

# Lecture 30 – Randomness, Pseudo Randomness, and Confidentiality

Stephen Checkoway

Oberlin College

Slides from Miller and Bailey's ECE 422

# Randomness and Pseudorandomness

# Review

Problem:

Integrity of message sent from Alice to Bob

Append bits to message that only Alice and Bob can make

Solution:

Message Authentication Code (MAC)

Practical solution:

Hash-based MAC (HMAC) –  $HMAC\text{-}SHA256_k(M)$

Where do these random keys  $k$  come from ... ?

*Careful:* We're often sloppy about what is "random"

## True Randomness

Output of a physical process that is inherently random

Scarce, and hard to get

## Pseudorandom Function (PRF)

Sampled from a family of functions using a key

## Pseudorandom generator (PRG)

Takes small seed that is really random

Generates a stream (arbitrarily long sequence) of numbers that are “as good as random”

Definition: **PRG** is secure if it's indistinguishable from a random stream of bits

Similar game to PRF definition:

1. We flip a coin secretly to get a bit **b**
2. If **b=0**, let **s** be a truly random stream  
If **b=1**, let **s** be **g<sub>k</sub>** for random secret **k**
3. Mallory can see as much of the output of **s** as they want
4. Mallory guesses **b** and wins if the guess is correct

**g** is a secure PRG if no winning strategy for Mallory (with more than a negligible advantage)

Here's a *simple PRG that works*:

**For some random  $k$  and PRF  $f$ ,**

**output:  $f_k(0) \parallel f_k(1) \parallel f_k(2) \parallel \dots$**

**Theorem:** If  $f$  is a secure PRF, and  $g$  is built from  $f$  by this construction, then  $g$  is a secure PRG.

**Proof:** Assume  $f$  is a secure PRF, we need to show that  $g$  is a secure PRG.

Proof by contradiction:

1. Assume  $g$  is *not* secure; so Mallory can win the PRG game
2. This gives Mallory a winning strategy for the PRF game:
  - a. query the PRF oracle with inputs 0, 1, 2, ... to get a stream
  - b. apply the PRG-distinguishing algorithm to this stream, if it's a random stream, then the oracle must be using a random function; if it's not a random stream, then the oracle must be using  $f$
3. Therefore, Mallory can win PRF game; this is a contradiction
4. Therefore,  $g$  is secure

## Where do we get true randomness?

Want “indistinguishable from random” which means: adversary can’t guess it

Gather lots of details about the computer that the adversary will have trouble guessing [\[Examples?\]](#)

Problem: Adversary can predict some of this

Problem: How do you know when you have enough randomness?

Modern OSes typically collect randomness, give you API calls to get it

e.g., Linux:

`/dev/random` gives output of a PRG, blocking if its entropy estimate is low

`/dev/urandom` gives output of the same PRG but nonblocking

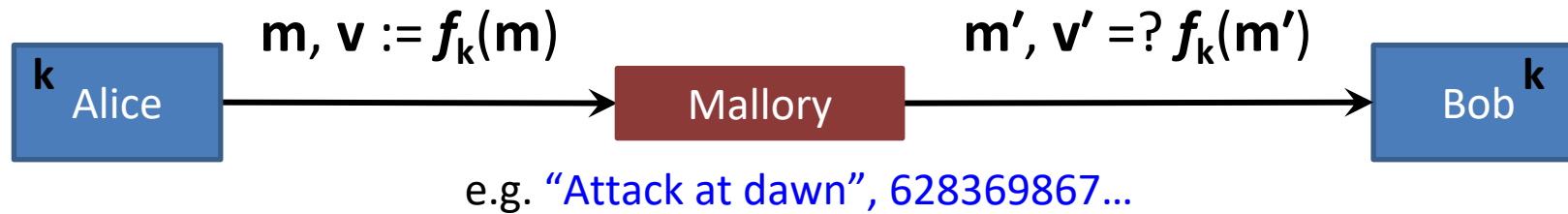
## Review: Message Integrity

**Integrity** of message sent over an untrusted channel

Alice must append bits to message that only Alice (or Bob) can make

Idealized solution: Random function

Practical solution:



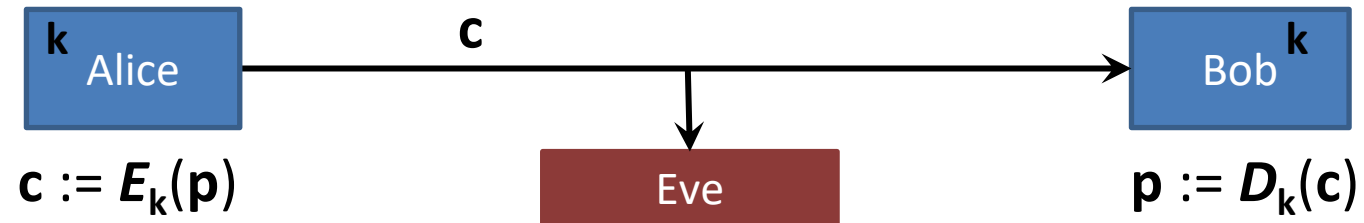
(Hash-based) MAC

$f_k$  is (we hope!) indistinguishable in practice from a random function, unless you know  $k$

Confidentiality

# Confidentiality

Goal: Keep contents of message  $\mathbf{p}$  secret from an *eavesdropper*



## Terminology

$\mathbf{p}$	plaintext
$\mathbf{c}$	ciphertext
$\mathbf{k}$	secret key
$\mathbf{E}$	encryption function
$\mathbf{D}$	decryption function

# Digression: Classical Cryptography

## Caesar Cipher

First recorded use: Julius Caesar (100-44 BC)

Replaces each plaintext letter with one a fixed number of places down the alphabet

Encryption:  $c_i := (p_i + k) \bmod 26$

Decryption:  $p_i := (c_i - k) \bmod 26$

e.g. ( $k=3$ ):

Plain:	ABCDEFGHIJKLMNOPQRSTUVWXYZ
+ Shift:	3333333333333333333333333333
= Cipher:	DEFGHIJKLMNOPQRSTUVWXYZABC

Plain:	cryptography	is	neat
+ Key:	33333333333333	33	3333
= Cipher:	FUBSWRJUDSKB	LV	QHDW

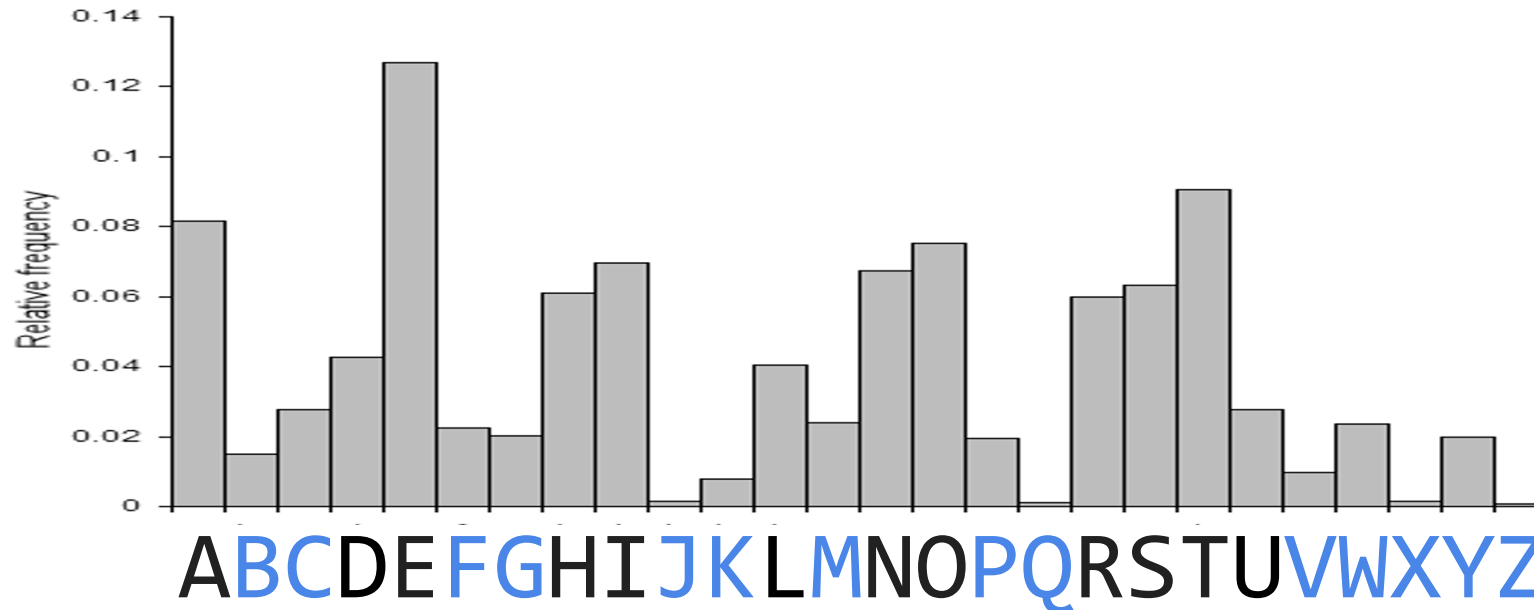
# Cryptanalysis of the Caesar Cipher

Only 26 possible keys:

Try every possible  $k$  by “*brute force*”

Can a computer recognize the right one?

Use *frequency analysis*: English text has distinctive letter frequency distribution



## Later advance: **Vigènere Cipher**

First described by Bellaso in 1553, later misattributed to Vigenère

Called «le chiffre indéchiffrable» (“the indecipherable cipher”)

Encrypts successive letters using a sequence of Caesar ciphers determined by the letters of a keyword

For an  $n$ -letter keyword  $\mathbf{k}$ ,

Encryption:  $\mathbf{c}_i := (\mathbf{p}_i + \mathbf{k}_{i \bmod n}) \bmod 26$

Decryption:  $\mathbf{p}_i := (\mathbf{c}_i - \mathbf{k}_{i \bmod n}) \bmod 26$

Example:  $\mathbf{k}=\text{ABC}$  (i.e.  $\mathbf{k}_0=0$ ,  $\mathbf{k}_1=1$ ,  $\mathbf{k}_2=2$ )

Plain:	bbbbbb	amazon
+Key:	012012	012012
=Cipher	bcdbcd	anczpp

# Cryptanalysis of the Vigenere Cipher

Simple, if we know the keyword length,  $n$ :

1. Break ciphertext into  $n$  slices
2. Solve each slice as a Caesar cipher

How to find  $n$ ? One way: [Kasiski method](#)

Published 1863 by Kasiski (earlier known to Babbage?)

Repeated strings in long plaintext will sometimes, by coincidence, be encrypted with same key letters

Plain:	<b>CRYPTO</b> ISSHORTFOR <b>CRYPTO</b> GRAPHY
+Key:	ABCDABCDABCDABCDABCDABCDABCD
=Cipher:	<b>CSASTP</b> KVSIQUTGQU <b>CSASTP</b> IUAQJB

Distance between repeated strings in ciphertext is likely a multiple of key length e.g., distance 16 implies  $n$  is 16, 8, 4, 2, 1

[What if key is as long as the plaintext?]

# Kerckhoff's Principles

1st: The system must be practically, if not mathematically, indecipherable;

**2nd: The system must not require secrecy and must not cause inconvenience should it fall into the hands of the enemy;**

3rd: The key must be able to be used in communique and retained without the help of written notes, and be changed or modified at the discretion of the correspondents;

4th: The system must be compatible with telegraphic communication;

5th: The system must be portable, and remain functional without the help of multiple people;

6th: Finally, it's necessary, given the circumstances in which the system will be applied, that it's easy to use, is undemanding, not overly stressful, and doesn't require the knowledge and observation of a long series of rules

“Schneier's law”

“Any fool can invent a cipher  
that he himself cannot break.”



<https://www.schneier.com/crypto-gram/archives/1998/1015.html#cipherdesign>

# One-time Pad (OTP)

Alice and Bob jointly generate a secret,  
very long, string of random bits  
(the one-time pad, **k**)

To encrypt:  $c_i = p_i \text{ xor } k_i$

To decrypt:  $p_i = c_i \text{ xor } k_i$

<b>a</b>	<b>b</b>	<b>a xor b</b>
0	0	0
0	1	1
1	0	1
1	1	0

$$a \text{ xor } b \text{ xor } b = a$$

$$a \text{ xor } b \text{ xor } a = b$$

“one-time” means you should never reuse any part of the pad.

If you do:

Let  $k_i$  be pad bit

Adversary learns  $(a \text{ xor } k_i)$  and  $(b \text{ xor } k_i)$

Adversary xors those to get  $(a \text{ xor } b)$ ,

which is useful to him [How?]

Provably secure [Why?]

Usually impractical [Why? Exceptions?]

Obvious idea: Use a **pseudorandom generator** instead of a truly random pad

(Recall: Secure **PRG** inputs a seed **k**, outputs a stream that is practically indistinguishable from true randomness unless you know **k**)

Called a **stream cipher**:

1. Start with shared secret key **k**
2. Alice & Bob each use **k** to seed the PRG
3. To encrypt, Alice XORs the next bit of her generator's output with the next bit of plaintext
4. To decrypt, Bob XORs the next bit of his generator's output with the next bit of ciphertext

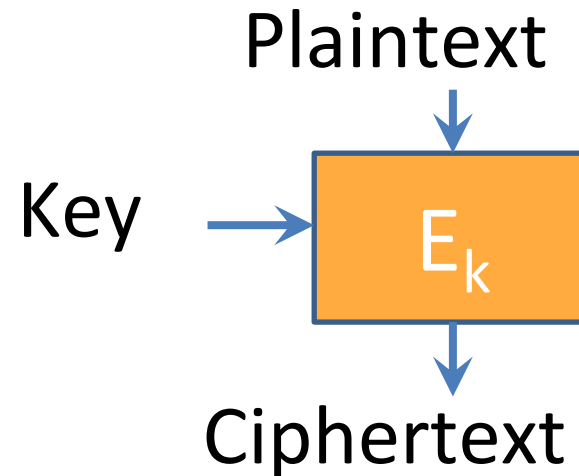
Works nicely, but: don't ever reuse the key, or the generator output bits

## Another approach: **Block Ciphers**

Functions that encrypts fixed-size blocks with a reusable key.

Inverse function decrypts when used with same key.

The most commonly used approach to encrypting for confidentiality.



A block cipher is not a pseudorandom function [Why?]

What we want instead: **pseudorandom permutation (PRP)**

function from  $n$ -bit input to  $n$ -bit output

distinct inputs yield distinct outputs (one-to-one)

Defined similarly to **PRF**:

practically indistinguishable from a

*random permutation* without secret  $k$

*Basic challenge:* Design a hairy function that is invertible, but only if you have the key

Minimal properties of a good block cipher:

- Highly nonlinear (“confusion”)
- Mixes input bits together (“diffusion”)
- Depends on the key

# Definition: a cipher is “Semantically Secure”

Similar game to PRF/PRG/PRP definition:

1. We flip a coin secretly to get a bit  $\mathbf{b}$ , random secret  $\mathbf{k}$
2. Mallory chooses arbitrary  $\mathbf{m}_i$  in  $\mathbf{M}$ , gets to see  $\mathbf{Enc}_k(\mathbf{m}_i)$
3. Mallory chooses two messages  $\mathbf{m}'_0$  and  $\mathbf{m}'_1$  not in  $\mathbf{M}$
4. If  $\mathbf{b}=0$ , let  $\mathbf{c}$  be  $\mathbf{Enc}_k(\mathbf{m}'_0)$   
If  $\mathbf{b}=1$ , let  $\mathbf{c}$  be  $\mathbf{Enc}_k(\mathbf{m}'_1)$
5. Mallory can see  $\mathbf{c}$
6. Mallory guesses  $\mathbf{b}$ , wins if guesses correctly

We can prove this follows from a PRP definition. **[Fun to try!]**

Also known as: IND-CPA “Chosen plaintext attack”

Today's most common block cipher:

## **AES** (Advanced Encryption Standard)

- Designed by NIST competition, long public comment/discussion period
- Widely believed to be secure,  
but we don't know how to prove it
- Variable **key size** and **block size**
- We'll use 128-bit key, 128-bit block  
(there are also versions with 192-bit and 256-bit keys; block size is still 128)
- Ten **rounds**: Split **k** into ten (or 12 or 14, depending on key size) **subkeys**, performs set of operations ten (or 12 or 14) times, each with diff. subkey

## Each AES round

128-bits in, 128-bit sub-key, 128-bits out

Four steps:

picture as operations on a  
4x4 grid of 8-bit values

### 1. Non-linear step

Run each byte through a non-linear function (lookup table)

### 2. Shift step: Circular-shift each row: $i^{\text{th}}$ row shifted by $i$ (0-3)

### 3. Linear-mix step

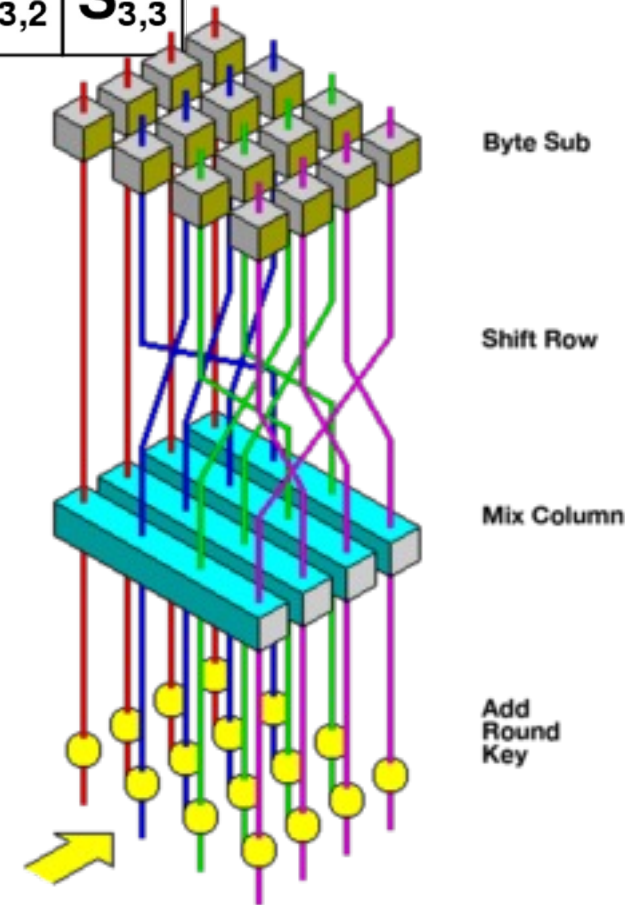
Treat each column as a 4-vector; multiply by constant invertible matrix

### 4. Key-addition step

XOR each byte with corresponding byte of round subkey

*To decrypt, just undo the steps, in reverse order*

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



Remaining problem:

How to encrypt longer messages?

## Padding:

Can only encrypt in units of cipher blocksize, but message might not be multiples of blocksize

*Solution:* Add padding to end of message

Must be able to recognize and remove padding afterward

Common approach: Add  $n$  bytes that have value  $n$

[Caution: What if message ends at a block boundary?]

## Cipher modes of operation

We know how to encrypt one block, but what about multiblock messages?

Different methods, called “cipher modes”

Straightforward (but bad) approach:

### **ECB mode (electronic codebook)**

Just encrypt each block independently

$$C_i := E_k(P_i)$$

[Disadvantages?]

## Cipher modes of operation

We know how to encrypt one block, but what about multiblock messages?

Different methods, called “cipher modes”

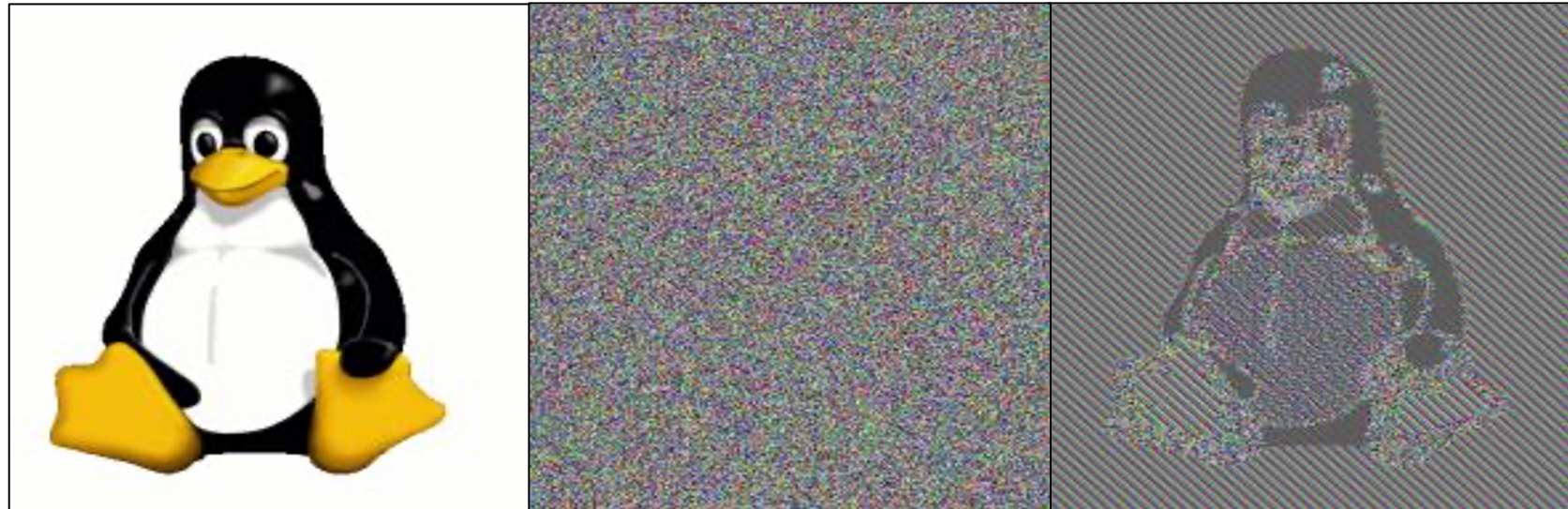
Straightforward (but bad) approach:

### ECB mode (electronic codebook)

Just encrypt each block independently

$$C_i := E_k(P_i)$$

[Disadvantages?]



Plaintext

Pseudorandom

ECB mode

Better (and common):

## **CBC mode (cipher-block chaining)**

*Fake-CBC* (for illustration only)

For each block  $\mathbf{P}_i$ :

1. Generate random block  $\mathbf{R}_i$
2.  $\mathbf{C}_i := (\mathbf{R}_i \parallel \mathbf{E}_k(\mathbf{P}_i \text{ xor } \mathbf{R}_i))$

[Pros and cons?]

# Real CBC

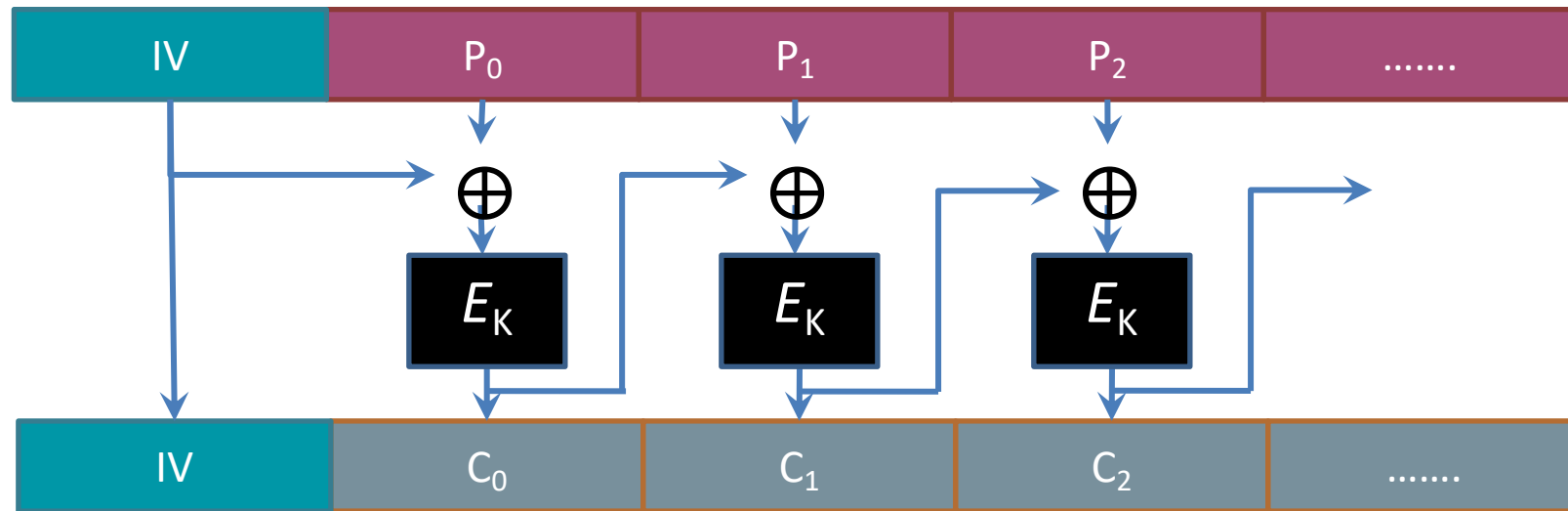
Replace  $R_i$  with  $C_{i-1}$

No need to send separately

Must still add one random  $R_{-1}$  to start, called “**initialization vector**” (“**IV**”)

Illustration: CBC Encryption

[Is CBC space-efficient?]



[Decryption?]

## Using OpenSSL to do AES encryption from the command line

**\$ KEY=\$(openssl rand -hex 16)** Generates a random string

**\$ openssl aes-128-cbc -in mymsg.txt -out mymsg.enc  
-p -K \${KEY} -iv \$(openssl rand -hex 16)**

**key=218EEFE192DE9D46DDCF6C6D12D480DD**

**iv =DBB272FE6486C4D9B09DBE464E080468**

Prints the key and IV

**\$ openssl aes-128-cbc -d -in mymsg.enc -out mymsg.txt  
-K \${KEY} -iv <iv from above>**

- By default, uses the standard padding described earlier
- Unfortunately, you have to handle prepending/extracting the IV on your own

## Other modes

OFB, CFB, etc. – used less often

## Counter mode

Essentially uses block cipher as a pseudorandom generator

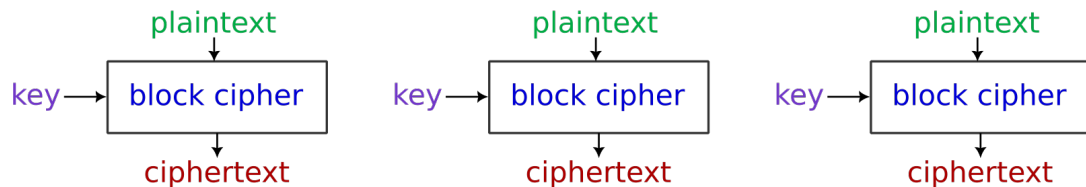
XOR  $i^{\text{th}}$  block of message with  $E_k(\text{message\_id} || i)$

[Why do we need message\_id?]

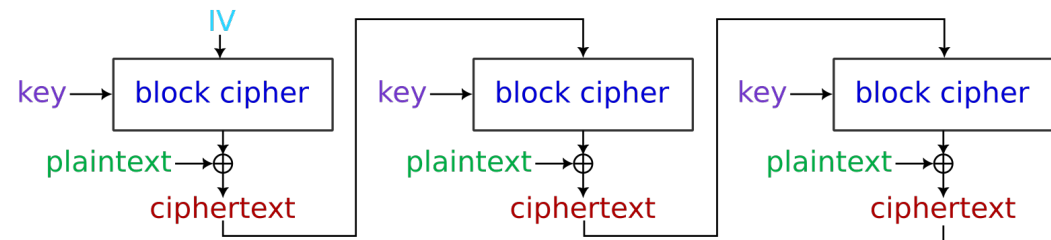
[Do we need a message\_id for CBC mode?]

[ Recover after errors? Decrypt in parallel? ]

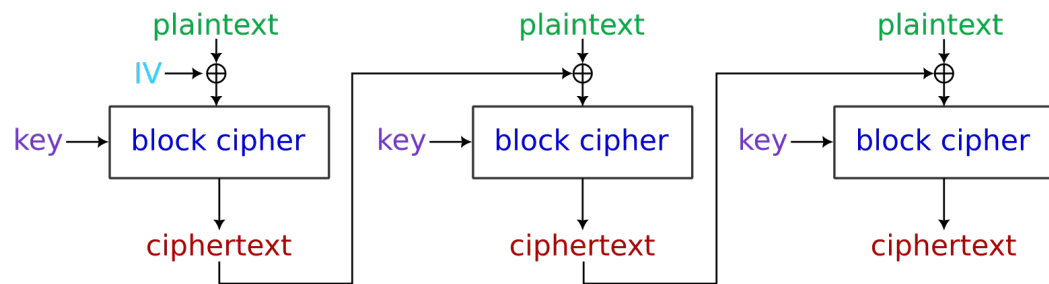
### Electronic codebook (ECB)



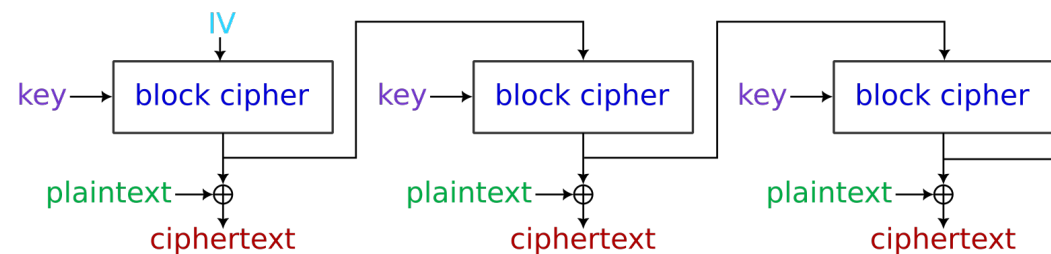
### Cipher feedback (CFB)



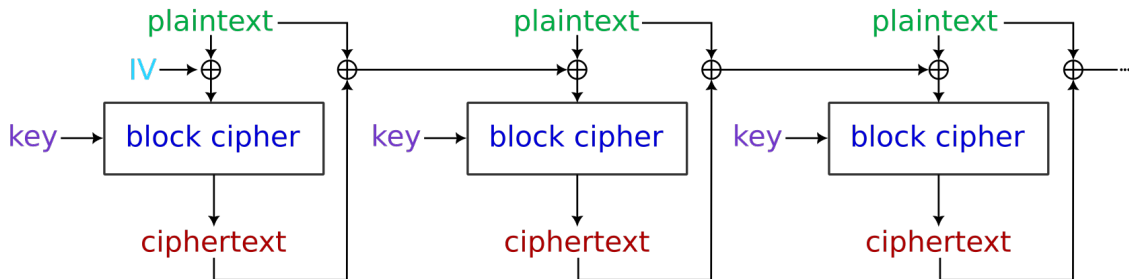
### Cipher block chaining (CBC)



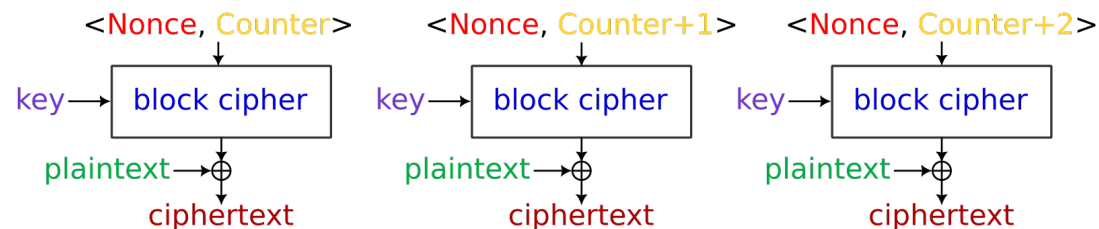
### Output feedback (OFB)



### Propagating cipher block chaining (PCBC)



### Counter (CTR)



# What is **NOT** covered by **Semantic Security**?

- **“Malleability” attacks**

Given just some ciphertexts, can the attacker create new ciphertexts that Bob decrypts the wrong value?

- **Encryption does NOT IMPLY integrity!**

Often you really want both (“authenticated encryption”)

- **Chosen Ciphertext attacks**

The “semantic security” definition does not allow the adversary to see decryptions of (potentially garbage) ciphertexts chosen by the adversary

Solution:        Encrypt-then-MAC

Better:         Use authenticated encryption modes: **GCM**, OCB, **CCM**, etc.

# CCM (counter with cipher block chaining message authentication code) mode

Combines CBC-MAC with counter mode encryption

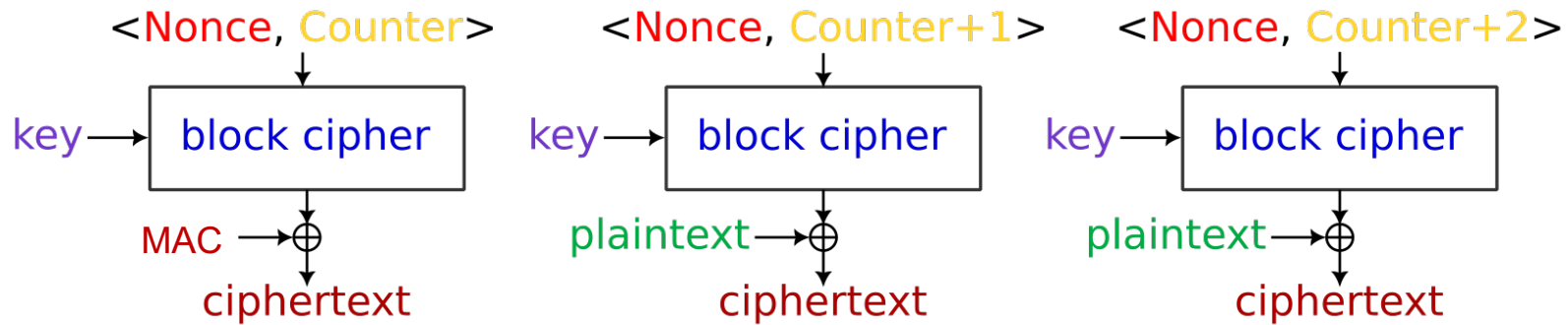
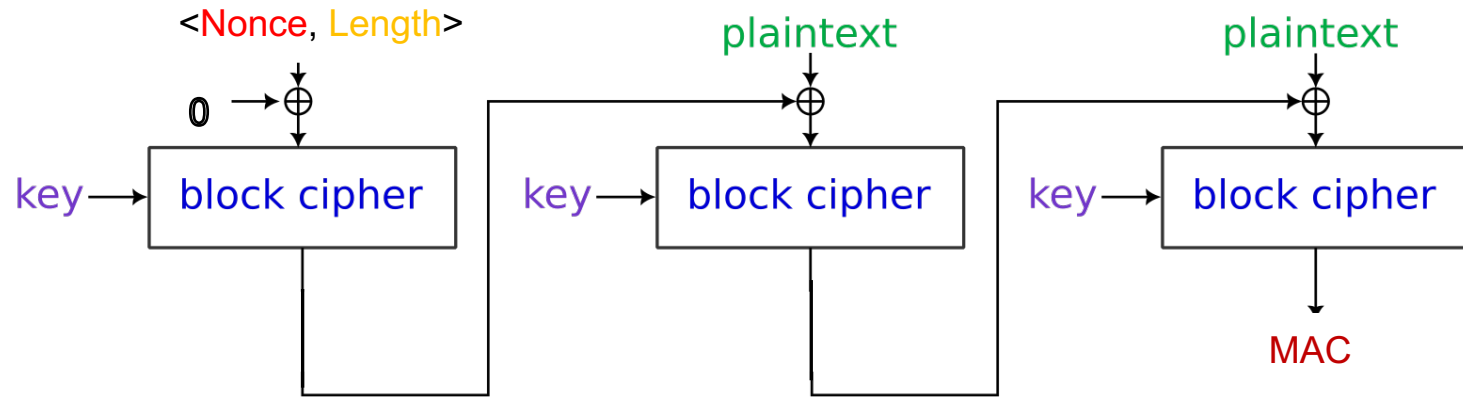
CBC-MAC uses the block cipher (AES) in CBC mode with an all-zeros initialization vector; the MAC tag is the last block encrypted

The MAC tag and the message are then encrypted in counter mode

There are some additional, minor details

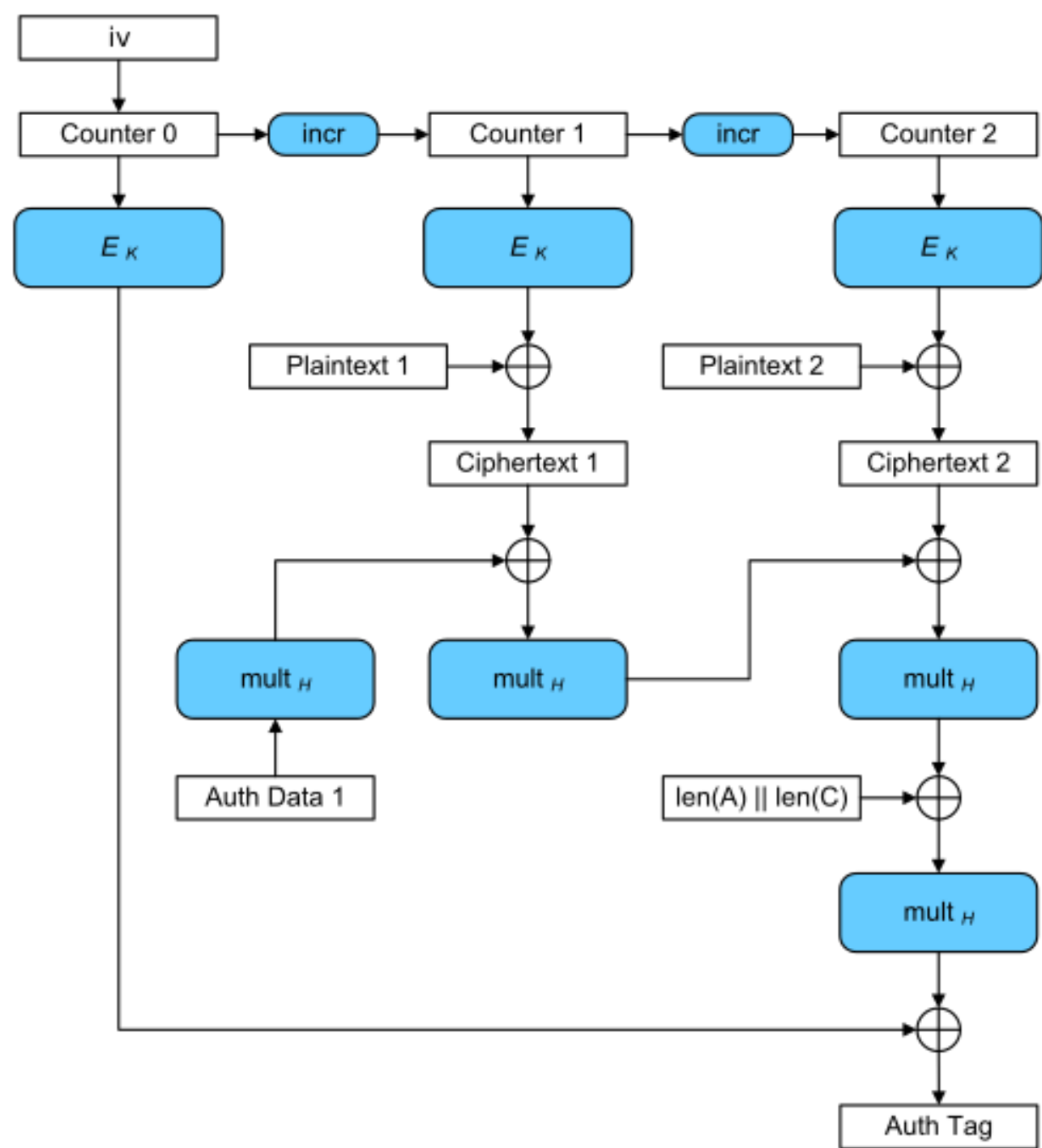
The next slide has a diagram

# CCM (some padding details omitted)



# GCM (Galois Counter mode)

It's complicated!



*Assumption we've been making so far:*

Alice and Bob ***shared a secret key*** in advance

**Amazing fact:**

Alice and Bob can have a **public** conversation to derive a shared key!

## **So Far**

Message Integrity

Randomness /Pseudorandomness

Confidentiality: Stream Ciphers, Block Ciphers

## **Next time...**

Key Exchange, Key Management, Public Key Crypto