CMSC414 Computer and Network Security

One Time Pad and Block Ciphers

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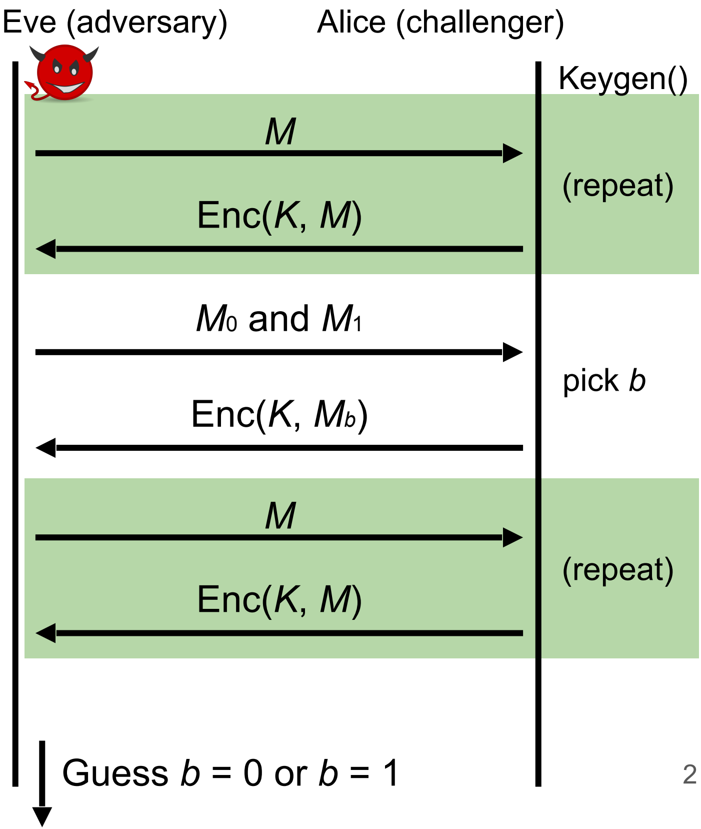
Credits: original slides from instructors and staff from CS161 at UC Berkeley. Blue slides will not be tested.

Recall the IND-CPA security definition

1. Eve may choose plaintexts to send to Alice and receives their ciphertexts
2. Eve issues a pair of plaintexts M_0 and M_1 to Alice
3. Alice randomly chooses either M_0 or M_1 to encrypt and sends the encryption back
   - Alice does not tell Eve which one was encrypted!
4. Eve may again choose plaintexts to send to Alice and receives their ciphertexts
5. Eventually, Eve outputs a guess as to whether Alice encrypted M_0 or M_1

An encryption scheme is IND-CPA secure if for all polynomial time attackers Eve:

- Eve can win wit bability ≤ 1/2 + Ɛ, where Ɛ is *negligible.*



Cryptography Roadmap

	Symmetric-key	Asymmetric-key
Confidentiality	● One-time pads ● Block ciphers with chaining modes (e.g. AES-CBC) ● Stream ciphers	● 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

Review: XOR

The XOR operator takes two bits and outputs one bit:

$0 \oplus 0 = 0$
$0 \oplus 1 = 1$
$1 \oplus 0 = 1$
$1 \oplus 1 = 0$

Useful properties of XOR:

$x \oplus 0 = x$
$x \oplus x = 0$
$x \oplus y = y \oplus x$
$(x \oplus y) \oplus z = x \oplus (y \oplus z)$
$(x \oplus y) \oplus x = y$

Review: XOR Algebra

- Algebra works on XOR too

$y \oplus 1 = 0$	Goal: Solve for y
$y \oplus 1 \oplus 1 = 0 \oplus 1$	XOR both sides by 1
$y = 1$	Simplify with identities

One-Time Pads: Key Generation

Alice

K	0	1	1	0	0	1	0	1	0	1	1	1

The key *K* is a randomly-chosen
b

Recall: We are in the symmetric-key setting, so we’ll assume Alice and Bob both know this key.

One-Time Pads: Encryption

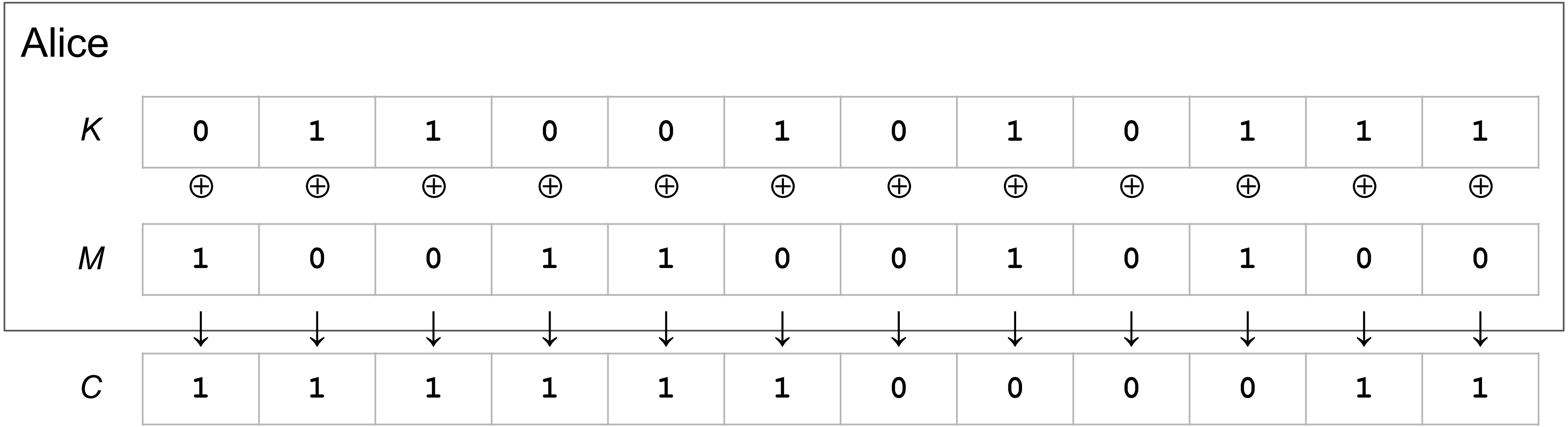
Alice

K	0	1	1	0	0	1	0	1	0	1	1	1
M	1	0	0	1	1	0	0	1	0	1	0	0

The plaintext *M* is the bitstring that Alice wants to encrypt.

Idea: Use XOR to scramble up *M* with the bits of *K*.

One-Time Pads: Encryption



Alice

K	0	1	1	0	0	1	0	1	0	1	1	1
	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
M	1	0	0	1	1	0	0	1	0	1	0	0
	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
C	1	1	1	1	1	1	0	0	0	0	1	1

Encryption algorithm: XOR each bit of *K* with the matching bit in *M*.

The ciphertext *C* is the encrypted bitstring that Alice sends to Bob over the insecure channel.

One-Time Pads: Decryption

Bob

K	0	1	1	0	0	1	0	1	0	1	1	1
C	1	1	1	1	1	1	0	0	0	0	1	1

Bob receives the ciphertext *C*. Bob knows the key *K*. How does Bob recover *M*?

One-Time Pads: Decryption

Bob

K	0	1	1	0	0	1	0	1	0	1	1	1
	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
C	1	1	1	1	1	1	0	0	0	0	1	1
	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
M	1	0	0	1	1	0	0	1	0	1	0	0

Decryption algorithm: XOR each bit of *K* with the matching bit in *C*.

One-Time Pad

- KeyGen()
    - Randomly generate an *n*-bit key, where *n* is the length of your message
        - Recall: For today, we assume that Alice and Bob can securely share this key
        - For one-time pads, we generate a *new* key for every message
- Enc(K, M) = $K \oplus M$
    - Bitwise XOR M and K to produce C
        - In other words: XOR the *i*th bit of the plaintext with the *i*th bit of the key.
        - $C_i = K_i \oplus M_i$
    - Alice and Bob use a different key for each encryption (this is the “one-time” in one-time pad).
- Dec(K, C) = $K \oplus C$
    - Bitwise XOR C and K to produce M
        - $M_i = K_i \oplus C_i$

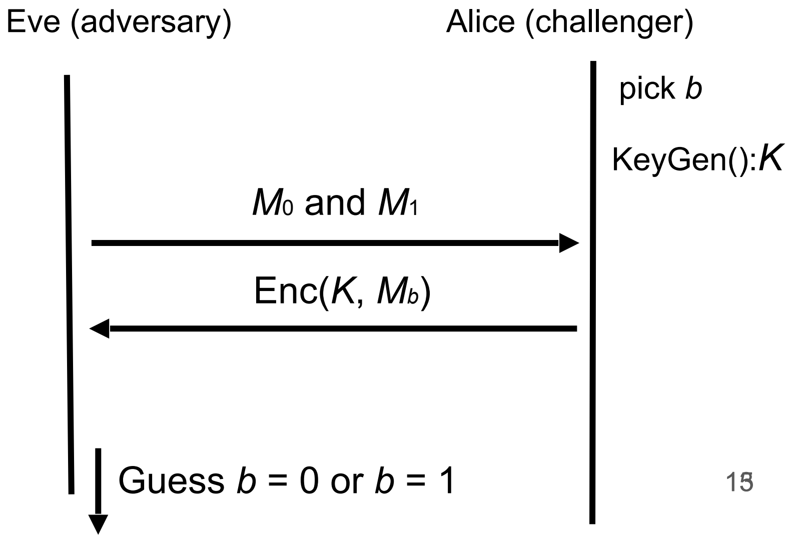
One-Time Pad: Correctness

- Correctness: If we encrypt and then decrypt, we should get the original message back

$$\begin{aligned}
\text{Enc}(K, M) &= K \oplus M && \text{Definition of encryption} \\
\text{Dec}(K, \text{Enc}(K, M)) &= \text{Dec}(K, K \oplus M) && \text{Decrypting the ciphertext} \\
&= K \oplus (K \oplus M) && \text{Definition of decryption} \\
&= M && \text{XOR property}
\end{aligned}$$

One-Time Pad: Security

- Recall our definition of confidentiality: The ciphertext should not give the attacker any additional information about the plaintext
- Recall our preliminary experiment (before IND-CPA) to test confidentiality from earlier:
  - If the probability that Eve correctly guesses which message was sent is 1/2, then the encryption scheme is confidential



Eve (adversary)

Alice (challenger)

pick b

KeyGen():K

M_0 and M_1

Enc(K, M_b)

Guess $b = 0$ or $b = 1$

One-Time Pad: Security

Possibility 0: Alice sends Enc(K, M_0)

The ciphertext is $C = K \oplus M_0$

Therefore, $K = C \oplus M_0$

Possibility 1: Alice sends Enc(K, M_1)

The ciphertext is $C = K \oplus M_1$

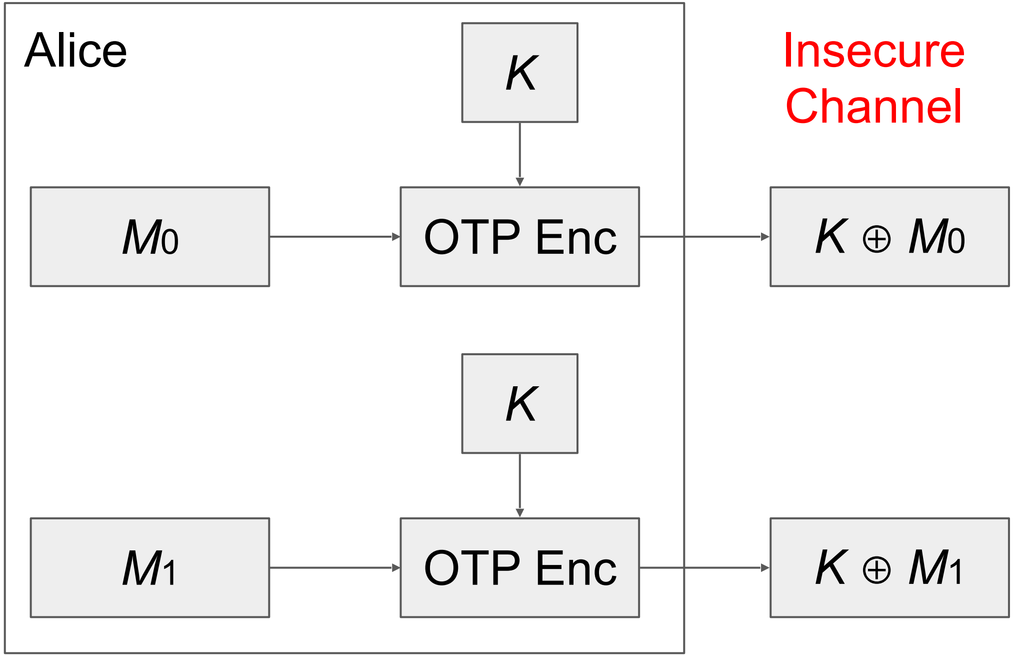
Therefore, $K = C \oplus M_1$

K was chosen randomly, so both possibilities are equally possible

Eve has learned no new information, so the scheme is *perfectly secure*

By "perfectly" we mean that any attacker has chance of winning the security game exactly ½ (not ½+epsilon)

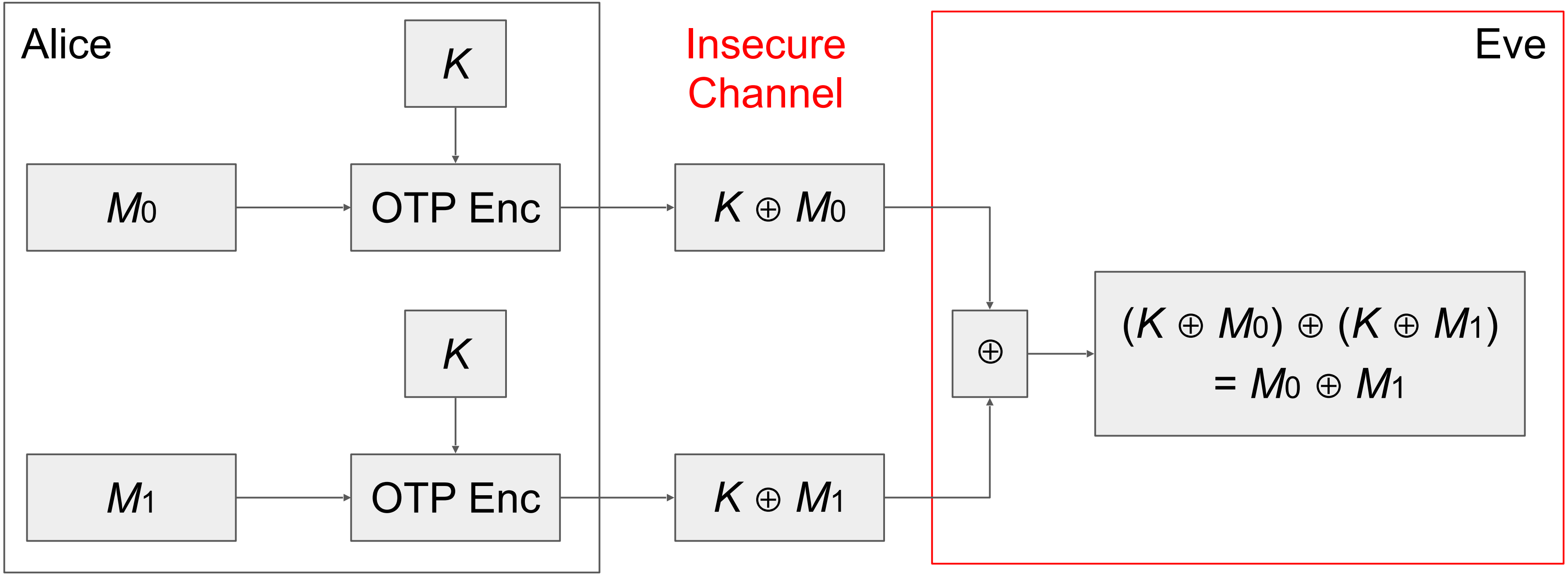
Two-Time Pads?



Eve sees two ciphertexts over the insecure channel.

What if we use the same key K to encrypt two different messages?

Two-Time Pads?



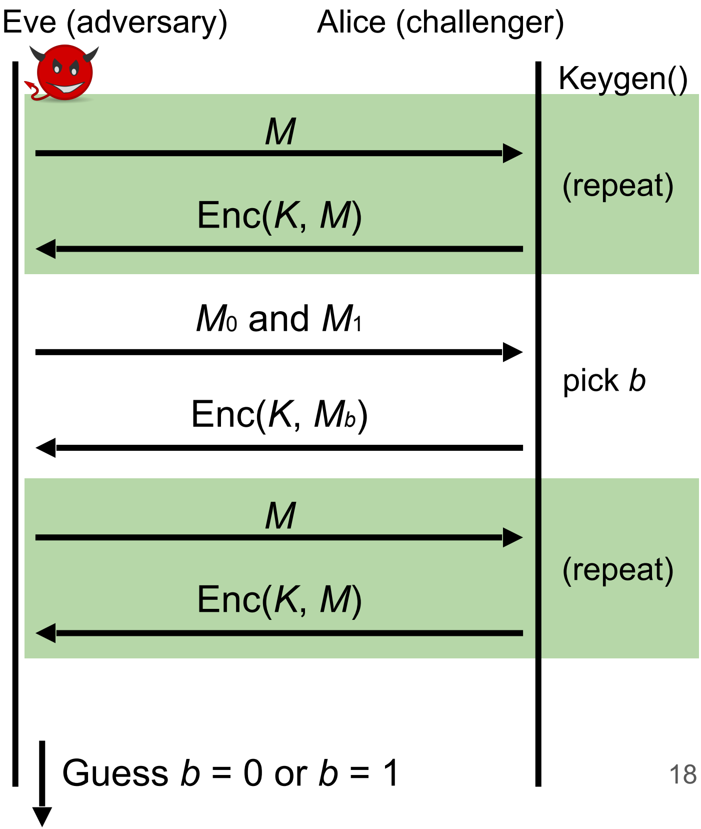
If Eve XORs the two ciphertexts, she learns $M_0 \oplus M_1$!

Two-Time Pads?

- What if we use the same key *twice*?
  - Alice encrypts M_0 and M_1 with the same key
  - Eve observes $K \oplus M_0$ and $K \oplus M_1$
  - Eve computes $(K \oplus M_0) \oplus (K \oplus M_1) = M_0 \oplus M_1$
    - Recall the XOR property: the *K*'s cancel out
- Eve has learned $M_0 \oplus M_1$. This is partial information about the messages!
  - In other words, Eve knows which bits in M_0 match bits in M_1
  - If Eve knows M_0, she can deduce M_1 (and vice-versa)
  - Eve can also guess M_0 and check that M_1 matches her guess for M_0
- Result: One-time pads are not secure if the key is reused
  - Alice and Bob must use a different key for every message!

One-Time Pad with Key Reuse does not offer IND-CPA

- What is an attack strategy?
- Many possible, e.g.
  - In the trial phase and the challenge phase, ask for "00" and "11", it is deterministic.



Impracticality of One-Time Pads

- Problem #1: Key generation
  - For security to hold, keys must be randomly generated for every message, and never reused
  - Randomness is expensive, as we'll see later
- Problem #2: Key distribution
  - To communicate an *n*-bit message, we need to securely communicate an *n*-bit key first
  - But if we have a way to securely communicate an *n*-bit key, we could have communicated the message directly!
- Communicate keys in advance
  - You have a secure channel now, but you won't have it later
  - Use the secure channel now to communicate keys in advance
  - Use one-time pad later to communicate over the insecure channel
  - And people can compute this by hand without computers!

One-Time Pads in Practice: Spies

- At home base, the spy obtains a large amount of key material (e.g. a book of random bits)
- In the field, the spy listens for secret messages from their home country
  - There are shortwave and terrestrial radio “number stations”
  - At a regular time, a voice gets on the air and reads a series of numbers
  - If you don’t know the key, this looks like a meaningless sequence of random numbers
  - If you know the key, you can decrypt the spy message!
- What if you don’t want to send anything to any spies?
  - Read out a list of random numbers anyway
  - Because one-time pad leaks no information, an eavesdropper can’t distinguish between an encrypted message and random numbers!

Two-Time Pads in Practice: VENONA

- Soviet spies used one-time pads for communication from their spies in the US
- During WWII, the Soviets started reusing key material
  - Uncertain whether it was just the cost of generating pads or what…
- VENONA was a US cryptanalysis project designed to break these messages
  - Included confirming/identifying the spies targeting the US Manhattan project
  - Project continued until 1980!
- Not declassified until 1995!
  - So secret even President Truman wasn’t informed about it
  - The Soviets found out about it in 1949 through their spy Ken Philby, but their one-time pad reuse was fixed after 1948 anyway
- **Takeaway**: Otherwise-secure cryptographic systems can fail very badly if used improperly!

Summary for one-time pads

- Symmetric encryption scheme: Alice and Bob share a secret key.
- Encryption and decryption: Bitwise XOR with the key.
- No information leakage if the key is never reused.
- Information leaks if the key is reused.
- Impractical for real-world usage, unless you’re a spy.

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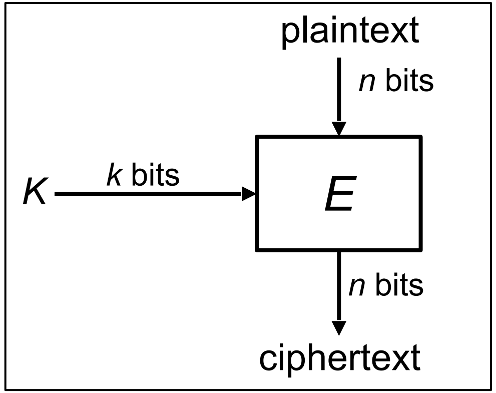
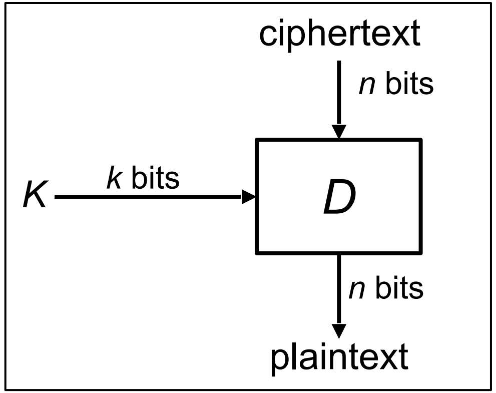
Block Ciphers: Definition

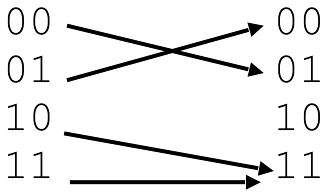
- **Block cipher**: A cryptographic scheme consisting of encode/decode algorithms for a fixed-sized block of bits:
- $E_K(M) \rightarrow C$: Encode
  - Inputs: k-bit key K and an n-bit plaintext M
  - Output: An n-bit ciphertext C
  - Sometimes written as: $\{0, 1\}^k \times \{0, 1\}^n \rightarrow \{0, 1\}^n$
- $D_K(C) \rightarrow M$: Decode
  - Inputs: a k-bit key, and an n-bit ciphertext C
  - Output: An n-bit plaintext
  - Sometimes written as: $\{0, 1\}^k \times \{0, 1\}^n \rightarrow \{0, 1\}^n$
  - The inverse of the encryption function
- Properties
  - **Correctness**: E_K is a permutation, D_K is its inverse
  - **Efficiency**: Encode/decode should be fast
  - **Security**: E behaves like a random permutation



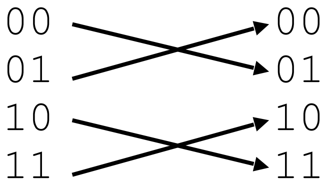


Block Ciphers: Correctness

- $E_K(M)$ must be a **permutation** (**bijective function**) on n-bit strings
    - Each input must correspond to exactly one unique output
- Intuition
    - Suppose $E_K(M)$ is not bijective
    - Then two inputs might correspond to the same output: $E(K, x_1) = E(K, x_2) = y$
    - Given ciphertext y, you can't uniquely decode. $D(K, y) = x_1$? $D(K, y) = x_2$?



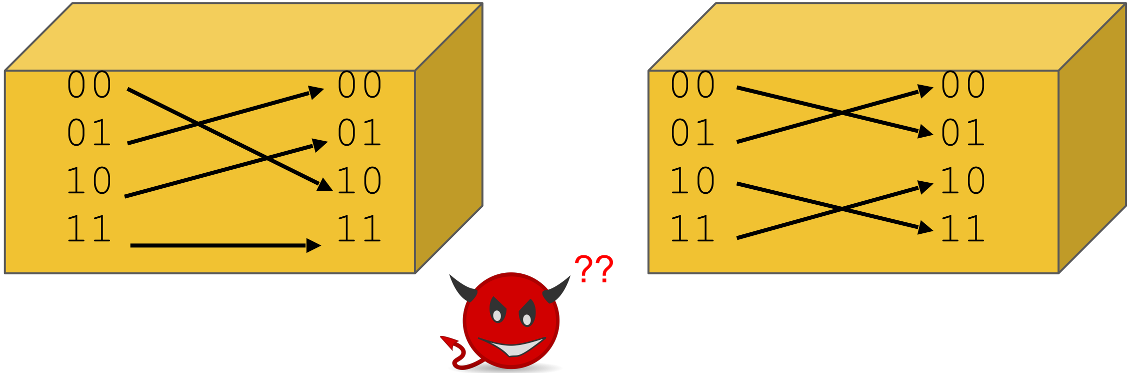
Not bijective: Two inputs encode to the same output



Bijective: Each input maps to exactly one unique output

Block Ciphers: Security

- A secure block cipher behaves like a randomly chosen permutation permutation from the set of all permutations on *n*-bit strings
  - A random permutation: Each *n*-bit input is mapped to one randomly-chosen *n*-bit output
- Defined by a distinguishing game
  - Eve gets two boxes: One is a randomly chosen permutation, and one is E_K with a randomly chosen key *K*
  - Eve should not be able to tell which is which with probability > ½+negl



One of these is E_K with a randomly chosen *K*, and the other one is a randomly chosen permutation. Eve can't distinguish them.

Block ciphers: Brute-force attacks?

- How hard is it to run a brute-force attack on a 128-bit key?
  - We have to try 2^{128} possibilities. How big is 2^{128}?
- Handy approximation: $2^{10} \approx 10^3$
  - $2^{128} = 2^{10*12.8} \approx (10^3)^{12.8} \approx (10^3)^{13} = 10^{39}$
- Suppose we have massive hardware that can try 10^9 (1 billion) keys in 1 nanosecond (a billionth of a second). That's 10^{18} keys per second
  - We'll need $10^{39} / 10^{18} = 10^{21}$ seconds. How long is that?
  - One year ≈ 3×10^7 seconds
  - 10^{21} seconds / $3\times10^7 \approx 3\times10^{13}$ years ≈ 30 trillion years
- **Takeaway**: Brute-forcing a 128-bit key takes astronomically long. Don't even try.

Block ciphers: Brute-force attacks?

- How hard is it to run a brute-force attack on a 256-bit key in the same time?
  - We need 10^{52} of the brute-force devices from before
  - If each brute-force device from before is 1 cubic millimeter, this would take 10^{43} cubic meters of space
  - That's the volume of 7×10^{15} suns!
  - For reference, the Milky Way galaxy has just 10^{11} stars
- **Takeaway**: Brute-force attacks on modern block ciphers are not possible, assuming the key is random and secret
  - 128-bit key? Definitely not happening.
  - 256-bit key? Lol no.

Block Ciphers: Efficiency

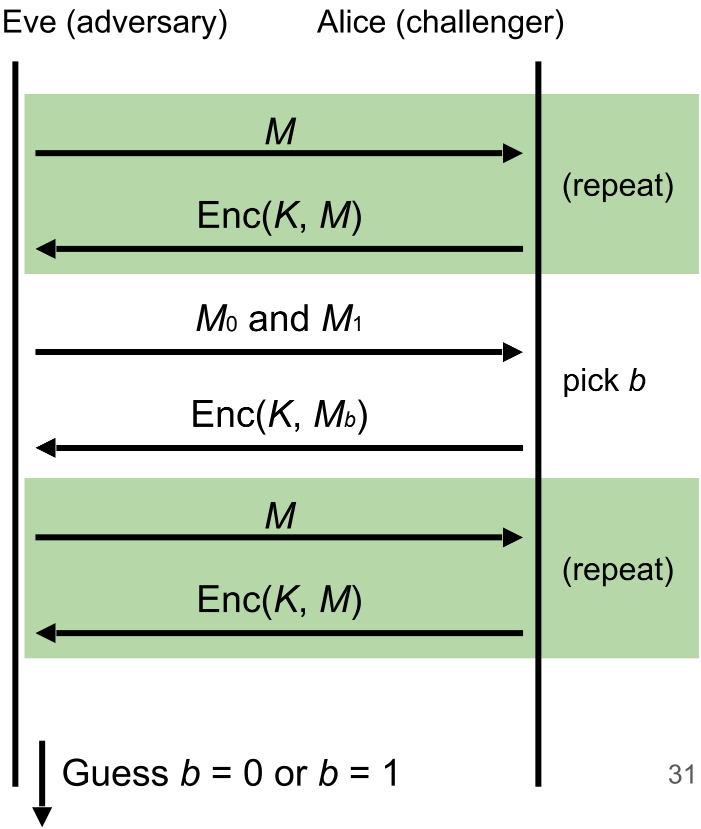
- Encryption and decryption should be computable in microseconds
  - Formally: KeyGen(), Enc(), and Dec(), should not take exponential time
- Block cipher algorithms typically use operations like XOR, bit-shifting, and small table lookups
  - Very fast on modern processors
- Modern CPUs provide dedicated hardware support for block ciphers

AES (Advanced Encryption Standard)

- 1997–2000: NIST (National Institute of Standards and Technology) in the US held a competition to pick a new block cipher standard
  - One of the finalists, Twofish, was designed by Berkeley professor and occasional CS 161 instructor David Wagner!
- Out of the 5 finalists:
  - Rijndael, Twofish, and Serpent had really good performance
  - RC6 had okay performance
  - Mars had bad performance
- On any given computing platform, Rijndael was *never* the fastest
- But on every computing platform, Rijndael was *always* the second-fastest
  - Twofish and Serpent each had at least one compute platform they were bad at
- Rijndael was selected as the new block cipher standard

Are Block Ciphers IND-CPA Secure?

- Consider the following adversary:
  - Eve sends two different messages M_0 and M_1
  - Eve receives either $E_K(M_0)$ or $E_K(M_1)$
  - Eve requests the encryption of M_0 again
  - Strategy: If the encryption of M_0 matches what she received, guess b = 0. Else, guess b = 1.
- Eve can win the IND-CPA game with probability 1!
  - Block ciphers are not IND-CPA secure because they are deterministic

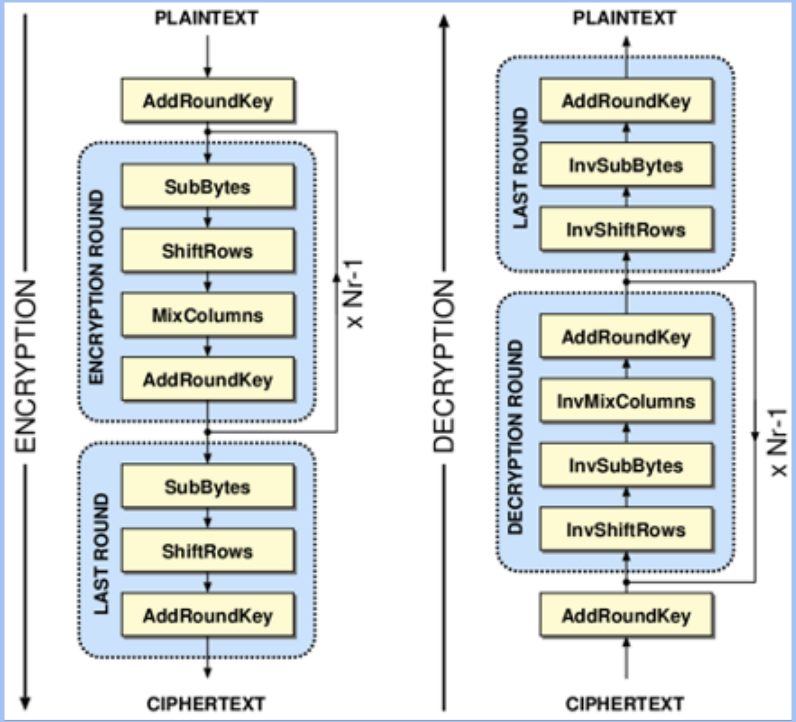


AES (Advanced Encryption Standard)

- Key size 128, 192, or 256 bits (k = 128, 192, or 256)
  - Use key size 256 these days
- Block size 128 bits (n = 128)
  - Note: The block size is still always 128 bits, regardless of key size
- You don’t need to know how AES works, but you do need to know its parameters
  - here’s a comic

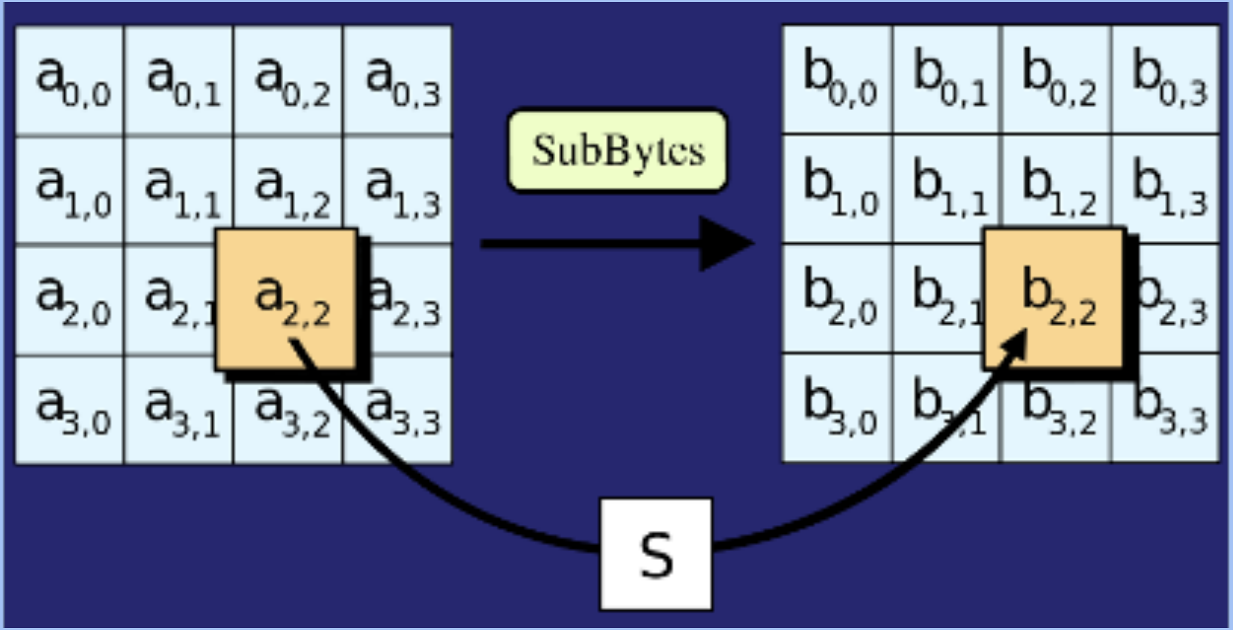
AES Algorithm

- Different key sizes use different numbers of rounds
  - 10 rounds for 128-bit keys
  - 12 rounds for 192-bit keys
  - 14 rounds for 256-bit keys
- Each round uses its own "round key" derived from the cipher key
- Each round:
  - SubBytes()
  - ShiftRows()
  - MixColumns() (if not last round)
  - AddRoundKey()



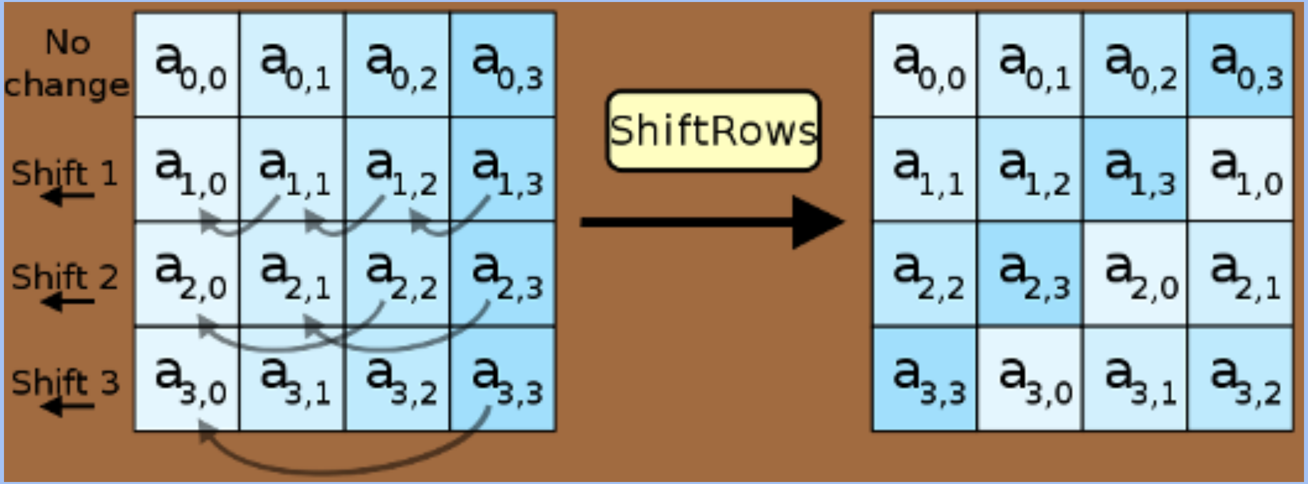
AES Algorithm: SubBytes()

- Replace each byte in the block with another byte using an 8-bit substitution box


$a_{0,0}$ $a_{0,1}$ $a_{0,2}$ $a_{0,3}$
$a_{1,0}$ $a_{1,1}$ $a_{1,2}$ $a_{1,3}$
$a_{2,0}$ $a_{2,1}$ $a_{2,2}$ $a_{2,3}$
$a_{3,0}$ $a_{3,1}$ $a_{3,2}$ $a_{3,3}$
SubBytes
$b_{0,0}$ $b_{0,1}$ $b_{0,2}$ $b_{0,3}$
$b_{1,0}$ $b_{1,1}$ $b_{1,2}$ $b_{1,3}$
$b_{2,0}$ $b_{2,1}$ $b_{2,2}$ $b_{2,3}$
$b_{3,0}$ $b_{3,1}$ $b_{3,2}$ $b_{3,3}$
S

AES Algorithm: ShiftRows()

- Cyclically shifts the bytes in each row by a certain offset
- The number of places each byte is shifted differs for each row

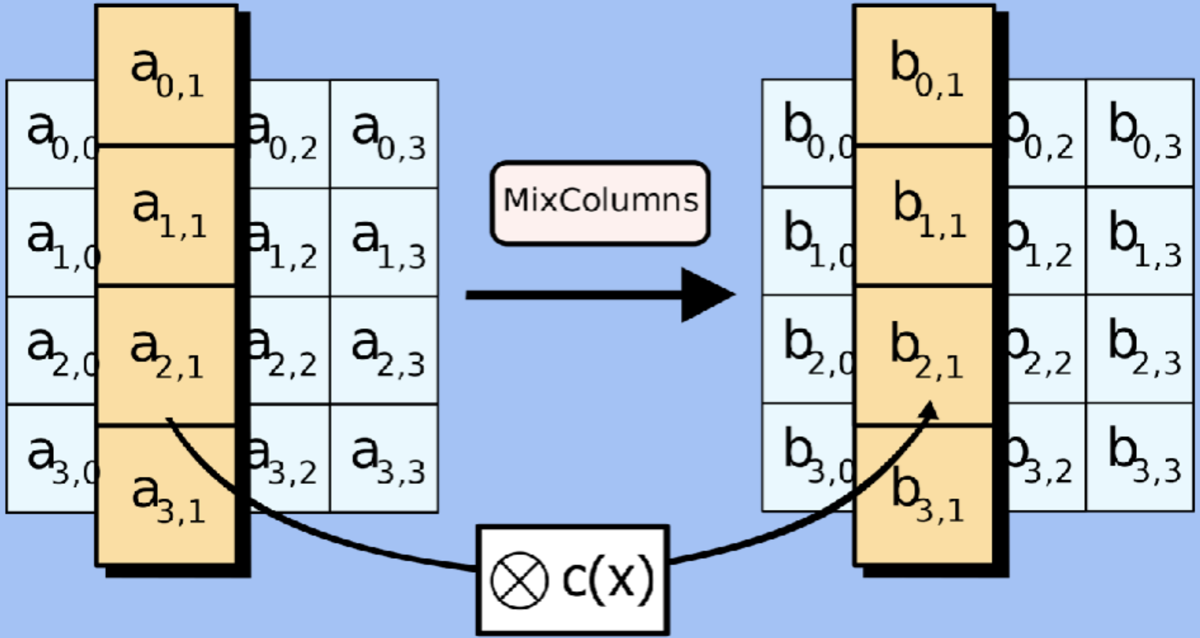


No change	$a_{0,0}$	$a_{0,1}$	$a_{0,2}$	$a_{0,3}$
Shift 1	$a_{1,0}$	$a_{1,1}$	$a_{1,2}$	$a_{1,3}$
Shift 2	$a_{2,0}$	$a_{2,1}$	$a_{2,2}$	$a_{2,3}$
Shift 3	$a_{3,0}$	$a_{3,1}$	$a_{3,2}$	$a_{3,3}$

$a_{0,0}$	$a_{0,1}$	$a_{0,2}$	$a_{0,3}$
$a_{1,1}$	$a_{1,2}$	$a_{1,3}$	$a_{1,0}$
$a_{2,2}$	$a_{2,3}$	$a_{2,0}$	$a_{2,1}$
$a_{3,3}$	$a_{3,0}$	$a_{3,1}$	$a_{3,2}$

AES Algorithm: MixColumns()

- Treats the 16-byte block as a 4 × 4 matrix and multiply it by by another matrix


$a_{0,0}$ $a_{0,1}$ $a_{0,2}$ $a_{0,3}$
$a_{1,0}$ $a_{1,1}$ $a_{1,2}$ $a_{1,3}$
$a_{2,0}$ $a_{2,1}$ $a_{2,2}$ $a_{2,3}$
$a_{3,0}$ $a_{3,1}$ $a_{3,2}$ $a_{3,3}$
MixColumns
$\otimes c(x)$
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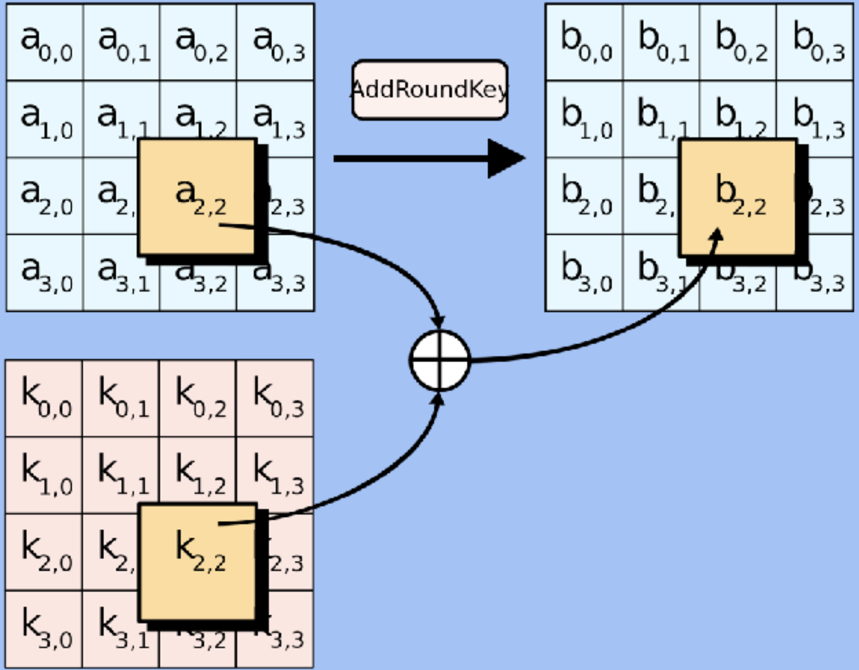
$b_{1,0}$ $b_{1,1}$ $b_{1,2}$ $b_{1,3}$
$b_{2,0}$ $b_{2,1}$ $b_{2,2}$ $b_{2,3}$
$b_{3,0}$ $b_{3,1}$ $b_{3,2}$ $b_{3,3}$

AES Algorithm: AddRoundKey()

- XOR the 16-byte block with the 16-byte round key


$a_{0,0}$ $a_{0,1}$ $a_{0,2}$ $a_{0,3}$
$a_{1,0}$ $a_{1,1}$ $a_{1,2}$ $a_{1,3}$
$a_{2,0}$ $a_{2,1}$ $a_{2,2}$ $a_{2,3}$
$a_{3,0}$ $a_{3,1}$ $a_{3,2}$ $a_{3,3}$
AddRoundKey
$b_{0,0}$ $b_{0,1}$ $b_{0,2}$ $b_{0,3}$
$b_{1,0}$ $b_{1,1}$ $b_{1,2}$ $b_{1,3}$
$b_{2,0}$ $b_{2,1}$ $b_{2,2}$ $b_{2,3}$
$b_{3,0}$ $b_{3,1}$ $b_{3,2}$ $b_{3,3}$
$\oplus$
$k_{0,0}$ $k_{0,1}$ $k_{0,2}$ $k_{0,3}$
$k_{1,0}$ $k_{1,1}$ $k_{1,2}$ $k_{1,3}$
$k_{2,0}$ $k_{2,1}$ $k_{2,2}$ $k_{2,3}$
$k_{3,0}$ $k_{3,1}$ $k_{3,2}$ $k_{3,3}$

AES (Advanced Encryption Standard)

- There is no formal proof that AES is secure (indistinguishable from a random permutation)
- However, in 20 years, nobody has been able to break it, so it is *assumed* to be secure
  - The NSA uses AES-256 for secrets they want to keep secure for the 40 years (even in the face of unknown breakthroughs in research)
- **Takeaway**: AES is the modern standard block cipher algorithm
  - The standard key size (128 bits) is large enough to prevent brute-force attacks

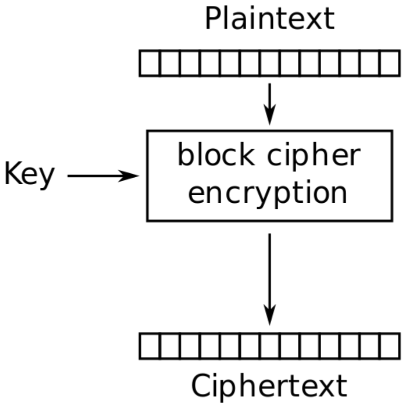
Issues with Block Ciphers

- Block ciphers are not IND-CPA secure, because they’re deterministic
    - A scheme is **deterministic** if the same input always produces the same output
    - No deterministic scheme can be IND-CPA secure because the adversary can always tell if the same message was encrypted twice
- Block ciphers can only encrypt messages of a fixed size
    - For example, AES can only encrypt-decrypt 128-bit messages
    - What if we want to encrypt something longer than 128 bits?
- To address these problems, we’ll add **modes of operation** that use block ciphers as a building block!

Scratchpad: Let’s design it together

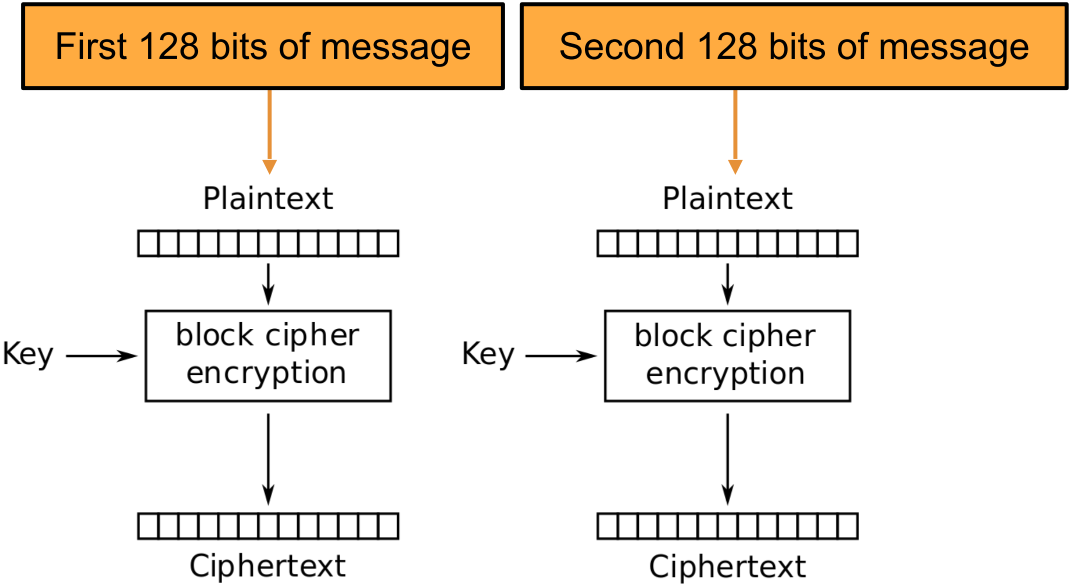
Here’s an AES block. Remember that it can only encrypt 128-bit messages.

How can we use AES to encrypt a longer message (say, 256 bits?)



Scratchpad: Let’s design it together

Idea: Let’s use AES twice!



First 128 bits of message

Second 128 bits of message

Plaintext

Key

block cipher encryption

Ciphertext

Plaintext

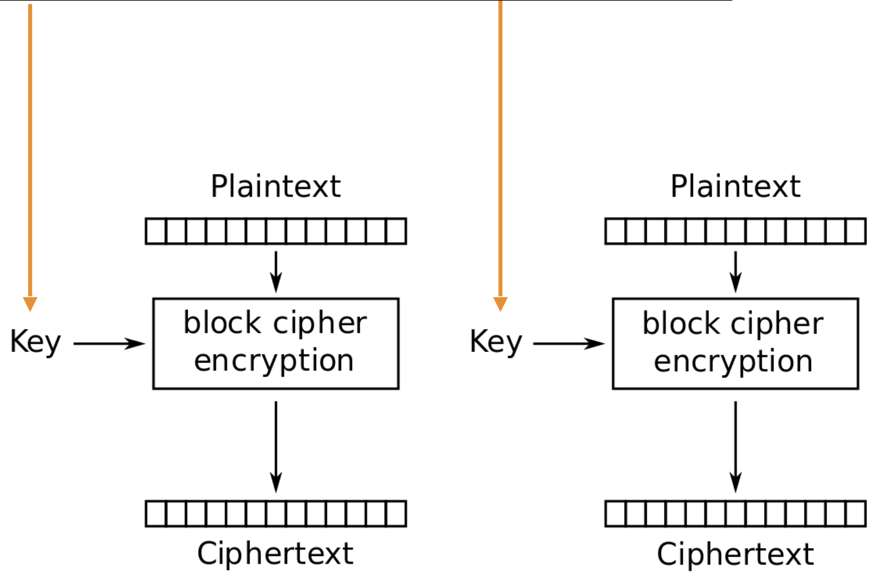
Key

block cipher encryption

Ciphertext

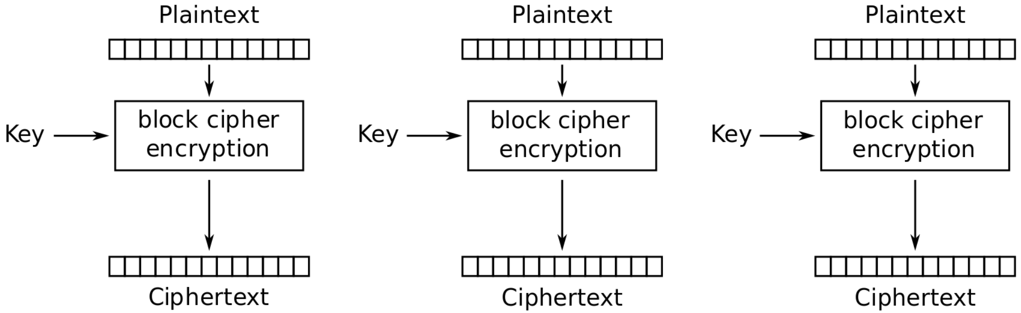
Scratchpad: Let's design it together

Note that we are using the same key twice. We want to avoid a situation like one-time pads where we need very long keys.



ECB Mode

- We've just designed **electronic code book (ECB) mode**
  - Enc(K, M) = C_1 || C_2 || … || C$_m$
  - Assume m is the number of blocks of plaintext in M, each of size n
- AES-ECB is not IND-CPA secure. Why?
  - Because ECB is deterministic

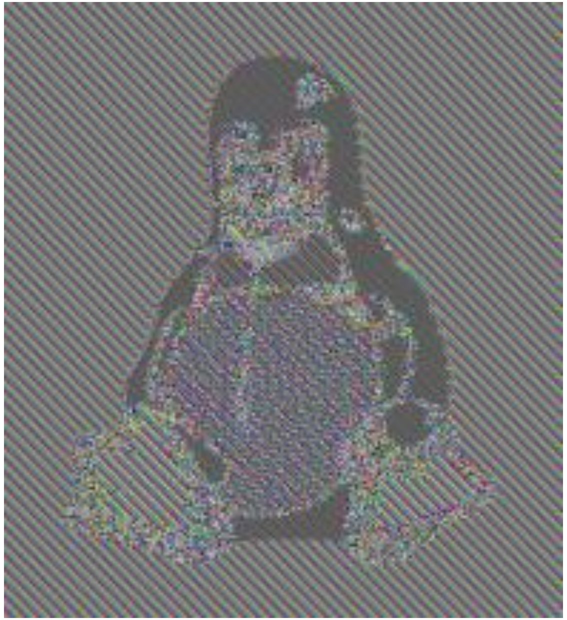


Electronic Codebook (ECB) mode encryption

ECB Mode: Penguin

Original image

ECB Mode: Penguin

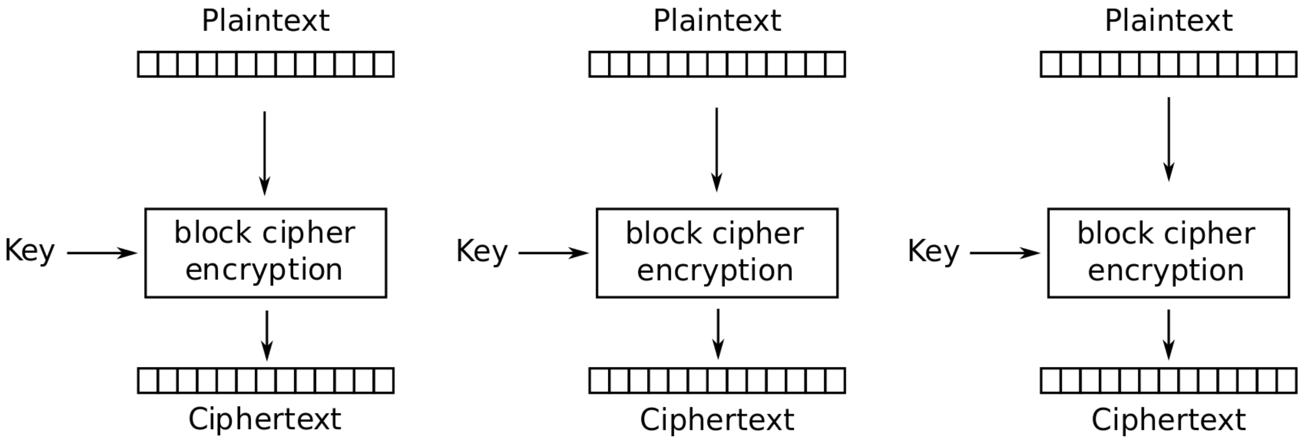


Encrypted with ECB

Scratchpad: Let’s design it together

Here’s ECB mode. It’s not IND-CPA secure because it’s deterministic.

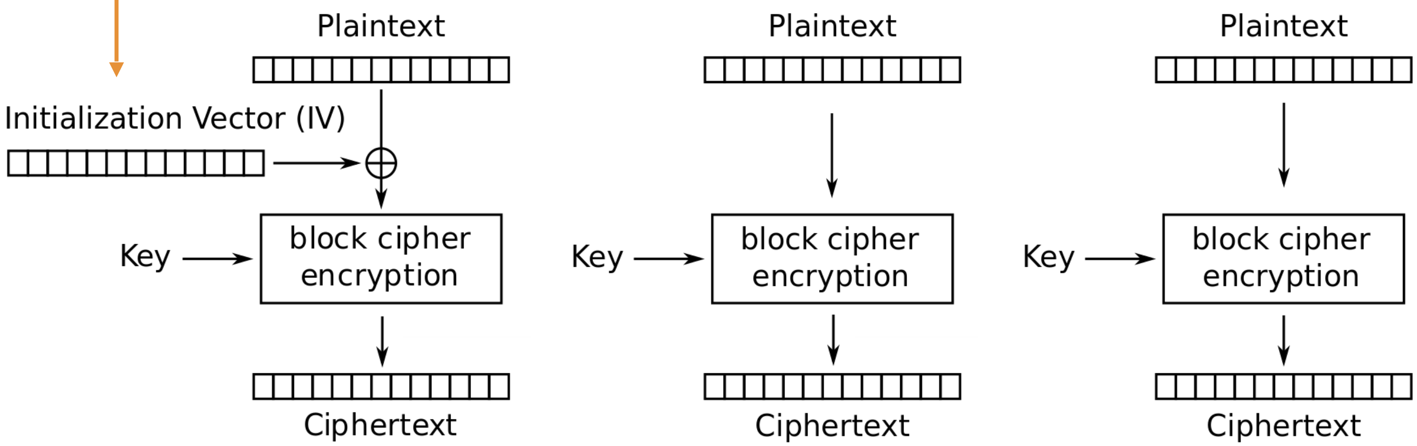
Let’s fix that by adding some randomness.



Scratchpad: Let’s design it together

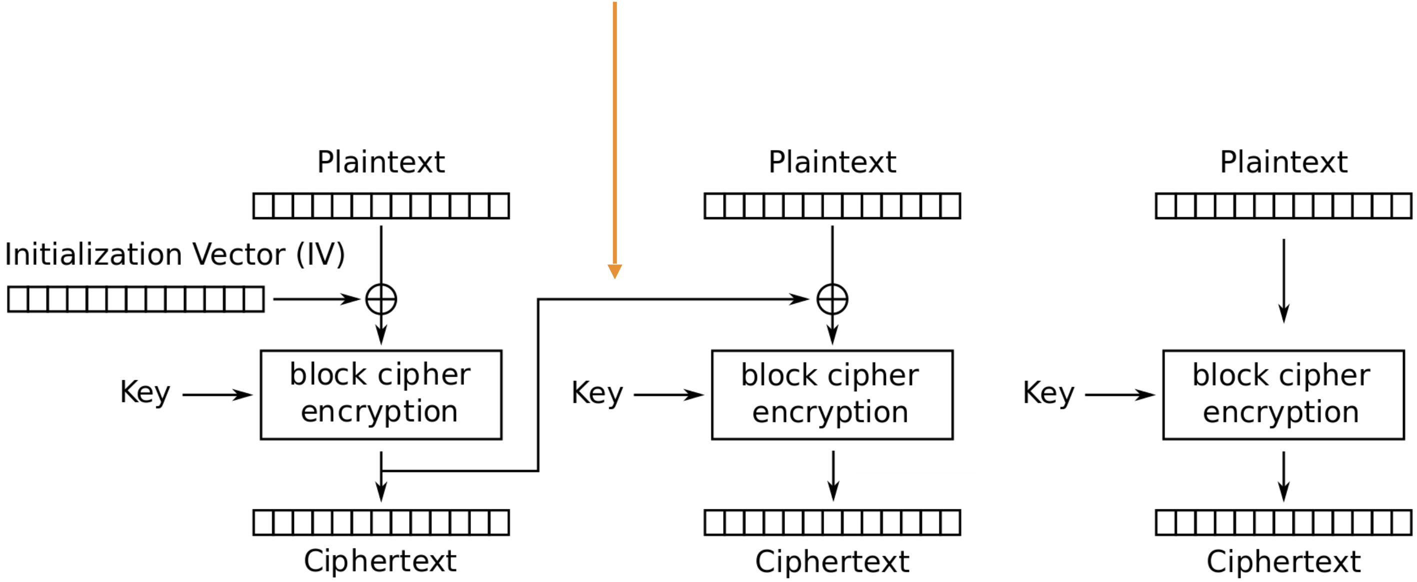
The **Initialization Vector (IV)** is different for every encryption. Now the first ciphertext block will be different for every encryption!

Okay, but the other blocks are still deterministic...



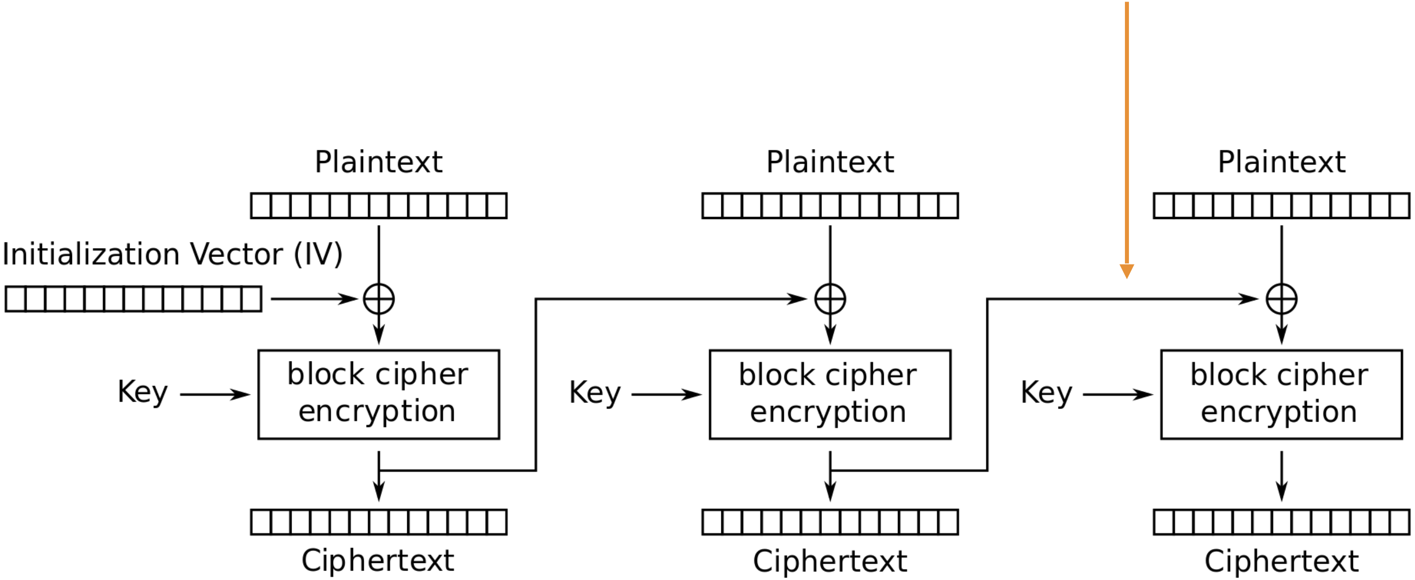
Scratchpad: Let’s design it together

Idea: The first ciphertext block was computed with some randomness. Let’s use it to add randomness to the second block.



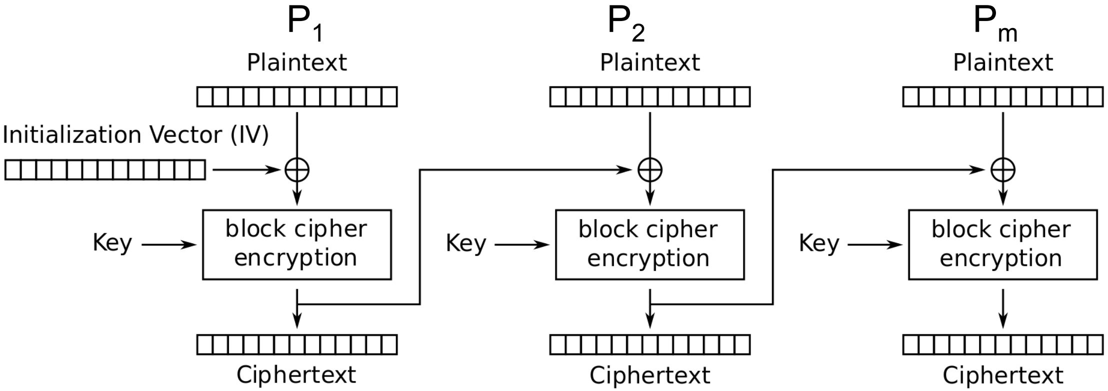
Scratchpad: Let’s design it together

Now the second ciphertext block has some randomness in it. Let’s use it to add randomness to the third block.



CBC Mode

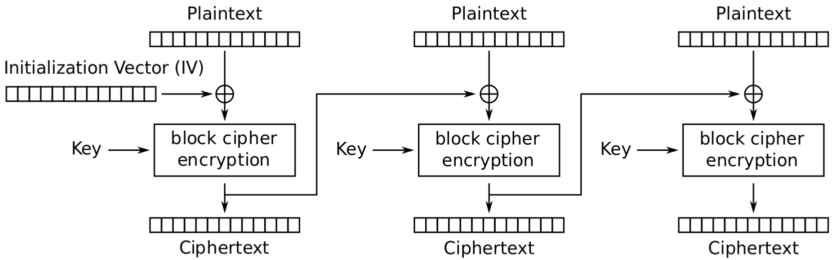
- We’ve just designed **cipher block chaining (CBC) mode**
- $C_i = E_K(M_i \oplus C_{i-1})$; $C_0 = IV$
- Enc(K, M):
  - Split M in m plaintext blocks $P_1 \dots P_m$ each of size n
  - Choose a random IV
  - Compute and output (IV, $C_1, \dots, C_m$) as the overall ciphertext
- How do we decrypt?



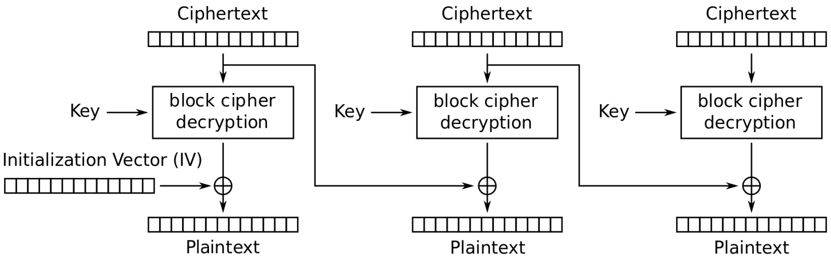
Cipher Block Chaining (CBC) mode encryption

CBC Mode: Decryption

- How do we decrypt CBC mode?
    - Parse ciphertext as (IV, C_1, …, C_m)
    - Decrypt each ciphertext and then XOR with IV or previous ciphertext



Cipher Block Chaining (CBC) mode encryption



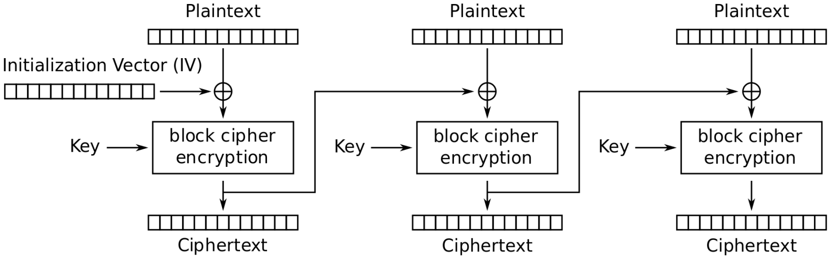
Cipher Block Chaining (CBC) mode decryption

CBC Mode: Decryption

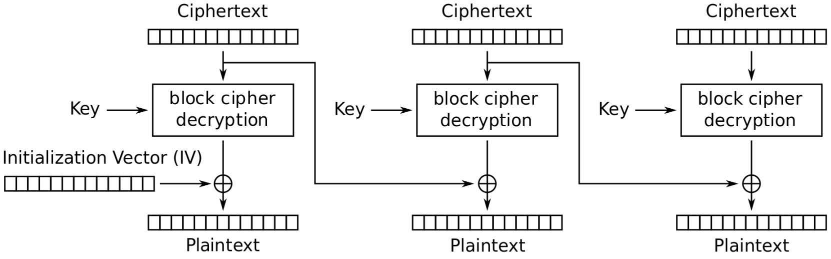
$$\begin{aligned}
C_i &= E_K(M_i \oplus C_{i-1}) && \text{Definition of encryption}\\
D_K(C_i) &= D_K(E_K(M_i \oplus C_{i-1})) && \text{Decrypting both sides}\\
D_K(C_i) &= M_i \oplus C_{i-1} && \text{Decryption and encryption cancel}\\
D_K(C_i) \oplus C_{i-1} &= M_i \oplus C_{i-1} \oplus C_{i-1} && \text{XOR both sides with } C_{i-1}\\
D_K(C_i) \oplus C_{i-1} &= M_i && \text{XOR property}
\end{aligned}$$

CBC Mode: Efficiency & Parallelism

- Can encryption be parallelized?
  - No, we have to wait for block i to finish before encrypting block i+1
- Can decryption be parallelized?
  - Yes, decryption only requires ciphertext as input



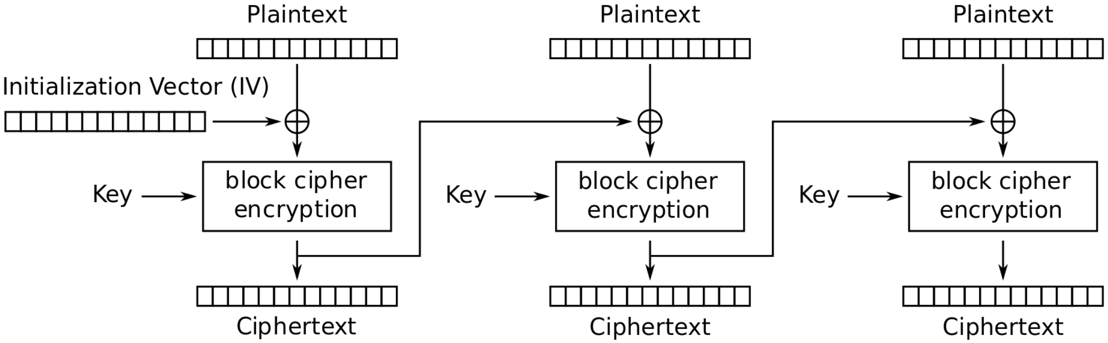
Cipher Block Chaining (CBC) mode encryption



Cipher Block Chaining (CBC) mode decryption

CBC Mode: Padding

- What if you want to encrypt a message that isn't a multiple of the block size?
  - AES-CBC is only defined if the plaintext length is a multiple of the block size
- Solution: Pad the message until it's a multiple of the block size
  - **Padding**: Adding dummy bytes at the end of the message until it's the proper length



Cipher Block Chaining (CBC) mode encryption

CBC Mode: Padding

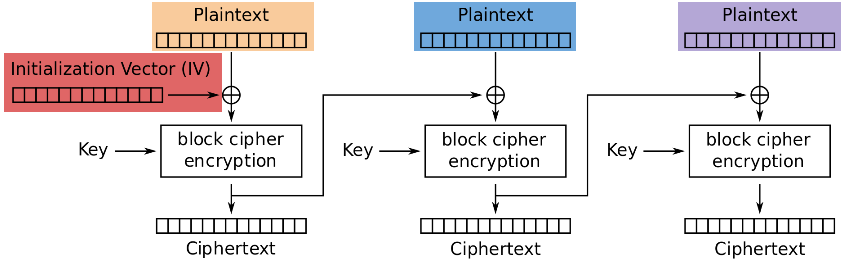
- What padding scheme should we use?
  - Padding with 0’s?
    - Doesn’t work: What if our message already ends with 0’s?
  - Padding with 1’s?
    - Same problem
- We need a scheme that can be unpadded without ambiguity
  - One scheme that works: Append a 1, then pad with 0’s
    - If plaintext is multiple of n, you still need to pad with an entire block
  - Another scheme: Pad with the number of padding bytes
    - So if you need 1 byte, pad with **01**; if you need 3 bytes, pad with **03 03 03**
    - If you need 0 padding bytes, pad an entire dummy block
    - This is called PKCS #7

CBC Mode: Security

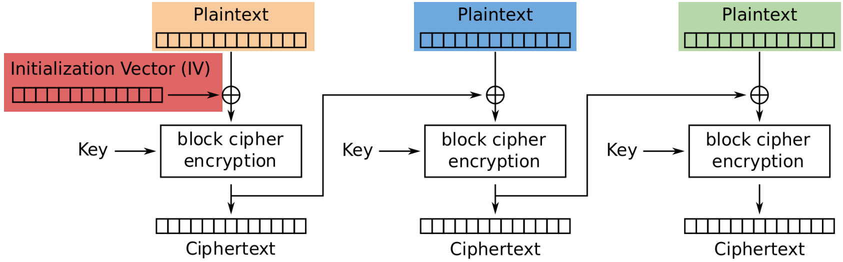
- AES-CBC is IND-CPA secure. With what assumption?
    - The IV must be randomly generated and never reused
- What happens if you reuse the IV?
    - The scheme becomes deterministic: No more IND-CPA security

CBC Mode: IV Reuse

- Consider two three-block messages: $P_1P_2P_3$ and $P_1P_2P_4$
  - The first two blocks are the same for both messages, but the last block is different
  - What if we encrypt them with the same IV?
- When the IV is reused, CBC mode reveals when two messages start with the same plaintext blocks, up to the first different plaintext block



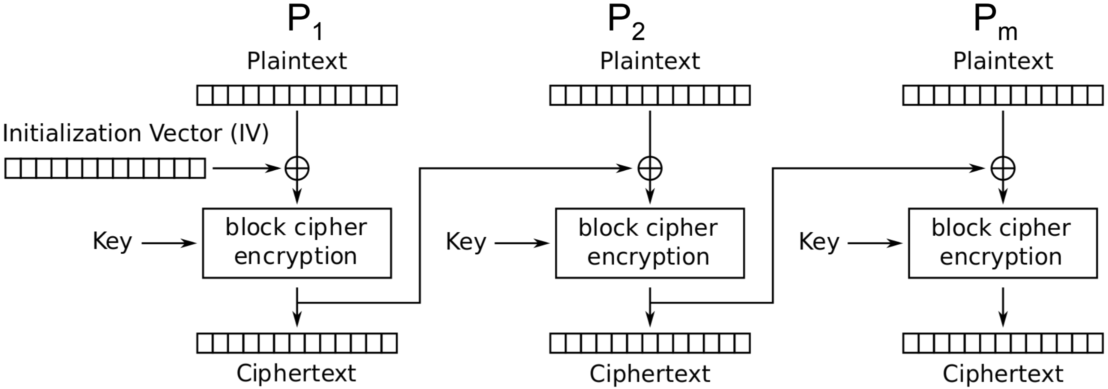
Cipher Block Chaining (CBC) mode encryption



Cipher Block Chaining (CBC) mode encryption

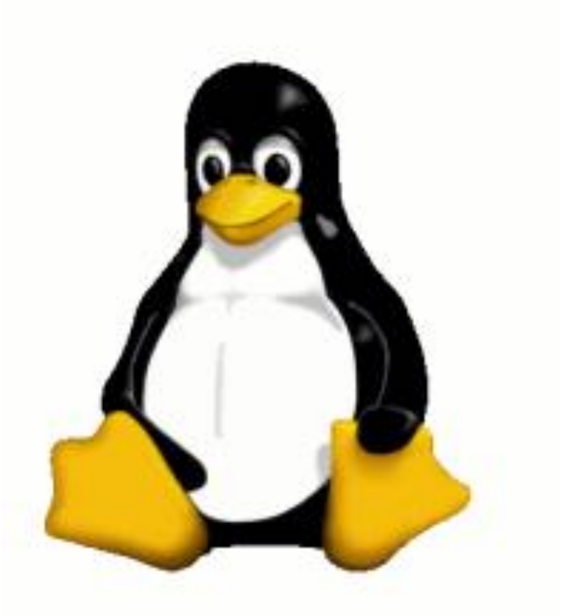
CBC Mode is IND-CPA (when used correctly)

- Enc(*K*, *M*):
  - Split M in m plaintext blocks $P_1 \ldots P_m$ each of size *n*
  - Choose random IV, compute and output (IV, C_1, …, C_m) as the overall ciphertext
- Why IND-CPA?
  - If there exists an attacker that wins in the IND-CPA game, then there exists an attacker that breaks the block cipher security. Proof is out of scope.



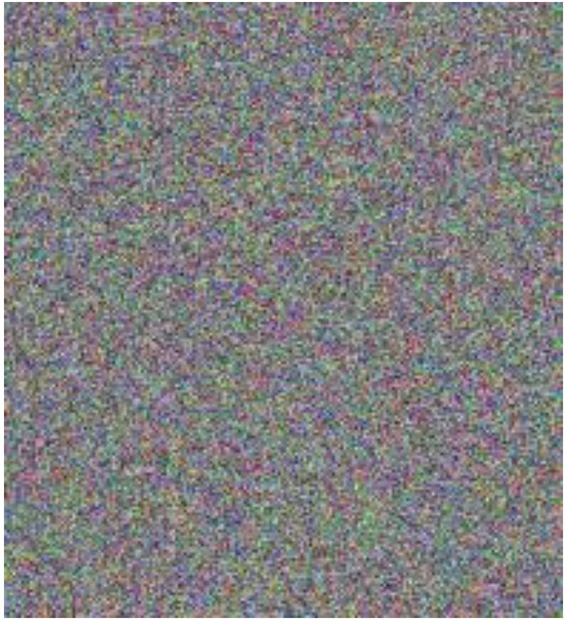
Cipher Block Chaining (CBC) mode encryption

CBC Mode: Penguin



Original image

CBC Mode: Penguin



Encrypted with CBC, with random IVs