Cryptographic Hashes and MACs

Adapted From CS 161 Fall 2022 - Lecture 7

Last Time: Block Ciphers

- Encryption: input a *k*-bit key and *n*-bit plaintext, receive *n*-bit ciphertext
- Decryption: input a *k*-bit key and *n*-bit ciphertext, receive *n*-bit plaintext
- Correctness: when the key is fixed, $E_K(M)$ should be bijective
- Security
  - Without the key, E_K(m) is computationally indistinguishable from a random permutation
  - Brute-force attacks take astronomically long and are not possible
- Efficiency: algorithms use XORs and bit-shifting (very fast)
- Implementation: AES is the modern standard
- Issues
  - Not IND-CPA secure because they're deterministic
  - Can only encrypt *n*-bit messages

Last Time: Block Cipher Modes of Operation

- ECB mode: Deterministic, so not IND-CPA secure
- CBC mode
  - IND-CPA secure, assuming no IV reuse
  - Encryption is not parallelizable
  - Decryption is parallelizable
  - Must pad plaintext to a multiple of the block size
  - IV reuse leads to leaking the existence of identical blocks at the start of the message
- CTR mode
  - IND-CPA secure, assuming no IV reuse
  - Encryption and decryption are parallelizable
  - Plaintext does not need to be padded
  - Nonce reuse leads to losing all security
- Lack of integrity and authenticity

Lack of Integrity and Authenticity

- Block ciphers are designed for *confidentiality* (IND-CPA)
- If an attacker tampers with the ciphertext, we are not guaranteed to detect it
- Remember Mallory: An *active* manipulator who wants to tamper with the message

Lack of Integrity and Authenticity

- Consider CTR mode
- What if Mallory tampers with the ciphertext using XOR?

	P	a	y		M	a	l		$	1	0	0
M	0x50	0x61	0x79	0x20	0x4d	0x61	0x6c	0x20	0x24	0x31	0x30	0x30

$\oplus$

$E_K(i)$	0x8a	0xe3	0x5e	0xcf	0x3b	0x40	0x46	0x57	0xb8	0x69	0xd2	0x96

=

C	0xda	0x82	0x27	0xef	0x76	0x21	0x2a	0x77	0x9c	0x58	0xe2	0xa6

Lack of Integrity and Authenticity

- Suppose Mallory knows the message *M*
- How can Mallory change the *M* to say **`Pay Mal $900`**?

	P	a	y		M	a	l		$	**1**	0	0
M	0x50	0x61	0x79	0x20	0x4d	0x61	0x6c	0x20	0x24	**0x31**	0x30	0x30

$\oplus$

$E_K(i)$	0x8a	0xe3	0x5e	0xcf	0x3b	0x40	0x46	0x57	0xb8	**0x69**	0xd2	0x96

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C	0xda	0x82	0x27	0xef	0x76	0x21	0x2a	0x77	0x9c	**0x58**	0xe2	0xa6

Lack of Integrity and Authenticity

$C_i = M_i \oplus \text{Pad}_i$	$\texttt{0x58} = \texttt{0x31} \oplus \text{Pad}_i$	Definition of CTR
$\text{Pad}_i = M_i \oplus C_i$	$\text{Pad}_i = \texttt{0x58} \oplus \texttt{0x31}$ $= \texttt{0x69}$	Solve for the *i*th byte of the pad
$C'_i = M'_i \oplus \text{Pad}_i$	$C'_i = \texttt{0x39} \oplus \texttt{0x69}$ $= \texttt{0x50}$	Compute the changed *i*th byte

C	0xda	0x82	0x27	0xef	0x76	0x21	0x2a	0x77	0x9c	**0x58**	0xe2	0xa6
C'	0xda	0x82	0x27	0xef	0x76	0x21	0x2a	0x77	0x9c	**0x50**	0xe2	0xa6

Lack of Integrity and Authenticity

- What happens when we decrypt *C*'?
    - The message looks like “Pay Mal $900” now!
    - Note: Mallory didn’t have to know the key; no integrity or authenticity for CTR mode!

C'	0xda	0x82	0x27	0xef	0x76	0x21	0x2a	0x77	0x9c	**0x50**	0xe2	0xa6

$\oplus$

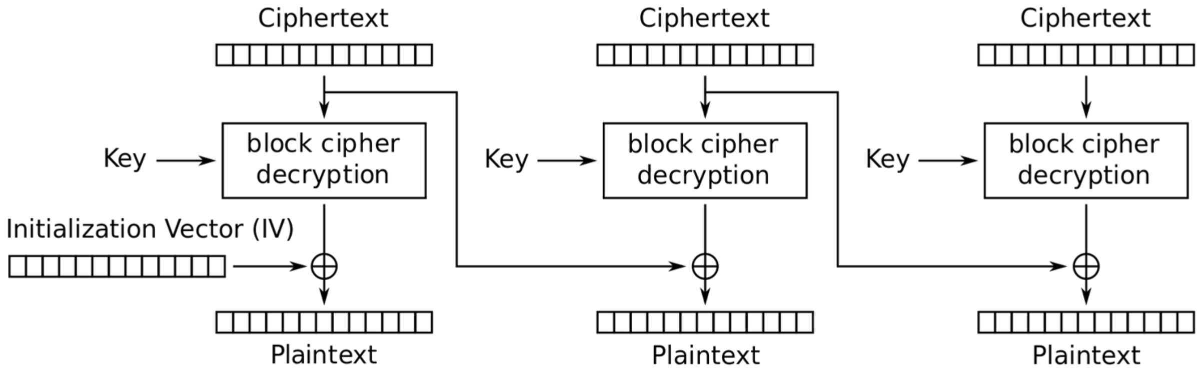
$E_K(i)$	0x8a	0xe3	0x5e	0xcf	0x3b	0x40	0x46	0x57	0xb8	**0x69**	0xd2	0x96

=

P'	0x50	0x61	0x79	0x20	0x4d	0x61	0x6c	0x20	0x24	**0x39**	0x30	0x30
	P	a	y		M	a	l		$	**9**	0	0

Lack of Integrity and Authenticity

- What about CBC?
    - Altering a bit of the ciphertext causes some blocks to become random gibberish
    - However, Bob cannot prove that Alice did not send random gibberish, so it still does *not* provide integrity or authenticity



Cipher Block Chaining (CBC) mode decryption

Today: Cryptography Hashes and MACs

- Hashing
  - Definition
  - Security: one-way, second preimage resistant, collision resistant
  - Examples
  - Length extension attacks
  - Application: Lowest-hash scheme
  - Do hashes provide integrity?
- MACs
  - Definition
  - Security: unforgeability
  - Example: HMAC
  - Do MACs provide integrity?
- Authenticated Encryption
  - Definition
  - Key Reuse
  - MAC-then-Encrypt or Encrypt-then-MAC?
  - AEAD Encryption Modes

Cryptographic Hashes

Textbook Chapter 7.1–7.3

Cryptography Roadmap

	Symmetric-key	Asymmetric-key
Confidentiality	● One-time pads ● Block ciphers with chaining modes (e.g. AES-CBC)	● RSA encryption ● ElGamal encryption
Integrity, Authentication	● MACs (e.g. HMAC)	● Digital signatures (e.g. RSA signatures)

- Hash functions
- Pseudorandom number generators
- Public key exchange (e.g. Diffie-Hellman)
- Key management (certificates)
- Password management

Cryptographic Hash Function: Definition

- Hash function: $H(M)$
  - Input: *Arbitrary* length message M
  - Output: *Fixed* length, n-bit hash
  - Sometimes written as $\{0, 1\}^* \rightarrow \{0, 1\}^n$
- Properties
  - **Correctness**: Deterministic
    - Hashing the same input always produces the same output
  - **Efficiency**: Efficient to compute
  - **Security**: One-way-ness (“preimage resistance”)
  - **Security**: Collision-resistance
  - **Security:** Random/unpredictability, no predictable patterns for how changing the input affects the output
    - Changing 1 bit in the input causes the output to be completely different
    - Also called “random oracle” assumption

Hash Function: Intuition

- A hash function provides a fixed-length “fingerprint” over a sequence of bits
- Example: Document comparison
  - If Alice and Bob both have a 1 GB document, they can both compute a hash over the document and (securely) communicate the hashes to each other
  - If the hashes are the same, the files must be the same, since they have the same “fingerprint”
  - If the hashes are different, the files must be different

Hash Function: One-way-ness or Preimage Resistance

- **Informal:** Given an output *y*, it is infeasible to find *any* input *x* such that *H*(*x*) = *y*
- **More formally:** For all polynomial time adversary,

  Pr[*x* chosen randomly from plaintext space; *y* = *H*(*x*):

  Adv(*y*) outputs *x′* s.t. *H*(*x′*) = *y*] is negligible
- Intuition: Here's an output. Can you find an input that hashes to this output?
  - Note: The adversary just needs to find *any* input, not necessarily the input that was actually used to generate the hash
- Example: Is H(x) = 1 one-way?
  - No, because given output 1, an attacker can return any number x

Hash Function: Collision Resistance

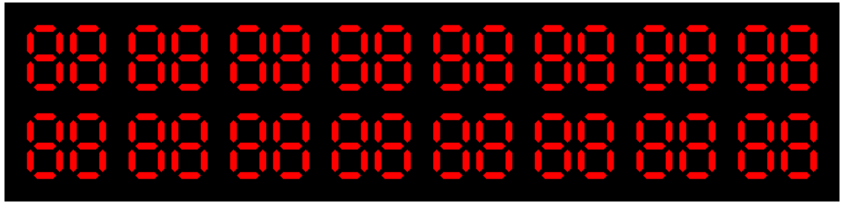
- **Collision**: Two different inputs with the same output
  - $x \neq x'$ and $H(x) = H(x')$
  - Can we design a hash function with no collisions?
    - No, because there are more inputs than outputs (pigeonhole principle)
  - However, we want to make finding collisions *infeasible* for an attacker
- **Collision resistance**: It is infeasible to (i.e. no polynomial time attacker can) find any pair of inputs $x' \neq x$ such that $H(x) = H(x')$
- Intuition: Can you find *any* two inputs that collide with the same hash output for *any* output?

Hash Function: Collision Resistance

- **Birthday attack**: Finding a collision on an *n*-bit output requires only $2^{n/2}$ tries on average
  - This is why a group of 23 people are >50% likely to have at least one birthday in common

Hash Function: Examples

- MD5
  - Output: 128 bits
  - Security: Completely broken
- SHA-1
  - Output: 160 bits
  - Security: Completely broken in 2017
  - Was known to be weak before 2017, but still used sometimes
- SHA-2
  - Output: 256, 384, or 512 bits (sometimes labeled SHA-256, SHA-384, SHA-512)
  - Not currently broken, but some variants are vulnerable to a length extension attack
  - Current standard
- SHA-3 (Keccak)
  - Output: 256, 384, or 512 bits
  - Current standard (not meant to replace SHA-2, just a different construction)


A GIF that displays its own MD5 hash

Length Extension Attacks

- **Length extension attack**: Given *H*(*x*) and the length of *x*, but not *x*, an attacker can create *H*(*x* || *m*) for any *m* of the attacker's choosing
  - See homework for a demo
  - Note: This doesn't violate any property of hash functions but is undesirable in some circumstances
- SHA-256 (256-bit version of SHA-2) is vulnerable
- SHA-3 is not vulnerable

Do hashes provide integrity?

- It depends on your threat model
- Scenario
  - Mozilla publishes a new version of Firefox on some download servers
  - Alice downloads the program binary
  - How can she be sure that nobody tampered with the program?
- Idea: use cryptographic hashes
  - Mozilla hashes the program binary and publishes the hash on its website
  - Alice hashes the binary she downloaded and checks that it matches the hash on the website
  - If Alice downloaded a malicious program, the hash would not match (tampering detected!)
  - An attacker can’t create a malicious program with the same hash (collision resistance)
- Threat model: We assume the attacker cannot modify the hash on the website
  - We have integrity, as long as we can communicate the hash securely

Do hashes provide integrity?

- It depends on your threat model
- Scenario
  - Alice and Bob want to communicate over an insecure channel
  - Mallory might tamper with messages
- Idea: Use cryptographic hashes
  - Alice sends her message with a cryptographic hash over the channel
  - Bob receives the message and computes a hash on the message
  - Bob checks that the hash he computed matches the hash sent by Alice
- Threat model: Mallory can modify the message *and the hash*
  - No integrity!

Do hashes provide integrity?

- It depends on your threat model
- If the attacker can modify the hash, hashes don’t provide integrity
- Main issue: Hashes are *unkeyed* functions
    - There is no secret key being used as input, so any attacker can compute a hash on any value
- Next: Use hashes to design schemes that provide integrity

Message Authentication Codes (MACs)

Textbook Chapter 8.1–8.3 & 8.5–8.6

Cryptography Roadmap

	Symmetric-key	Asymmetric-key
Confidentiality	● One-time pads ● Block ciphers with chaining modes (e.g. AES-CBC)	● RSA encryption ● ElGamal encryption
Integrity, Authentication	● MACs (e.g. HMAC)	● Digital signatures (e.g. RSA signatures)

- Hash functions
- Pseudorandom number generators
- Public key exchange (e.g. Diffie-Hellman)

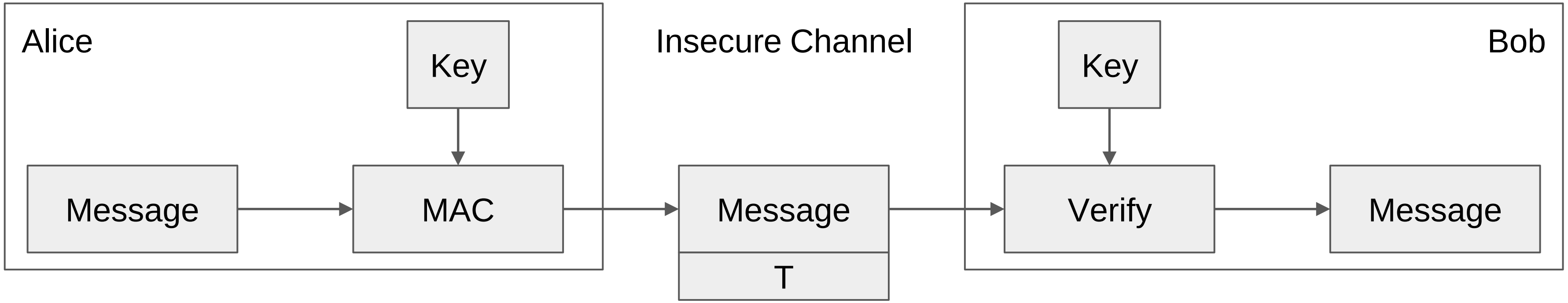
- Key management (certificates)
- Password management

How to Provide Integrity

- Reminder: We’re still in the symmetric-key setting
    - Assume that Alice and Bob share a secret key, and attackers don’t know the key
- We want to attach some piece of information to *prove* that someone with the key sent this message
    - This piece of information can only be generated by someone with the key

MACs: Usage

- Alice wants to send *M* to Bob, but doesn't want Mallory to tamper with it
- Alice sends *M* and *T* = MAC(*K*, *M*) to Bob
- Bob receives *M* and *T*
- Bob computes MAC(*K*, *M*) and checks that it matches *T*
- If the MACs match, Bob is confident the message has not been tampered with (integrity)



MACs: Definition

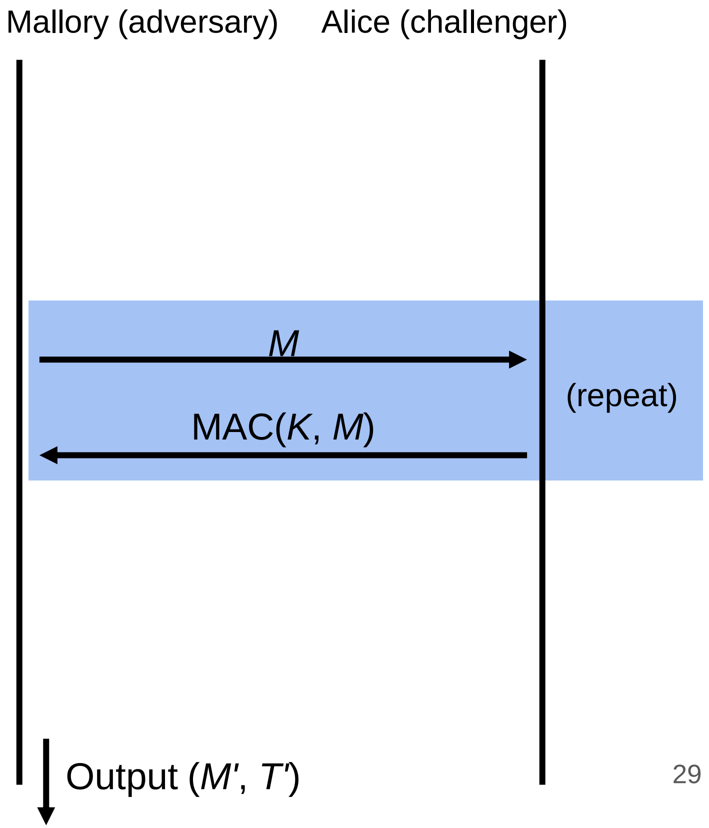
- Two parts:
  - KeyGen() → *K*: Generate a key *K*
  - MAC(*K*, *M*) → *T*: Generate a tag *T* for the message *M* using key *K*
    - Inputs: A secret key and an arbitrary-length message
    - Output: A fixed-length **tag** on the message
- Properties
  - **Correctness**: Determinism
    - Note: Some more complicated MAC schemes have an additional Verify(*K*, *M*, *T*) function that don't require determinism, but this is out of scope
  - **Efficiency**: Computing a MAC should be efficient
  - **Security**: EU-CPA (existentially unforgeable under chosen plaintext attack)

Defining Integrity: EU-CPA

- A secure MAC is **existentially unforgeable**: without the key, an attacker cannot create a valid tag on a message
  - Mallory cannot generate MAC(K, M') without K
  - Mallory cannot find any $M' \neq M$ such that MAC(K, M') = MAC(K, M)
- Formally defined by a security game: existential unforgeability under chosen-plaintext attack, or EU-CPA
- MACs should be unforgeable under chosen plaintext attack
  - Intuition: Like IND-CPA, but for integrity and authenticity
  - Even if Mallory can trick Alice into creating MACs for messages that Mallory chooses, Mallory cannot create a valid MAC on a message that she hasn't seen before

Defining Integrity: EU-CPA

1. Mallory may send messages to Alice and receive their tags
2. Eventually, Mallory creates a message-tag pair (*M'*, *T'*)
    - *M'* cannot be a message that Mallory requested earlier
    - If *T'* is a valid tag for *M'*, then Mallory wins. Otherwise, she loses.
    - A scheme is EU-CPA secure if for *all* polynomial time adversaries, the probability of winning is 0 or negligible



Example: NMAC

- Can we use secure cryptographic hashes to build a secure MAC?
  - Intuition: Hash output is unpredictable and looks random, so let's hash the key and the message together
- KeyGen():
  - Output two random, n-bit keys K_1 and K_2, where n is the length of the hash output
- NMAC(K_1, K_2, M):
  - Output $H(K_1 \| H(K_2 \| M))$
- NMAC is EU-CPA secure if the two keys are different
  - Provably secure if the underlying hash function is secure
- Intuition: Using two hashes prevents a length extension attack
  - Otherwise, an attacker who sees a tag for M could generate a tag for $M \| M'$

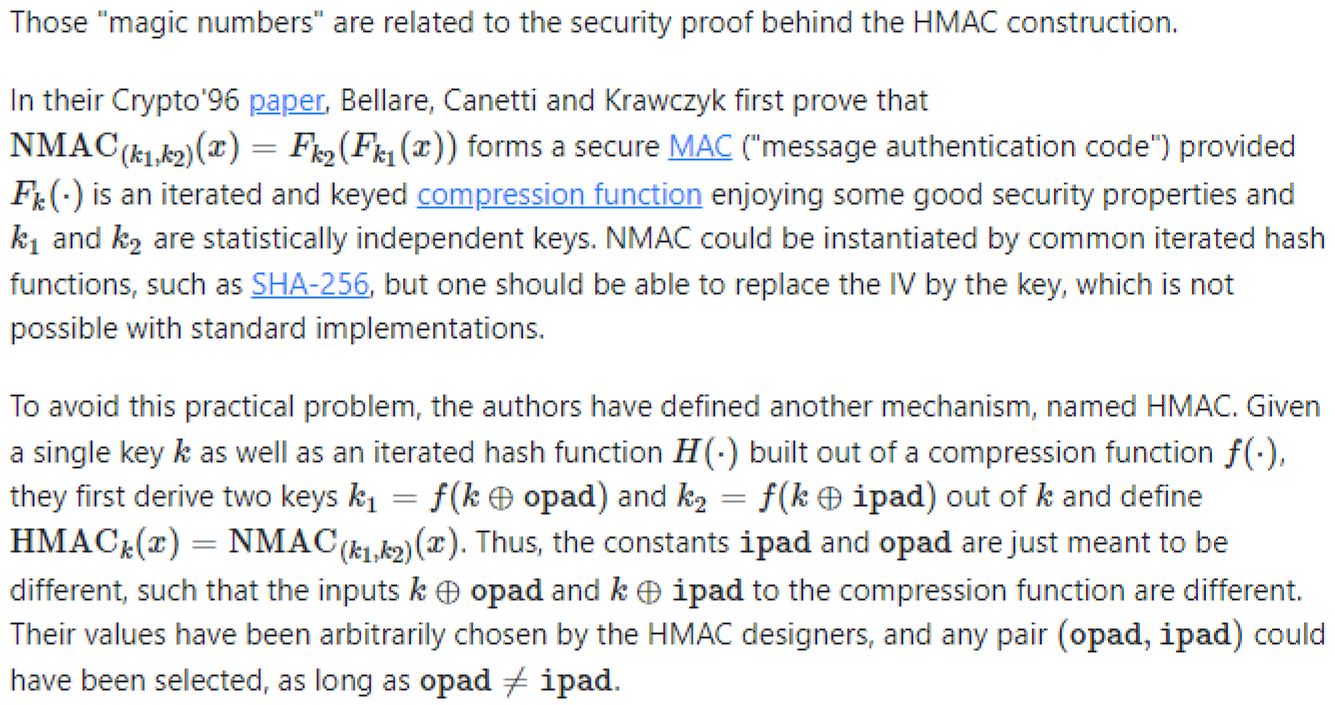
Example: HMAC

- Issues with NMAC:
  - Recall: NMAC(K_1, K_2, M) = $H(K_1 \mathbin{\|} H(K_2 \mathbin{\|} M))$
  - We need two different keys
  - NMAC requires the keys to be the same length as the hash output (n bits)
  - Can we use NMAC to design a scheme that uses one key?
- HMAC(K, M):
  - Compute K' as a version of K that is the length of the hash output
    - If K is too short, pad K with 0's to make it n bits (be careful with keys that are too short and lack randomness)
    - If K is too long, hash it so it's n bits
  - Output $H((K' \oplus opad) \mathbin{\|} H((K' \oplus ipad) \mathbin{\|} M))$

Example: HMAC

- HMAC(K, M):
  - Compute K' as a version of K that is the length of the hash output
    - If K is too short, pad K with 0's to make it n bits (be careful with keys that are too short and lack randomness)
    - If K is too long, hash it so it's n bits
  - Output $H((K' \oplus opad) \| H((K' \oplus ipad) \| M))$
- Use K' to derive two different keys
  - *opad* (outer pad) is the hard-coded byte **`0x5c`** repeated until it's the same length as K'
  - *ipad* (inner pad) is the hard-coded byte **`0x36`** repeated until it's the same length as K'
  - As long as *opad* and *ipad* are different, you'll get two different keys
  - For paranoia, the designers chose two very different bit patterns, even though they theoretically need only differ in one bit

HMAC Magic Numbers: 0x5c and 0x36



Those "magic numbers" are related to the security proof behind the HMAC construction.

In their Crypto'96 paper, Bellare, Canetti and Krawczyk first prove that $\mathbf{NMAC}_{(k_1,k_2)}(x) = F_{k_2}(F_{k_1}(x))$ forms a secure MAC ("message authentication code") provided $F_k(\cdot)$ is an iterated and keyed compression function enjoying some good security properties and k_1 and k_2 are statistically independent keys. NMAC could be instantiated by common iterated hash functions, such as SHA-256, but one should be able to replace the IV by the key, which is not possible with standard implementations.

To avoid this practical problem, the authors have defined another mechanism, named HMAC. Given a single key k as well as an iterated hash function $H(\cdot)$ built out of a compression function $f(\cdot)$, they first derive two keys $k_1 = f(k \oplus \mathbf{opad})$ and $k_2 = f(k \oplus \mathbf{ipad})$ out of k and define $\mathbf{HMAC}_k(x) = \mathbf{NMAC}_{(k_1,k_2)}(x)$. Thus, the constants $\mathbf{ipad}$ and $\mathbf{opad}$ are just meant to be different, such that the inputs $k \oplus \mathbf{opad}$ and $k \oplus \mathbf{ipad}$ to the compression function are different. Their values have been arbitrarily chosen by the HMAC designers, and any pair $(\mathbf{opad}, \mathbf{ipad})$ could have been selected, as long as $\mathbf{opad} \neq \mathbf{ipad}$.

https://crypto.stackexchange.com/questions/3005/what-do-the-magic-numbers-0x5c-and-0x36-in-the-opad-ipad-calc-in-hmac-do

HMAC Properties

- HMAC(K, M) = H(($K' \oplus opad$) || H(($K' \oplus ipad$) || M))
- HMAC is a hash function, so it has the properties of the underlying hash too
    - It is collision resistant
    - Given HMAC(K, M) and K, an attacker can’t learn M
    - If the underlying hash is secure, HMAC doesn’t reveal M, but it is still deterministic
- You can’t verify a tag T if you don’t have K
    - This means that an attacker can’t brute-force the message M without knowing K

Do MACs provide integrity?

- Do MACs provide integrity?
  - Yes. An attacker cannot tamper with the message without being detected
- Do MACs provide authenticity?
  - It depends on your threat model
  - If a message has a valid MAC, you can be sure it came from *someone with the secret key*, but you can't narrow it down to one person
  - If only two people have the secret key, MACs provide authenticity: it has a valid MAC, and it's not from me, so it must be from the other person
- Do MACs provide confidentiality?
  - MACs are deterministic ⇒ No IND-CPA security
  - MACs in general have no confidentiality guarantees; they can leak information about the message
    - HMAC doesn't leak information about the message, but it's still deterministic, so it's not IND-CPA secure

Authenticated Encryption

Textbook Chapter 8.7 & 8.8

Cryptography Roadmap

	Symmetric-key	Asymmetric-key
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- Hash functions
- Pseudorandom number generators
- Public key exchange (e.g. Diffie-Hellman)

- Key management (certificates)
- Password management

Authenticated Encryption: Definition

- **Authenticated encryption** (**AE**): A scheme that simultaneously guarantees confidentiality and integrity (and authenticity, depending on your threat model) on a message
- Two ways of achieving authenticated encryption:
    - Combine schemes that provide confidentiality with schemes that provide integrity
    - Use a scheme that is designed to provide confidentiality and integrity

Combining Schemes: Let’s design it together

- You can use:
  - An IND-CPA encryption scheme (e.g. AES-CBC): Enc(K, M) and Dec(K, M)
  - An unforgeable MAC scheme (e.g. HMAC): MAC(K, M)
- First attempt: Alice sends Enc(K_1, M) and MAC(K_2, M)
  - Integrity? Yes, attacker can’t tamper with the MAC
  - Confidentiality? No, the MAC is not IND-CPA secure
- Idea: Let’s compute the MAC on the *ciphertext* instead of the plaintext: Enc(K_1, M) and MAC(k_2, Enc(K_1, M))
  - Integrity? Yes, attacker can’t tamper with the MAC
  - Confidentiality? Yes, the MAC might leak info about the ciphertext, but that’s okay
- Idea: Let’s encrypt the MAC too: Enc(K_1, M || MAC(K_2, M))
  - Integrity? Yes, attacker can’t tamper with the MAC
  - Confidentiality? Yes, everything is encrypted

MAC-then-Encrypt or Encrypt-then-MAC?

- MAC-then-encrypt
    - First compute MAC(K_2, M)
    - Then encrypt the message and the MAC together: Enc(K_1, M || MAC(K_2, M))
- Encrypt-then-MAC
    - First compute Enc(K_1, M)
    - Then MAC the ciphertext: MAC(K_2, Enc(K_1, M))
- Which is better?
    - In theory, both are IND-CPA and EU-CPA secure if applied properly
    - MAC-then-encrypt has a flaw: You don’t know if tampering has occurred until after decrypting
        - Attacker can supply arbitrary tampered input, and you always have to decrypt it
        - Passing attacker-chosen input through the decryption function can cause side-channel leaks
- **Always use encrypt-then-MAC** because it’s more robust to mistakes

Key Reuse

- **Key reuse**: Using the same key in two different use cases
  - Note: Using the same key multiple times for the same use (e.g. computing HMACs on different messages in the same context with the same key) is not key reuse
- Reusing keys can cause the underlying algorithms to interfere with each other and affect security guarantees
  - Example: If you use a block-cipher-based MAC algorithm and a block cipher chaining mode, the underlying block ciphers may no longer be secure
  - Thinking about these attacks is hard

Key Reuse

- Simplest solution: Do not reuse keys! One key per *use*.
  - Encrypt a piece of data and MAC a piece of data?
    - Different use; different key
  - MAC one of Alice’s messages to Bob and MAC one of Bob’s messages to Alice?
    - Different use; different key
  - Encrypt one of Alice’s files and encrypt another one of Alice’s files?
    - It’s *probably* fine to use the same key, but cryptographic design is tricky to get right!
  - Encrypt user metadata, encrypt file metadata, and encrypt file data?
    - You’ll have to think about this in Project 2!

TLS 1.0 “Lucky 13” Attack

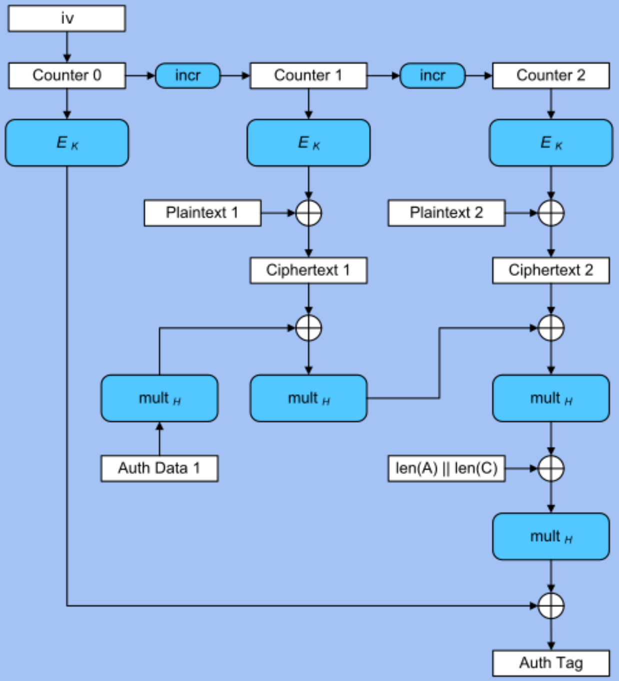
- TLS: A protocol for sending encrypted and authenticated messages over the Internet (we’ll study it more in the networking unit)
- TLS 1.0 uses MAC-then-encrypt: $\text{Enc}(K_1, M \,||\, \text{MAC}(K_2, M))$
  - The encryption algorithm is AES-CBC
- The Lucky 13 attack abuses MAC-then-encrypt to read encrypted messages
  - Guess a byte of plaintext and change the ciphertext accordingly
  - The MAC will error, but the time it takes to error is different depending on if the guess is correct
  - Attacker measures how long it takes to error in order to learn information about plaintext
  - TLS will send the message again if the MAC errors, so the attacker can guess repeatedly
- Takeaways
  - Side channel attack: The algorithm is proved secure, but poor implementation made it vulnerable
  - Always encrypt-then-MAC
  - You’ll try a similar attack in Homework 2!

AEAD Encryption

- Second method for authenticated encryption: Use a scheme that is designed to provide confidentiality, integrity, and authenticity
- **Authenticated encryption with additional data** (**AEAD**): An algorithm that provides both confidentiality and integrity over the plaintext and integrity over *additional data*
  - Additional data is usually context (e.g. memory address), so you can't change the context without breaking the MAC
- Great if used correctly: No more worrying about MAC-then-encrypt
  - If you use AEAD incorrectly, you lose *both* confidentiality and integrity/authentication
  - Example of correct usage: Using a crypto library with AEAD

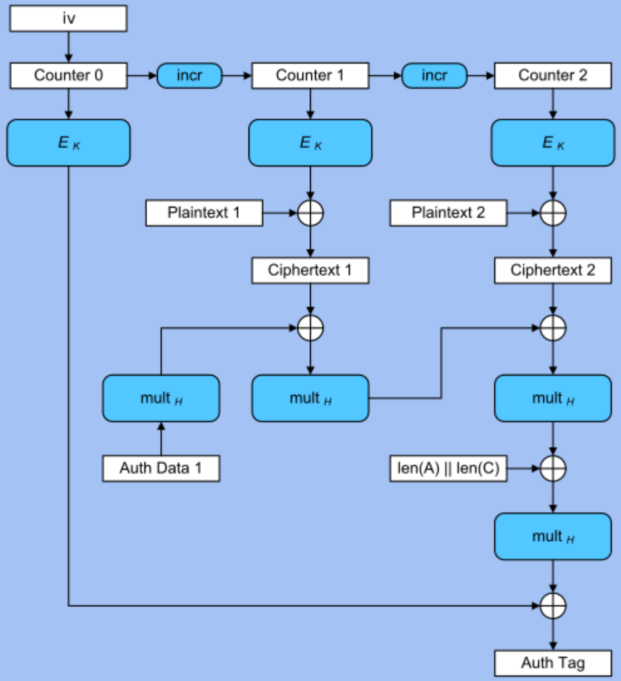
AEAD Example: Galois Counter Mode (GCM)

- **Galois Counter Mode** (**GCM**): An AEAD block cipher mode of operation
- *E*E_K is standard block cipher encryption
- mult_H is 128-bit multiplication over a special field (Galois multiplication)
    - Don’t worry about the math



AEAD Example: Galois Counter Mode (GCM)

- Very fast mode of operation
  - Fully parallel encryption
  - Galois multiplication isn't parallelizable, but it's very fast
- Drawbacks
  - IV reuse leads to loss of confidentiality, integrity, and authentication
  - This wouldn't happen if you used AES-CTR and HMAC-SHA256
  - Implementing Galois implementation is difficult and easy to screw up
- **Takeaway**: GCM provides integrity and confidentiality, but if you misuse it, it's even worse than CTR mode



Hashes: Summary

- Map arbitrary-length input to fixed-length output
- Output is deterministic and unpredictable
- Security properties
  - One way: Given an output y, it is infeasible to find any input x such that $H(x) = y$.
  - Second preimage resistant: Given an input x, it is infeasible to find another input $x' \neq x$ such that $H(x) = H(x')$.
  - Collision resistant: It is infeasible to find another any pair of inputs $x' \neq x$ such that $H(x) = H(x')$.
- Some hashes are vulnerable to length extension attacks
- Application: Lowest hash scheme
- Hashes don’t provide integrity (unless you can publish the hash securely)

MACs: Summary

- Inputs: a secret key and a message
- Output: a tag on the message
- A secure MAC is unforgeable: Even if Mallory can trick Alice into creating MACs for messages that Mallory chooses, Mallory cannot create a valid MAC on a message that she hasn't seen before
    - Example: HMAC(K, M) = $H((K' \oplus opad) \| H((K' \oplus ipad) \| M))$
- MACs do not provide confidentiality

Authenticated Encryption: Summary

- Authenticated encryption: A scheme that simultaneously guarantees confidentiality and integrity (and authenticity) on a message
- First approach: Combine schemes that provide confidentiality with schemes that provide integrity and authenticity
    - MAC-then-encrypt: Enc(K_1, M || MAC(K_2, M))
    - Encrypt-then-MAC: Enc(K_1, M) || MAC(K_2, Enc(K_1, M))
    - Always use Encrypt-then-MAC because it's more robust to mistakes
- Second approach: Use AEAD encryption modes designed to provide confidentiality, integrity, and authenticity
    - Drawback: Incorrectly using AEAD modes leads to losing *both* confidentiality and integrity/authentication

Next Time

- Symmetric-key encryption schemes need randomness. How do we securely generate random numbers?
- When discussing symmetric-key schemes, we assumed Alice and Bob managed to share a secret key. How can Alice and Bob share a symmetric key over an insecure channel?