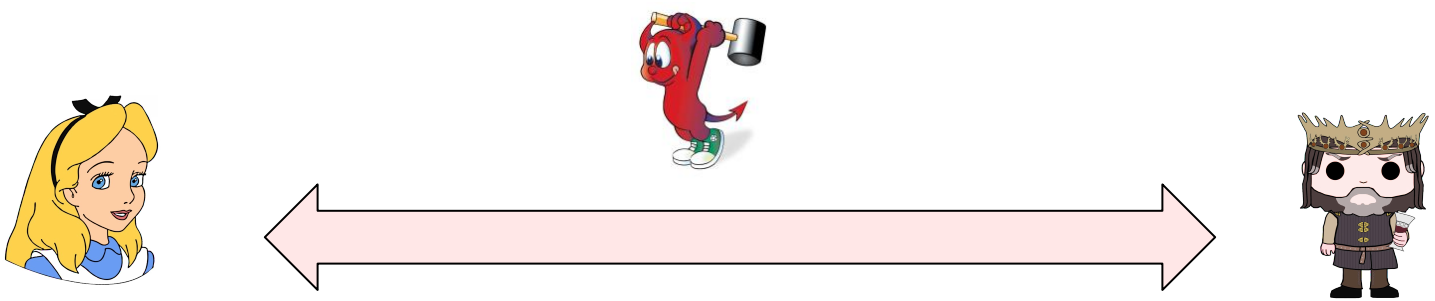
Reminder: Passive vs Active Attacks

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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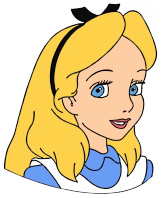
Reminder: Malleability of OTP

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



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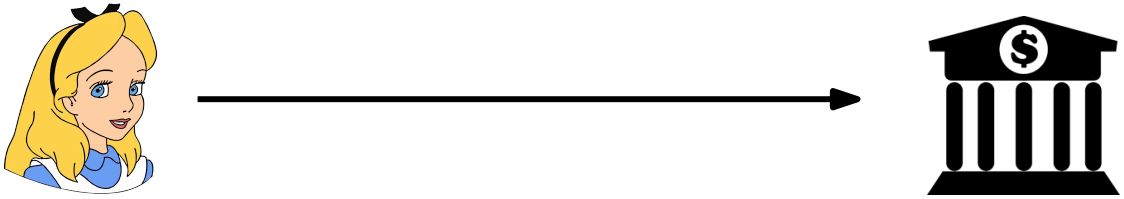

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- The message is encrypted with a one-time pad

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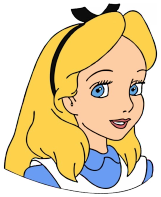

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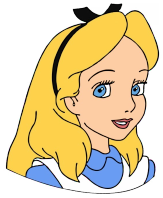

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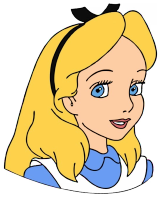

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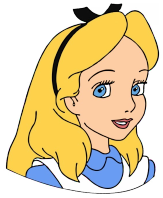

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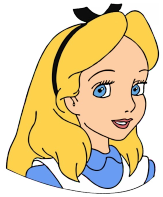

$c = \underbrace{00110110001010100000110101}_{\texttt{PAY}}\underbrace{11010001\ldots10001101}_{\texttt{IBAN}}\underbrace{10111110100100}$

$\oplus$

Changes to the ciphertext result in predictable changes to the plaintext

The scheme is **malleable**!

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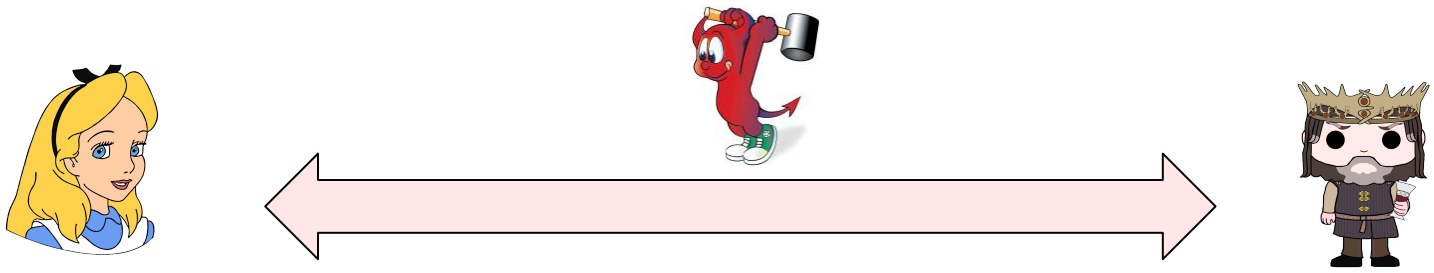

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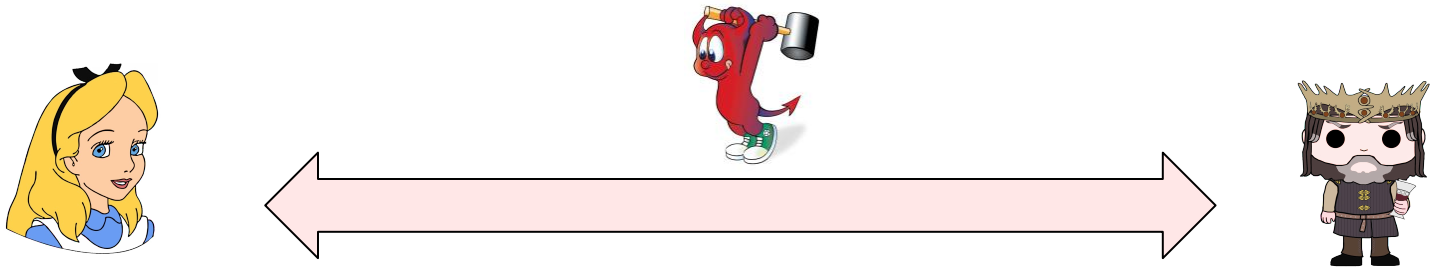

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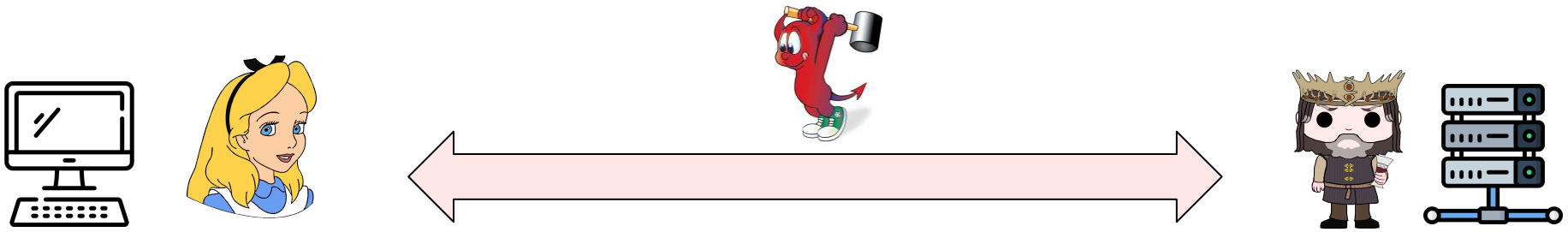

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Many protocols close a connection or request a retransmission when a bad message is received

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

Encryption oracle

Decryption oracle

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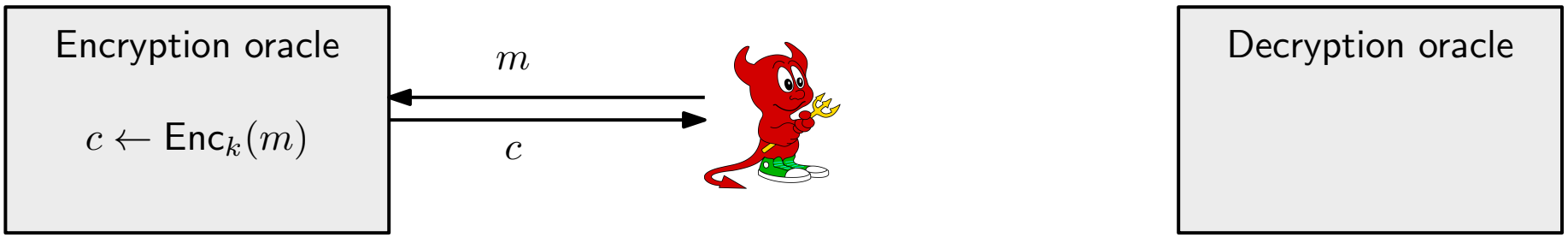

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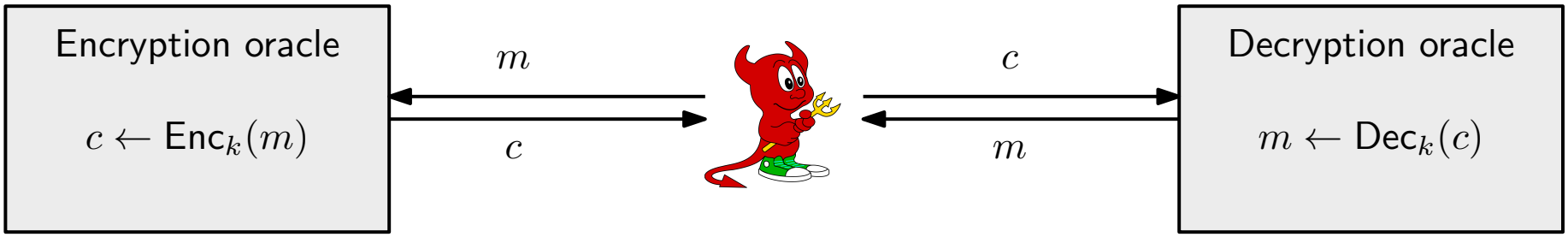

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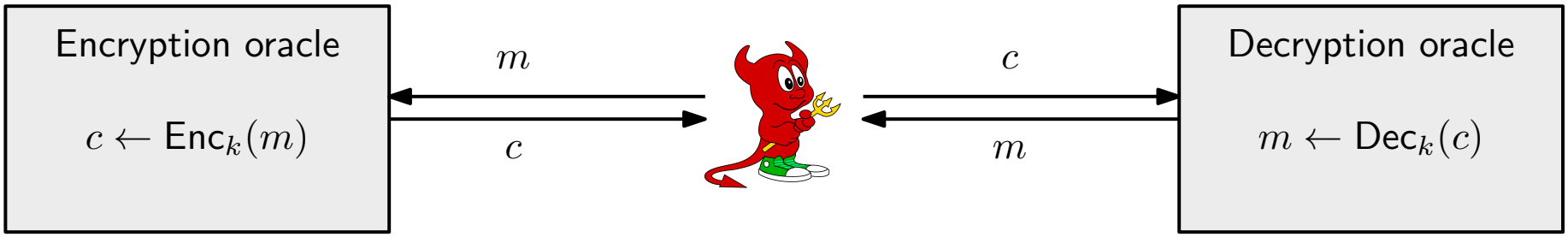

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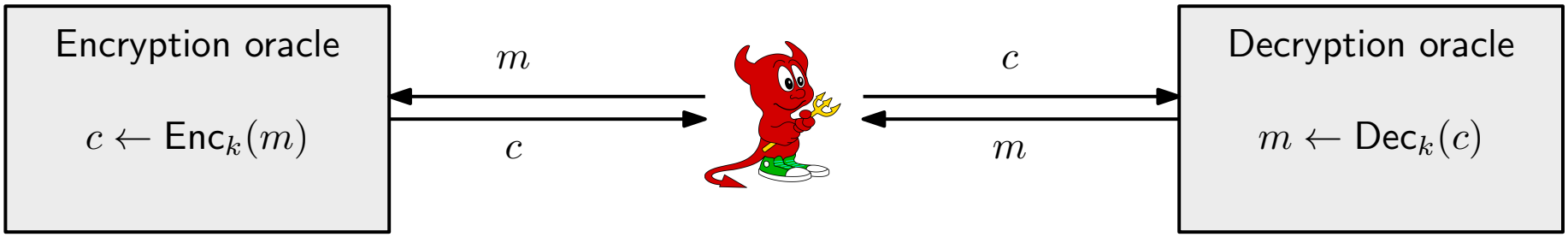

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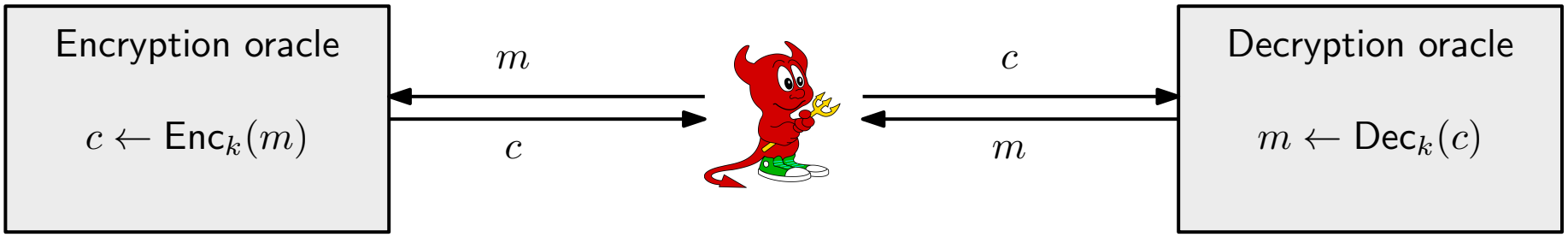

The $\mathsf{PrivK}^{\mathsf{cca}}_{\mathcal{A},\Pi}$ experiment

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 $\mathsf{Dec}_k(\cdot)$
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- 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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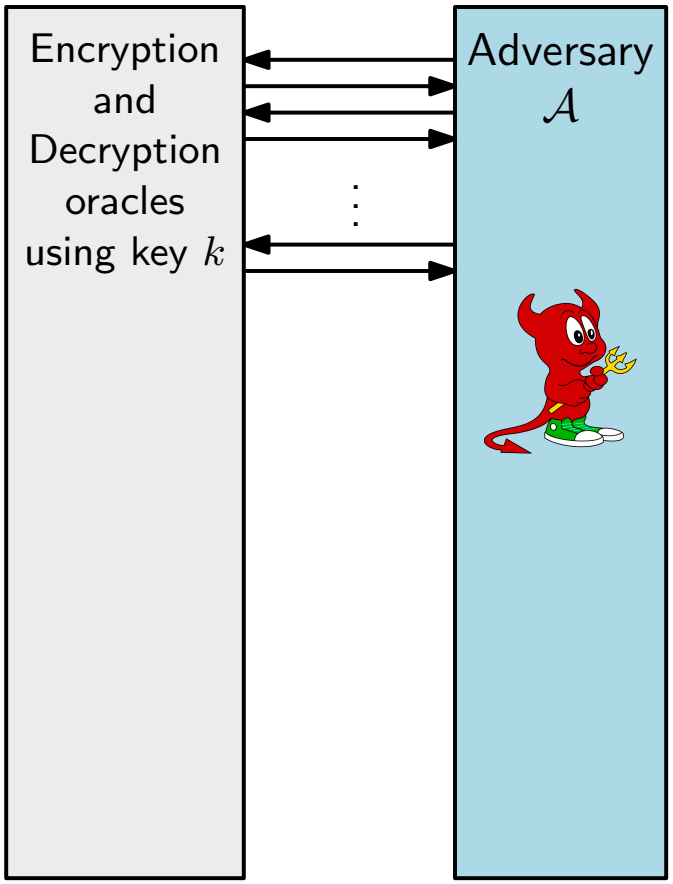

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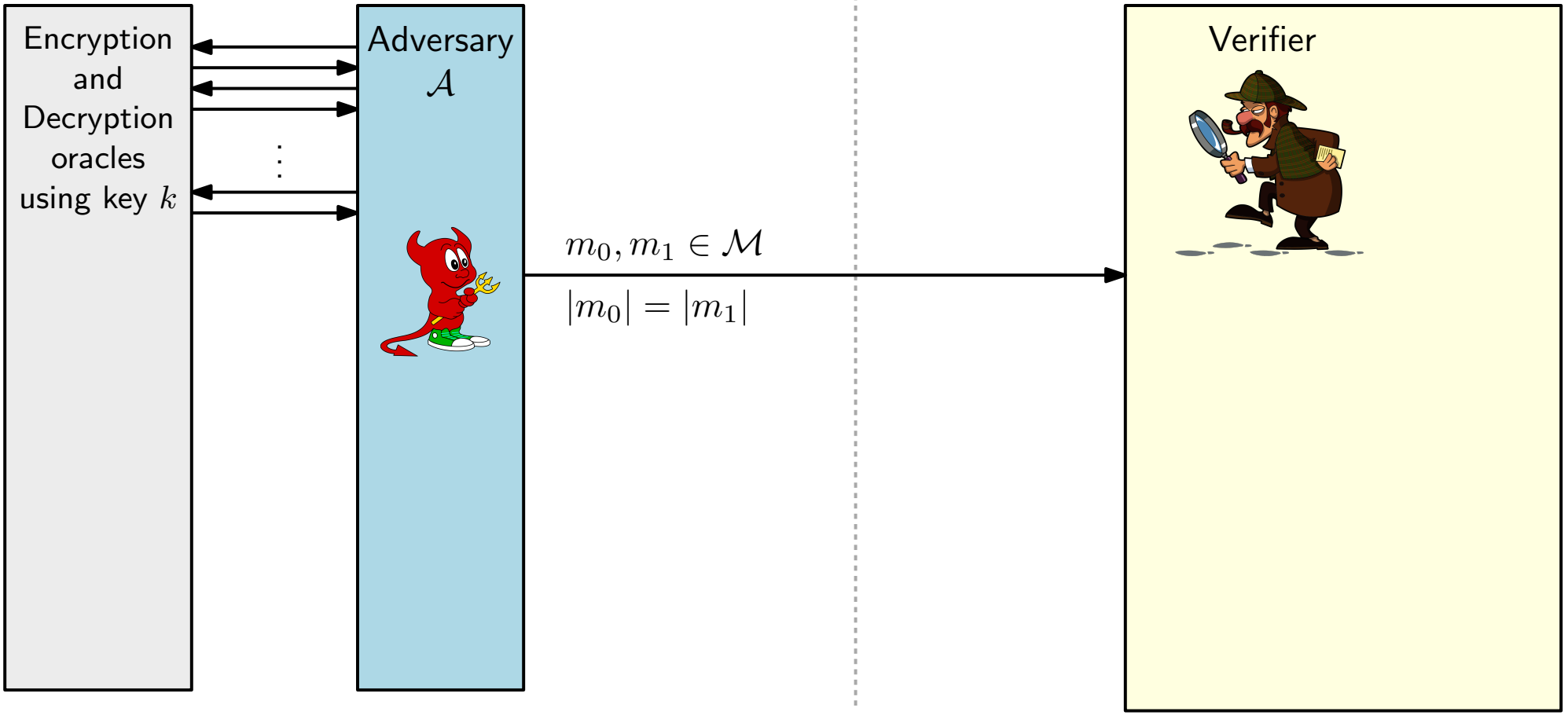

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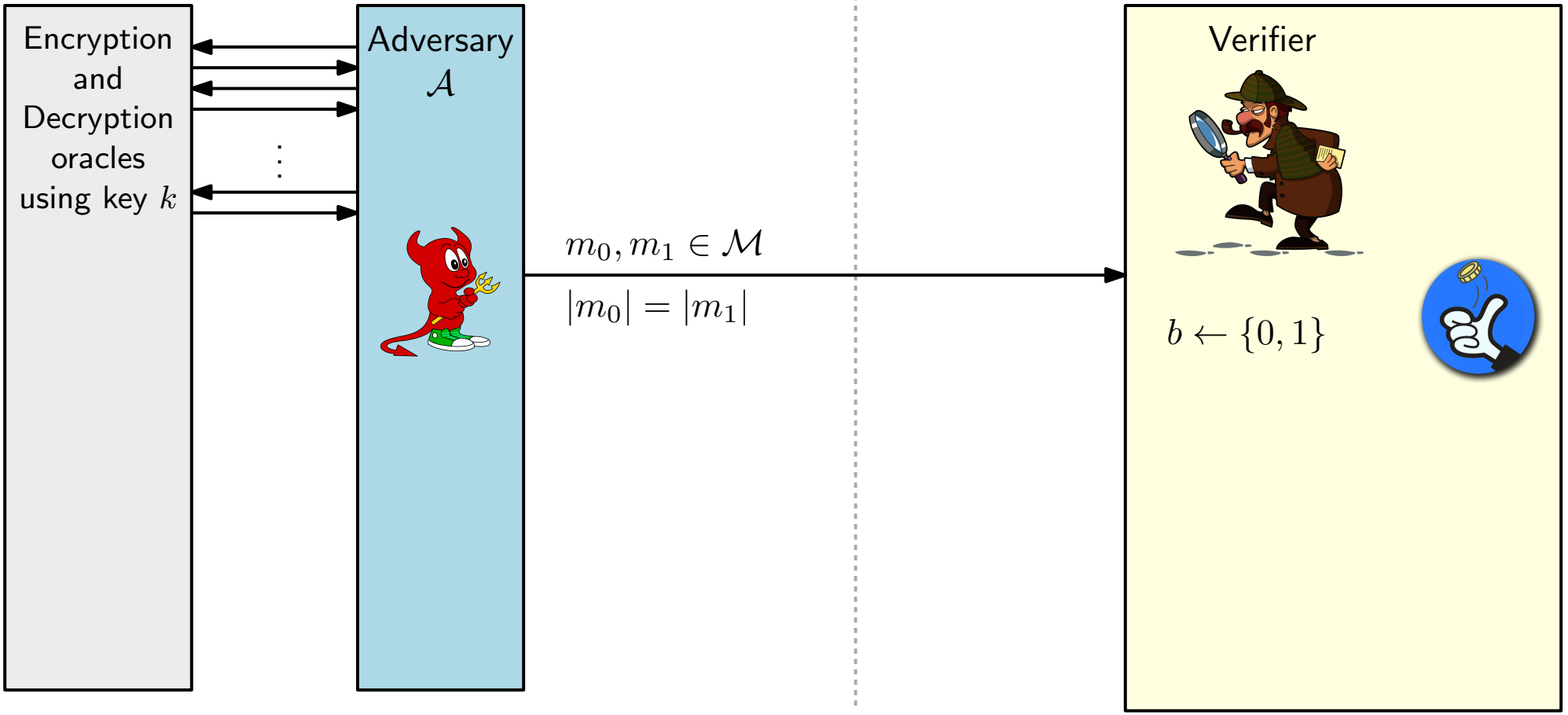

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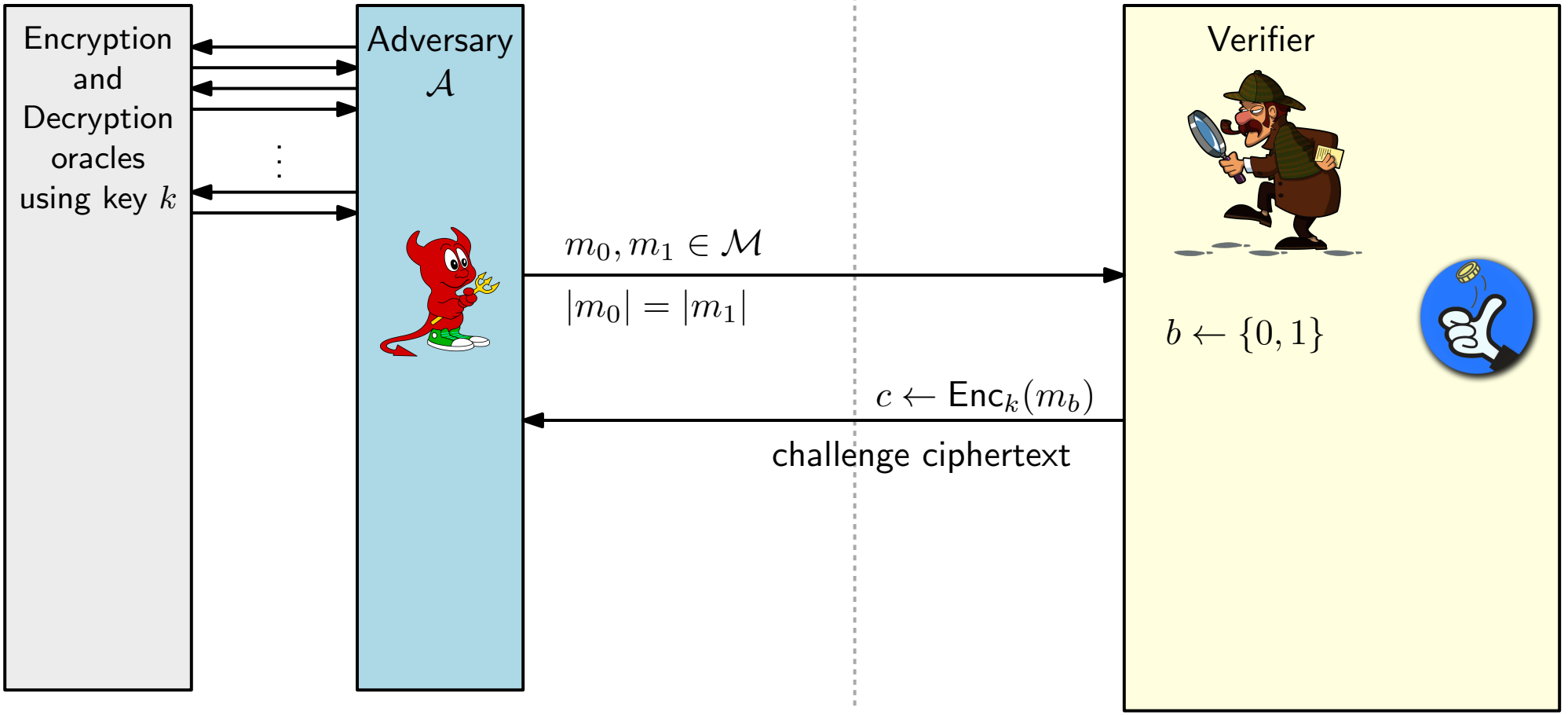

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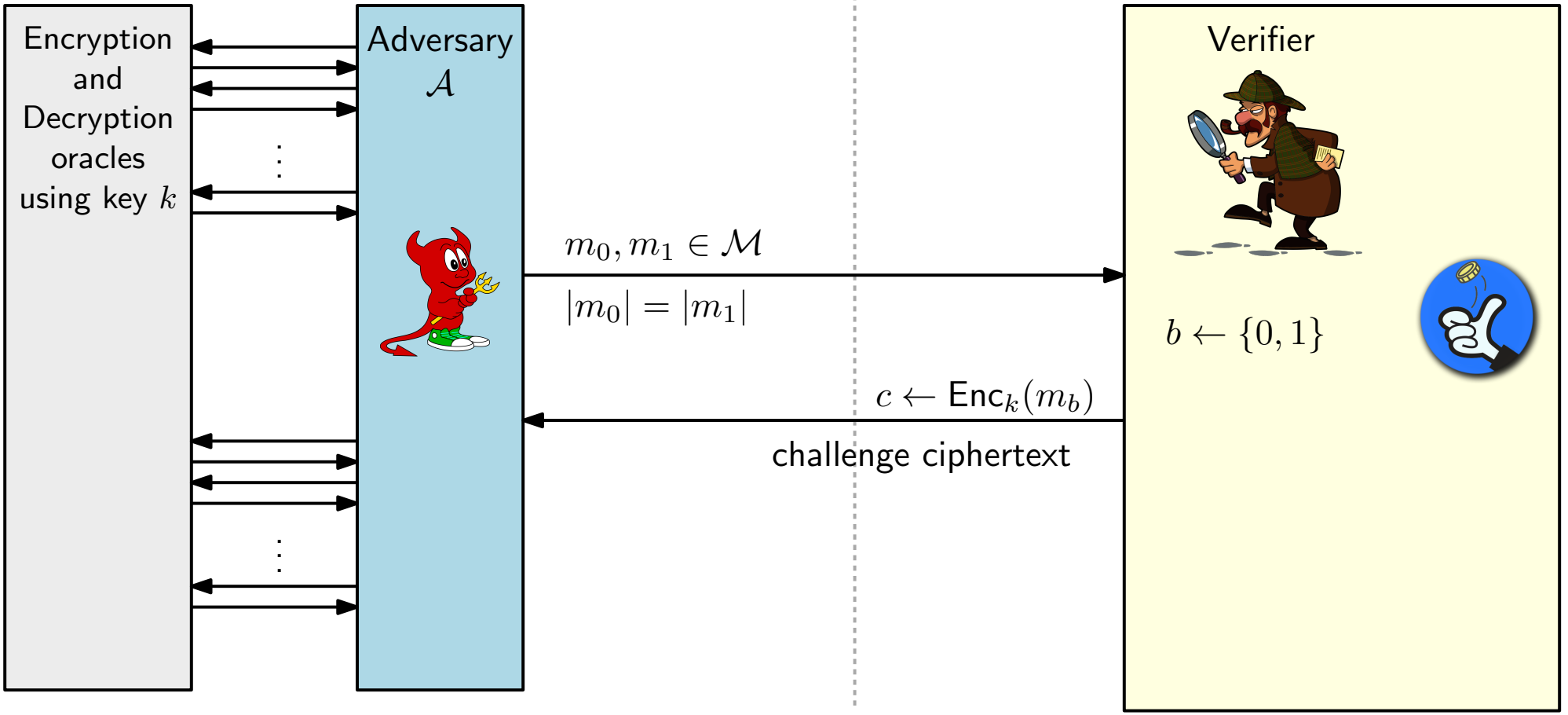

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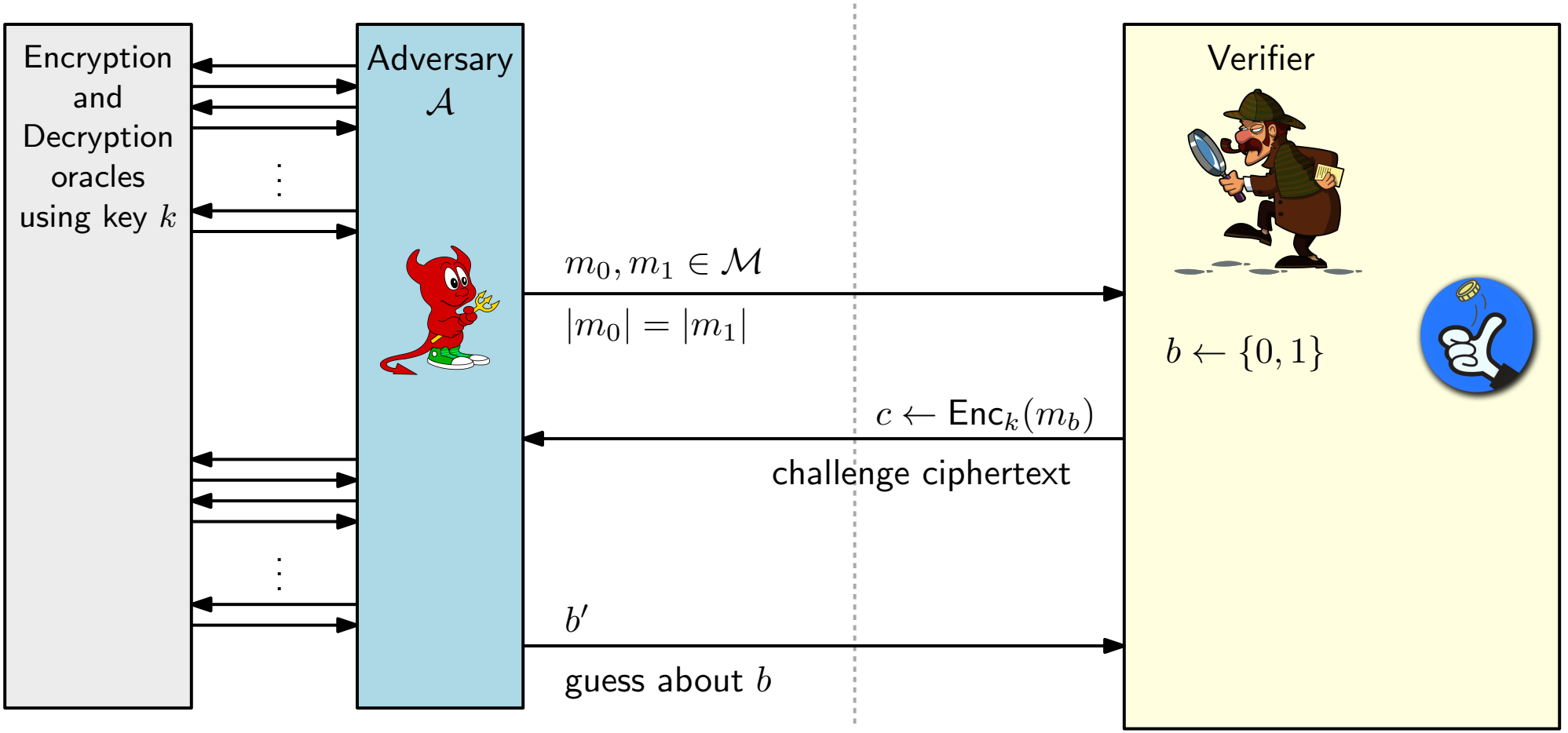

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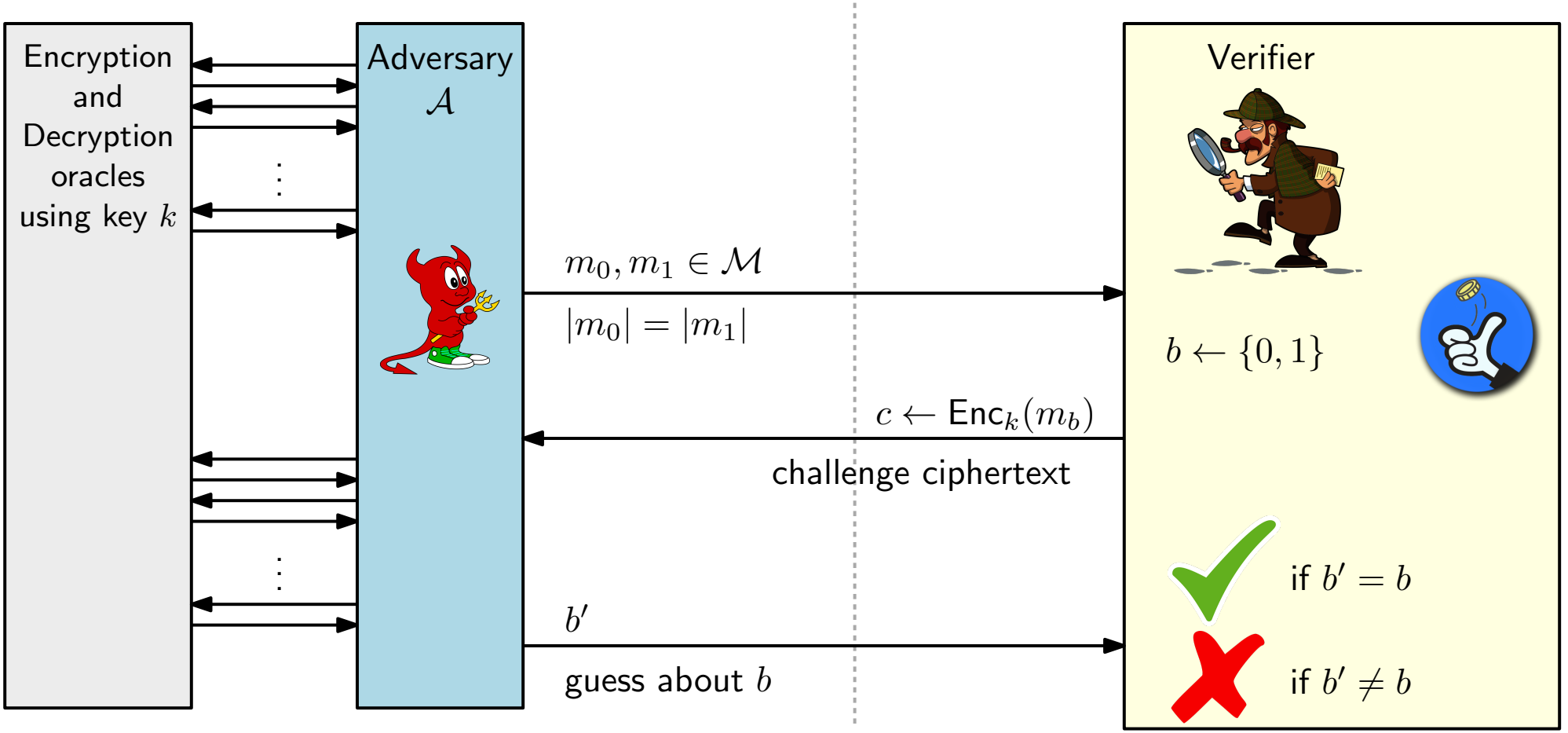

Definition of CCA security

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:*

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

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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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

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

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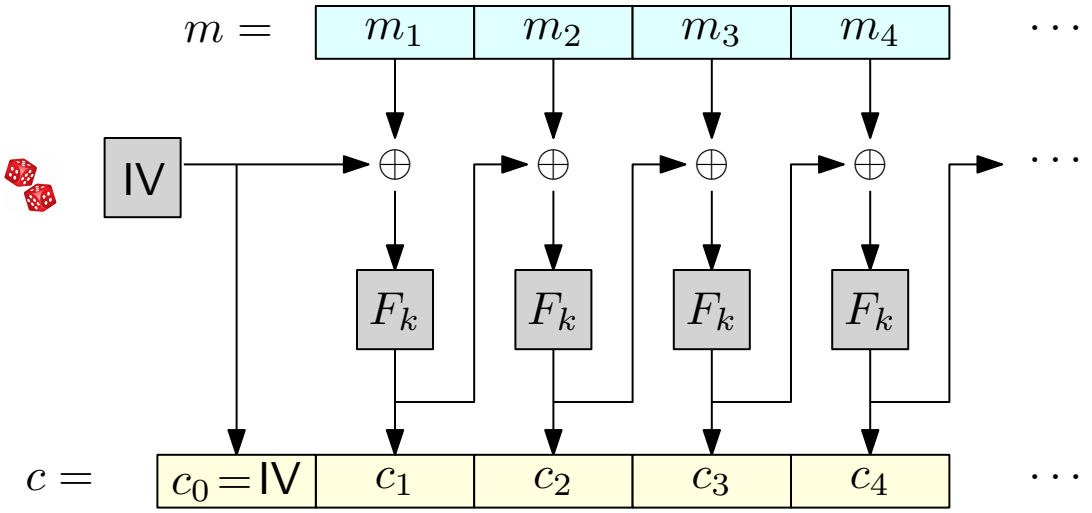
Reminder: block ciphers in CBC mode



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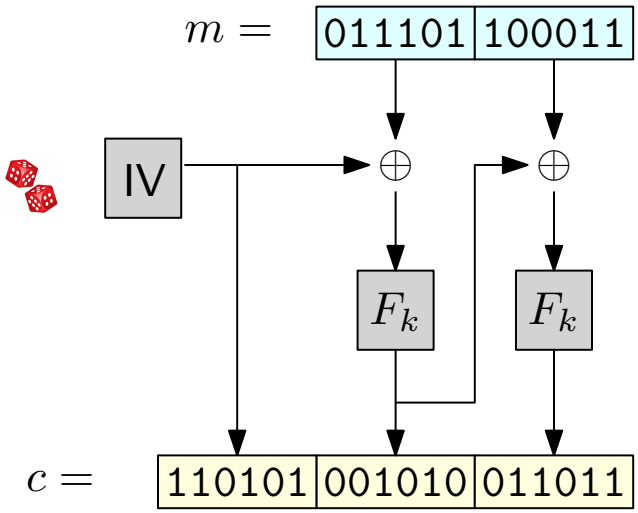

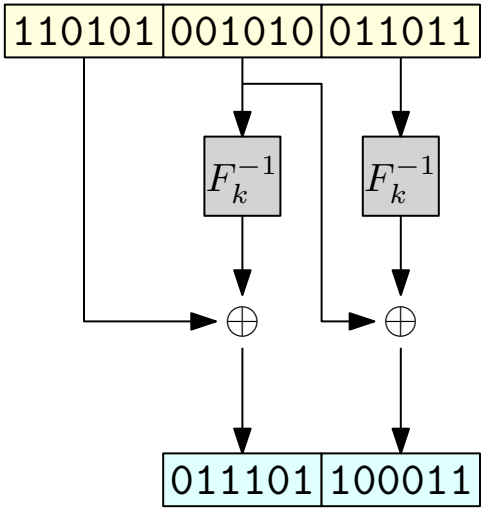

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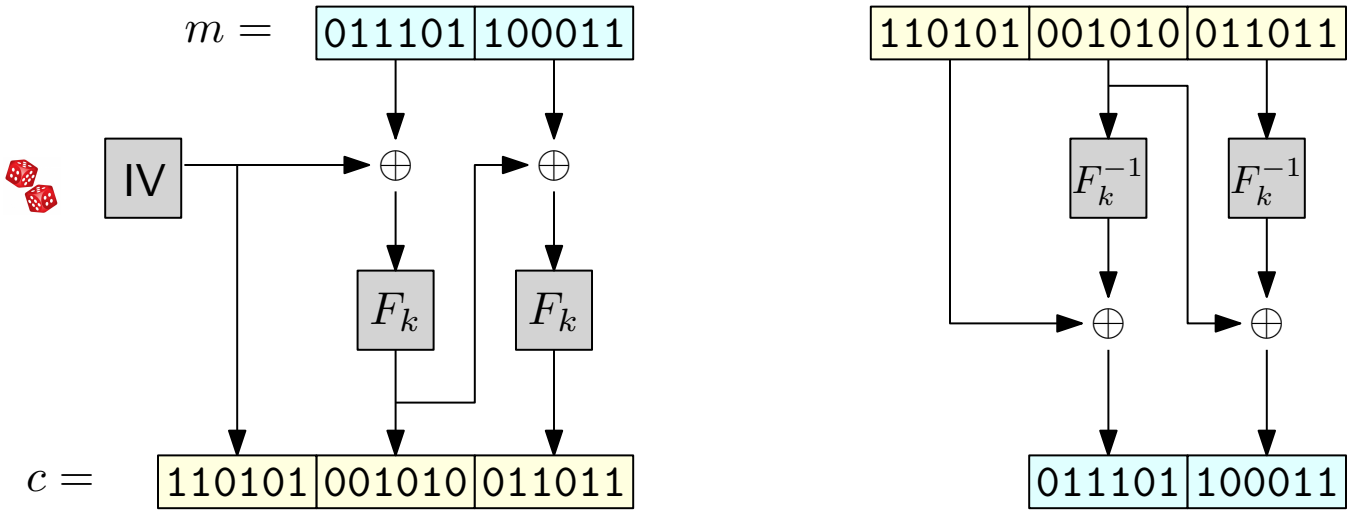

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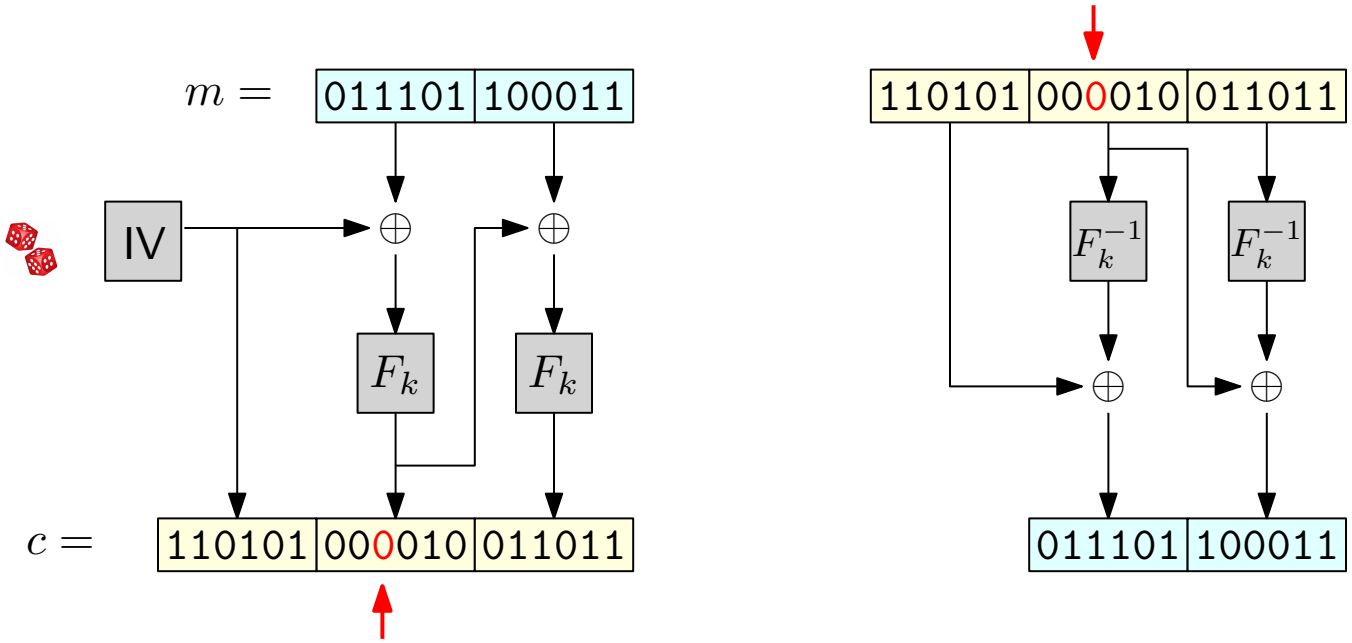

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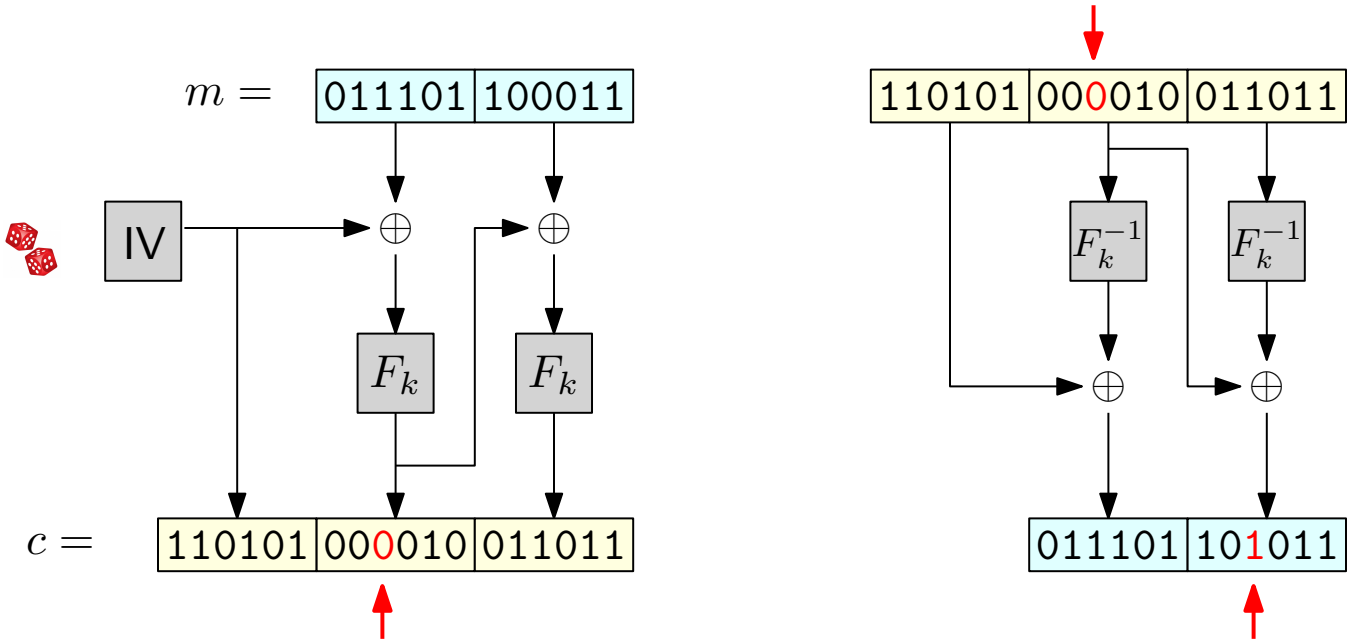

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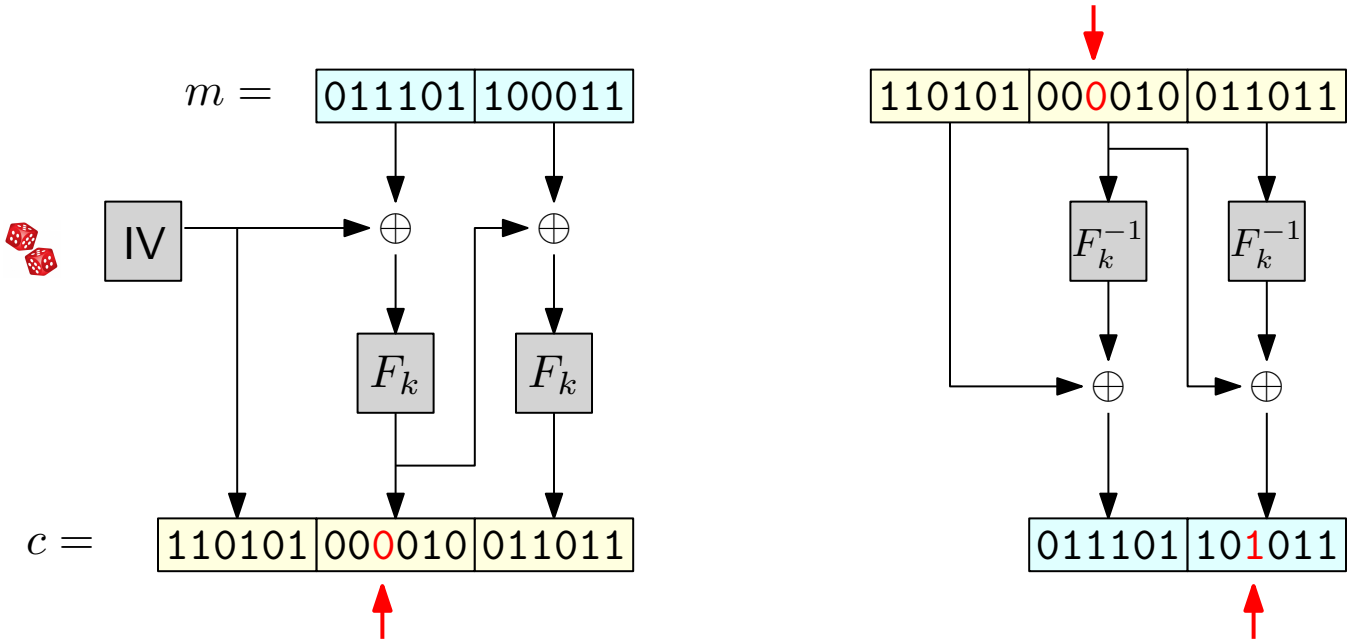

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In general, if we XOR the i-th block of the ciphertext with Δ, this causes the $(i+1)$-th block of the plaintext to be XOR-ed with Δ after decryption

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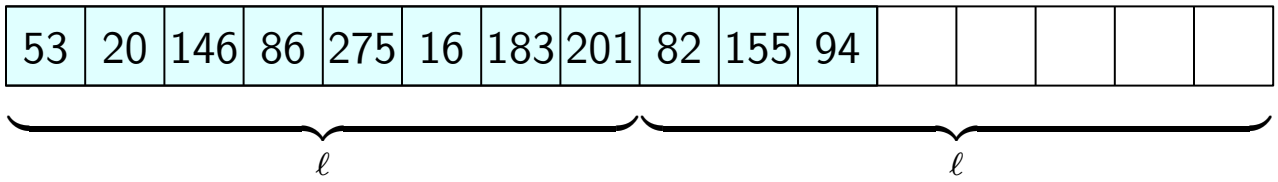

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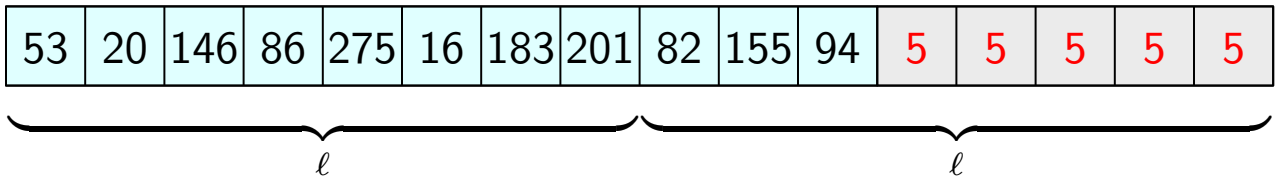

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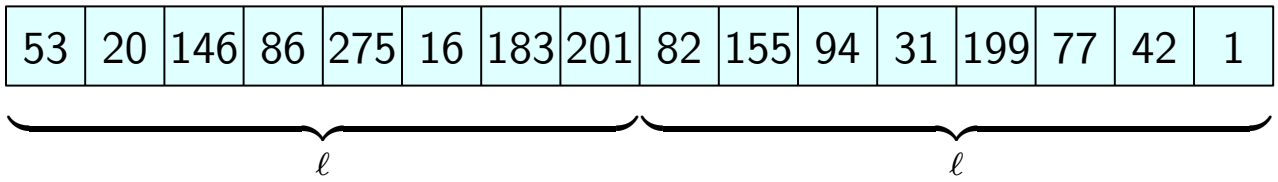

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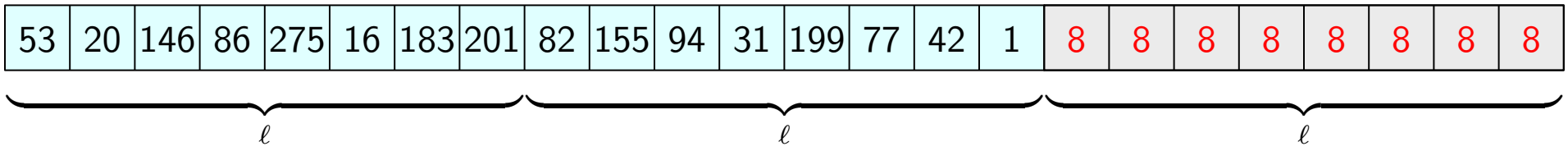

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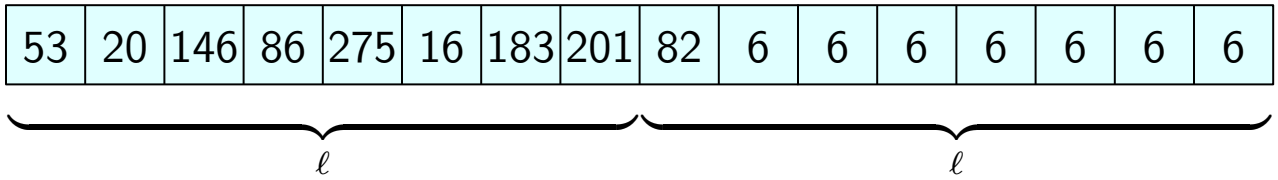

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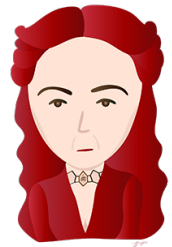
We model the ability of the adversary to tell whether the padding of (the plaintext corresponding to a) ciphertext is valid, with a **padding oracle**



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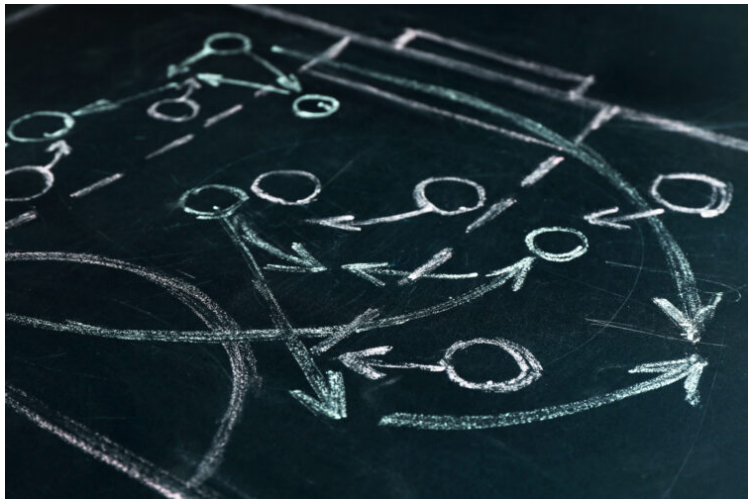

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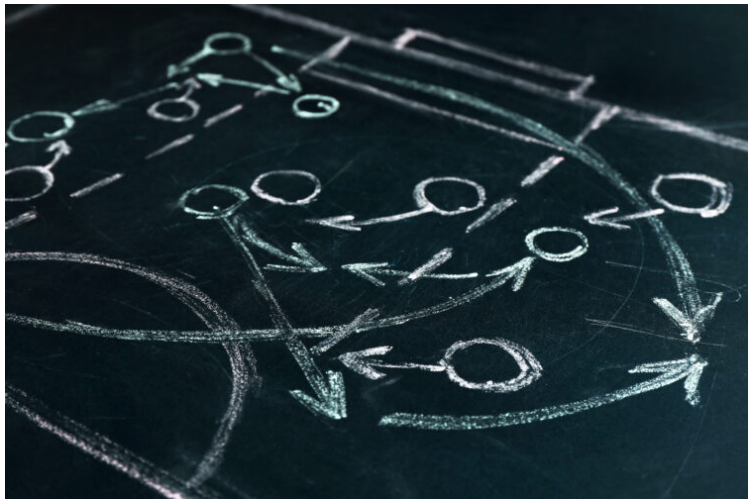
2) Repeat the following until the whole plaintext is recovered:

- 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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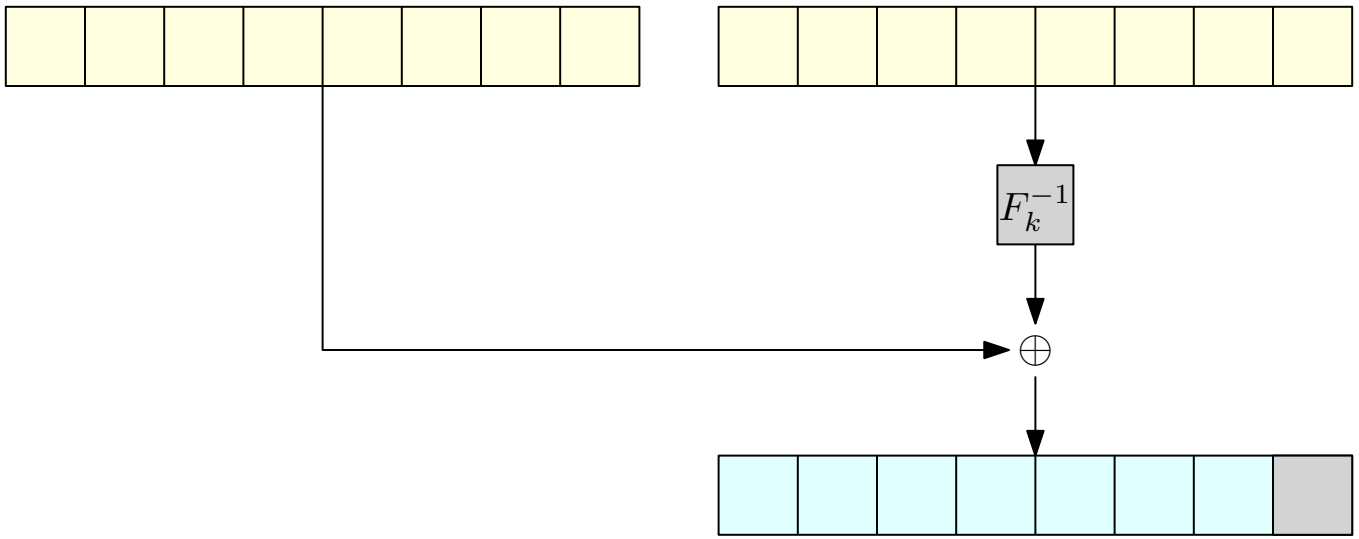

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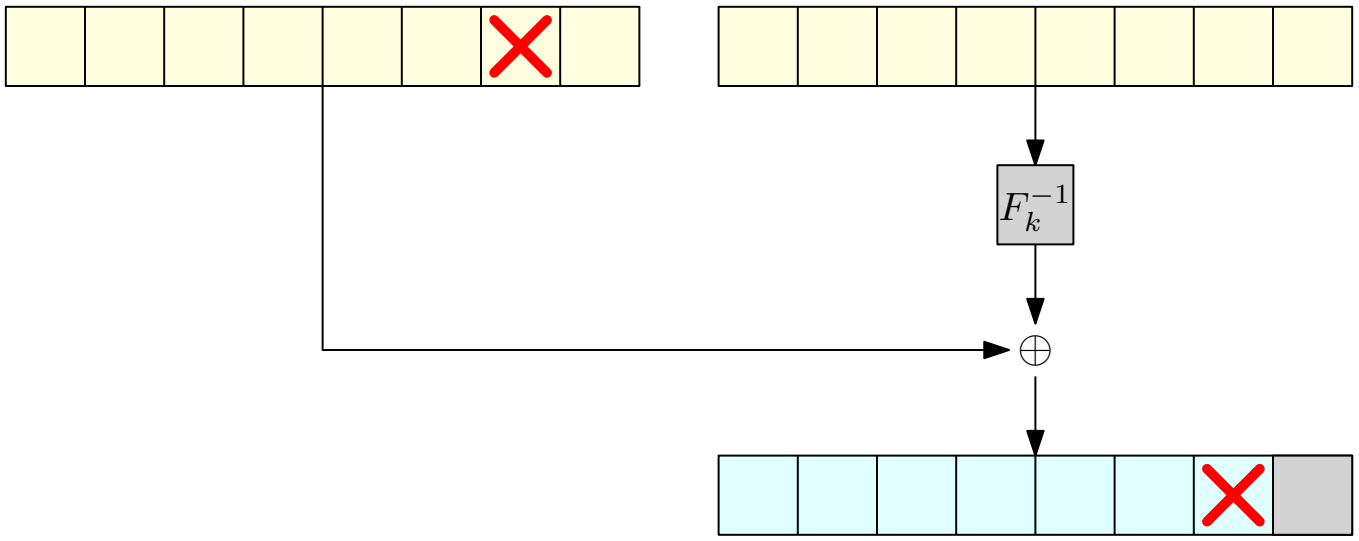

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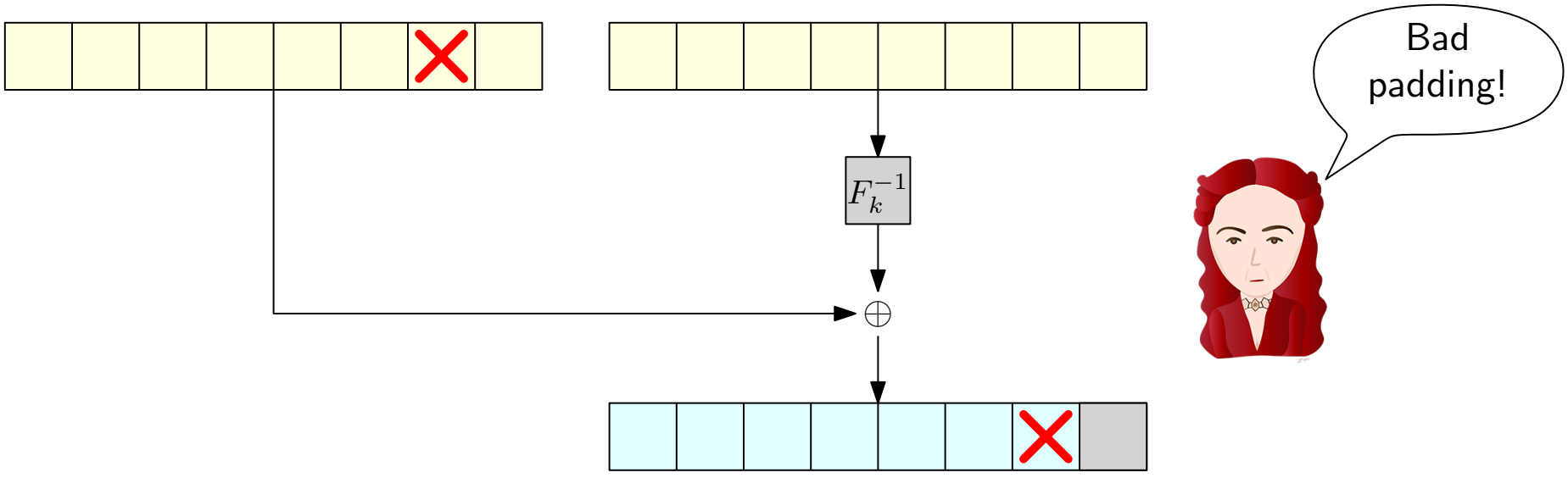

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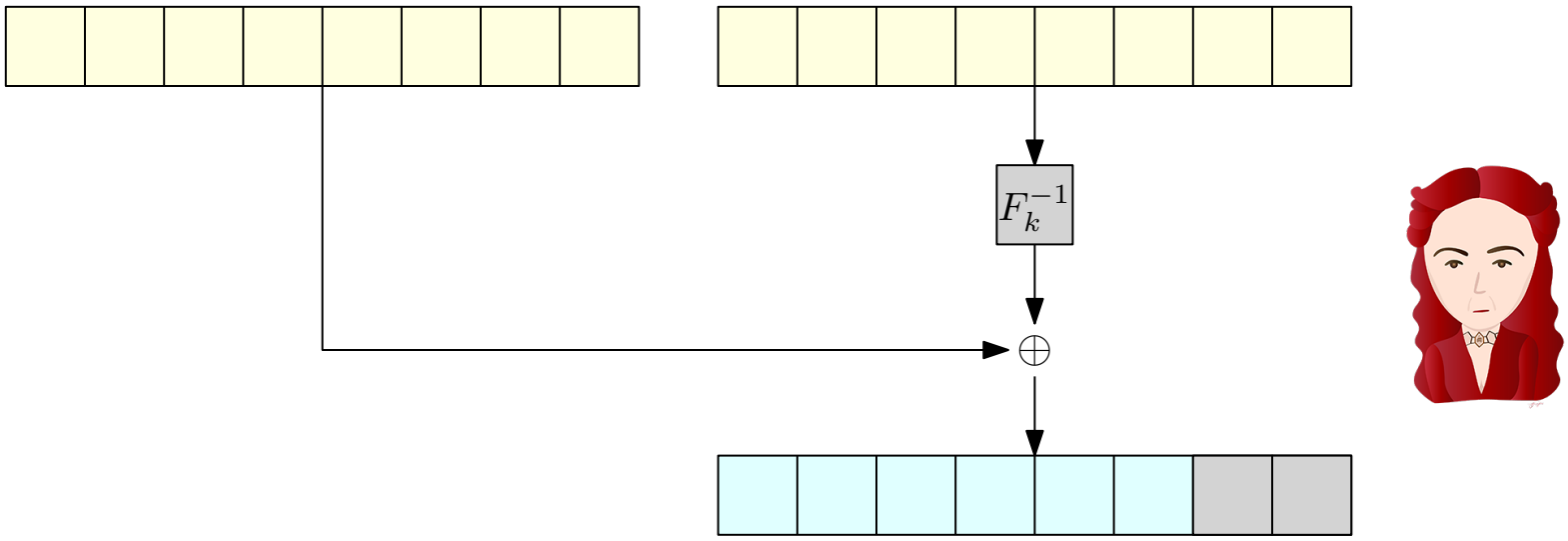

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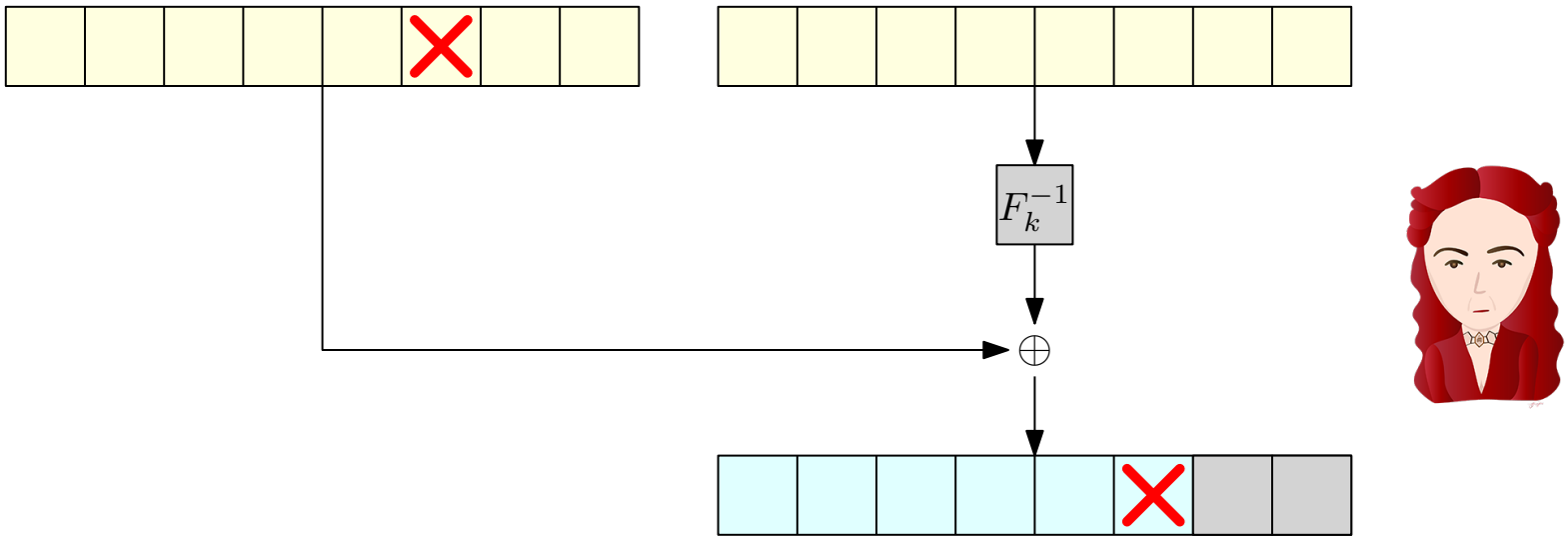

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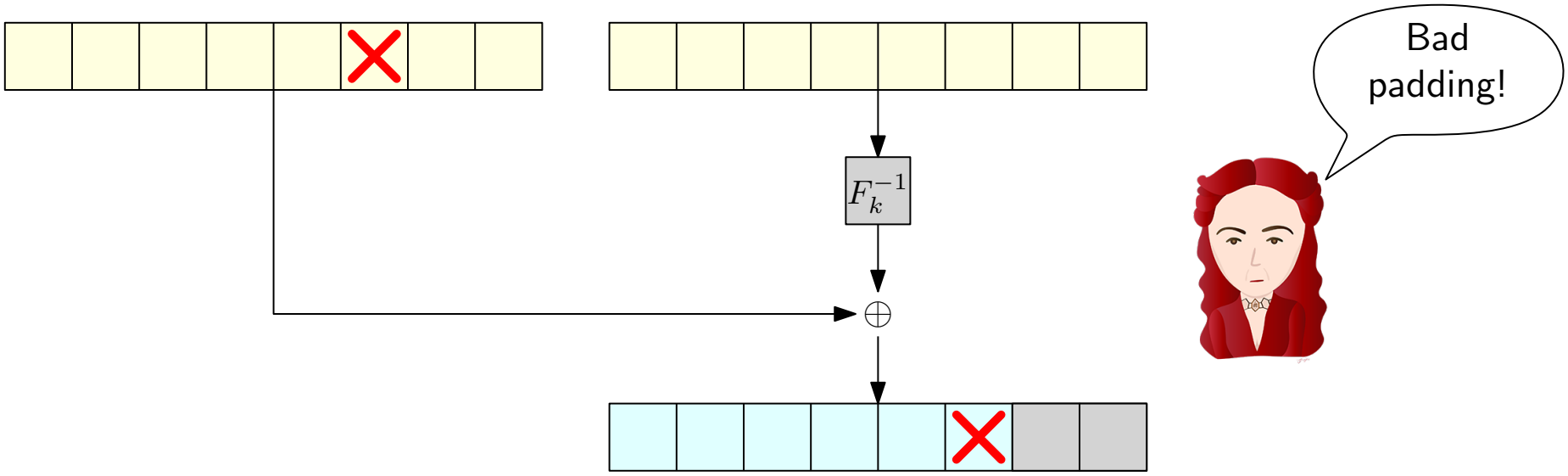

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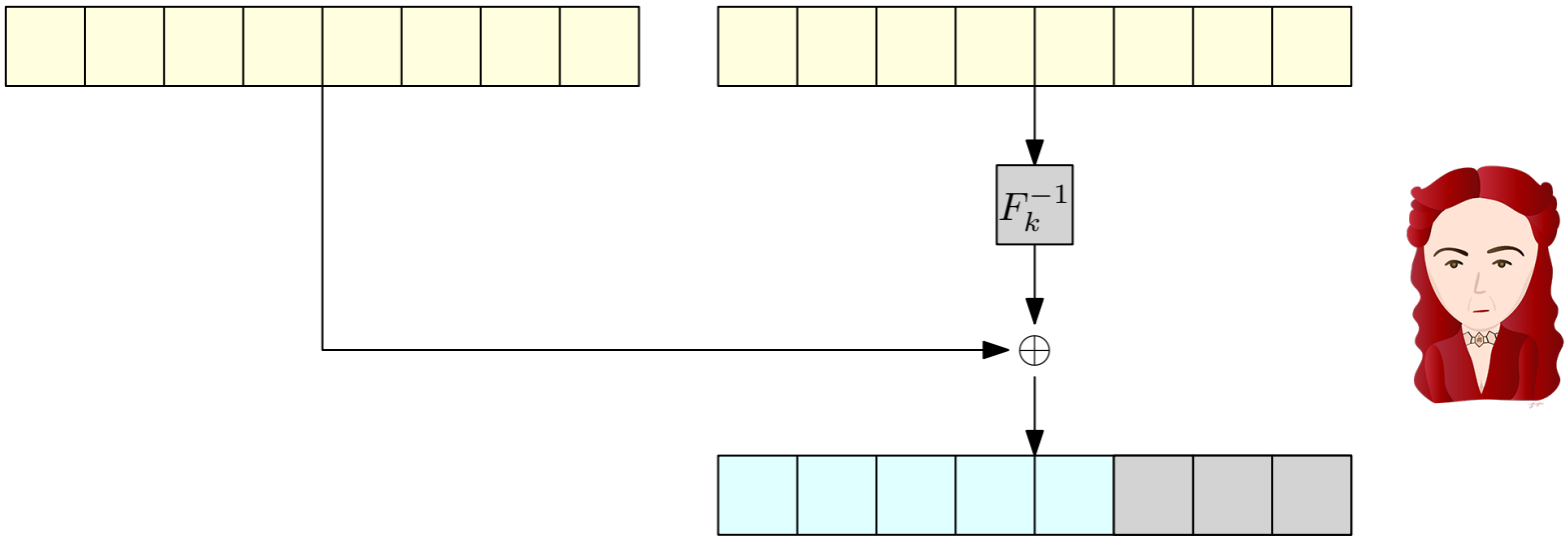

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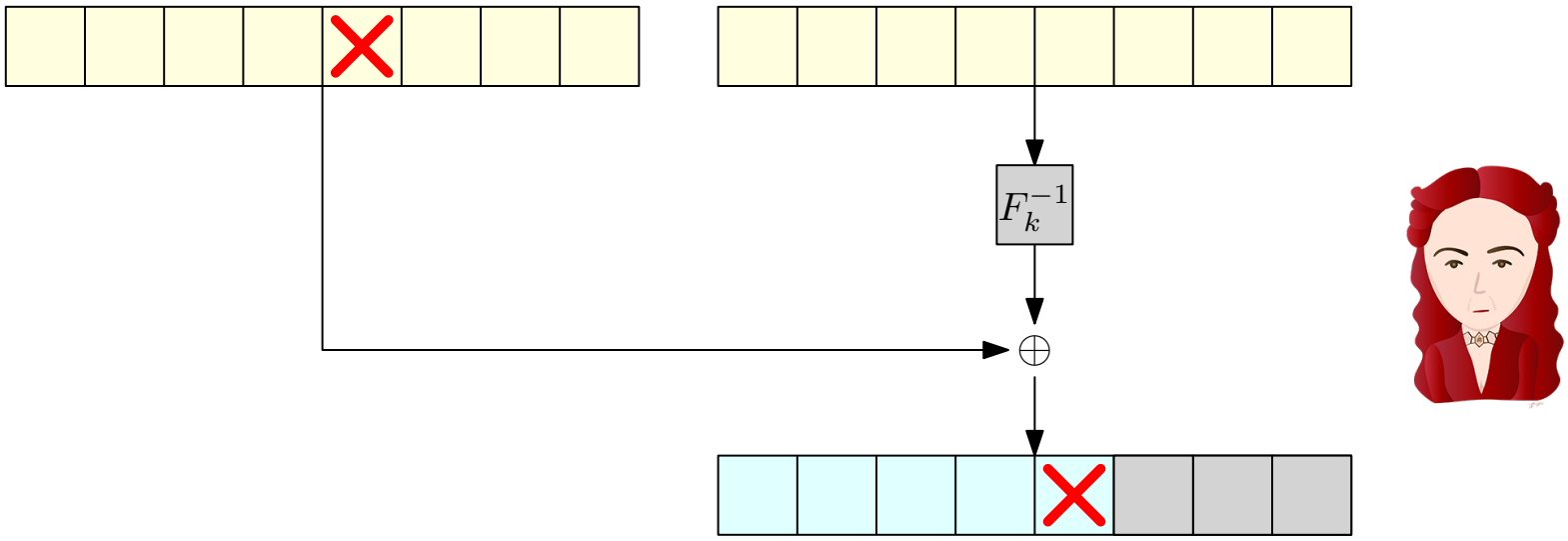

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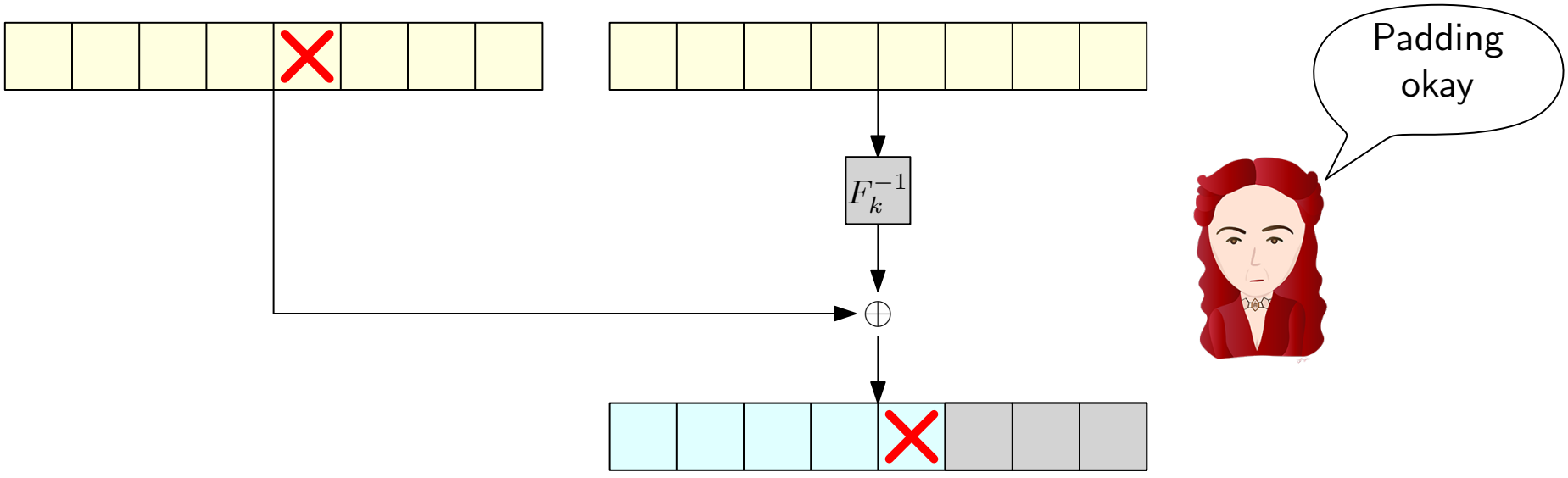

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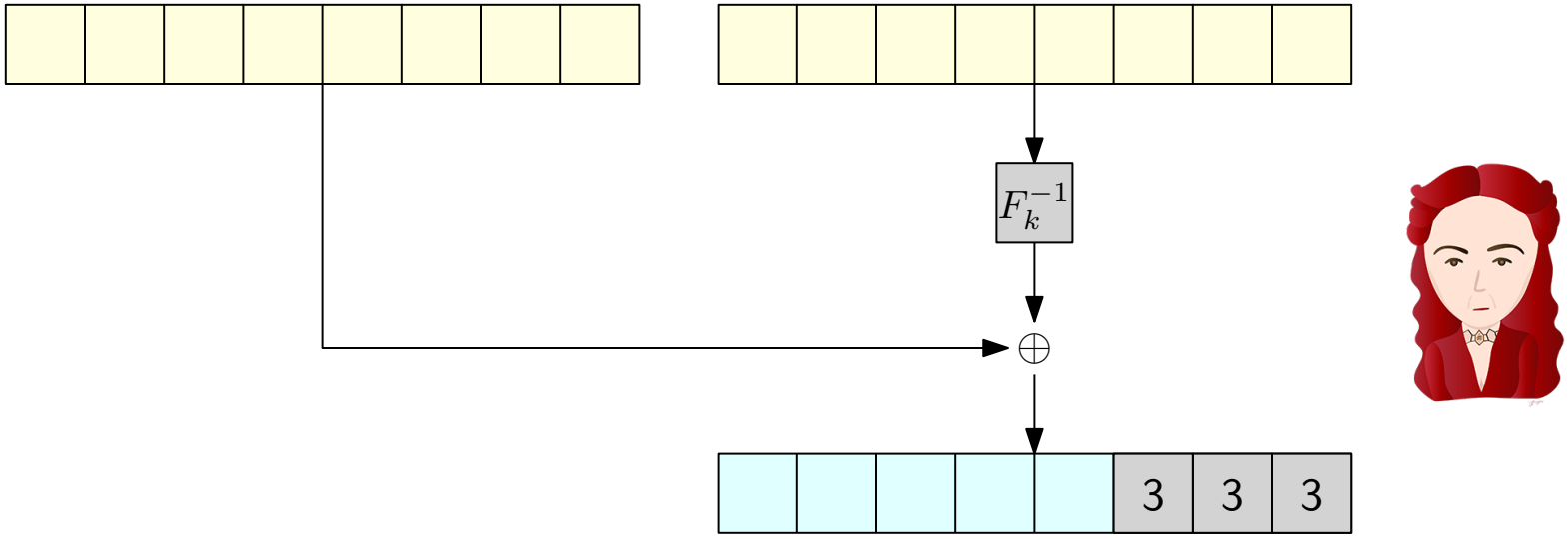

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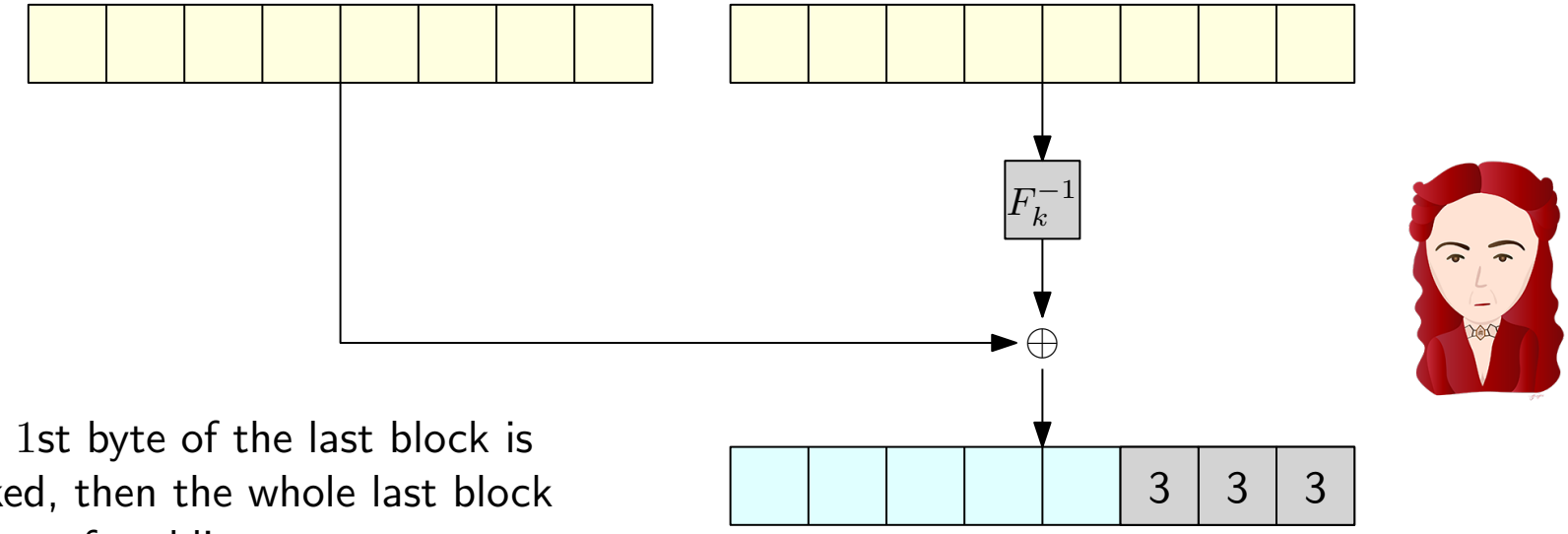
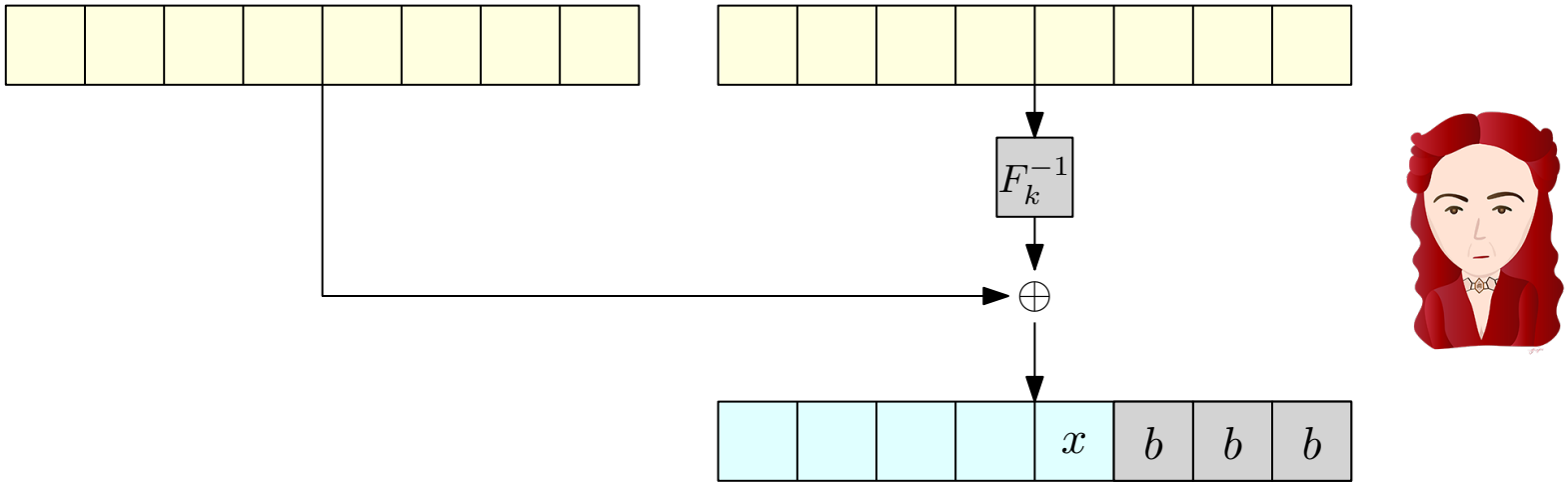


If the 1st byte of the last block is checked, then the whole last block consists of padding

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



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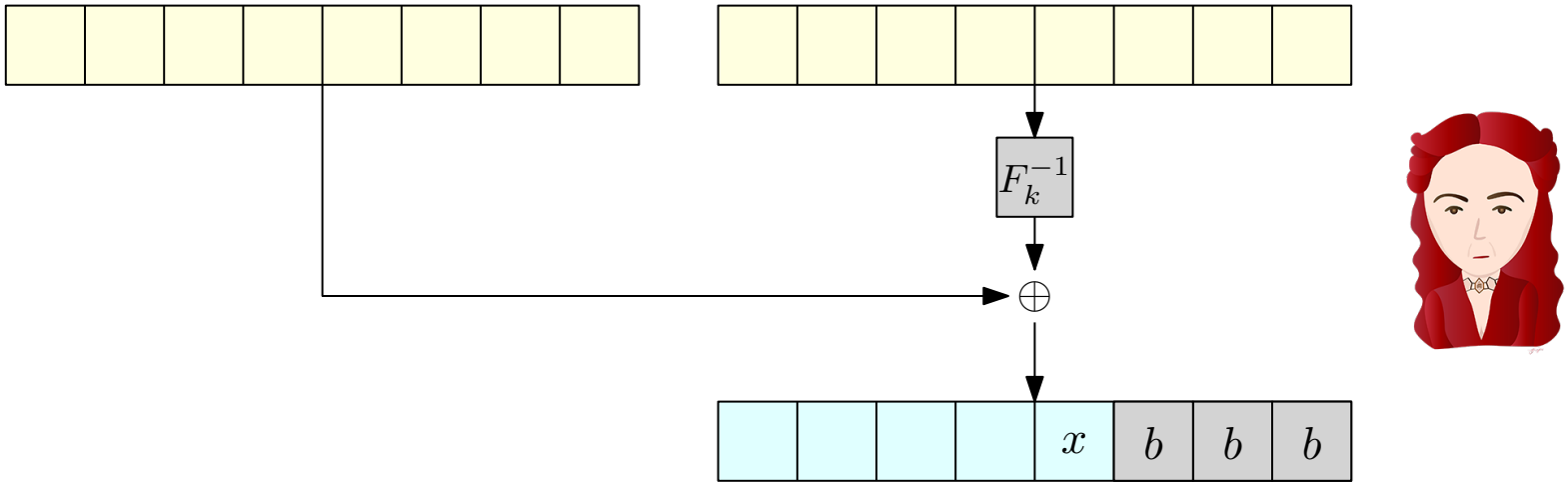
Suppose, for simplicity, that the last block does not consist entirely of padding



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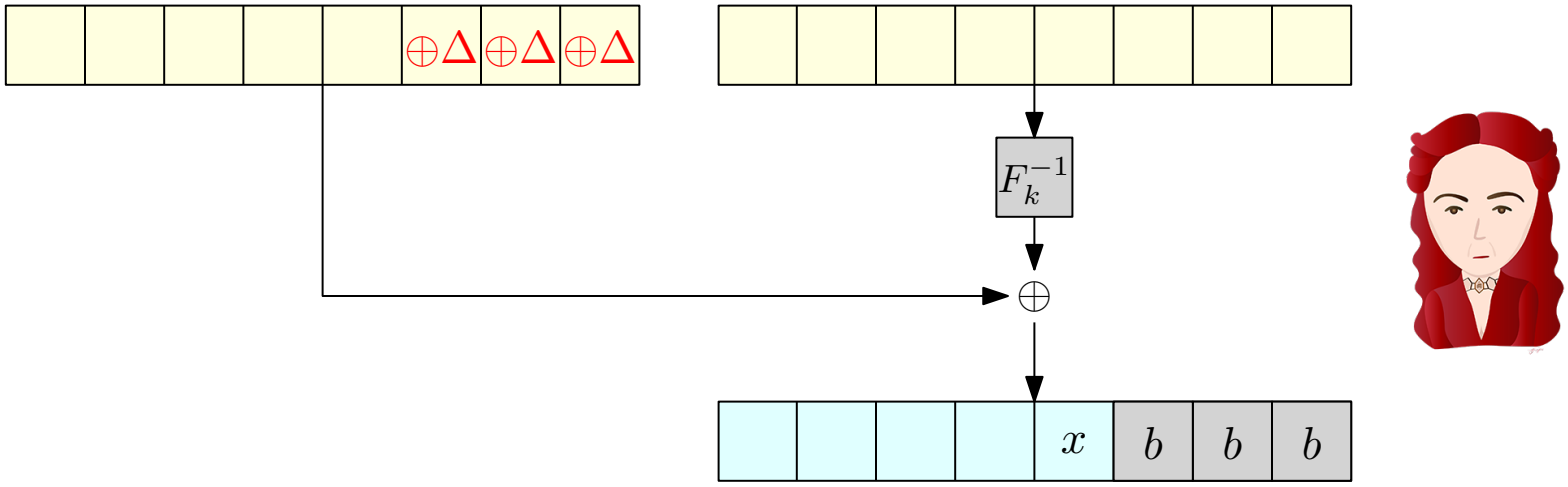

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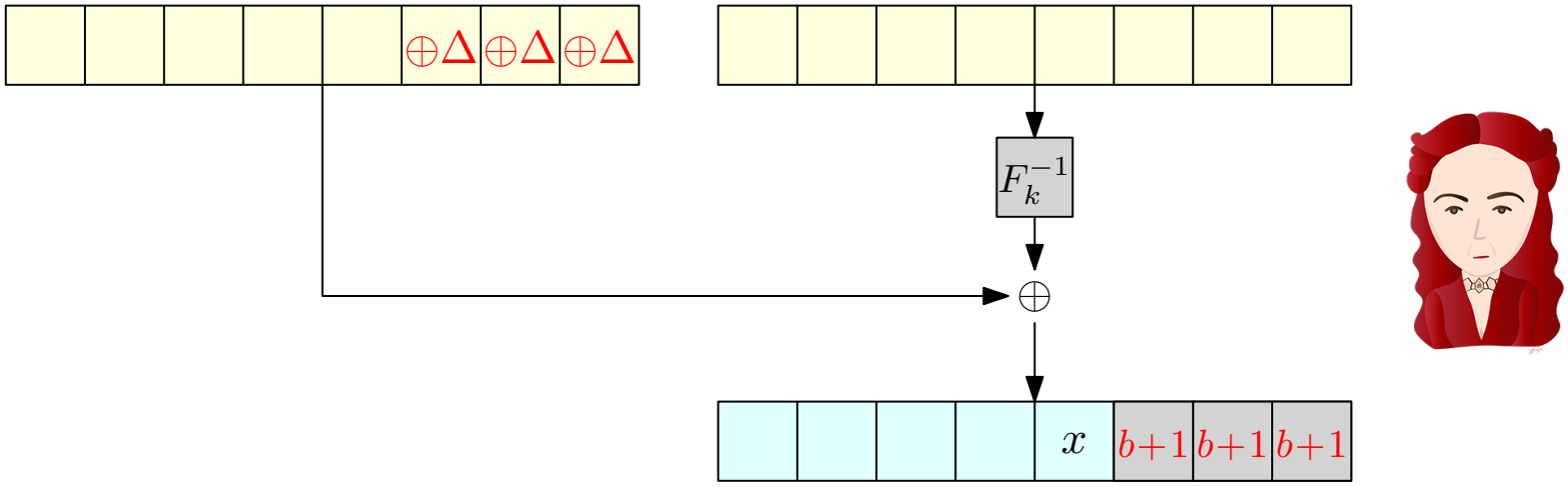
- This changes the last b blocks of the plaintext to from b to $b \oplus b \oplus (b+1) = b+1$



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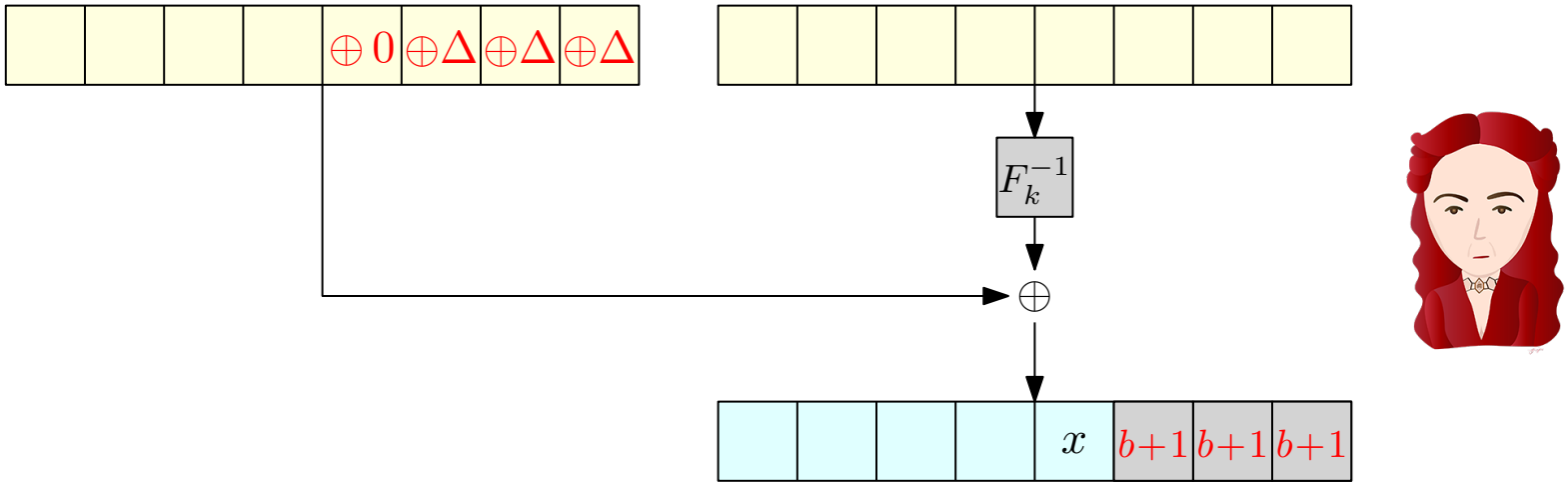
For all possible values $i \in \{0, \ldots, 255\}$

- XOR the $(b+1)$-to-last byte of the one-to-last block of the ciphertext with i



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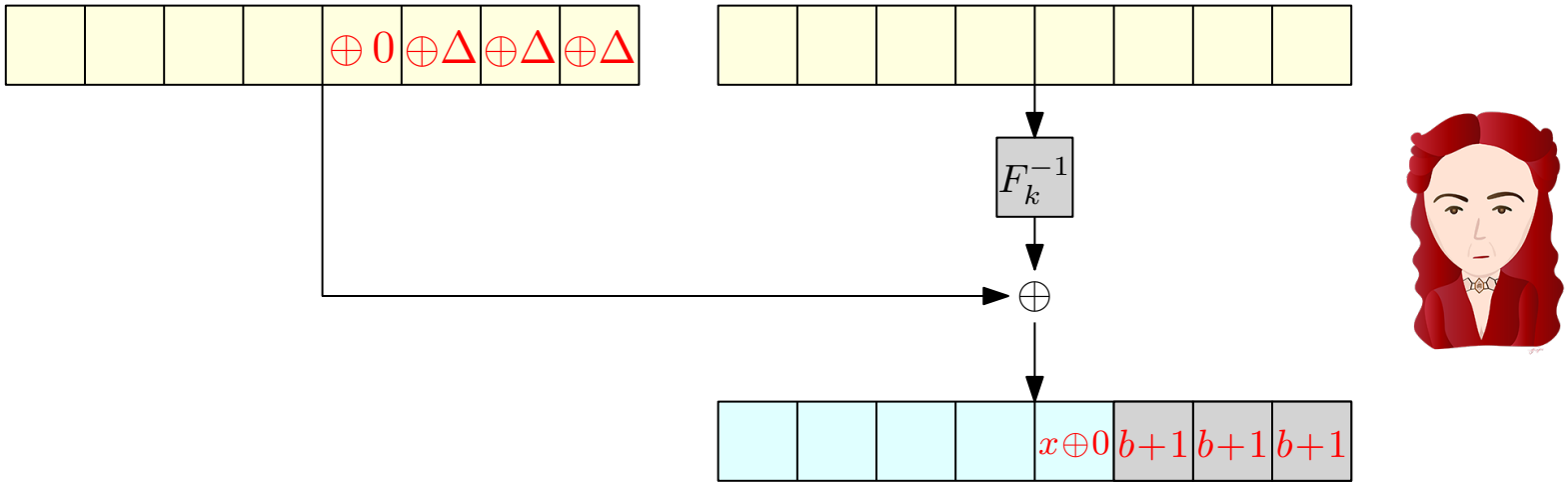

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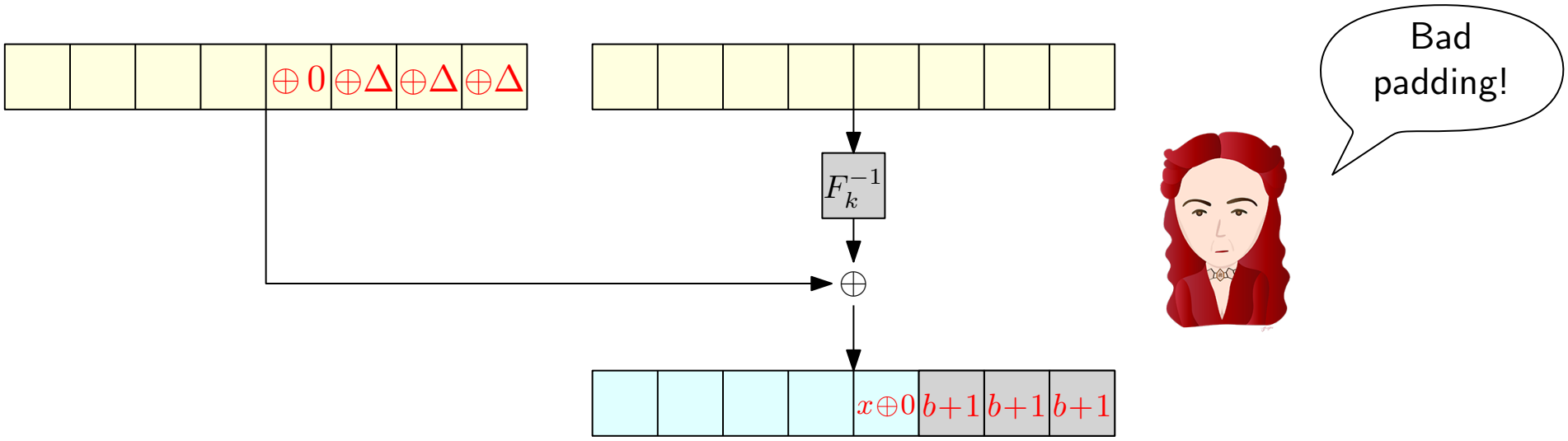

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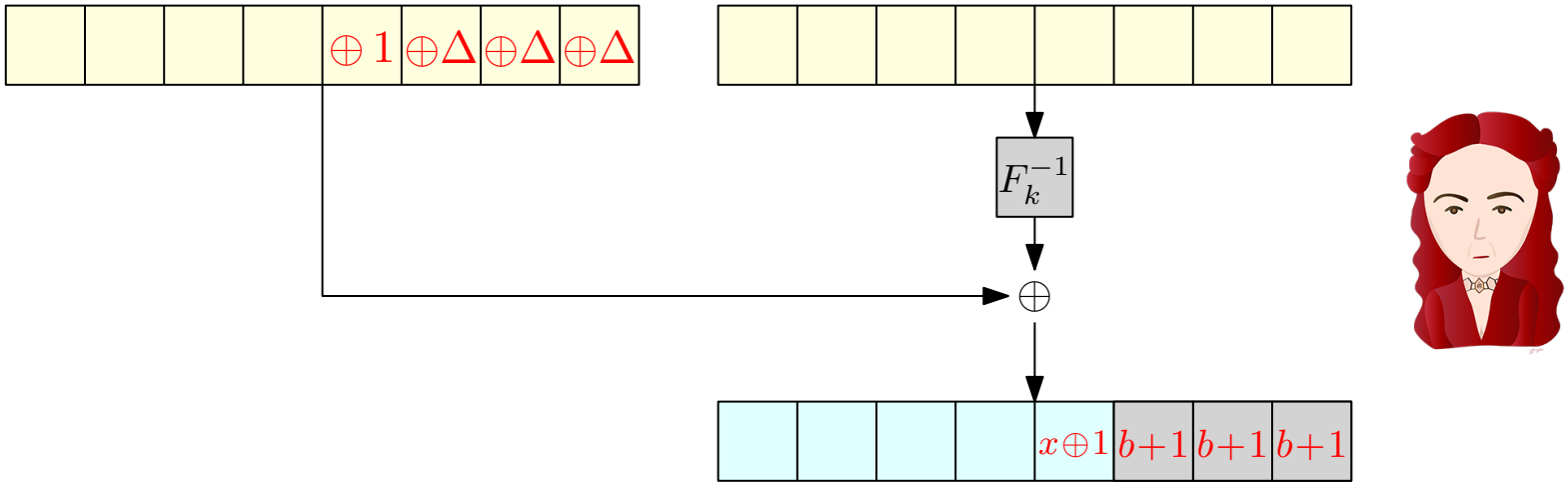

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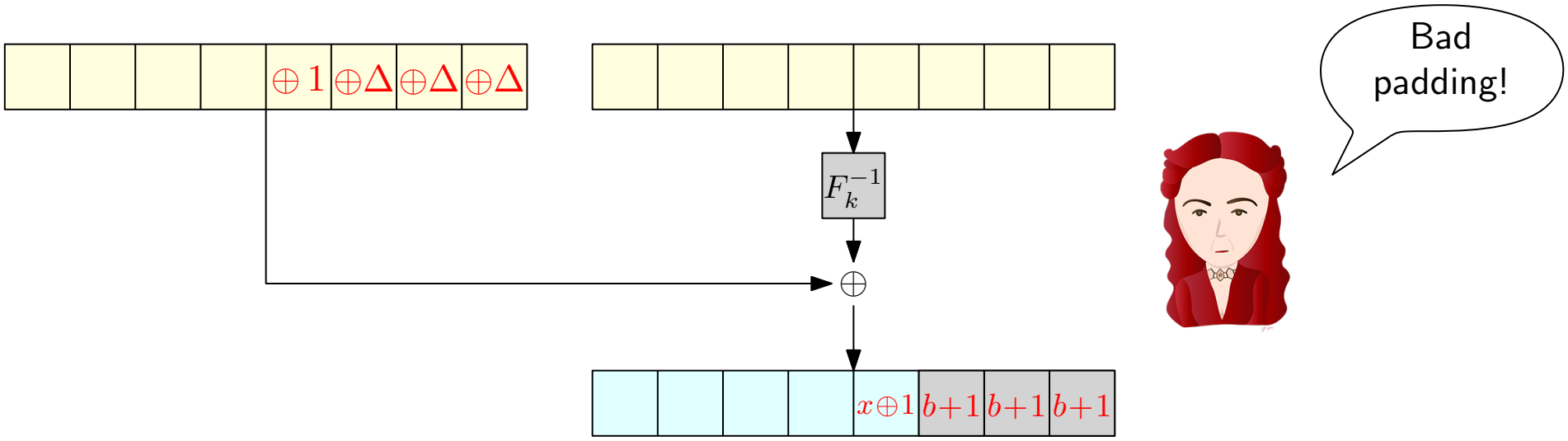

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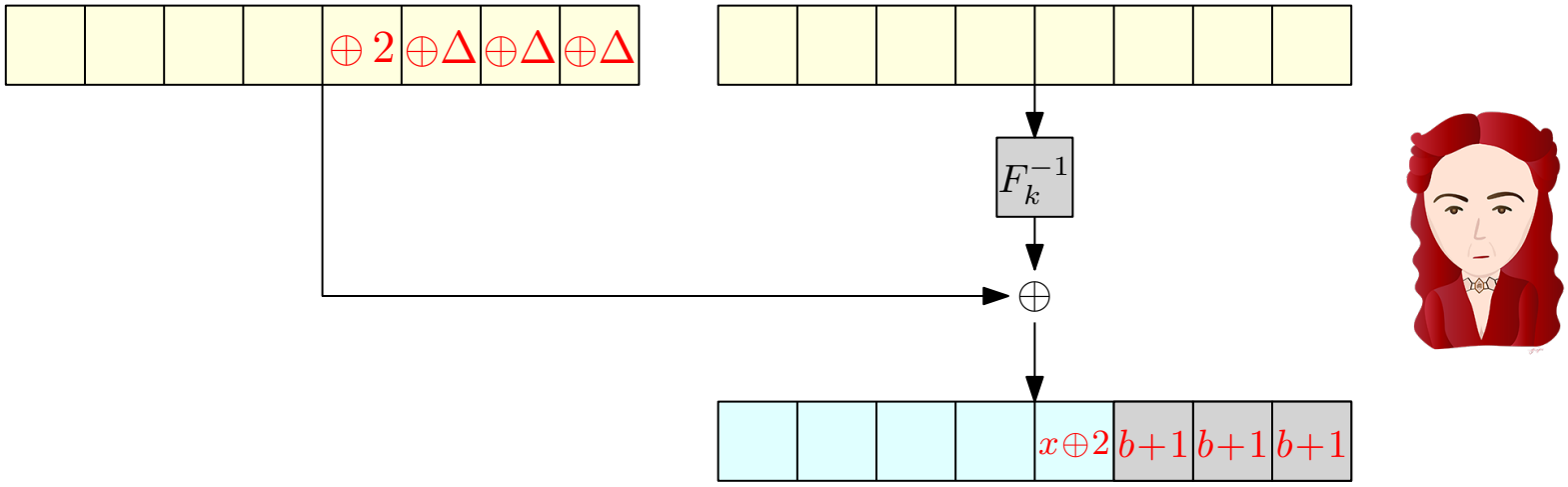

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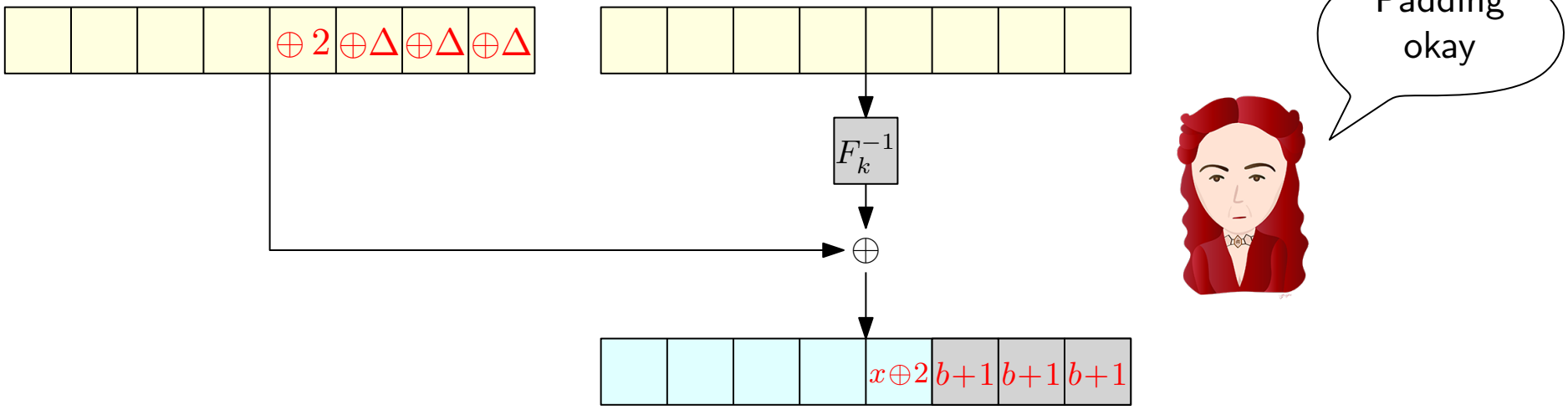

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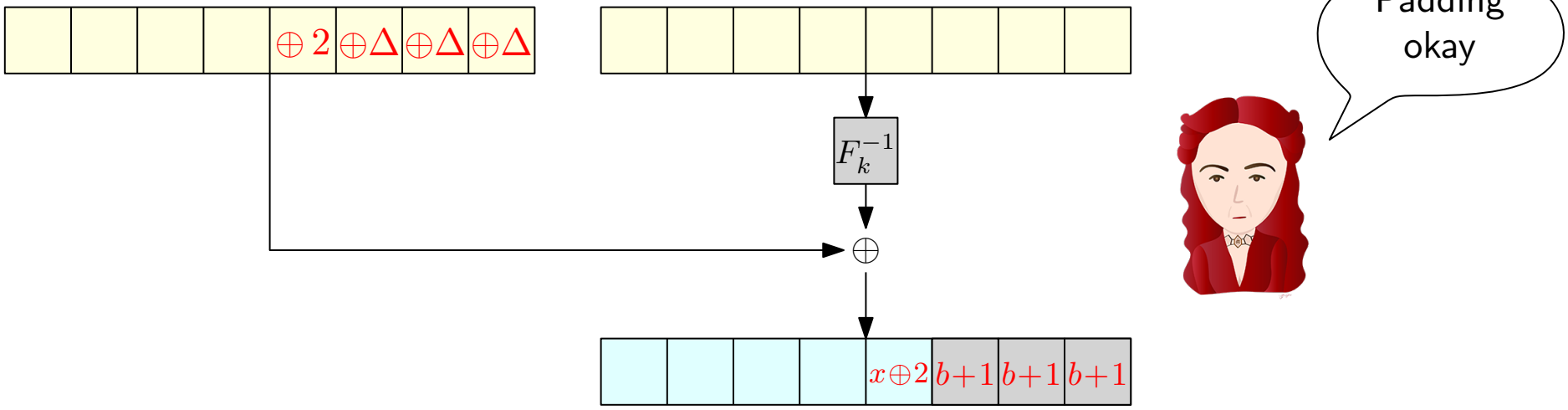

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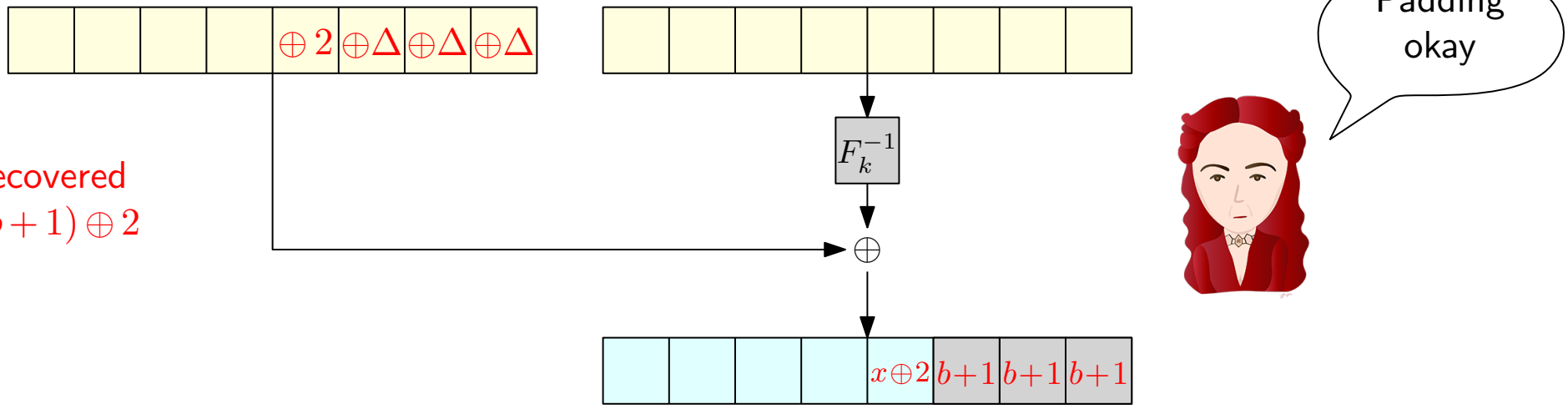

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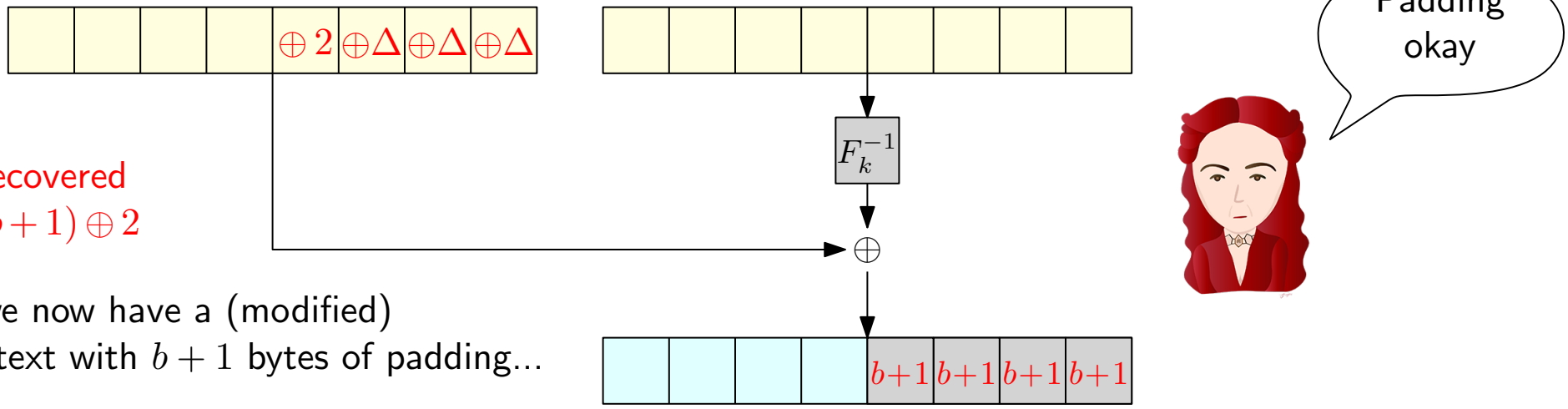

We recovered
$x = (b+1) \oplus 2$

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

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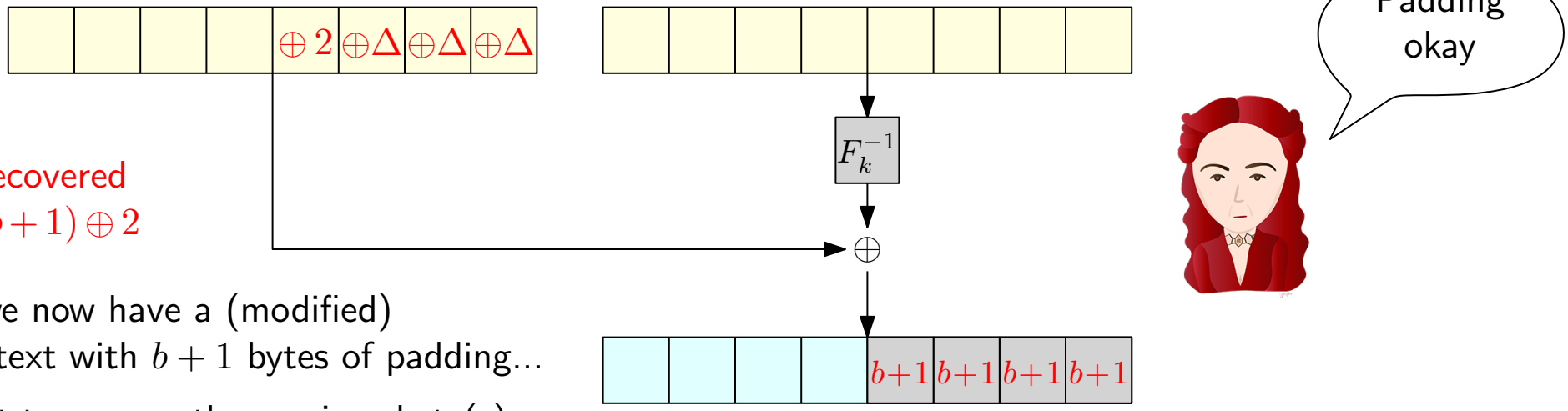

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Repeat to recover the previous byte(s)...

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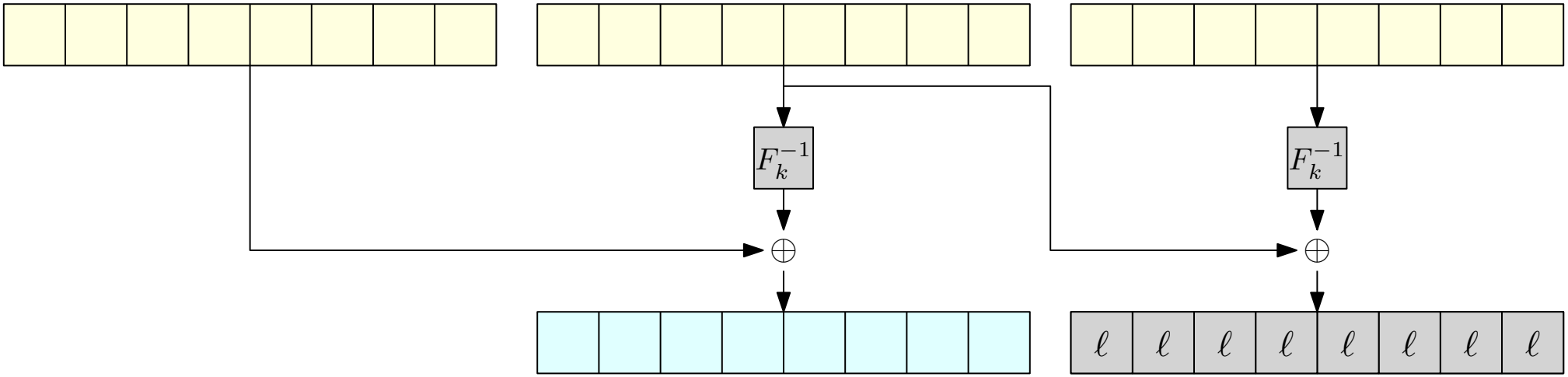
What do we do if/when the last block of the ciphertext consists entirely of padding?

- 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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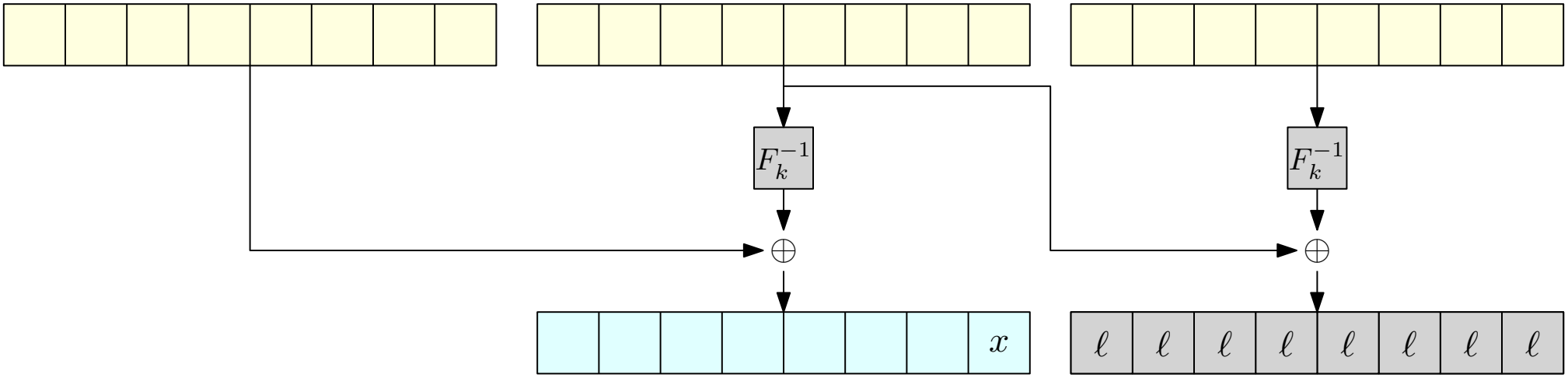

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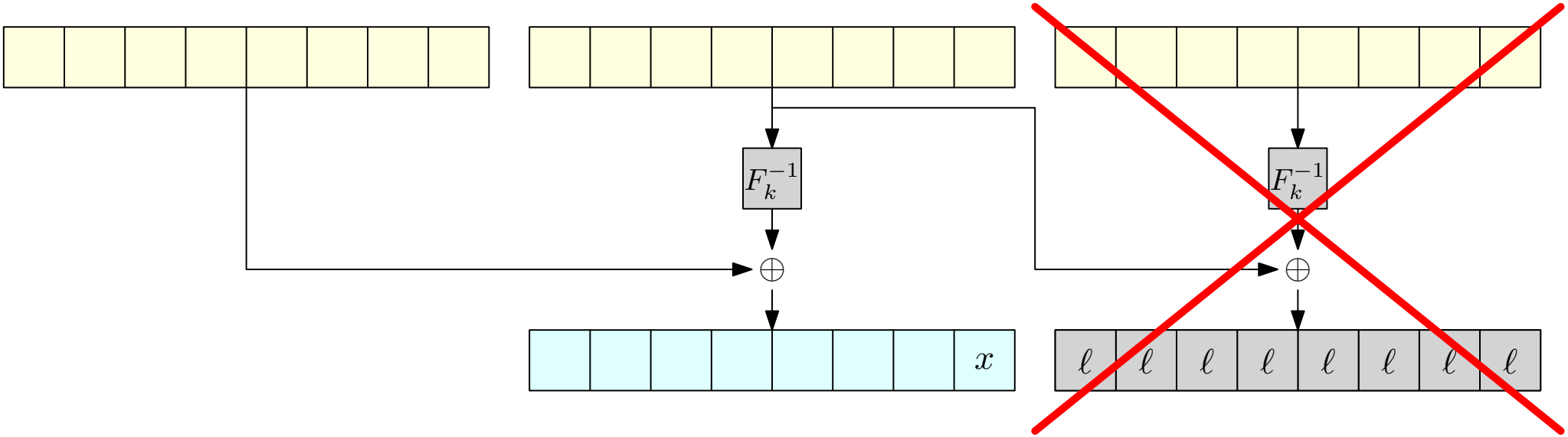
Permanently drop the last block of the ciphertext



Recovering the previous block

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

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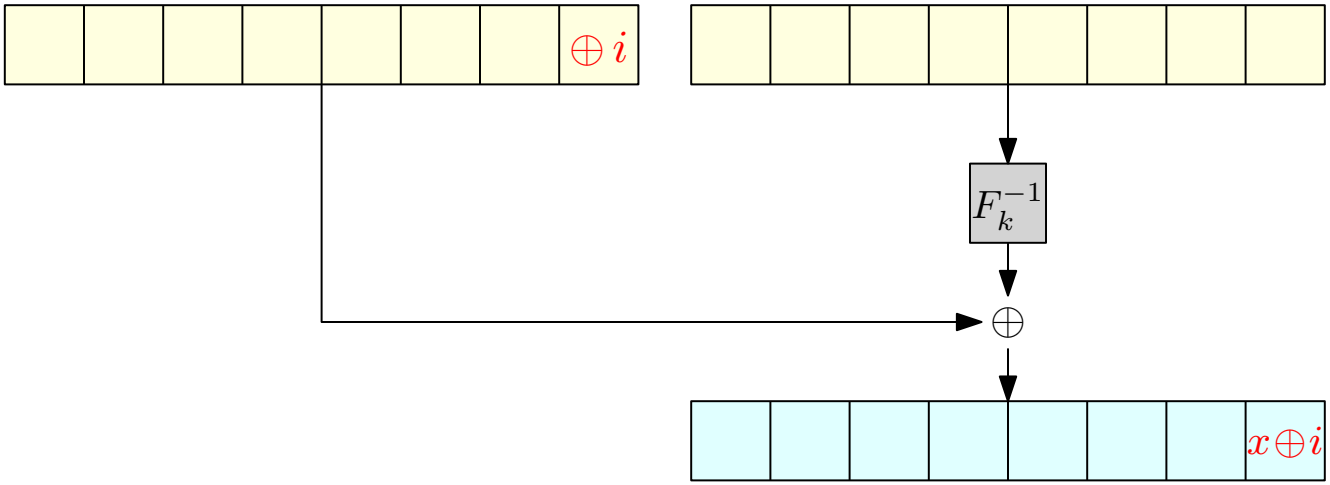

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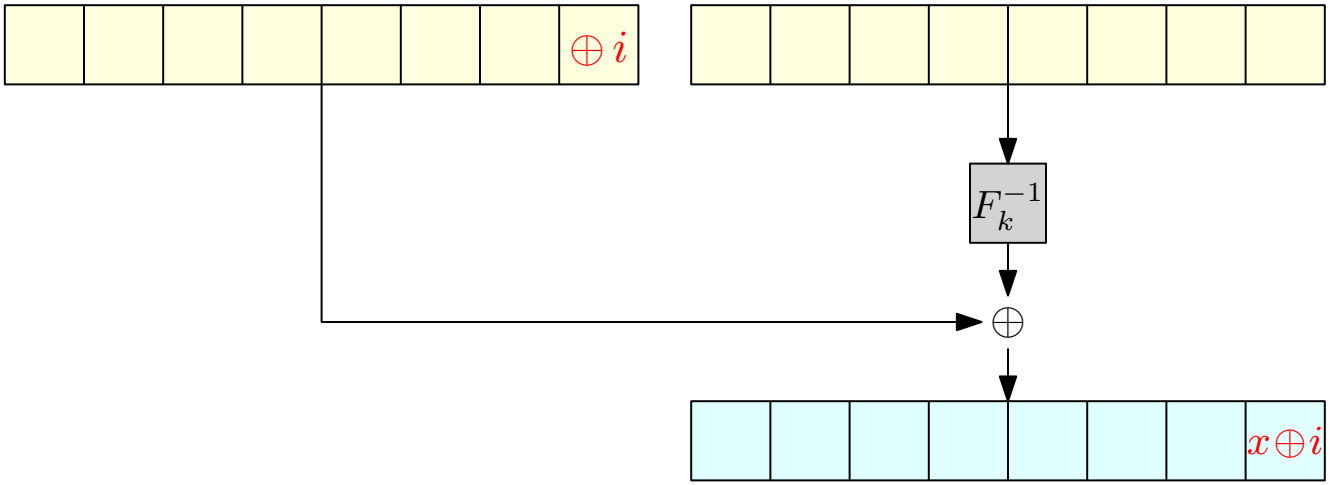

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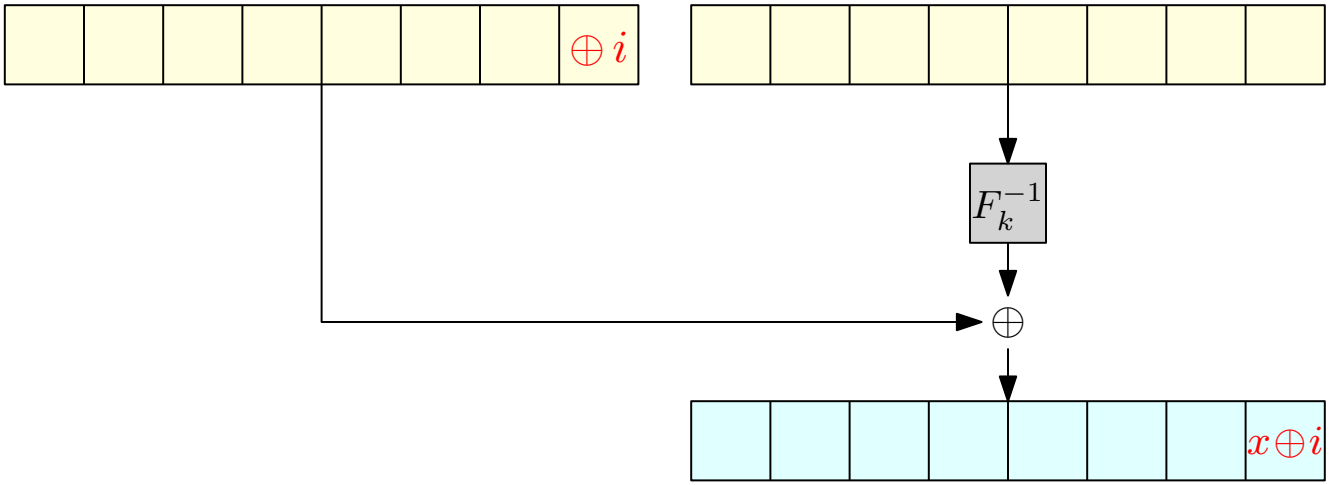

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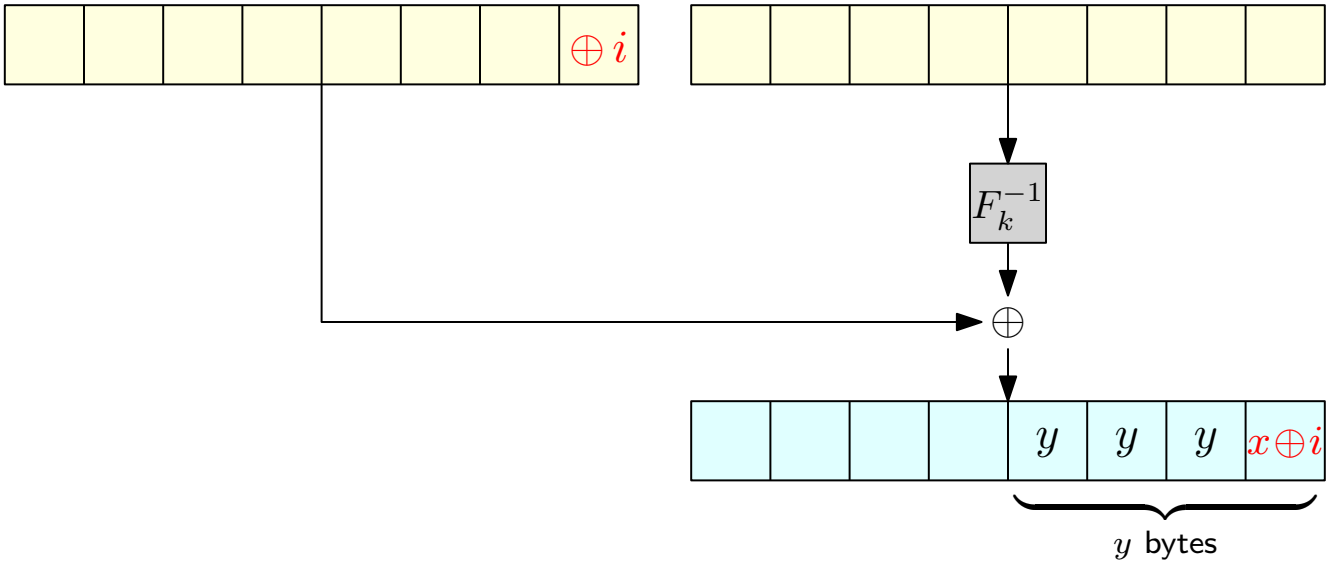

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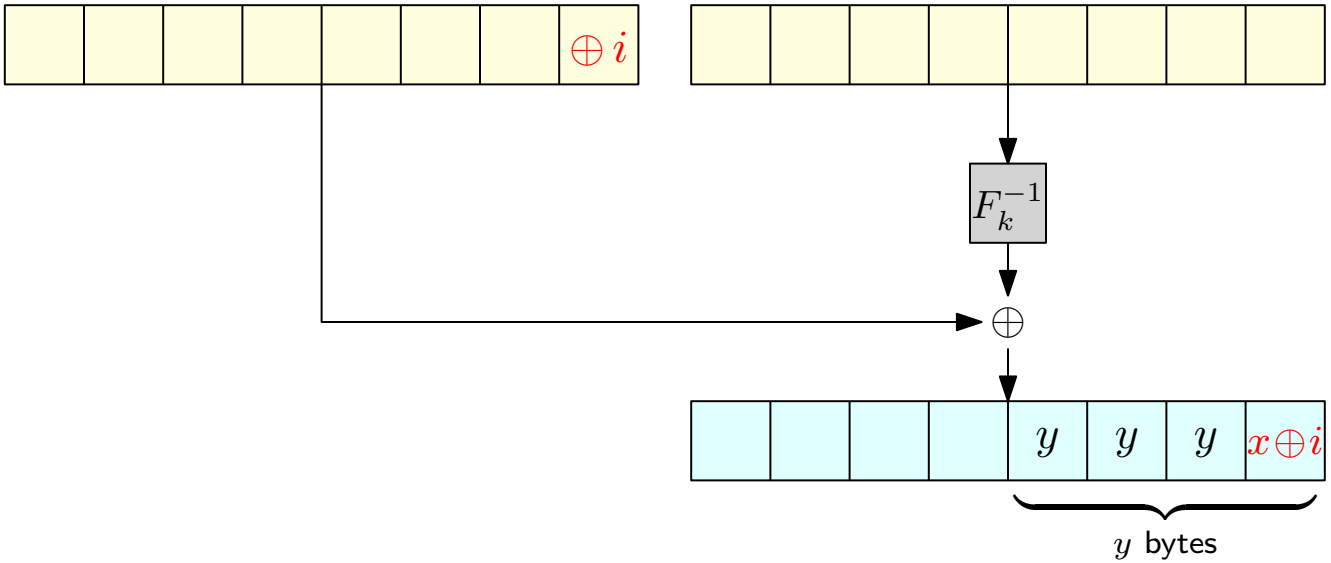

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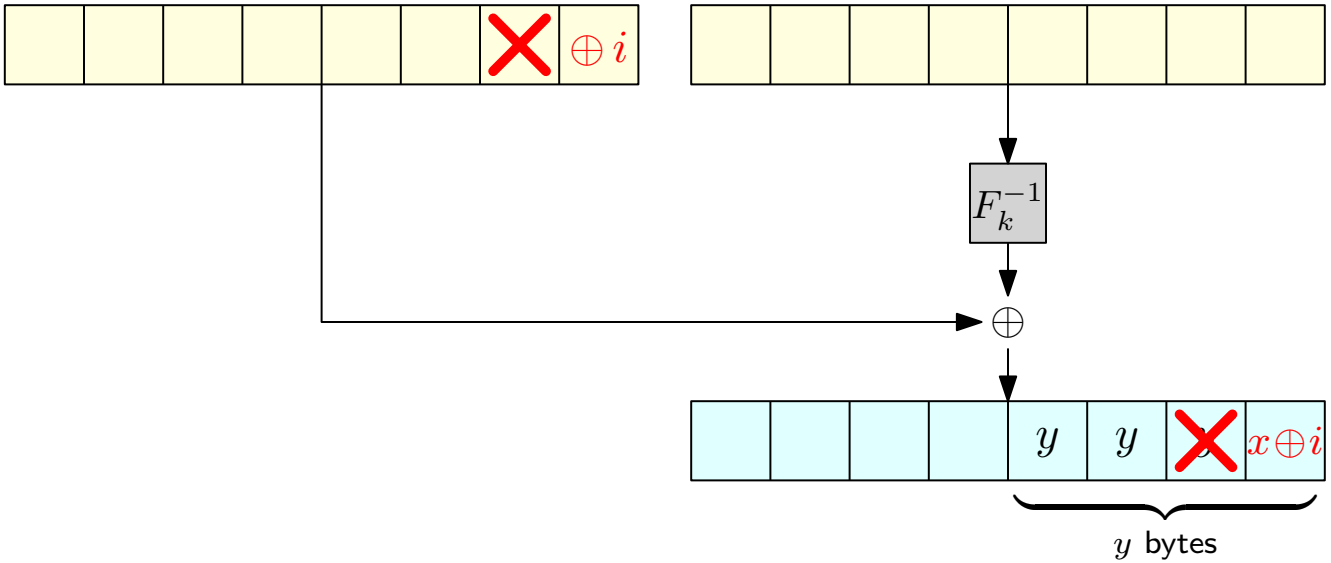

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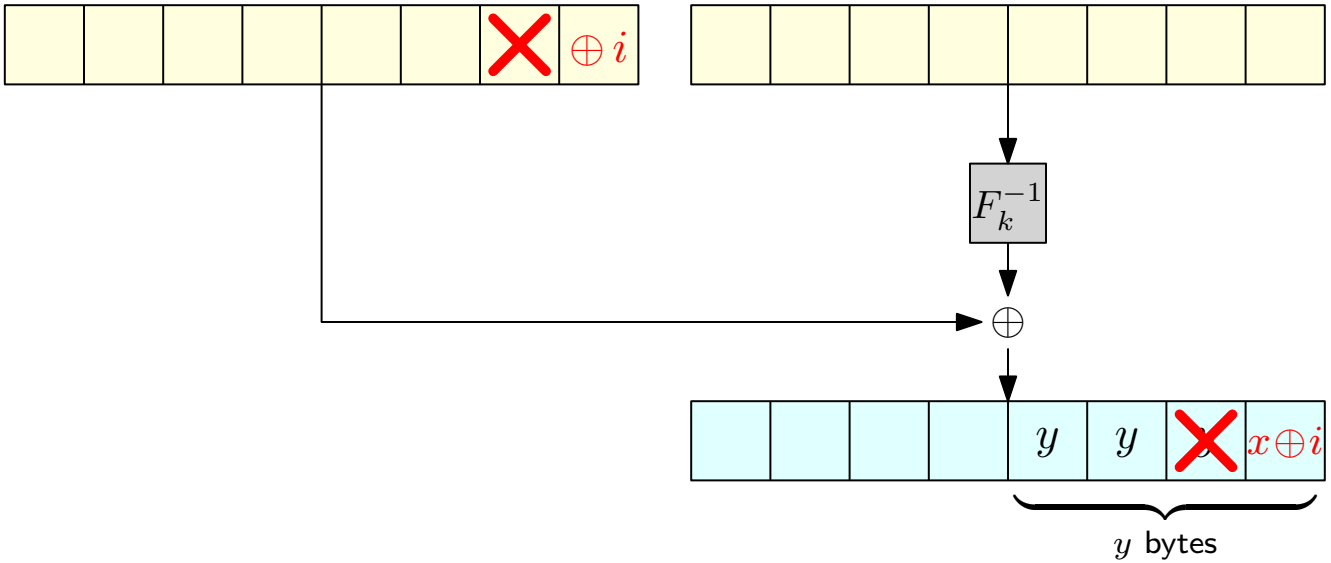

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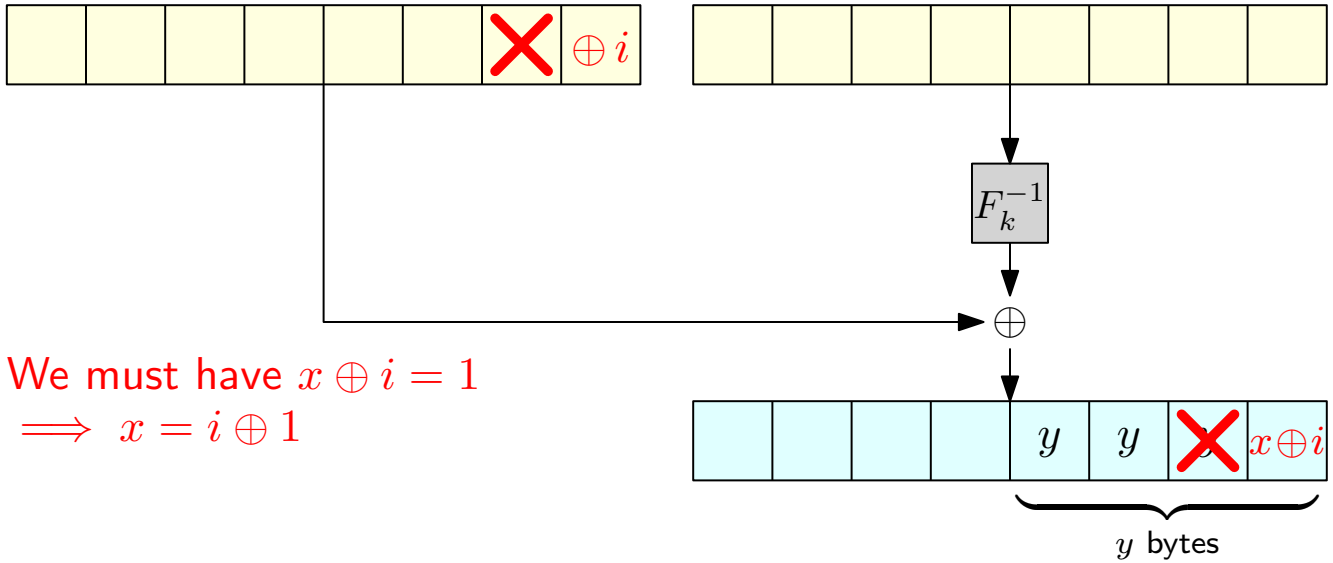

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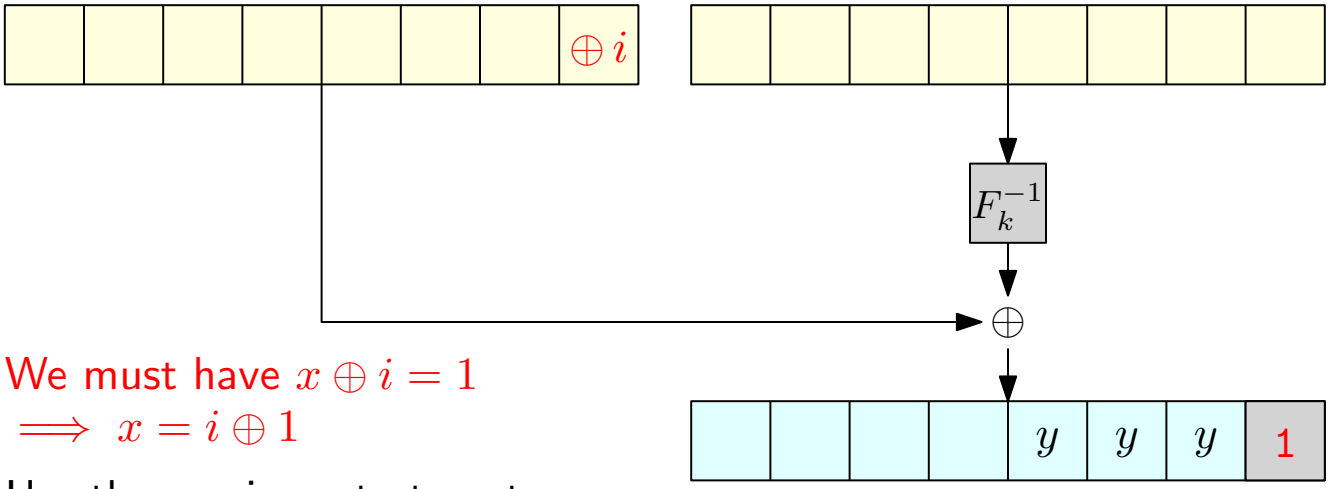

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Use the previous strategy to recover the rest of the block

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
  - $\leq 256 + 1$ attempts to learn the last byte of a block
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  E.g., padding oracle attacks against SSL, IPSec, Steam...

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- In fact, we are going to achieve an even stronger security guarantee:

  Authenticated Encryption

Authenticated Encryption

- 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 $\text{Enc-forge}_{\mathcal{A},\Pi}(n)$:

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

Encryption
and
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oracles
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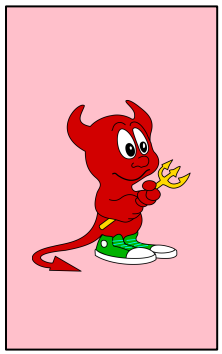

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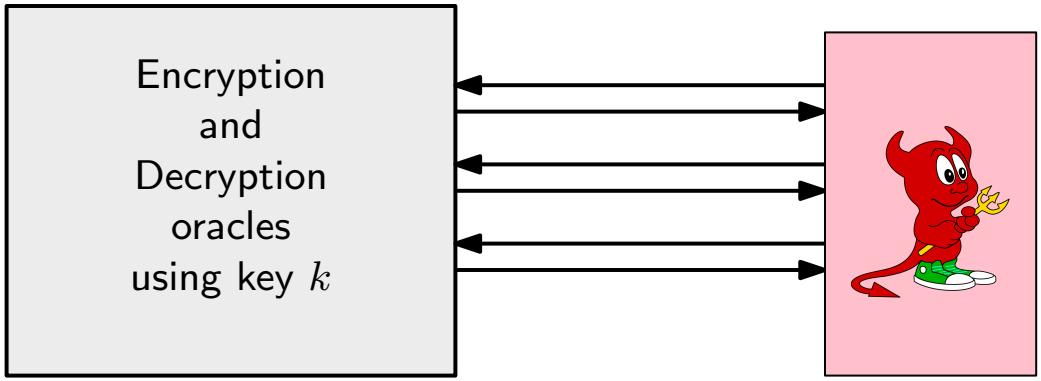

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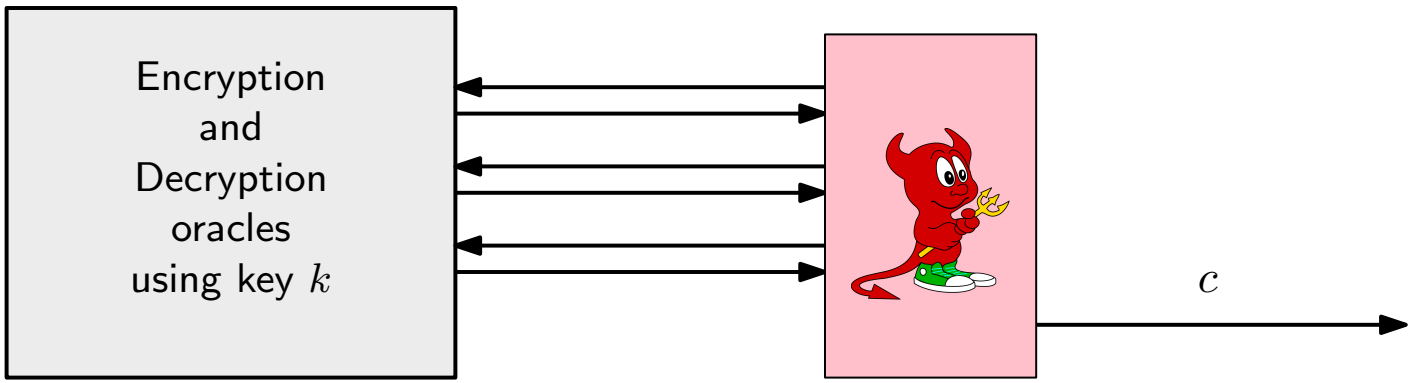

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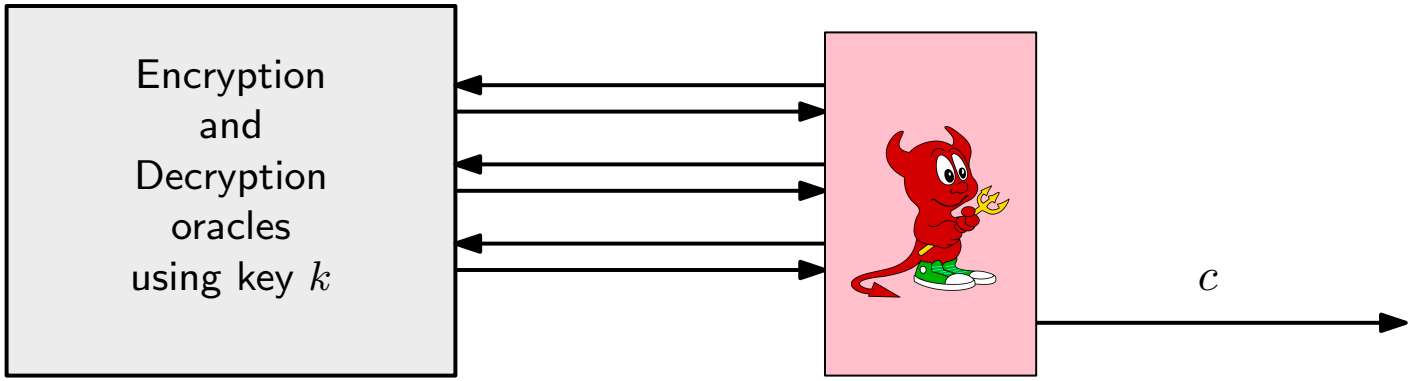

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The key is kept secret from $\mathcal{A}$

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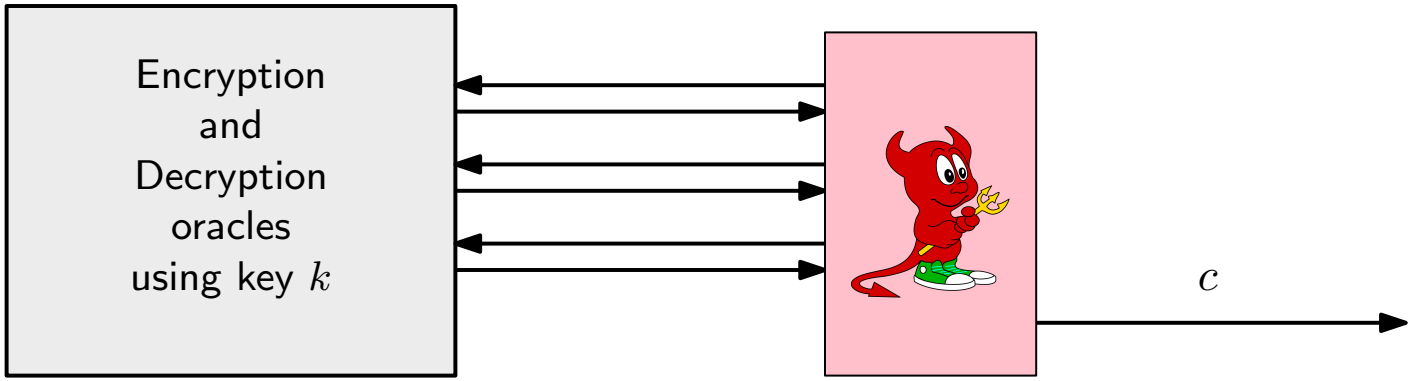

Definition of Authenticated Encryption

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

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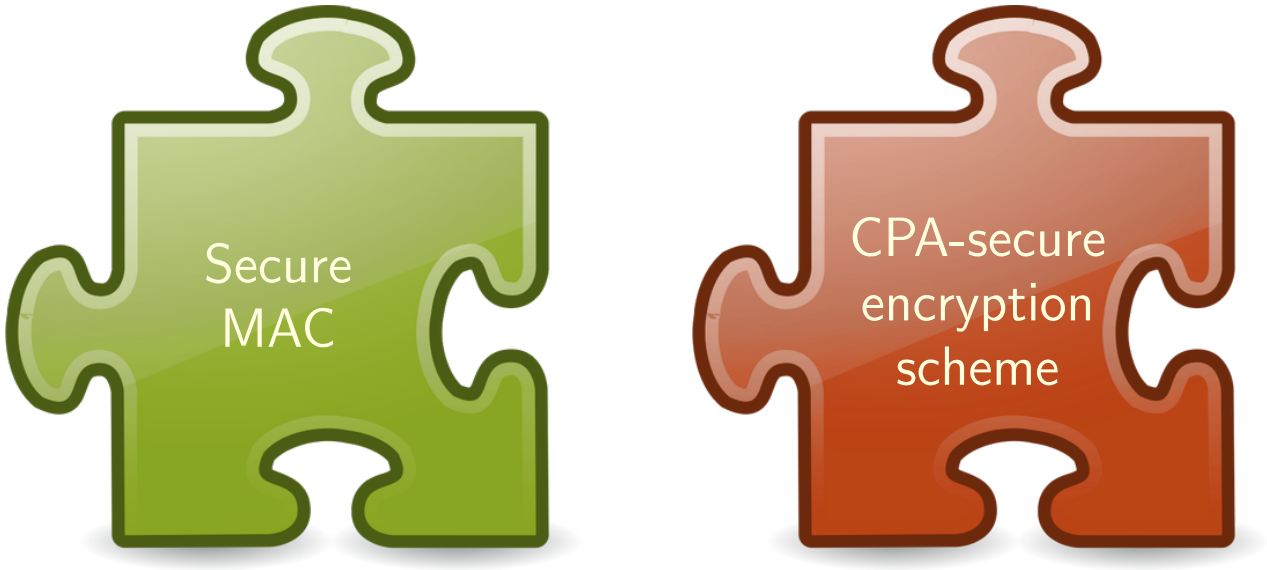
Modular Construction of Authenticated Encryption schemes

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?

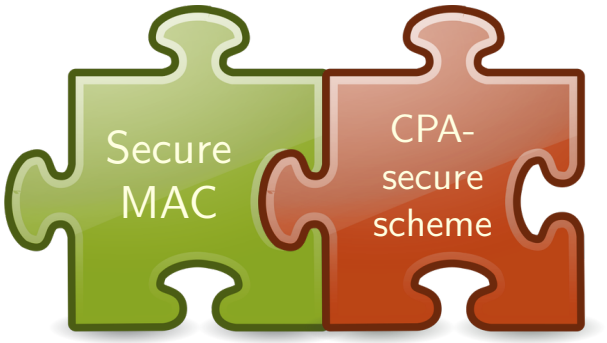
- Pick any secure MAC
- Pick any CPA-secure encryption scheme
- Combine them (somehow)



Combining MACs and CPA-secure encryption schemes

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

Ideas?



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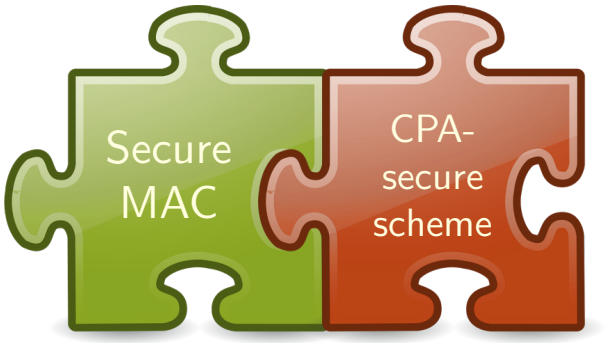

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Three natural choices:

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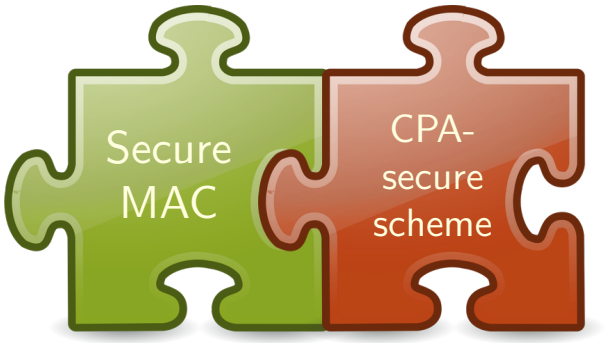

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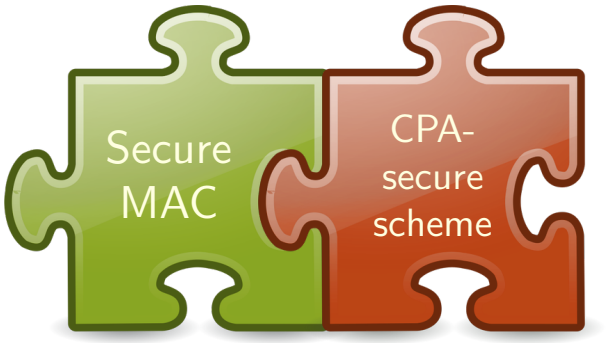

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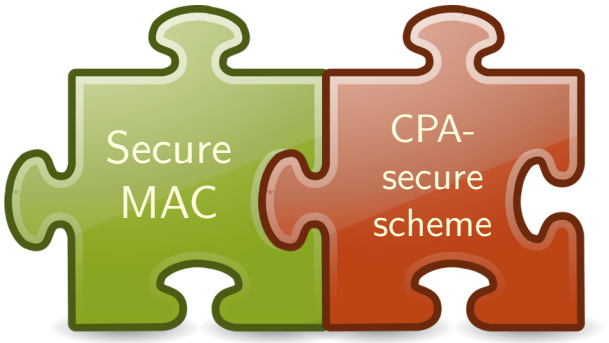

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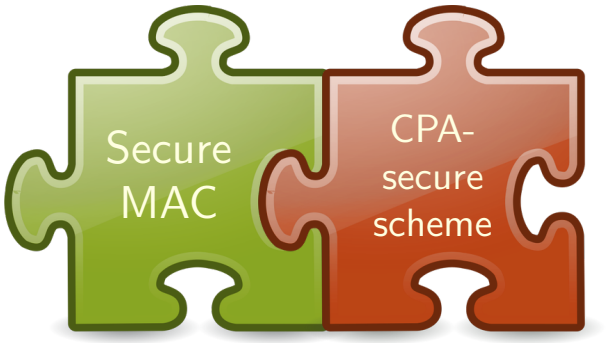

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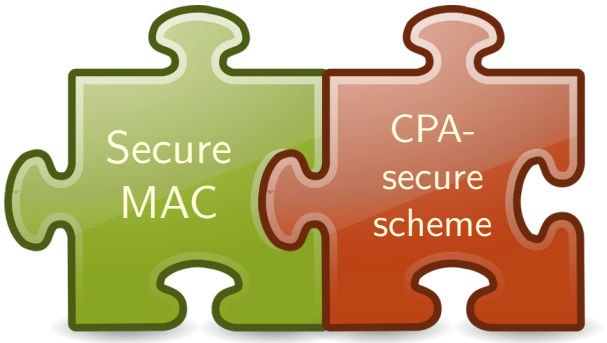

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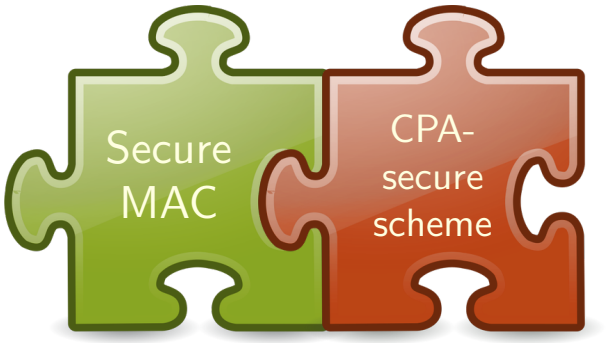

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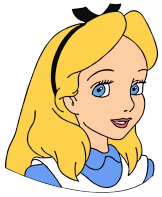
Encrypt and Authenticate

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

k_1, k_2 

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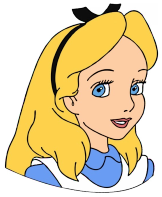
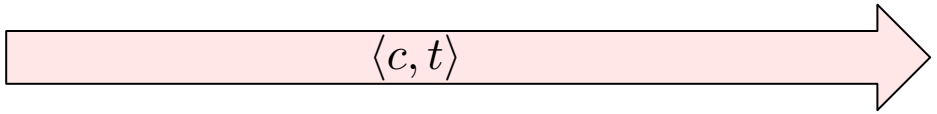
k_1, k_2 



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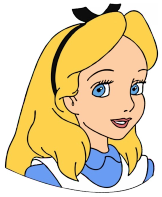

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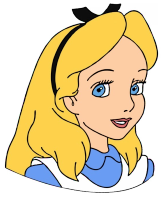
k_1, k_2  $\langle c, t \rangle$  k_1, k_2

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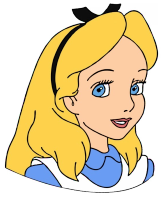

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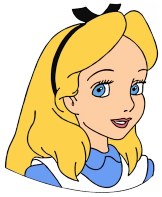
k_1, k_2  $\langle c, t \rangle$  k_1, k_2

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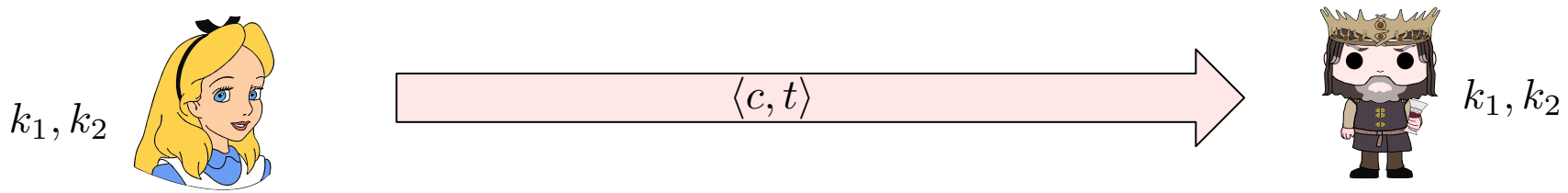

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This scheme is not even CPA-secure!

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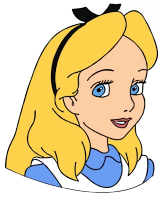
k_1, k_2  c  k_1, k_2

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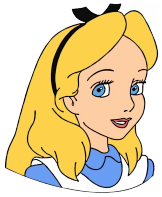

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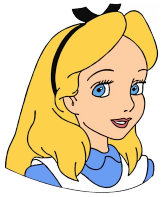

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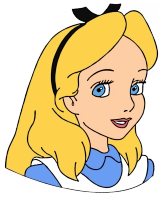
k_1, k_2  c  k_1, k_2

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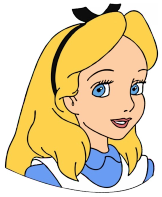
k_1, k_2  c  k_1, k_2

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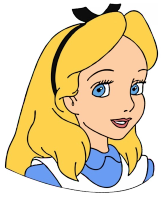
k_1, k_2  c  k_1, k_2

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

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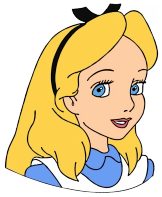
k_1, k_2 

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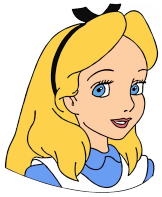

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Keys (w. security parameter n):

- $k_1 \leftarrow \mathsf{Gen}_E(1^n)$
- $k_2 \leftarrow \mathsf{Gen}_M(1^n)$
- Return $k_1 \,\|\, k_2$

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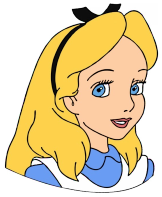
- Otherwise return $\perp$

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

Encrypt then Authenticate

Encrypting m:

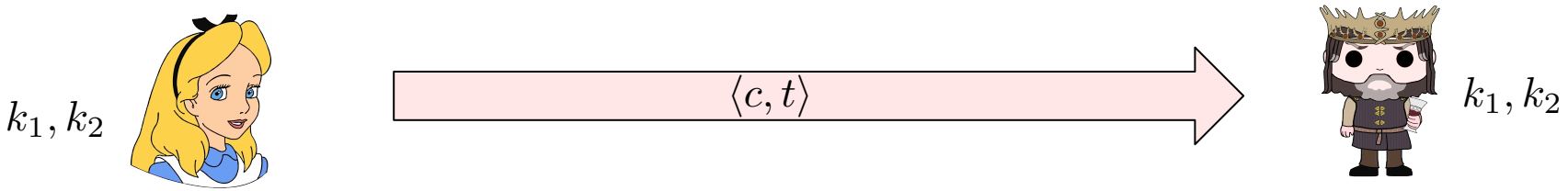
- $c \leftarrow \mathsf{Enc}_{k_1}(m)$
- $t \leftarrow \mathsf{Mac}_{k_2}(c)$
- Return the ciphertext $\langle c, t \rangle$

Keys (w. security parameter n):

- $k_1 \leftarrow \mathsf{Gen}_E(1^n)$
- $k_2 \leftarrow \mathsf{Gen}_M(1^n)$
- Return $k_1 \| k_2$

Decrypting $\langle c, t \rangle$:

- If $\mathsf{Vrfy}_{k_2}(c, t) = 1$:
  - $m \leftarrow \mathsf{Dec}_{k_1}(c)$
  - Return m
- Otherwise return $\perp$



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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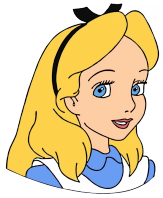

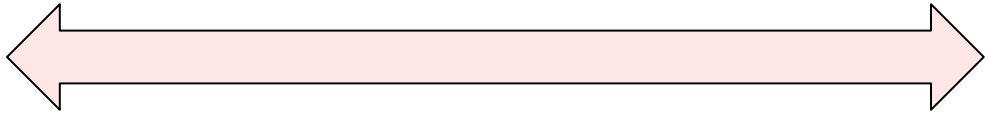

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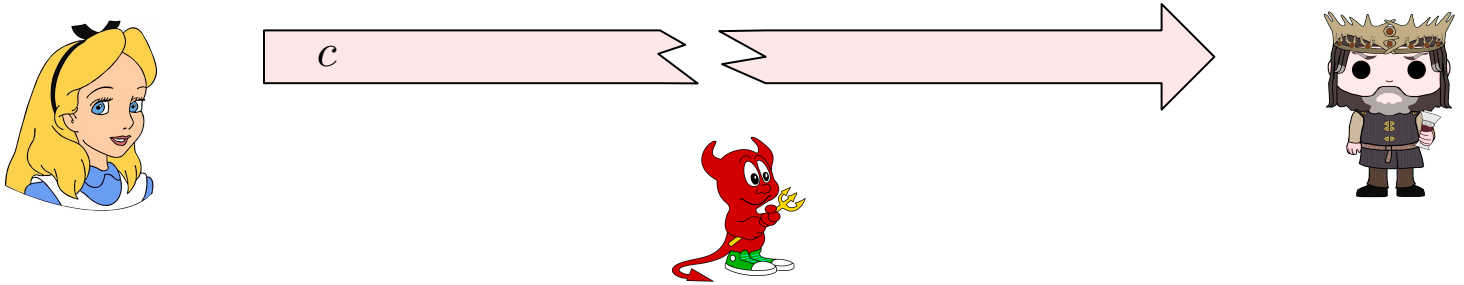
Message dropping:



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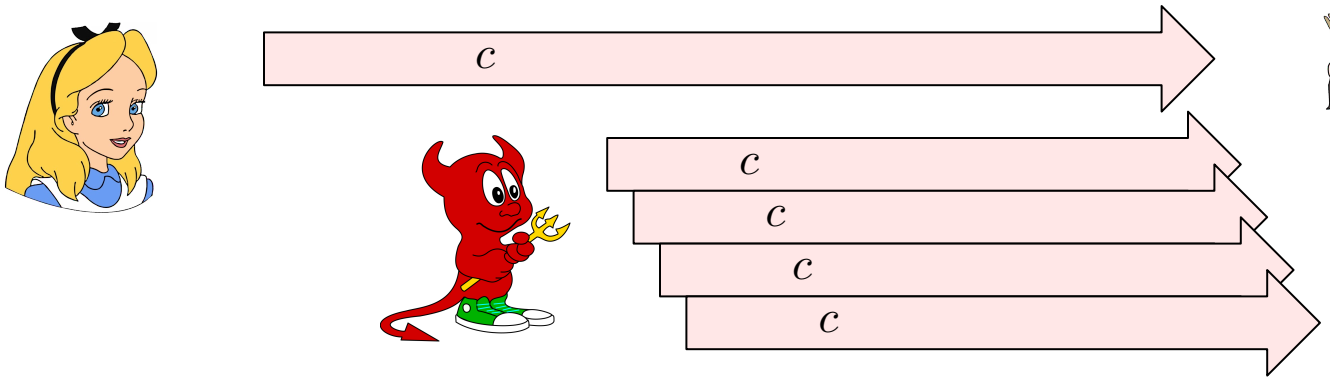
Replay attack (we have already encountered this attack):



Secure Sessions

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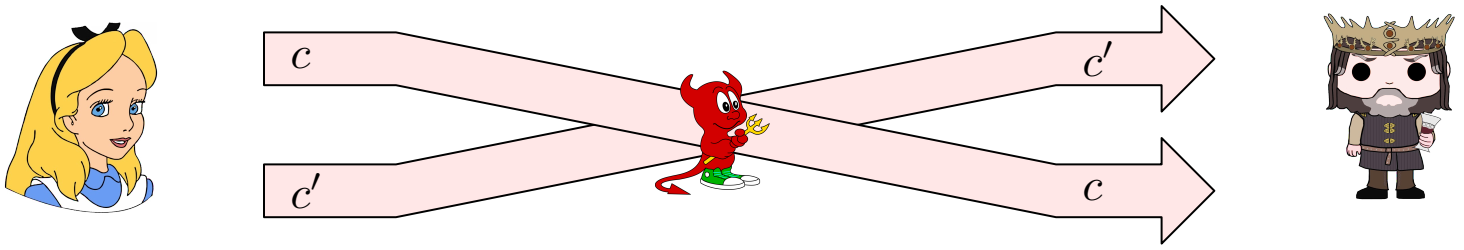
Re-ordering attack (the adversary reorders messages, not blocks):



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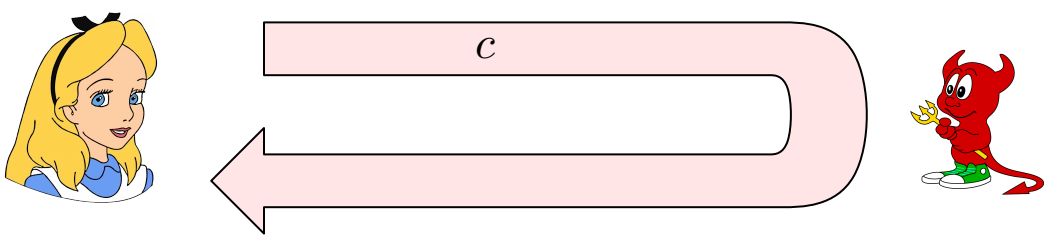
Reflection attack



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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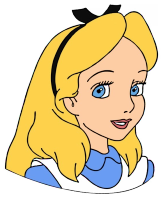
Reflection attack

- 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



$\mathsf{Enc}_k(0 \,\|\, 1 \,\|\, m_1)$

$\mathsf{Enc}_k(0 \,\|\, 2 \,\|\, m_2)$

$\mathsf{Enc}_k(1 \,\|\, 1 \,\|\, m_3)$

$\mathsf{Enc}_k(0 \,\|\, 3 \,\|\, m_4)$

$\mathsf{Enc}_k(1 \,\|\, 2 \,\|\, m_5)$