Authenticated Encryption

Active attacks on CPA-secure encryption

Recap: the story so far

Confidentiality: semantic security against a CPA attack

- Encryption secure against **eavesdropping only**

Integrity:

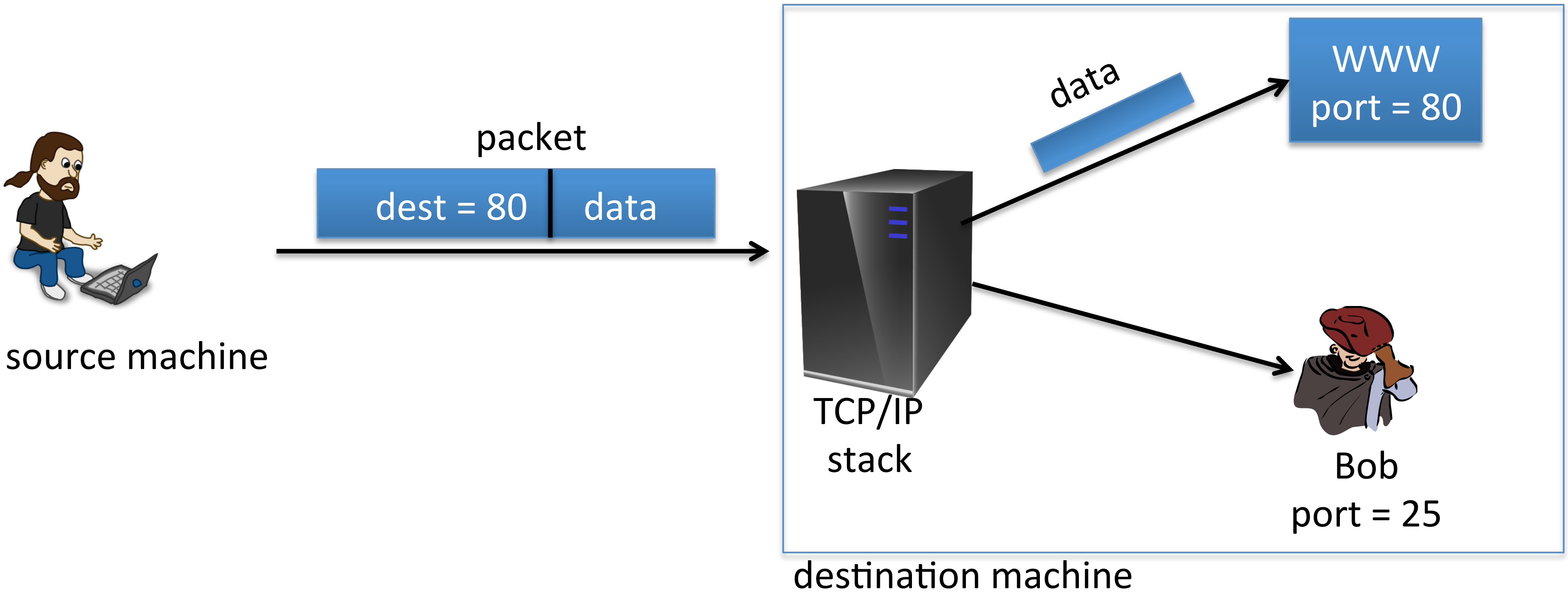
- Existential unforgeability under a chosen message attack
- CBC-MAC, HMAC, PMAC, CW-MAC

This module: encryption secure against **tampering** (active adversary)

- Ensuring both confidentiality and integrity

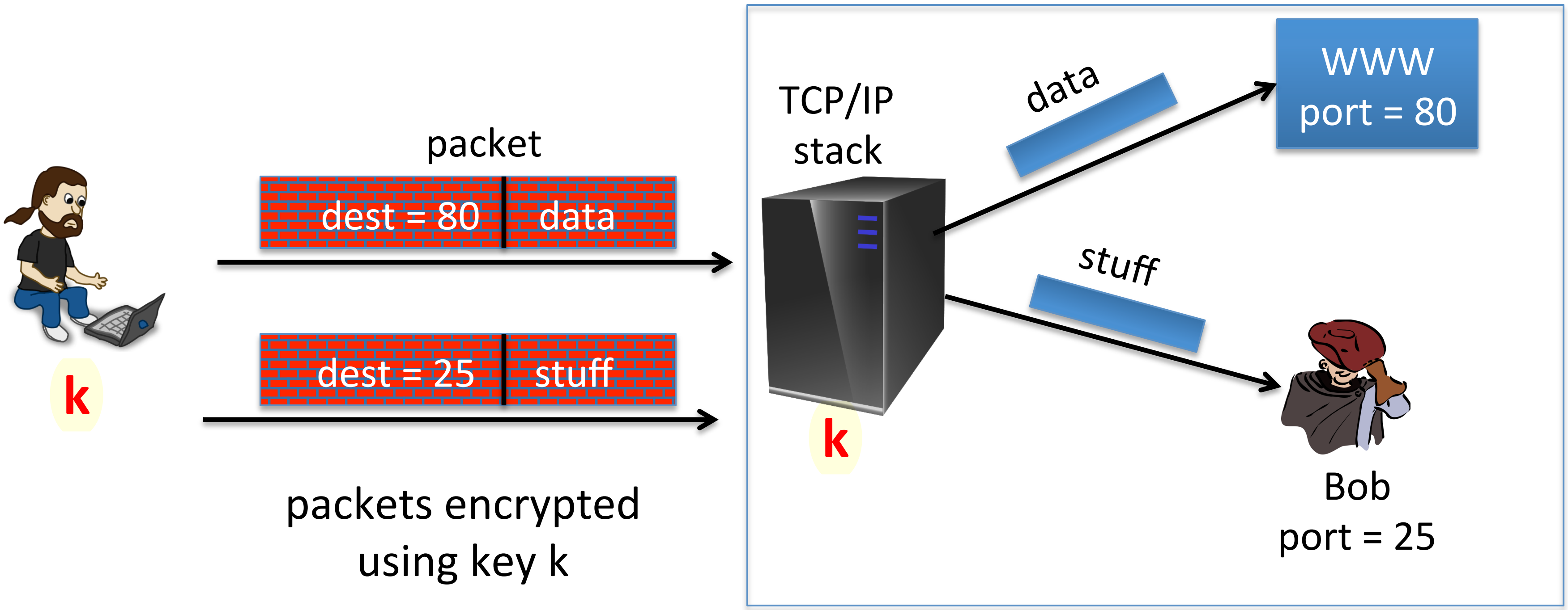
Sample tampering attacks

TCP/IP: (highly abstracted)



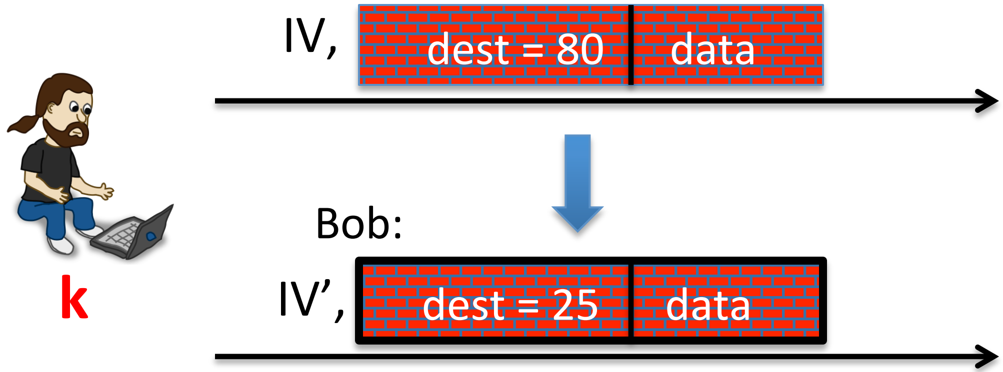
Sample tampering attacks

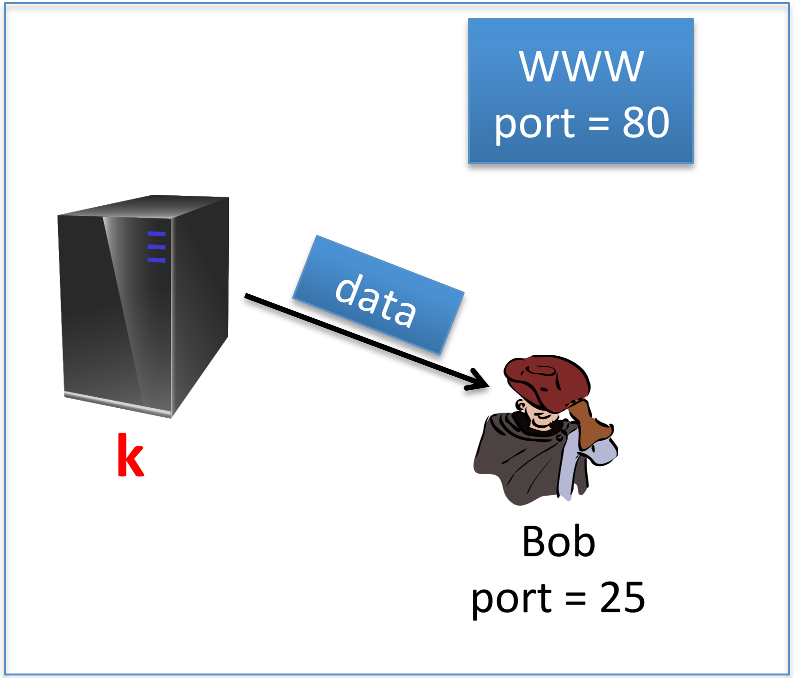
IPsec: (highly abstracted)



Reading someone else's data

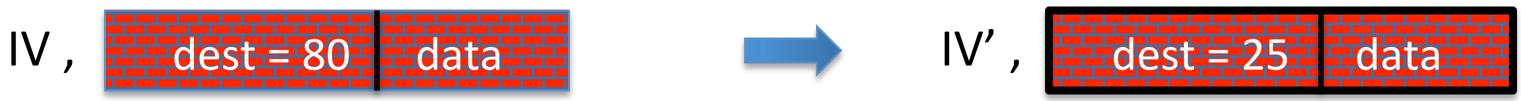
Note: attacker obtains decryption of any ciphertext
beginning with "dest=25"





Easy to do for CBC with rand. IV

(only IV is changed)



Encryption is done with CBC with a random IV.

What should IV' be?

$m[0] = D(k, c[0]) \oplus IV$ = "dest=80…"

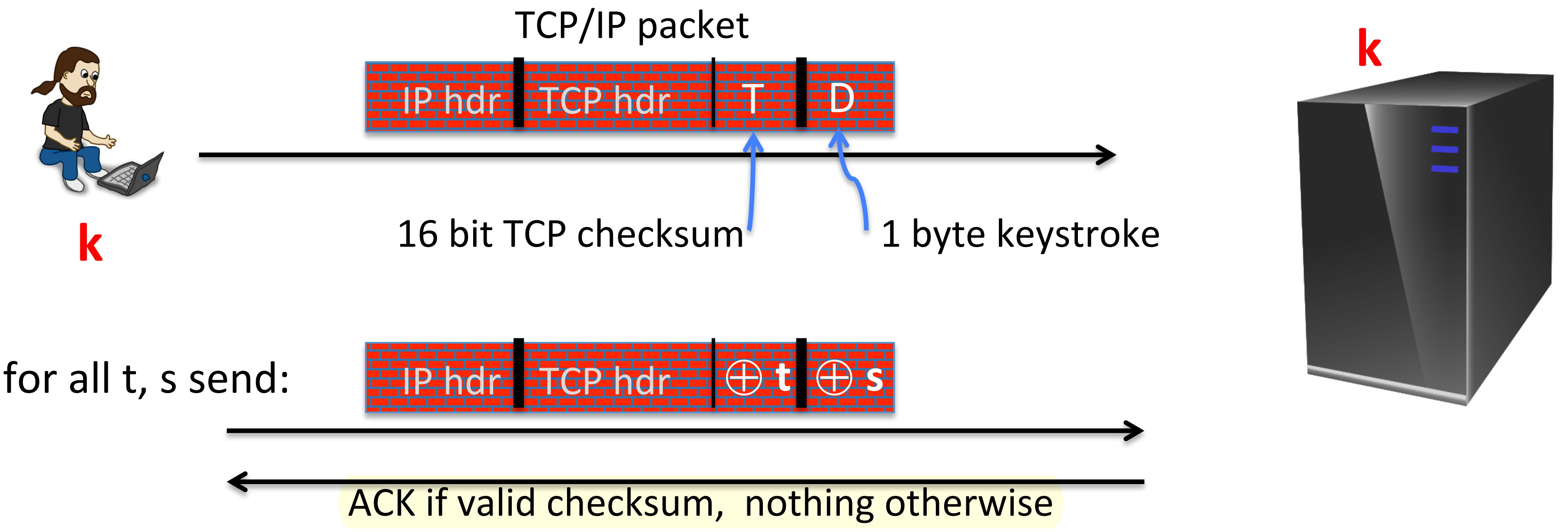
- IV' = IV $\oplus$ (…25…)
- IV' = IV $\oplus$ (…80…)
- IV' = IV $\oplus$ (…80…) $\oplus$ (…25…)
- It can't be done

$$D(k, c[0]) \oplus IV' = \overbrace{D(k, c[0]) \oplus IV}^{\cancel{\ldots 80 \ldots}} \oplus \cancel{80} \oplus 25$$

$$= \ldots 25 \ldots$$

An attack using only network access

Remote terminal app.: each keystroke encrypted with CTR mode



$\{ \ \text{checksum(hdr, D)} = t \oplus \text{checksum(hdr, } D\oplus s) \ \} \Rightarrow$ can find D

The lesson

CPA security cannot guarantee secrecy under active attacks.

Only use one of two modes:

- If message needs integrity but no confidentiality:
  use a **MAC**

- If message needs both integrity and confidentiality:
  use **authenticated encryption** modes (this module)

End of Segment

Authenticated Encryption

Definitions

Goals

An **authenticated encryption** system (E,D) is a cipher where

As usual: $E: K \times M \times N \longrightarrow C$

but $D: K \times C \times N \longrightarrow M \cup \{\perp\}$

ciphertext is rejected

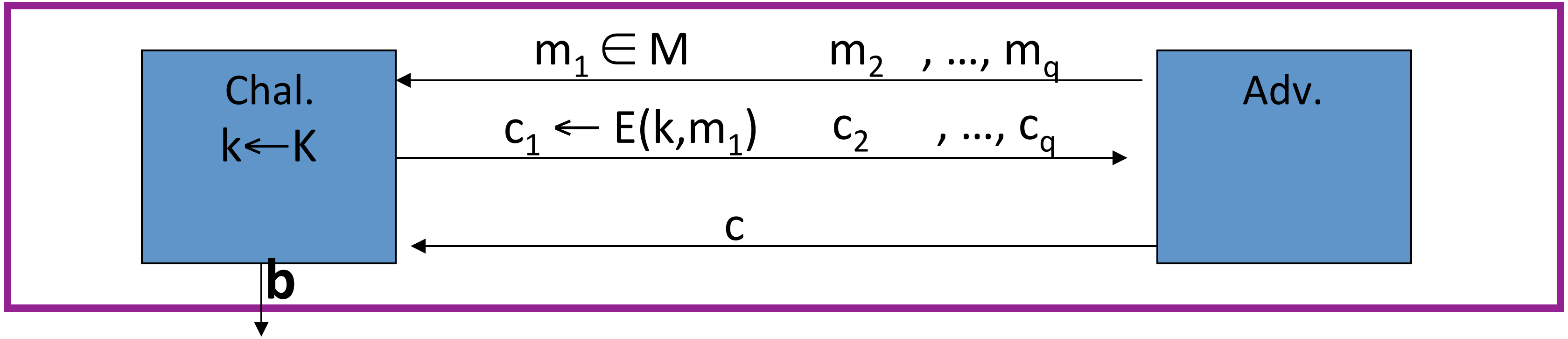
Security: the system must provide

- sem. security under a CPA attack, and
- **ciphertext integrity:**

  attacker cannot create new ciphertexts that decrypt properly

Ciphertext integrity

Let (E,D) be a cipher with message space M.



$$
\begin{cases} \mathbf{b}=1 & \text{if } D(k,c) \neq \perp \text{ and } c \notin \{c_1, \dots, c_q\} \\ \mathbf{b}=0 & \text{otherwise} \end{cases}
$$

Def: (E,D) has **<u>ciphertext integrity</u>** if for all "efficient" A:

$\mathrm{Adv_{CI}}[A,E] = \Pr[\text{Chal. outputs } 1]$ is "negligible."

Authenticated encryption

Def: cipher (E,D) provides **authenticated encryption (AE)** if it is

(1) semantically secure under CPA, and

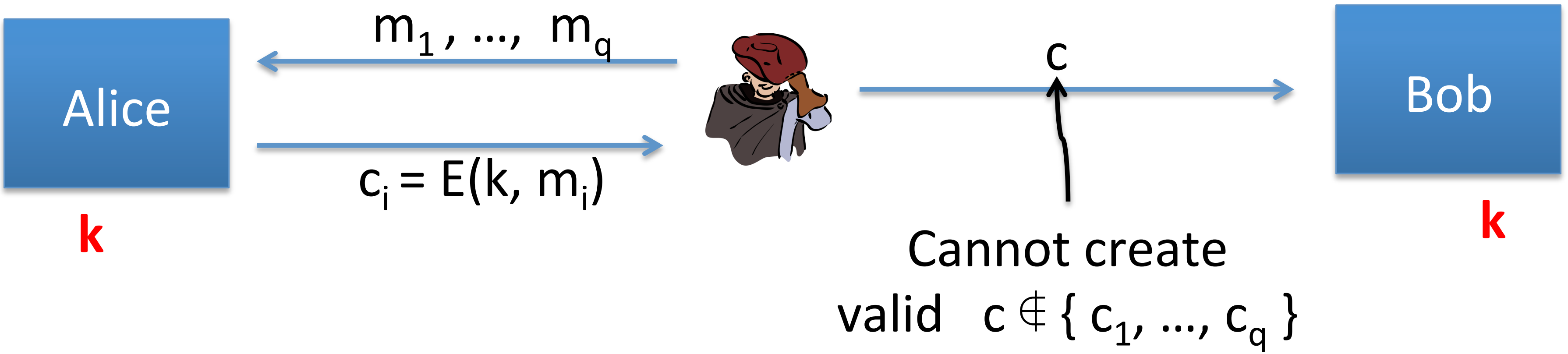
(2) has ciphertext integrity

Bad example: CBC with rand. IV does not provide AE

- $D(k,\cdot)$ never outputs $\perp$, hence adv. easily wins CI game

Implication 1: authenticity

Attacker cannot fool Bob into thinking a message was sent from Alice



$\Rightarrow$ if $D(k,c) \neq \perp$ Bob knows message is from someone who knows k
(but message could be a replay)

Implication 2

Authenticated encryption $\Rightarrow$

Security against **chosen ciphertext attacks**

(next segment)

End of Segment

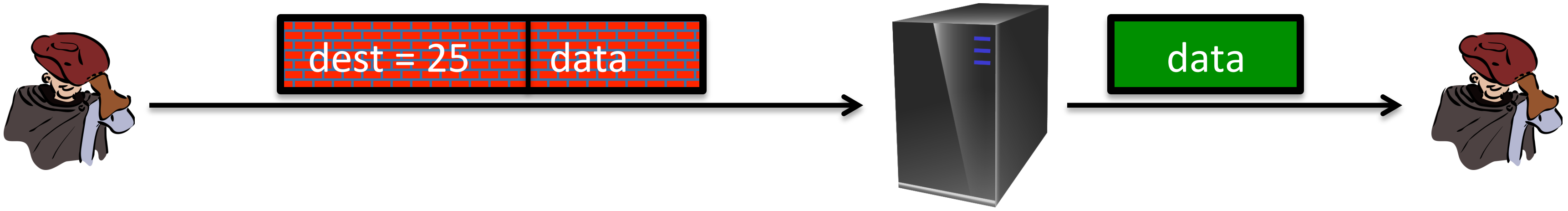
Authenticated Encryption

Chosen ciphertext attacks

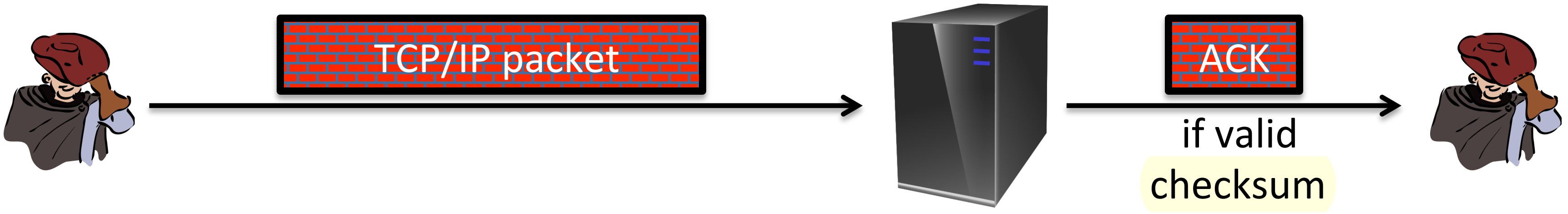
Example chosen ciphertext attacks

Adversary has ciphertext c that it wants to decrypt

- Often, adv. can fool server into decrypting **certain** ciphertexts (not c)



- Often, adversary can learn partial information about plaintext



Chosen ciphertext security

Adversary's power: both CPA and CCA

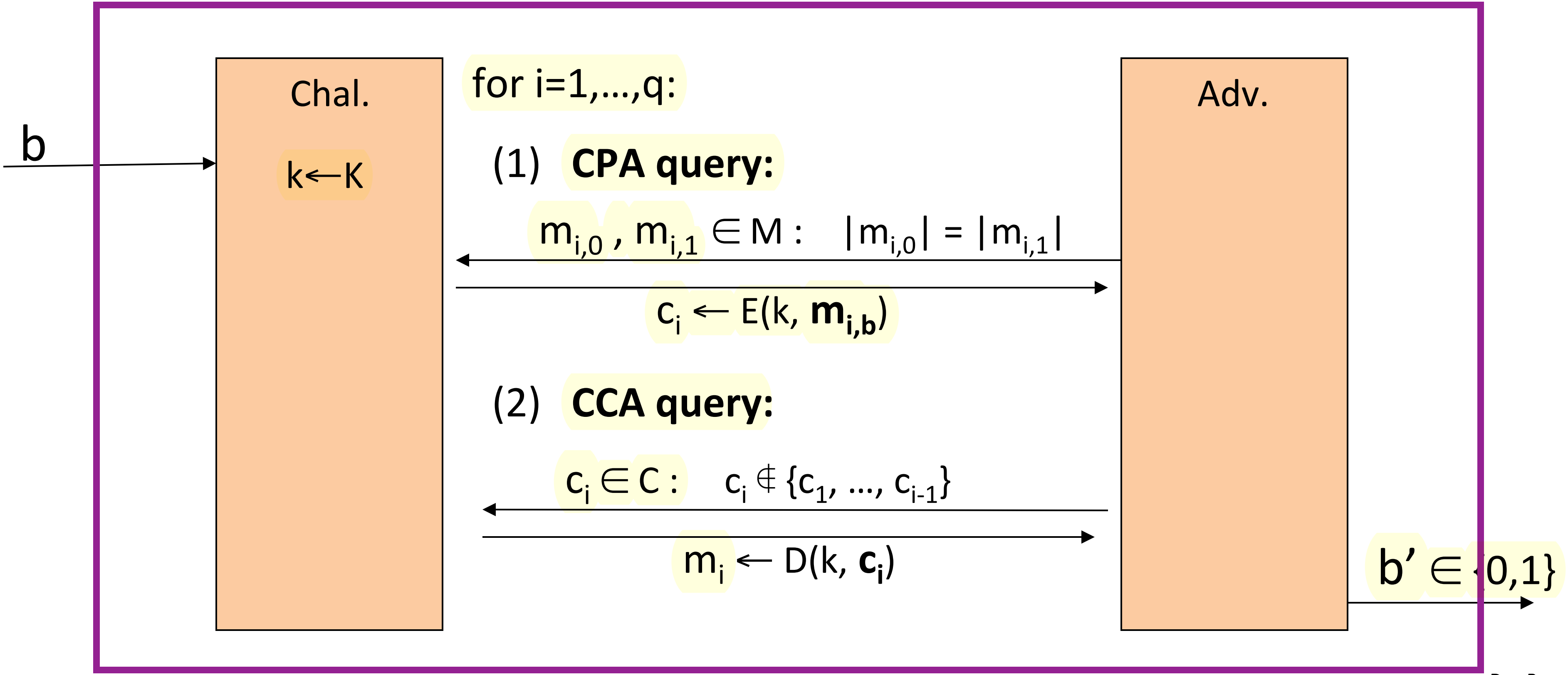
- Can obtain the encryption of arbitrary messages of his choice
- Can decrypt any ciphertext of his choice, other than challenge

(conservative modeling of real life)

Adversary's goal: Break sematic security

Chosen ciphertext security: definition

$\mathbb{E} = (E,D)$ cipher defined over (K,M,C). For $b=0,1$ define EXP(b):

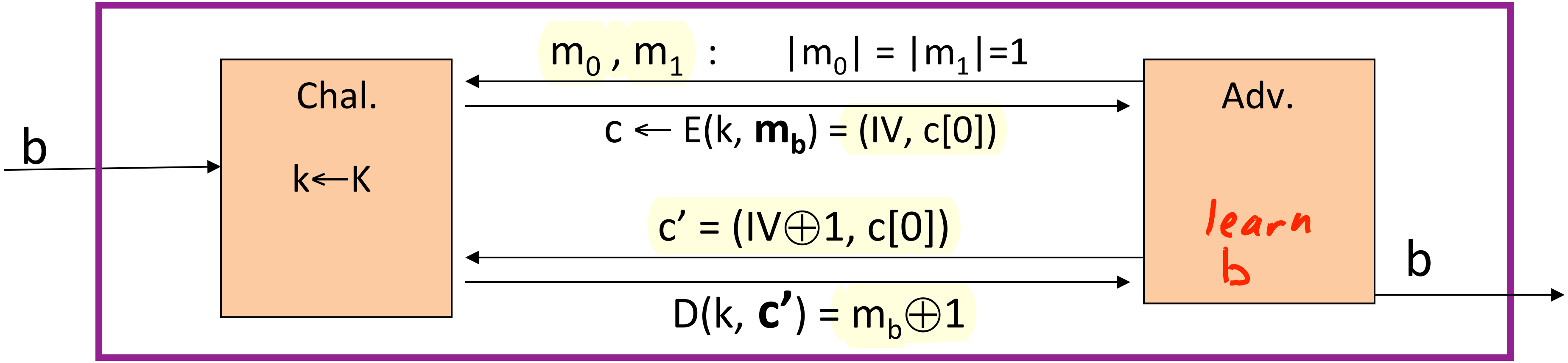


Chosen ciphertext security: definition

E is CCA secure if for all "efficient" A:

$$\text{Adv}_{\text{CCA}}[A,E] = \left| \Pr[\text{EXP}(0)=1] - \Pr[\text{EXP}(1)=1] \right| \text{ is "negligible."}$$

Example: CBC with rand. IV is not CCA-secure



Authenticated enc. ⇒ CCA security

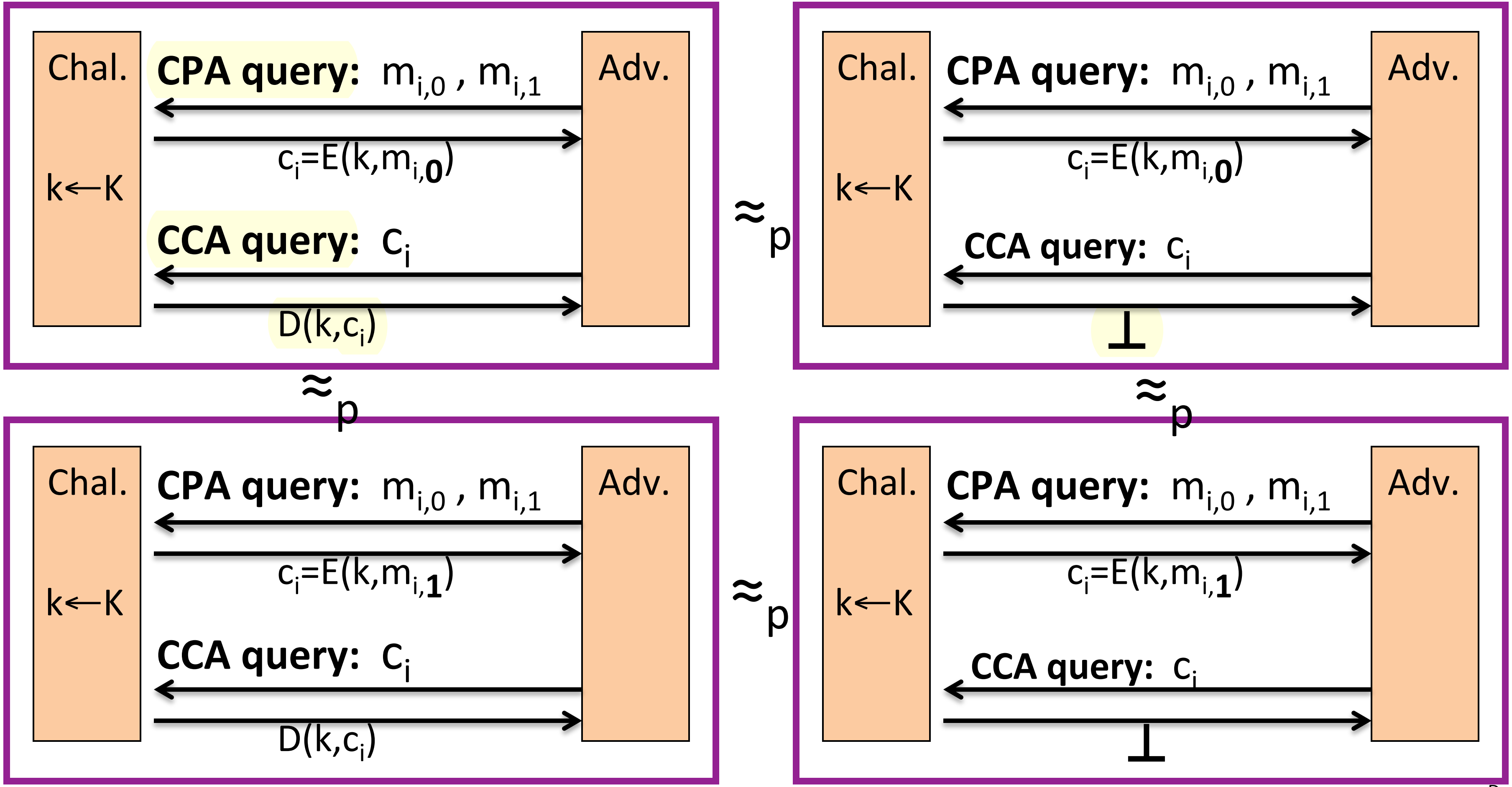
<u>Thm</u>: Let (E,D) be a cipher that provides AE.

Then (E,D) is CCA secure !

In particular, for any q-query eff. A there exist eff. B_1, B_2 s.t.

$$\text{Adv}_{\text{CCA}}[A,E] \le 2q \cdot \text{Adv}_{\text{CI}}[B_1,E] + \text{Adv}_{\text{CPA}}[B_2,E]$$

Proof by pictures



So what?

Authenticated encryption:

- ensures confidentiality against an active adversary that can decrypt some ciphertexts

Limitations:

- does not prevent replay attacks
- does not account for side channels (timing)

End of Segment

Authenticated Encryption

Constructions from ciphers and MACs

… but first, some history

Authenticated Encryption (AE): introduced in 2000 [KY'00, BN'00]

Crypto APIs before then: (e.g. MS-CAPI) crypto API

- Provide API for CPA-secure encryption (e.g. CBC with rand. IV)
- Provide API for MAC (e.g. HMAC)

Every project had to combine the two itself without a well defined goal

- Not all combinations provide AE …

Combining MAC and ENC (CCA)

Encryption key k_E. MAC key = k_I

Option 1: (SSL)

msg m $\Rightarrow$ msg m | tag [$S(k_I, m)$] $\Rightarrow$ $E(k_E, m \| tag)$

Option 2: (IPsec)

always correct

msg m $\Rightarrow$ $E(k_E, m)$ $\Rightarrow$ tag [$S(k_I, c)$]

Option 3: (SSH)

msg m $\Rightarrow$ $E(k_E, m)$ $\Rightarrow$ tag [$S(k_I, m)$]

A.E. Theorems

Let (E,D) be CPA secure cipher and (S,V) secure MAC. Then:

1. **Encrypt-then-MAC**: always provides A.E.

2. **MAC-then-encrypt**: may be insecure against CCA attacks

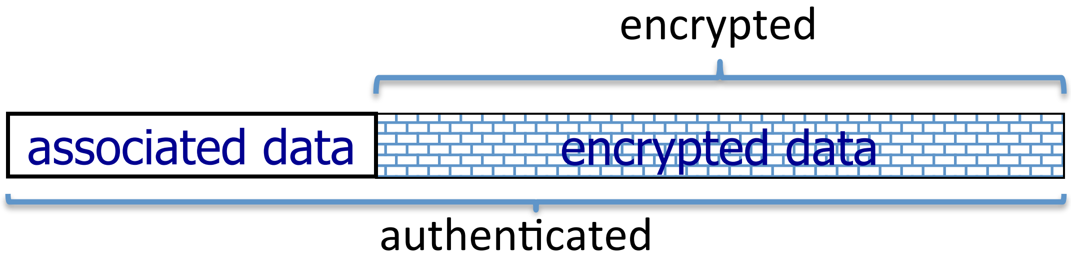
however: when (E,D) is rand-CTR mode or rand-CBC
M-then-E provides A.E.

for rand-CTR mode, one-time MAC is sufficient

Standards (at a high level)

- **GCM:** CTR mode encryption then CW-MAC
  (accelerated via Intel's PCLMULQDQ instruction)
- **CCM:** CBC-MAC then CTR mode encryption (802.11i)
- **EAX:** CTR mode encryption then CMAC

All support AEAD: (auth. enc. with associated data). All are nonce-based.



An example API (OpenSSL)

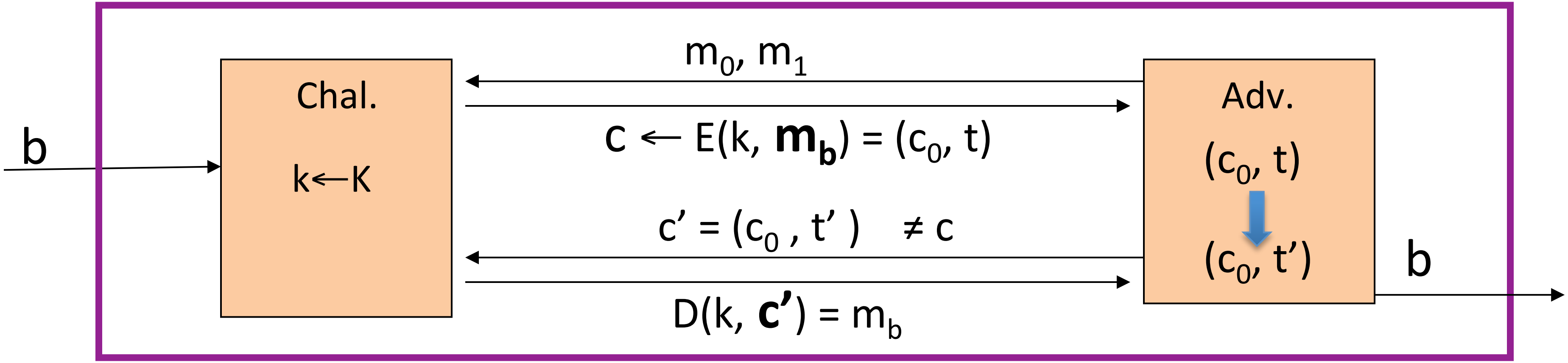
```
int AES_GCM_Init(AES_GCM_CTX *ain,
        unsigned char *nonce,  unsigned long noncelen,
        unsigned char *key,  unsigned int klen )

int AES_GCM_EncryptUpdate(AES_GCM_CTX *a,
        unsigned char *aad,  unsigned long aadlen,
        unsigned char *data,  unsigned long datalen,
        unsigned char *out,  unsigned long *outlen)
```

MAC Security -- an explanation

Recall: MAC security implies $(m, t) \not\Rightarrow (m, t')$

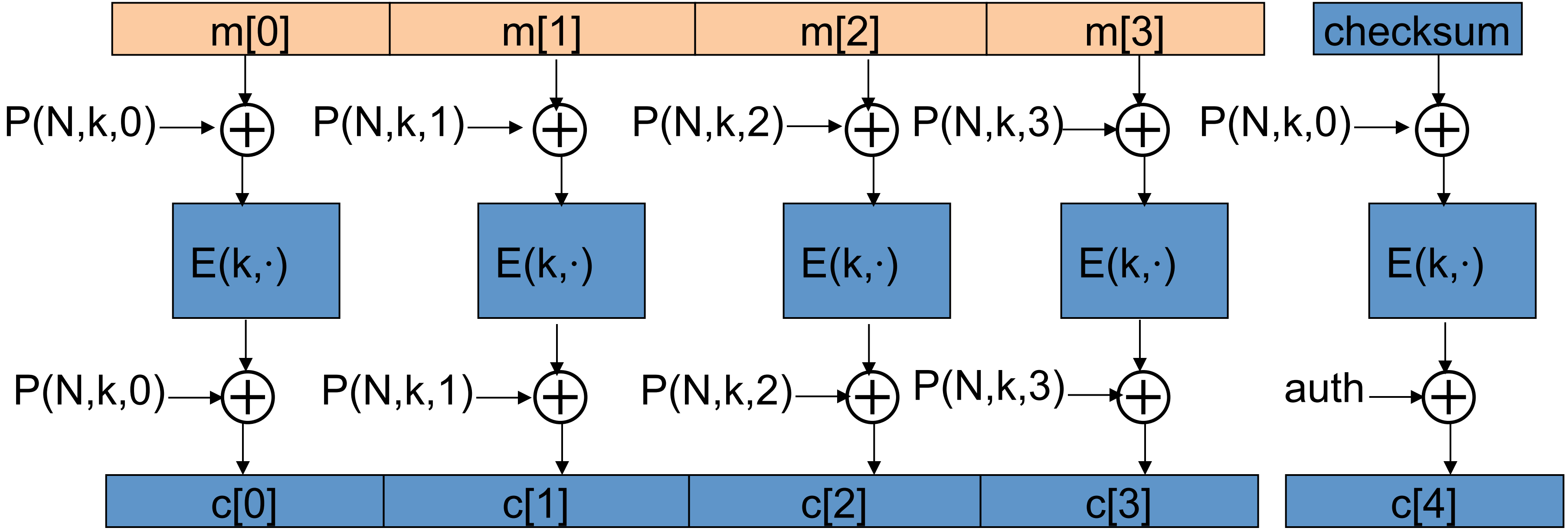
Why? Suppose not: $(m, t) \longrightarrow (m, t')$

Then Encrypt-then-MAC would not have Ciphertext Integrity !!



OCB: a direct construction from a PRP

More efficient authenticated encryption: one E() op. per block.



Performance:

Crypto++ 5.6.0 [Wei Dai]

AMD Opteron, 2.2 GHz (Linux)

Cipher	code size	Speed (MB/sec)		
AES/GCM	large**	108	AES/CTR	139
AES/CCM	smaller	61	AES/CBC	109
AES/EAX	smaller	61		
			AES/CMAC	109
AES/OCB		129*	HMAC/SHA1	147

* extrapolated from Ted Kravitz's results ** non-Intel machines

End of Segment

Authenticated Encryption

Case study: TLS

The TLS Record Protocol (TLS 1.2)

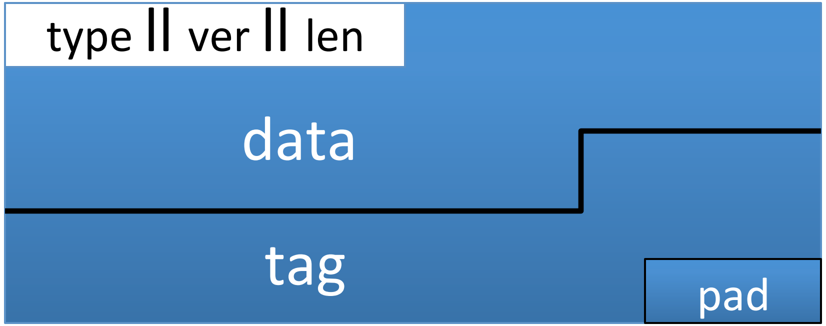
$k_{b \to s}$, $k_{s \to b}$ $\qquad$ $k_{b \to s}$, $k_{s \to b}$

Unidirectional keys: $\quad k_{b \to s}$ and $k_{s \to b}$

Stateful encryption:

- Each side maintains two 64-bit counters: $\quad ctr_{b \to s}$, $ctr_{s \to b}$
- Init. to 0 when session started. $\quad$ ctr++ for every record.
- Purpose: $\quad$ replay defense

TLS record: encryption (CBC AES-128, HMAC-SHA1)



$k_{b\to s} = (k_{mac}, k_{enc})$

not transmitted in packet

Browser side **enc($k_{b\to s}$, data, $ctr_{b\to s}$) :**

step 1: tag $\leftarrow$ S(k_{mac} , [$++ctr_{b\to s}$ || header || data])

step 2: pad [header || data || tag] to AES block size

step 3: CBC encrypt with k_{enc} and new random IV

step 4: prepend header

TLS record: decryption (CBC AES-128, HMAC-SHA1)

Server side **dec($k_{b\to s}$, record, $ctr_{b\to s}$)** :

step 1: CBC decrypt record using k_{enc}

step 2: check pad format: send bad_record_mac if invalid

step 3: check tag on [$++ctr_{b\to s}$ ll header ll data]

send bad_record_mac if invalid

Provides authenticated encryption

(provided no other info. is leaked during decryption)

Bugs in older versions (prior to TLS 1.1)

IV for CBC is predictable: (chained IV)

IV for next record is last ciphertext block of current record.

Not CPA secure. (a practical exploit: BEAST attack)

Padding oracle: during decryption

if pad is invalid send decryption failed alert

if mac is invalid send bad_record_mac alert

$\Rightarrow$ attacker learns info. about plaintext (attack in next segment)

Lesson: when decryption fails, do not explain why

Leaking the length

The TLS header leaks the length of TLS records

- Lengths can also be inferred by observing network traffic

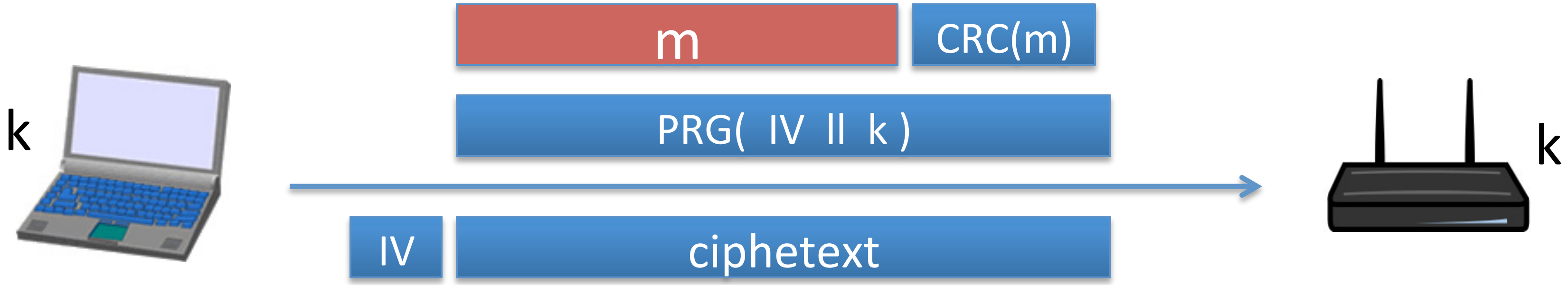
For many web applications, leaking lengths reveals sensitive info:

- In tax preparation sites, lengths indicate the type of return being filed which leaks information about the user's income
- In healthcare sites, lengths leaks what page the user is viewing
- In Google maps, lengths leaks the location being requested

No easy solution

802.11b WEP: how not to do it

802.11b WEP:



Previously discussed problems:

two time pad and related PRG seeds

Active attacks

Fact: CRC is linear, i.e. $\forall$ m,p: **CRC(m $\oplus$ p) = CRC(m) $\oplus$ F(p)**

WEP ciphertext: IV | dest-port = 80 data | CRC

$\oplus$

attacker: 000.......00.....**XX**...0000... | **F(XX)**

XX = 25$\oplus$80

IV | dest-port = 25 data | CRC’

Upon decryption: CRC is valid, but ciphertext is changed !!

End of Segment

Authenticated Encryption

CBC paddings attacks

Recap

Authenticated encryption: CPA security + ciphertext integrity

- Confidentiality in presence of **active** adversary
- Prevents chosen-ciphertext attacks

Limitation: cannot help bad implementations … (this segment)

Authenticated encryption modes:

- Standards: GCM, CCM, EAX
- General construction: encrypt-then-MAC

The TLS record protocol (CBC encryption)

Decryption: **dec($k_{b\to s}$, record, $ctr_{b\to s}$) :**

step 1: CBC decrypt record using k_{enc}

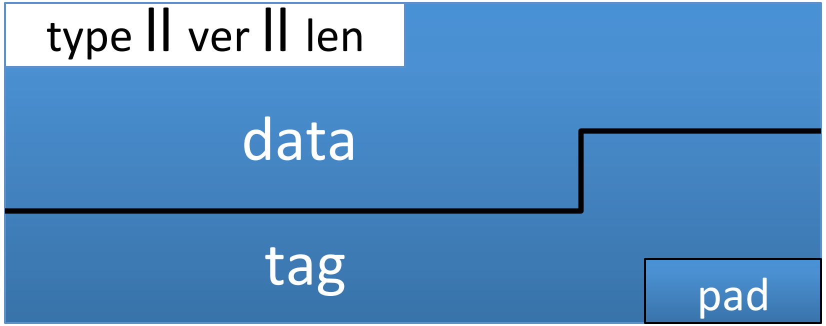
step 2: check pad format: abort if invalid

step 3: check tag on [$++ctr_{b\to s}$ ll header ll data]

abort if invalid

Two types of error:

- **padding error**
- **MAC error**



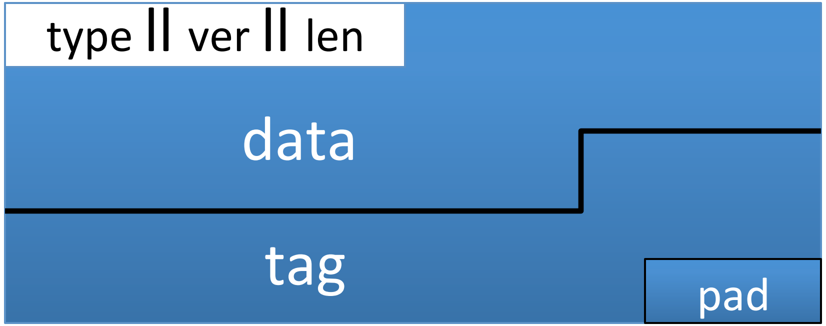
Padding oracle

Suppose attacker can differentiate the two errors (pad error, MAC error):

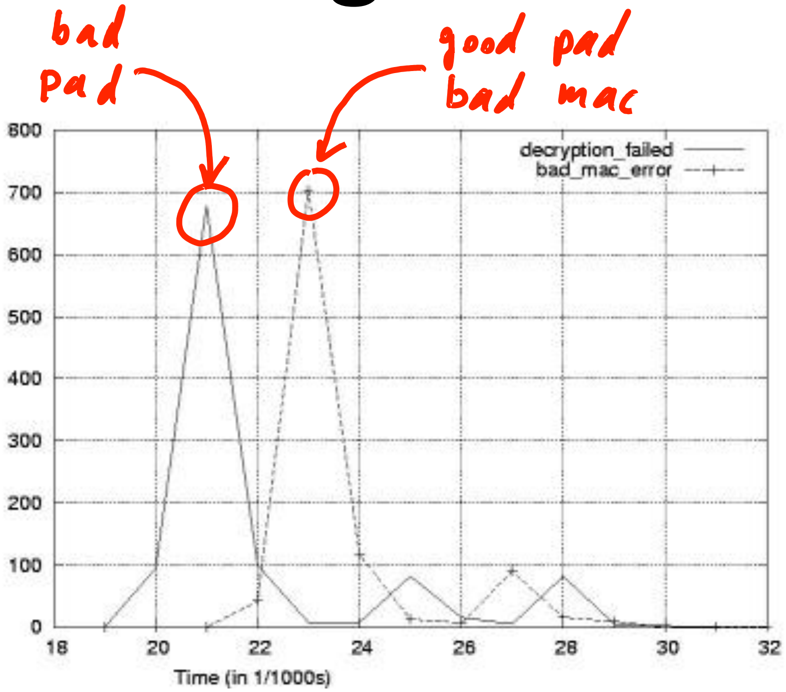
⇒ **Padding oracle**:

attacker submits ciphertext and learns if last bytes of plaintext are a valid pad

Nice example of a **chosen ciphertext attack**



Padding oracle via timing OpenSSL



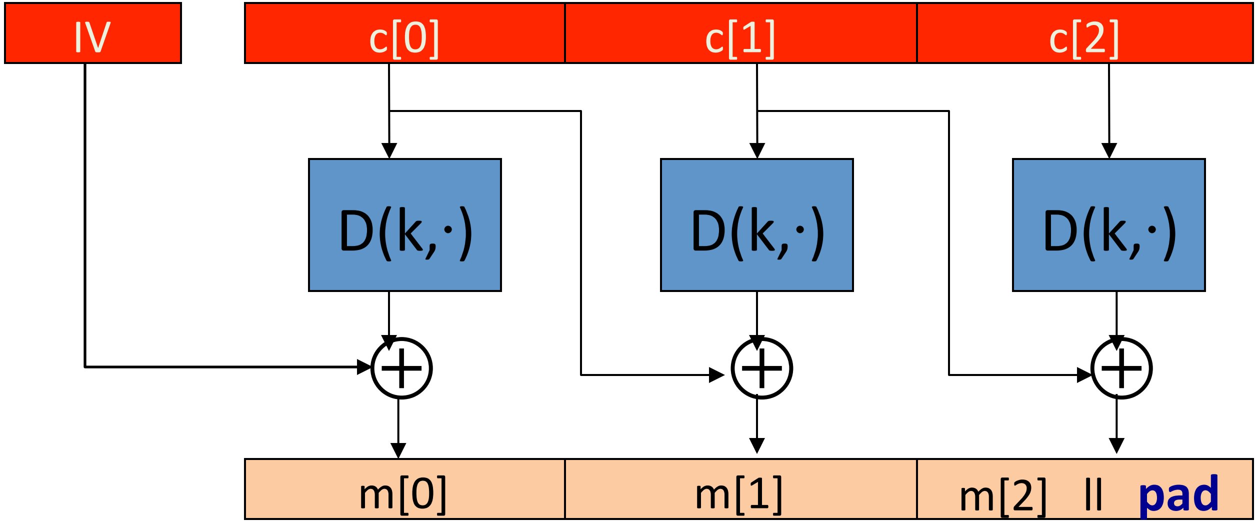
Credit: Brice Canvel

(fixed in OpenSSL 0.9.7a)

In older TLS 1.0: padding oracle due to different alert messages.

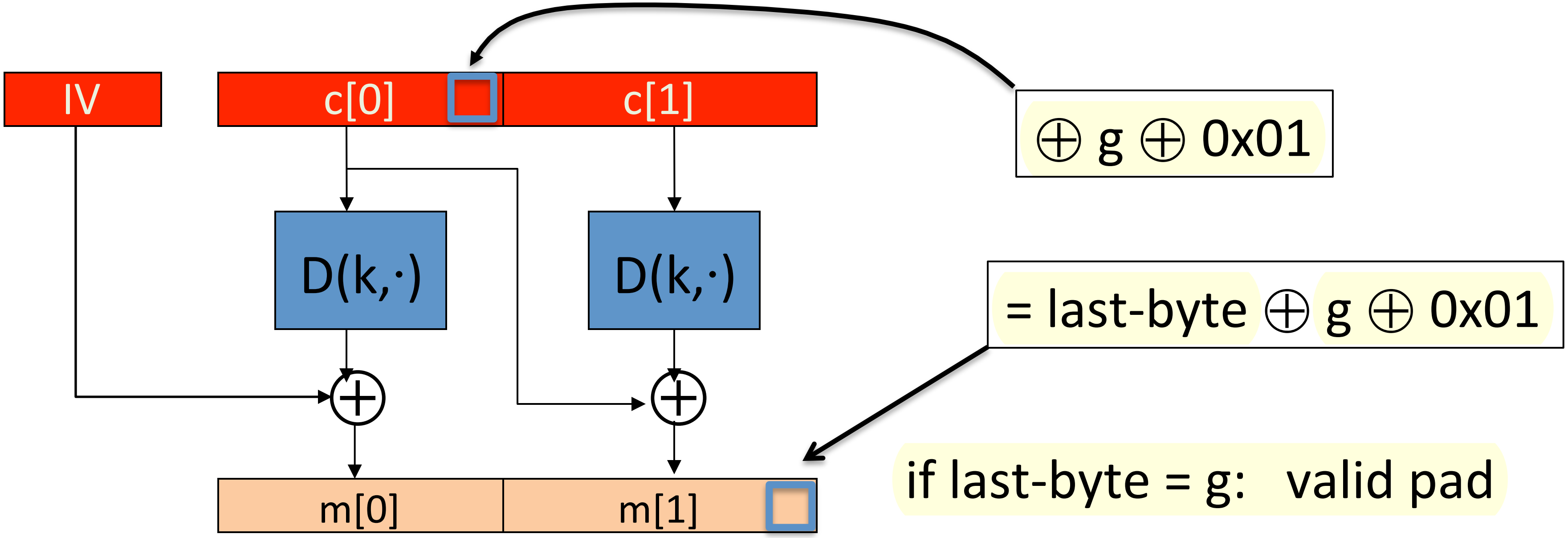
Using a padding oracle (CBC encryption)

Attacker has ciphertext **c = (c[0], c[1], c[2])** and it wants **m[1]**



Using a padding oracle (CBC encryption)

step 1: let **g** be a guess for the last byte of m[1]



if last-byte = g: valid pad

otherwise: invalid pad

Using a padding oracle (CBC encryption)

Attack: submit **(IV, c'[0], c[1])** to padding oracle

$\Rightarrow$ attacker learns if last-byte = g

Repeat with g = 0,1, …, 255 to learn last byte of m[1]

Then use a (02, 02) pad to learn the next byte and so on …

IMAP over TLS

Problem: TLS renegotiates key when an invalid record is received

Enter IMAP over TLS: (protocol for reading email)

- Every five minutes client sends login message to server:
  LOGIN "username" "password"

- Exact same attack works, despite new keys
  ⇒ recovers password in a few hours.

Lesson

1. Encrypt-then-MAC would completely avoid this problem:

   MAC is checked first and ciphertext discarded if invalid

2. MAC-then-CBC provides A.E., but padding oracle destroys it

Will this attack work if TLS used counter mode instead of CBC?

(i.e. use MAC-then-CTR)

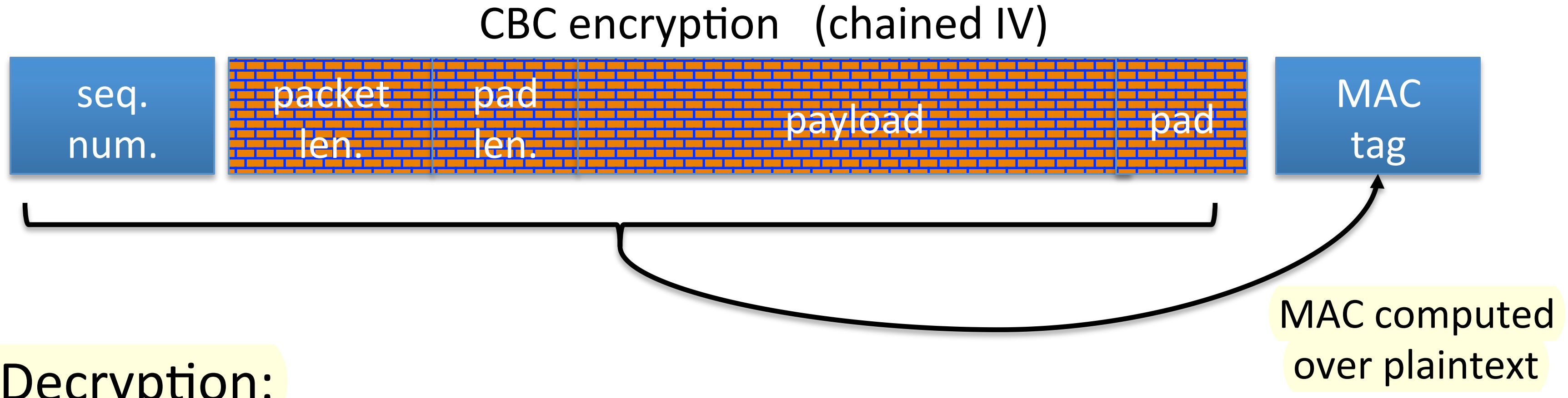
- Yes, padding oracles affect all encryption schemes
- It depends on what block cipher is used
- No, counter mode need not use padding
-

End of Segment

Authenticated Encryption

Attacking non-atomic decryption

SSH Binary Packet Protocol

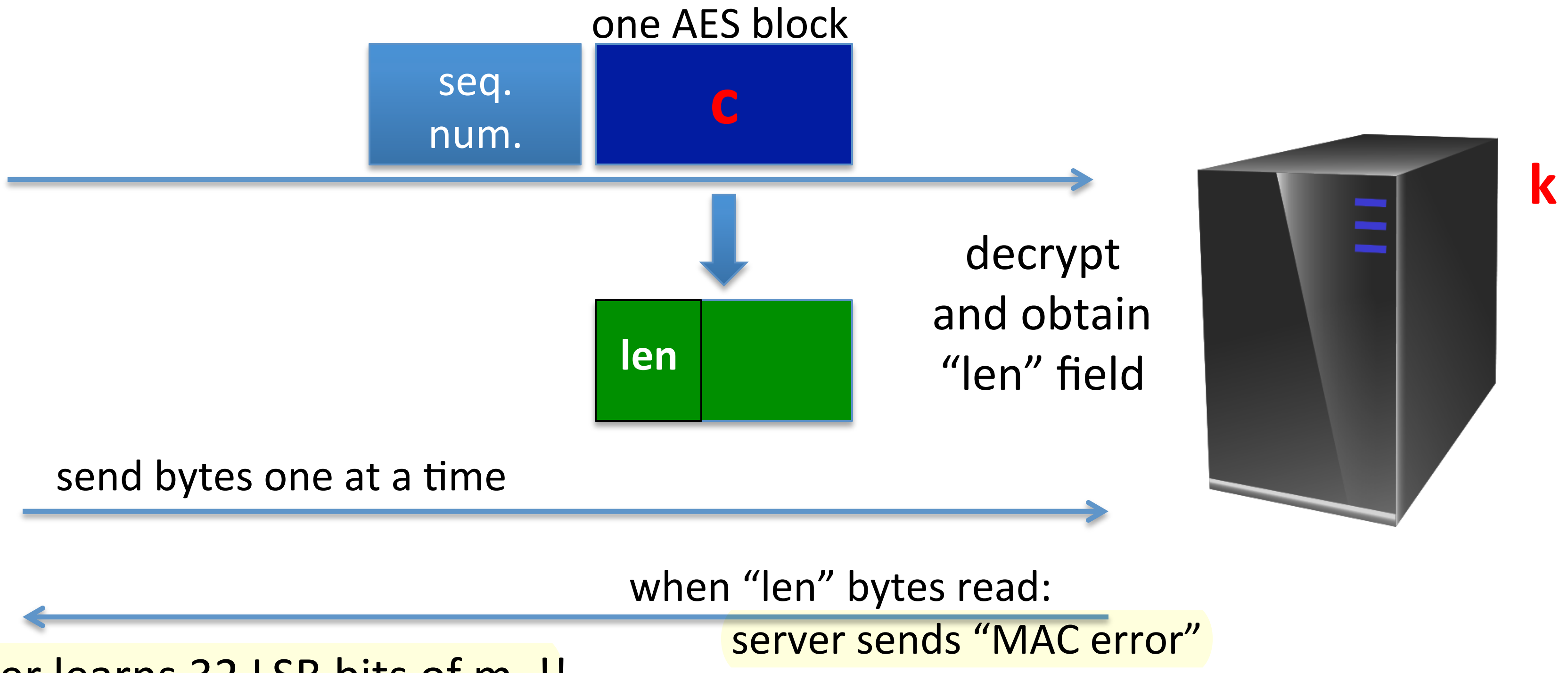


Decryption:

- step 1: decrypt packet length field only (!)
- step 2: read as many packets as length specifies
- step 3: decrypt remaining ciphertext blocks
- step 4: check MAC tag and send error response if invalid

An attack on the enc. length field (simplified)

Attacker has <u>one</u> ciphertext block **c = AES(k, m)** and it wants **m**



attacker learns 32 LSB bits of m !!

Lesson

The problem: (1) non-atomic decrypt

(2) len field decrypted and used before it is authenticated

How would you redesign SSH to resist this attack?

- Send the length field unencrypted (but MAC-ed)
- Replace encrypt-and-MAC by encrypt-then-MAC
- Add a MAC of (seq-num, length) right after the len field
- Remove the length field and identify packet boundary by verifying the MAC after every received byte

Further reading

- The Order of Encryption and Authentication for Protecting Communications, H. Krawczyk, Crypto 2001.
- Authenticated-Encryption with Associated-Data, P. Rogaway, Proc. of CCS 2002.
- Password Interception in a SSL/TLS Channel, B. Canvel, A. Hiltgen, S. Vaudenay, M. Vuagnoux, Crypto 2003.
- Plaintext Recovery Attacks Against SSH, M. Albrecht, K. Paterson and G. Watson, IEEE S&P 2009
- Problem areas for the IP security protocols, S. Bellovin, Usenix Security 1996.

End of Segment