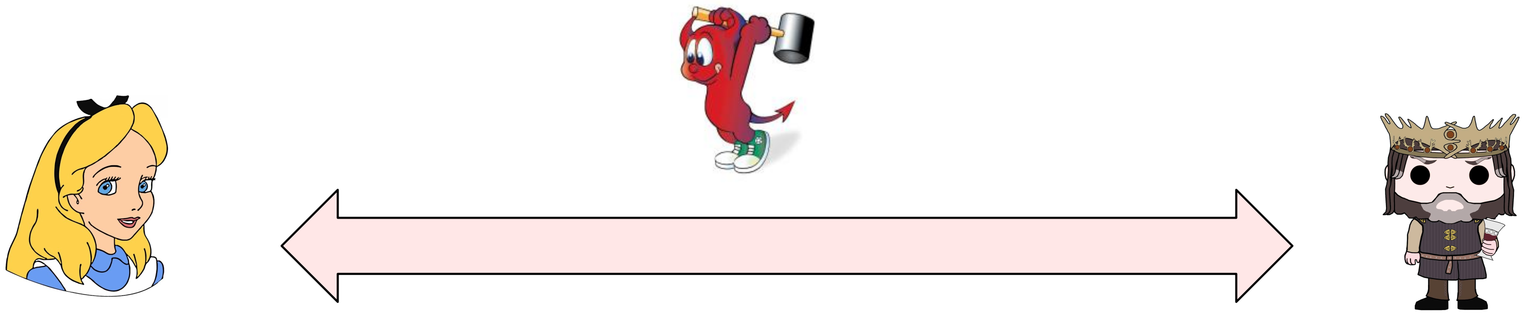
Reminder: Passive vs Active Attacks

We are now considering **active** attacks:

- The attacker has full control over the channel
- Can alter the message contents
- Can drop messages
- Can forge new messages



Reminder: Secrecy vs Integrity

There are two important guarantees that we would like to achieve against an active adversary 

Secrecy:

- This is what we have been concerned with so far.
- The adversary should not be able to (easily) learn (any information about) the plaintexts

Integrity (& Authentication):

- The adversary is not able to tamper with the messages
- The message originated from the intended party
- The message has not been modified in transit

Integrity and Secrecy are **orthogonal** concerns

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Secrecy:

Secrecy against active adversaries?

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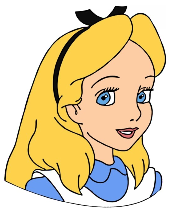
Reminder: Malleability of OTP

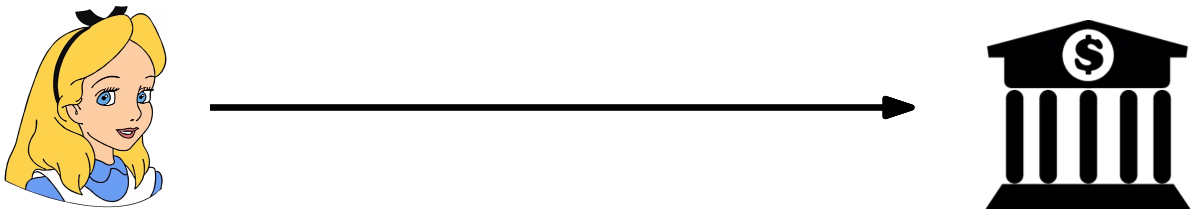
- Alice buys an item from the adversary for 5.20€
- Alice makes a wire transfer from her bank's website



Reminder: Malleability of OTP

- Alice buys an item from the adversary for 5.20€
- Alice makes a wire transfer from her bank's website
- The bank website sends a message of the form
  PAY <RECIPIENT_IBAN> <AMOUNT> to the bank's backend

$$m = \underbrace{\texttt{010100000100000101011001}}_{\texttt{PAY}}\underbrace{\texttt{01001001}\ldots\texttt{00110010}}_{\texttt{IBAN}}\underbrace{\texttt{0000000100000100}}_{\texttt{AMOUNT (520)}}$$



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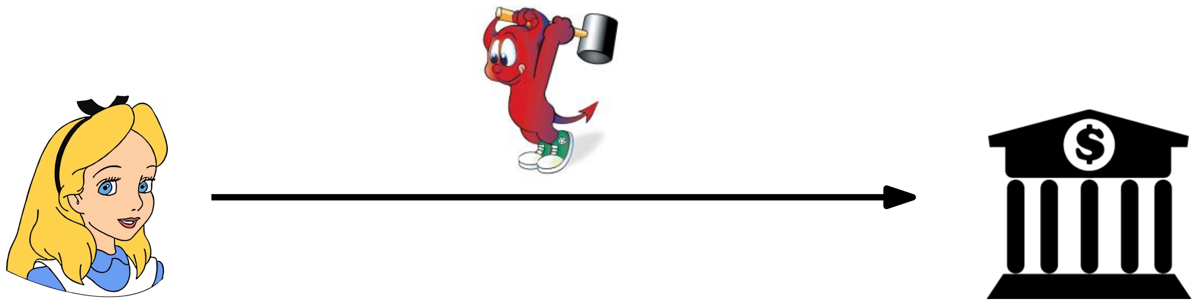
- The message is encrypted with a one-time pad



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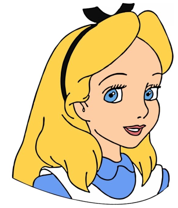

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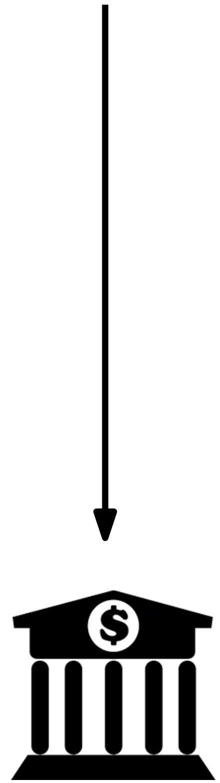

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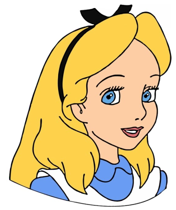

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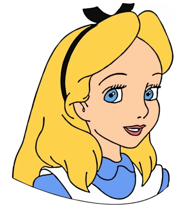

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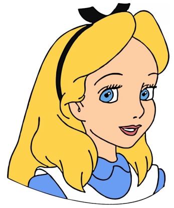

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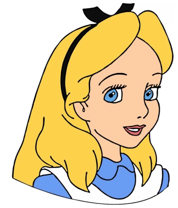
$m =$ 010100000100000101011001 01001001 . . . 00110010 0000000100000100

PAY — IBAN — AMOUNT (520)



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PAY — IBAN

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IBAN — AMOUNT

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PAY — IBAN — AMOUNT (33028)

Changes to the ciphertext result in predictable changes to the plaintext

The scheme is **malleable**!

Malleability and CCA security

- All the encryption schemes we have seen so far are malleable!
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Chosen-ciphertext attack

The adversary can learn the ciphertexts corresponding to one or more plaintexts of its choice

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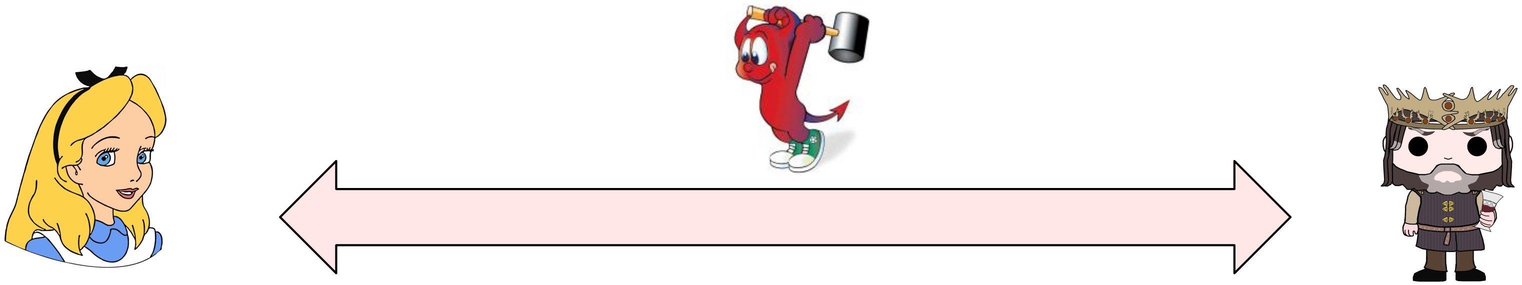

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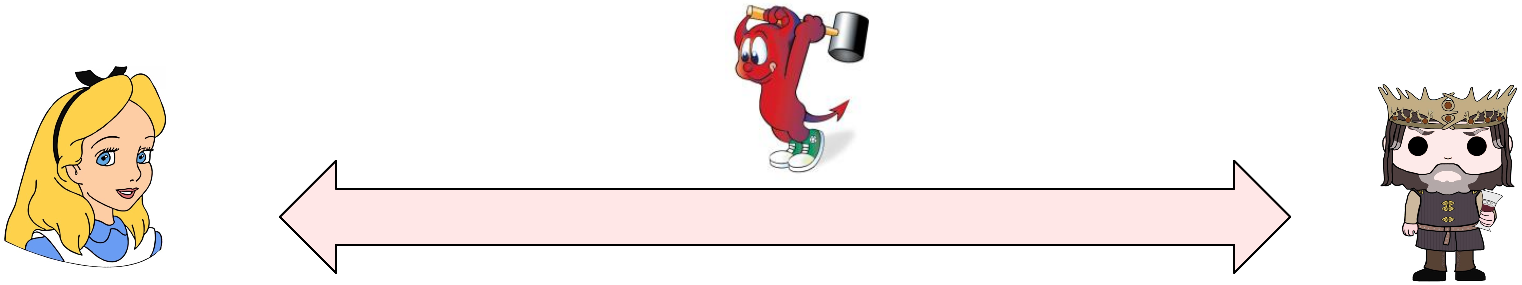

The adversary modifies/injects traffic and observes Bob response

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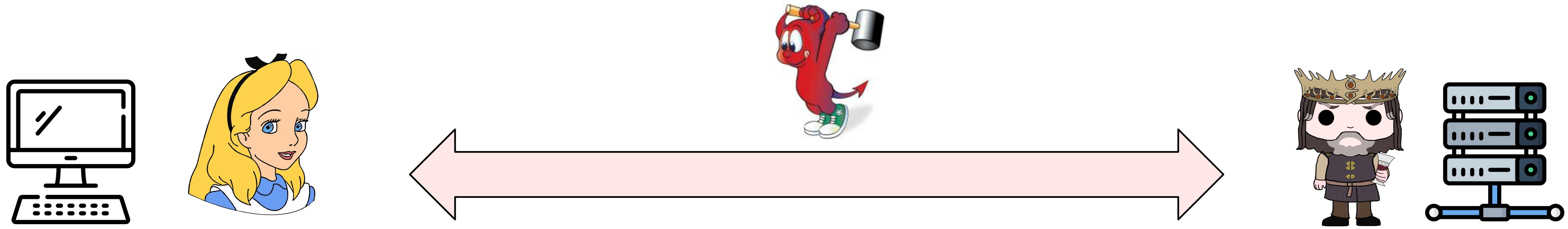

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Many protocols close a connection or request a retransmission when a bad message is received

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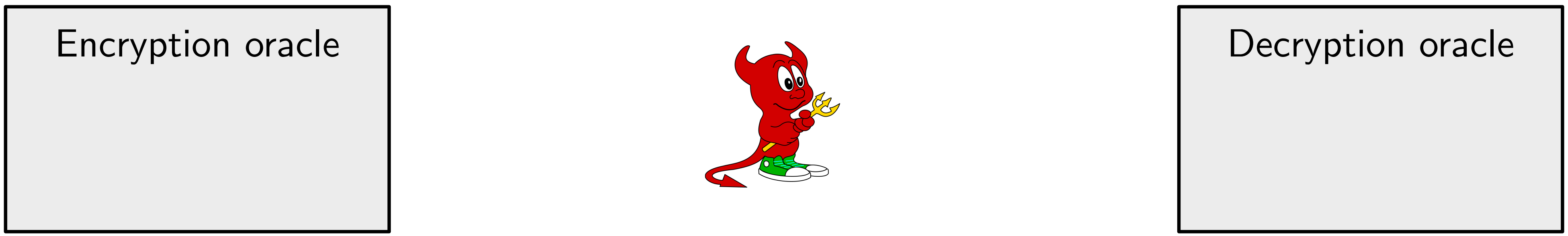
Chosen Ciphertext Attacks (CCA)

What **security guarantee** do we want to achieve against such an adversary?

We define a suitable experiment to capture the security guarantee

Modeling CCA security

A key $k \leftarrow \mathsf{Gen}(1^n)$ is generated and the adversary $\mathcal{A}$ has access to both an **encryption oracle** and a **decryption oracle**



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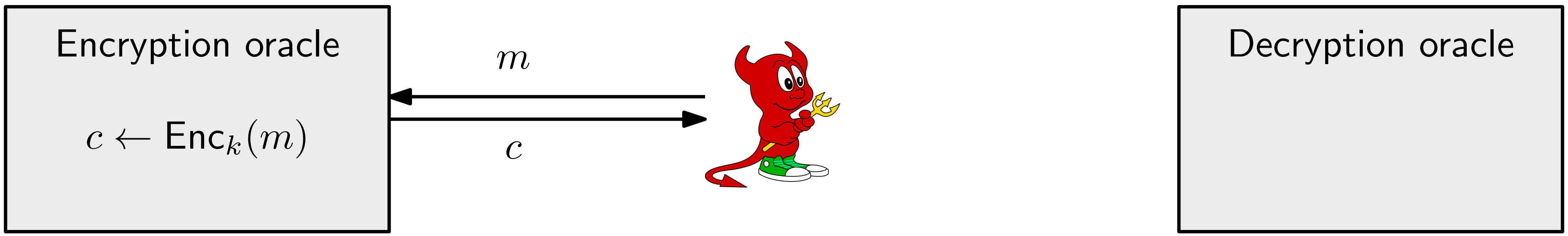

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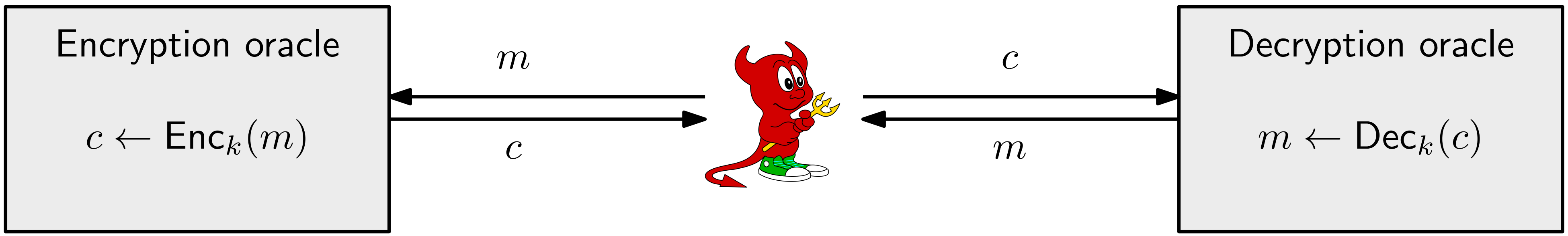

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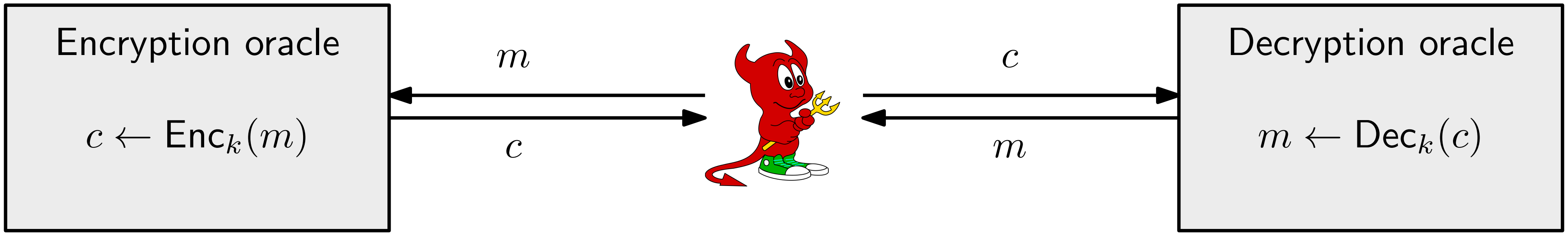

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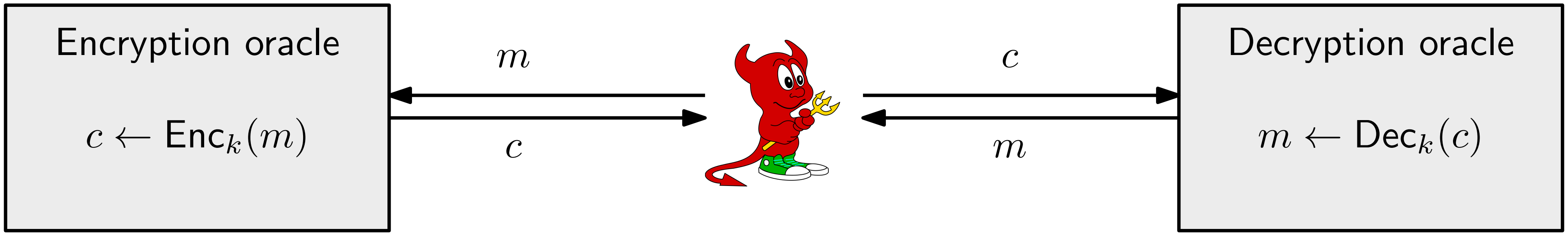

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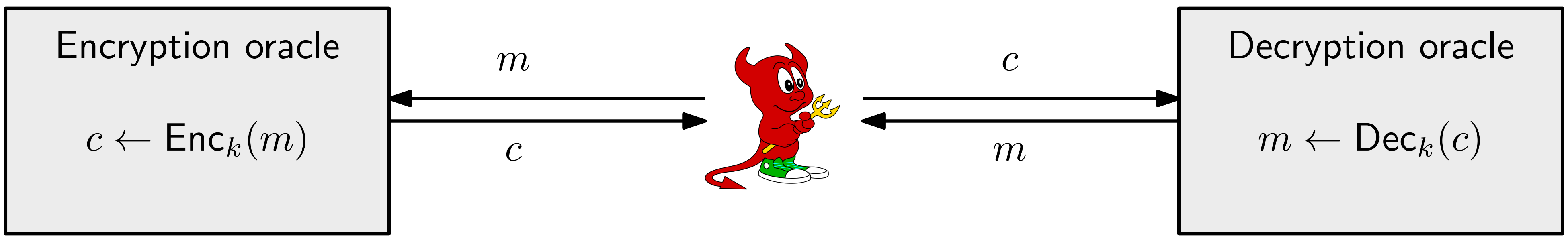

The $\mathsf{PrivK}^{\mathsf{cca}}_{\mathcal{A},\Pi}$ experiment

Formally, if $\Pi = (\mathsf{Gen}, \mathsf{Enc}, \mathsf{Dec})$ is a private key encryption scheme with message space $\mathcal{M}$, we denote the following experiment by $\mathsf{PrivK}^{\mathsf{cca}}_{\mathcal{A},\Pi}(n)$

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- $\mathcal{A}$ can interact with an encryption oracle that provides access to $\mathsf{Enc}_k(\cdot)$ **and** with a decryption oracle that provides access to $\mathsf{Dec}_k(\cdot)$
- $\mathcal{A}$ chooses two distinct messages $m_0, m_1 \in \mathcal{M}$ with $|m_0| = |m_1|$
- A uniform random bit $b \in \{0, 1\}$ is generated
- The *challenge ciphertext* c is computed by $\mathsf{Enc}_k(m_b)$, and given to $\mathcal{A}$
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$\mathcal{A}$ is not allowed to request a decryption of c

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Encryption and Decryption oracles using key k

Adversary $\mathcal{A}$

Verifier

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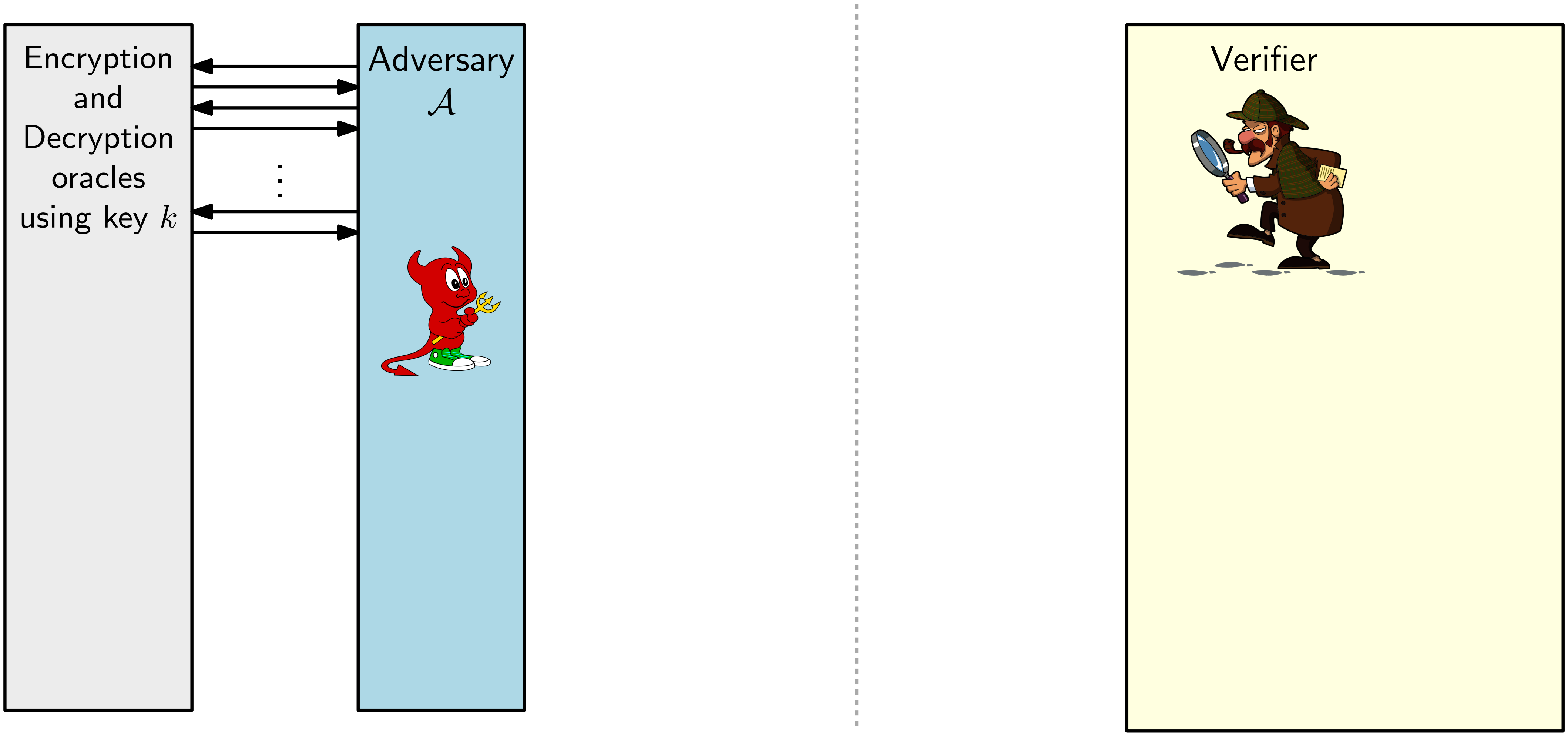

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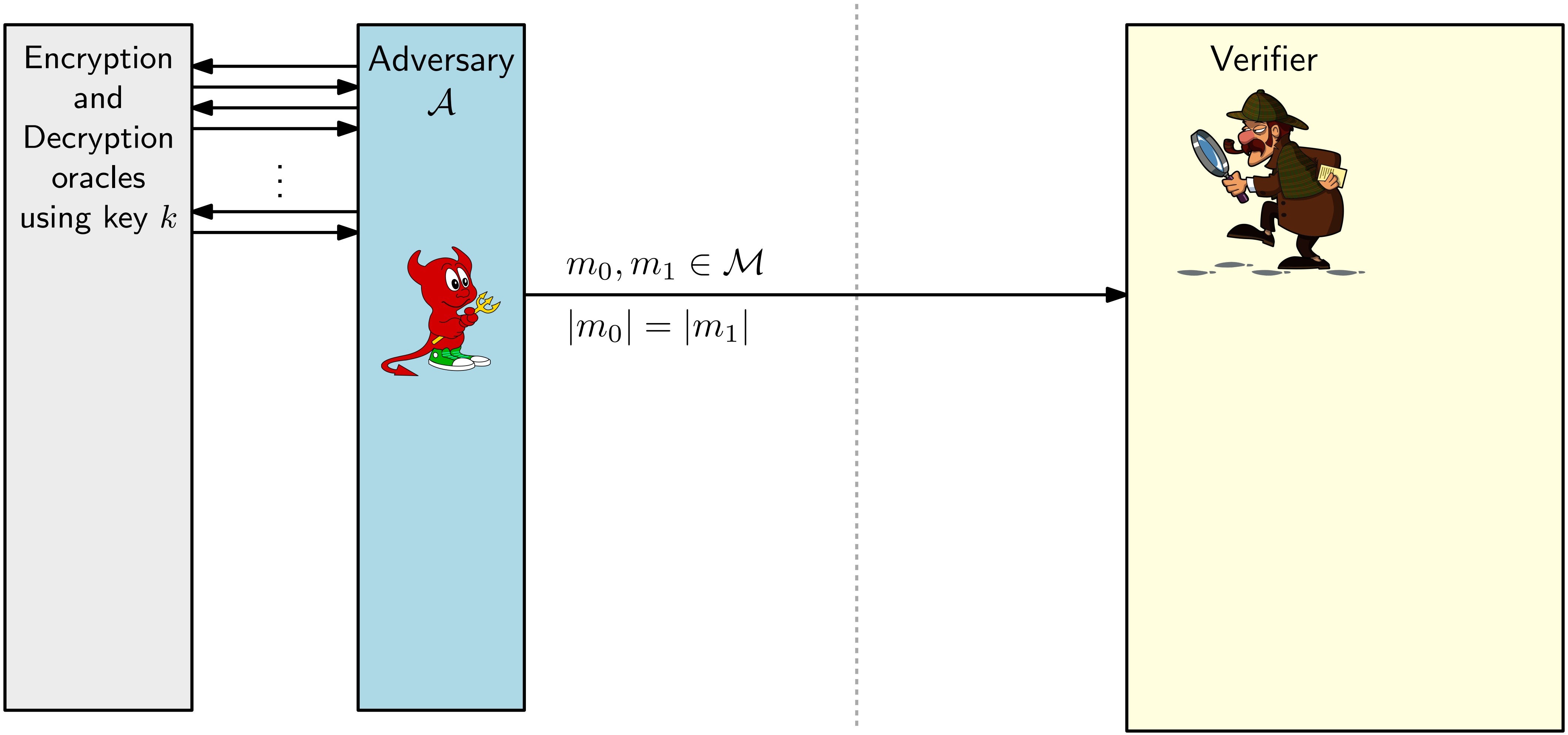

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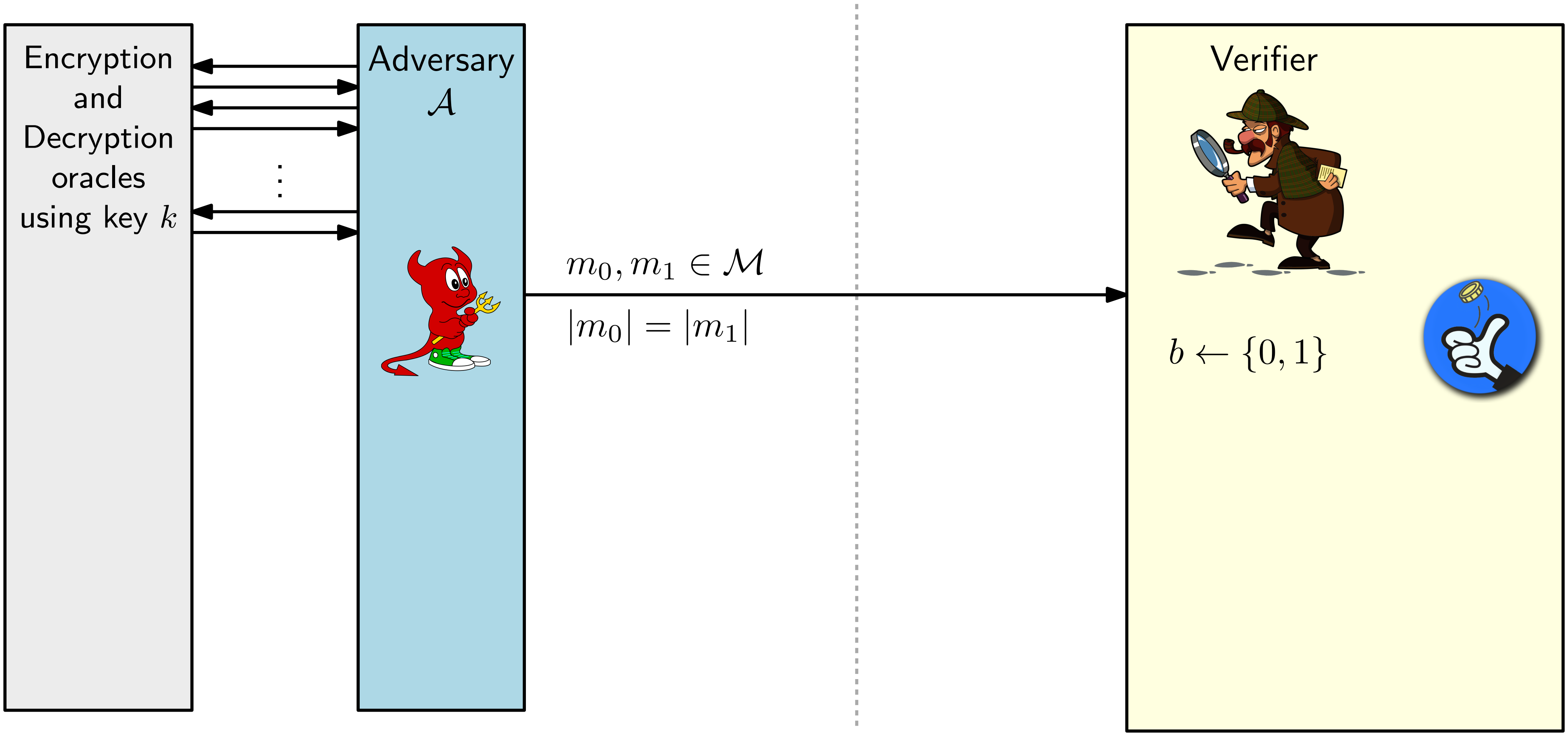

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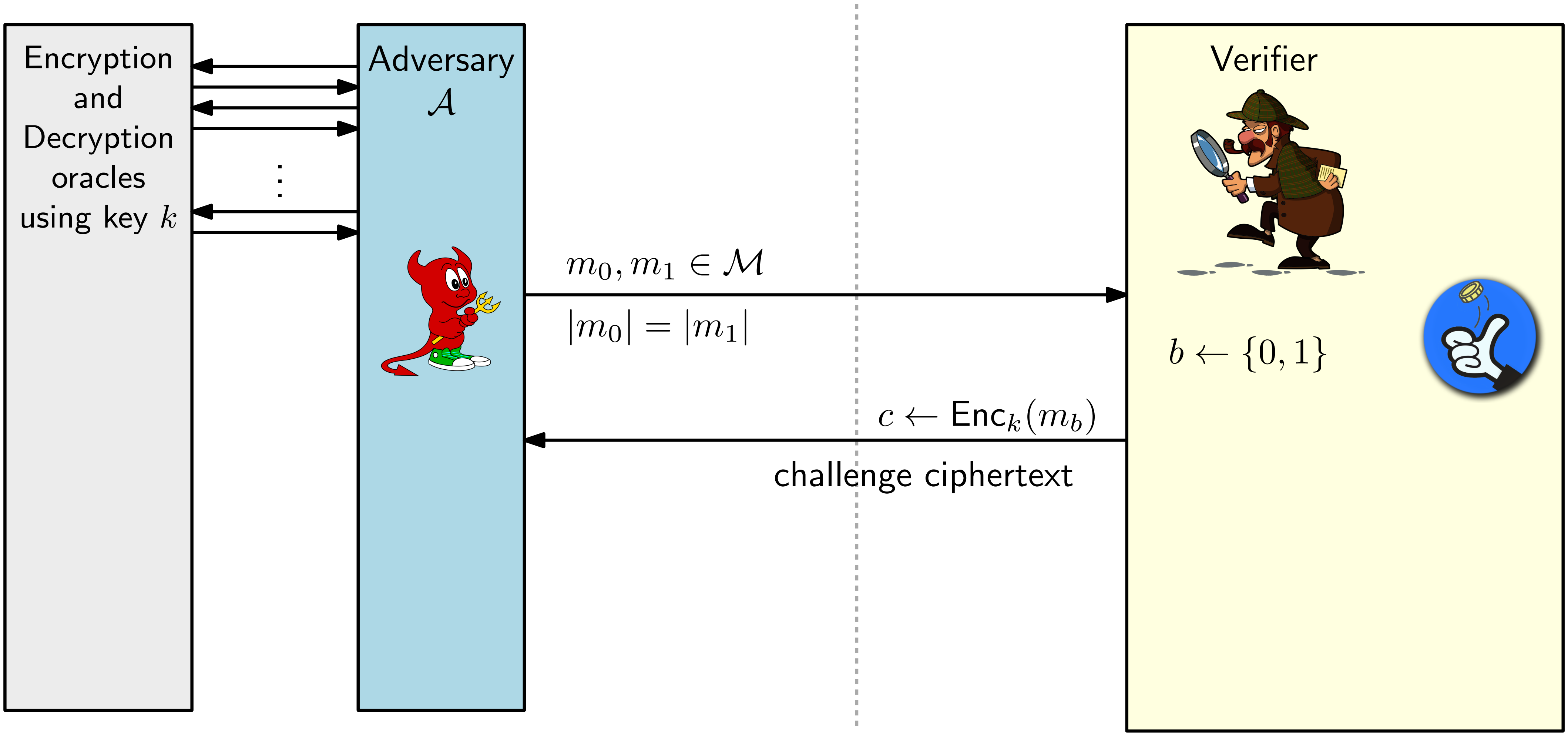

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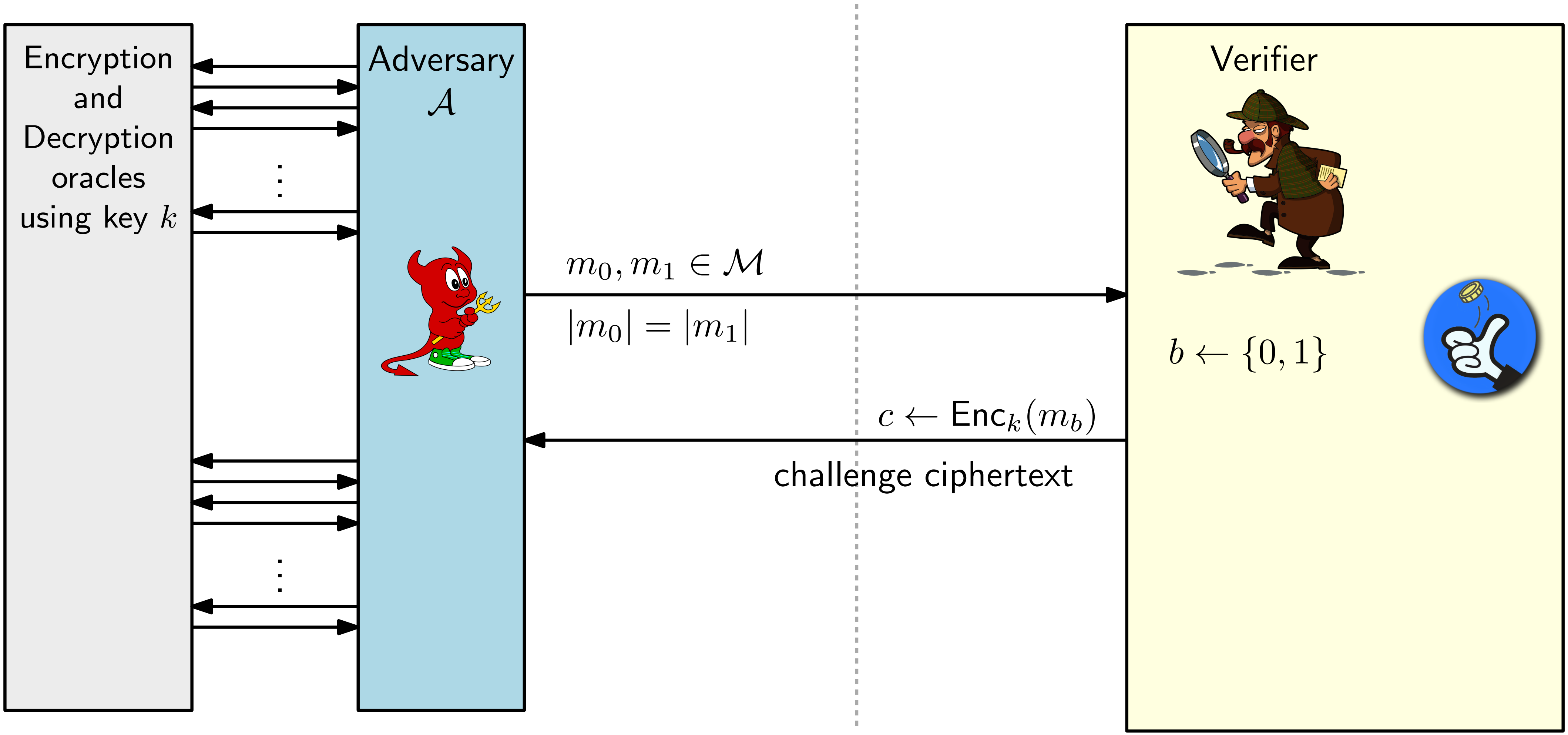

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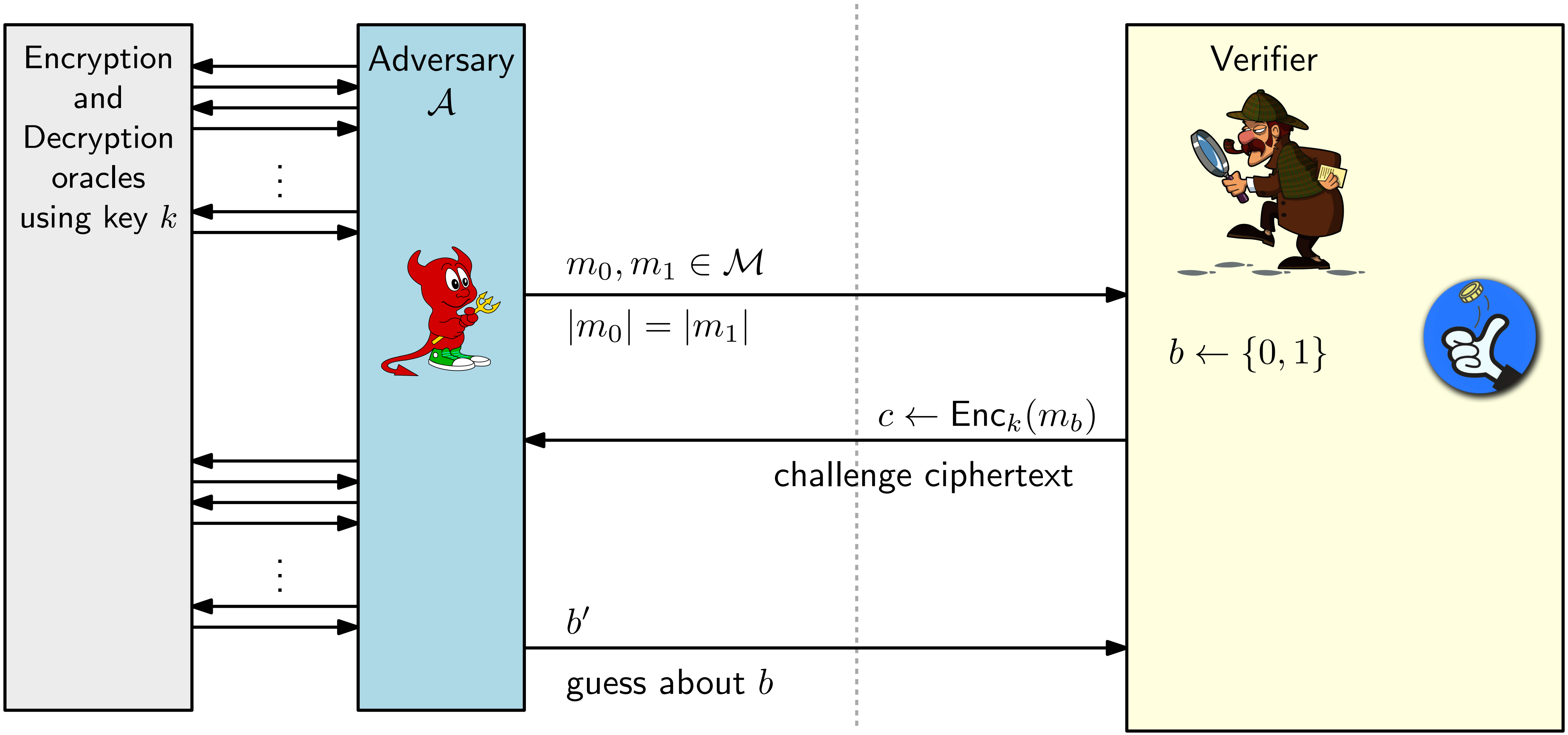

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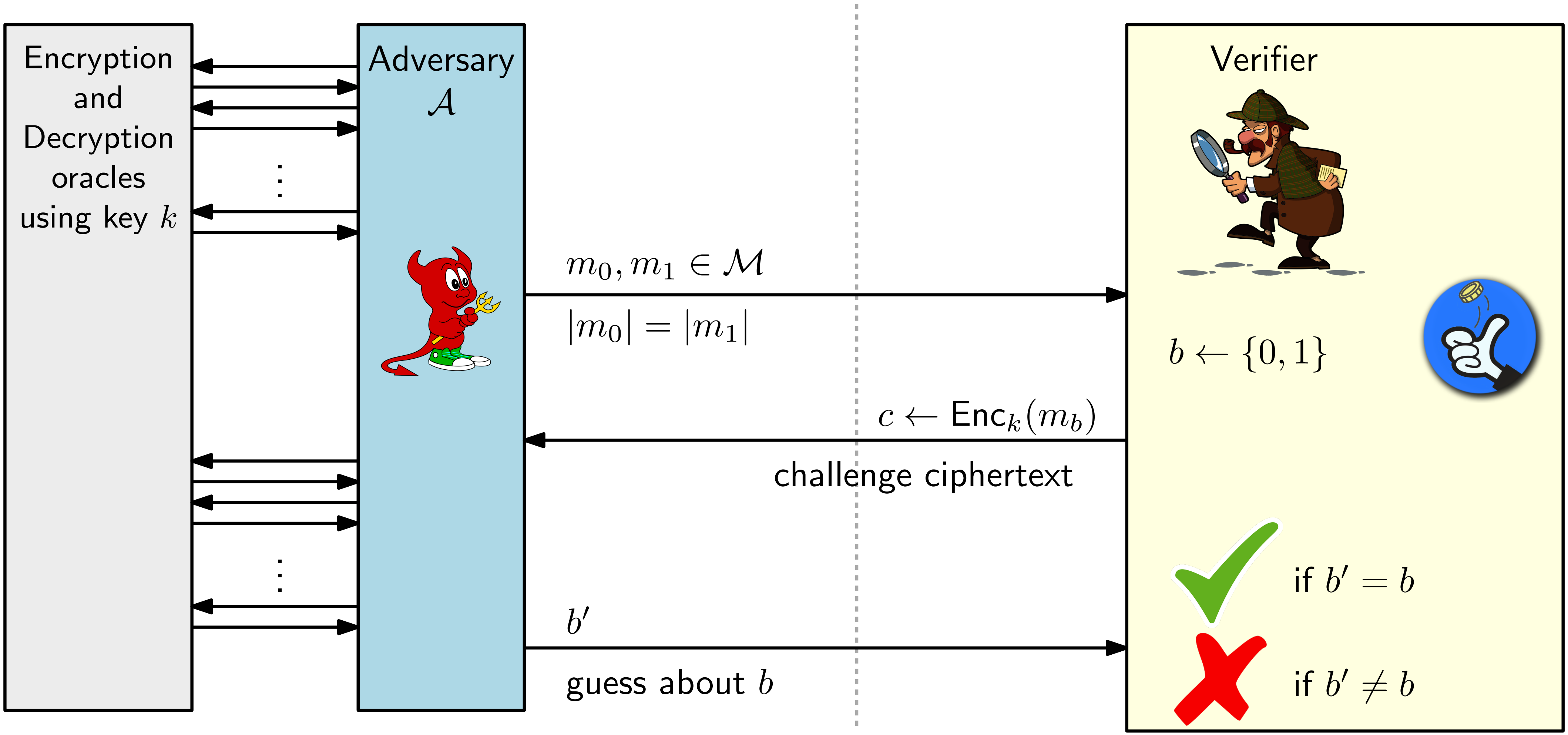

Definition of CCA security

Definition: *A private key encryption scheme* Π *has indistinguishable encryptions under a chosen-ciphertext attack (is* **CCA-secure***) if, for every probabilistic polynomial-time adversary* $\mathcal{A}$*, there is a negligible function* ε *such that:*

$$\Pr[\mathit{PrivK}^{cca}_{\mathcal{A},\Pi}(n) = 1] \leq \frac{1}{2} + \varepsilon(n)$$

Is the definition realistic?

The definition models the case in which an attacker can obtain the decryption of **any ciphertext** of its choice (except for the challenge ciphertext)

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- Recall the Midway island example: the US could have sent an encrypted message containing the fragment `AF` and observed Japan's response

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We take a **worst-case** approach:

- No assumption on how strong real-world adversaries are
- If an encryption scheme withstands a stronger adversary than real-world ones, security is not compromised

Malleability and CCA-security

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- The plaintext m' matches the modified version of some message m_i (i.e., the version of m_i in which the expected change took place)

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By taking the contrapositive: CAA-security **implies** non-malleability!

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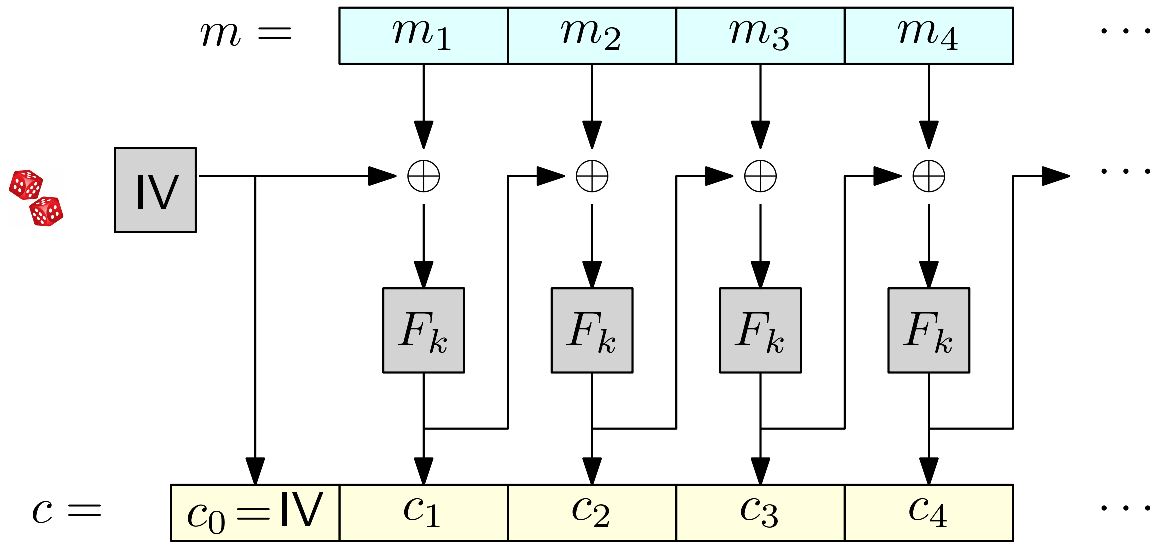
Reminder: block ciphers in CBC mode



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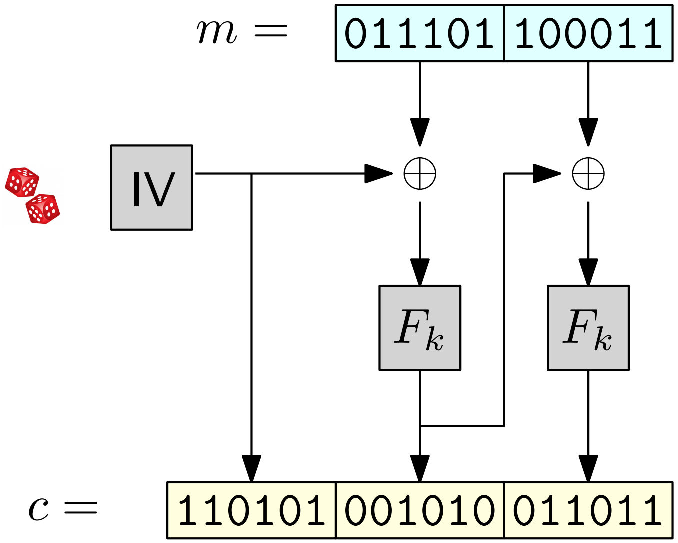

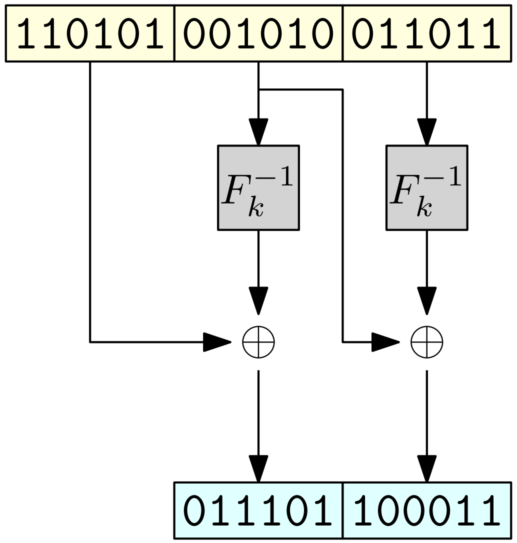

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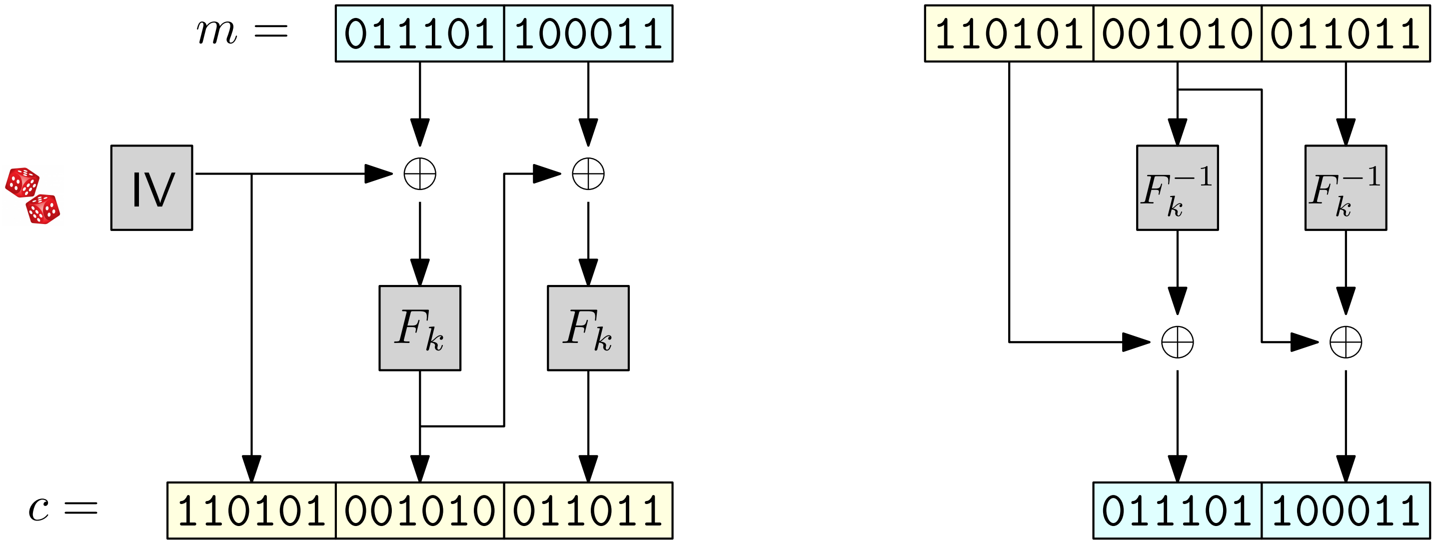

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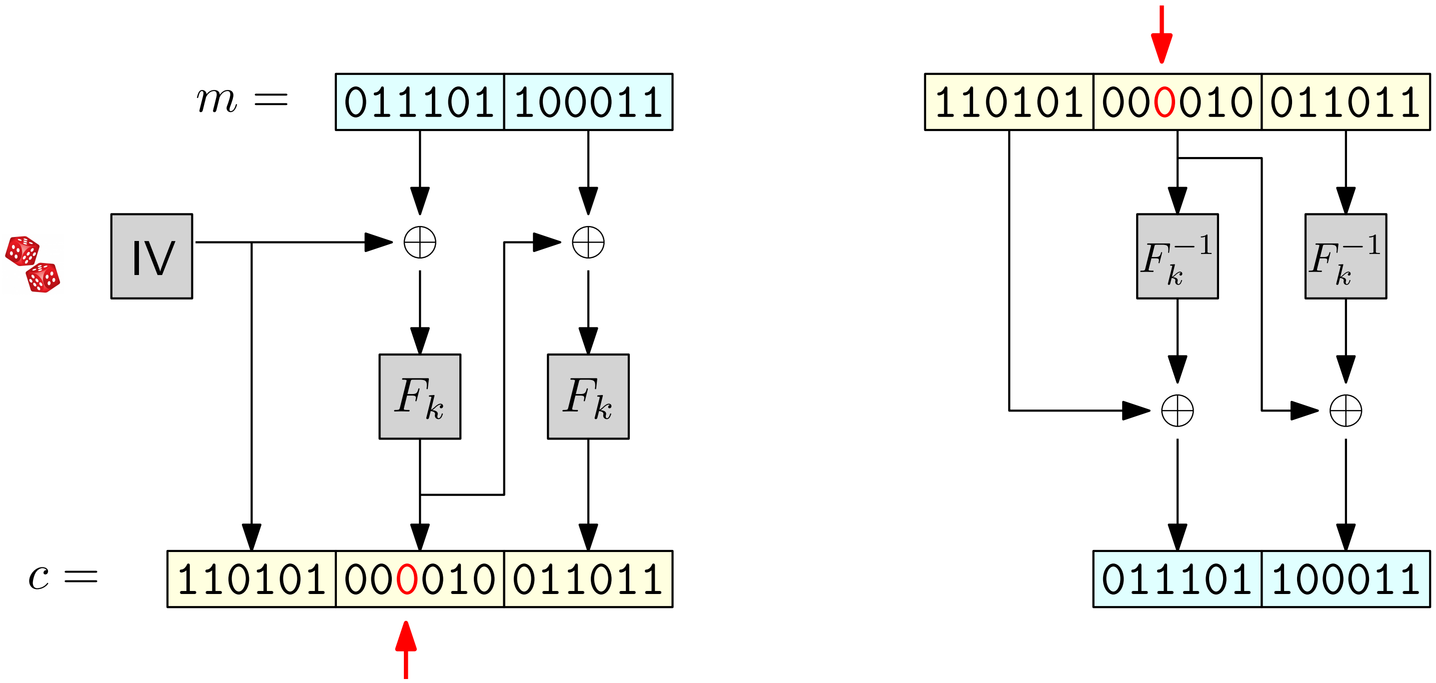

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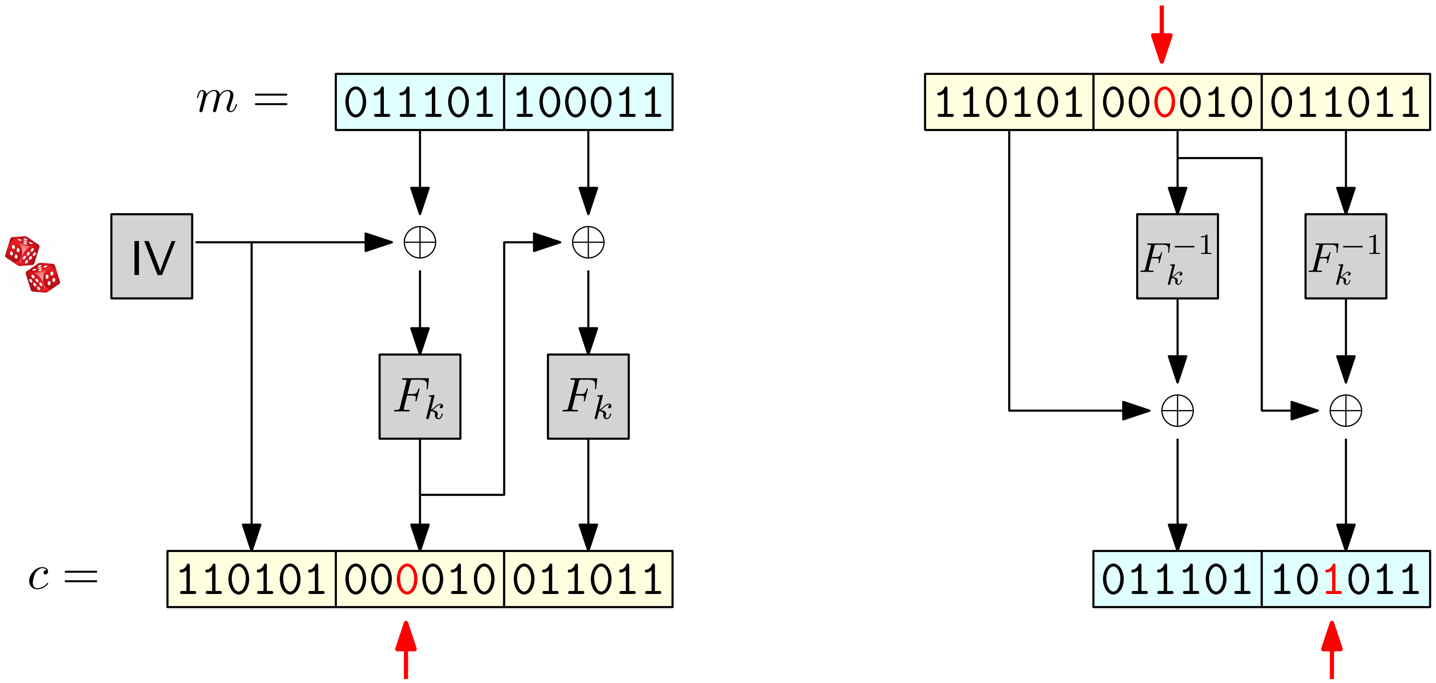

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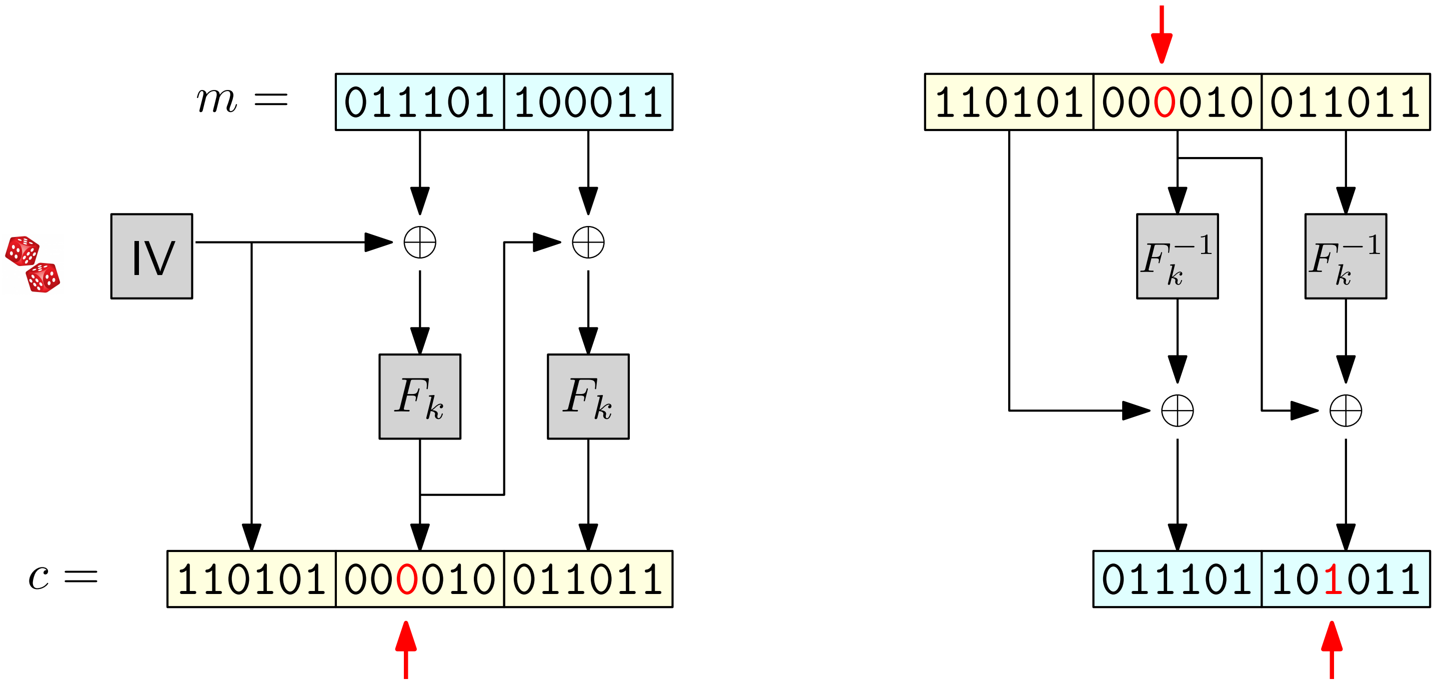

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In general, if we XOR the i-th block of the ciphertext with Δ, this causes the $(i+1)$-th block of the plaintext to be XOR-ed with Δ after decryption

Message padding and PKCS #7

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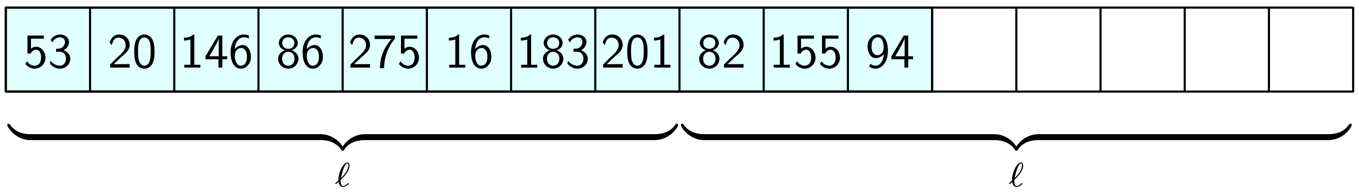

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(first 8 bytes: ℓ; last 8 bytes: ℓ)

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ℓ								ℓ							

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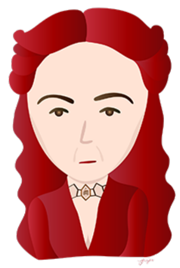
We model the ability of the adversary to tell whether the padding of (the plaintext corresponding to a) ciphertext is valid, with a **padding oracle**



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Attack plan:

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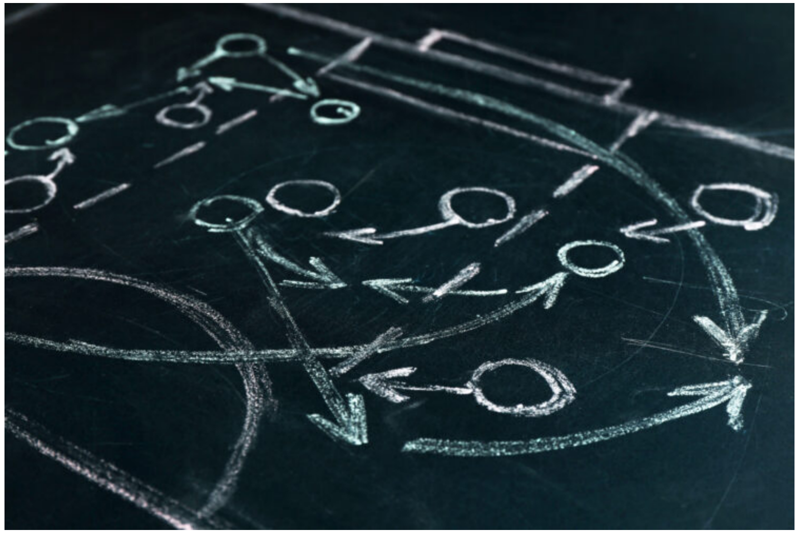


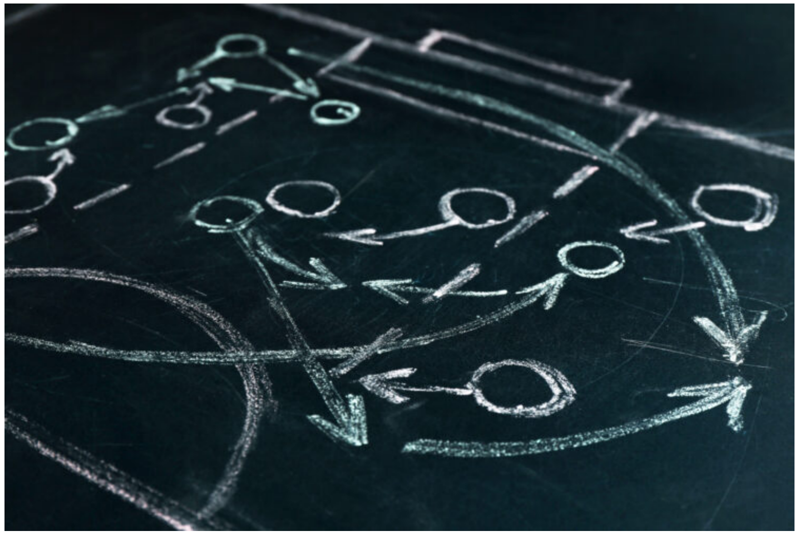
Exploiting a Padding Oracle

Attack plan:

1) Figure out how long is the padding

2) Repeat the following until the whole plaintext is recovered:

- Extend the knowledge of the last i bytes of the plaintext (initially $i = 0$) to the last $i + 1$ bytes of the plaintext



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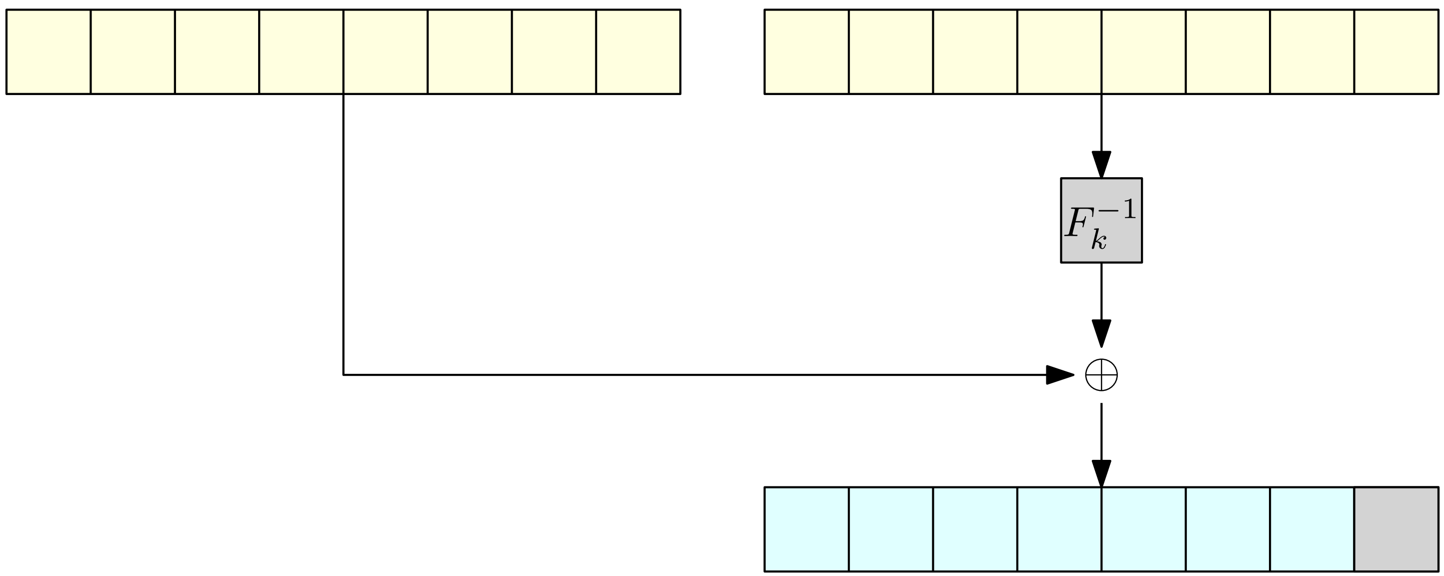

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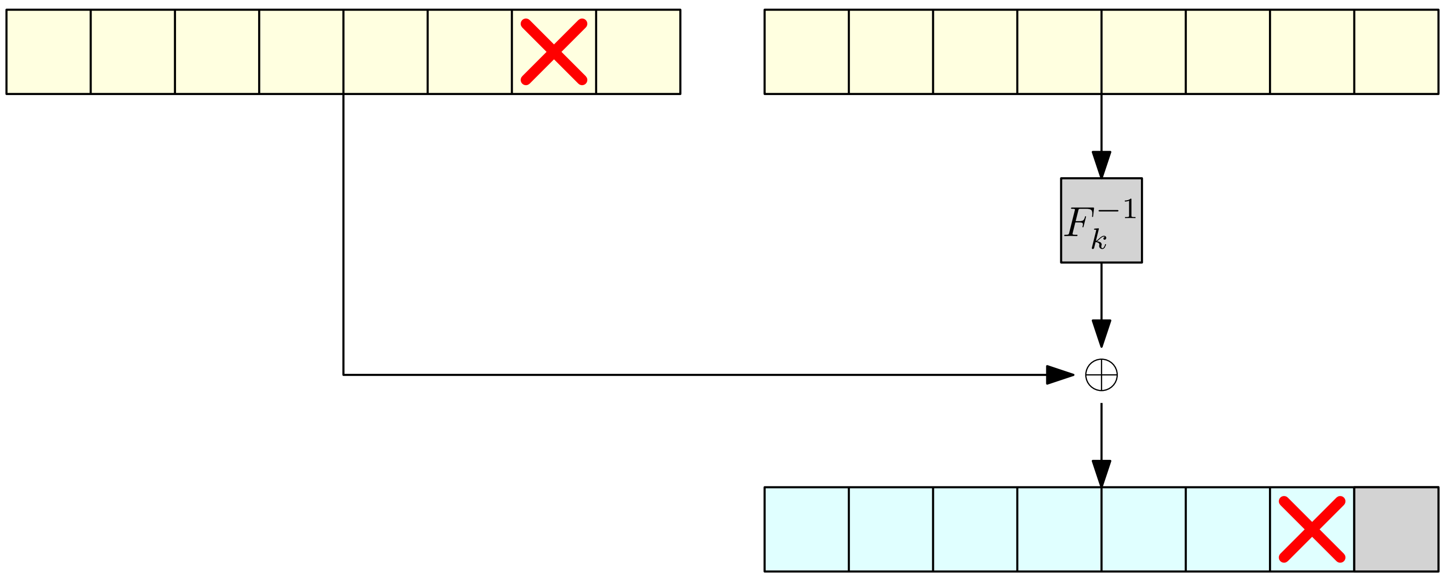

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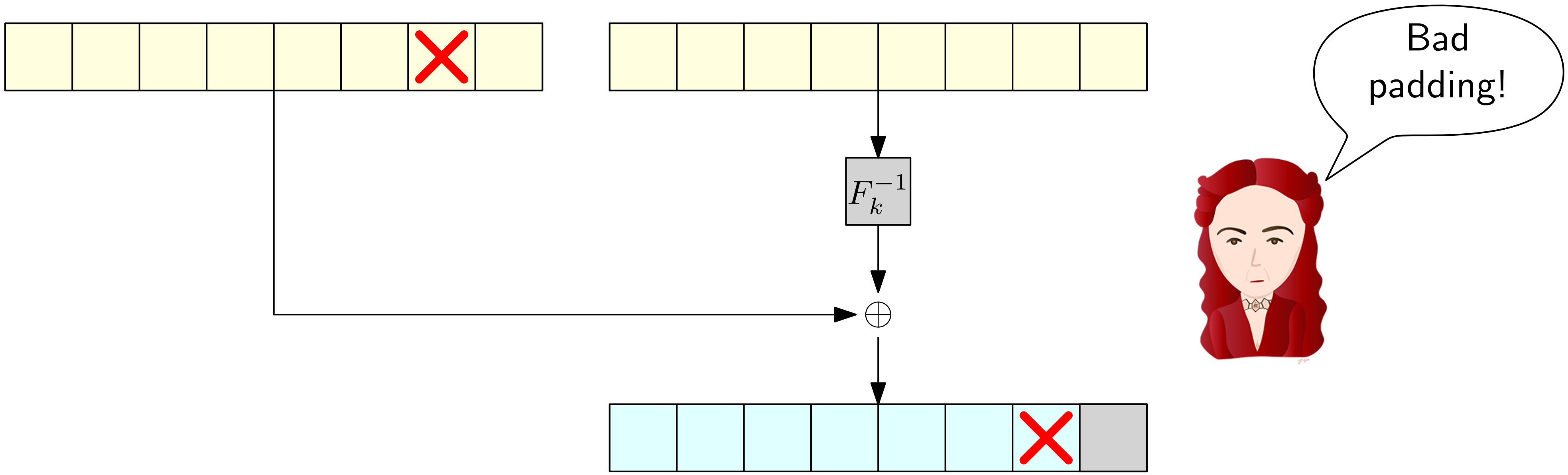

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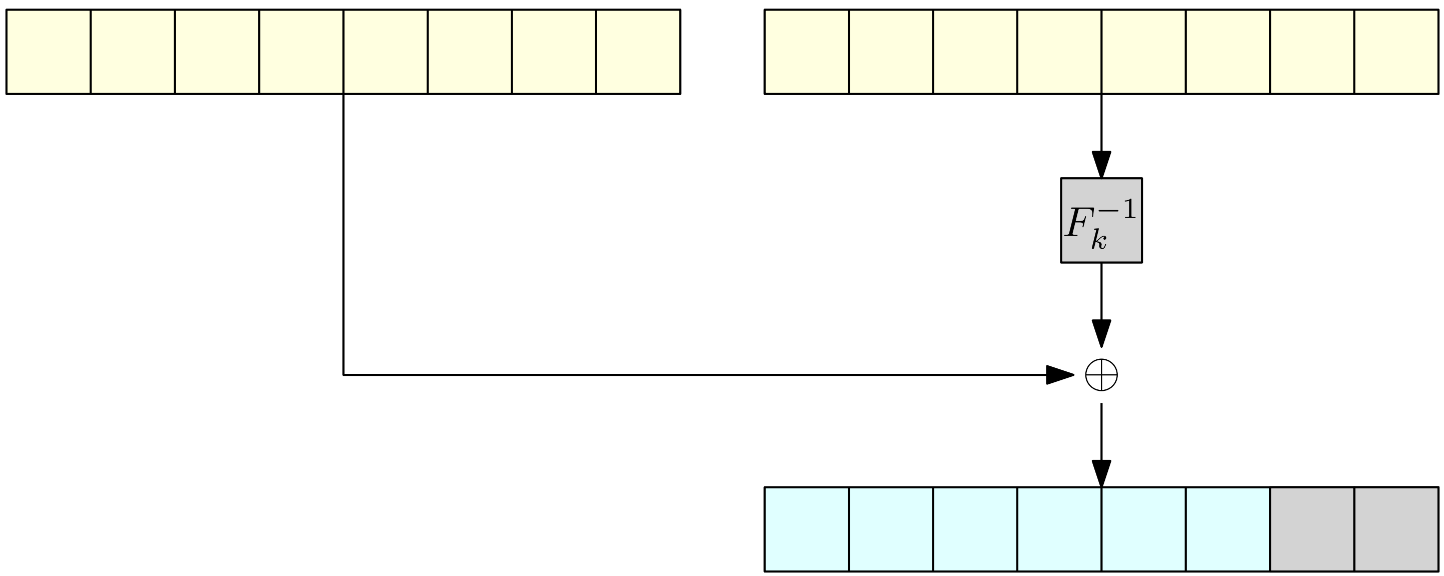

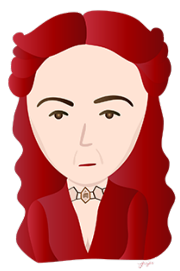

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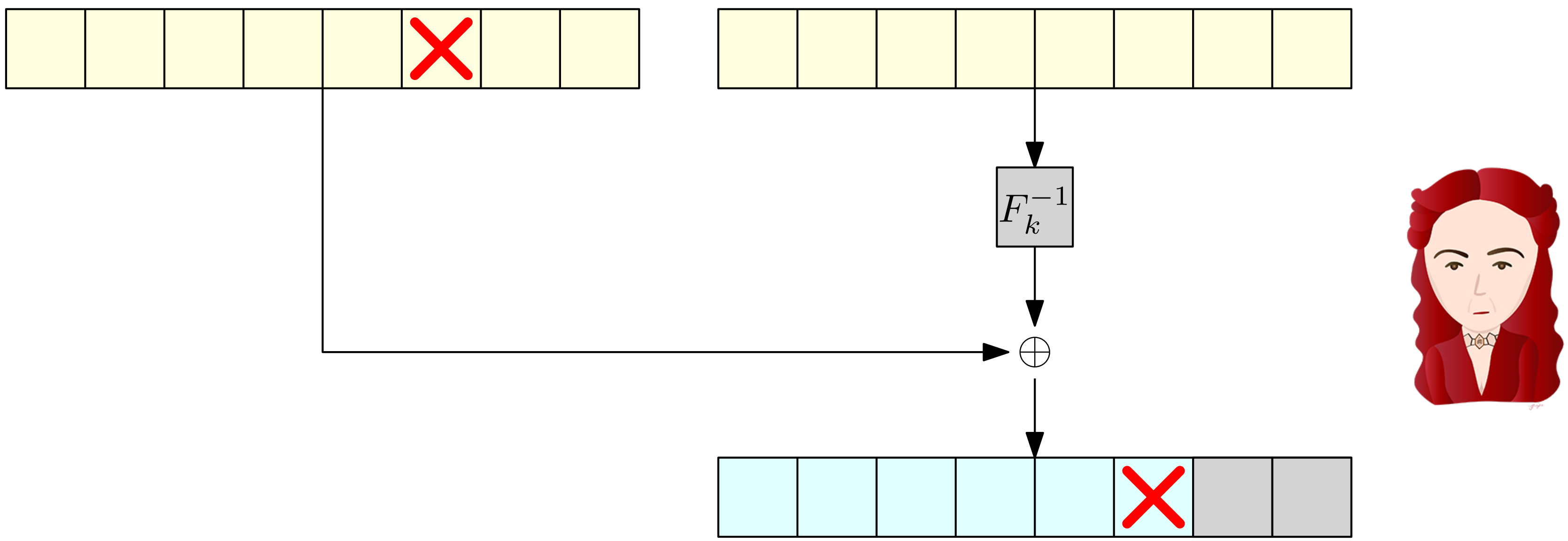

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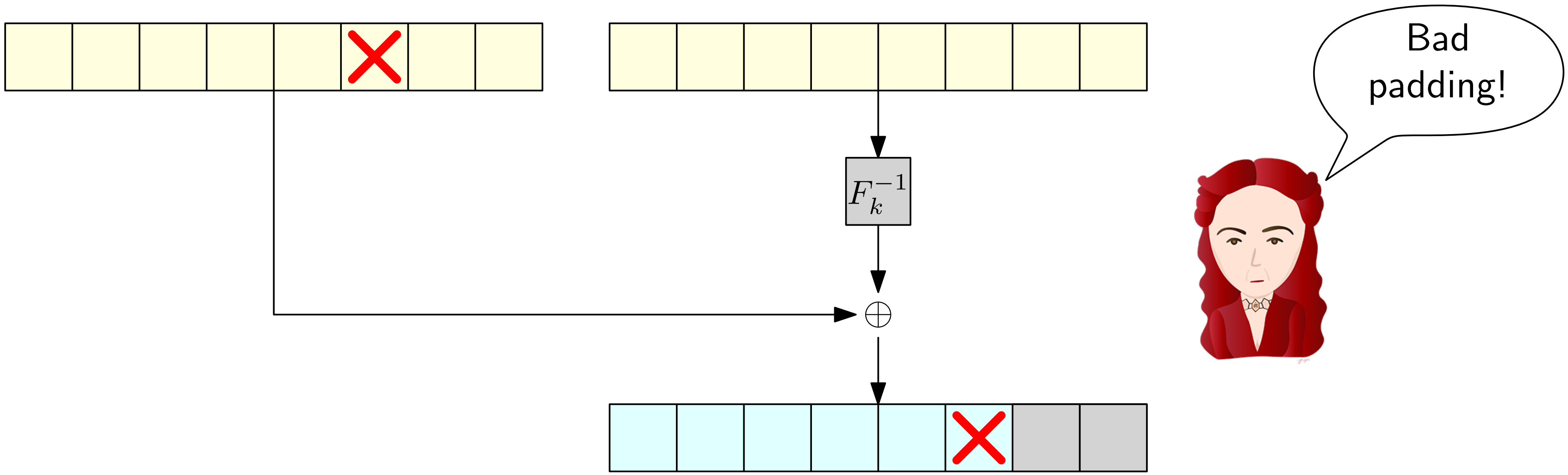

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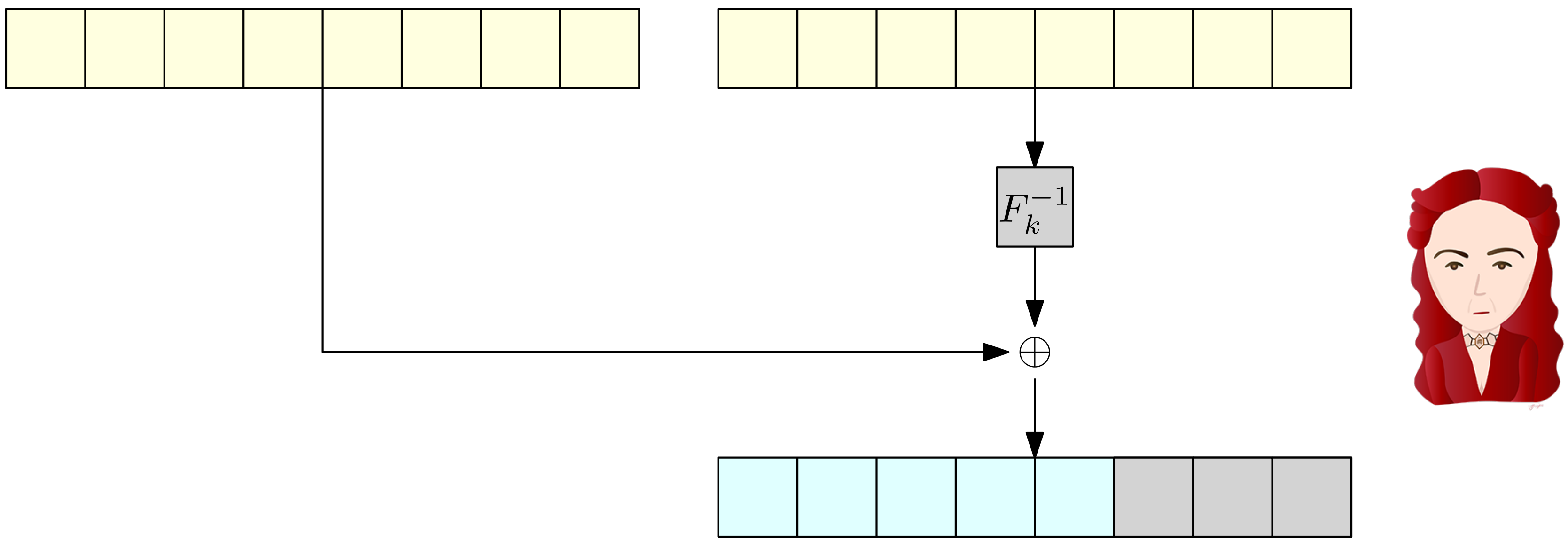

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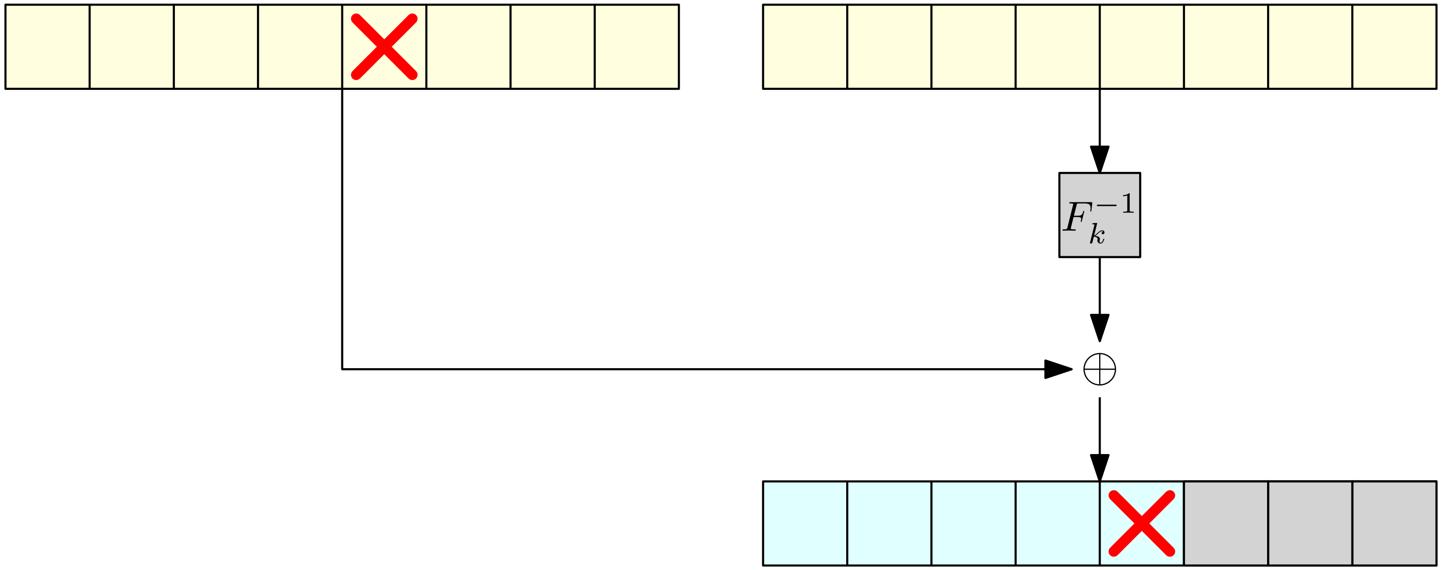

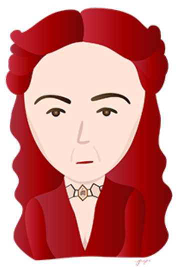

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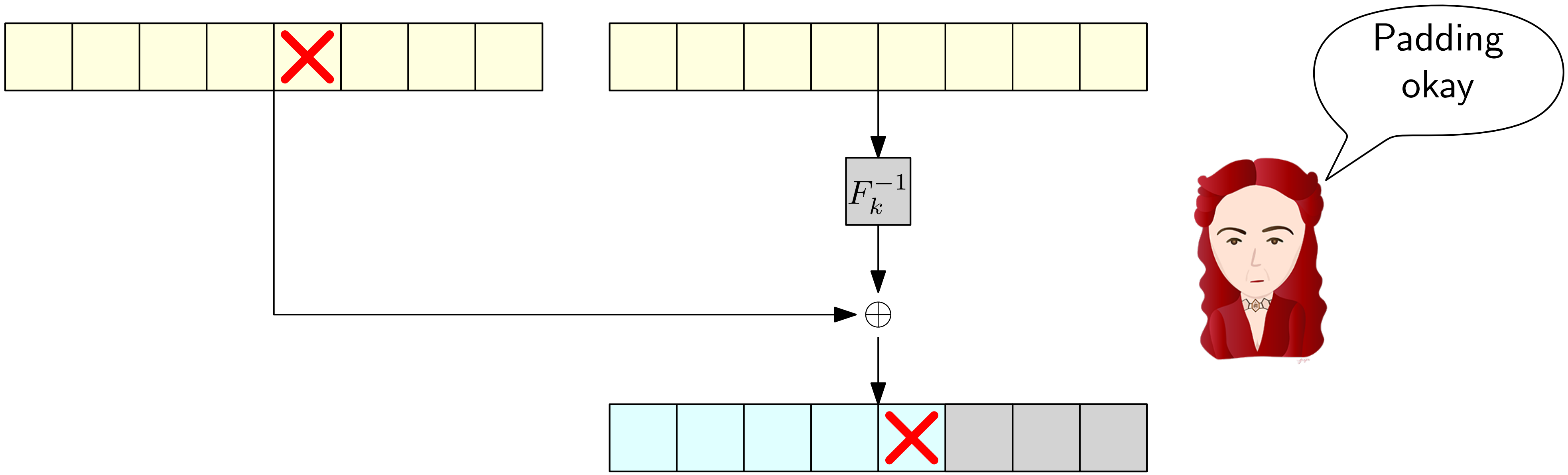

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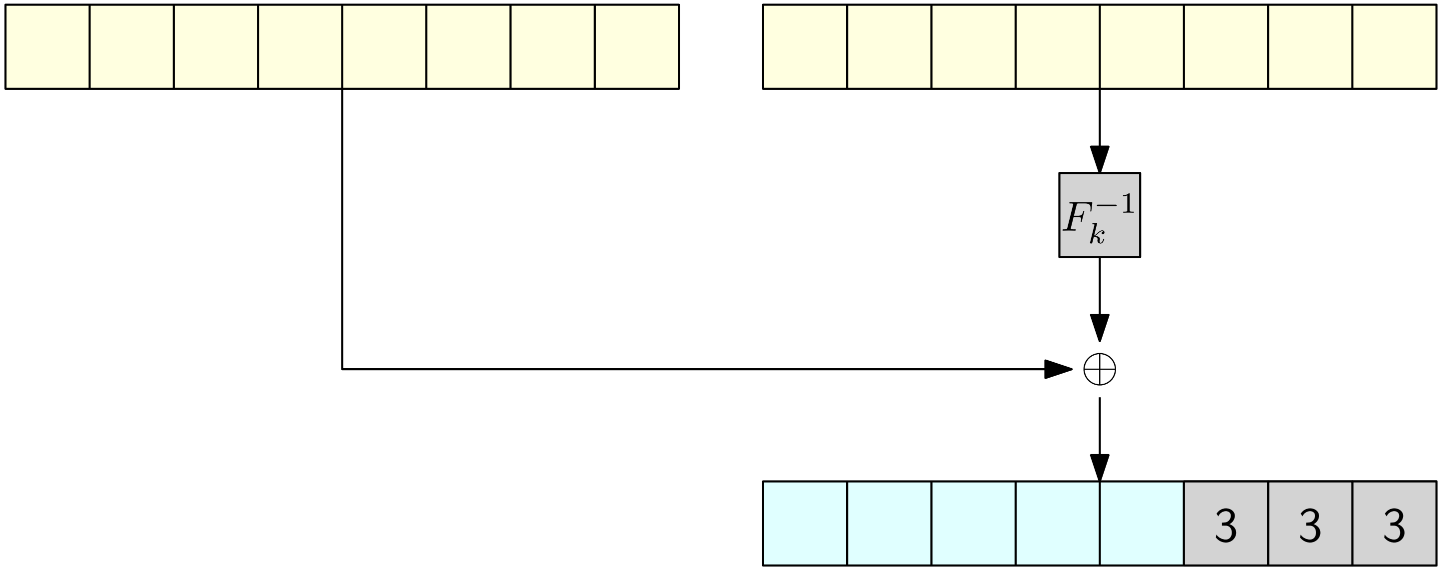

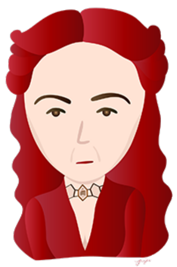

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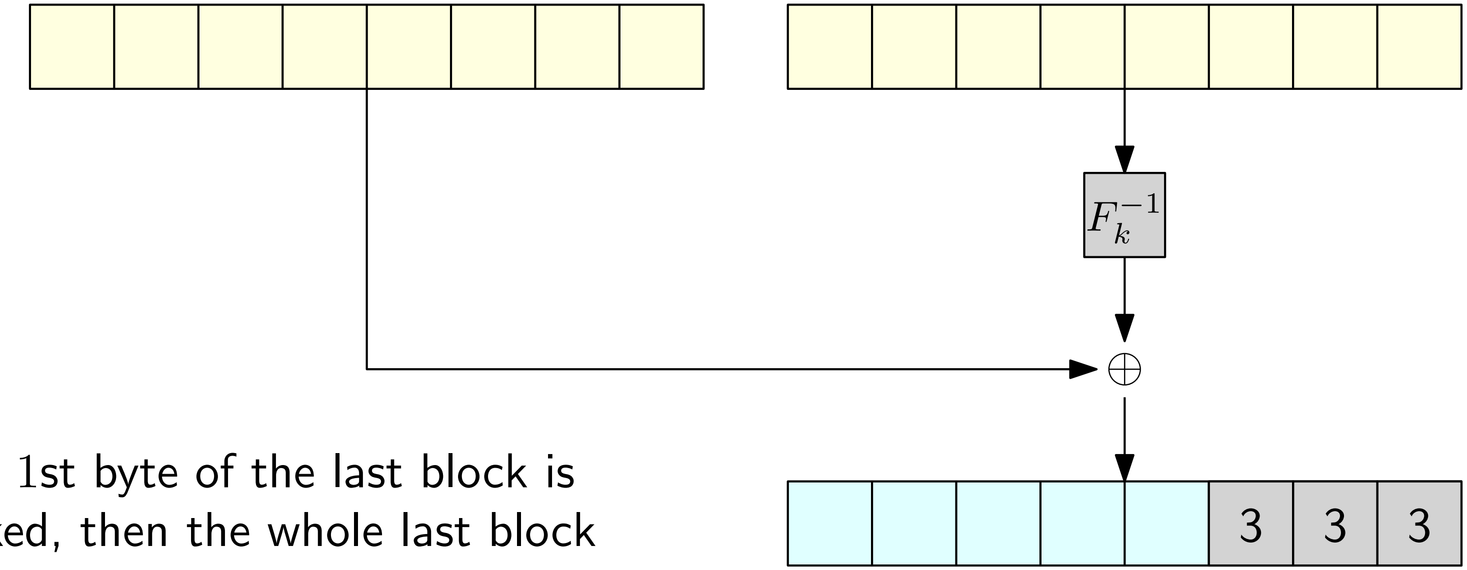

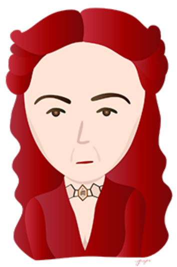

If the 1st byte of the last block is checked, then the whole last block consists of padding

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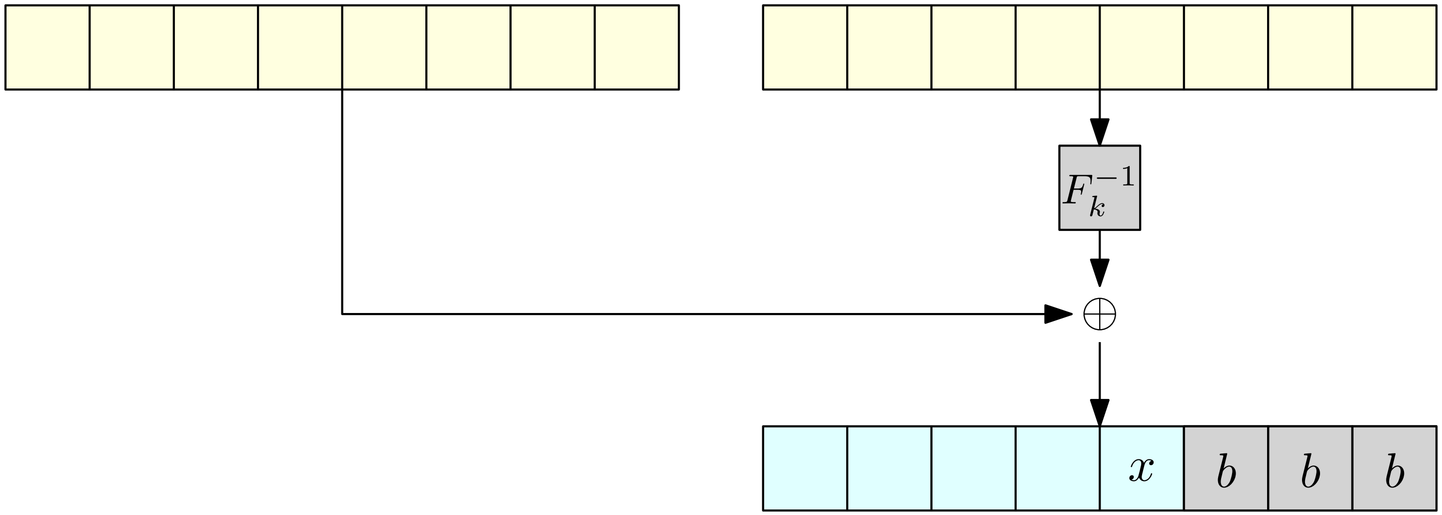
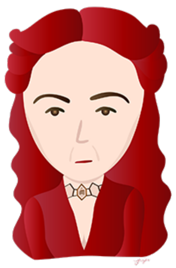
We now know that the last b bytes of the plaintext all have value b. We want to recover the last byte x of the (unpadded) message





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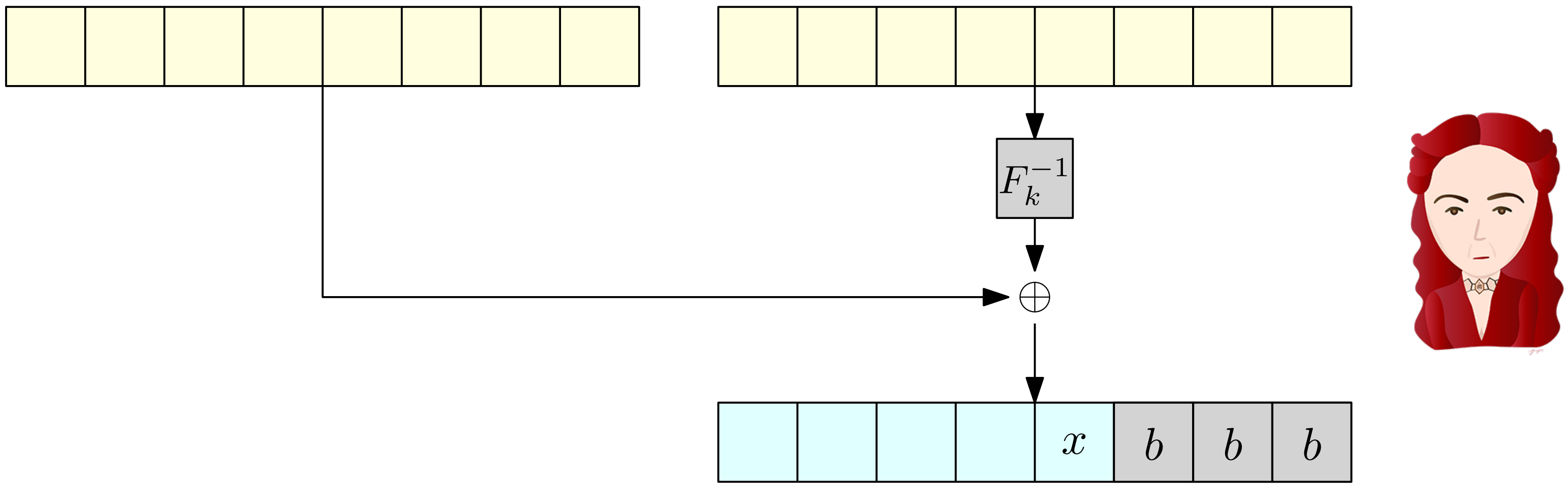

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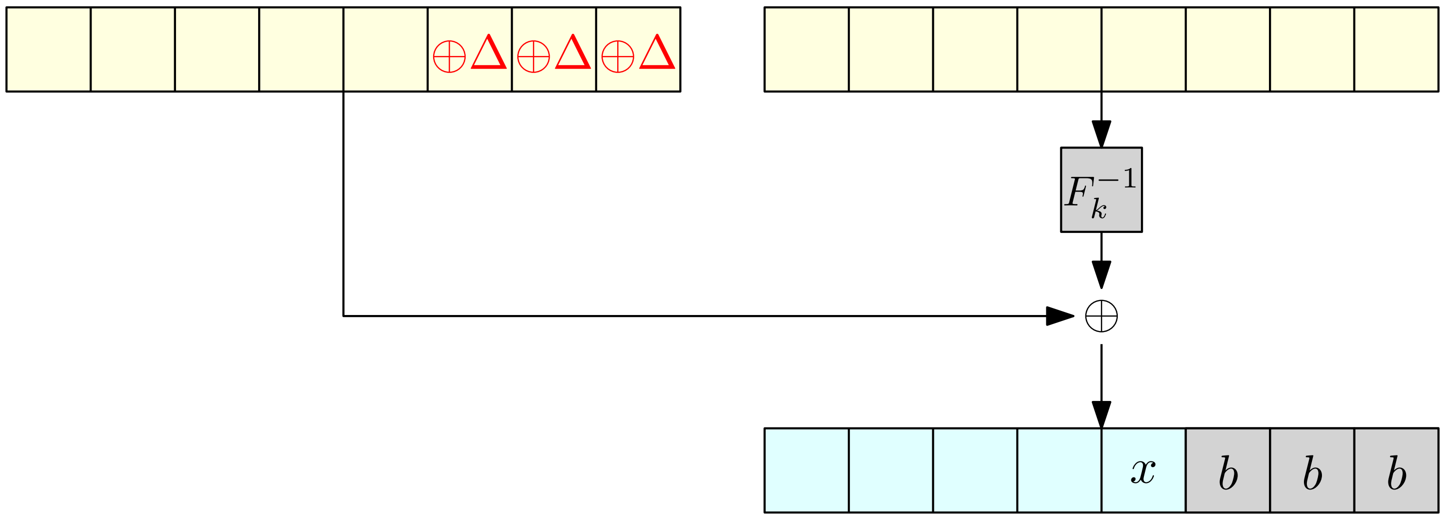
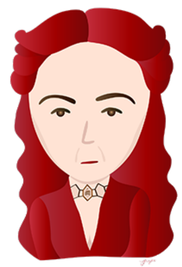
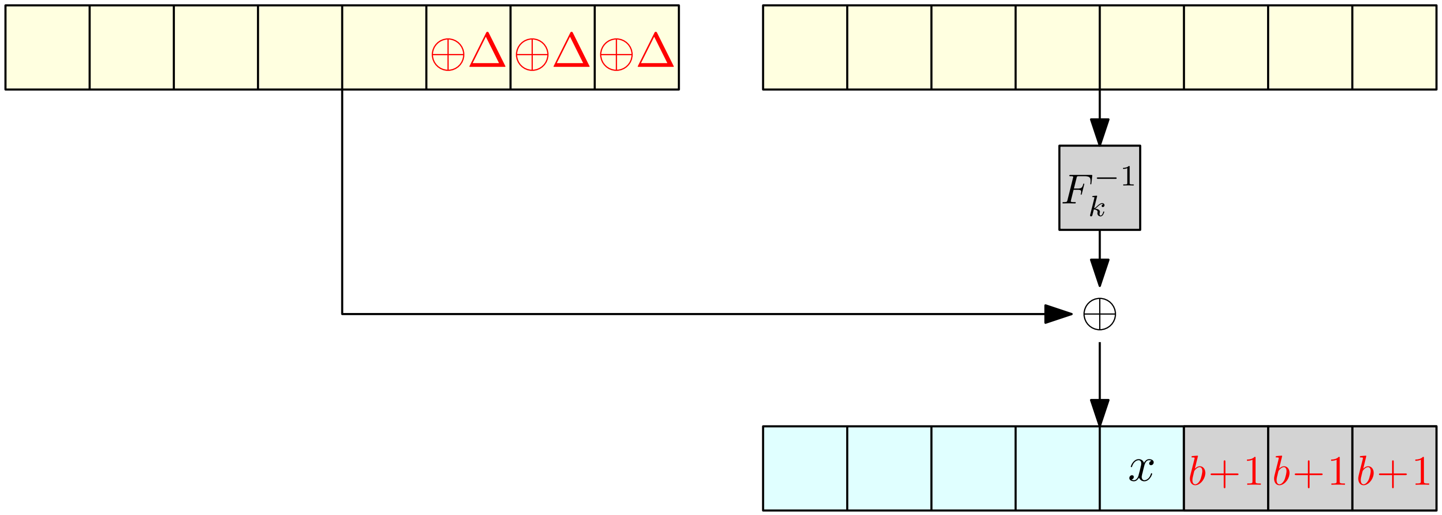


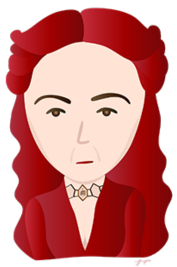


Recovering the last byte of the plaintext

We now know that the last b bytes of the plaintext all have value b. We want to recover the last byte x of the (unpadded) message

- XOR the last b bytes of the one-to-last block of the ciphertext with $\Delta = b \oplus (b+1)$
- This changes the last b blocks of the plaintext to from b to $b \oplus b \oplus (b+1) = b+1$





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For all possible values $i \in \{0, \ldots, 255\}$

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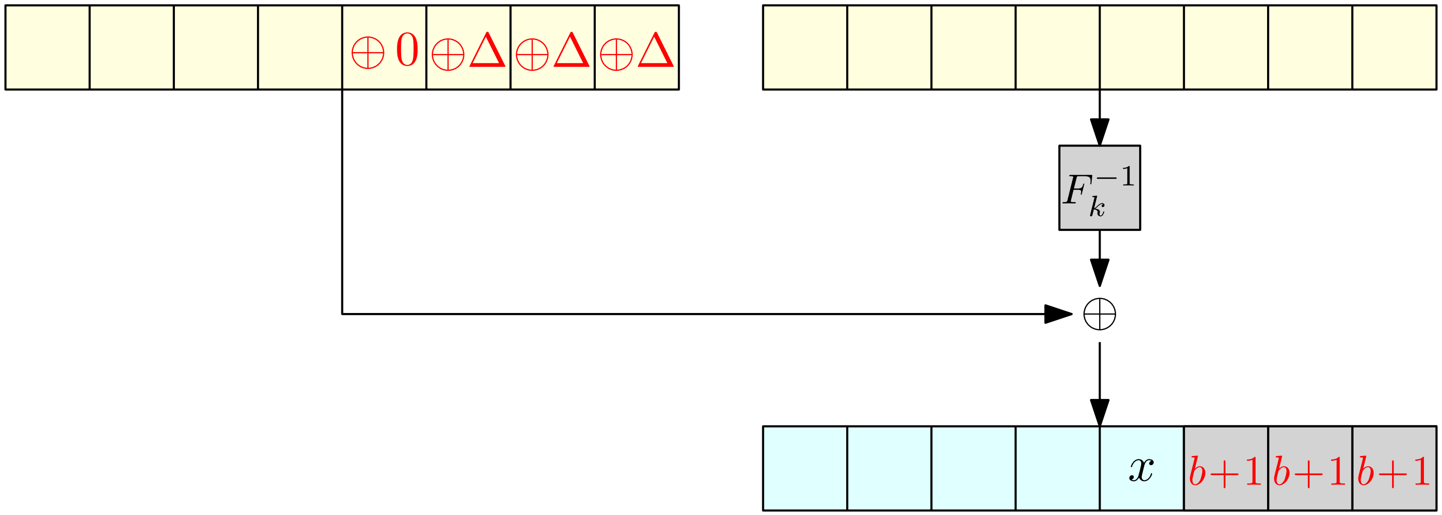

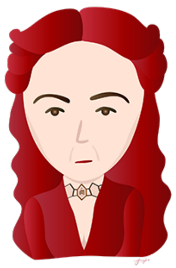

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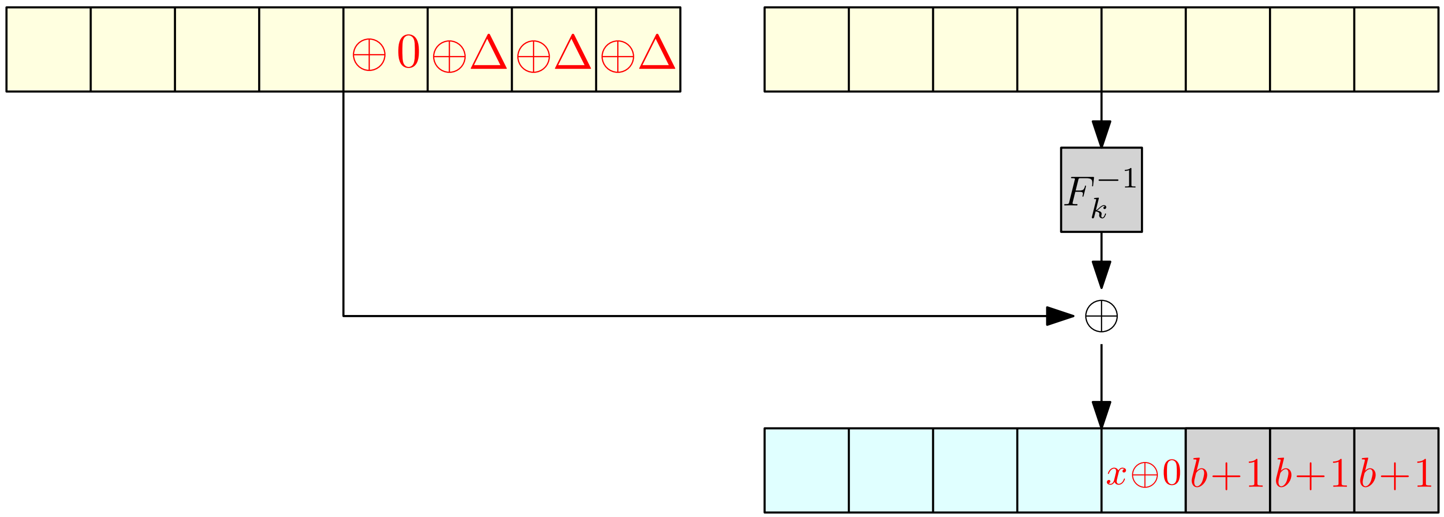

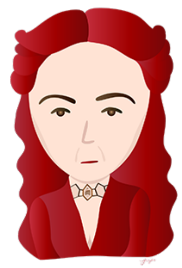

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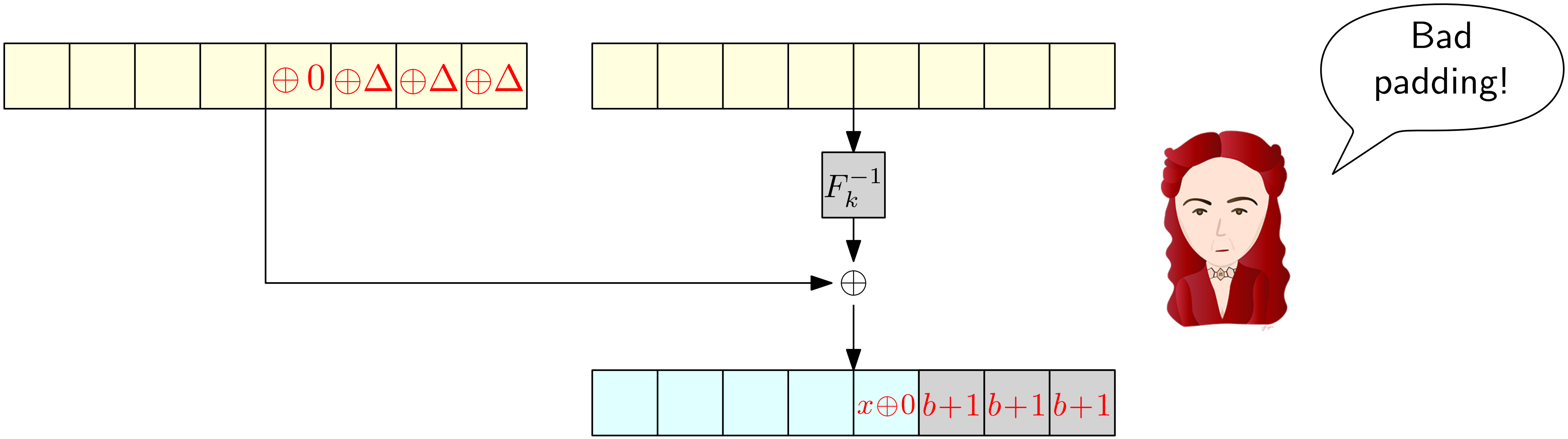

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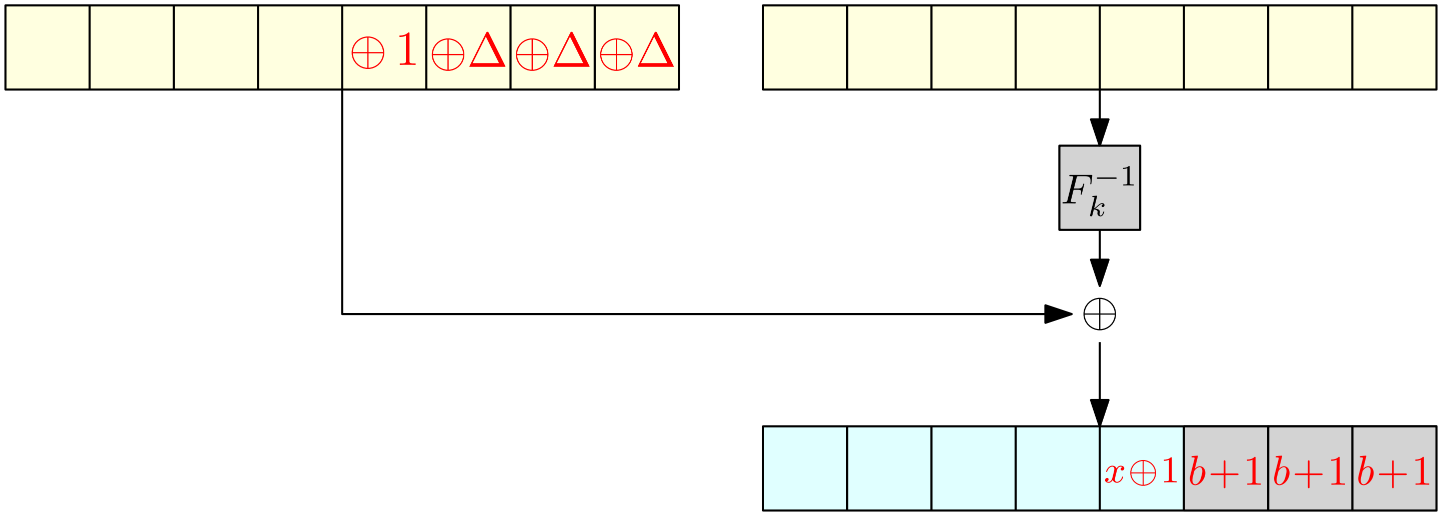

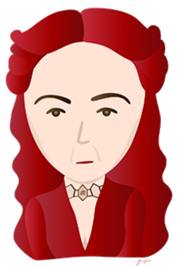

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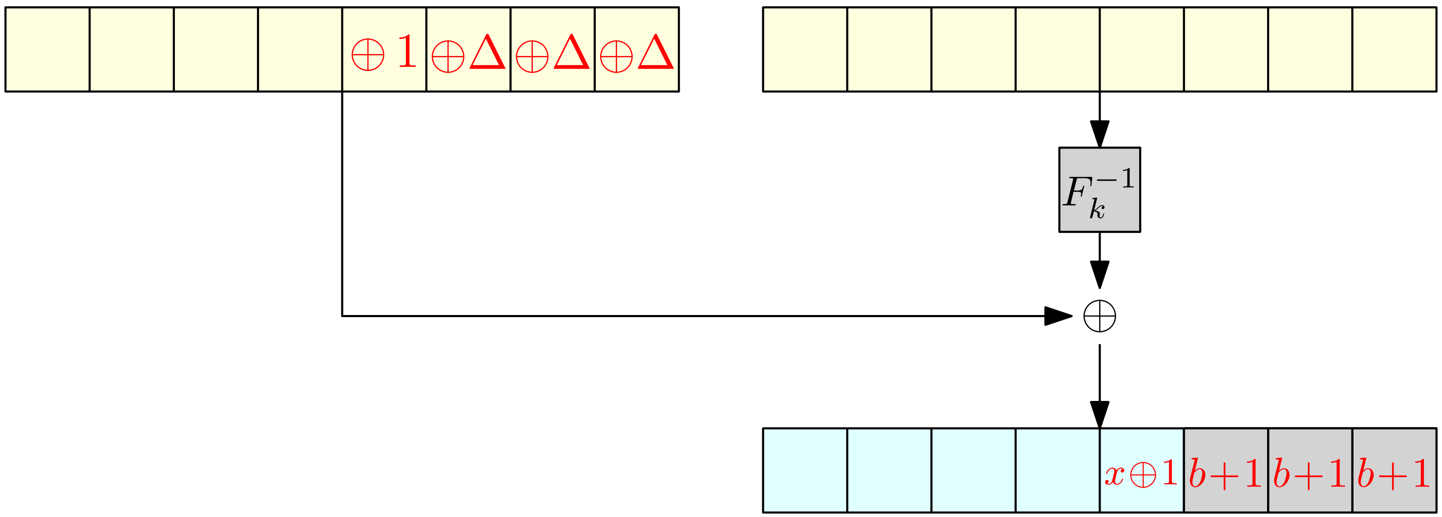

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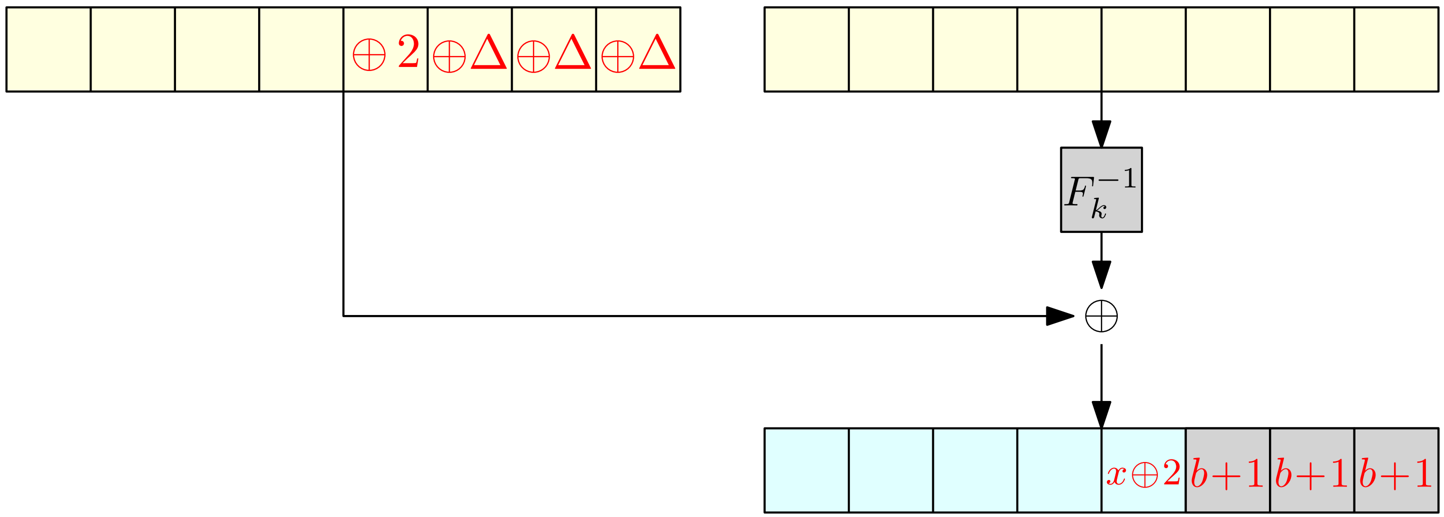

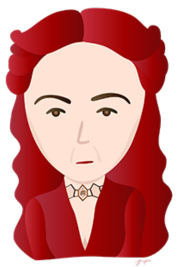

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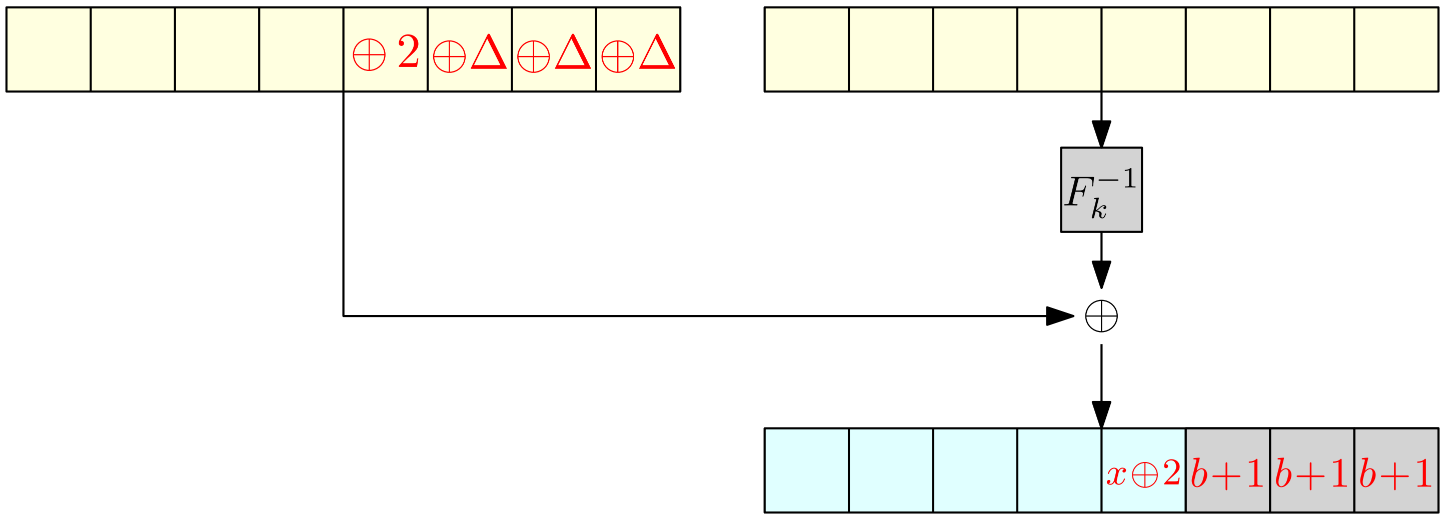

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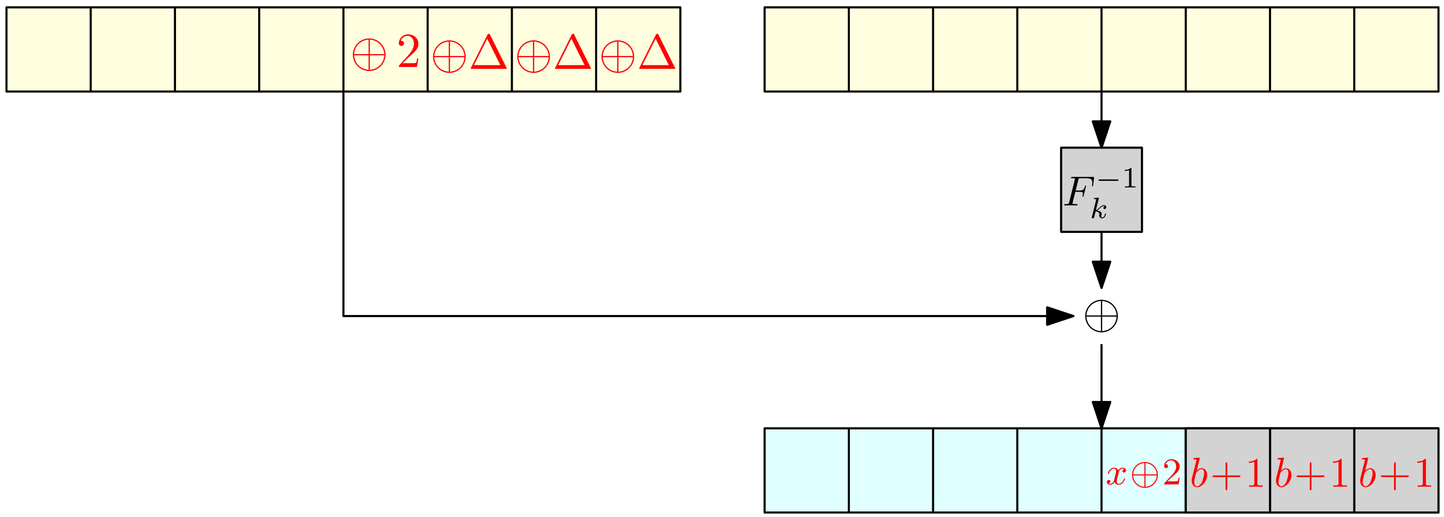

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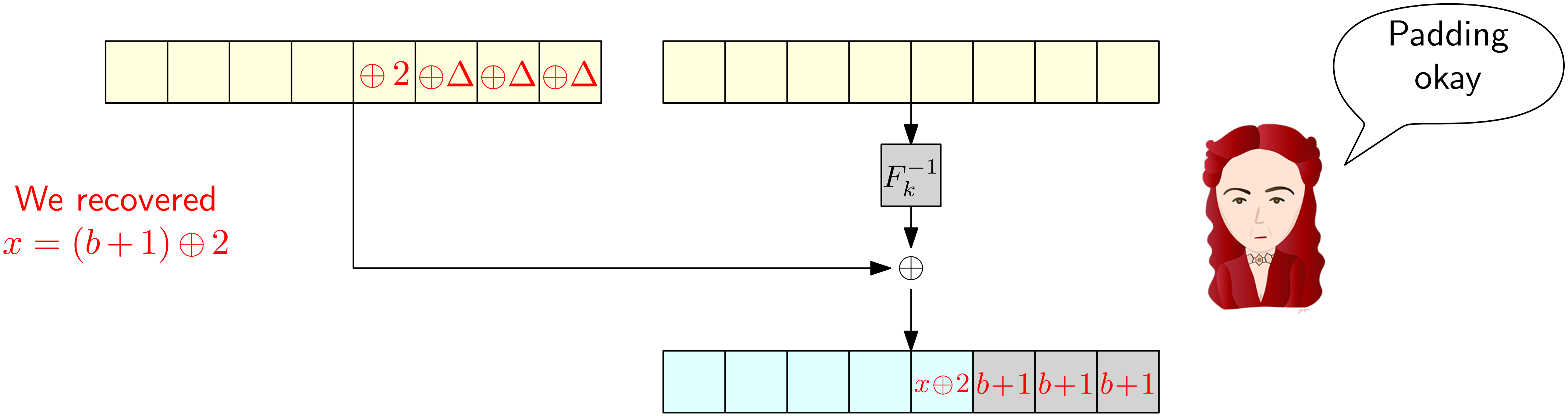

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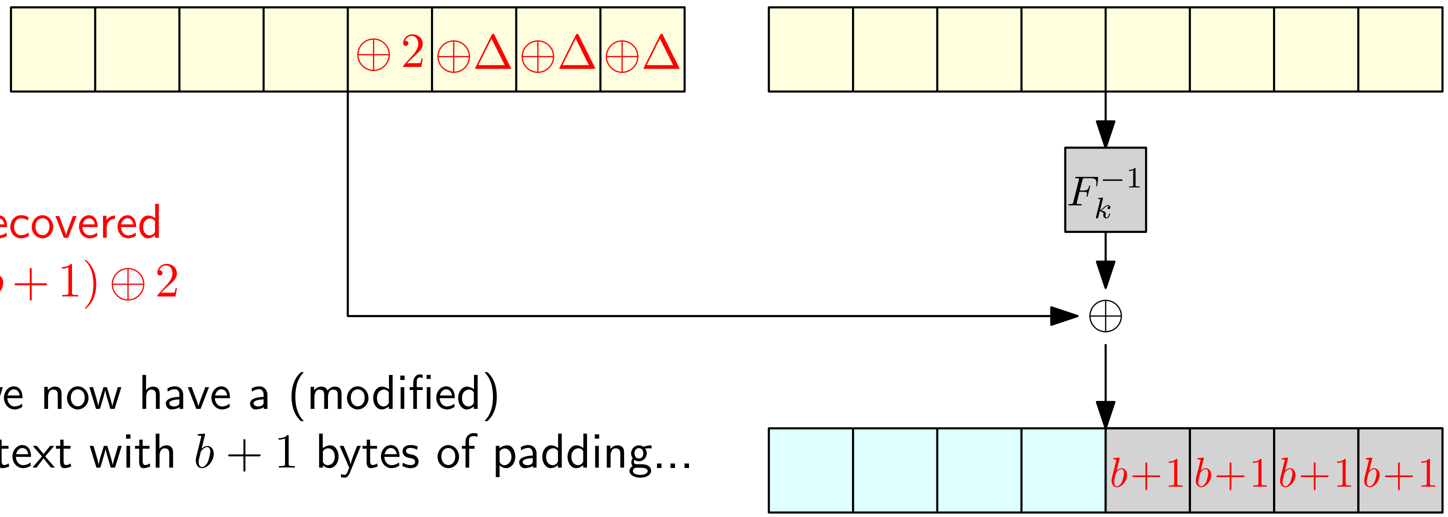

And we now have a (modified) ciphertext with $b+1$ bytes of padding...

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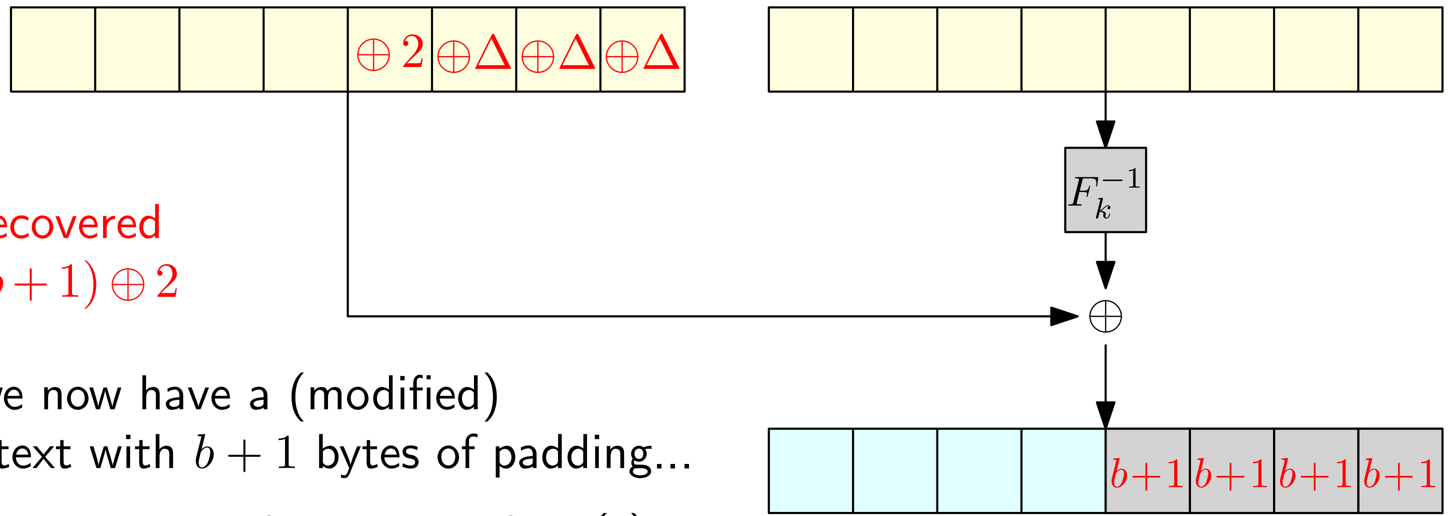

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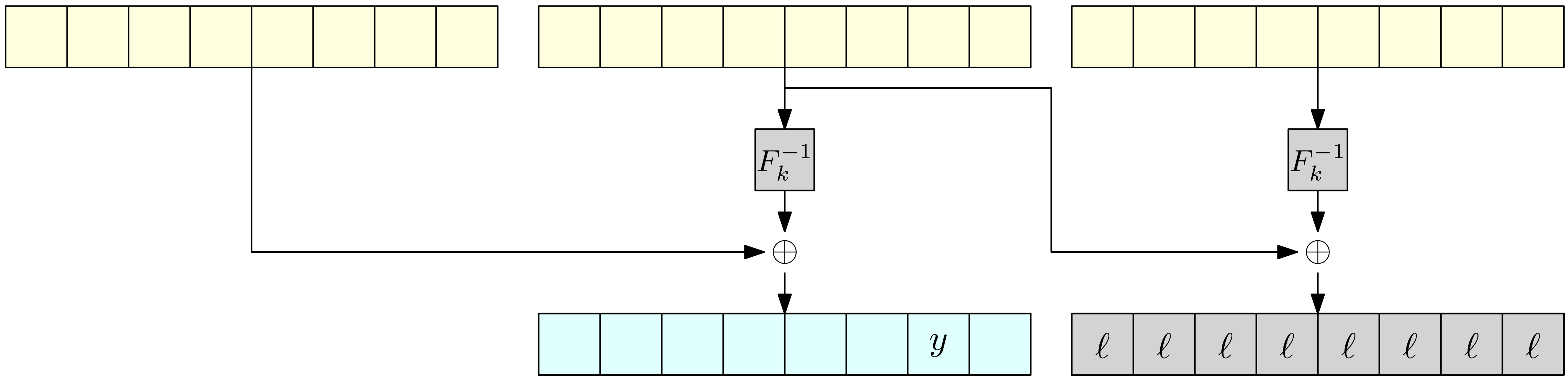
And we now have a (modified) ciphertext with $b+1$ bytes of padding...

Repeat to recover the previous byte(s)...

Recovering the previous block

What do we do if/when the last block of the ciphertext consists entirely of padding?

- This can happen on the original ciphertext, or on one of the modified ciphertext after the last block of plaintext has been recovered



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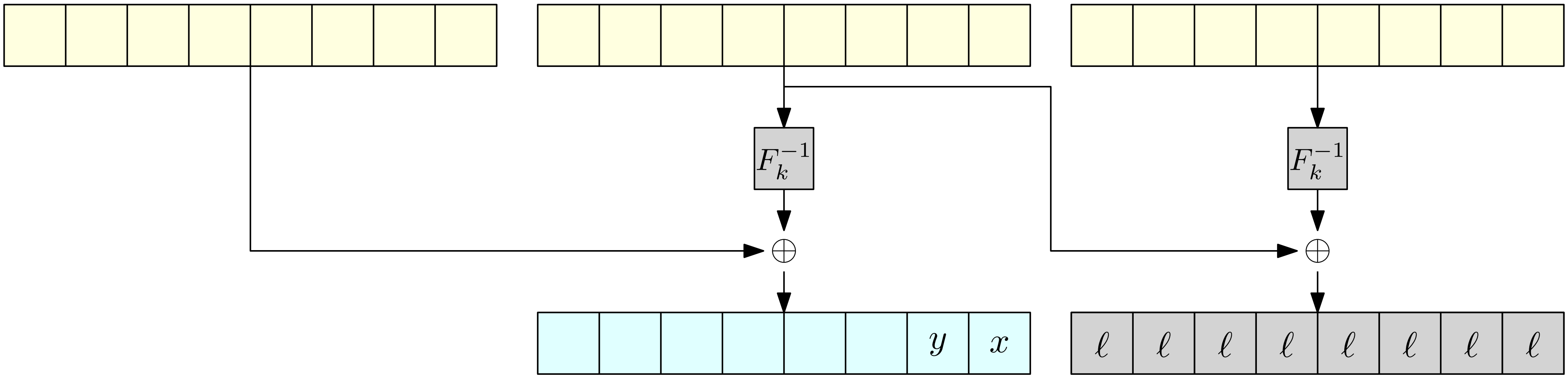

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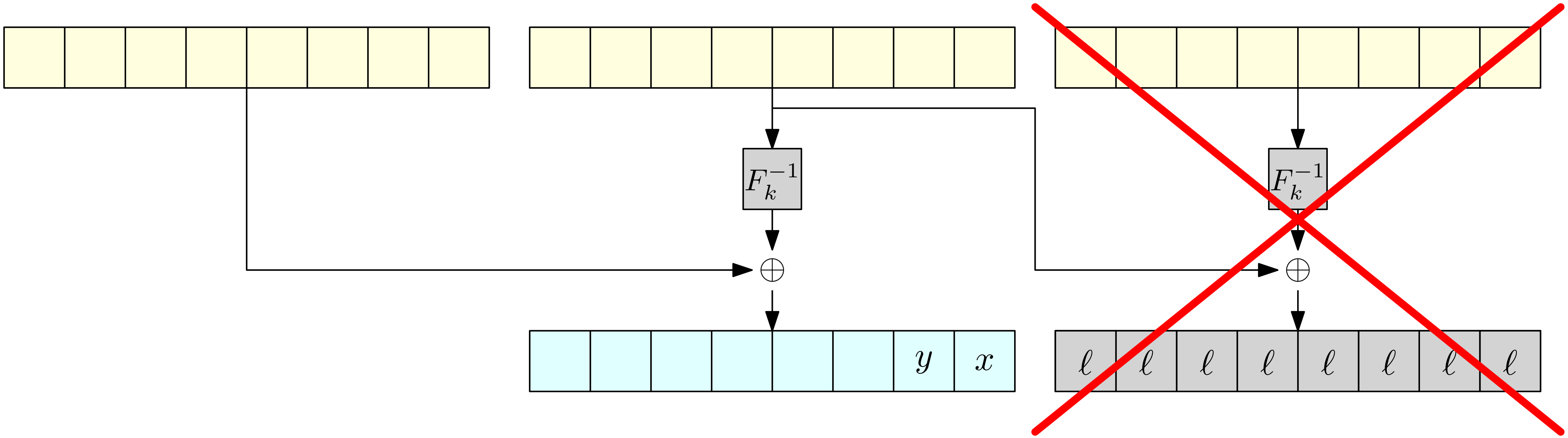
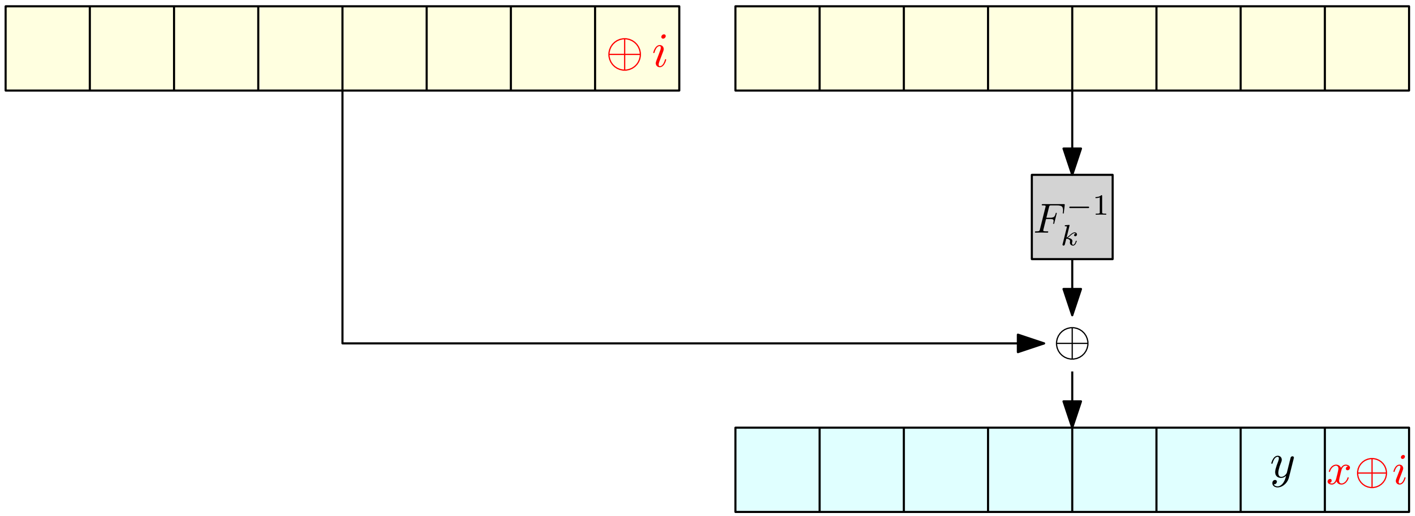
Permanently drop the last block of the ciphertext



Recovering the previous block

Try to transform x into a 1 (which is a valid 1-byte padding of the remaining ciphertext)

- For every $i \in \{0, \ldots, 255\}$, XOR x with i (by XOR-ing the previous block of the ciphertext)



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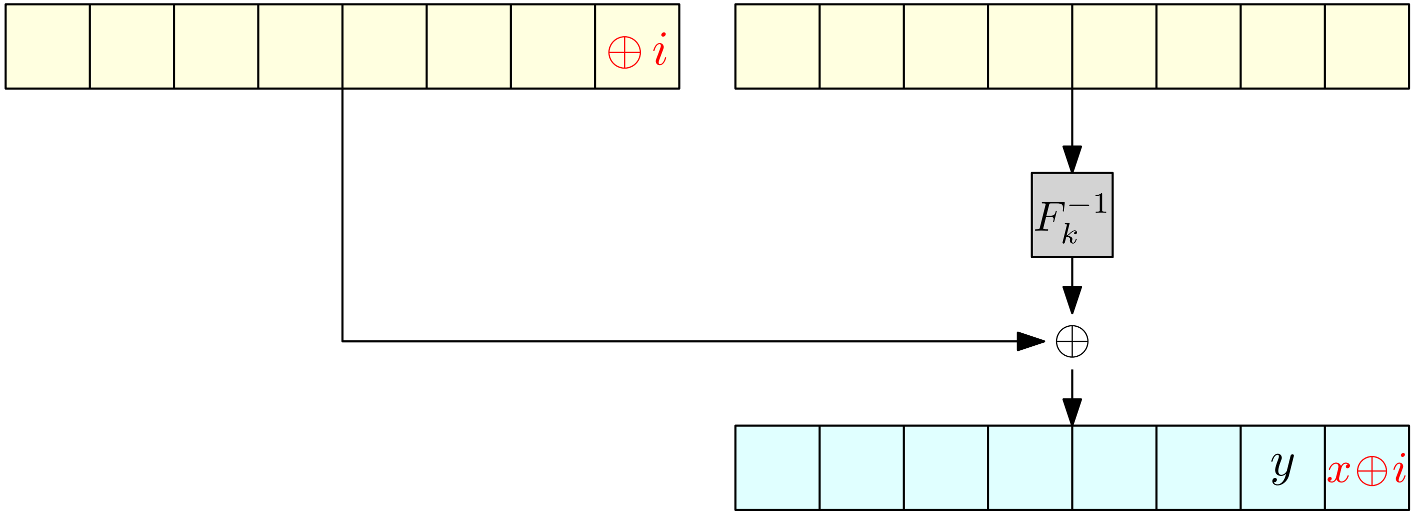

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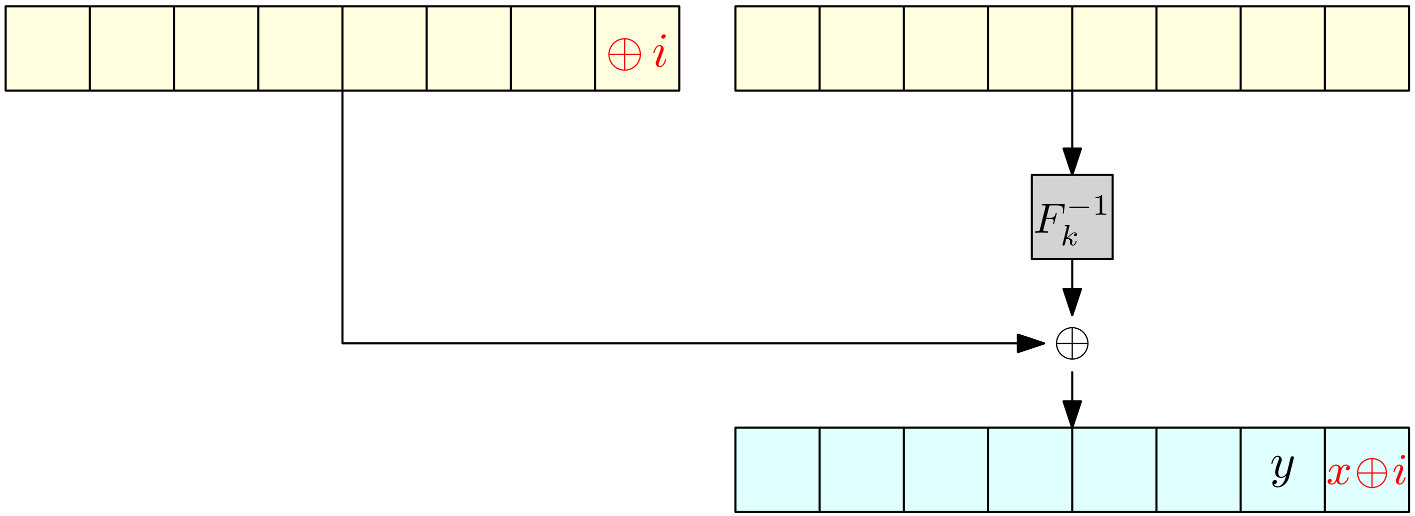

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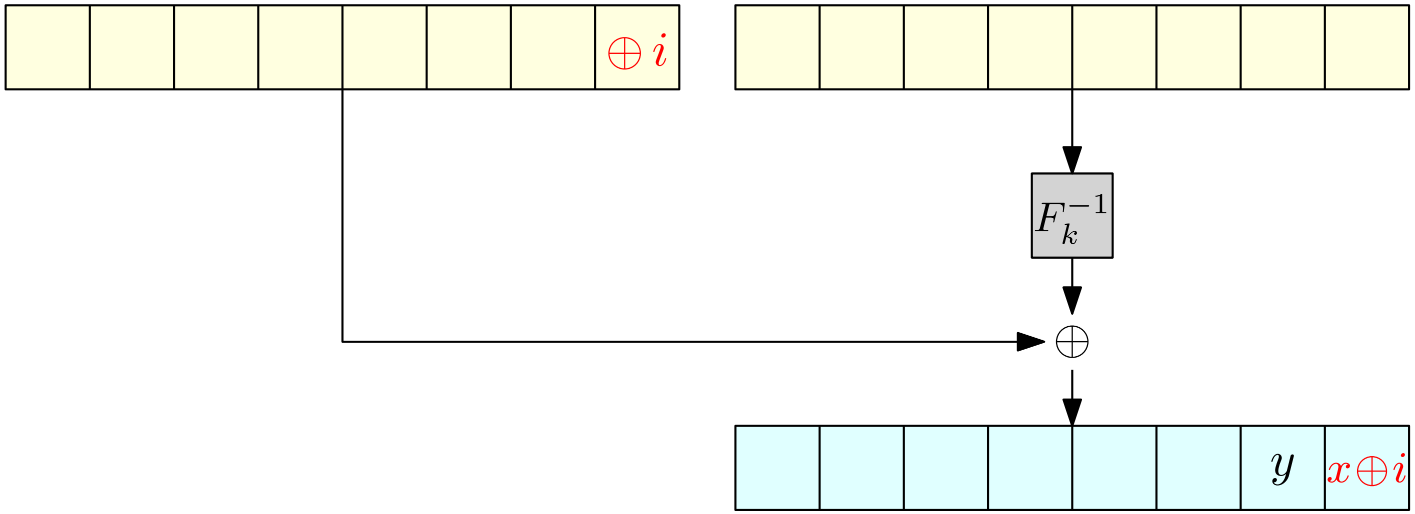

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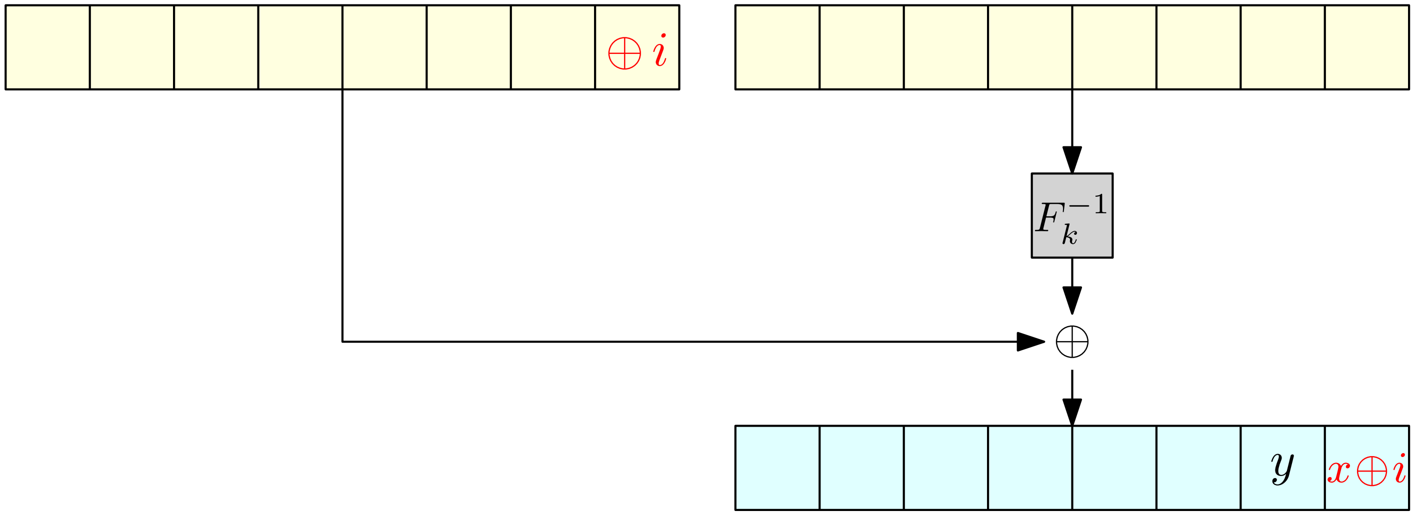

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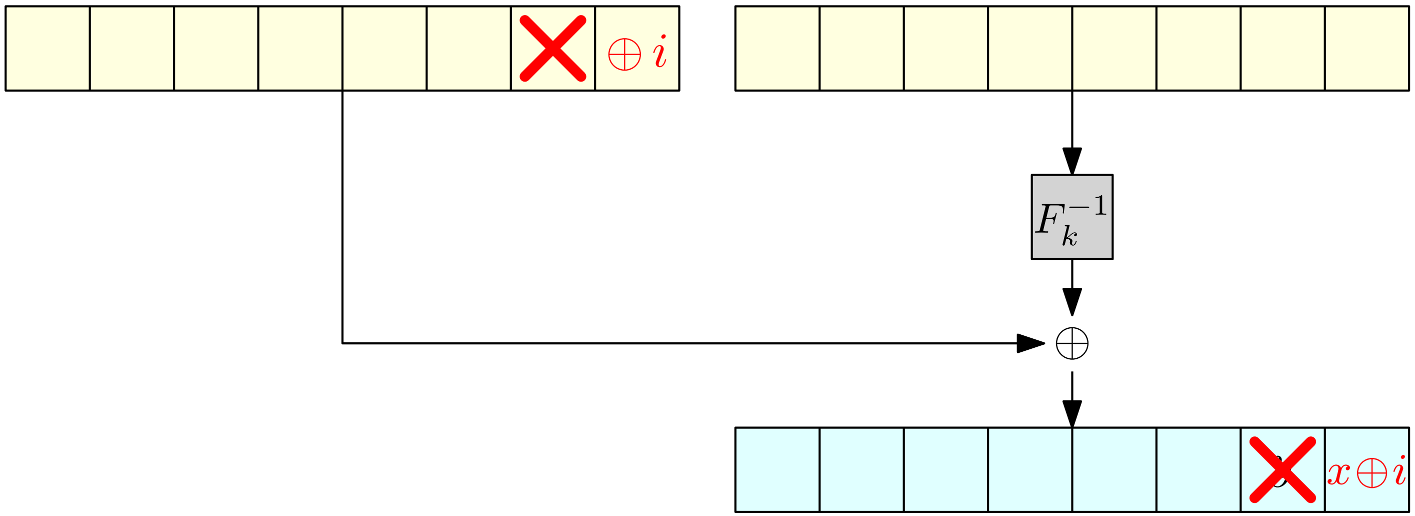

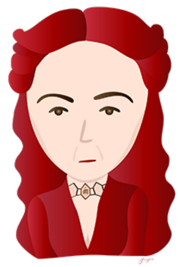

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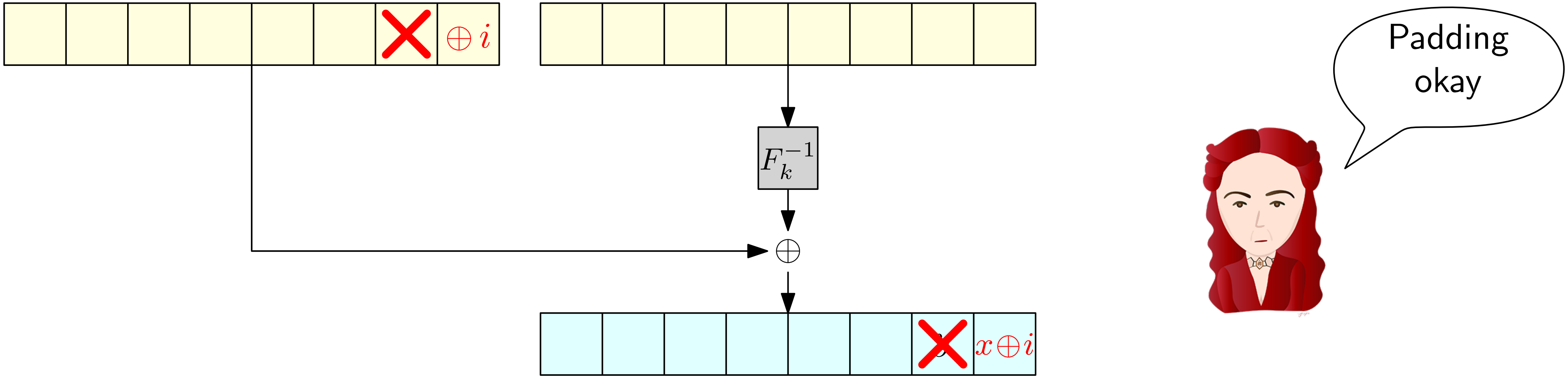

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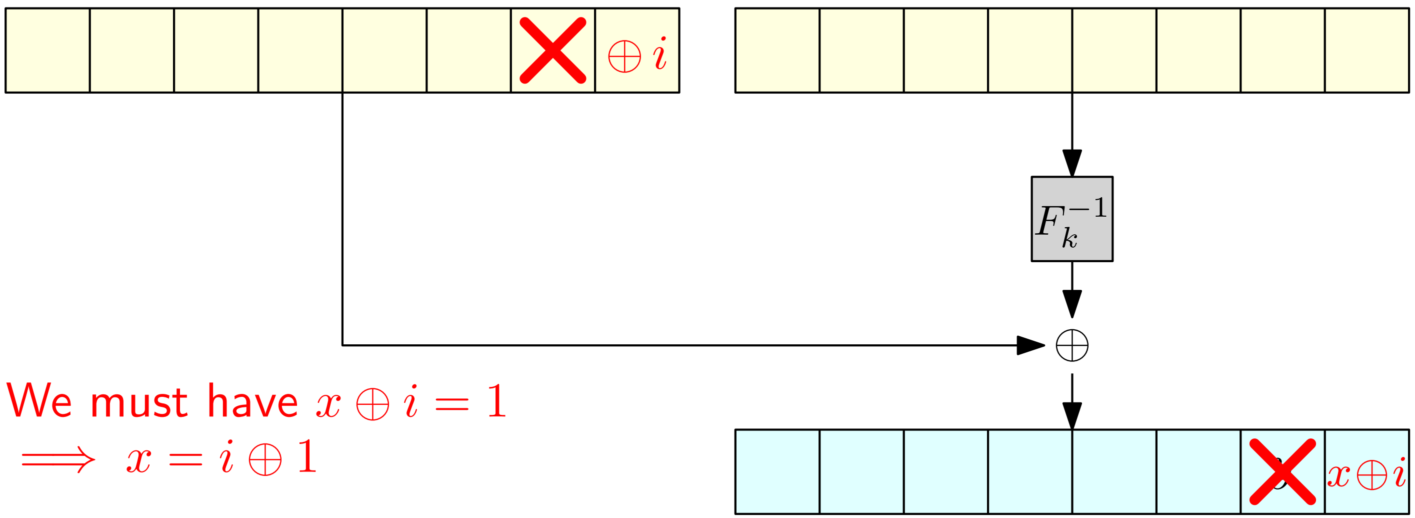

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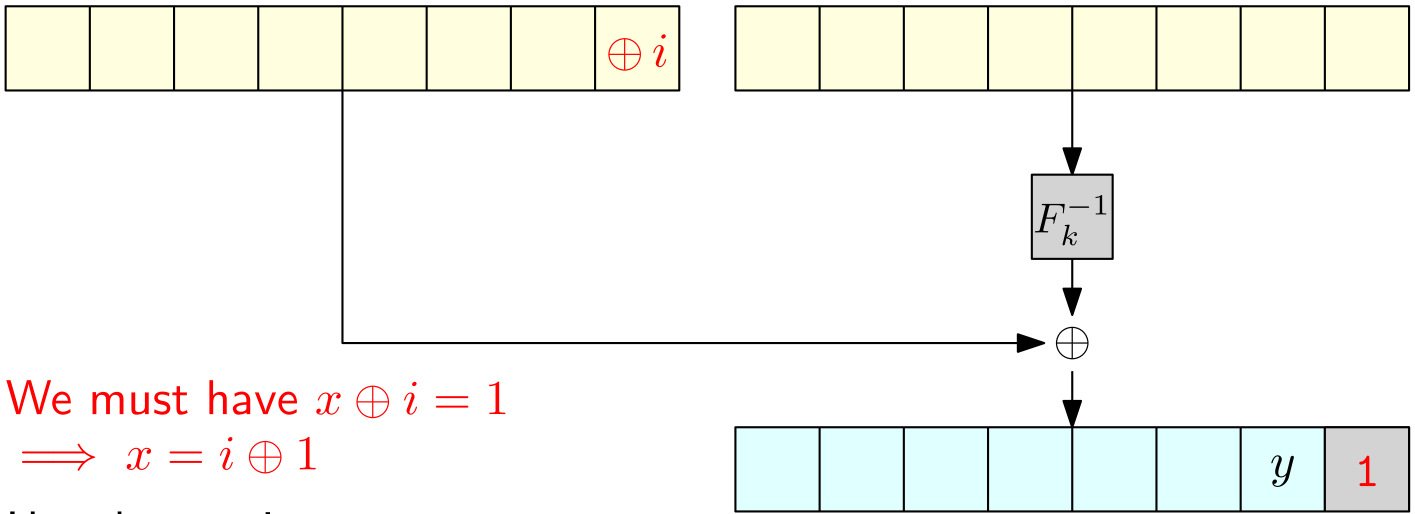

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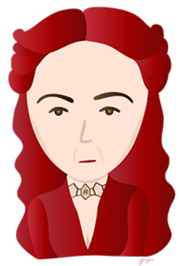
Use the previous strategy to recover the rest of the block



Padding Oracle Attack: Complexity?

- At most ℓ attempts to learn the length of the padding
- At most 257 attempts to learn a byte of the ciphertext
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At most $\ell + 257 \cdot |m|$ decryption attempts

Linear in $|m|$ and ℓ!

CCA Security and Authenticated Encryption

- Chosen-ciphertext attacks are not just a theoretical threat

  E.g., padding oracle attacks against SSL, IPSec, Steam...

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- Fortunately we can build CCA-secure encryption schemes from CPA-secure encryption schemes
- In fact, we are going to achieve an even stronger security guarantee:

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- We know how to achieve secrecy against passive adversaries
- We know how to achieve integrity against active adversaries

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- **Integrity requirement:** unforgeability

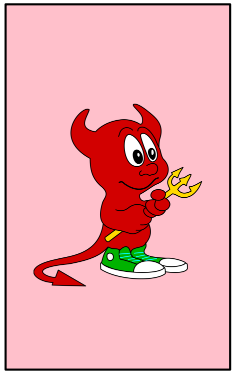
  Intuition: The adversary cannot efficiently provide any valid ciphertext
  (unless it corresponds to a message that was already encrypted by the honest parties)

The Unforgeability Experiment (adapted for AE)

Let $\Pi = (\mathsf{Gen}, \mathsf{Enc}, \mathsf{Dec})$ be an encryption scheme. We name the following experiment $\mathsf{Enc\text{-}forge}_{\mathcal{A},\Pi}(n)$:

- A key k is generated using $\mathsf{Gen}(1^n)$

Encryption
and
Decryption
oracles
using key k



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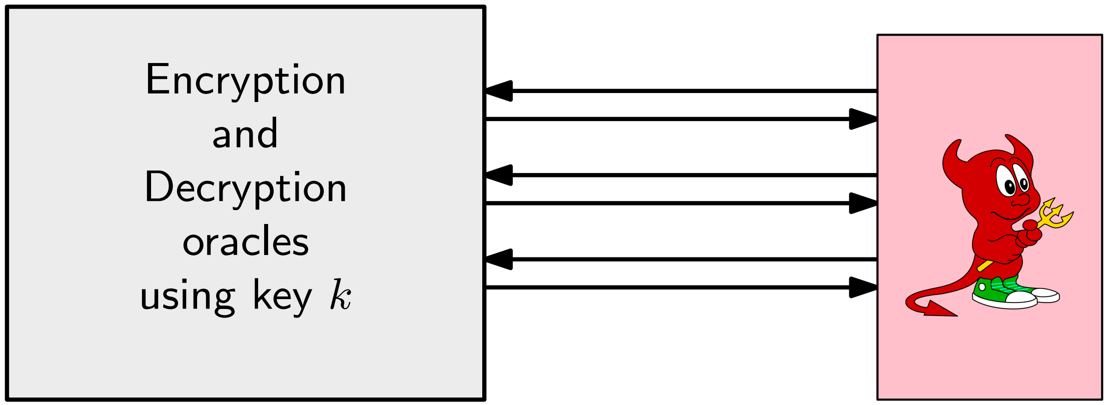

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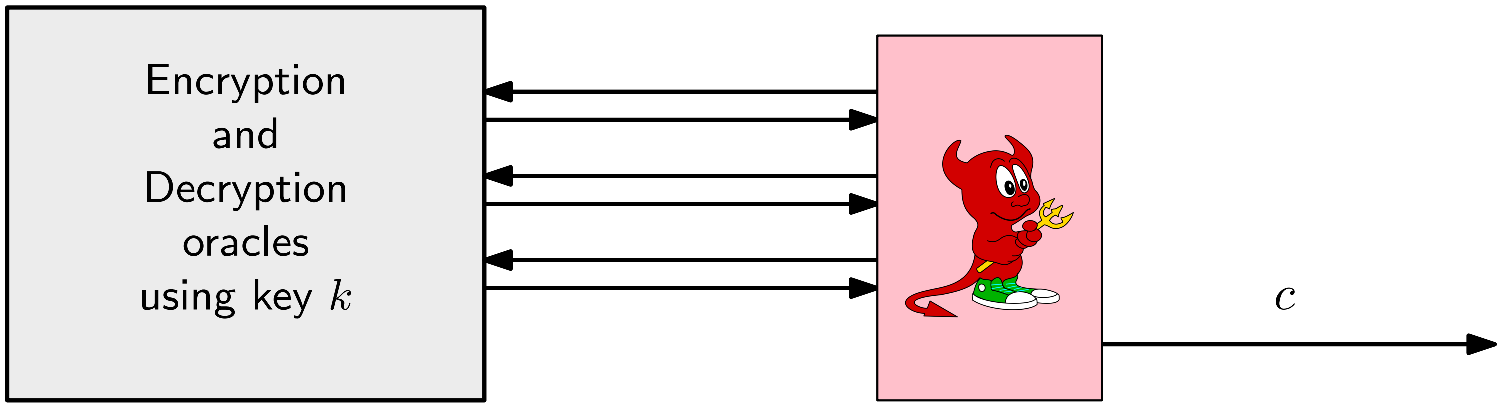

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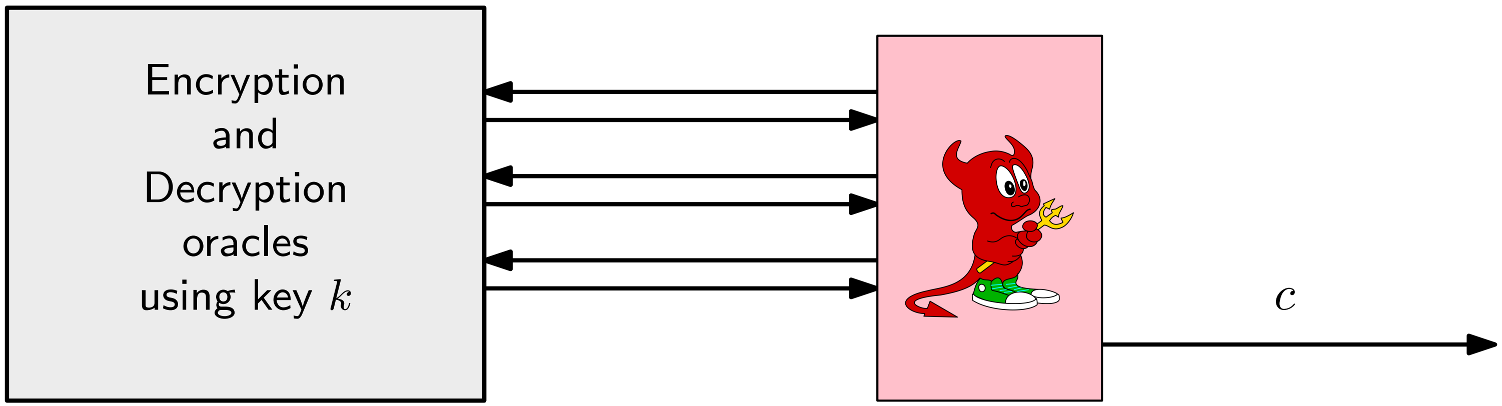
- Let $m \leftarrow \mathsf{Dec}_k(c)$
- The outcome of the experiment is 1 if $m \neq \perp$ and the adversary never queried the encryption oracle with m. Otherwise the outcome is 0.



The Unforgeability Experiment (adapted for AE)

Let $\Pi = (\mathsf{Gen}, \mathsf{Enc}, \mathsf{Dec})$ be an encryption scheme. We name the following experiment $\mathsf{Enc\text{-}forge}_{\mathcal{A},\Pi}(n)$:

- A key k is generated using $\mathsf{Gen}(1^n)$

The key is kept secret from $\mathcal{A}$

- The adversary $\mathcal{A}$ can interact with an encryption oracle providing access to $\mathsf{Enc}_k(\cdot)$ and with a decryption oracle providing access to $\mathsf{Dec}_k(\cdot)$
- The adversary outputs a ciphertext c
- Let $m \leftarrow \mathsf{Dec}_k(c)$
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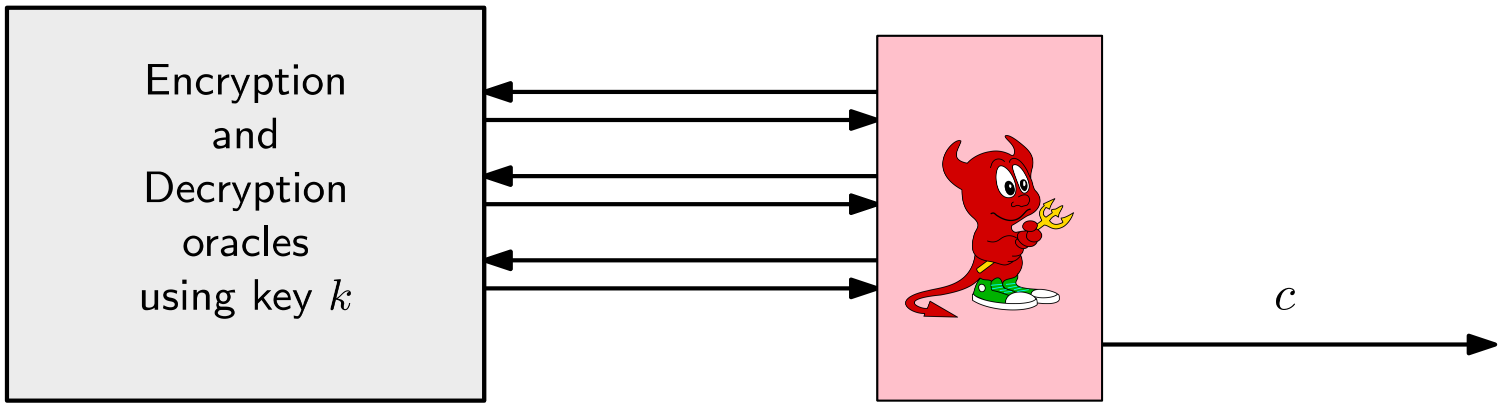

Definition of Authenticated Encryption

Definition: *A private key encryption scheme* Π *is* **unforgeable** *if, for every probabilistic polynomial-time adversary* $\mathcal{A}$*, there is a negligible function* ε *such that:*

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Notice that AE $\implies$ **CCA-security**

There is also an equivalent definition of authenticated encryption based on a single experiment. See the textbook if interested.

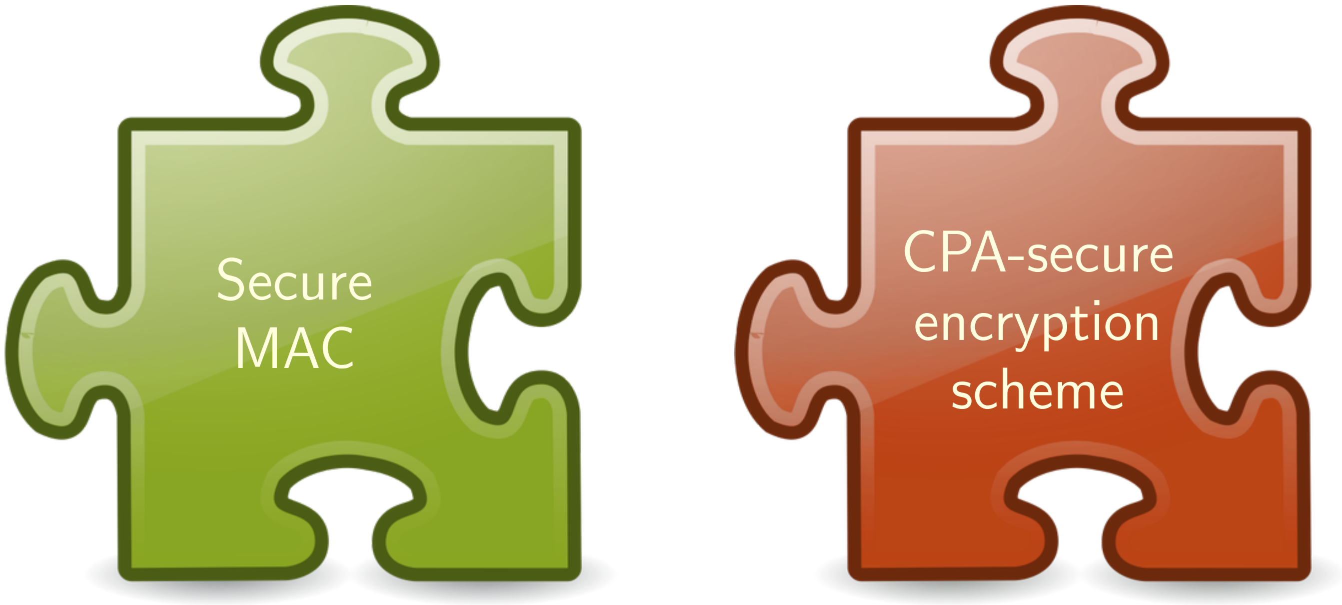
Modular Construction of Authenticated Encryption schemes

Can we design an Authenticated Encryption scheme in a modular way?

Modular Construction of Authenticated Encryption schemes

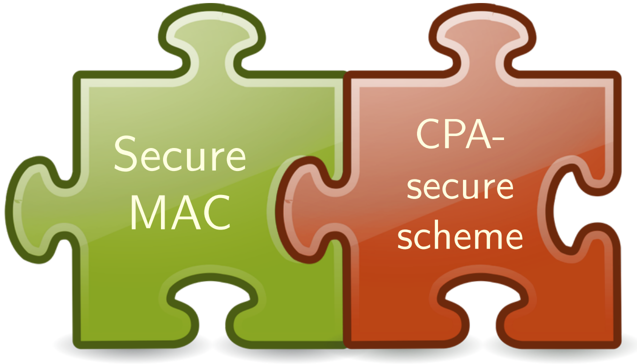
Can we design an Authenticated Encryption scheme in a modular way?

- Pick any secure MAC
- Pick any CPA-secure encryption scheme
- Combine them (somehow)



Combining MACs and CPA-secure encryption schemes

How do we combine MACs with CPA-secure encryption schemes?



Ideas?

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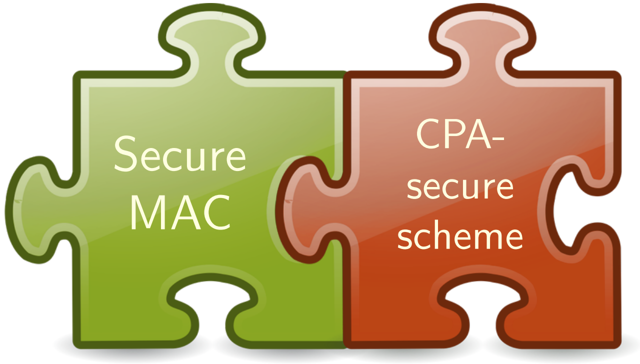

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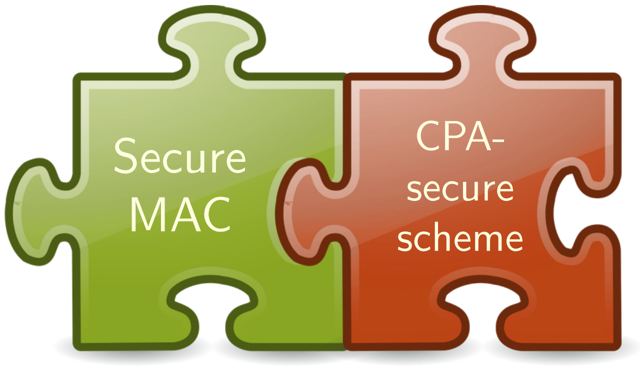

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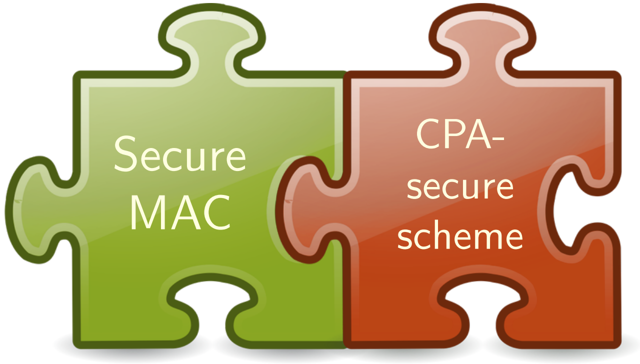

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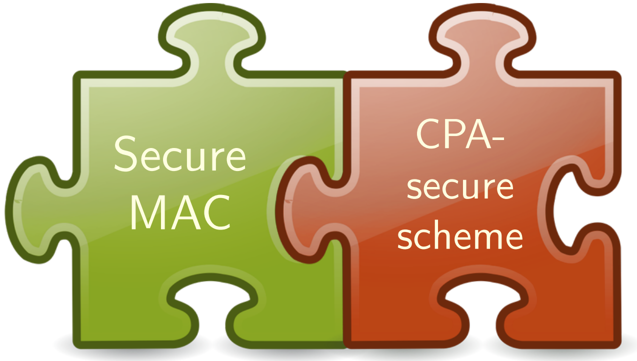

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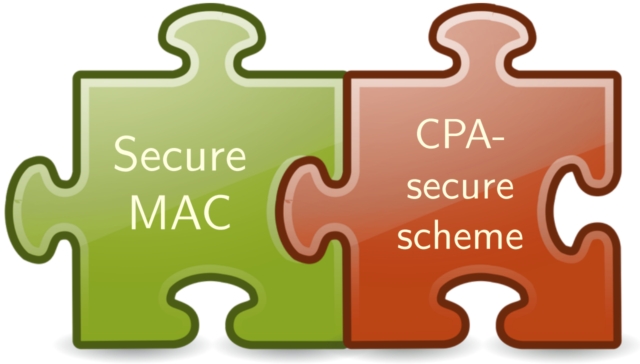

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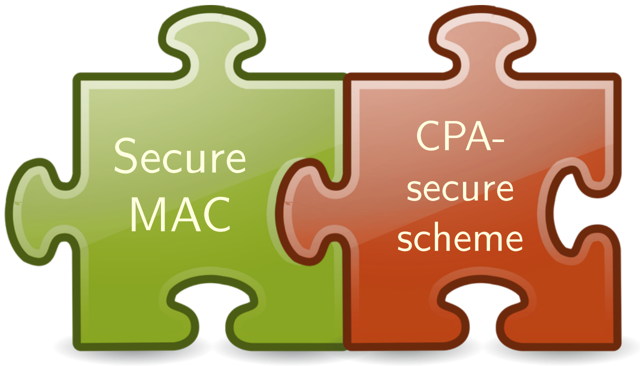

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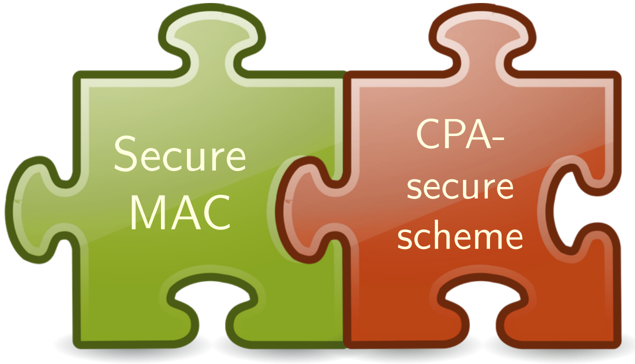

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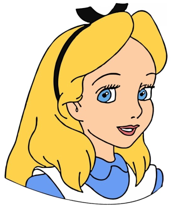
Encrypt and Authenticate

Pick two **independent** keys k_1 and k_2 for encryption and MAC, respectively

k_1, k_2 

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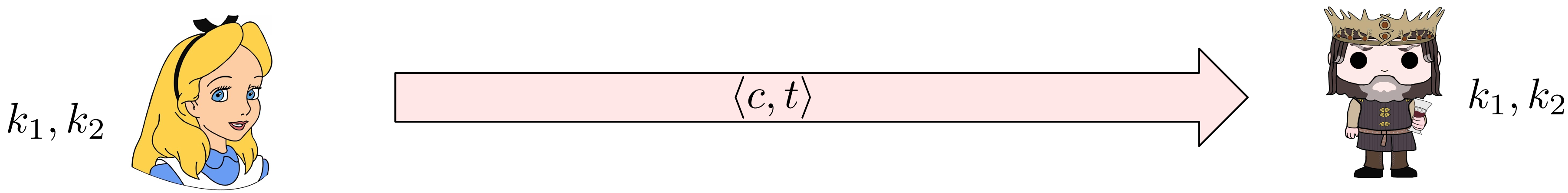

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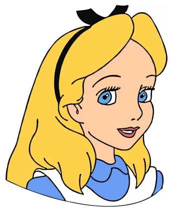

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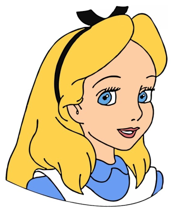
k_1, k_2 

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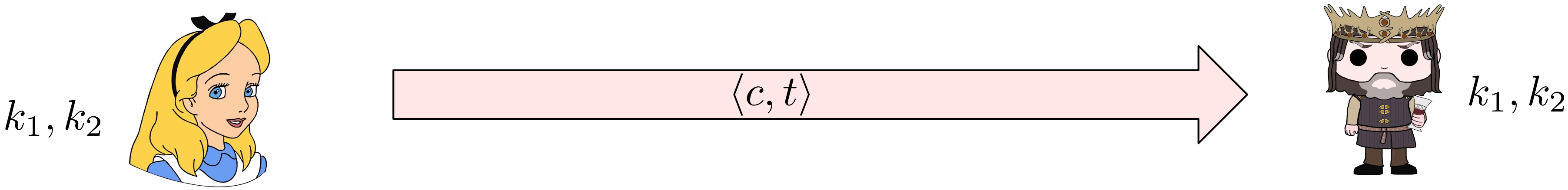

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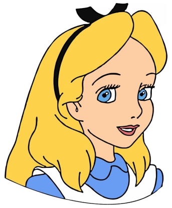

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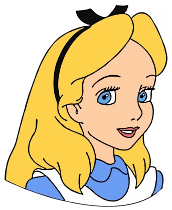
k_1, k_2  $\langle c, t \rangle$ →  k_1, k_2

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This scheme is not even CPA-secure!

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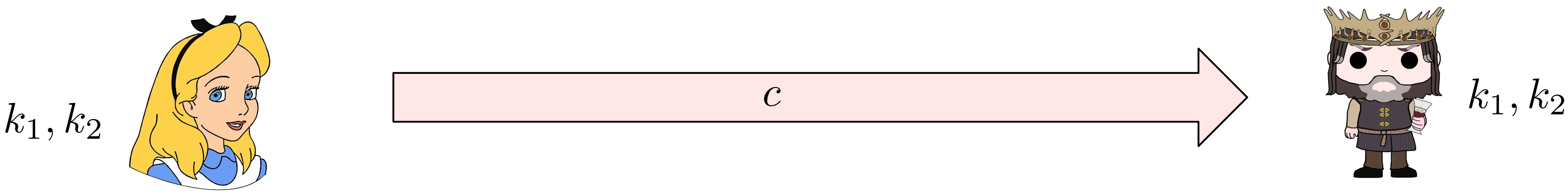

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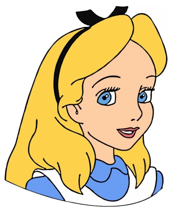

c

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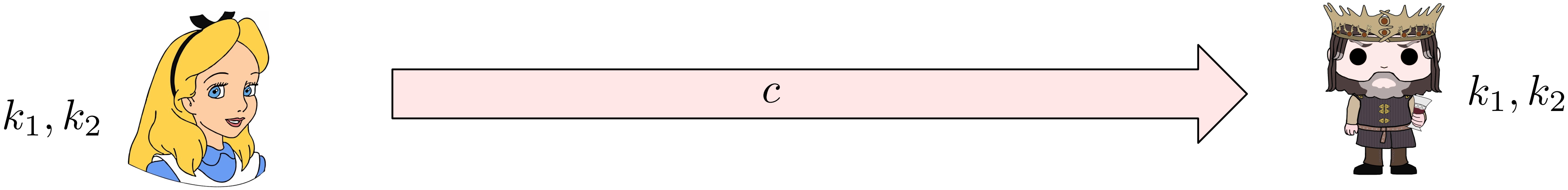

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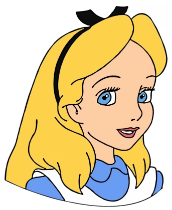

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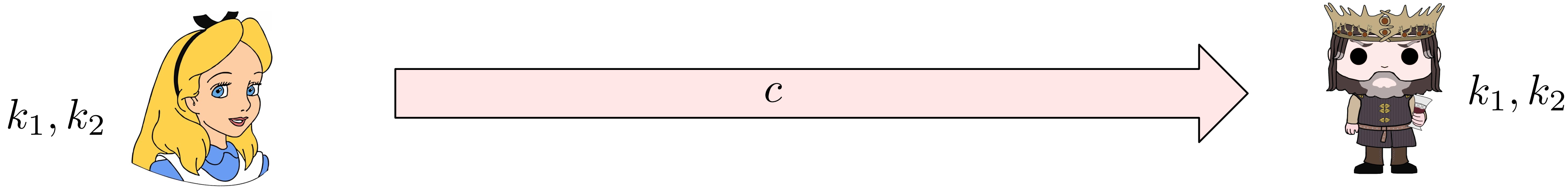

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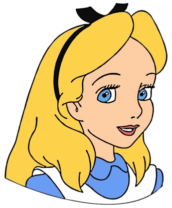

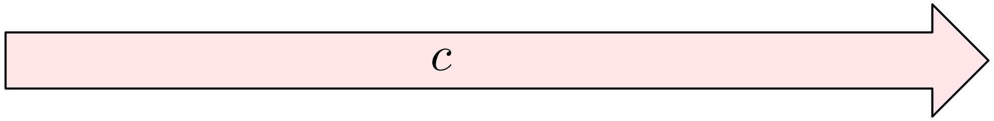

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- There are other counterexamples that do not rely on padding errors

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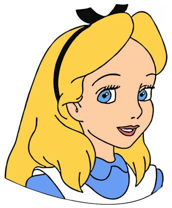
k_1, k_2  $\langle c, t \rangle$ →  k_1, k_2

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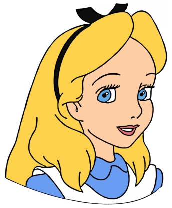

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- $k_1 \leftarrow \mathsf{Gen}_E(1^n)$
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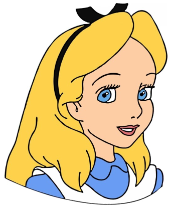

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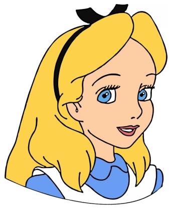


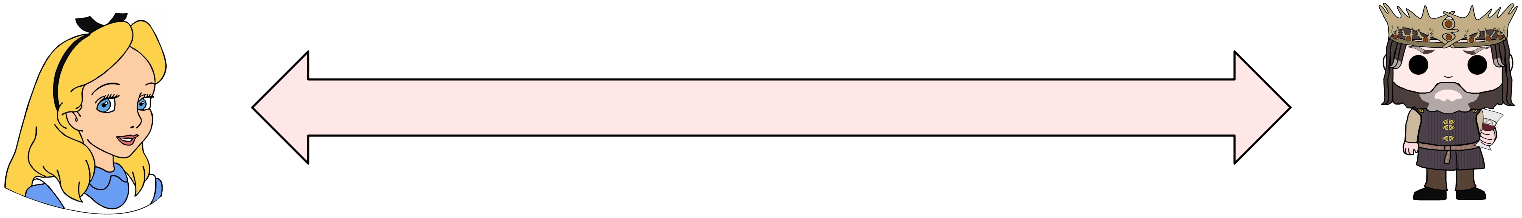
$\langle c, t \rangle$

k_1, k_2

Theorem: If $(\mathsf{Gen}_E, \mathsf{Enc}, \mathsf{Dec})$ is a CPA-secure private-key encryption scheme, and $(\mathsf{Gen}_M, \mathsf{Mac}, \mathsf{Vrfy})$ is a strongly secure message authentication code, then the above construction is an authenticated encryption scheme.

Secure Sessions

Alice and Bob wish to communicate securely (over an insecure channel) over the course of a *communication session* (a period of time over which they maintain state) exchanging multiple messages



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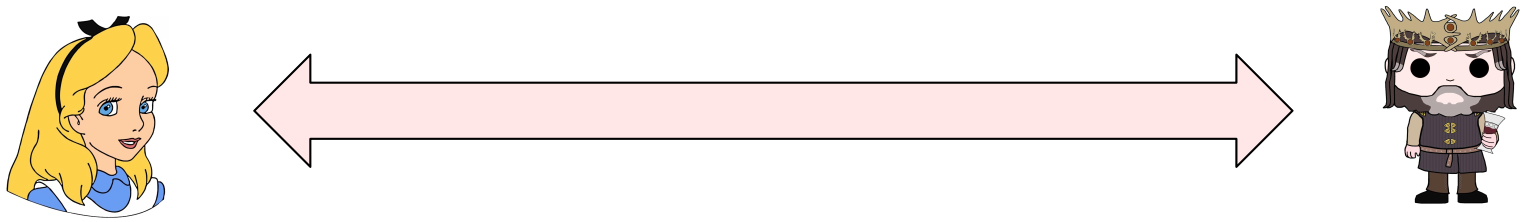

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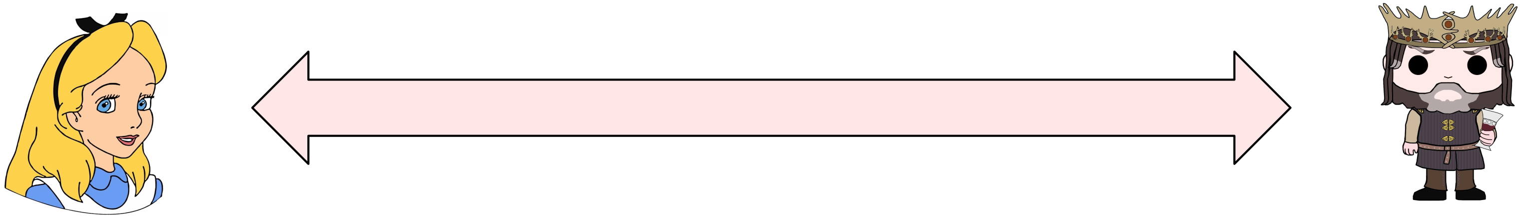

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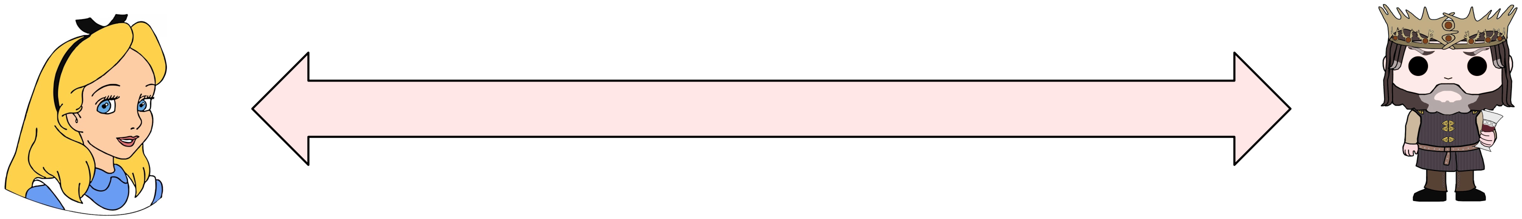

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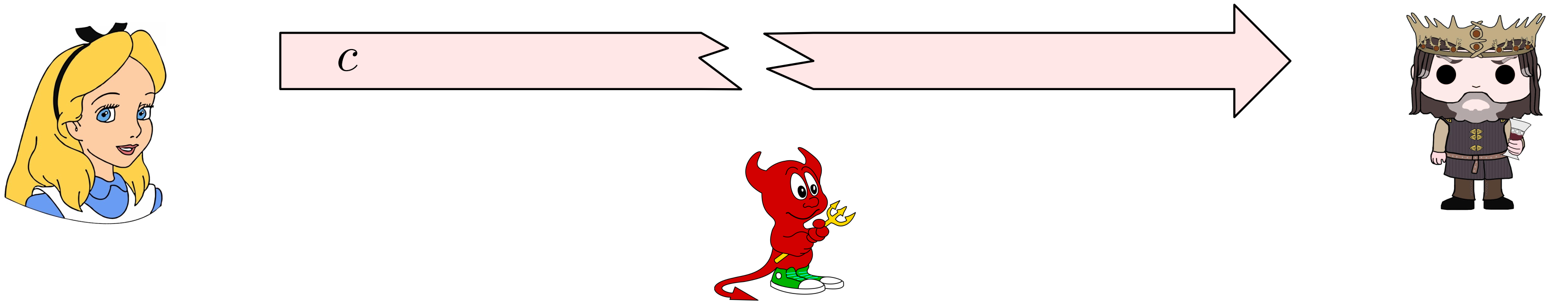
Message dropping:



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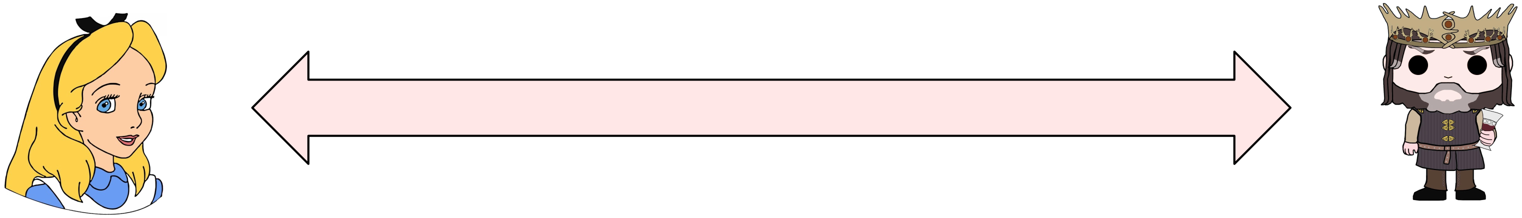
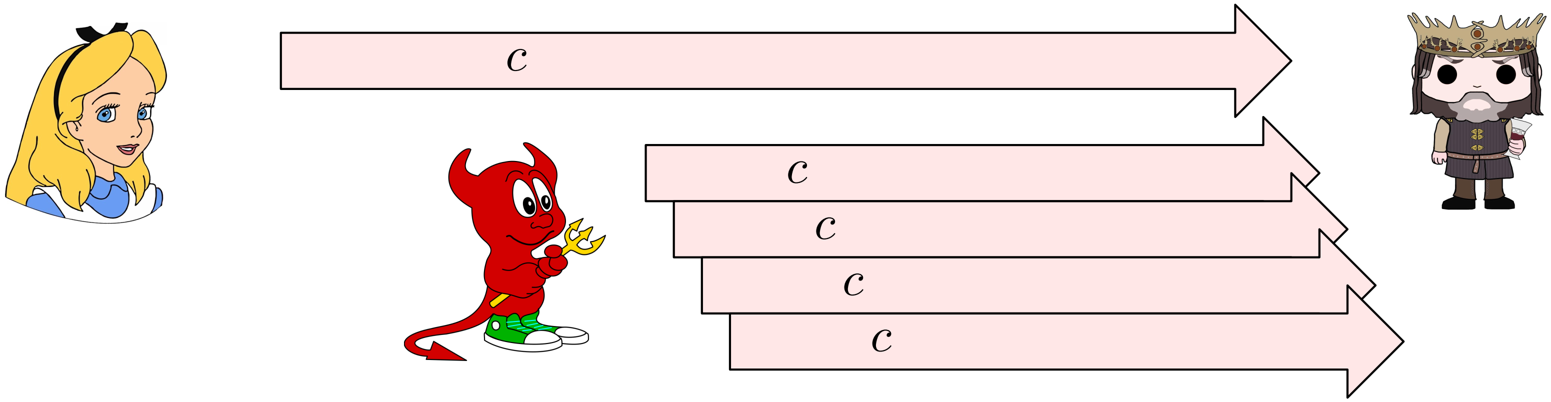


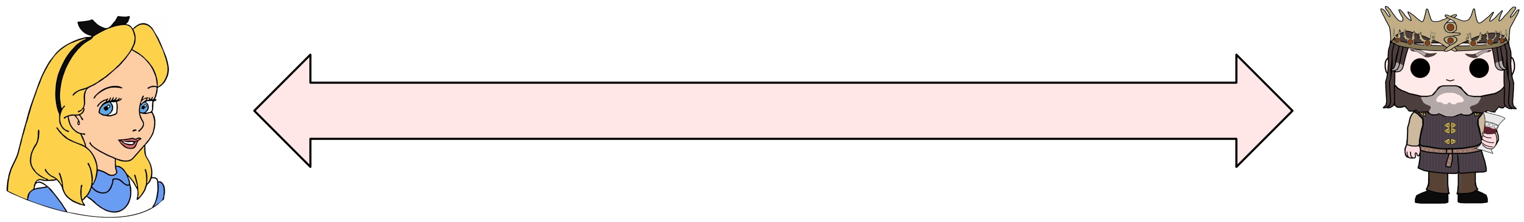
~~Easy! Just use Authenticated Encryption~~ Not so fast...

Replay attack (we have already encountered this attack):



Secure Sessions

Alice and Bob wish to communicate securely (over an insecure channel) over the course of a *communication session* (a period of time over which they maintain state) exchanging multiple messages



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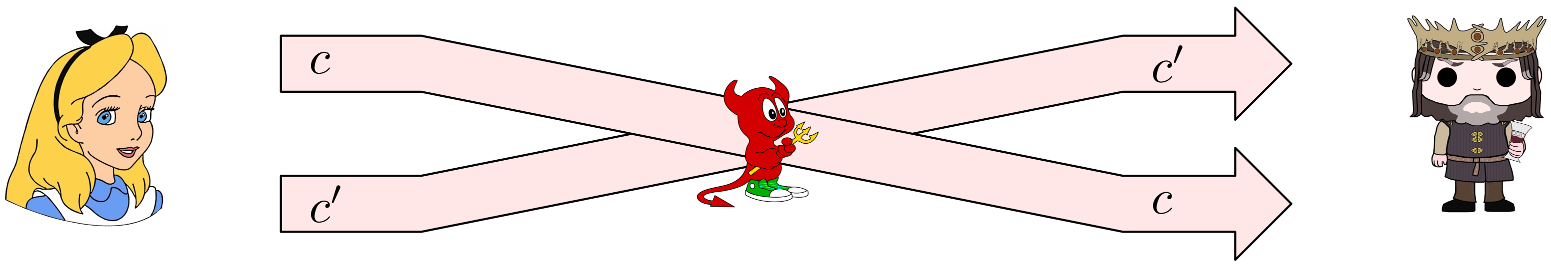
Re-ordering attack (the adversary reorders messages, not blocks):



Secure Sessions

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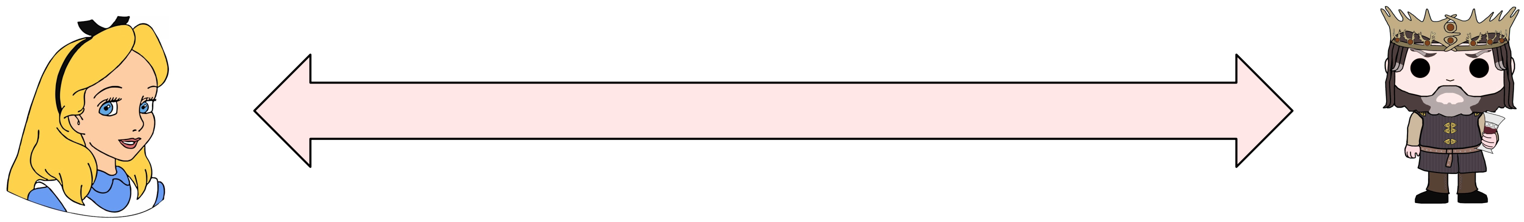

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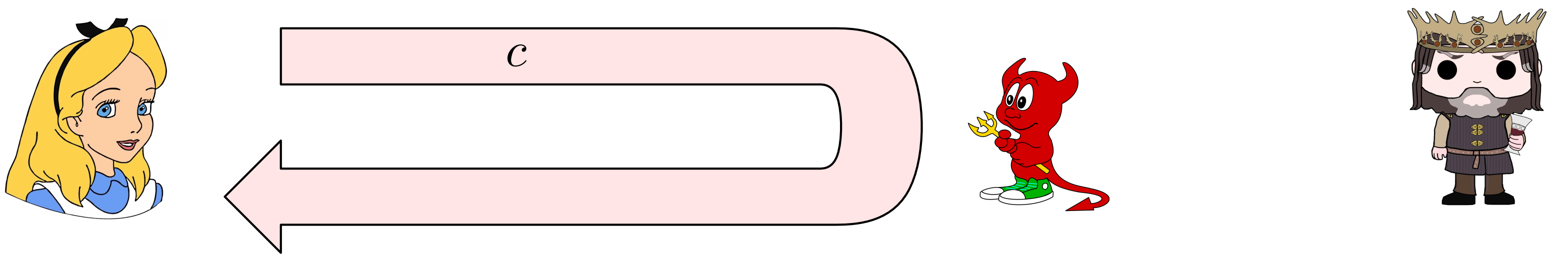
Reflection attack



Secure Sessions

How do we defend from these attacks?

Message dropping, **Replay attacks** and **Re-ordering attacks**:

- Send a counter along with each message
- The recipient checks that the received counters are consecutive numbers
- Message dropping cannot be prevented, but we can at least detect it if a subsequent message reaches the recipient

Secure Sessions

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Reflection attack

- Add a directionality bit d to each message
- E.g., $d = 0$ if the message is sent from Alice to Bob and $d = 1$ if the message is sent from Bob to Alice
- Need to agree on direction. E.g., in a client/server connection we might assign $d = 0$ to the client and $d = 1$ to the server

Secure Sessions