CS489/698 Privacy, Cryptography, Network and Data Security

Basics of Cryptography

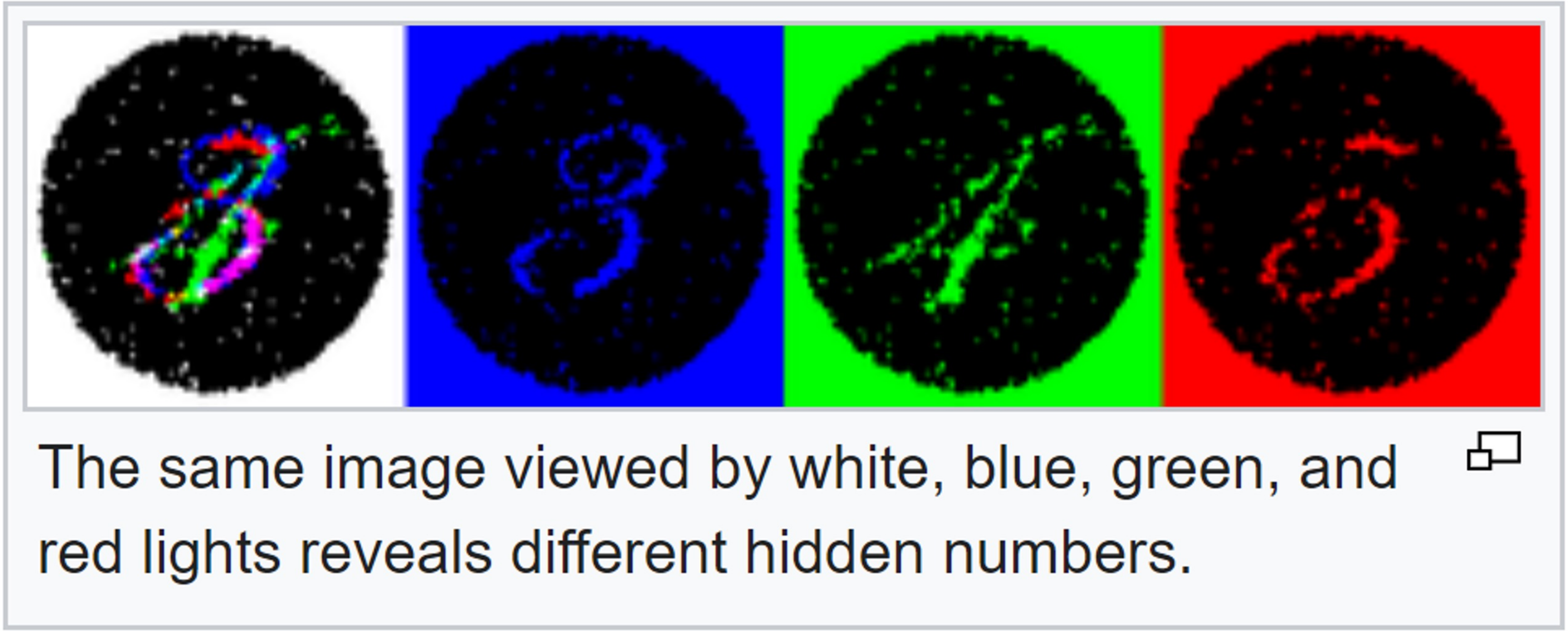
Spring 2024, Monday/Wednesday 11:30-12:50am

Learning Outcomes

- Identify attack techniques and apply them (cryptanalysis)
- Explain building blocks of modern cryptography
- Explain how modern cryptography properties arose

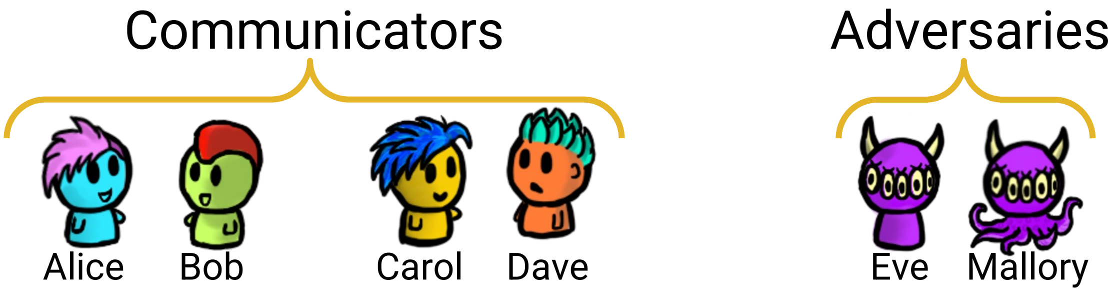
Goal: Basically, know what cryptography tools exist and how to securely use them. Build a foundation of primitives for more complicated “applied cryptography” later.

Steganography- Secretly “hidden” messages



The same image viewed by white, blue, green, and red lights reveals different hidden numbers.

Cryptography - Writing “secret” messages

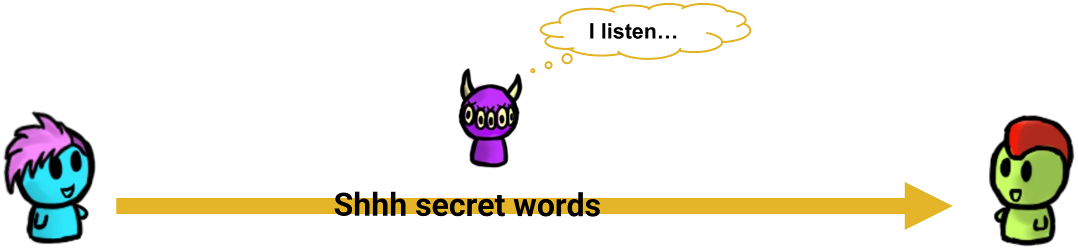


Communicators

Alice Bob Carol Dave

Adversaries

Eve Mallory

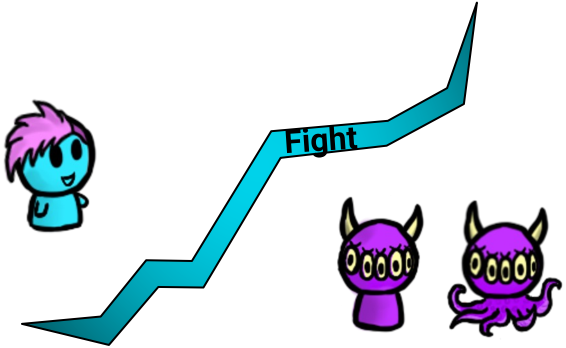


I listen…

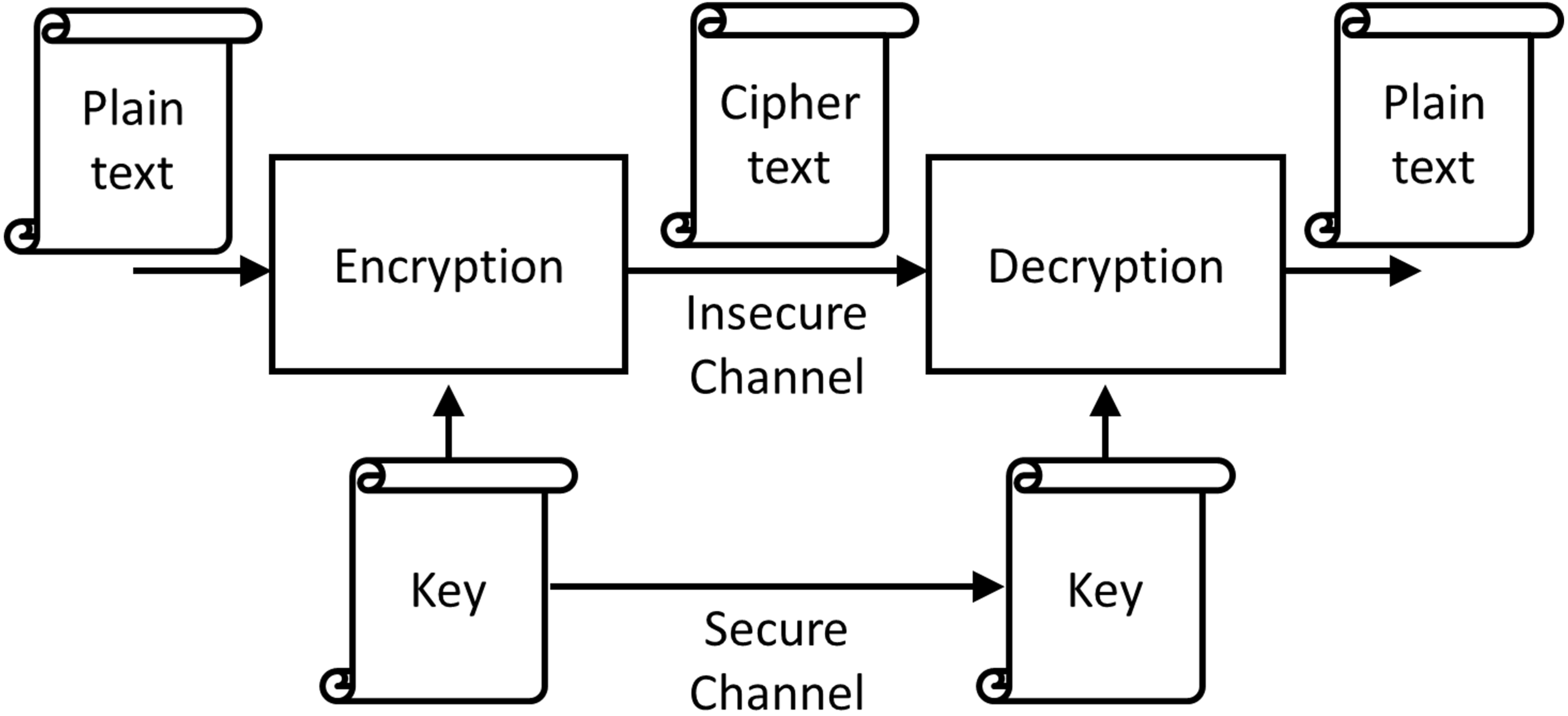
Shhh secret words

Remember CIA? Different A for Crypto Power ⚡

- **C**onfidentiality, prevent Eve **reading** Alice's messages
- Integrity, prevent Mallory from **changing** Alice's messages
- **A**uthenticity, Prevent Mallory from **impersonating** Alice



Cryptography - Path for Secret Messages



Historical Ciphers: Example One

FUBSWRJUDSKB

CRYPTOGRAPHY

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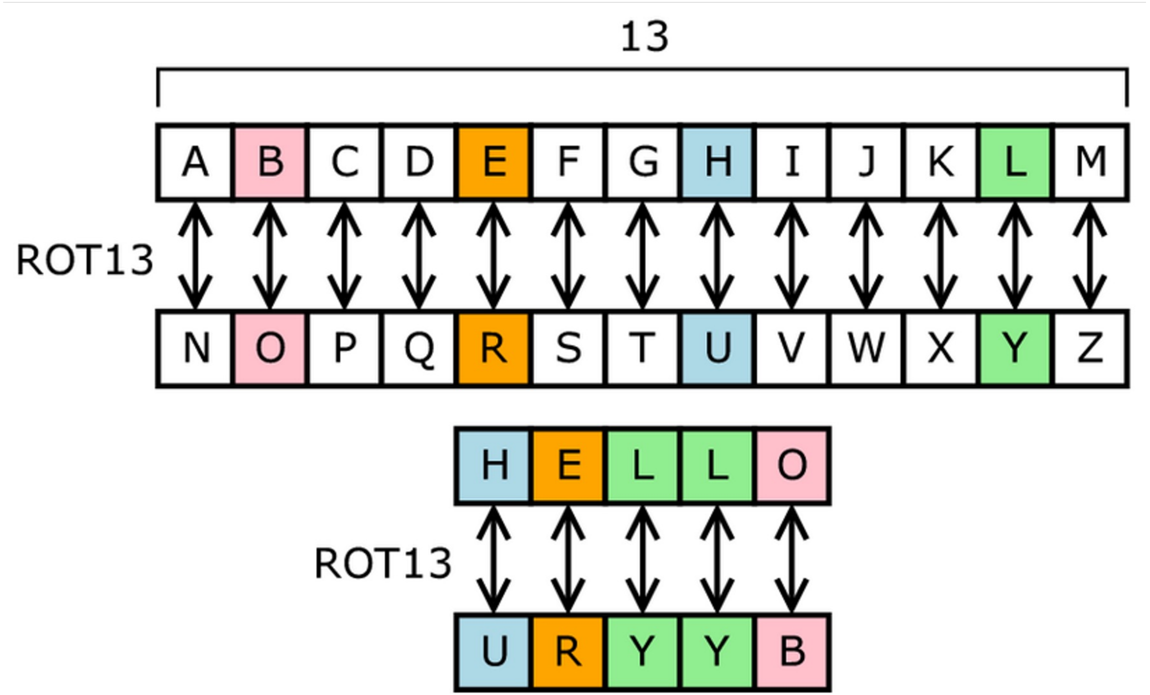
FUBSWRJUDSKB

CRYPTOGRAPHY

Substitution Cipher (shift 3)

Caesar Cipher



A B C D E F G H I J K L M

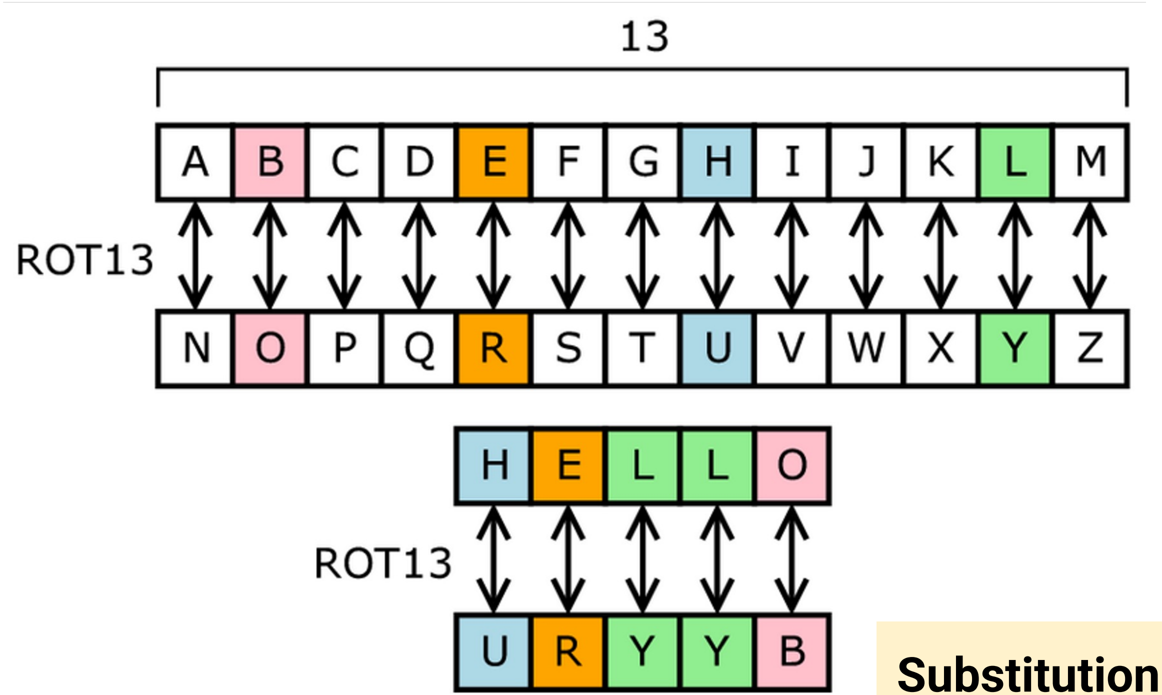
N O P Q R S T U V W X Y Z

H E L L O

U R Y Y B

Image source: wikipedia

Caesar Cipher



Substitution Cipher (shift 13)

Image source: wikipedia

Shift and Substitution Ciphers

Replace symbols (letters) by others

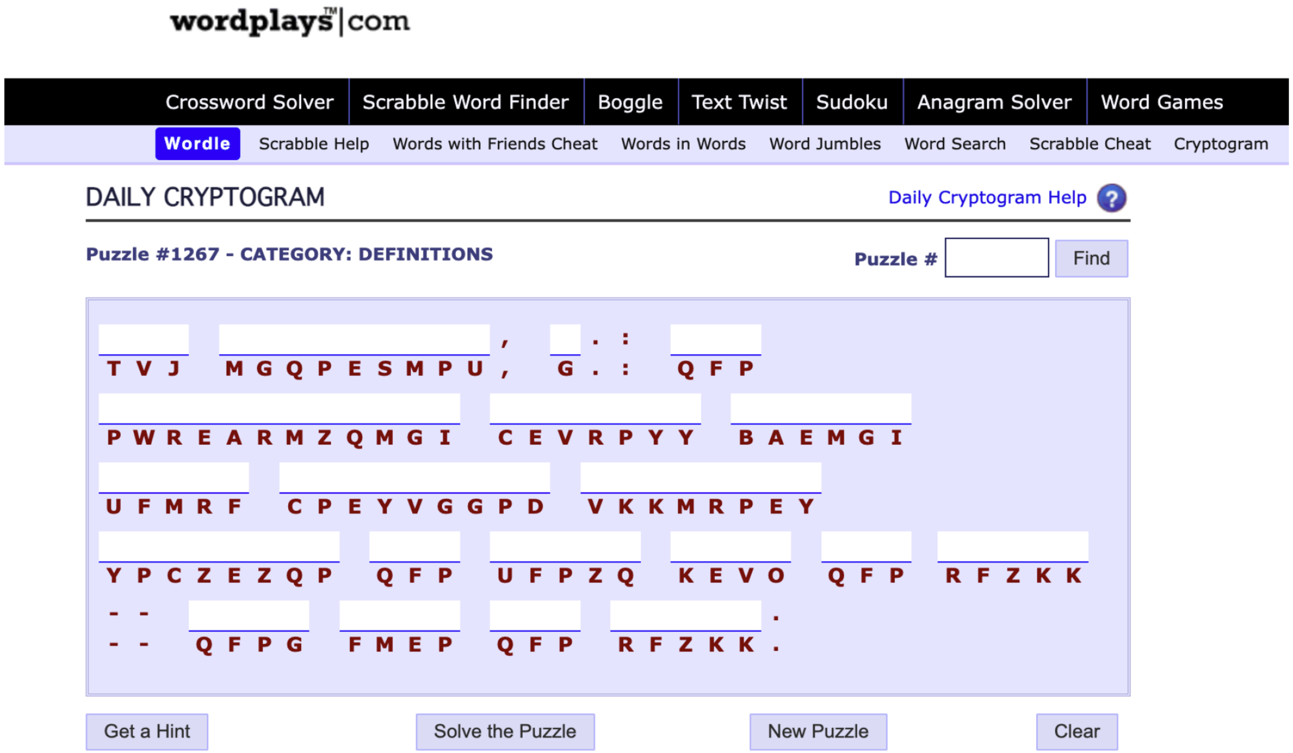
- Using a rule e.g., $y = x + 3 \pmod{26}$, Caesar‘s cipher Key: 3
- Using a table e.g, Key: table

Cryptanalysis - Analyzing “secret” messages

Mwahaha

We will learn the secretsssss.

Historical Ciphers: Example Two



DAILY CRYPTOGRAM

Puzzle #1267 - CATEGORY: DEFINITIONS

TVJ MGQPESMPU, G.: QFP

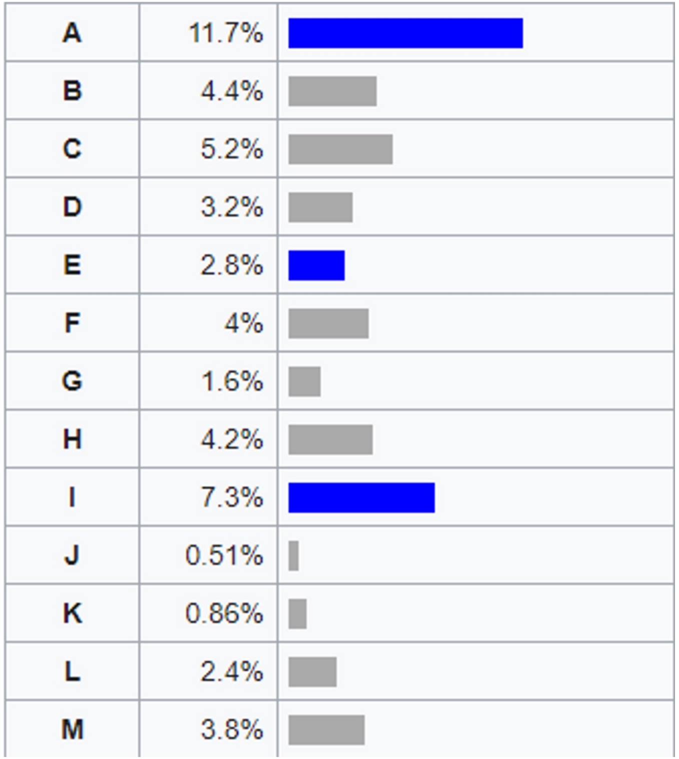
PWREARMZQMGI CEVRPYY BAEMGI

UFMRF CPEYVGGPD VKKMRPEY

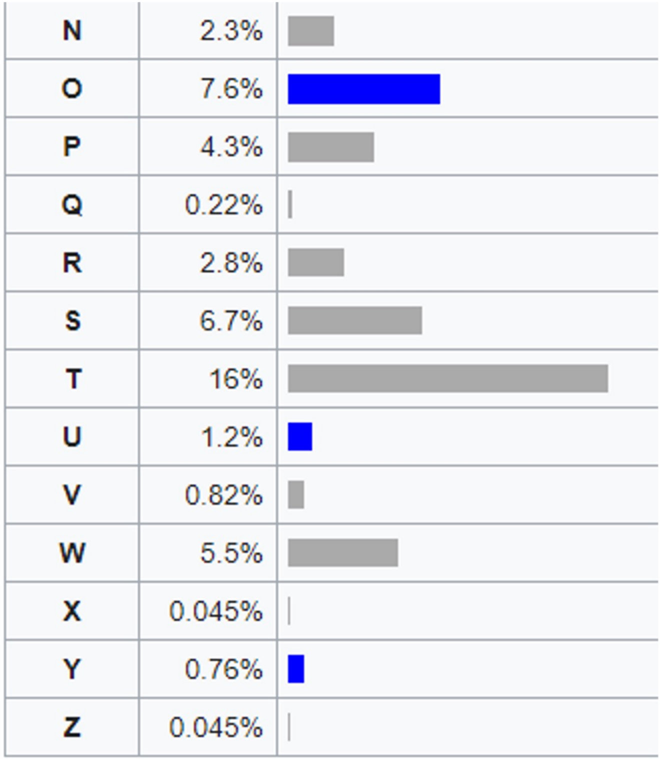
YPCZEZQP QFP UFPZQ KEVO QFP RFZKK

-- QFPG FMEP QFP RFZKK.

English Frequency

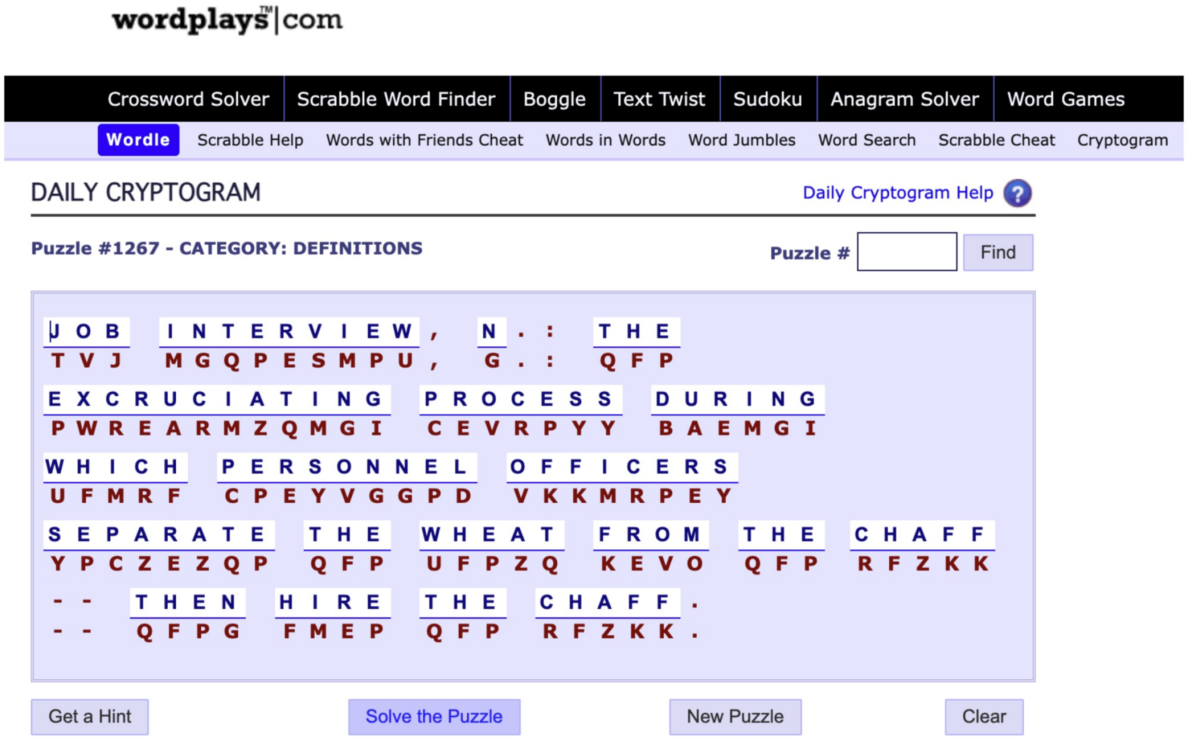


A	11.7%	🟦
B	4.4%	▬
C	5.2%	▬
D	3.2%	▬
E	2.8%	🟦
F	4%	▬
G	1.6%	▬
H	4.2%	▬
I	7.3%	🟦
J	0.51%	▬
K	0.86%	▬
L	2.4%	▬
M	3.8%	▬



N	2.3%	▬
O	7.6%	🟦
P	4.3%	▬
Q	0.22%	▬
R	2.8%	▬
S	6.7%	▬
T	16%	▬
U	1.2%	🟦
V	0.82%	▬
W	5.5%	▬
X	0.045%	▬
Y	0.76%	🟦
Z	0.045%	▬

Historical Ciphers: Example Two

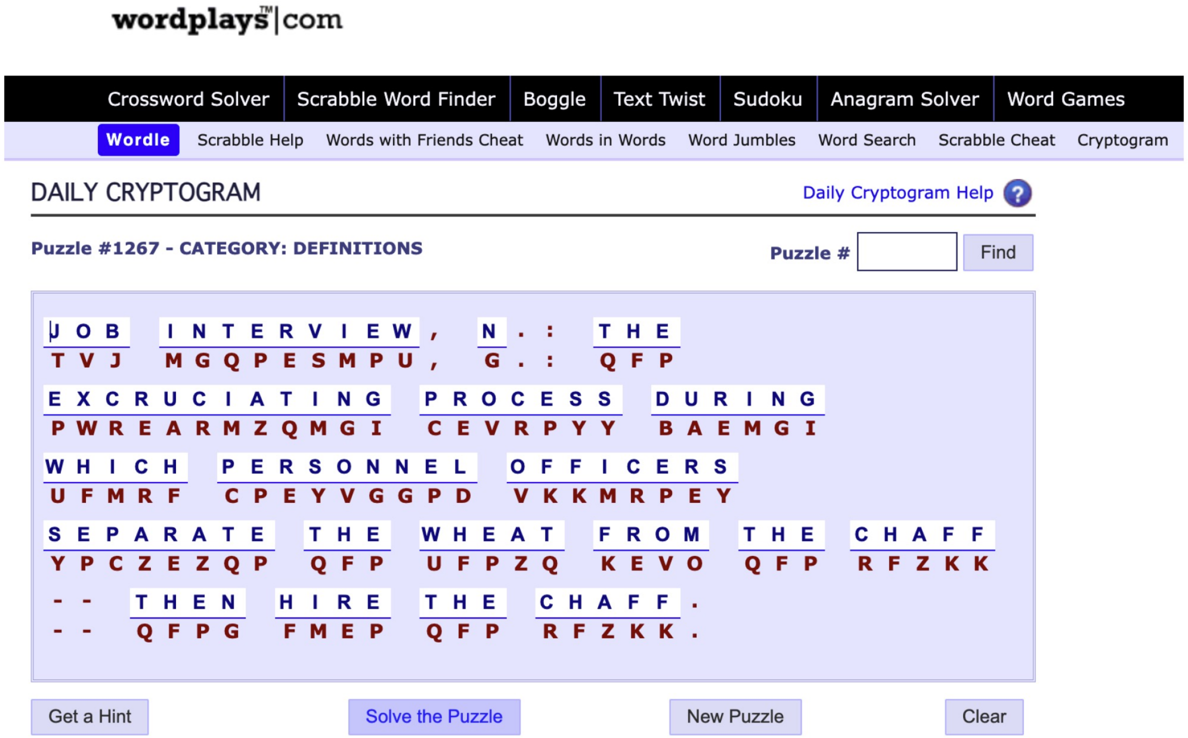


DAILY CRYPTOGRAM

Puzzle #1267 - CATEGORY: DEFINITIONS

```
JOB INTERVIEW, N.: THE
TVJ MGQPESMPU, G.: QFP
EXCRUCIATING PROCESS DURING
PWREARMZQMGI CEVRPYY BAEMGI
WHICH PERSONNEL OFFICERS
UFMRF CPEYVGGPD VKKMRPEY
SEPARATE THE WHEAT FROM THE CHAFF
YPCZEZQP QFP UFPZQ KEVO QFP RFZKK
-- THEN HIRE THE CHAFF.
-- QFPG FMEP QFP RFZKK.
```

Historical Ciphers: Example Two



DAILY CRYPTOGRAM

Puzzle #1267 - CATEGORY: DEFINITIONS

Puzzle #

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TVJ MGQPESMPU, G.: QFP

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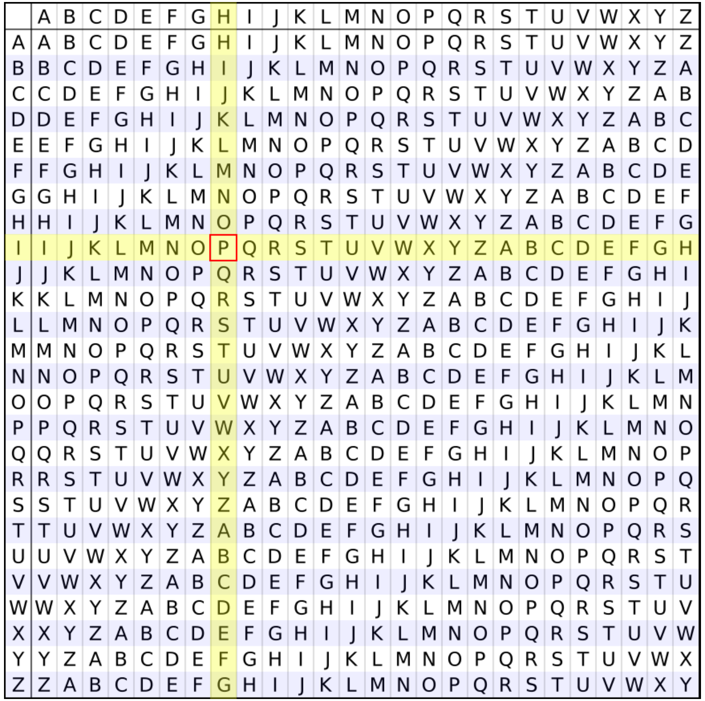
Kerckhoff Principle

The security of a cryptosystem should solely depend on the secrecy of the key, but never on the secrecy of the algorithms.

Historical Ciphers: Example Three – Vigenère



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
A	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
B	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A
C	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B
D	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C
E	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D
F	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E
G	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F
H	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G
I	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H
J	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I
K	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J
L	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K
M	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L
N	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M
O	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N
P	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Q	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
R	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
S	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
T	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
U	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
V	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
W	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
X	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
Y	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
Z	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y

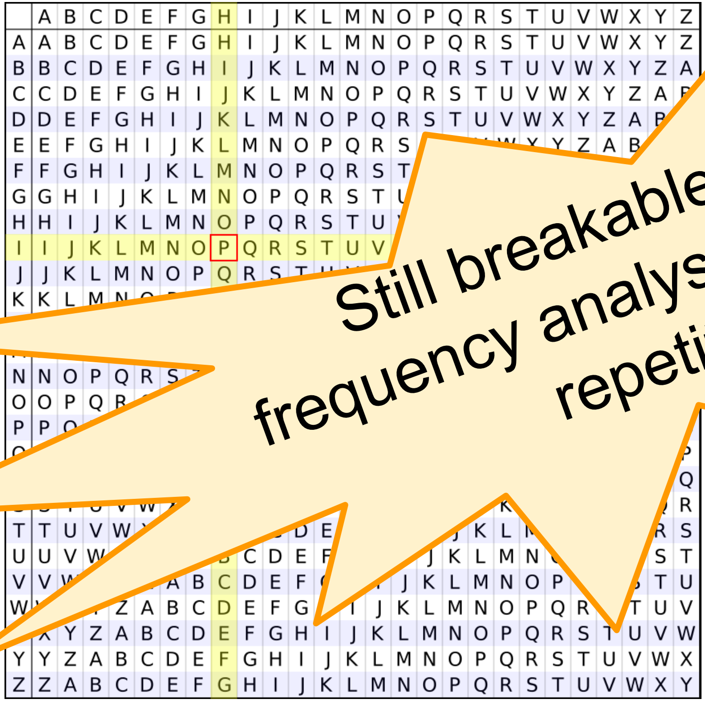
Key: KEYKE

Message: HELLO

Ciphertext: RIJVS

Poly-Alphabetic Substitution Cipher

Historical Ciphers: Example Three – Vigenère



Still breakable through frequency analysis (due to key repetition)

YKE

Message: HELLO

Ciphertext: RIJVS

Poly-Alphabetic Substitution Cipher

Historical Ciphers: Example Four

LECTURE SECURITY AND CRYPTOGRAPHY I

↓

LENGECDRCUCATRRPUIYHRTPYEYTISAO

Historical Ciphers: Example Four

LECTURES

ECURITYA

NDCRYPTO

GRAPHYI

→ **LENG**ECDRCUCATRRPUIYHRTPYEYTISAO

Transposition Cipher

Historical Ciphers: Example Four

LECTURES

ECURITYA

NDCRYP

GRA

YHRTPYEYTISAO

Shannon’s maxim!!!! (design assuming adversaries will learn the algorithm)

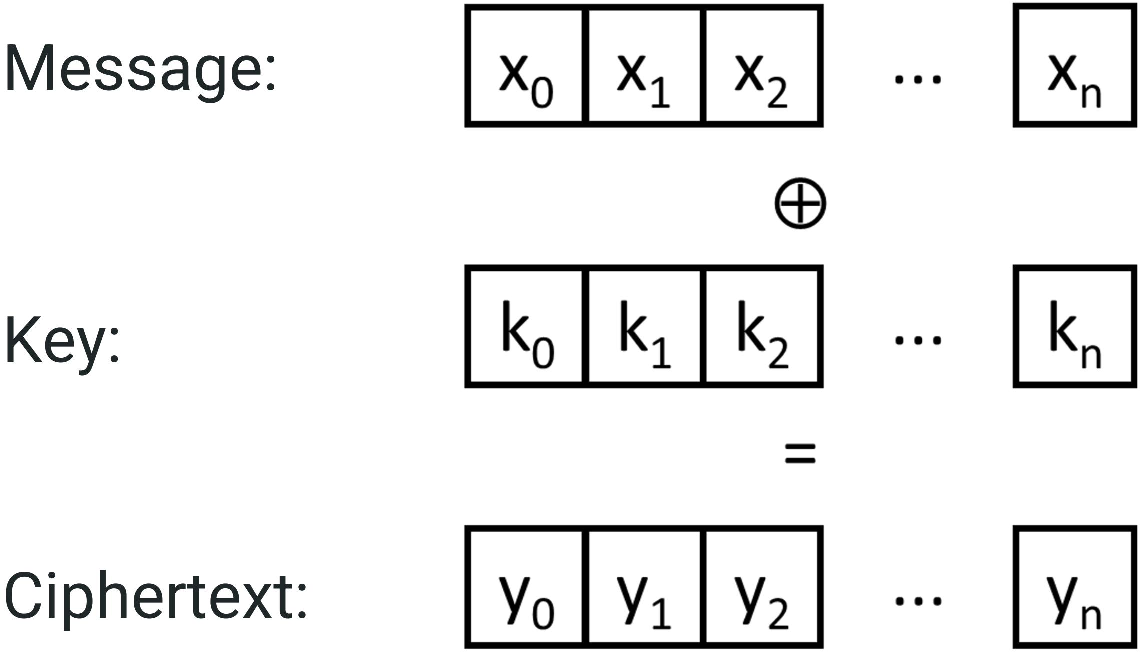
Transposition Cipher

Shannon’s Maxim & Kerkhoff’s Principle:

- Security shouldn’t rely on the secrecy of the method
- Do use public algorithms with secret “keys”
- The adversaries target is… the key

Idea: Easier to change a “short” key than your whole system.
(e.g., Recovery)

Unconditionally Secure: One-Time Pad



Message: x_0 x_1 x_2 … x_n

$\oplus$

Key: k_0 k_1 k_2 … k_n

=

Ciphertext: y_0 y_1 y_2 … y_n

Rule: $y_i = x_i + k_i \pmod{2}$

Provable Security for One-Time Pad

<Ciphertext is uniformly distributed independent of the plaintext distribution>

x_i = 0 with probability p (x_i = 1: 1-p),

k_i = 0 with probability 0.5 (k_i = 1: 0.5),

y_i = 0 with probability:

$$\begin{aligned} p(y_i = 0) &= p(x_i = 0)\, p(k_i = 0) + p(x_i = 1)\, p(k_i = 1) \\ &= 0.5p + 0.5(1-p) \\ &= 0.5 \end{aligned}$$

Provable Security for One-Time Pad

Every ciphertext *y* can be decrypted **into every arbitrary plaintext** *x* using the **key** *k*

Consequently the <u>ciphertext cannot contain any information about the plaintext</u>

Encryption is “deniable”

Well…this sucks for me…

What if it is a Many-Time Pad?

Key: K

Ciphertext_1= message_1 xor K = `2c1549100043130b1000290a1b`

Ciphertext_2= message_2 xor K = `3f16421617175203114c020b1c`

Hmmm… how can I relate these messages together?

What if it is a Many-Time Pad?

Key: K

Ciphertext$_1$ xor Ciphertext$_2$=

message$_1$ xor K xor message$_2$ xor K =

message$_1$ xor message$_2$ = `13030b0617544108014c2b0107`

What if it is a Many-Time Pad?

message$_1$ xor message$_2$ = `13030b0617544108014c2b0107`

Suppose message$_1$ starts with “Alice” `(414C696365)`

- message$_2$ seems to start with readable text (“Rober”)

Is “Alice” here…?

What if it is a Many-Time Pad?

message$_1$ xor message$_2$ = `13030b0617544108014c2b0107`

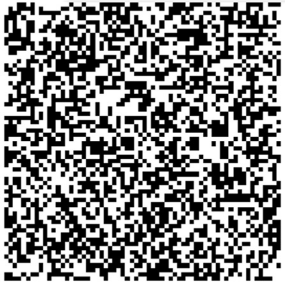
Suppose message$_1$ starts with “Alice” `(416C696365)`

- message$_2$ seems to start with readable text (“Rober”)

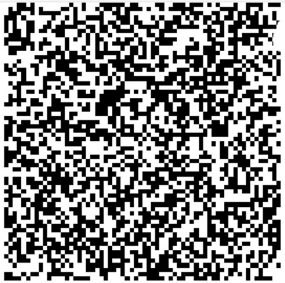
Suppose it starts with “Alice and Bob” `(416C69636520616E6420426F62)`

- message2 is fully readable now! (“Robert feline”)

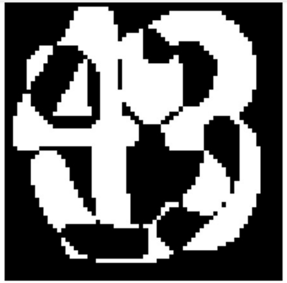
Many-time pad? Messages Lack True Randomness



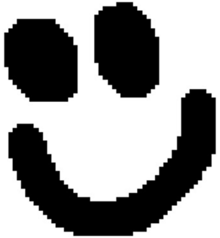
C_1



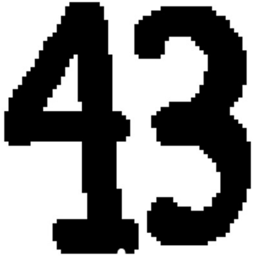
C_2



$C_1 \oplus C_2$



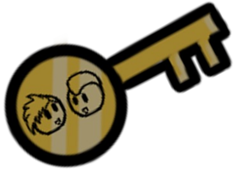
M_2

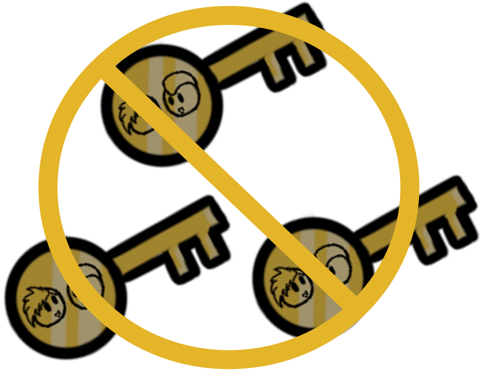


M_1

One-Time Pad - Conditions…

- Key uniformly random
- Only used once
- Key as long as the message





So…Cryptography?

- Simple substitution/transposition is insecure
- One-Time Pad is inefficient over the secure channel
  - Keys as long as messages – think about encrypting GBs of data!

Goal: Securely communicate “a lot” of information on an insecure channel while requiring “limited” communication over a secure channel

Now what?

Substitution is insecure…

Transposition is insecure…

Key reuse using XOR (one-time pad) is insecure…

BUT…

Repeat it often enough and it can be regarded as secure

Now what?

Substitution is insecure…

Transposition is i

Key reuse d) is insecure…

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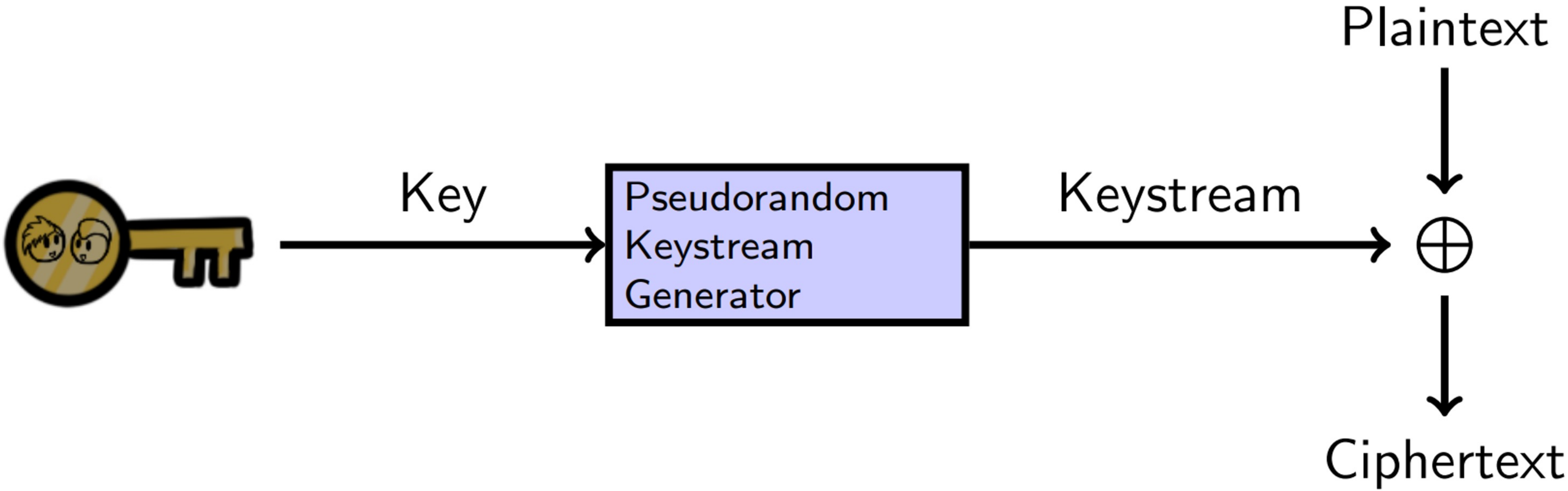
Repeat it often enough and it can be regarded as secure

Stream Ciphers and Block Ciphers

Stream Cipher?

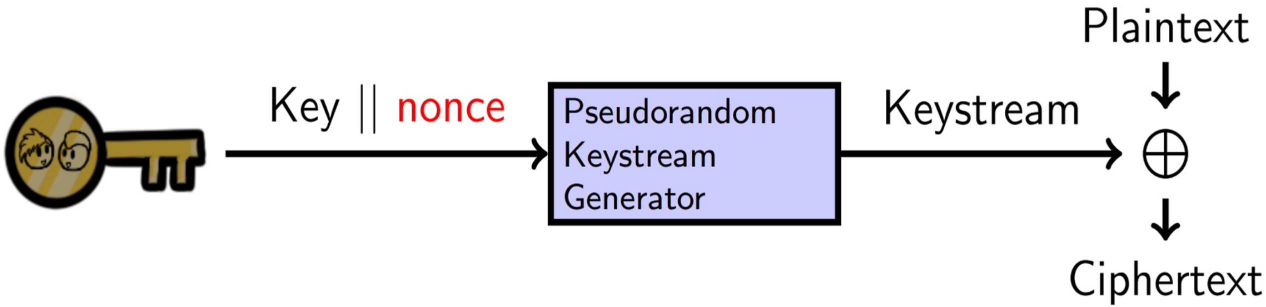


Fun(?) Facts:

- RC4 was the most common stream cipher on the Internet but deprecated.
- ChaCha increasingly popular (Chrome and Android), and SNOW3G in mobile phone networks.

Stream Ciphers Share Conditions with OTP

- Stream ciphers can be very fast
  - This is useful if you need to send a lot of data securely
- But they can be tricky to use correctly!
  - We saw the issues of re-using a key! (two-time pad)
  - **Solution:** concatenate key with nonce (which does not need to be a secret)



Fun(?) Facts:

- WEP, PPTP are great examples of how not to use stream ciphers

Bit by bit…. but do you have to?

- Weakness of streams…one bit at a time?
  - What happens in a stream cipher if you change just one bit of the plaintext?

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A: You only change a bit in the ciphertext

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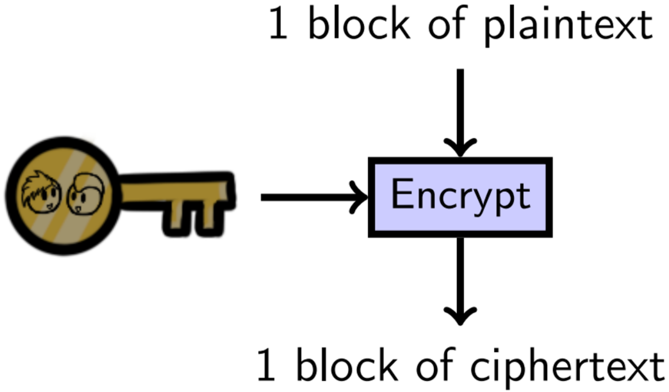
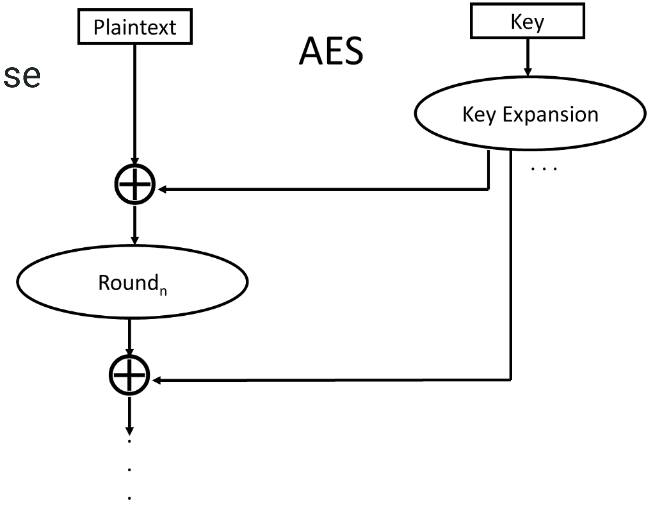
Q: Can we do better?



Block ciphers!!!

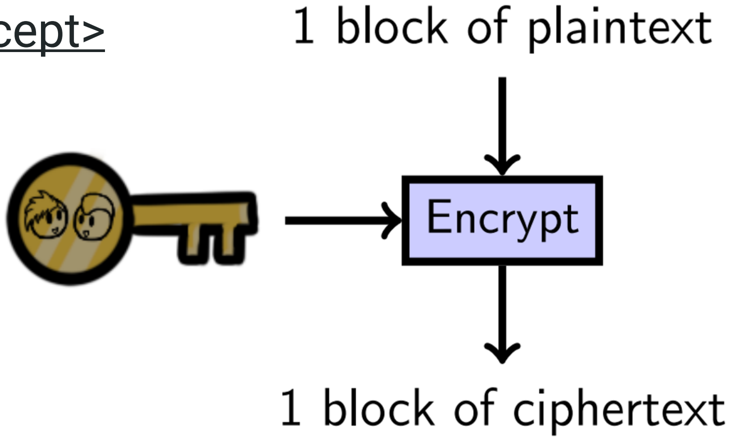
Block Ciphers

- Welcome, use of block ciphers
  - Block ciphers operate on the message one block at a time
  - Blocks are usually 64 or 128 bits long
- **AES**, the current standard
  - You better have a very…very good reason to choose otherwise

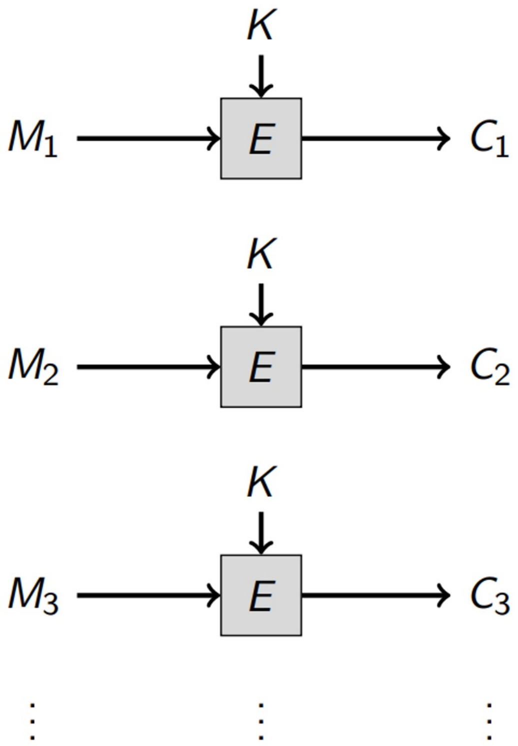


Two Catches with Block Ciphers

- Message is **shorter** than one block?
  - Requires padding
- Message is **longer** than a block?
  - Requires modes of operation <new concept>

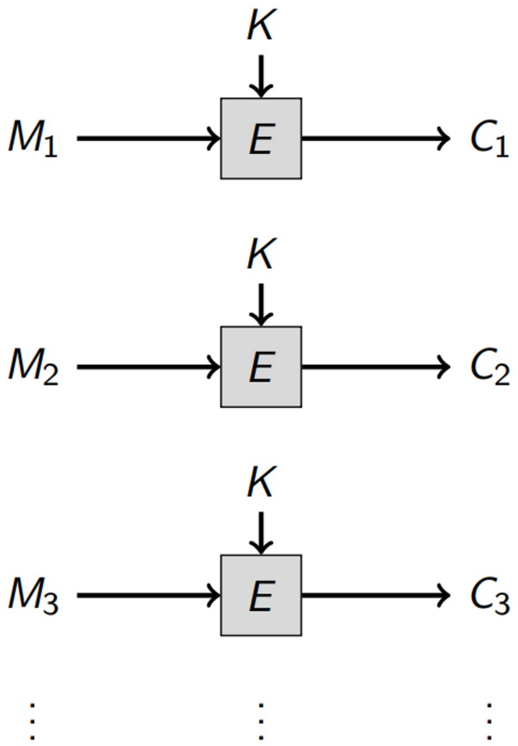


Block Ciphers and Modes of Operation: ECB Mode



- ECB: Electronic Code Book
- Encrypts each successive block separately

Block Ciphers and Modes of Operation: ECB Mode



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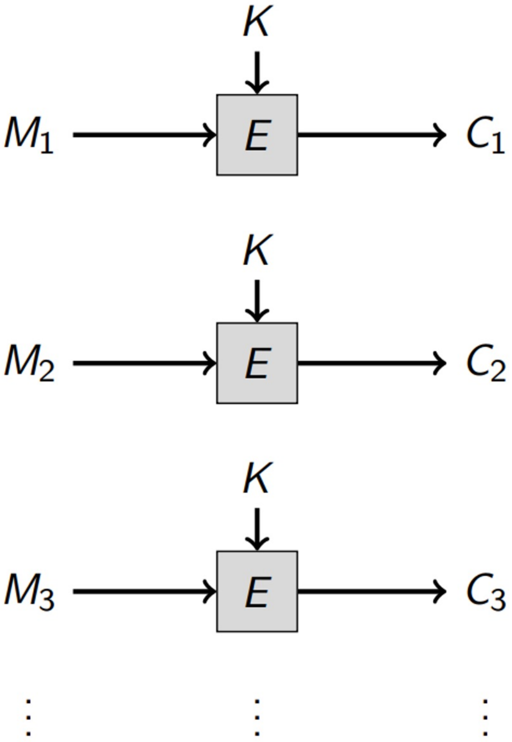
Q: What happens if the plaintext M has some blocks that are identical, $M_i = M_j$?

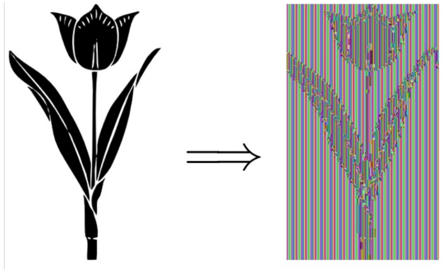
Block Ciphers and Modes of Operation: ECB Mode



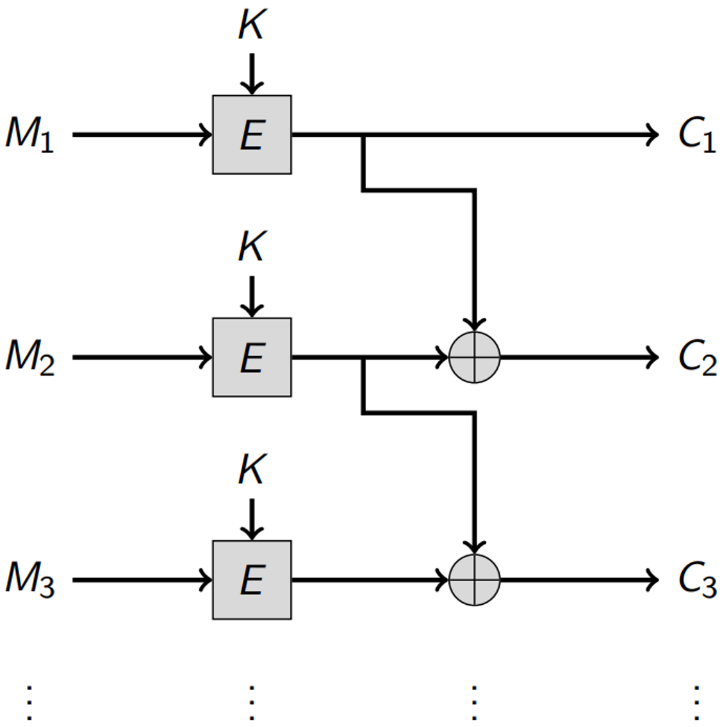
- ECB: Electronic Code Book
- Encrypts each successive block separately

Q: What happens if the plaintext M has some blocks that are identical, $M_i = M_j$?

A: $C_i = E_K(M_i)$, $C_j = E_K(M_j) \Rightarrow C_i = C_j$



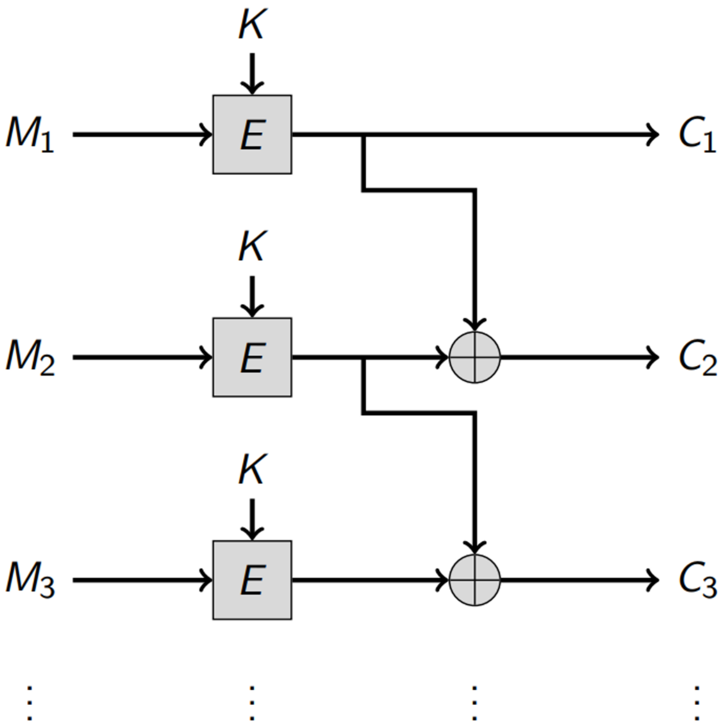
Attempt 1: Fixing ECB$_1$



- Provide “feedback” among different blocks, to avoid repeating patterns…

Q: Fix repeating patterns? Are there other issues?

Attempt 1: Fixing ECB$_1$

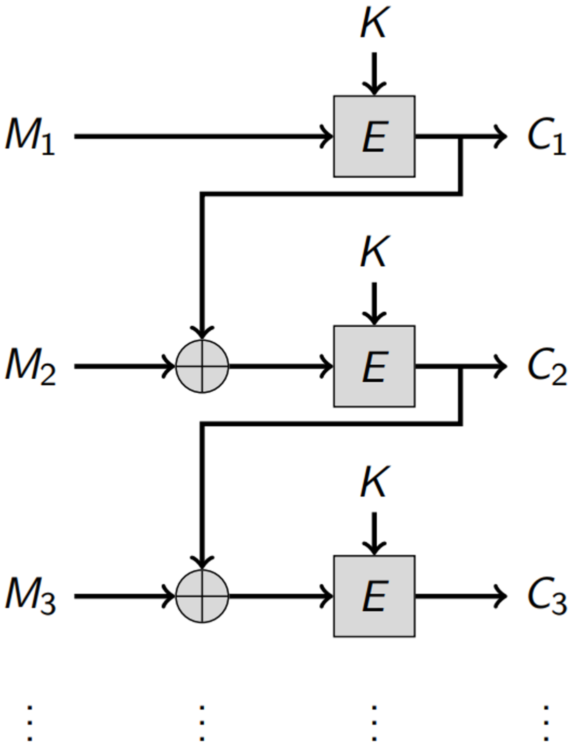


- Provide “feedback” among different blocks, to avoid repeating patterns…

Q: Fix repeating patterns? Are there other issues?

A: We can un-do the XOR if we get all the ciphertexts. This basically does not improve compared to ECB.

Attempt 2: ECB$_2$!!!

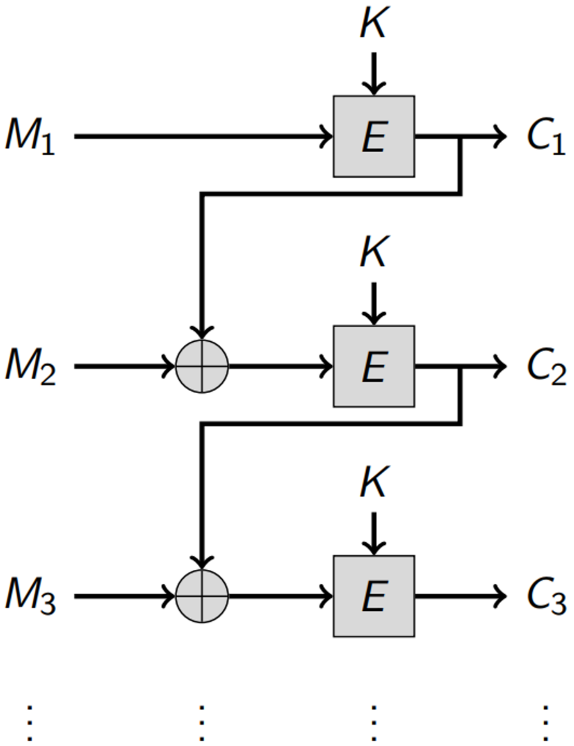


Q: Spot the difference?

Q: Is it fixed this time?

Q: Does this avoid repeating patterns among blocks?

Attempt 2: ECB$_2$!!!



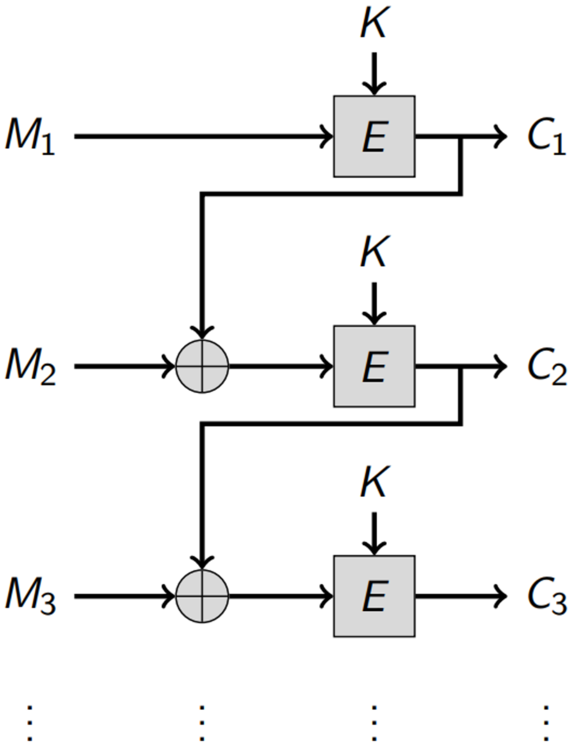
Q: Spot the difference?

Q: Is it fixed this time?

Q: Does this avoid repeating patterns among blocks?

Q: What would happen if we encrypt the message twice with the same key?

Attempt 2: ECB_2!!!



Q: Spot the difference?

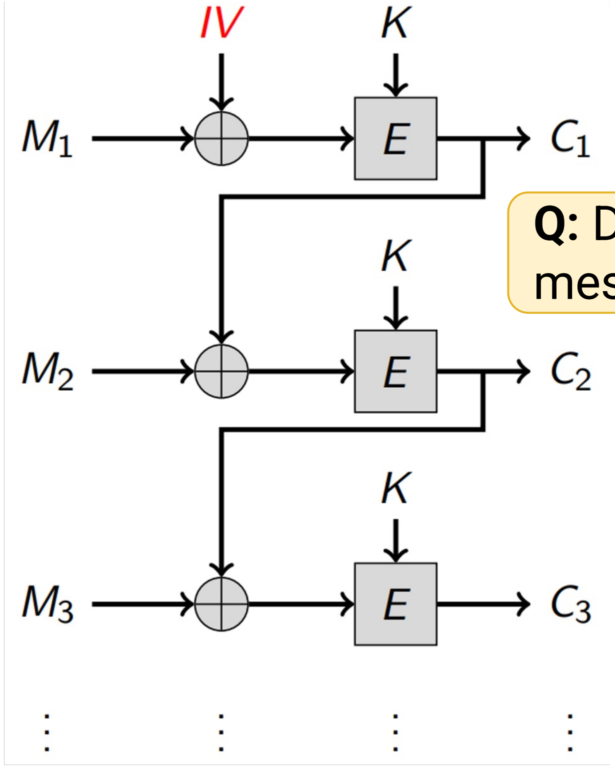
Q: Is it fixed this time?

Q: Does this avoid repeating patterns among blocks?

Q: What would happen if we encrypt the message twice with the same key?

A: for M = N,
C = E_K (M), Y = E_K (N) ⇒ C = Y

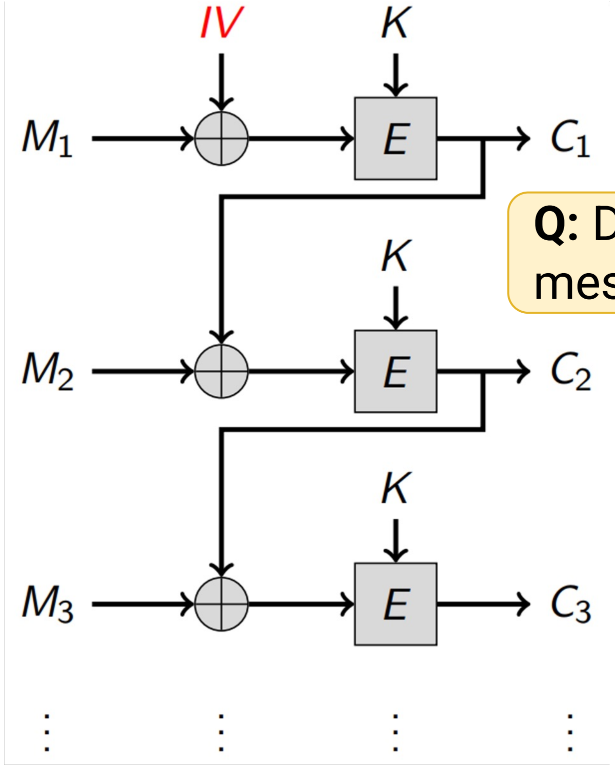
New Plan: Cipher Block Chaining (CBC) Mode



Q: Does this solve the issue of encrypting equal blocks?

Q: Does this solve the issue of encrypting equal messages/plaintexts?

New Plan: Cipher Block Chaining (CBC) Mode



Q: Does this solve the issue of encrypting equal blocks?

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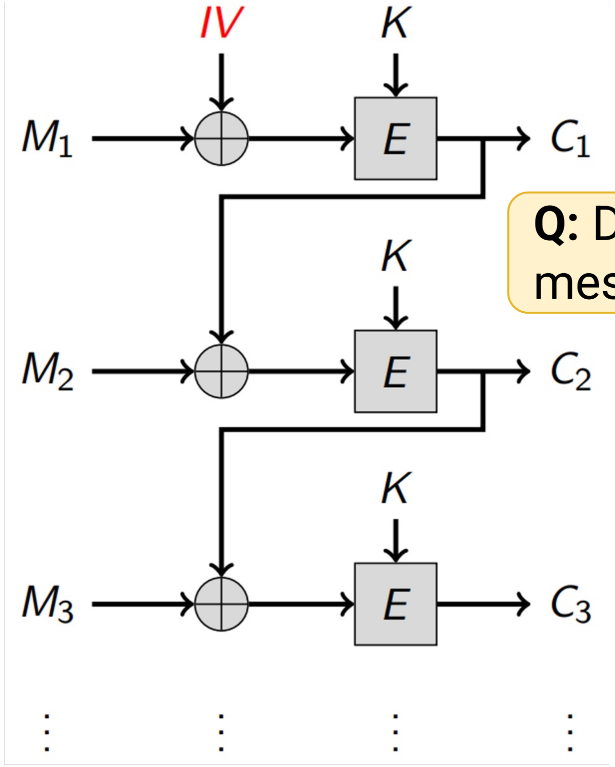
A: Yes!!!

New Plan: Cipher Block Chaining (CBC) Mode



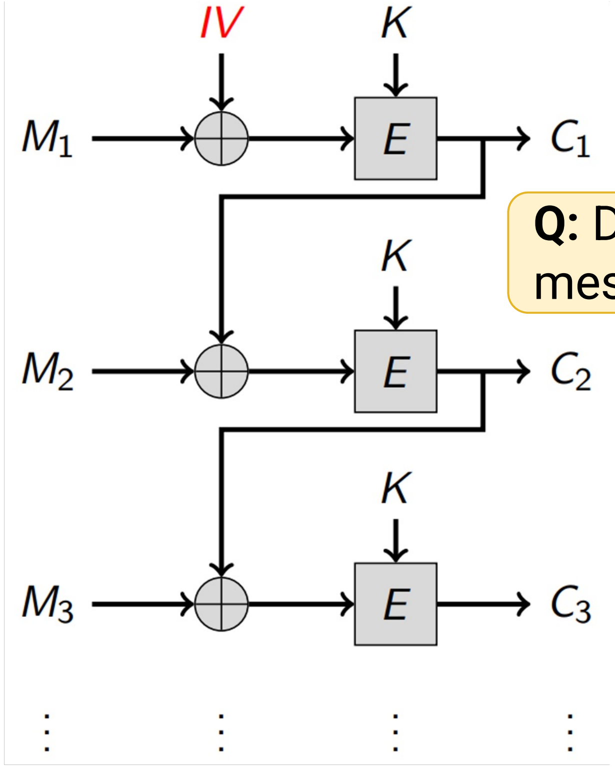
Q: Does this solve the issue of encrypting equal blocks?

Q: Does this solve the issue of encrypting equal messages/plaintexts?

A: Yes!!!

Q: Can we share IV in the clear?

New Plan: Cipher Block Chaining (CBC) Mode



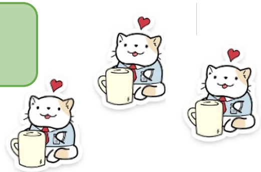
Q: Does this solve the issue of encrypting equal blocks?

Q: Does this solve the issue of encrypting equal messages/plaintexts?

A: Yes!!!

Q: Can we share IV in the clear?

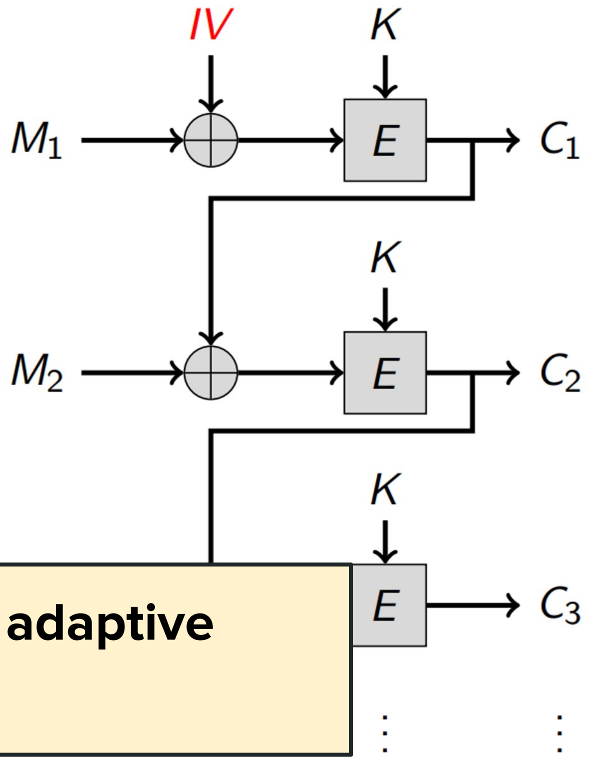
A: Yes!!!



IV, an initialization vector, nonce, salt.

Recall CBC Mode for Block Ciphers:

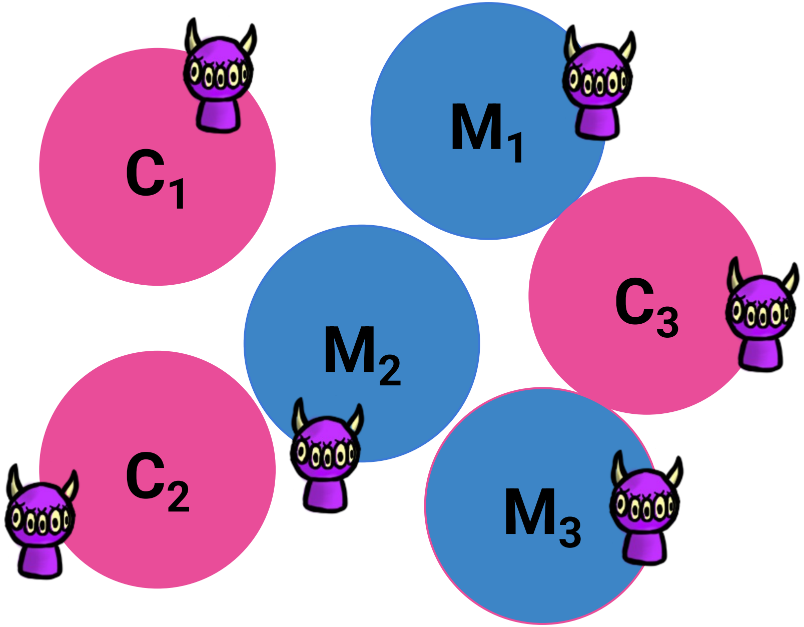
1. Generate a secret key k
2. Encrypt m using k and a generated IV
3. Decrypt c using k and the IV to get m



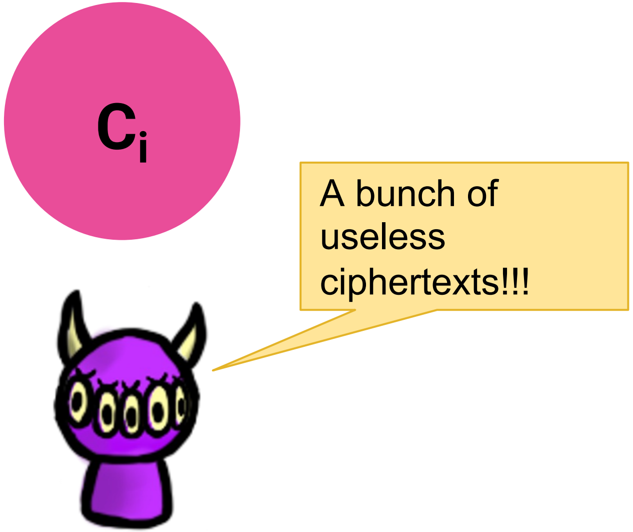
Security Goal: indistinguishability under adaptive chosen ciphertext attack (IND-CCA2)

Cipher Security, IND-CCA2

Indistinguishability under Adaptive Chosen Ciphertext Attack



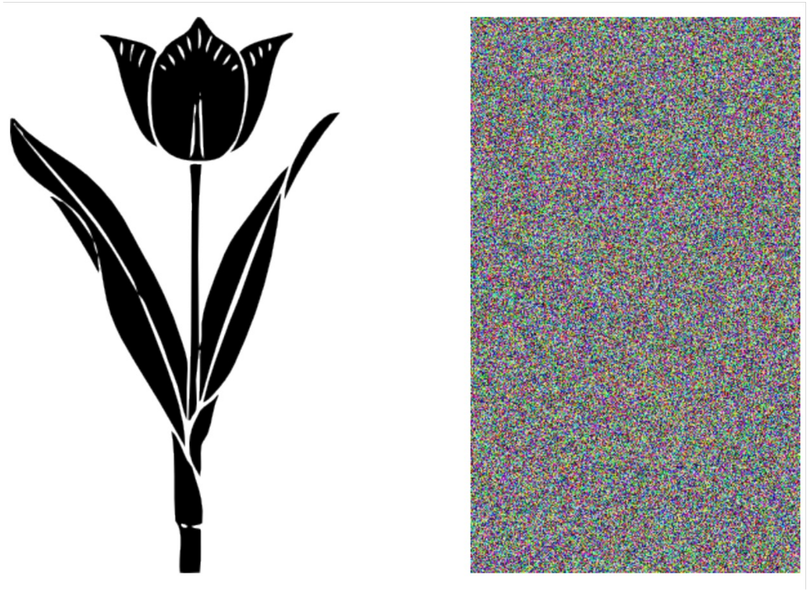
Adaptive chosen ciphertext attack



Eve cannot distinguish whether C_i is from M_1 or M_2

Modes of Operation Collection

- e.g., Cipher Block Chaining **(CBC)**, Counter **(CTR)**, and Galois Counter **(GCM)** modes
- Patterns in the plaintext are no longer exposed because these modes involve some kind of “feedback” among blocks.
- But you need an **IV**



So…now what?

- How do Alice and Bob share the secret key?
    - Meet in person; diplomatic courier…
- In general this is very hard

Or, we invent new technology!!

Spoiler Alert: it’s already been invented…

Stay tuned!