

# 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**

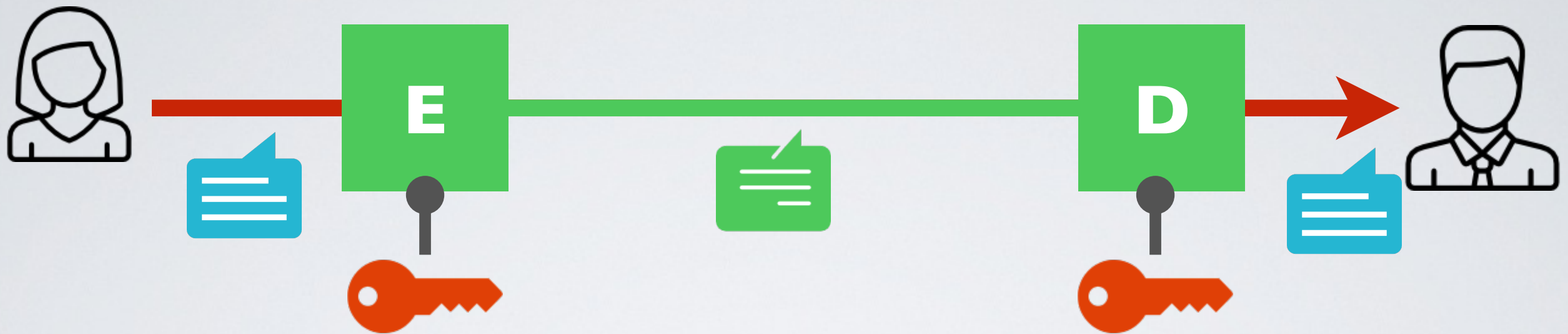
You know one or several pairs of chosen plaintext and their corresponding ciphertexts

- **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 (and ChaCha20)*

## **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

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

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

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

**Problem** : known-plaintext attack

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

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

# 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

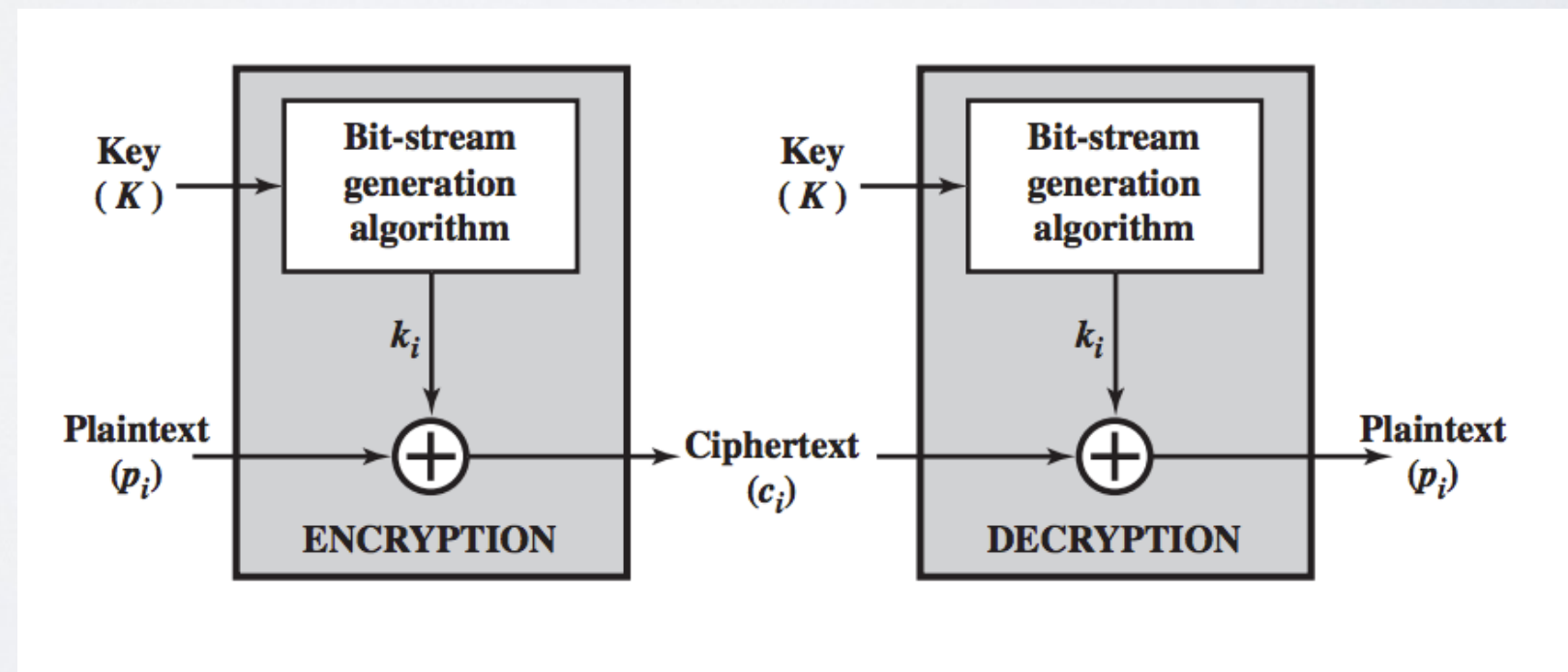
```
int getRandomNumber()  
{  
    return 4; // chosen by fair dice roll.  
             // guaranteed to be random.  
}
```

## 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 !

# RC4 - Rivest Cipher 4

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

Very simple implementation

Designed in 1987 ... but broken in 2015

[Home](#) / [Business Software](#)

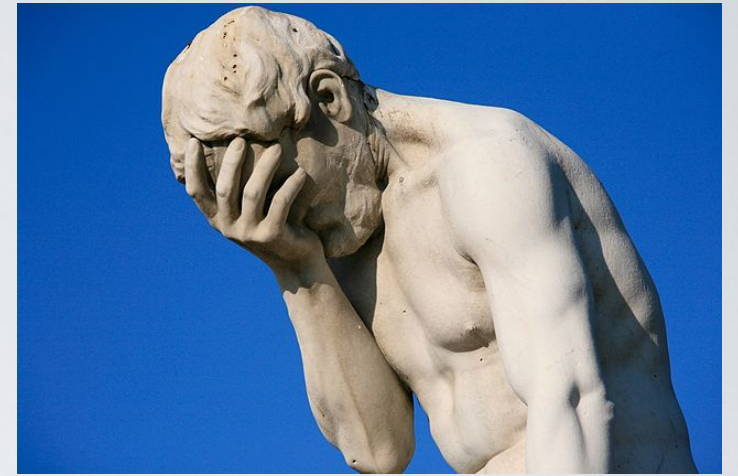
# 'Serious' Microsoft Office Encryption Flaw Uncovered

 [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.

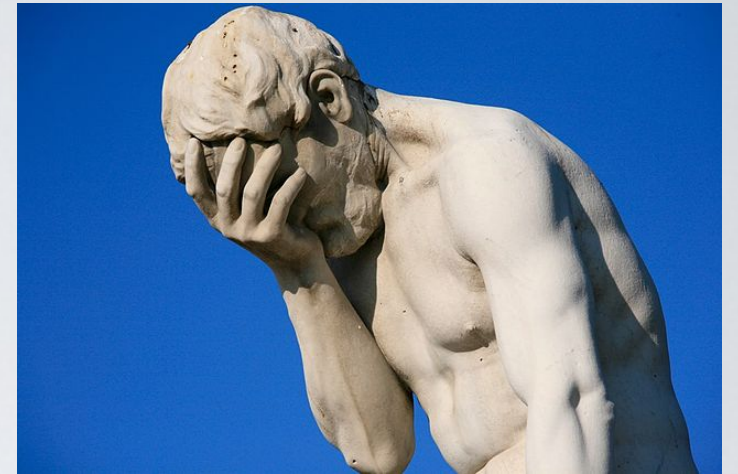
"I think this is a serious flaw--it is highly exploitable. It is not a theoretical attack," says Zimmermann, referring to a flaw in Microsoft's use of RC4 document encryption unearthed recently by a researcher in Singapore.



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

$$\text{RC4\_key} = \text{IV} + \text{SSID\_password}$$

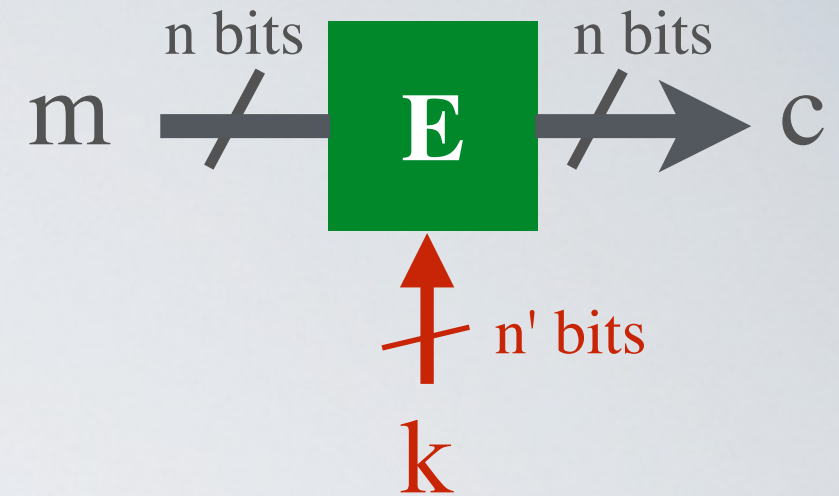
- ⦿ 50% chance the same IV will be used again after 5000 packets

# Salsa20 (and ChaCha20)

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

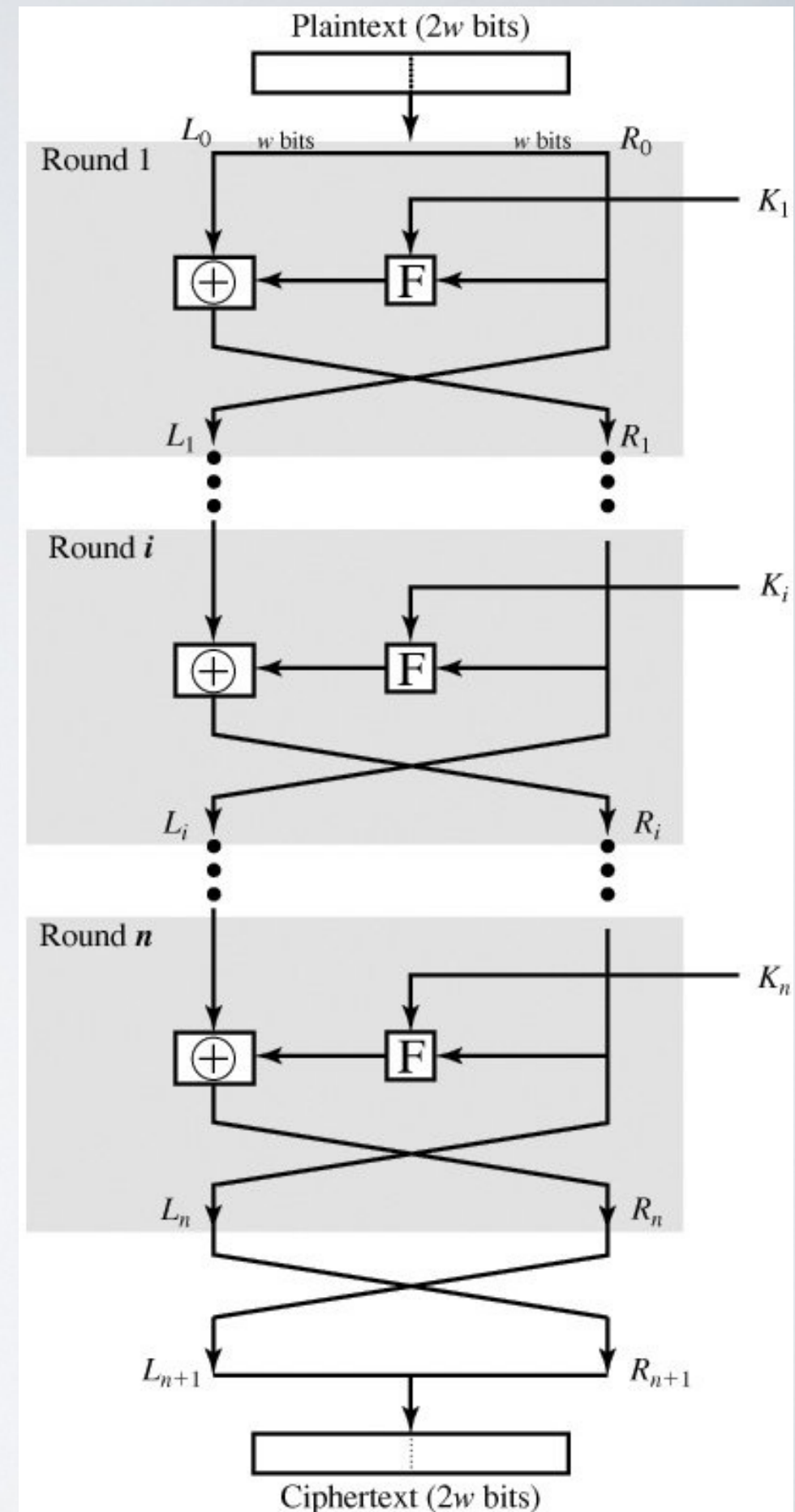
# (FYI) Feistel Network

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

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

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 FPGAs

- 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** winner was announced

# Rijndael 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"><li>• Basic operations : <math>\oplus</math>, <math>+</math>, shift</li><li>• Small code : 98k</li></ul>

Adopted by the NIST in December 2001

# (pure) Encryption Modes

a.k.a. how to encrypt long messages

**ECB - Electronic Code Book**

**CBC - Cipher Block Chaining**

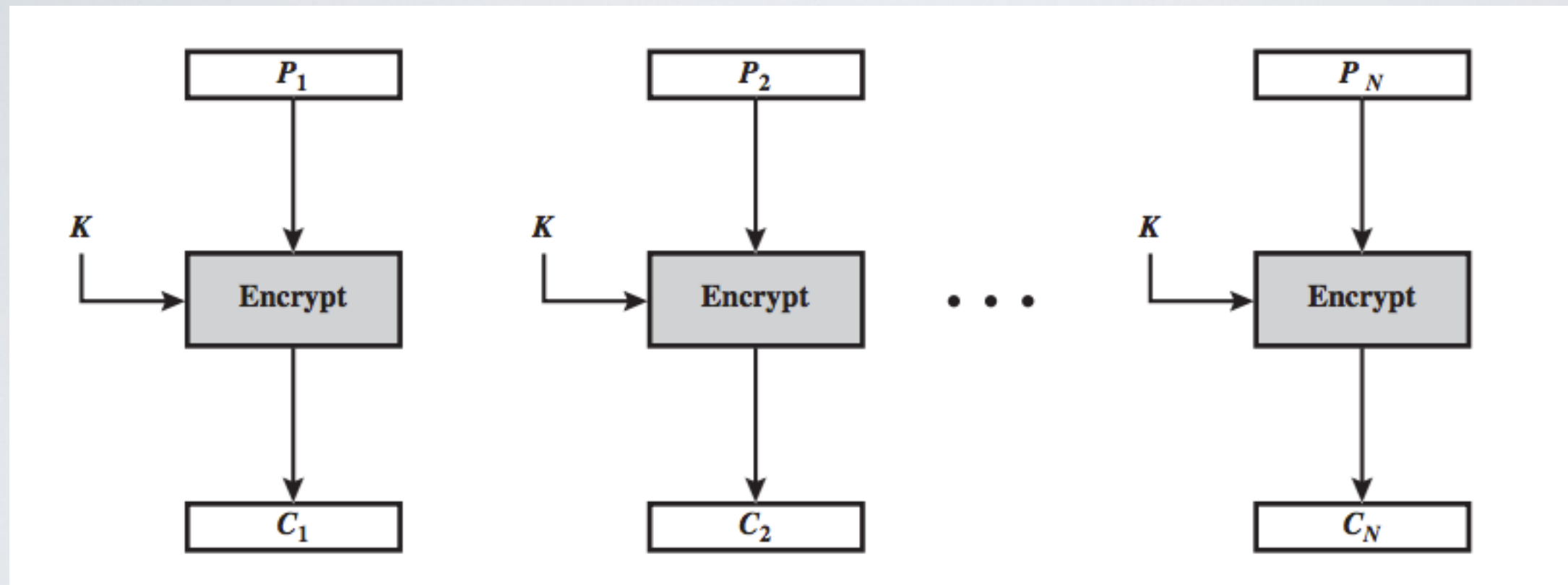
CFB - Cipher Feedback

OFB - Output Feedback

**CTR - Counter**



# ECB - Electronic Code Book (a.k.a Block Mode)



Each plaintext block is encrypted independently with the key

✓ Block can be encrypted in parallel

⦿ The same block is encrypted to the same ciphertext

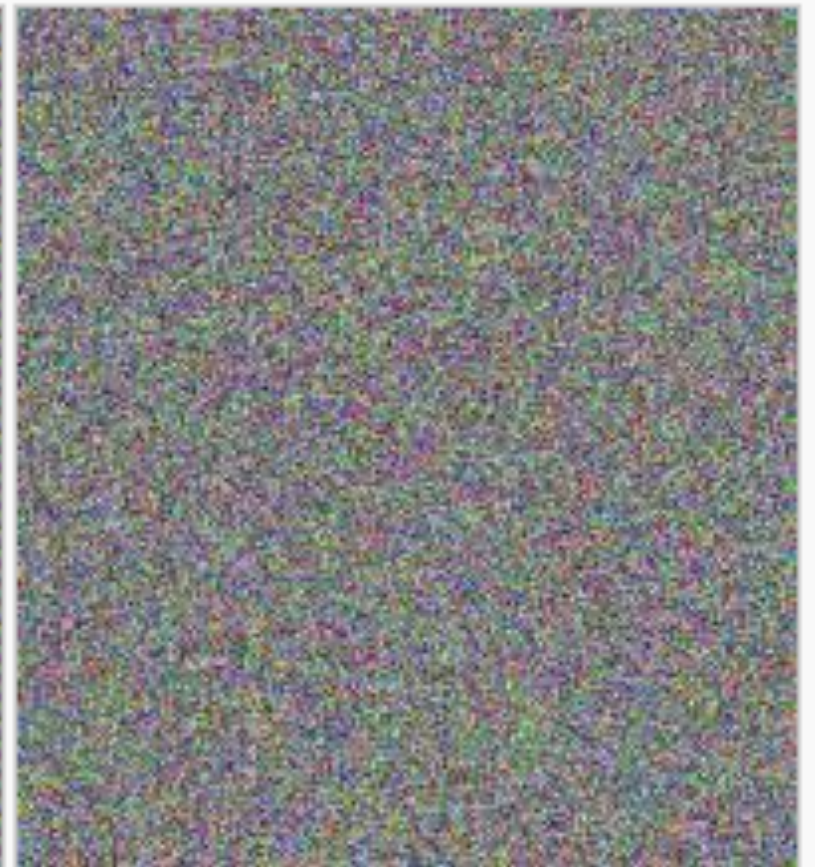
# How bad is ECB mode with a large data?



Original image



Encrypted using ECB mode



Modes other than ECB result in pseudo-randomness

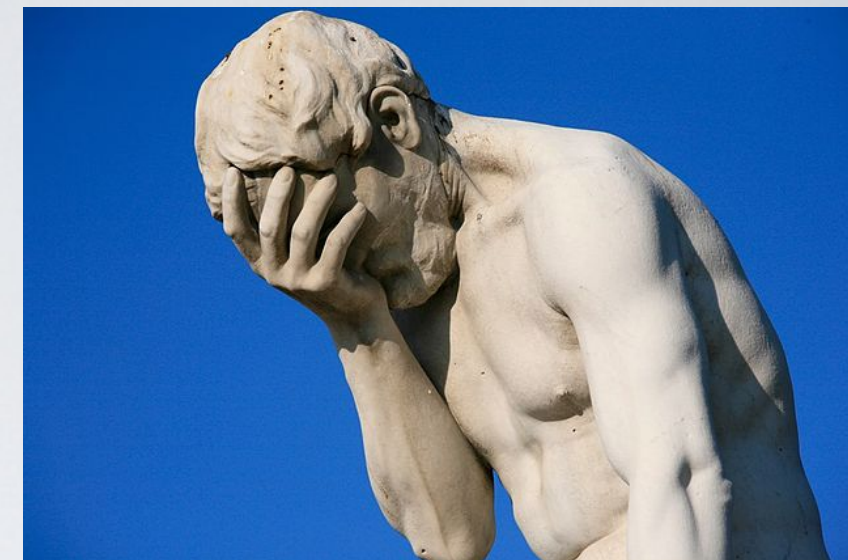
source: *Wikimedia*



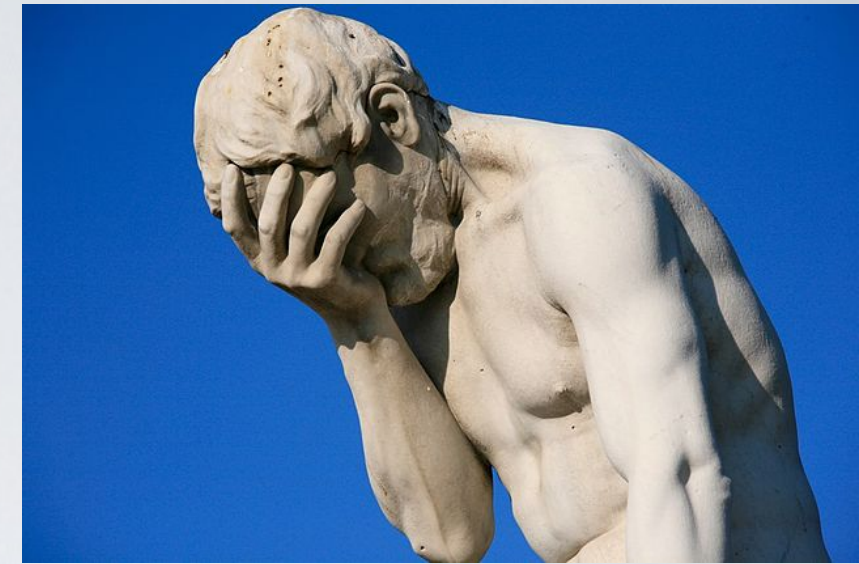
HACKERS RECENTLY LEAKED **153 MILLION** ADOBE USER EMAILS, ENCRYPTED PASSWORDS, AND PASSWORD HINTS. ADOBE ENCRYPTED THE PASSWORDS IMPROPERLY, MISUSING BLOCK-MODE 3DES. THE RESULT IS SOMETHING WONDERFUL:

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



source: XKCD



## Simple Illustration of Zoom Encryption Failure



by Davi Ottenheimer on April 10, 2020

The Citizen Lab [April 3rd, 2020 report](#) broke the news on Zoom using weak encryption and gave this top-level finding:

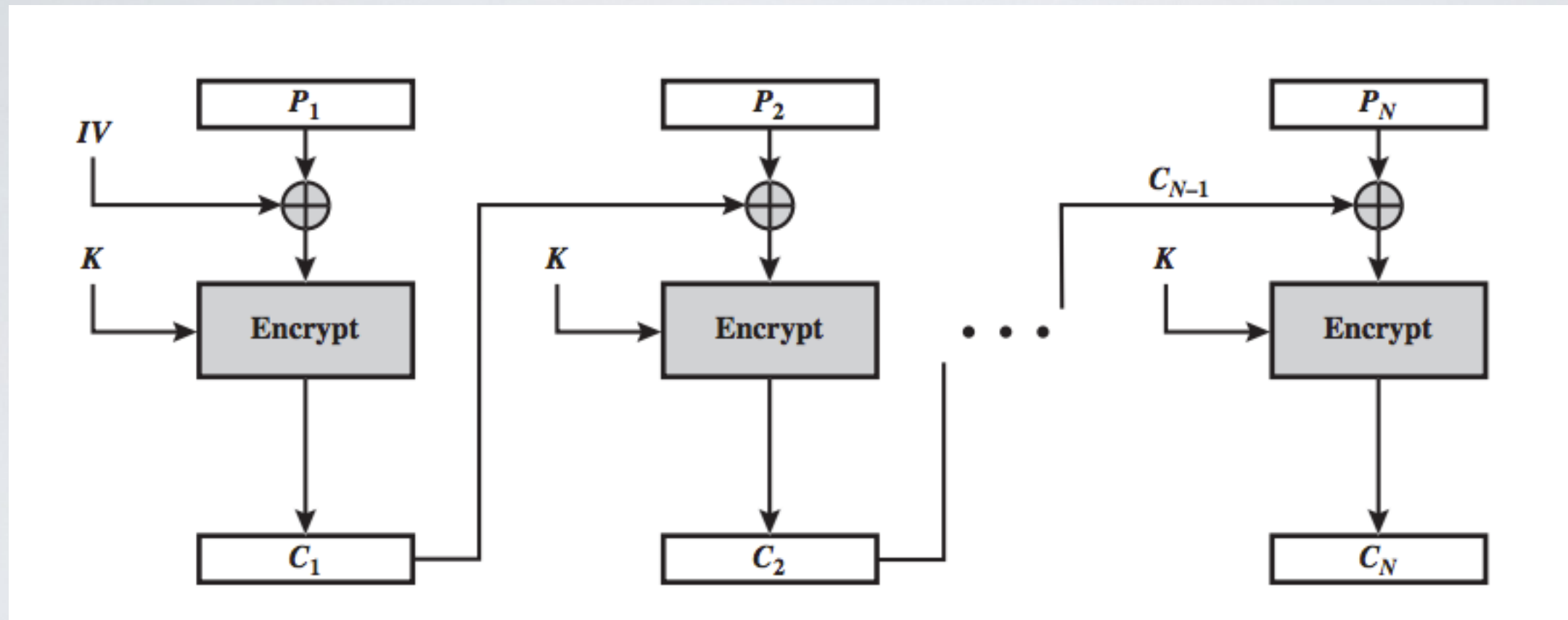
“

Zoom [documentation](#) claims that the app uses “AES-256” encryption for meetings where possible. However, we find that in each Zoom meeting, a single AES-128 key is used in ECB mode by all participants to encrypt and decrypt audio and video. The use of ECB mode is not recommended because patterns present in the plaintext are preserved during encryption.

source: *Security Boulevard*



# CBC - Cipher Block Chaining (a.k.a Chaining Mode)



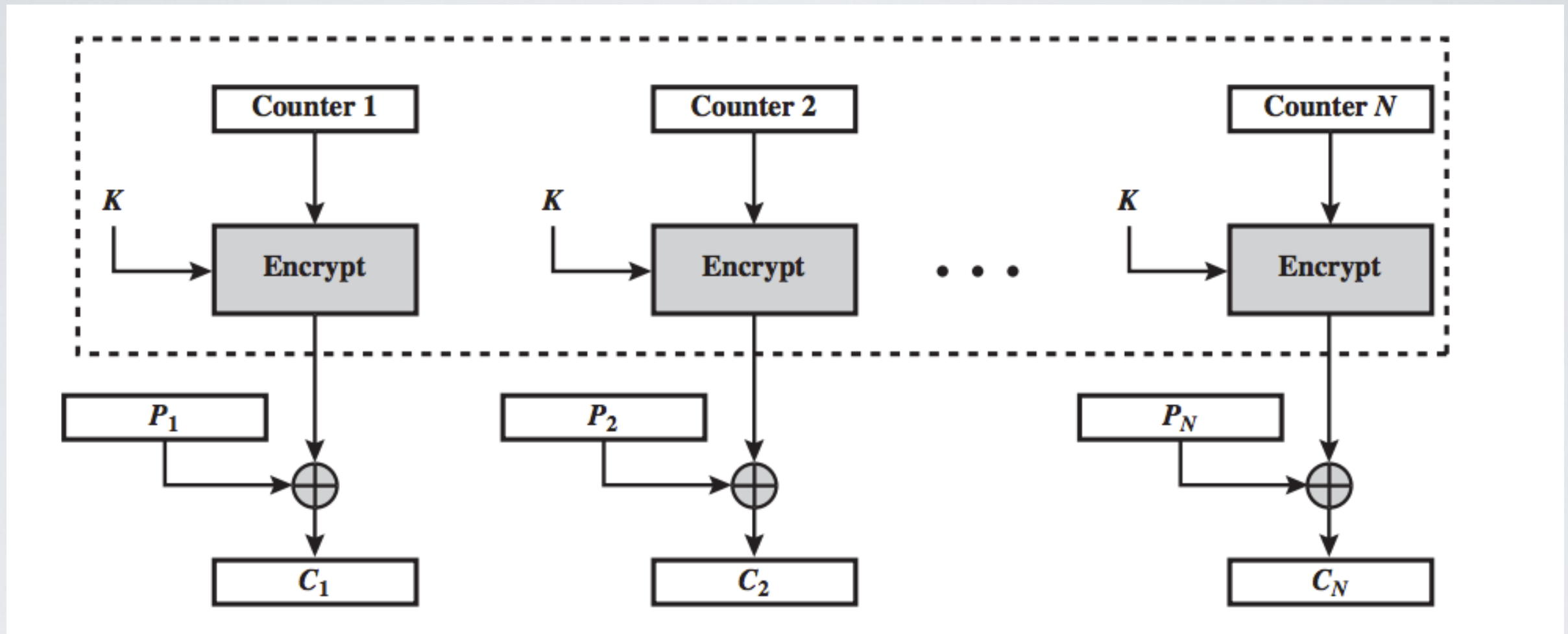
Introduce some randomness using the previous ciphertext block

✓ Repeating plaintext blocks are not exposed in the ciphertext

⦿ No parallelism

➡ The Initialization Vector should be known by the recipient

# CTR - Counter Mode



Introduce some randomness using a counter

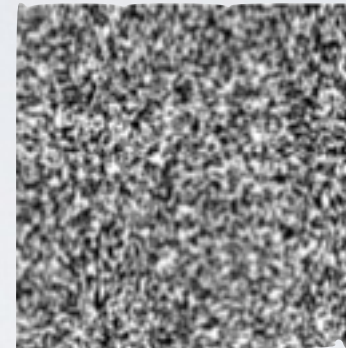
✓ High entropy and parallelism

⦿ Behaves as a stream cipher - sensitive to key-reused attack

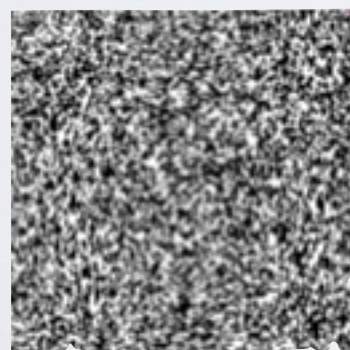
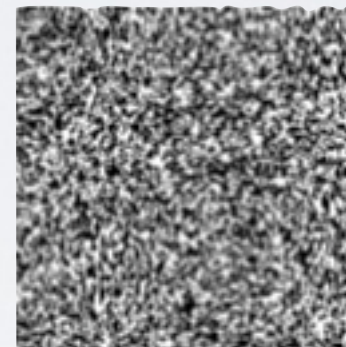
# Key-reused attack on CTR



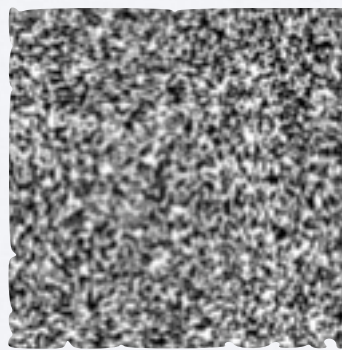
$$\oplus K =$$



$$\oplus K =$$



$$\oplus$$



$$=$$



# 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

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

- ➡ AES is fast enough ( $\sim 1.3$  cycles per byte)  
to be used as the go-to cipher for any application

<https://security.stackexchange.com/questions/22905/how-long-would-it-take-a-single-processor-with-the-aes-ni-instruction-set-to-bru>

# Preventing Key Reused Attacks

At best, use a fresh symmetric key every time

- Key exchange problem

At least, change the seed to never it use it twice

- ✓ All modern stream cipher (Salsa/Chacha) and good encryption mode for block cipher (CBC, CTR) take a nonce
- ➡ Generate this nonce randomly and sent it in clear with cyphertext

Are we secured?



# Security goals vs attacker's model

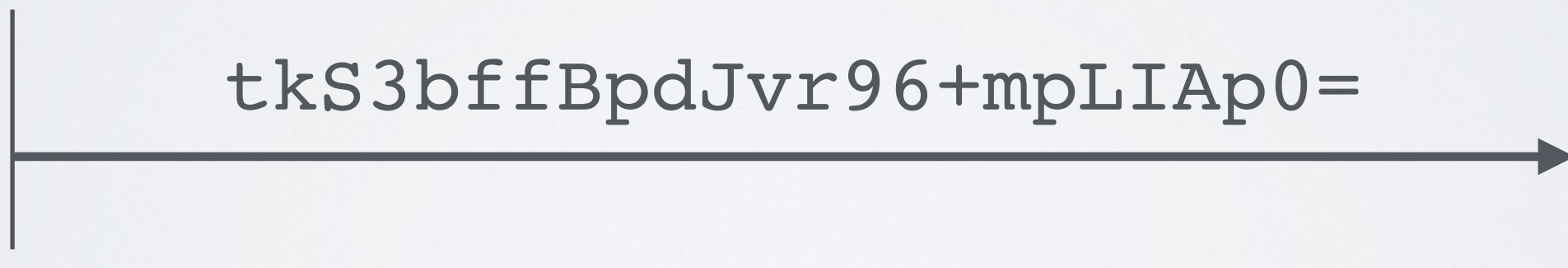


Let us consider **confidentiality, integrity and availability**

(pure) encryption ensures confidentiality ...



$E_k(m) = \text{tkS3bffBp} \dots$

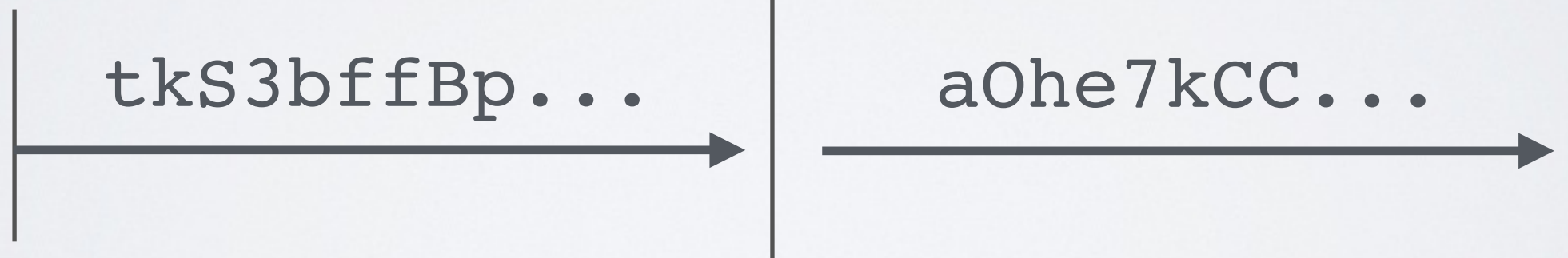


$D_k(\text{"tkS3bffBp} \dots \text{"}) = m$

... but does not ensure integrity !



$E_K(m) = \text{tkS3bffBp} \dots$



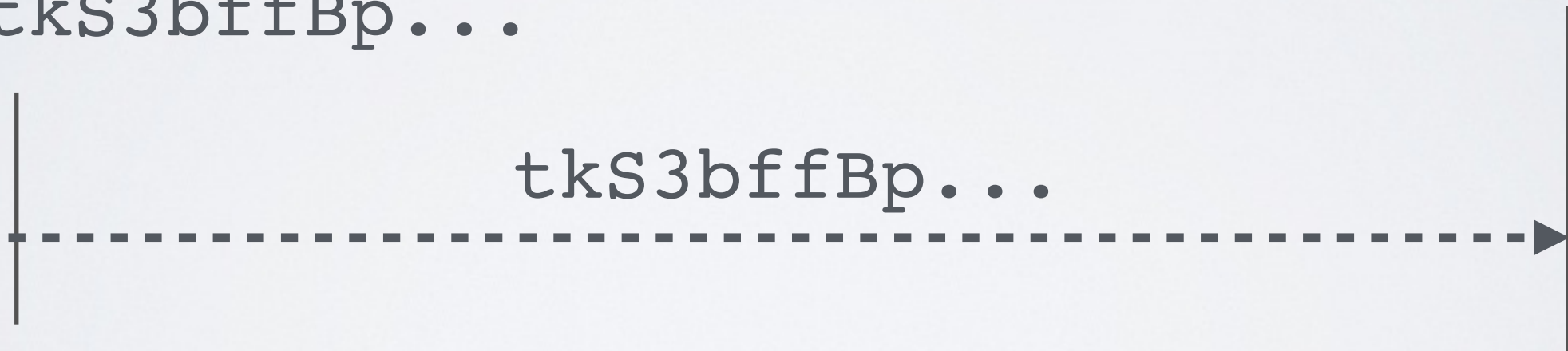
$D_K(\text{"a0he7kCC} \dots \text{"}) = m'$

● Encrypting a message does not authenticate it

One more issue ...



$E_k(m) = \text{tkS3bffBp} \dots$



● How does Alice and Bob agree on a symmetric key?