

Cryptographic Hashes and MACs

ITIS 6200/8200 Fall 2023

Last Time: Block Ciphers

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- 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

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- 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

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- 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

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- 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

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

M	P	a	y		M	a	l		\$	1	0	0
	0x50	0x61	0x79	0x20	0x4d	0x61	0x6c	0x20	0x24	0x31	0x30	0x30
\oplus												
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Lack of Integrity and Authenticity

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

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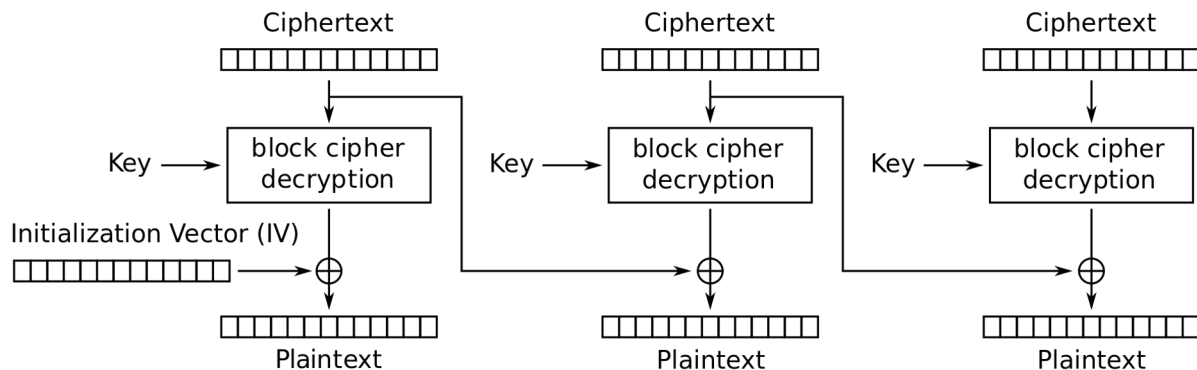
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P'	0x50	0x61	0x79	0x20	0x4d	0x61	0x6c	0x20	0x24	0x39	0x30	0x30
	P	a	y		M	a	l		\$	9	0	0

Lack of Integrity and Authenticity

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- 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

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- 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

Cryptography Roadmap

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	Symmetric-key	Asymmetric-key
Confidentiality	<ul style="list-style-type: none">● One-time pads● Block ciphers with chaining modes (e.g. AES-CBC)	<ul style="list-style-type: none">● RSA encryption● ElGamal encryption
Integrity, Authentication	<ul style="list-style-type: none">● MACs (e.g. HMAC)	<ul style="list-style-type: none">● 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

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- Hash function: $H(M)$
 - Input: *Arbitrary* length message M
 - Output: *Fixed* length, n -bit hash
- 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

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- 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

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- **Informal:** Given an output y , it is infeasible to find *any* input x such that $H(x) = y$
- 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

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- **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

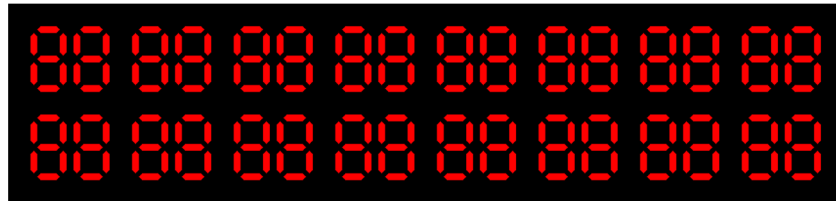
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- **Birthday attack:** Finding a collision on an n -bit output requires only $2^{n/2}$ tries on average
 - This is why a group of 23 people are >50% likely to have at least one birthday in common

Hash Function: Examples

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- 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

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- **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
 - Note: This doesn't violate any property of hash functions but is undesirable
- **Example:**
 - Alice and Bob both have grade A in the ITIS 6200 course
 - Alice is sending a message M and hash $H(M)$ to Bob:
 - $M = \text{"Alice's grade is A!"}$
 - $H(M) = 231fac801f63e30cd921477ddd30c866$
 - Mallory can perform length extension attack to create a new message M' and $H(M')$
 - $M' = \text{"Alice's grade is A! Bob's grade is D!"}$
 - $H(M') = 894729e572d96d9ff15d8a569d2fc5e0$
 - When Bob receives the message, he would think this is a message sent by Alice.
- MD5, SHA-1, SHA-256 (256-bit version of SHA-2) are vulnerable
- SHA-3 is not vulnerable

Do hashes provide integrity?

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- 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?

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- 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?

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- 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)

Cryptography Roadmap

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	Symmetric-key	Asymmetric-key
Confidentiality	<ul style="list-style-type: none">● One-time pads● Block ciphers with chaining modes (e.g. AES-CBC)	<ul style="list-style-type: none">● RSA encryption● ElGamal encryption
Integrity, Authentication	<ul style="list-style-type: none">● MACs (e.g. HMAC)	<ul style="list-style-type: none">● 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

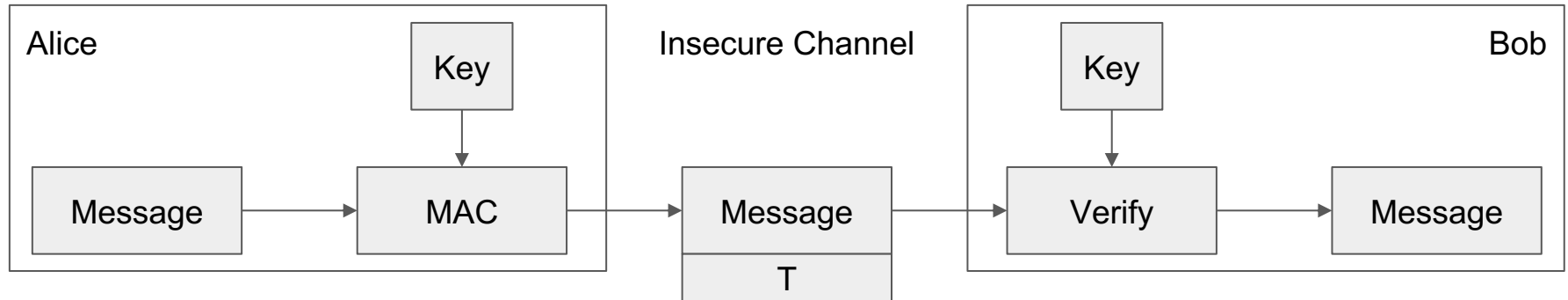
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- Reminder: We're still in the symmetric-key setting
 - Assume that Alice and Bob share a secret key, and attackers don't know the key
- We want to attach some piece of information to *prove* that someone with the key sent this message
 - This piece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

MACs: Usage

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



MACs: Definition

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- Two parts:
 - $\text{KeyGen}() \rightarrow K$: Generate a key K
 - $\text{MAC}(K, M) \rightarrow T$: 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 $\text{Verify}(K, M, T)$ 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

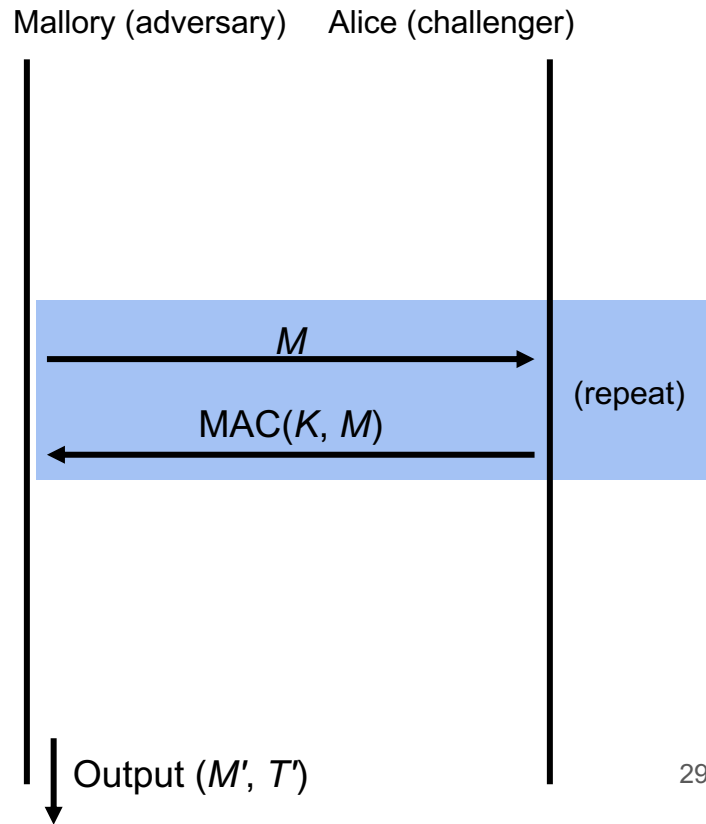
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- A secure MAC is **existentially unforgeable**: without the key, an attacker cannot create a valid tag on a message
 - Mallory cannot generate $\text{MAC}(K, M')$ without K
 - Mallory cannot find any $M' \neq M$ such that $\text{MAC}(K, M') = \text{MAC}(K, M)$
 - **Otherwise**, Mallory can send M' and $\text{MAC}(K, M')$ to Bob, and Bob won't notice a problem
- 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

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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

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- 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

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- Issues with NMAC:
 - Recall: $\text{NMAC}(K_1, K_2, M) = H(K_1 \parallel H(K_2 \parallel M))$
 - 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?
- $\text{HMAC}(K, M)$:
 - 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 $H(K' \oplus opad \parallel H(K' \oplus ipad \parallel M))$

Example: HMAC

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- 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 $H((K' \oplus \text{opad}) \parallel H((K' \oplus \text{ipad}) \parallel M))$
- 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 Properties

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- $\text{HMAC}(K, M) = H((K' \oplus \text{opad}) \parallel H((K' \oplus \text{ipad}) \parallel M))$
- HMAC is a hash function, so it has the properties of the underlying hash too
 - It is collision resistant
 - Given $\text{HMAC}(K, M)$ 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?

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- 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 \Rightarrow 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

Cryptography Roadmap

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

- Key management (certificates)
- Password management

Authenticated Encryption: Definition

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- **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

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- You can use:
 - An IND-CPA encryption scheme (e.g. AES-CBC): $\text{Enc}(K, M)$ and $\text{Dec}(K, M)$
 - An unforgeable MAC scheme (e.g. HMAC): $\text{MAC}(K, M)$
- First attempt: Alice sends $\text{Enc}(K_1, M)$ and $\text{MAC}(K_2, M)$
 - 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:
 $\text{Enc}(K_1, M)$ and $\text{MAC}(K_2, \text{Enc}(K_1, M))$
 - 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: $\text{Enc}(K_1, M \parallel \text{MAC}(K_2, M))$
 - Integrity? Yes, attacker can't tamper with the MAC
 - Confidentiality? Yes, everything is encrypted

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

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- MAC-then-encrypt
 - First compute $\text{MAC}(K_2, M)$
 - Then encrypt the message and the MAC together: $\text{Enc}(K_1, M \parallel \text{MAC}(K_2, M))$
- Encrypt-then-MAC
 - First compute $\text{Enc}(K_1, M)$
 - Then MAC the ciphertext: $\text{MAC}(K_2, \text{Enc}(K_1, M))$
- 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

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- **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

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- 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!

TLS 1.0 “Lucky 13” Attack

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- 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: $\text{Enc}(K_1, M \parallel \text{MAC}(K_2, M))$
 - 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 (timing channel): The algorithm is proved secure, but poor implementation made it vulnerable
 - Always encrypt-then-MAC

AEAD Encryption

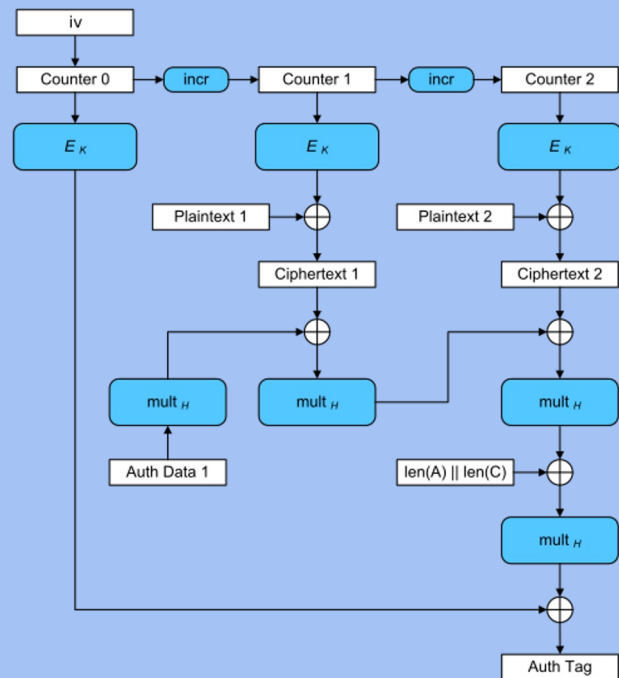
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- Second method for authenticated encryption: Use a scheme that is designed to provide confidentiality, integrity, and authenticity
- **Authenticated encryption with additional data (AEAD)**: An algorithm that provides both confidentiality and integrity 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)

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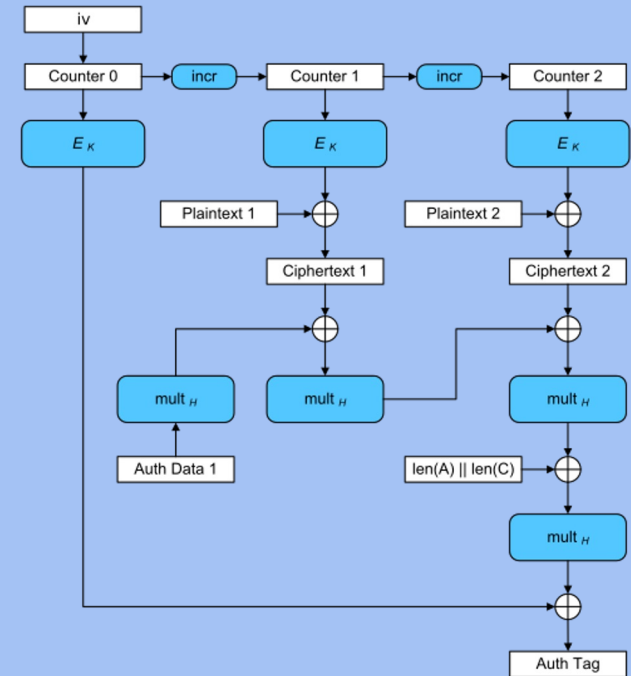
- **Galois Counter Mode (GCM):** An AEAD block cipher mode of operation
- E_K is standard block cipher encryption
- mult_H is 128-bit multiplication over a special field (Galois multiplication)
 - Don't worry about the math



AEAD Example: Galois Counter Mode (GCM)

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- 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

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- 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

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- 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: $\text{HMAC}(K, M) = H((K' \oplus \text{opad}) \parallel H((K' \oplus \text{ipad}) \parallel M))$
- MACs do not provide confidentiality

Authenticated Encryption: Summary

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- 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: $\text{Enc}(K_1, M \parallel \text{MAC}(K_2, M))$
 - Encrypt-then-MAC: $\text{Enc}(K_1, M) \parallel \text{MAC}(K_2, \text{Enc}(K_1, M))$
 - 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

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- 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?