Block Cipher Chaining Modes (cont’d) & Cryptographic Hashes

CS 161 Spring 2023 - Lecture 7

Announcements

- Project 1 (Q1–Q7, plus write-up) is due Friday, February 9th at 11:59 PM PT.
  - When you are writing your write-up please explain the vulnerability and your exploit in a detailed manner. Your write-up should include the logical steps you take when you are coming up with your exploit as well as the magic numbers you found using GDB.
  - Please make sure you fill out the OH template when you are making your ticket. The tickets that don't provide this template will not be taken.
- Homework 2 is due Friday, February 9th at 11:59 PM PT.
- The midterm is on Thursday, February 29th from 7:00-9:00 PM PT.
  - If you would like to request an alternate exam time or remote exam, or have DSP accommodations or any special requests, please fill out the Exam Logistics Form by Monday, February 19, 11:59 PM PT.

Last Time: Block Ciphers

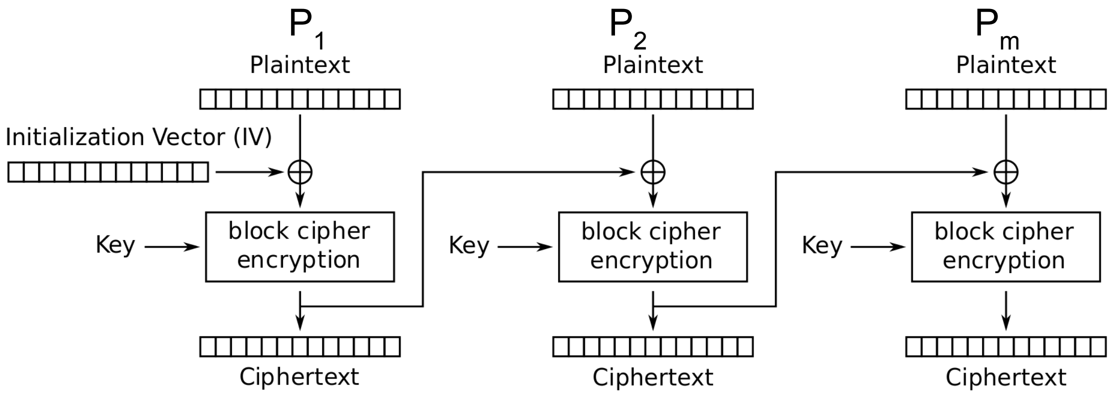
- Encryption: input a *k*-bit key and *n*-bit plaintext, receive *n*-bit ciphertext
- Decryption: input a *k*-bit key and *n*-bit ciphertext, receive *n*-bit plaintext
- Correctness: when the key is fixed, $E_K(M)$ should be bijective
- Security
  - Without the key, $E_K(m)$ is computationally indistinguishable 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

Block Cipher Modes of Operation: Summary

- 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

Recall: CBC Mode

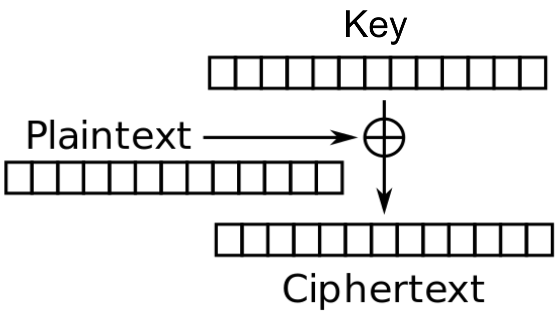
- We've just designed **cipher block chaining (CBC) mode**
- $C_i = E_K(M_i \oplus C_{i-1})$; $C_0 = IV$
- Enc(K, M):
  - Split M in m plaintext blocks $P_1 \ldots P_m$ each of size n
  - Choose a random IV
  - Compute and output $(IV, C_1, \ldots, C_m)$ as the overall ciphertext
- How do we decrypt?



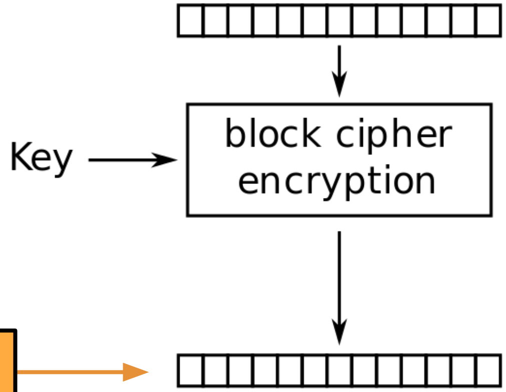
Cipher Block Chaining (CBC) mode encryption

CTR Mode Scratchpad: Let's design it together

One-time pads are secure if we never reuse the key.



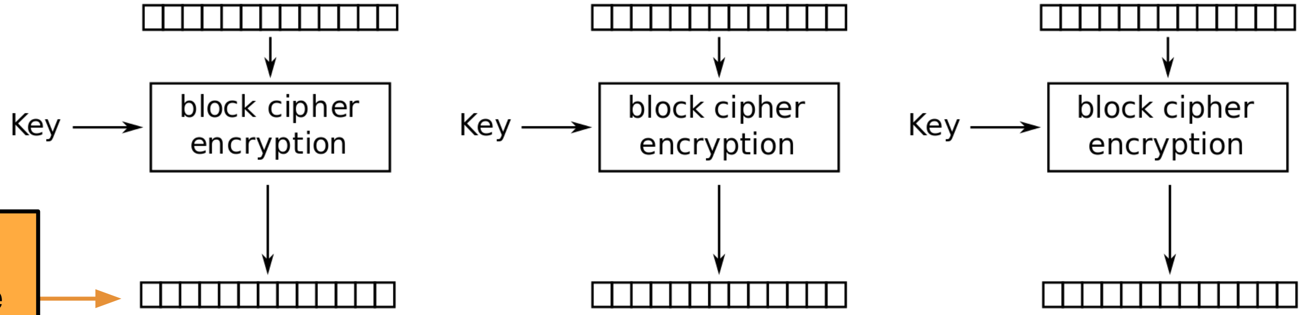
CTR Mode Scratchpad: Let's design it together



If the attacker doesn't know the key, the block cipher output looks random.

New idea: Can we use block ciphers to simulate a one-time pad?

CTR Mode Scratchpad: Let's design it together

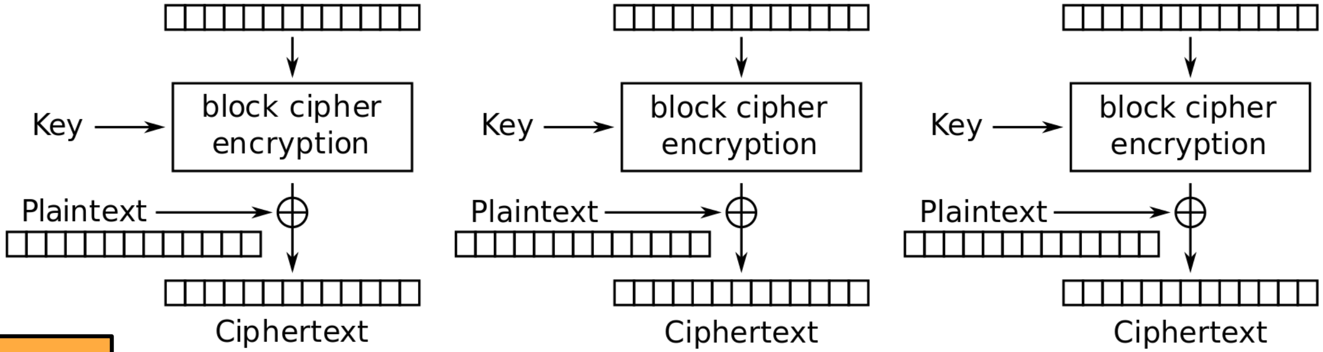


If the attacker doesn't know the key, all of these outputs look random.

CTR Mode Scratchpad: Let's design it together

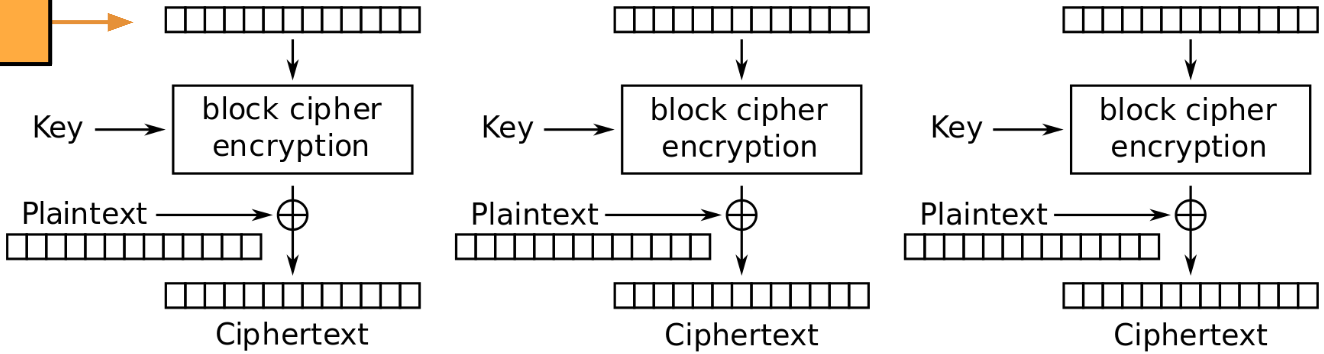
Idea: Use this random-looking output as a one-time pad!

Remember one-time pads: XOR the pad with plaintext to get ciphertext



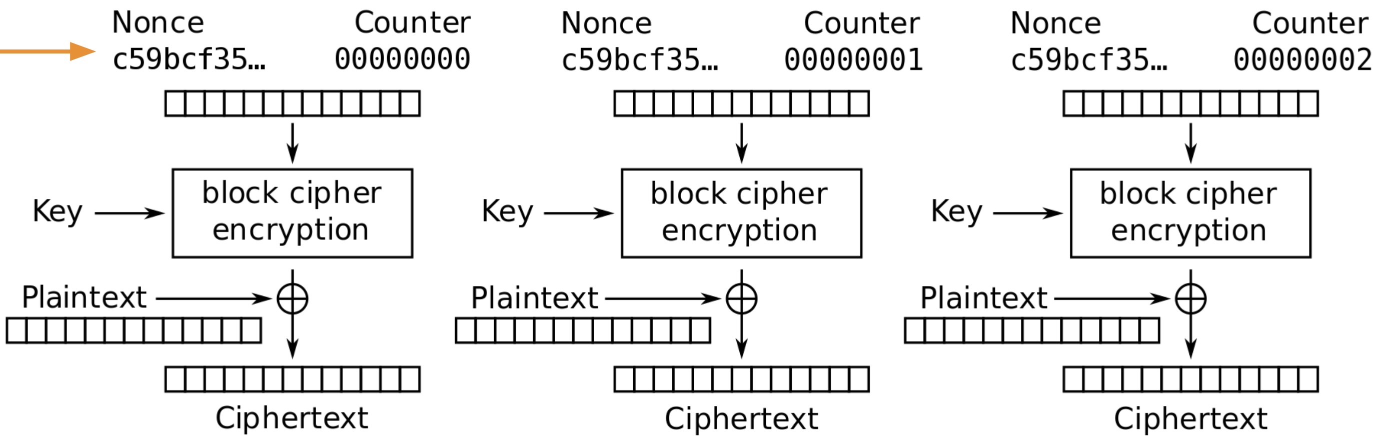
CTR Mode Scratchpad: Let's design it together

What do we use as input to the block cipher?



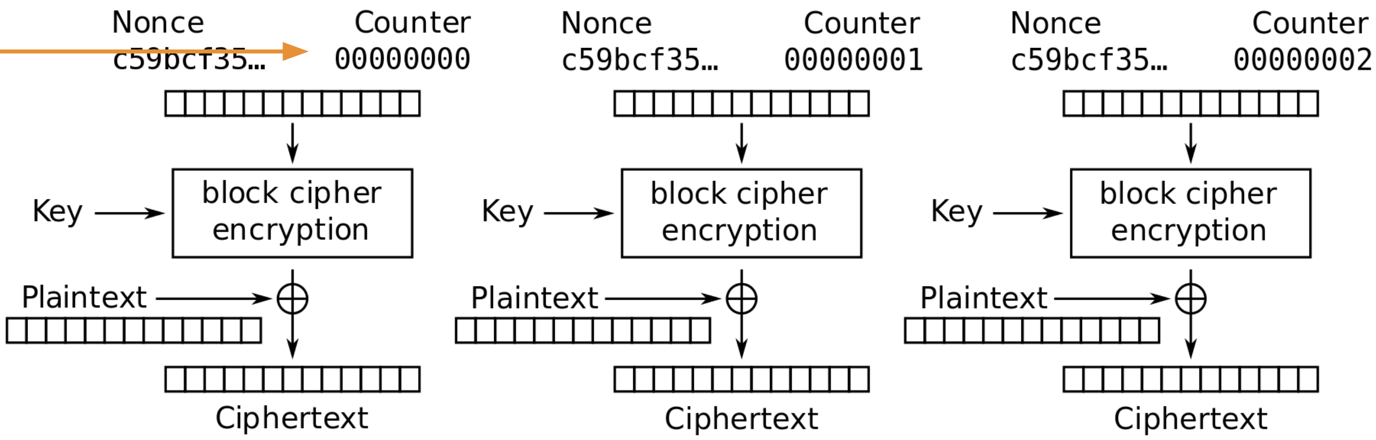
CTR Mode Scratchpad: Let's design it together

IND-CPA schemes need randomness, so let's put a random **nonce** here!



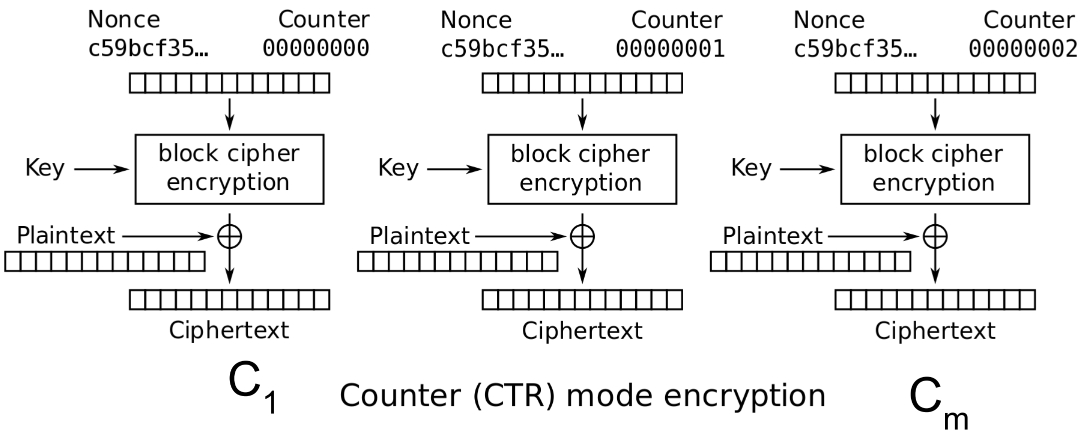
CTR Mode Scratchpad: Let's design it together

The **counter** increments per block to ensure each block cipher output is different.



CTR (Counter) Mode

- Note: the random value is named the nonce here, but the idea is the same as the IV in CBC mode
- Overall ciphertext is (Nonce, C_1, …, C_m)

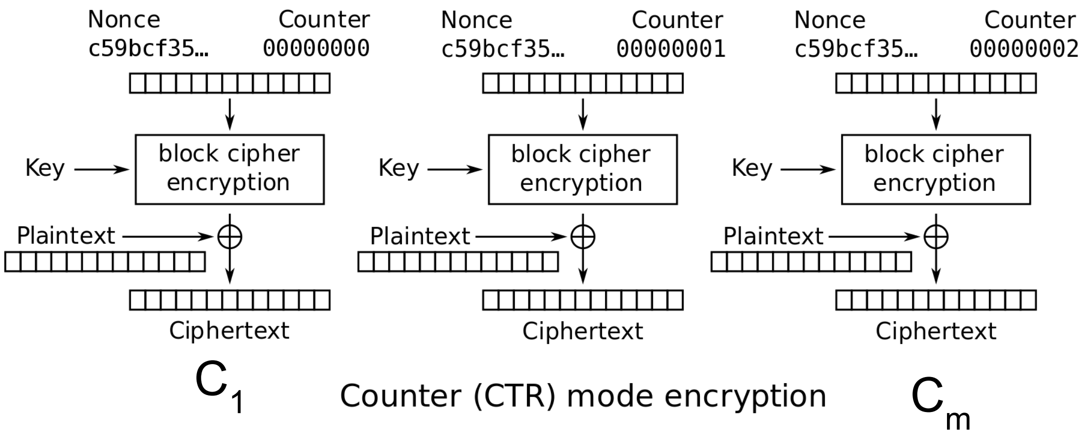


Counter (CTR) mode encryption

CTR Mode

- Enc(K, M):
  - Split M in plaintext blocks $P_1 \ldots P_m$ (each of block size n)
  - Choose random nonce
  - Compute and output (Nonce, C_1, …, C_m)

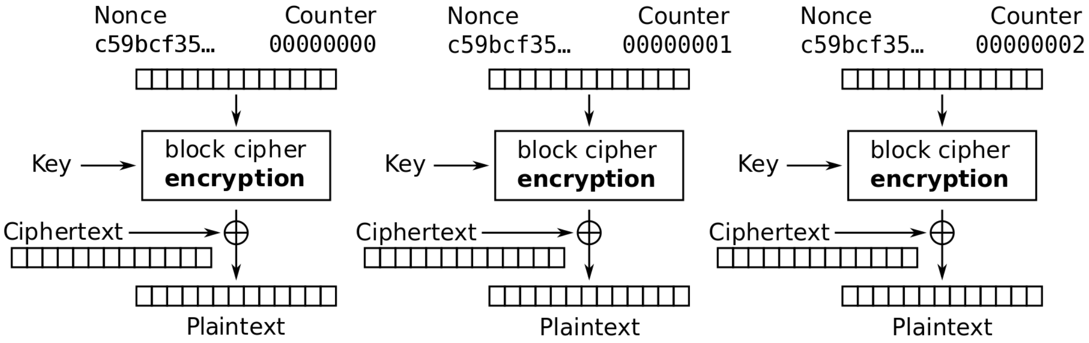
How do you decrypt?



Counter (CTR) mode encryption

CTR Mode: Decryption

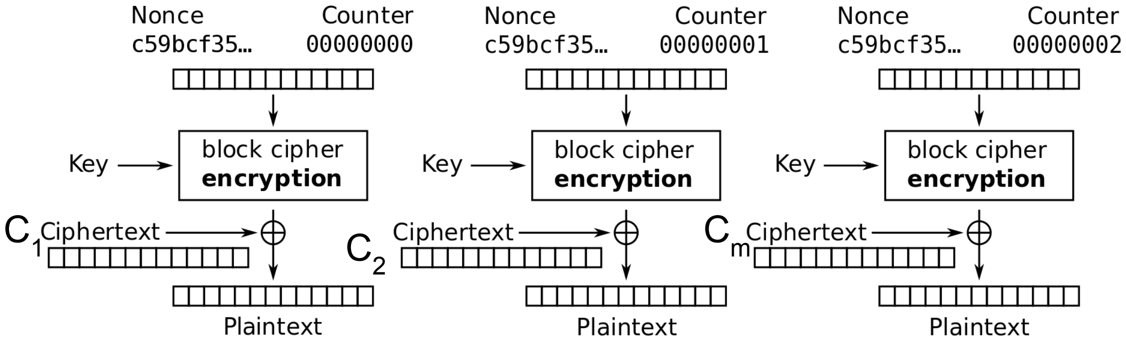
- Recall one-time pad: XOR with ciphertext to get plaintext
- Note: we are only using block cipher encryption, not decryption



Counter (CTR) mode decryption

CTR Mode: Decryption

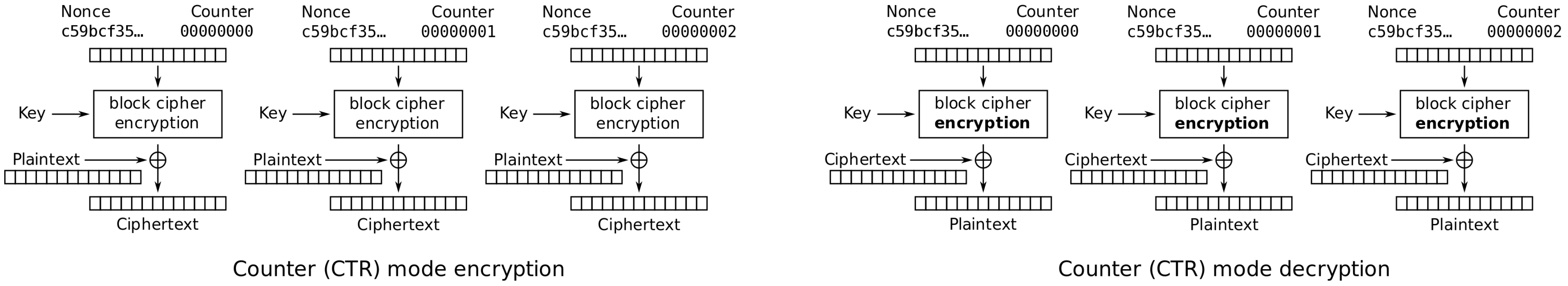
- Dec(K, C):
  - Parse C into (nonce, C_1, …, C_m)
  - Compute P_i by XORing Ci with output of E_k on nonce and counter
  - Concatenate resulting plaintexts and output M = P_1 … P_m



Counter (CTR) mode decryption

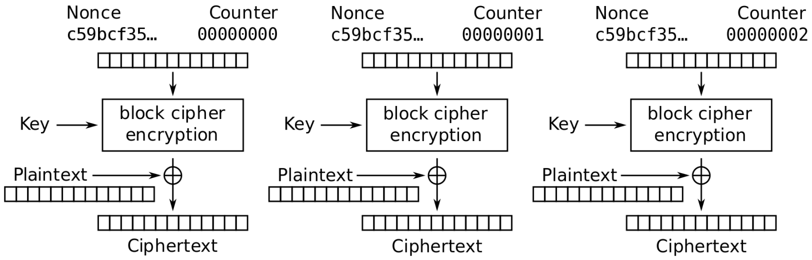
CTR Mode: Efficiency

- Can encryption be parallelized?
  - Yes
- Can decryption be parallelized?
  - Yes

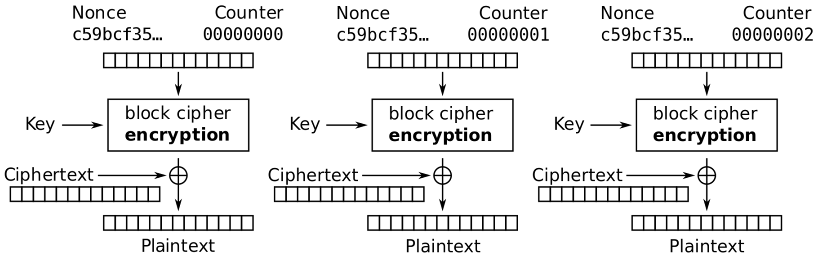


CTR Mode: Padding

- Do we need to pad messages?
  - No! We can just cut off the parts of the XOR that are longer than the message.



Counter (CTR) mode encryption



Counter (CTR) mode decryption

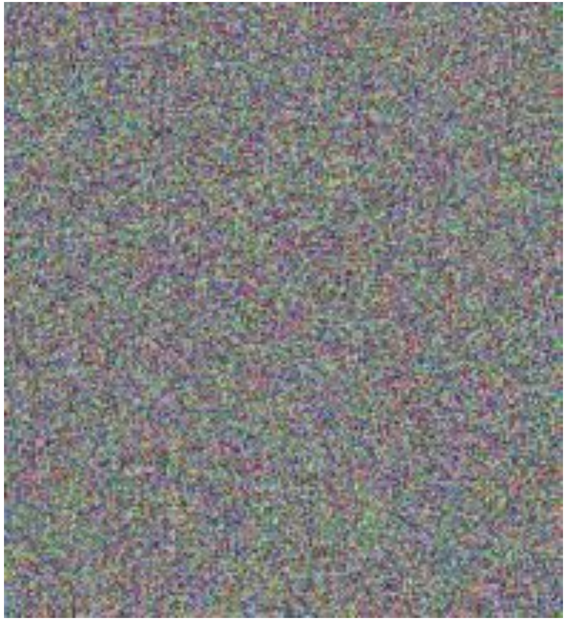
CTR Mode: Security

- AES-CTR is IND-CPA secure. With what assumption?
- The nonce should never be reused (random generation helps here)
  - And in general less than $2^{n/2}$ blocks are encrypted
- What happens if you reuse the nonce?
- Equivalent to reusing a key in a one-time pad
  - Recall: Key reuse in a one-time pad is catastrophic: usually leaks enough information for an attacker to deduce the entire plaintext

CTR Mode: Penguin

Original image

CTR Mode: Penguin



Encrypted with CTR, with random nonces

IVs and Nonces

- **Initialization vector** (**IV**): A random, but public, one-use value to introduce randomness into the algorithm
  - For CTR mode, we say that you use a **nonce** (number used once), since the value has to be unique, not necessarily random.
  - In this class, we use IV and nonce interchangeably
- **Never reuse IVs**
  - In some algorithms, IV/nonce reuse leaks limited information (e.g. CBC)
  - In some algorithms, IV/nonce reuse leads to catastrophic failure (e.g. CTR)

IVs and Nonces

- Thinking about the consequences of IV/nonce reuse is hard
- What if the IV/nonce is not reused, but the attacker can predict future values?
  - Now you have to think about more attacks
  - We’ll analyze this more in discussion: it really depends on the encryption function
- Solution: Randomly generate a new IV/nonce for every encryption
  - If the nonce is 128 bits or longer, the probability of generating the same IV/nonce twice is astronomically small (basically 0)
  - Now you don’t have to think about IV/nonce reuse attacks!

The summer 2020 CS 61A exam mistake

- The TAs used a Python library for AES
  - A bad library for other reasons besides this example
- When they invoked CTR mode encryption, they didn't specify an IV
  - Assumption: the crypto library would add a random IV for them
  - Reality: the crypto library defaulted to IV = 0 every time
- The same IV was used to encrypt multiple exam questions
- All security was lost!
  - Any CS 161 student could have seen the exam beforehand
- **Takeaway**: Do not reuse IVs
- **Takeaway**: Real world cryptosystems are hard. Do *not* implement your own cryptosystems (without proper training beyond this class).

Comparing Modes of Operation

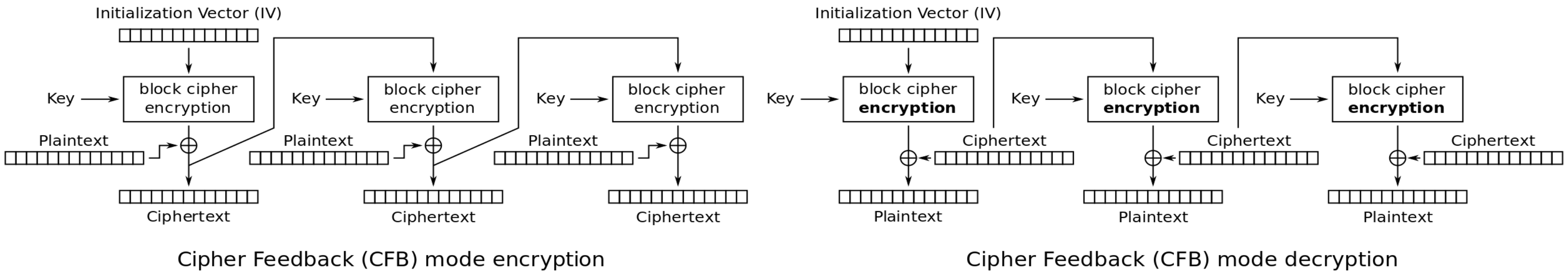
- If you need high performance, which mode is better?
  - CTR mode, because you can parallelize both encryption and decryption
- If you're paranoid about security, which mode is better?
  - CBC mode is better
- Theoretically, CBC and CTR mode are equally secure if used properly
  - However, if used improperly (IV/nonce reuse), CBC only leaks partial information, and CTR fails catastrophically
    - Consider human factors: Systems should be as secure as possible even when implemented *incorrectly*
  - IV failures on CTR mode have resulted in multiple real-world security incidents!

Other Modes of Operation

- Other modes exist besides CBC and CTR
- Trade-offs:
  - Do we need to pad messages?
  - How robust is the scheme if we use it incorrectly?
  - Can we parallelize encryption/decryption?

CFB Mode

- Also IND-CPA
- Try to analyze the trade-offs yourself:
  - Do we need to pad messages?
  - How robust is the scheme if we use it incorrectly?
  - Can we parallelize encryption/decryption?



CFB Mode

- Try to analyze the trade-offs yourself:
  - Do we need to pad messages?
    - No
  - How robust is the scheme if we use it incorrectly?
    - Similar effects as CBC mode, but a bit worse if you reuse the IV
  - Can we parallelize encryption/decryption?
    - Only decryption is parallelizable

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`

=

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

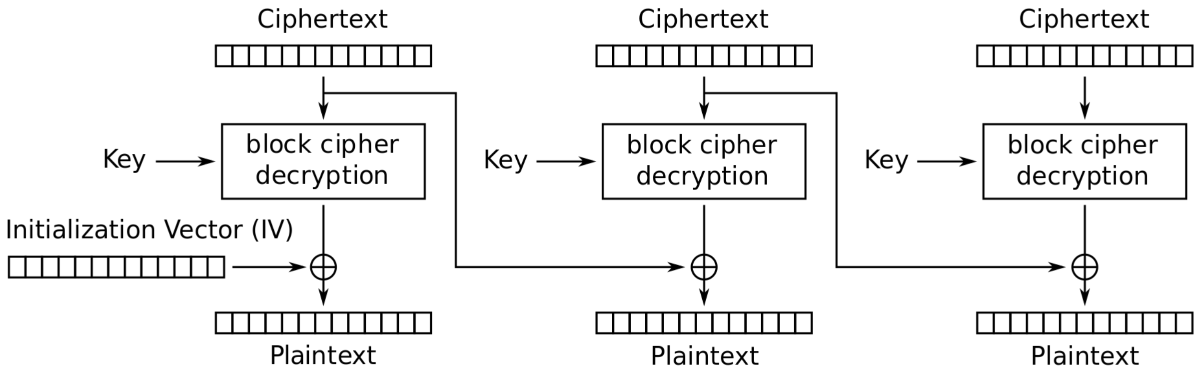
Lack of Integrity and Authenticity

- 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
							⊕					
$E_K(i)$	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 doesn't know 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
- Example: Is H(a cow) = a burger one-way?
  - Most likely because you cannot come up with a cow that creates the exact burger

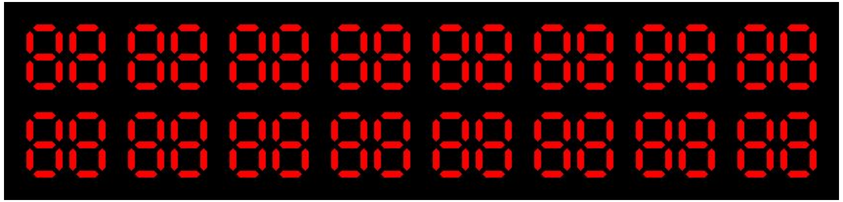
Hash Function: Collision Resistance

- **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



A GIF that displays its own MD5 hash

- 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)

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
  - 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)

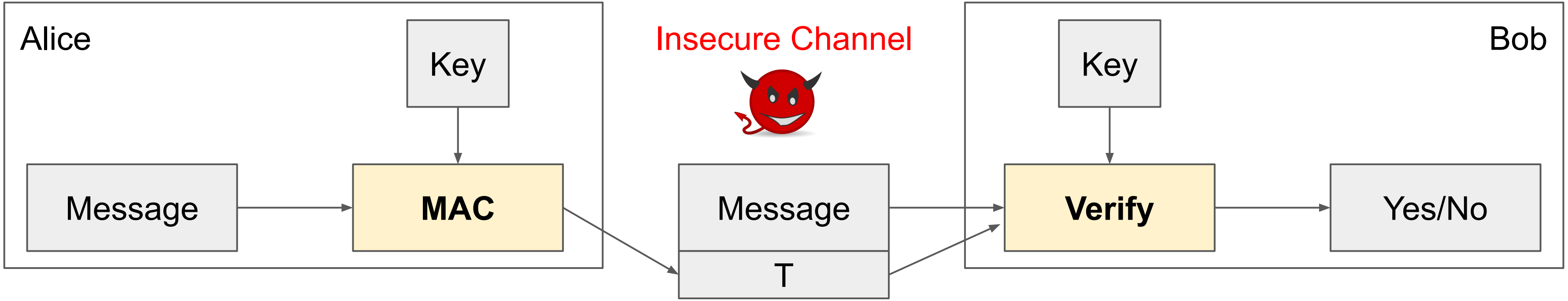
- Hash functions
- Pseudorandom number generators
- Public key exchange (e.g. Diffie-Hellman)
- Key management (certificates)
- Password management

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 recomputes 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.
3. A scheme is EU-CPA secure if for *all* polynomial time adversaries, the probability of winning is 0 or negligible