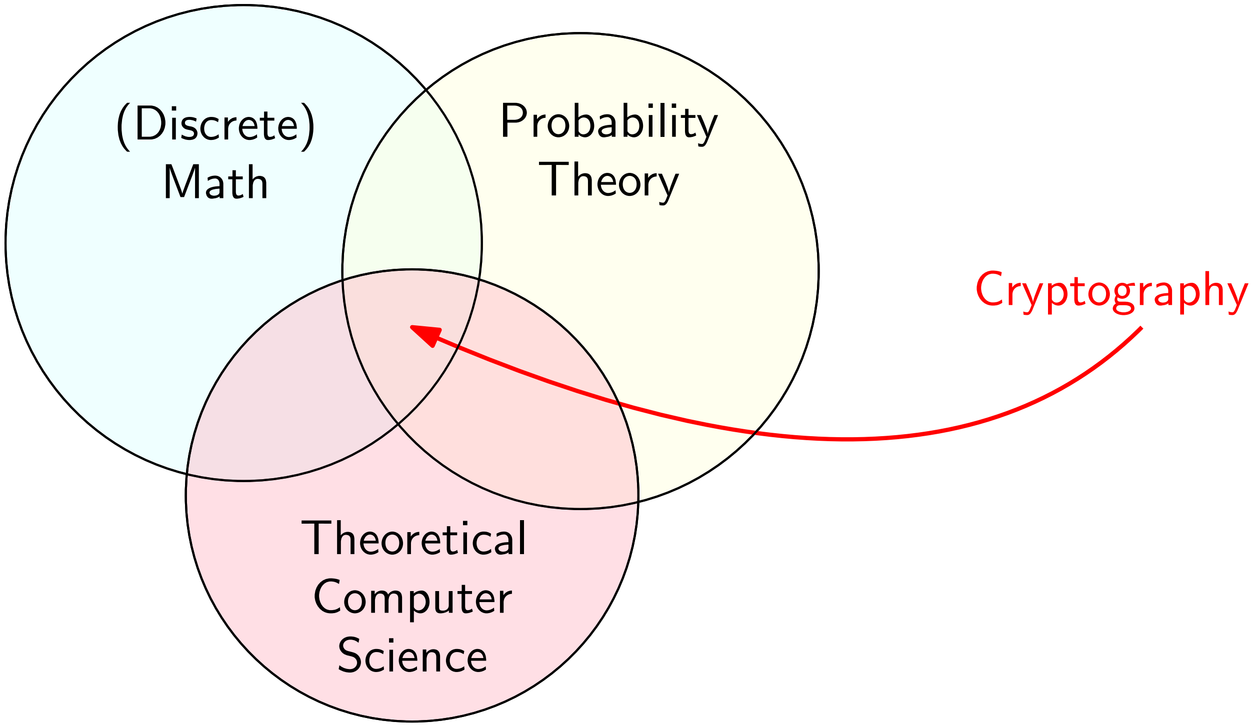

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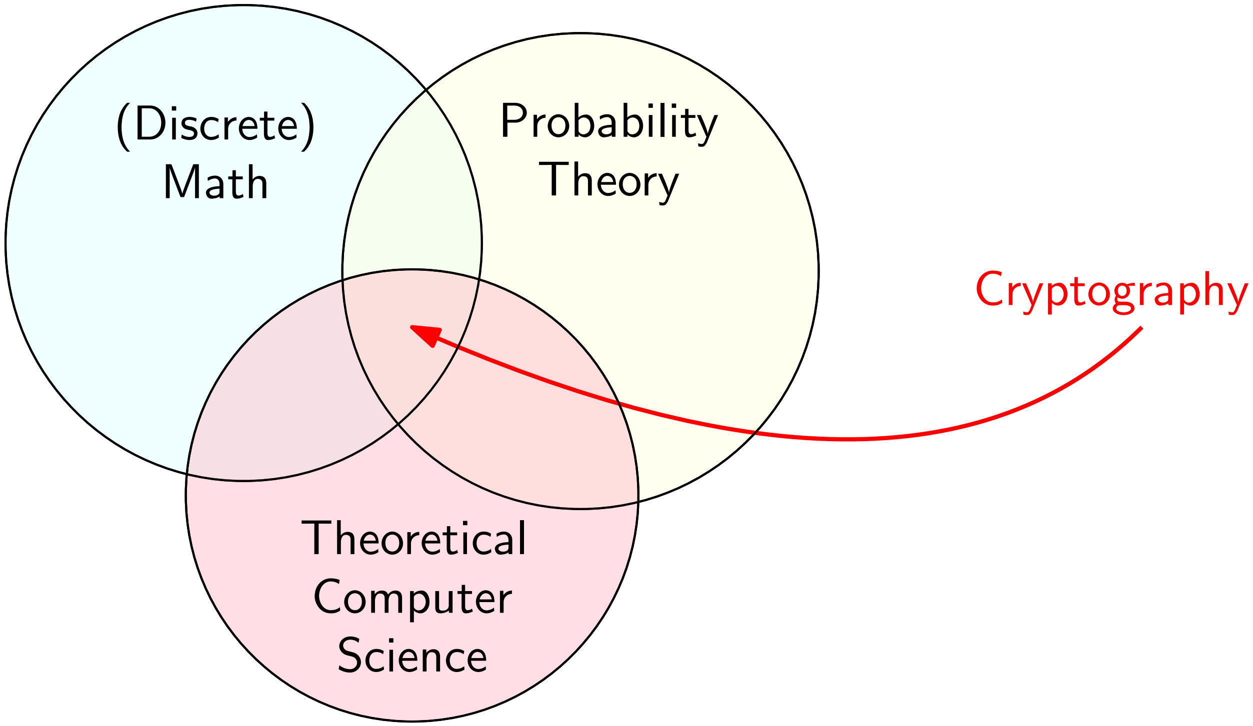

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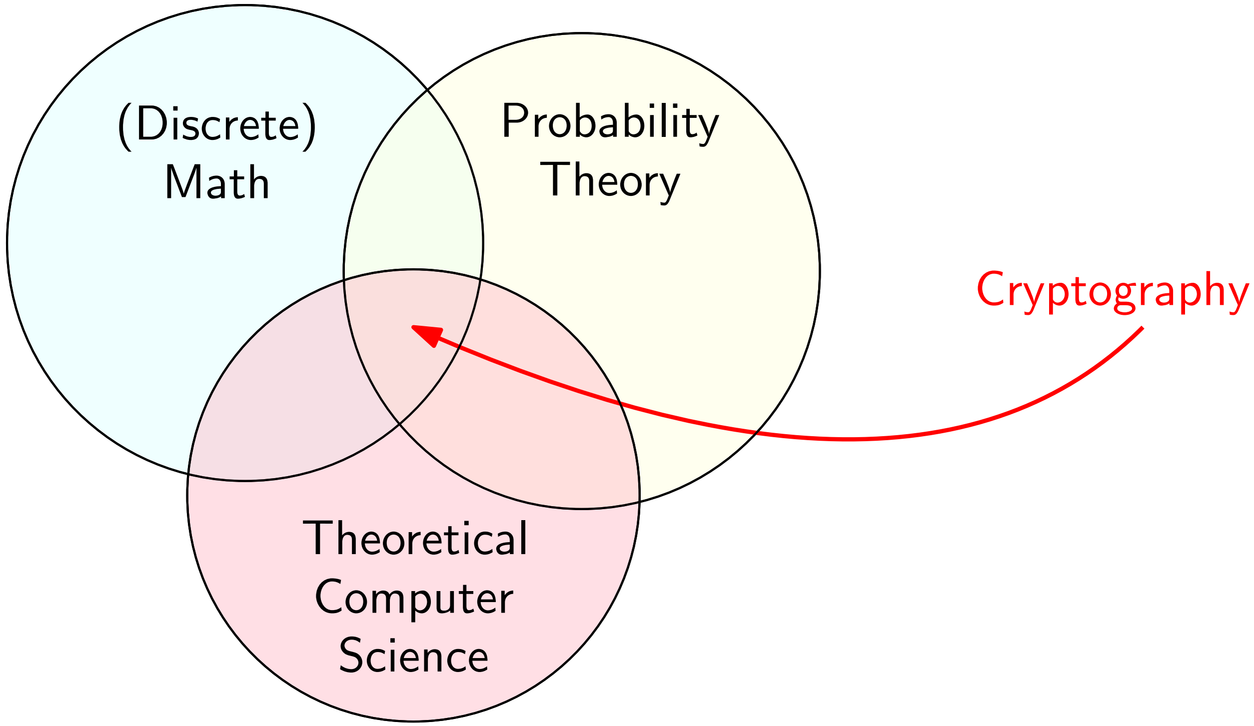

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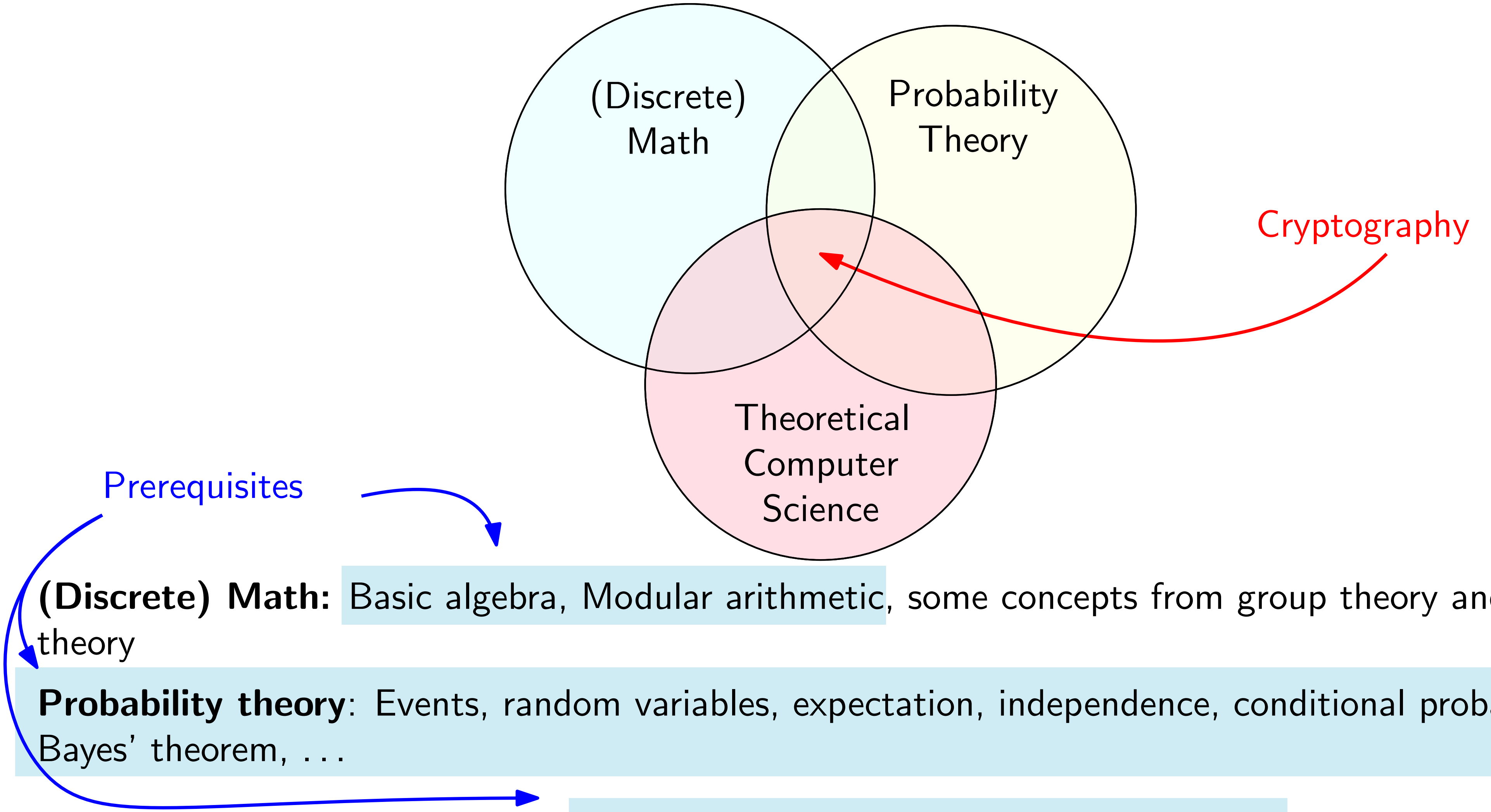

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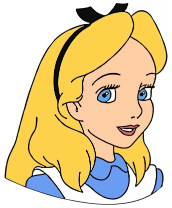
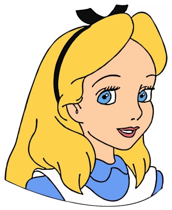


Two entities wish to communicate

Why cryptography?

Alice



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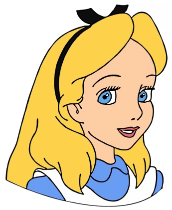

Bob

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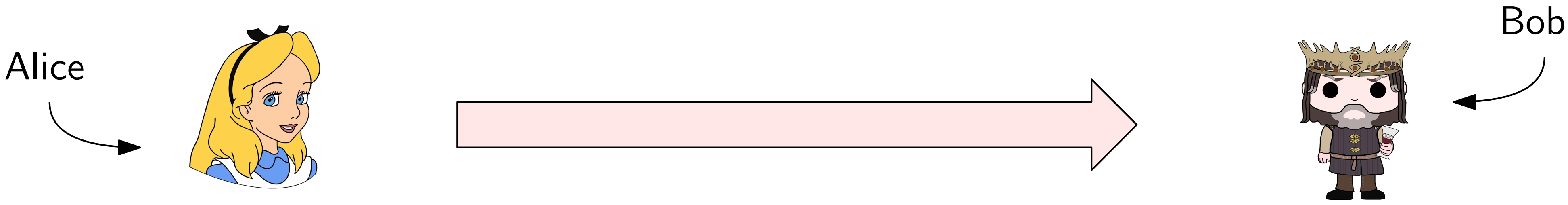

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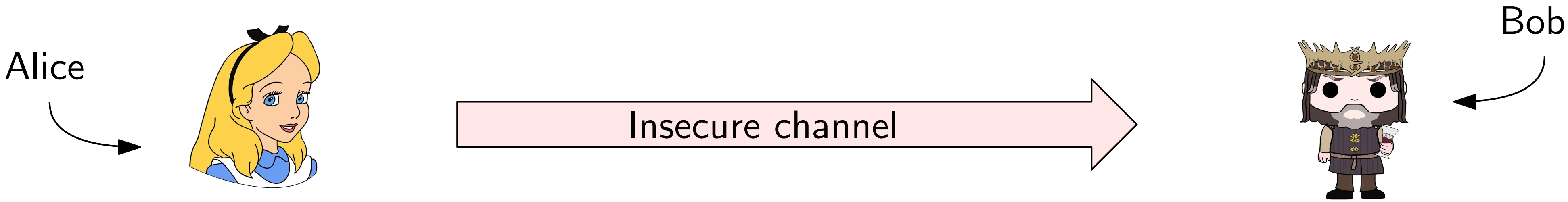

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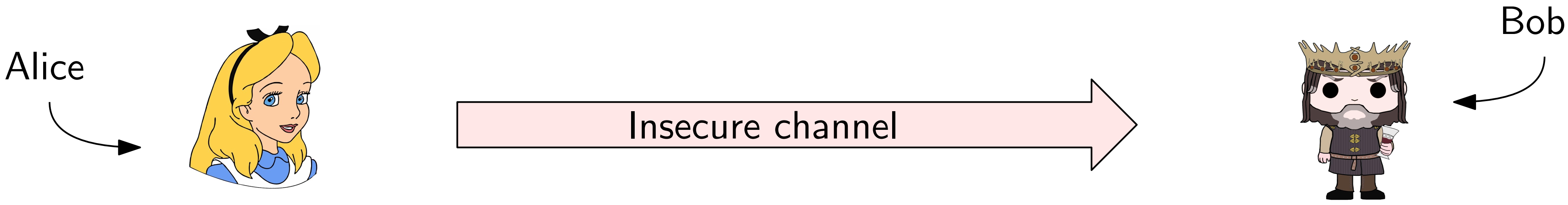

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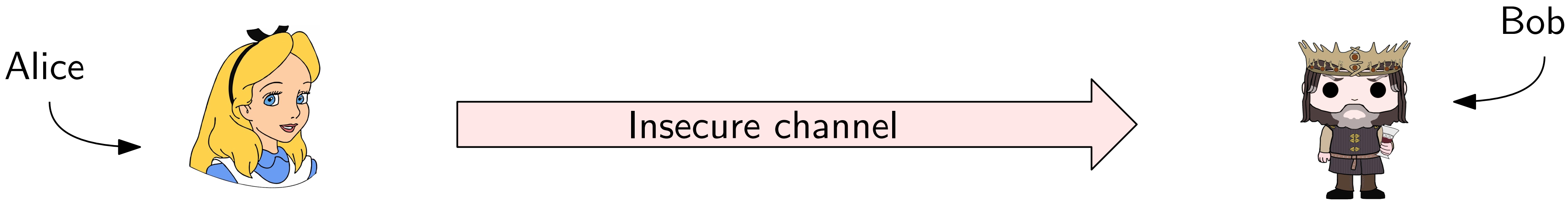

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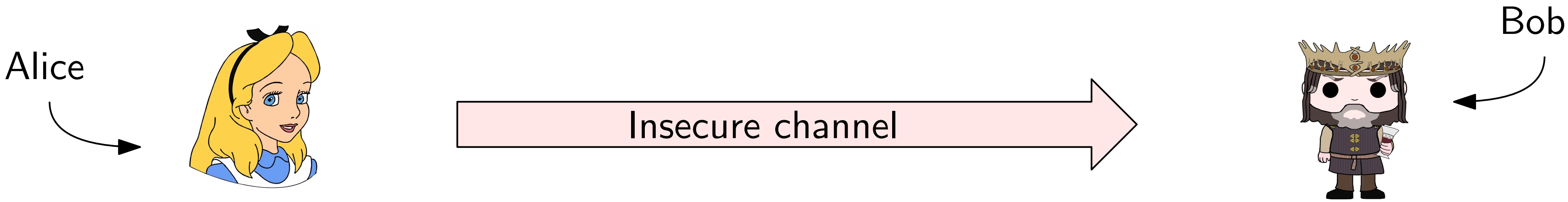

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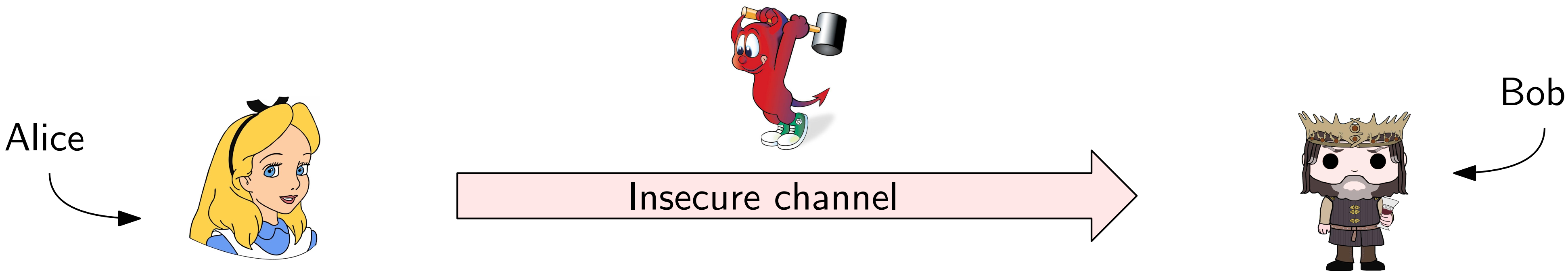

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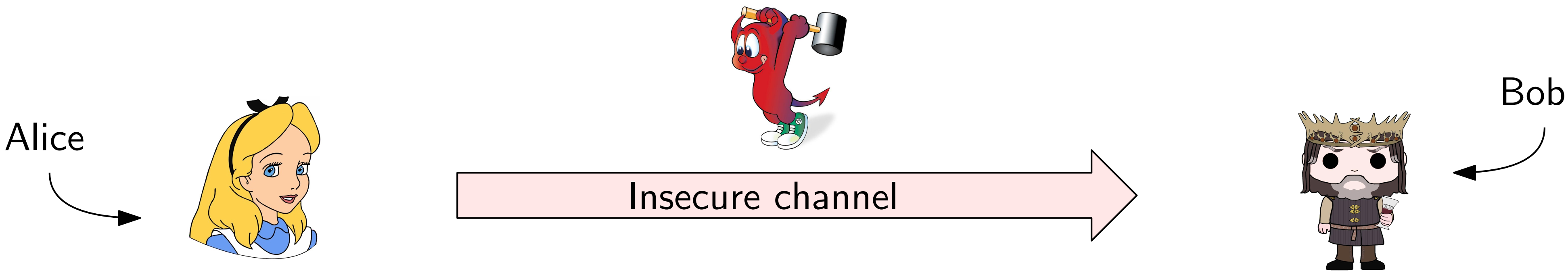

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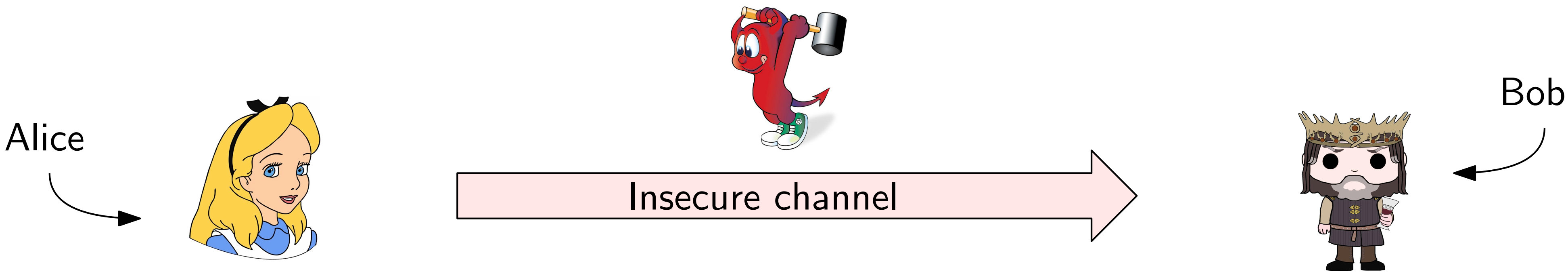

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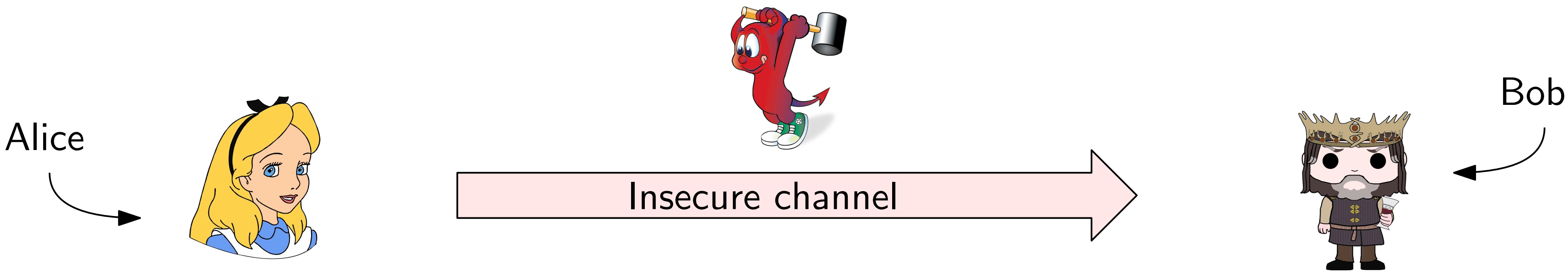

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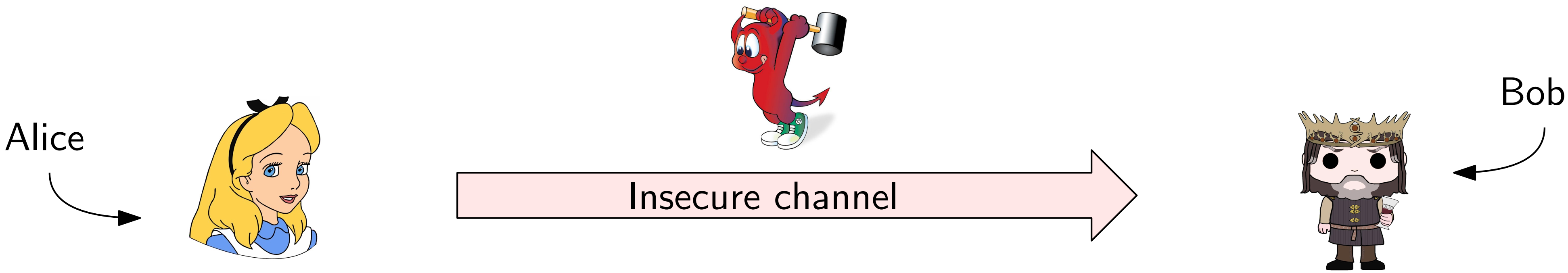

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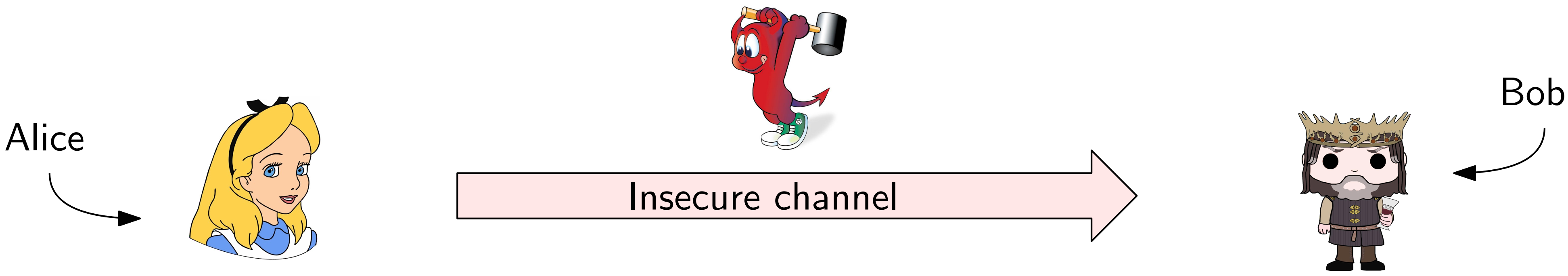

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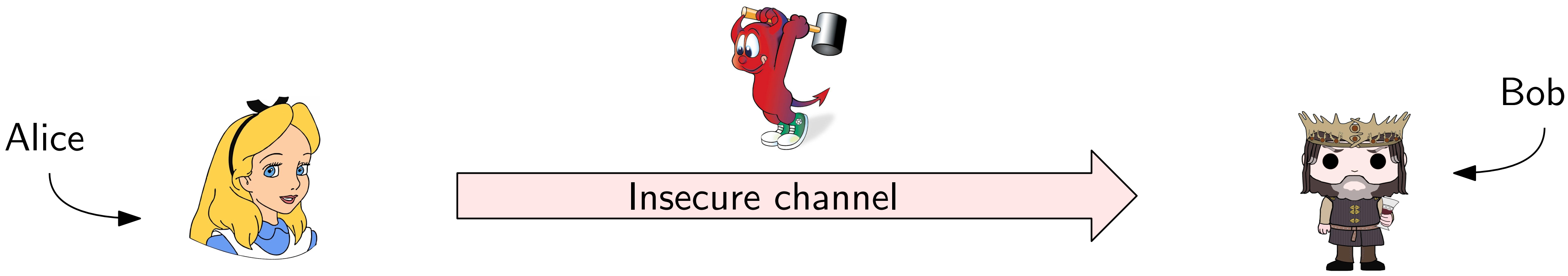

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- **Integrity:** it is not possible to alter the contents of a message sent across the channel (without the tampering being detected)

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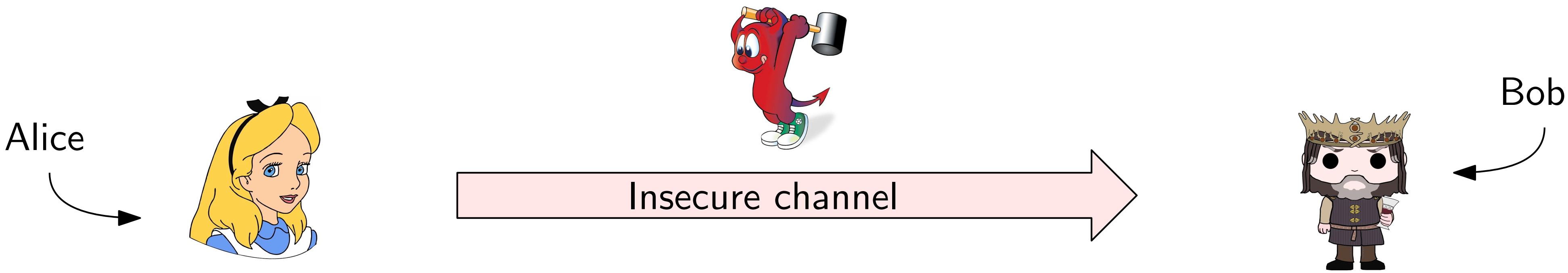

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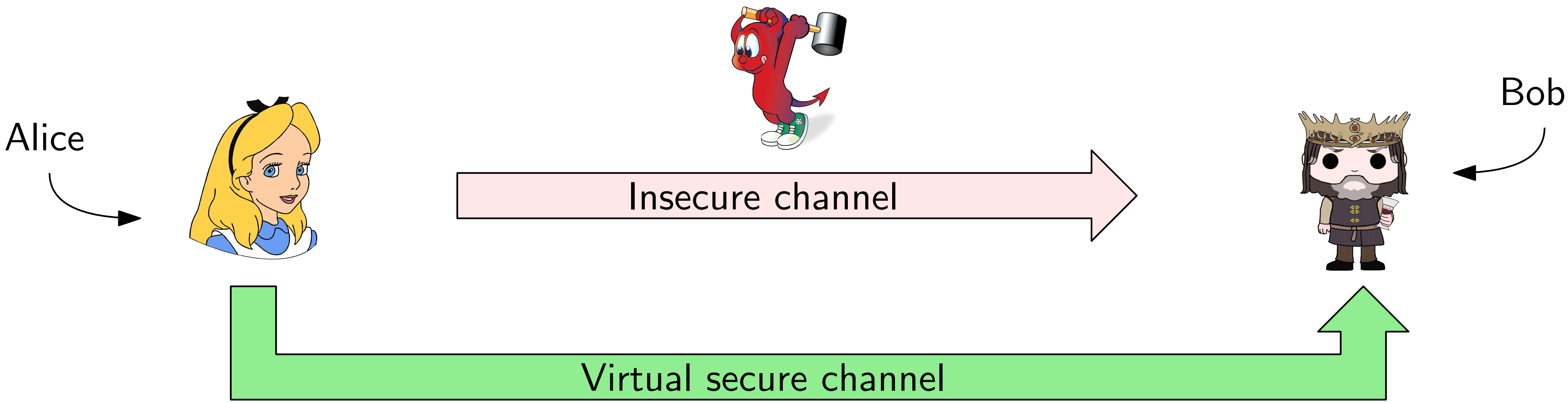

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- Key distribution

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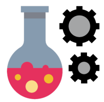
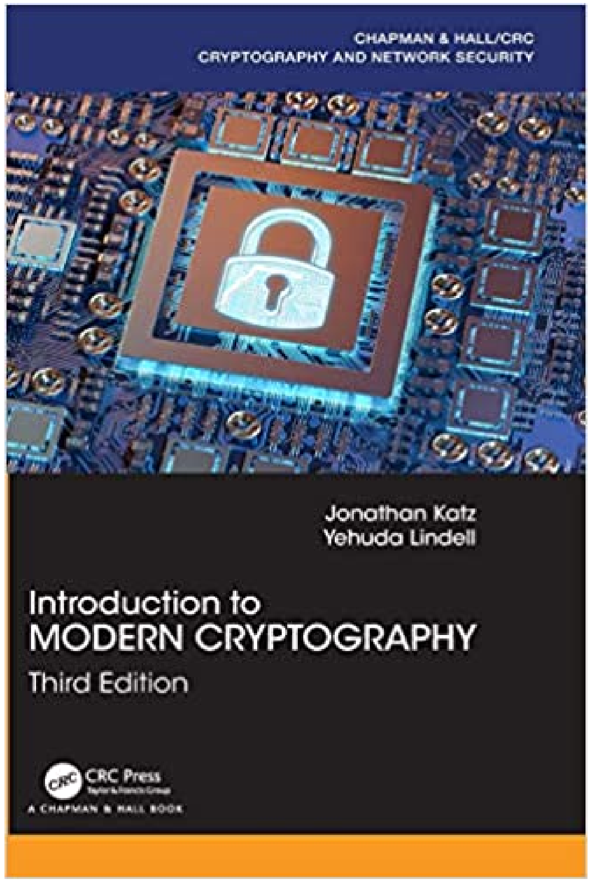
} Public-key cryptography

- Advanced applications: secret sharing, multiparty computation, zero-knowledge proofs



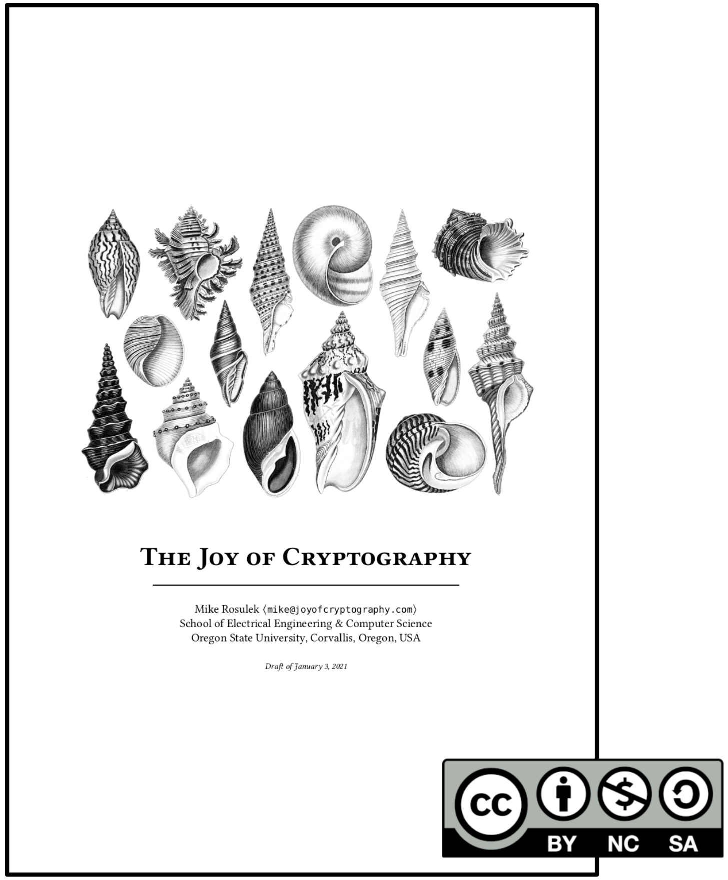
Books



Introduction to Modern Cryptography

Jonathan Katz, Yehuda Lindell

ISBN: 978-0815354369



The Joy Of Cryptography

Mike Rosulek

`https://joyofcryptography.com/`

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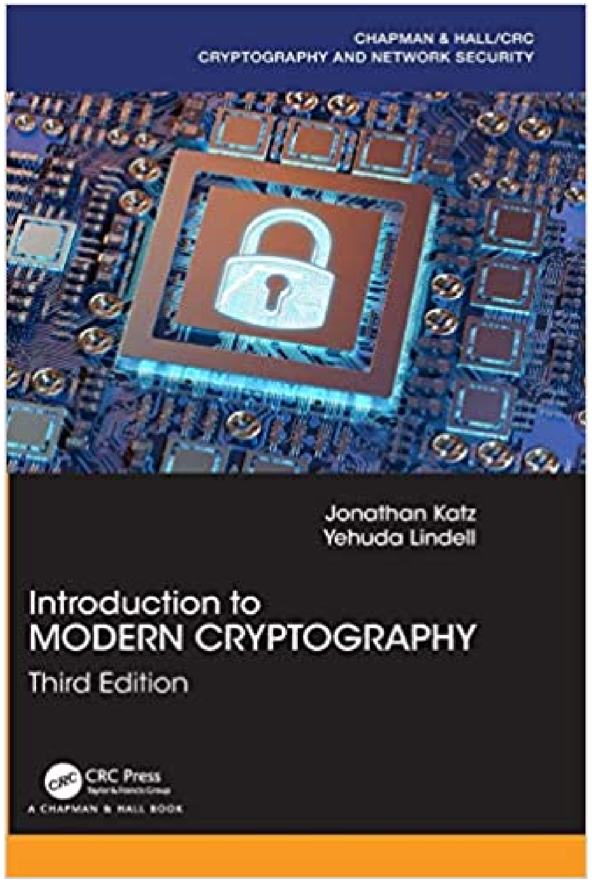

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We will use the same notation

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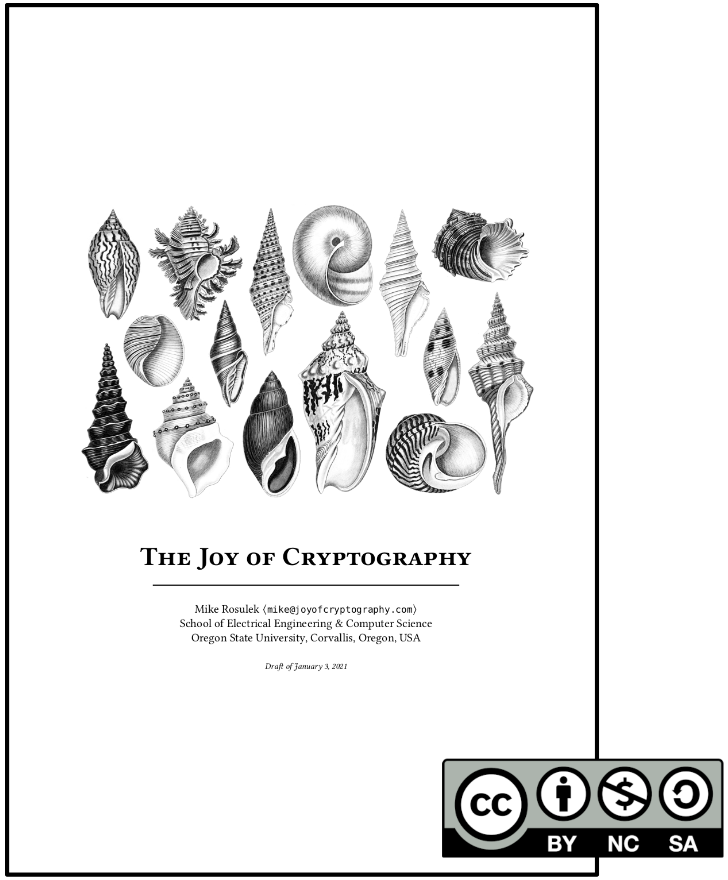

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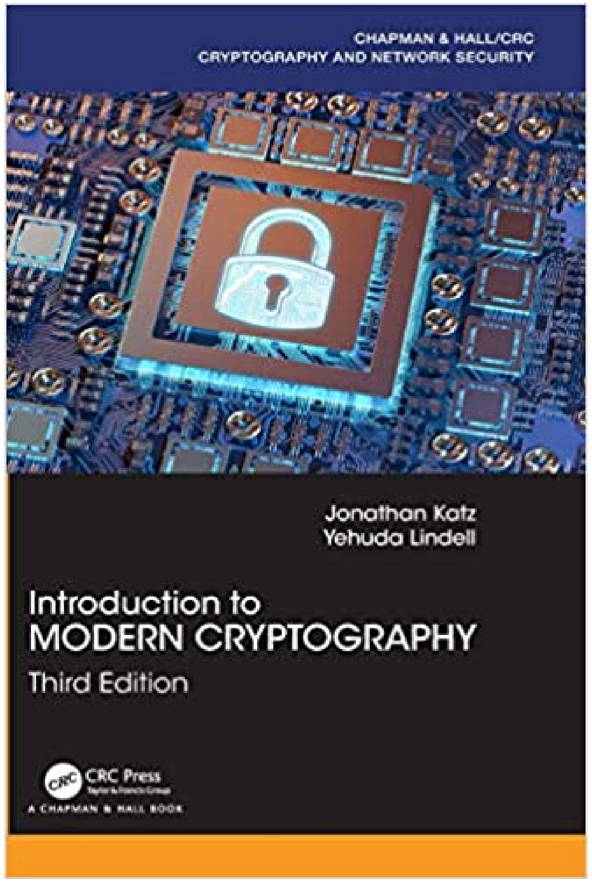

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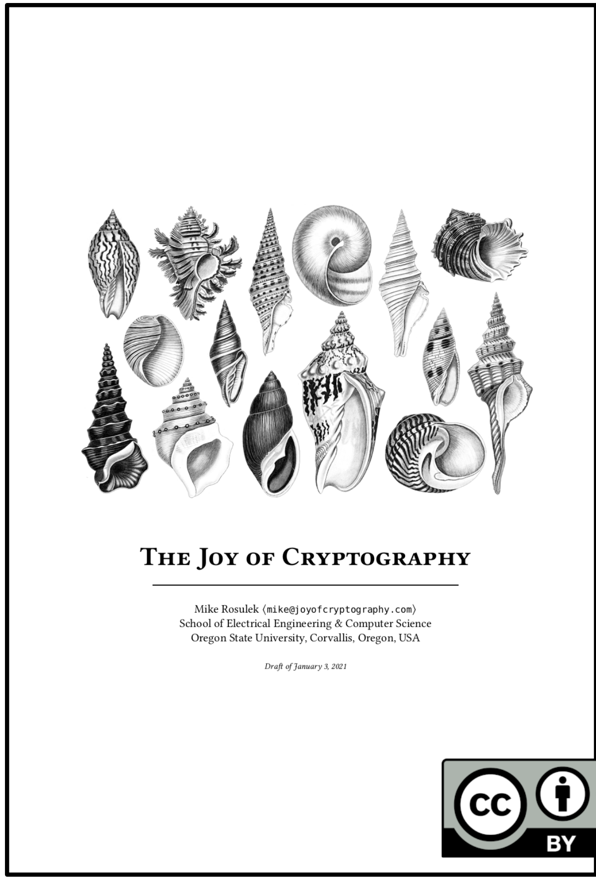
Freely Available
Uses different notation.



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Exams

Written exam:

- Questions on the theoretical concepts (e.g., security definitions)

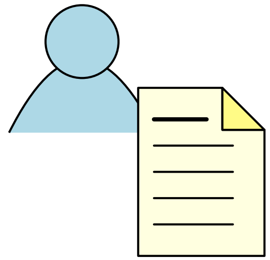
- Exercises (e.g., prove security, carry out an attack, etc. . .)

Some advanced applications

Secret Sharing

Imagine some sensitive information that is kept by a single agent

- A master encryption key 
- Your bitcoin wallet 
- Nuclear codes 
- ...



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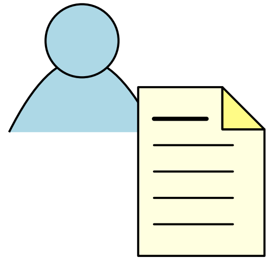
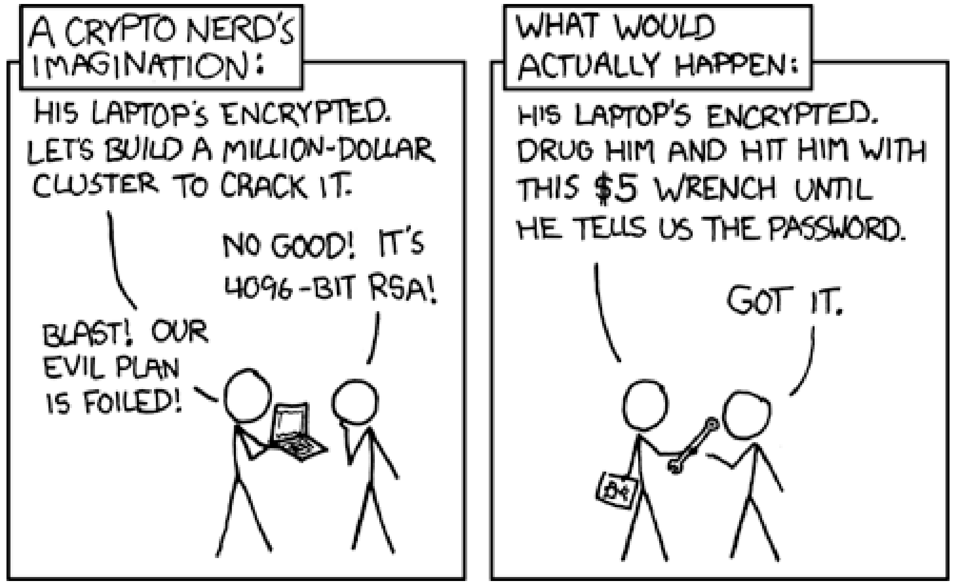


Single point of failure!



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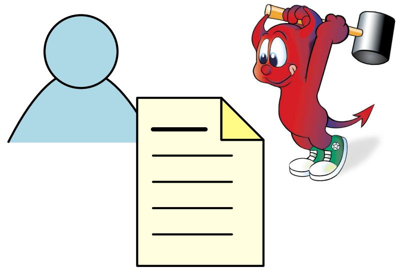

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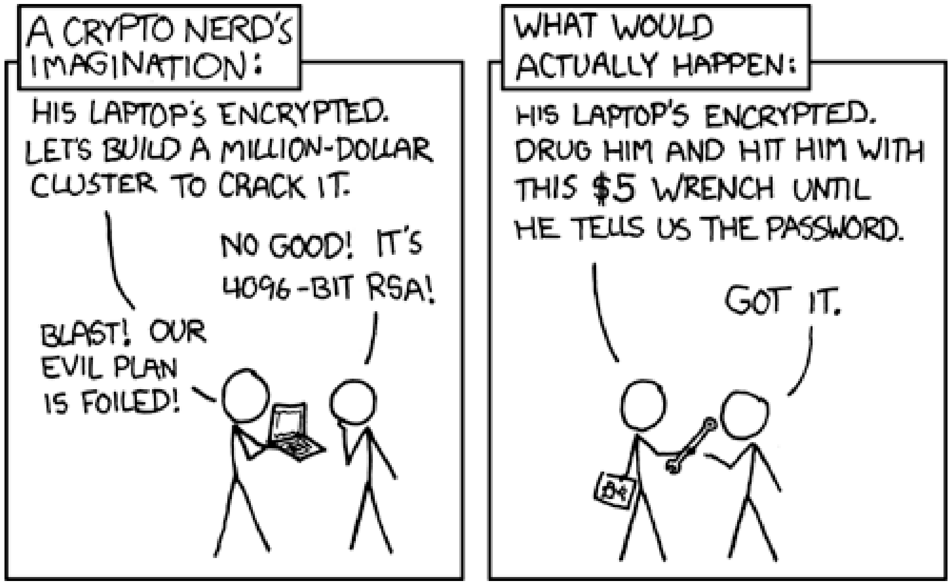

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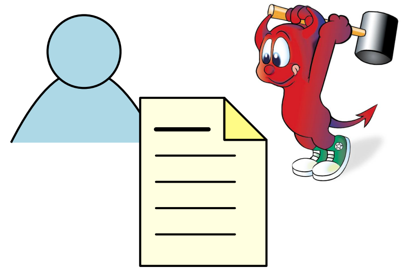

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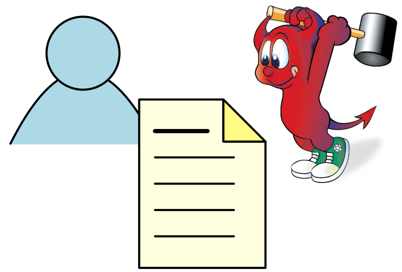

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"Magic box"

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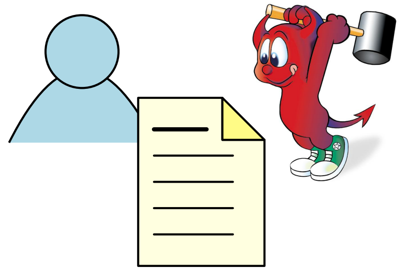

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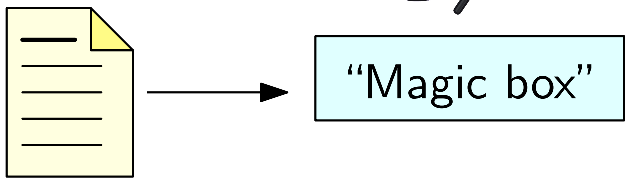

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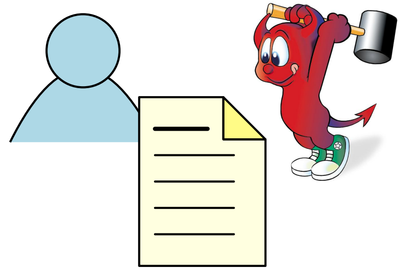

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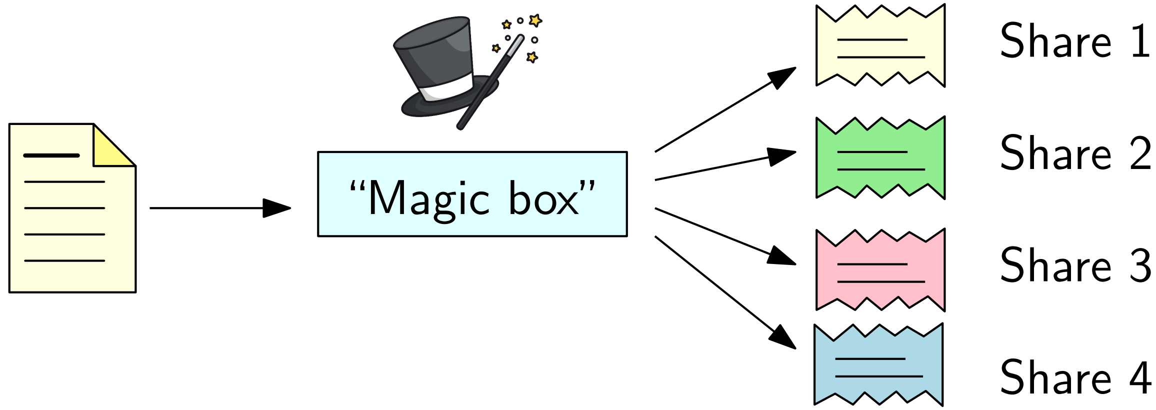

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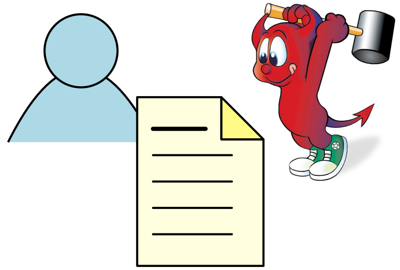

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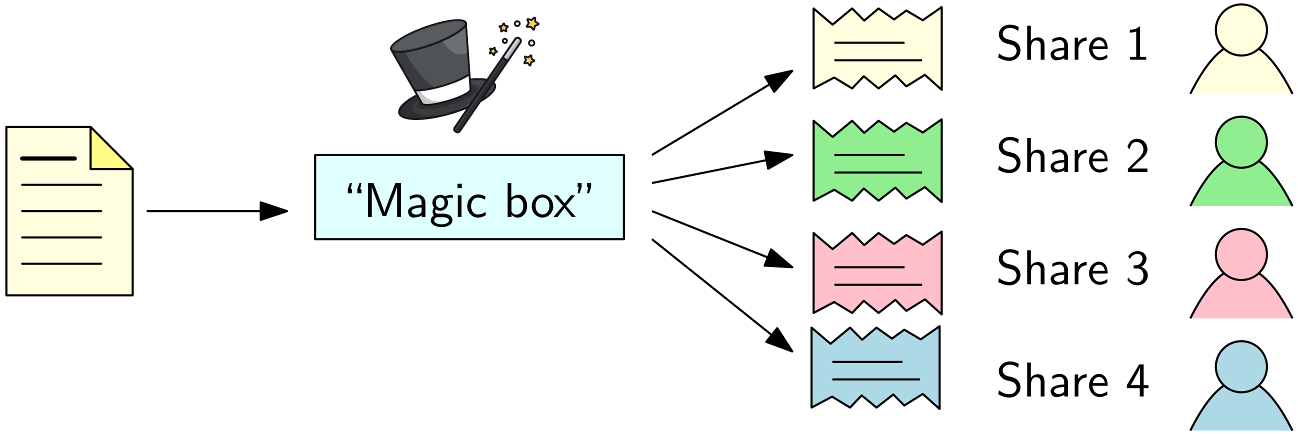

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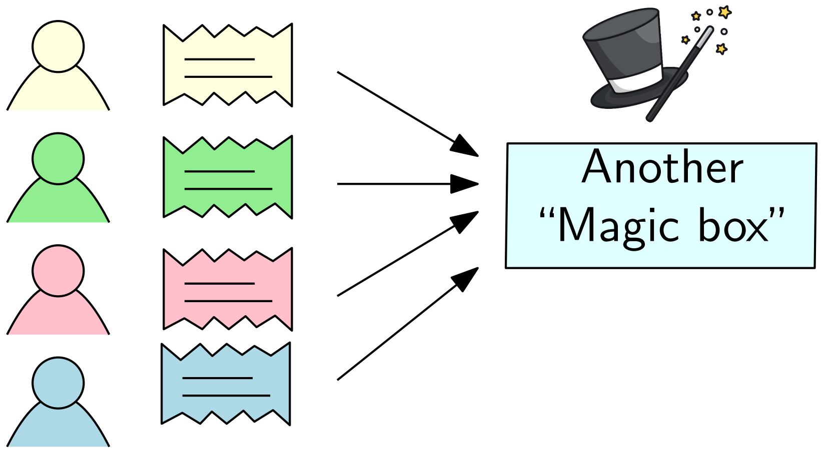

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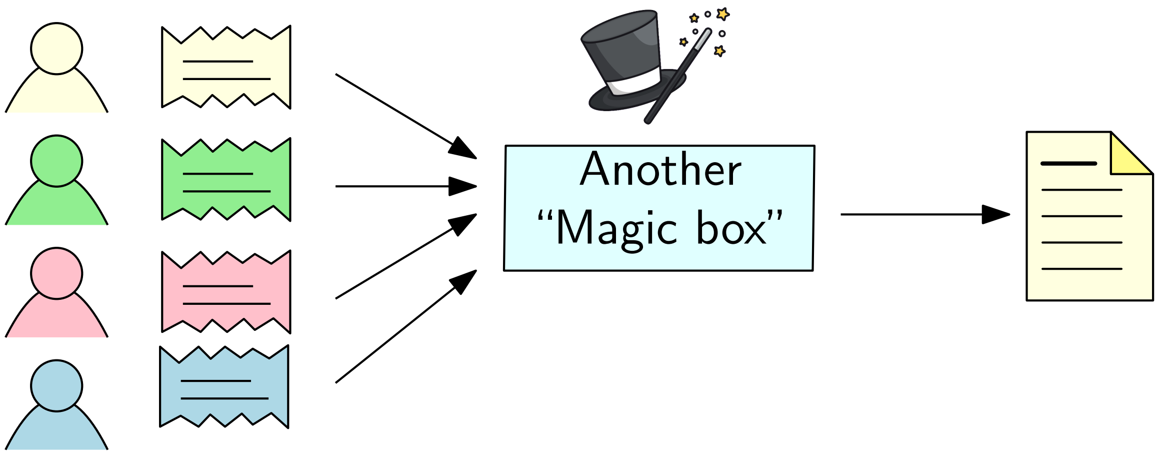

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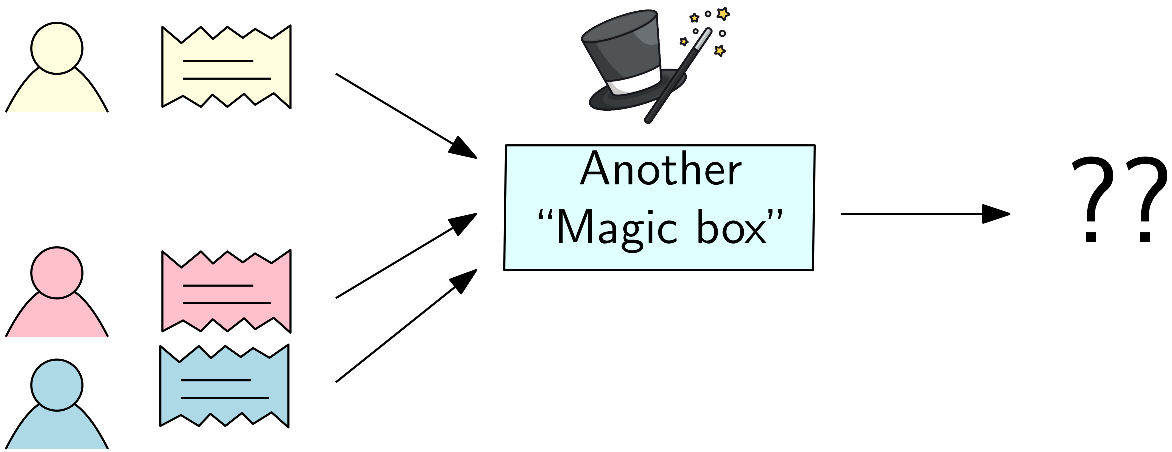

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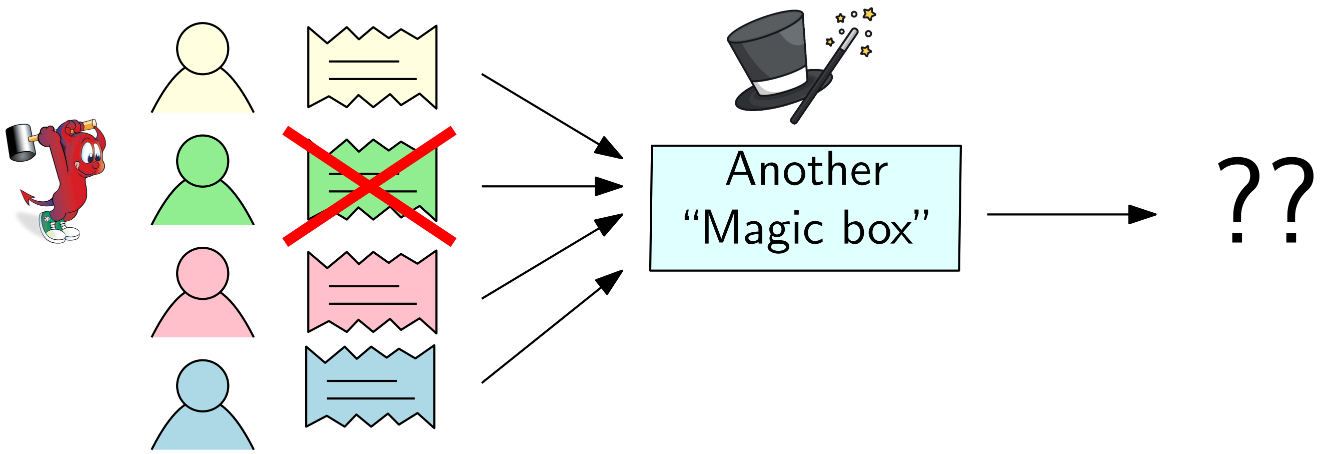

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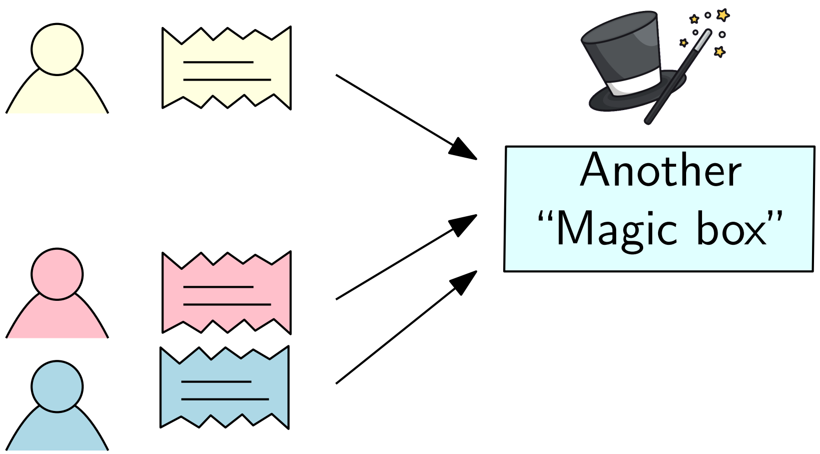

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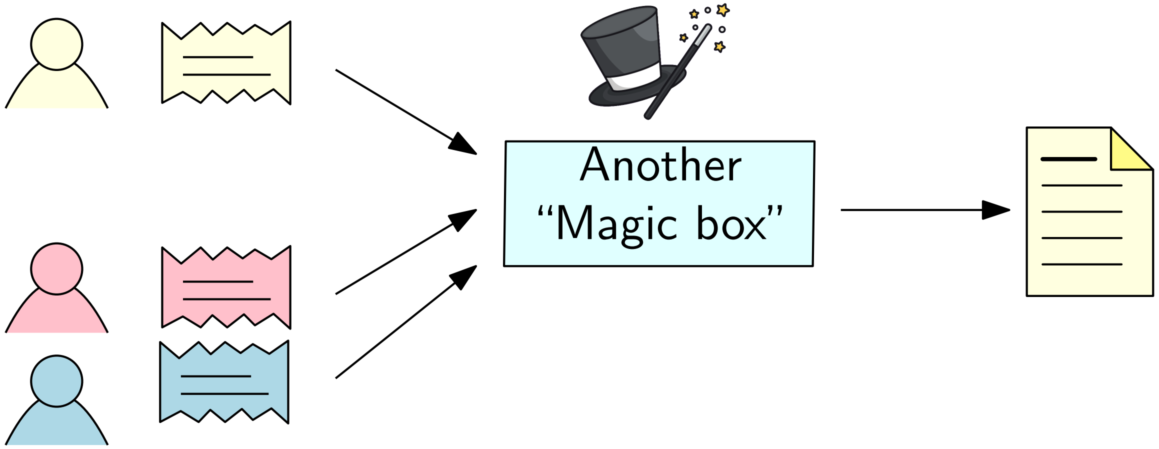

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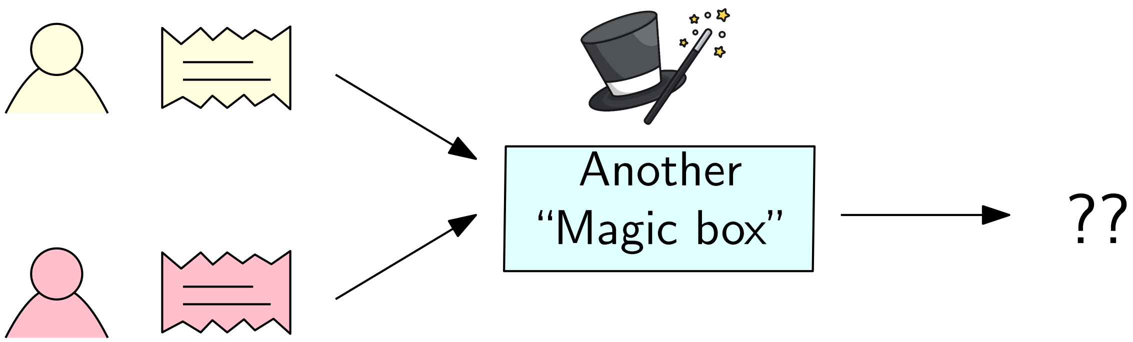

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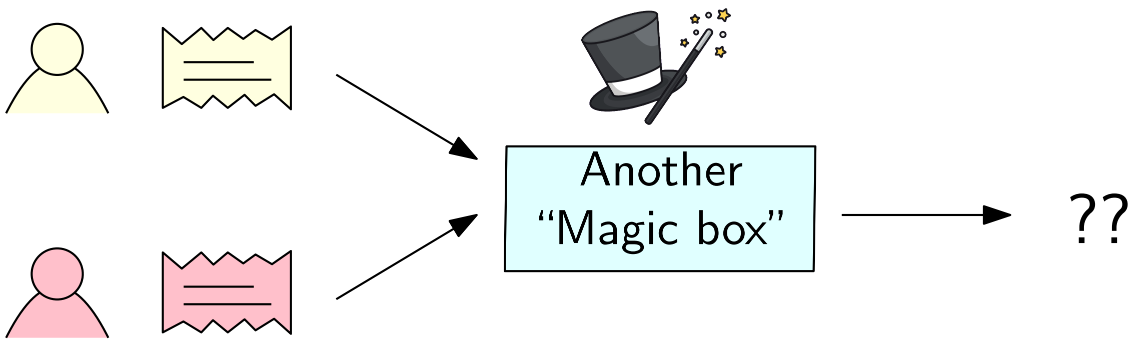
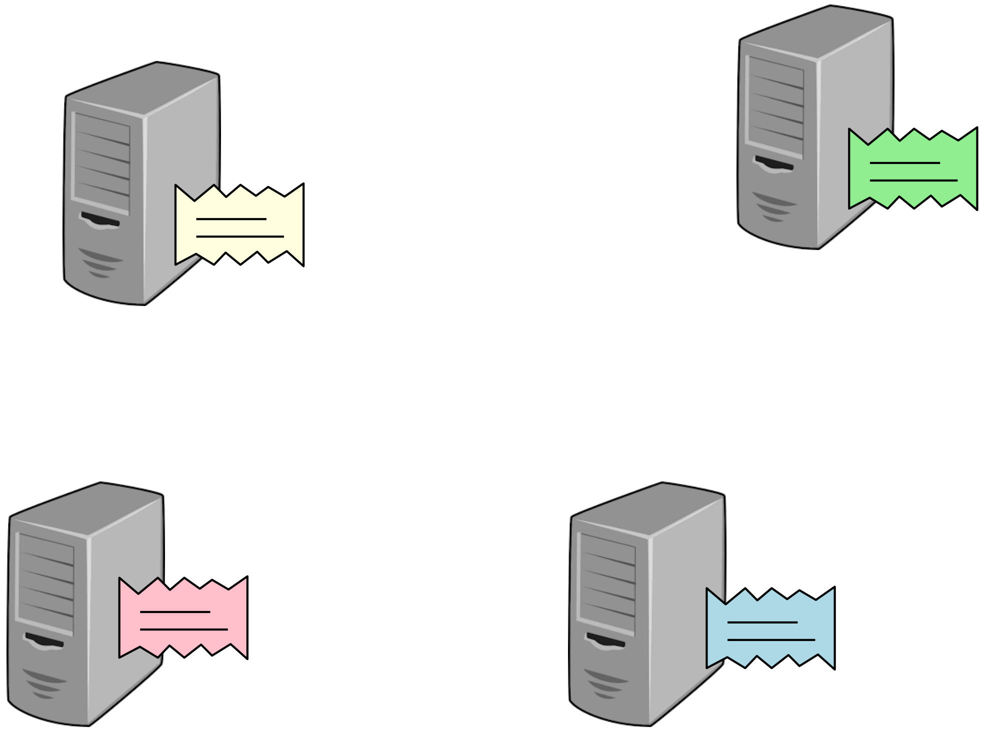


t**-out-of-**n **threshold secret-sharing scheme**

Secret Sharing

- Agents can be different servers connected over the Internet



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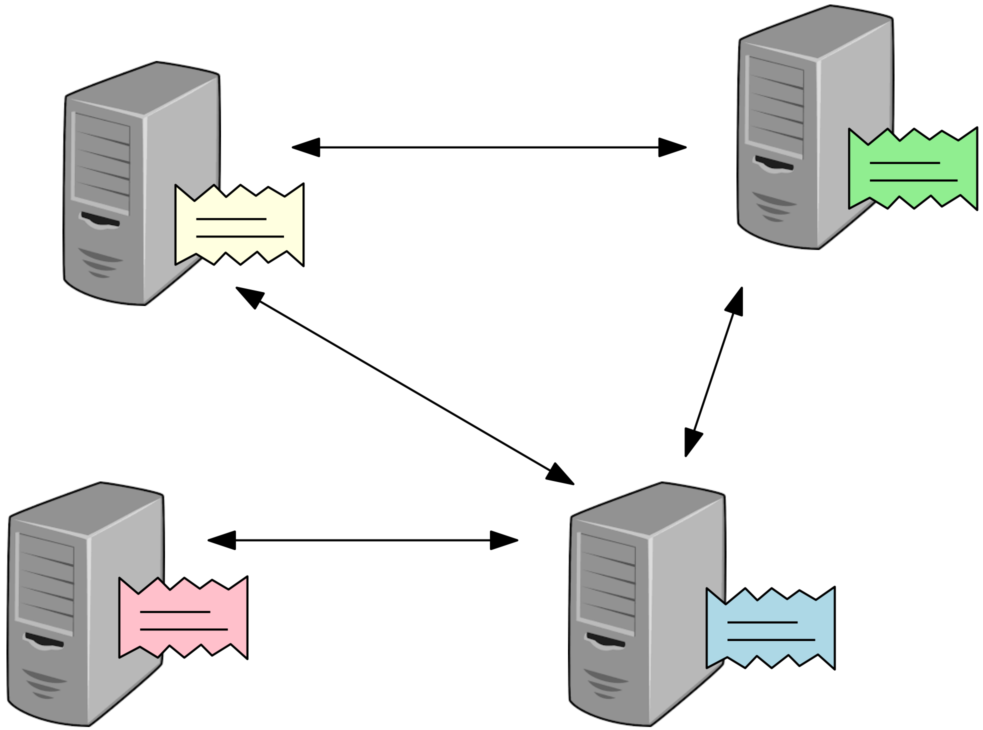

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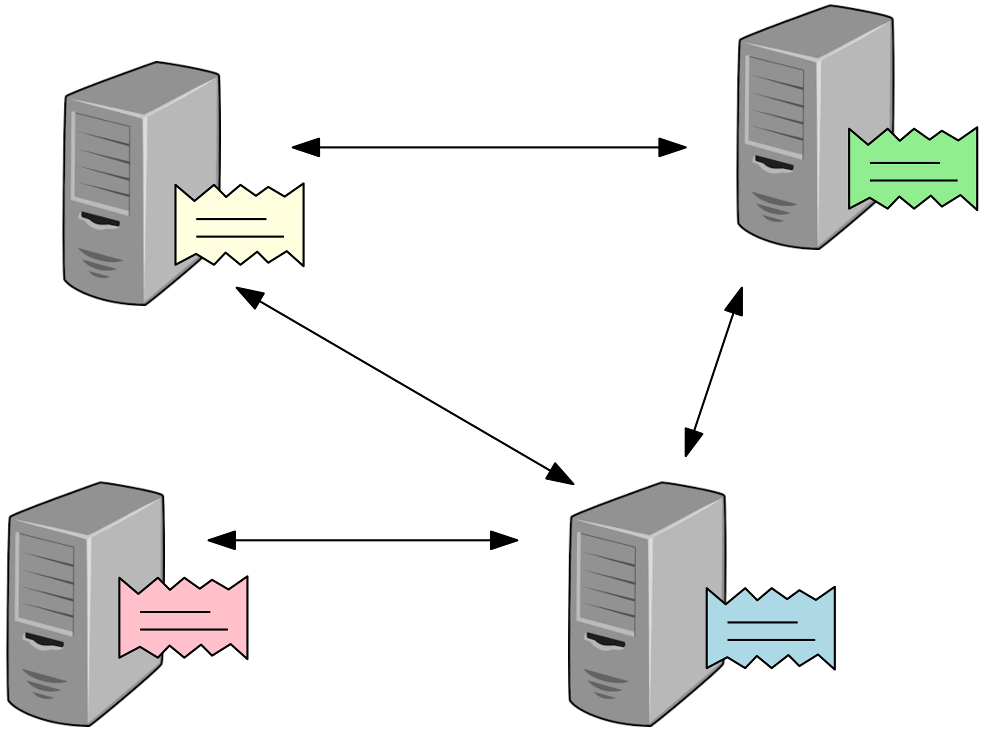

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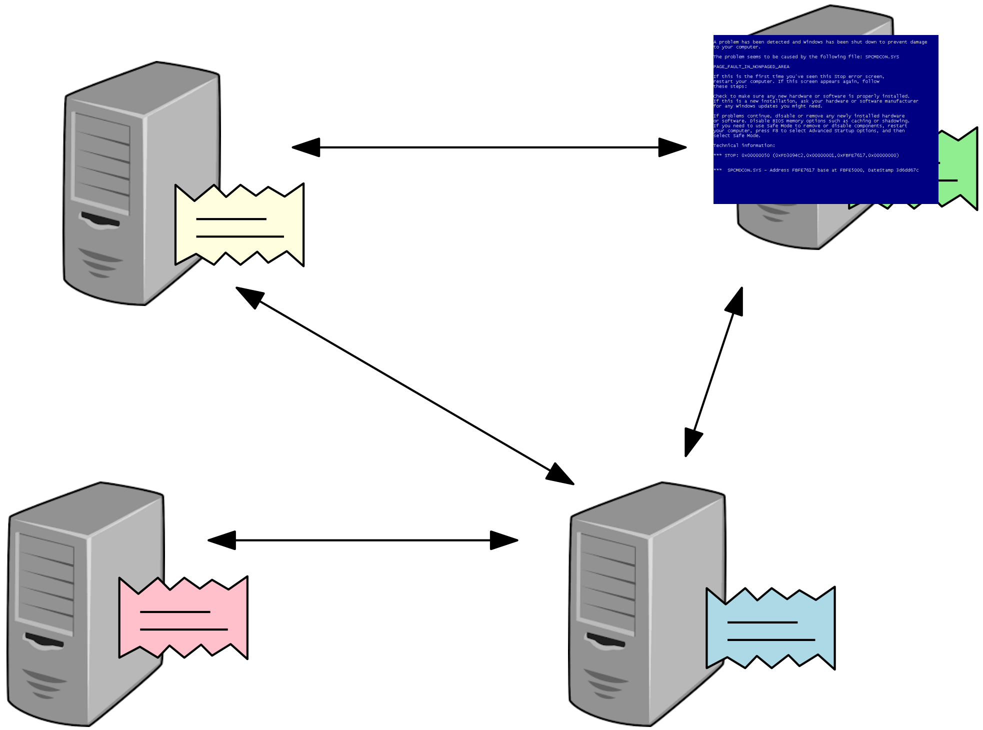


- The system remains secure if $< t$ servers are compromised
- The system remains operational (the secret can be recovered) if $\leq n - t$ servers are unavailable

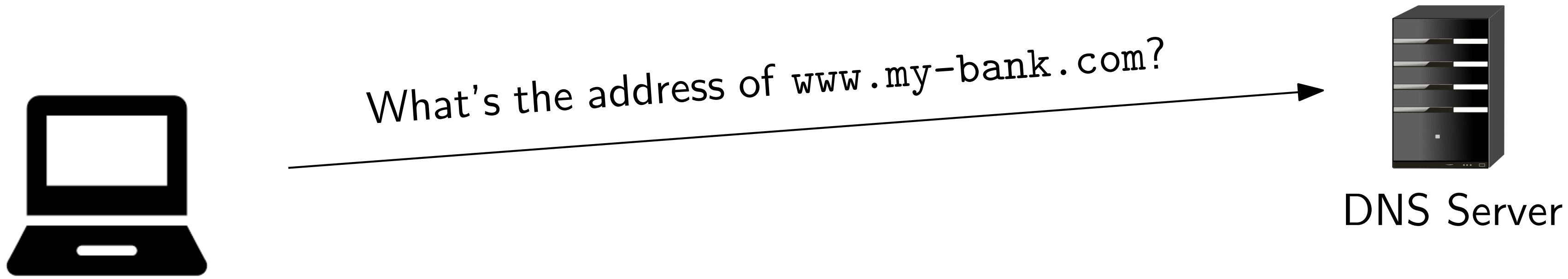
DNSSEC

The Domain Name System is the system responsible for converting human-readable domain names into IP addresses

DNS Server

DNSSEC

The Domain Name System is the system responsible for converting human-readable domain names into IP addresses



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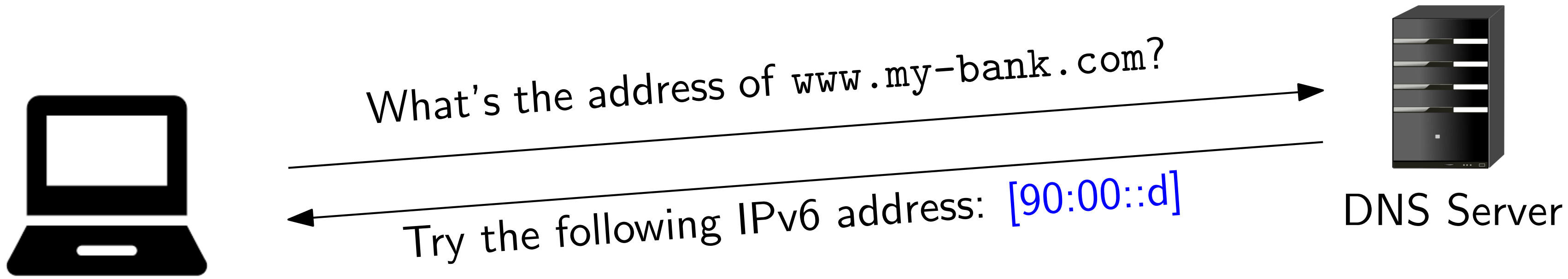

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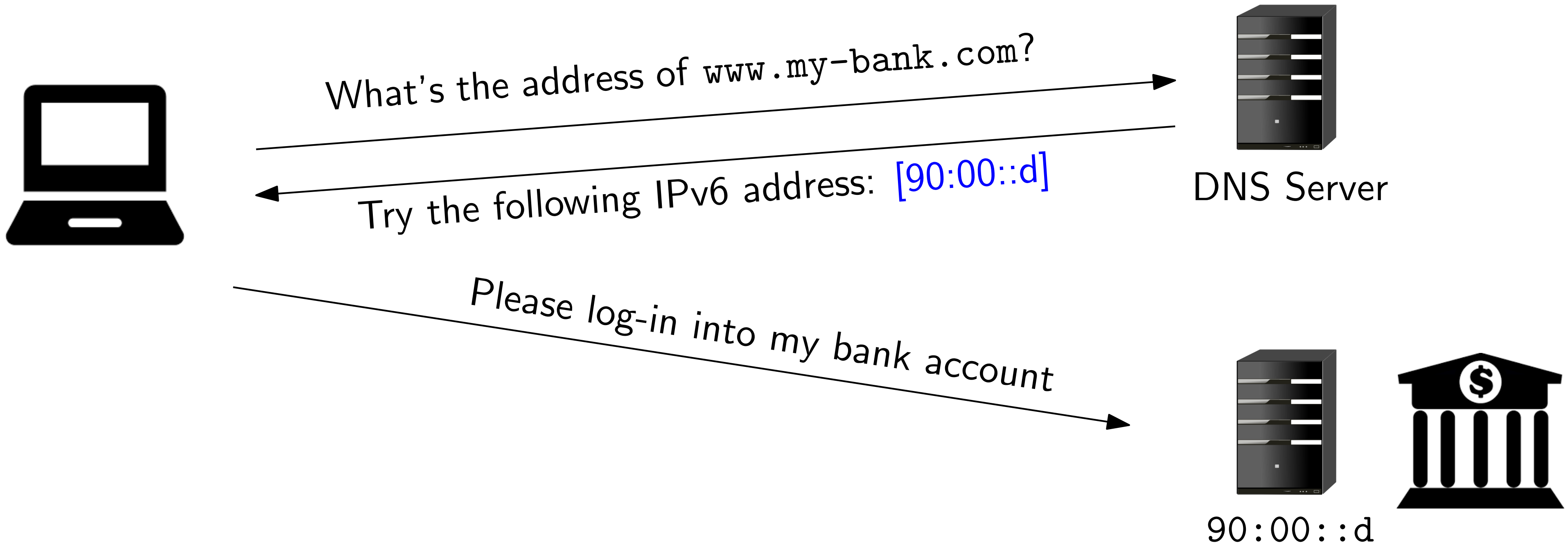

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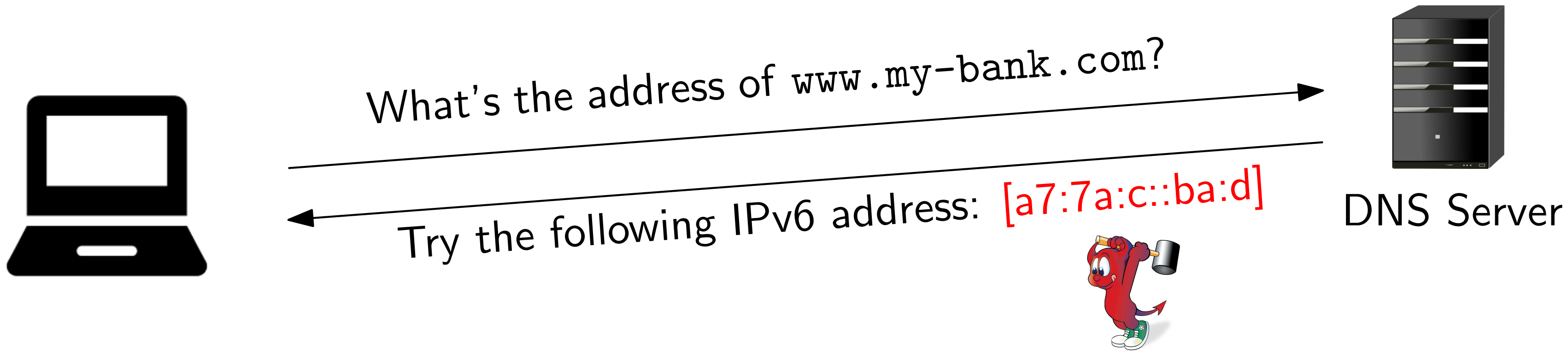

An attacker can tamper with DNS responses and convince the client that `www.my-bank.com` resides on a malicious server

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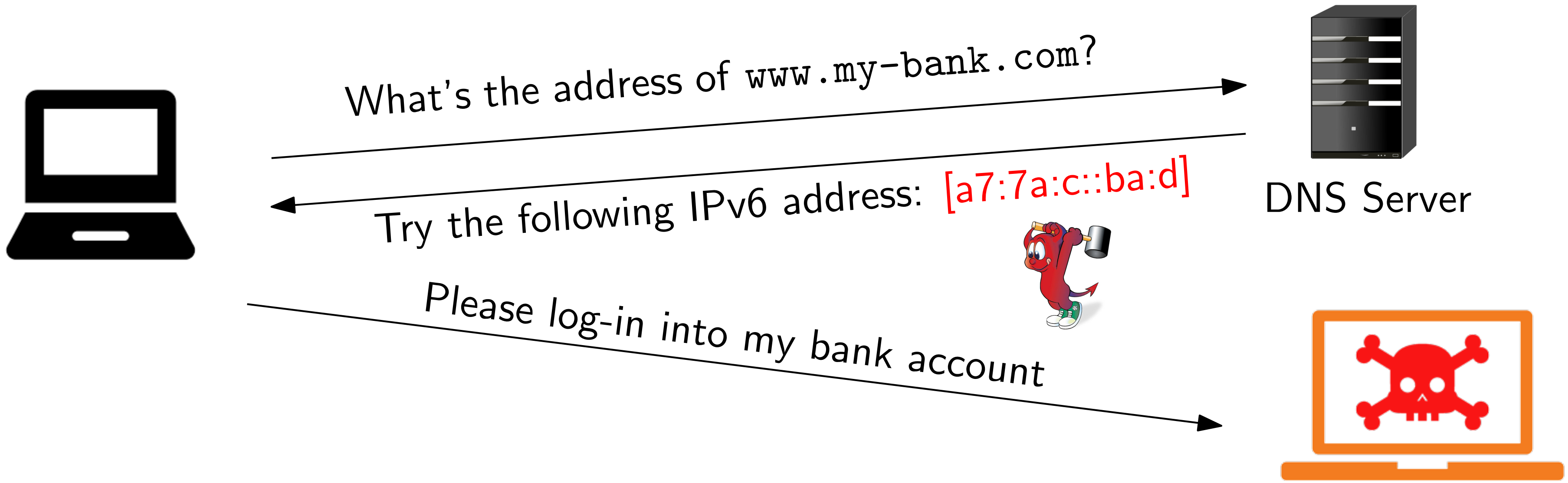

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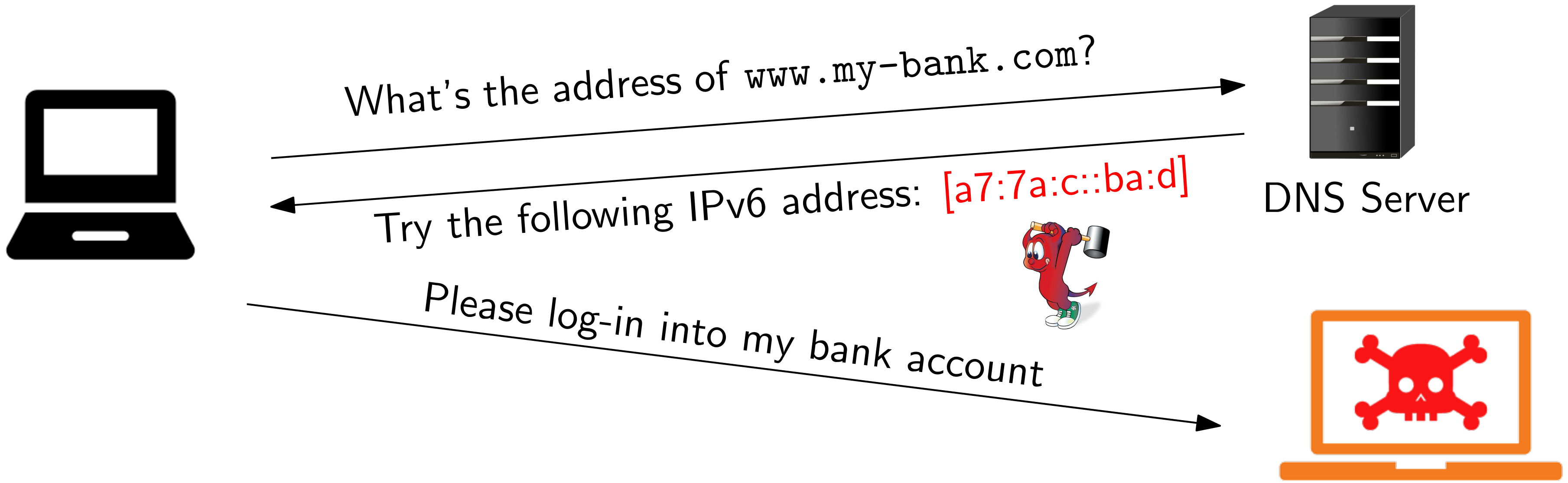

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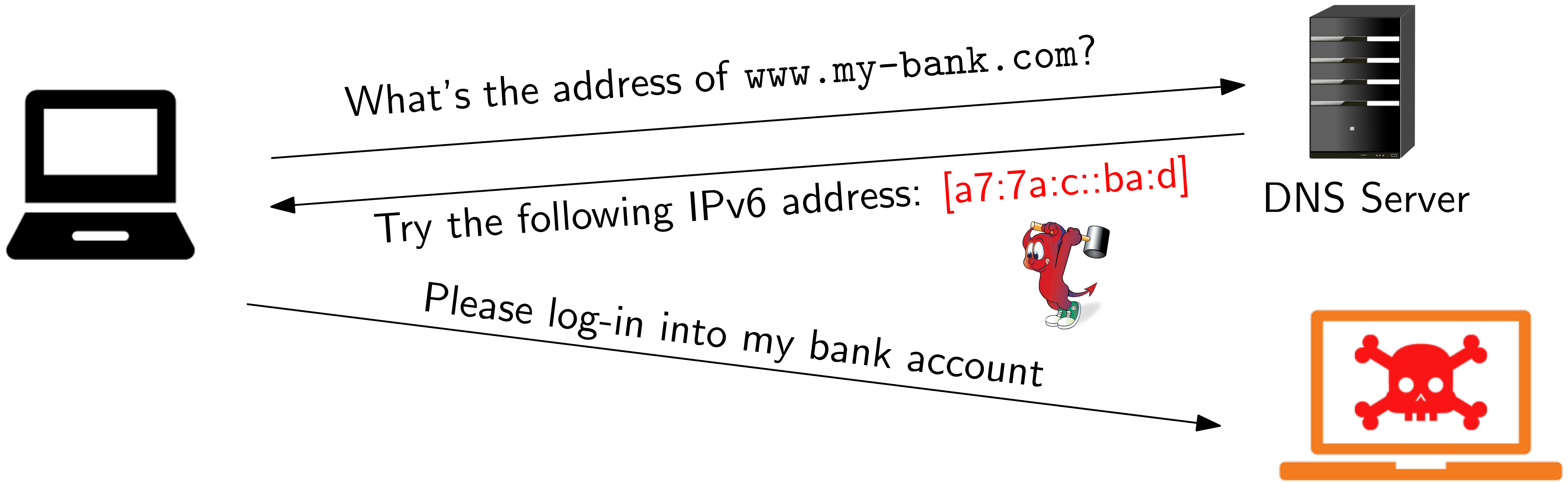

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Who can be trusted with the master cryptographic keys to the system?

DNSSEC

DNSSEC is managed by the Internet Corporation for Assigned Names and Numbers (ICANN)

The master key is split into 7 pieces and distributed on smart cards to 7 geographically diverse people

> *At least five key-holding members of this fellowship would have to meet at a secure data center in the United States to reboot [DNSSEC] in case of a very unlikely system collapse.*
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> *"If you round up five of these guys, they can decrypt [the root key] should the West Coast fall in the water and the East Coast get hit by a nuclear bomb"*
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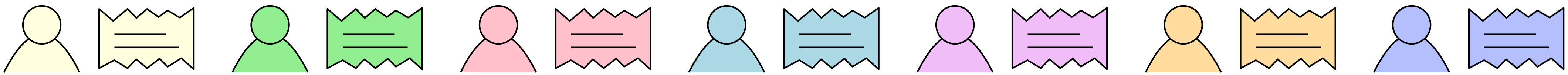

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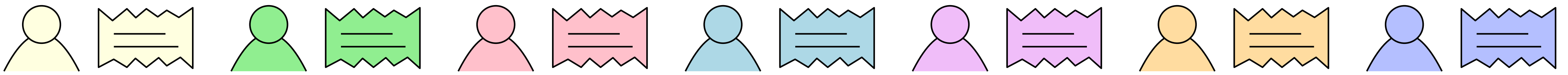
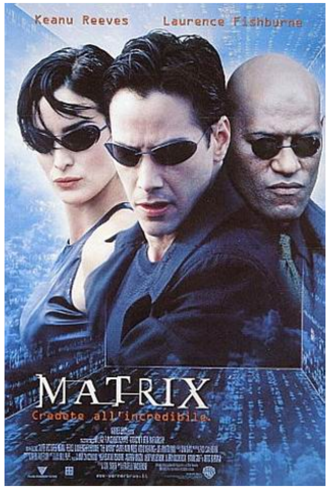
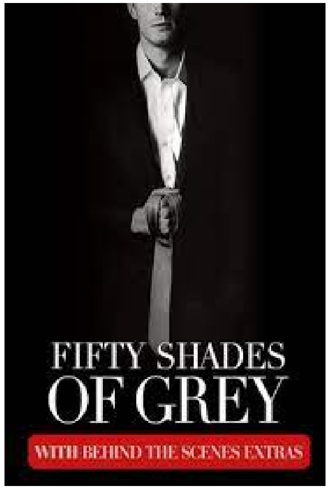


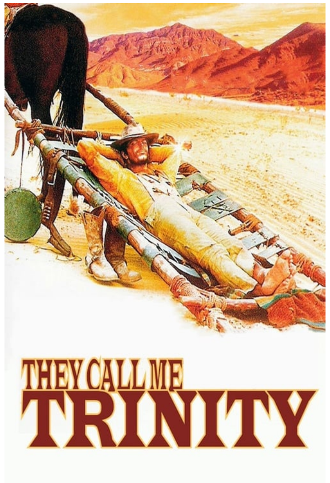
$n = 7$ $t = 5$ 5-out-of-7 threshold secret-sharing scheme

Choosing a movie with secret preferences

Alice and Bob want to decide on a movie to watch







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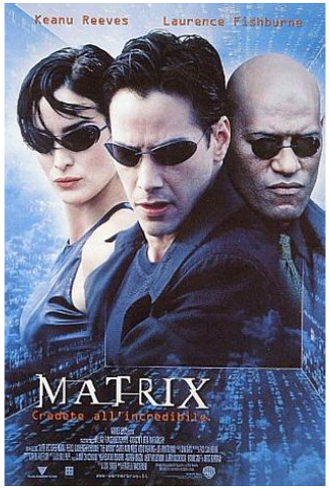

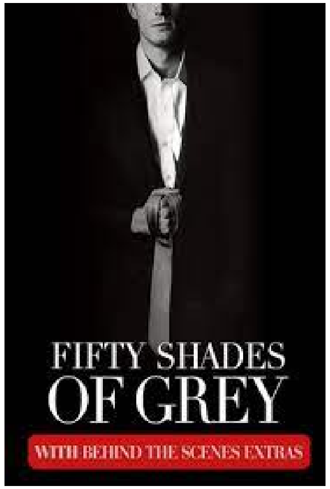

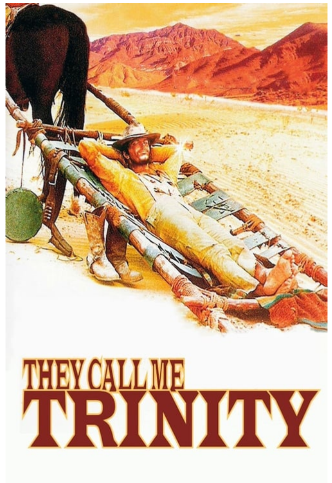

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However, they don't want to reveal that they like a movie unless the other person also likes it

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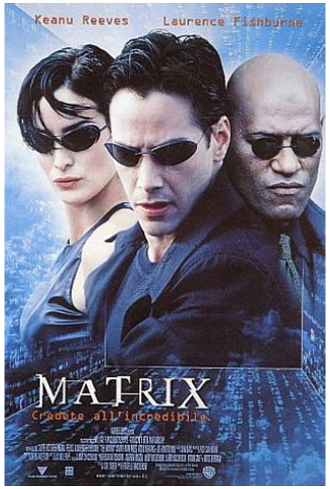

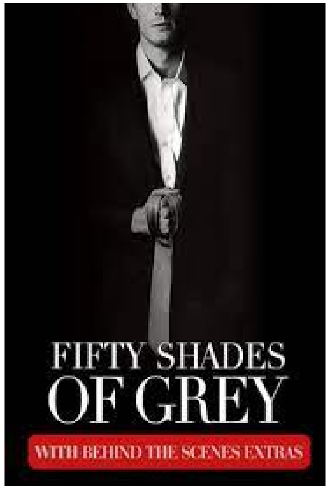

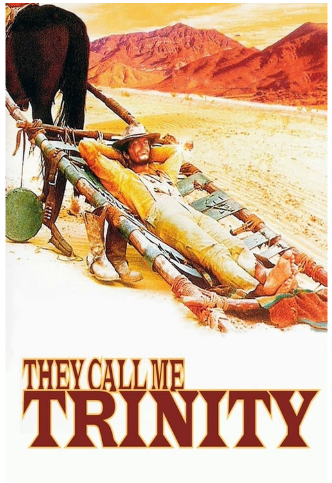

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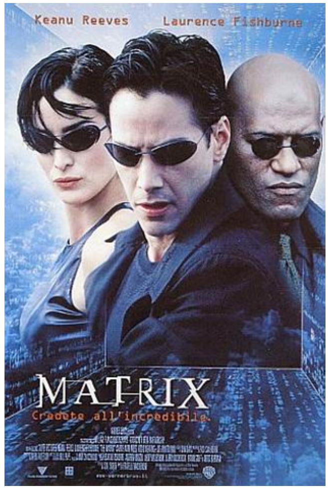

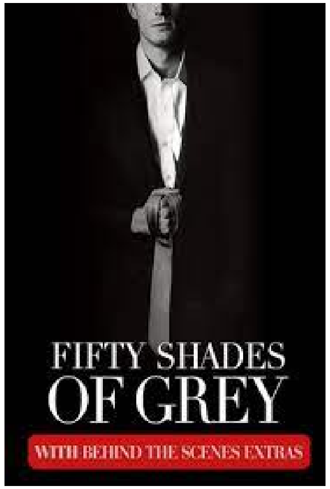

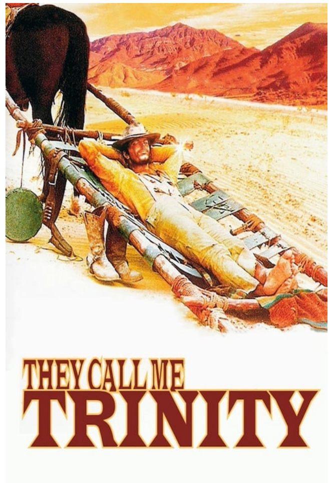

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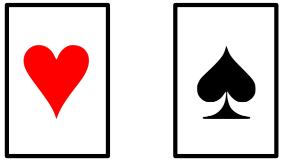
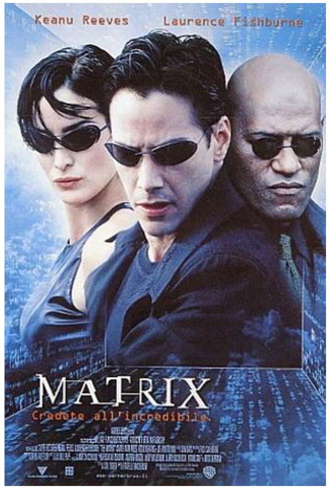
Alice and Bob are **honest** (they follow the protocol) but **curious**

Choosing a movie with secret preferences

They will use some cards with two different faces, say hearts and spades





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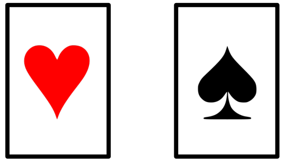
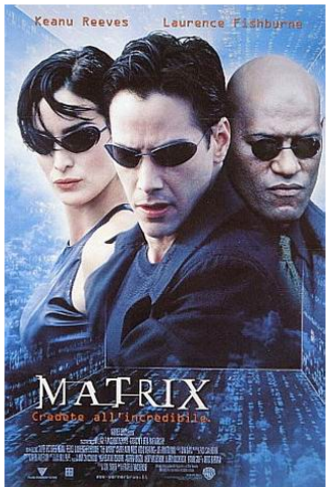
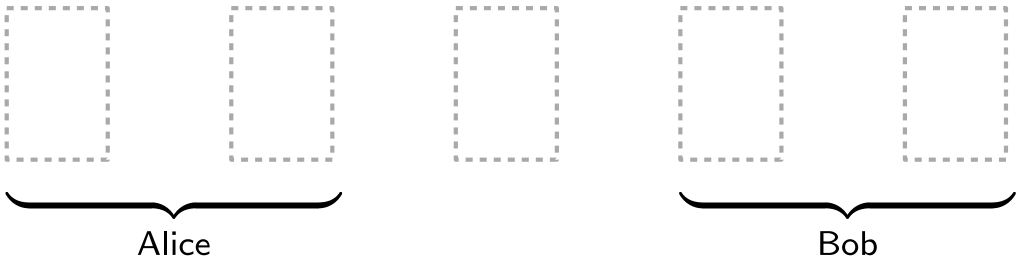
They will place 5 cards in a row on a table







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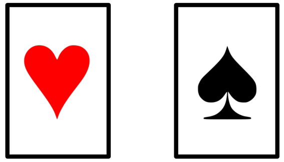

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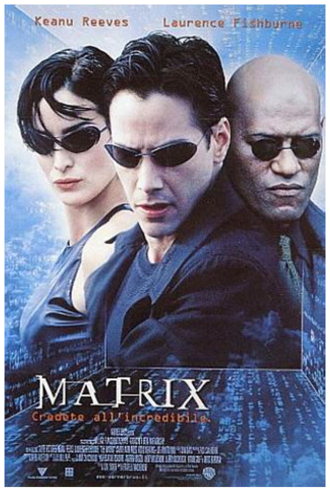
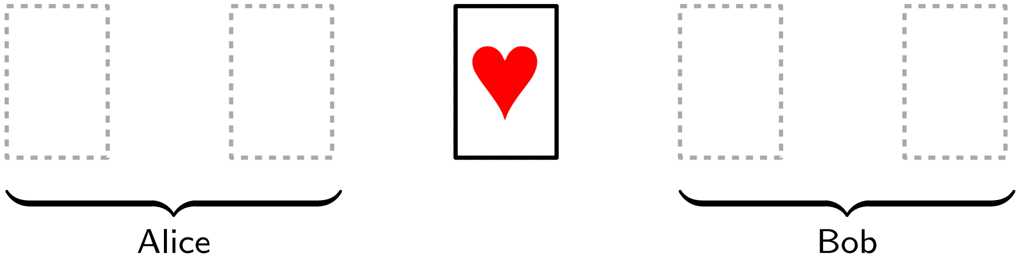
The middle card is face up and is always a hearts card





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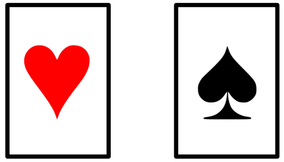

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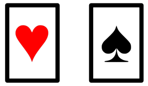
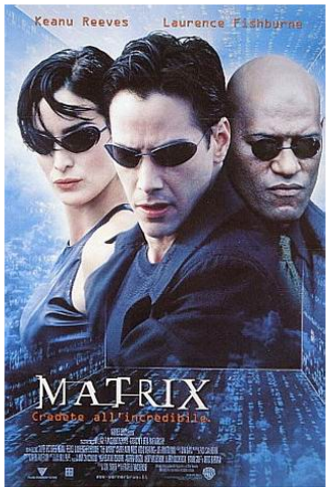
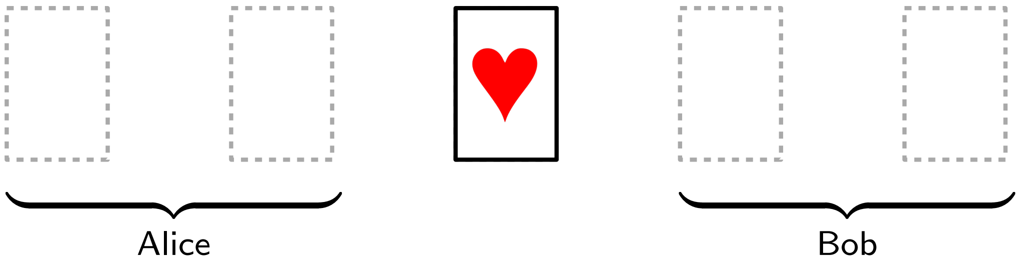
Each of Alice and Bob has a hearts card and a spades card 





Choosing a movie with secret preferences

If Alice likes the movie, she will place her two cards **face down** in the order ♠ ♥

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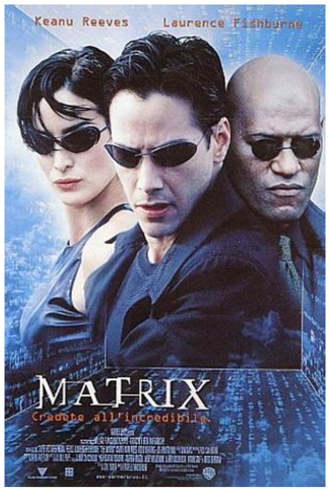

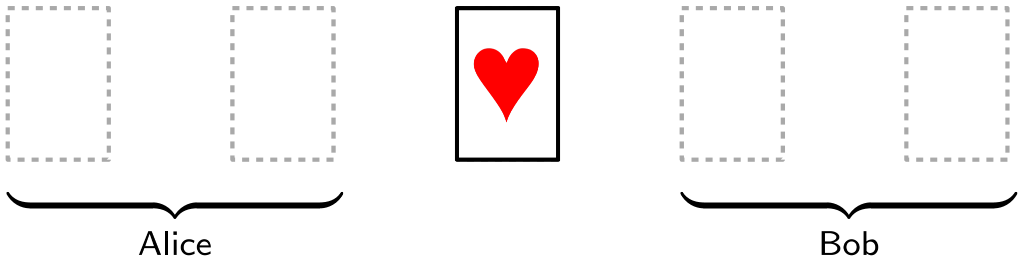

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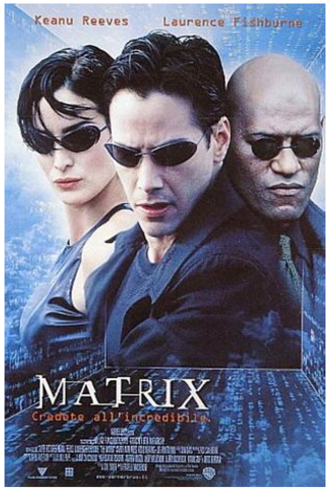

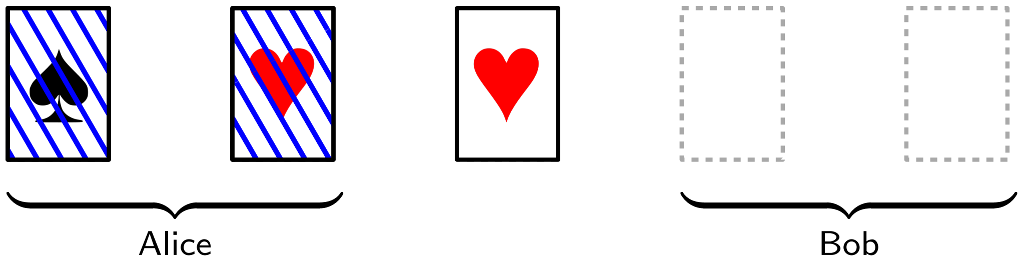

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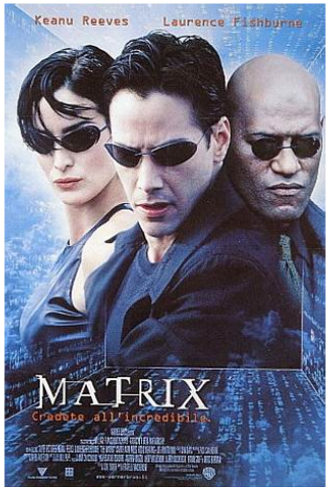

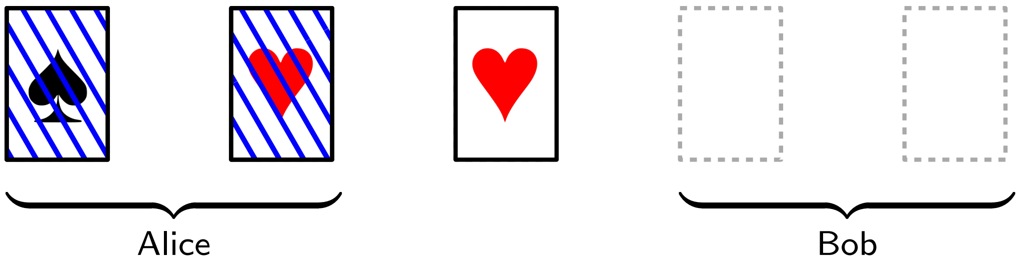

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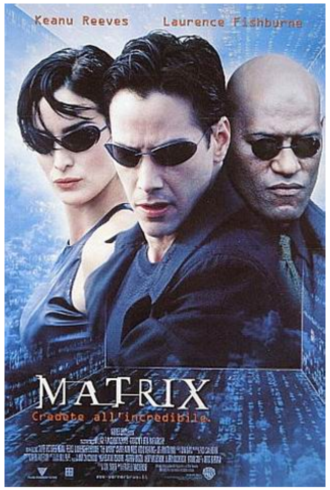
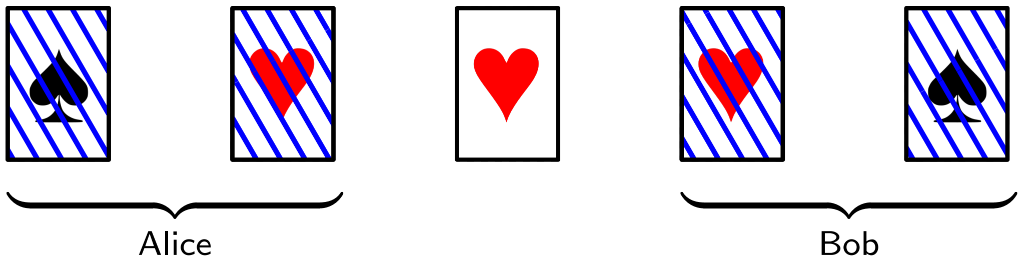
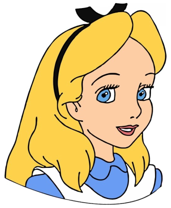
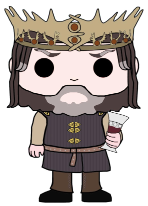




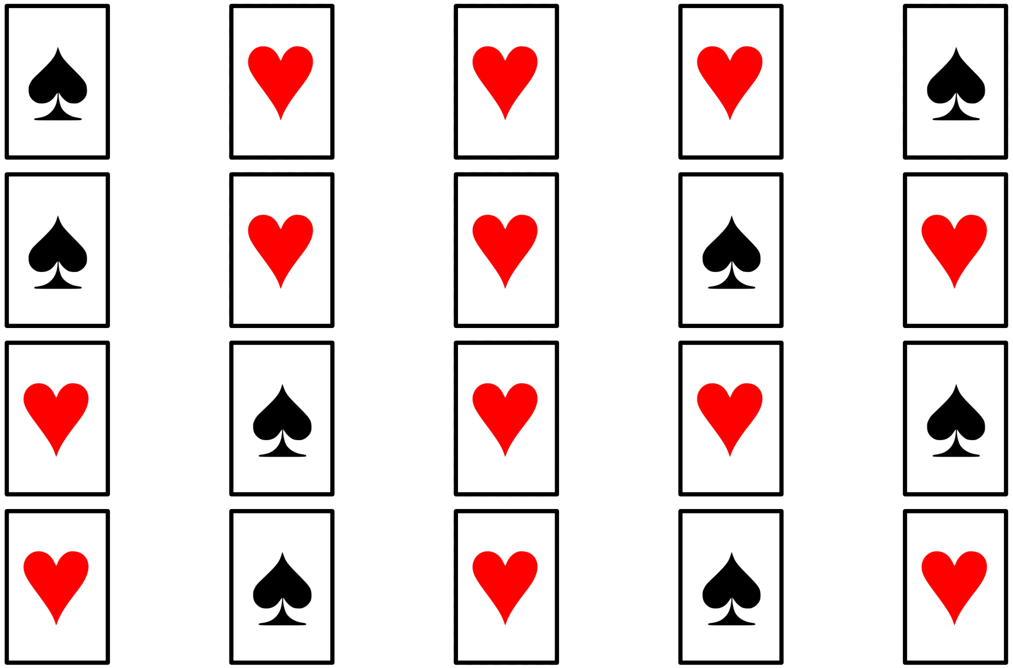
Choosing a movie with secret preferences

Possible configurations:





Yes	Yes
Yes	No
No	Yes
No	No



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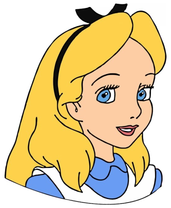

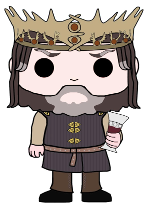

Yes	Yes
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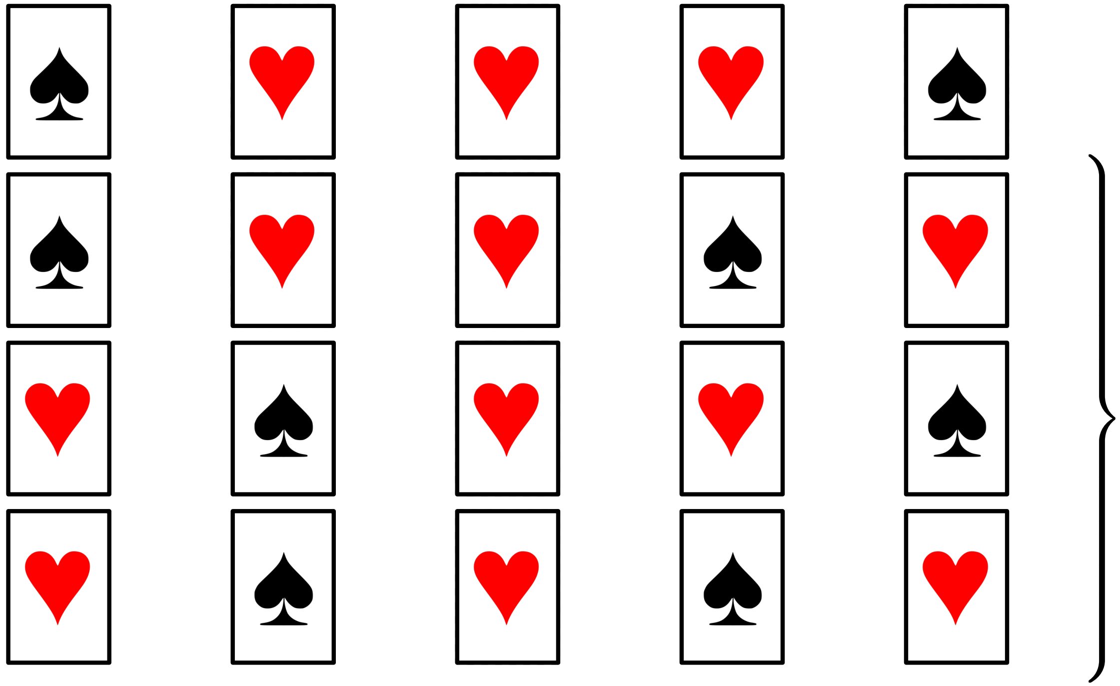
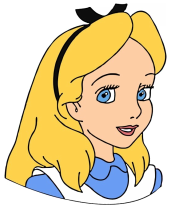
No	Yes
No	No



Rotations

Choosing a movie with secret preferences

Possible configurations:

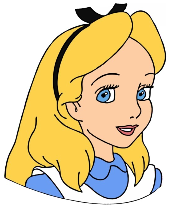
Alice	Bob					
Yes	Yes	♠	♥	♥	♥	♠
Yes	No	♠	♥	♥	♠	♥
No	Yes	♥	♠	♥	♥	♠
No	No	♥	♠	♥	♠	♥

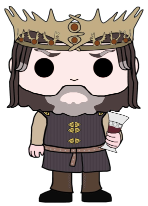
Rotations

There are three hearts in a row if and only if both Alice and Bob like the movie

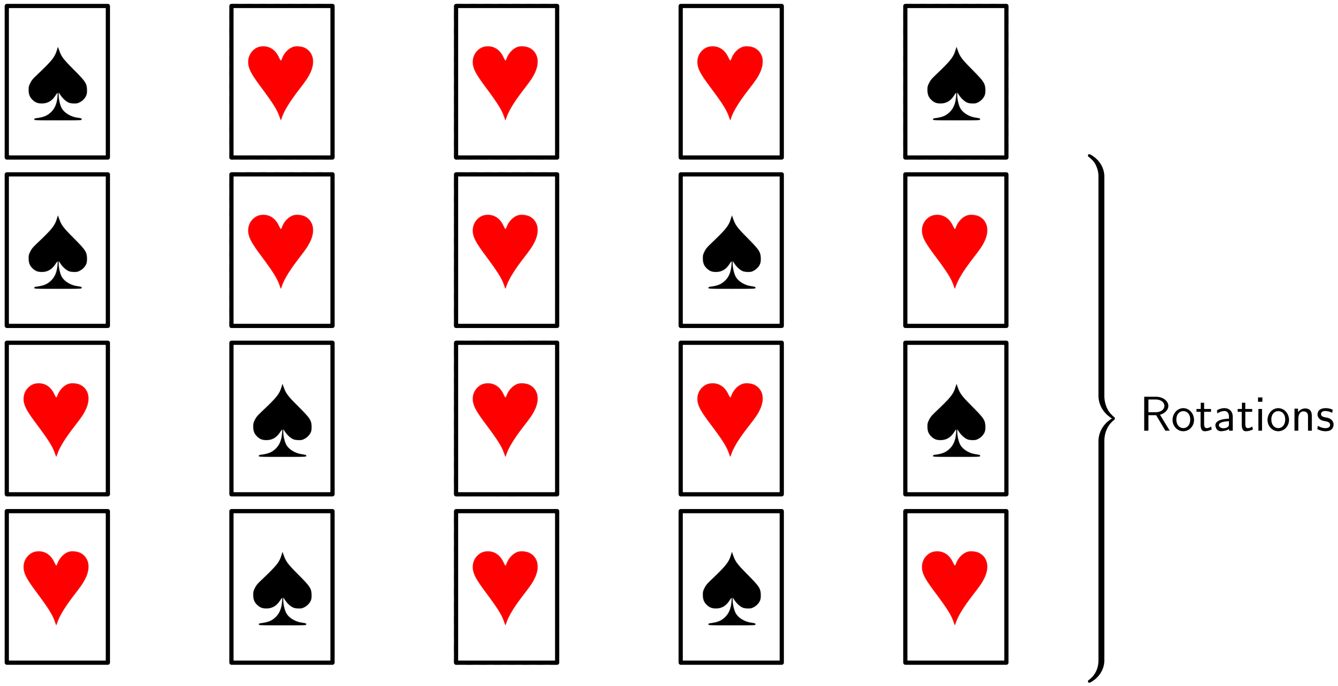
Choosing a movie with secret preferences

Possible configurations:





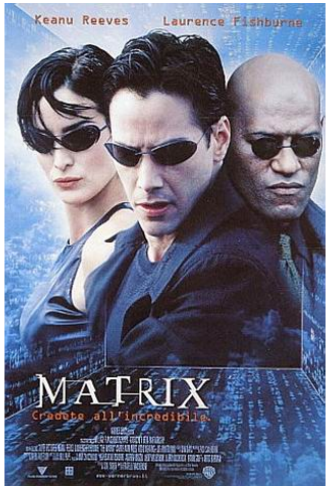
Yes	Yes
Yes	No
No	Yes
No	No

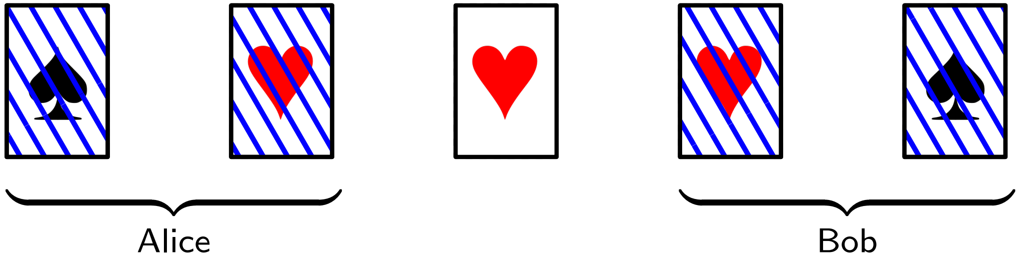


There are three hearts in a row if and only if both Alice and Bob like the movie

This holds (in a modular sense) even if any rotations of the cards is considered!

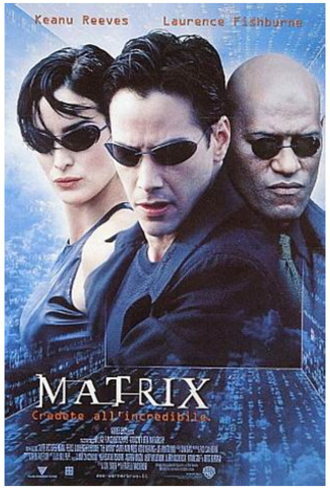
Choosing a movie with secret preferences

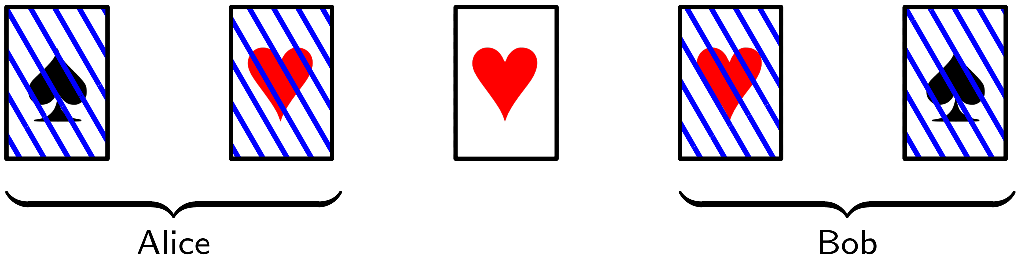




Alice and Bob pile up the cards, **all face down**, ensuring that their order is preserved

Choosing a movie with secret preferences





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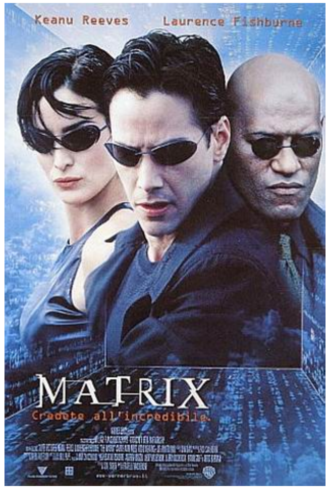
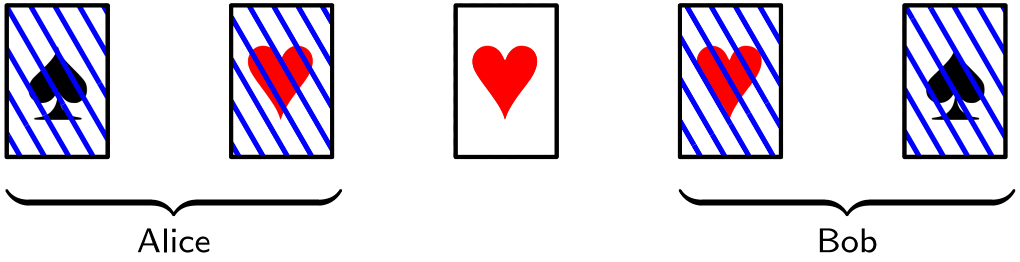
Alice and Bob take turns cutting the deck (i.e., they perform a rotation)

Choosing a movie with secret preferences





Alice and Bob pile up the cards, **all face down**, ensuring that their order is preserved

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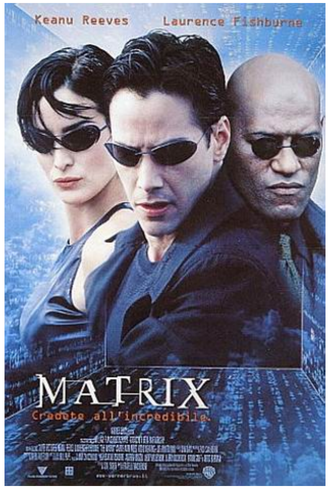
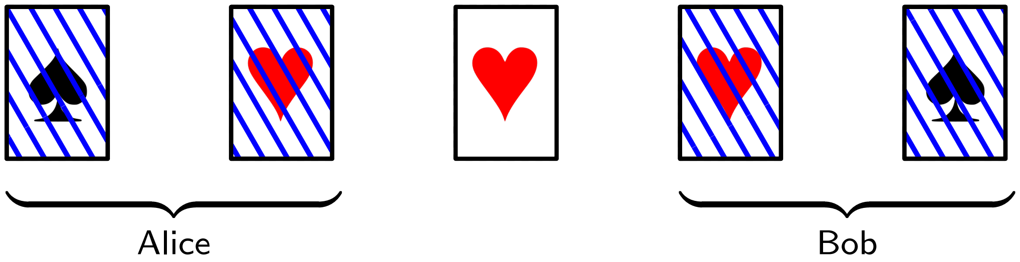
Alice and Bob reveal the cards and watch the movie if and only if there are 3 consecutive hearts (in a modular fashion), otherwise they "pass"

Choosing a movie with secret preferences





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Alice and Bob take turns cutting the deck (i.e., they perform a rotation)

Alice and Bob reveal the cards and watch the movie if and only if there are 3 consecutive hearts (in a modular fashion), otherwise they “pass”

Observation: If they end up not watching the movie, all possible “pass” configurations are equiprobable

Secure Multiparty Computation

The previous scenario is a secure multiparty computation problem:

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In the movie selection problem:

- $n = 2$
- $s_1, s_2 \in \{\text{pass}, \text{watch}\}$
- $f(s_1, s_2) = \begin{cases} \text{watch} & \text{if } s_1 = s_2 = \text{watch} \\ \text{pass} & \text{otherwise} \end{cases}$

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In the movie selection problem:

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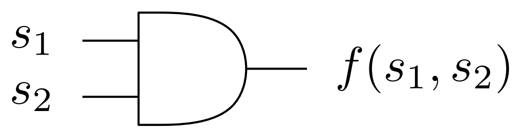

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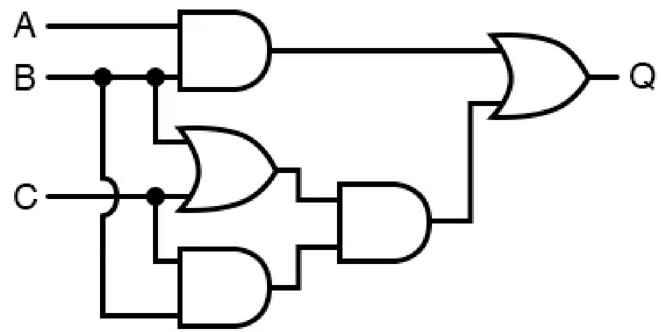

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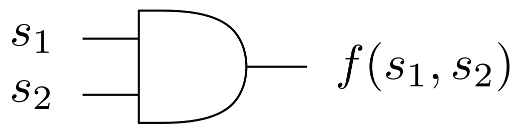


What about arbitrary circuits?

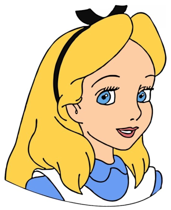
Zero Knowledge Proofs

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

Zero Knowledge Proofs

5	3	4	6	7	8	9	1	2
6	7	2	1	9	5	3	4	8
1	9	8	3	4	2	5	6	7
8	5	9	7	6	1	4	2	3
4	2	6	8	5	3	7	9	1
7	1	3	9	2	4	8	5	6
9	6	1	5	3	7	2	8	4
2	8	7	4	1	9	6	3	5
3	4	5	2	8	6	1	7	9

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

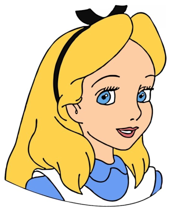


Zero Knowledge Proofs

5	3	4	6	7	8	9	1	2
6	7	2	1	9	5	3	4	8
1	9	8	3	4	2	5	6	7
8	5	9	7	6	1	4	2	3
4	2	6	8	5	3	7	9	1
7	1	3	9	2	4	8	5	6
9	6	1	5	3	7	2	8	4
2	8	7	4	1	9	6	3	5
3	4	5	2	8	6	1	7	9

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

I know a solution to this Sudoku instance

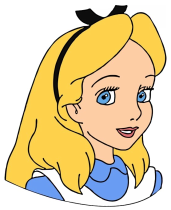


Zero Knowledge Proofs

5	3	4	6	7	8	9	1	2
6	7	2	1	9	5	3	4	8
1	9	8	3	4	2	5	6	7
8	5	9	7	6	1	4	2	3
4	2	6	8	5	3	7	9	1
7	1	3	9	2	4	8	5	6
9	6	1	5	3	7	2	8	4
2	8	7	4	1	9	6	3	5
3	4	5	2	8	6	1	7	9

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

Really? Show it to me!

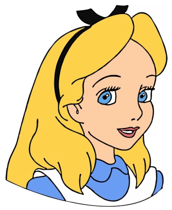


Zero Knowledge Proofs

5	3	4	6	7	8	9	1	2
6	7	2	1	9	5	3	4	8
1	9	8	3	4	2	5	6	7
8	5	9	7	6	1	4	2	3
4	2	6	8	5	3	7	9	1
7	1	3	9	2	4	8	5	6
9	6	1	5	3	7	2	8	4
2	8	7	4	1	9	6	3	5
3	4	5	2	8	6	1	7	9

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

I don't want to reveal it to you

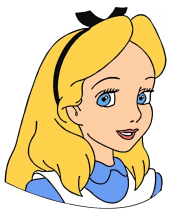


Zero Knowledge Proofs

5	3	4	6	7	8	9	1	2
6	7	2	1	9	5	3	4	8
1	9	8	3	4	2	5	6	7
8	5	9	7	6	1	4	2	3
4	2	6	8	5	3	7	9	1
7	1	3	9	2	4	8	5	6
9	6	1	5	3	7	2	8	4
2	8	7	4	1	9	6	3	5
3	4	5	2	8	6	1	7	9

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

Then I don't believe you
really have a solution

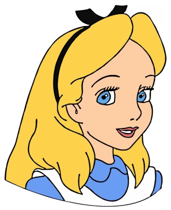


Zero Knowledge Proofs

5	3	4	6	7	8	9	1	2
6	7	2	1	9	5	3	4	8
1	9	8	3	4	2	5	6	7
8	5	9	7	6	1	4	2	3
4	2	6	8	5	3	7	9	1
7	1	3	9	2	4	8	5	6
9	6	1	5	3	7	2	8	4
2	8	7	4	1	9	6	3	5
3	4	5	2	8	6	1	7	9

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

I can prove to you that I have a solution without revealing anything about it



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5	3	4	6	7	8	9	1	2
6	7	2	1	9	5	3	4	8
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4	2	6	8	5	3	7	9	1
7	1	3	9	2	4	8	5	6
9	6	1	5	3	7	2	8	4
2	8	7	4	1	9	6	3	5
3	4	5	2	8	6	1	7	9

5	3			7				
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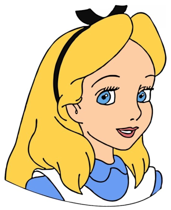
				8			7	9



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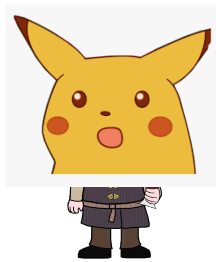

Zero Knowledge Proofs

5	3	4	6	7	8	9	1	2
6	7	2	1	9	5	3	4	8
1	9	8	3	4	2	5	6	7
8	5	9	7	6	1	4	2	3
4	2	6	8	5	3	7	9	1
7	1	3	9	2	4	8	5	6
9	6	1	5	3	7	2	8	4
2	8	7	4	1	9	6	3	5
3	4	5	2	8	6	1	7	9

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

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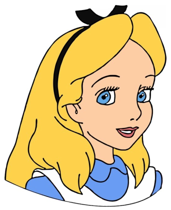
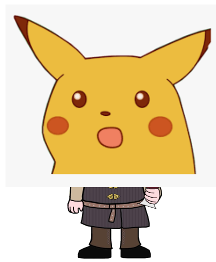


Zero Knowledge protocol

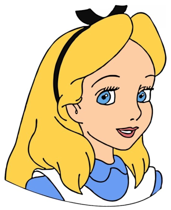


Zero Knowledge Proofs

5	3	4	6	7	8	9	1	2
6	7	2	1	9	5	3	4	8
1	9	8	3	4	2	5	6	7
8	5	9	7	6	1	4	2	3
4	2	6	8	5	3	7	9	1
7	1	3	9	2	4	8	5	6
9	6	1	5	3	7	2	8	4
2	8	7	4	1	9	6	3	5
3	4	5	2	8	6	1	7	9

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

I am now convinced
you have the solution



Zero Knowledge protocol

Zero Knowledge Proofs

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

Hey, Charlie!
Alice has a solution to
this Sudoku instance

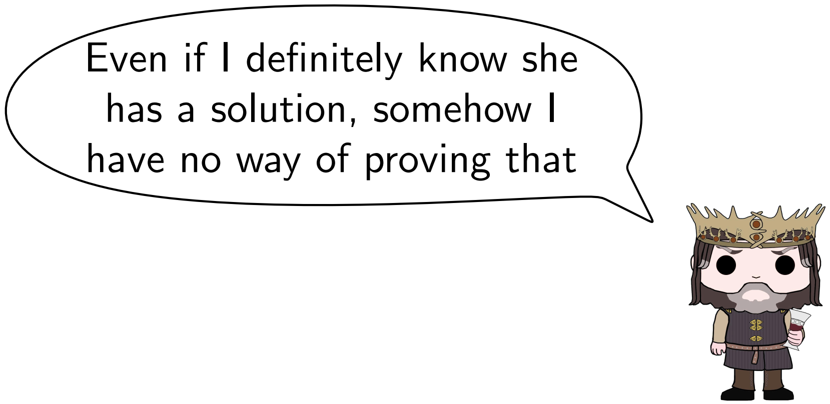
Zero Knowledge Proofs

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

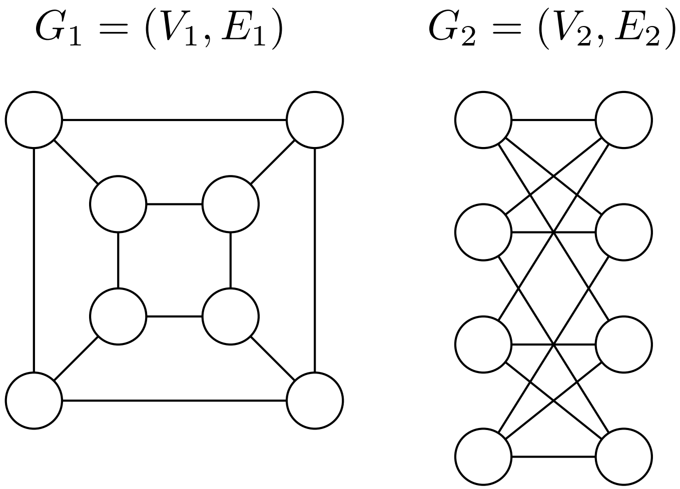
Prove it!

Zero Knowledge Proofs

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9



Zero Knowledge Proofs

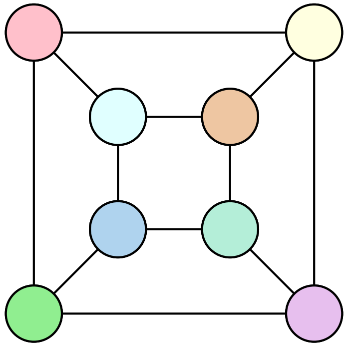


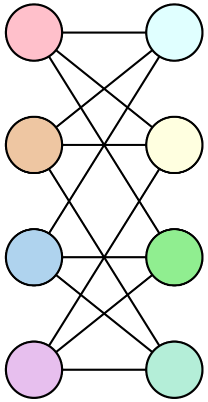
Graph isomorphism problem

G_1 is isomorphic to G_2 iff $\exists$ bijection $\pi : V_1 \to V_2$ s.t. $(u,v) \in E_1 \iff (\pi(u), \pi(v)) \in E_2$.

Zero Knowledge Proofs

$G_1 = (V_1, E_1)$ $G_2 = (V_2, E_2)$





Graph isomorphism problem

G_1 is isomorphic to G_2 iff $\exists$ bijection $\pi : V_1 \to V_2$ s.t. $(u, v) \in E_1 \iff (\pi(u), \pi(v)) \in E_2$.

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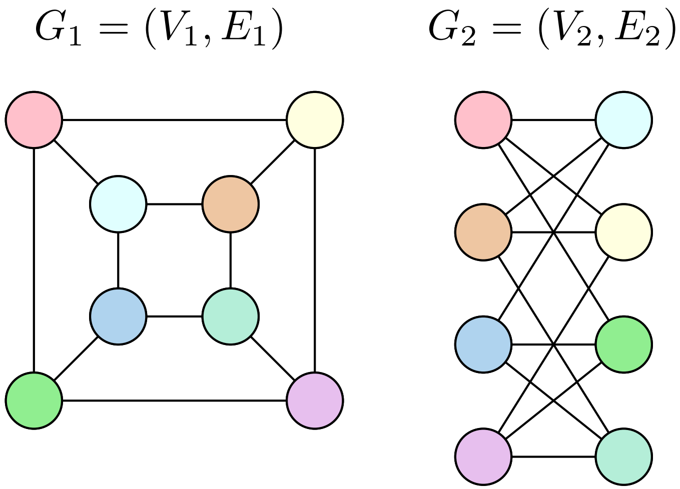

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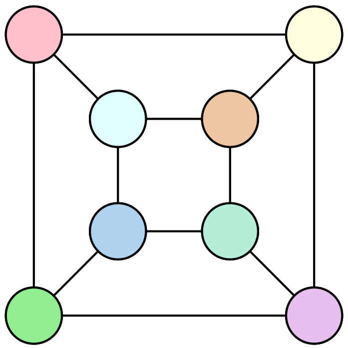

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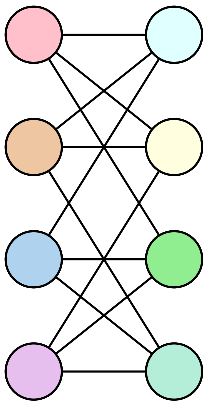

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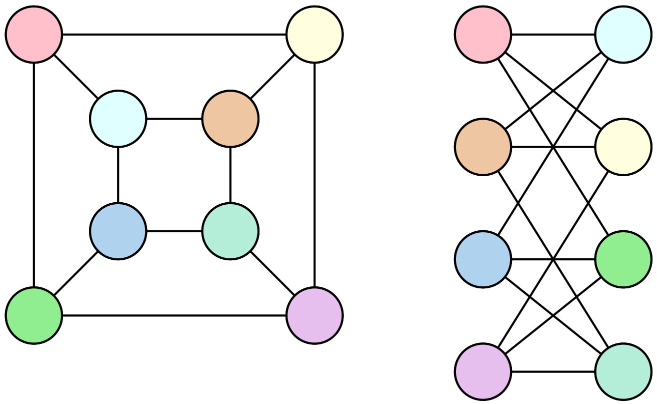

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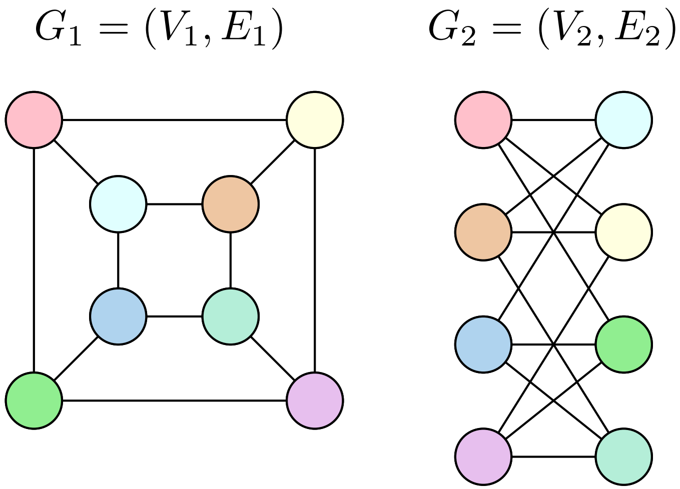

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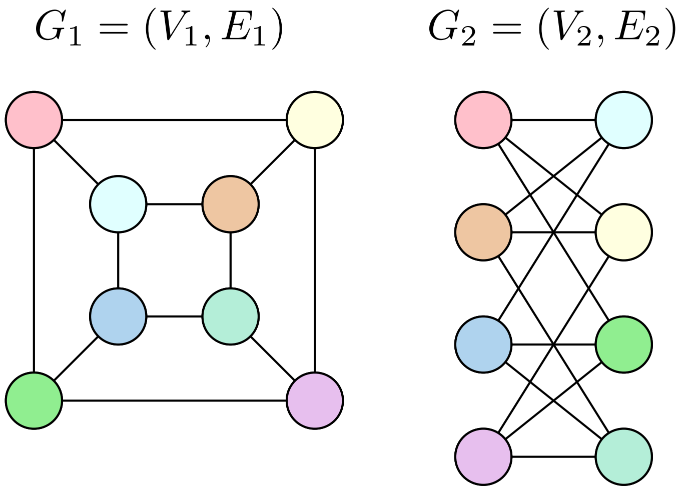

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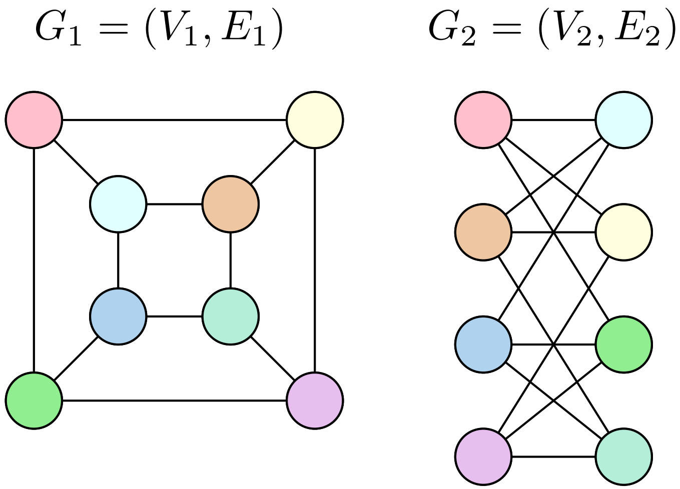

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Alice can use a Zero Knowledge protocol to convince bob that G_1 and G_2 are isomorphic without revealing π

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Basic definitions

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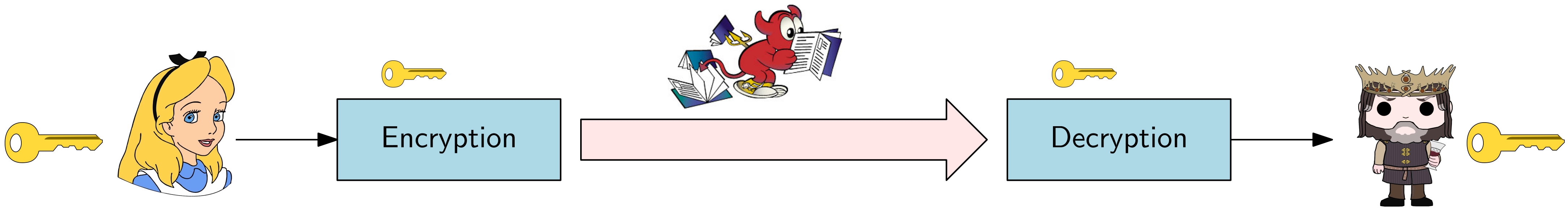

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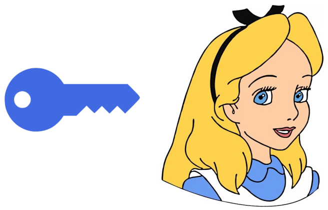

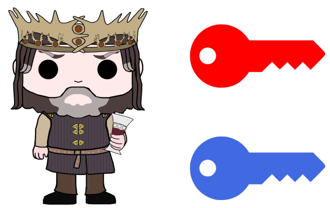

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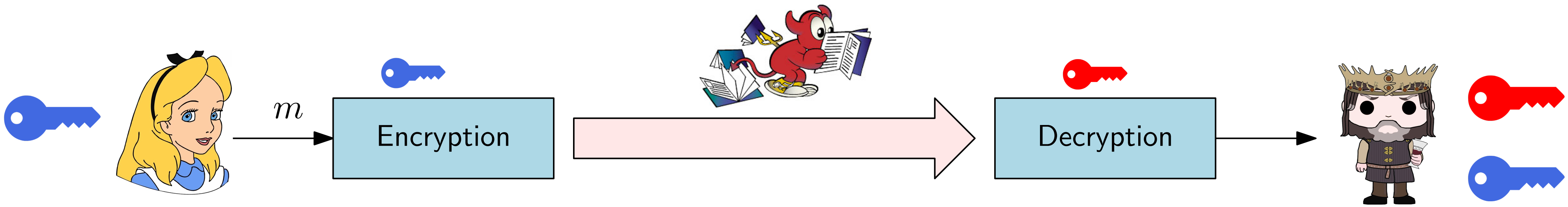

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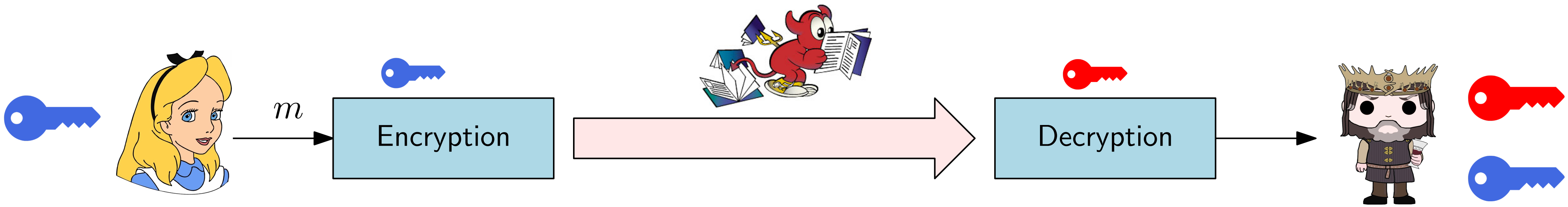

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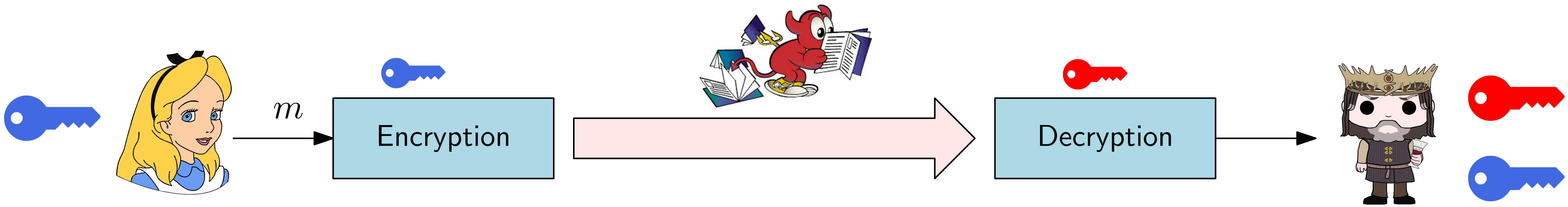

For now, we will only be concerned with private-key cryptography

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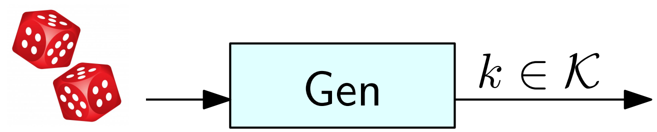

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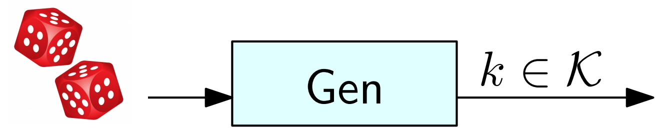

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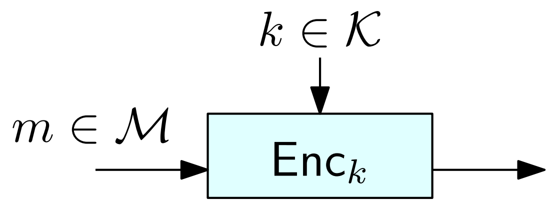

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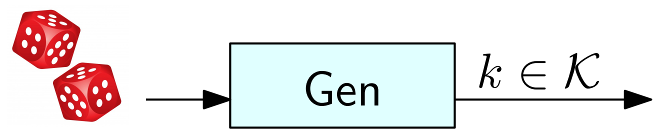

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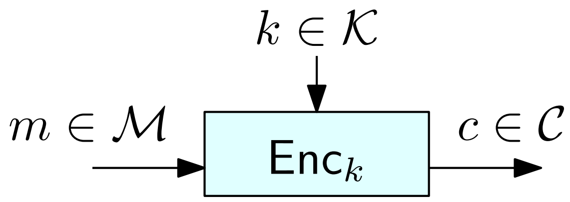

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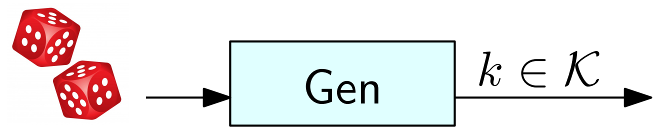

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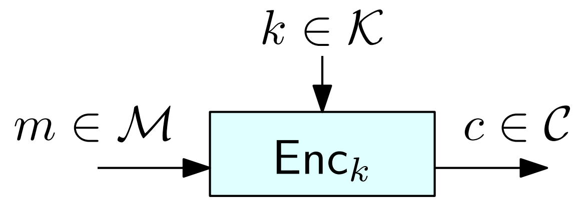

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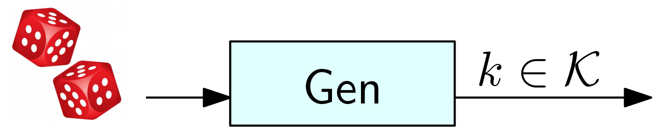

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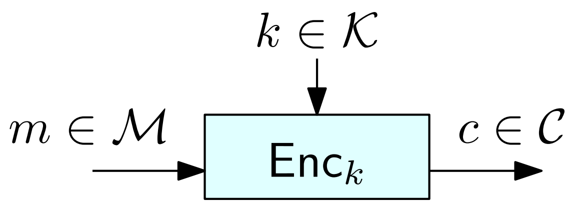

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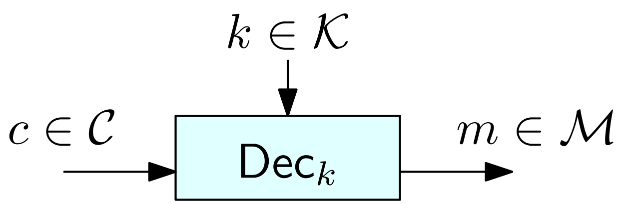

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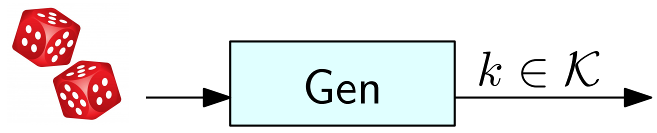

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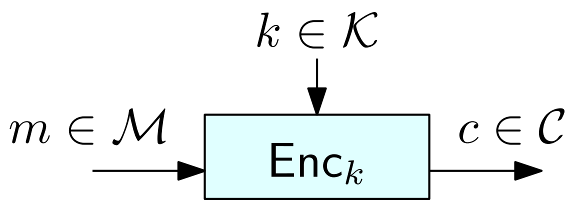

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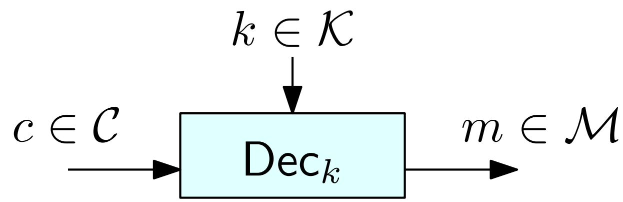

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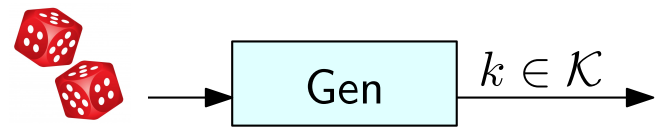

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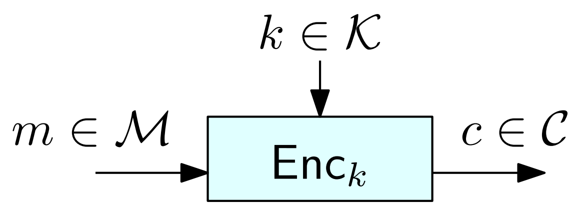

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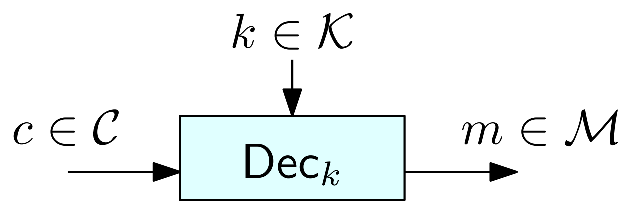

Perfect correctness: $\forall k \in \mathcal{K}, m \in \mathcal{M}$ if c can be output by $\text{Enc}_k(m)$ then $\text{Dec}_k(c) = m$

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If the key is leaked, it is easy to replace it

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- No need for Bob to implement Alice's weird scheme on his own
  (Bob can use public, vetted, implementations of well-known schemes)