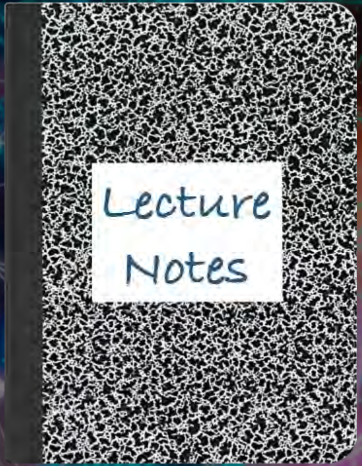
CS 419: Computer Security

Week 2: Cryptography
Symmetric Cryptography



Paul Krzyzanowski

cryptography

κρυπτός → hidden

γραφία → writing

A secret manner of writing, … Generally, the art of writing or solving ciphers.

— *Oxford English Dictionary*

cryptanalysis

↙ ↘

κρυπός → hidden

ἀνάλυσις → action of loosing, solution of a problem

The analysis and decryption of encrypted text or information without prior knowledge of the keys.

— *Oxford English Dictionary*

cryptology

↙ ↘

κρυπός — *λογια*

↓ ↓

hidden — **speaking (knowledge)**

1967 D. Kahn, *Codebreakers* p. xvi, Cryptology is the science that embraces cryptography and cryptanalysis, but the term 'cryptology' sometimes loosely designates the entire dual field of both rendering signals secure and extracting information from them.

— *Oxford English Dictionary*

Cryptography ≠ Security

Cryptography may be a component of a secure system

Just adding cryptography may not make a system secure

Cryptography: what is it good for?

- **Confidentiality**
  - Others cannot read contents of the message
- **Authentication**
  - Determine origin of message
- **Integrity**
  - Verify that message has not been modified
- **Nonrepudiation**
  - Sender should not be able to falsely deny that a message was sent

Terms

Plaintext (cleartext) message P

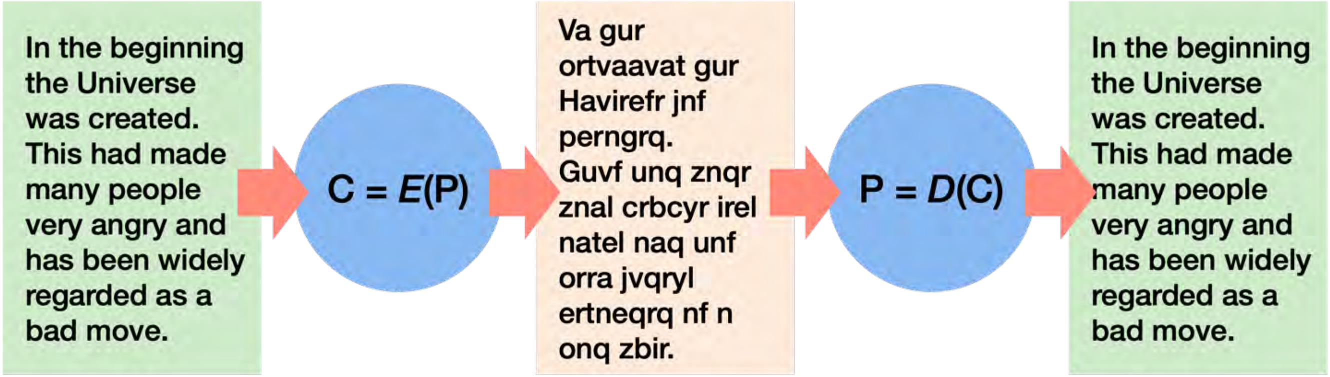
Encryption *E*(P)

Produces Ciphertext, C = *E*(P)

Decryption, P = *D*(C)

Cryptosystem
Encryption & decryption algorithms for a specific cipher

Cipher = cryptographic algorithm



Obfuscation and Secret Algorithms

- **Obfuscation**
  - The algorithm takes plaintext as input and creates ciphertext
  - All security rests in the algorithm
  - Vulnerable to leaking and reverse engineering
  - Useless once exposed
- **Secret algorithms**
  - No peer review to validate its effectiveness (who will test it?)

Many proprietary algorithms have been reverse-engineered and found to be weak

- **A5/1, A5/2** – used in GSM encryption
- **RC3, RC4** – used in SSL, WEP (Wired Equivalent Privacy) on Wi-Fi networks
- **Crypto AG** – a Swiss company that added backdoors under direction of the CIA and German BND
- **DECT Standard Cipher (DSC)** – used in cordless phones
- **Content Scrambling System (CSS)** – DVD encryption
- **HDCP (High-Bandwidth Digital Content Protection)** – HDTV interface
- **Advanced Access Content System** – Blu-ray encryption
- **Firewire** protocol
- **Enigma** cipher machine – German WWII cipher
- Every NATO and Warsaw Pact algorithm during Cold War

Schneier's Law

Any person can invent a security system so clever that she or he can't think of how to break it.

"Anyone, from the most clueless amateur to the best cryptographer, can create an algorithm that he himself can't break. It's not even hard."

— Bruce Schneier

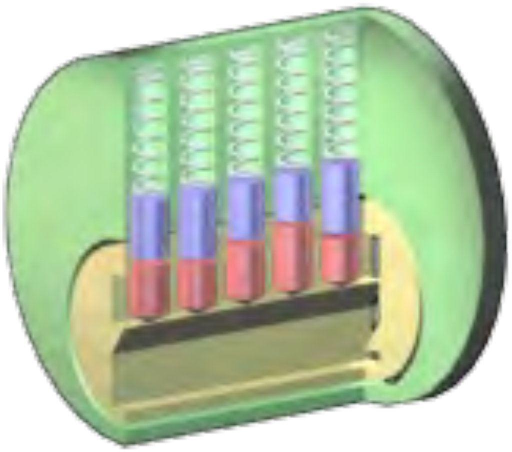
See https://en.wikipedia.org/wiki/Category:Broken_cryptography_algorithms

Shared algorithms & secret keys

The key

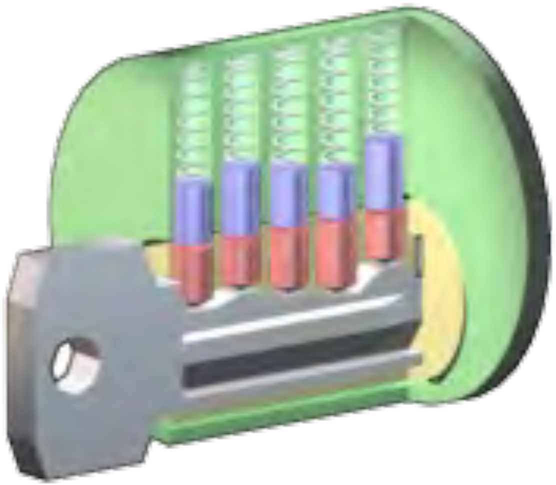
BTW, the above is a *bump key*. See http://en.wikipedia.org/wiki/Lock_bumping

The lock



Source: en.wikipedia.org/wiki/Pin_tumbler_lock

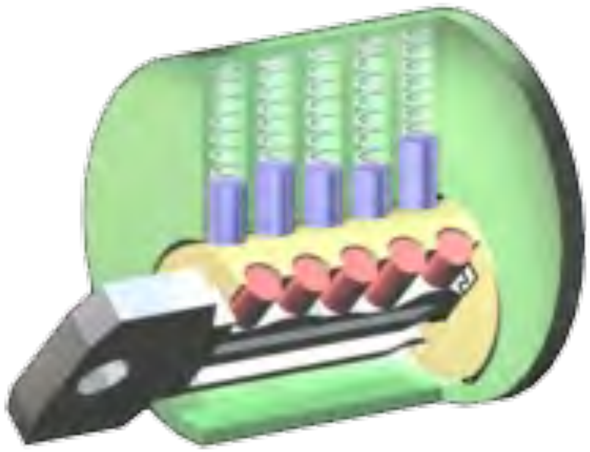
The key & lock



Source: en.wikipedia.org/wiki/Pin_tumbler_lock

The key & lock

- **We understand how the mechanism works:**
  - Strengths
  - Weaknesses
- **Based on this understanding, we can assess how much to trust the key & lock**



Source: en.wikipedia.org/wiki/Pin_tumbler_lock

Kerckhoffs's Principle (1883)

A cryptosystem should be secure even if everything about the system, except the key, is public knowledge

Security should rest entirely on the secrecy of the key

Symmetric Ciphers

One shared secret key, *K*, for encryption & decryption

$$C = E_K(P)$$

$$P = D_K(C)$$

Classic Cryptosystems:
Substitution Ciphers

Atbash (אתבש) – Ancient Hebrew cipher

MY CAT HAS FLEAS

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

NBXZGSZHUOVZH

c. 600 BCE

No information (key) needs to be conveyed!

<u>Origin of the name:</u>
א – alef (1st letter),
ת – tav (last letter),
ב – bet (2nd),
ש – shin (2nd to last)

ת	ש	ר	ק	צ	פ	ע	ס	נ	מ	ל	כ	י	ט	ח	ז	ו	ה	ד	ג	ב	א
א	ב	ג	ד	ה	ו	ז	ח	ט	י	כ	ל	מ	נ	ס	ע	פ	צ	ק	ר	ש	ת

India – Mlecchita vikalpa: Kautiliya

"The art of understanding writing in cypher, and the writing of words in a peculiar way"

Kautiliya

- Documented in the Kama Sutra
- Phonetic substitution scheme used in India 400 BCE – 200 CE
- Short & long vowels are exchanged with consonants

a	ā	i	ī	u	ū	ṛ	ṝ	ḷ	ḹ	e	ai	o	au	ṃ	ḩ	ñ	ś	ṣ	s	i	r	l	u
kh	g	gh	ṅ	ch	j	jh	ñ	ṭh	ḍ	ḍh	ṇ	th	d	dh	n	ph	b	bh	m	y	r	l	v

Cæsar cipher

Earliest documented military use of cryptography

- **Julius Caesar c. 60 BCE**
  - Documented by the Roman historian Suetonius in *De Vita Caesarum*
- **Shift cipher: simple form of a substitution cipher**
- **Each letter replaced by one *n* positions away modulo alphabet size**

  n = shift value = key

  Caesar used *n* = 3

Cæsar 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
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

Cæsar 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
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

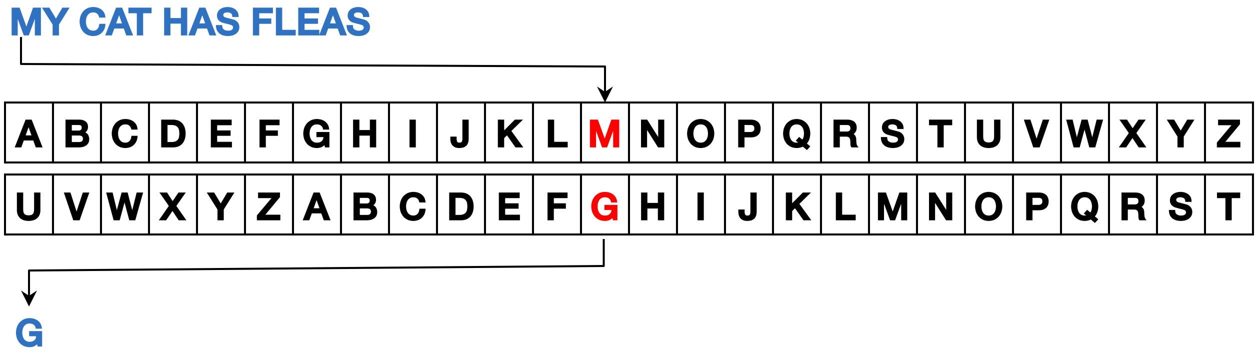
→ *shift alphabet by n (6)*

Cæsar cipher

MY CAT HAS FLEAS

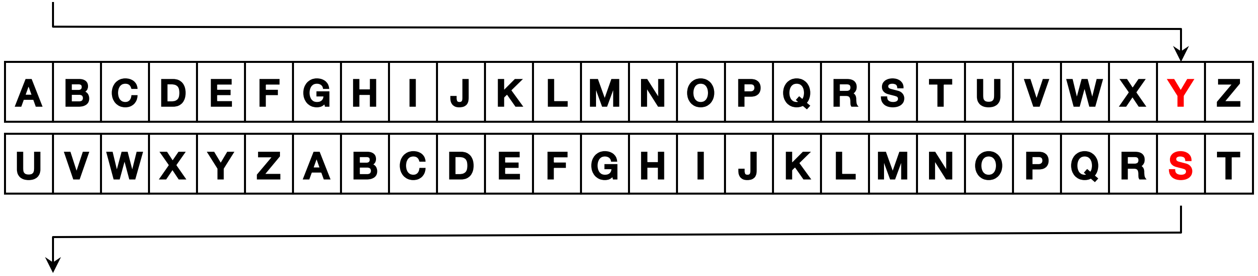
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T

Cæsar cipher



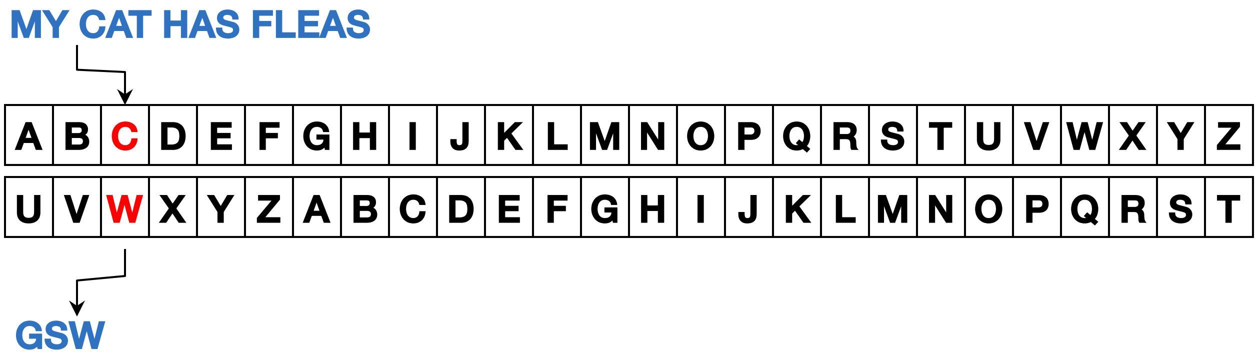
Cæsar cipher

MY CAT HAS FLEAS

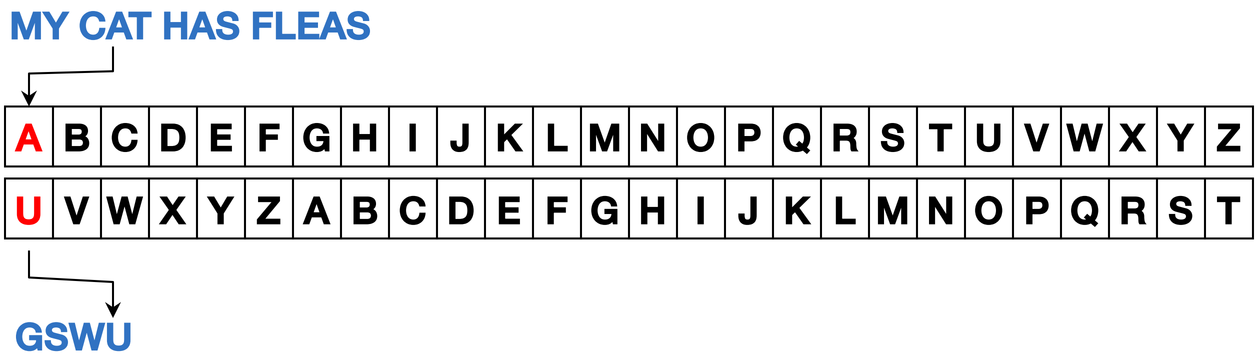


GS

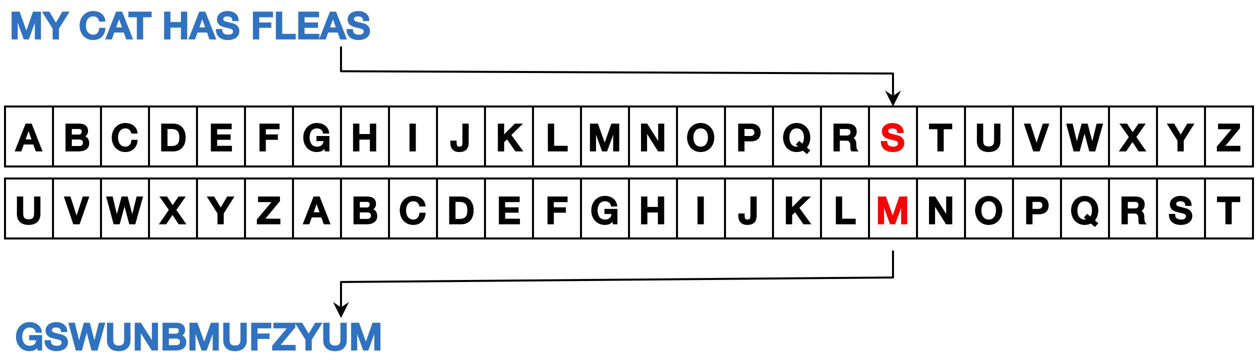
Cæsar cipher



Cæsar cipher



Cæsar cipher



- One piece of information is needed for decryption: *shift value*
- Trivially easy to crack
  (25 possibilities for a 26-character alphabet)

Monoalphabetic substitution cipher

MY CAT HAS FLEAS

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

IVSMXAMBQCLMB

Monoalphabetic = constant mapping between plaintext and ciphertext

General case: arbitrary mapping
(instead of a Cæsar cipher, where the letters are in an alphabetic sequence but shifted)

Both sides must have the same substitution alphabet

Monoalphabetic substitution cipher: frequency analysis

Easy to decode: vulnerable to frequency analysis

	Moby Dick (1.2M chars)		Shakespeare (55.8M chars)
e	12.300%	e	11.797%
o	7.282%	o	8.299%
d	4.015%	d	3.943%
b	1.773%	b	1.634%
x	0.108%	x	0.140%

Common digrams

TH (3.56%), HE (3.07%), IN (2.43%), ER (2.05%), AN, RE, …

Common trigrams

THE, ING, AND, HER, ERE, …

Shannon Entropy

Shannon Entropy is a measure of the uncertainty or randomness in a set of data

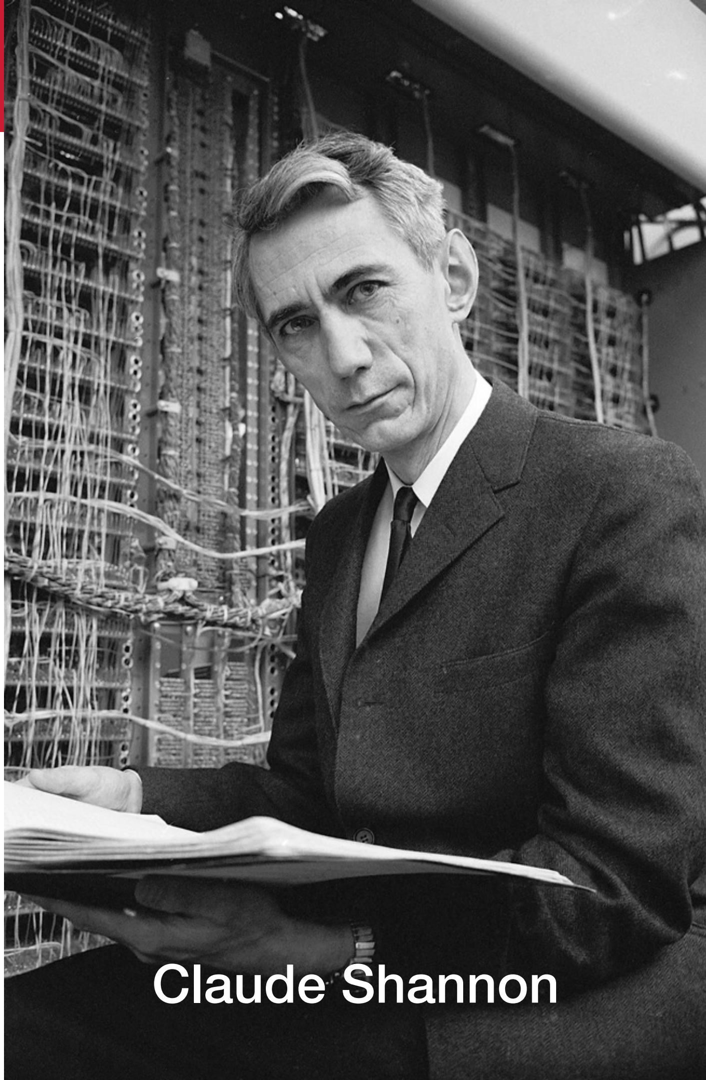
$$H(X) = -\sum P(x) \log_2 P(x)$$

where $P(x)$ is the probability of occurrence of a particular outcome x

It measures the amount of information in bits

High entropy = more randomness

⇒ which is what we want for ciphertext



Entropy

- **If all letters were equally probable, the entropy would be $\log_2 26 = 4.70$ bits of information per byte**
  - Moby Dick text: entropy = 4.175
  - Shakespeare texts: entropy = 4.19
- **Monoalphabetic substitution ciphers don't increase entropy**
  - The frequency of characters remains the same – they're just different characters

Increase entropy by enabling the same character to be encrypted differently in different parts of the message

If each letter probability is the same:

$$H = -\sum_{i=1}^{26} \frac{1}{26} \log_2 \left(\frac{1}{26}\right)$$

$$H = -26 \times \frac{1}{26} \log_2 \left(\frac{1}{26}\right)$$

$$H = -\log_2 \left(\frac{1}{26}\right)$$

$$H = \log_2(26)$$

$$H = 4.7004$$

Polyalphabetic substitution ciphers

- **Designed to thwart frequency analysis techniques**
  - Different ciphertext symbols can represent the same plaintext symbol
    1 → *many* relationship between letter and substitution
- **Leon Battista Alberti: 1466**
  - Two disks
  - Line up predetermined letter on inner disk with outer disk
  - Plaintext on inner → ciphertext on outer
  - After *n* symbols, the disk is rotated to a new alignment

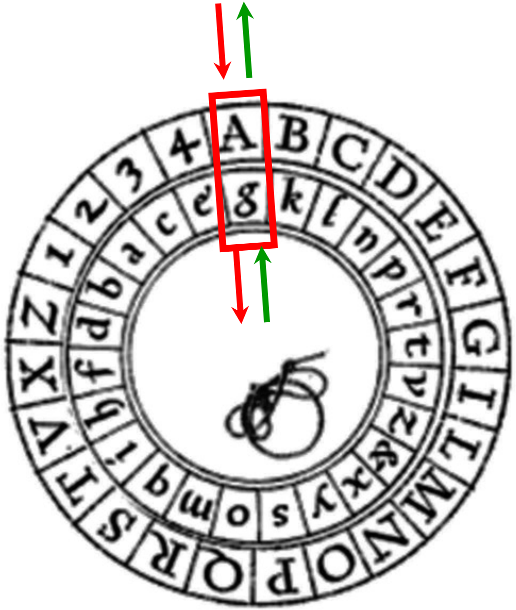


Image source: https://en.wikipedia.org/wiki/Alberti_cipher_disk

encrypt: A→g
decrypt: g→A

http://dabblesandbabbles.com/printable-secret-decoder-wheel/

Vigenère polyalphabetic cipher

Blaise de Vigenère, court of Henry III of France, 1518

No need for a disk: use table and key word to encipher a message

	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

Vigenère polyalphabetic cipher

- **Repeat keyword over text: (e.g., key=FACE)**

  Keystream: `FA CEF ACE FACEF ....`

  Plaintext: `MY CAT HAS FLEAS`

- **Encrypt: find intersection:**

  row = keystream letter

  column = plaintext (message) letter

- **Decrypt: find column**
  - Row = keystream letter, search for ciphertext
  - Column heading = plaintext letter

- **Message is encrypted with as many substitution ciphers as there are unique letters in the keyword**

	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

Vigenère polyalphabetic cipher

plaintext letter

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

keytext letter

ciphertext letter

Vigenère polyalphabetic cipher

```
FA CEF ACE FACEF
MY CAT HAS FLEAS
R
```

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	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	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	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	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	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	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	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

Vigenère polyalphabetic cipher

```
FA CEF ACE FACEF
MY CAT HAS FLEAS
----------------
RY
```

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	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	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	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	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	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	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	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

Vigenère polyalphabetic cipher

```
FA CEF ACE FACEF
MY CAT HAS FLEAS
RY E
```

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	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	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	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	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	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	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	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

Vigenère polyalphabetic cipher

```
FA CEF ACE FACEF
MY CAT HAS FLEAS
----------------
RY EE
```

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	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	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	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	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	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	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	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

Vigenère polyalphabetic cipher

```
FA CEF ACE FACEF
MY CAT HAS FLEAS
----------------
RY EEY
```

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	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	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	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	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	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	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	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

Vigenère polyalphabetic cipher

```
FA CEF ACE FACEF
MY CAT HAS FLEAS
----------------
RY EEY HCW KLGEX
```

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	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	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	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	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	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	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	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

Vigenère polyalphabetic cipher

"The rebels reposed their major trust, however, in the Vigenère, sometimes using it in the form of a brass cipher disc. In theory, it was an excellent choice, for so far as the South knew the cipher was unbreakable. In practice, it proved a dismal failure. For one thing, transmission errors that added or subtracted a letter ... unmeshed the key from the cipher and caused no end of difficulty. Once Major Cunningham of General Kirby-Smith's staff tried for twelve hours to decipher a garbled message; he finally gave up in disgust and galloped around the Union flank to the sender to find out what it said."

http://rz1.razorpoint.com/index.html

Cryptanalysis of the Vigenère cipher

It was hard to break with long keys and small amounts of ciphertext

Cryptanalysis of the Vigenère cipher

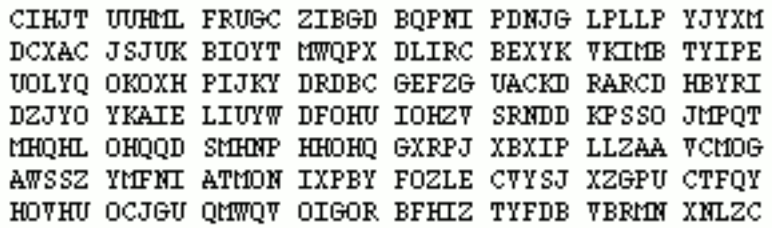
1. Determine key length
   - Count coincidences – identical sets of characters *n* characters apart
   - Key length is likely to be the separation with the maximum # of coincidences

2. Determine values of each character of the key
   - You know the length of the key – that's the # of Caesar ciphers you have
   - Do a frequency analysis of each position of the key

One-time pad

We can achieve maximum entropy by using a truly random key that is as long as the message

- **Invented in 1917**
- **Large non-repeating set of *random* key letters originally written on a pad**



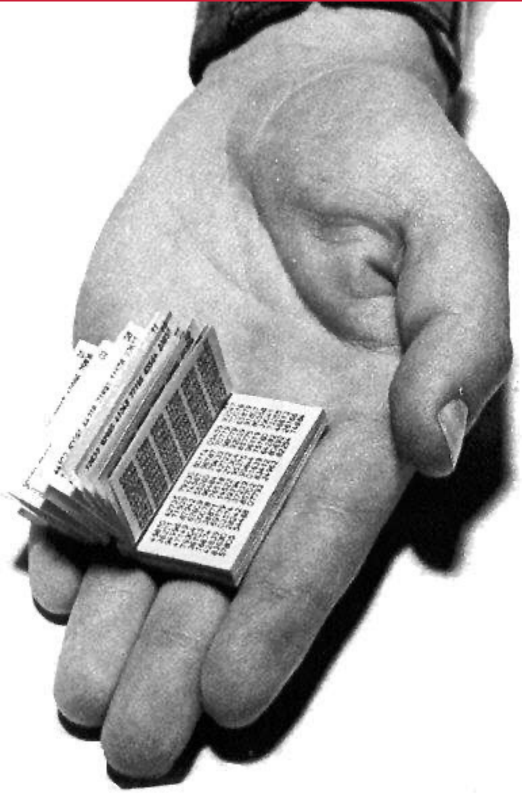
```
CIHJT UUHML FRUGC ZIBGD BQPNI PDNJG LPLLP YJYXM
DCXAC JSJUK BIOYT MWQPX DLIRC BEXYK VKIMB TYIPE
UOLYQ OKOXH PIJKY DRDBC GEFZG UACKD RARCD HBYRI
DZJYO YKAIE LIUYW DFOHU IOHZV SRNDD KPSSO JMPQT
MHQHL OHQQD SMHNP HHOHQ GXRPJ XBXIP LLZAA VCMOG
AWSSZ YMFNI ATMON IXPBY FOZLE CVYSJ XZGPU CTFQY
HOVHU OCJGU QMWQV OIGOR BFHIZ TYFDB VBRMN XNLZC
```

- **Each key letter on the pad encrypts exactly one plaintext character**
  - Encryption is addition of characters modulo *alphabet size* (26)
- **Sender destroys pad pages that have been used**
- **Receiver maintains an identical pad**

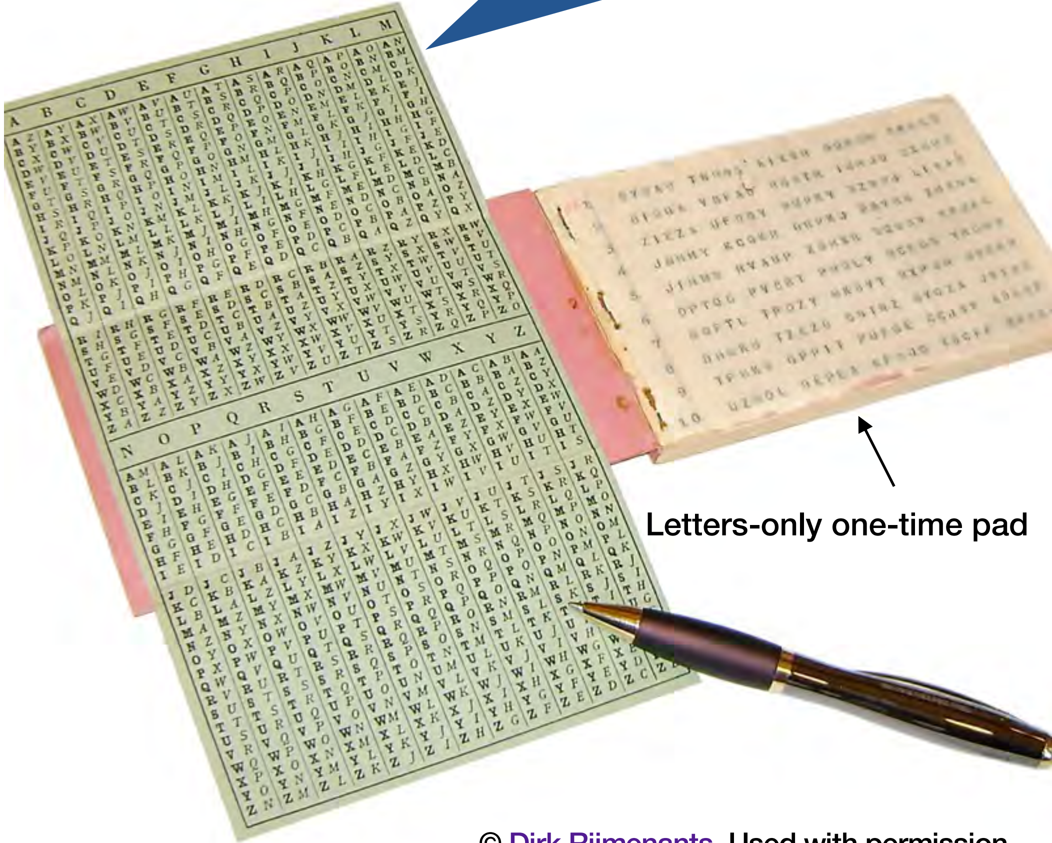
The one-time pad is the only provably secure encryption scheme

https://en.wikipedia.org/wiki/File:OneTimePadExcerpt.agr.png

Some one-time pads



A Russian One-time pad, captured by MI5
Photo from ramnum.com. Used with permission



One-time pad

If pad contains

`KWXOPWMAELGHW…`

and we want to encrypt

`MY CAT HAS FLEAS`

Ciphertext =

`WUZOIDMSJWKHO`

```
M + K mod 26 = W
Y + W mod 26 = U
C + X mod 26 = Z
A + O mod 26 = O
T + P mod 26 = I
H + W mod 26 = D
A + M mod 26 = M
S + A mod 26 = S
F + E mod 26 = J
L + L mod 26 = W
E + G mod 26 = K
A + H mod 26 = H
S + W mod 26 = O
```

One-time pad

The same ciphertext can decrypt to *anything* depending on the key!

Same ciphertext:

`WUZOIDMSJWKHO`

With a pad containing:

`DNVLUXEACWVSQ...`

Produces:

`THE DOG IS HAPPY`

```
W - D mod 26 = T
U - N mod 26 = H
Z - V mod 26 = E
O - L mod 26 = D
I - U mod 26 = O
D - X mod 26 = G
M - E mod 26 = I
S - A mod 26 = S
J - C mod 26 = H
W - W mod 26 = A
K - V mod 26 = P
H - S mod 26 = P
O - Q mod 26 = Y
```

Digression: exclusive-or

Boolean logic refresher: AND

AND (∧): clears bits

AND clears bits

- AND 1 – keep the bit
- AND 0 – clear the bit

Truth table

$$1 \wedge 1 = 1$$

$$1 \wedge 0 = 0$$

$$0 \wedge 1 = 0$$

$$0 \wedge 0 = 0$$

If you clear a bit, you will never know if it used to be a 0 or a 1

Boolean logic refresher: OR

OR (∨): sets bits

OR sets bits

- OR 1 – set the bit
- OR 0 – keep the bit

Truth table

$1 \vee 1 = 1$

$1 \vee 0 = 1$

$0 \vee 1 = 1$

$0 \vee 0 = 0$

If you set a bit, you will never know if it used to be a 0 or a 1

Boolean logic refresher: XOR

XOR (⊕): flips bits

XOR flips bits

- XOR 1 – flip the bit
- XOR 0 – keep the bit as it is

Truth table

$$1 \oplus 1 = 0$$

$$1 \oplus 0 = 1$$

$$0 \oplus 1 = 1$$

$$0 \oplus 0 = 1$$

If you flip a bit, you can restore it by XORing it with 1 again

XOR in cryptography

We use XOR operations a lot in cryptography

They allow us to flip certain bits to encrypt and later unflip to decrypt

	0 1 1 1 0 0 0 0	0 1 1 0 1 0 1 1	plaintext = 0x70 0x6b
⊕	1 0 1 0 1 1 0 0	1 0 1 1 1 0 0 1	⊕ key = 0xac 0xb9
	1 1 0 1 1 1 0 0	1 1 0 1 0 0 1 0	ciphertext = 0xdc 0xd2
⊕	1 0 1 0 1 1 0 0	1 0 1 1 1 0 0 1	⊕ key = 0xac 0xb9
	0 1 1 1 0 0 0 0	0 1 1 0 1 0 1 1	result = 0x70 0x6b

plaintext recovered!

End of digression

One-time pads in computers

Can be extended to binary data

- Random key sequence as long as the message
- Exclusive-or key sequence with message
- Receiver has the same key sequence

One-time pad – C code

```
void onetimepad(void)
{
    FILE *if = fopen("intext", "r");
    FILE *kf = fopen("keytext", "r");
    FILE *of = fopen("outtext", "w");
    int c, k;

    while ((c = getc(if)) != EOF) {
        k = getc(kf);
        putc((c^k), of);
    }
    fclose(if); fclose(kf); fclose(of);
}
```

One-time pads provide **perfect secrecy**

Perfect secrecy

- Ciphertext conveys no information about the content of plaintext
- *Achieved only if the key is random and as long as the plaintext*

Problems with one-time pads:

- Key needs to be as long as the message!
- Key storage and distribution can be problematic
- Keys have to be generated randomly
  - Cannot use pseudo-random number generator
- Cannot reuse key sequence
- Sender and receiver *must* remain synchronized (e.g., cannot lose any part of the message)

Random numbers

"Anyone who considers arithmetical methods of producing random digits is, of course, in a state of sin"

– John von Neumann, 1951

- **Pseudo-random generators**
  - Linear feedback shift registers
  - Multiplicative lagged Fibonacci generators
  - Linear congruential generator
- **Obtain randomness from:**
  - Time between keystrokes
  - Various network/kernel events
  - Cosmic rays
  - Electrical noise, thermal noise
  - Other encrypted messages

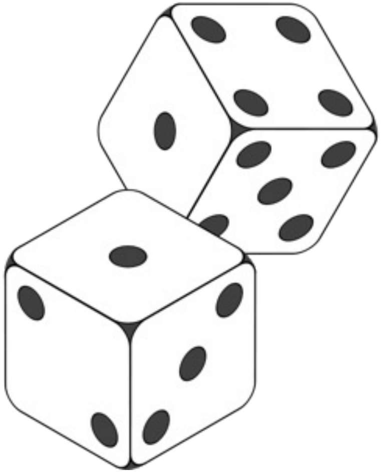


Image from Wikimedia Commons

Ongoing research for random number generators

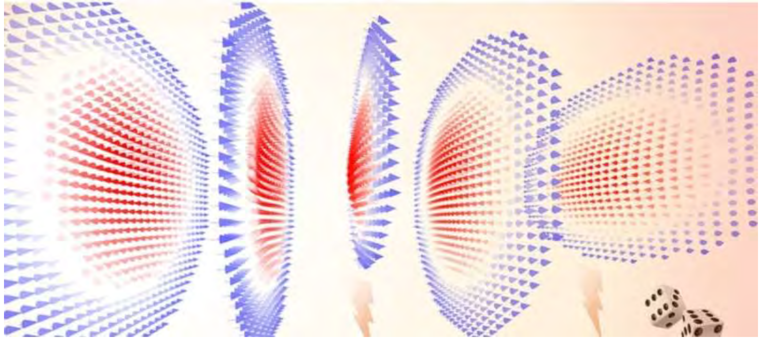
Researchers use tiny magnetic swirls to generate true random numbers

PHYS.ORG

by Brown University
February 7, 2022

Whether for use in cybersecurity, gaming or scientific simulation, the world needs true random numbers, but generating them is harder than one might think. But a group of Brown University physicists has developed a technique that can potentially generate millions of random digits per second by harnessing the behavior of skyrmions—tiny magnetic anomalies that arise in certain two-dimensional materials.

Their research, published in Nature Communications, reveals previously unexplored dynamics of single skyrmions, the researchers say. Discovered around a half-decade ago, skyrmions have sparked interest in physics as a path toward next-generation computing devices that take advantage of the magnetic properties of particles—a field known as spintronics.



Magnetic swirls called skyrmions fluctuate randomly in size, a behavior that can be harnessed to generate true random numbers. Credit: Xiao lab / Brown University

https://phys.org/news/2022-02-tiny-magnetic-swirls-true-random.html

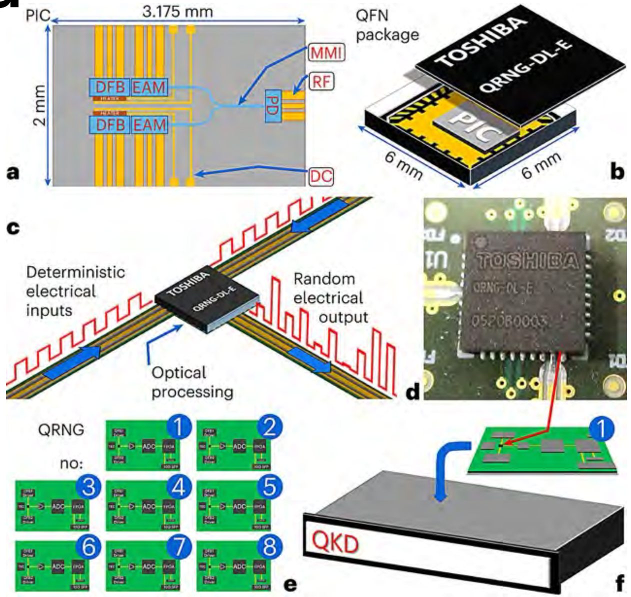
Ongoing research for random number generators

New quantum random number generator achieves 2 Gbit/s speed

by Ingrid Fadelli
June 11, 2024

The reliable generation of random numbers has become a central component of information and communications technology. In fact, random number generators, algorithms or devices that can produce random sequences of numbers, are now helping to secure communications between different devices, produce statistical samples, and for various other applications.

Researchers at Toshiba Europe Ltd. recently developed a new quantum random number generator (QRNG) based on a photonic integrated circuit that can be directly integrated in electronic devices. This QRNG, introduced in a paper published in *Nature Electronics*, can securely and robustly generate random numbers at a remarkable speed of 2 Gbit s^{-1}.



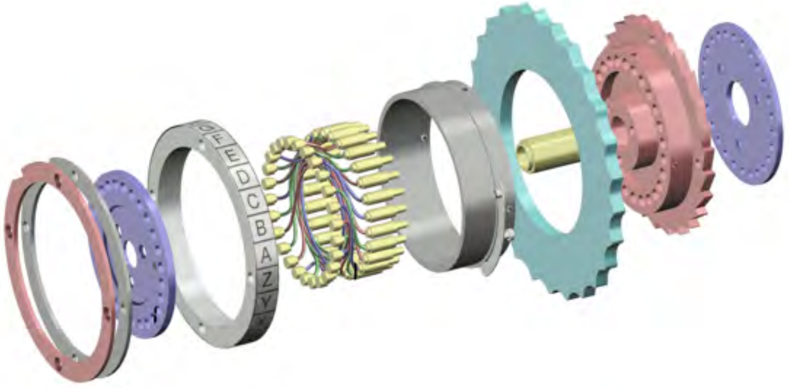
https://techxplore.com/news/2024-06-quantum-random-generator-gbits.html

Rotor machines

1920s: mechanical devices used for automating encryption

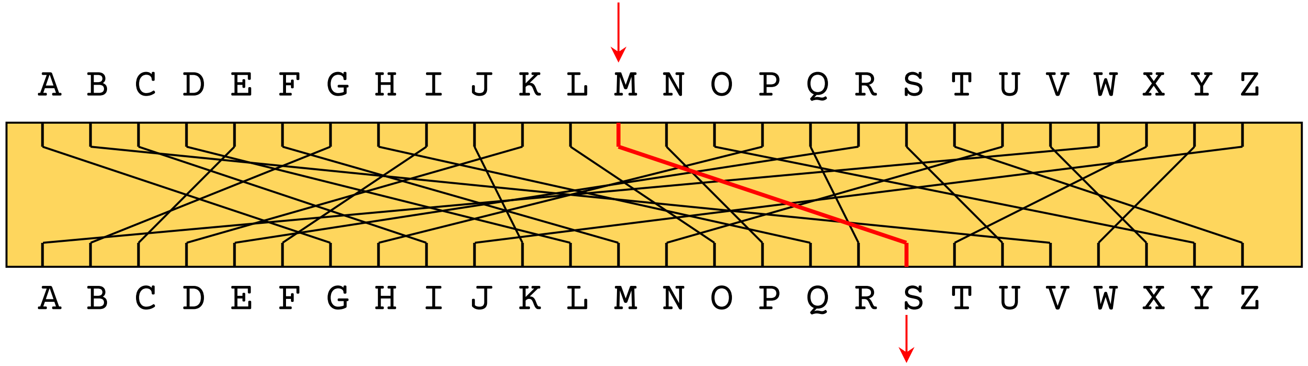
Rotor machine:

- Set of independently rotating cylinders (rotors) through which electrical pulses flow
- Each rotor has input & output pin for each letter of the alphabet
  - Each rotor implements a substitution cipher
- Output of each rotor is fed into the next rotor
- Together they implement a version of the Vigenère cipher



Rotor machines

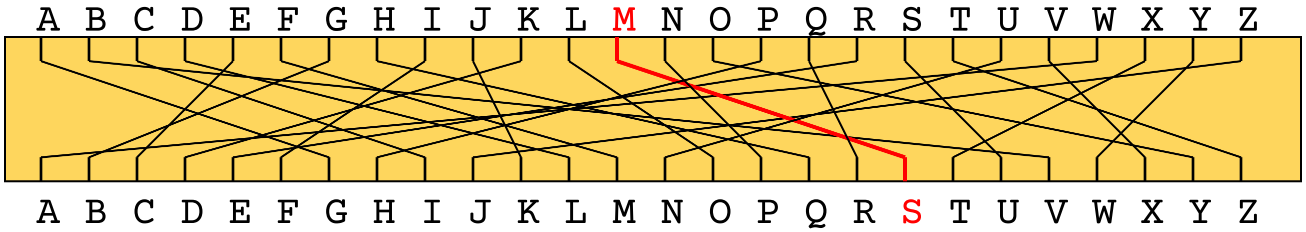
Simplest rotor machine: single cylinder



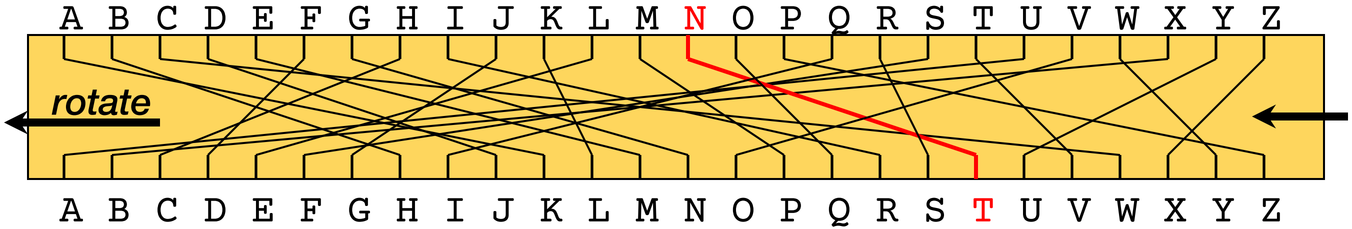
After a character is entered, the cylinder rotates one position

- Internal connections shifted by one
- Polyalphabetic substitution cipher with a period of 26

Single cylinder rotor machine



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



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

Multi-cylinder rotor machines

- **Single cylinder rotor machine**
  - Substitution cipher with a period = length of the alphabet (e.g., 26)
- **Multi-cylinder rotor machine**
  - Feed output of one cylinder as input to the next one
  - First rotor advances after the character is entered
  - The second rotor advances after a full period of the first
  - Polyalphabetic substitution cipher

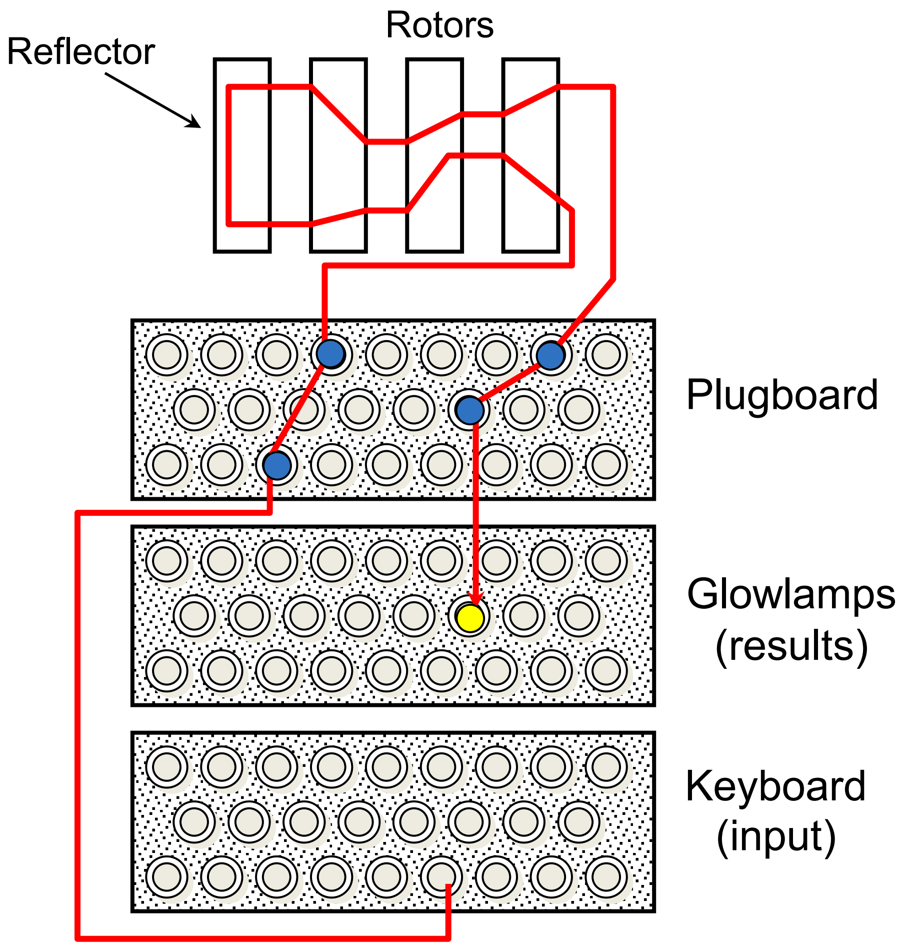
    Period = $(\text{length of alphabet})^{\text{number of rotors}}$

    - 3 26-char cylinders ⇒ 26^3 = 17,576 substitution alphabets
    - 5 26-char cylinders ⇒ 26^5 = 11,881,367 substitution alphabets

Enigma

- **Enigma machine used in Germany during WWII**
- **Three rotor system**
  - $26^3 = 17{,}576$ possible rotor positions
- **Input data permuted via patch panel before sending to rotor engine**
- **Data from last rotor reflected back through rotors**
  ⇒ makes encryption symmetric
- **Need to know initial settings of rotor**
  - setting was *f(date)* in a book of codes
- **Broken by group at Bletchley Park (Alan Turing)**

Enigma


Reflector
Rotors
Plugboard
Glowlamps
(results)
Keyboard
(input)

Enigma successor: Soviet Union's Fialka

The Soviet Union needed a more secure cipher than Enigma

- **Rotor machine with 10 rotors and 30 contacts/rotor**
  - Fialka: $30^{10} = 5.9 \times 10^{14}$ possible rotor positions
  - Enigma: $26^3 = 17{,}576$ possible rotor positions
- **Punched cards configure initial settings**
- **More complex stepping mechanism than Enigma**
- **Various versions used by Warsaw Pact countries into the 1990s**

Soviet Union Fialka - Rotors

Classic Cryptosystems:

Transposition Ciphers

Transposition ciphers

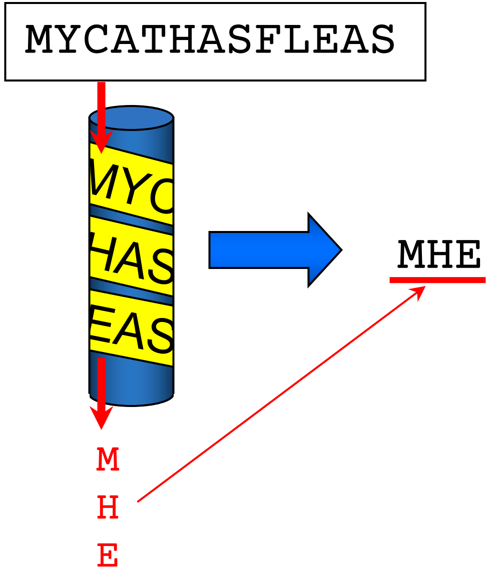
- **Permute letters in plaintext according to specific rules**
- **Knowledge of rules will allow messages to be decrypted**
- **First documented use by Spartans in the 5th century BCE**
  - **Scytale** (*rhymes with Italy*) = staff cipher

Transposition ciphers:

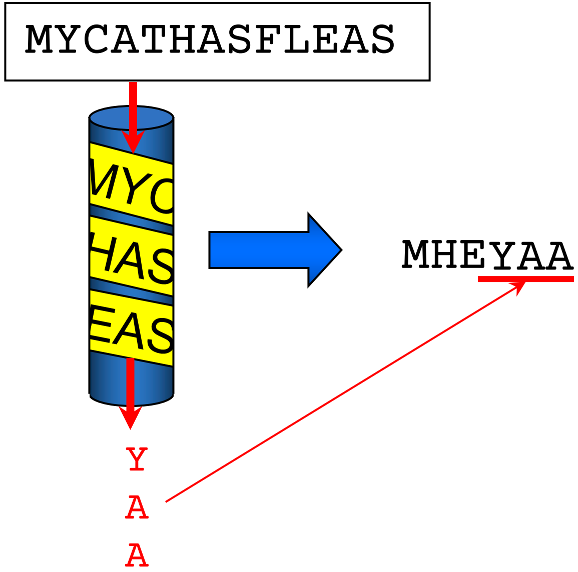
- Scramble the letters of the plaintext
- Split common letter sequences to increase the entropy of digraphs and trigraphs

Transposition ciphers: **scytale**

Secret = diameter of scytale

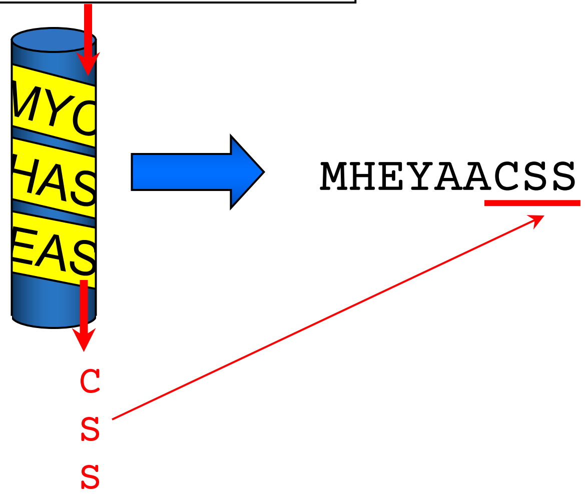


Transposition ciphers: scytale

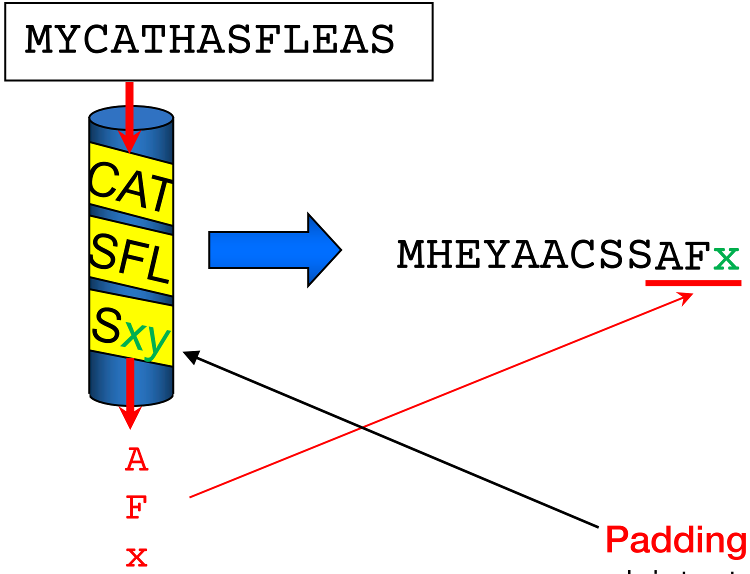


Transposition ciphers: **scytale**

MYCATHASFLEAS

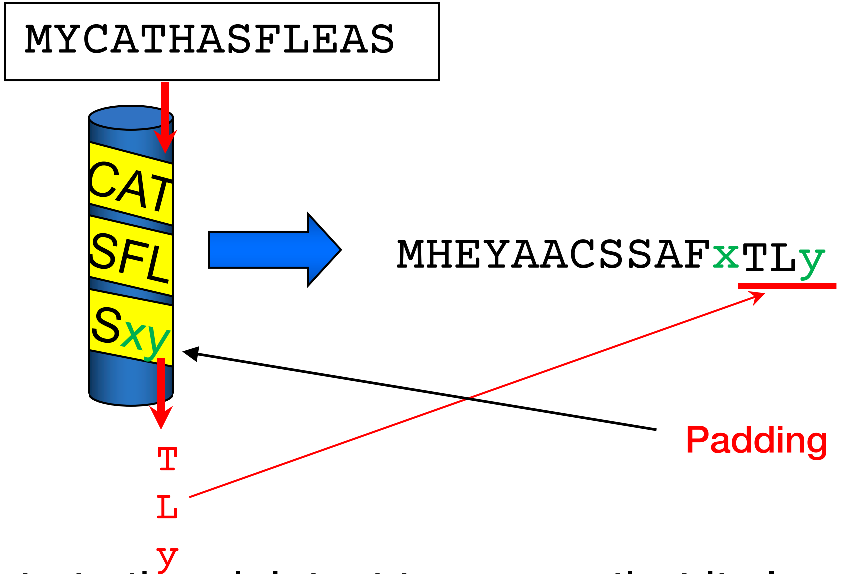


Transposition ciphers: **scytale**



Padding: adding data to the plaintext (usually at the end) before encryption

Transposition ciphers: **scytale**

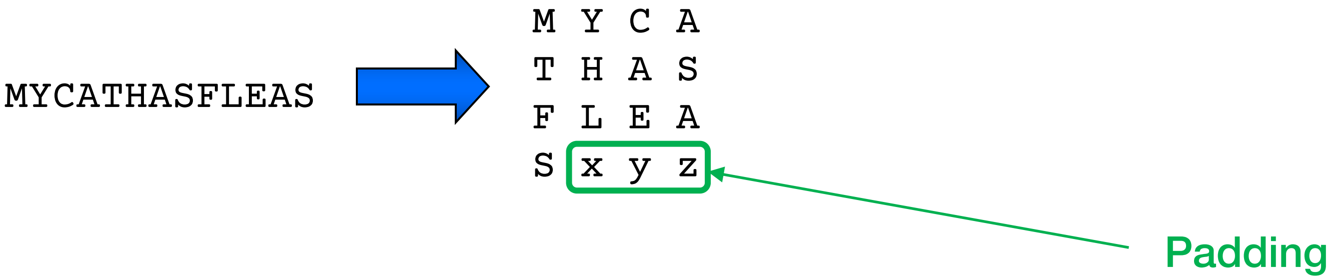


Padding: adding extra data to the plaintext to ensure that its length is a multiple of a specific block size

Scytale as a set of columns

Table version of scytale

- Enter data horizontally, read it vertically
- Secrecy is the width of the table



Scytale as a set of columns

Table version of scytale

- Enter data horizontally, read it vertically
- Secrecy is the width of the table

MYCATHASFLEAS →

M	Y	C	A
T	H	A	S
F	L	E	A
S	x	y	z

→ MTFS

Scytale as a set of columns

Table version of scytale

- Enter data horizontally, read it vertically
- Secrecy is the width of the table

MYCATHASFLEAS →

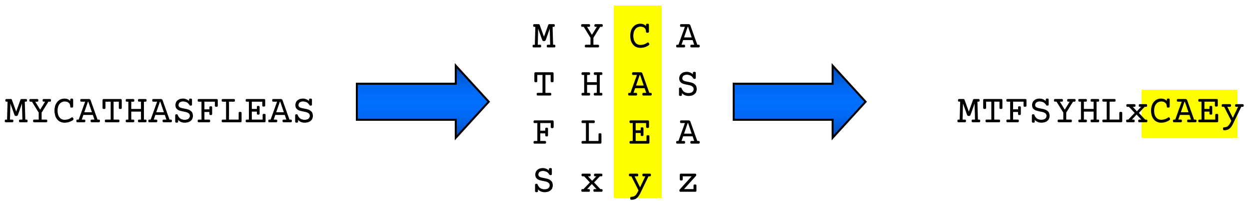
M	Y	C	A
T	H	A	S
F	L	E	A
S	x	y	z

→ MTFSYHLx

Scytale as a set of columns

Table version of scytale

- Enter data horizontally, read it vertically
- Secrecy is the width of the table



Scytale as a set of columns

Table version of scytale

- Enter data horizontally, read it vertically
- Secrecy is the width of the table

`MYCATHASFLEAS`

M	Y	C	A
T	H	A	S
F	L	E	A
S	x	y	z

`MTFSYHLxCAEyASAz`

Columnar transposition cipher

Add a key

- Created in the mid 1600s – used by the French, Japanese, & Russians into the 20th century
- Key word defines the width of the table and the sequence of reading the columns
- Read down columns, sorting by key letters

MYCATHASFLEAS →

	F	A	R	E
Key:	3	1	4	2
	M	Y	C	A
	T	H	A	S
	F	L	E	A
	S	x	y	z

Padding (x y z)

Key word: FARE

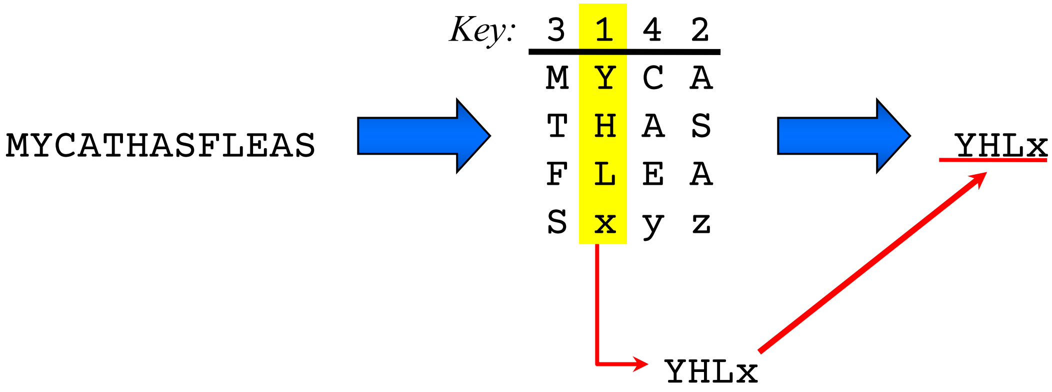
↓

Sort sequence: 3, 1, 4, 2

Columnar transposition cipher

Add a key

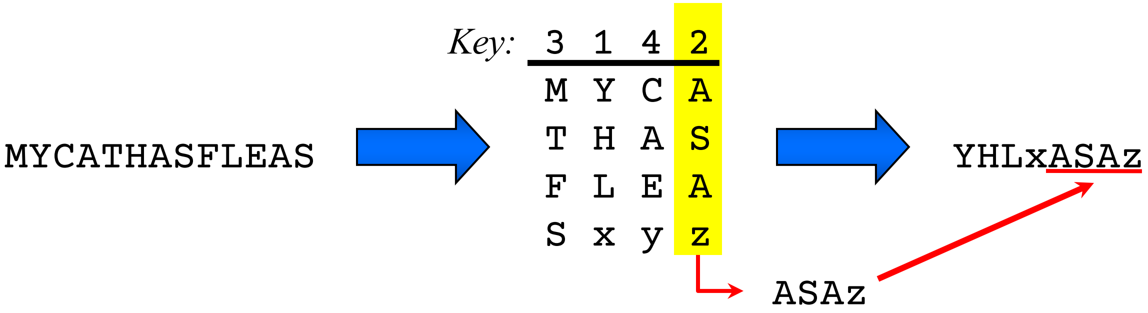
- Shuffle columns based on the sorting of letters in the key word
- Read down columns



Columnar transposition cipher

Add a key

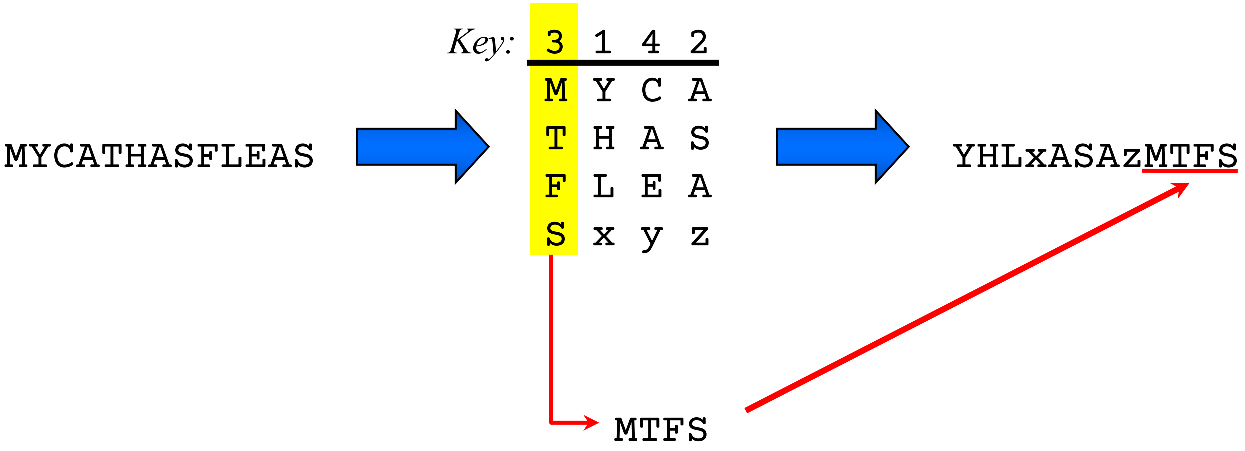
- Shuffle columns based on the sorting of letters in the key word
- Read down columns



Columnar transposition cipher

Add a key

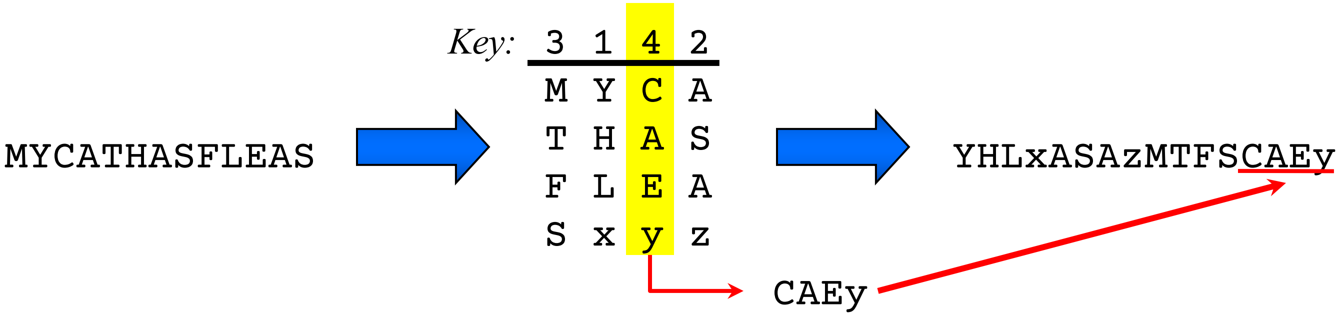
- Shuffle columns based on the sorting of letters in the key word
- Read down columns



Columnar transposition cipher

Add a key

- Shuffle columns based on the sorting of letters in the key word
- Read down columns



Columnar transposition cipher

Add a key

- Shuffle columns based on the sorting of letters in the key word
- Read down columns

MYCATHASFLEAS →

Key:

3	1	4	2
M	Y	C	A
T	H	A	S
F	L	E	A
S	x	y	z

→ YHLxASAzMTFSCAEy

Transposition cipher

- **Not vulnerable to frequency analysis**
- **Entropy of characters does not change**
  - But the entropy of digraphs and trigraphs increases because common sequences are broken through scrambling the characters
- **The scytale is trivial to attack**
  - Make all possible matrices that would fit the ciphertext
  - Write ciphertext across rows
  - See if the columns contain legible content
- **Scrambled columns make it a bit harder**
  - Need to permute columns of matrices

Combined ciphers

- **Combine transposition with substitution ciphers**
  - German ADFGVX cipher (1918, World War I)
  - Playfair cipher (Charles Wheatstone, 1854)
- **Great for increasing entropy of characters, digraphs, trigraphs, …**
- **But was troublesome to implement (before computers)**
  - Difficult with pencil-and-paper or electromechanical cryptography
  - Except for the simplest ciphers, requires memory to store blocks of data for transposition

Properties of a good cryptosystem

Kerckhoffs's Principle of Cryptography

Kerckhoffs's Principle - 1883

A cryptosystem should be secure even if everything about the system, except the key, is public knowledge

In other words …

"One ought to design systems under the assumption that the enemy will immediately gain full familiarity with them." - Claude Shannon, 1949

What this means:

If you don't know the key, you will have to do an exhaustive search (try all combinations) – the amount of effort to decrypt data without knowing the key is proportional to the length of the key

Properties of a good cryptosystem: keys

1. **Kerckhoffs's Principle:** The secrecy should reside in the key, not the algorithm
2. **High Entropy:** Ciphertext should be indistinguishable from random values
3. **There should be no way to extract the original plaintext or the key short of enumerating all possible keys (a brute-force attack)**
   - **Non-invertible**: the ciphertext cannot be decrypted without the key.
   - This is true even if the attacker has many (P, C) pairs or can supply an arbitrary amount of plaintext to be encrypted and see the resulting ciphertext.
4. **The keys should be large enough that an exhaustive search is not feasible**
   - Because all secrecy is in the key, we need a key large enough that testing all values is not possible in a reasonable amount of time (even on a network of the fastest computers we expect to have 20 years from now).
   - **A cipher is no stronger than its key length**
     - If the key is too short, an attacker a brute-force search may be feasible
     - A cipher may be a lot weaker than its key length
5. **The cipher should not contain weak keys**
   - There should be no keys that result in weaker security

Keys and the power of 2

- **Each extra bit added to a key doubles the search space**
- **Suppose it takes 1 second to search through all keys with a 20-bit key**

key length	number of keys	search time	1000 petaFLOPs supercomputer*
20 bits	1,048,576	1 second	0.001 seconds
21 bits	2,097,152	2 seconds	0.002 seconds
32 bits	4.3×10^{9}	~ 1 hour	4.3 seconds
56 bits	7.2×10^{16}	2,178 years	2.2 years
64 bits	1.8×10^{19}	> 557,000 years	584 years
128 bits	3.4×10^{29}	1.0×10^{25} years	1.1×10^{22} years
256 bits	1.2×10^{77}	3.5×10^{63} years	3.7×10^{60} years

Distributed & custom hardware efforts typically allow us to test between 1 and >100 billion 64-bit (e.g., RC5) keys per second

*Assume the supercomputer can test 1 billion keys per second

About keys

Keys should be

Protected

If attackers get hold of the keys, they can decrypt ciphertext

Random

Keys should be unpredictable

Short term (ideally): Used for a limited time

Less (P,C) data gives cryptanalysts less data to analyze

Properties of a good cryptosystem (continued)

Also nice to have:

5. **Keys and algorithms should be as simple as possible and operate on any data**
   - There shouldn't be restrictions on the values of keys, the data that could be encrypted, or how to do the encryption
   - Restrictions on keys make searches easier and will require longer keys.
   - Complex algorithms will increase the likelihood of implementation errors
6. **The size of the ciphertext should be the same size as the plaintext**
   - You don't want your effective bandwidth cut in half because the ciphertext is 2x the size of plaintext
   - Sometimes we might need to pad the data but that's a small number of bytes regardless of the input size
7. **Encryption and decryption should be efficient**
   - We want to encourage the use of secure cryptography where it is needed and not have people avoid it because it slows down data access
8. **The algorithm has been extensively analyzed**
   - We don't want the latest – we want an algorithm that has been studied carefully for years by many experts

Shannon's Properties: Confusion and Diffusion

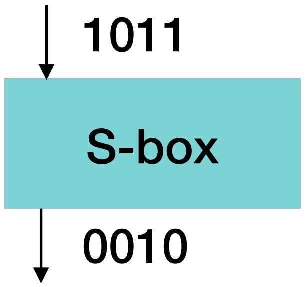
Claude Shannon defined two operational goals of a cipher:

- **Confusion**
  - There is no direct correlation between a bit of the key and the resulting ciphertext
  - Every bit of ciphertext depends on various bits of the key. You cannot find a connection between a bit of the key and a bit of the ciphertext.
  - Generally implemented through substitution
  - *Confusion hides the relationship between the key and ciphertext*
- **Diffusion**
  - The plaintext information is **spread** throughout the cipher so that a change in one bit of plaintext will change, on average, half of the bits in the ciphertext will change.
  - Generally implemented through transposition
  - *Diffusion tries to make the relationship between the plaintext and ciphertext as complicated as possible*

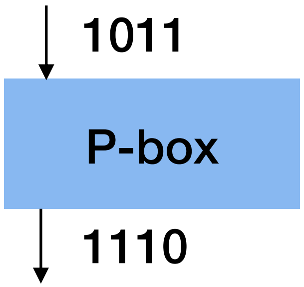
Computer Cryptography

Properties

- **Operate on arbitrary binary data: $P = \{0, 1\}^n$**
- **Kerckhoffs's Principle: the secrecy resides in the key**
- **Shannon's properties**
  - **Confusion**: no direct correlation between a bit of the key and the resulting ciphertext
  - **Diffusion**: Changing one bit of input should change, on average, ½ of output bits
- **Main mechanisms**



Substitute one sequence of bits into a different sequence (non-linear transformation)
⇒ **provide confusion**



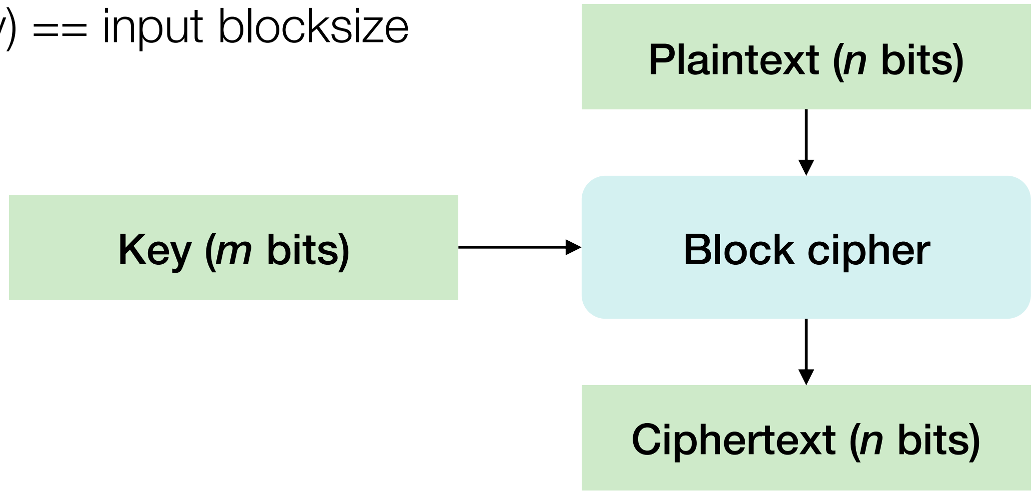
Transposition (permutation): Shuffle bits between the input and output
⇒ **provide diffusion**

Block ciphers

Block ciphers dominate computer cryptography

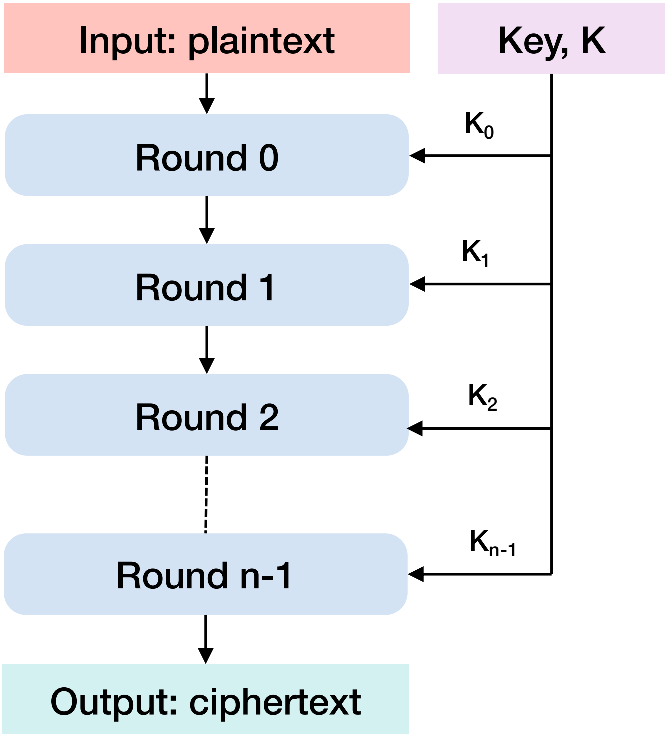
Encrypt a fixed number of bits (a *block*) at a time

Output blocksize (usually) == input blocksize



Block ciphers

- **Block ciphers encrypt a *block* of plaintext at a time**
- **DES & AES are two popular block ciphers**
  - DES: 64-bit blocks
  - AES: 128-bit blocks
- **Block ciphers are usually iterative ciphers**
  - The encryption process is an iteration through several ***round*** operations
  - A single round does not provide perfect confusion or diffusion



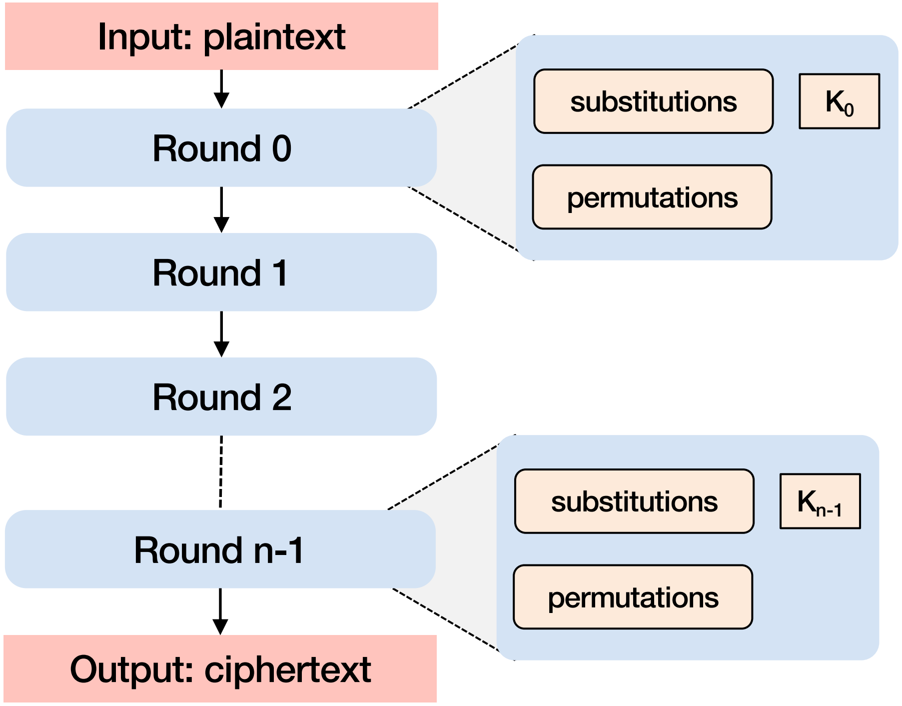
Structure of block ciphers

- **Multiple rounds of combining the plaintext with the key**
- **Optional:**
  - Convert key to an internal subkey – different for each round
- **DES: 16 rounds**
- **AES: 10-14 rounds, depending on key length**

Sounds easy … but is difficult to design

Block cipher rounds

Each round consists of substitutions & permutations = SP Network



Substitution = S-box

- Table lookup
- Converts a small block of input to a block of output

Permutation

- Scrambles the bits in a prescribed order

Key application per round

- Subkey, K_n, per round derived from the key
- Can drive behavior of s-boxes
- May be XORed with the output of each round

Create *Confusion & Diffusion*

- Confusion: no direct correlation between a bit of the key and resulting ciphertext
- Diffusion: Changing one bit of input should change, on average, ½ of output bits

DES

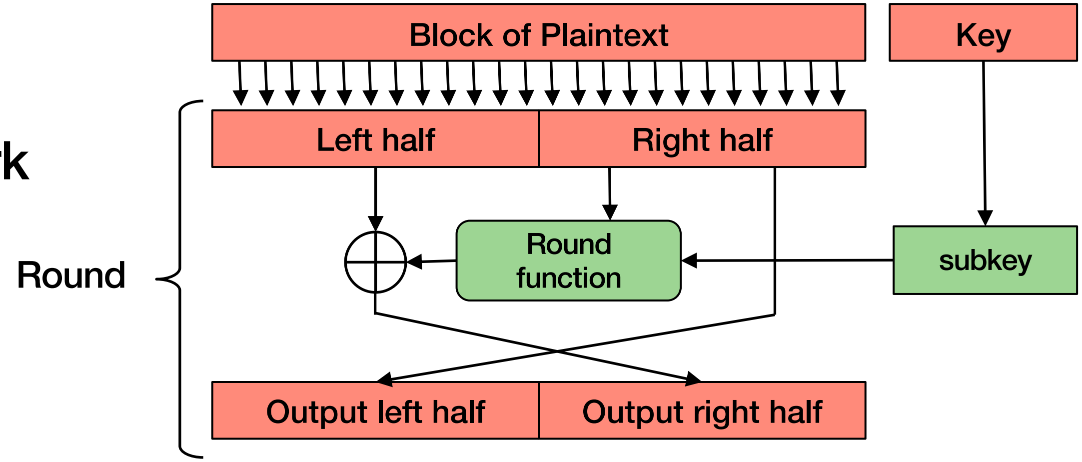
Data Encryption Standard

- Developed in the early 1970s by IBM and modified by the NSA
- Adopted as a federal standard in 1976

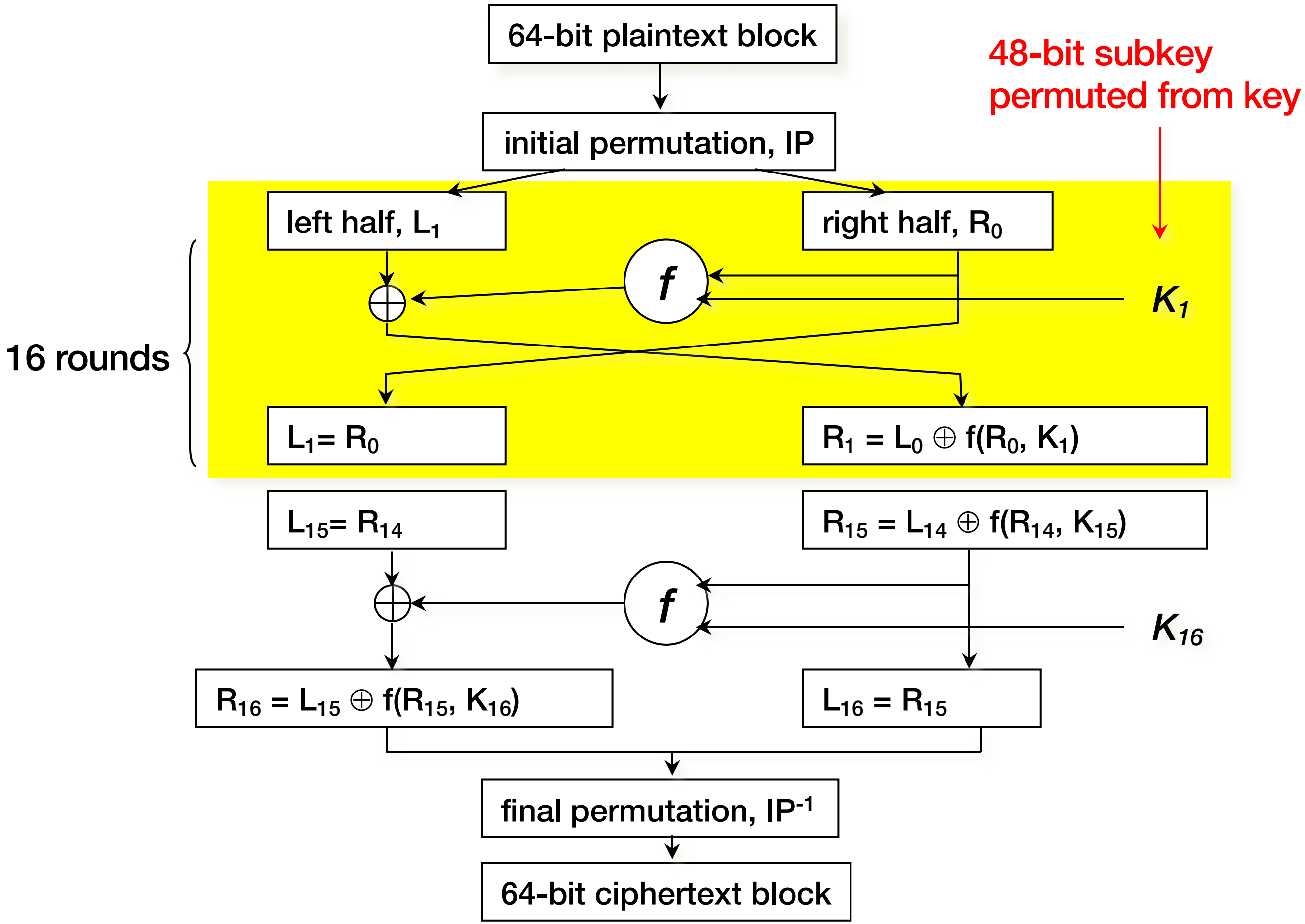
- **Block cipher, 64-bit blocks, 56-bit key**
- **Substitution followed by a permutation**
  - Transposition and XORs based on a subkey derived from the key
  - 16 rounds

Feistel cipher

- **DES is a type of Feistel cipher, which is a form of a block cipher**
- **Plaintext block is split in two**
  - *Round* function applied to one half of the block
  - Output of the round function is XORed with the other half of the block
  - Halves are swapped
- **This is a Feistel Network rather than an SP Network**

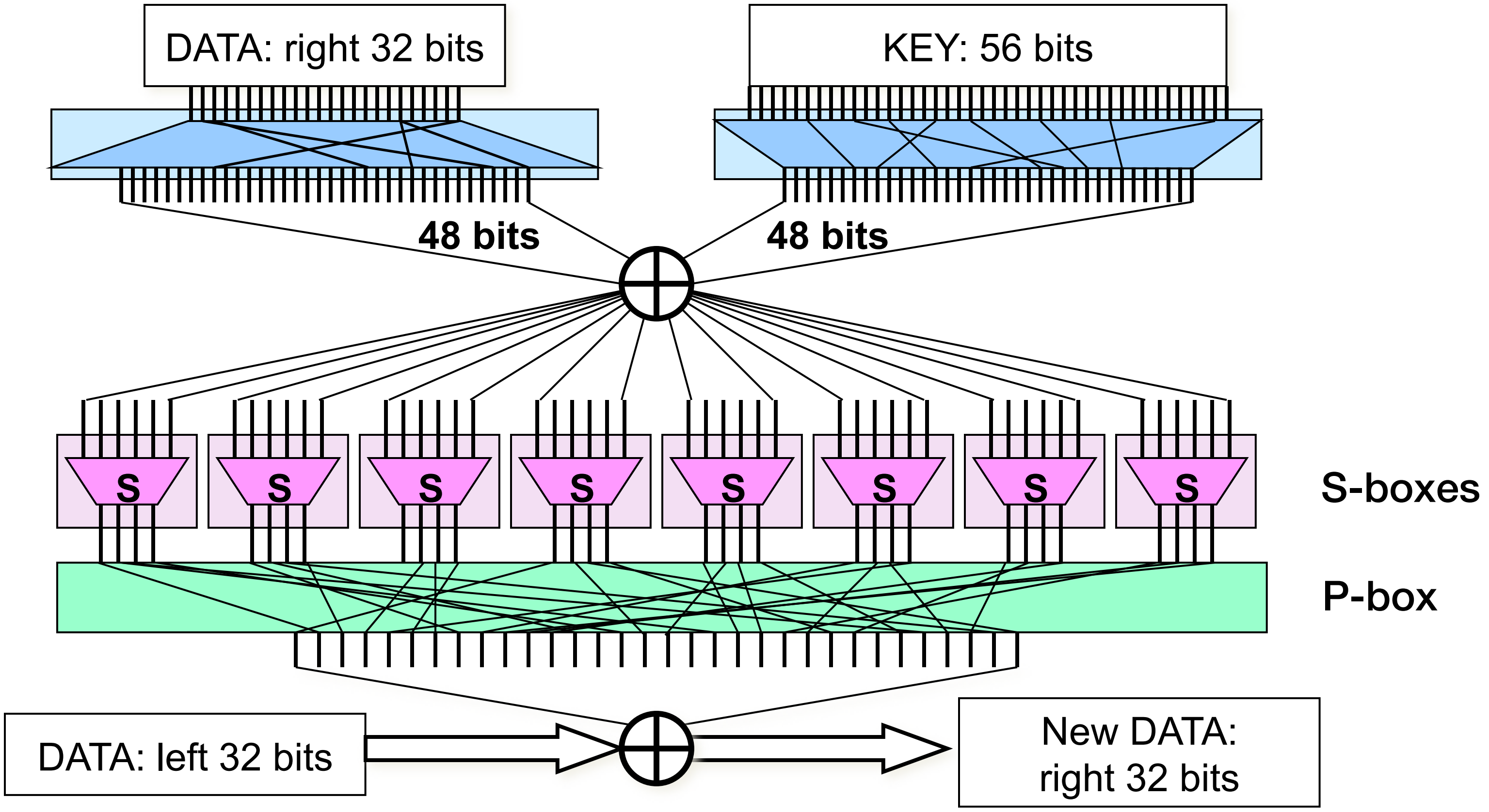


DES



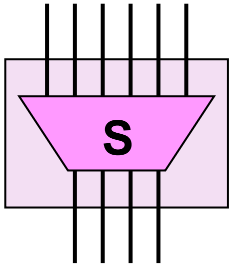
64-bit plaintext block
initial permutation, IP
48-bit subkey permuted from key
left half, L_1
right half, R_0
f
K_1
16 rounds
$L_1 = R_0$
$R_1 = L_0 \oplus f(R_0, K_1)$
$L_{15} = R_{14}$
$R_{15} = L_{14} \oplus f(R_{14}, K_{15})$
f
K_{16}
$R_{16} = L_{15} \oplus f(R_{15}, K_{16})$
$L_{16} = R_{15}$
final permutation, IP^{-1}
64-bit ciphertext block

DES: *f* per round



DES: S-boxes

- **After compressed key is XORed with expanded block**
  - 48-bit result moves to substitution operation via eight substitution boxes (s-boxes)



- **Each S-box has**
  - 6-bit input
  - 4-bit output
- **48 bits divided into eight 6-bit sub-blocks**
- **Each block is operated by a separate S-box**
- **Net result: 48-bit input generates 32-bit output**
- **S-boxes are key components of DES's security**

S-boxes are used in symmetric block ciphers to add *confusion*: hide the relationship of any ciphertext from any plaintext & key bits.

Implemented as a table lookup

Is DES secure?

- **56-bit key makes DES relatively weak**
  - $2^{56} = 7.2 \times 10^{16}$ keys
  - Brute-force attack
- **By the late 1990's:**
  - DES cracker machines built to crack DES keys in a few hours
  - DES Deep Crack: 90 billion keys/second
  - Distributed.net: tested 250 billion keys/second
- **2000s < 1 day**
  - 2006: COPACOBANA: Custom FPGA-based DES cracker for < $10,000
  - 2012: cloud-based service
    crack MS-CHAPv2 authentication (which uses DES) on sale for $20 vs. $200

https://boingboing.net/2012/09/24/exhaust-all-of-des-and-crack-a.html

Increasing The Key

Can double encryption work for DES?

Useless if we could find a key K such that:

$$E_K(P) = E_{K2}(E_{K1}(P))$$

This does not hold for DES (luckily!)

Double DES

Vulnerable to *meet-in-the-middle* attack

If we know some pair (*P*, *C*), then:

[1] Encrypt *P* for all 2^{56} values of K_1

[2] Decrypt *C* for all 2^{56} values of K_2

For each match where [1] == [2]

- Test the two keys against another *P*, *C* pair
- If match, you are assured that you have the key
- The complexity is 2×2^{56} rather than $2^{2 \times 56}$

Triple DES key lengths

Triple DES with two 56-bit keys (112-bit key):

$$C = E_{K1}(D_{K2}(E_{K1}(P)))$$

Triple DES with three 56-bit keys (168-bit key):

$$C = E_{K3}(D_{K2}(E_{K1}(P)))$$

Decryption used in middle step for compatibility with DES ($K_1=K_2=K_3$)

$$C = E_K(D_K(E_K(P))) \equiv C = E_{K1}(P)$$

DES Disadvantages

- **DES has been shown to have some weaknesses**
  - Key can be recovered using 2^{47} chosen plaintexts or 2^{43} known plaintexts
  - *Note that this is not a practical amount of data to get for a real attack!*
- **Short block size (8 bytes = 2^8 = 64 bits)**
- **The real weakness of DES is its 56-bit key**
  - Exhaustive search requires 2^{55} iterations on average
- **3DES solves the key size problem: we can have keys up to 168 bits**
  - Differential & linear cryptanalysis is not effective here: the three layers of encryption use 48 rounds instead of 16 making it infeasible to reconstruct s-box activity
- **But DES is relatively slow – and 3DES is 3x slower**
  - It was designed with hardware encryption in mind: and 3DES is 3x slower than DES

AES (Advanced Encryption Standard)

- **U.S. NIST held a competition for a new algorithm**
  - Received 15 submissions
  - No NSA tampering allowed
  - Three variations (key lengths) of the Rijndael family of ciphers won
- **Block cipher: 128-bit blocks**
  - AES is *not* a Feistel cipher – it uses the entire block in each round
  - DES used 64-bit blocks but encrypted half the data in each round
- **Successor to DES as a standard encryption algorithm**
  - DES: 56-bit key
  - AES: 128, 192, or 256-bit keys

AES … successor to DES

From NIST:

> *Assuming that one could build a machine that could recover a DES key in a second (i.e., try 2^{56} keys per second), then it would take that machine approximately 149 trillion years to crack a 128-bit AES key. To put that into perspective, the universe is believed to be less than 20 billion years old.*

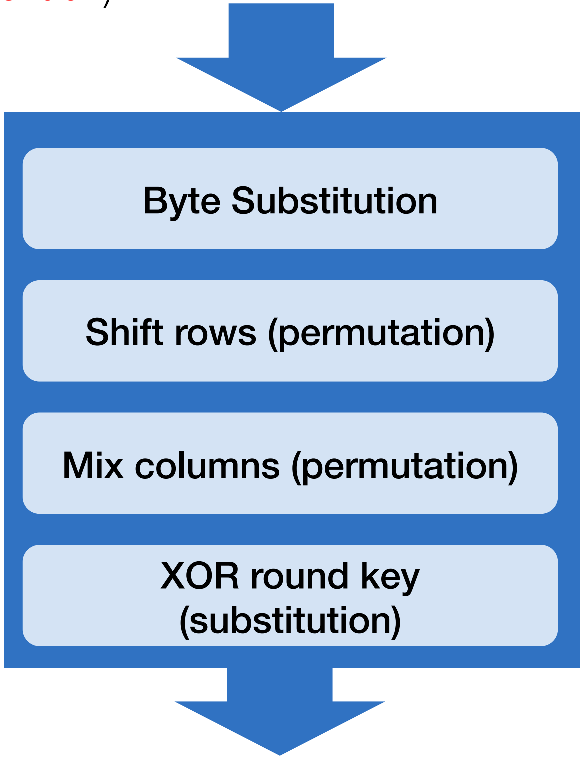
https://www.nist.gov/news-events/news/2001/12/commerce-secretary-announces-new-standard-global-information-security

AES (Advanced Encryption Standard)

- **Iterative cipher, just like most other block ciphers**
  – Each round is a set of substitutions & permutations
- **Variable number of rounds**
  – DES always used 16 rounds
  – AES:
    - 10 rounds: 128-bit key
    - 12 rounds: 192-bit key
    - 14 rounds: 256-bit key
  – A **subkey** (“round key”) derived from the key is computed for each round
    - DES used this too

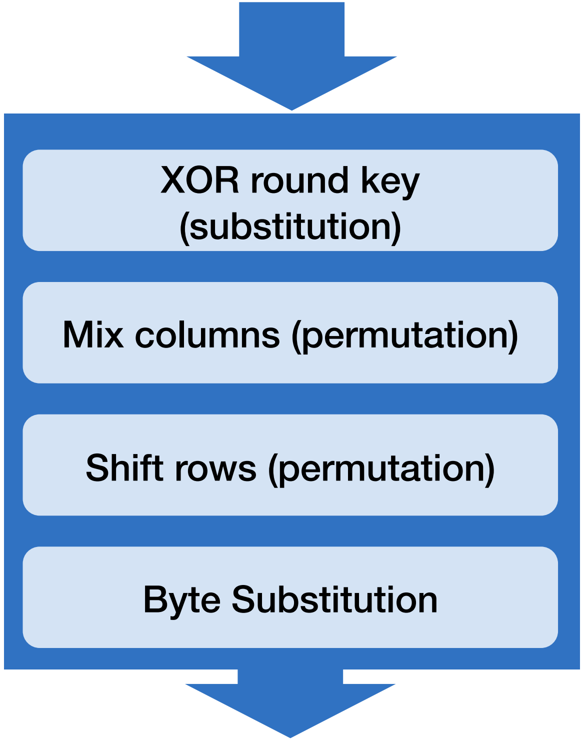
Each AES Round

- **Step 1: Byte Substitution (s-boxes)**
  - Substitute 16 input bytes by looking each one up in a table (s-box)
  - Result is a 4x4 matrix
- **Step 2: Shift rows**
  - Each row is shifted to the left (wrapping around to the right)
  - 1st row not shifted; 2nd row shifted 1 position to the left; 3rd row shifted 2 positions; 4th row shifted three positions
- **Step 3: Mix columns**
  - 4 bytes in each column are transformed
  - This creates a new 4x4 matrix
- **Step 4: XOR round key**
  - XOR the 128 bits of the round key with the 16 bytes of the matrix in step 3



AES Decryption

Same rounds
… but in reverse order



AES Advantages

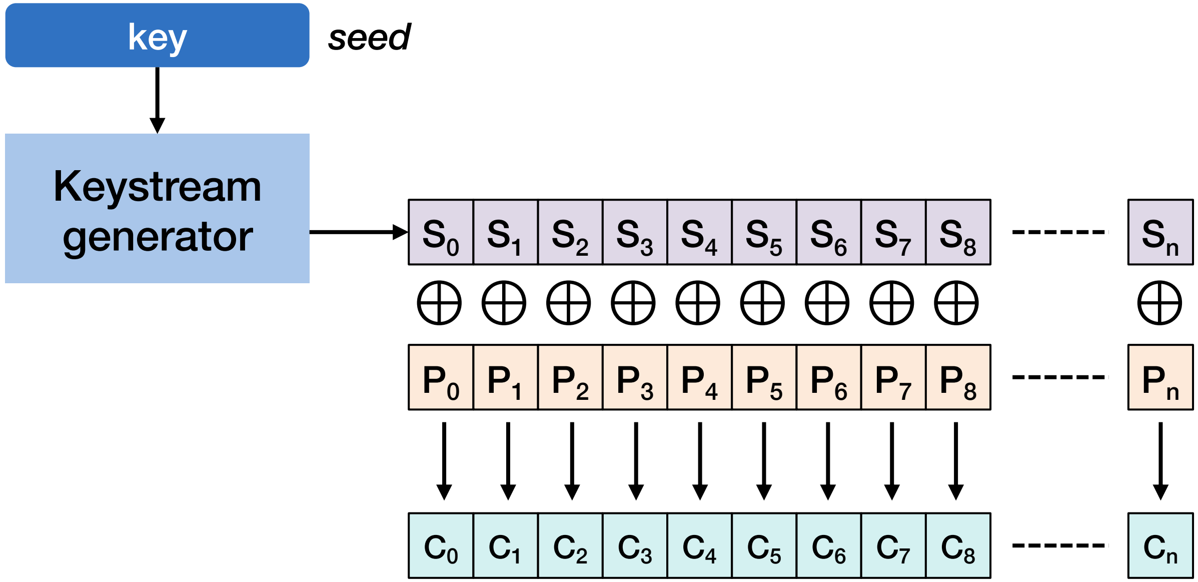
- **Larger block size: 128 bits vs 64 bits**
- **Larger & varying key sizes: 128, 192, and 256 bits**
  - 128 bits is complex enough to prevent brute-force searches
- **No significant academic attacks beyond brute force search**
  - Resistant against linear cryptanalysis thanks to bigger S-boxes
    - S-box = lookup table that adds non-linearity to a set of bits via transposition & flipping
  - DES: 6-bit inputs & 4-bit outputs
  - AES: 8-bit inputs & 8-bit outputs
- **Typically 5-10x faster in software than 3DES**

Attacks against AES

- **Attacks have been found**
  - This does ***not*** mean that AES is insecure!
- **Because of the attacks:**
  - AES-128 has computational complexity of $2^{126.1}$ (~126 bits)
  - AES-192 has computational complexity of $2^{189.7}$ (~190 bits)
  - AES-256 has computational complexity of $2^{254.9}$ (~255 bits)
- **Increasing AES security**
  - The security of AES can be increased by increasing the number of rounds in the algorithm
  - However, AES-128 still has a sufficient safety margin to make exhaustive search attacks impractical

Stream ciphers – simulate a one-time pad

Key stream generator produces a sequence of **pseudo-random** bytes



$$C_i = S_i \oplus P_i$$

Stream ciphers

Can never reuse a key

$$C = A \oplus K$$

$$C' = B \oplus K$$

$$C \oplus C' = A \oplus K \oplus B \oplus K = A \oplus B$$

Guess *A* to get *K* and see if *B* makes sense

Or… if you have **known plaintext** A and the corresponding ciphertext C, you can extract the key:

$$K = A \oplus C$$

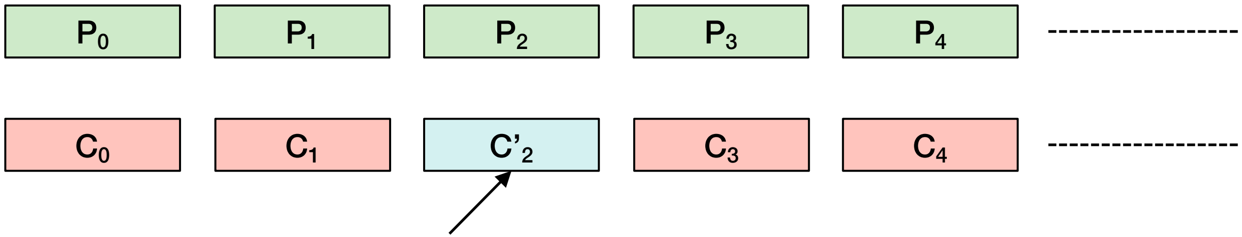
Popular symmetric block ciphers

AES (Advanced Encryption Standard)	• FIPS standard since 2002 • 128, 192, or 256-bit keys; operates on 128-bit blocks • By far the most widely used symmetric encryption algorithm
DES (Data Encryption Standard)	• FIPS standard from1976-2002 • 56-bit key; operates on 64-bit (8-byte) blocks • Triple DES recommended since 1999 (112 or 168 bits) • Not actively used anymore; AES is better by any measure
Blowfish	• Key length from 23-448 bits; 64-bit blocks • Optimized for 32-bit CPUs
Twofish	• Successor to Blowfish; key length from 128, 192, 256 bits; 128-bit blocks • Competed against AES for standardization
ChaCha20	• Stream cipher • 256-bit key generated from a user-supplied key • One of the fastest encryption algorithms

Cipher modes

Not a good idea to use block ciphers directly

- **Streams of data are broken into *k*-byte blocks**
  - Each block encrypted separately
  - This is called **Electronic Codebook** (**ECB**)
- **Problems**
  1. Same plaintext results in identical encrypted blocks
     Enemy can build up a code book of plaintext/ciphertext matches
  2. Attacker can add/delete/replace blocks

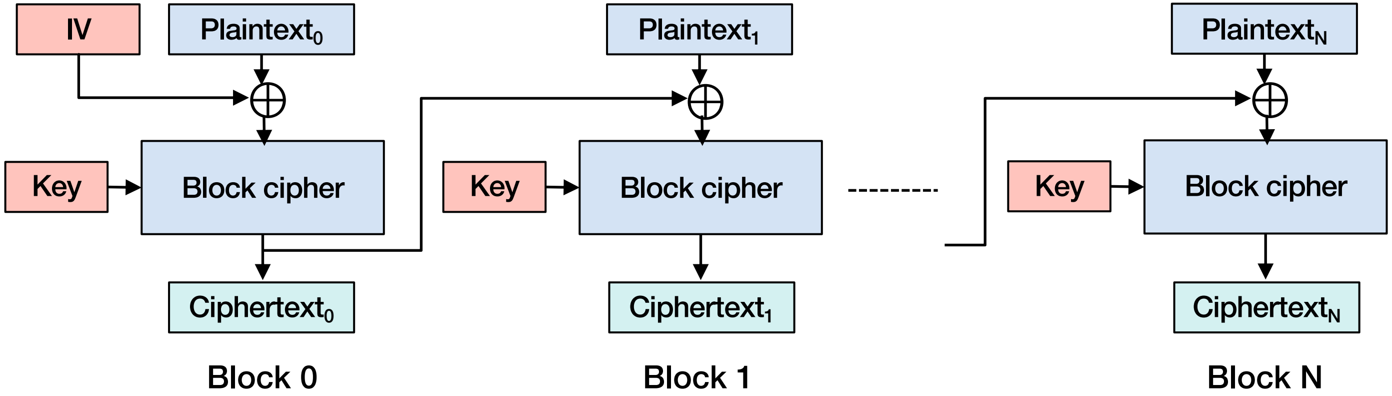


Intruder can replace blocks (e.g., with ciphertext from previous messages)

Cipher Block Chaining (CBC) mode

- **Random** **initialization vector (IV)** **= bunch of *k* random bits**
  - Non-secret: both parties need to know this
- **Exclusive-or with first plaintext block – then encrypt the block**
- **Take exclusive-or of the result with the next plaintext block**

$$c_i = E_K(m_i) \oplus c_{i-1}$$

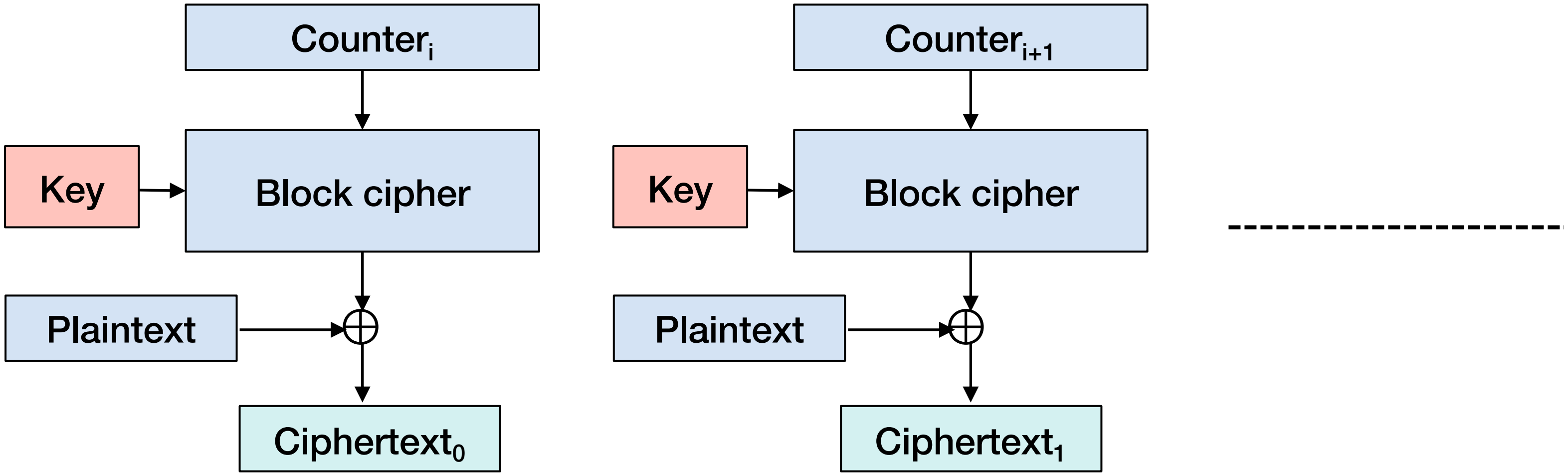


CBC Observations

- **Identical plaintext does not produce the same ciphertext**
  - Unless all previous blocks are identical
- **Each block is a function of all previous blocks**
- **An attacker can still cause data corruption**

Block encryption: Counter (CTR) mode

- **Random starting counter = bunch of *k* random bits, just like IV**
  - Any function producing a non-repeating sequence
    (an incrementing number is a common function)
- **Encrypt the counter with the key**
- **Exclusive-or result with plaintext block**



Cryptanalysis

Cryptographic attacks

- **Chosen plaintext**
  - Attacker can create plaintext and see the corresponding ciphertext
- **Known plaintext**
  - Attacker has access to both plaintext & ciphertext but doesn’t get to choose the text
- **Ciphertext-only**
  - The attacker only sees ciphertext
  - Popular in movies but rarely practical in real life

Differential Cryptanalysis

Examine how changes in input affect changes in output

- **Discover where a cipher exhibits non-random behavior**
  - These properties can be used to extract the secret key
  - Applied to block ciphers, stream ciphers, and hash functions (functions that flip & move bits vs. mathematical operations)

- **Chosen plaintext attack is normally used**
  - Attacker must be able to choose the plaintext and see the corresponding cipher text

Differential Cryptanalysis

- **Provide plaintext with known differences**
  - See how those differences appear in the ciphertext
- **The properties depend on the key and the s-boxes in the algorithm**
- **Do this with lots and lots of known *plaintext-ciphertext* sets**
- **Statistical differences, if found, may allow a key to be recovered faster than with a brute-force search**
  - You may deduce that certain keys are not worth trying

Linear Cryptanalysis

Create a predictive approximation of inputs to outputs

- **Instead of looking for differences, linear cryptanalysis attempts to come up with a linear formula (e.g., a bunch of *xor* operations) that connects certain input bits, output bits, and key bits with a probability higher than random**
  - Goal is to approximate the behavior of s-boxes
- **Part 1: construct linear equations**
  - Find high correlations
- **Part 2: guess key bits**
  - Guess enough bits so that a brute force attack becomes feasible

Linear Cryptanalysis

It will *not* recreate the working of the cipher

- You just hope to find non-random behavior that gives you insight on what bits of the key might matter

- **Works better than differential cryptanalysis for known plaintext**
  - Differential cryptanalysis works best with chosen plaintext

- **Linear & differential cryptanalysis will rarely recover a key but may be able to reduce the number of keys that need to be searched**

The End