# Using Cryptography to Protect Confidentiality

Thierry Sans

# Overview

- **Symmetric Encryption**
  - Stream Cipher
  - Block Cipher (and block cipher modes)
- **Asymmetric Encryption**
- **Key Exchange**

# Symmetric Encryption

# 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

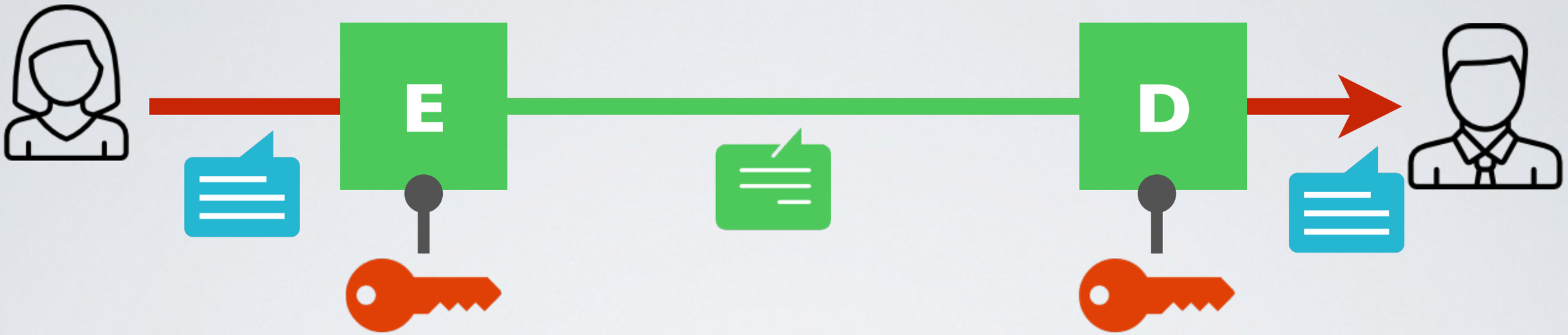
- **Known plaintext**
  You know one or several pairs of random plaintext and their corresponding ciphertexts

- **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 $\mathbf{k}$ is used for encryption $\mathbf{E}$ and decryption $\mathbf{D}$

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

# Two Families of Symmetric Encryption Schemes

**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

# Symmetric Encryption

# **Stream Cipher**

# XOR Cipher (a.k.a Vernham Cipher)

## a modern version of Vigenere

**Use** ⊕ 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

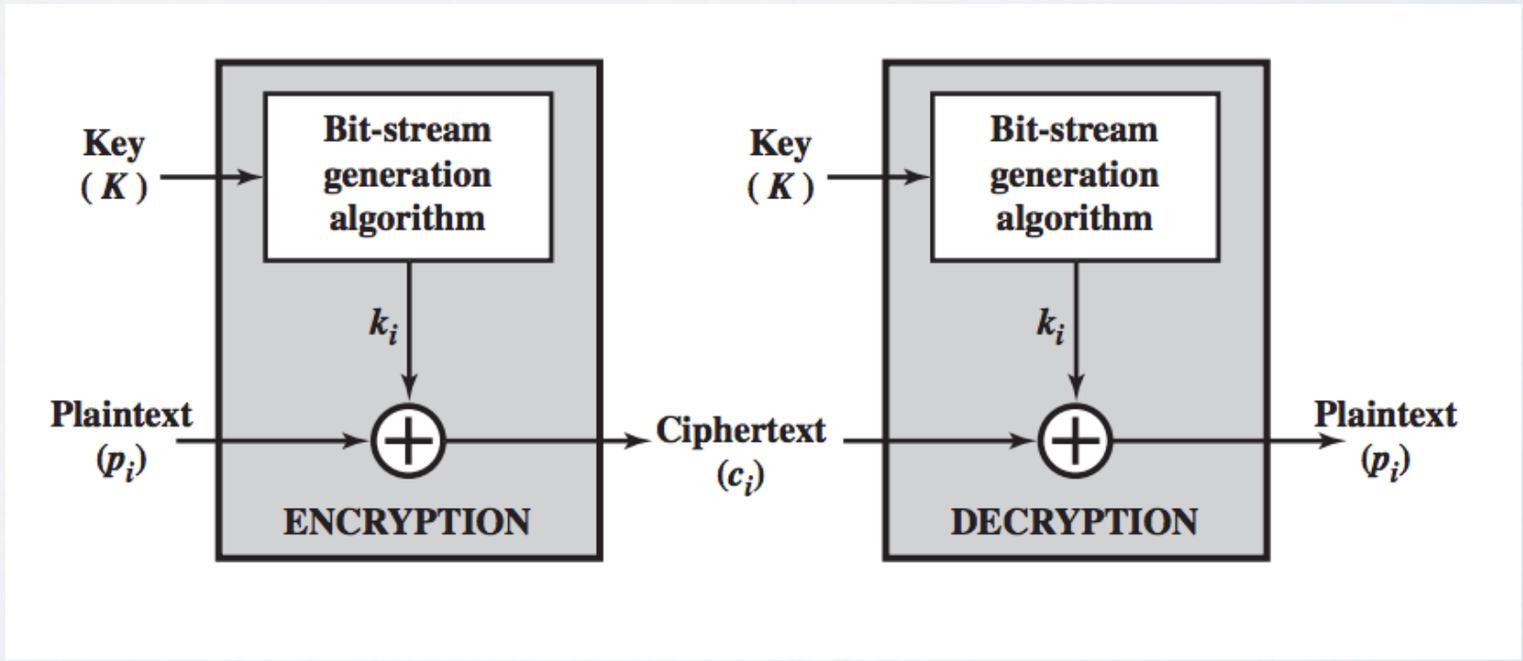
```
int getRandomNumber()
{
    return 4;  // chosen by fair dice roll.
               // guaranteed to be random.
}
```

## True Random Number Generator

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

## Pseudo-Random Generator

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



# Stream cipher

Can we use $\mathbf{k}$ 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

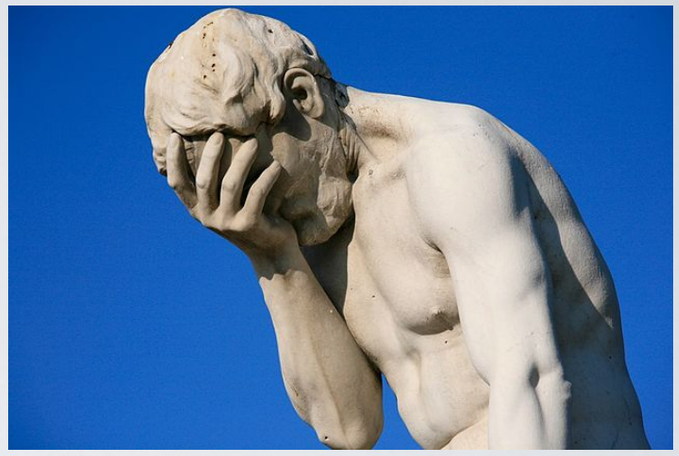
# 'Serious' Microsoft Office Encryption Flaw Uncovered

COMMENTS

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

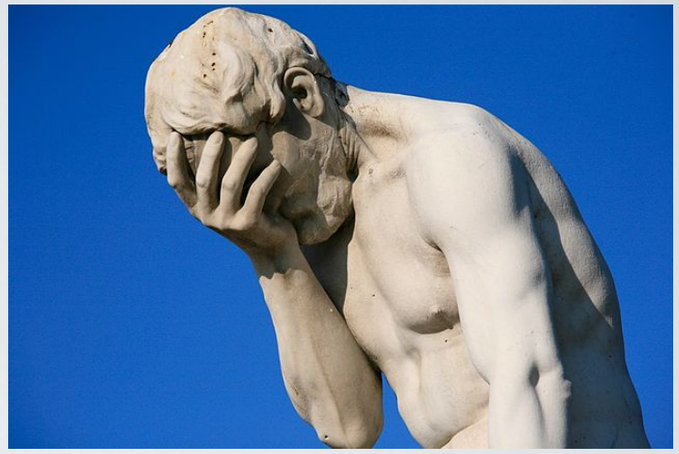
Cryptography expert Phil Zimmermann says he believes a flaw recently discovered in Microsoft Office's Word and Excel encryption is serious and warrants immediate attention.

"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

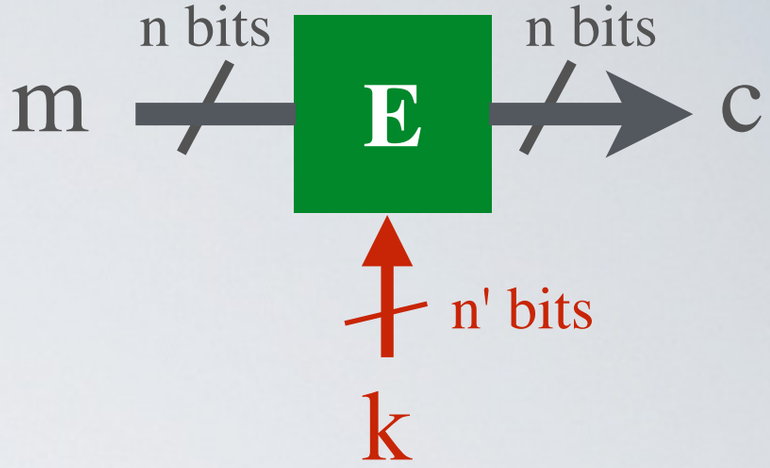
# Salsa20 (and ChaCha20)

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

# Symmetric Encryption

# **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

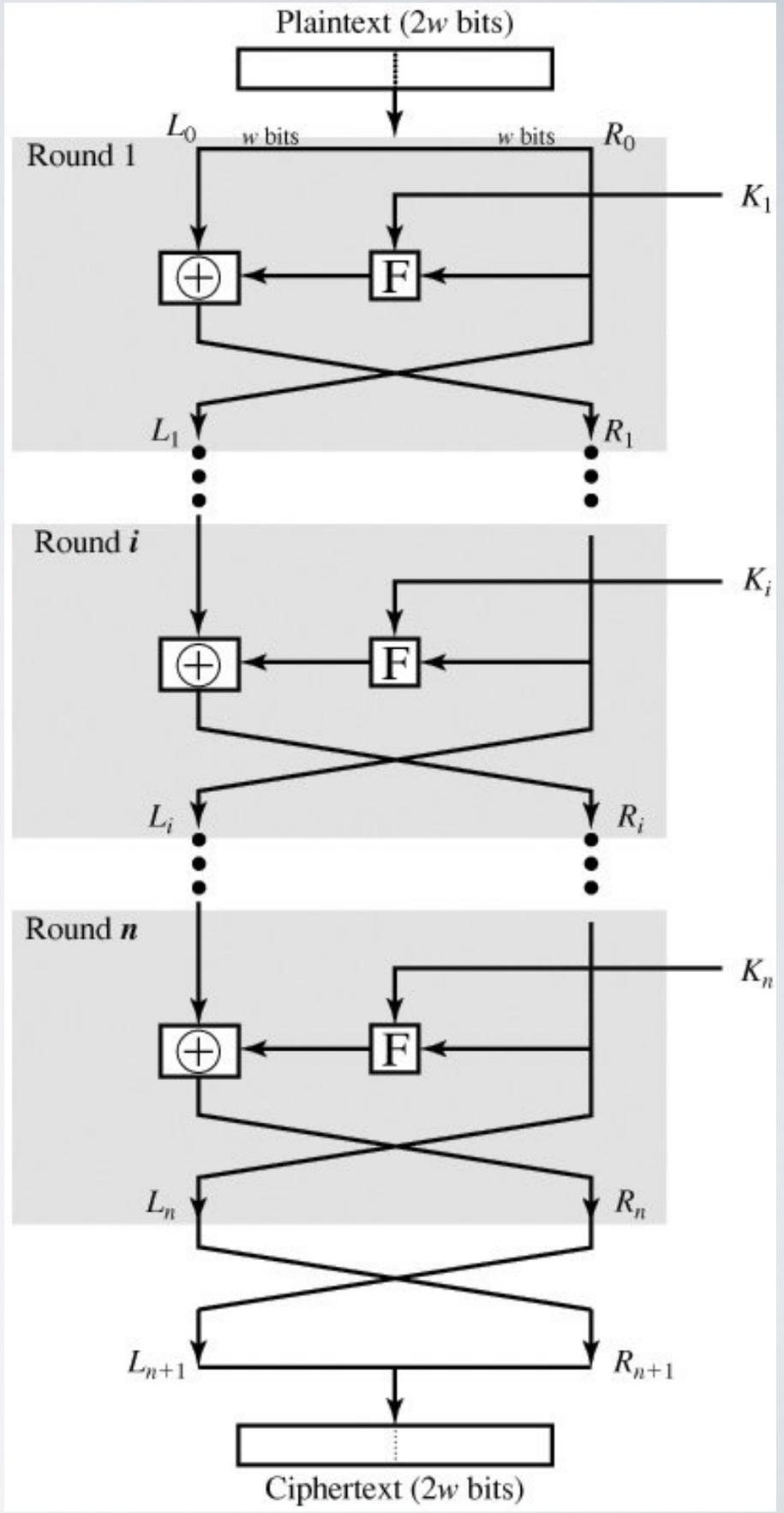
$L_i = R_{i-1}$

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

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<br>• 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**

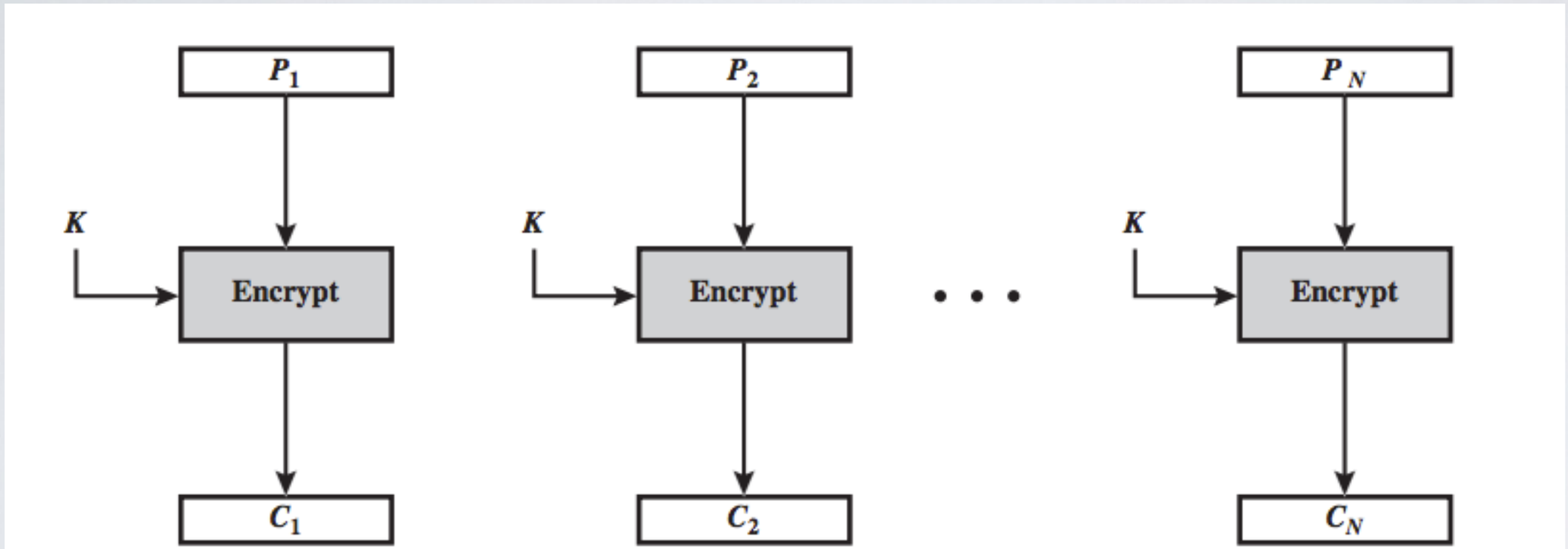
**CBC - Cipher Block Chaining**

CFB - Cipher Feedback

OFB - Output Feedback

**CTR - Counter**

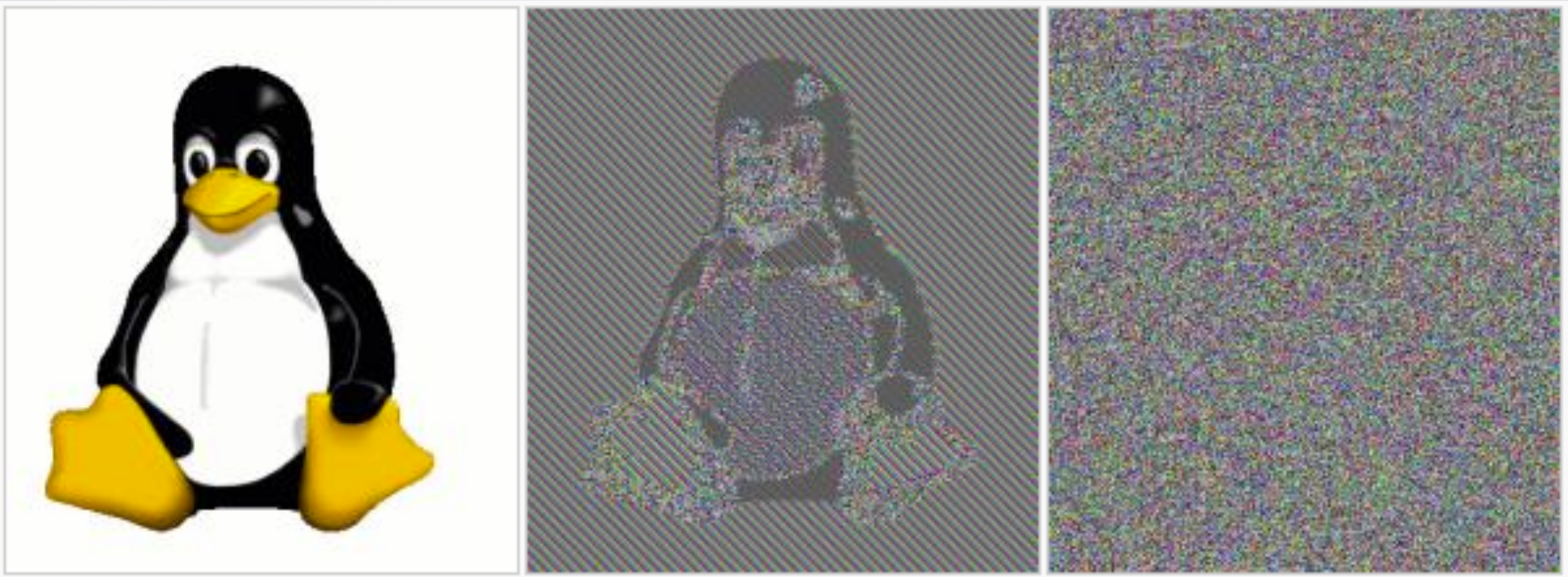
# ECB - Electronic Code Book (a.k.a Block Mode)




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

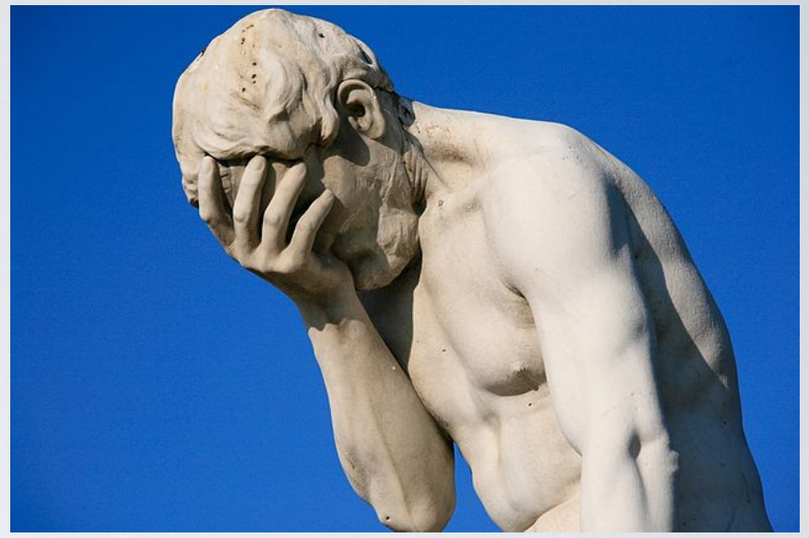
source: *Wikimedia*

HACKERS RECENTLY LEAKED **153 MILLION** ADOBE USER EMAILS, ENCRYPTED PASSWORDS, AND PASSWORD HINTS.

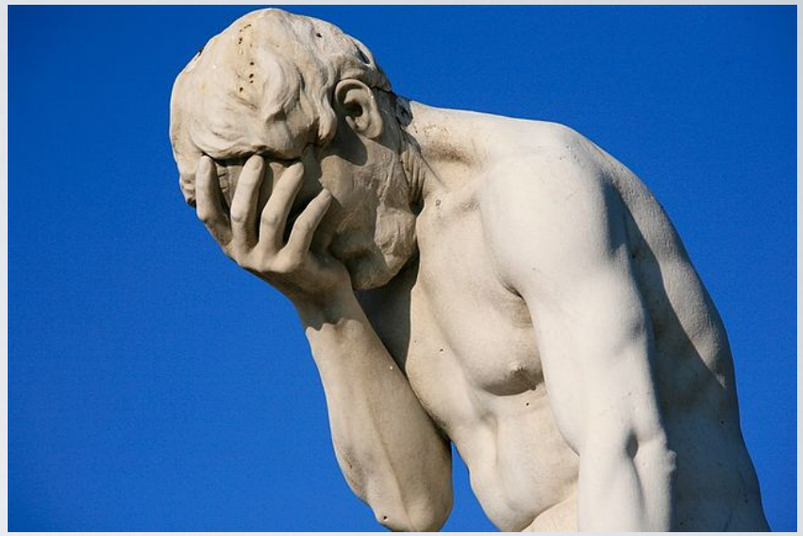
ADOBE ENCRYPTED THE PASSWORDS IMPROPERLY, MISUSING BLOCK-MODE 3DES. THE RESULT IS SOMETHING WONDERFUL:

| USER PASSWORD | | HINT |
|---|---|---|
| 4e18acc1ab27a2d6 | | WEATHER VANE SWORD |
| 4e18acc1ab27a2d6 | | |
| 4e18acc1ab27a2d6 | a0a2876eb1ea1fca | NAME 1 |
| 8babb6299e06eb6d | | DUH |
| 8babb6299e06eb6d | a0a2876eb1ea1fca | |
| 8babb6299e06eb6d | 85e9da81a8a78adc | 57 |
| 4e18acc1ab27a2d6 | | FAVORITE OF 12 APOSTLES |
| 1ab29ae86da6e5ca | 7a2d6a0a2876eb1e | WITH YOUR OWN HAND YOU HAVE DONE ALL THIS |
| a1f9b2b6299e7a2b | eadec1e6ab797397 | SEXY EARLOBES |
| a1f9b2b6299e7a2b | 617ab0277727ad85 | BEST TOS EPISODE |
| 39738b7adb068af7 | 617ab0277727ad85 | SUGARLAND |
| 1ab29ae86da6e5ca | | NAME + JERSEY # |
| 877ab7889d3862b1 | | ALPHA |
| 877ab7889d3862b1 | | |
| 877ab7889d3862b1 | | |
| 877ab7889d3862b1 | | OBVIOUS |
| 877ab7889d3862b1 | | MICHAEL JACKSON |
| 38a7c9279cadeb44 | 9dca1d79d4dec6d5 | |
| 38a7c9279cadeb44 | 9dca1d79d4dec6d5 | HE DID THE MASH, HE DID THE |
| 38a7c9279cadeb44 | | PURLOINED |
| a8ae5745a2b7af7a | 9dca1d79d4dec6d5 | FAV WATER-3 POKEMON |

THE GREATEST CROSSWORD PUZZLE IN THE HISTORY OF THE WORLD



source: *XKCD*



# Simple Illustration of Zoom Encryption Failure

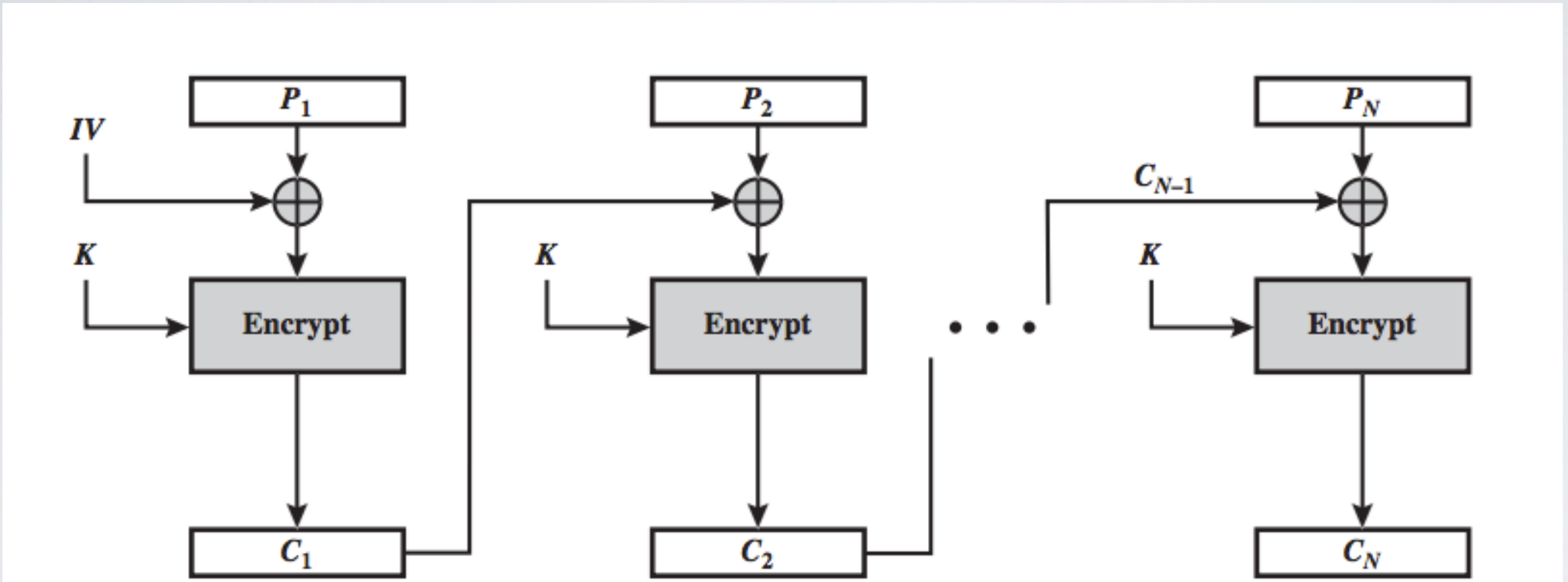
by Davi Ottenheimer on April 10, 2020

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*

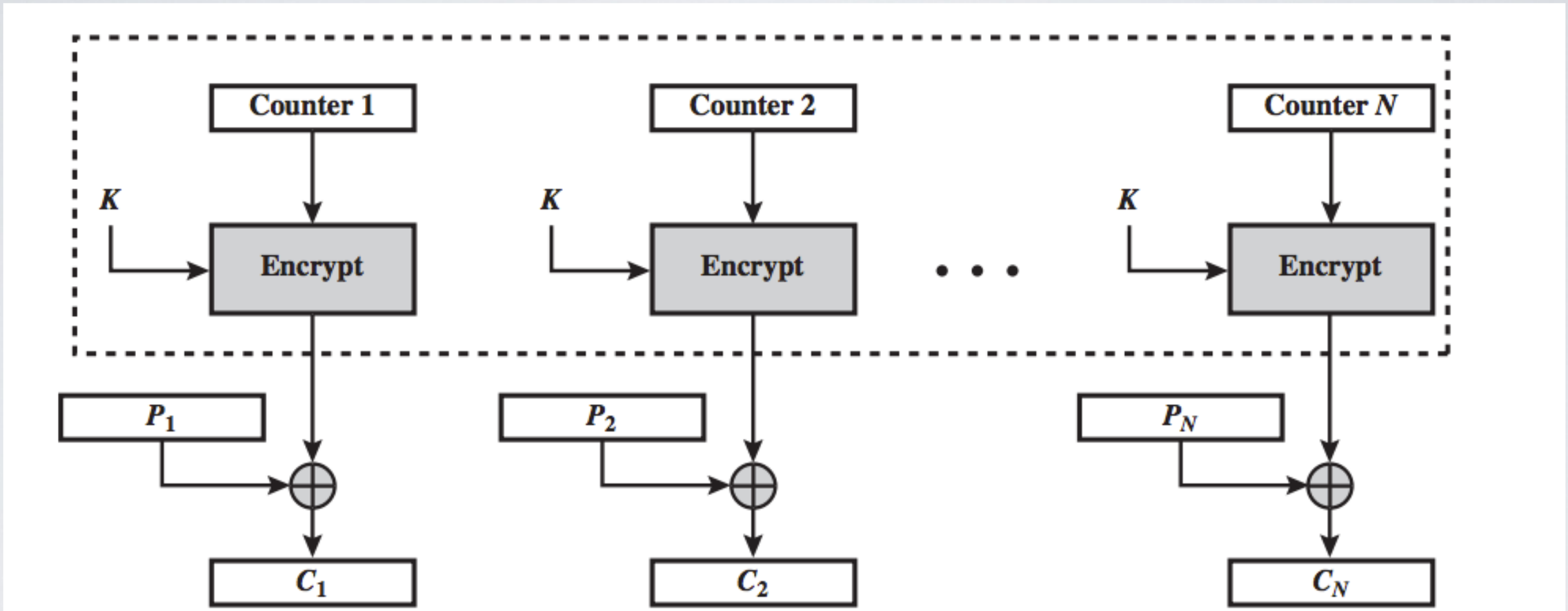
# CBC - Cipher Block Chaining (a.k.a Chaining Mode)




Introduce some <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

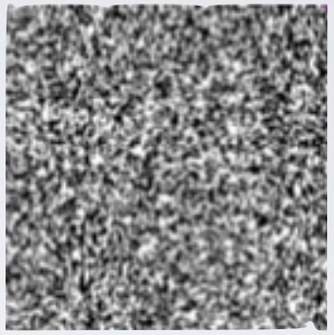



Introduce some randomness using a counter

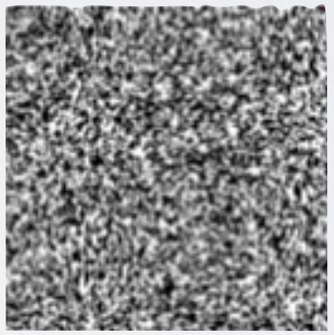
- ✓ High entropy and parallelism
- ◉ Behaves as a stream cipher - sensitive to key-reused attack

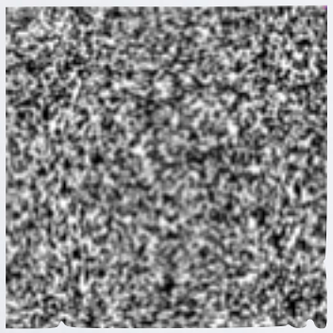
# Key-reused attack on CTR


$\oplus$ K =

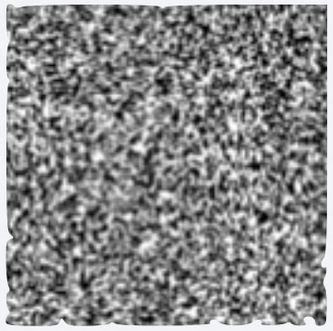


$\oplus$ K =





$\oplus$



=

# Symmetric Encryption

# 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

# Are we secured?

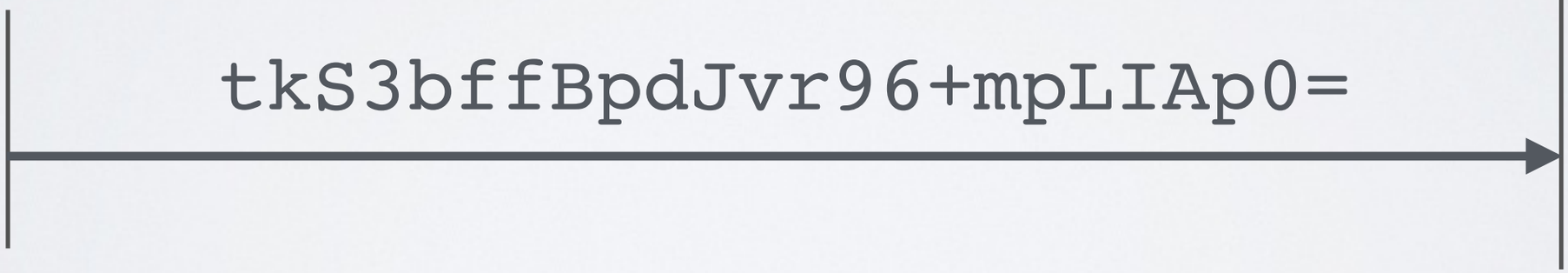
# Security goals vs attacker's model

Interception
Modification
Fabrication
Interruption

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

# (pure) encryption ensures confidentiality ...


$E_k(m) = \texttt{tkS3bffBp...}$

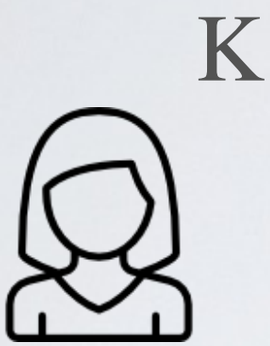



$D_k(\texttt{"tkS3bffBp..."}) = m$

# ... but does not ensure integrity !


- Encrypting a message does not authenticate it

# One more issue ...





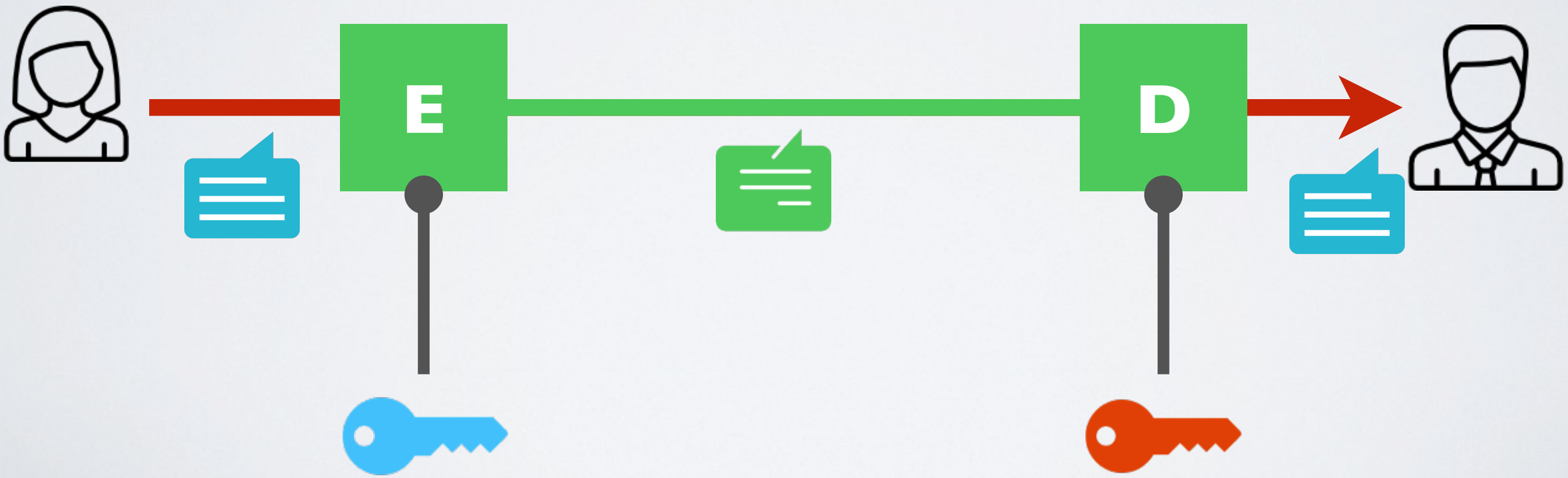
$E_k(m)$ = `tkS3bffBp...`


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

# Asymmetric Encryption

# Asymmetric encryption
# a.k.a Public Key Cryptography

- ➡ The public key for encryption
- ➡ The private key for decryption

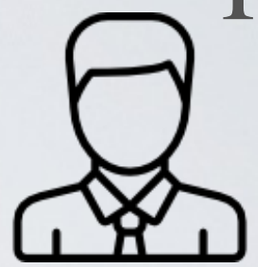


# Asymmetric keys

$\mathbf{Ks_A}, \mathbf{Kp_A}$

$\mathbf{Kp_A}$

$\mathbf{Kp_A}$

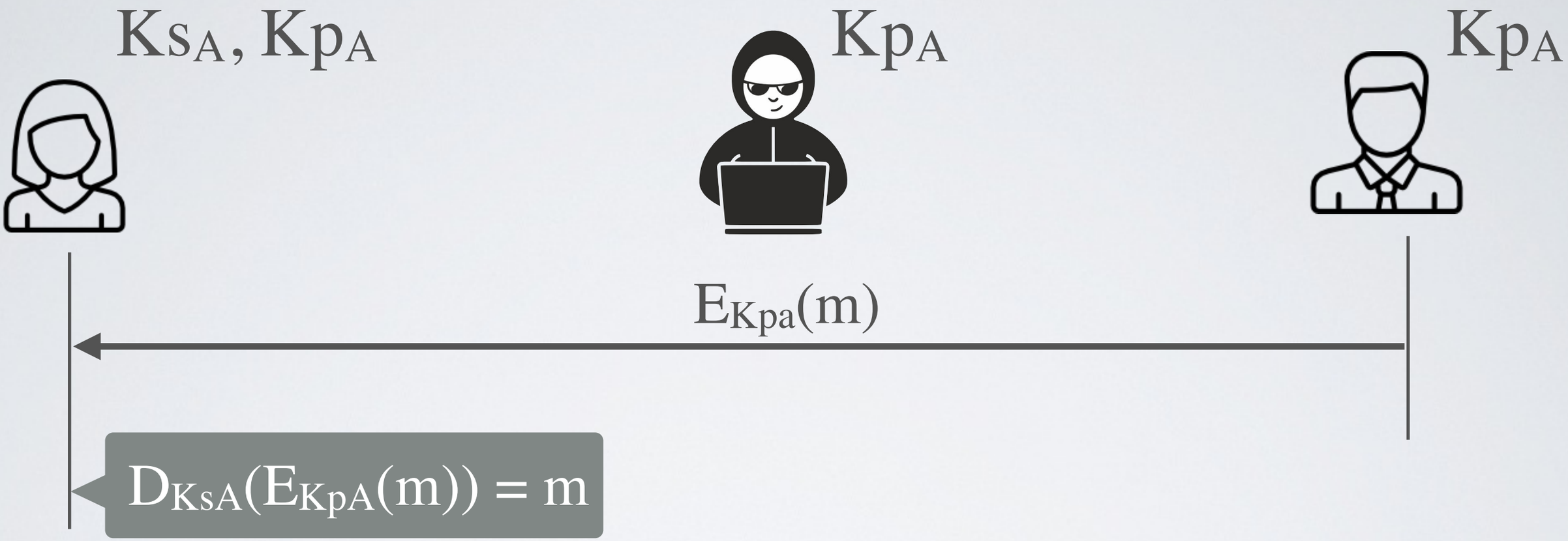


Alice generates a pair of asymmetric keys

- $\mathbf{Ks_A}$ is the secret key that Alice keeps for herself
- $\mathbf{Kp_A}$ is the public key that Alice gives to everyone (even Mallory)

➡ These two keys $\mathbf{Ks_A}$ and $\mathbf{Kp_A}$ work together

# Asymmetric encryption for **confidentiality**




Bob encrypts a message $\mathbf{m}$ with Alice's public key $\mathbf{Kp_A}$

➡ Nobody can decrypt $\mathbf{m}$, except Alice with her private key $\mathbf{Ks_A}$

✓ Confidentiality without the need to exchange a secret key

# Functional Requirements

$D_{Ks}(E_{Kp}(m)) = m$ and $D_{Kp}(E_{Ks}(m)) = m$ for every pair $(Kp, Ks)$

- ✓ Generating a pair $(Kp, Ks)$ is easy to compute (polynomial)
- ✓ Encryption is easy to compute (either polynomial or linear)
- ✓ Decryption is easy to compute (either polynomial or linear)
- ◉ Finding a matching key $Ks$ for a given $Kp$ is hard (exponential)
- ◉ Decryption without knowing the corresponding key is hard (exponential)

# RSA - Rivest, Shamir and Alderman

| | |
|---|---|
| Key Size | 1024 - 4096 |
| Speed | ~ factor of $10^6$ cycles / byte<br>• Key generation: 10 - 100 ms<br>• Encryption: 0.2 - 2 ms<br>• Decryption: 5 - 10 ms |
| Mathematical Foundation | Prime number theory |

# Number Theory - Prime numbers

**Prime Numbers**

- $p$ is prime if $1$ and $p$ are its only divisors  e.g $3, 5, 7, 11$ …
- $p$ and $q$ are relatively prime (a.k.a. coprime)  if $\gcd(p,q) = 1$

  e.g $\gcd(4,5) = 1$

➡ There are infinitely many primes

**Euler-Fermat Theorem**

If $n = p \,.\, q$ and $z = (p-1).(q-1)$

and $a$ such that $a$ and $n$ are relative primes

Then  $a^z \equiv 1 \pmod{n}$

# Computational Complexity

**Easy problems** with prime numbers

- Generating a prime number p
- Addition, multiplication, exponentiation
- Inversion, solving linear equations

**Hard problem** with prime numbers

- Factoring primes
  e.g. given $\mathbf{n}$ find $\mathbf{p}$ and $\mathbf{q}$ such that $\mathbf{n = p \cdot q}$

# RSA - generating the key pair

1. Pick $\mathbf{p}$ and $\mathbf{q}$ two large prime numbers and calculate $\mathbf{n = p \,.\, q}$ (see primality tests)
2. Compute $\mathbf{z = (p\text{-}1).(q\text{-}1)}$
3. Pick a prime number $\mathbf{e < z}$ such that $\mathbf{e}$ and $\mathbf{z}$ are relative primes

➡ (e,n) is the **public key**

4. Solve the linear equation $\mathbf{e * d = 1\ (\ mod\ z\ )}$ to find $\mathbf{d}$

➡ (d,n) is the **private key**
however p and q must be kept secret too

# RSA - encryption and decryption

Given $\mathbf{Kp} = (\mathbf{e}, \mathbf{n})$ and $\mathbf{Ks} = (\mathbf{d}, \mathbf{n})$

➡ Encryption : $E_{kp}(m) = m^e \bmod n = c$

➡ Decryption : $D_{ks}(c) = c^d \bmod n = m$

➡ **$(m^e)^d \bmod n = (m^d)^e \bmod n = m$**

# The security of RSA

**RSA Labs Challenge** : factoring primes set

| Key length | Year | Time |
|---|---|---|
| 140 | 1999 | 1 month |
| 155 | 1999 | 4 months |
| 160 | 2003 | 20 days |
| 200 | 2005 | 18 months |
| 768 | 2009 | 3 years |

Challenges are no longer active

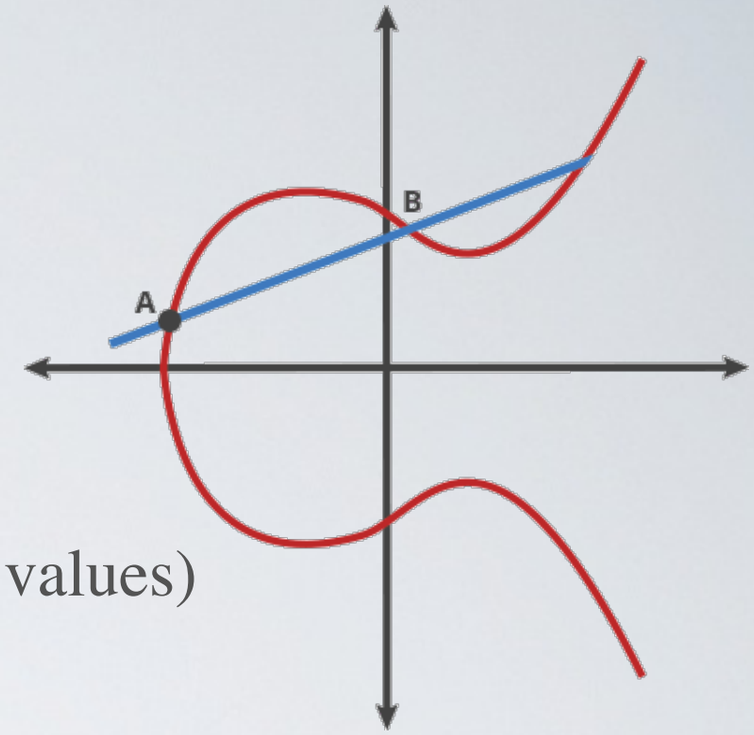
# ECC - Elliptic-Curve Cryptography

| | |
|---|---|
| Key Size | 256 or 448 bits |
| Speed | ~ factor of $10^6$ cycles / operation<br>• Key generation: 1 - 5 ms (way faster than RSA)<br>• Encryption: 1 - 5 ms<br>• Decryption: 1 - 5 ms |
| Mathematical Foundation | Elliptic curves over finite fields |

# Main ECC Standards

| | secp256k1 | curve25519 | curve448 |
|---|---|---|---|
| Year | 2000 | 2005 | 2014 |
| Inventor | Standards for Efficient Cryptography Group (SECG) | Daniel J. Bernstein | Mike Hamburg |
| Key Size | 256 | 256 | 448 |
| Applications | Bitcoin Ethereum | TLS, TOR Signal Protocol Monero, Zcash | TLS |
| Performances | + | ++ | +++ |

# Elliptic Curve Cryptography




Use Elliptic-curve for generating a cryptographic public-key pair
The algorithm is based on two public pieces:

- The curve equation $y^2 = x^3 + ax + b$ (a and b are fixed values)
- The generator point (fixed value)

When generating a key pair

1. the user "choose a random number" (within a given range) as private key
2. then derived the public key from the curve

✓ Smaller key sizes: 256 bits EC keys has the same entropy as RSA 3072 bits

✓ Can be used for digital signature (ECDSA algorithm)

✓ Can be used for key agreement (ECDH algorithm)

https://blog.cloudflare.com/a-relatively-easy-to-understand-primer-on-elliptic-curve-cryptography/

# Symmetric vs Asymmetric

# Key length and Key n-bit security

- RSA has very long keys, 1024, 2048 and 4096 are common
- ECC has shorter keys, 256 and 448 are common
- Is it more secure than symmetric crypto with key lengths of 56, 128, 192, 256 ?

➡ Key lengths **do not compare !**

| RSA | ECC | Effective key length |
|---|---|---|
| 1,024 | | 80 |
| 2,048 | | 112 |
| 3,072 | 256 | 128 |
| 4096 | | 140 |
| 15,360 | 448 | 224 ~ 256 |

# Asymmetric vs Symmetric

| | Symmetric | Asymmetric |
|---|---|---|
| pro | Fast | No key agreement |
| cons | Key agreement | Very slow |

The best of both worlds

- Use asymmetric encryption to encrypt a shared key (or hash)
- Use symmetric encryption to encrypt message

$$E_{Kp}(m) = RSA_{Kp}(k), AES_k(m)$$

Naive approach

# Key Exchange Protocols

# Naive key exchange using asymmetric encryption

Generate $Ks_A$, $Kp_A$

$Kp_A$

Generate $k$

$E_{KpA}(k), E_k(m)$

1. Decrypt $k = D_{KsA}(E_{KpA}(k))$
2. Decrypt $m = D_k(E_k(m))$

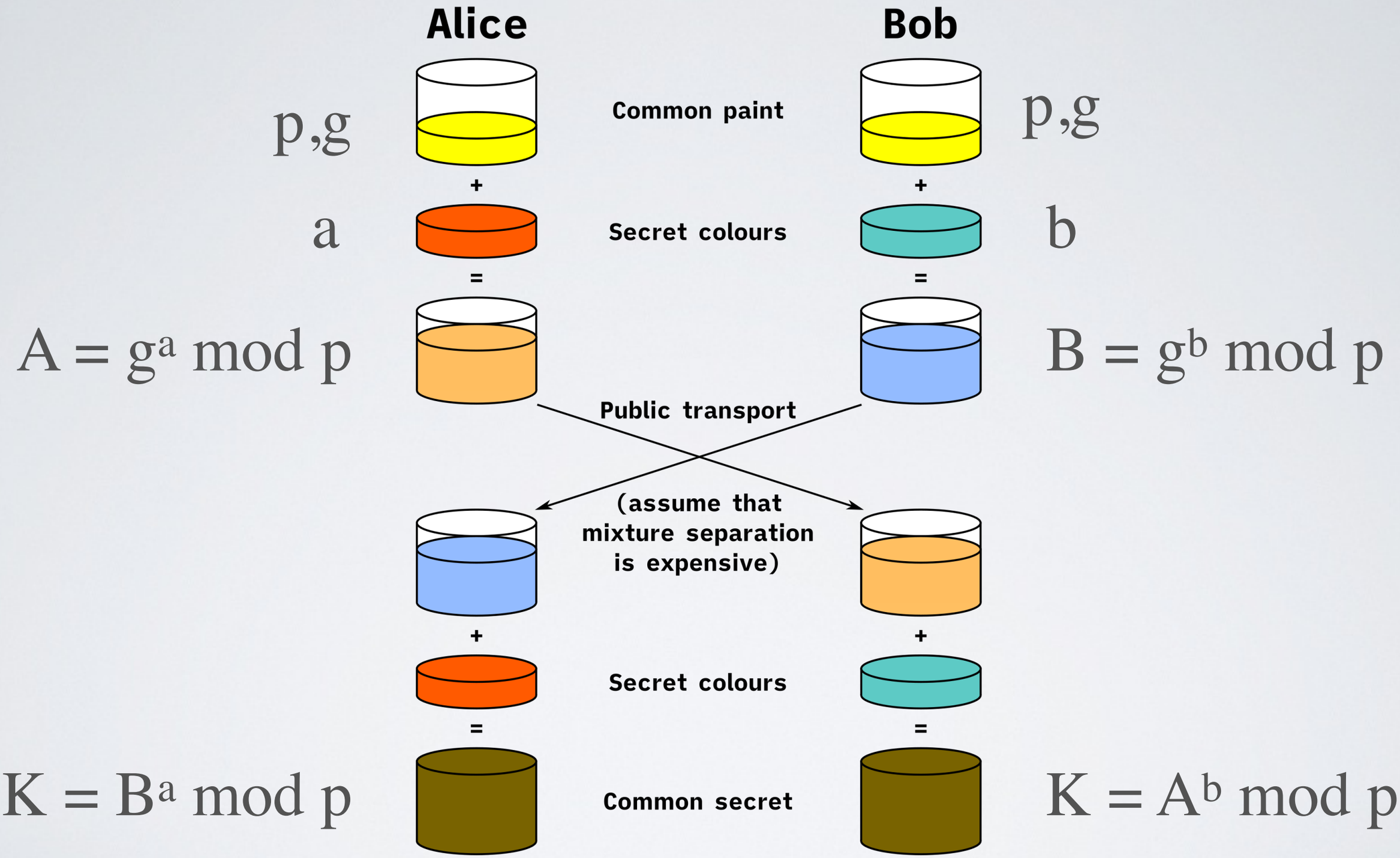
- Protecting the shared key is the **responsibility of Alice only**
- Generating the shared key is the **responsibility of Bob only**

# What is the solution?

Could Alice and Bob could magically come up with a key without exchanging it over the network?

➡ The magic is called **Diffie-Hellman-Merkle Protocol**

# The Diffie-Hellman-Merkel key exchange protocol




$$K = g^{ab} \bmod p = (g^a \bmod p)^b \bmod p = (g^b \bmod p)^a \bmod p$$

# The Diffie-Hellman-Merkel key exchange protocol

1. Generates public numbers $p$ and $g$ such that $g$ if co-prime to $p-1$
2. Generates a secret number $a$
3. Sends $A = g^a \bmod p$ to Bob

$A, p, g$

1. Generates a secret number $b$
2. Sends $B = g^b \bmod p$ back to Alice
3. Calculates the key $K = A^b \bmod p$

$B$

4. Calculates the key $K = B^a \bmod p$

# Diffie-Hellman-Merkle in practice

- $\mathbf{g}$ is small (either 3, 5 or 7 and fixed in practice)
- $\mathbf{p}$ is at least 2048 bits (and fixed in practice)
- private keys $\mathbf{a}$ and $\mathbf{b}$ are 2048 bits as well

➡ So the public values $\mathbf{A}$ and $\mathbf{B}$
and the master key $\mathbf{k}$ are 2048 bits

➡ Use $\mathbf{k}$ to derive an AES key using a Key Derivation Function
(usually HKDF - the HMAC-based Extract-and-Expand key derivation function)

# Elliptic Curve Diffie-Hellman-Merkle (ECDH)

- Generate a symmetric key $k$ from two distinct asymmetric key pairs: $K_{pA}$, $K_{sA}$ and $K_{pB}$, $K_{sB}$

$$k = ECDH(K_{sA}, K_{pB}) = ECDH(K_{sB}, K_{pA})$$

# ECDH Key exchange

Generate $Ks_A$, $Kp_A$

$Kp_A$

1. Generate $Ks_B$, $Kp_B$
2. Derive $k = ECDH(Ks_B, Kp_A)$

$Kp_B, E_k(m)$

1. Derive $k = ECDH(Ks_A, Kp_B)$
2. Decrypt $m = D_k(E_k(m))$

**Diffie-Hellman-Merkle** provides a way to generate a shared key from two asymmetric key pairs

$$ECDH(Ks_A, Kp_B) = ECDH(Ks_B, Kp_A) = k$$

- ✓ Mutual contribution to the key generation
- ✓ No need to send the encrypted shared key

# A widely used key exchange protocol

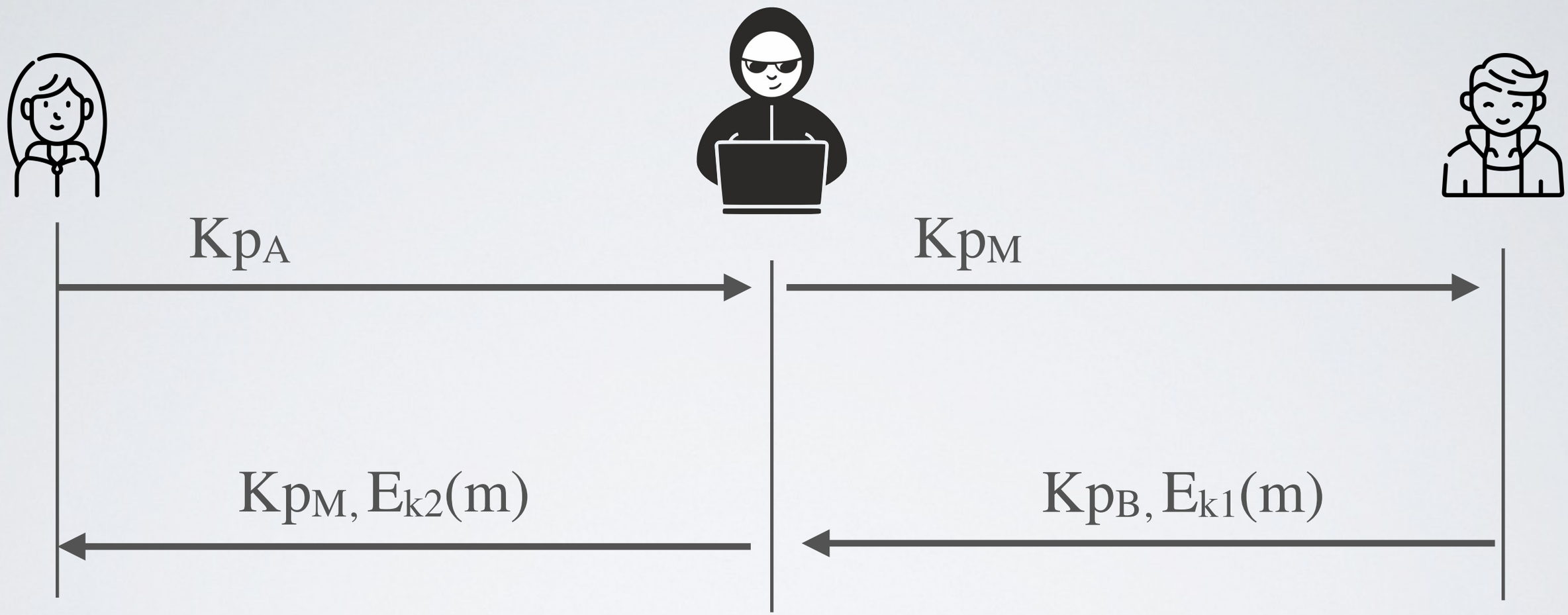
ECDH is in many protocols

- SSH
- TLS (used by HTTPS)
- Signal (used by most messaging apps like Whatsapp)
- and so on …

✓ It is fast and requires two exchanges only

◉ But how to make sure Alice is talking to Bob and vice-versa? Diffie-Hellman-Merkle alone **does not ensure authentication**

# Are we done yet?




- ✓ Encryption and key exchange protects against confidentiality ...
- ◉ ... but not **does not protect integrity**