Symmetric Encryption

Thierry Sans

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

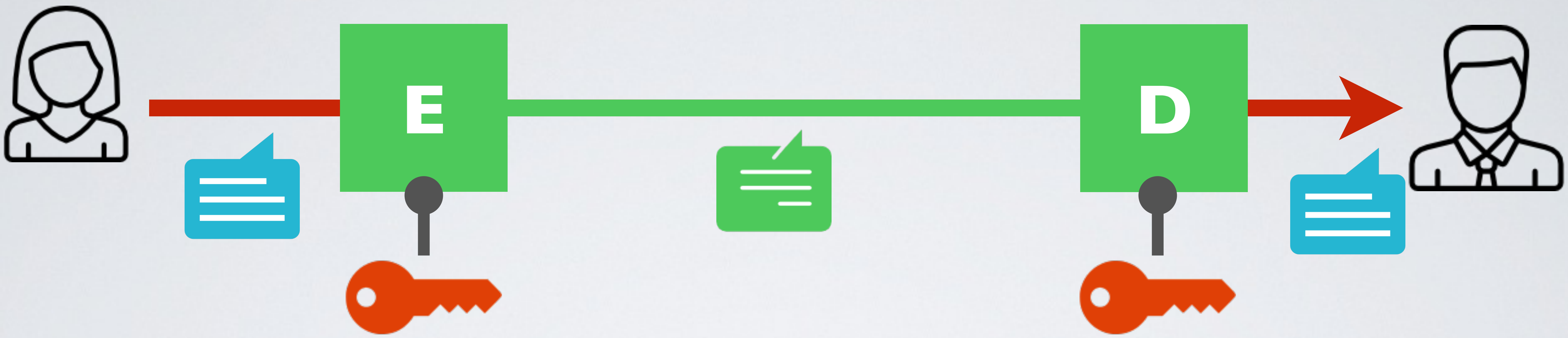
4. **Randomization**
   Repeated encryptions of the same text are different

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

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

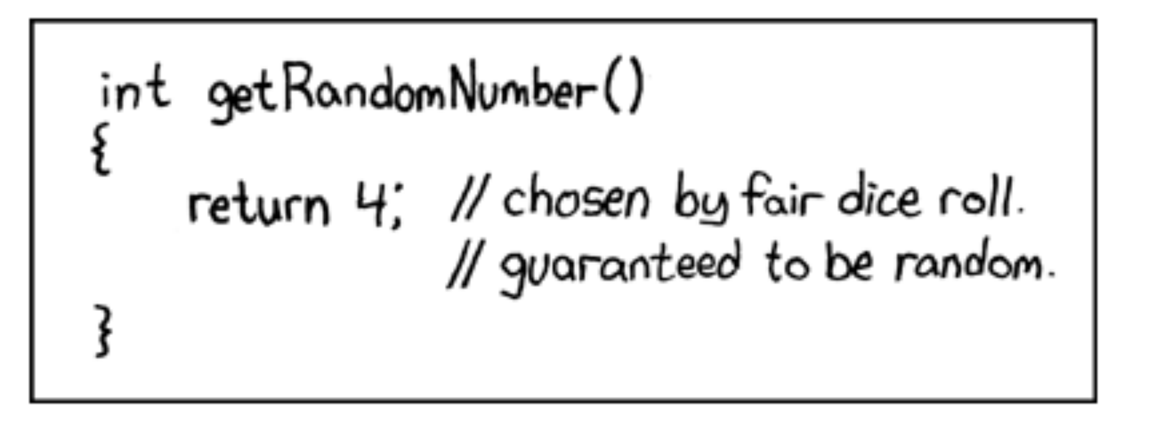
Problem : Key-reused attack (a.k.a two-time pad)

$$C_1 = k \oplus m_1$$
$$C_2 = k \oplus m_2$$

so $C_1 \oplus C_2 = (k \oplus m_1) \oplus (k \oplus m_2)$
$= (m_1 \oplus m_2) \oplus 0$
$= (m_1 \oplus m_2)$

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

Random Number Generator

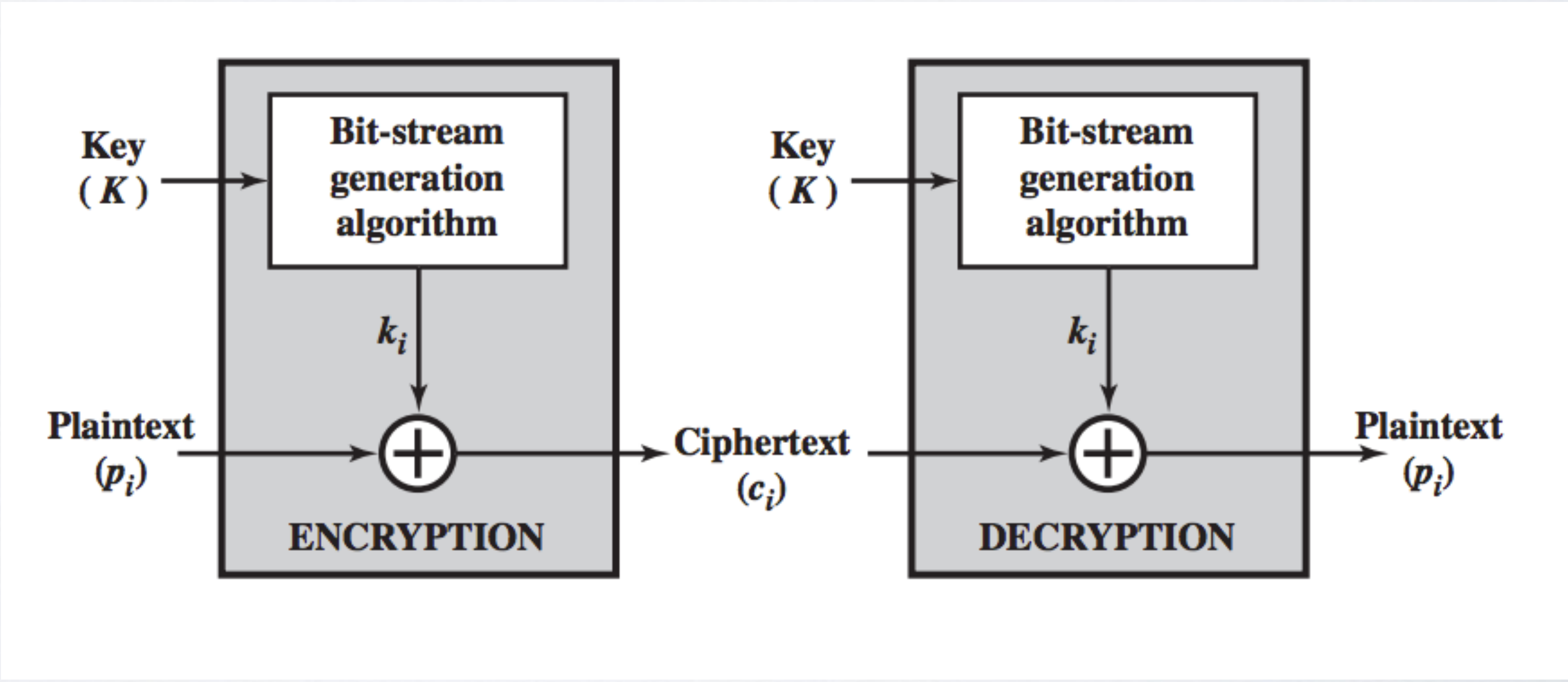


True Random Number Generator

➡ <u>No</u>, because we want to be able to encrypt and decrypt

Pseudo-Random Generator

➡ Stretch a a fixed-size <u>seed</u> to obtain an unbounded random sequence



Stream cipher

Can we use **k** as a seed?

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

➡ 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

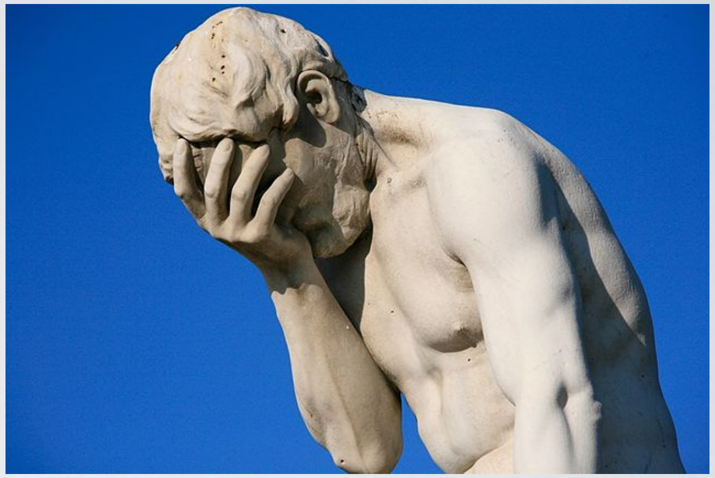
'Serious' Microsoft Office Encryption Flaw Uncovered

COMMENTS

By John E. Dunn, IDG News Service
Jan 27, 2005 4:00 PM

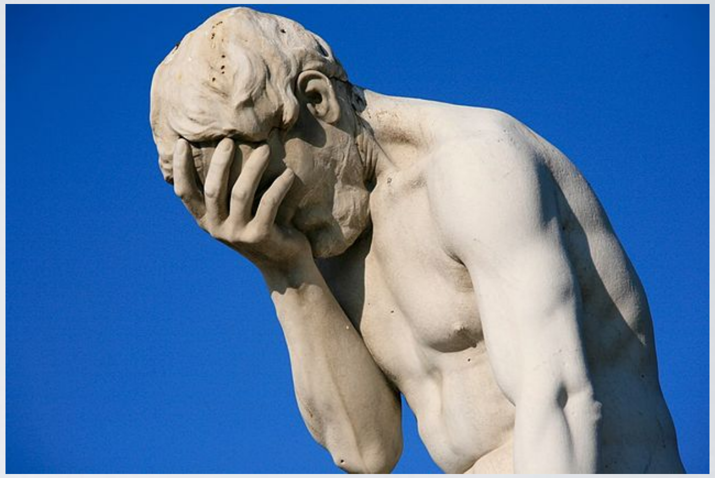
Cryptography expert Phil Zimmermann says he believes a flaw recently discovered in Microsoft Office's Word and Excel encryption is serious and warrants immediate attention.

"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

RC4_key = IV + SSID_password

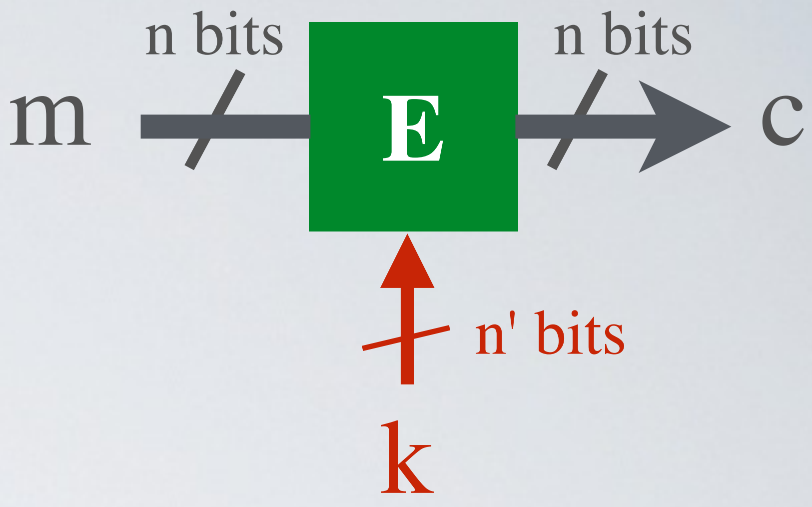
◉ 50% chance the same IV will be used again after 5000 packets

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

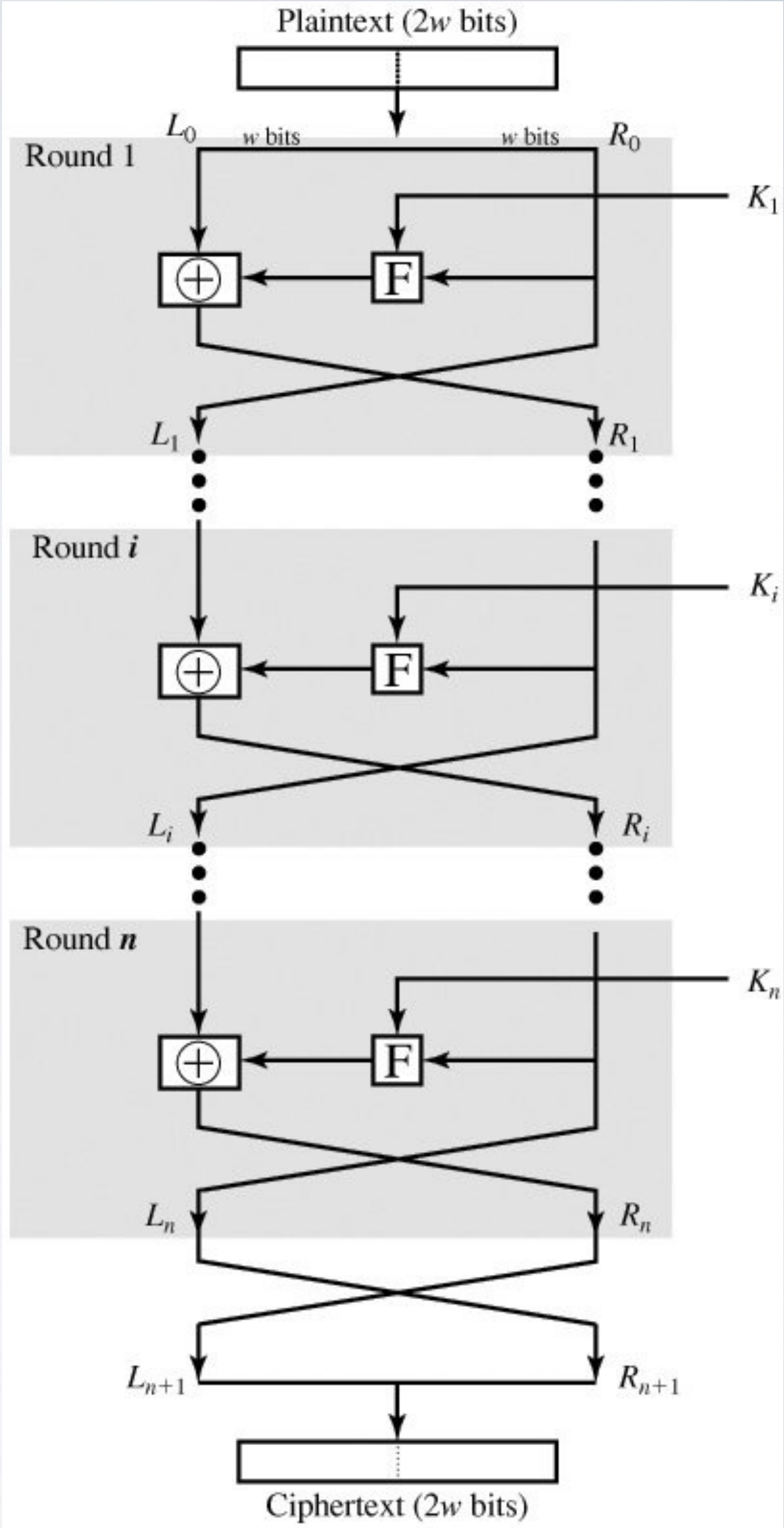
$L_i = R_{i-1}$

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

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



"Cryptography and Network Security" by *William Stalllings*

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 ?

$$2DES_{k1,k2}(m) = E_{k2}(E_{k1}(m))$$

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

1. Brute force $E_{k1}(m)$ and save results in a table called TE (2^{56} entries)
2. Brute force $D_{k2}(c)$ 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	• Basic operations : ⊕, + , shift • Small code : 98k

Adopted by the NIST in December 2001

(pure) Encryption Modes
a.k.a. how to encrypt long messages

ECB - Electronic Code Book

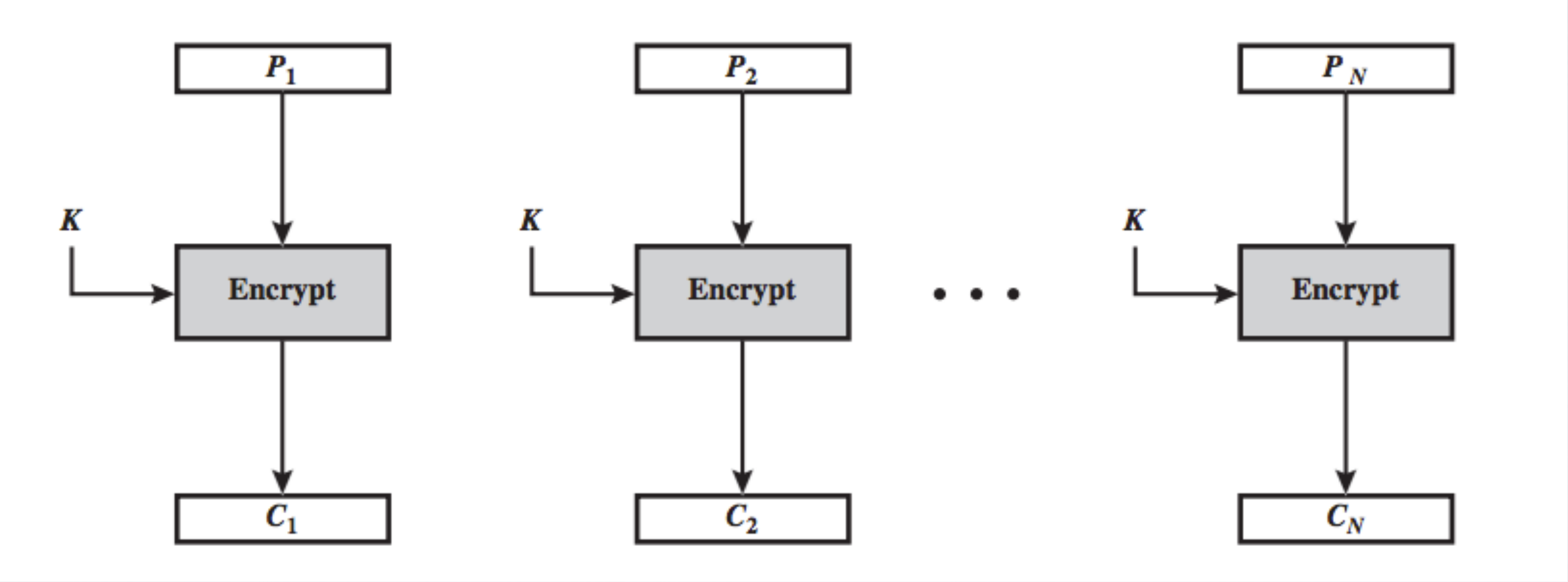
CBC - Cipher Block Chaining

CFB - Cipher Feedback

OFB - Output Feedback

CTR - Counter

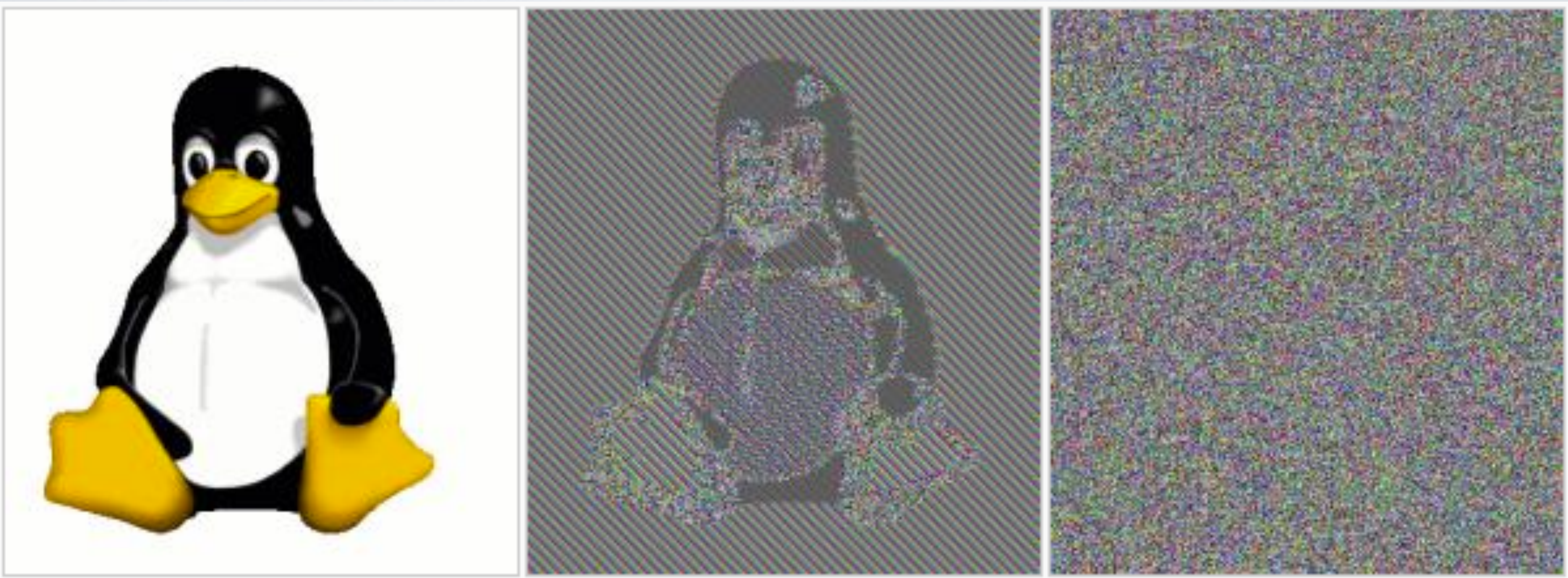
ECB - Electronic Code Book (a.k.a Block Mode)



Each plaintext block is encrypted <u>independently with the key</u>

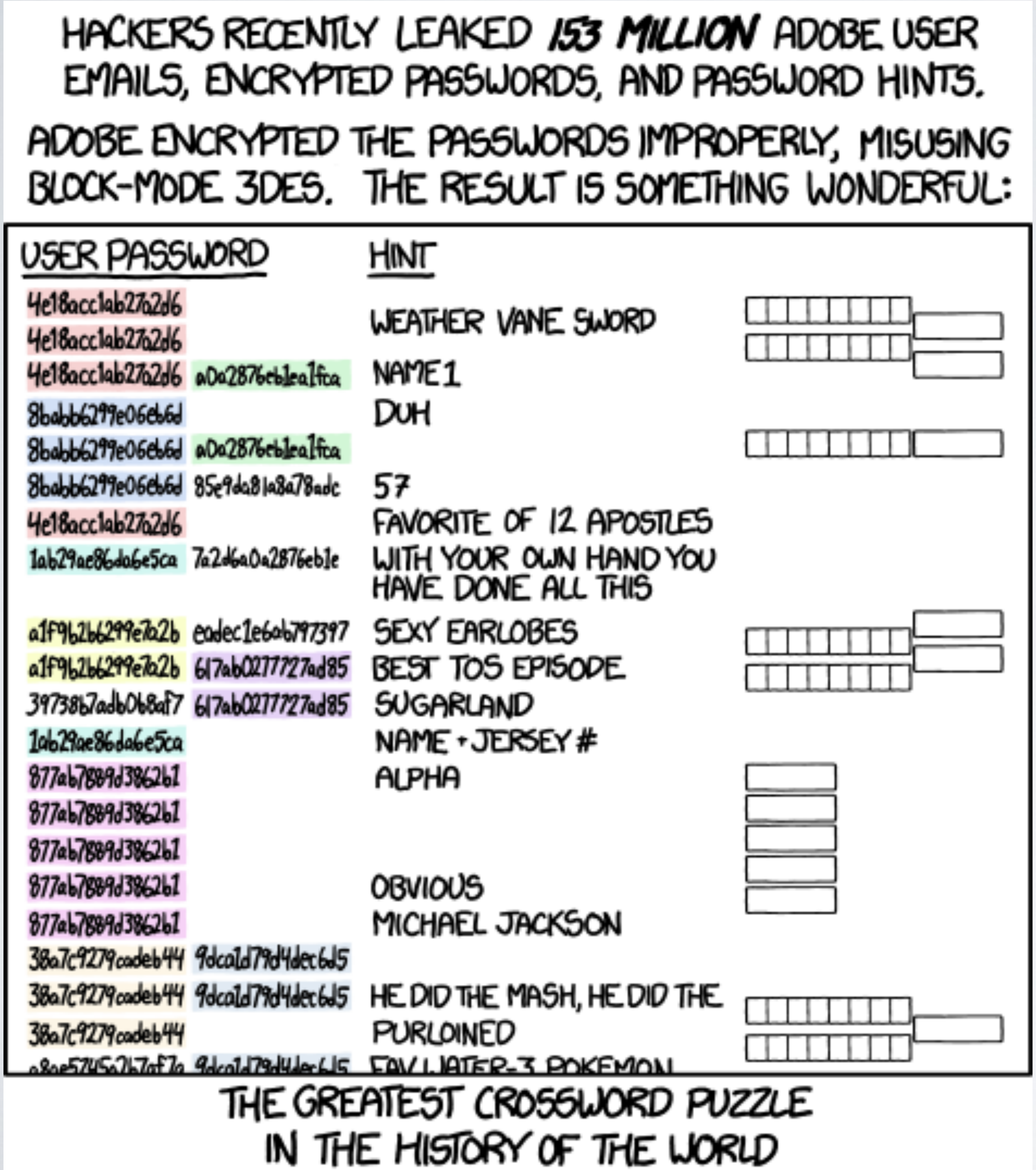
- ✓ Block can be encrypted in parallel
- ◉ The same block is encrypted to the same ciphertext

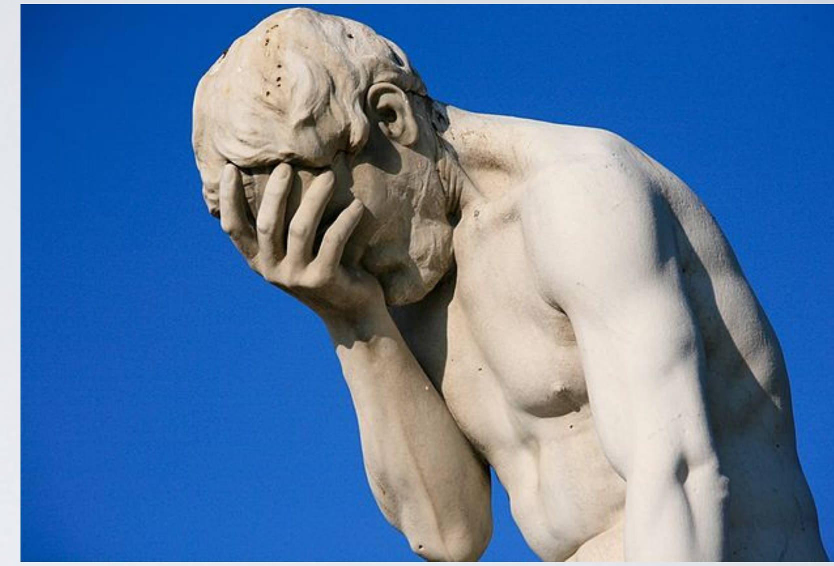
How bad is ECB mode with a large data?



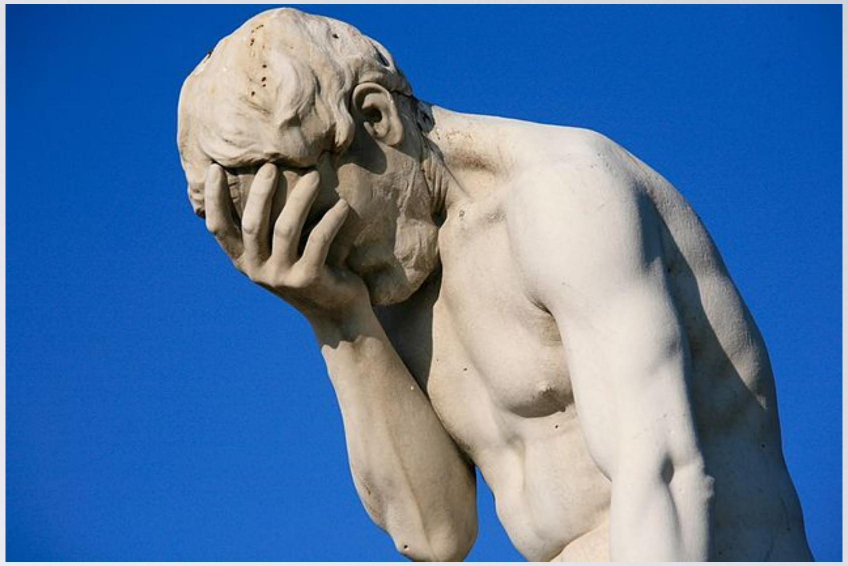
Original image | Encrypted using ECB mode | Modes other than ECB result in pseudo-randomness

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
4e18acc1ab27a2d6
WEATHER VANE SWORD
4e18acc1ab27a2d6 a0a2876eb1ea1fca
NAME1
8babb6299e06eb6d
DUH
8babb6299e06eb6d a0a2876eb1ea1fca
8babb6299e06eb6d 85e9da81a8a78adc
57
4e18acc1ab27a2d6
FAVORITE OF 12 APOSTLES
1ab29ae86da6e5ca 7a2d6a0a2876eb1e
WITH YOUR OWN HAND YOU HAVE DONE ALL THIS
a1f96266299e7a2b eadec1e6ab797397
SEXY EARLOBES
a1f96266299e7a2b 617ab0277727ad85
BEST TOS EPISODE
39738b7adb0b8af7 617ab0277727ad85
SUGARLAND
1ab29ae86da6e5ca
NAME + JERSEY #
877ab7889d3862b1
ALPHA
877ab7889d3862b1
877ab7889d3862b1
877ab7889d3862b1
OBVIOUS
877ab7889d3862b1
MICHAEL JACKSON
38a7c9279cadeb44 9dcald79d4dec6d5
38a7c9279cadeb44 9dcald79d4dec6d5
HE DID THE MASH, HE DID THE
38a7c9279cadeb44
PURLOINED
THE GREATEST CROSSWORD PUZZLE IN THE HISTORY OF THE WORLD



source: *XKCD*



Simple Illustration of Zoom Encryption Failure

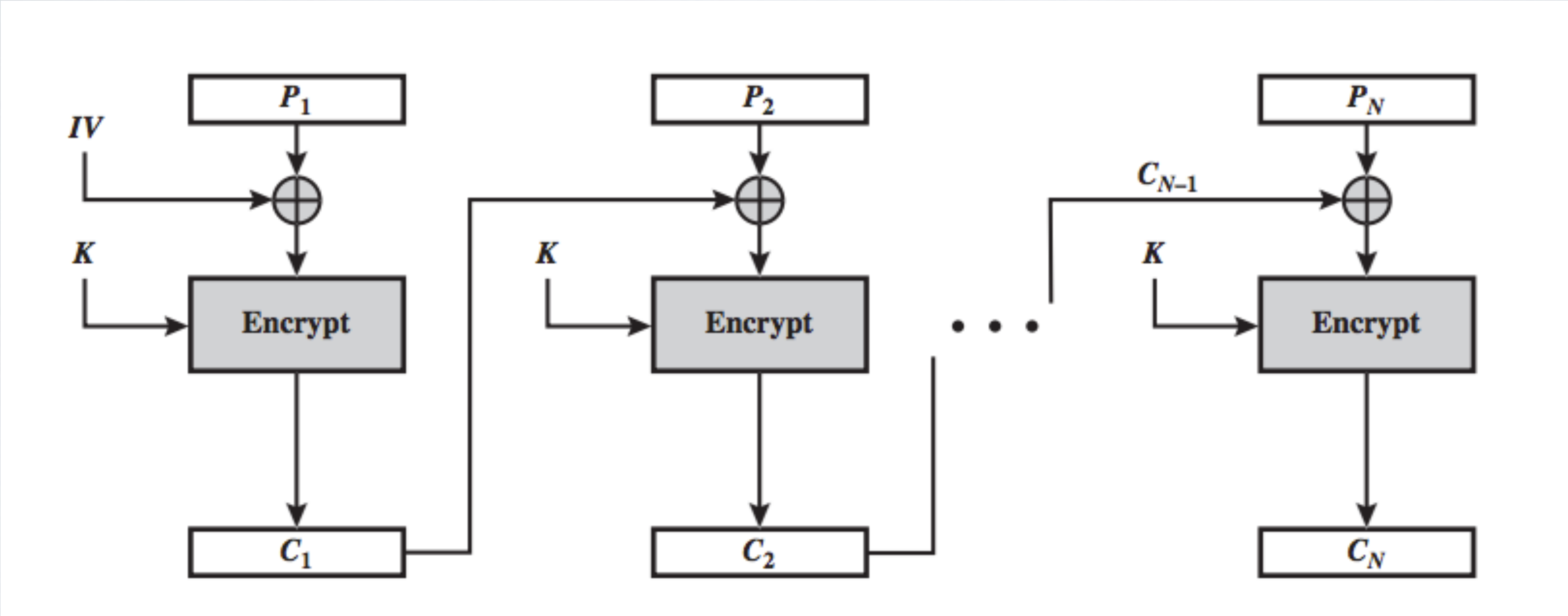
by Davi Ottenheimer on April 10, 2020

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*

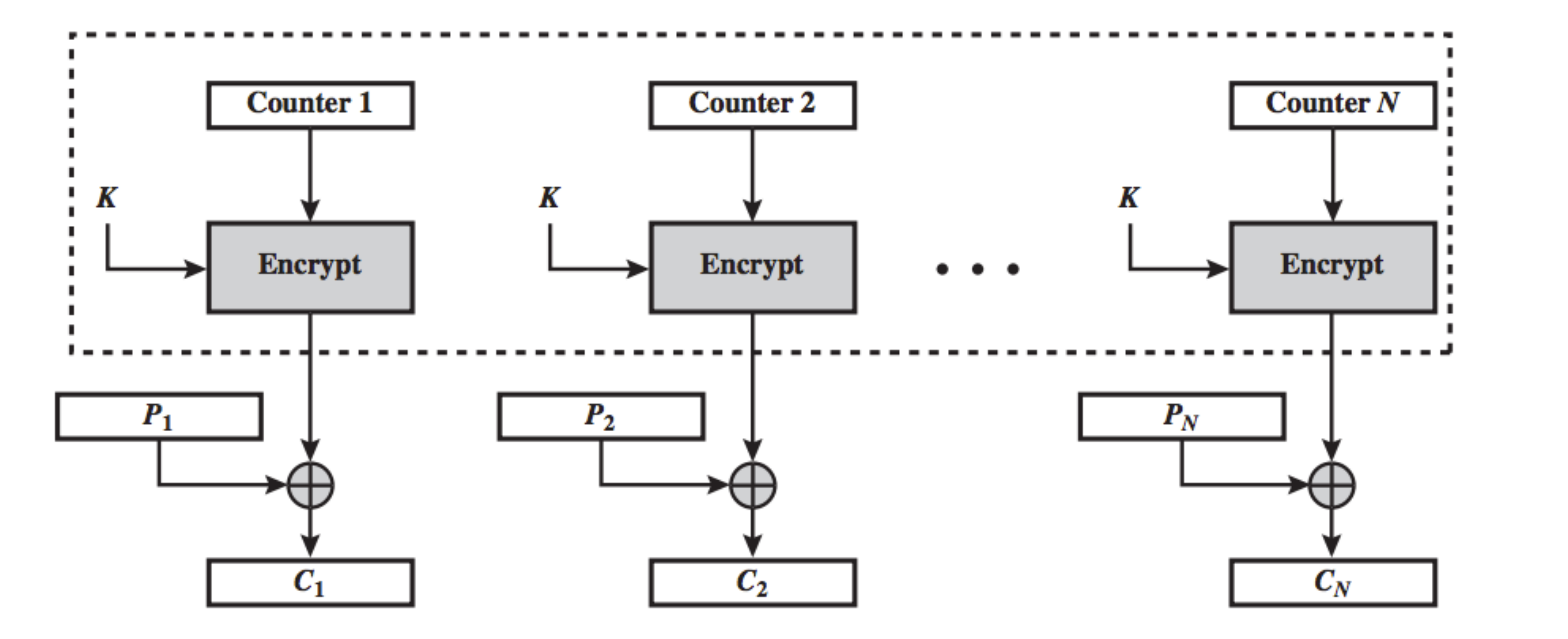
CBC - Cipher Block Chaining (a.k.a Chaining Mode)



Introduce some <u>randomness</u> 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

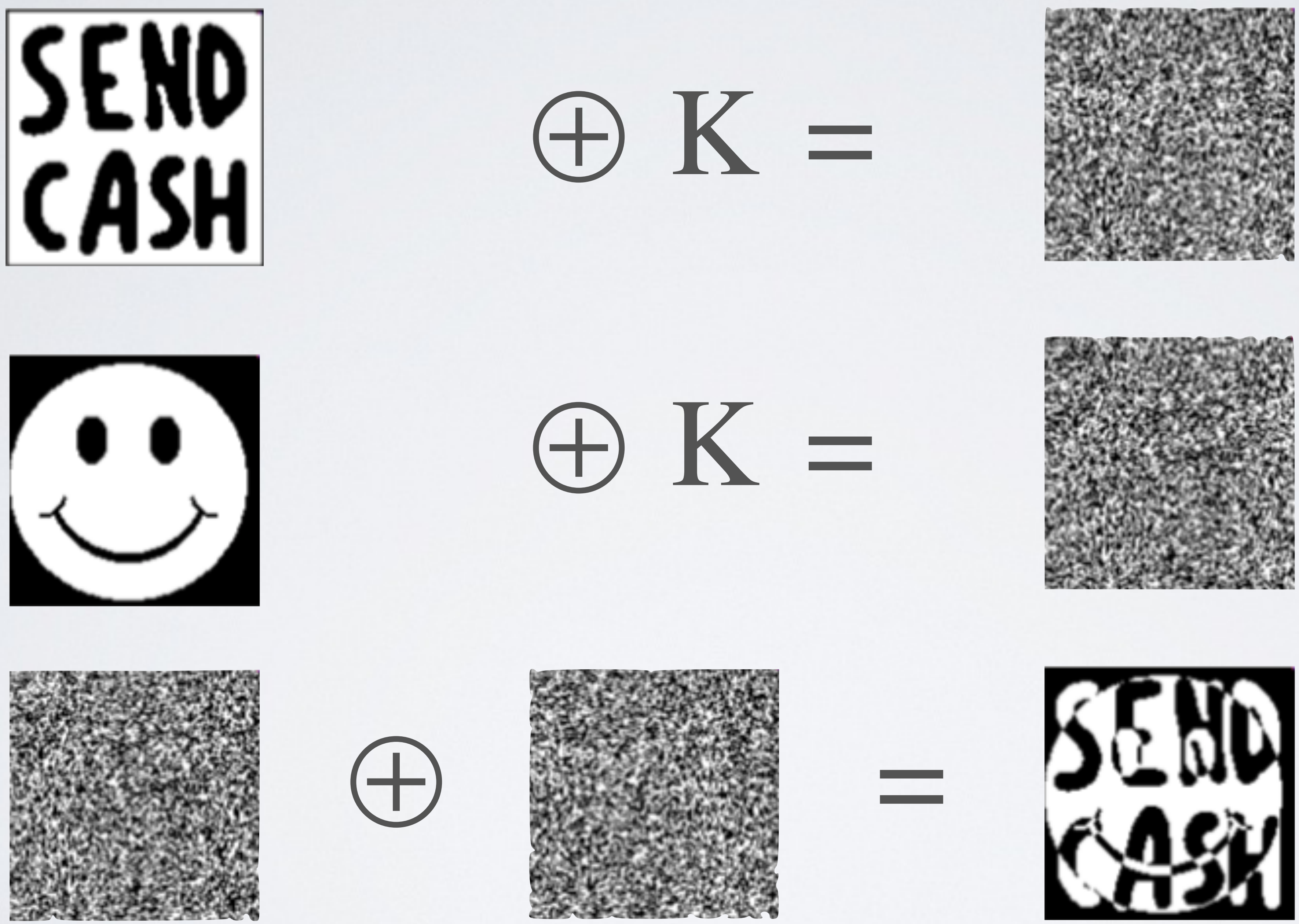
CTR - Counter Mode



Introduce some <u>randomness</u> using a counter

- ✓ High entropy and parallelism
- ◉ Behaves as a stream cipher - sensitive to key-reused attack

Key-reused attack on CTR



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 (~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

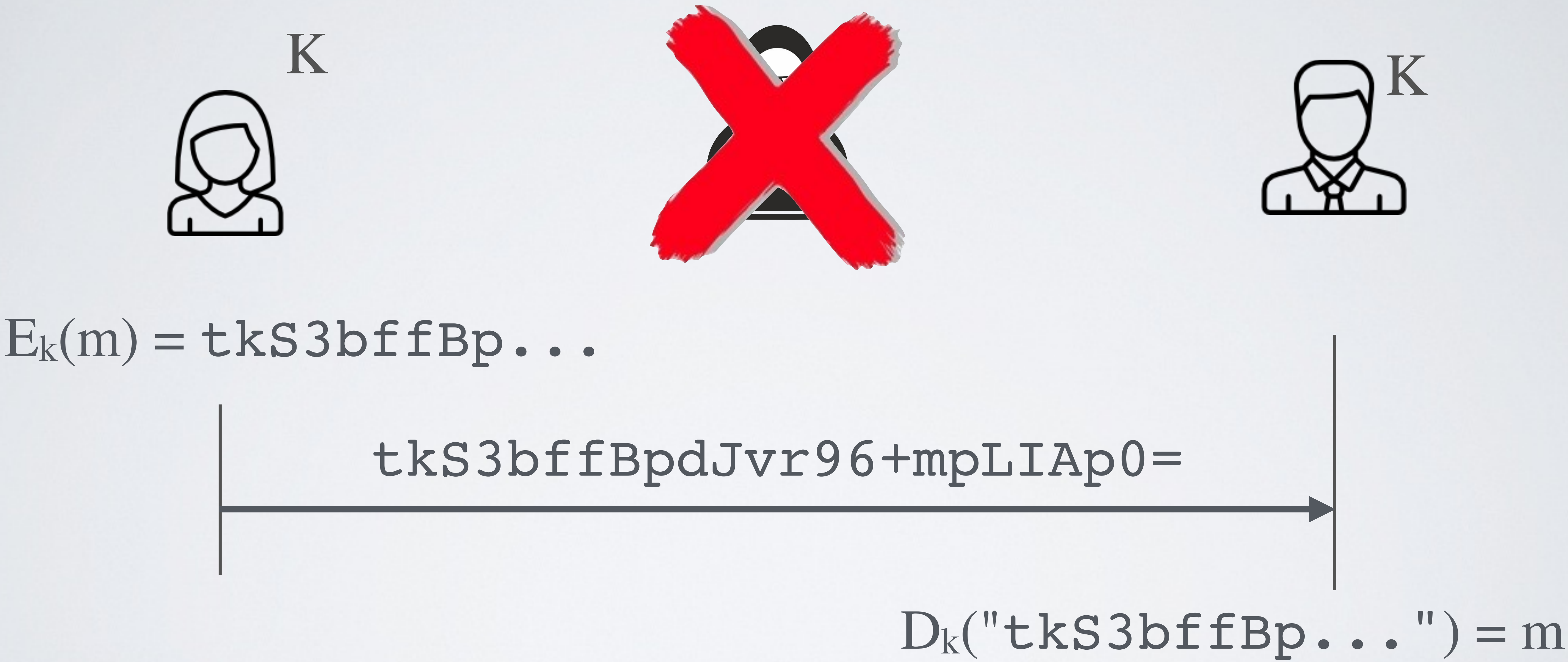
Are we secured?

Security goals vs attacker's model

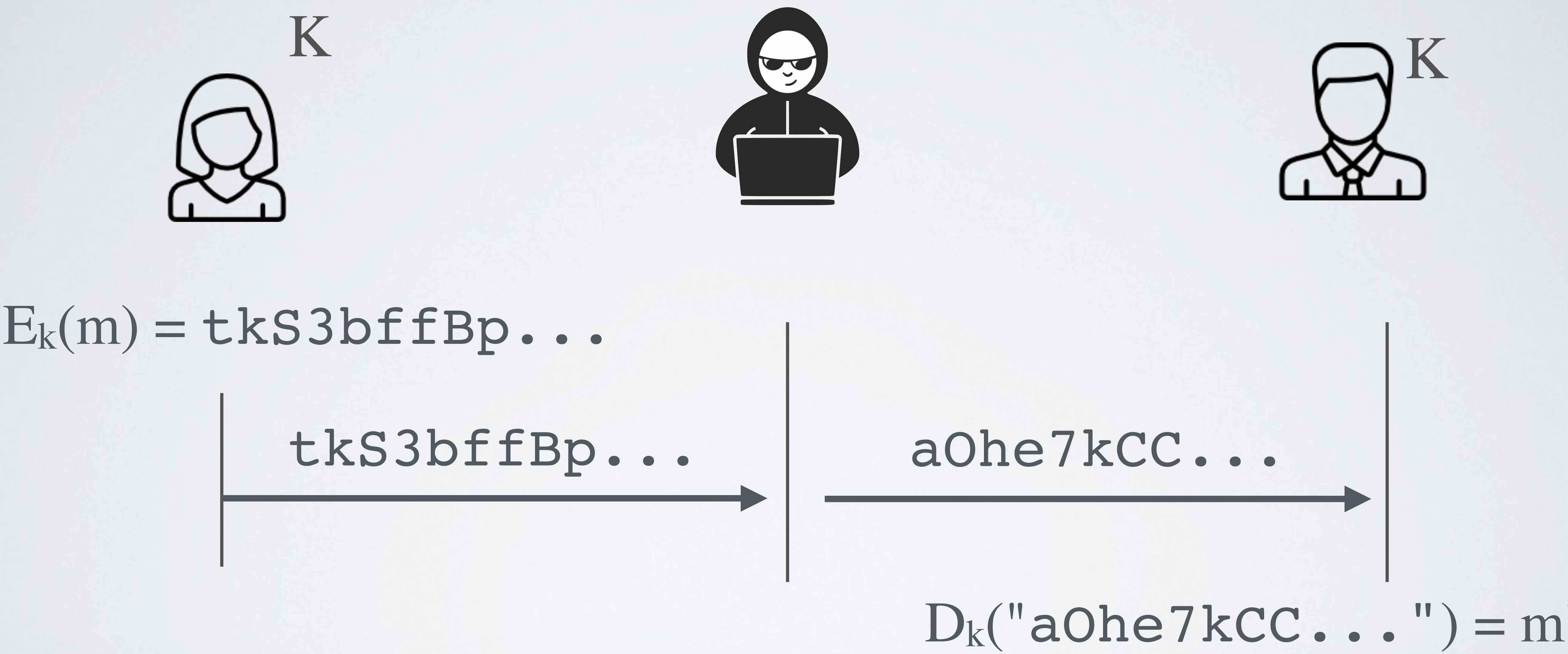
Interception
Modification
Fabrication
Interruption

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

(pure) encryption ensures confidentiality ...

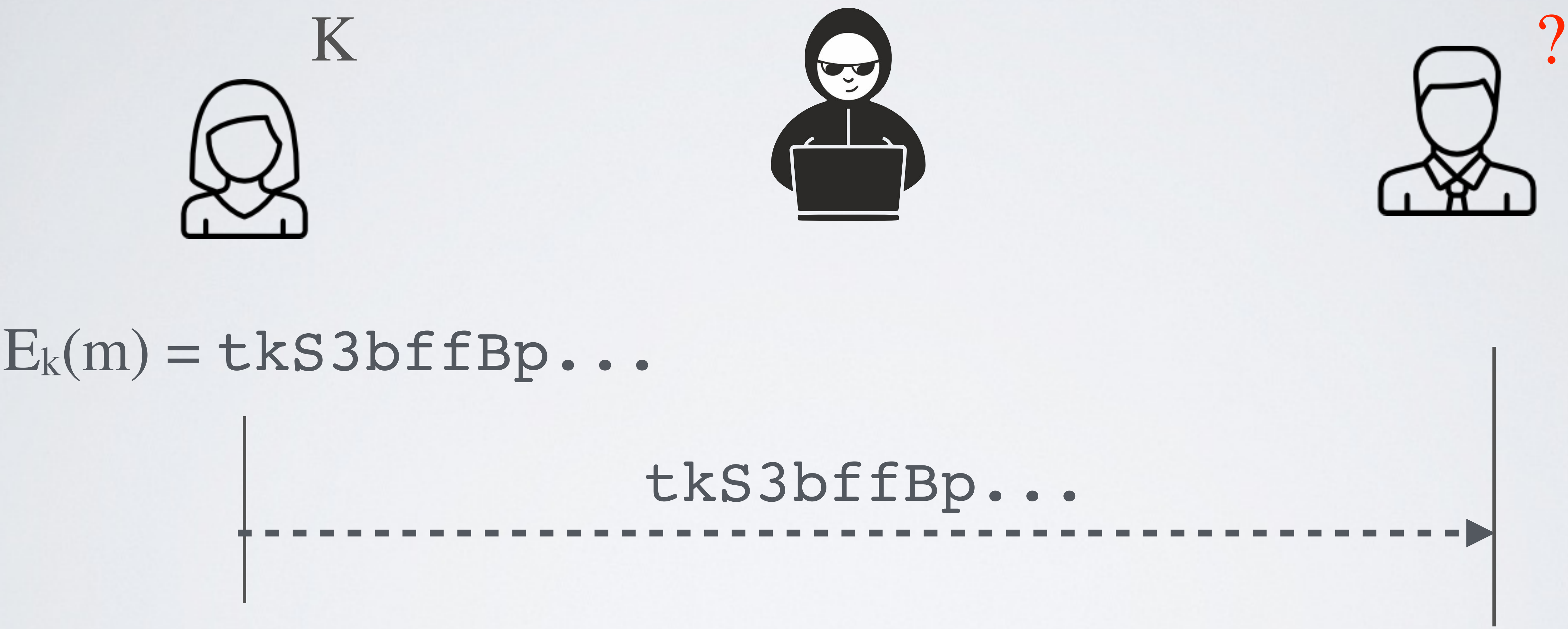


... but does not ensure integrity !



- Encrypting a message does not authenticate it

One more issue ...



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