Information Systems and **Network Security**

Docente: Stefano Leucci

Email: `stefano.leucci@univaq.it`

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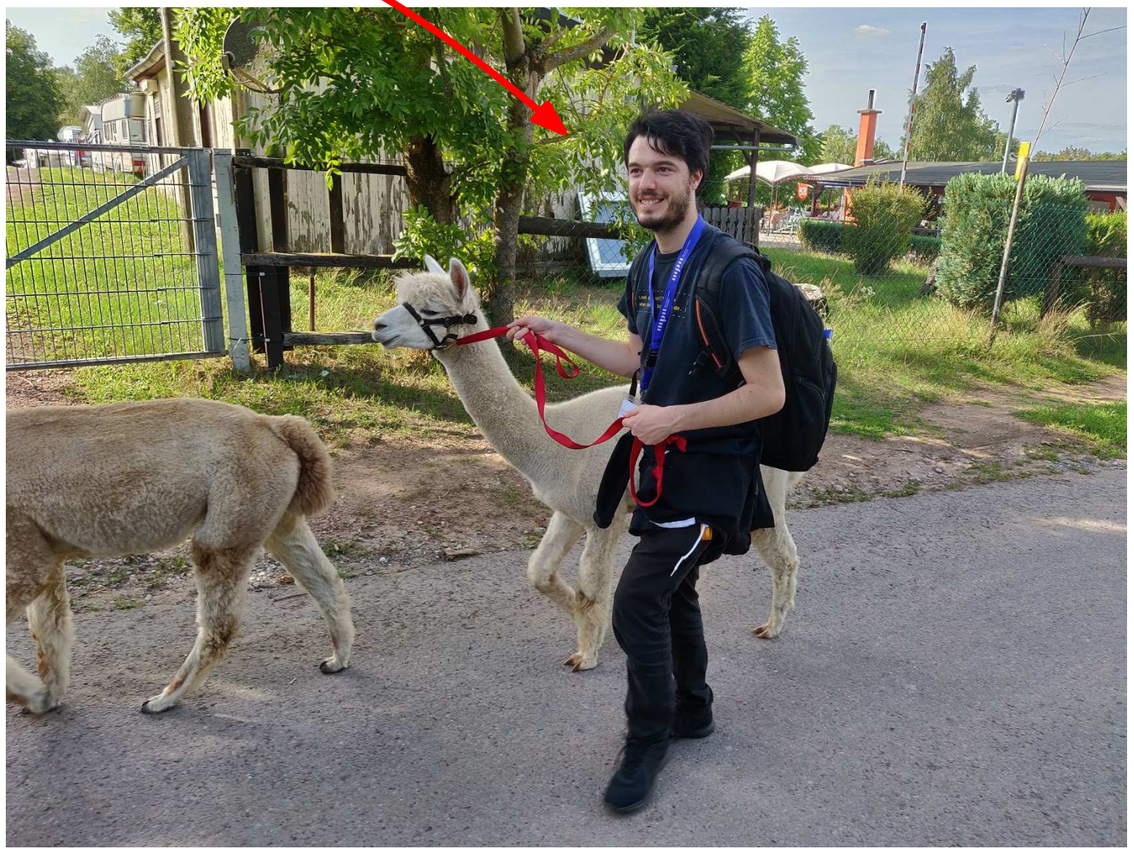

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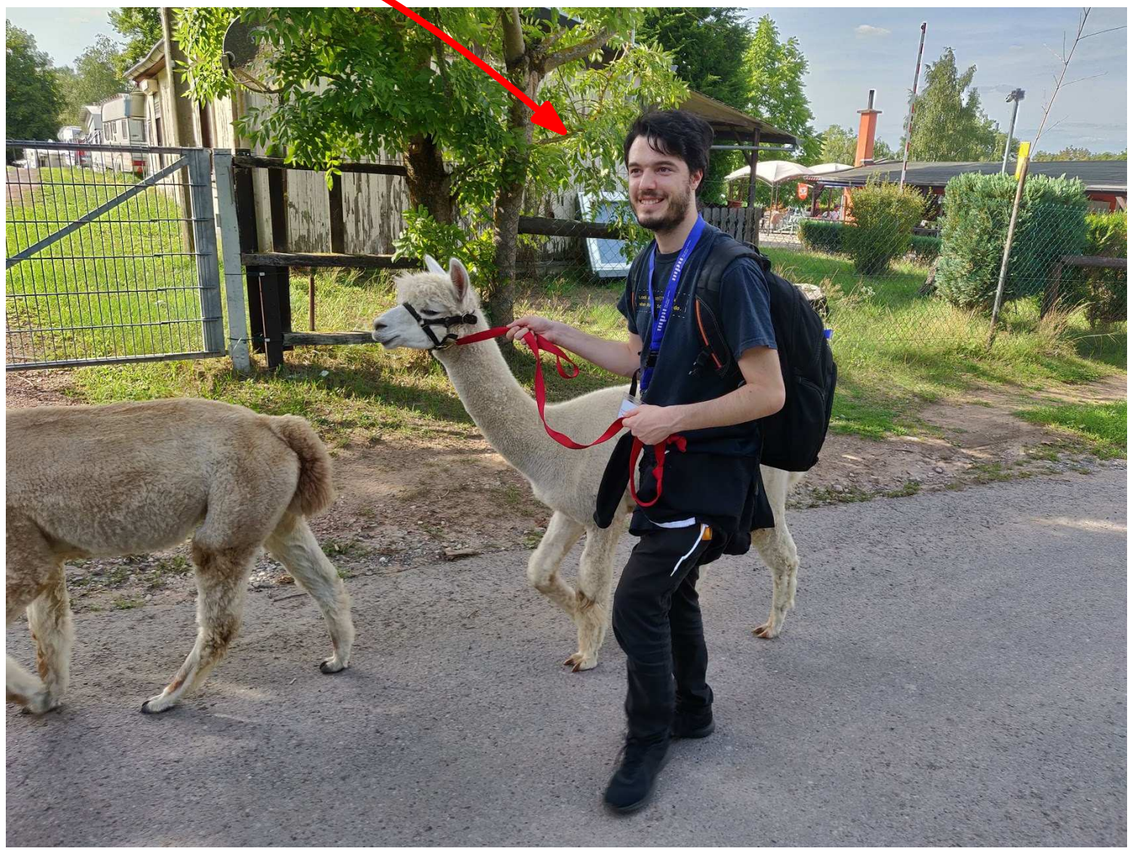

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Basic Info

Course length: 48 hours (6 CFU)

- 24 lectures

When/where:

- Tuesday 16:30 – 18:30 **Room:** C1.16
- Thursday 11:30 – 13:30 **Room:** C1.16

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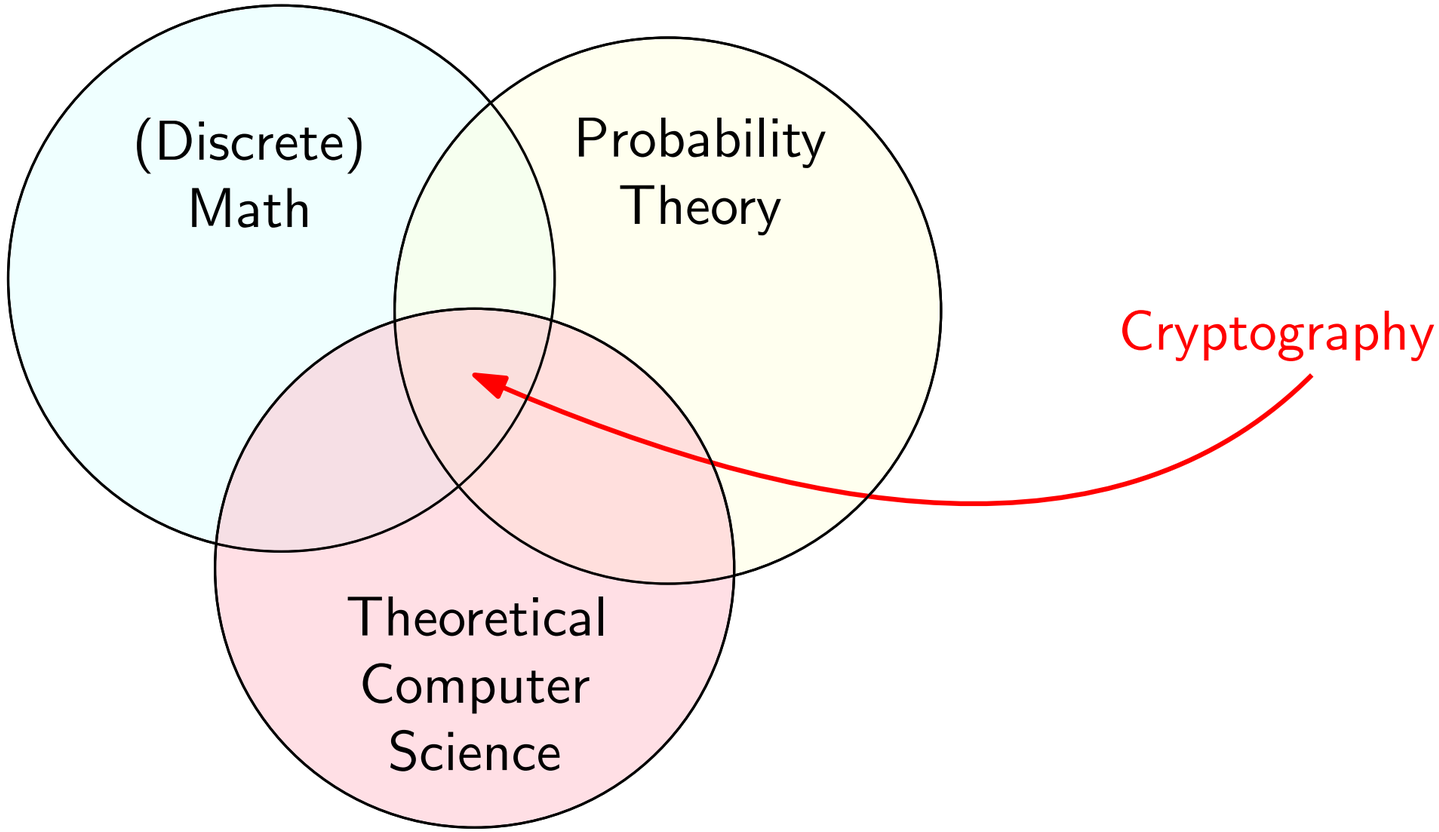
Office hours:

- Thursday 14:30 – 16:30
- Please send an email to `stefano.leucci@gmail.com` or ask before/after class

Course material:

`https://people.disim.univaq.it/~stefanoleucci/isns25/`

Ingredients of Cryptography



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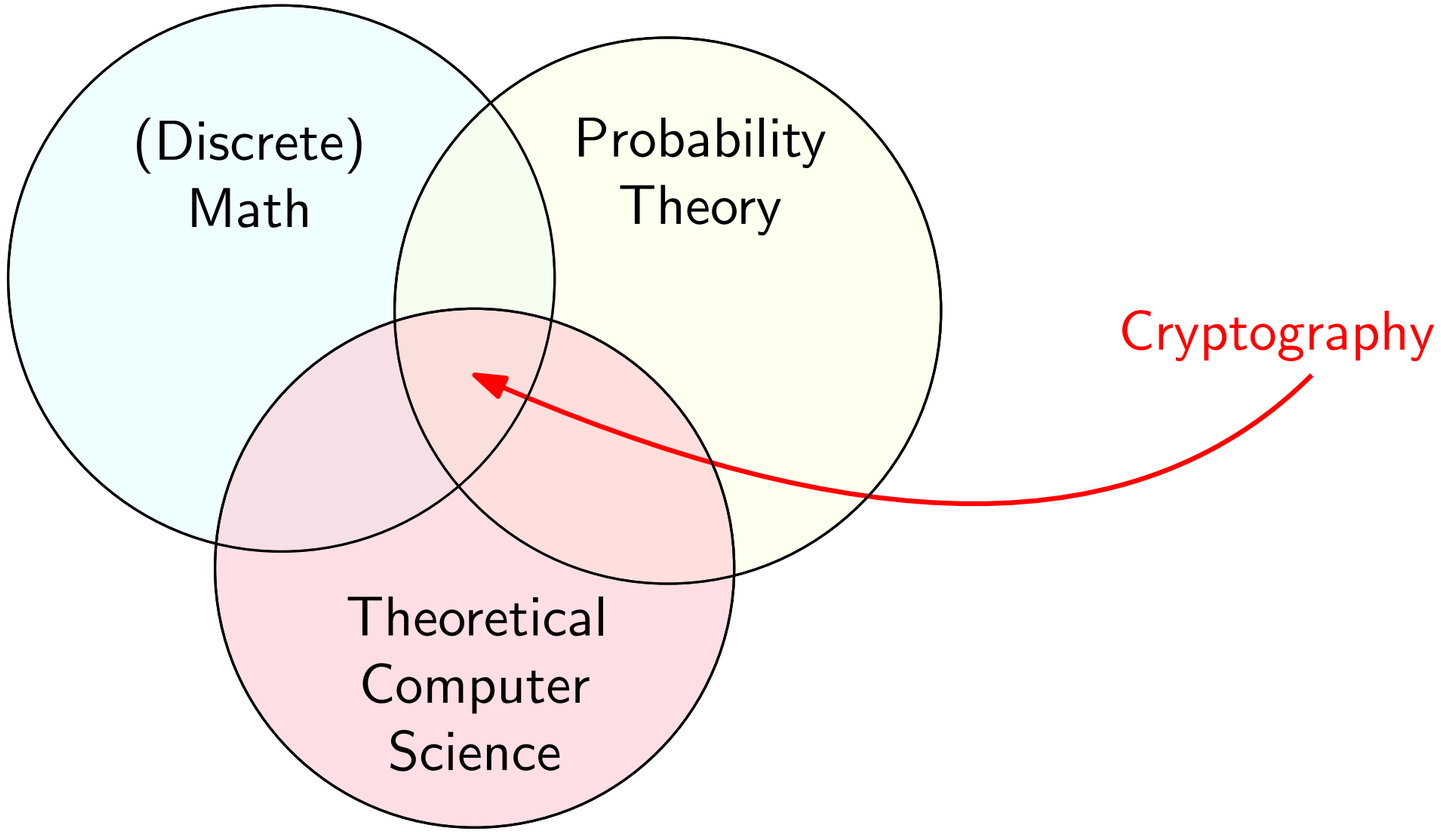

(Discrete) Math: Basic algebra, Modular arithmetic, some concepts from group theory and number theory

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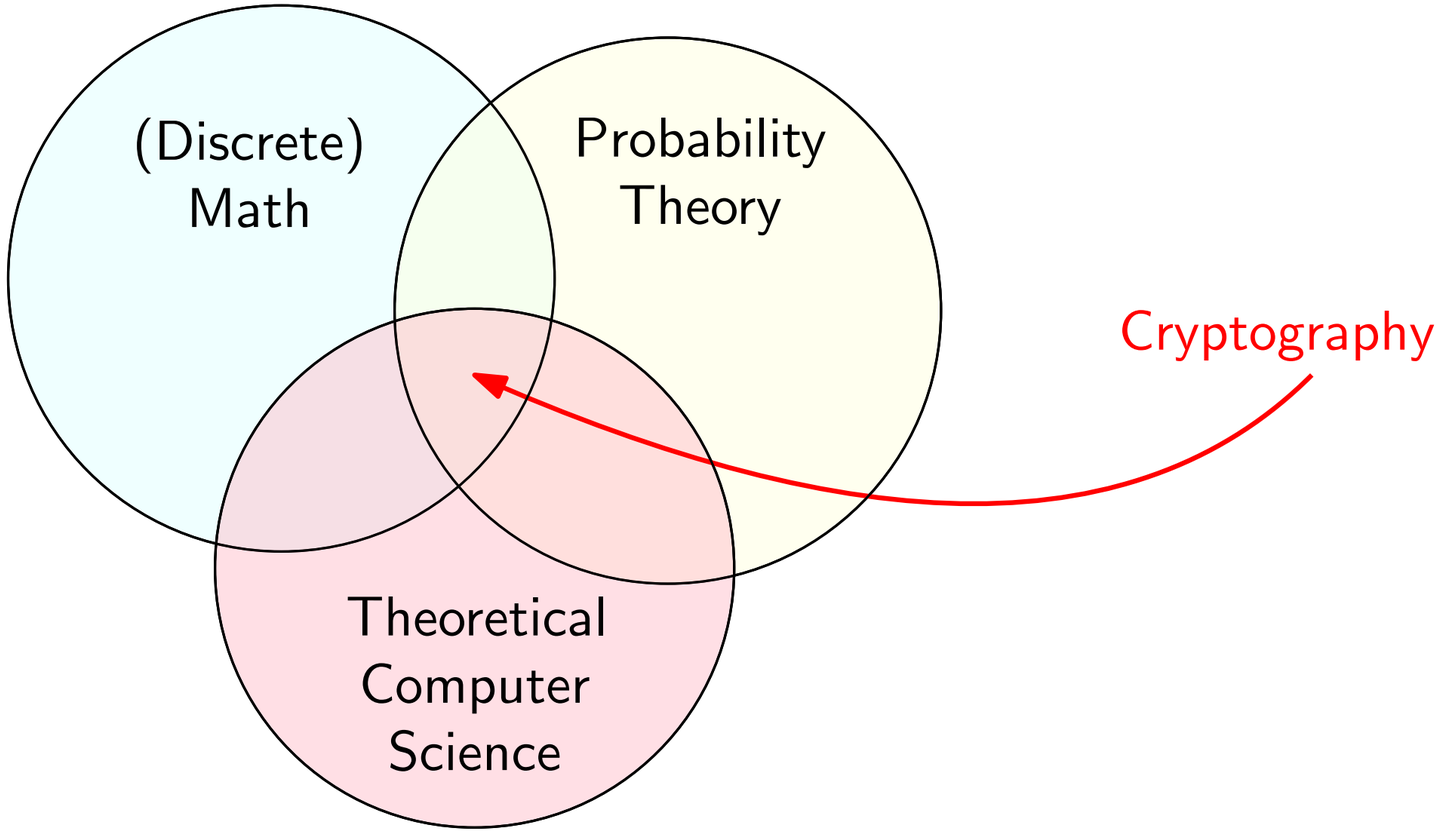

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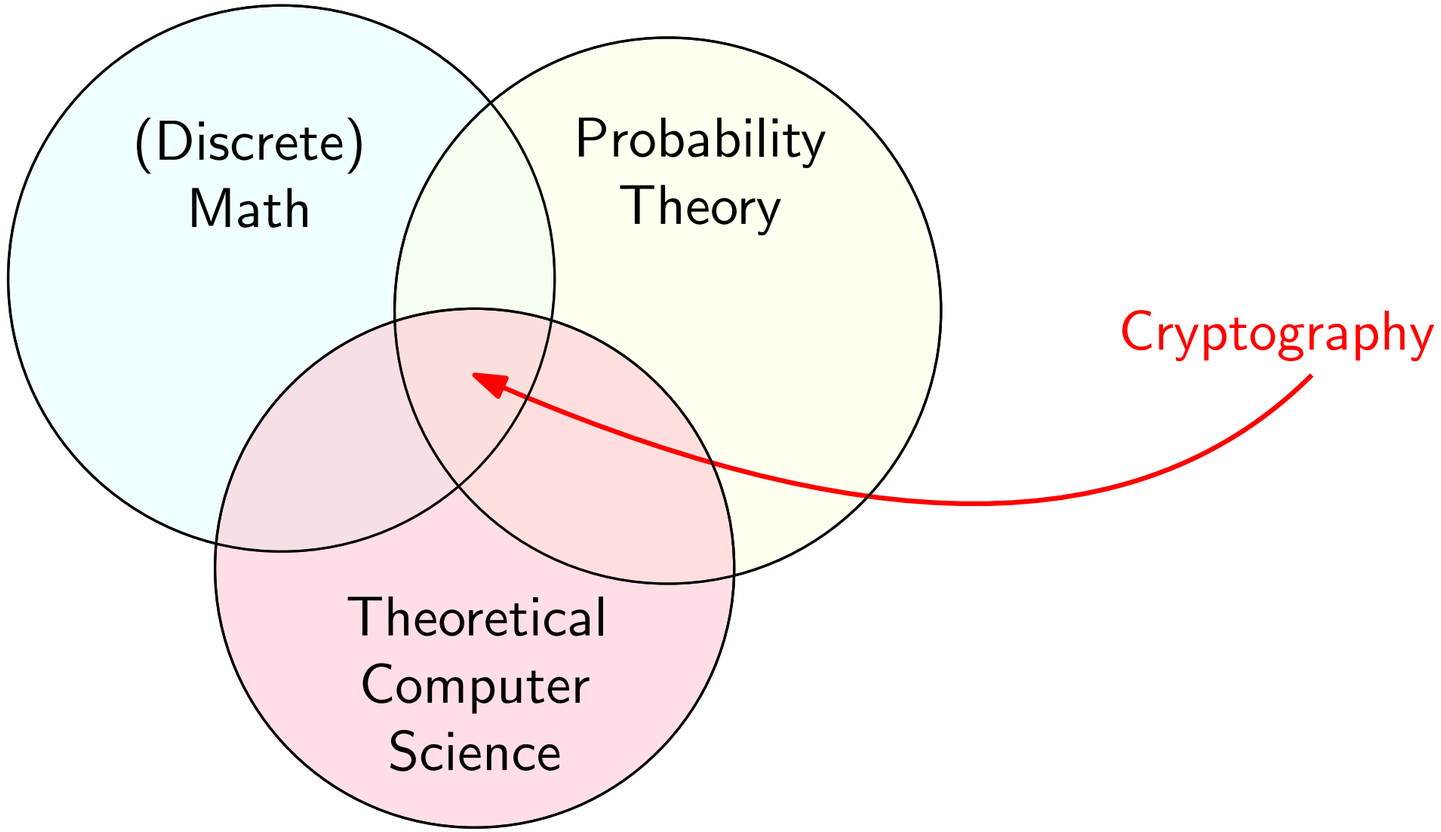

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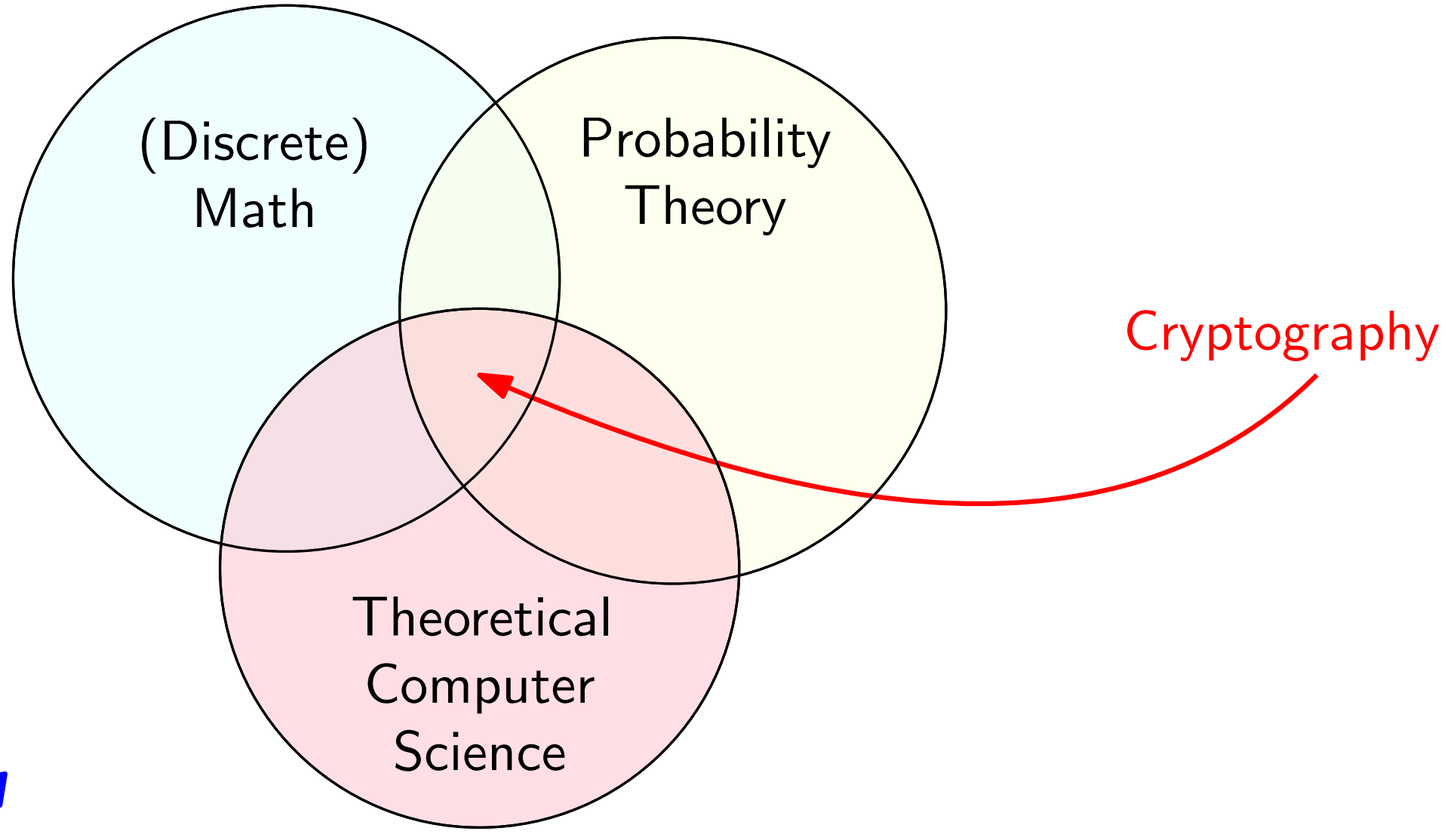

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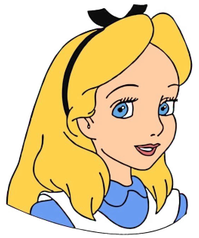
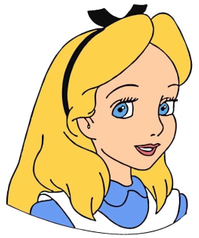


Two entities wish to communicate

Why cryptography?

Alice



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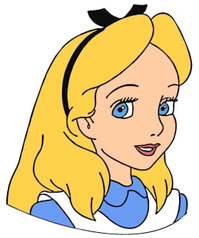

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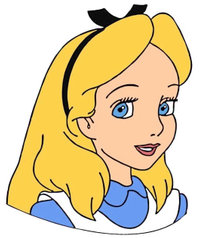

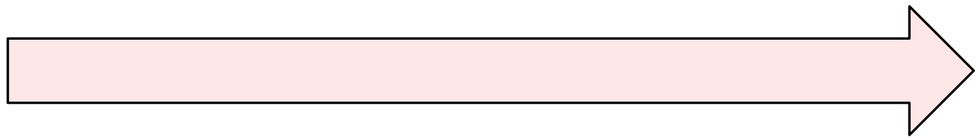

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Alice can send a message to Bob through a communication channel

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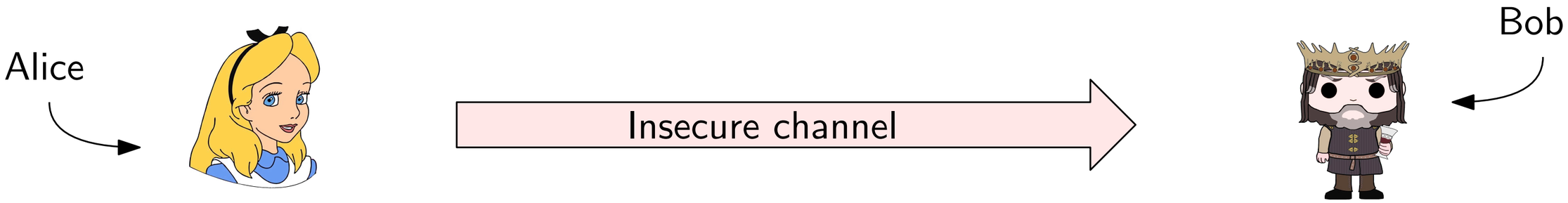

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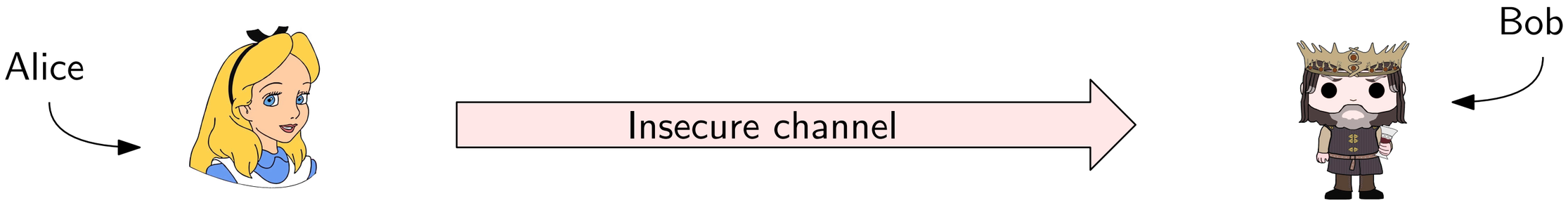

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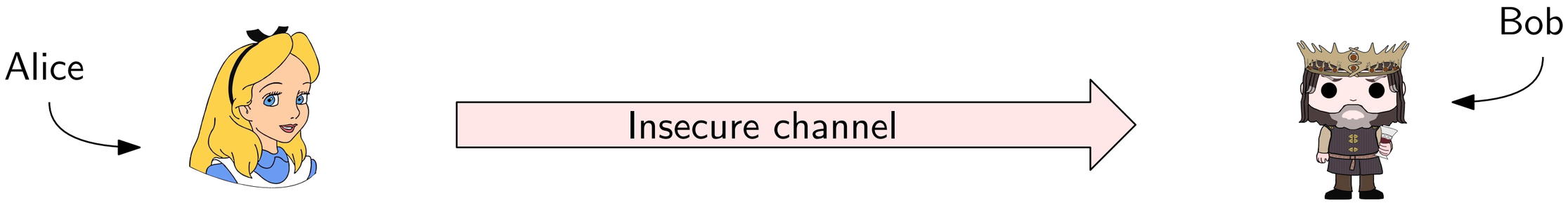

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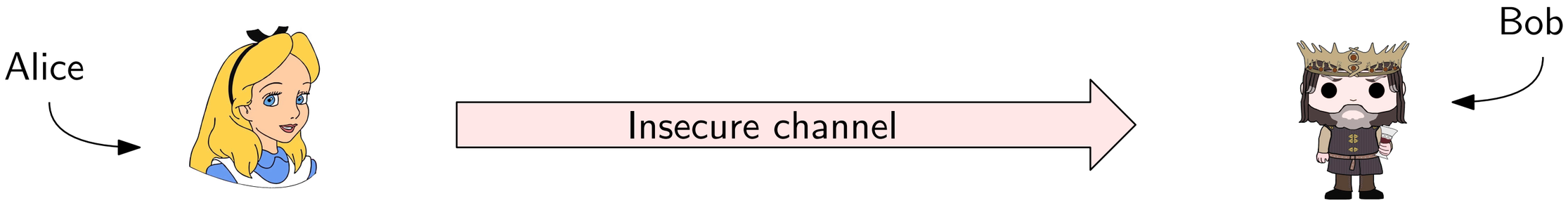

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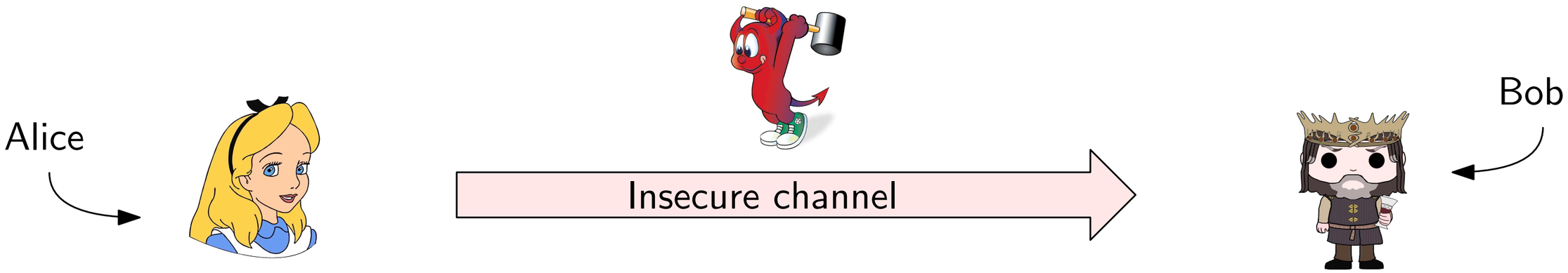

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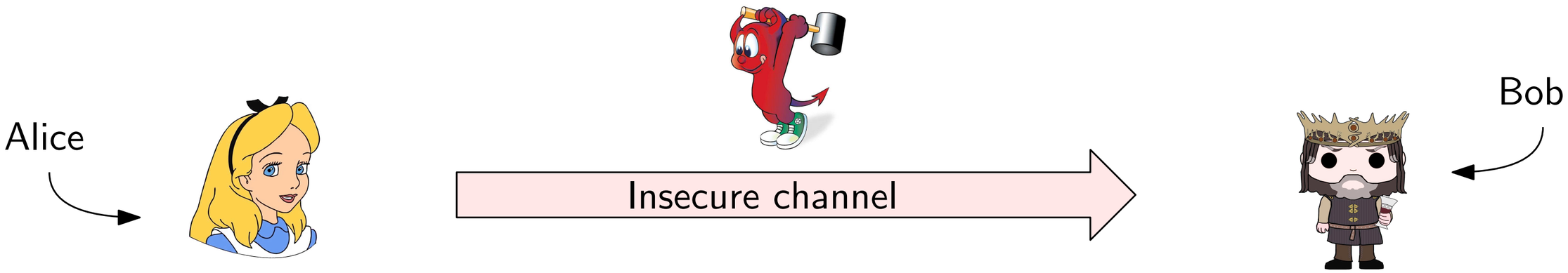

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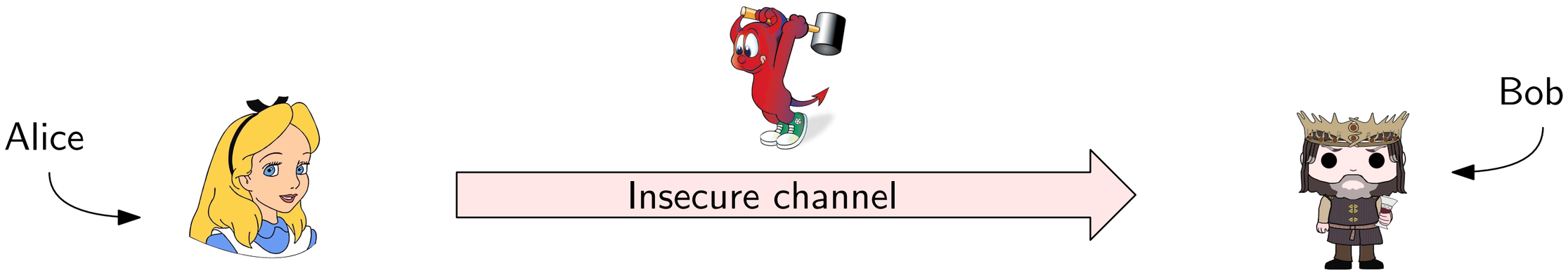

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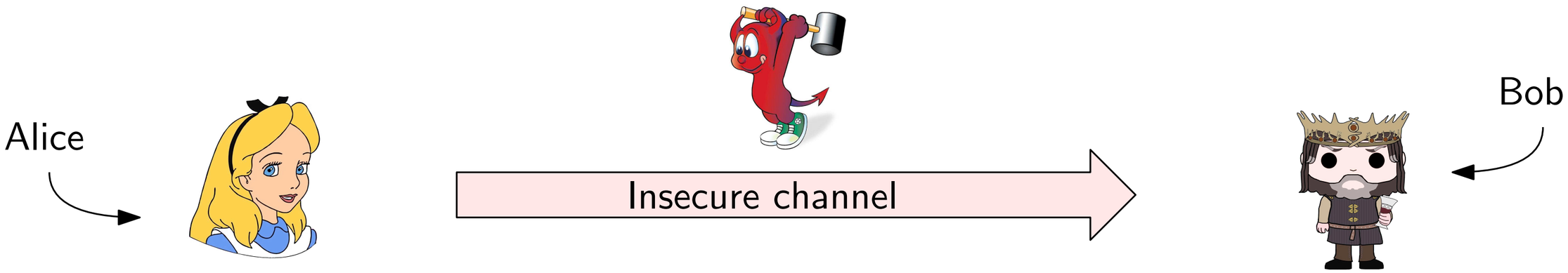

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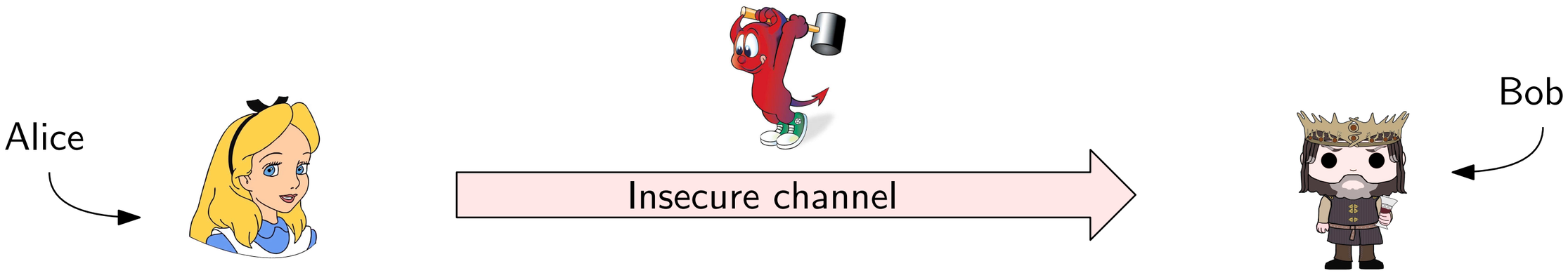

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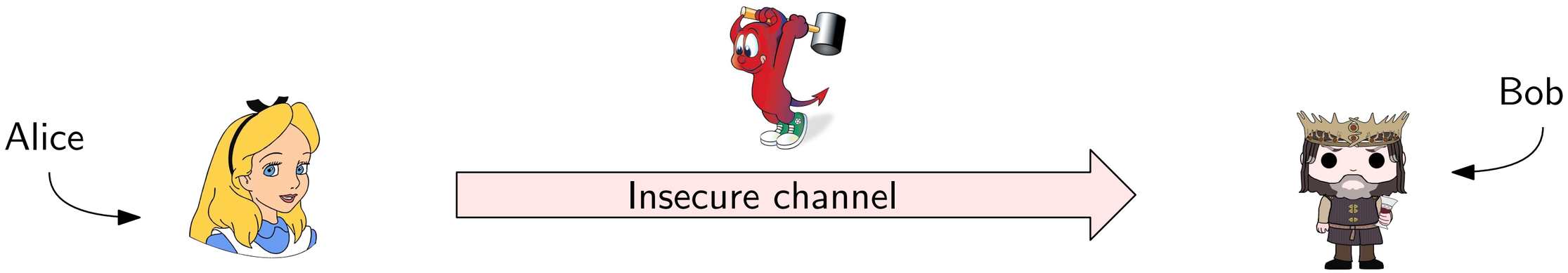

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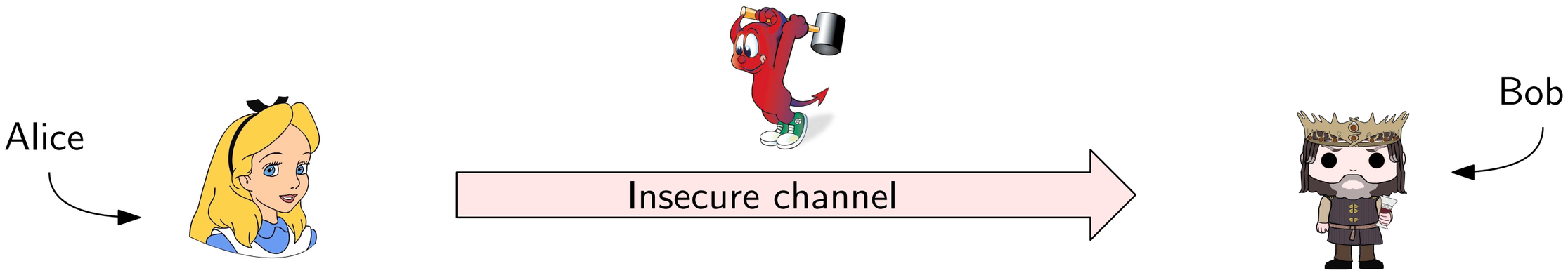

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- **Authentication:** any message received by Bob can be confirmed to have originated from Alice (we can detect any message injected by the adversary)
- **Integrity:** it is not possible to alter the contents of a message sent across the channel (without the tampering being detected)

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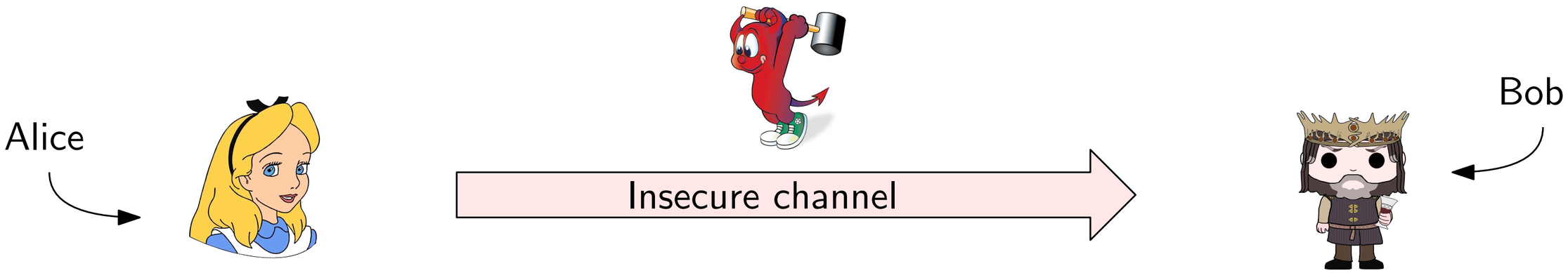

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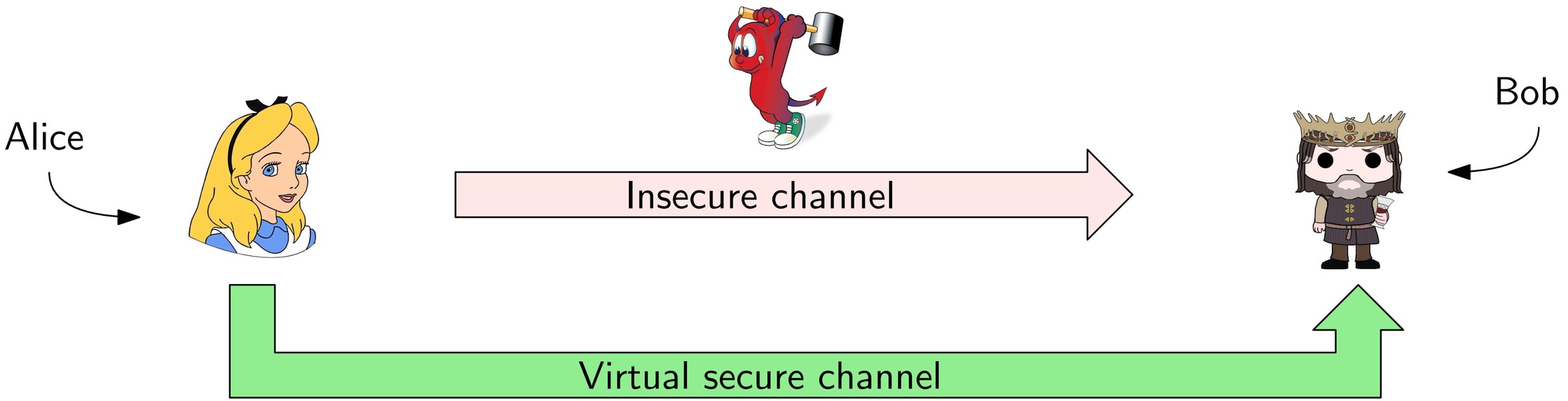

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- Key distribution

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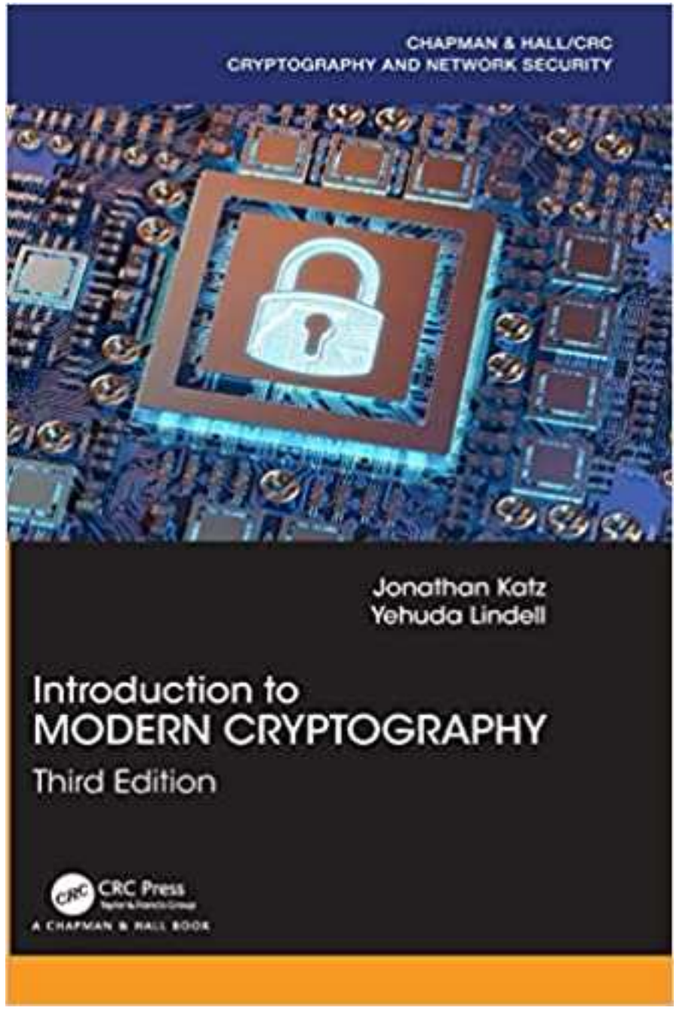
} Public-key cryptography

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

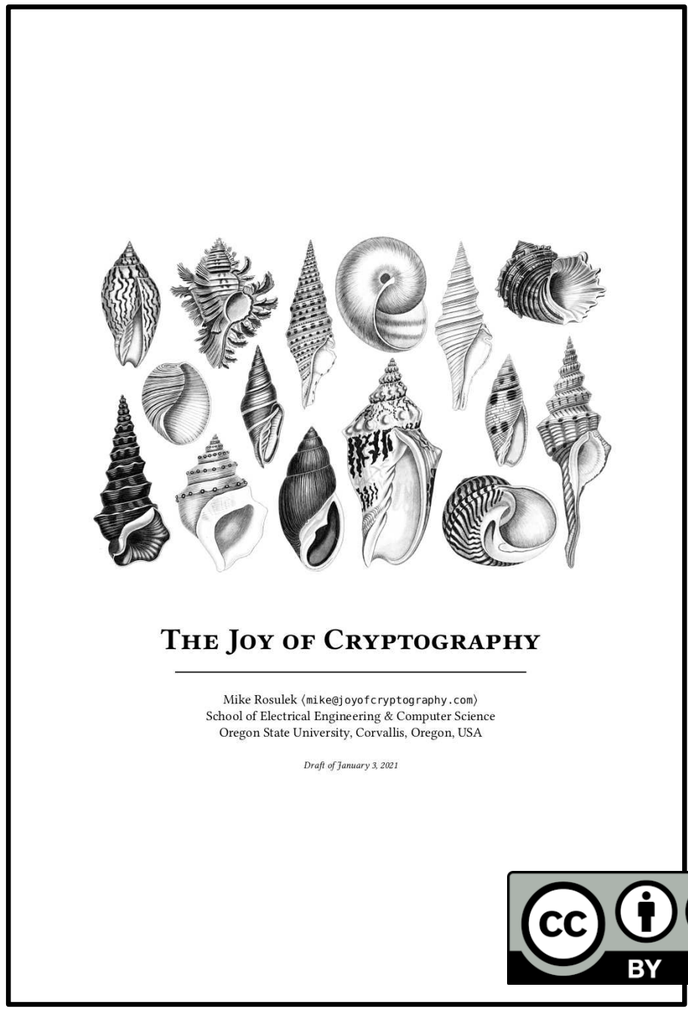
Books



Introduction to Modern Cryptography

Jonathan Katz, Yehuda Lindell

ISBN: 978-0815354369



The Joy Of Cryptography

Mike Rosulek

https://joyofcryptography.com/

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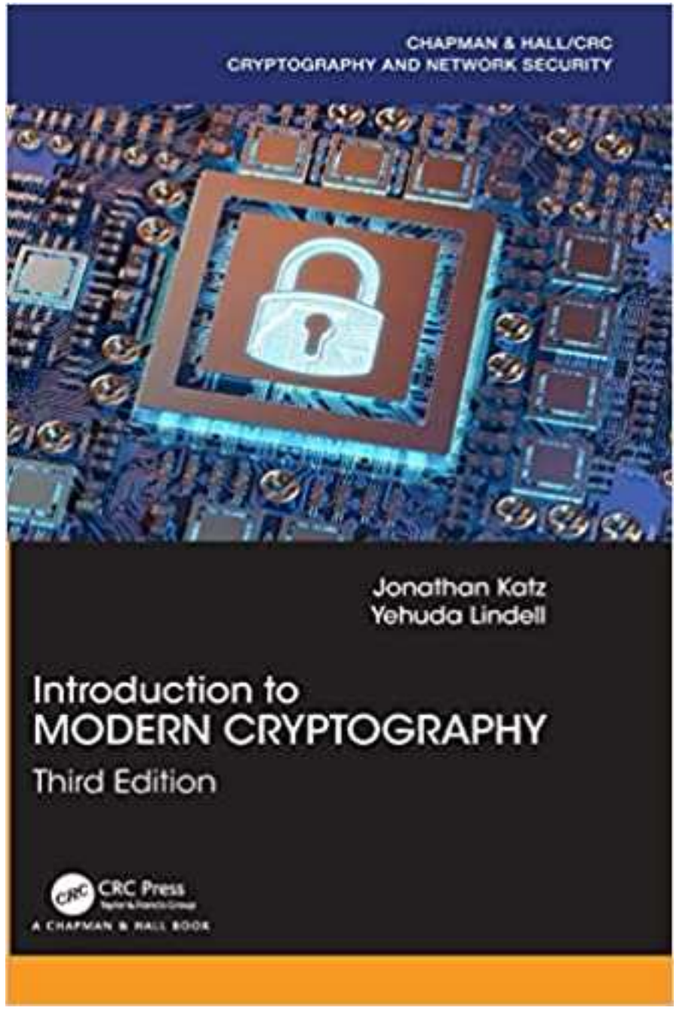

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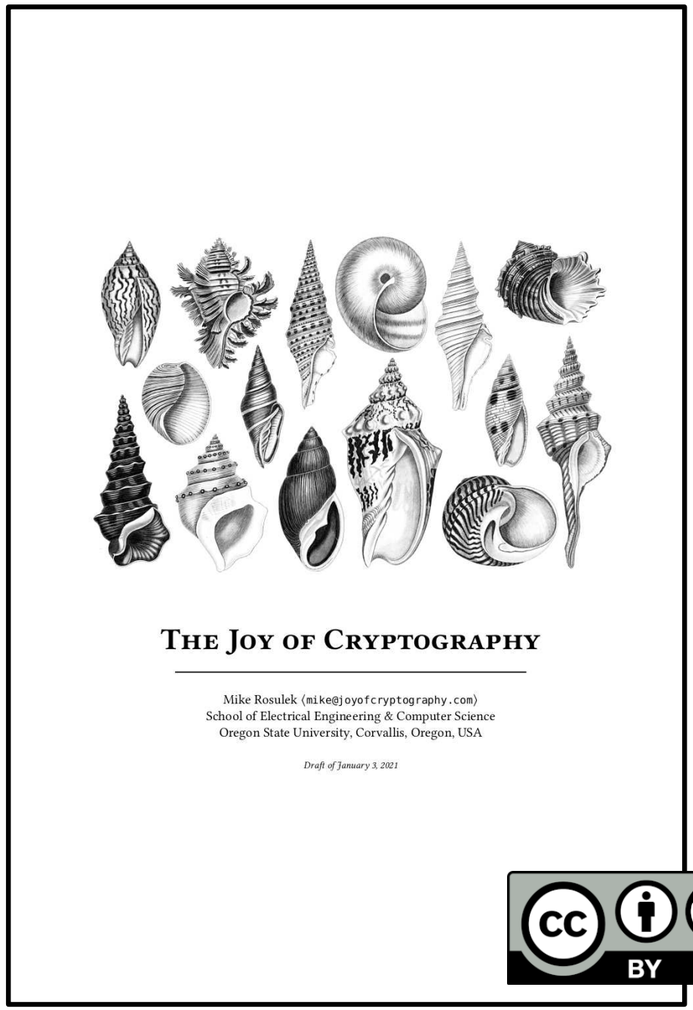

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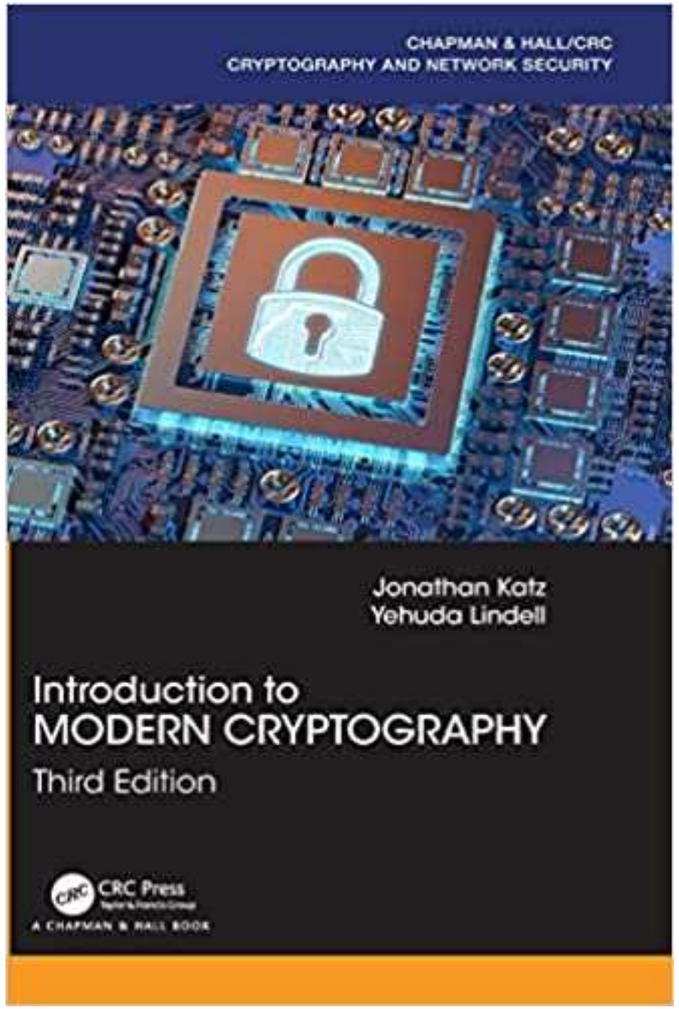

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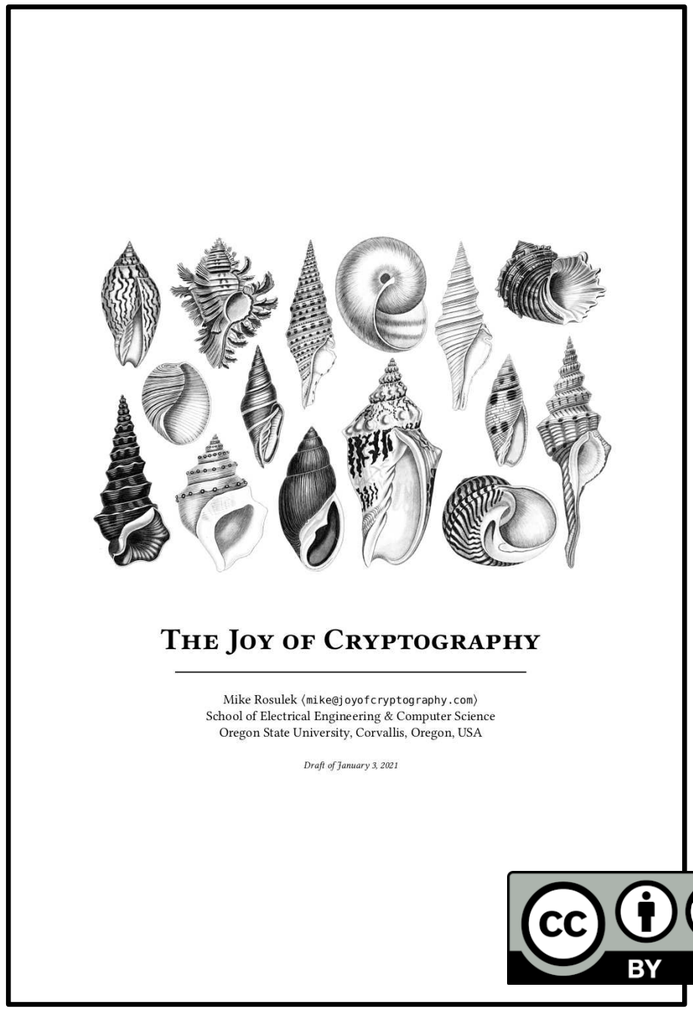

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Exams

Written exam:

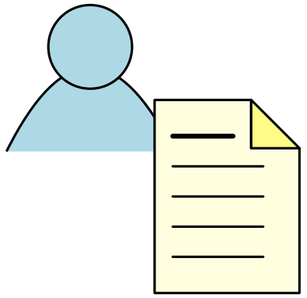
- Questions on the theoretical concepts (e.g., security definitions)
- Exercises (e.g., prove security, carry out an attack, etc. . .)

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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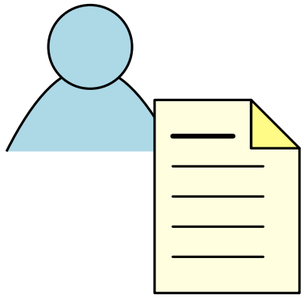

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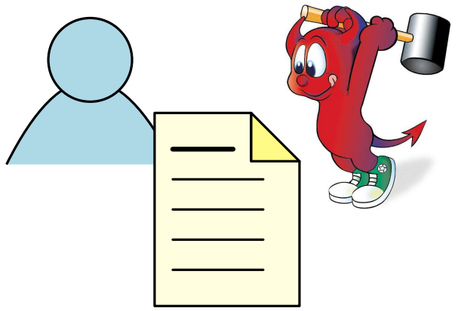

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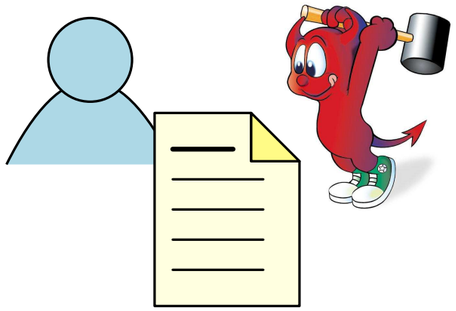

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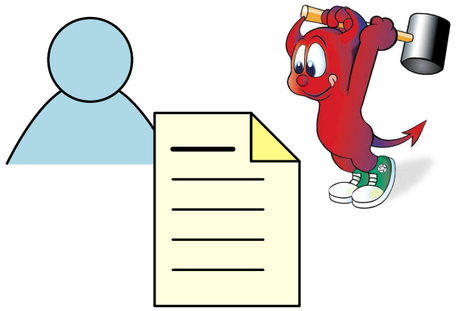

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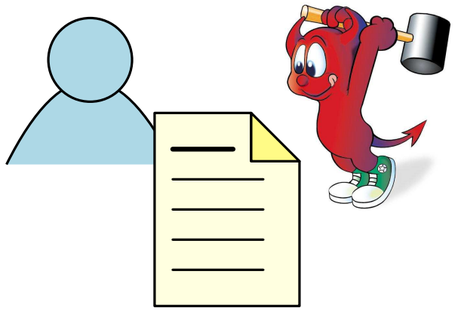

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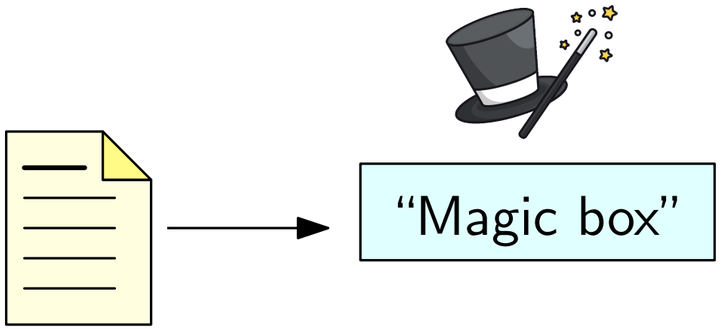

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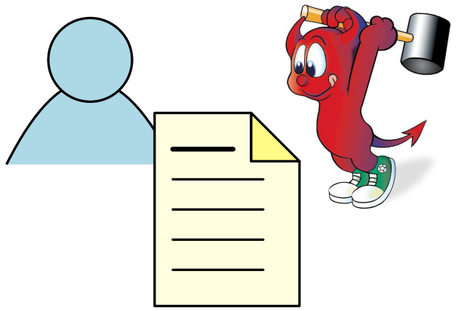

Single point of failure!

An attacker can compromise one machine and steal the sensitive information

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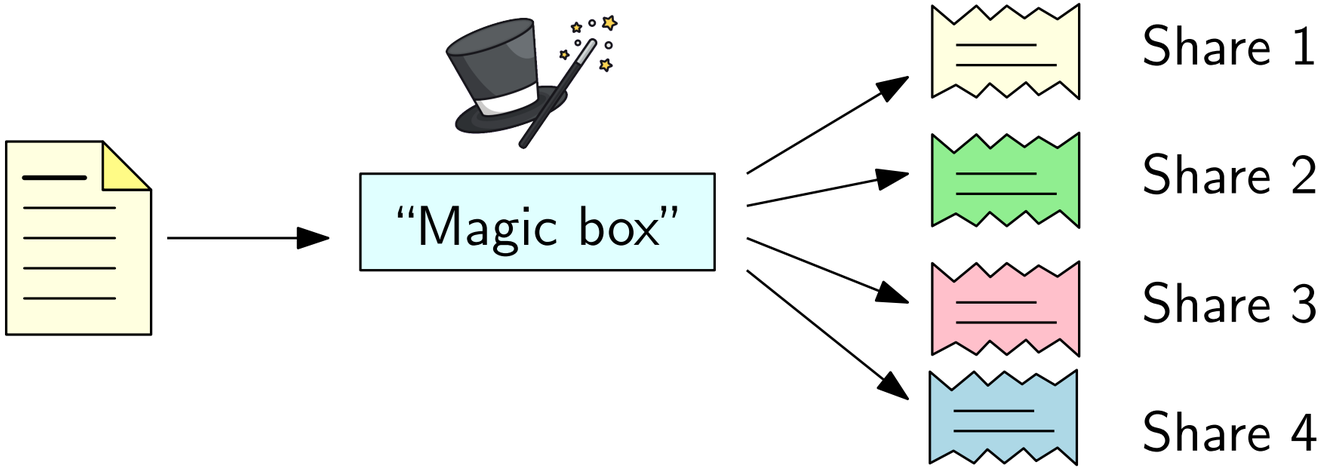
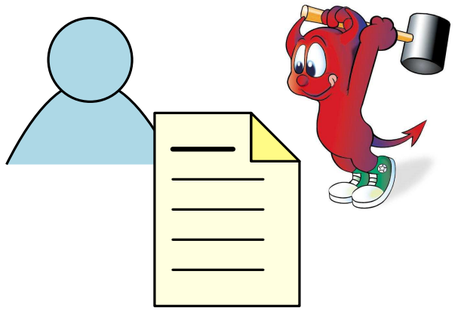


Secret Sharing

Imagine some sensitive information that is kept by a single agent

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



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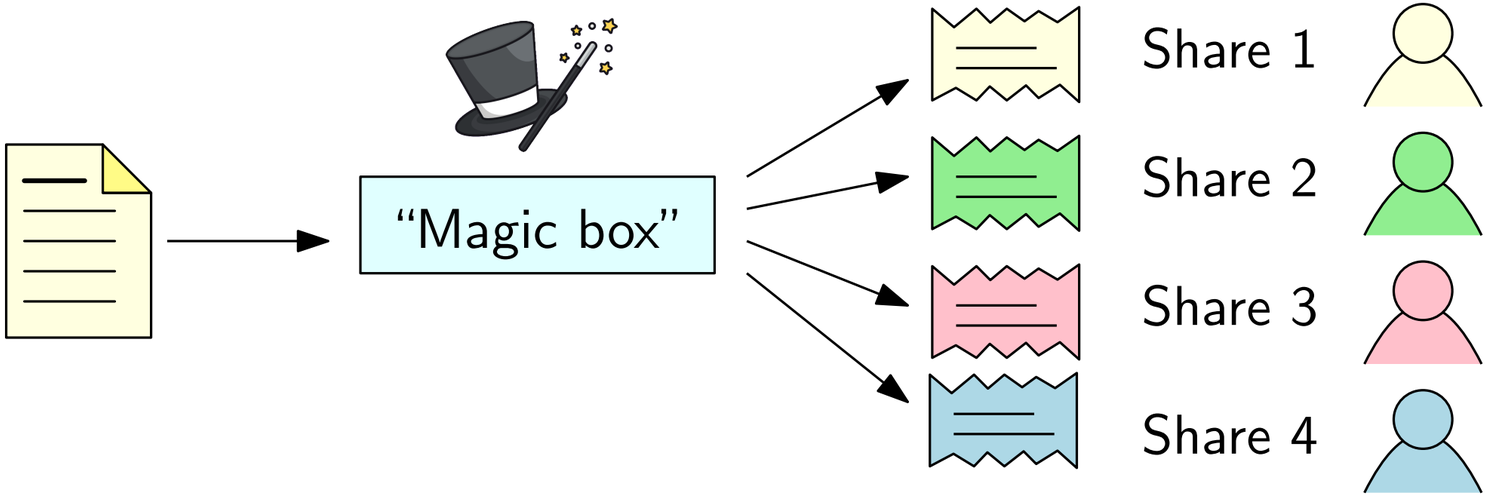

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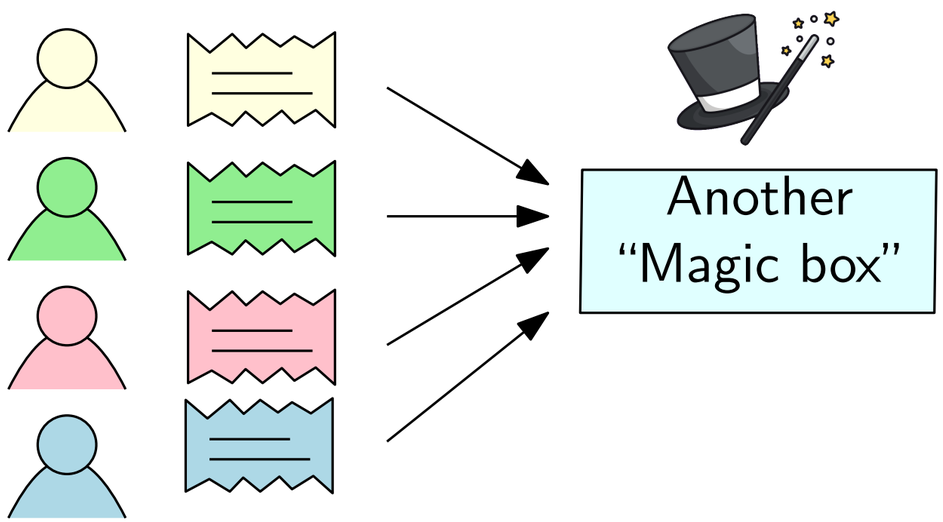

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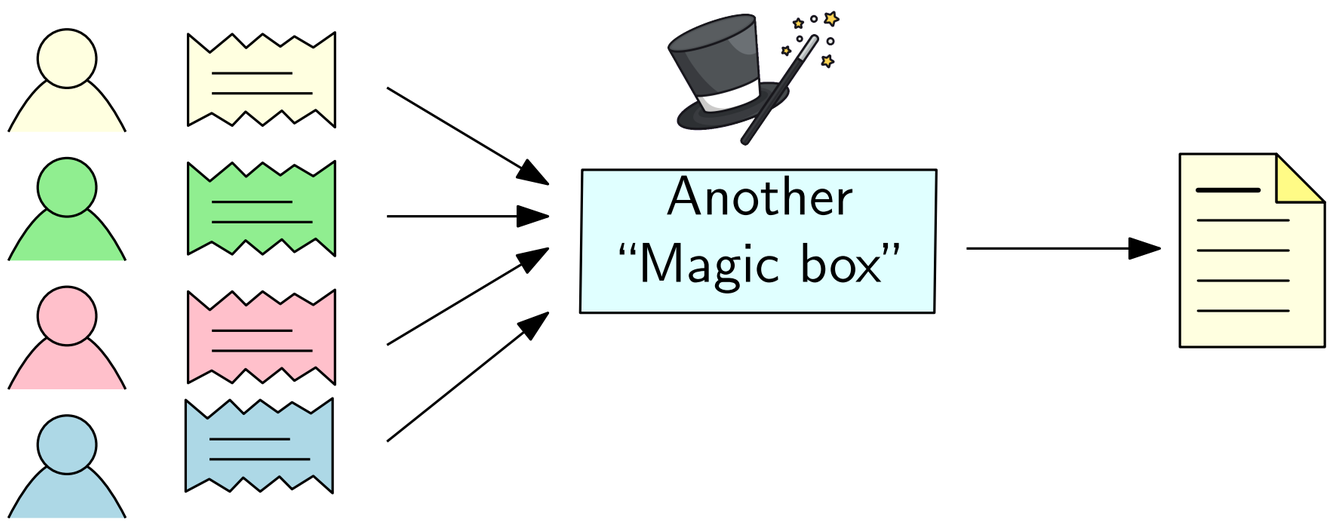

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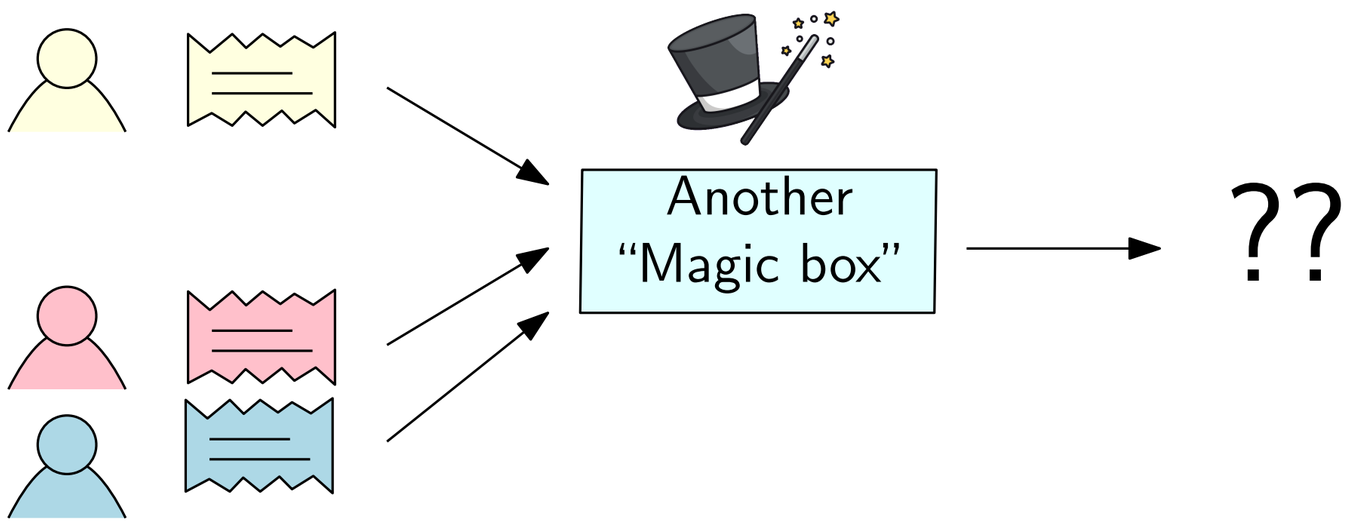

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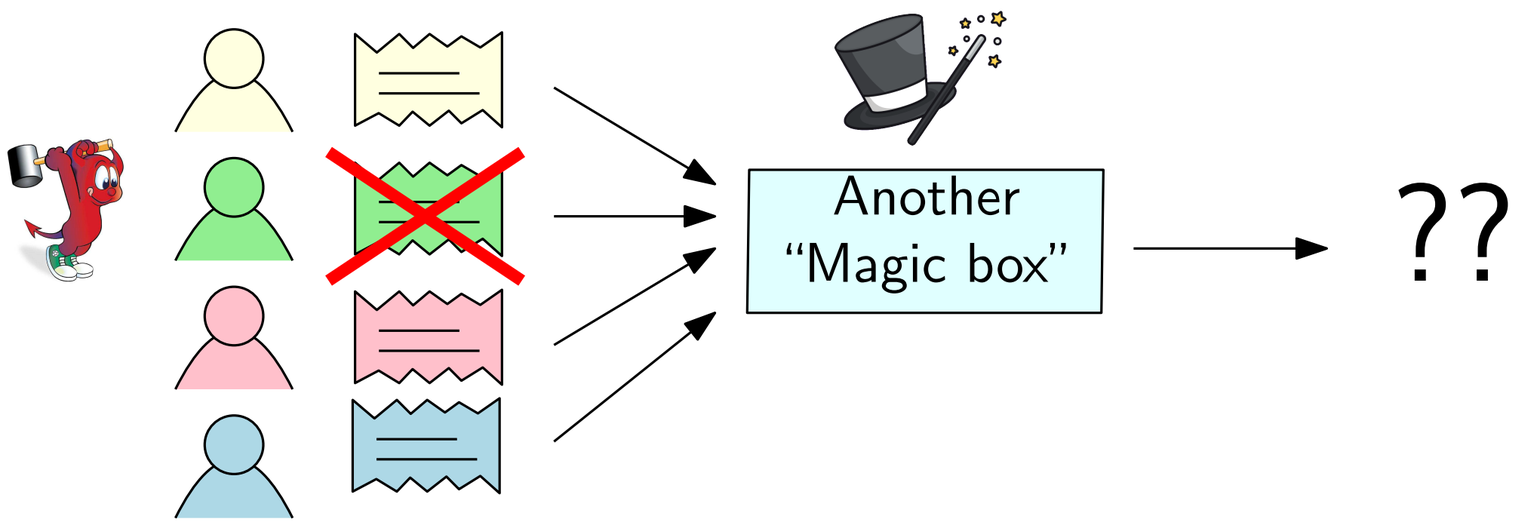

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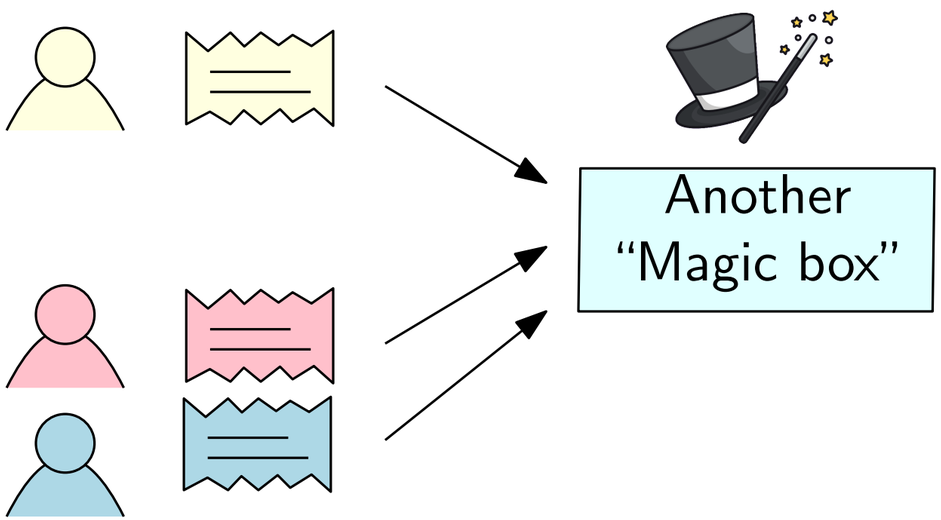

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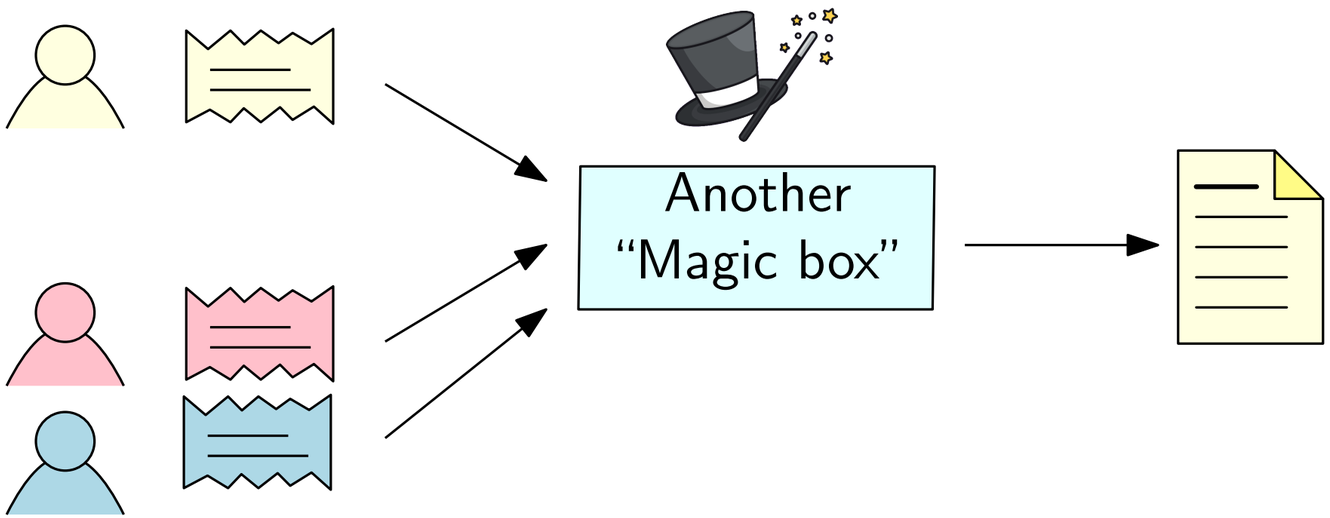

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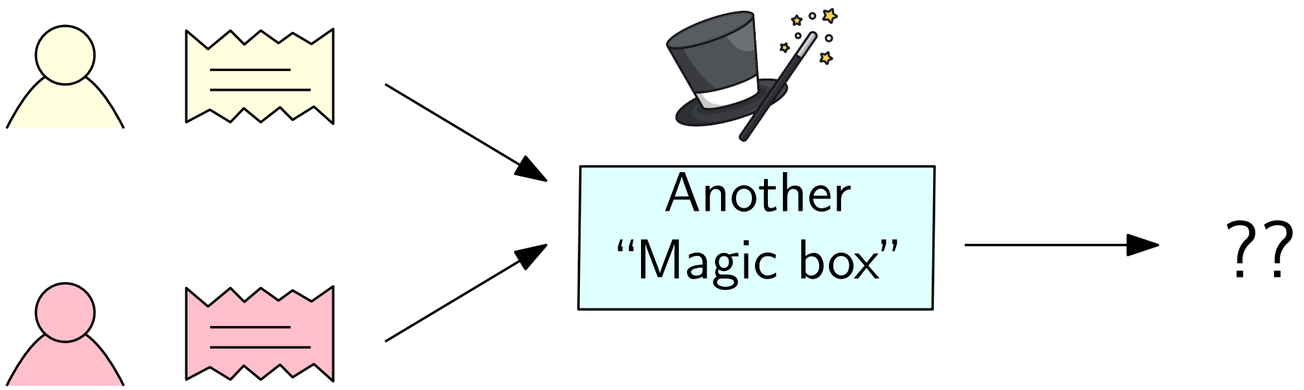

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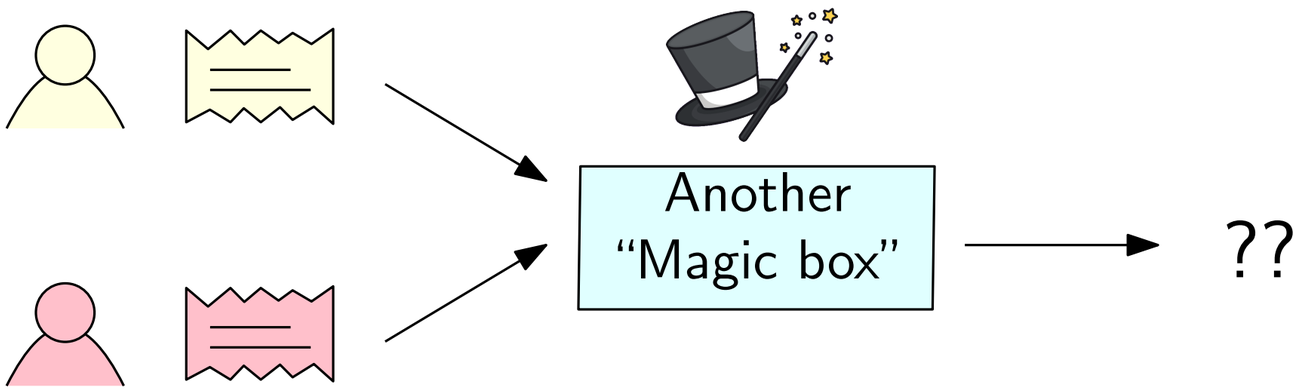
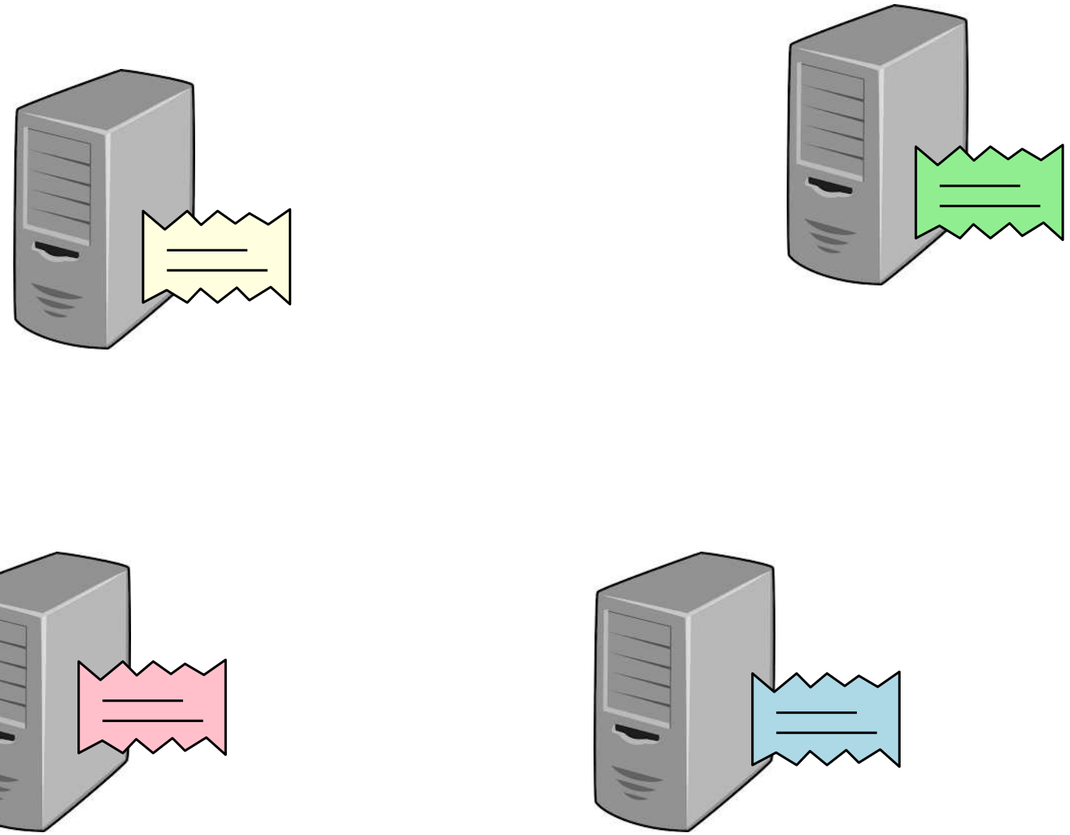


t-out-of-n threshold secret-sharing scheme

Secret Sharing

- Agents can be different servers connected over the Internet



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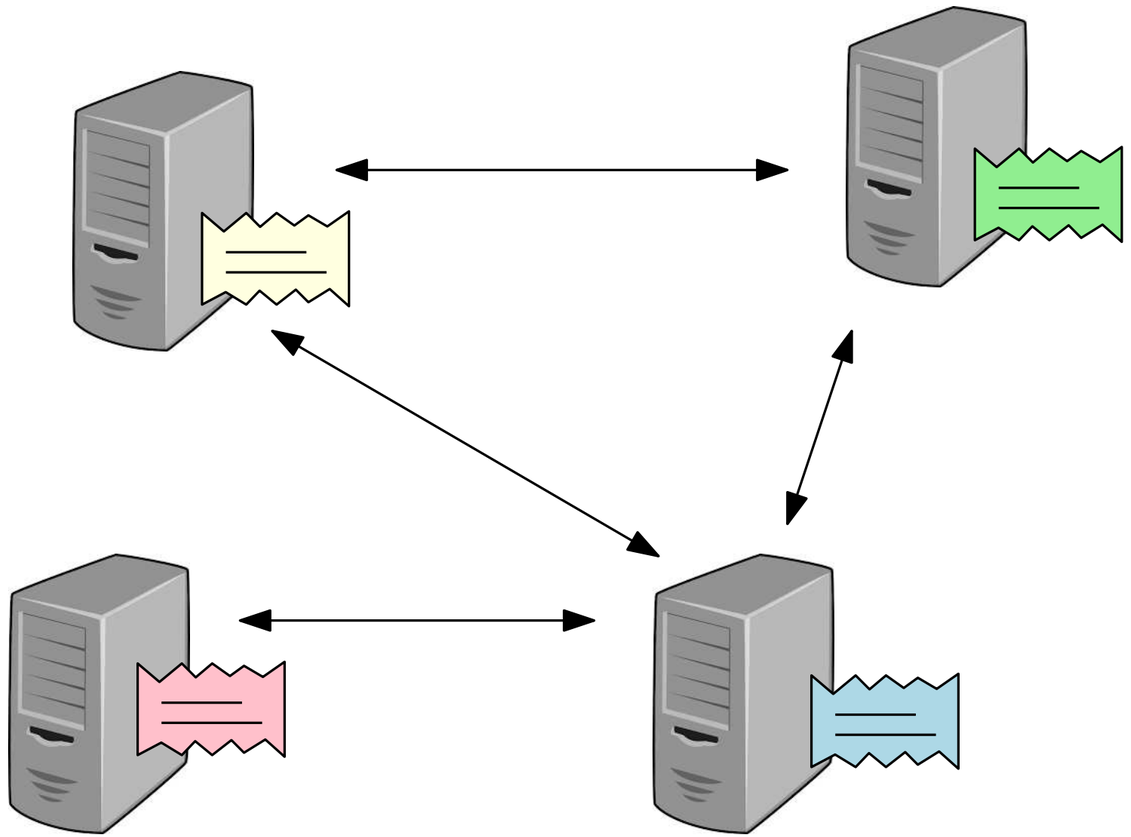

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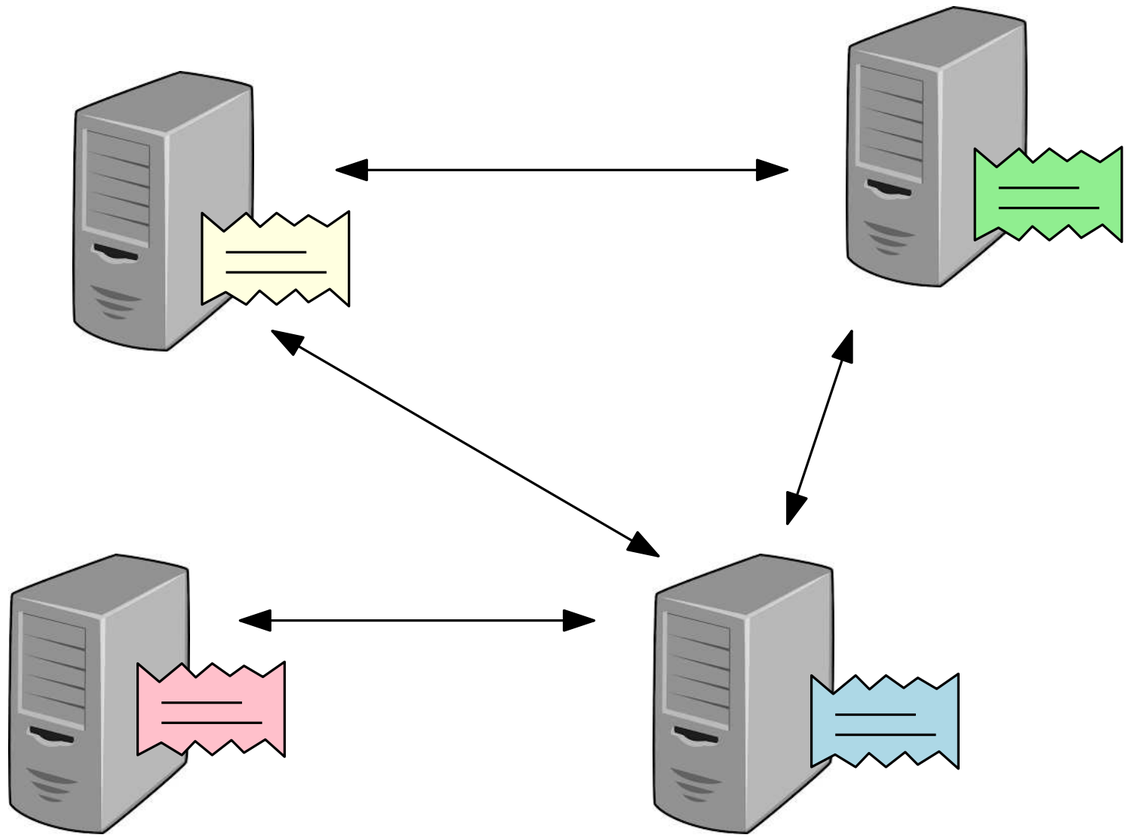

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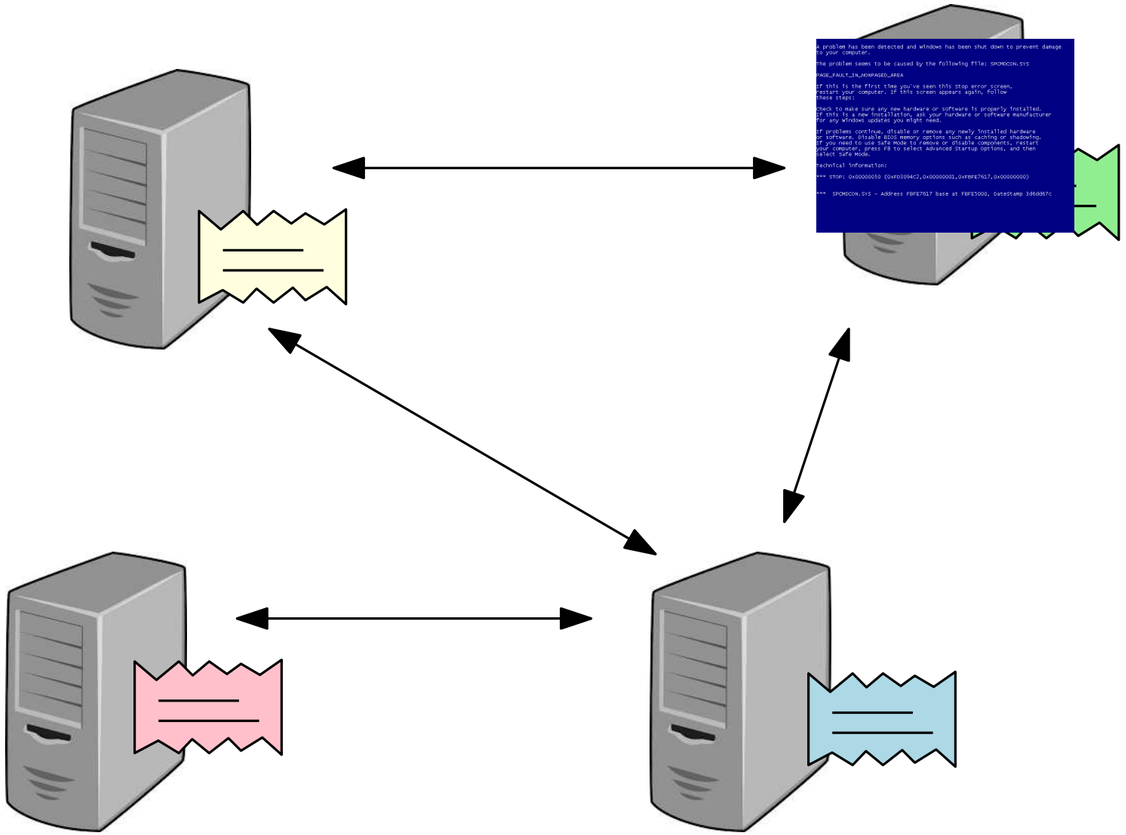

- The system remains secure if $< t$ servers are compromised
- The system remains operational (the secret can be recovered) if $\leq n - t$ servers are unavailable

DNSSEC

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

DNS Server

DNSSEC

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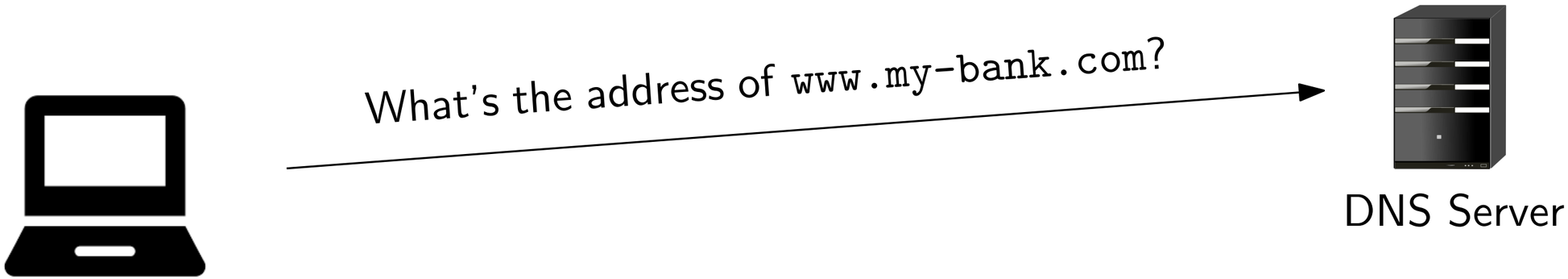

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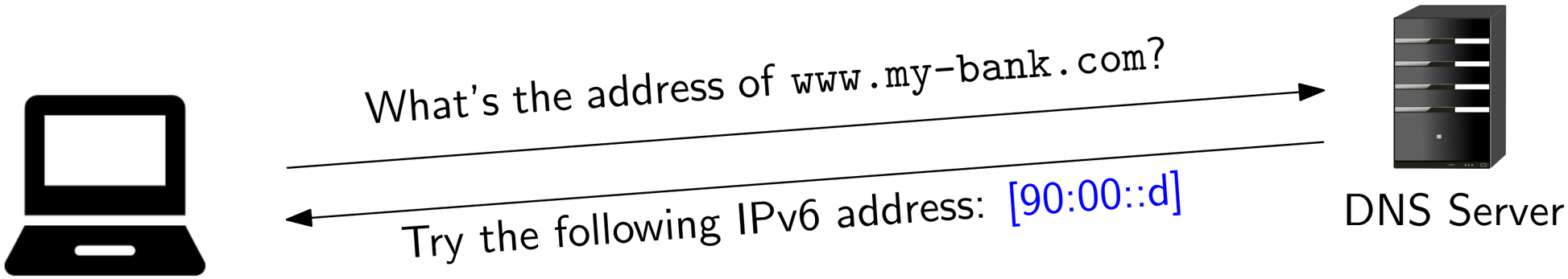

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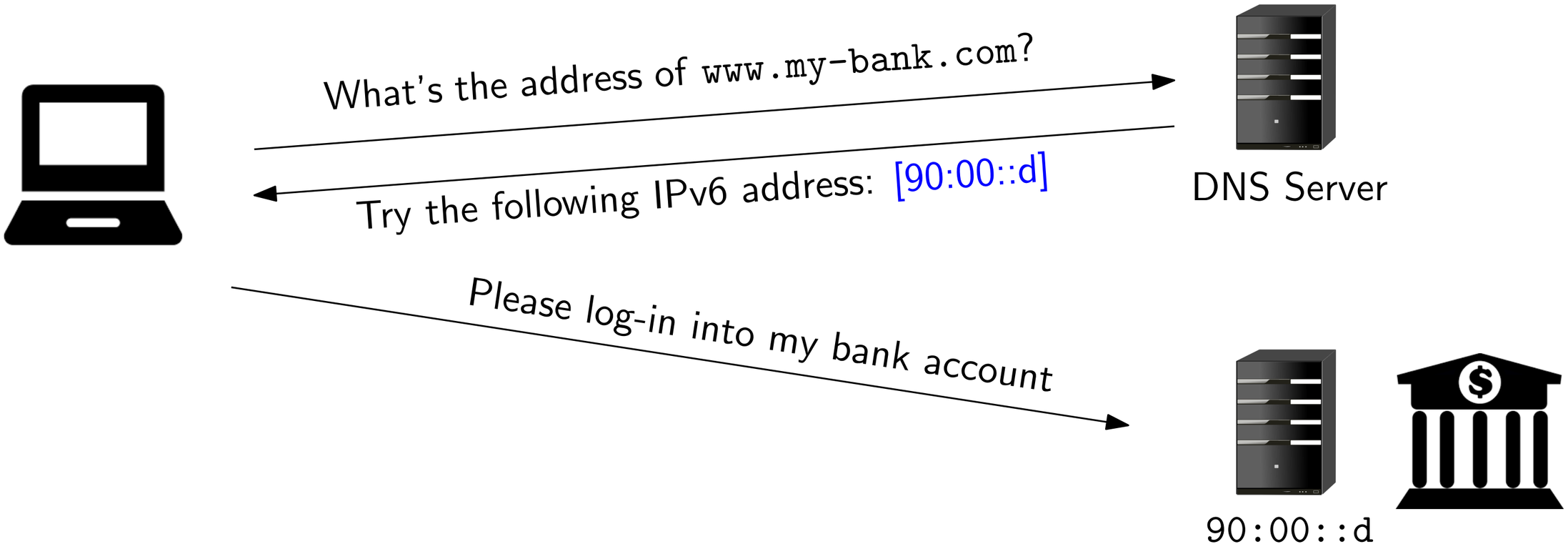

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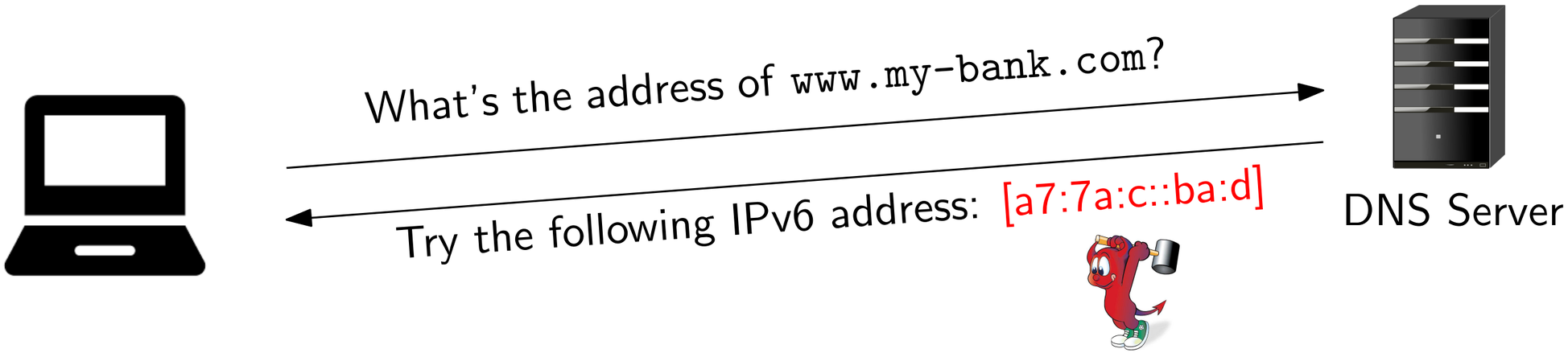

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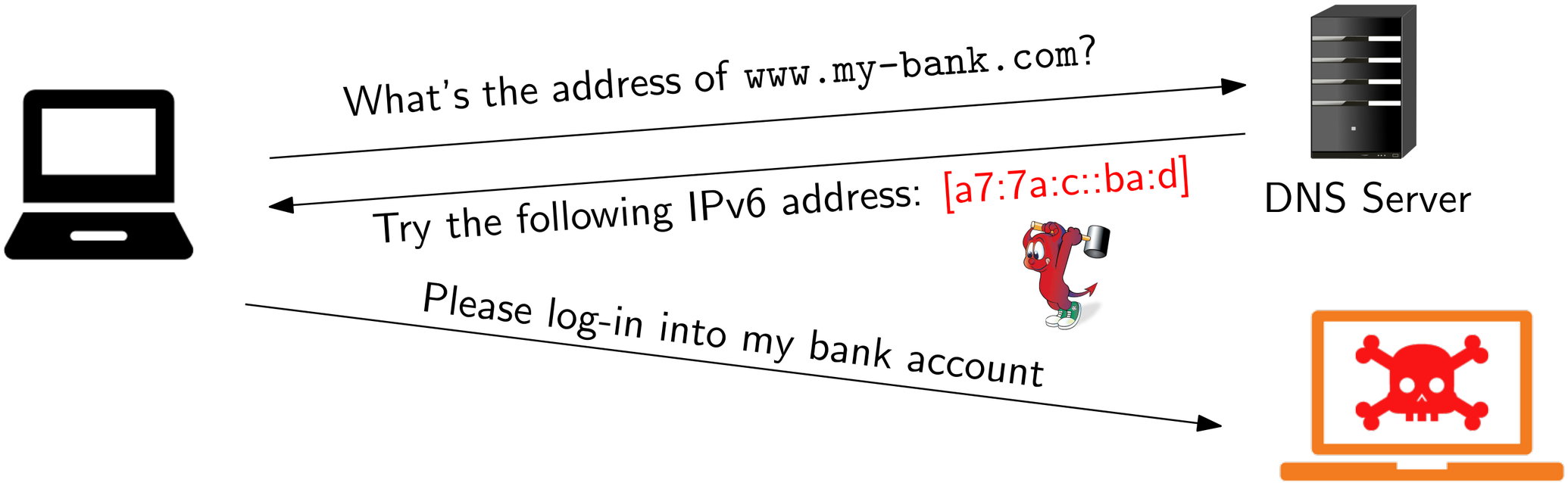

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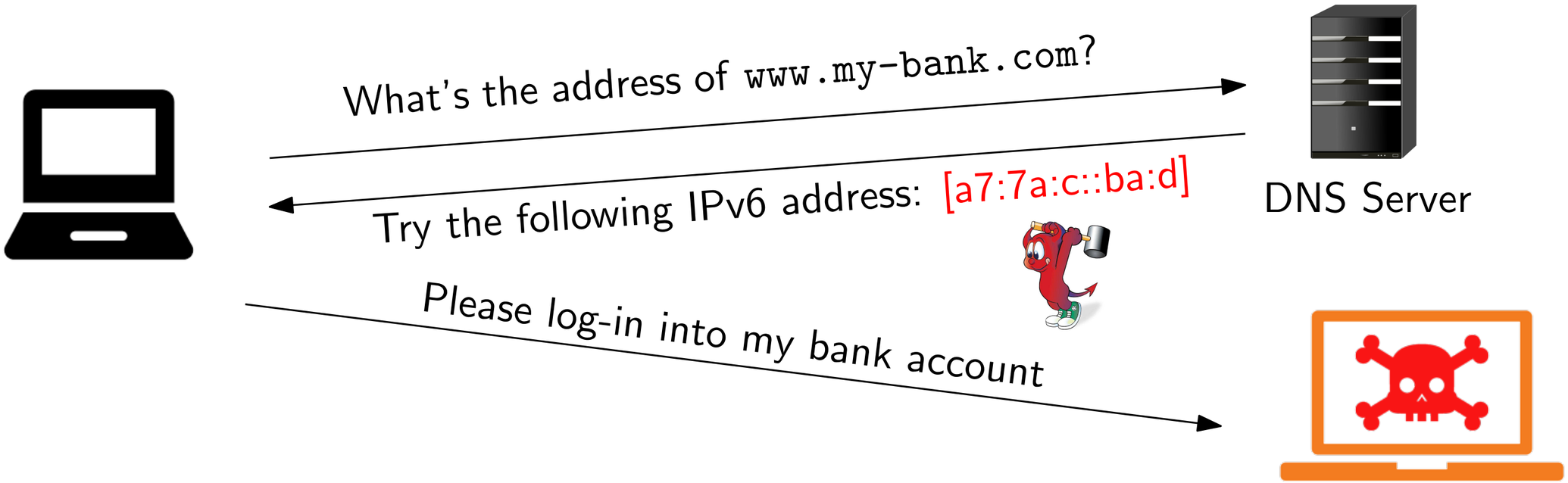

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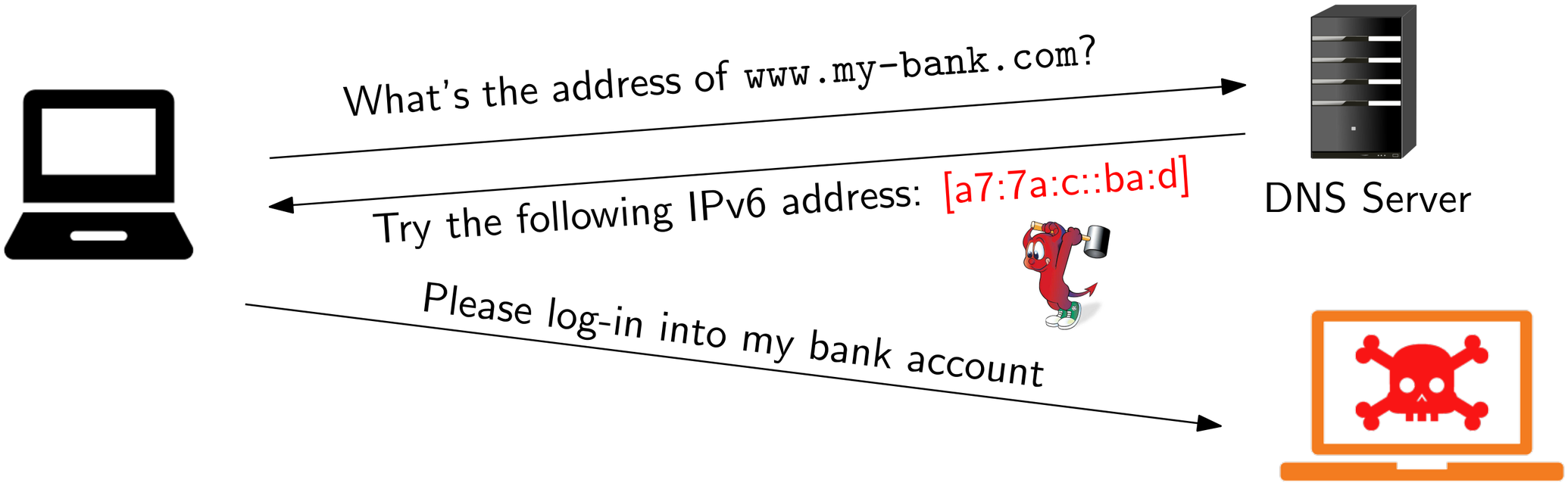

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Who can be trusted with the master cryptographic keys to the system?

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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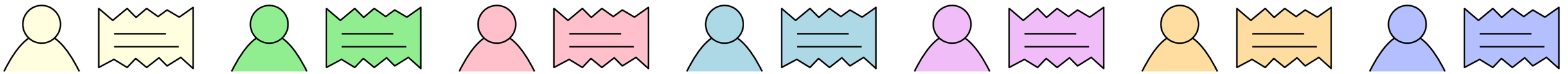

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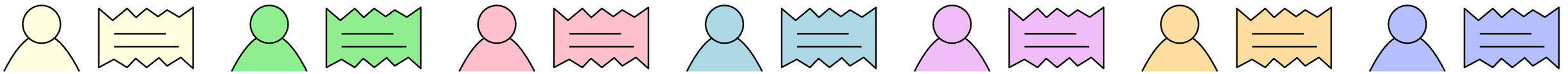
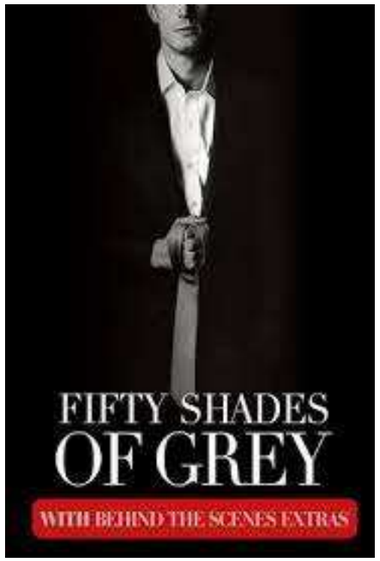


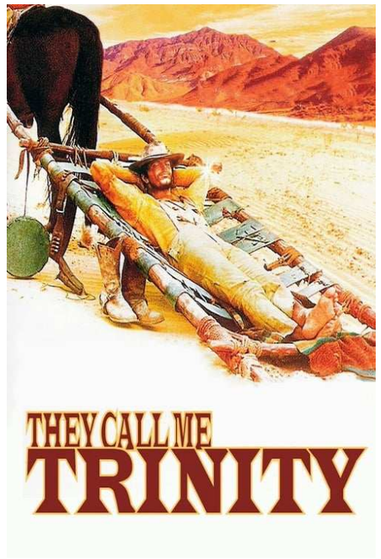
$n = 7$ $t = 5$

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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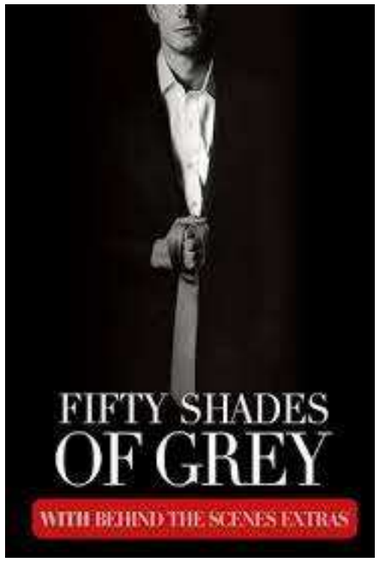

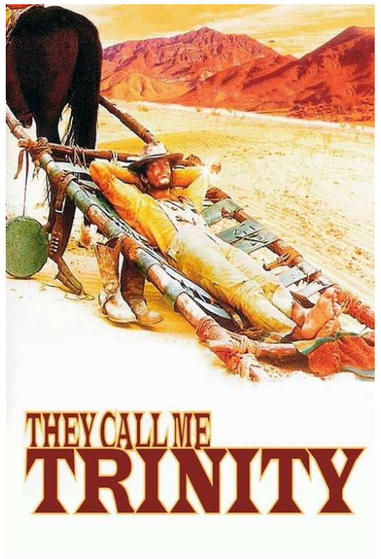

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However, they don't want to reveal that they like a movie unless the other person also likes it

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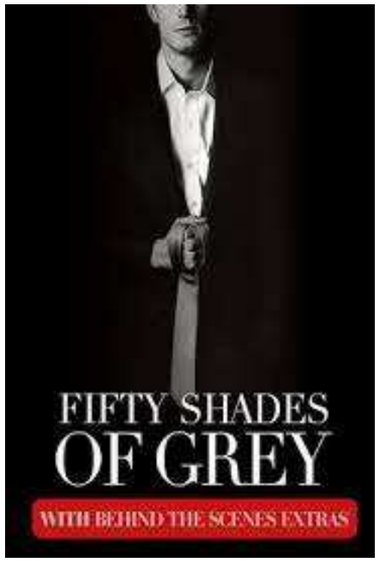

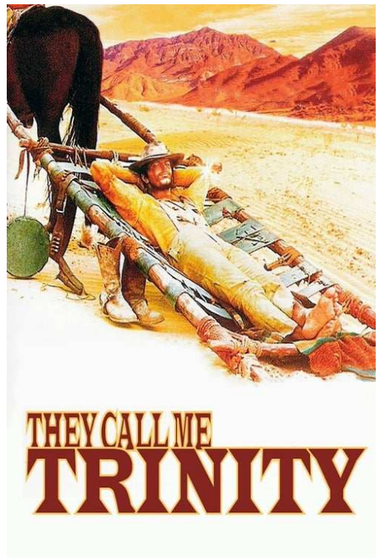

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- Voting is done using a secure **2-party computation protocol**

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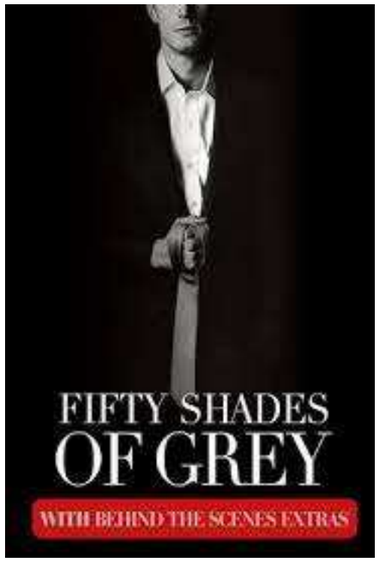

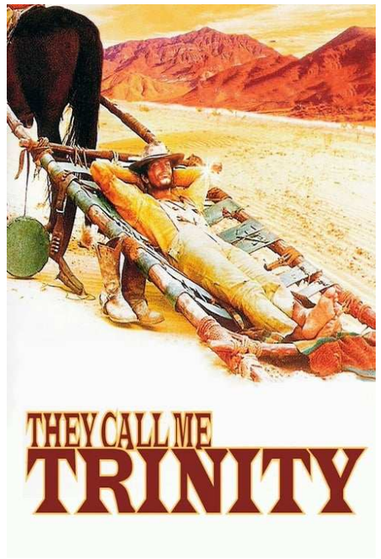

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Alice and Bob are **honest** (they follow the protocol) but **curious**

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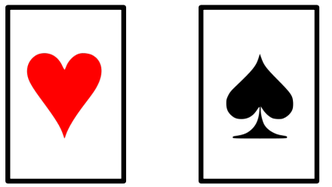
They will use some cards with two different faces, say hearts and spades



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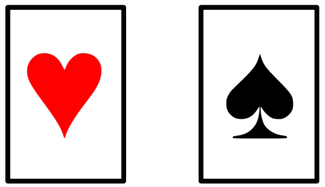
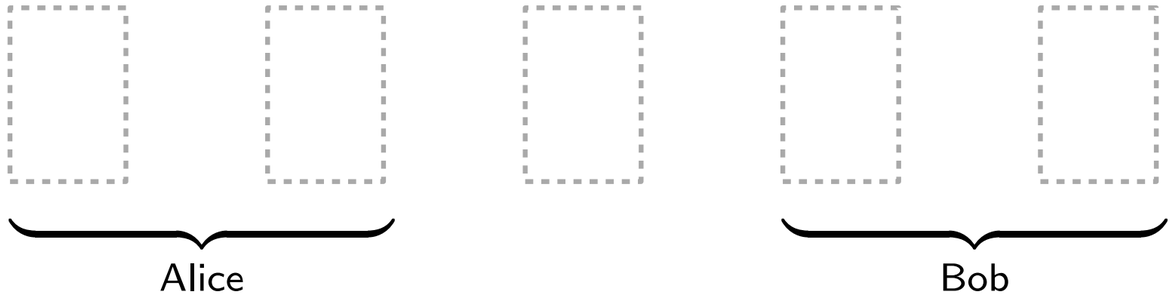


They will place 5 cards in a row on a table



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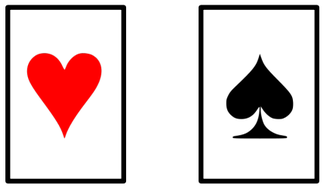

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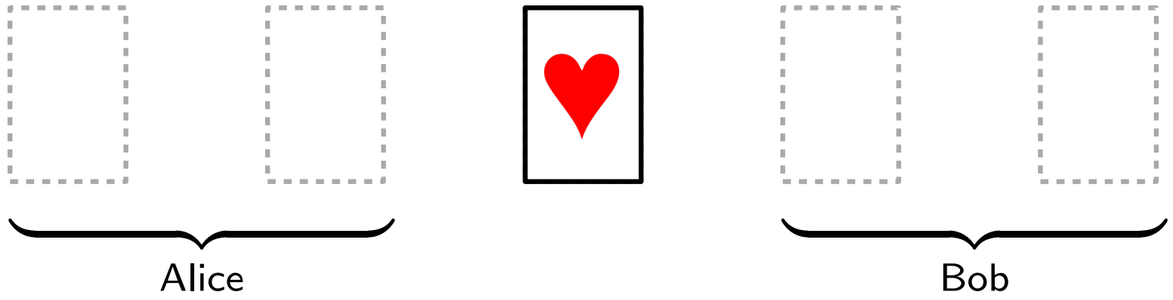

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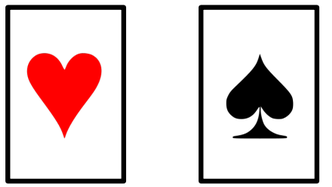

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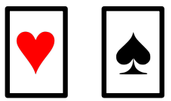
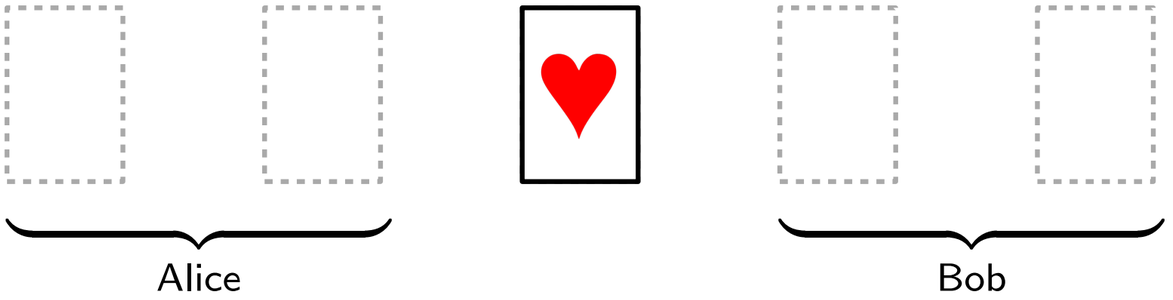
Each of Alice and Bob has a hearts card and a spades card





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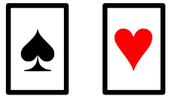
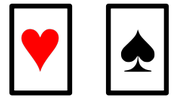
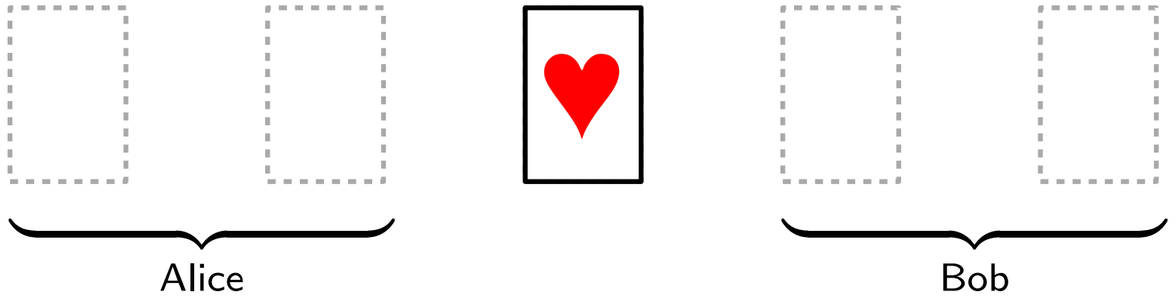
If Alice likes the movie, she will place her two cards **face down** in the order 

Otherwise she will place her two cards **face down** in the order 



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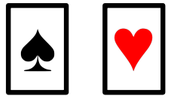
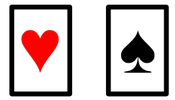
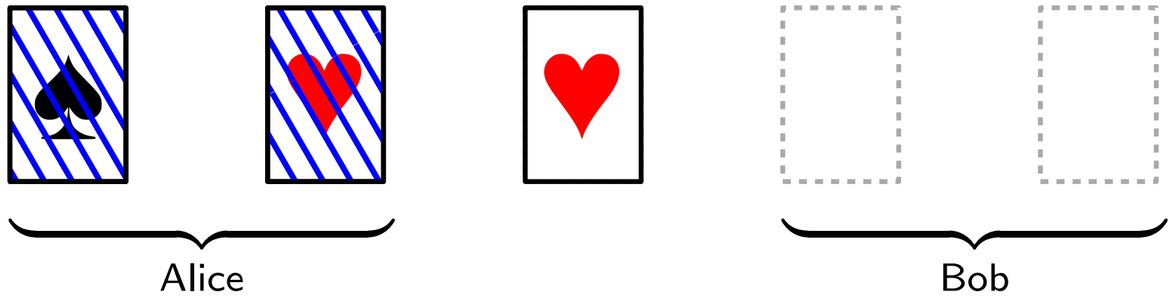
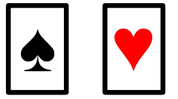
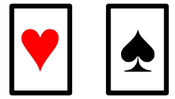
If Alice likes the movie, she will place her two cards **face down** in the order 

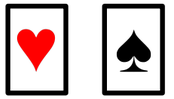
Otherwise she will place her two cards **face down** in the order 

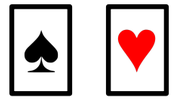


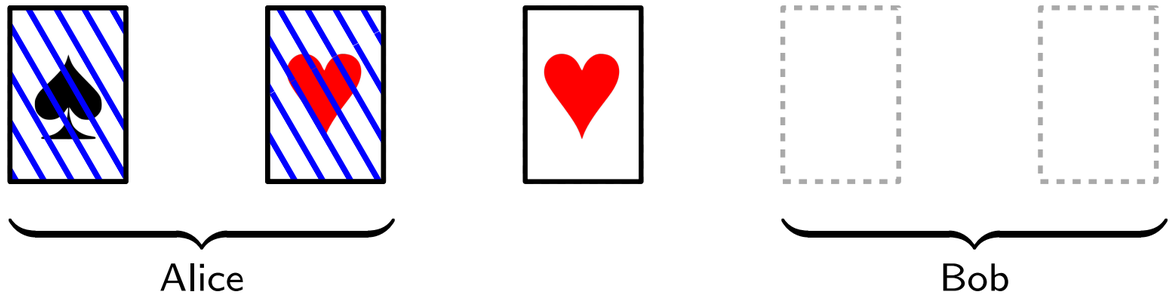
Choosing a movie with secret preferences

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

Otherwise she will place her two cards **face down** in the order 

If Bob likes the movie, he will place his two cards **face down** in the order 

Otherwise he will place his two cards **face down** in the order 



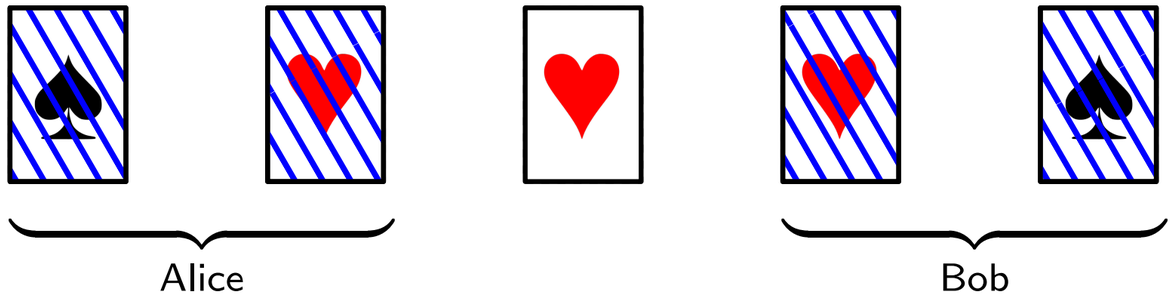
Choosing a movie with secret preferences

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

Otherwise she will place her two cards **face down** in the order ♥ ♠

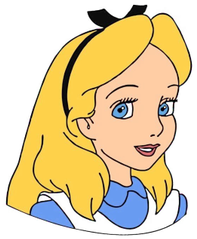
If Bob likes the movie, he will place his two cards **face down** in the order ♥ ♠

Otherwise he will place his two cards **face down** in the order ♠ ♥

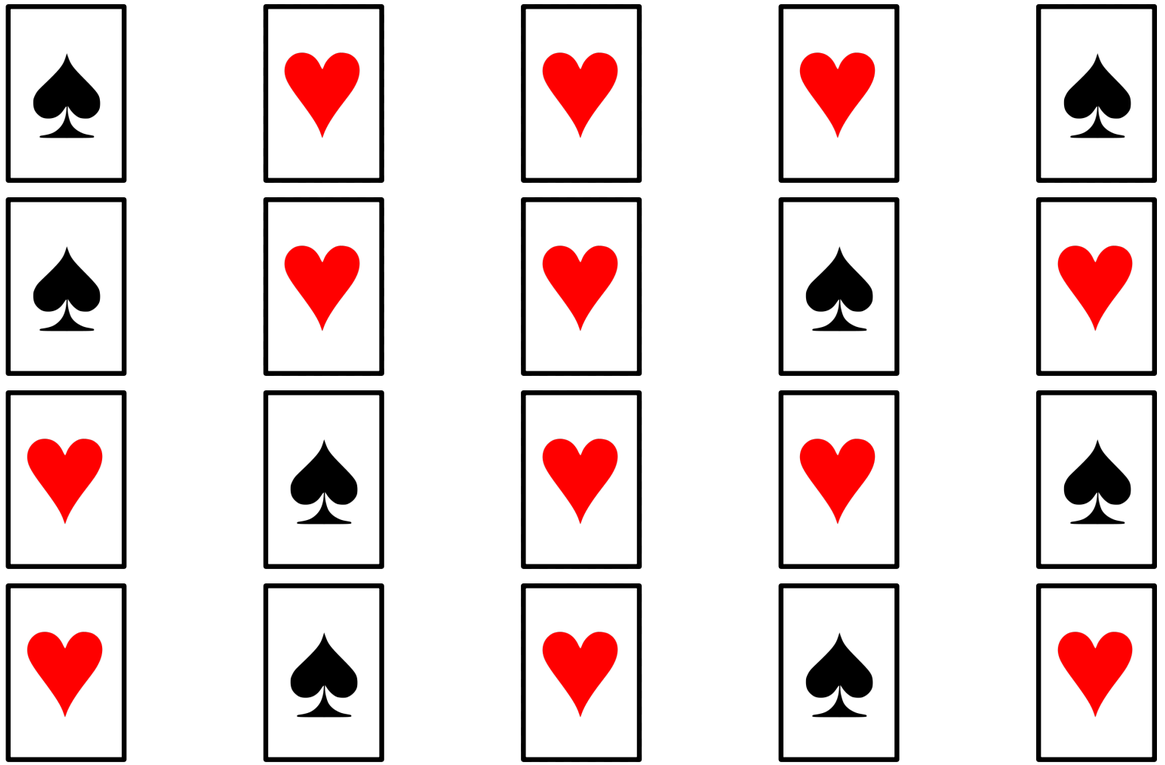


Choosing a movie with secret preferences

Possible configurations:



Yes	Yes
Yes	No
No	Yes
No	No



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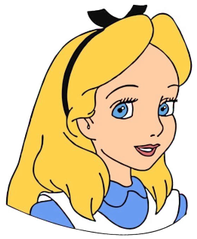
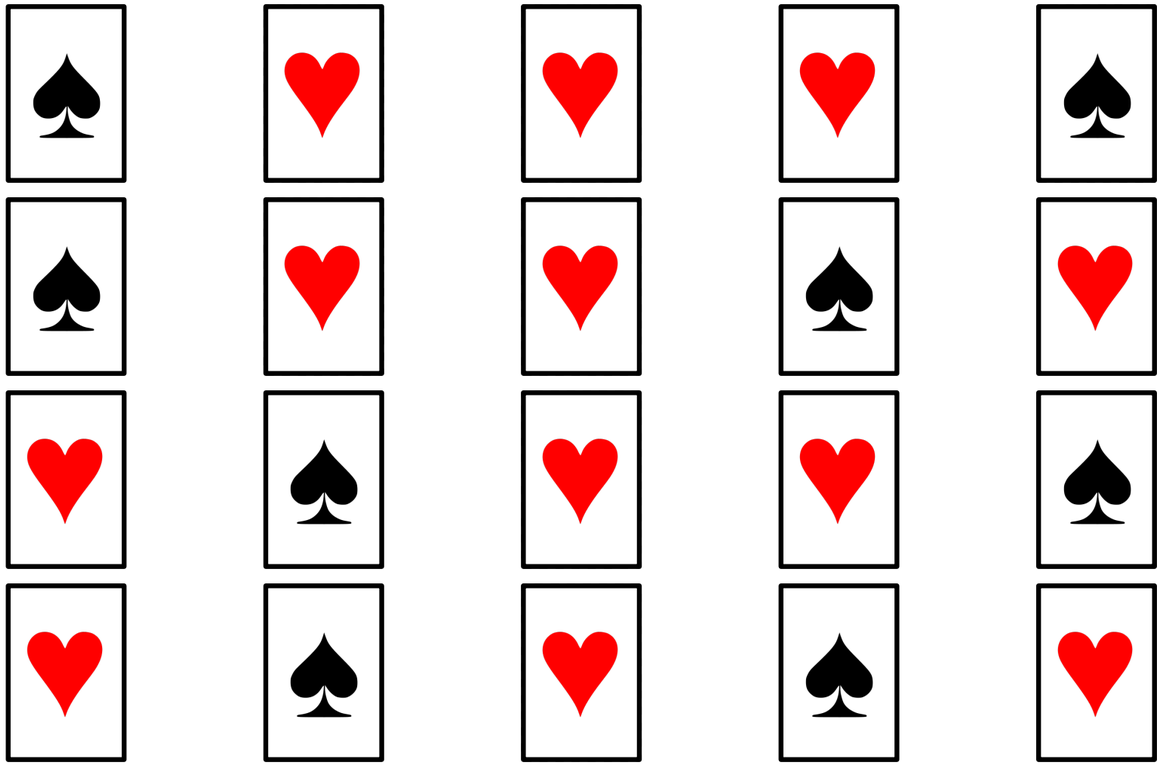


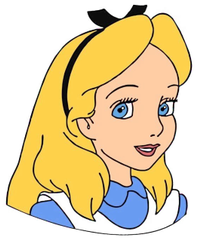
Yes	Yes
Yes	No
No	Yes
No	No



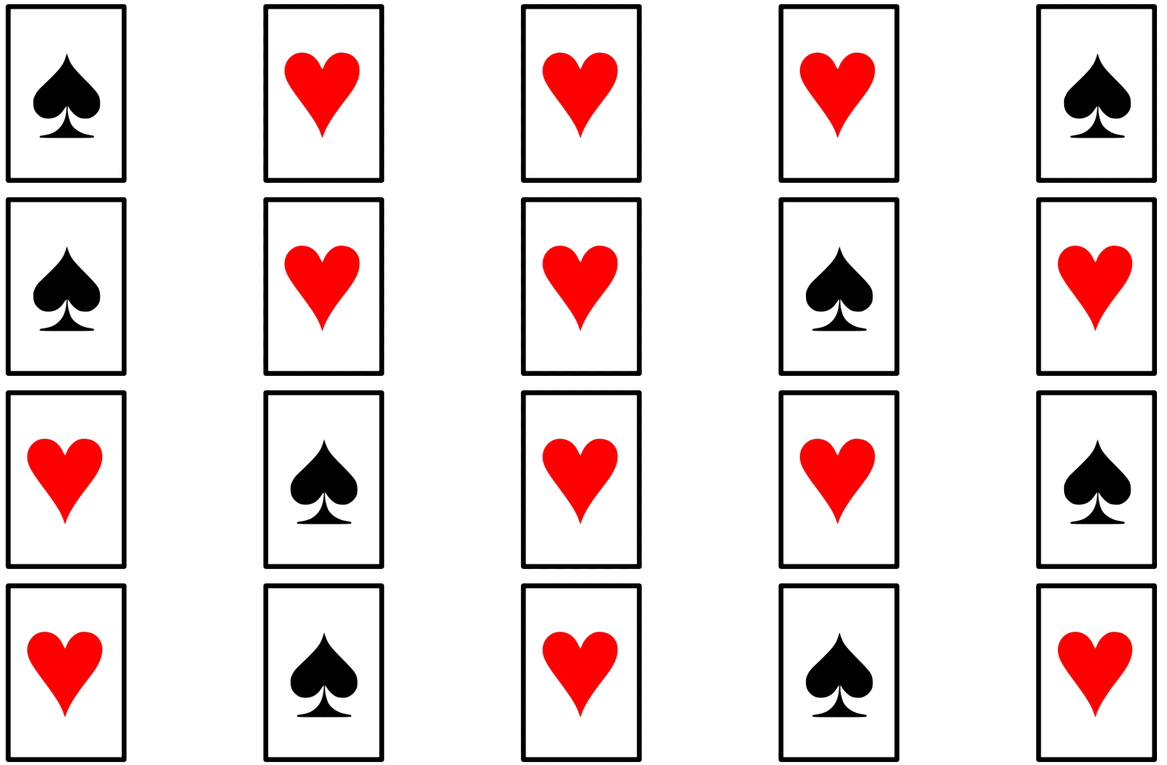
Rotations

Choosing a movie with secret preferences

Possible configurations:



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

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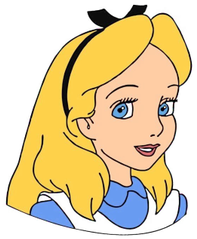
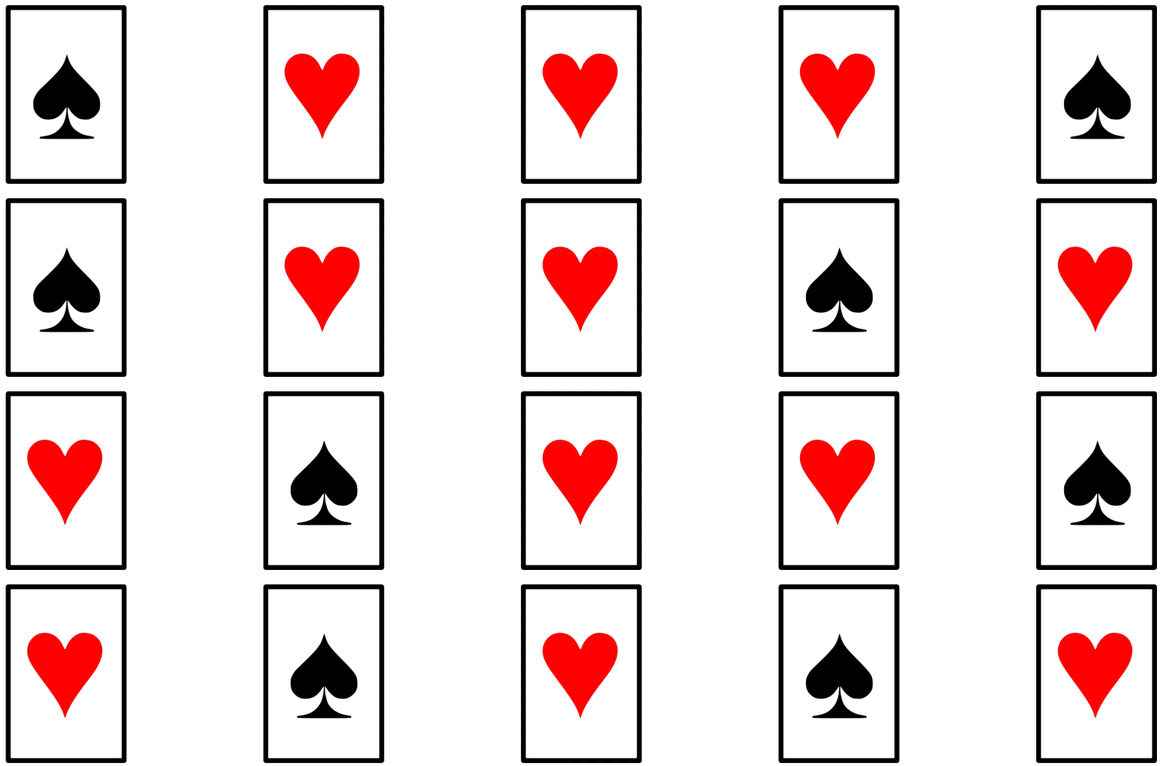


Yes	Yes
Yes	No
No	Yes
No	No

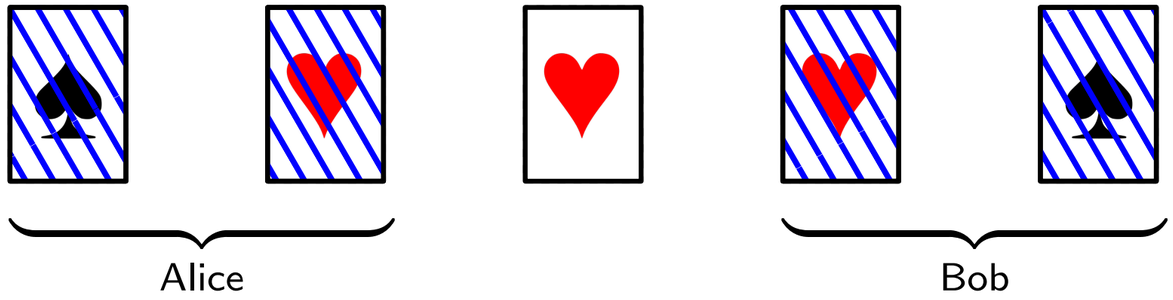


Rotations

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

This holds (in a modular sense) even if any rotation 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

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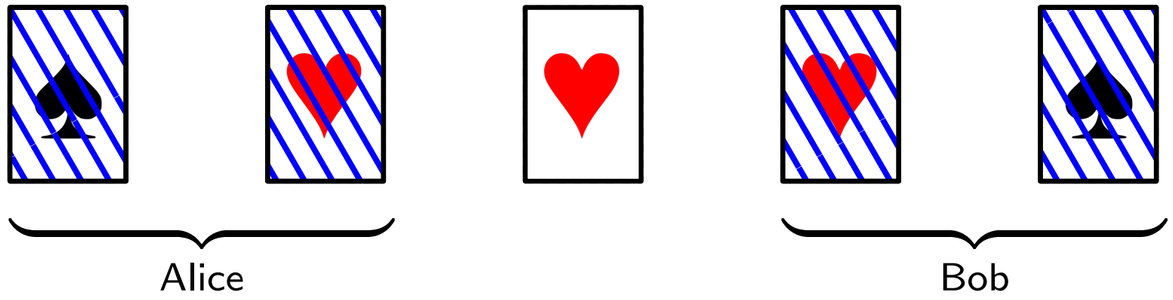
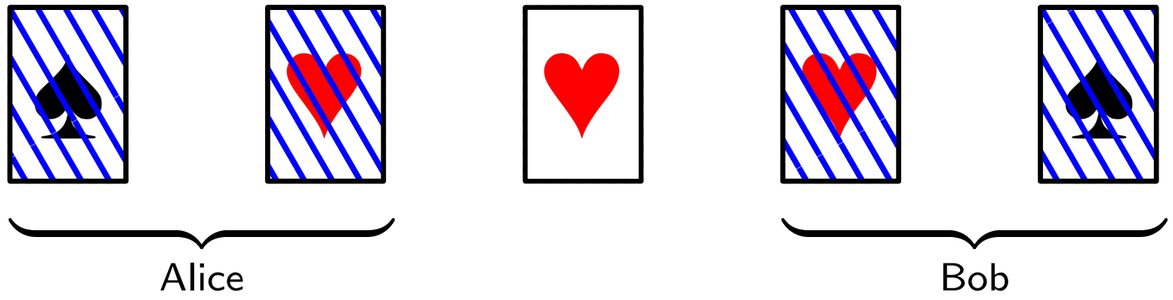


Alice and Bob pile up the cards, **all face down**, ensuring that their order is preserved

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

Choosing a movie with secret preferences



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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"

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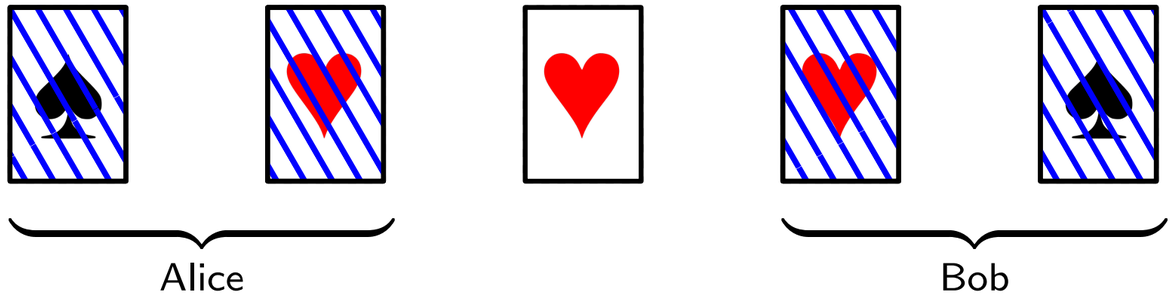

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Observation: If they end up not watching the movie, all possible "pass" configurations are equiprobable

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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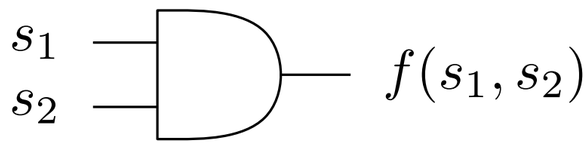

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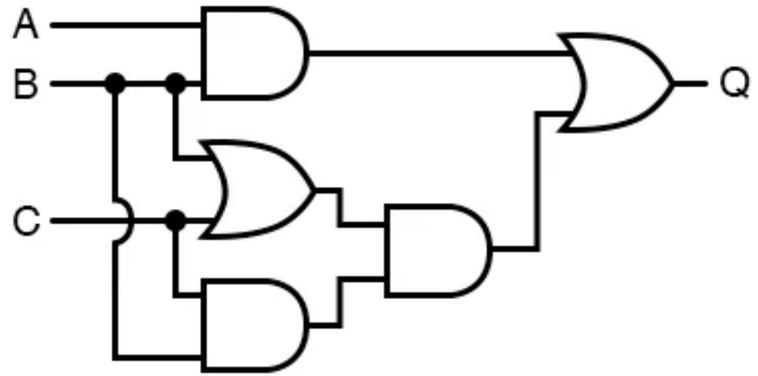

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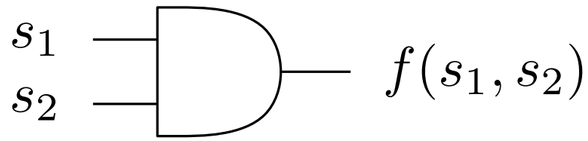


What about arbitrary circuits?

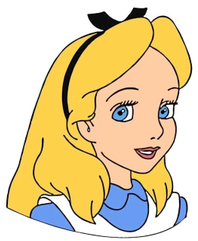
Zero Knowledge Proofs

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

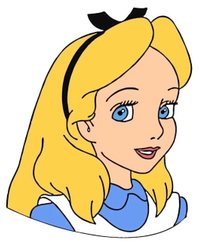
5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9



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

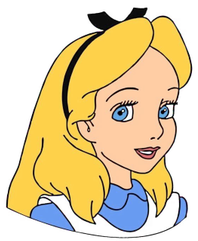


I know a solution to this Sudoku instance

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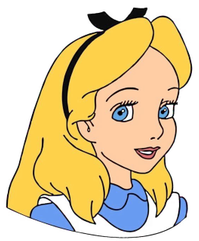

I don't want to reveal it to you

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
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7				2				6
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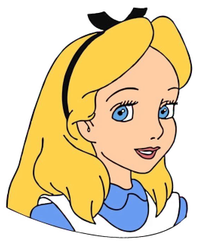
			4	1	9			5
				8			7	9



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
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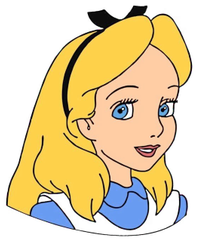

I can prove to you that I have a solution without revealing anything about it

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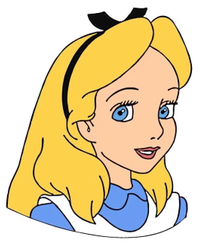

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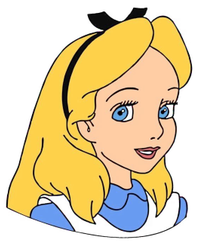
4	2	6	8	5	3	7	9	1
7	1	3	9	2	4	8	5	6
9	6	1	5	3	7	2	8	4
2	8	7	4	1	9	6	3	5
3	4	5	2	8	6	1	7	9

5	3			7				
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

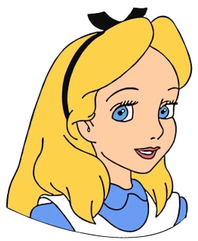
Zero Knowledge protocol

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!

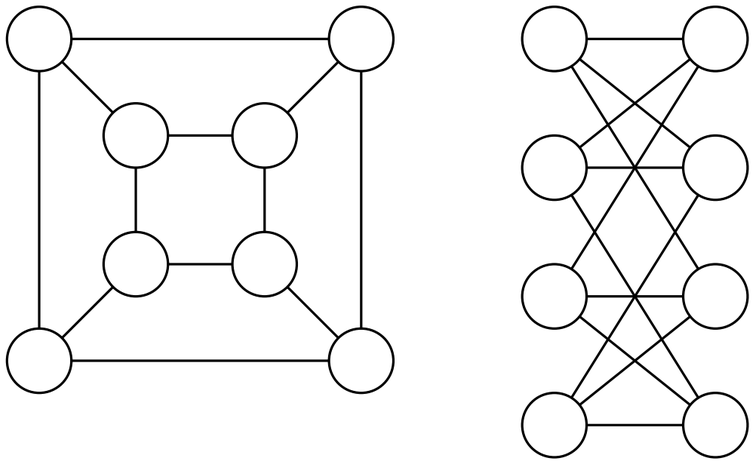
Zero Knowledge Proofs

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

Even if I definitely know she has a solution, somehow I have no way of proving that

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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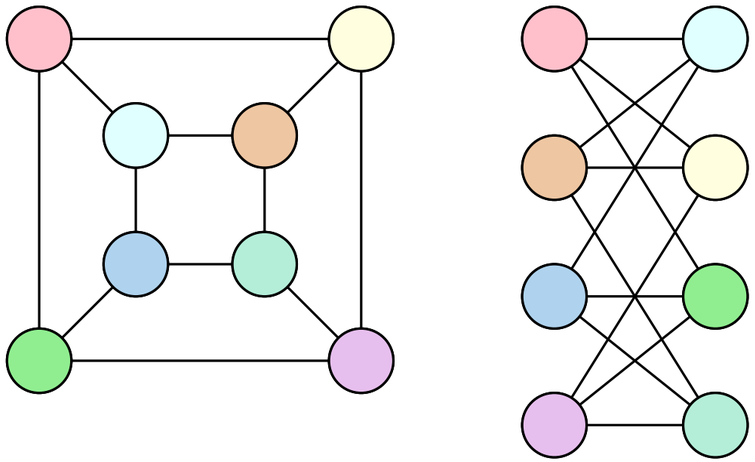

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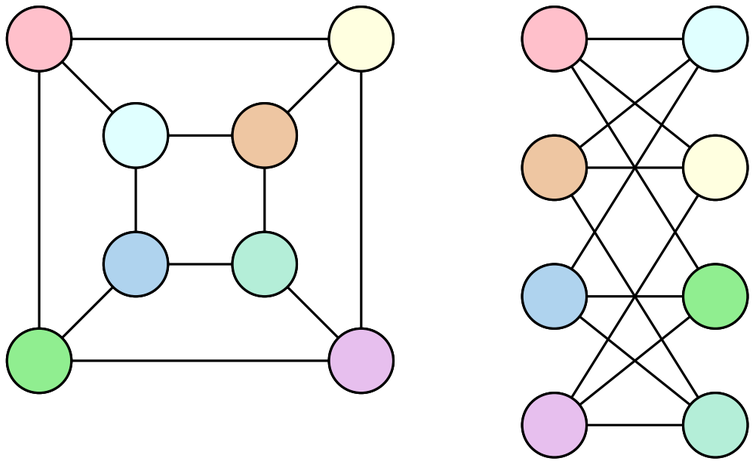

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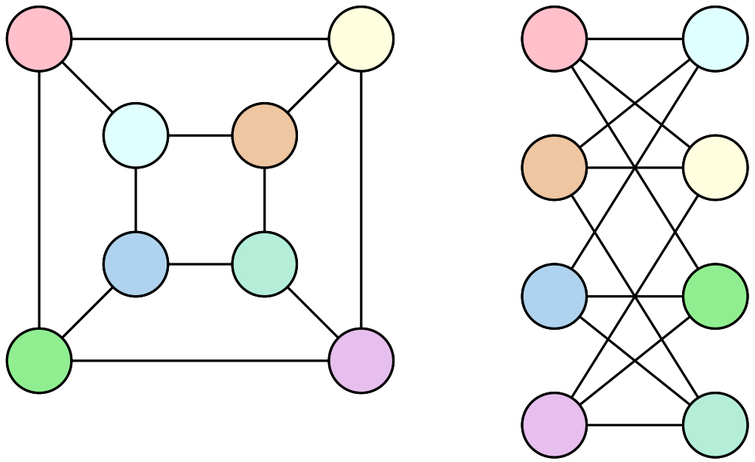

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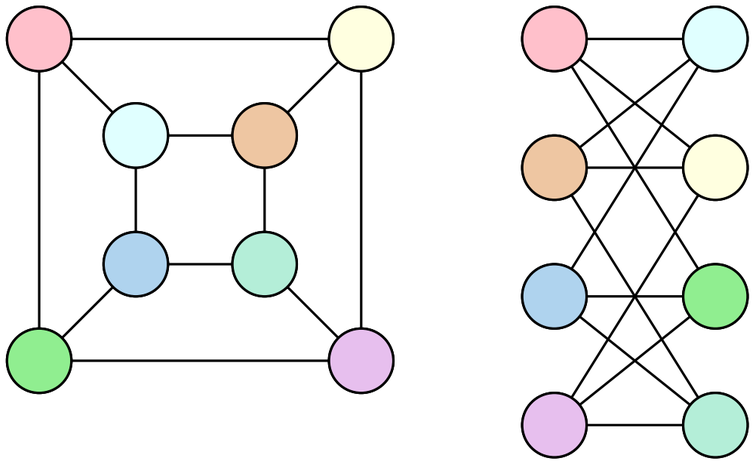

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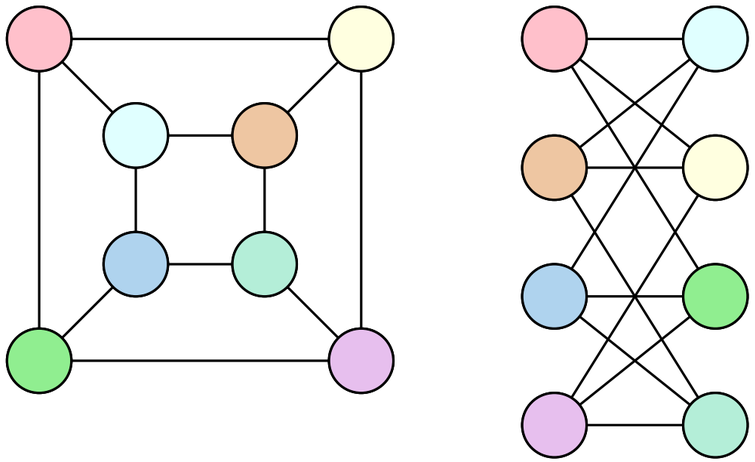

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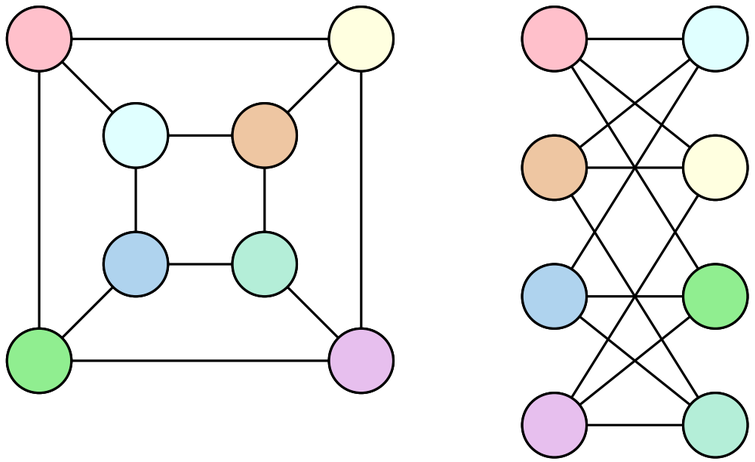

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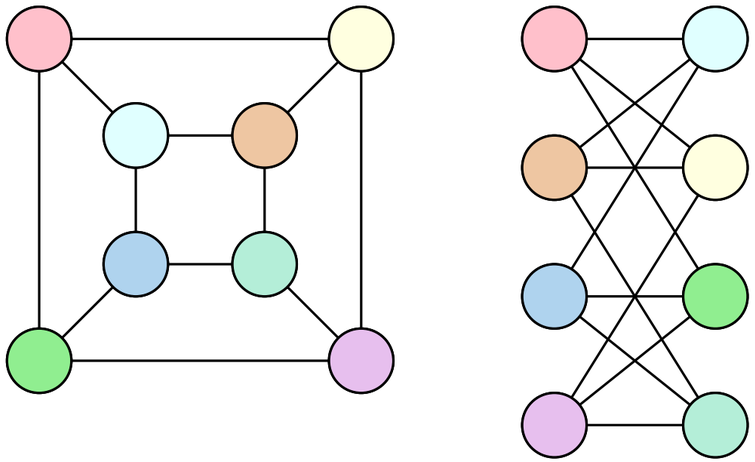

Alice knows an isomorphism π between G_1 and G_2

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

Graph isomorphism problem

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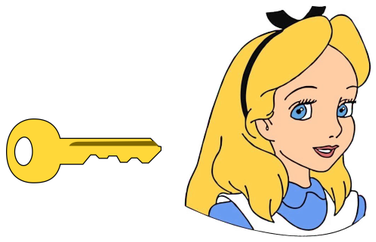
Basic definitions

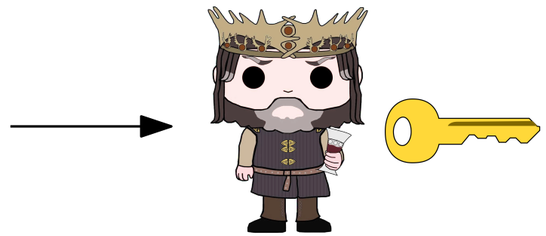
Types of cryptography

There are two broad settings in which encryption is used:

The **private-key** or **symmetric** setting:

- Alice and Bob have a **shared, secret** key





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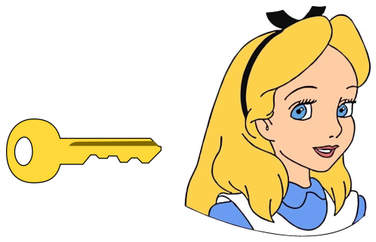

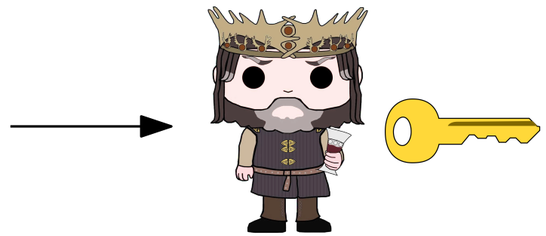

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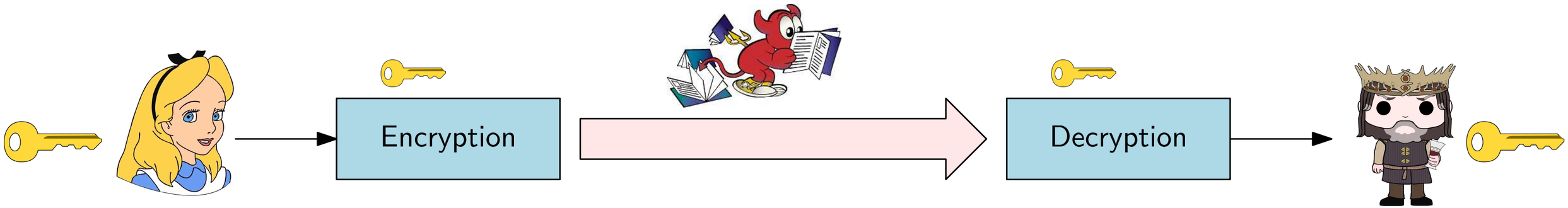

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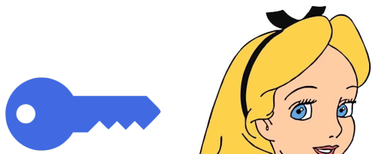

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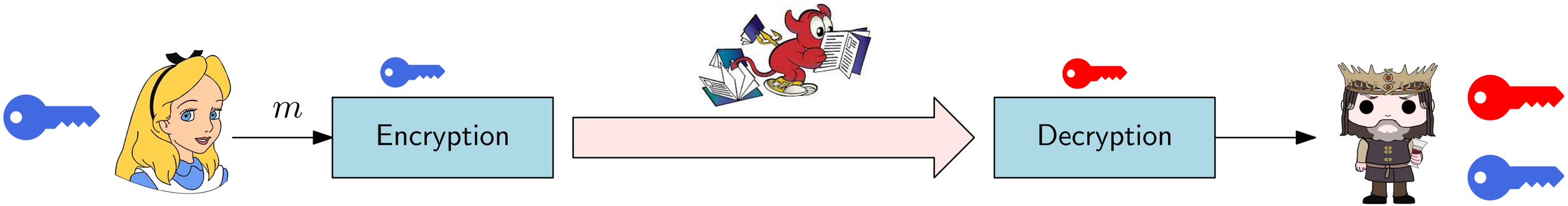

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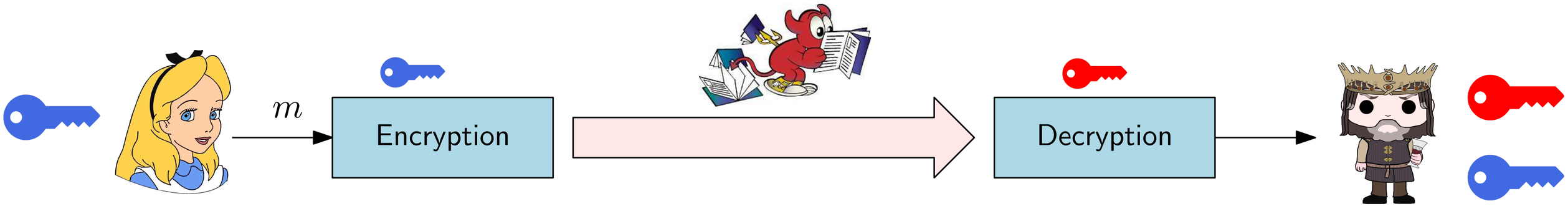

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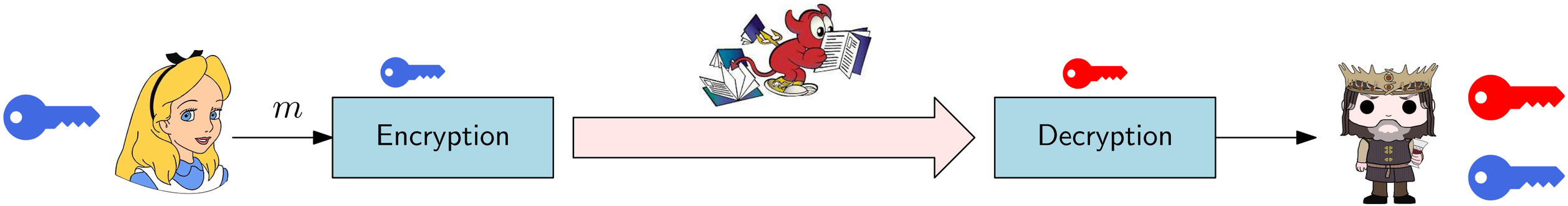

For now, we will only be concerned with private-key cryptography

Private-key cryptography

A private-key encryption scheme consists of three algorithms:

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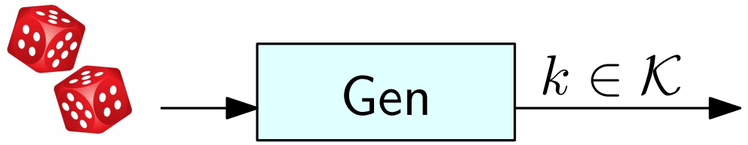

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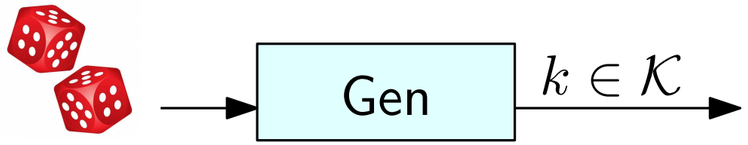

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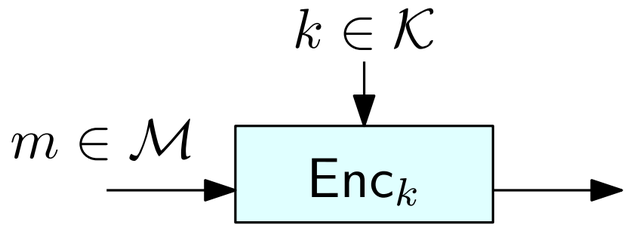

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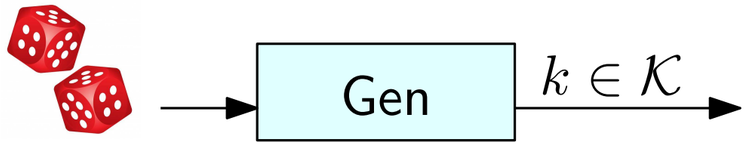

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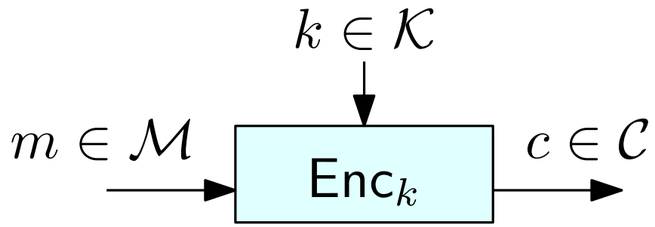

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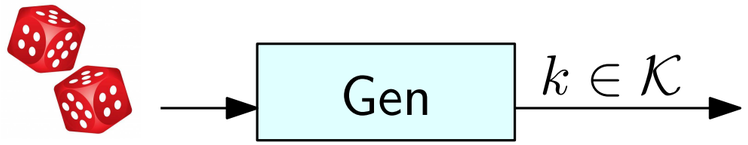

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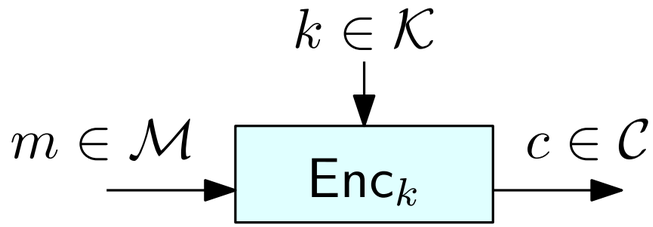

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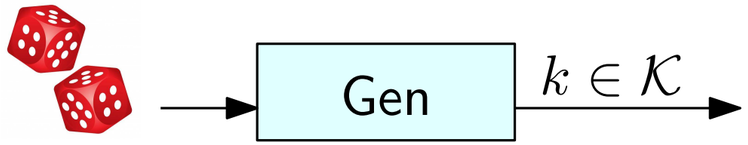

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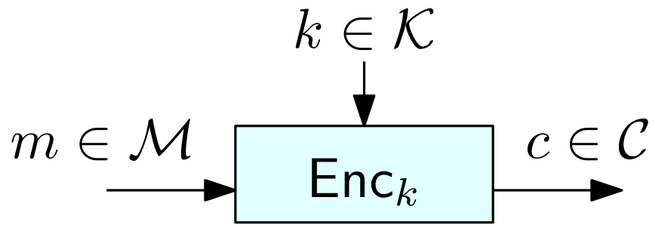

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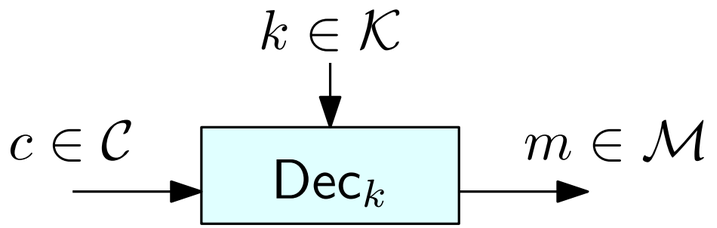

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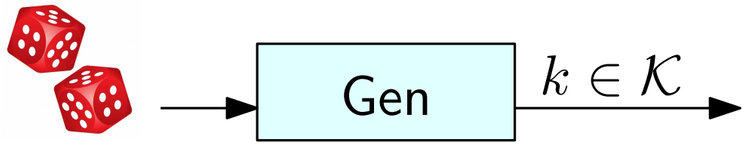

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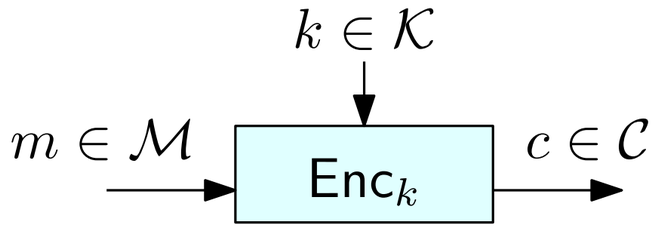

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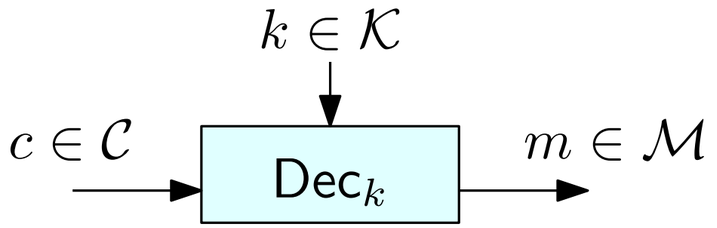

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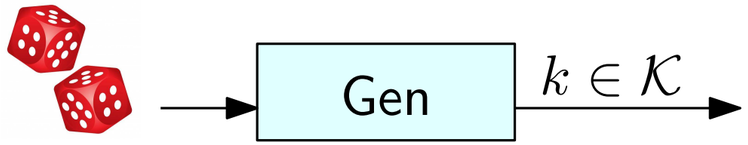

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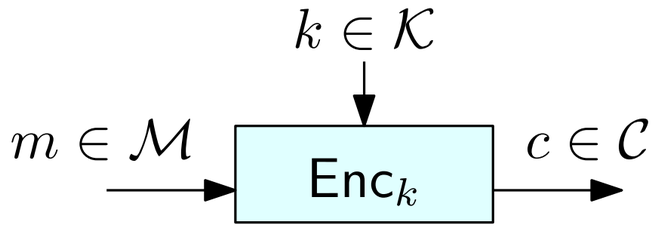

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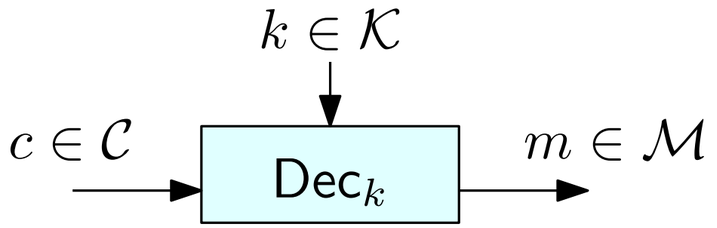

Perfect correctness: $\forall k \in \mathcal{K}, m \in \mathcal{M}$ if c can be output by $\text{Enc}_k(m)$ then $\text{Dec}_k(c) = m$

Kerckhoffs' principle

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

No security through obscurity

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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)