CSE 3400 - Introduction to Computer & Network Security
(aka: Introduction to Cybersecurity)

Lecture 5
Message Authentication Codes

Ghada Almashaqbeh
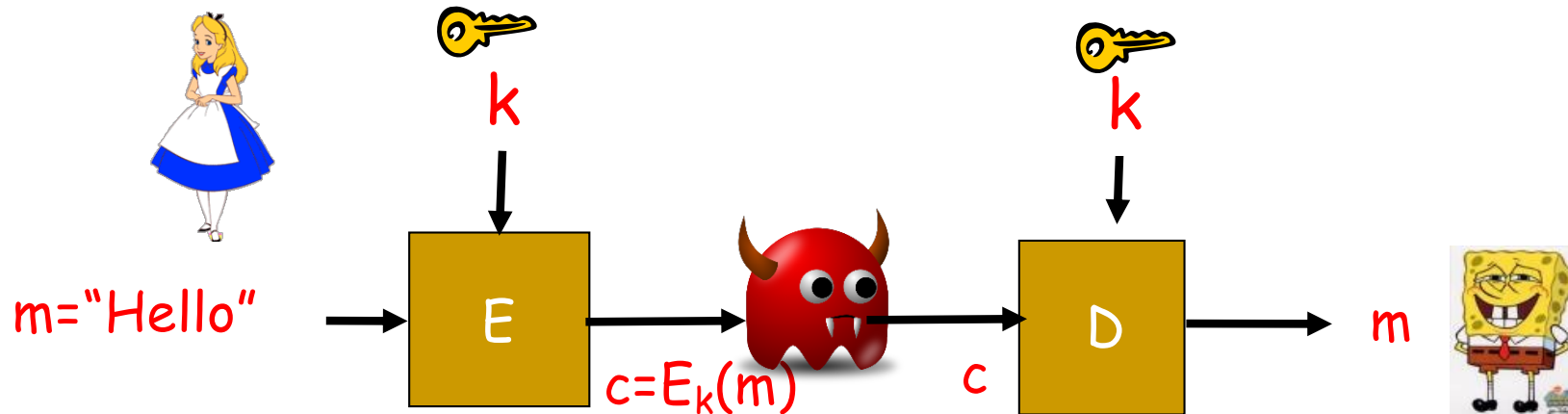## UConn

From Textbook Slides by Prof. Amir Herzberg

UConn

Outline

- Motivation.

- Message authentication codes (MACs) definition.

- MAC security definition.

- MAC constructions.

- Combining message authentication and encryption.

Encryption Ensures Confidentiality

m="Hello" → E → $c=E_k(m)$ → 😈 → c → D → m

k (Alice's key) → E

k → D

- ❑ Man-in-the-Middle attacker 'learns nothing' about message

Integrity and Authentication?

m="Hello"   k $c=E_k(m)$ c'   k $m'=D_k(c')$ m'="Bye"
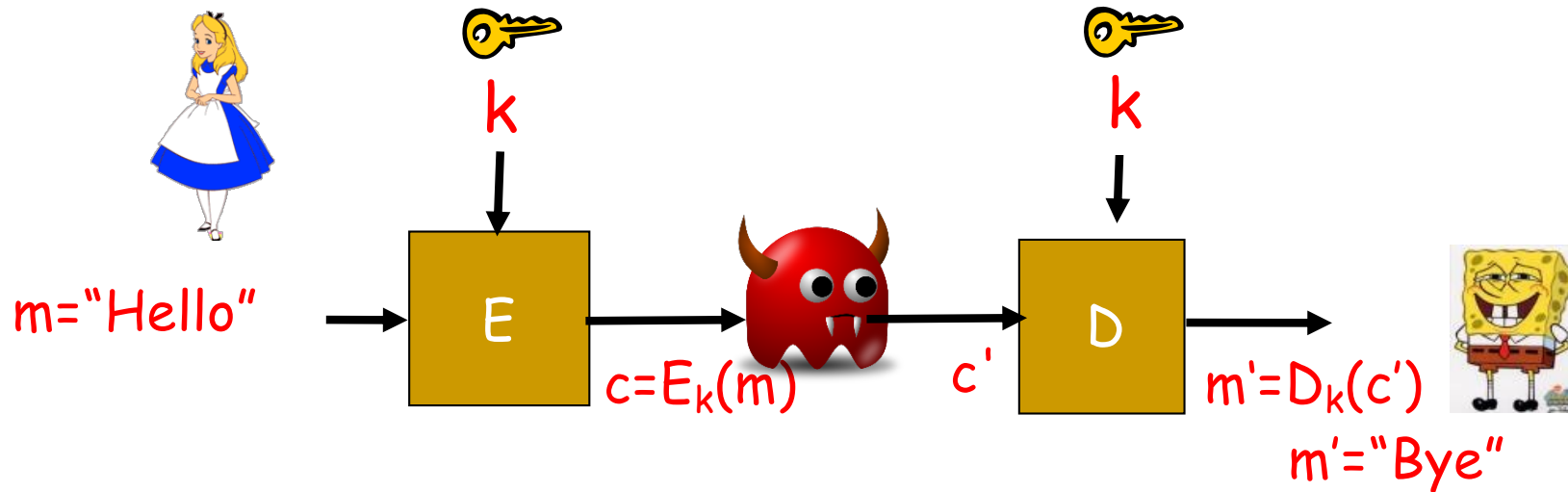
❑ How can the recipient know that the message was not tampered with and it is the original one sent by the sender?

Does Encryption Prevent Forgery?

- ❑ Cannot be guaranteed.
    - ❑ Several secure encryption schemes are malleable (an attacker might be able to alter the ciphertext, and hence, the decrypted plaintext will be different).
- ❑ Clearly not for bitwise stream ciphers (& OTP).
    - ❑ Given $c = m \oplus k$, attacker can send $c \oplus mask$, to invert any bit in decrypted message.
- ❑ Example, send "Pay Bob $100" encrypted using OTP.
    - ❑ Eve can change it to "Pay Eve $100" (note that this is a KPA attacker). How?
        - ❑ Take the ciphertext of the letter "B" above, denote it as c[4].
        - ❑ Note that c[4] = k[4] $\oplus$ "B" (note that we do know the key!)
        - ❑ Compute a mask that does the following: c[4] $\oplus$ mask = k[4] $\oplus$ "E" (this boils down to computing "B" $\oplus$ mask = "E")
        - ❑ Repeat that for the rest of the letters.

Message Authentication Codes (MACs)

- A MAC allows a recipient to **validate** that a message was **not tampered** with and that it was sent by a **key holder**

It is a symmetric key setup!

Valid MAC $\Rightarrow$ Only Sponge and I know k. So he sent m.

$m=$"Hi", $MAC_k(m)$

Key k

Key k

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Message Authentication Codes (MACs)

- Use shared key k to authenticate messages
- Pair *(tag , m)* is <u>valid</u> *iff tag=MAC$_k$(m)*
- Very efficient
- Does not support non-repudiation!
  - Sponge may say that the key k has been stolen. Someone else sent the message.

$k = ??$

$MAC_k(Bye) = ??$

"Hi"
+
$MAC_k("Hi")$

"Bye"
+
tag ??

Alice

Key k

Key k
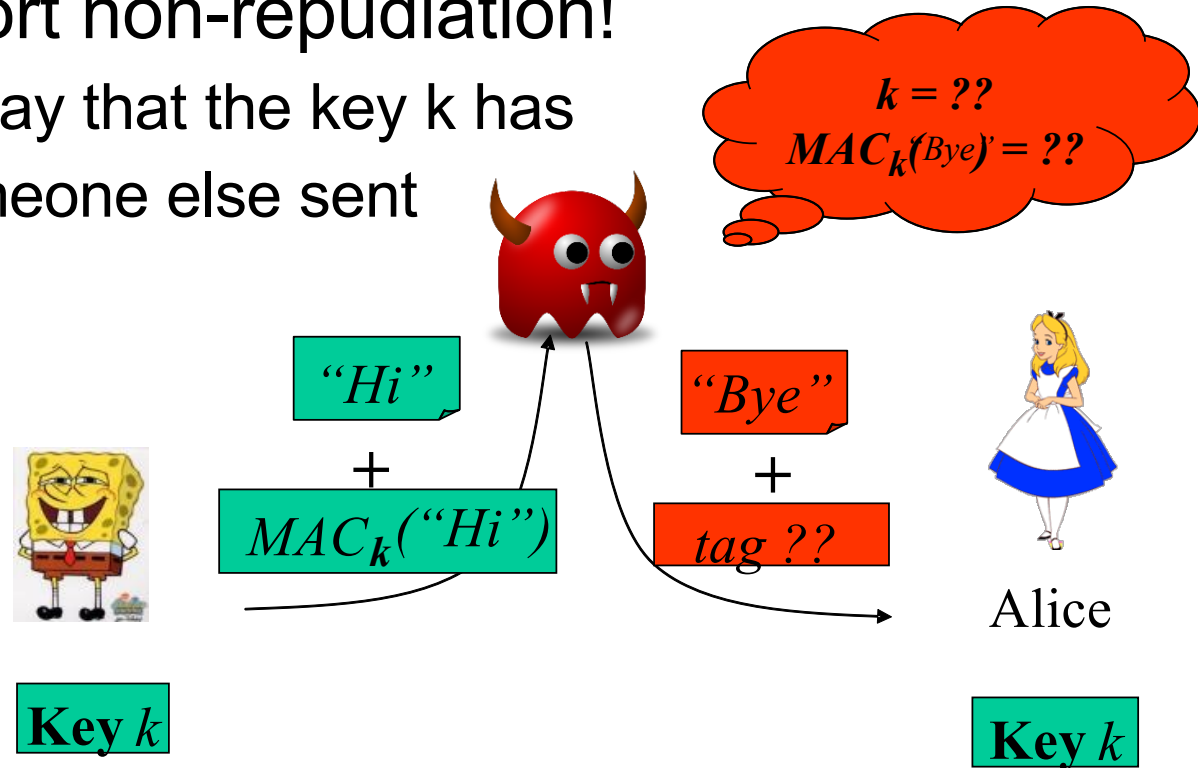
Defining MAC Security

- Following the `conservative design principle':
- Consider most powerful attacker
  - Let attacker receive tag for every message it wants (so it has an oracle access to MAC_k).
- And `easiest' attacker-success criteria
  - Attacker wins if it can produce a valid tag for any message
    - Except for these that the attacker asked to authenticate

MAC Security Definition

Definition 3.1 (MAC). *An l-bit* Message Authentication Code (MAC) *over domain D, is a function $F : \{0,1\}^* \times D \to \{0,1\}^l$, such that for all PPT algorithms $\mathcal{A}$, the* advantage $\varepsilon_{F,\mathcal{A}}^{MAC}(n)$ *is* negligible *in n, i.e., smaller than any positive polynomial for sufficiently large n (as $n \to \infty$), where:*

$$\varepsilon_{F,\mathcal{A}}^{MAC}(n) \equiv \Pr_{k \xleftarrow{\$} \{0,1\}^n} \left[(m, F_k(m)) \leftarrow \mathcal{A}^{F_k(\cdot \mid \text{except } m)}(1^n) \right] - \frac{1}{2^l} \qquad (3.1)$$

Where the probability is taken over the random choice of an n bit key, $k \xleftarrow{\$} \{0,1\}^n$, as well as over the coin tosses of $\mathcal{A}$.

On the Use of MACs

- $MAC_k(m)$ may expose information about $m!$
  - Example: Let *MAC* be any secure MAC. Define $MAC'_k(m)=MAC_k(m)||LSb(m)$, where *LSb* is least significant bit.
- MAC shows a key-holder computed it
  - Could be any key holder (even recipient)…
- Replay attacks: an old message (and its tag) is being resent.
  - Need to Ensure freshness (more about this later).

$m=$ *"Hi"*, $MAC_k(m)$

Cat, Sponge (or I) sent *m*.

Key *k*   Key *k*   Key *k*
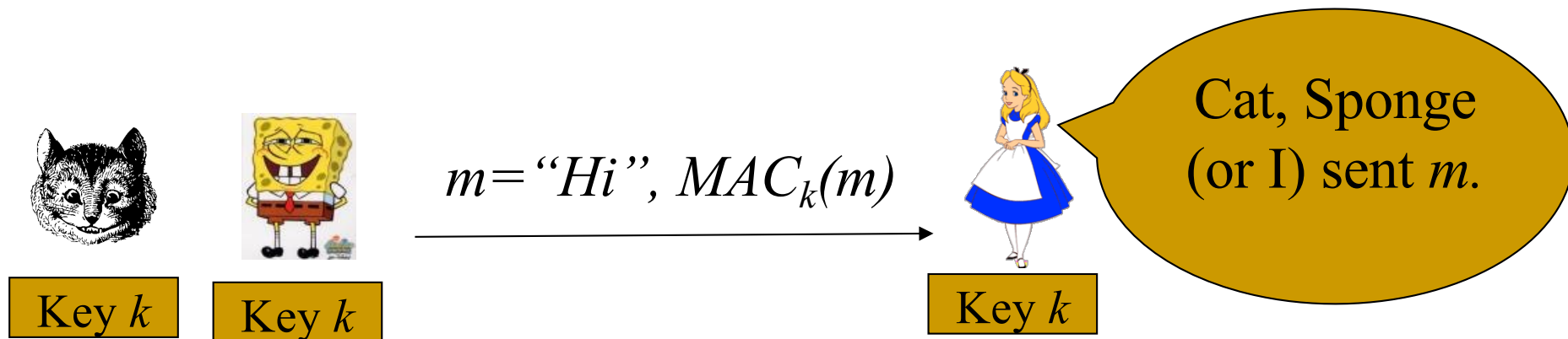
Constructing MAC: Three Approaches

1. Design `from scratch`, validate security by failure to cryptanalyze
   - Huge effort, risk → do only for few `building blocks`
   - Maybe from EDC (Error Detection Code), but it is not secure for every EDC.

2. Robust combiner of (two) MAC candidates:
   - $MAC_{k,k'}(m)=f_k(m)||f'_{k'}(m), MAC_{k,k'}(m)=f_k(m)\oplus f'_{k'}(m)$ are

     secure MAC, if *either f* <u>or *f'*</u> is a secure MAC.

3. Provable-secure constructions from:
   - PRF/PRP/Block ciphers (next)
     - First: PRF/PRP → Fixed-Input-Length (FIL) MAC
   - Hash functions (later) – even more efficient.

Theorem: every PRF is also a MAC

Let F be a PRF from domain D to range $\{0,1\}^l$.
Then F is also an l-bit MAC for D.

- Proof sketch: construct an attacker against PRF using the attacker against the MAC.
  - For a random function, the outcome of any `new' value is random.
    - So, probability of guessing is 2^{-l}.
  - If a `new' outcome of a PRF can be guessed with significantly higher probability (which is the MAC over a new message), then we can distinguish between it and a random function! ■

Every PRF is also a MAC

- A PRF is a MAC for l-bit messages.
- *(l.n)*-bit FIL MAC from n-bit PRP (block cipher): use CBC-MAC – a variant of CBC
  - What standard crypto function can we use as a PRF?
  - A block cipher ? But …

Using a Block Cipher for MAC

- **Problem 1:** block cipher is PRP, not PRF

  - Solution: the switching lemma says that a PRP is also a PRF !

  - Note: PRP→PRF reduction involves loss in concrete security (larger advantage):

  $$\left| \varepsilon_{\mathcal{A},E}^{PRF}(n) - \varepsilon_{\mathcal{A},E}^{PRP}(n) \right| < \frac{q^2}{2 \cdot |D|}$$

 - Some other constructions reduce this loss but we will not discuss them

Using a Block Cipher for MAC

- **Problem 2:** block ciphers are defined only for (short) fixed input length (FIL)

  - Ideally a MAC should work for any input string (Variable Input Length – VIL)

  - We already had a similar problem… where?

    - Block ciphers.

  - We solved by using various encryption modes of operation.

  - A solution for MACs: the CBC-MAC mode of operation!

Cipher Block Chaining MAC: CBC-MAC

Split plaintext *m into* blocks

Fixed, known (zero) Initialization Vector (*IV*)
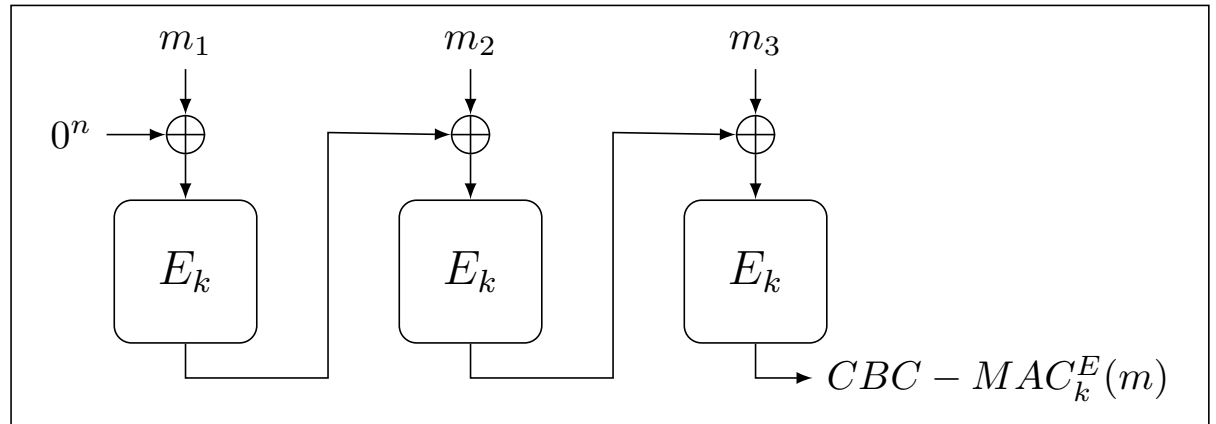
The tag is the cipher of the last block

$$CBC\text{-}MAC^E_k(m_1||m_2||..||m_l) = E_k(m_l \oplus E_k(...E_k(m_1))))$$

Recall: MACs are deterministic functions

CBC-MAC

❑ Widely deployed standard

❑ More efficient 'modes' exist

    ❑ E.g., allow for parallel computation.

❑ It is also provably secure.

Theorem [BKR94]: if E is a FIL-PRF for domain $\{0,1\}^n$, then $CBC\text{-}MAC^E$ is a PRF for domain $\{0,1\}^{ln}$ (for $l>1$).

    ▪ Corollary: ... then $CBC\text{-}MAC^E$ is a $\{0,1\}^{ln}$-MAC

But what of VIL (variable-length input) MAC?

CBC-MAC-based VIL-MAC

- ## Is CBC-MAC^E a VIL-MAC?

  - ### *No!*

    - Ask for $b=CBC\text{-}MAC^E_k(a)=E_k(a)$;

    - then output (ac, b) so $m = ac$ with $tag = b$ where $c= a \oplus b$.

    - This is valid, since the attacker did not ask the oracle for a tag for *ac* and *b* for *ac* is a valid tag since
    $CBC\text{-}MAC^E_k(ac)=E_k(c \oplus E_k(a))=E_k(c \oplus b)= E_k(a \oplus b \oplus b)= E_k(a)= b.$

- ## Solution: prepend message length (called CMAC)

  - ### Let $CMAC^E_k(m)=CBC\text{-}MAC^E_k(L(m)||m)$

    - Where $L(m)$ is a 1-block encoding of $|m|$

  - ### CMAC is a secure VIL MAC construction!

Combining Authentication and Encryption

- ❑ For confidentiality, use encryption

- ❑ For authentication, use MAC

- ❑ For <u>both</u> confidentiality <u>and</u> authentication?
    - ❑ Option 1: Combine MAC and encryption
        - ❑ Possible pitfalls (vulnerabilities)
    - ❑ Option 2: authenticated-encryption schemes (or modes)
        - ❑ Easier to deploy (securely)
        - ❑ Generic combination of MAC and Encryption schemes
        - ❑ Or direct combined constructions (can be more efficient)
            - ❑ Might be ad-hoc or rely on complex or less-tested security assumptions.

Generic MAC and Encryption Combinations

- Three standards, three ways…
  - Authenticate and encrypt (A&E):
    - $c = Enc(m)$, $tag = MAC(m)$, send (c, tag)

  - Authenticate then encrypt (AtE):
    - $tag = MAC(m)$, $c = Enc(m, tag)$, send c

  - Encrypt then authenticate (EtA):
    - $c = Enc(m)$, $tag = MAC(c)$, send (c, tag)

- Some of these may be vulnerable even when combining some <u>secure</u> encryption and MAC schemes!

Security of Generic MAC/Enc Combinations

- ❑ **A&E may be vulnerable!**
  - ❑ Example:
    - ❑ Let MAC be any secure MAC scheme
    - ❑ Let $MAC'_{k'}(m) = MAC_{k'}(m) || lsb(m)$
    - ❑ MAC' is a secure MAC.
    - ❑ But A&E(m) leaks least significant bit of m (even if the encryption scheme is secure!!!).
  - ❑ Recall that the security guarantee of a MAC is about integrity (or preventing forgery)!
    - ❑ It has nothing to do with confidentiality!

- ❑ **What about AtE, EtA ?**
  - ❑ AtE: also may be vulnerable (not IND-CPA)!

Security of Generic MAC/Enc Combinations

- How about EtA ? **Provably CCA-Secure** [CK01]!
  - ➔ Secure encryption; otherwise attack Enc(m) by appending MAC
  - ➔ Secure authentication, since any change in (c, MAC(c)) is detected
  - Also: reject fake messages w/o decryption ➔ efficiency and foil Denial of Service (DoS), CCA attacks
  - Note: using separate keys for Enc and MAC; what if we use same key?

Keys for MAC and Encryption?

Using same key for MAC+Encryption? Insecure
- ❑ Exercise: show (contrived) examples vulnerabilities:
    - ❑ A&E: both vulnerable…
$$E_{k',k''}(m) = E'_{k'}(m)||k''$$
$$MAC_{k',k''}(m) = MAC_{k''}(m)||k'$$
    - ❑ AtE: vulnerable authentication (is encryption vulnerable?)
$$E_{k',k''}(m) = E'_{k'}(m)||k''$$
    - ❑ EtA: both vulnerable (exercise: attack on authentication)
$$MAC_{k',k''}(m) = MAC_{k''}(m)||k'$$

- ❑ So: should we use two independent keys?
    - ❑ Overhead: key generation, transmission, storage
- ❑ Exercise: secure enc+MAC – using a single key!

Solution: $k_{mac} := PRF_k(`MAC'), k_{enc} := PRF_k(`Encrypt')$

Conclusion

- **MAC – Message Authentication Code**
    - Sender appends `tag` (MAC) to message, recipient verifies tag using shared secret key

- **Construction from block cipher**

- **Next:**
    - Crypto-hash functions
    - Constructing MAC from hash function: HMAC

Examples of MAC Constructions

❑ On the whiteboard.

Covered Material From the Textbook

❑ Chapter 3

    ❑ All except sections 3.7.2 and 3.7.5

Thank You!