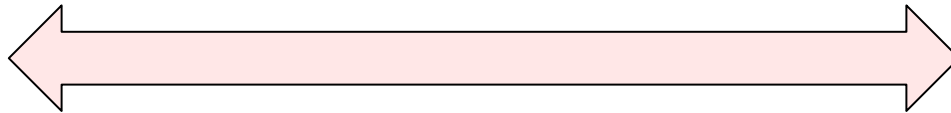
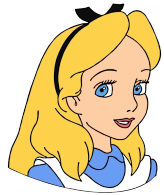


Reminder: Passive vs Active Attacks

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

DONE!
(Message Authentication Codes)

Integrity and Secrecy are **orthogonal** concerns

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Secrecy:

Secrecy against active adversaries?

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Reminder: Malleability of OTP

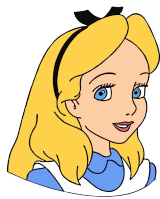
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PAY <RECIPIENT_IBAN> <AMOUNT> to the bank's backend

$m = \underbrace{010100000100000101011001}_{\text{PAY}} \underbrace{01001001\dots00110010}_{\text{IBAN}} \underbrace{0000000100000100}_{\text{AMOUNT (520)}}$

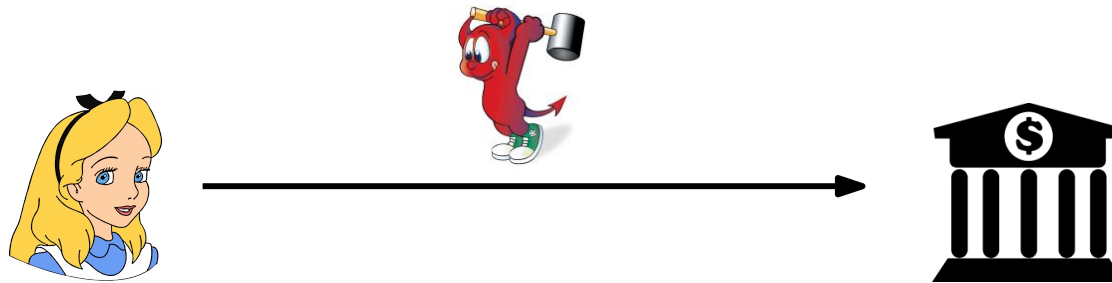


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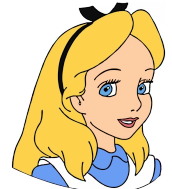
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 PAY IBAN AMOUNT



Changes to the ciphertext result in predictable changes to the plaintext
The scheme is malleable!

c' 001 ... 10001101 0011111010010010
 IBAN AMOUNT

c' 010100000100000101011001 01001001 ... 00110010 1000000100000100
 PAY IBAN AMOUNT (33028)



Malleability and CCA security

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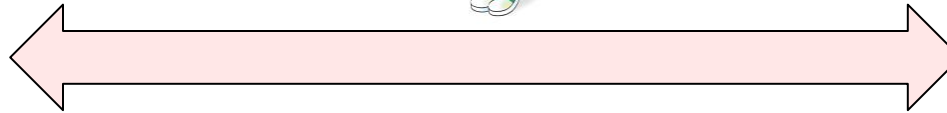
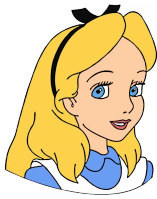
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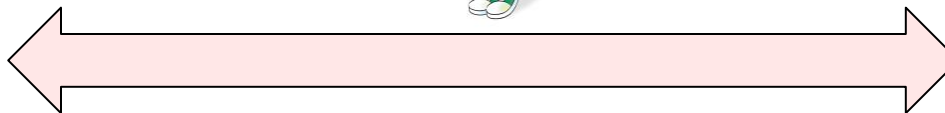
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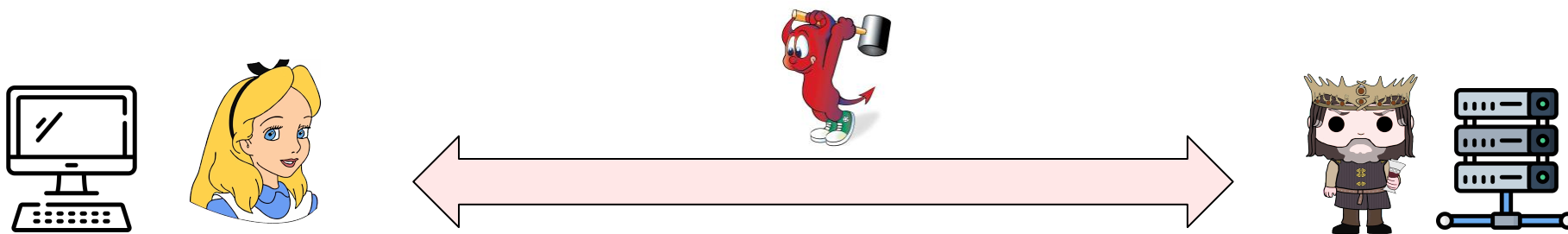
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Many protocols close a connection or request a retransmission when a bad message is received

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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

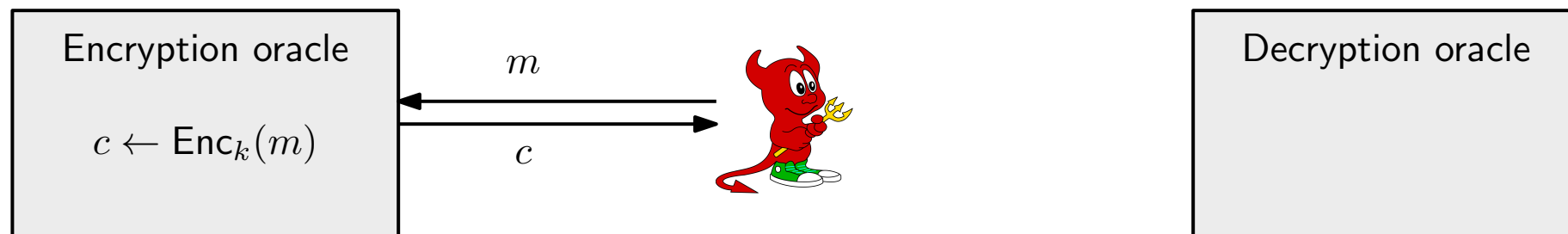


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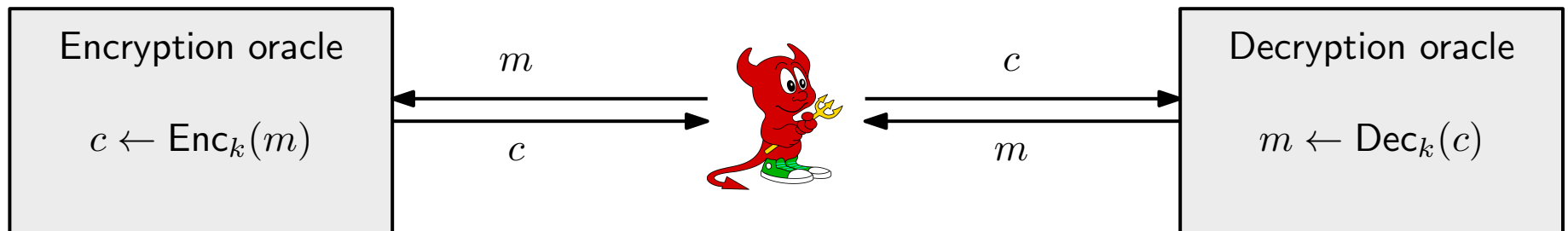
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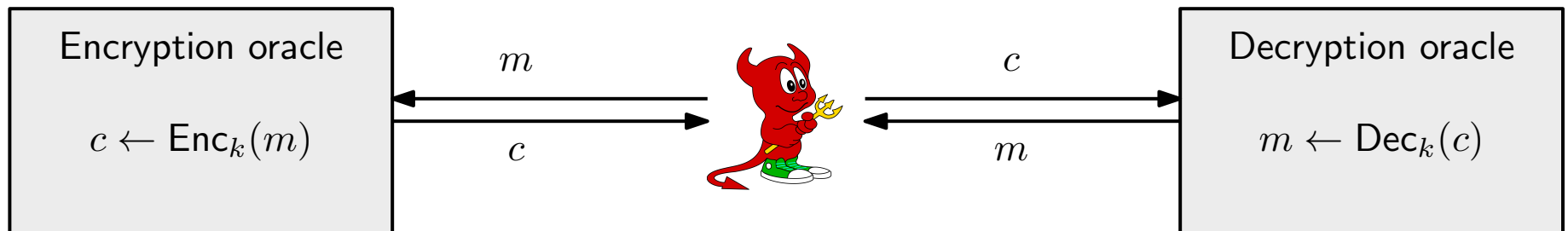
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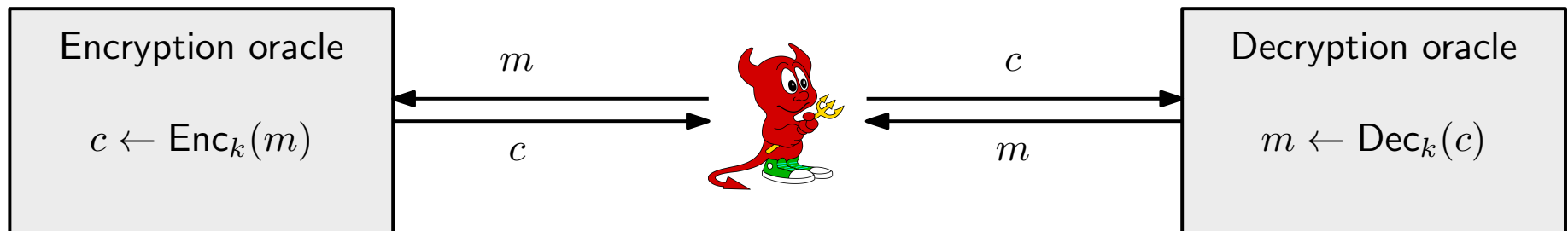
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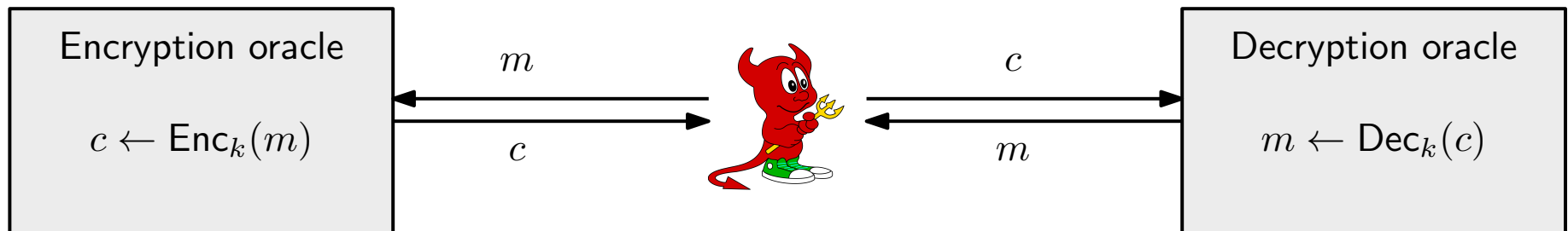
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The $\text{PrivK}_{\mathcal{A},\Pi}^{\text{cca}}$ experiment

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

- A key $k \leftarrow \text{Gen}(1^n)$ is generated
- \mathcal{A} can interact with an encryption oracle that provides access to $\text{Enc}_k(\cdot)$ **and** with a decryption oracle that provides access to $\text{Dec}_k(\cdot)$
- \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 $\text{Enc}_k(m_b)$, and given to \mathcal{A}
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Encryption
and
Decryption
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Adversary
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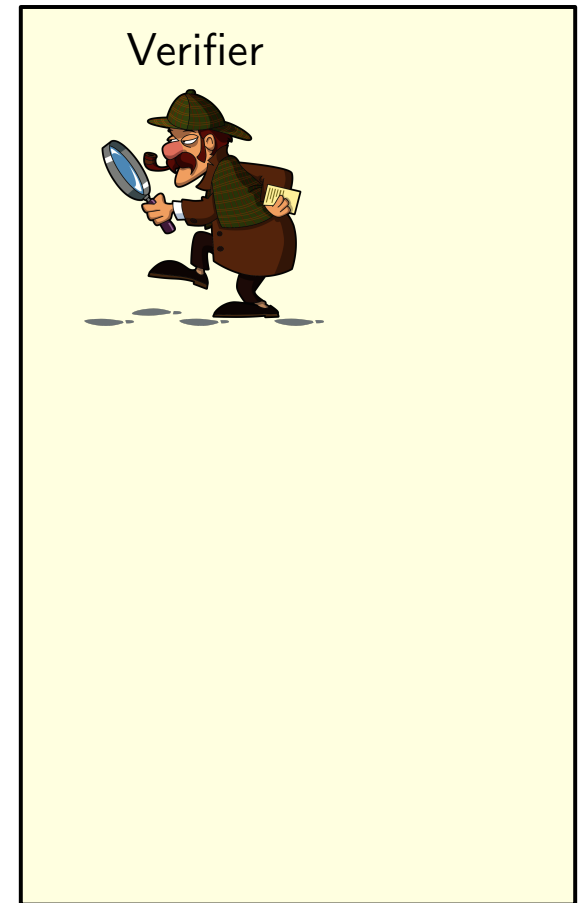
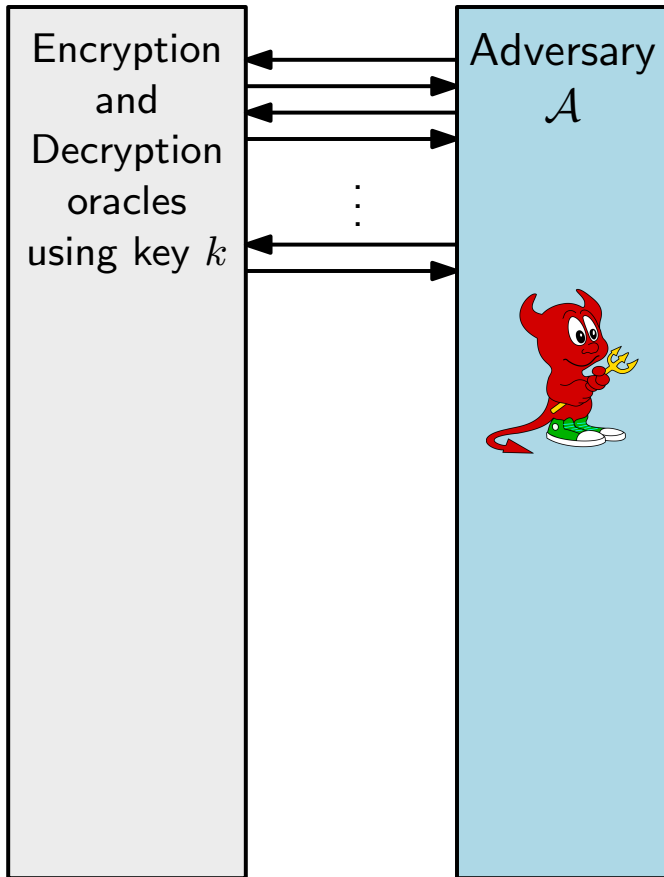


Verifier



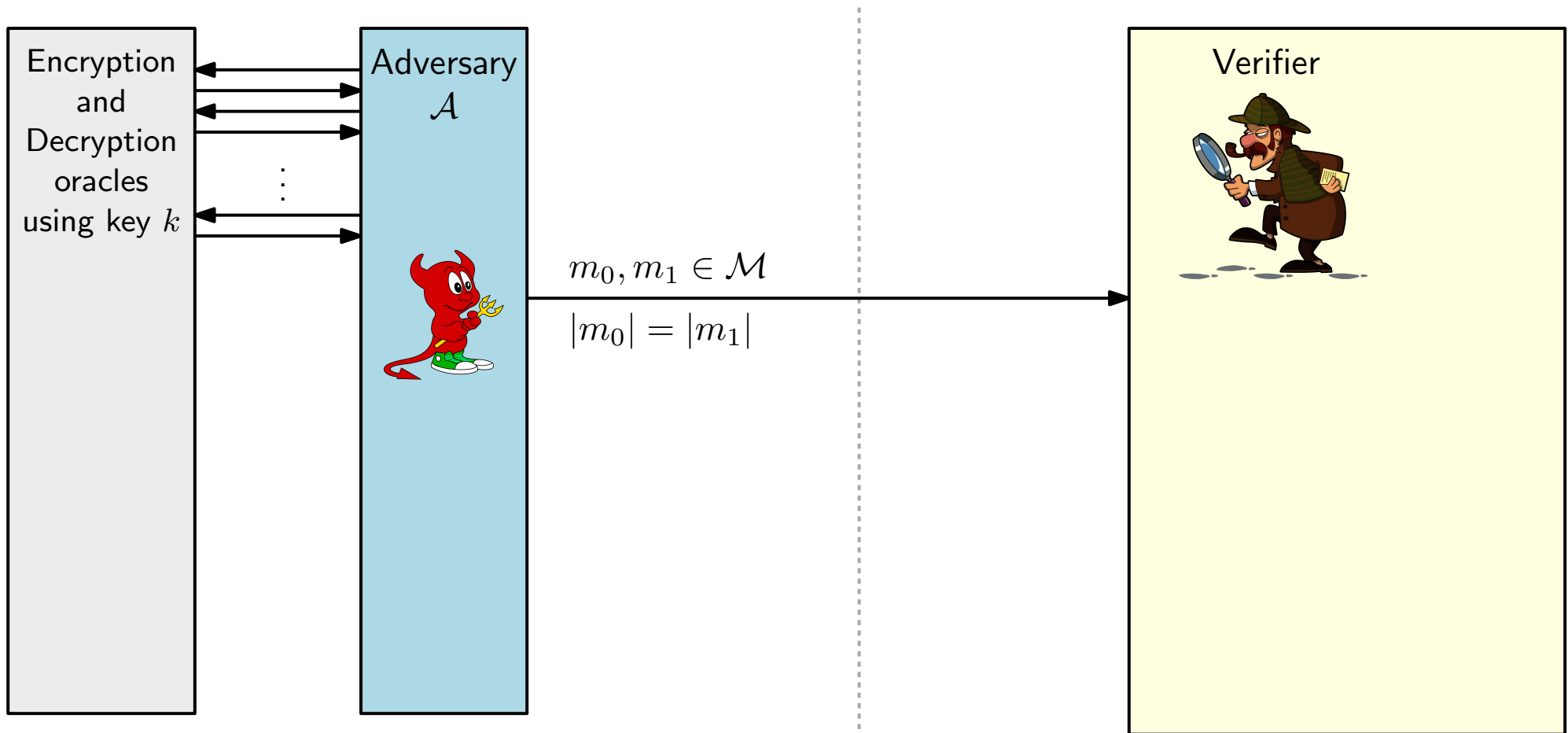
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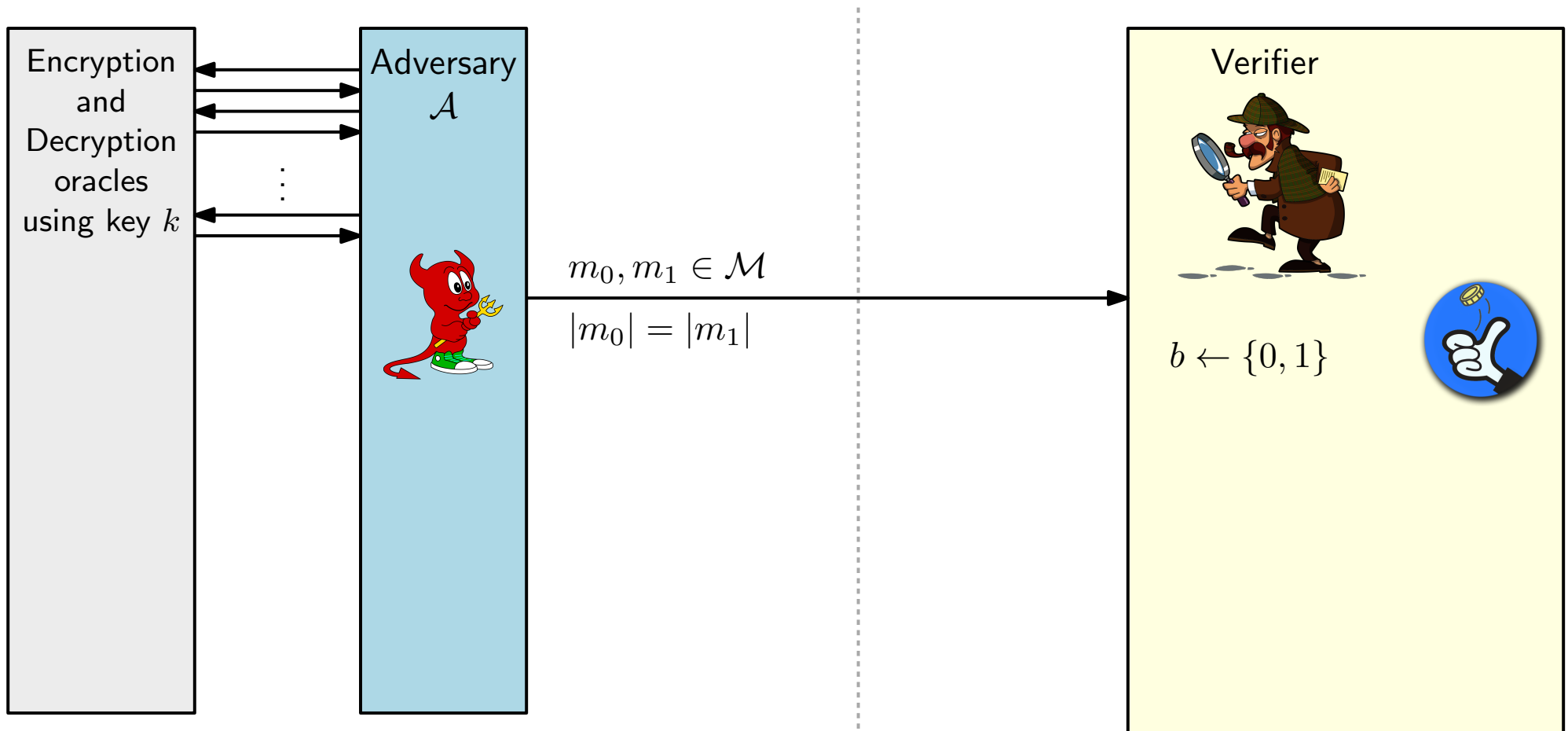
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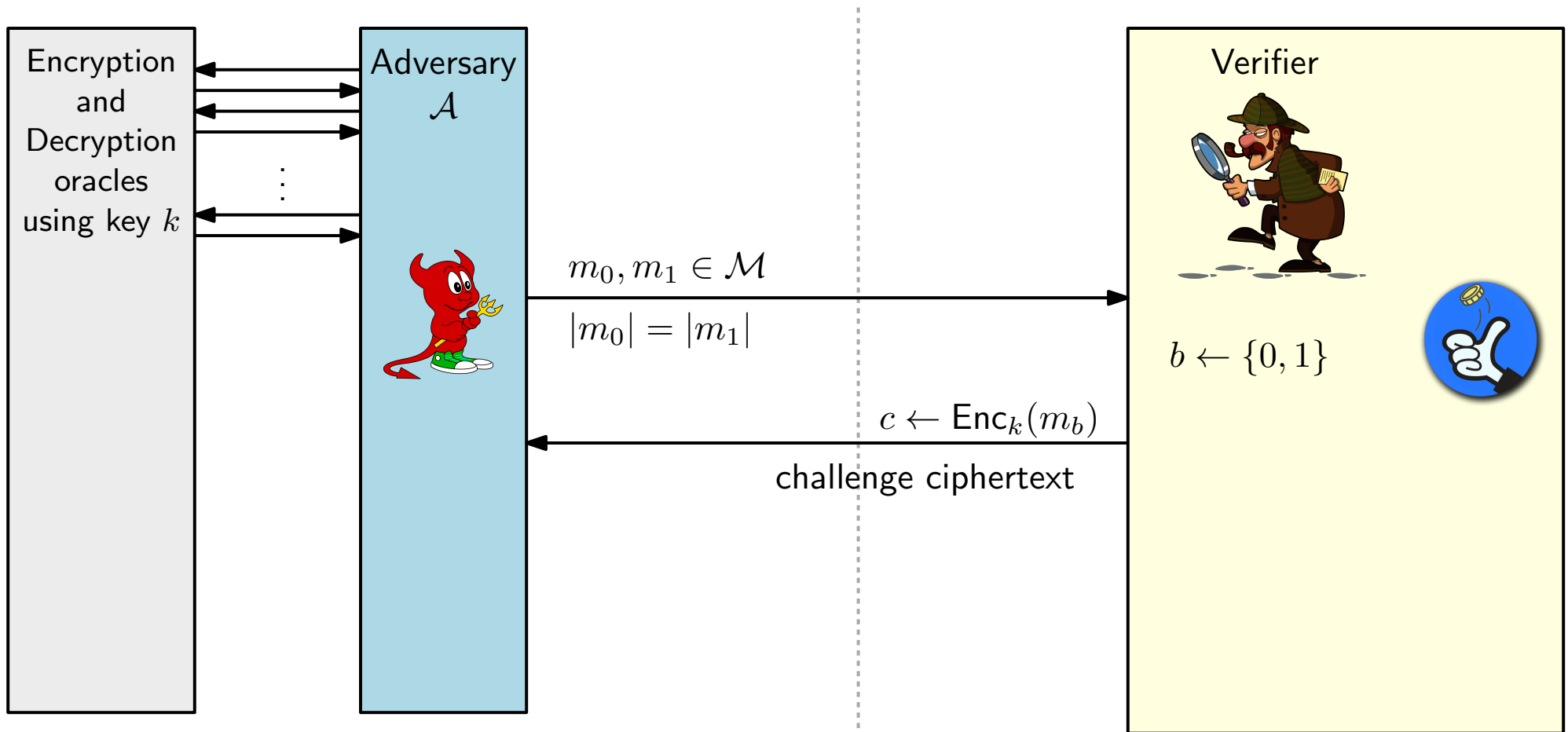
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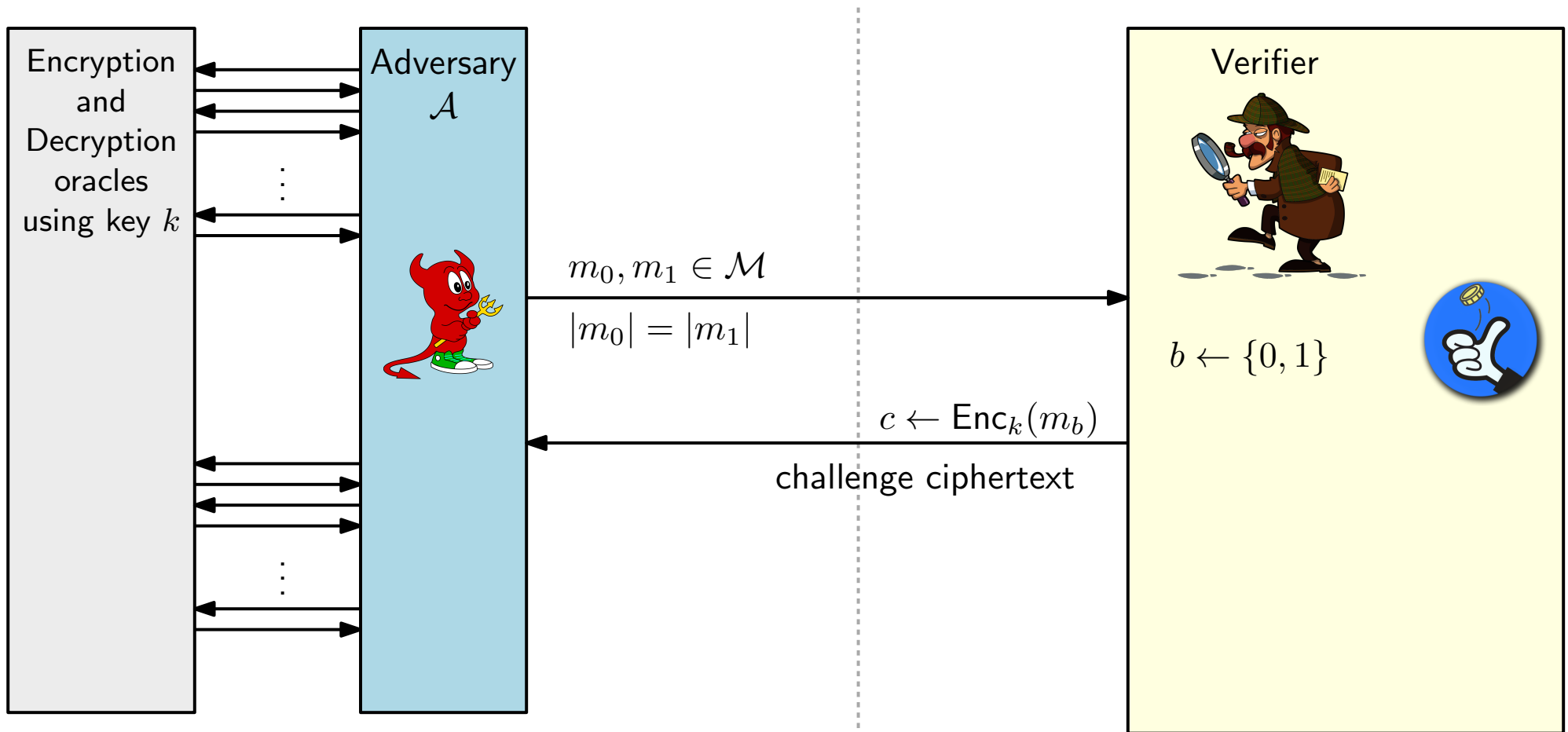
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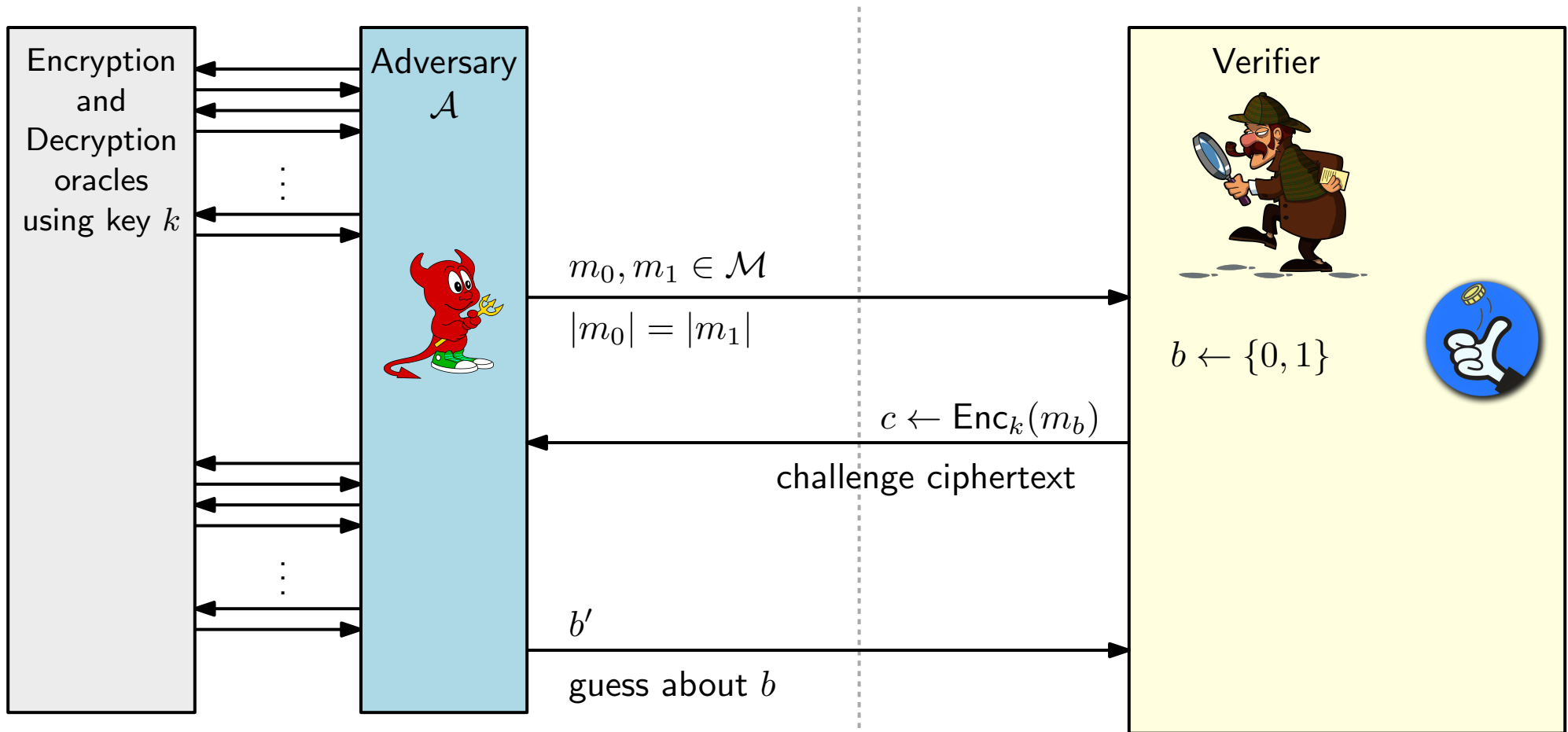
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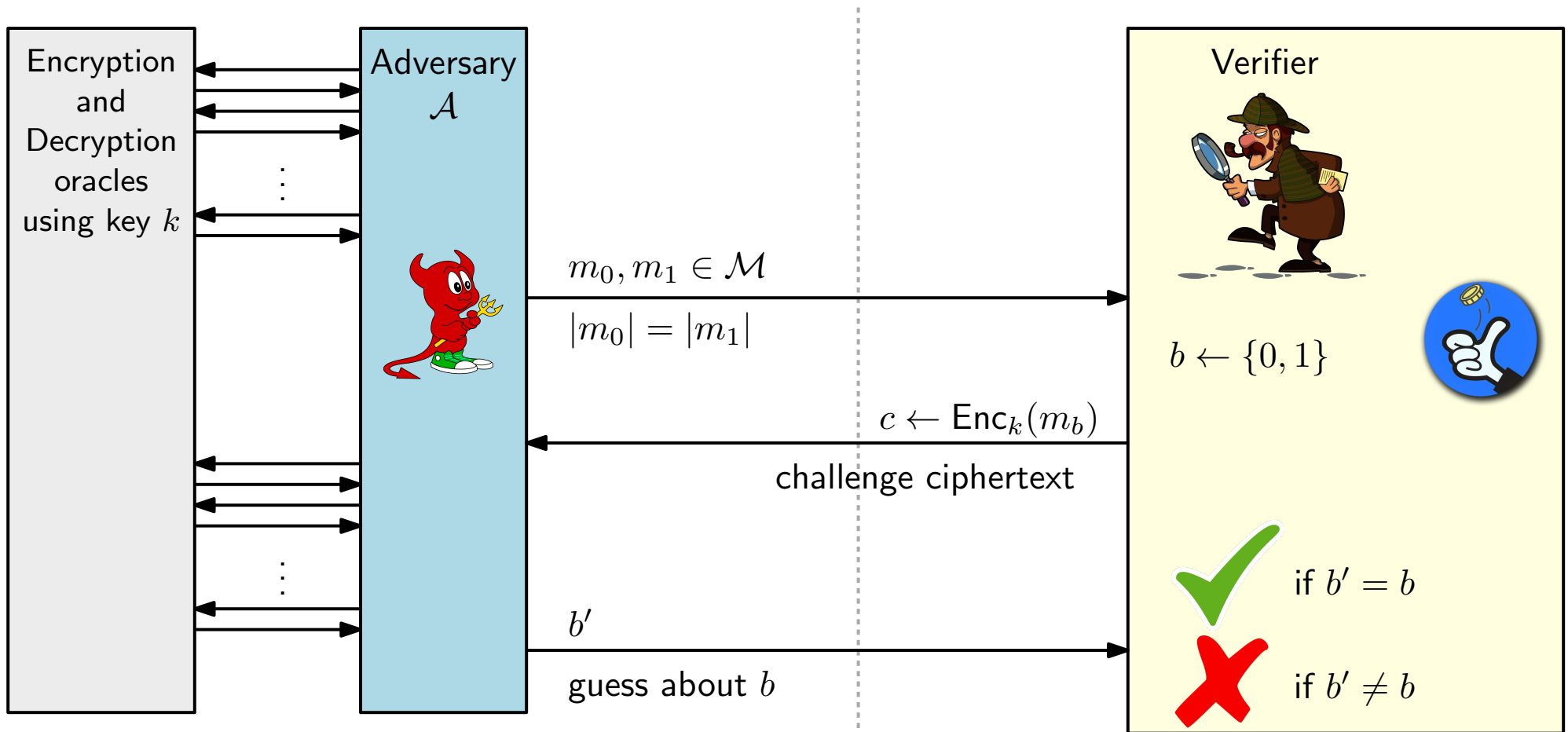
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Definition of CCA security

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:

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

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: CCA-security **implies** non-malleability!

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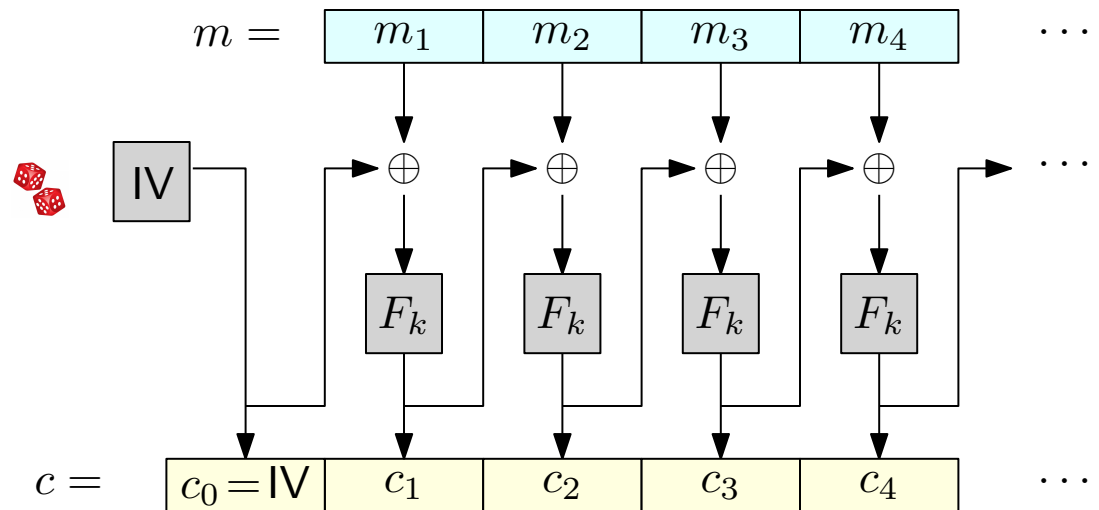
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- This scenario happens in the real world...
... In fact, this attack has been used against SSL!

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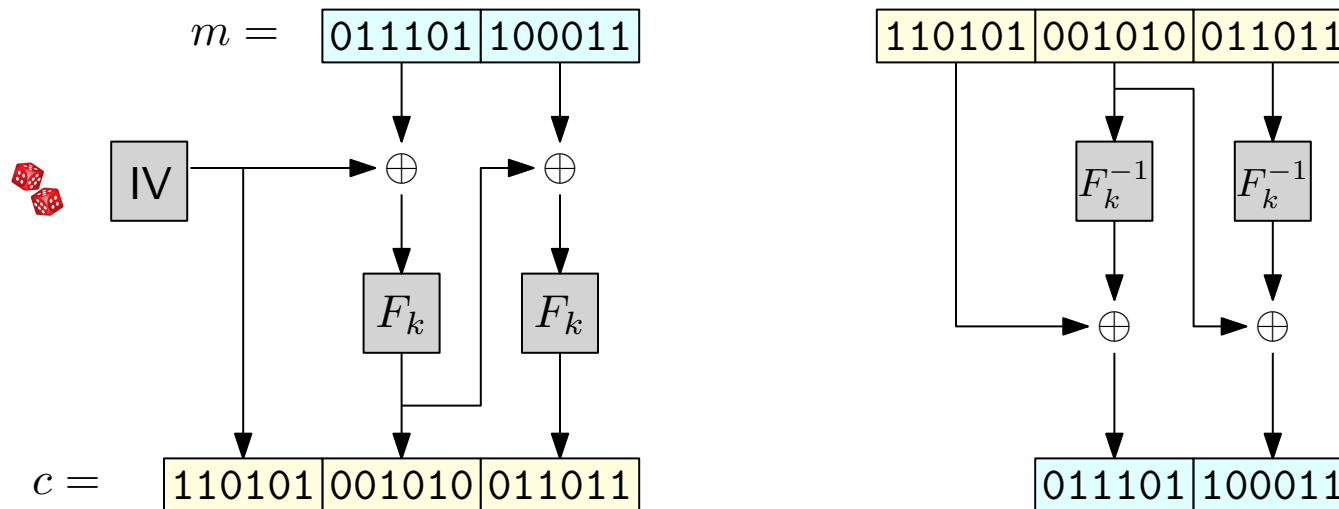
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- This scenario happens in the real world...
... In fact, this attack has been used against SSL!

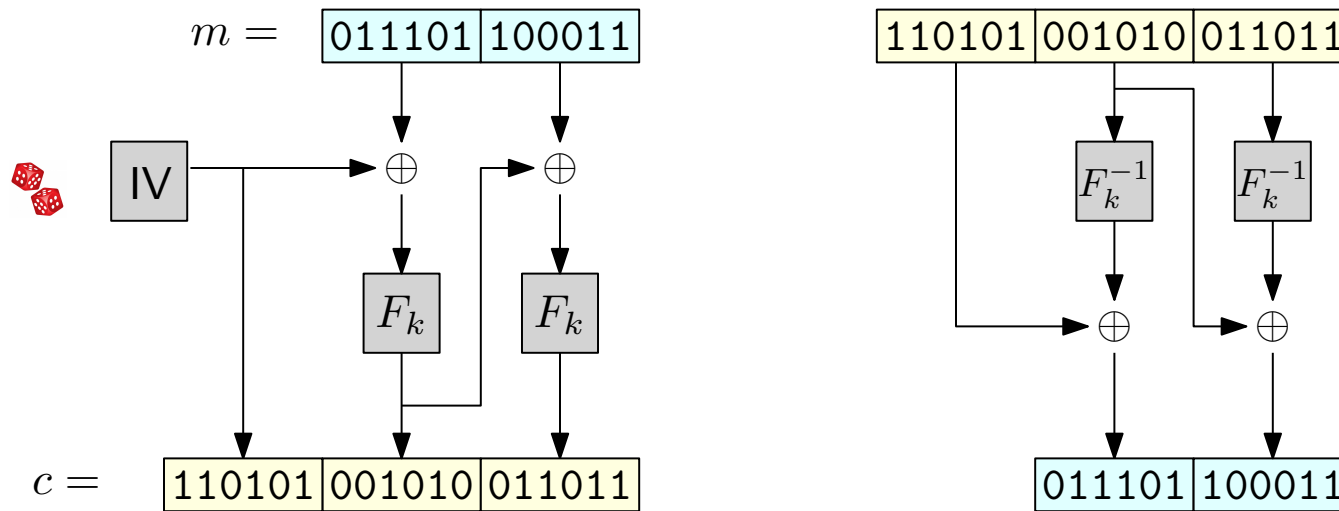
Reminder: block ciphers in CBC mode



Malleability of CBC mode

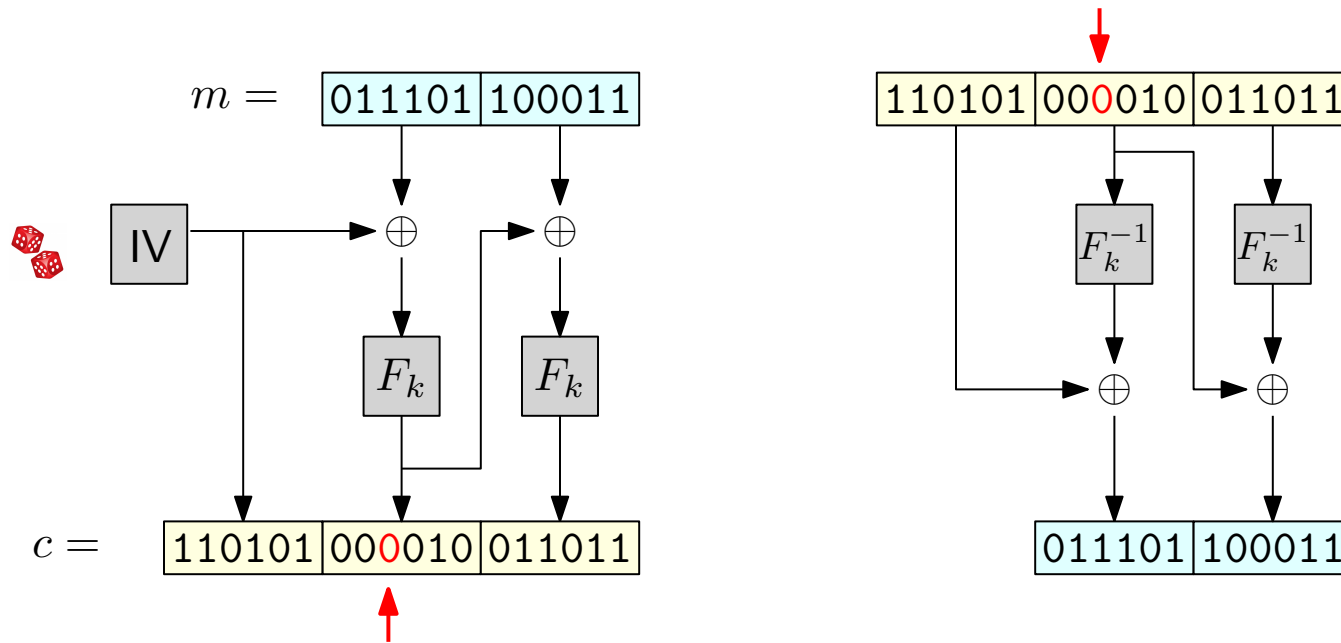


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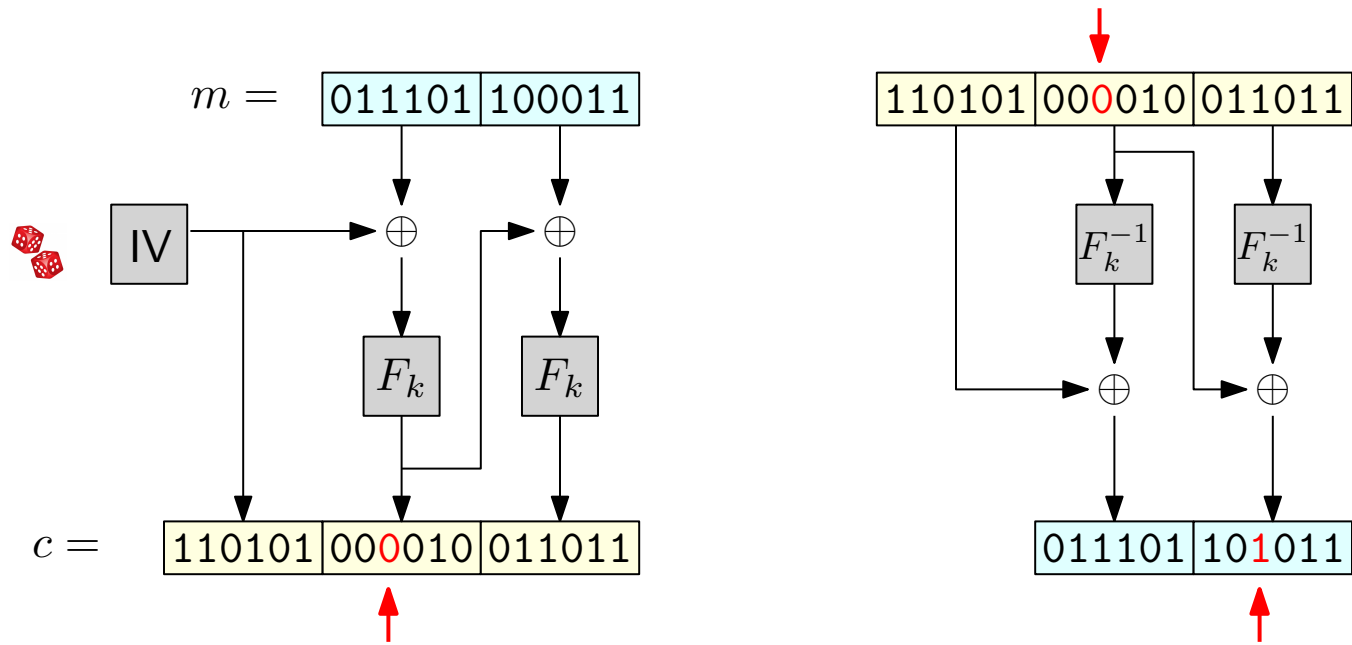
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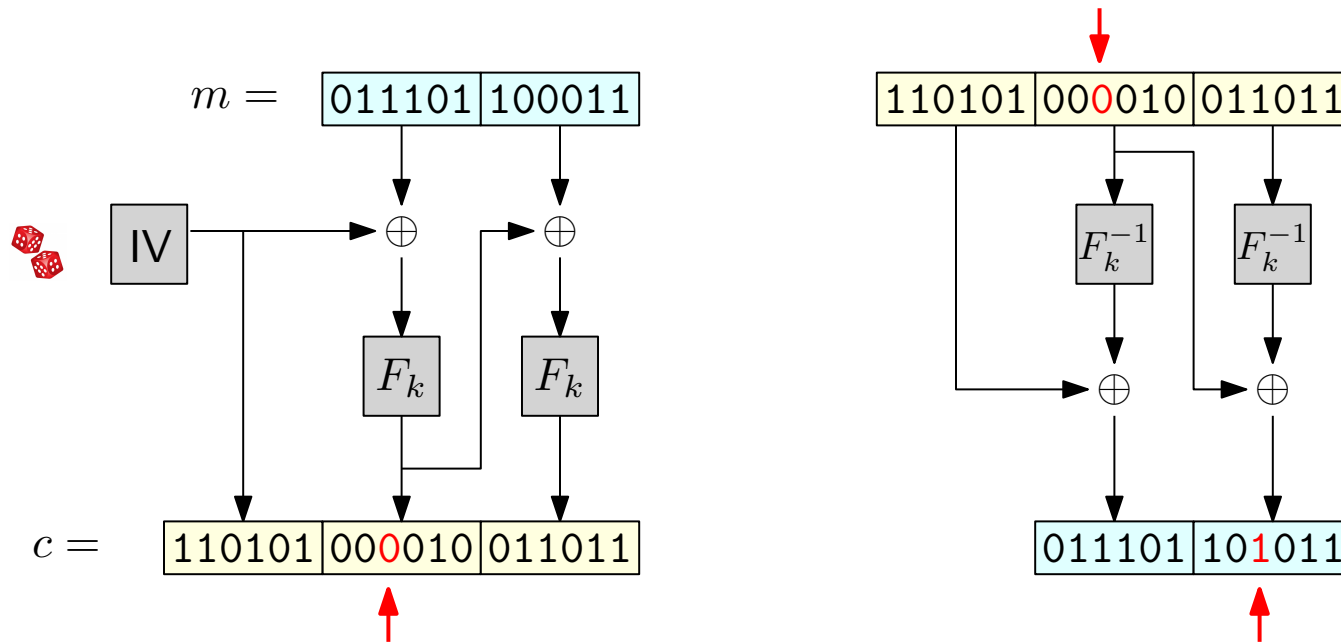
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In general, if we XOR the i -th block of the ciphertext with Δ , this causes the $(i + 1)$ -th block of the plaintext to be XOR-ed with Δ after decryption

Message padding and PKCS #7

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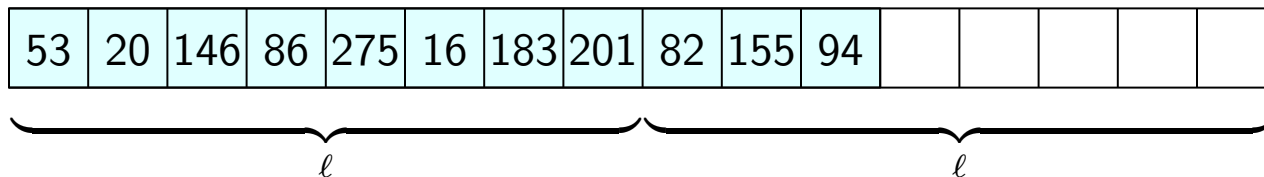
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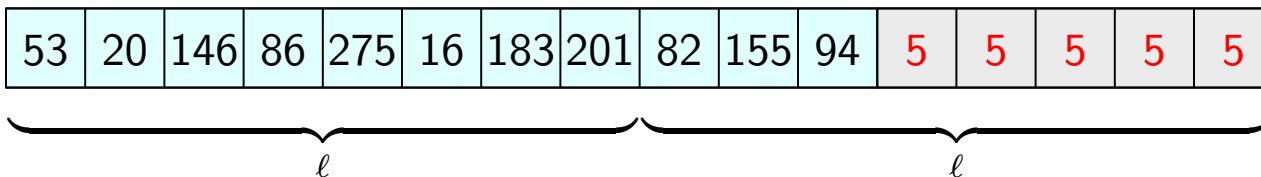
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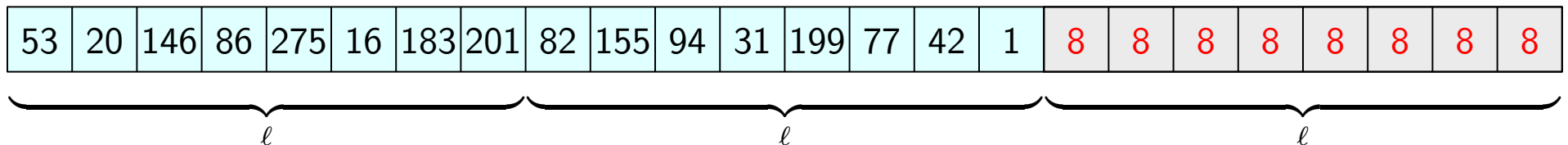
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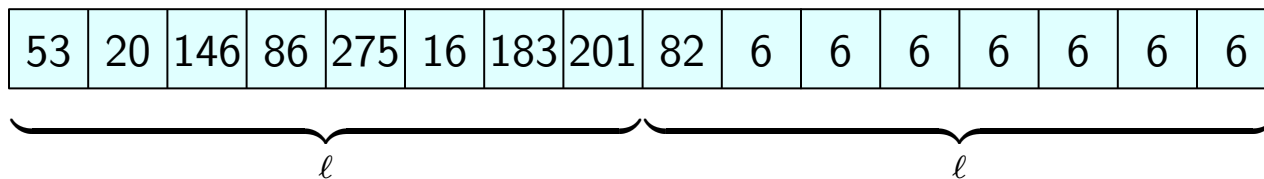
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We model the ability of the adversary to tell whether the padding of (the plaintext corresponding to) a ciphertext is valid, with a **padding oracle**



Exploiting a Padding Oracle

Attack plan:

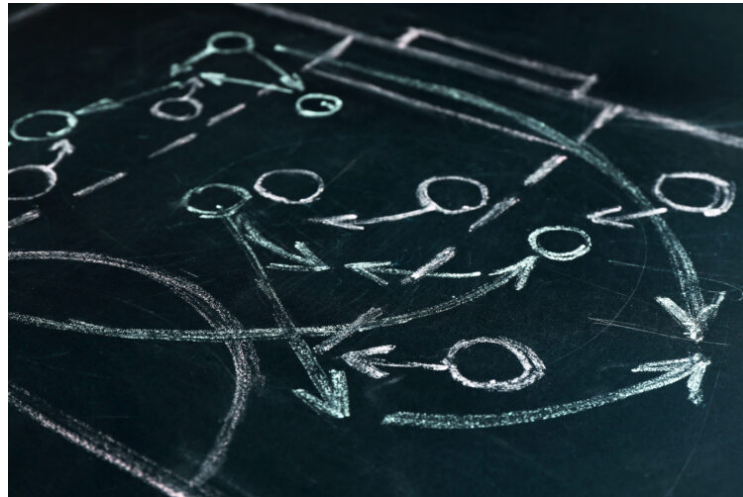
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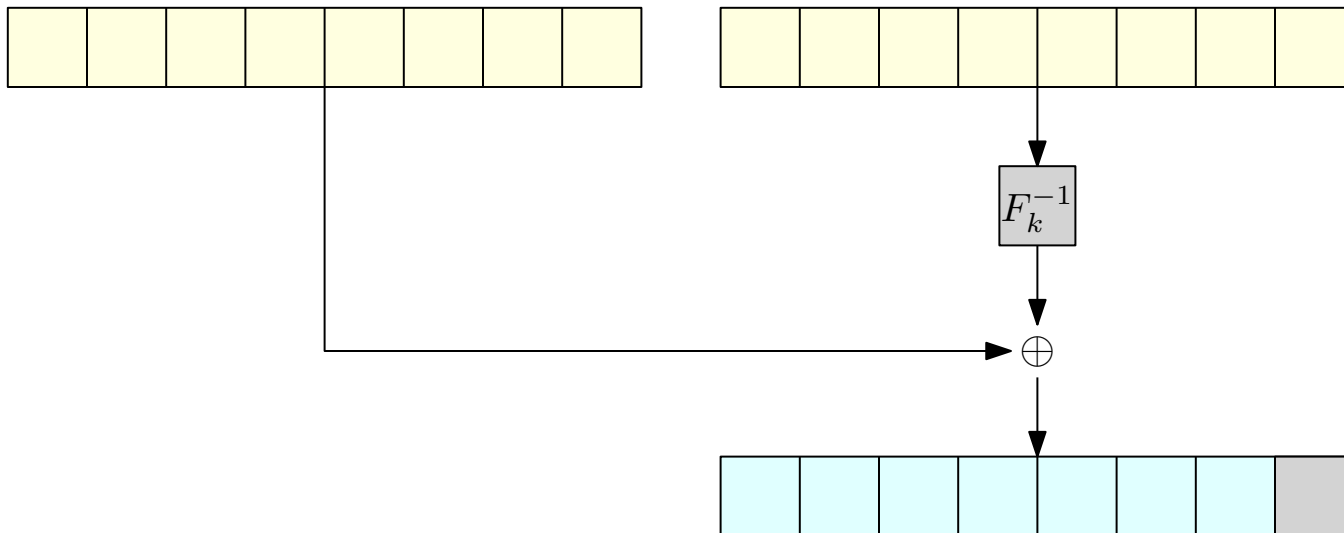
Attack plan:

- 1) Figure out the length of 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



Determining the length of the padding

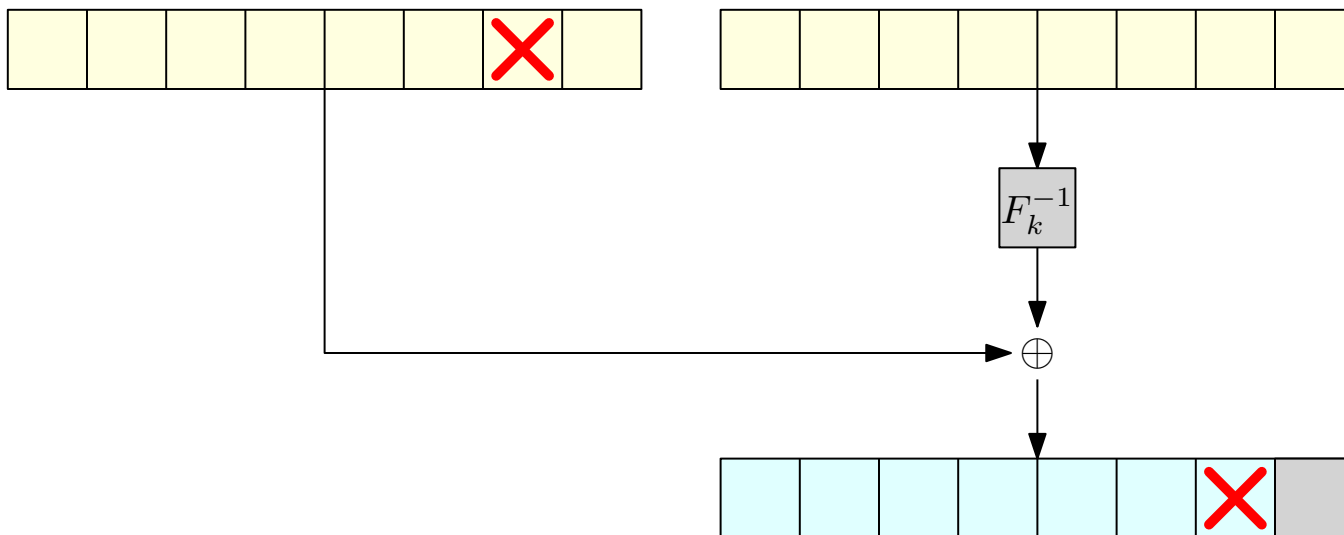
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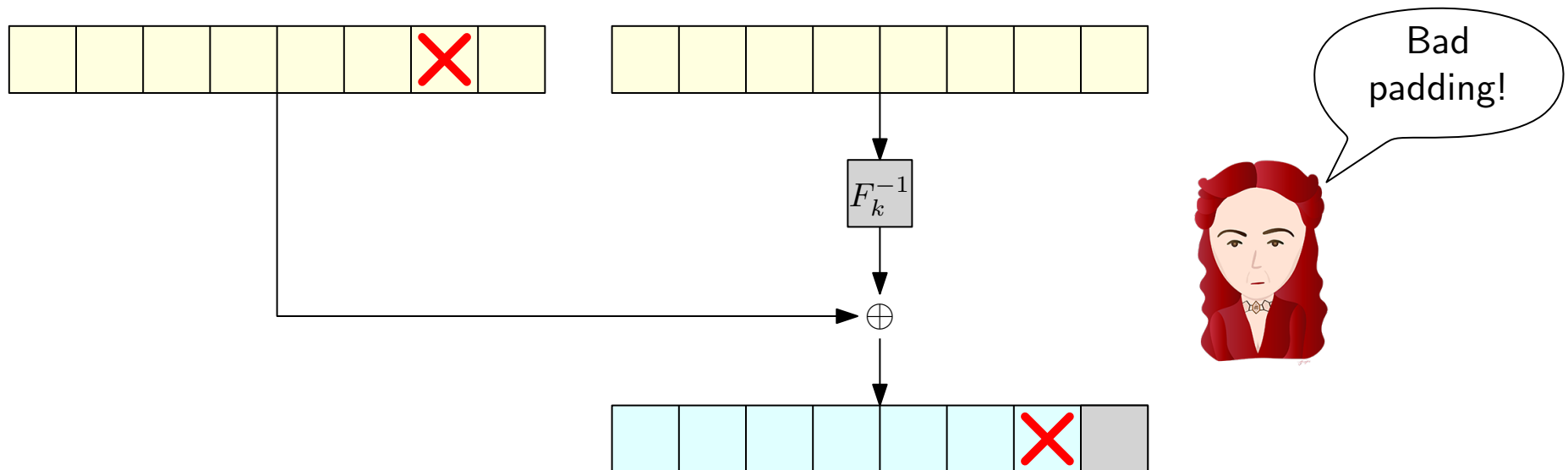
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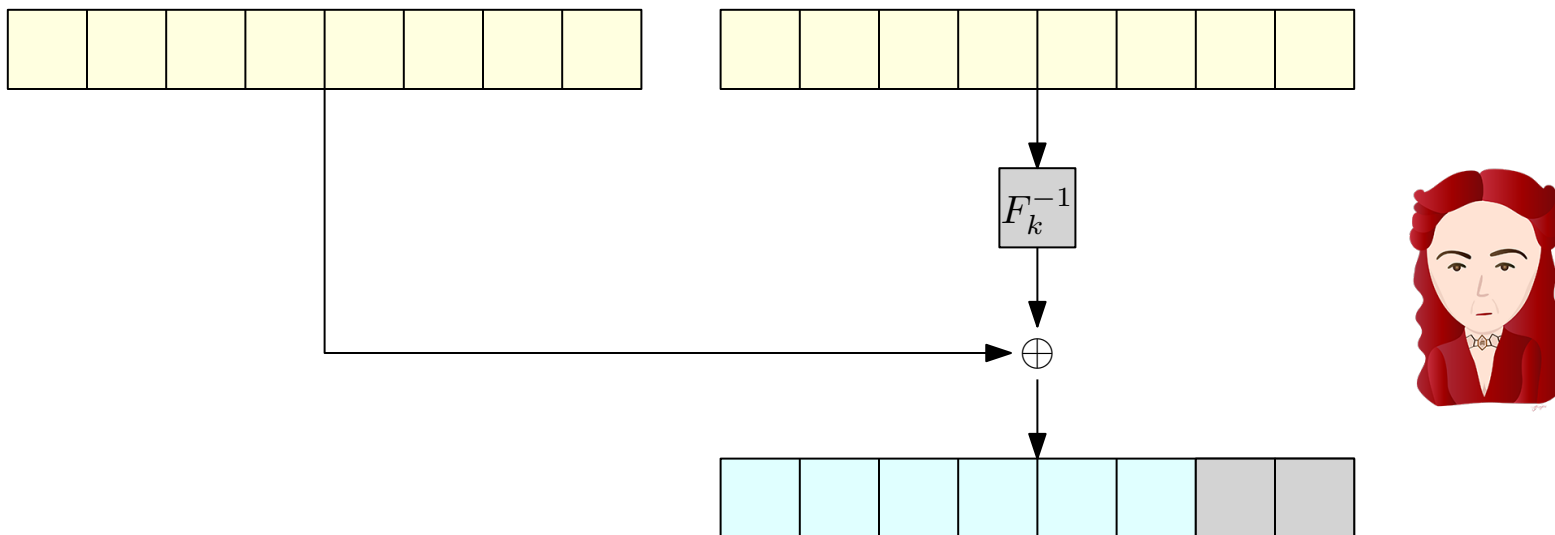
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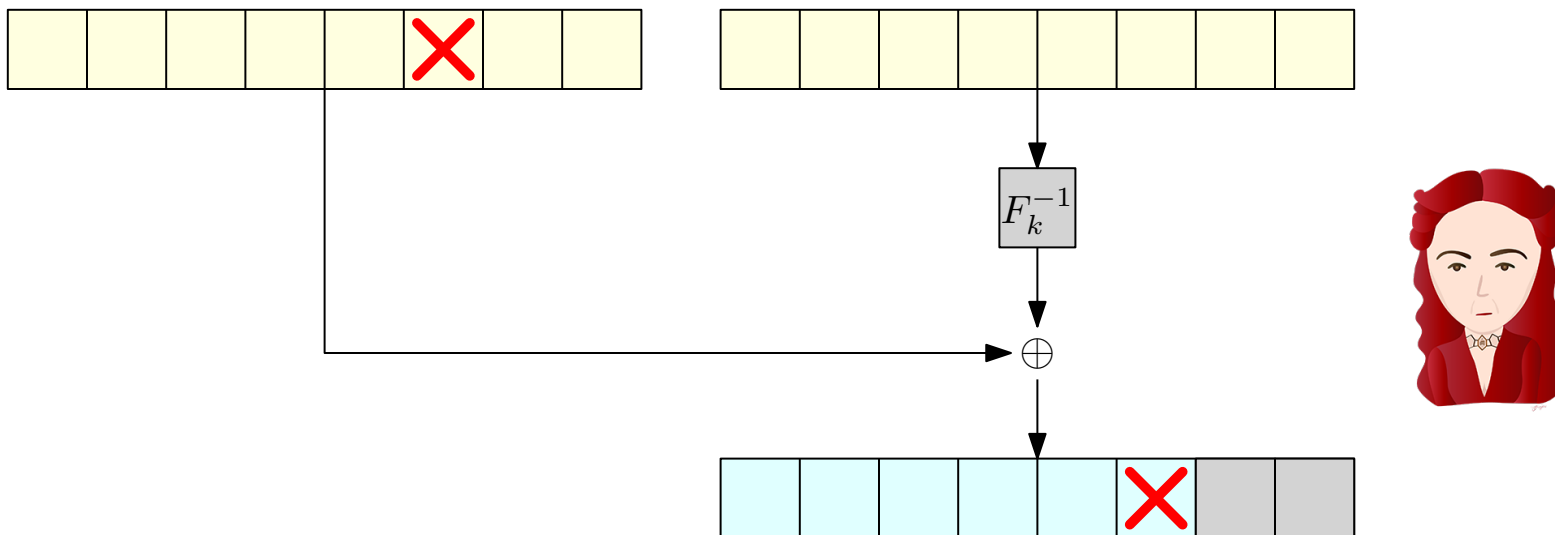
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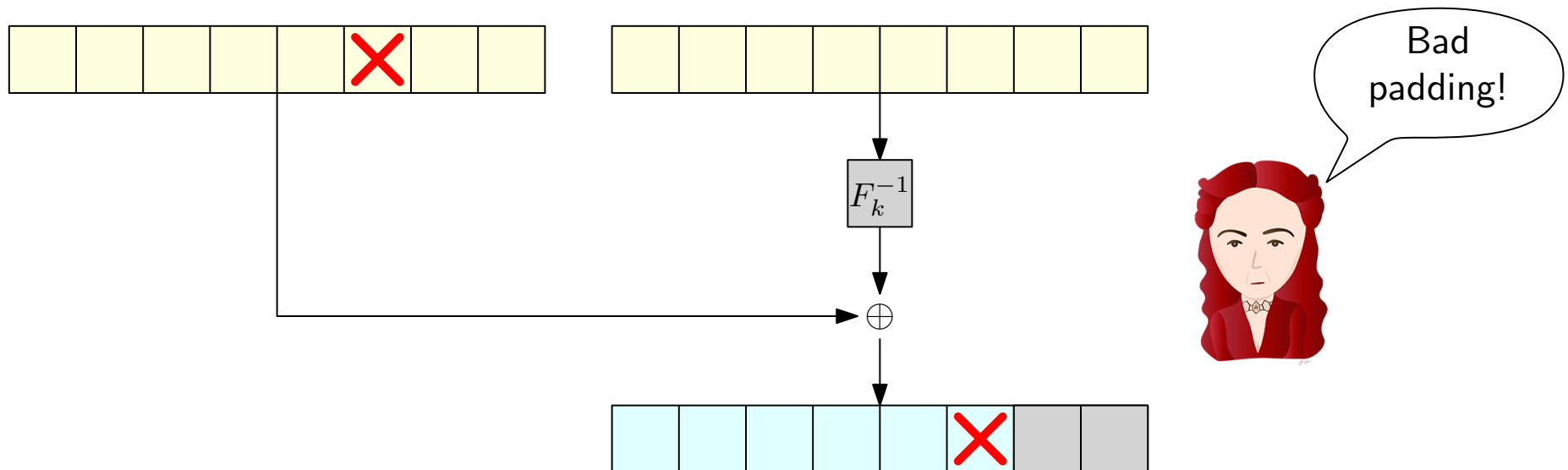
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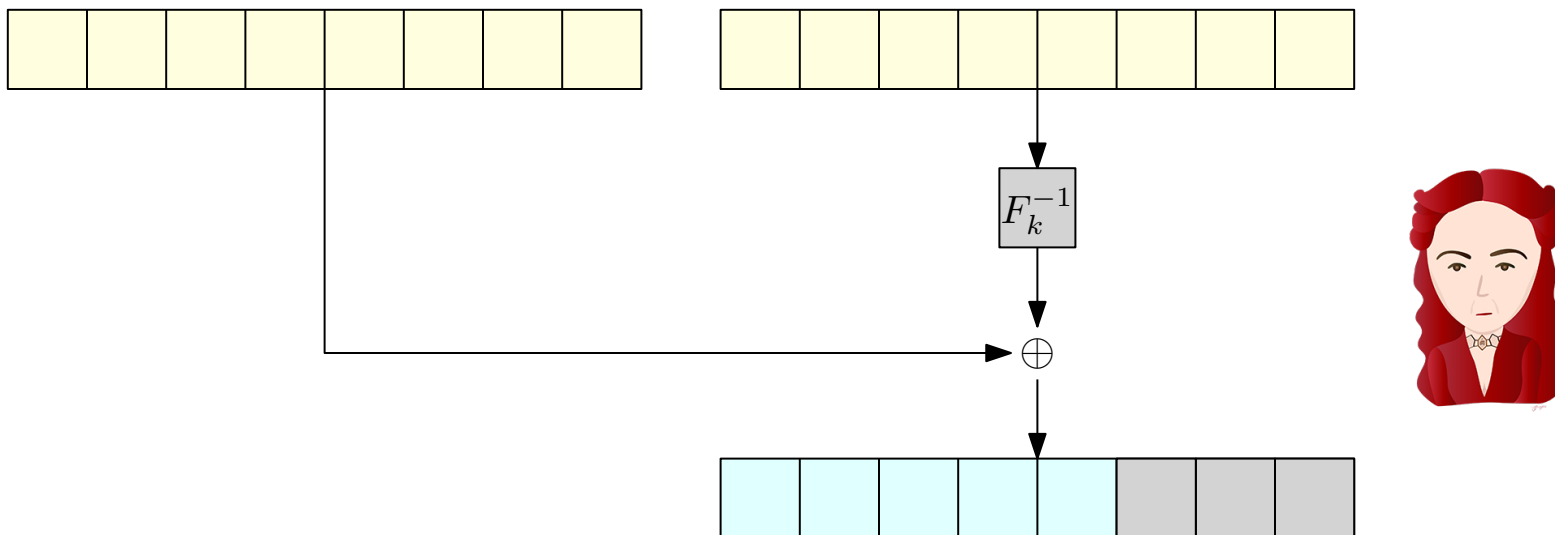
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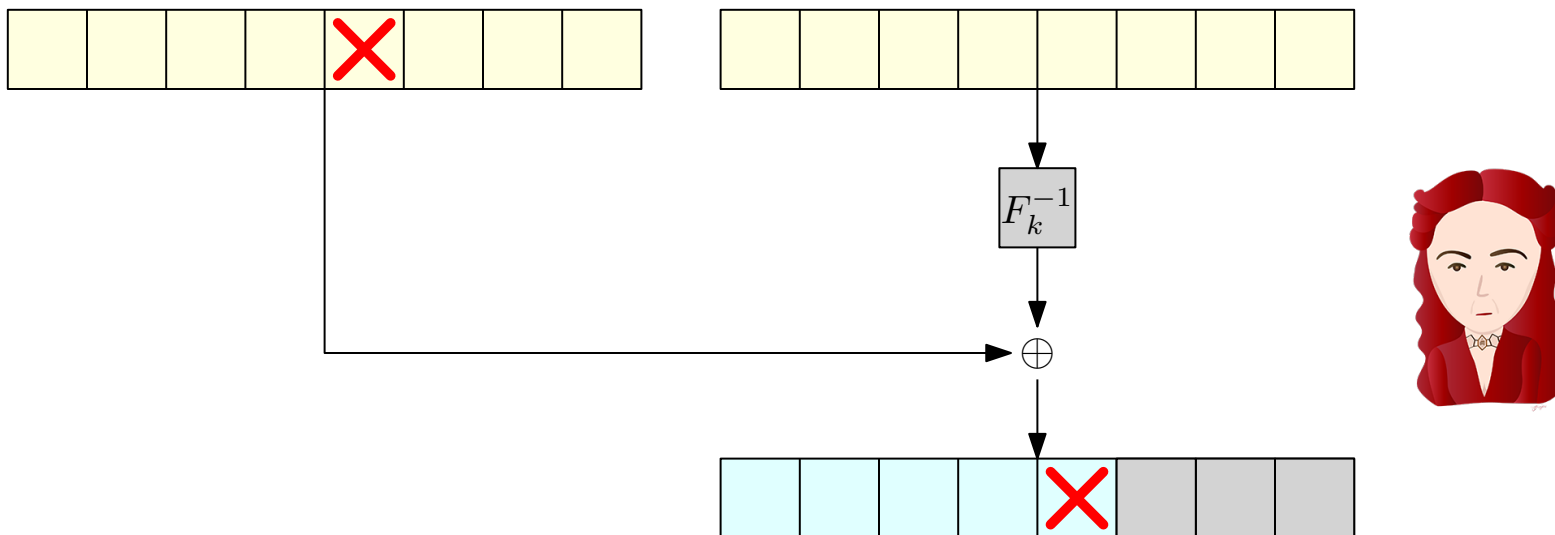
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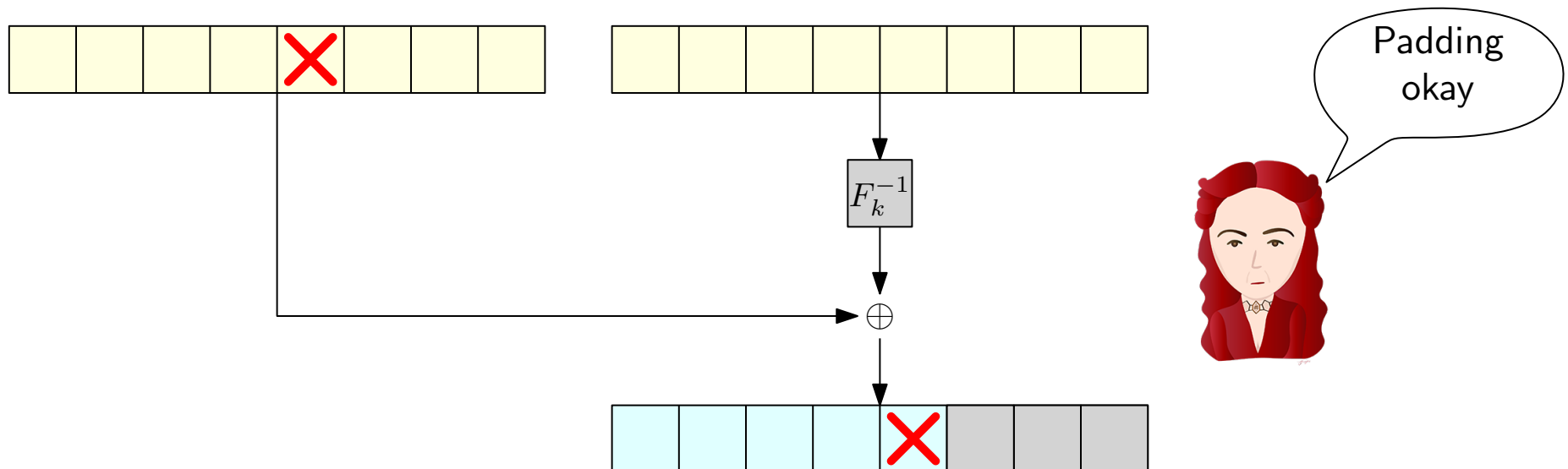
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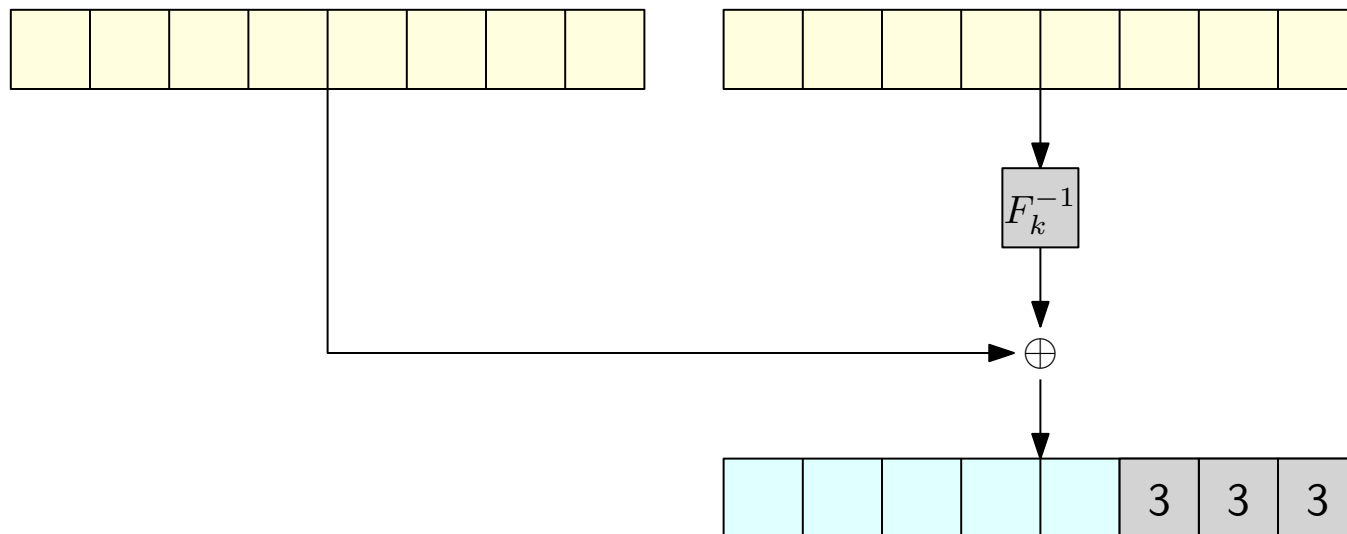
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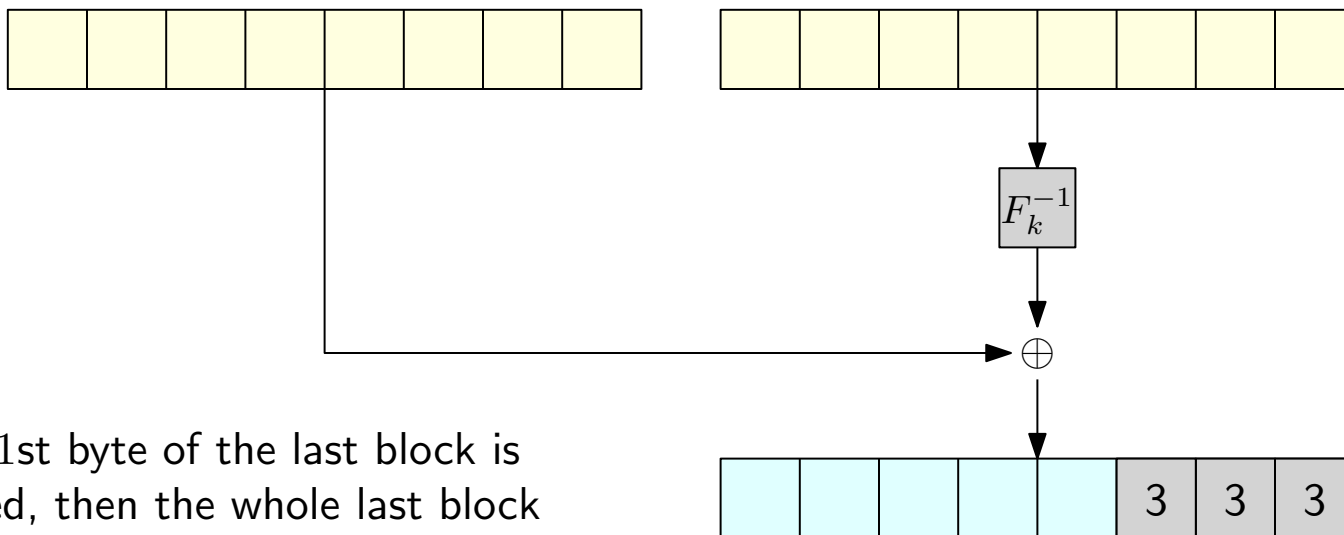
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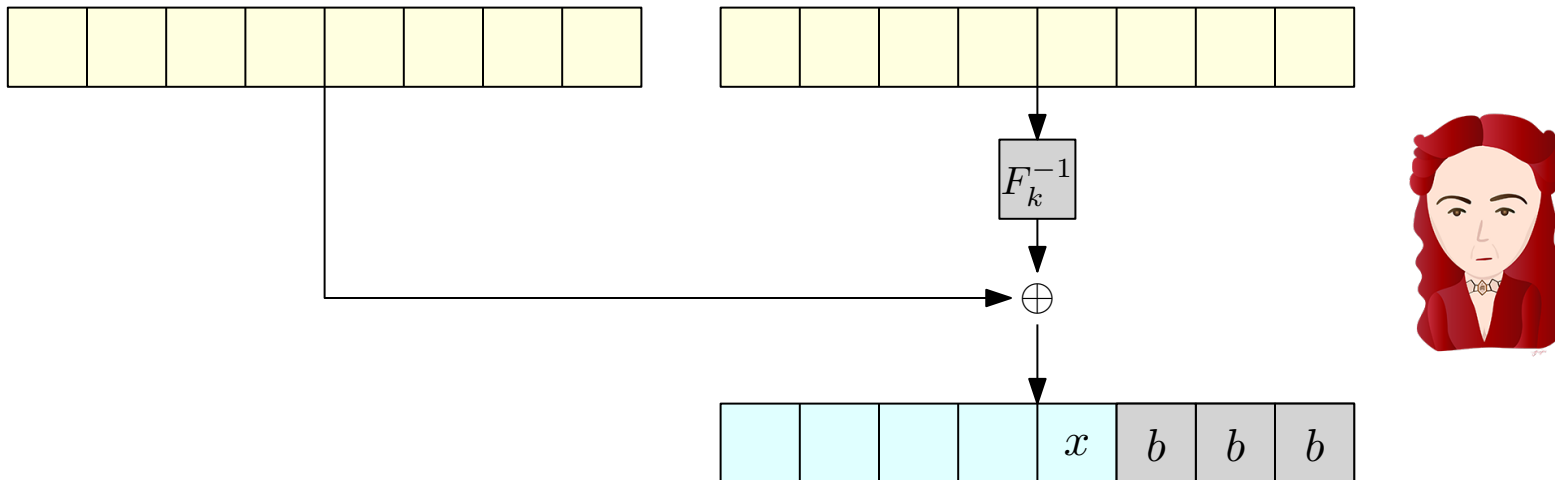
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If the 1st byte of the last block is checked, then the whole last block consists of padding

Recovering the last byte of the plaintext

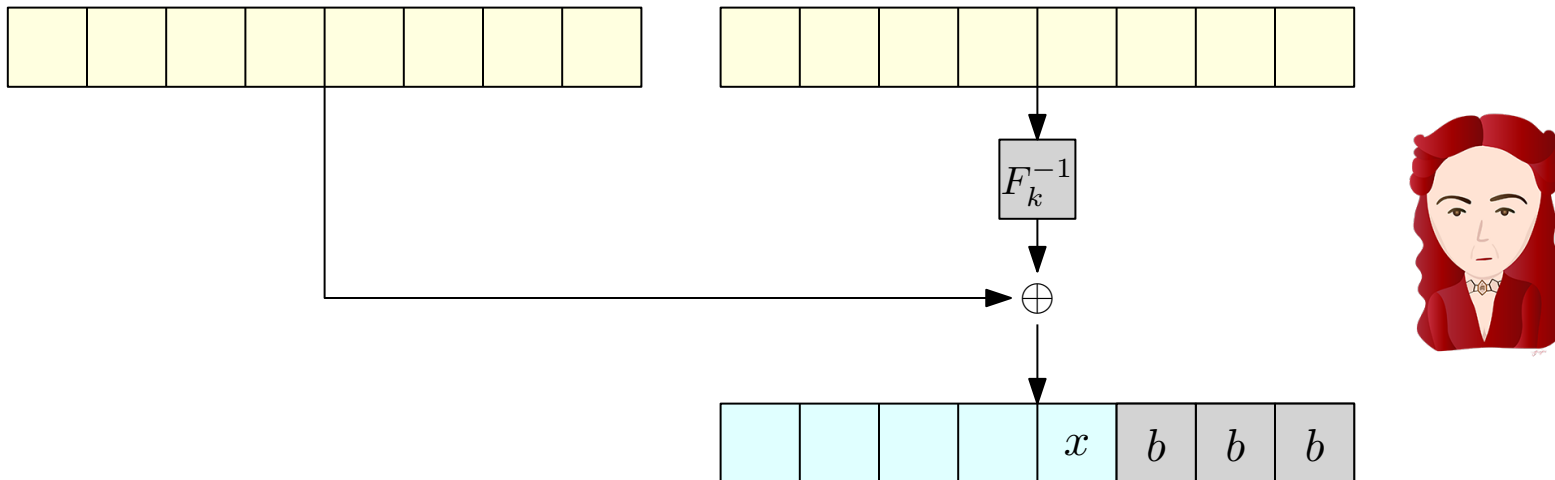
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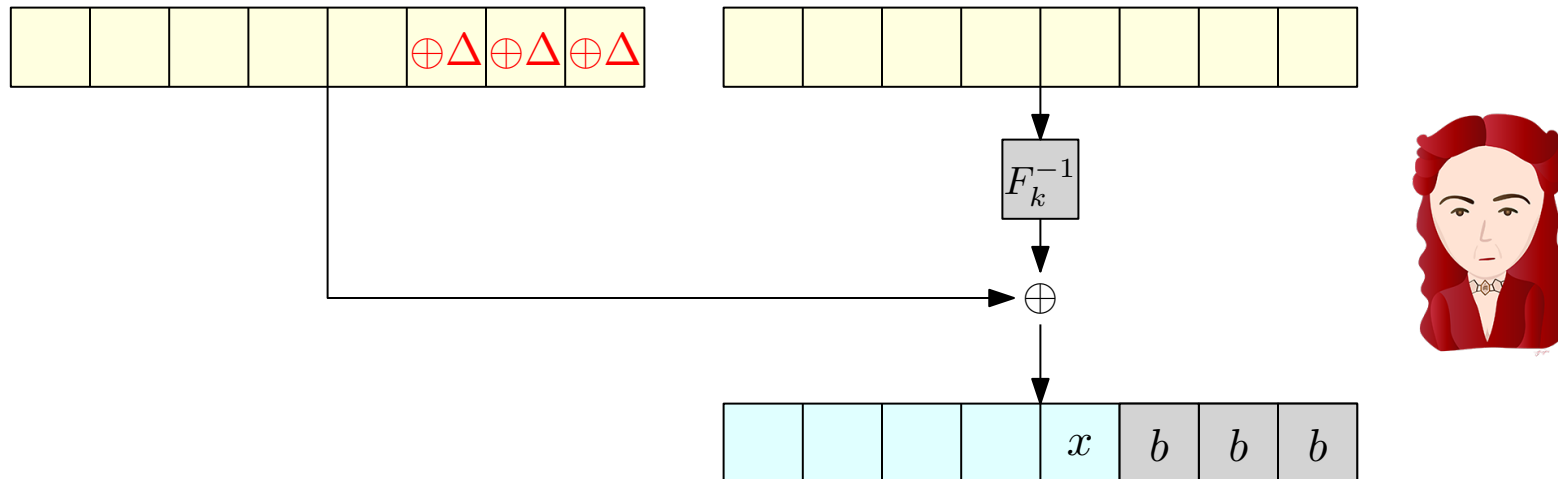
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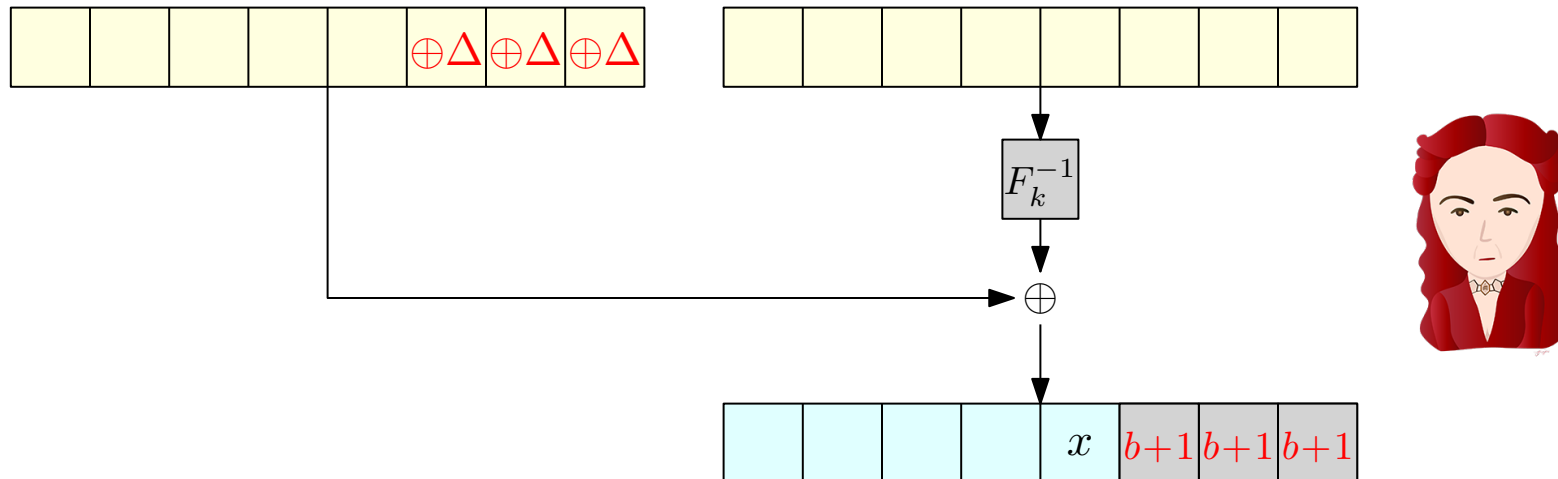
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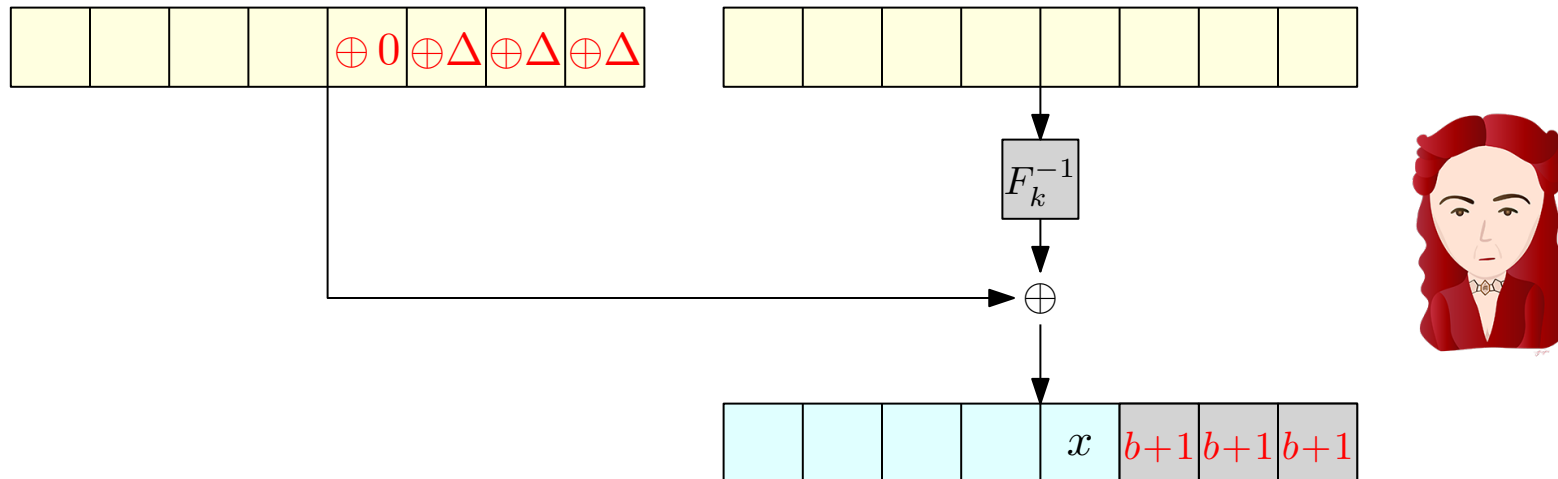
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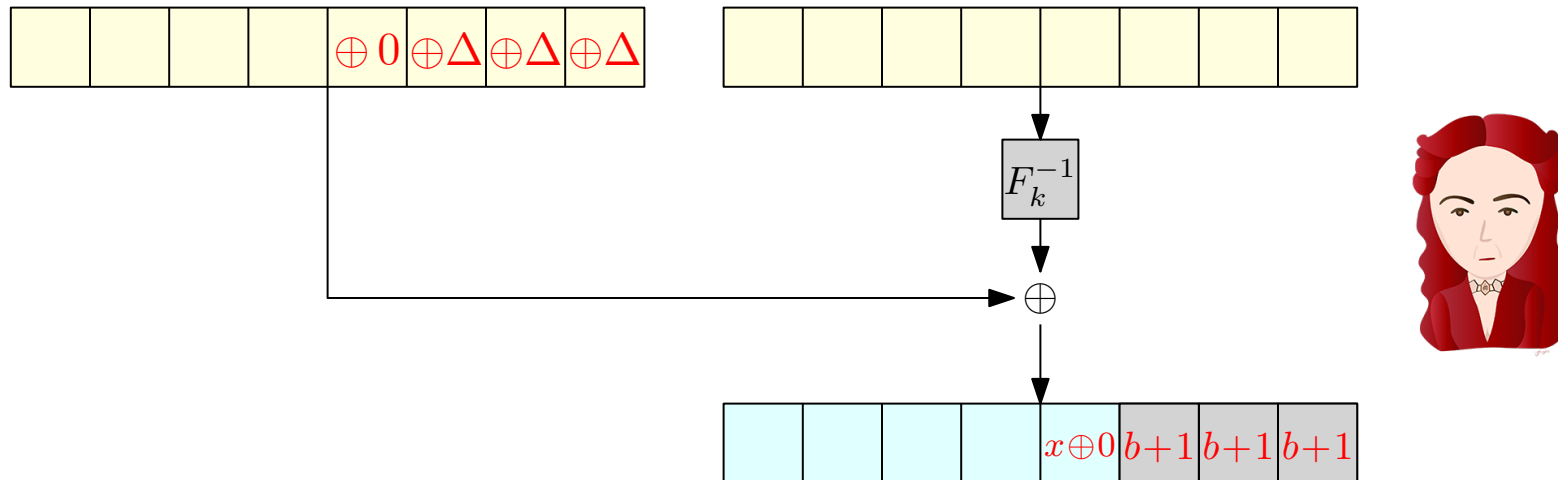
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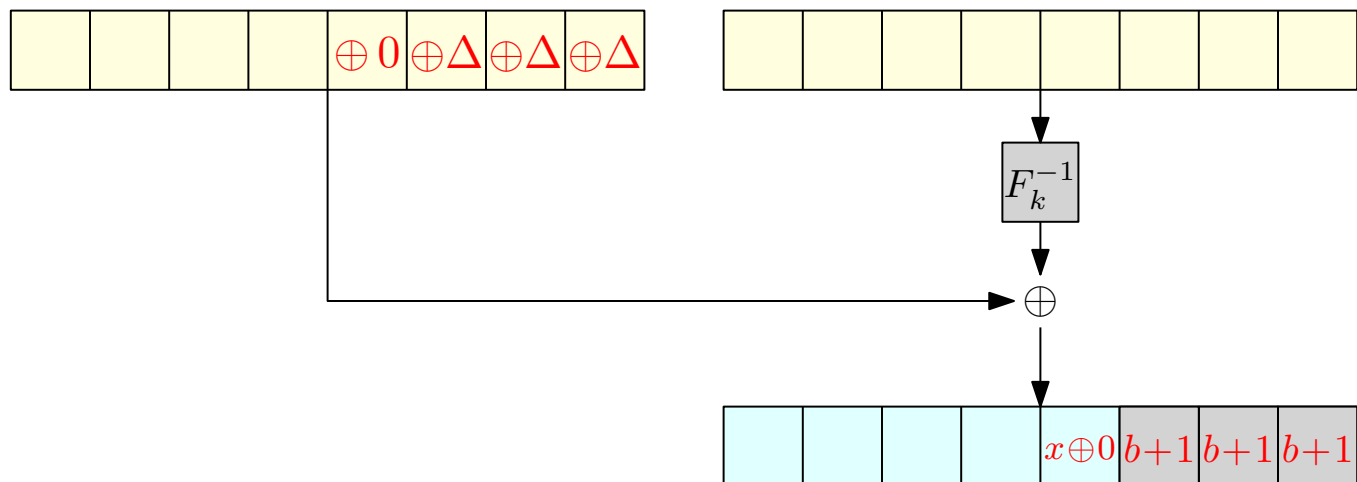
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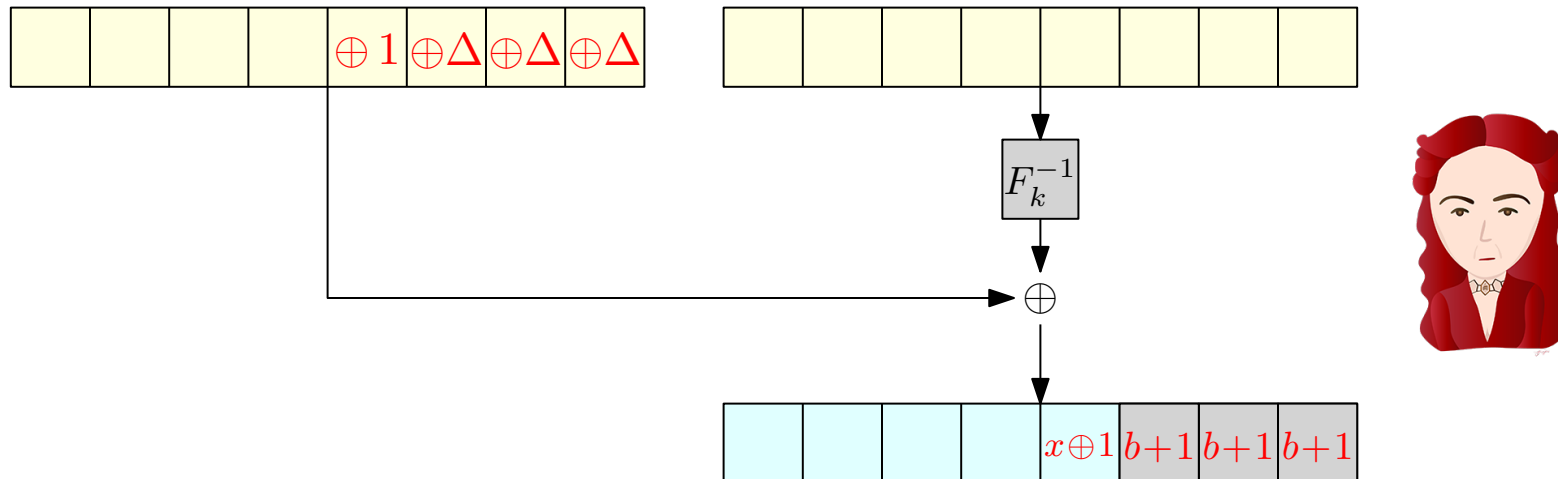


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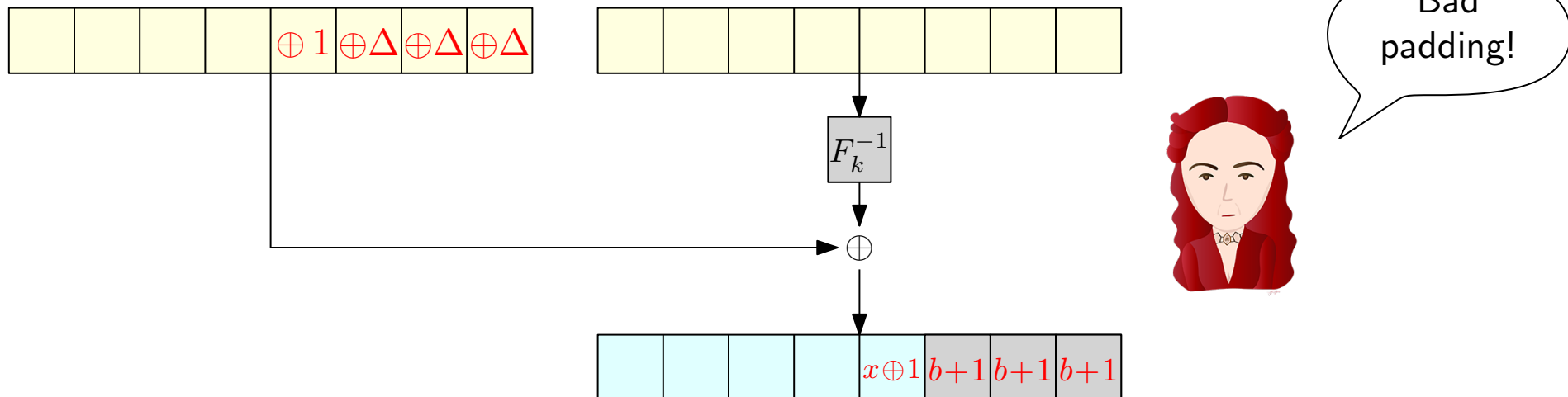
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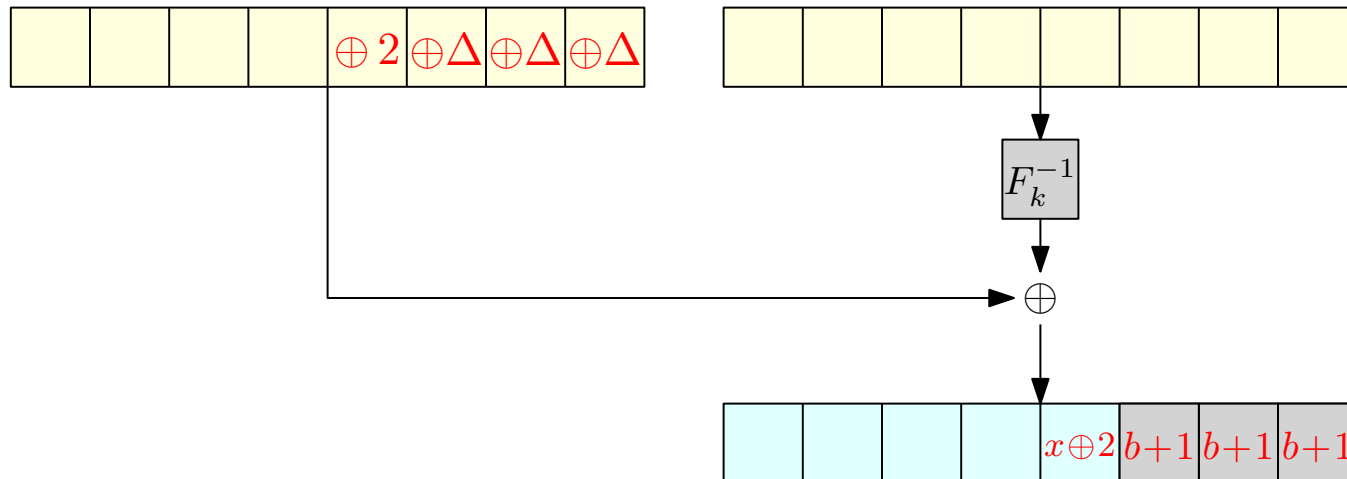
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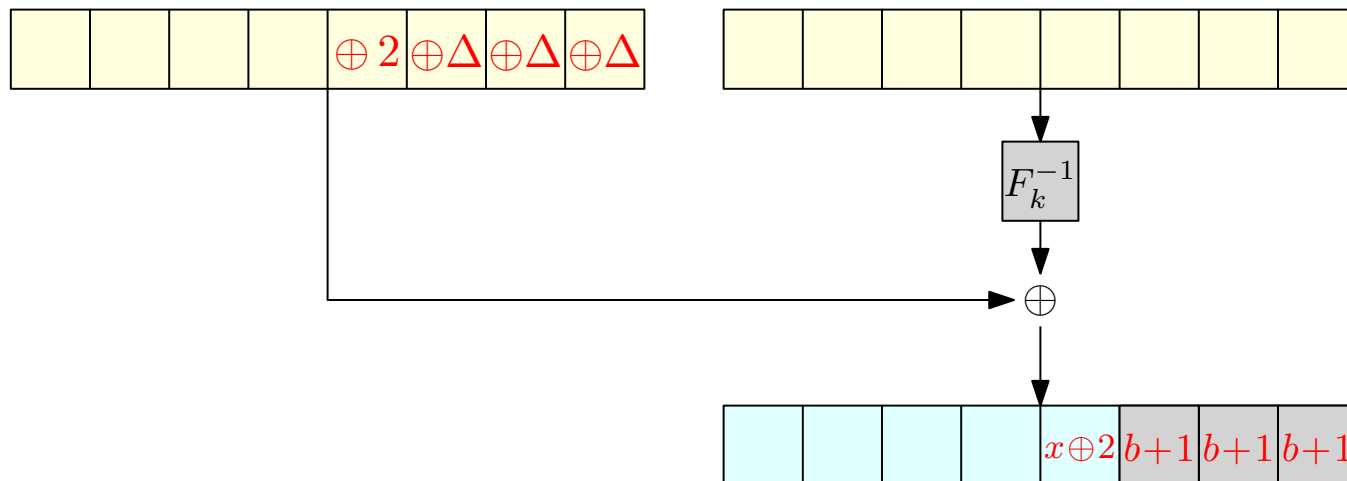
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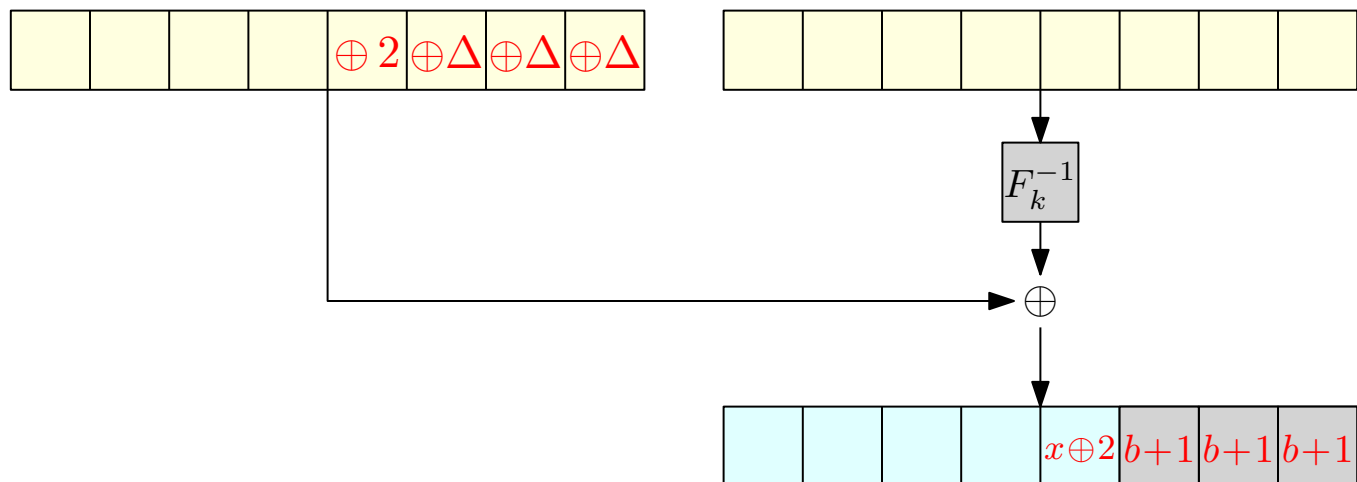


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okay

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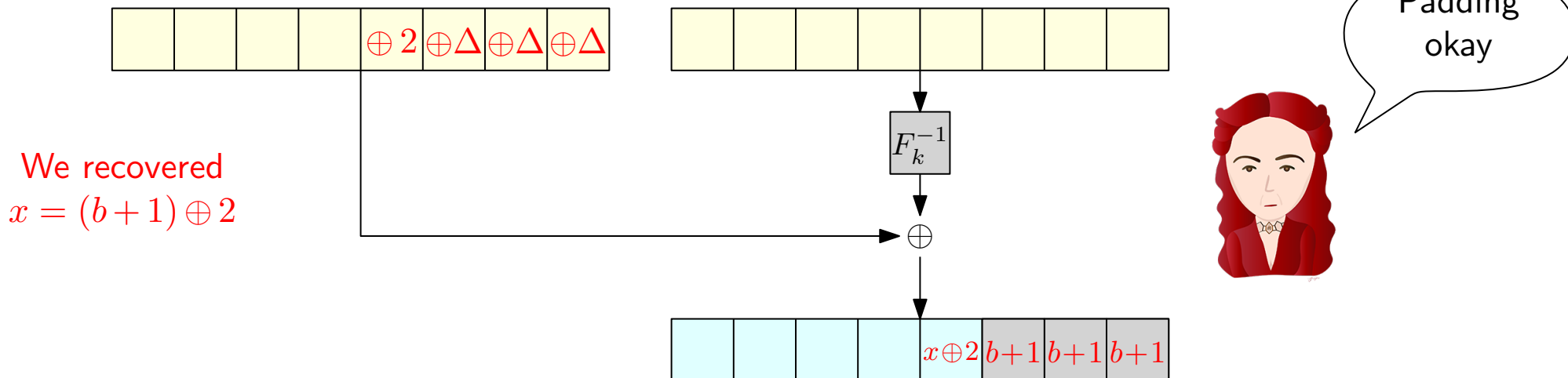


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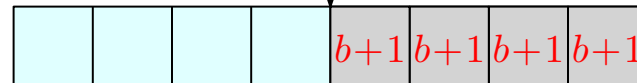
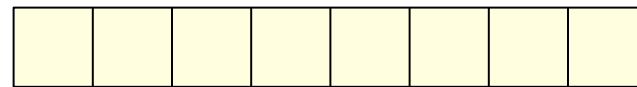
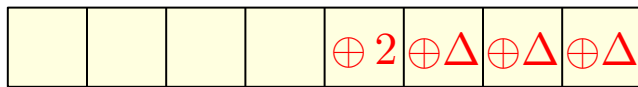
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- If the new ciphertext causes no error, then $x \oplus i = b + 1 \implies x = (b + 1) \oplus i$



Recovering the last byte of the plaintext

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

- XOR the $(b + 1)$ -to-last byte of the one-to-last block of the ciphertext with i
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 $x = (b + 1) \oplus 2$

And we now have a (modified)
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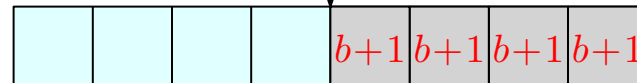
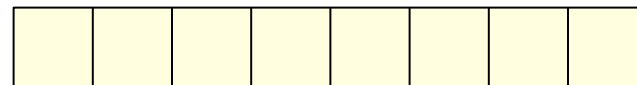
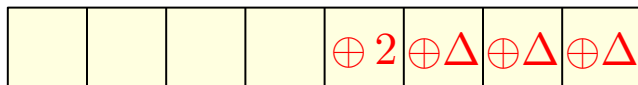


Padding
okay

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

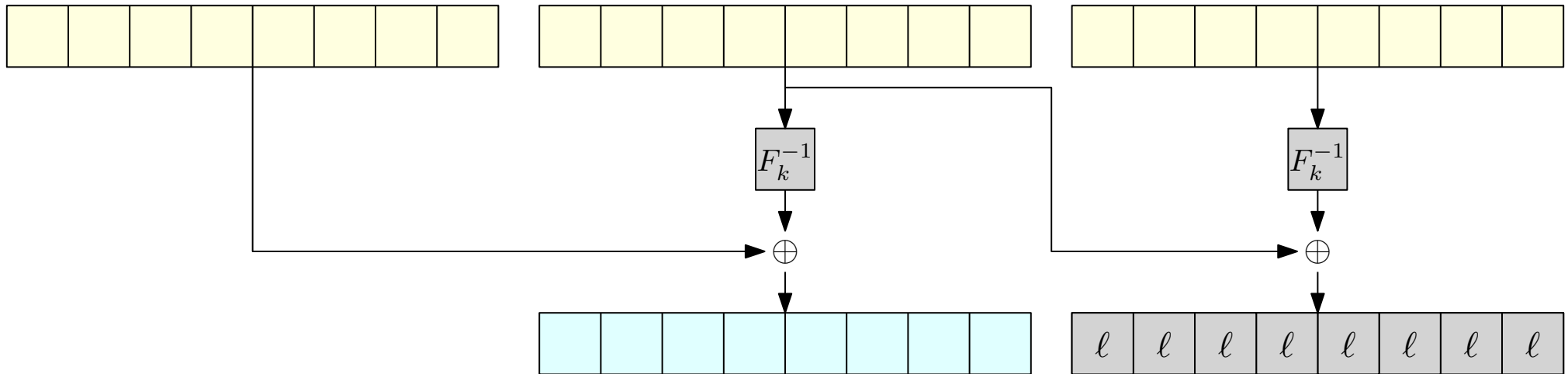


Padding
okay

Recovering the previous block

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

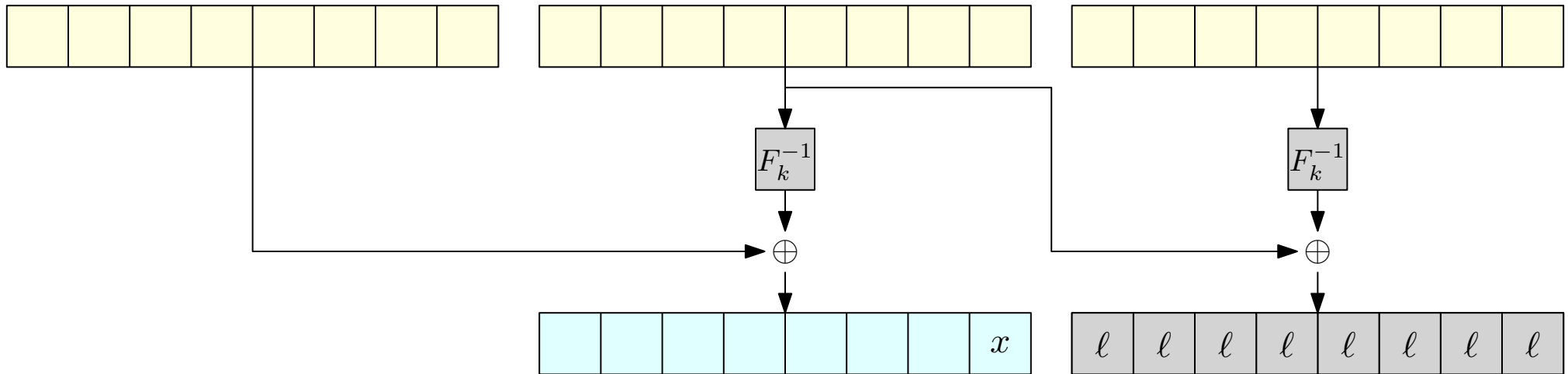
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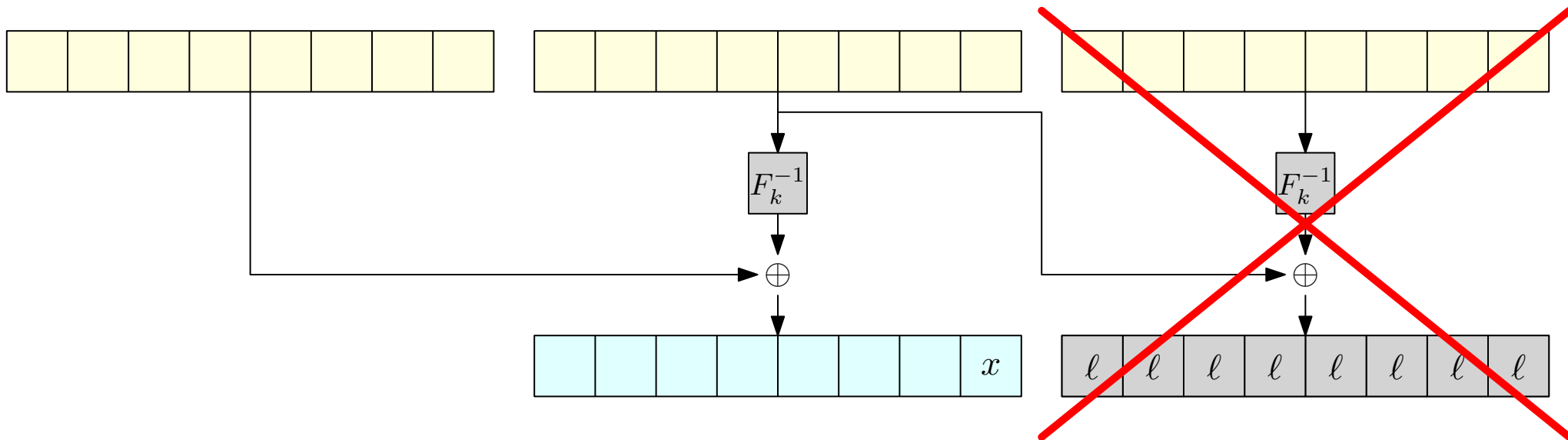


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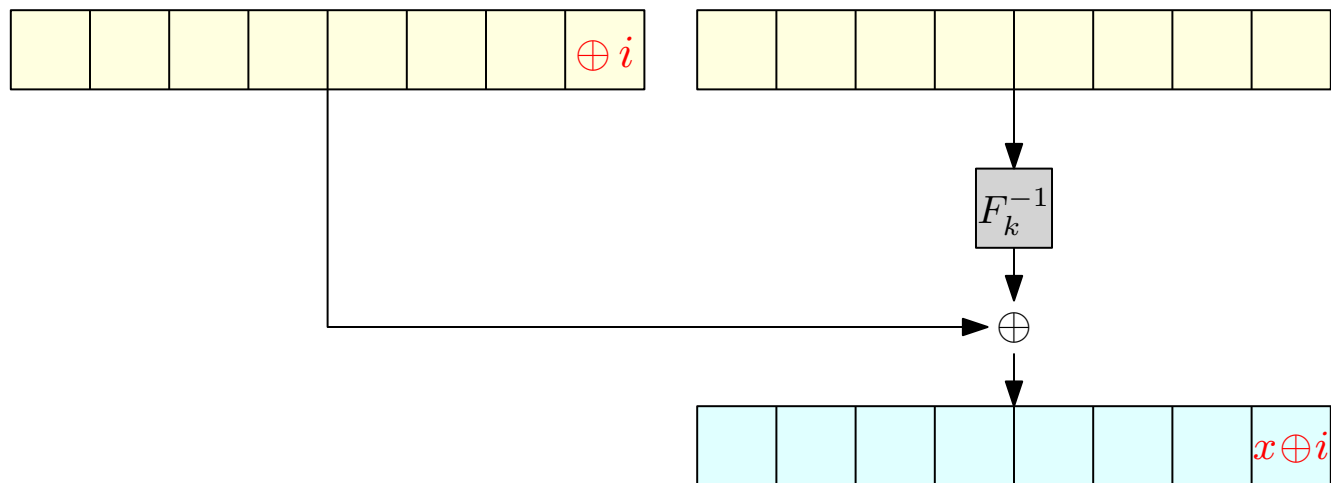
Permanently drop the last block of the ciphertext



Recovering the previous block

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

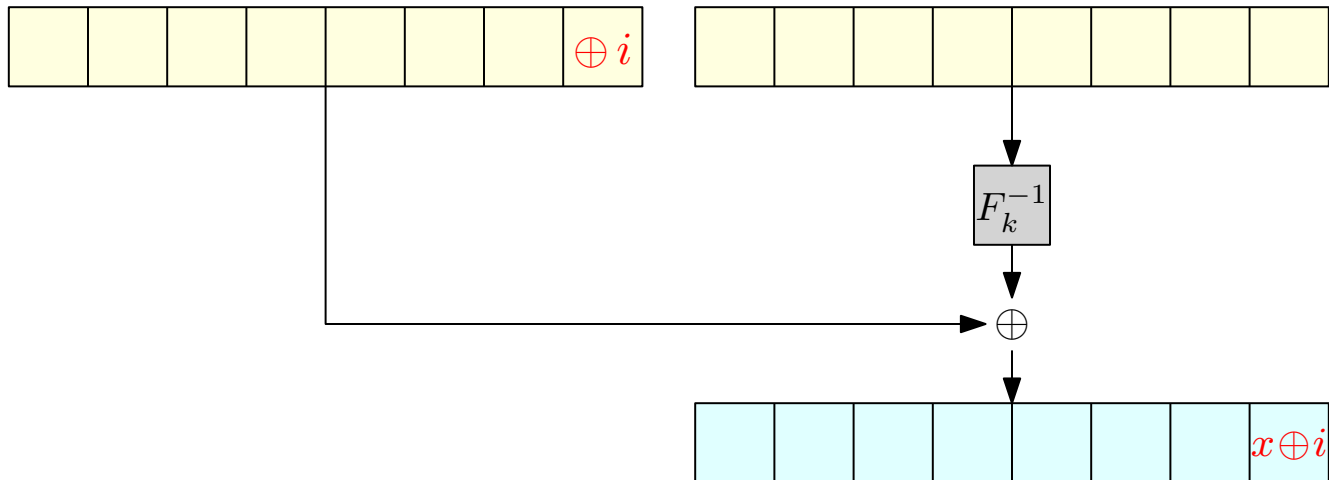
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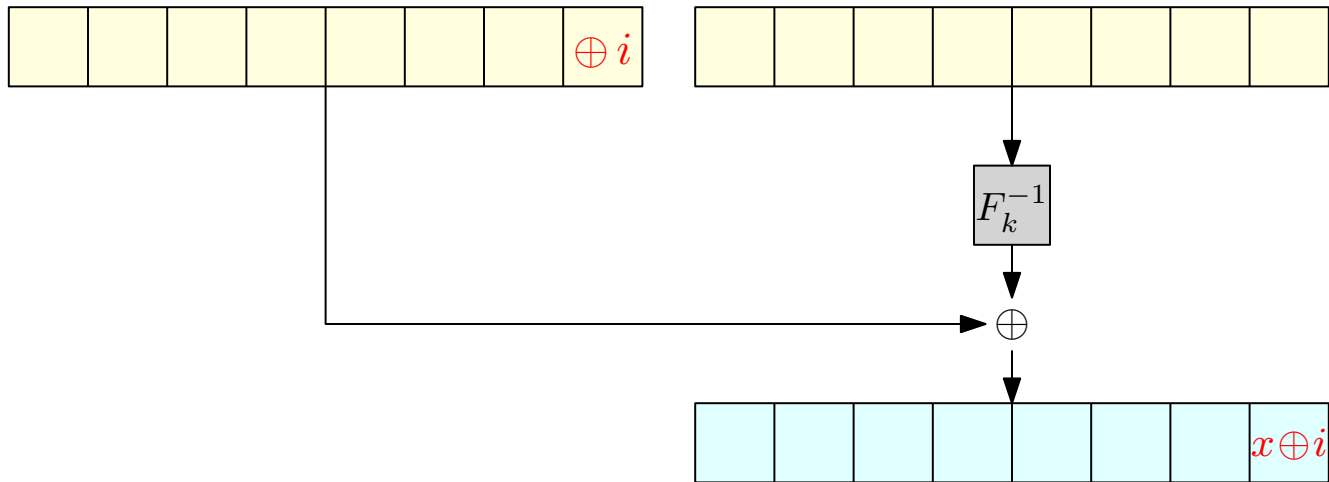


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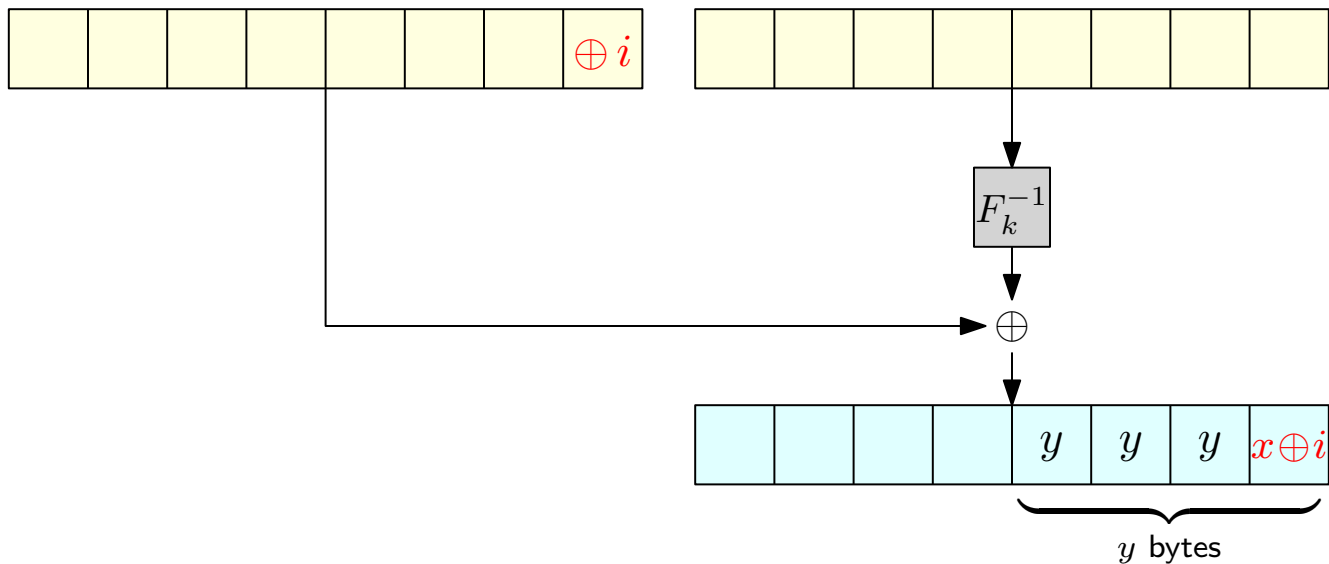


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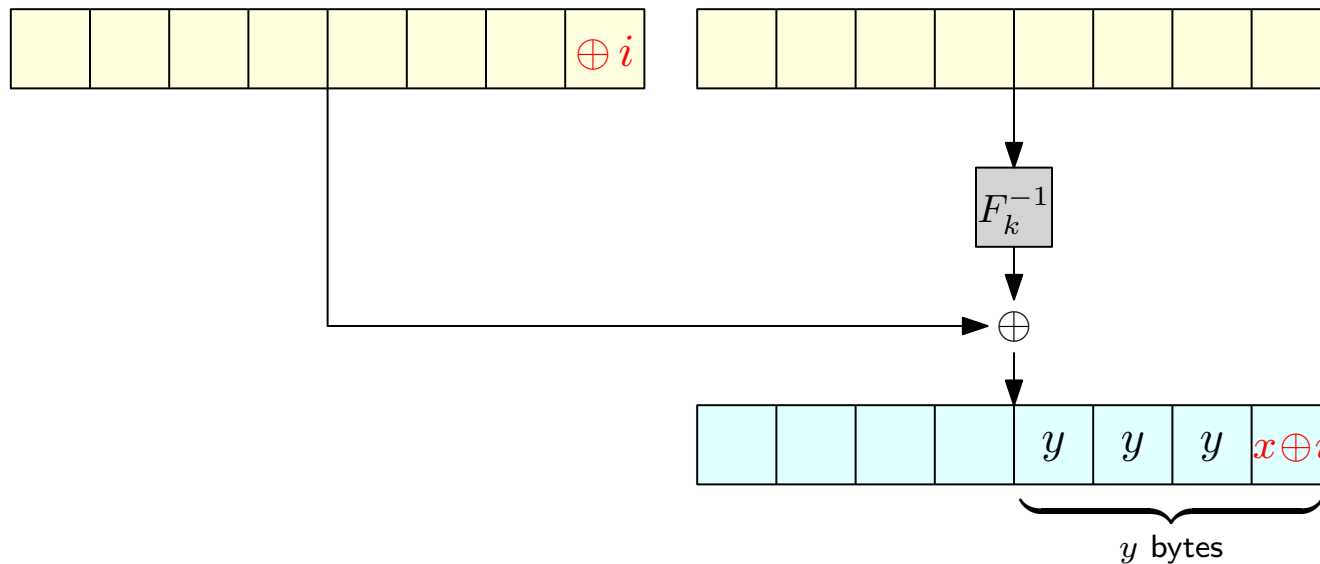
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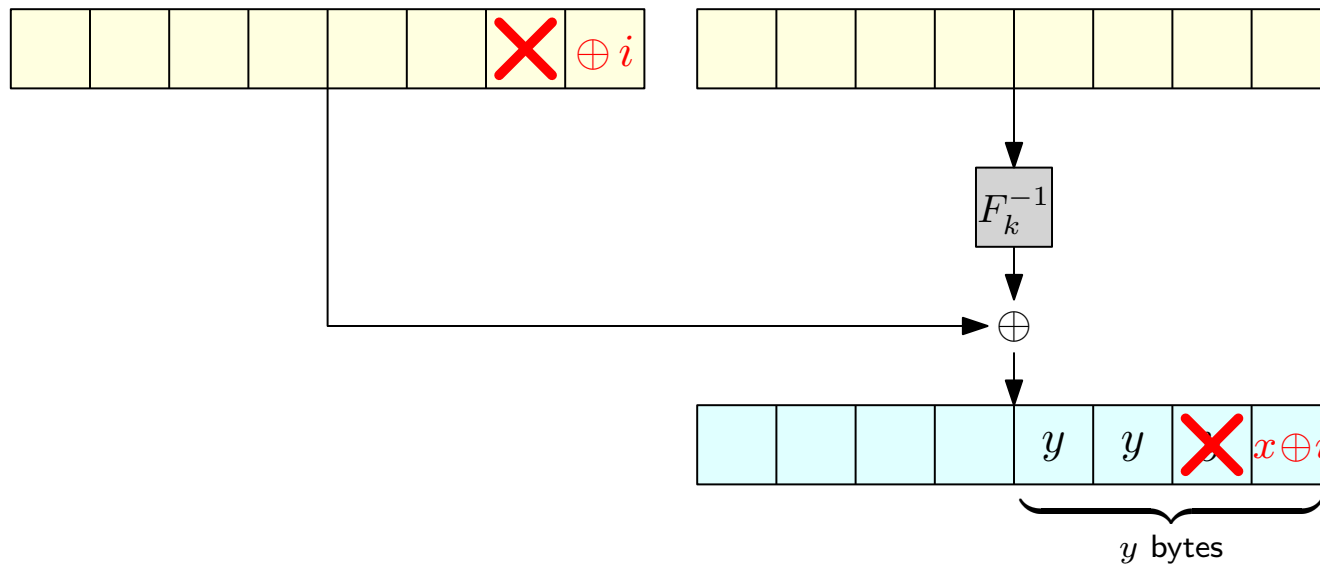
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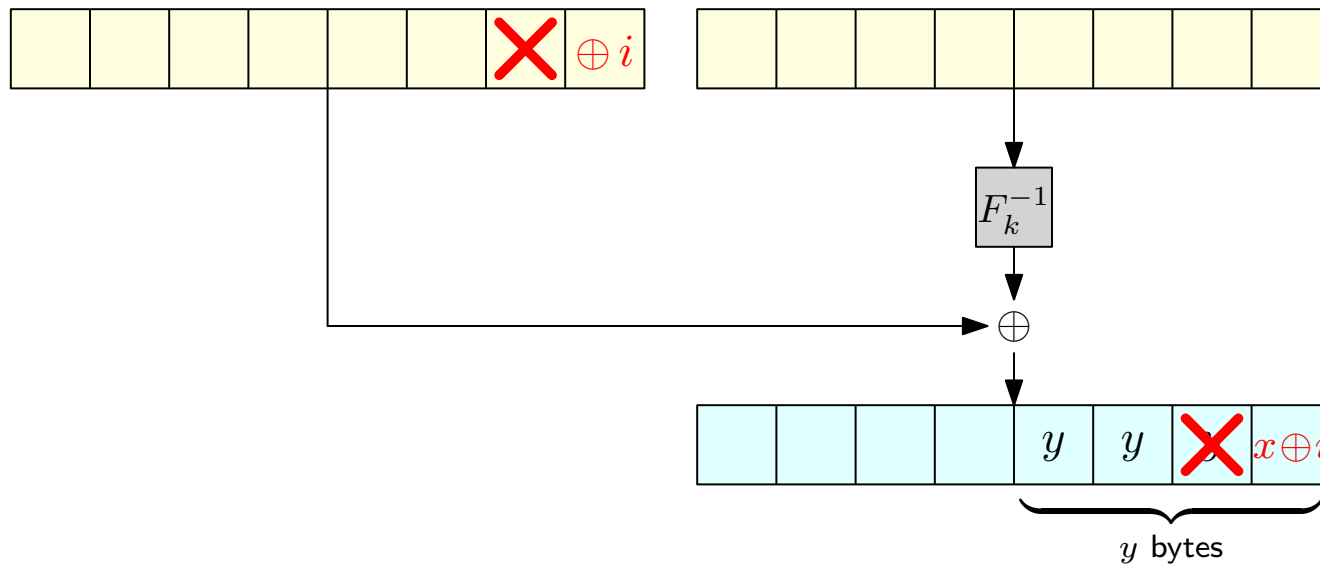
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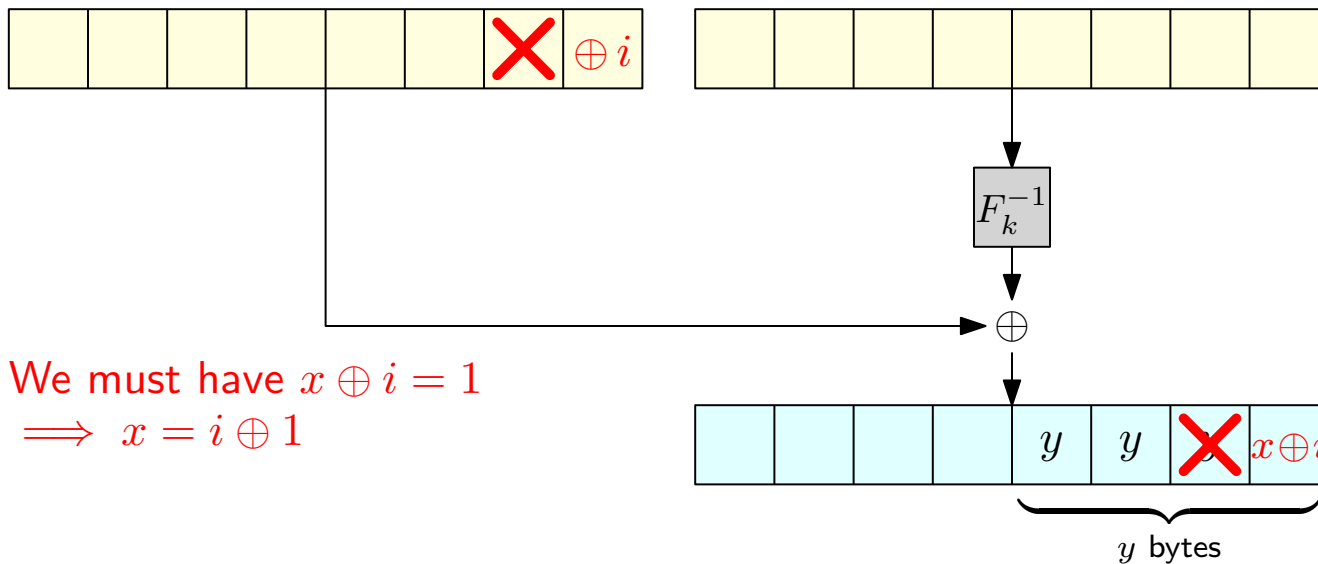
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Padding okay

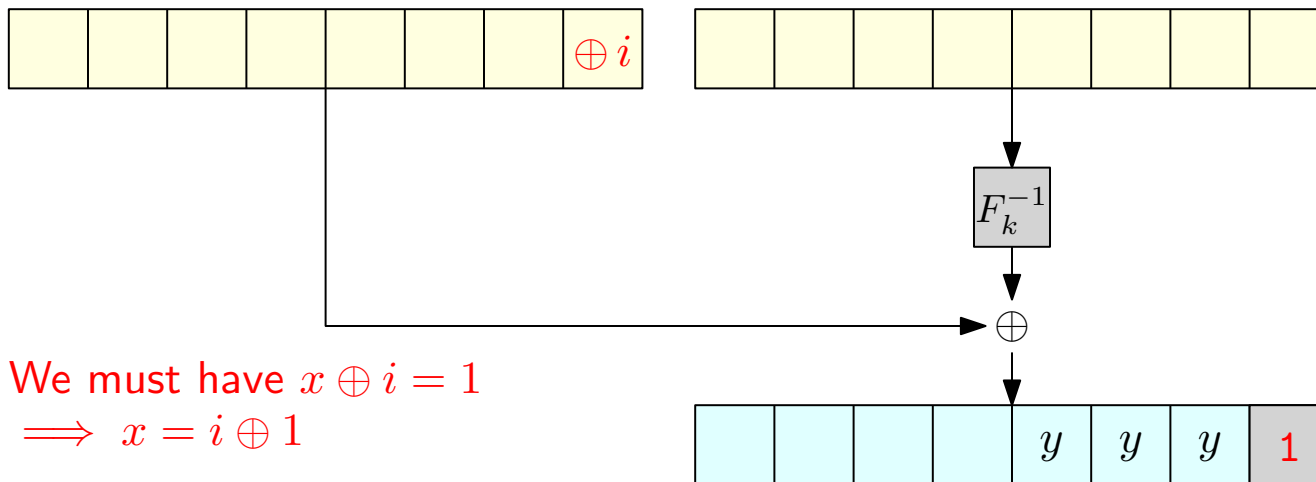
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Use the previous strategy to recover the rest of the block

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
 - ≤ 256 attempts to learn each of the other bytes

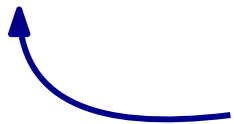
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At most $\ell + 257 \cdot |m|$ decryption attempts



Linear in $|m|$ and ℓ !

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

Authenticated Encryption

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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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Intuition: The adversary cannot efficiently learn anything about the plaintext even if it can tamper with the ciphertext
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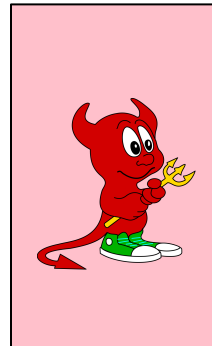
Intuition: The adversary cannot efficiently provide any valid plaintext
(unless it corresponds to a message that was already encrypted by the honest parties)

The Unforgeability Experiment (adapted for AE)

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

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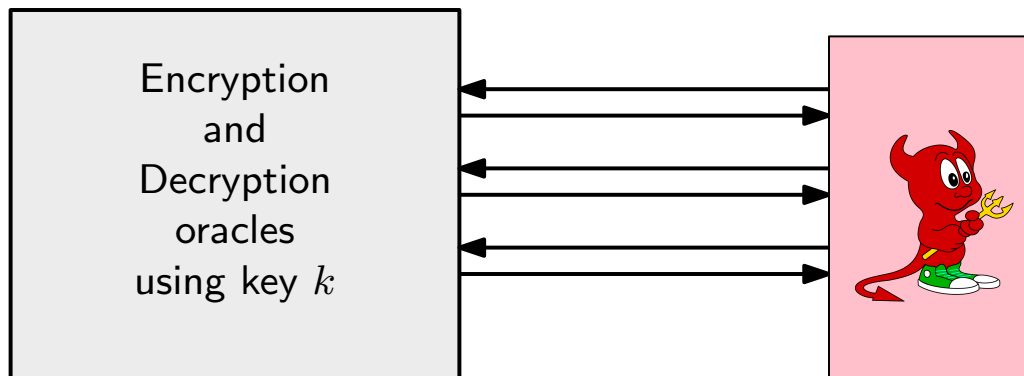
Encryption
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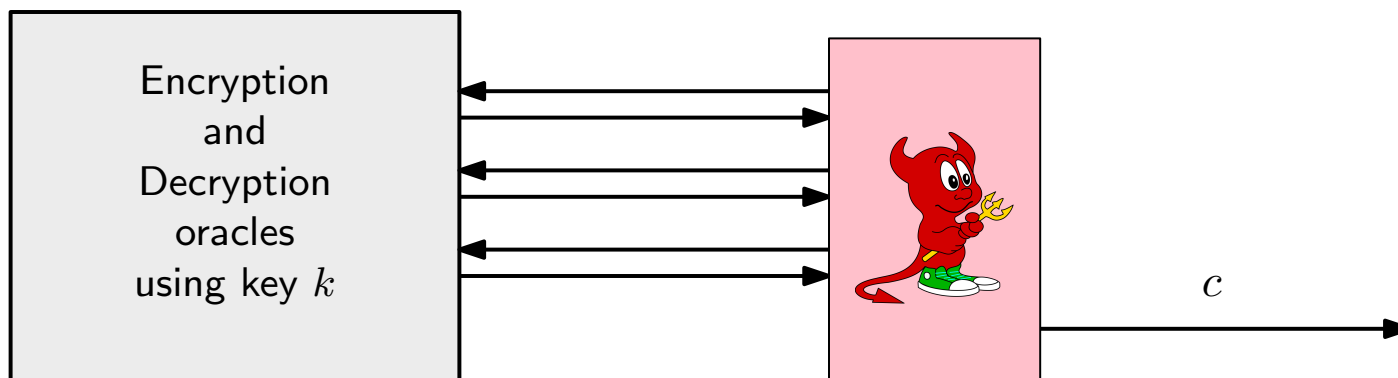
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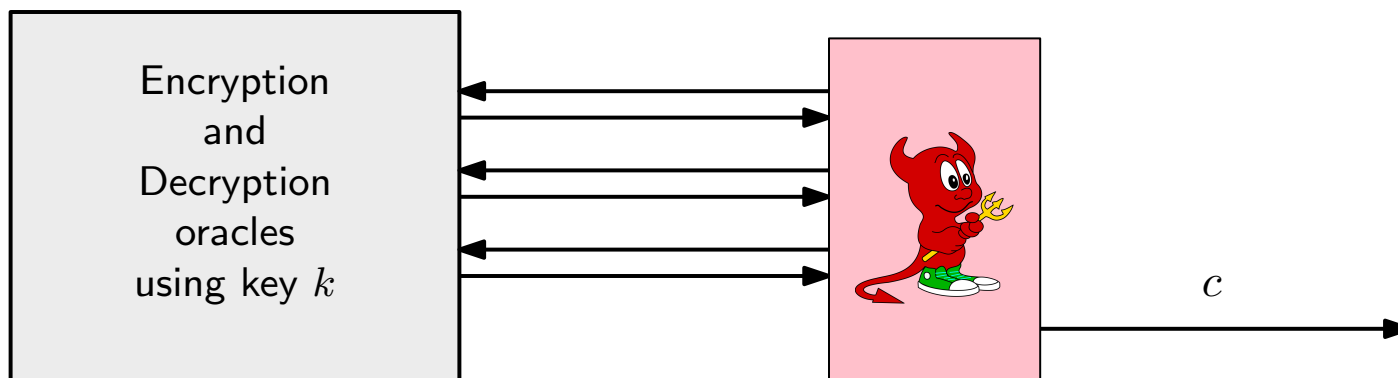
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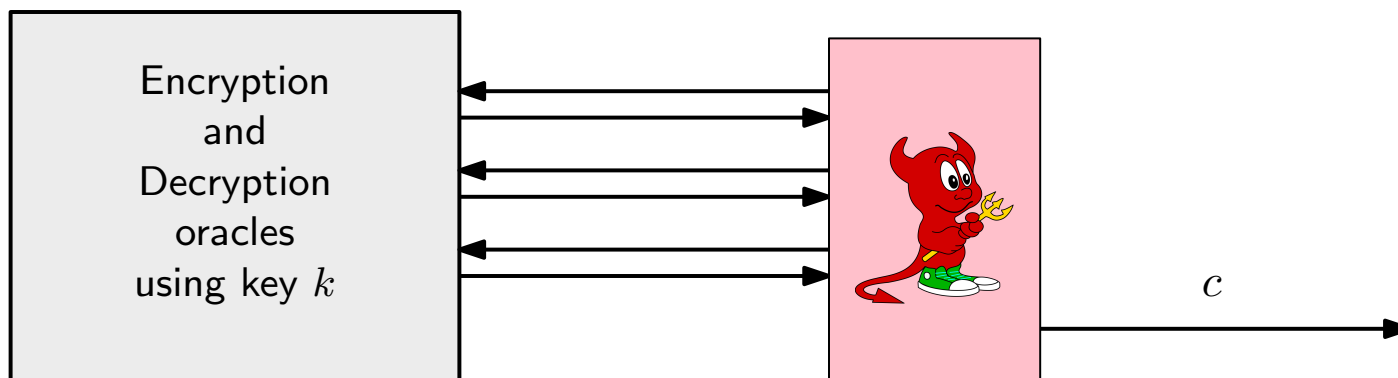
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Notice that AE \implies CCA-security

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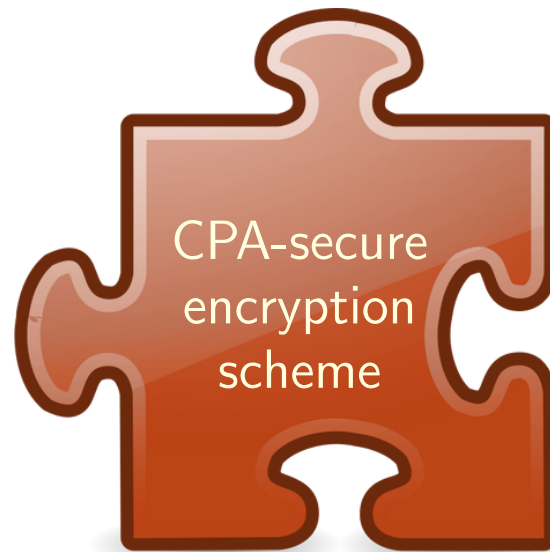
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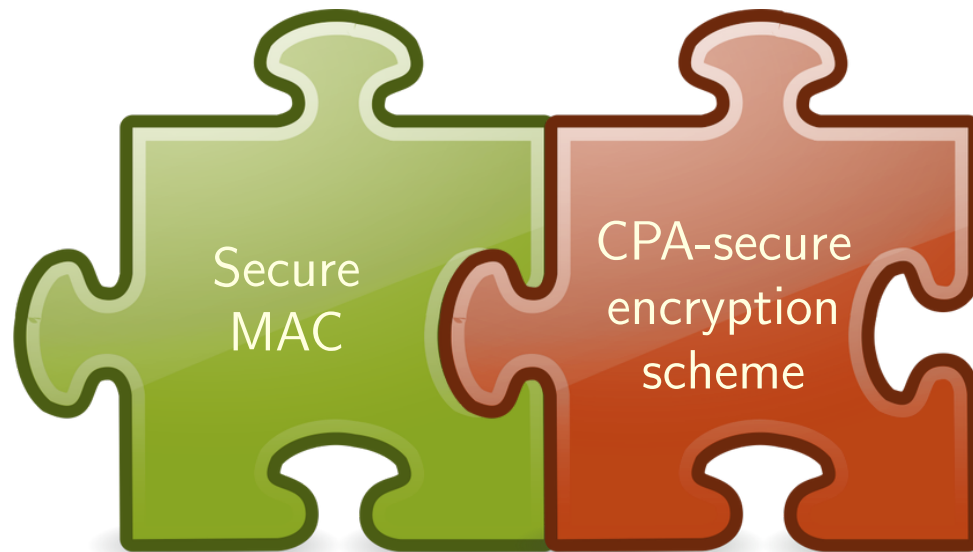
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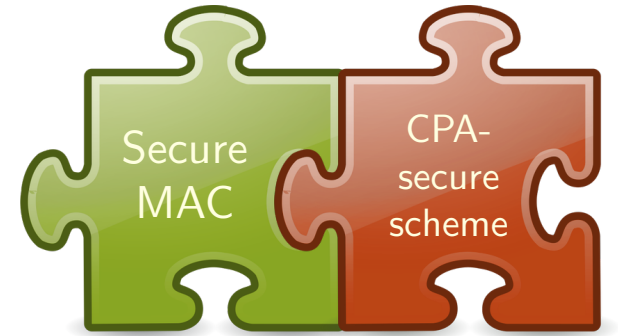
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Combining MACs and CPA-secure encryption schemes

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

Ideas?



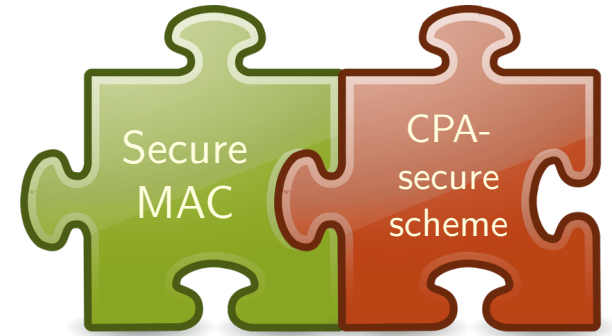
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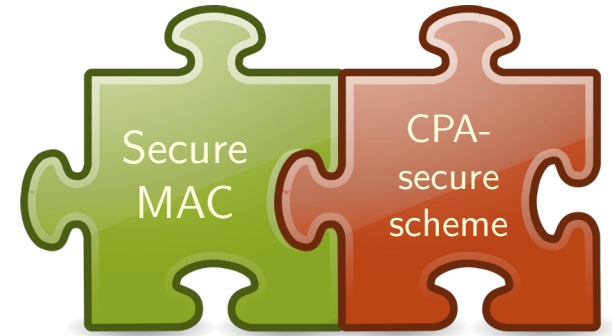
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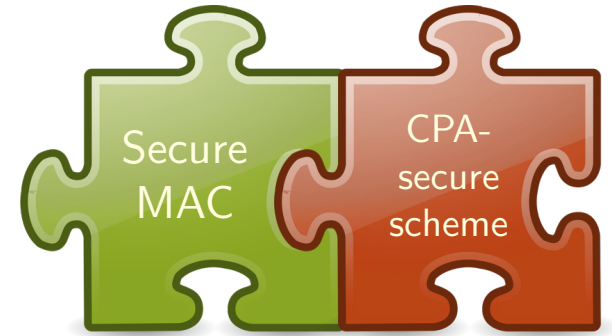
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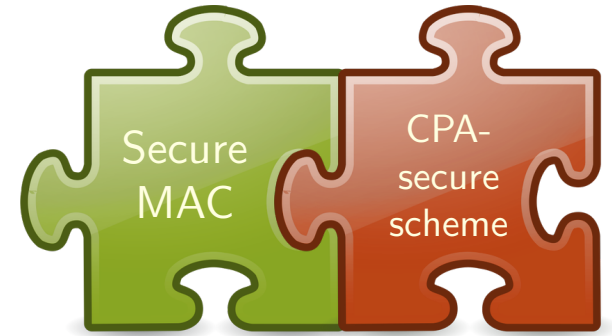
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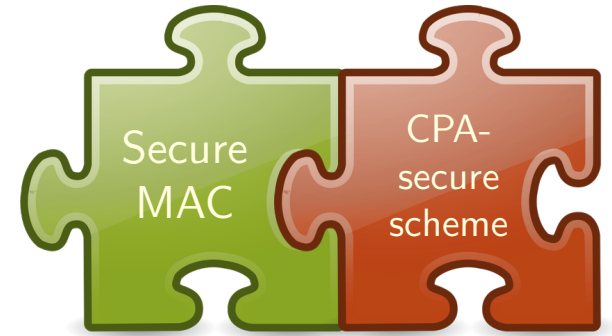
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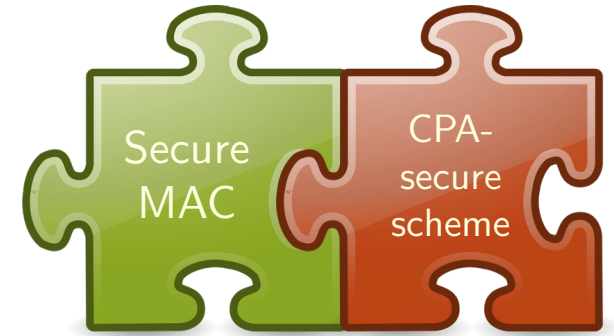
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Still bad

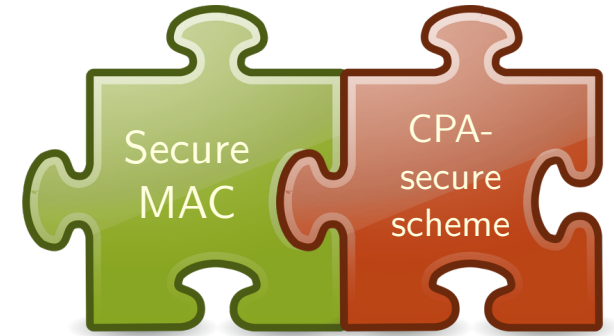


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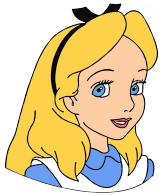
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Pick two **independent** keys k_1 and k_2 for encryption and MAC, respectively

k_1, k_2



k_1, k_2

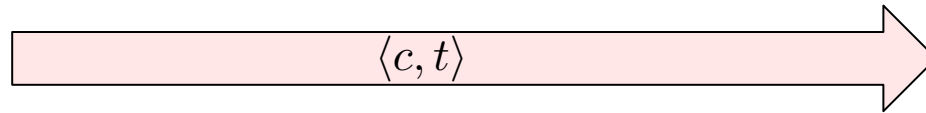
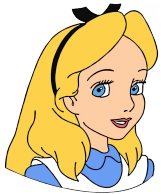
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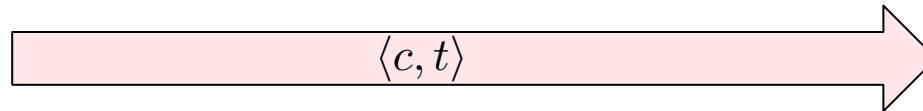
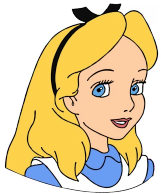
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Decrypting $\langle c, t \rangle$:

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

k_1, k_2



$\langle c, t \rangle$



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Encrypt and Authenticate

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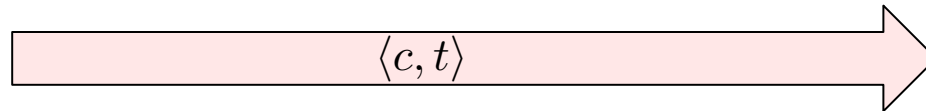
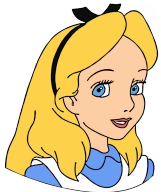
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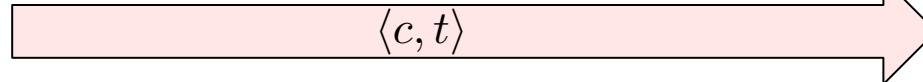
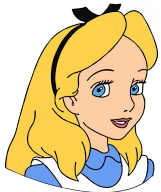
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- The tag t is not required to hide any information about m
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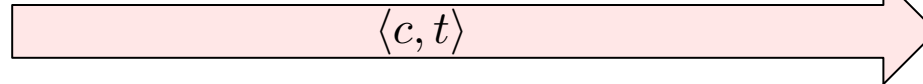
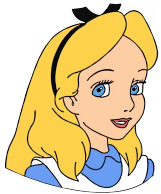
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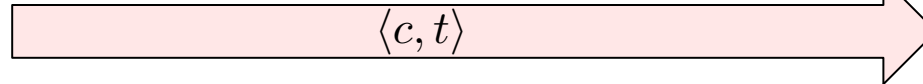
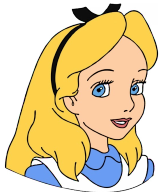
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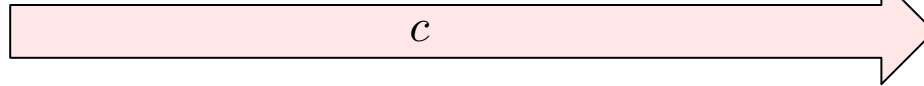
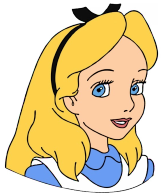
This scheme is not even CPA-secure!

Authenticate then Encrypt

Encrypting m :

- $t \leftarrow \text{Mac}_{k_2}(m)$
- $c \leftarrow \text{Enc}_{k_1}(m \parallel t)$
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k_1, k_2



c



k_1, k_2

Authenticate then Encrypt

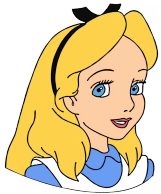
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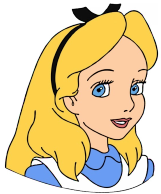
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Problems?

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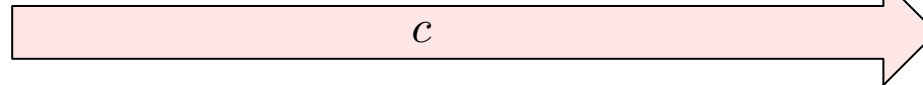
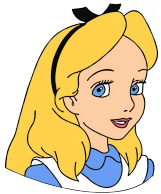
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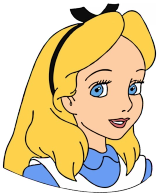
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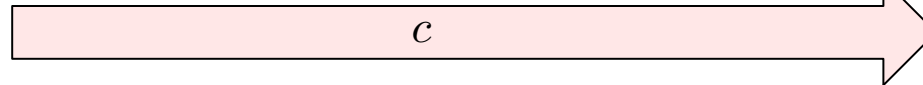
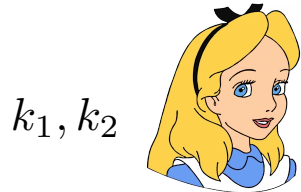
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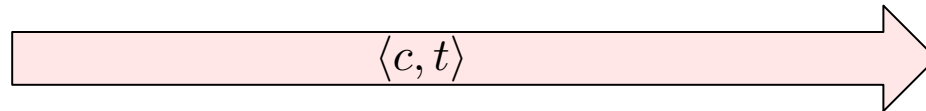
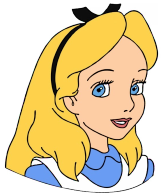
- If encryption requires padding and the padding is wrong, an error can be raised by $\text{Dec}_{k_1}(c)$
- If the encryption scheme is malleable and the padding error is leaked to the user, the adversary has a **padding oracle**
- There are other counterexamples that do not rely on padding errors

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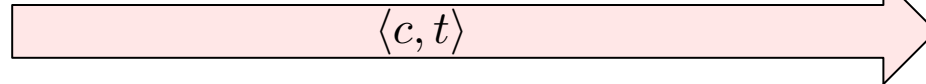
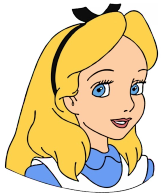
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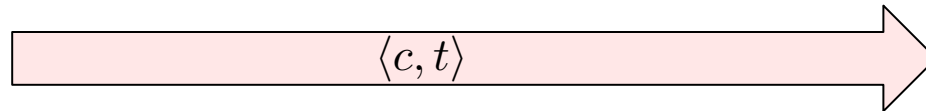
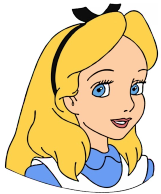
Keys (w. security parameter n):

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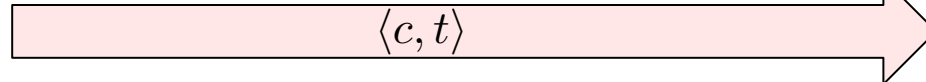
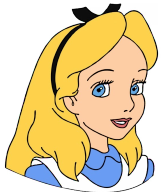
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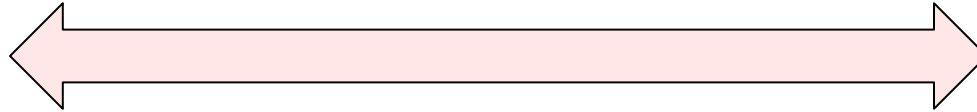
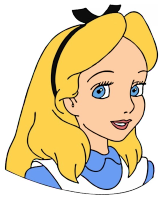


k_1, k_2

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

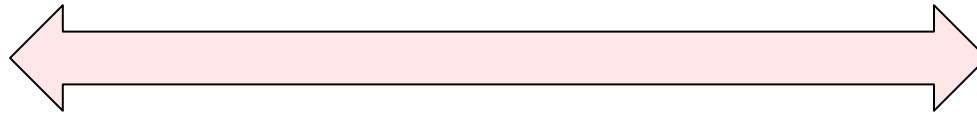
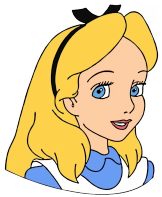
Secure Sessions

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



Secure Sessions

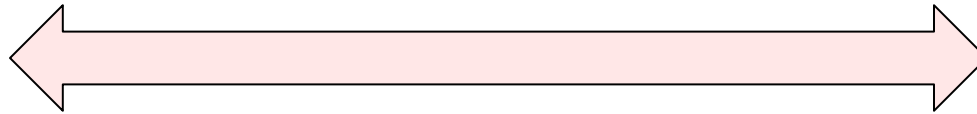
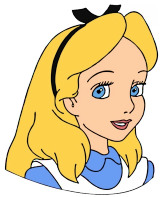
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Easy! Just use Authenticated Encryption

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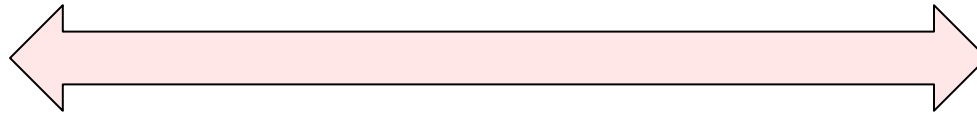
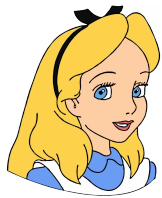


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Not so fast...

Secure Sessions

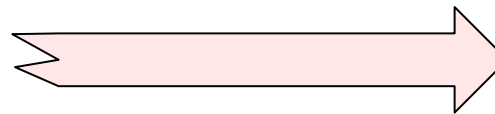
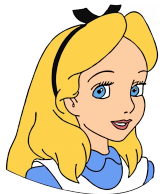
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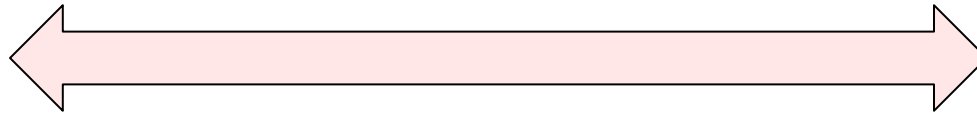
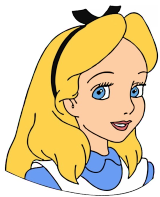
Not so fast...

Message dropping:



Secure Sessions

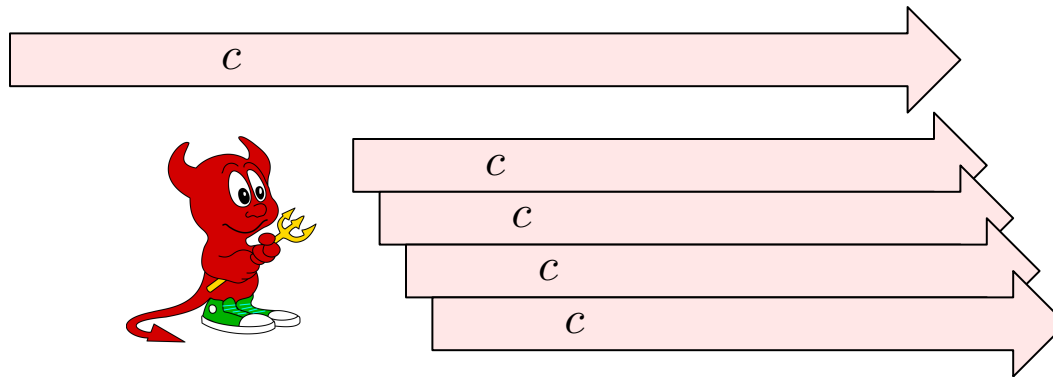
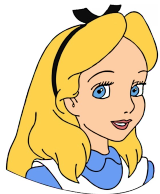
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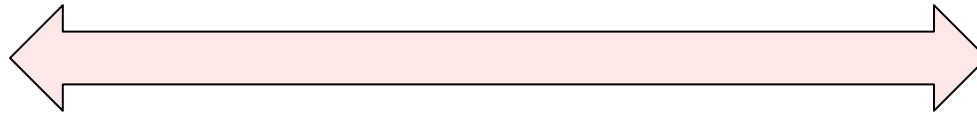
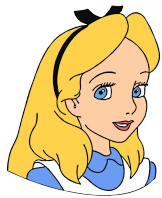
Not so fast...

Replay attack (we have already encountered this attack):



Secure Sessions

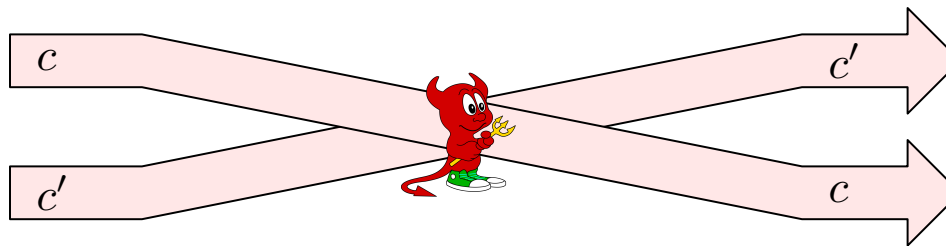
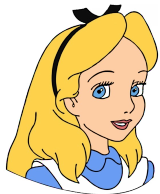
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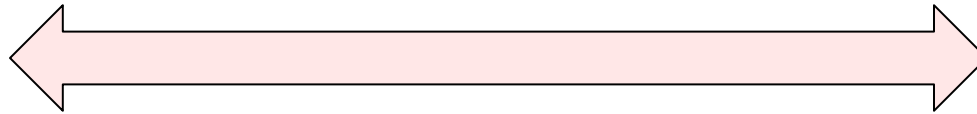
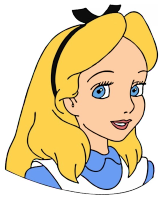
Not so fast...

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



Secure Sessions

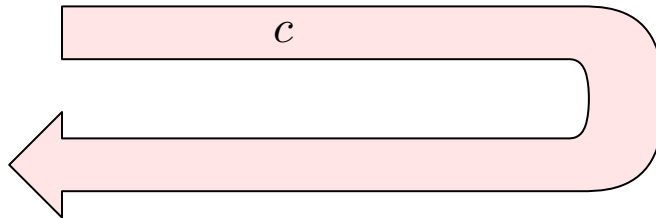
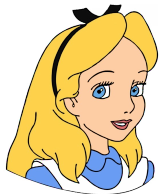
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Reflection attack



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

