

Symmetric Encryption

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Design principles (reminder)

1. **Kerkoff Principle**

The security of a cryptosystem must not rely on keeping the algorithm secret

2. **Diffusion**

Mixing-up symbols

3. **Confusion**

Replacing a symbol with another

4. **Randomization**

Repeated encryptions of the same text are different

The attacker's model

- **Exhaustive Search**

Try all possible n keys (in average it takes $n/2$ tries)

- **Ciphertext only**

You know one or several random ciphertexts

- **Known plaintext**

You know one or several pairs of random plaintext and their corresponding ciphertexts

- **Chosen plaintext**

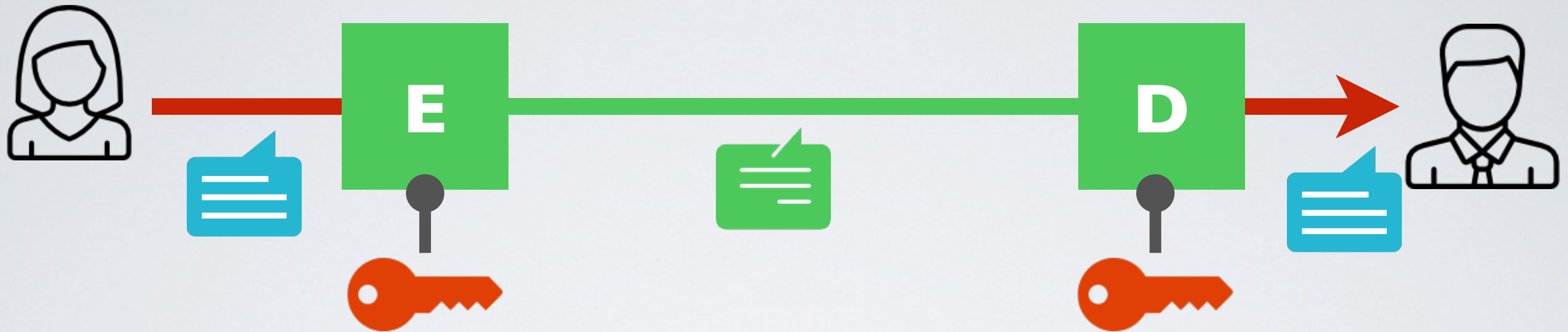
You know one or several pairs of chosen plaintext and their corresponding ciphertexts

- **Chosen ciphertext**

You know one or several pairs of plaintext and their corresponding chosen ciphertexts

➔ **A good crypto system resists all attacks**

Functional Requirements



➔ The same key k is used for encryption E and decryption D

1. $D_k(E_k(m))=m$ for every k , E_k is an injection with inverse D_k
2. $E_k(m)$ is easy to compute (either polynomial or linear)
3. $D_k(c)$ is easy to compute (either polynomial or linear)
4. $c = E_k(m)$ finding m is hard without k (exponential)

Outline

Stream cipher

RC4 - Rivest Cipher 4 (now deprecated)

Salsa20

Block cipher

- Encryption standards

DES (and 3DES) - Data Encryption Standard (now deprecated)

AES - Advanced Encryption Standard

- Block cipher modes of operation

Stream Cipher

XOR Cipher (a.k.a Vernham Cipher)

a modern version of Vigenere

Use \oplus to combine the message and the key

$$E_k(m) = k \oplus m$$

$$D_k(c) = k \oplus c$$

Problem : known-plaintext attack

$$D_k(E_k(m)) = k \oplus (k \oplus m) = m$$

$$\text{so } k = (k \oplus m) \oplus m$$

$$x \oplus x = 0$$

$$x \oplus 0 = x$$

Mauborgne Cipher - a modern version of OTP

Use a random stream as encryption key

➡ Defeats the know-plaintext attack

Problem : Key-reused attack (a.k.a two-time pad)

$$C_1 = k \oplus m_1$$

$$C_2 = k \oplus m_2$$

$$\begin{aligned}\text{so } C_1 \oplus C_2 &= (k \oplus m_1) \oplus (k \oplus m_2) \\ &= (m_1 \oplus m_2) \oplus 0 \\ &= (m_1 \oplus m_2)\end{aligned}$$

$x \oplus x = 0$
$x \oplus 0 = x$

Random Number Generator

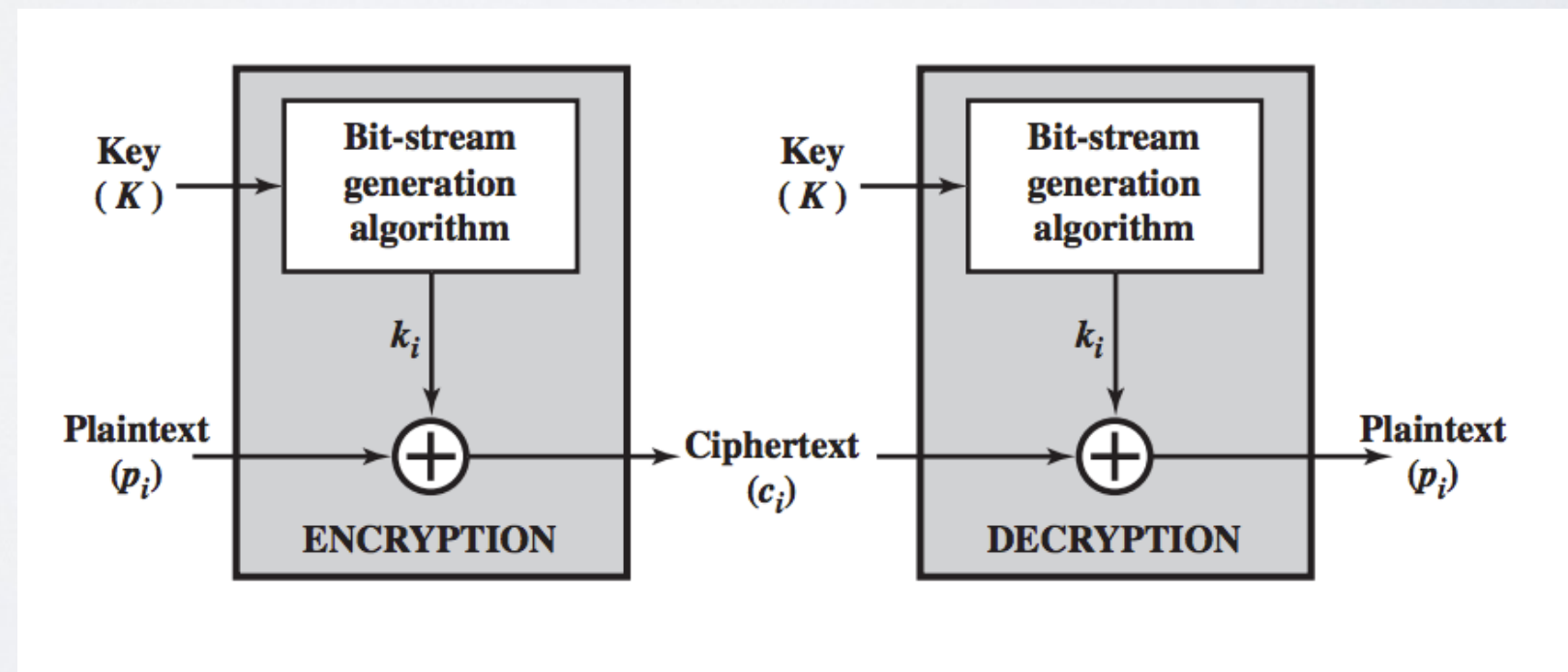
```
int getRandomNumber()  
{  
    return 4; // chosen by fair dice roll.  
             // guaranteed to be random.  
}
```

True Random Number Generator

➔ No, because we want to be able to encrypt and decrypt

Pseudo-Random Generator

➔ Stretch a fixed-size seed to obtain an unbounded random sequence



Stream cipher

Can we use k as a seed?

$$E_k(m) = m \oplus \text{RNG}(k)$$

➡ Be careful of key reused attack !

Typical usage : choose a new iv and send it using another encryption scheme E'

$$E_k(m) = (E'_k(iv) , m \oplus \text{RNG}(iv))$$

RC4 - Rivest Cipher 4

Key Size	40 - 2048 bits
Speed	~ 8 cycles / byte

Very simple implementation

Designed in 1987 ... but broken in 2015

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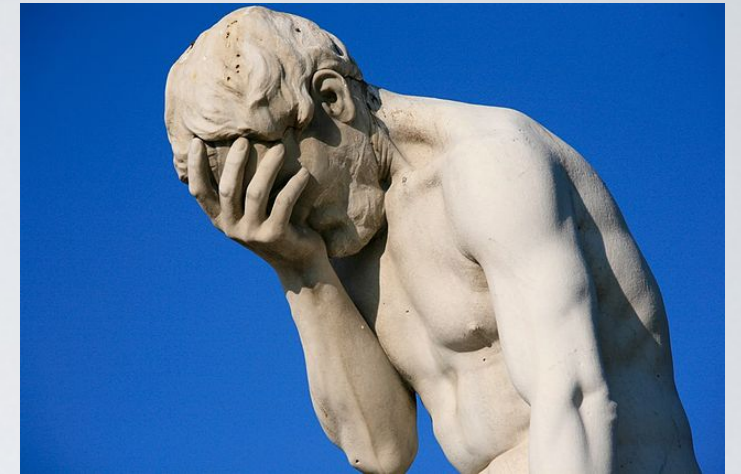
'Serious' Microsoft Office Encryption Flaw Uncovered

 [COMMENTS](#)

By [John E. Dunn](#), IDG News Service
Jan 27, 2005 4:00 PM

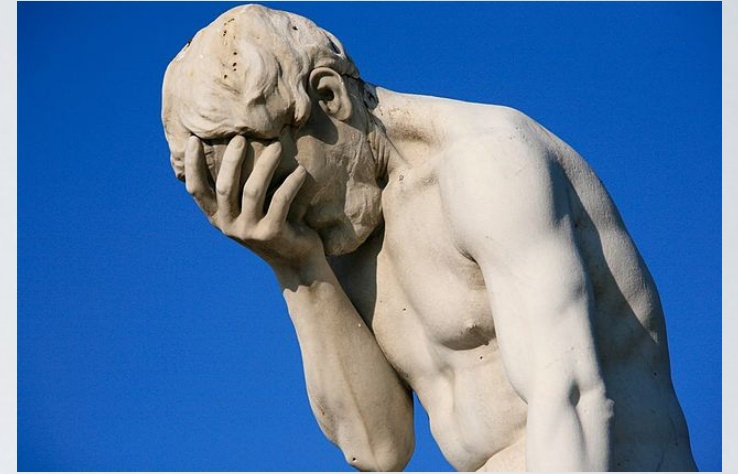
Cryptography expert Phil Zimmermann says he believes a flaw recently discovered in Microsoft Office's Word and Excel encryption is serious and warrants immediate attention.

"I think this is a serious flaw--it is highly exploitable. It is not a theoretical attack," says Zimmermann, referring to a flaw in Microsoft's use of RC4 document encryption unearthed recently by a researcher in Singapore.



MS Word and Excel 2003 used the same key to re-encrypt documents after editing changes

WEP - Wired Equivalent Privacy



- ➔ A random number IV (24 bits only) transmitted in clear between the clients and the base station

$$\text{RC4_key} = \text{IV} + \text{SSID_password}$$

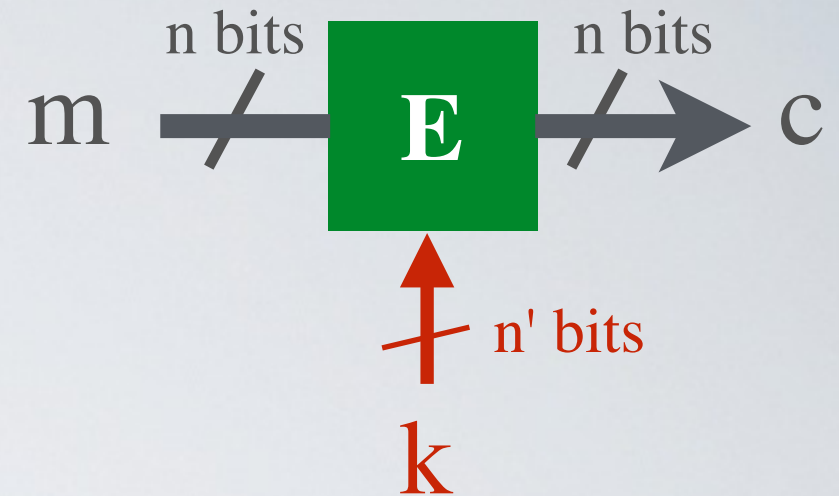
- ⦿ 50% chance the same IV will be used again after 5000 packets

Salsa20

Key Size	128 or 256 bits
Speed	~ 4 cycles / byte

Block Cipher

Ideal block cipher



- Combines confusion (substitution) and diffusion (permutation)
 - Changing single bit in plaintext block or key results in changes to approximately half the ciphertext bits
- ➡ Completely obscure statistical properties of the original message
- ➡ A known-plaintext attack does not reveal the key

DES - Data Encryption Standard

Block size	64 bits
Key Size	56 bits
Speed	~ 50 cycles per byte
Algorithm	Feistel Network

Timeline

- **1972** NBS call for proposals
- **1974** IBM Lucifer proposal
analyzed by DOD and enhanced by NSA
- **1976** adopted as standard
- **2004** NIST withdraws the standard

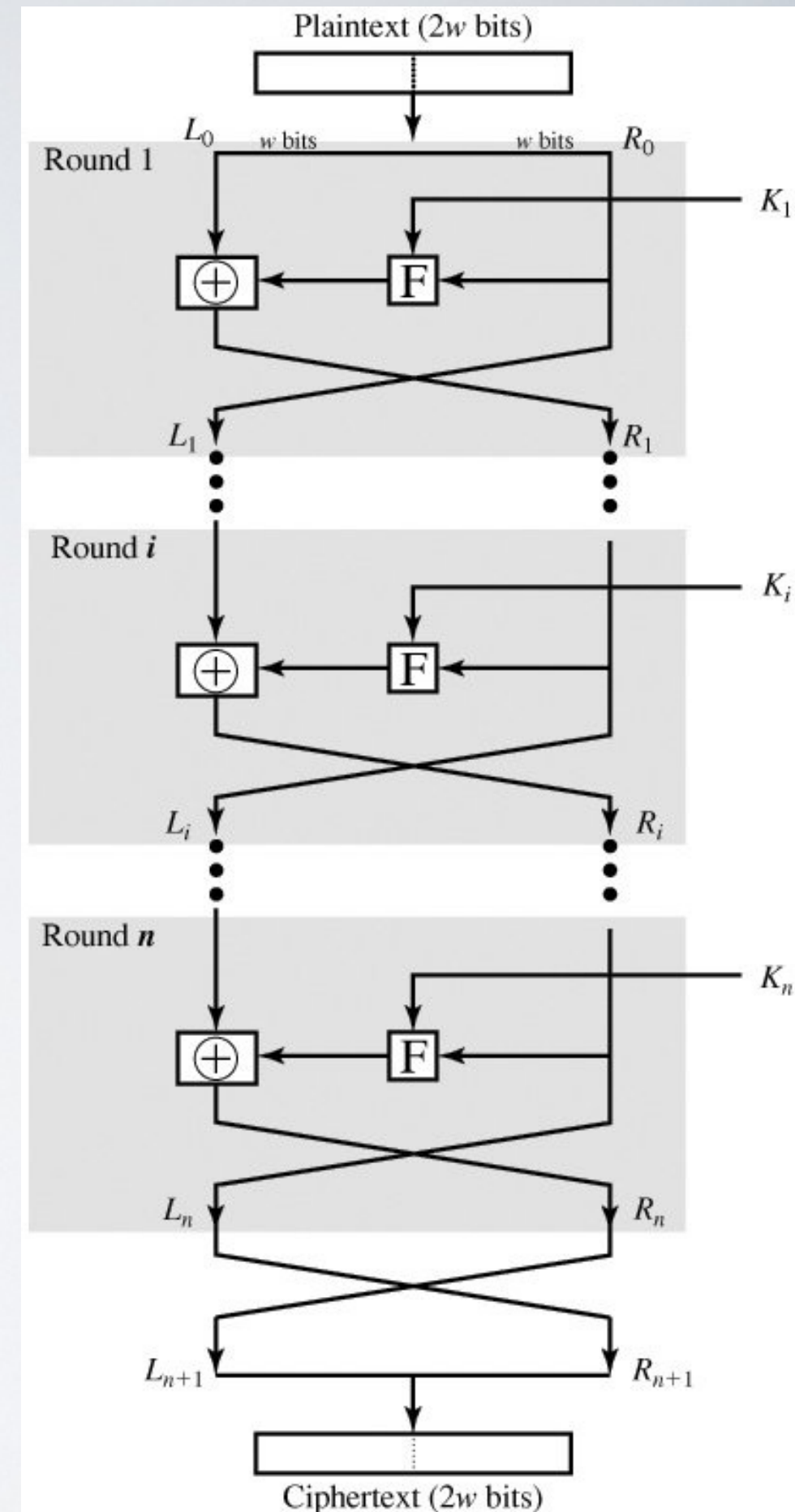
Feistel Network

$$L_i = R_{i-1}$$

$$R_i = L_{i-1} \oplus F_i(R_{i-1}, k_i)$$

Properties:

- F is an arbitrary function that scrambles the input based on a key
 - F is not necessary invertible
 - A Feistel Network is invertible
- ➡ Achieves confusion and diffusion



Security of DES - DES Challenges (brute force contests)

1998 *Deep Crack*, the EFF's DES cracking machine used 1,856 custom chips

- Speed : matter of days
- Cost : \$250,000

2006 *COPACOBANA*, the COst-optimized Parallel COdeBreaker used 120 FCPGAs

- Speed : less than 24h
- Cost : \$10,000

How about 2DES ?

$$2DES_{k_1, k_2}(m) = E_{k_2}(E_{k_1}(m))$$

Meet-in-the-middle attack - known-plaintext attack

1. Brute force $E_{k_1}(m)$ and save results in a table called TE (2^{56} entries)
2. Brute force $D_{k_2}(c)$ and save results in a table called TD (2^{56} entries)
3. Match the two tables together to get the key candidates
 - ➡ The more plaintext you know, the lesser key candidates
 - ➡ Effective key-length (entropy) is **57 bits**
 - ➡ This attacks applies to every encryption algorithm used as such

3DES (Triple DES)

$$3DES_{k1,k2,k3}(m) = E_{k3}(D_{k2}(E_{k1}(m)))$$

- ➡ Effective key length (entropy) : 112 bits
- ✓ Very popular, used in PGP, TLS (SSL) ...
- ⦿ But terribly slow

AES - Advanced Encryption Standard

Timeline

- **1996** NIST issues public call for proposal
- **1998** 15 algorithms selected
- **2001** winners were announced

Rijindael by *J. Daemen and V. Rijmen*

Block size	128 bits
Key Size	128, 192, 256 bits
Speed	~18-20 cycles / byte
Mathematical Foundation	Galois Fields
Implementation	<ul style="list-style-type: none">• Basic operations : \oplus, $+$, shift• Small code : 98k

Adopted by the NIST in December 2001

Encryption Modes

a.k.a. how to encrypt long messages

ECB - Electronic Code Book

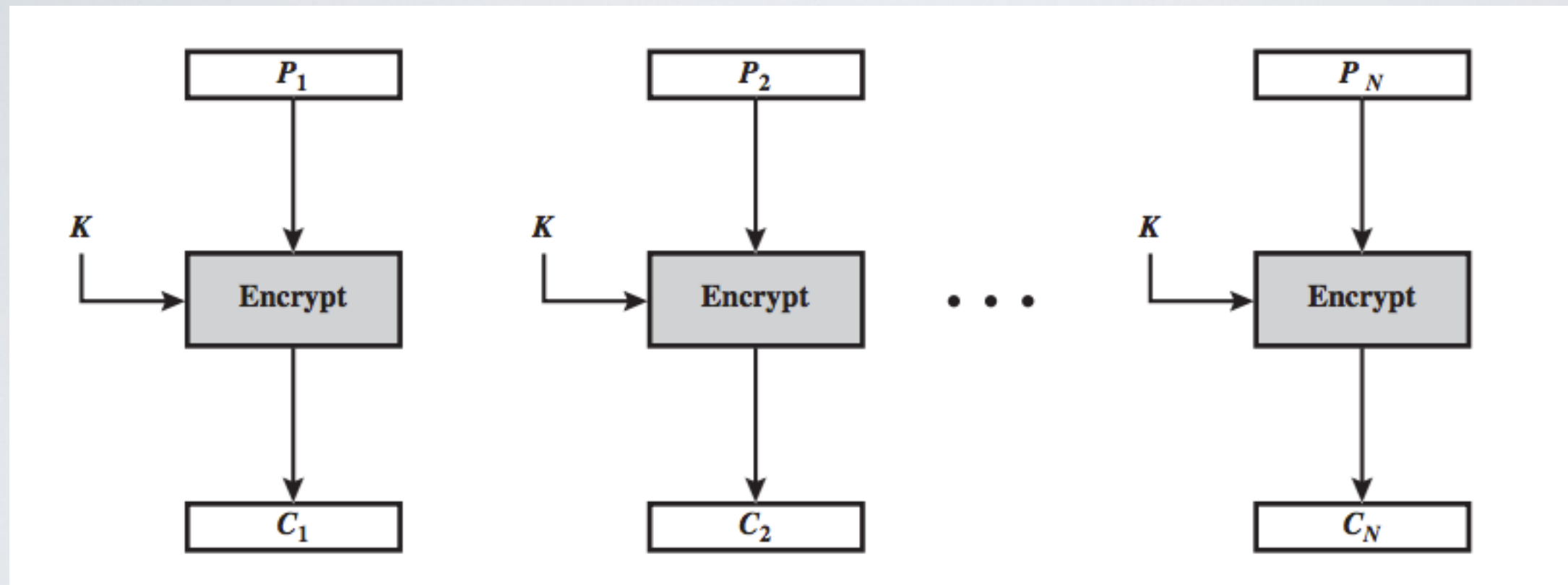
CBC - Cipher Block Chaining

CFB - Cipher Feedback

OFB - Output Feedback

CTR - Counter

ECB - Electronic Code Book



Each plaintext block is encrypted independently with the key

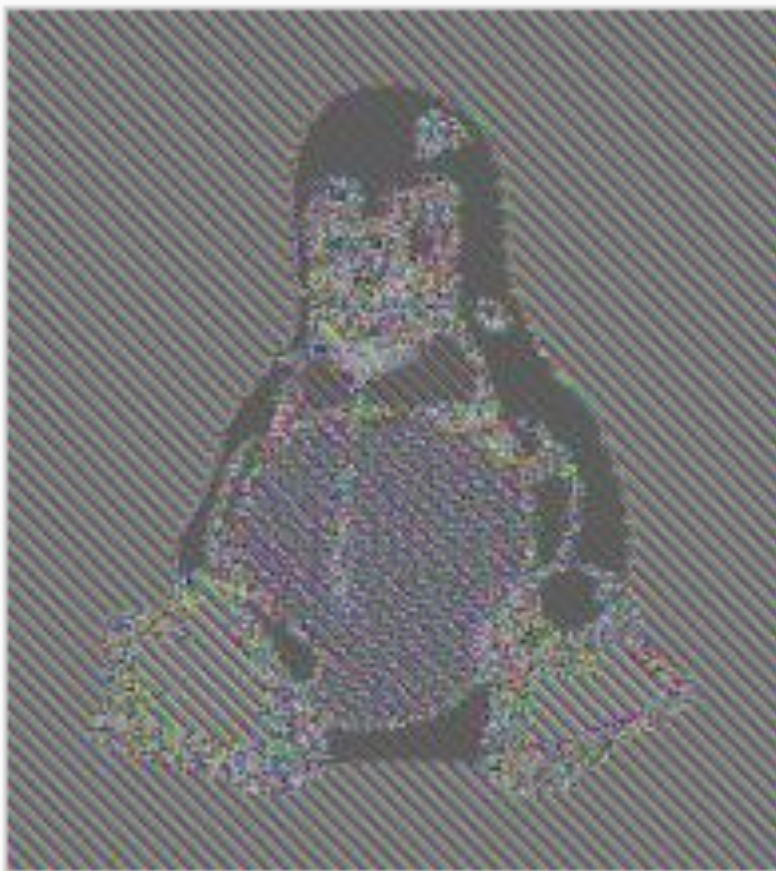
✓ Block can be encrypted in parallel

⦿ The same block is encrypted to the same ciphertext

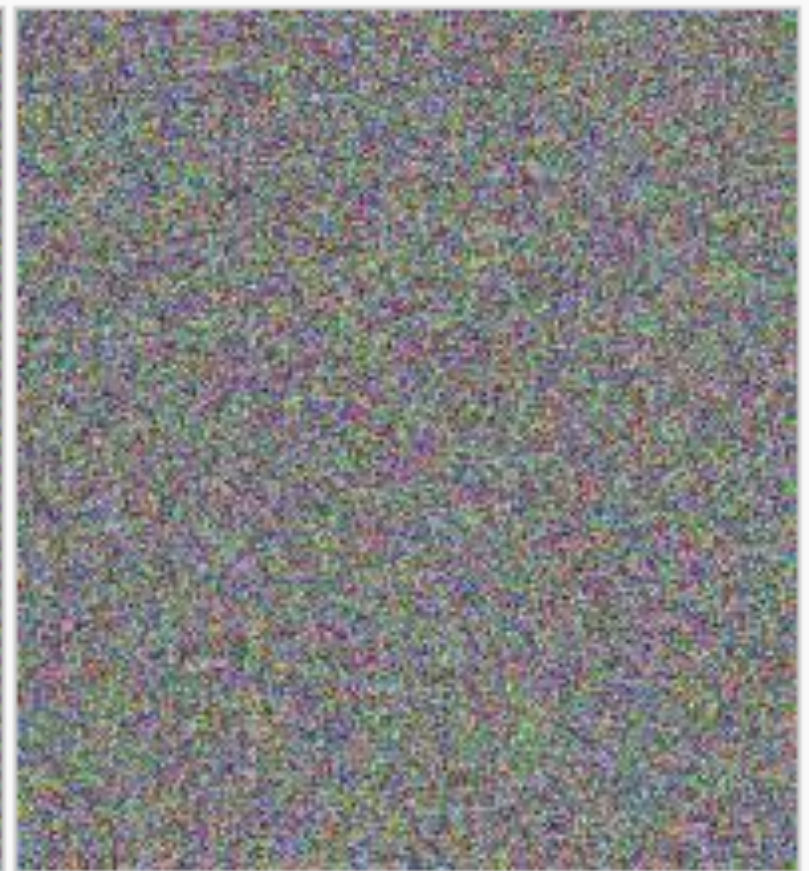
How bad is ECB mode with a large data?



Original image



Encrypted using ECB mode

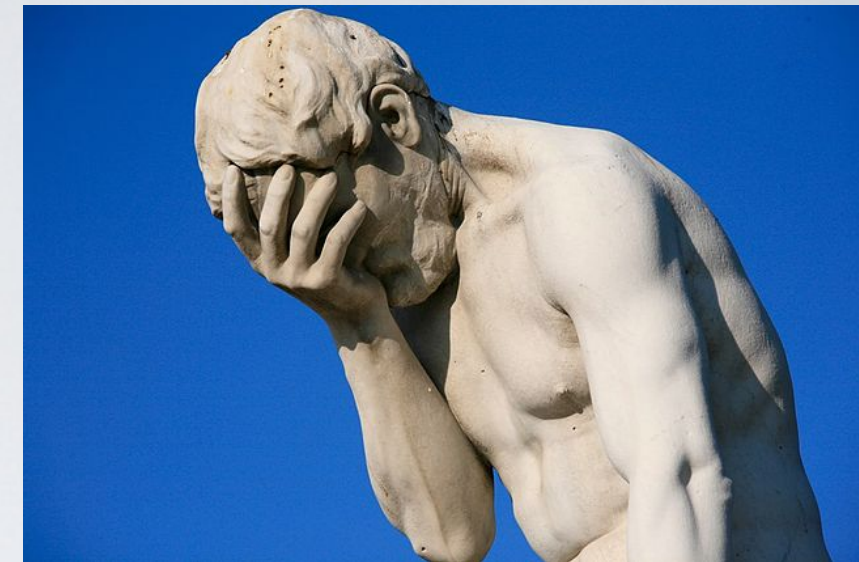


Modes other than ECB result in pseudo-randomness

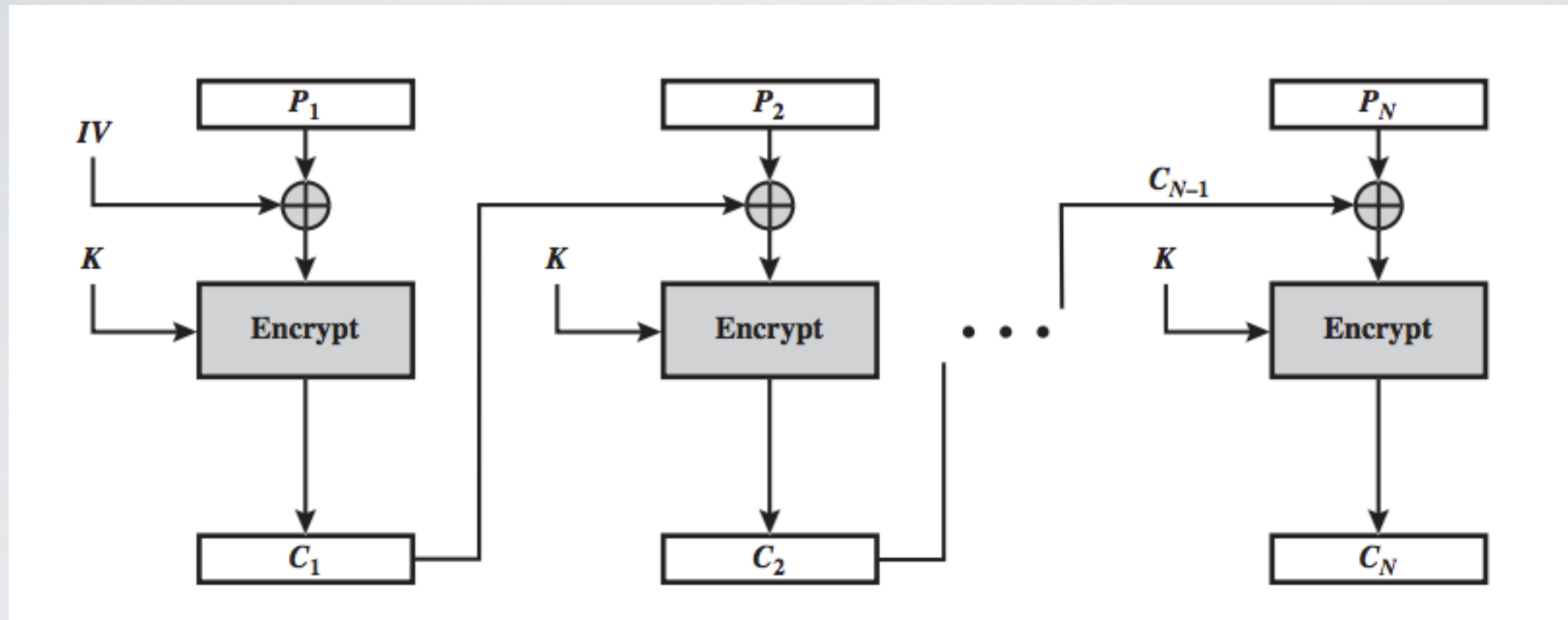
HACKERS RECENTLY LEAKED **153 MILLION** ADOBE USER EMAILS, ENCRYPTED PASSWORDS, AND PASSWORD HINTS. ADOBE ENCRYPTED THE PASSWORDS IMPROPERLY, MISUSING BLOCK-MODE 3DES. THE RESULT IS SOMETHING WONDERFUL:

USER	PASSWORD	HINT	
4e18acc1ab27a2d6		WEATHER VANE SWORD	<input type="text"/>
4e18acc1ab27a2d6			<input type="text"/>
4e18acc1ab27a2d6	a0a2876eb1ea1fca	NAME 1	<input type="text"/>
8babbb6299e06eb6d		DUH	
8babbb6299e06eb6d	a0a2876eb1ea1fca		<input type="text"/>
8babbb6299e06eb6d	85e9da81a8a78adc	57	
4e18acc1ab27a2d6		FAVORITE OF 12 APOSTLES	
1ab29ae86da6e5ca	7a2d6a0a2876eb1e	WITH YOUR OWN HAND YOU HAVE DONE ALL THIS	
a1f9b2b6299e7a2b	e0dec1e6ab797397	SEXY EARLOBES	<input type="text"/>
a1f9b2b6299e7a2b	617ab0277727ad85	BEST TOS EPISODE	<input type="text"/>
39738b7adb0b8af7	617ab0277727ad85	SUGARLAND	
1ab29ae86da6e5ca		NAME + JERSEY #	
877ab7889d3862b1		ALPHA	<input type="text"/>
877ab7889d3862b1			<input type="text"/>
877ab7889d3862b1			<input type="text"/>
877ab7889d3862b1		OBVIOUS	<input type="text"/>
877ab7889d3862b1		MICHAEL JACKSON	<input type="text"/>
38a7c9279codeb44	9dca1d79d4dec6d5		
38a7c9279codeb44	9dca1d79d4dec6d5	HE DID THE MASH, HE DID THE	<input type="text"/>
38a7c9279codeb44		PURLOINED	<input type="text"/>
08ae5745a7b7af7a	9dca1d79d4dec6d5	FAV. LATER-3 POKEMON	

THE GREATEST CROSSWORD PUZZLE
IN THE HISTORY OF THE WORLD



CBC - Cipher Block Chaining



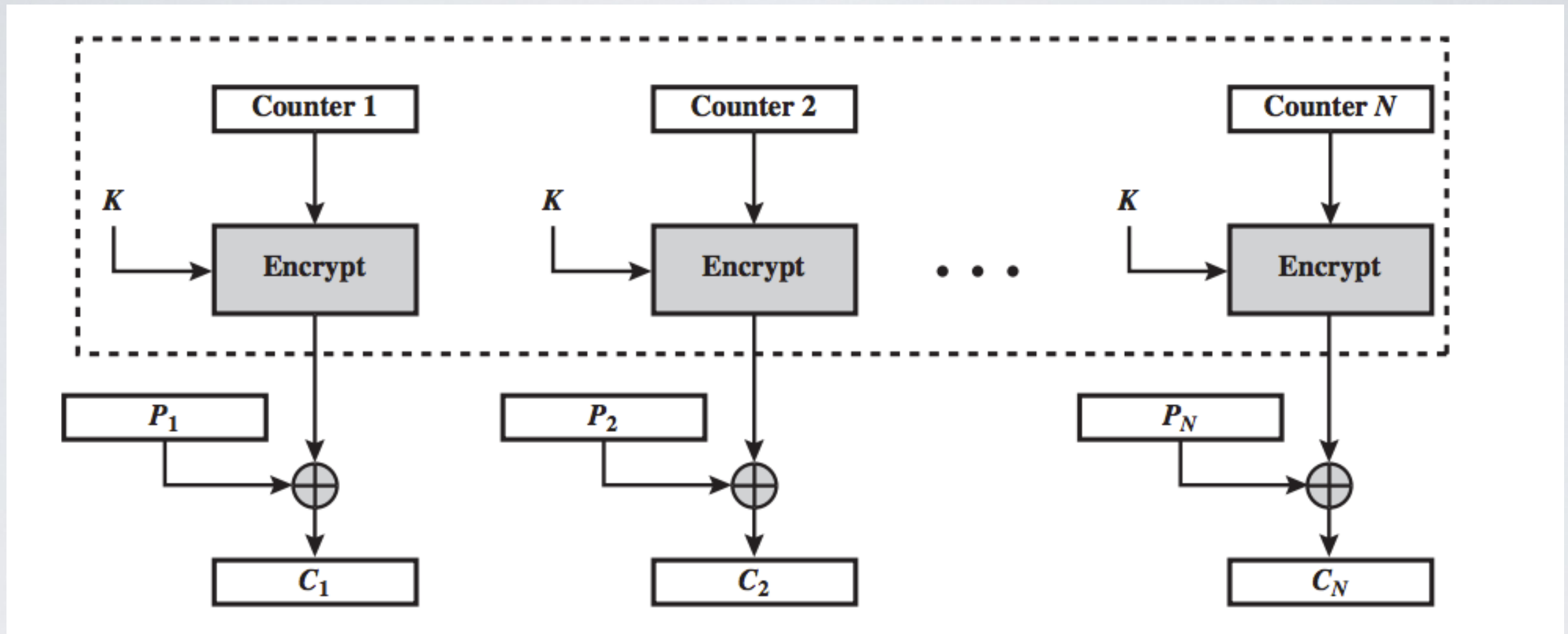
Introduce some randomness using the previous ciphertext block

✓ Repeating plaintext blocks are not exposed in the ciphertext

⦿ No parallelism

➡ The Initialization Vector should not be known by the opponent and must be sent separately (ECB mode for instance)

CTR - Counter



Introduce some randomness using a counter

✓ High entropy and parallelism

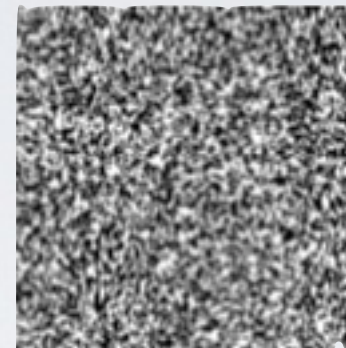
⦿ Sensitive to key-reused attack

➡ Popular usage : IPsec (coming soon in this course)

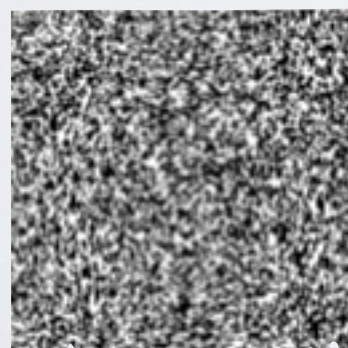
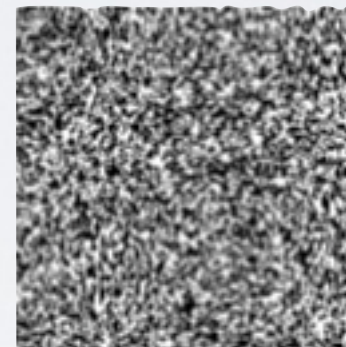
Key-reused attack on CTR



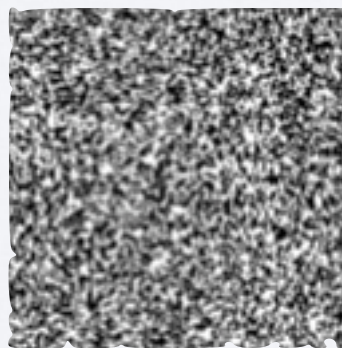
$$\oplus K =$$



$$\oplus K =$$



$$\oplus$$



$$=$$



Stream Cipher vs Block Cipher

	Stream Cipher	Block Cipher
Approach	Encrypt one symbol of plaintext directly into a symbol of ciphertext	Encrypt a group of plaintext symbols as one block
Pro	Fast	High diffusion
Cons	Low diffusion	Slow

Stream cipher and block cipher are often used together

- Stream cipher for encrypting large volume of data
- Block cipher for encrypting fresh pseudo-random seeds

Latest Trends

RC4 has shown serious weaknesses since 2015

AES is now hardware accelerated (AES-NI native instruction)

➡ AES-CTR is fast enough (~ 1.3 cycles per byte)
to be used as a stream cipher

<https://www.cryptopp.com/benchmarks.html>