CIS 5371, Fall 2025

Authenticated Encryption

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Agenda

1. AE and Its Security Definitions

2. Failed Ways to Build AE

3. Generic Compositions

4. Padding-Oracle Attack on SSL/TLS

So Far

Transfer $5 to account 12345

K

K

K

Privacy **Authenticity**

Encryption scheme

Authenticated Encryption

Achieve **both** of these aims

MAC

Authenticated Encryption (AE)

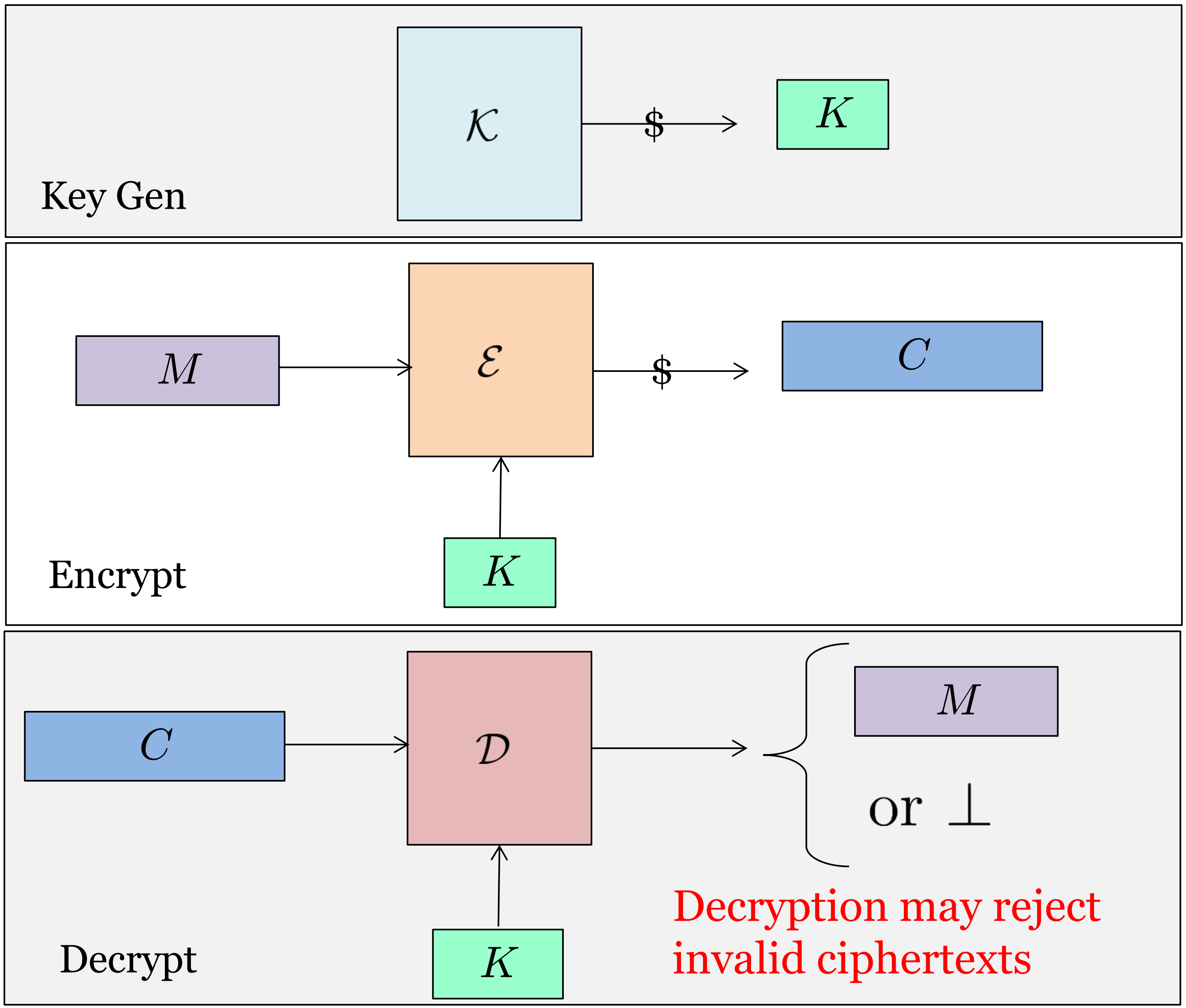
Emerged ~ 2000

Begin with two **realizations**

1. Authenticity is routinely needed/assumed
2. "Standard" privacy mechanisms don't provide it

Provide an easier-to-correctly-use abstraction boundary

AE Syntax



$\mathcal{K}$
$
K
Key Gen
M
$\mathcal{E}$
$
C
K
Encrypt
C
$\mathcal{D}$
M
or $\perp$
K
Decrypt
Decryption may reject invalid ciphertexts

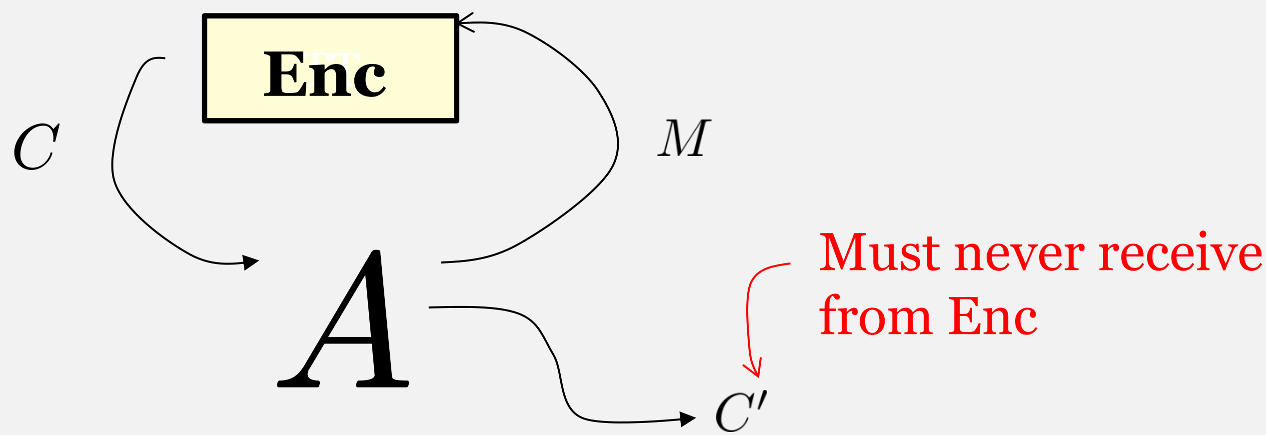
Defining Security for AE

Authenticity

-Use Left-or-Right security for privacy

Auth $_{\mathcal{E}}$

procedure Initialize$()$	**procedure Enc**(M)	**procedure Finalize**(C')
$K \xleftarrow{\$} \mathcal{K}$	Return $\mathcal{E}_K(M)$	Return $(\mathcal{D}_K(C') \neq \perp)$



$$\mathbf{Adv}^{\mathrm{auth}}_{\mathcal{T}}(A) = \Pr[\mathrm{Auth}^{A}_{\mathcal{E}} \Rightarrow 1]$$

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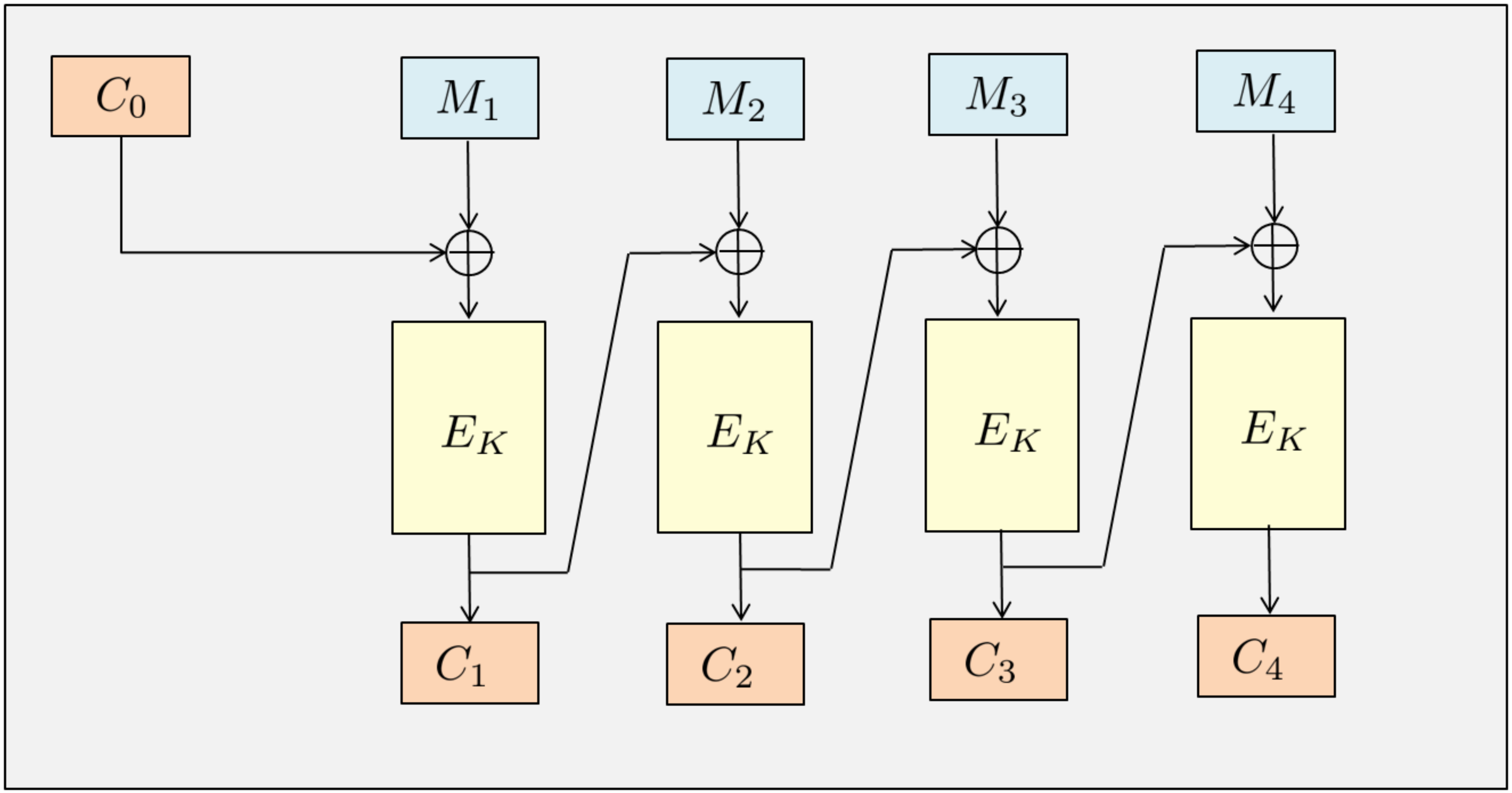
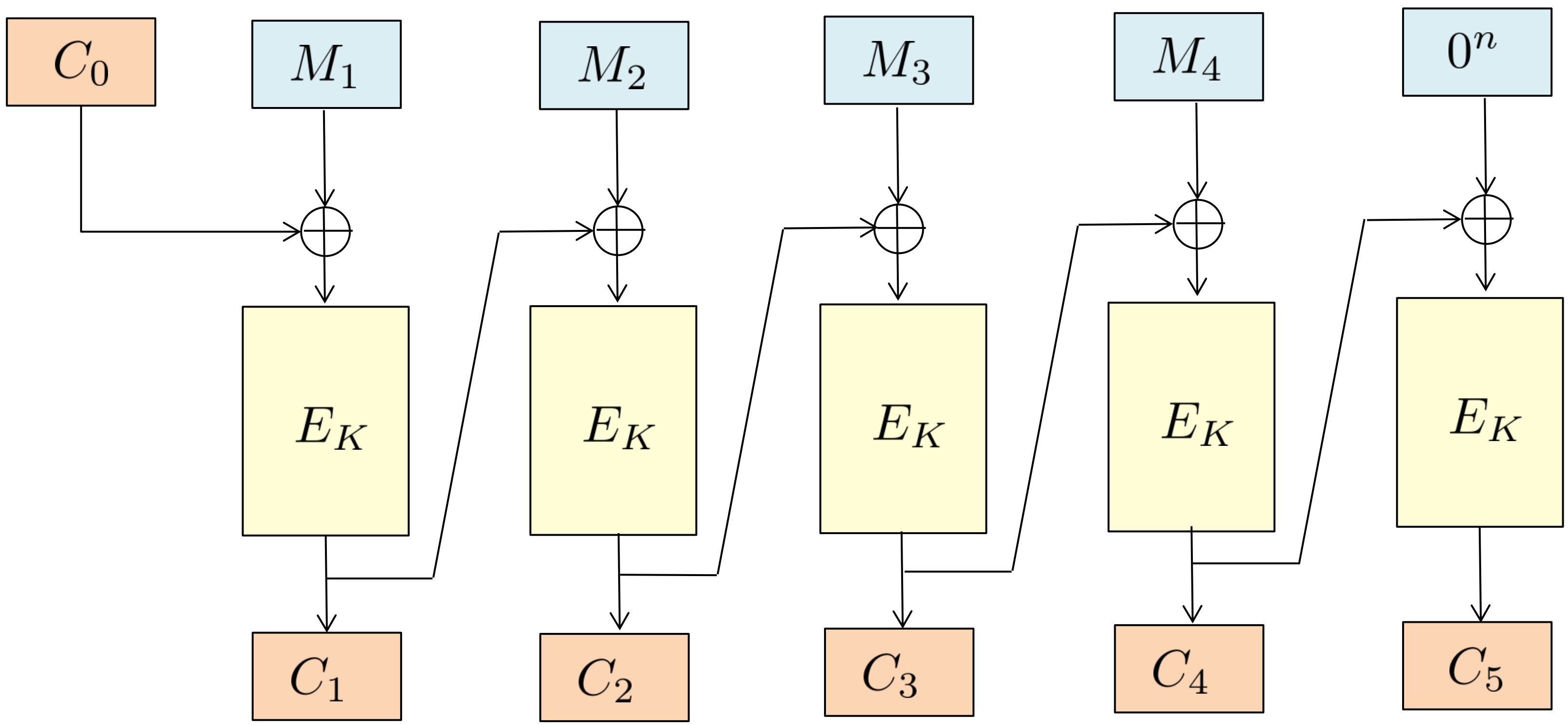
Plain Encryption Doesn't Provide Authenticity



Question: Does CBC provide authenticity?

Answer: No, because any ciphertext has valid decryption

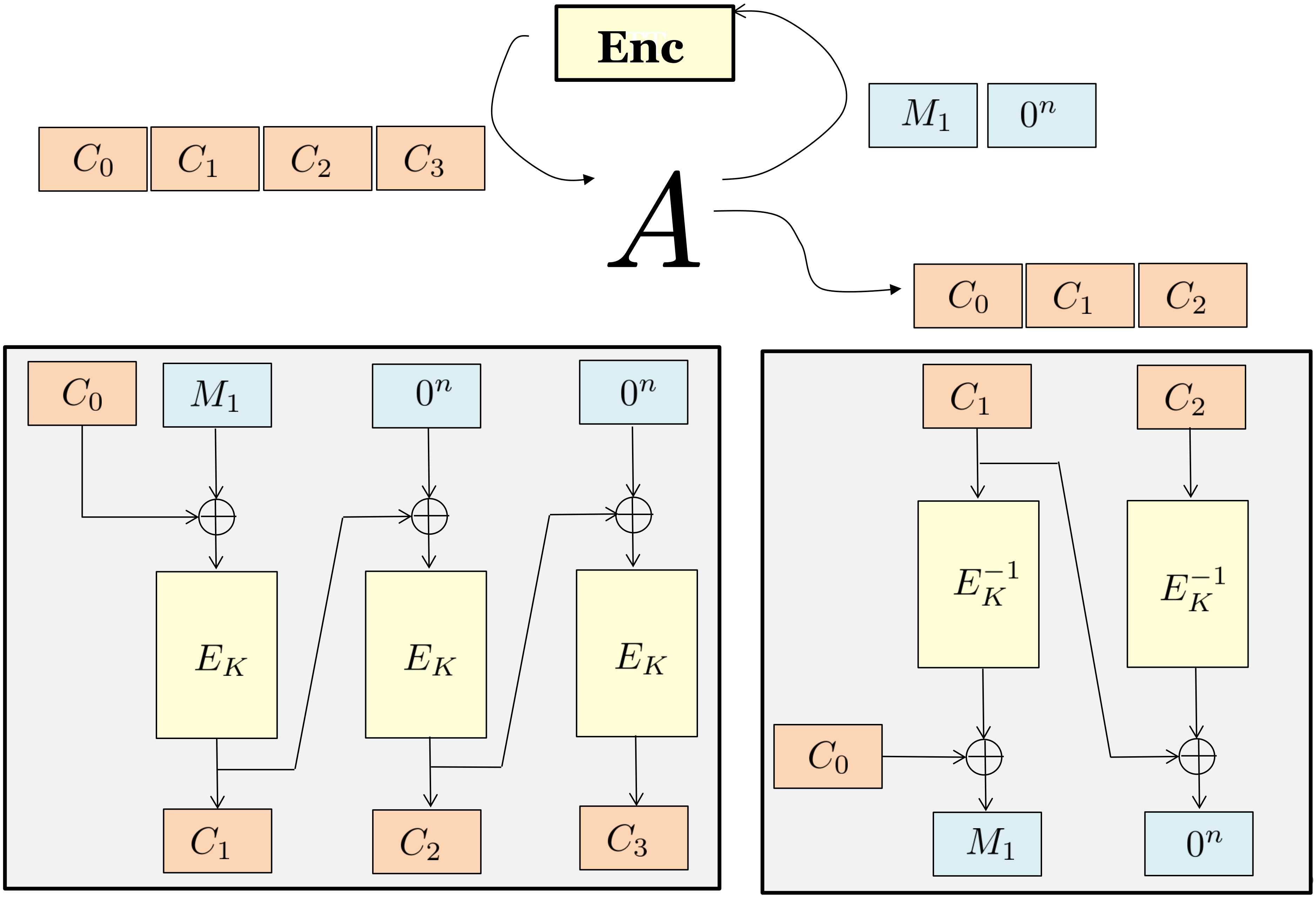
A Bad Fix: CBC with Redundancy



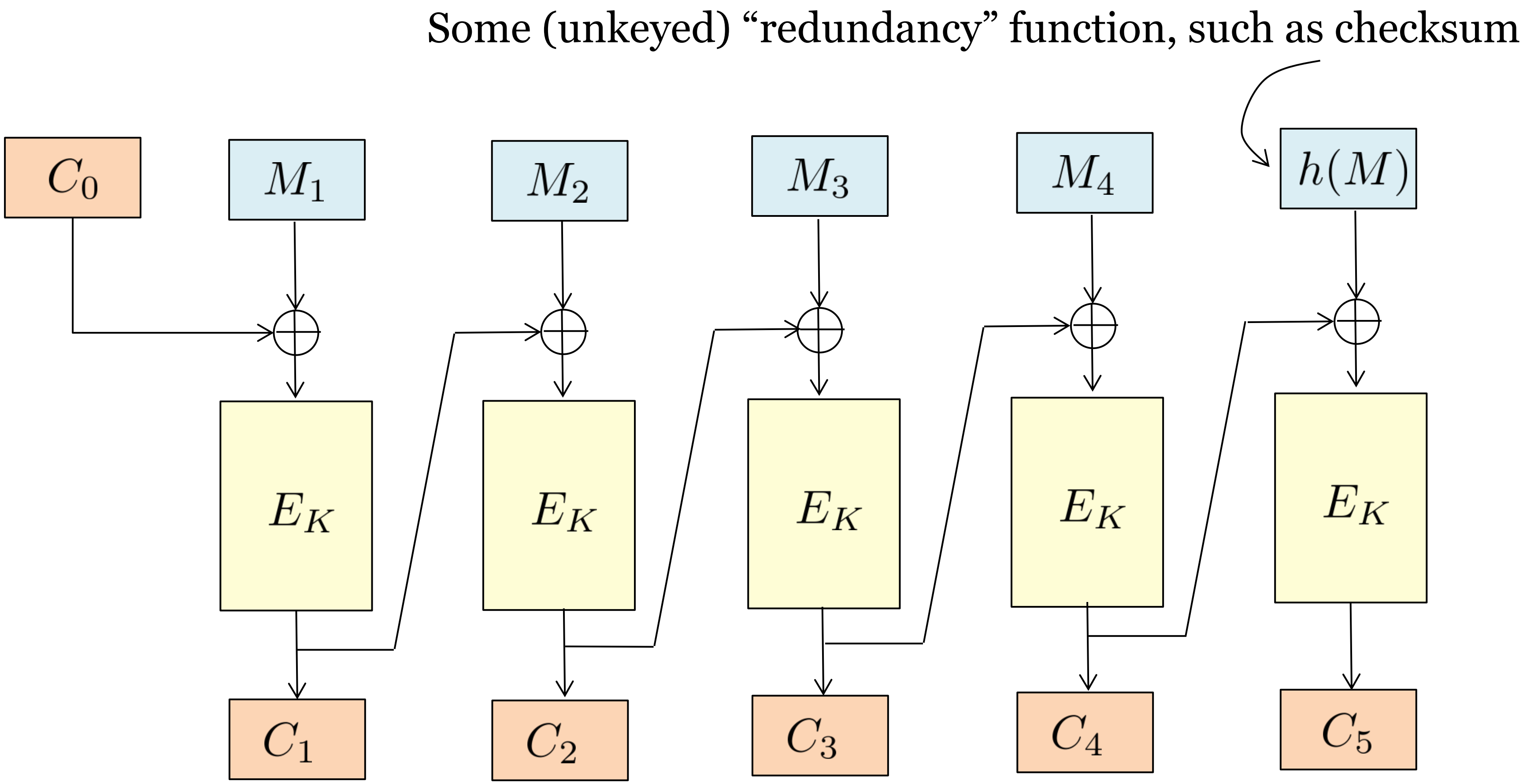
On decryption, verify the decrypted last block is zero.

Question: Break the authenticity of this scheme with a single Enc query

An Attack



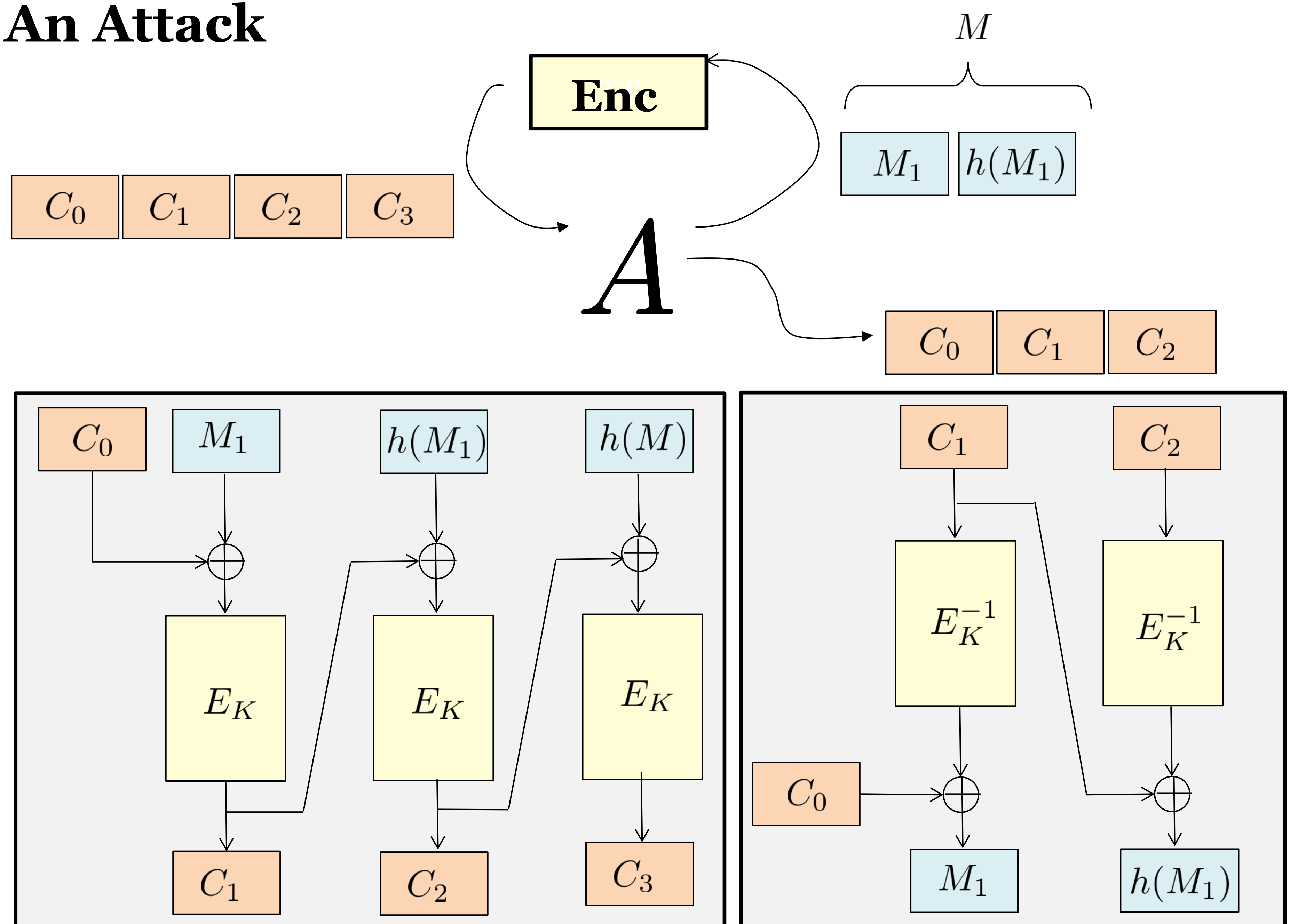
Complex Redundancy Doesn't Help



The redundancy is verified upon decryption

Question: Break the authenticity of this scheme with a single Enc query

An Attack

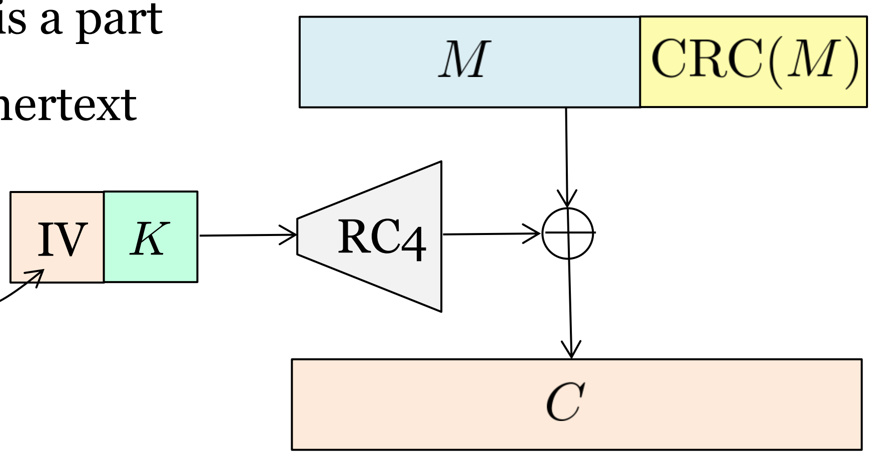

Enc
M
M_1
$h(M_1)$
C_0 C_1 C_2 C_3
A
C_0 C_1 C_2
C_0
M_1
$h(M_1)$
$h(M)$
E_K
E_K
E_K
C_1 C_2 C_3
C_1
C_2
E_K^{-1}
E_K^{-1}
C_0
M_1
$h(M_1)$

A Case Study: WEP

Used in IEEE WiFi standard

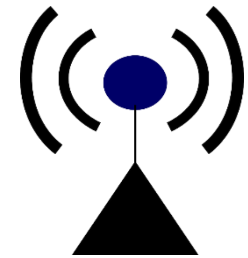
24-bit IV is a part

of the ciphertext



Attack 1: Exploiting Short IV

$\mathrm{IV}_1 \| C_1$ $\mathrm{IV}_2 \| C_2$ $\cdots$

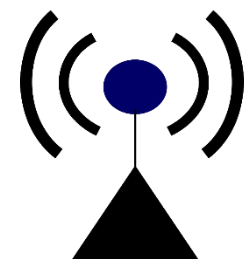


Assume all messages are of the same length, and fairly long

Goal: recover at least one message

Attack 1: Exploiting Short IV

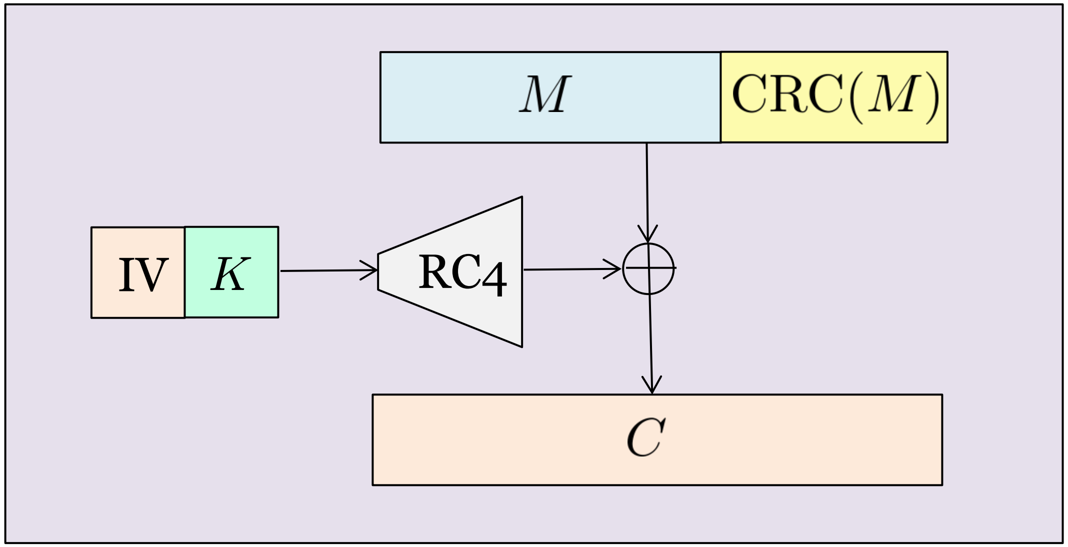
$\mathrm{IV}_1 \| C_1$ $\mathrm{IV}_2 \| C_2$ …



Aim for an IV collision

For 24-bit IV's, how many ctx to wait for collision prob ≈ 0.5?

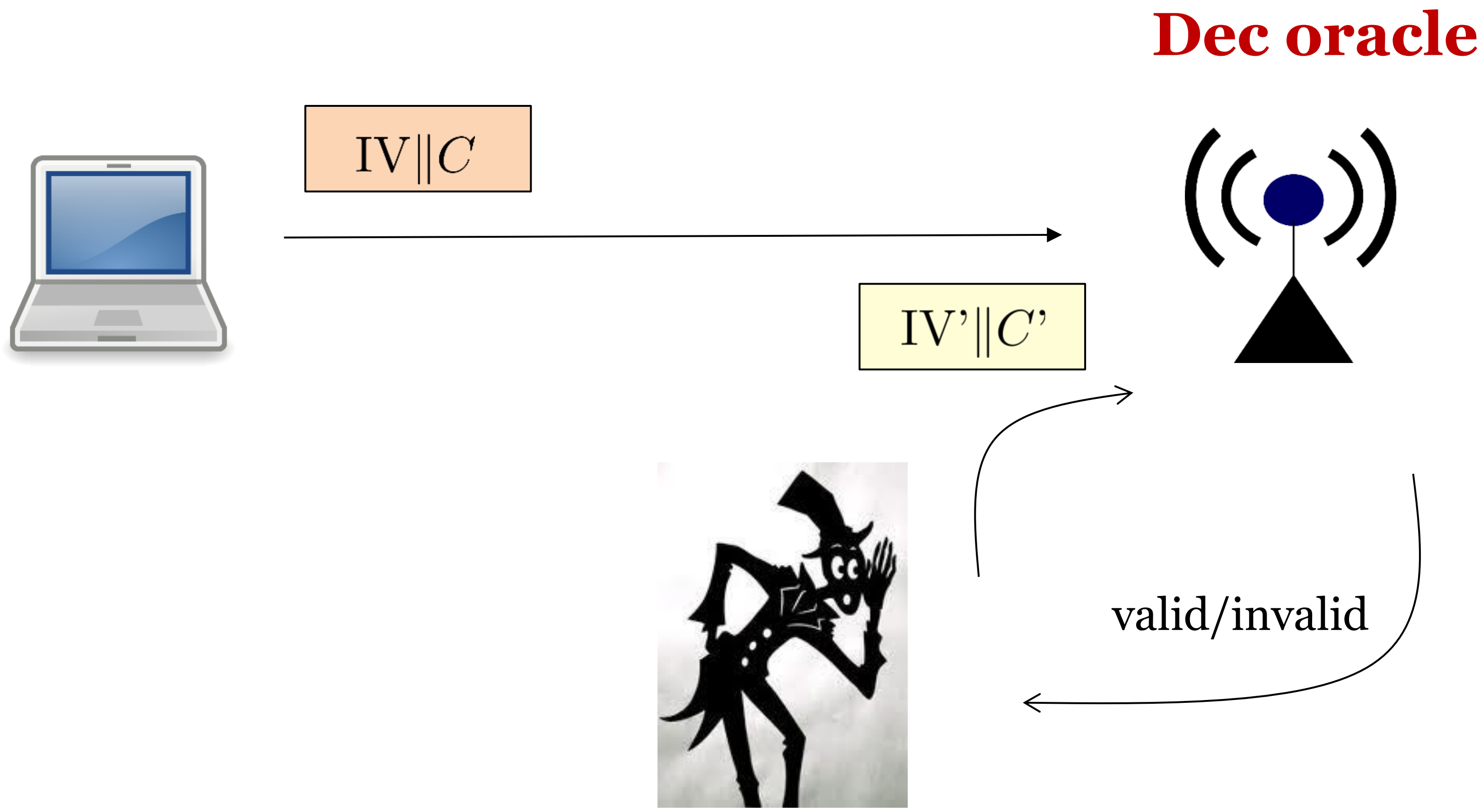
Attack 1: Exploiting Short IV



$$\underbrace{\boxed{\mathrm{IV}\|C_1}\quad\boxed{\mathrm{IV}\|C_2}}$$

Same IV, can recover $M_1 \oplus M_2$

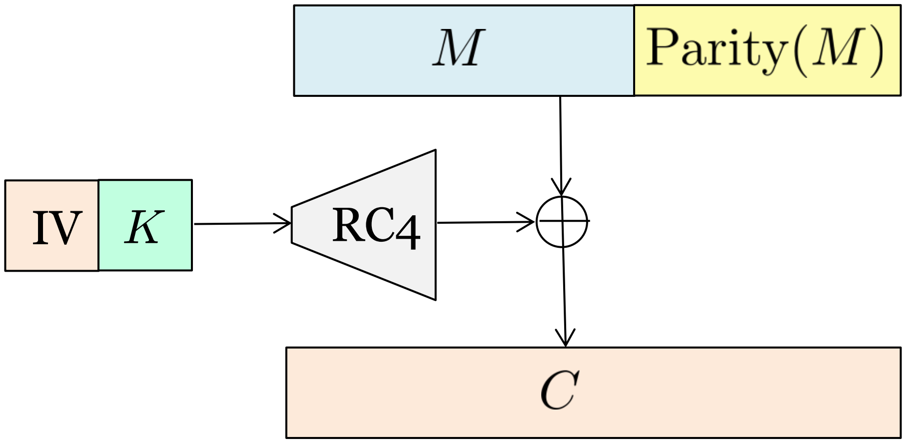
Attack 2: Chop-Chop Attack



Goal: recover the underlying message by exploiting Dec queries

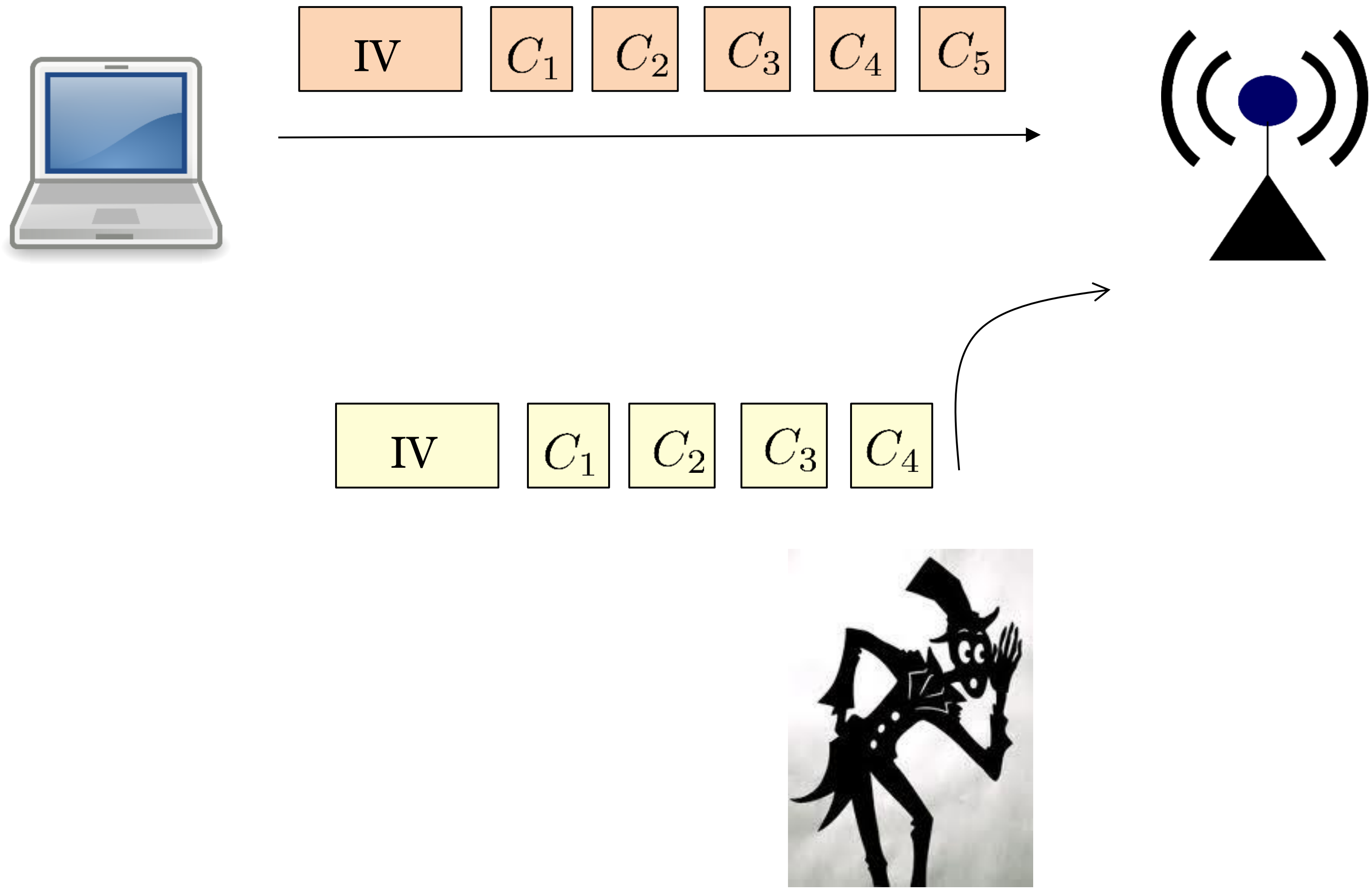
Attack 2: Chop-Chop Attack

Illustrated Via A Simpler Variant of WEP

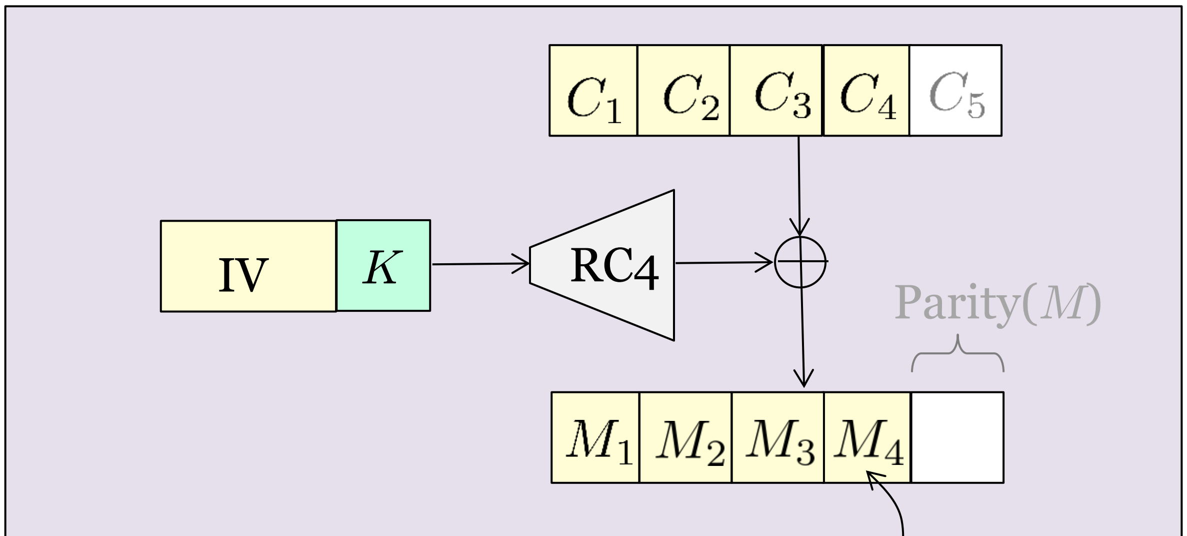


Example: $\text{Parity}(10011) = 1 \oplus 0 \oplus 0 \oplus 1 \oplus 1 = 1$

Attack 2: Chop-Chop Attack
Illustrated For 4-bit Message

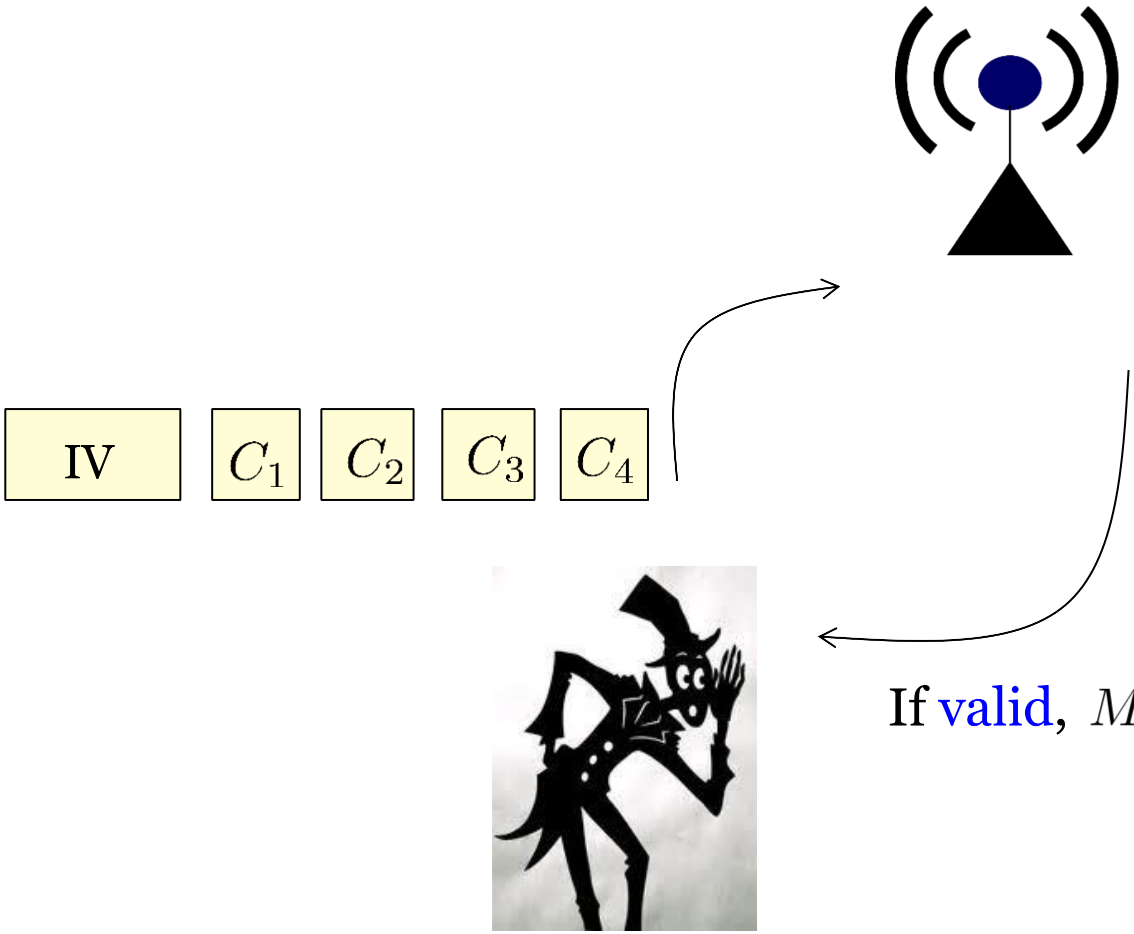


Decryption In CloseUp



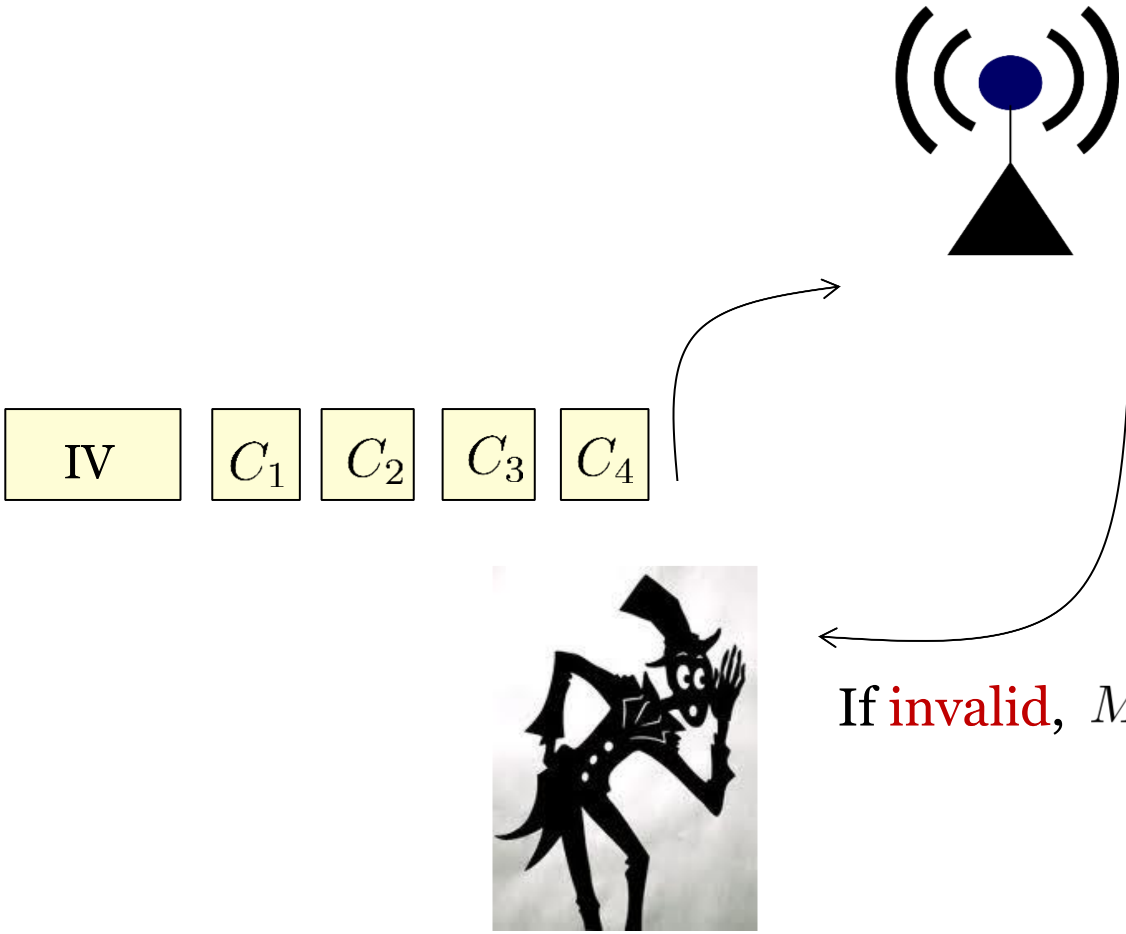
Compare with $\text{Parity}(M_1 M_2 M_3)$

Exploit Decryption Response



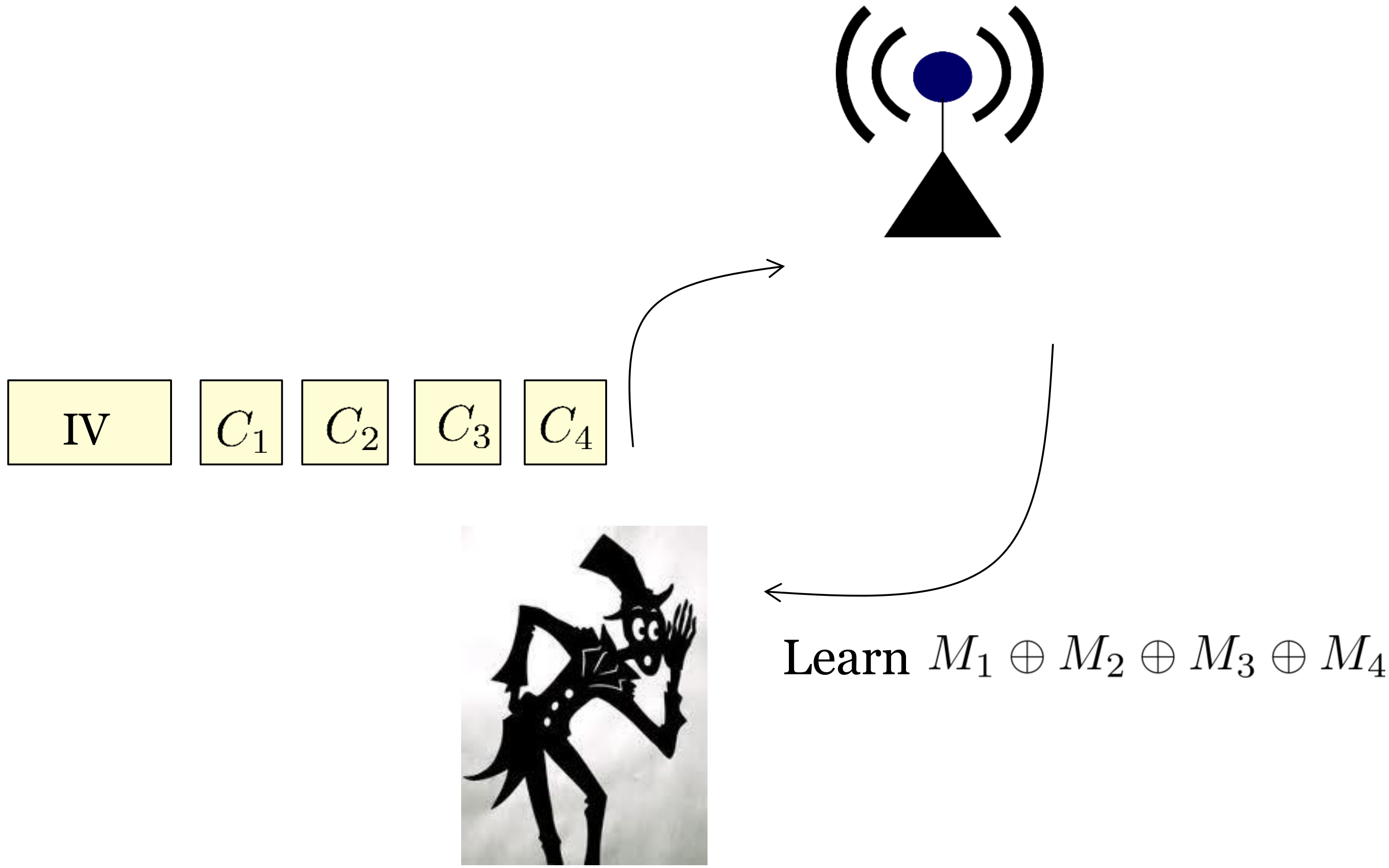
If valid, $M_1 \oplus M_2 \oplus M_3 \oplus M_4 = 0$

Exploit Decryption Response

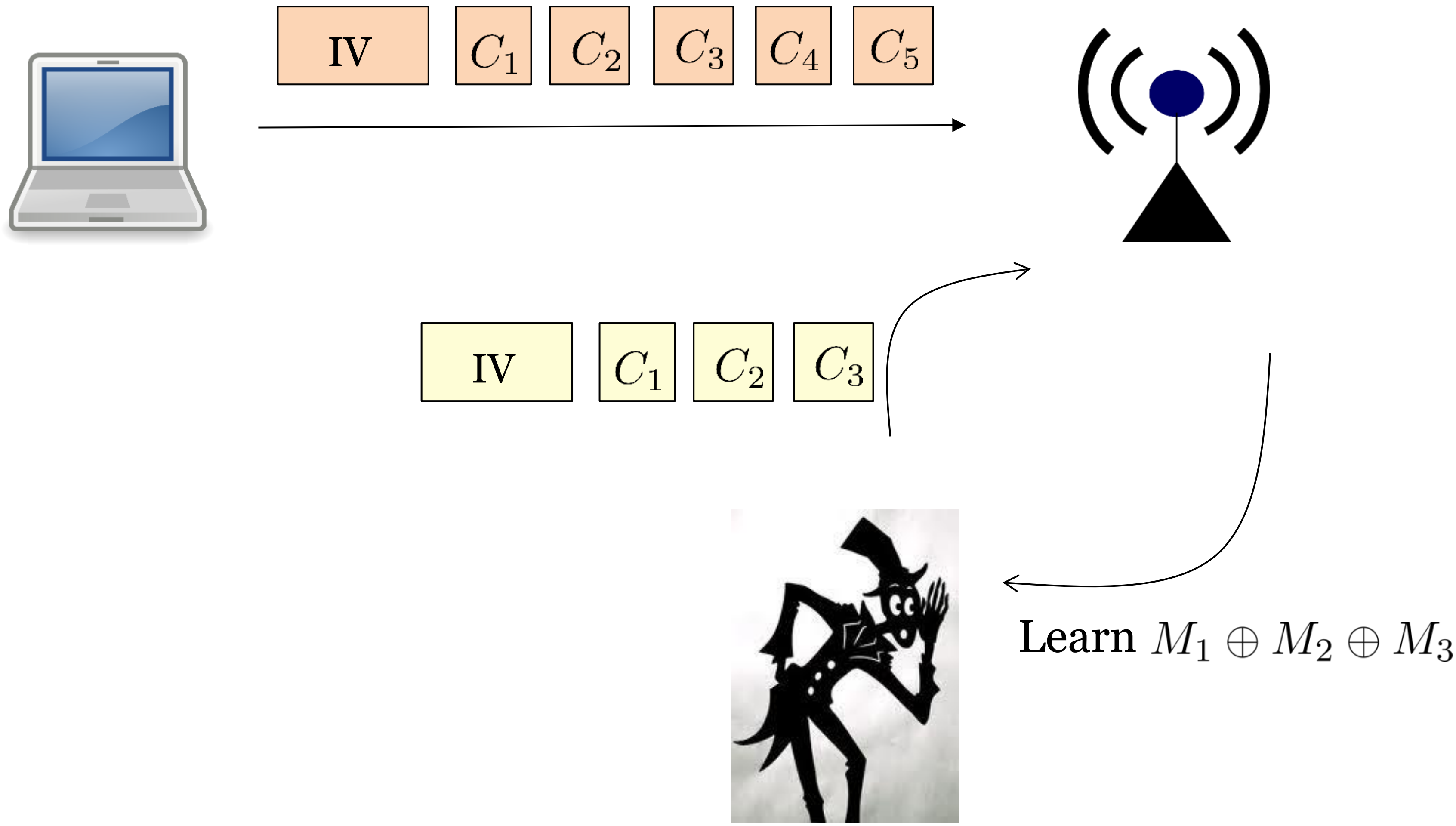


If invalid, $M_1 \oplus M_2 \oplus M_3 \oplus M_4 = 1$

Exploit Decryption Response



Exploit Decryption Even Further



Solve A System of Linear Equations

$$\begin{cases} M_1 \oplus M_2 \oplus M_3 \oplus M_4 = \square \\ M_1 \oplus M_2 \oplus M_3 = \square \\ M_1 \oplus M_2 = \square \\ M_1 = \square \end{cases}$$

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3. **Generic Compositions**

4. Padding-Oracle Attack on SSL/TLS

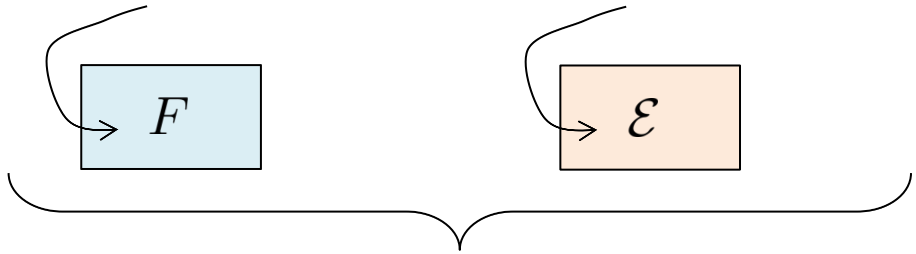
Constructing AE: Generic Composition

A good PRF, such as

Encrypted CBC-MAC

Privacy-only encryption

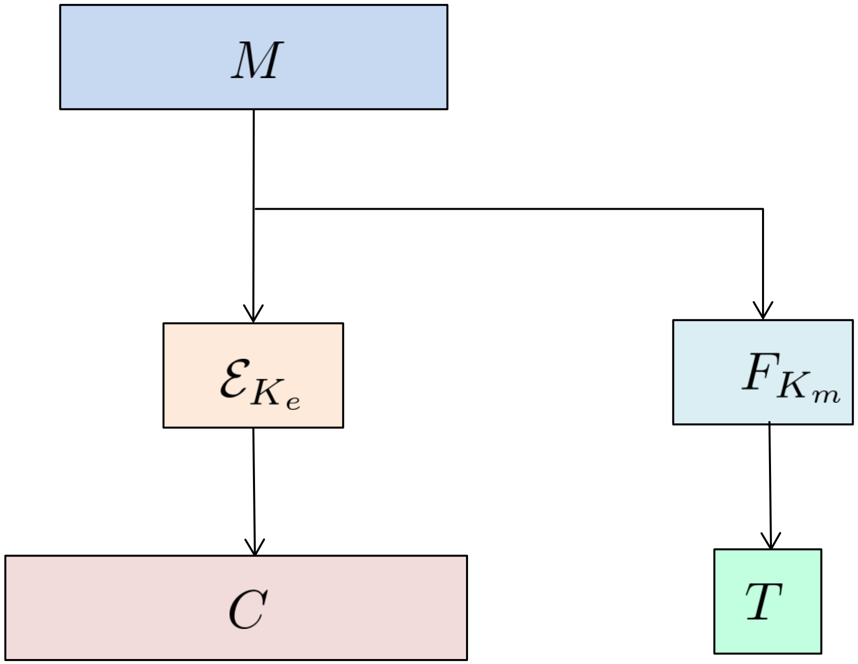
(such as CTR/CBC)



Compose them to build AE

Method	Usage
Encrypt-and-MAC	SSH
MAC-then-Encrypt	SSL/TLS
Encrypt-then-MAC	IPSec

Encrypt-and-MAC: Simple Composition



Privacy	Authenticity
No	No

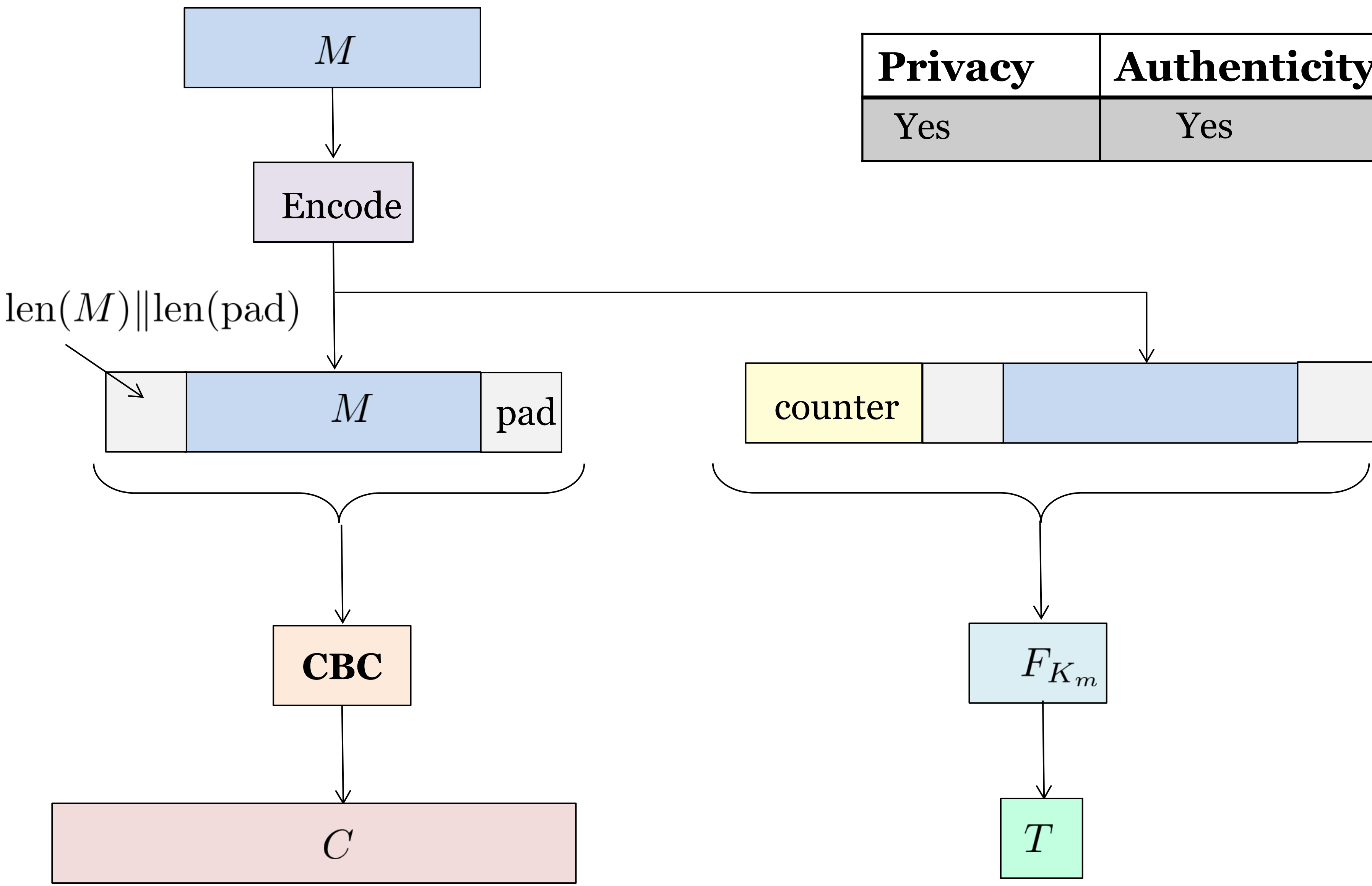
for some bad encryption scheme

No privacy: encrypting the same message results in the same tag

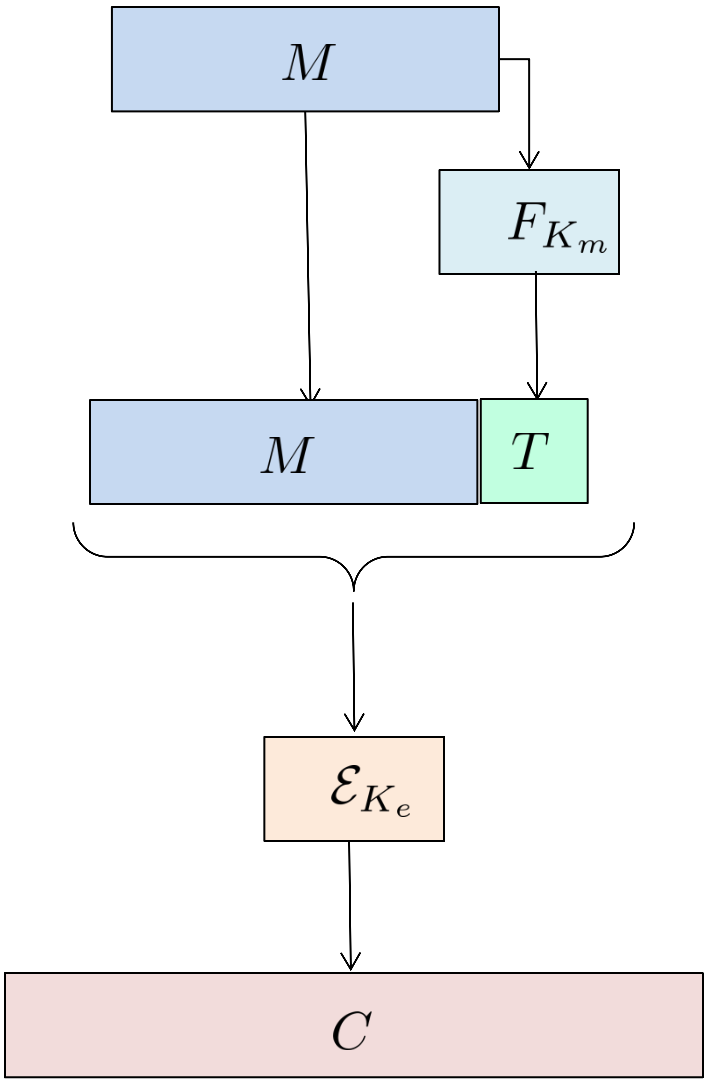
No authenticity if one can modify C such that decryption is unchanged.

Encrypt-and-MAC in SSH

Privacy	Authenticity
Yes	Yes



MAC-then-Encrypt

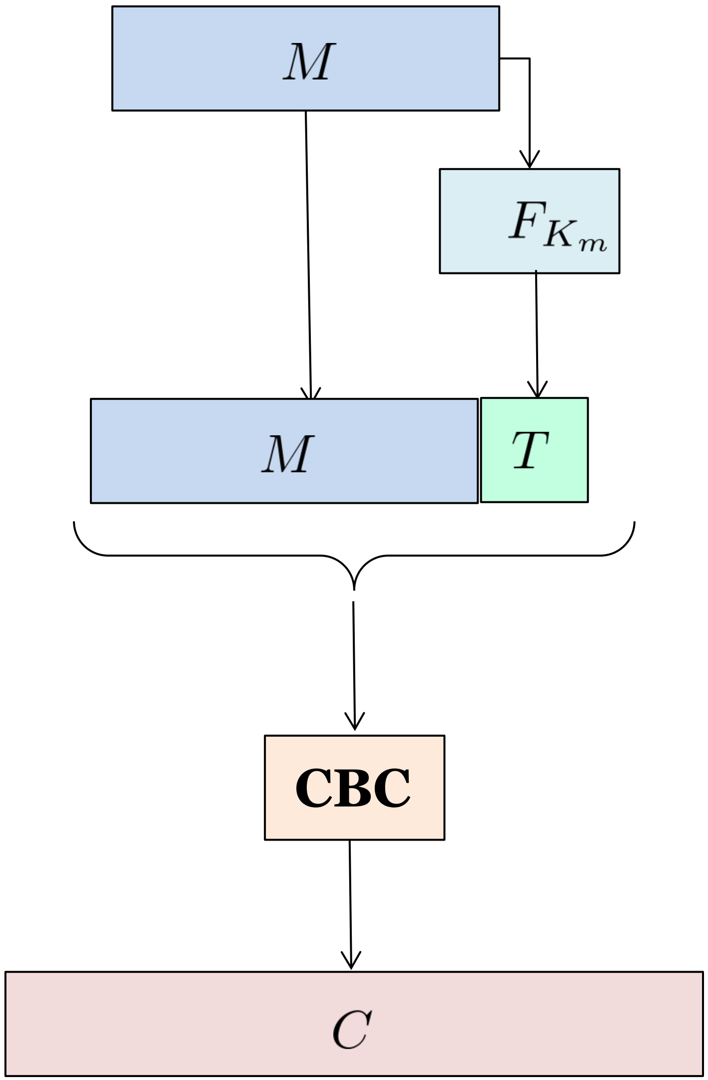


Privacy	Authenticity
Yes	No

for some bad encryption scheme

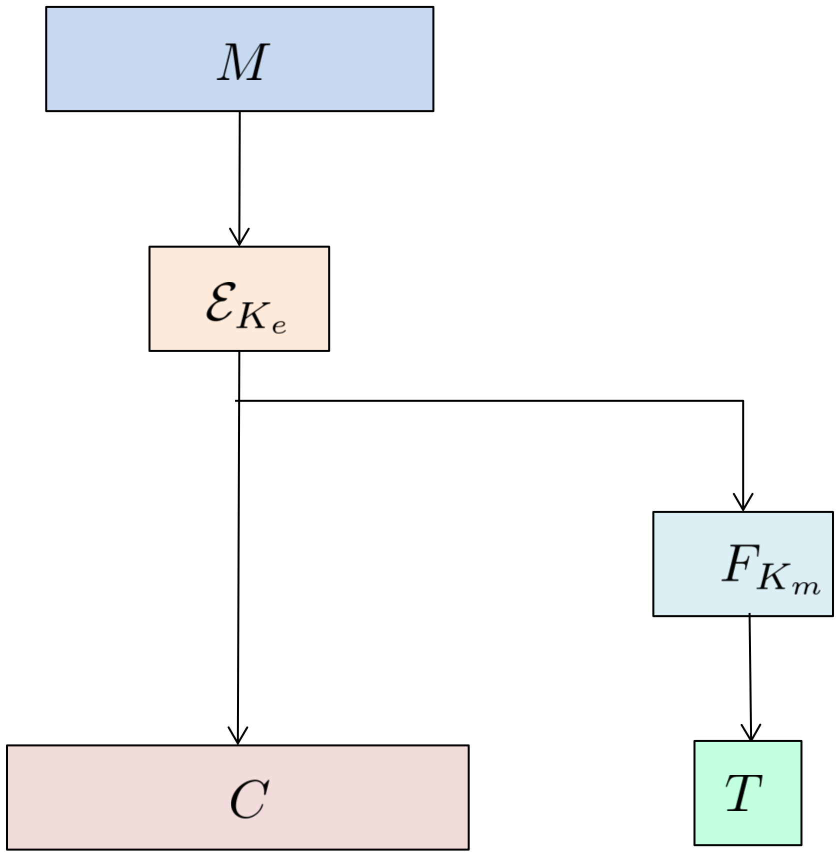
No authenticity if one can modify C such that decryption is unchanged.

MAC-then-Encrypt in TLS



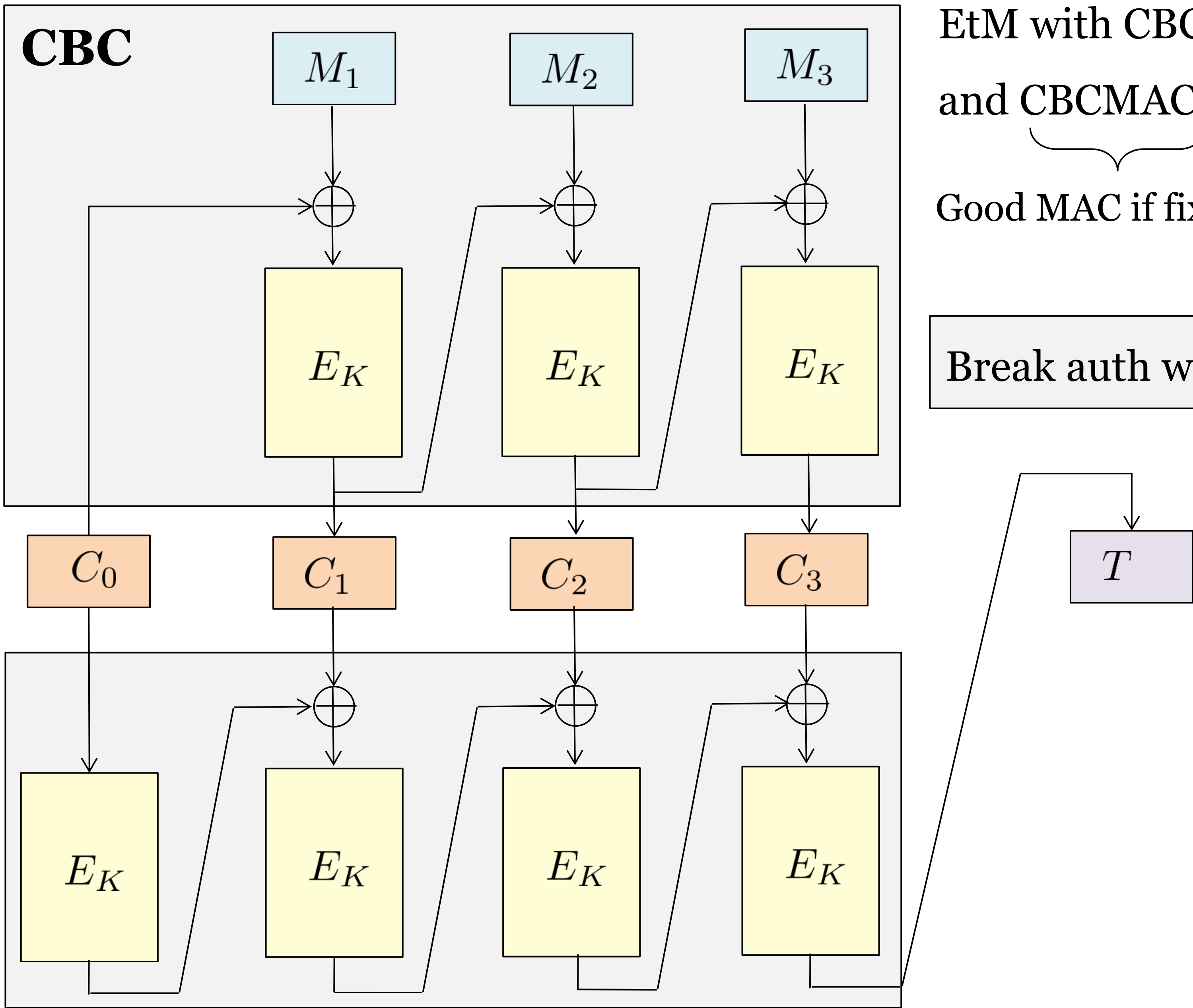
Privacy	Authenticity
Yes	Yes

Encrypt-then-MAC



Privacy	Authenticity
Yes	Yes

Reusing Key May Lead to Attacks

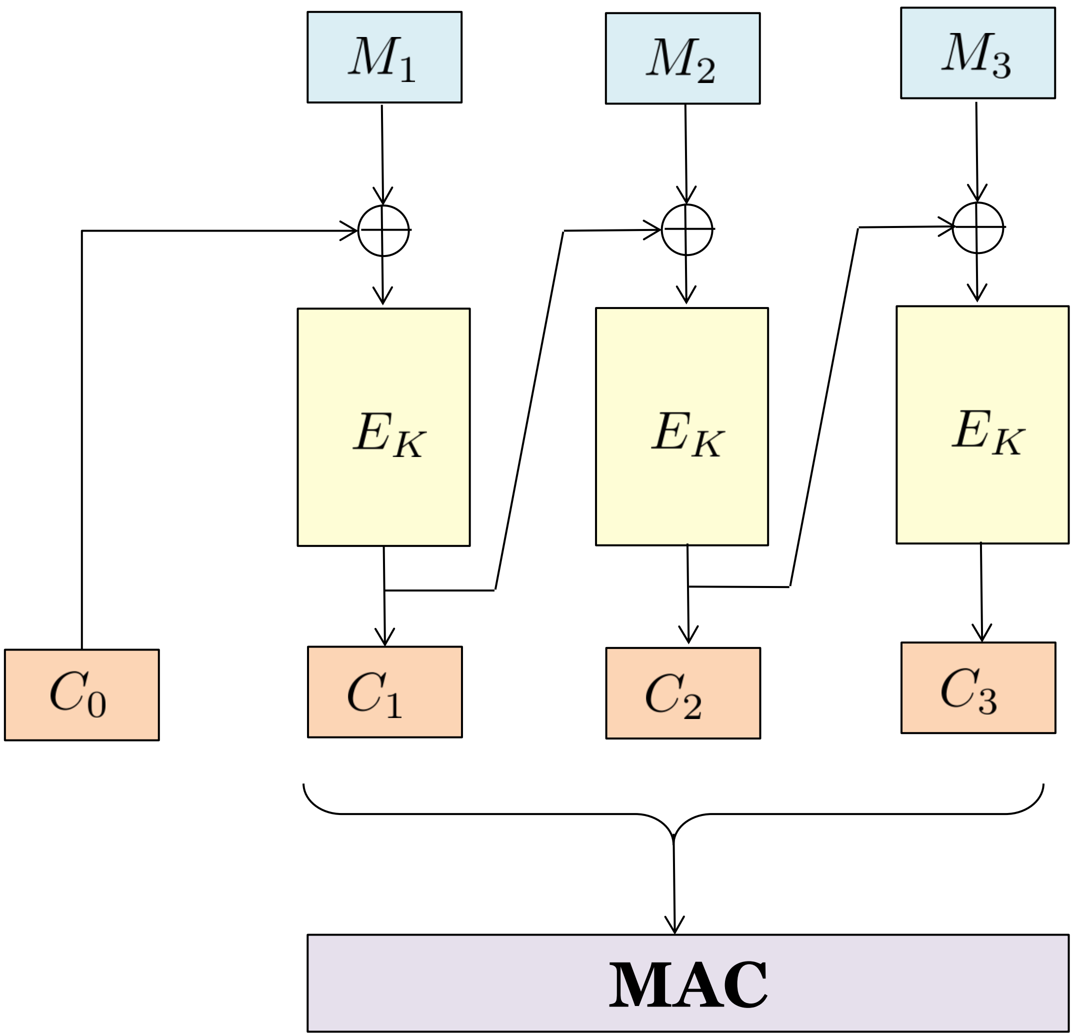


EtM with CBC encryption and $\underbrace{\text{CBCMAC}}_{\text{Good MAC if fixed input length}}$, **same** key

Break auth with one query

A Common Pitfall in Implementing EtM

Happened in ISO 1972 standard, and in RNCryptor of iOS



Forget to feed IV into MAC

Break auth with one query

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4. **Padding-Oracle Attack on SSL/TLS**

The Padding-Oracle Attack

“Lucky Thirteen” attack snarfs cookies protected by SSL encryption

Exploit is the latest to subvert crypto used to secure Web transactions.

by D

Meaner POODLE bug that bypasses TLS crypto bites 10 percent of websites

Some of the world's leading sites are vulnerable to an easier, more simplified attack.

by D

Researchers poke hole in custom crypto built for Amazon Web Services

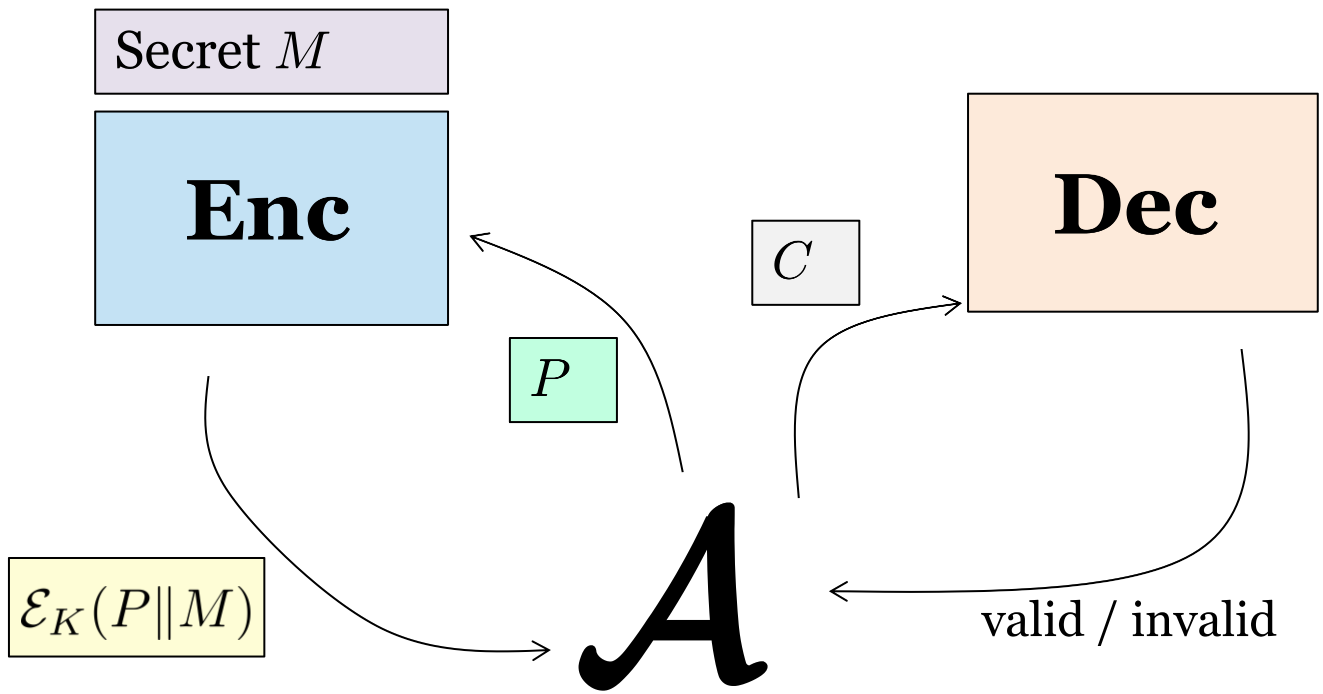
Even when engineers do everything by the book, secure crypto is still hard.

by D

New TLS encryption-busting attack also impacts the newer TLS 1.3

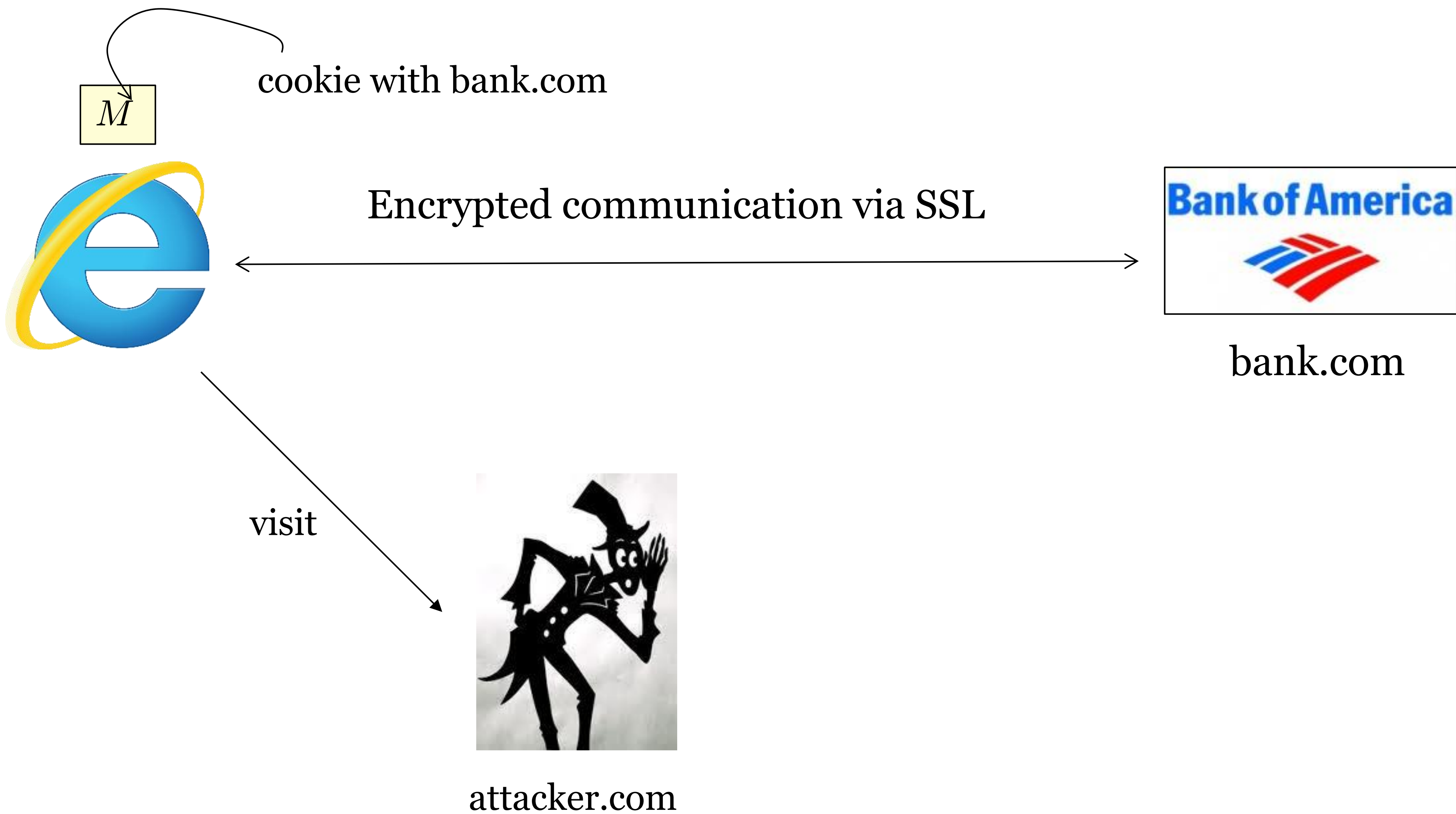
Researchers discover yet another Bleichenbacher attack variation (yawn!).

Attack Model: Chosen Prefix Secret Suffix

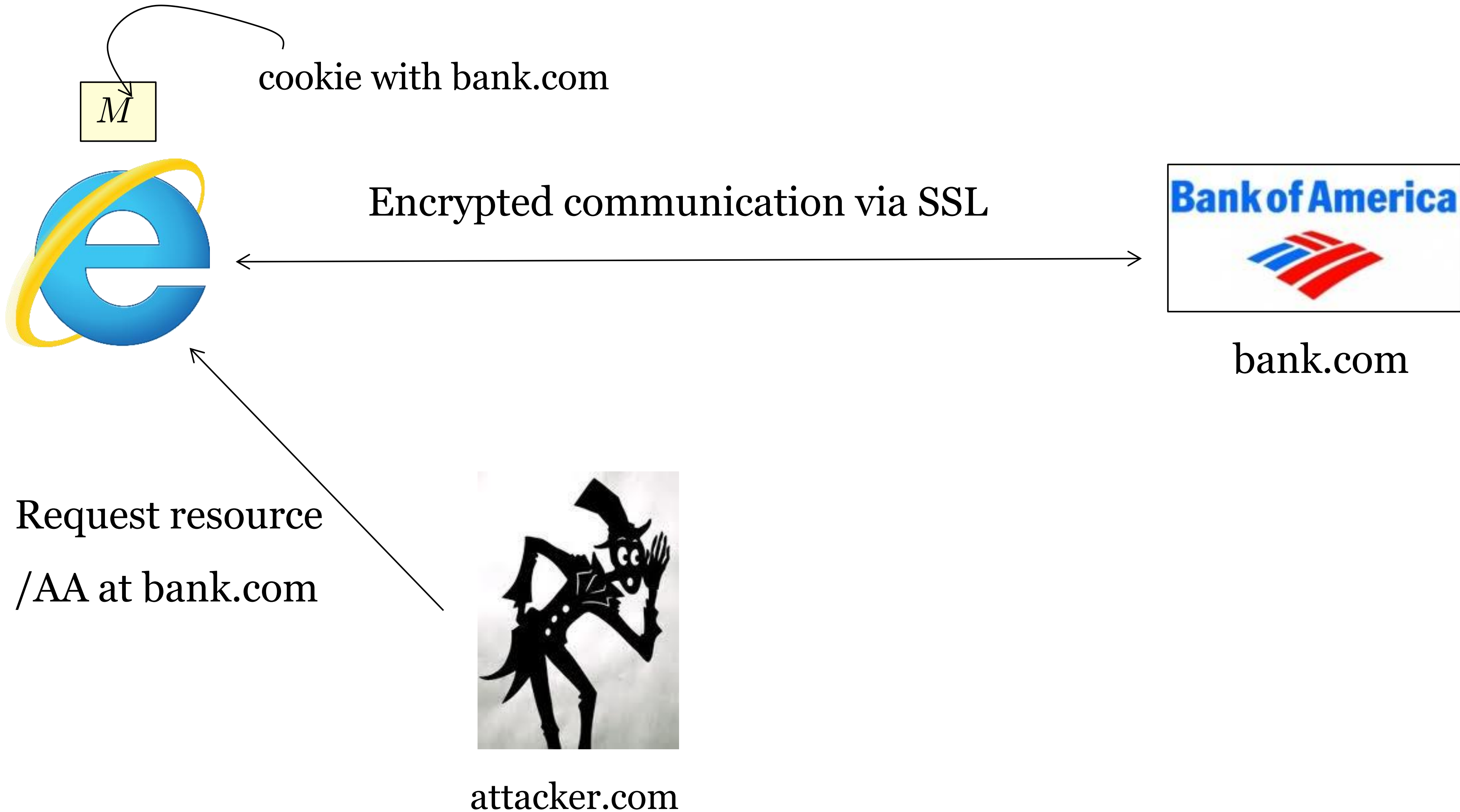


Goal: Recover M

This Model Is Realistic: Attacking SSL



This Model Is Realistic: Attacking SSL



This Model Is Realistic: Attacking SSL

M

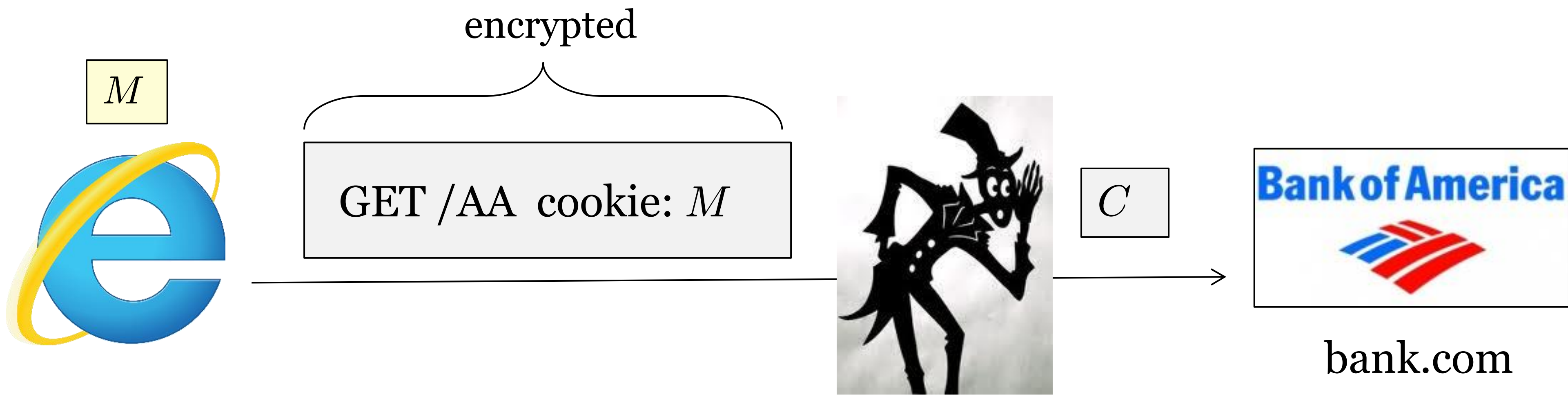
encrypted

GET /AA cookie: M

bank.com

attacker.com

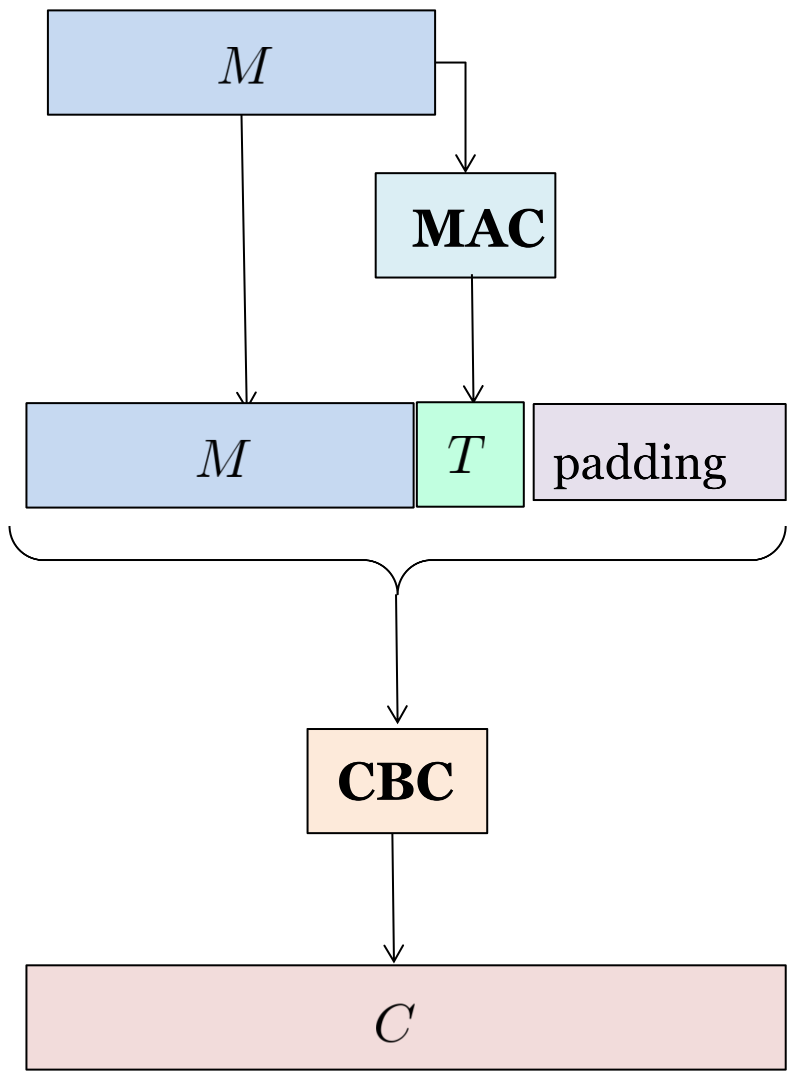
This Model Is Realistic: Attacking SSL



Enc oracle

Dec oracle

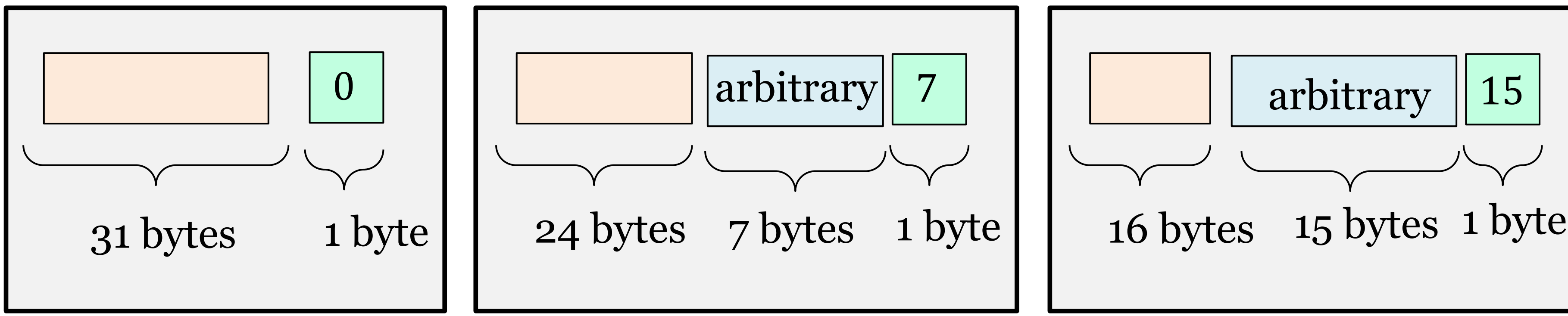
Encryption In SSL: MAC-then-Encrypt



Padding In SSL Encryption

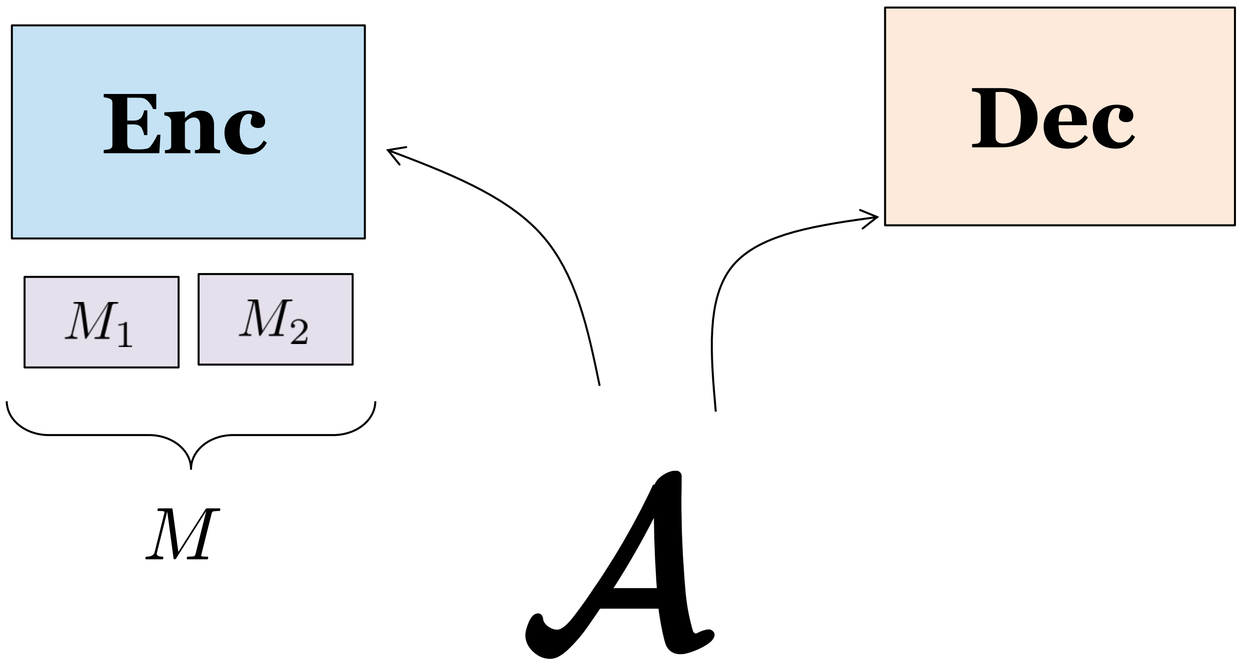
block length is 16 bytes

Consider byte strings only



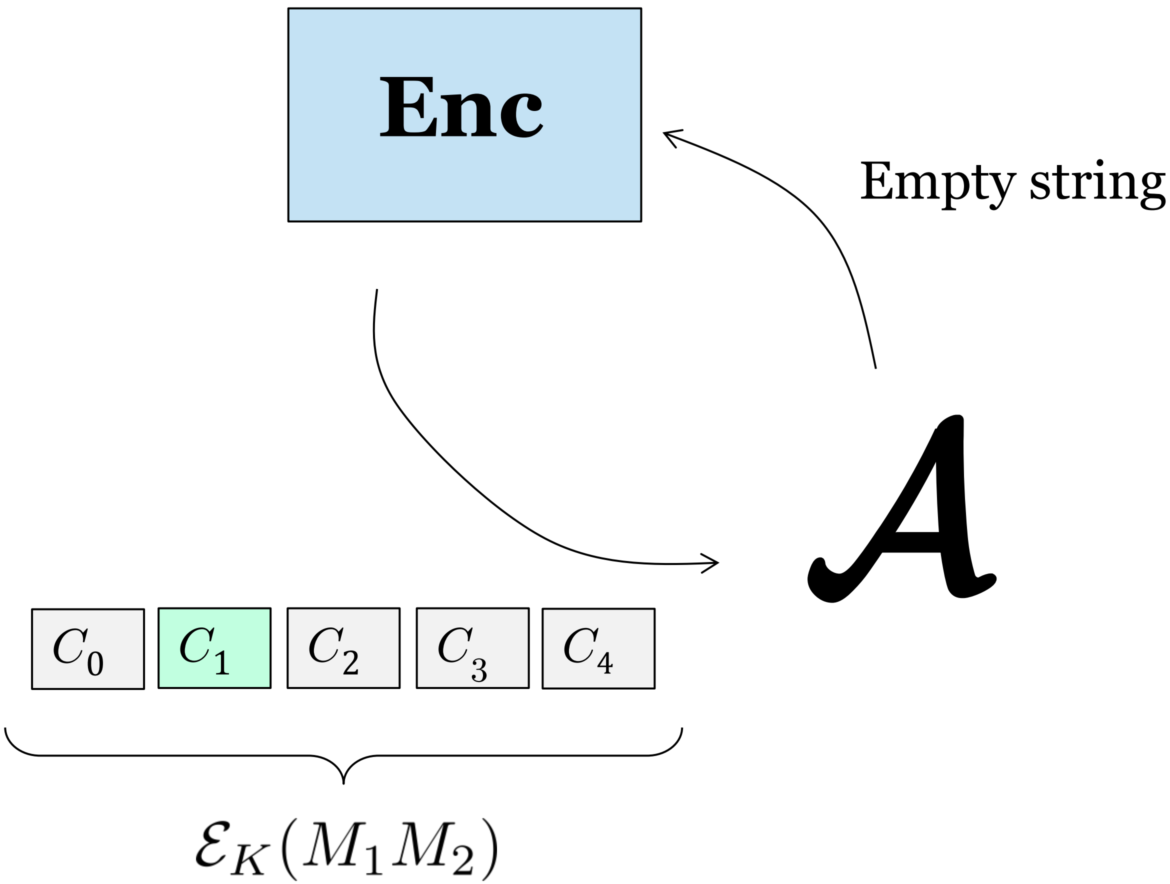
The Attack in Action

Illustration For Two-block Message

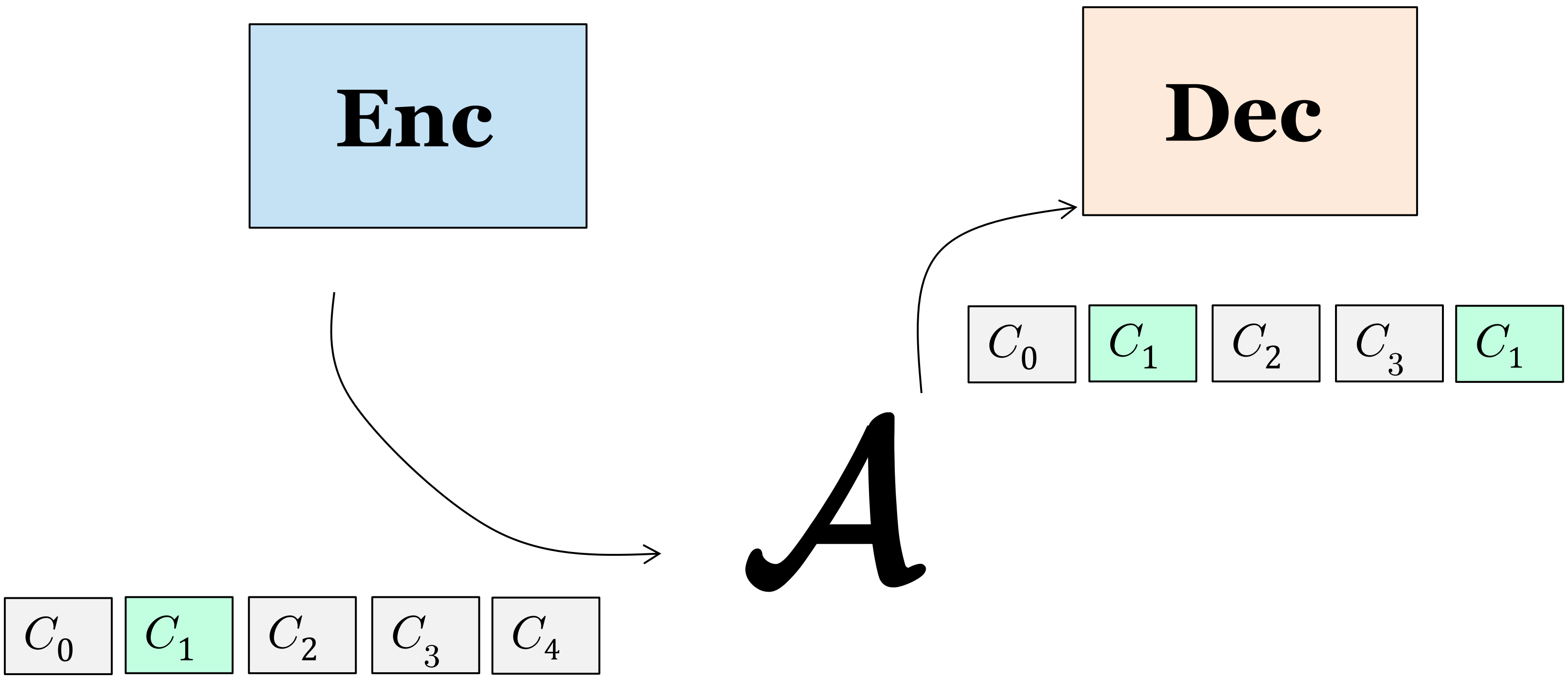


Aim: Recover the message byte by byte

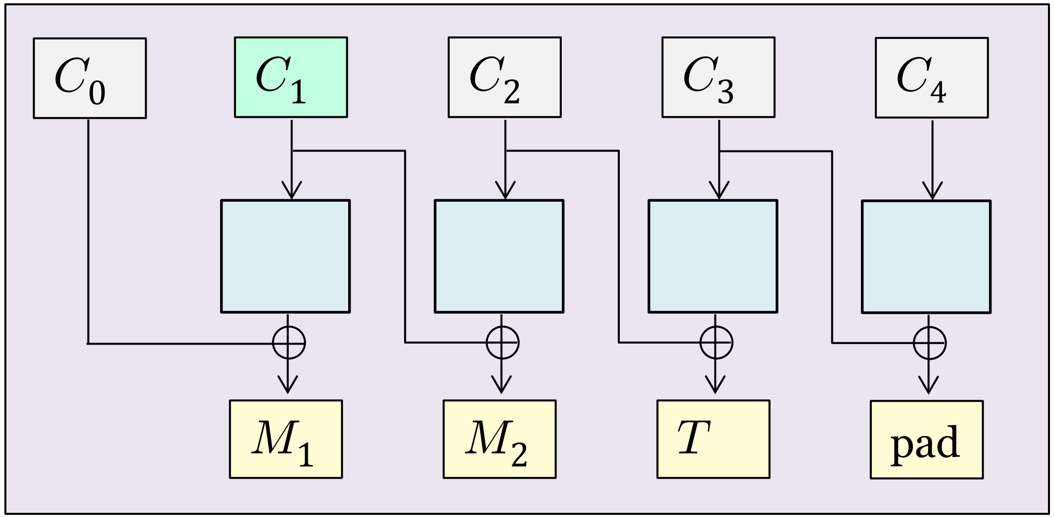
Recover Last Byte of First Block



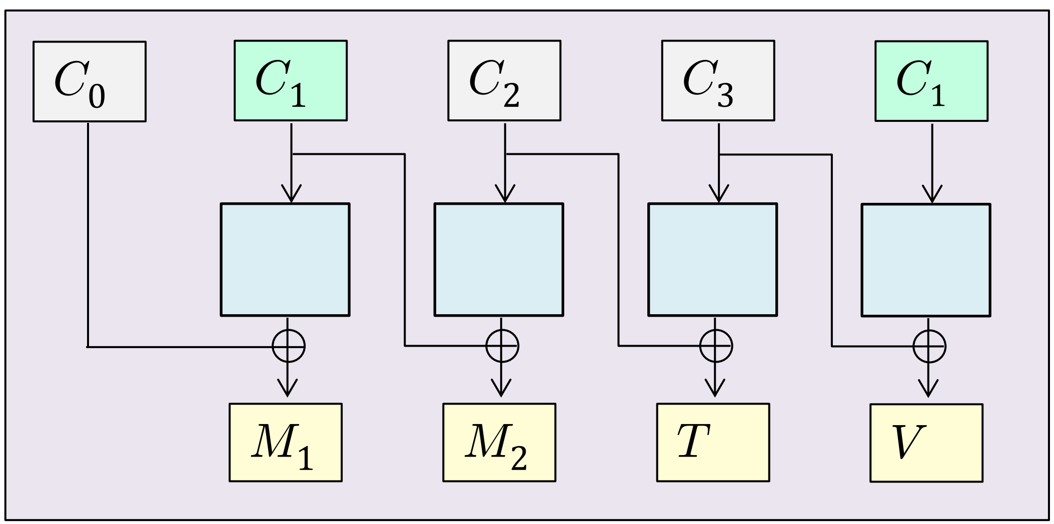
Recover Last Byte of First Block



CBC Decryption



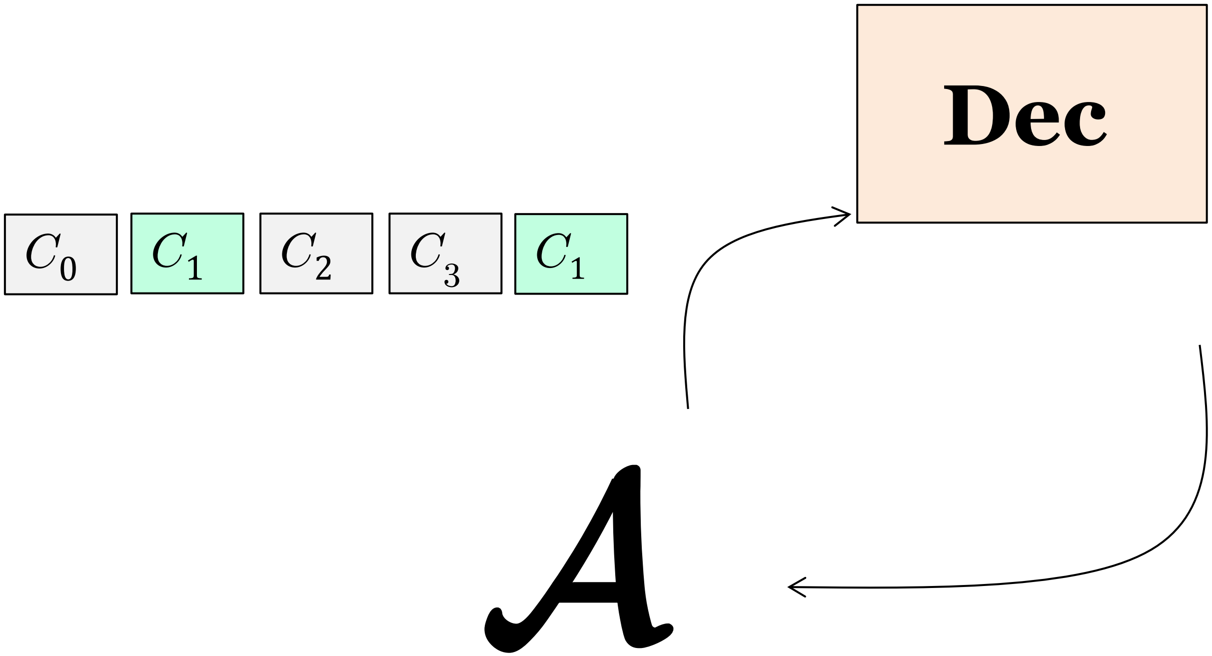
$$V = M_1 \oplus C_0 \oplus C_3$$



To pass MAC check, want the last byte of V to be 15

Pass with prob ~ 1/256

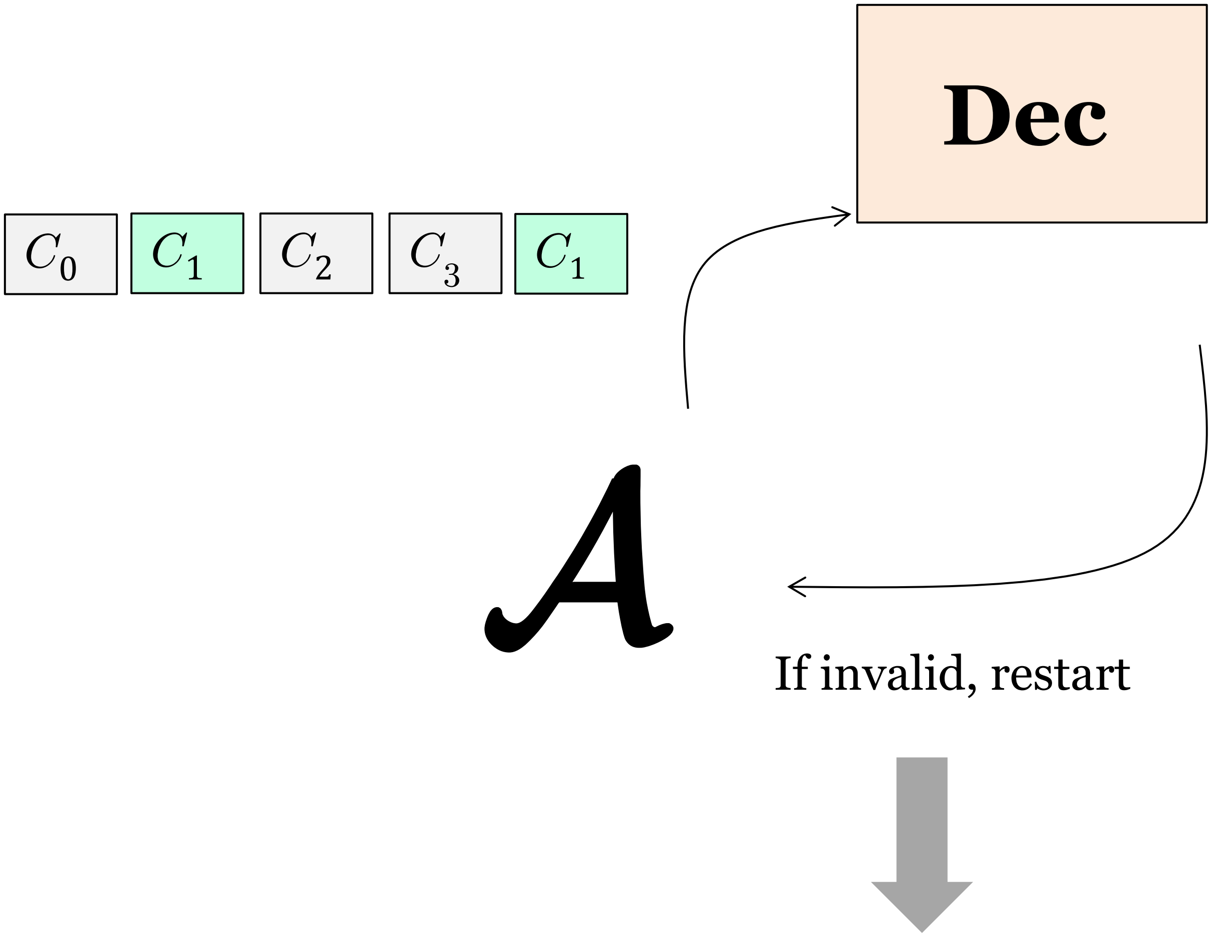
Exploit Decryption Output



If valid, last byte of $V = M_1 \oplus C_0 \oplus C_3$ is 15

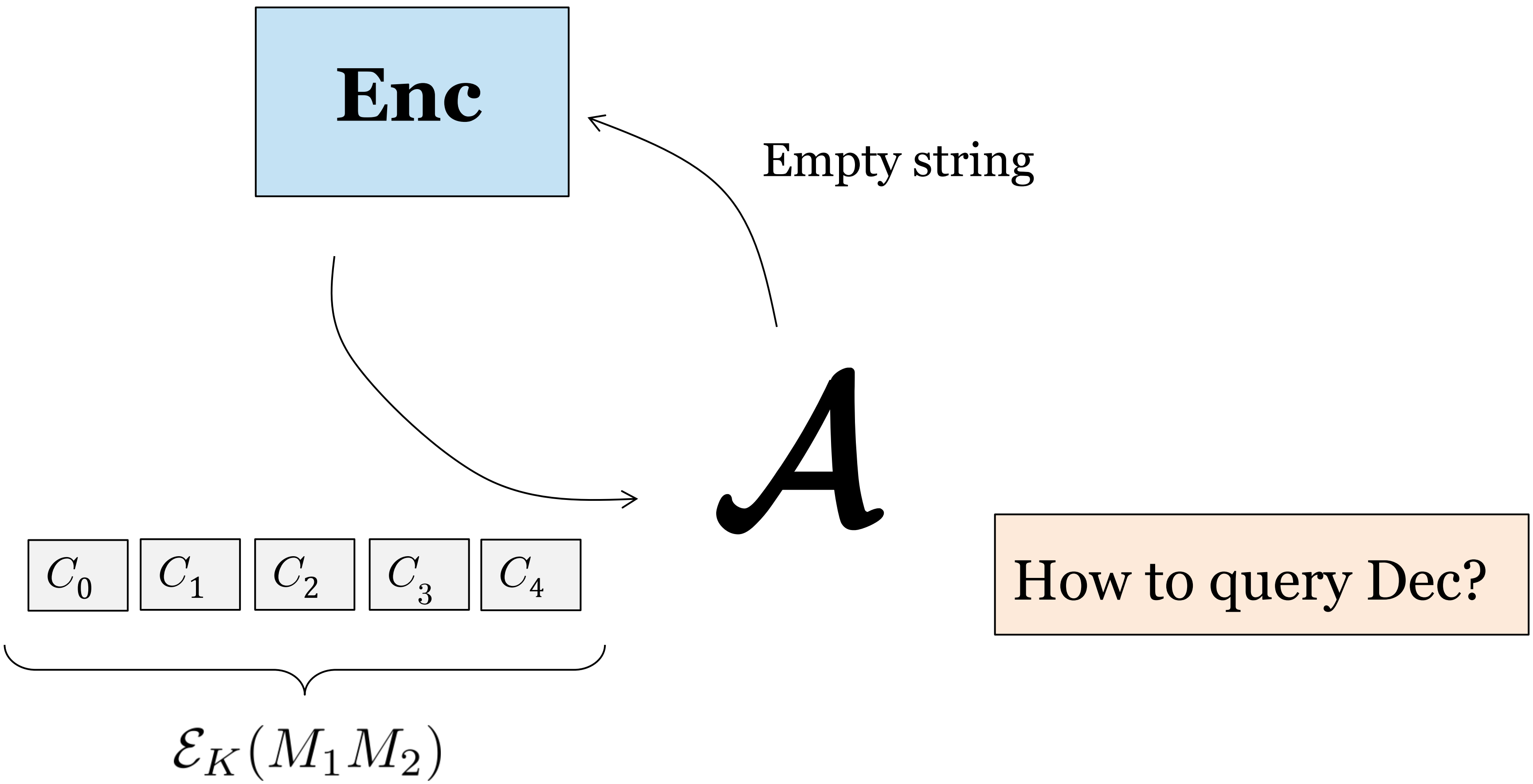
Learn last byte of M_1

Exploit Decryption Output

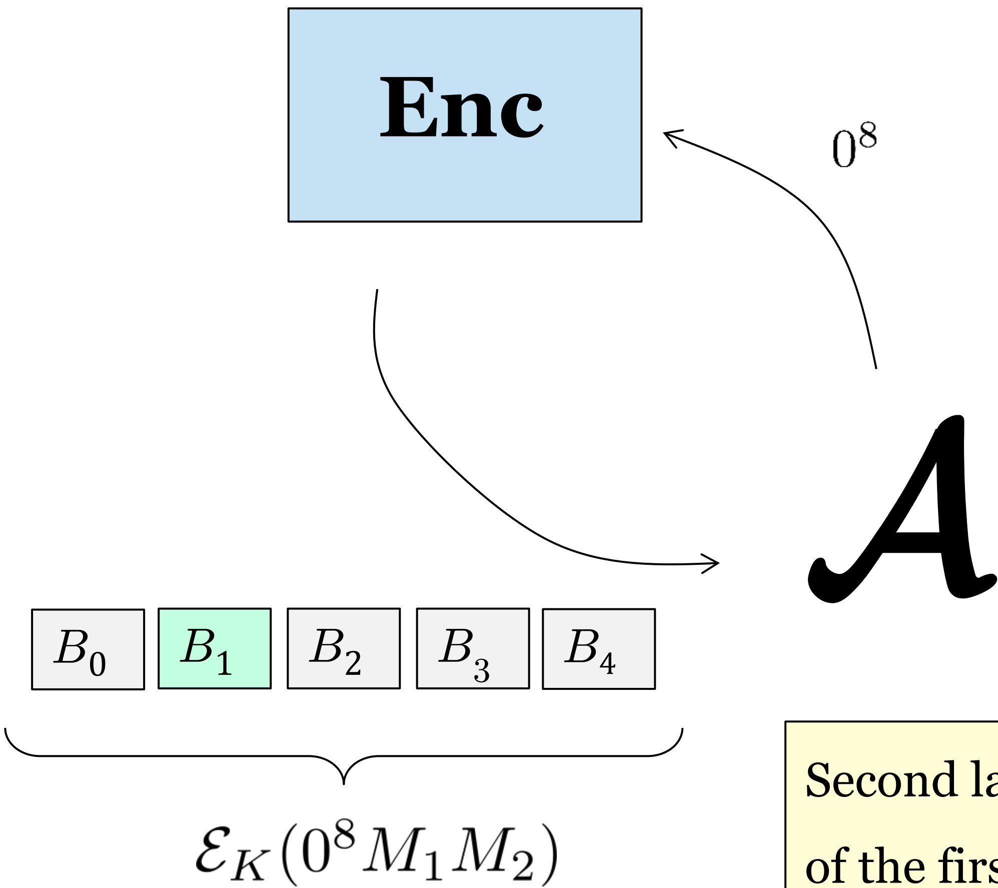


After t attempts, succeed with prob $\sim 1 - (1 - 1/256)^t$ times

Practice: Recover Last Byte of Second Block

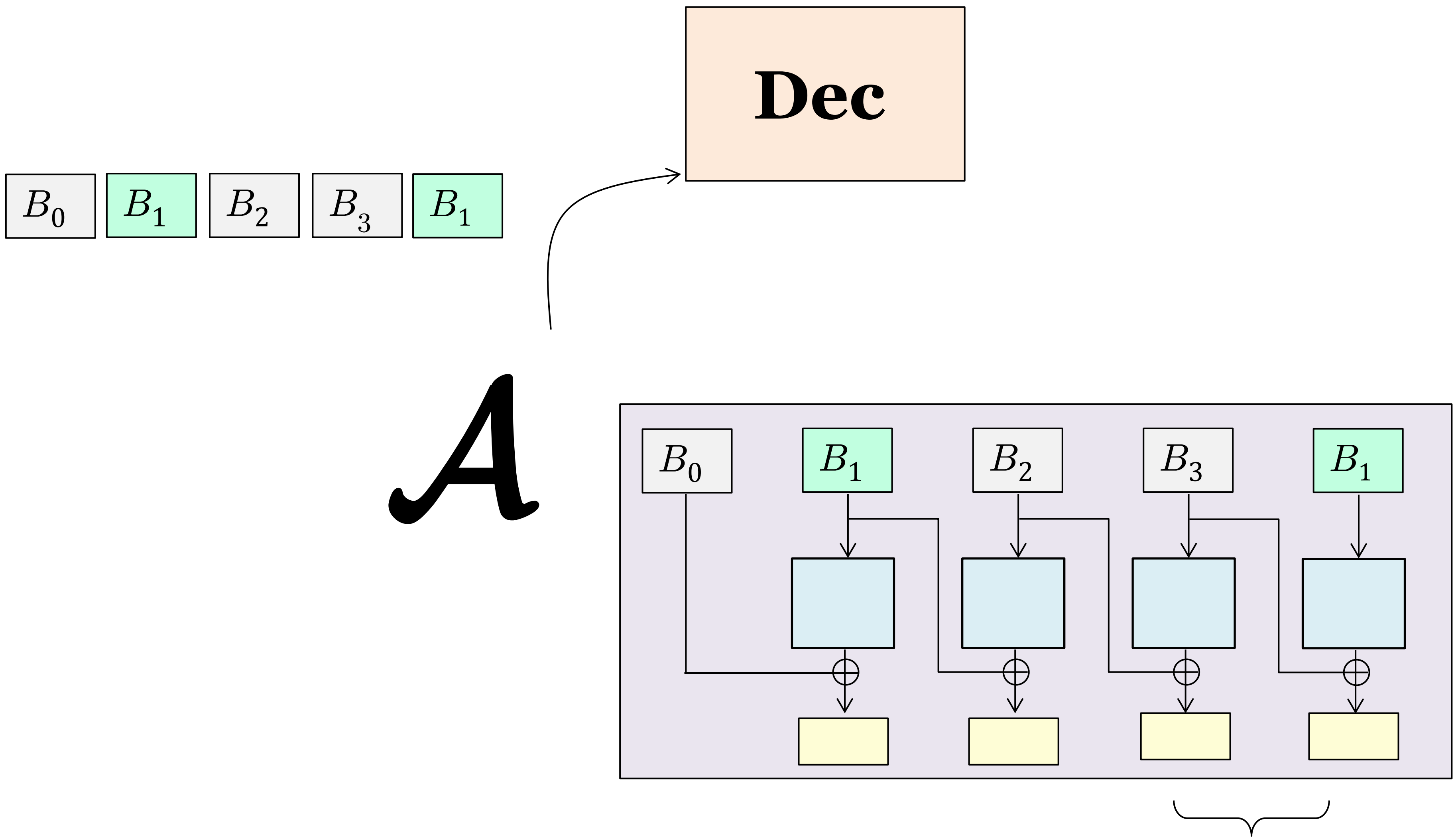


Recover Second Last Byte of First Block



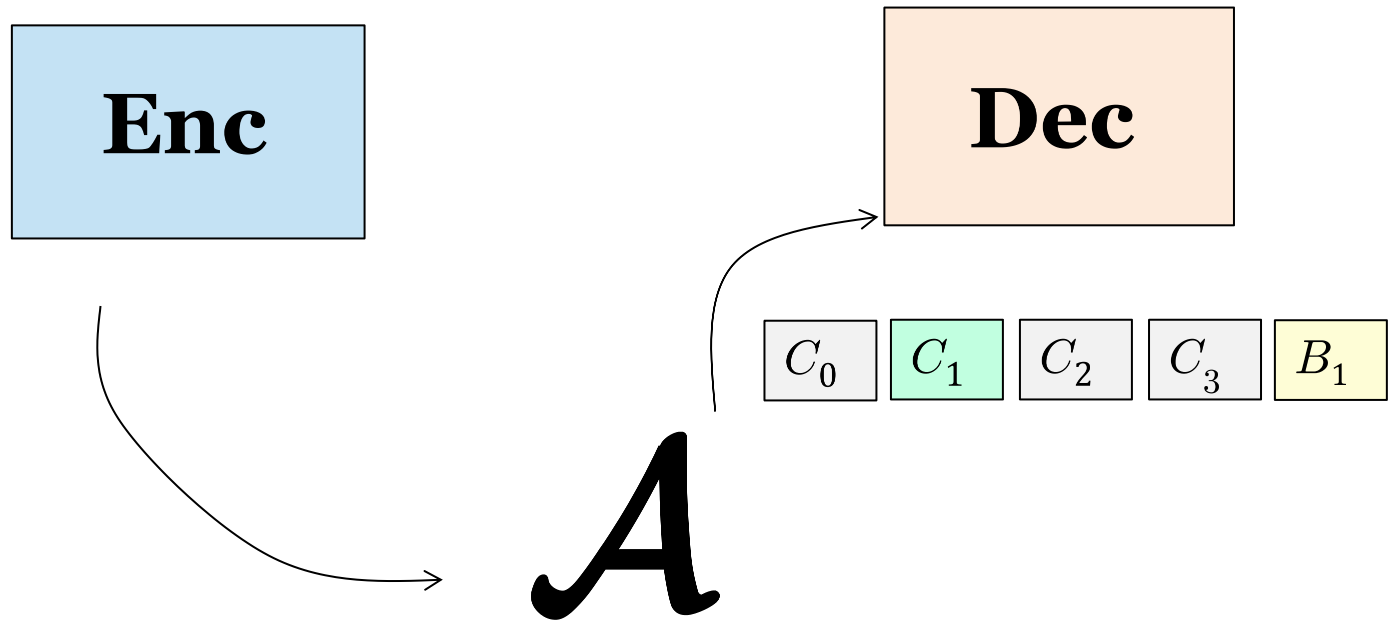
Second last byte of M_1 is now the **last byte** of the first block of $0^8 M_1 M_2$

Querying Dec: A Wrong Approach



This is the tag position, but the last byte is overwritten

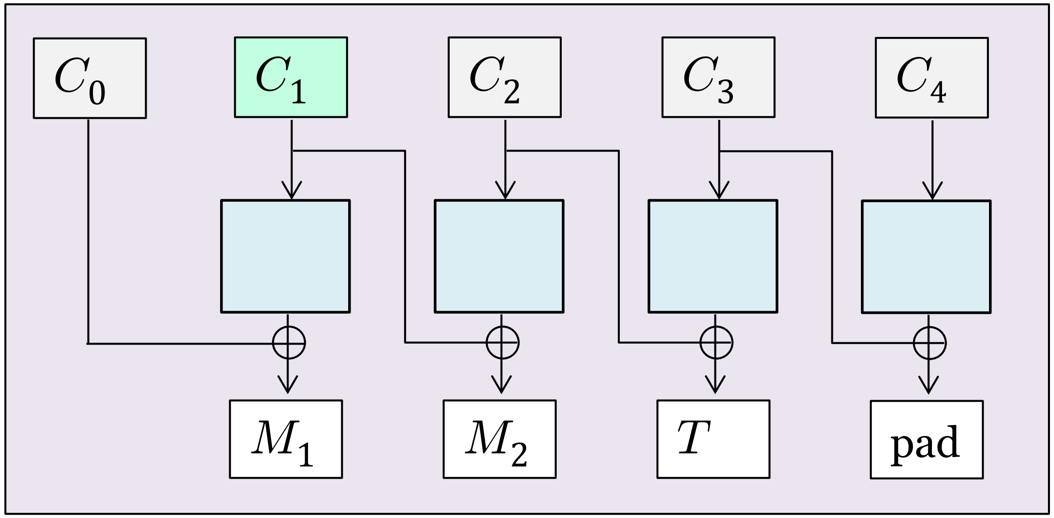
How To Query Dec

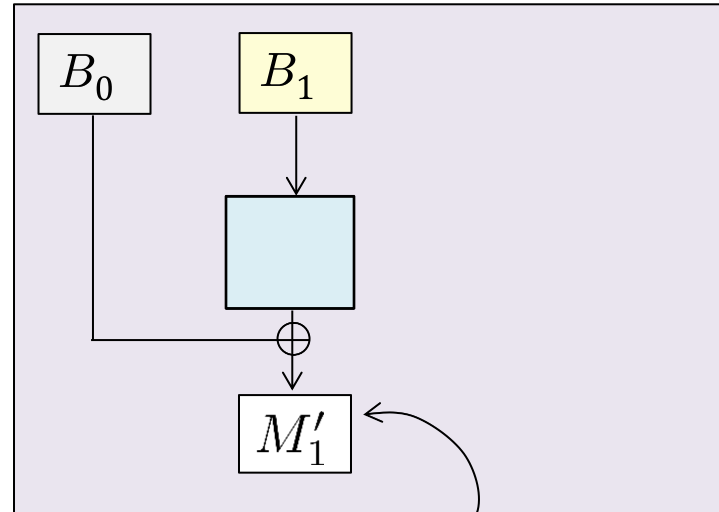


$$\mathcal{E}_K(M_1M_2) = \boxed{C_0}\,\boxed{C_1}\,\boxed{C_2}\,\boxed{C_3}\,\boxed{C_4}$$

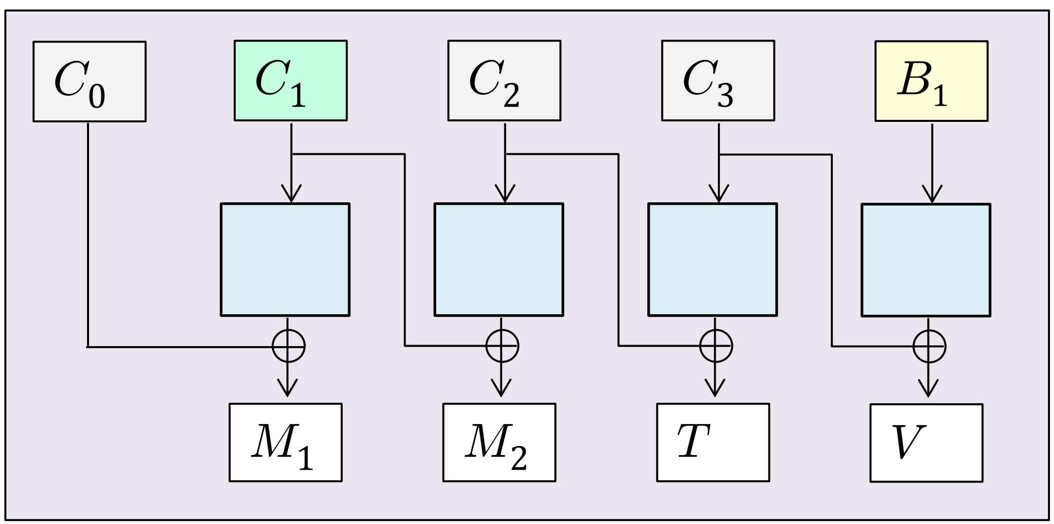
$$\mathcal{E}_K(0^8M_1M_2) = \boxed{B_0}\,\boxed{B_1}\,\boxed{B_2}\,\boxed{B_3}\,\boxed{B_4}$$

CBC Decryption





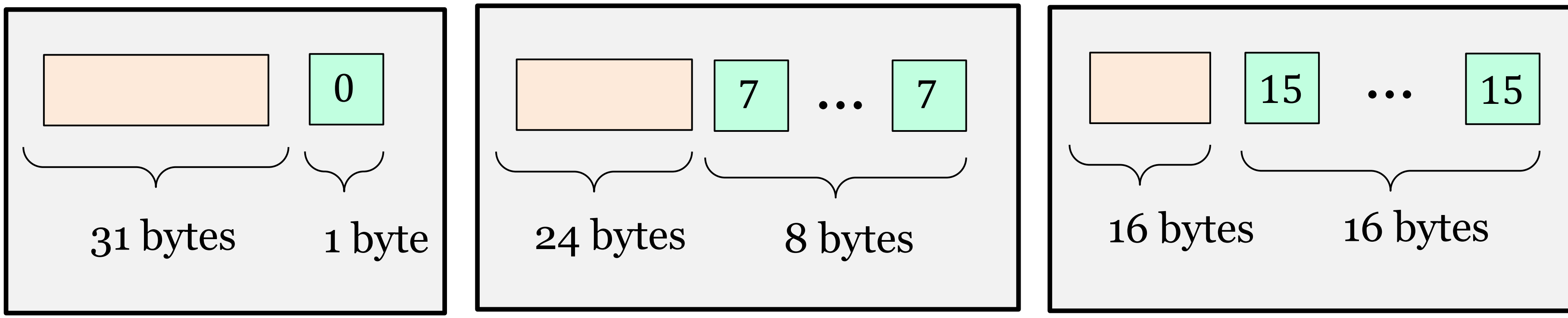
0^8 then 15 bytes of M_1



$$V = M_1' \oplus B_0 \oplus C_3$$

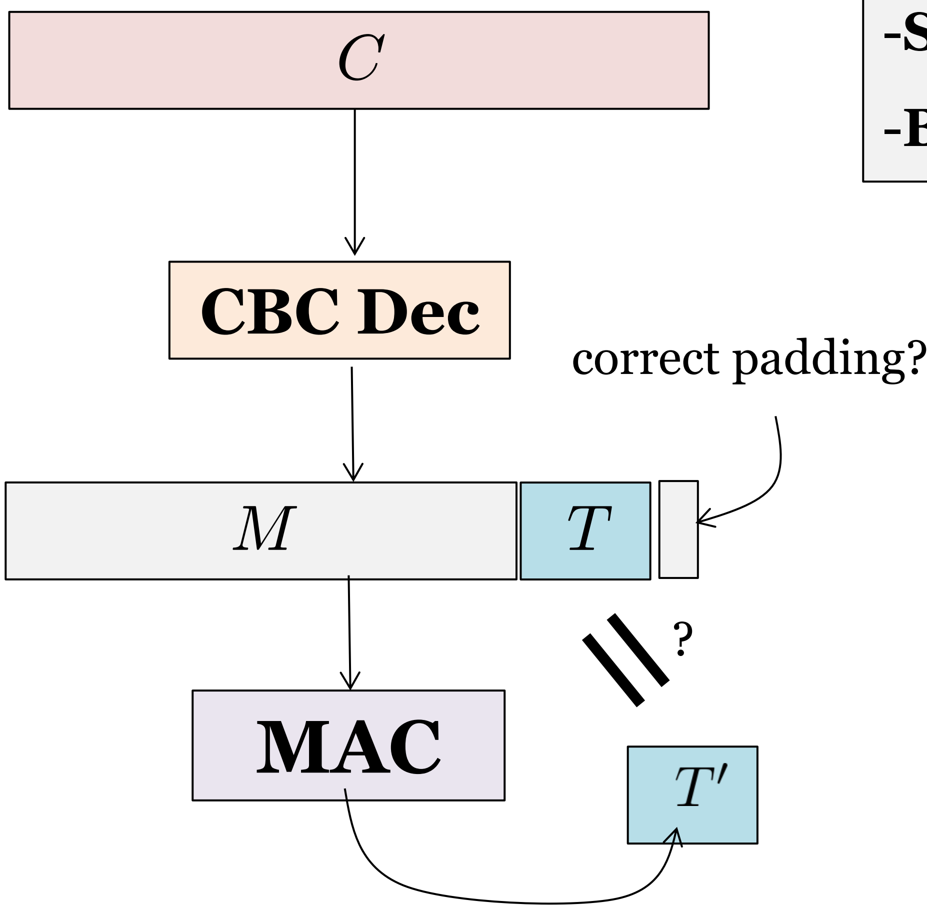
Learn last byte of M_1'

Patching Via Different Padding



Secure if implement properly

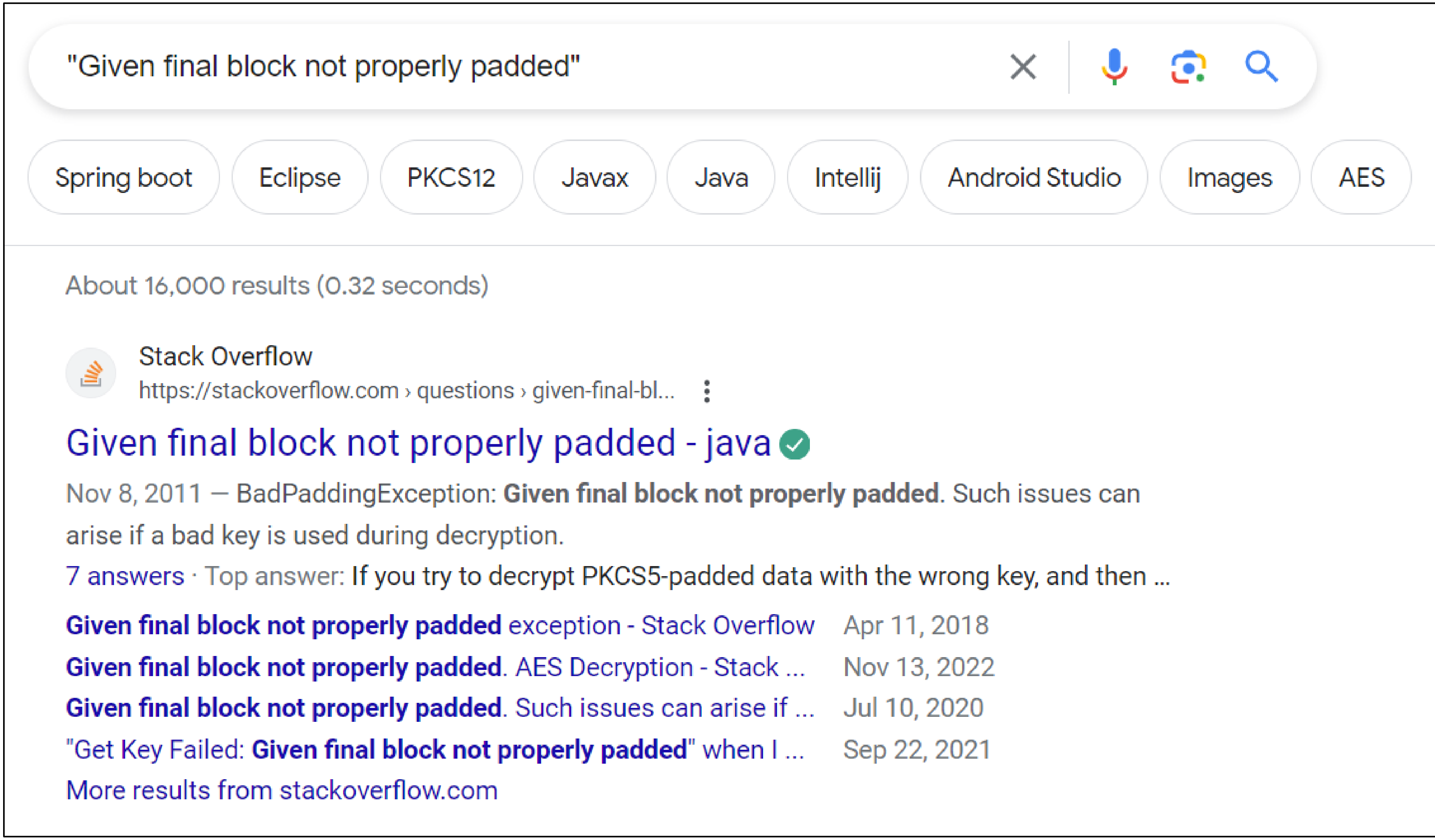
Careless Implementation Leads To Attack



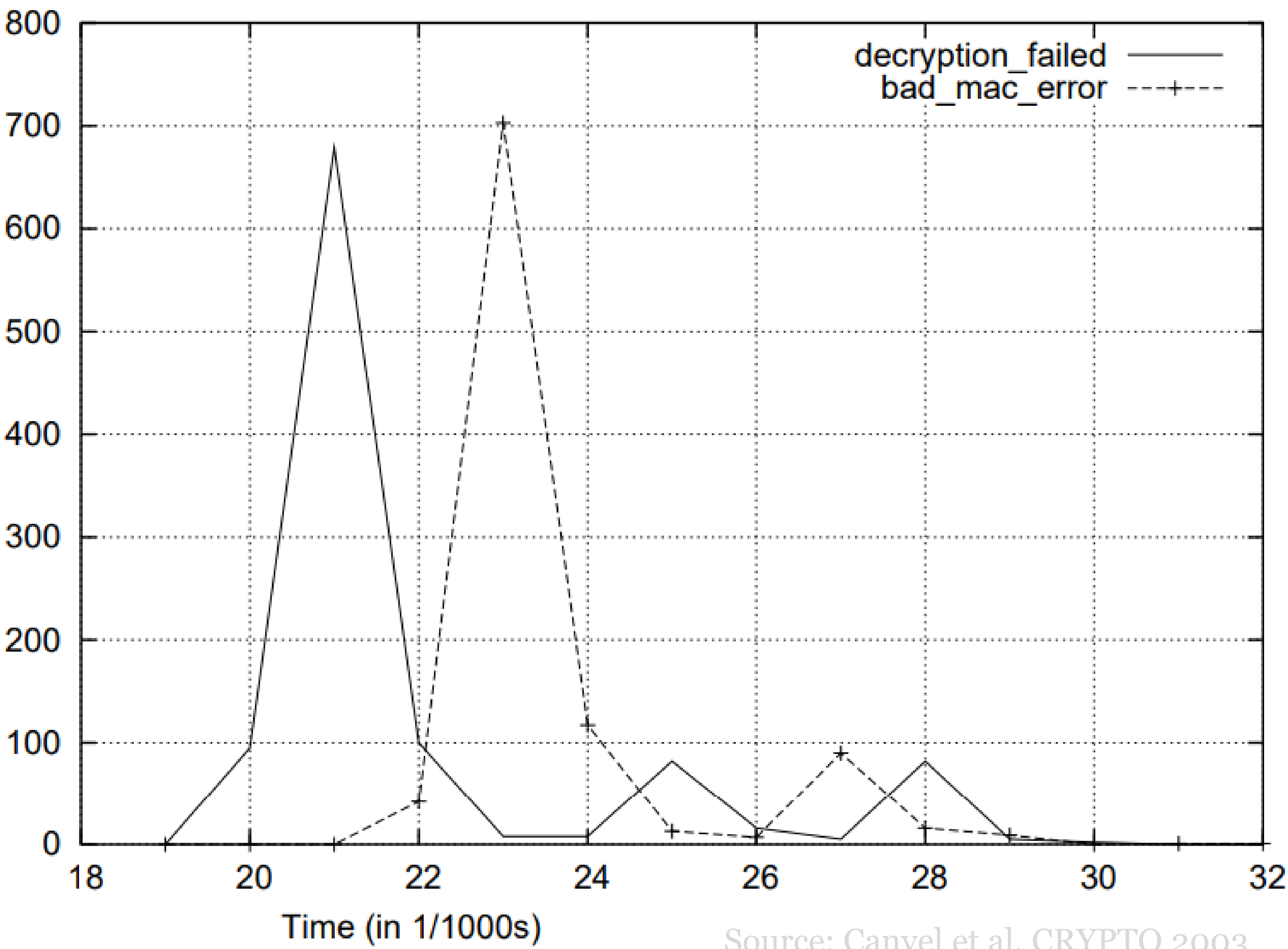
-**Secure** if return a single error signal

-**Broken** if tell what kind of error it is.

Scanning For Vulnerable Implementations

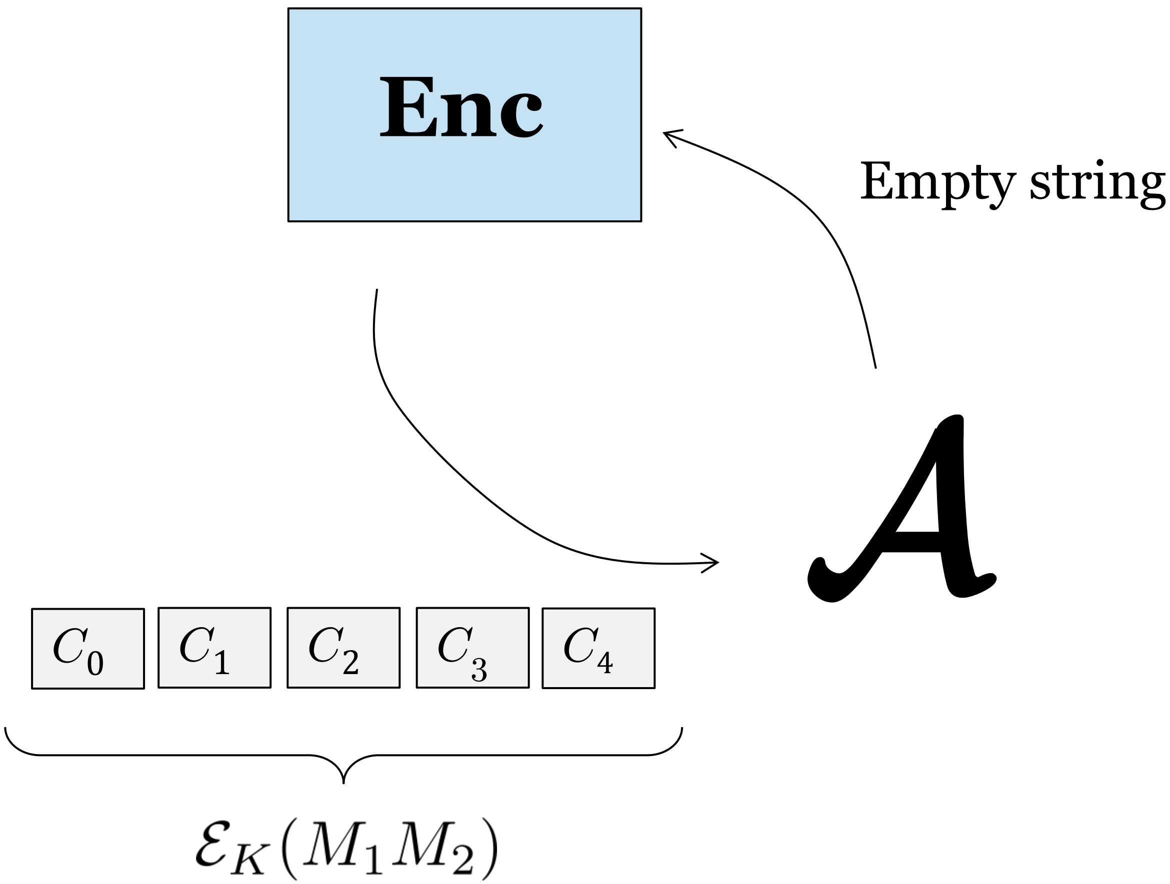


Implementation Is Hard: Timing Leakage

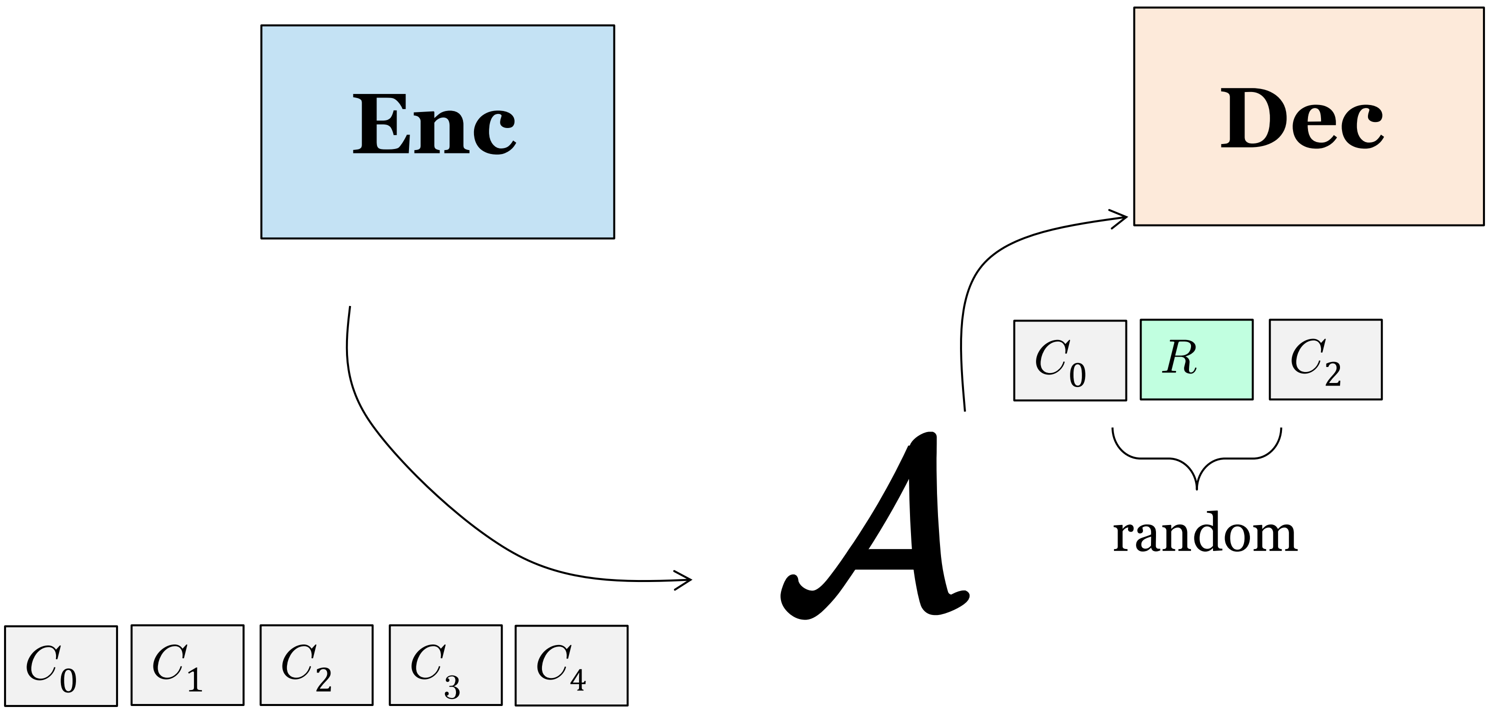


Source: Canvel et al, CRYPTO 2003

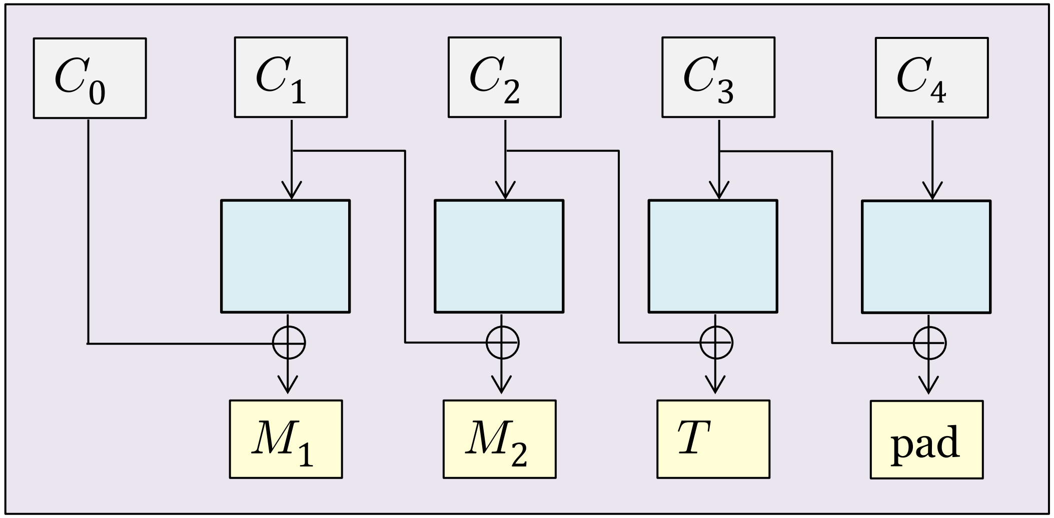
How To Attack
Illustration For Two-block Message



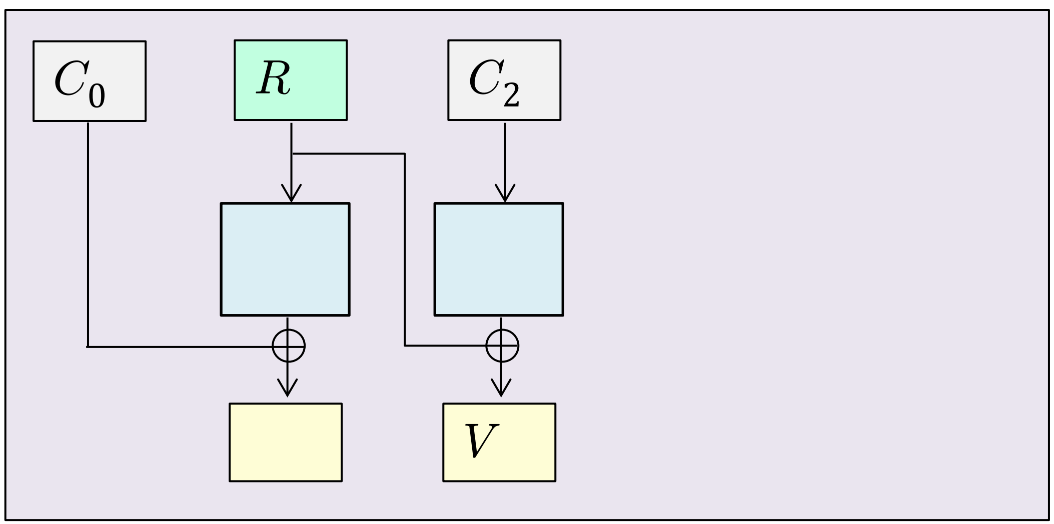
Recover Last Byte of Second Block



CBC Decryption



$$V = M_2 \oplus C_1 \oplus R$$



If V ends with a zero byte

Bad tag signal