Cryptography: Symmetric encryption

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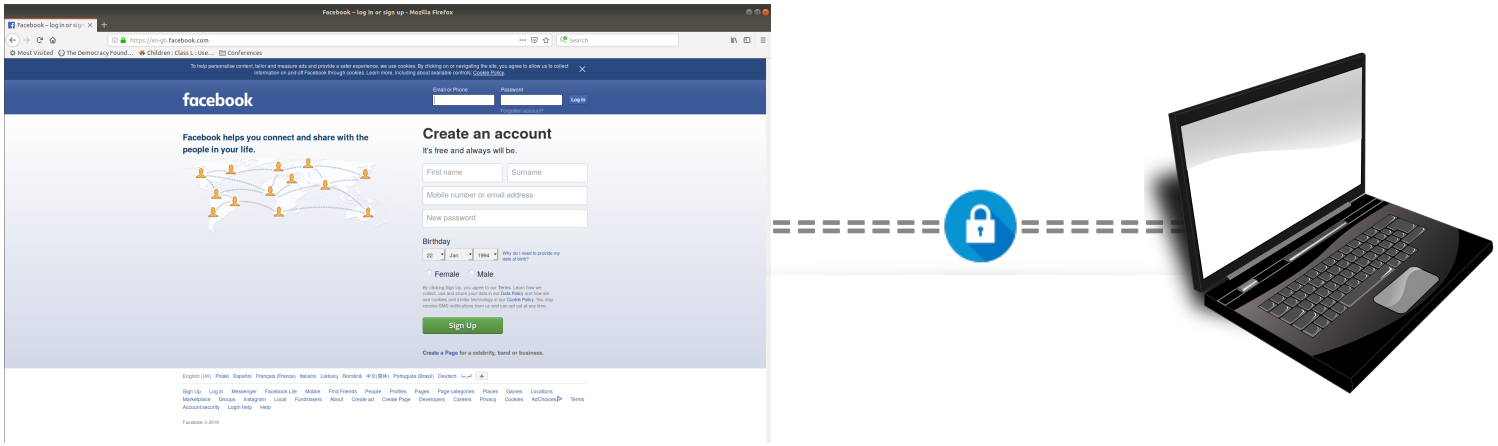
Goal: confidentiality

- Secure communications



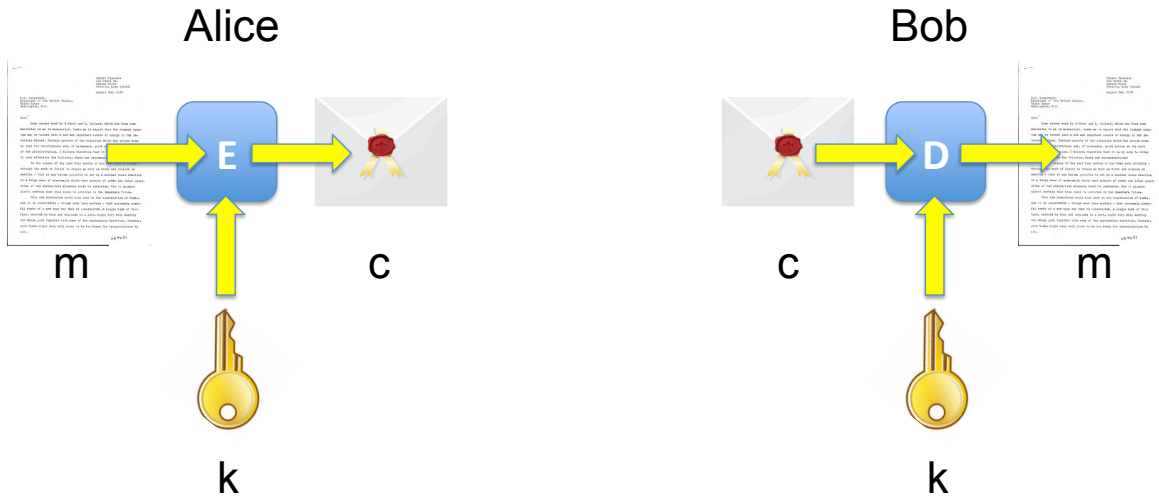
- File protection

Symmetric encryption schemes

A symmetric cipher consists of two algorithms

- encryption algorithm $E: \mathcal{K} \times \mathcal{M} \to \mathcal{C}$
- decryption algorithm $D: \mathcal{K} \times \mathcal{C} \to \mathcal{M}$

st. $\forall k \in \mathcal{K}$, and $\forall m \in \mathcal{M}$, $D(k, E(k, m)) = m$



- same key k to encrypt and decrypt
- the key k is secret: only known to Alice and Bob

What is a good encryption scheme?

An encryption scheme is secure against a given adversary, if this adversary cannot

- recover the secret key k
- recover the plaintext m underlying a ciphertext c
- recover any bits of the plaintext m underlying a ciphertext c
- ...

Kerckhoff's principle

The architecture and design of a security system/mechanism should be made public

No security through obscurity!

- The encryption (E) and decryption (D) algorithms are public
- The security relies entirely on the secrecy of the key

Open design allows for a system to be scrutinised by many users, white hat hackers, academics, *etc.*
$\rightsquigarrow$ early discovery and corrections of flaws/vulnerabilities

Adversary's capabilities

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The attacker know the encryption/decryption algorithms but may have access to :

- Ciphertext only attack - some ciphertexts $c_1, \ldots, c_n$
- Known plaintext attack some plaintext/ciphertext pairs (m_1, c_1), $\ldots$, (m_n, c_n) st. $c_i = E(k, m_i)$)
- Chosen plaintext attack (CPA) - he has access to encryption oracle - can trick user to encrypt messages $m_1, \ldots, m_n$ of his choice
- Chosen ciphertext attack (CCA) - he has access to decryption oracle - can trick user to decrypt ciphertexts $c_1, \ldots, c_n$ of his choice
- unlimited, or polynomial, or realistic ($\leq 2^{80}$) computational power

Brute-force attack - attack on all schemes

- Try all possible keys $k \in \mathcal{K}$ - requires some knowledge about the structure of plaintext

- Making exhaustive search unfeasible:
  - $\mathcal{K}$ should be sufficiently large, *i.e.* keys should be sufficiently long
  - Keys should be sampled uniformly at random from $\mathcal{K}$

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$$
\begin{array}{rcccccccc}
k & = & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \\
m & = & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \\
\hline
c & = & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 0
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- Consistency: $D(k, E(k,m)) = k \oplus (k \oplus m) = m$

Perfect secrecy

Definition

A cipher (E, D) over $(\mathcal{M}, \mathcal{C}, \mathcal{K})$ satisfies perfect secrecy if for all messages $m_1, m_2 \in \mathcal{M}$ of same length ($|m_1| = |m_2|$), and for all ciphertexts $c \in \mathcal{C}$

$$|Pr(E(k, m_1) = c) - Pr(E(k, m_2) = c)| \leq \epsilon$$

where $k \xleftarrow{r} \mathcal{K}$ and ϵ is some "negligible quantity".

OTP satisfies perfect secrecy

Theorem (Shannon 1949)

The One-Time Pad satisfies perfect secrecy

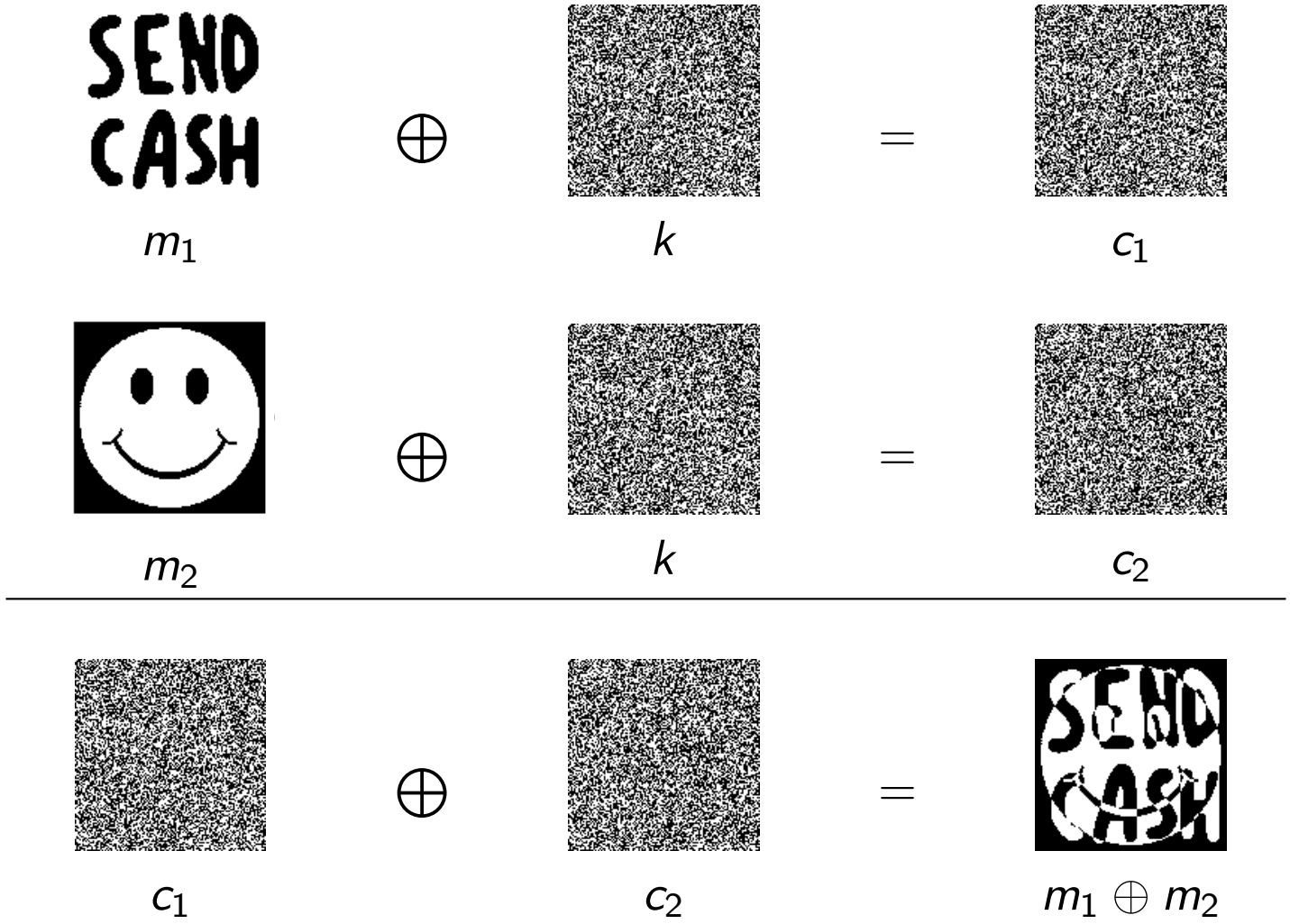
Proof: We first note that for all messages $m \in \mathcal{M}$ and all ciphertexts $c \in \mathcal{C}$

$$\begin{aligned} Pr(E(k,m) = c) &= \frac{\#\{k \in \mathcal{K}:\ k \oplus m = c\}}{\#\mathcal{K}} \\ &= \frac{\#\{k \in \mathcal{K}:\ k = m \oplus c\}}{\#\mathcal{K}} \\ &= \frac{1}{\#\mathcal{K}} \end{aligned}$$

where $k \xleftarrow{r} \mathcal{K}$.
Thus, for all messages $m_1, m_2 \in \mathcal{M}$, and for all ciphertexts $c \in \mathcal{C}$

$$|Pr(E(k,m_1) = c) - Pr(E(k,m_2) = c)| \leq \left| \frac{1}{\#\mathcal{K}} - \frac{1}{\#\mathcal{K}} \right| = 0$$

Two-time pad attacks



Source: Cryptosmith and David Lowry-Duda, `crypto.stackexchange.com/`

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  - OTP is malleable
    given the ciphertext $c = E(k, m)$ with $m = \text{"}to\ bob : secret\ text\text{"}$, it is possible to compute the ciphertext $c' = E(k, m')$ with
    $m' = \text{"}to\ eve : secret\ text\text{"}$
    $c' := c \oplus \text{"}to\ bob : 00 \ldots 00\text{"} \oplus \text{"}to\ eve : 00 \ldots 00\text{"}$

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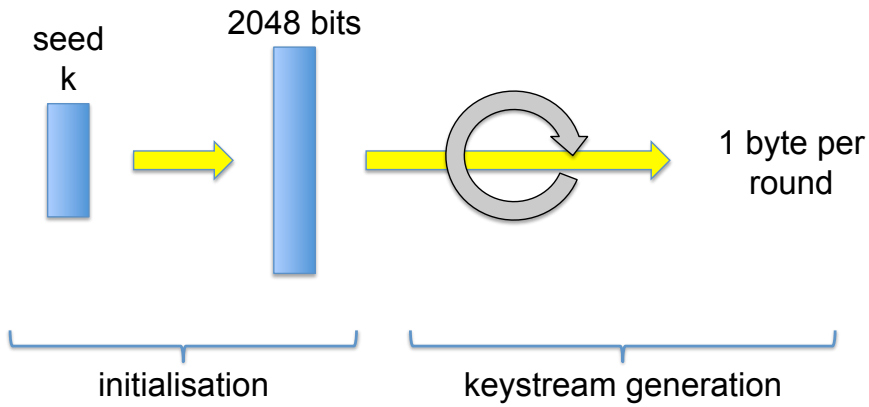

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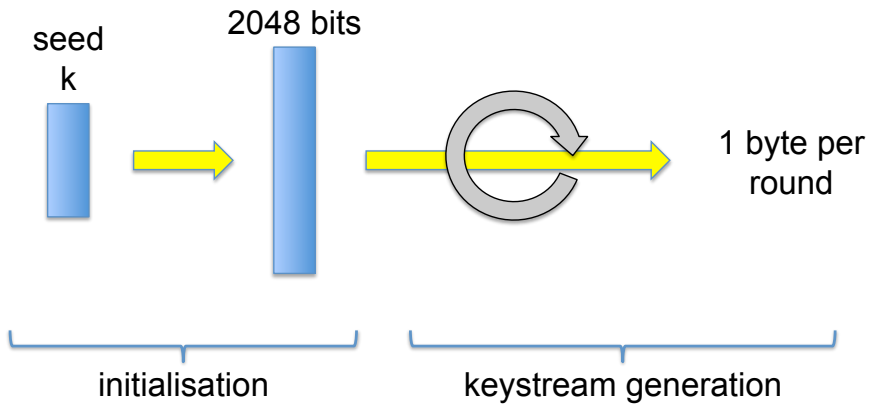

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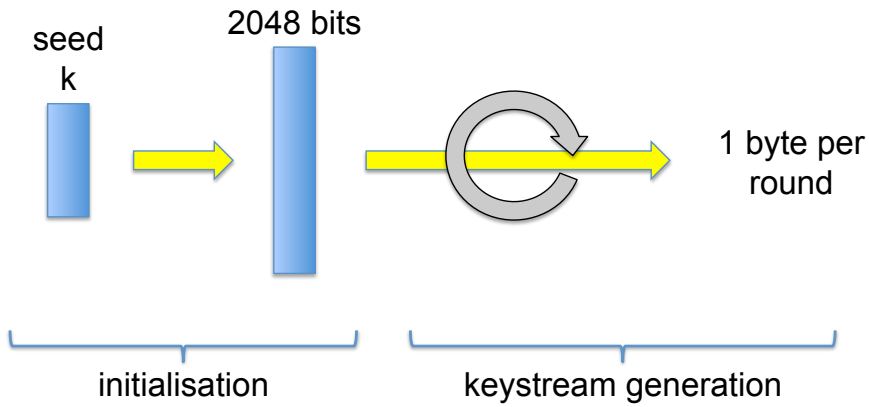

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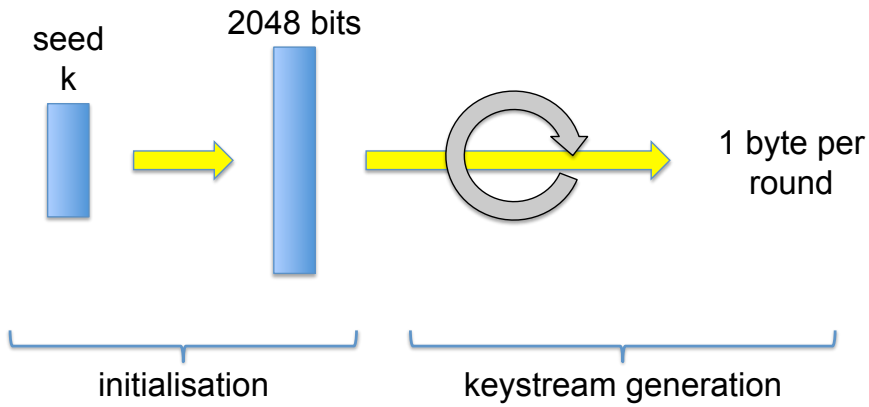

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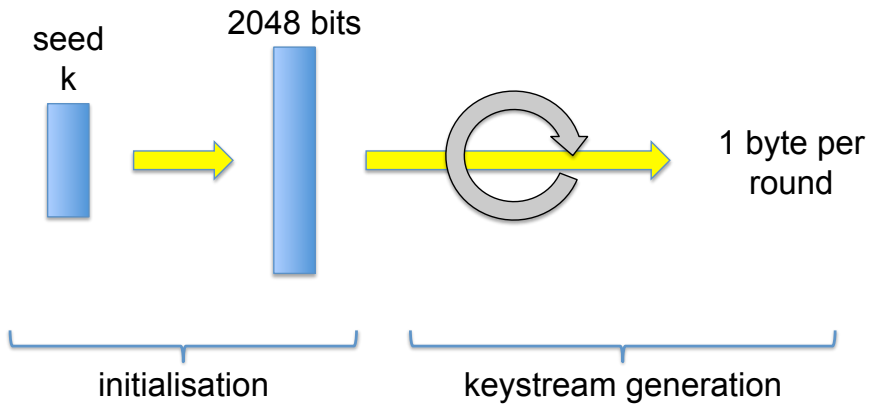

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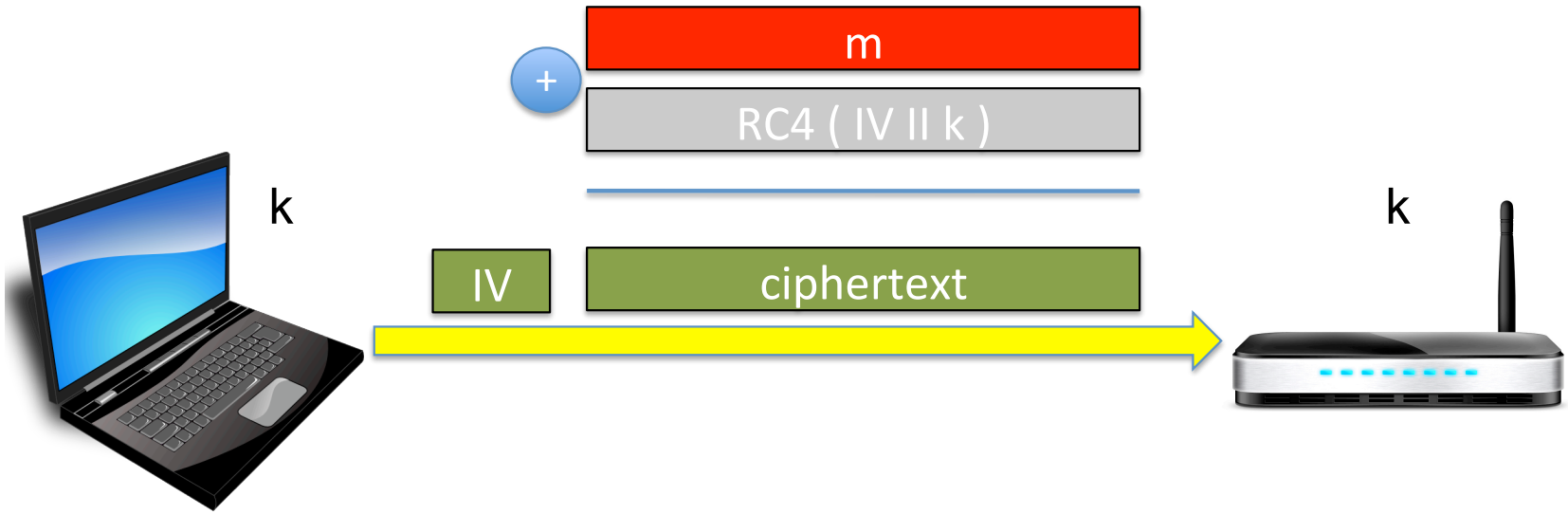
WEP uses RC4



Initialisation Vector (IV): 24-bits long string

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- two-time pad attack: IV is 24 bits long, so the key is reused after at most 2^{24} frames
  $\longrightarrow$ use longer IVs
- Fluhrer, Mantin and Shamir (FMS) attack (related keys attack):
  - the keys only differ in the 24 bits IV
  - first bytes of key stream known because standard headers are always sent
  - for certain IVs knowing m bytes of key and keystream means you can deduce byte $m + 1$ of key

  $\longrightarrow$ instead of using related IVs, generate IVs using a PRG

Weaknesses of TLS

MUST READ THESE TEN CITIES ARE HOME TO THE BIGGEST BOTNETS

RC4 NOMORE crypto exploit used to decrypt user cookies in mere hours

Websites using RC4 encryption need to change their protocols as exploits using design flaws are now far easier to perform.

By Charlie Osborne for Zero Day | July 20, 2015 -- 10:21 GMT (11:21 BST) | Topic: Security

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Android BitCoin attack

ars TECHNICA BIZ & IT TECH SCIENCE POLICY CARS GAMING & CULTURE FORUMS SIGN IN

RANDOM THEFT —

All Android-created Bitcoin wallets vulnerable to theft

Android Java SecureRandom function flaw undermines security of Android wallets.

LEE HUTCHINSON - 8/12/2013, 3:15 PM

Xurxo Martínez

Bitcoin.org released a security advisory over the weekend warning the Bitcoin community that any Bitcoin wallet generated on any Android device is insecure and open to theft. The insecurity appears to stem from a flaw in the Android Java SecureRandom class, which under certain circumstances can

Modern stream ciphers

Project eStream: project to "identify new stream ciphers suitable for widespread adoption", organised by the EU ECRYPT network

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Conjecture

These eStream stream ciphers are "secure"

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- Many attacks dues to poor implementations of cryptography

Cryptography: Block ciphers

Block ciphers

A block cipher with parameters k and ℓ is a pair of deterministic algorithms (E, D) such that

- Encryption $E : \{0,1\}^k \times \{0,1\}^\ell \to \{0,1\}^\ell$
- Decryption $D : \{0,1\}^k \times \{0,1\}^\ell \to \{0,1\}^\ell$

Examples:

3DES: $\ell = 64,\ k = 168$

AES: $\ell = 128,\ k = 128, 192, 256$

Data Encryption Standard (DES)

- Early 1970s: Horst Feistel designs Lucifer at IBM
  $k = 128$ bits, $\ell = 128$ bits
- 1973: NBS calls for block cipher proposals.
  $\longrightarrow$ IBM submits a variant of Lucifer.
- 1976: NBS adopts DES as a federal standard
  $k = 56$ bits, $\ell = 64$ bits
- 1997: DES broken by exhaustive search
- 2001: NIST adopts AES to replace DES
  $k = 128, 192, 256$ bits, $\ell = 128$ bits

Widely deployed in banking (ATM machines) and commerce

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$\Rightarrow$ DES is badly broken! Do not use it in new projects!!

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    $E_{3DES}((K_1, K_2, K_3), M) = E_{DES}(K_1, D_{DES}(K_2, E_{DES}(K_3, M)))$
    $\longrightarrow \; K_1 = K_2 = K_3 \Rightarrow DES$

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  - $D_{3DES} : (\{0,1\}^k)^3 \times \{0,1\}^\ell \to \{0,1\}^\ell$
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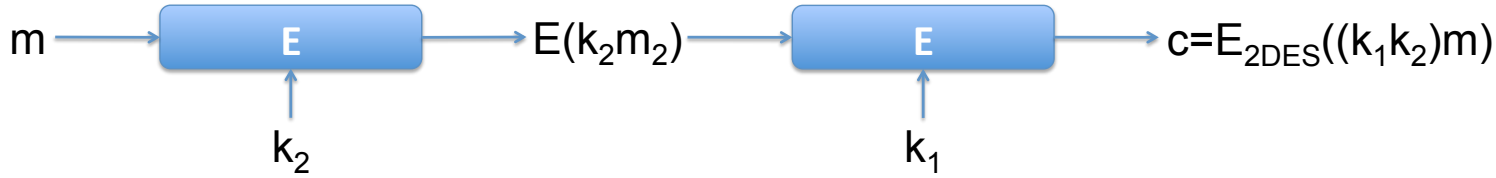

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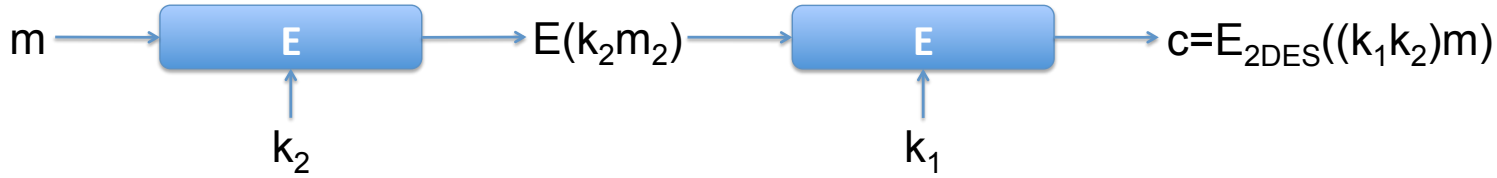

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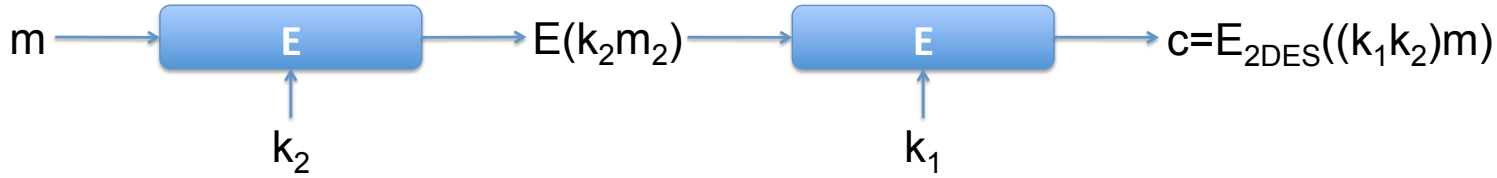

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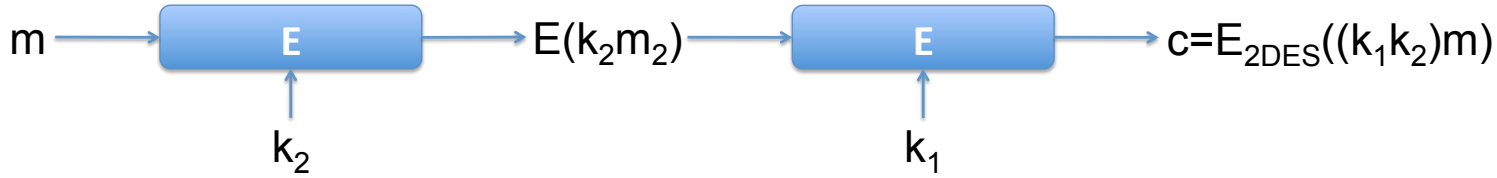

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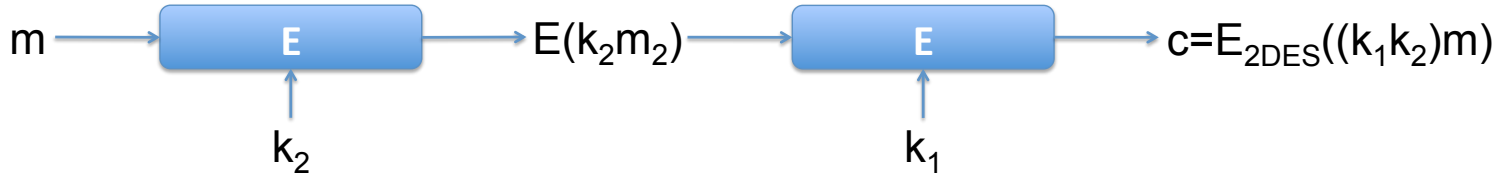

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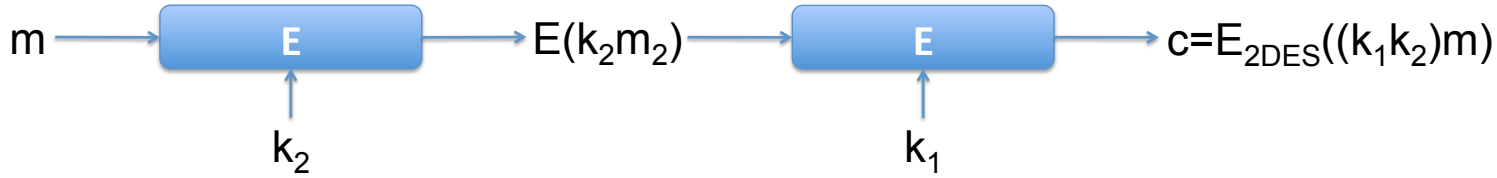

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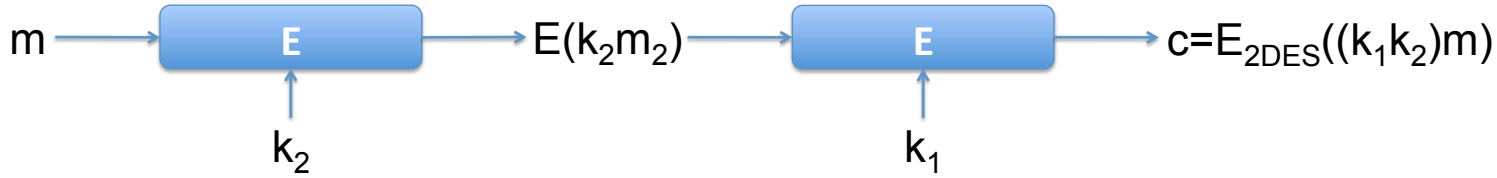

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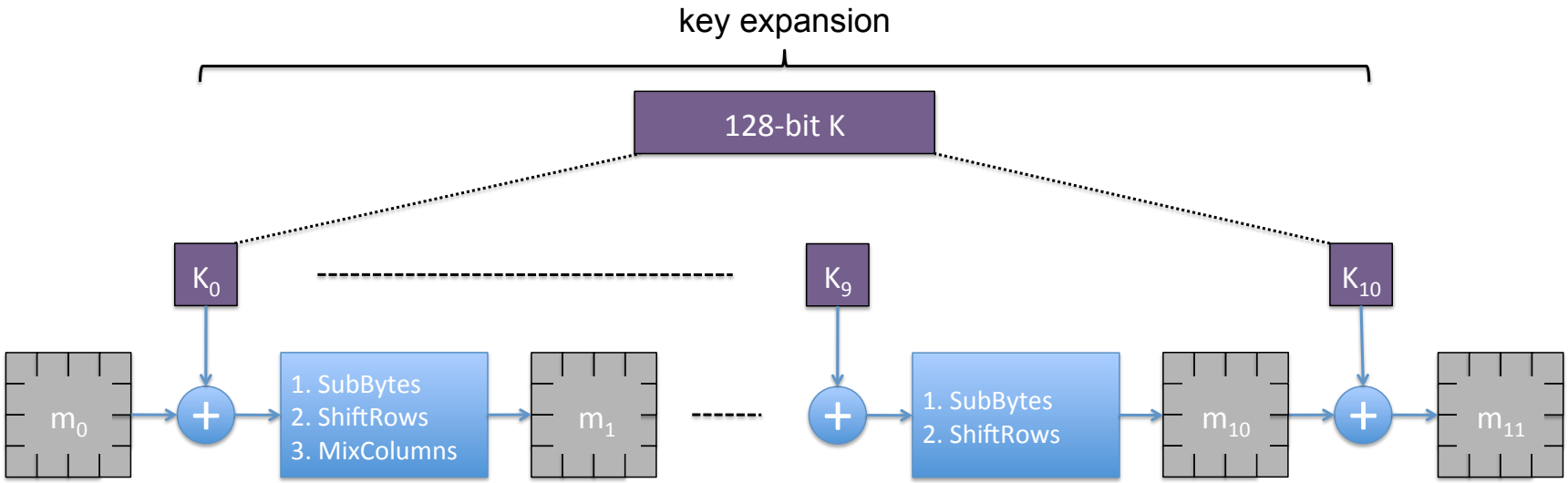
- Similar attack on 3DES in time 2^{118}

The Advanced Encryption Standard (AES)

- Goal: replace 3DES which is too slow (3DES is 3 times as slow as DES)
- 2001: NIST adopts Rijndael as AES
- Block size $\ell = 128$ bits, Key size $k = 128, 192, 256$ bits

AES: encryption circuit



- m_i : 4×4 byte matrix, K_i: 128-bit key
- m_0: plaintext, m_{11}: ciphertext
- at the last round MixColumns is not applied

Attacks on AES

- **Related-key attack** on the 192-bit and 256-bit versions of AES: exploits the AES key schedule [A. Biryukov, D. Khovratovich (2009)]
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$\Rightarrow$ Existing attacks on AES-128 are still not practical, but should use AES-192 and AES-256 in new projects!

Additional protection against quantum computers.

Using block ciphers

Goal

Encrypt M using a block cipher operating on blocks of length ℓ when $|M| \neq \ell$

Padding - $|M| \leq \ell$

- Bit padding - append a *set bit* ('1') at the end of message, and then append as many *reset bits* ('0') required
  Example: padding a 52-bits message for a 64-bits block:
  11010011 01010110 10010000 00111010 10110101 01011010 1111**1000 00000000**
  padding a 64-bits message M for 64-bits blocks requires adding a padding block:

  M|**10000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000**

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  Example: padding a 4-bytes message for 8-bytes blocks:
  DD DD DD DD **00 00 00 04**
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  DD DD DD DD DD DD DD DD | **00 00 00 00 00 00 00 08**

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- PKCS#7 - byte padding - the value of each added byte is the total number of padding bytes. The padding will be 01, or 02 02, or 03 03 03, or 04 04 04 04, *etc.*
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- The ciphertext corresponding to M is the concatenation of the C_is
  $$\Rightarrow \; C = C_1 \,||\, C_2 \,||\, \ldots \,||\, C_m$$

Weakness of ECB

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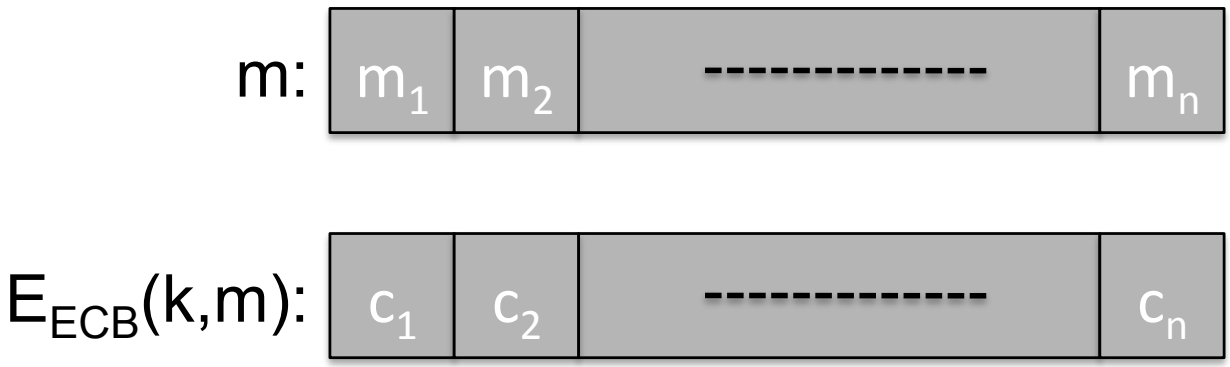

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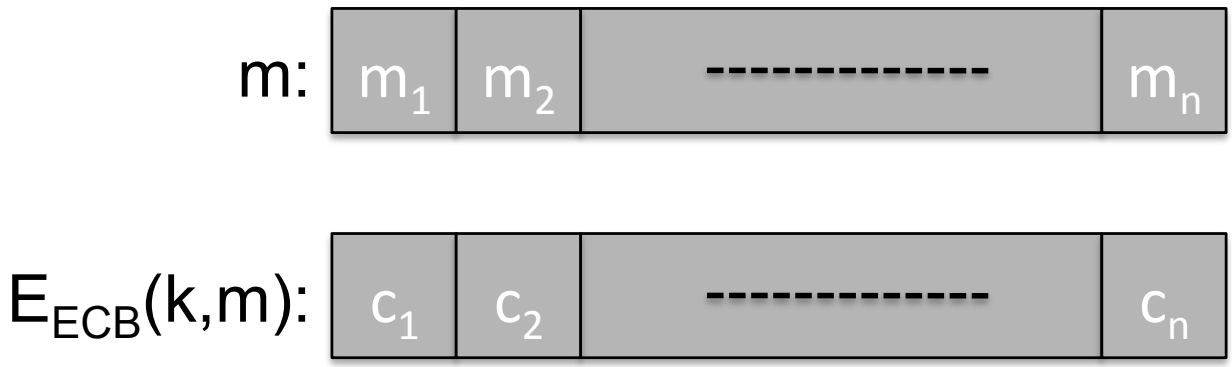

Problem: $\forall i, j.\ m_i = m_j \ \Rightarrow\ c_i = E(k, m_i) = E(k, m_j) = c_j$

$\Rightarrow$ Malleable and weak to frequency analysis!

Weakness of ECB in pictures

Original image

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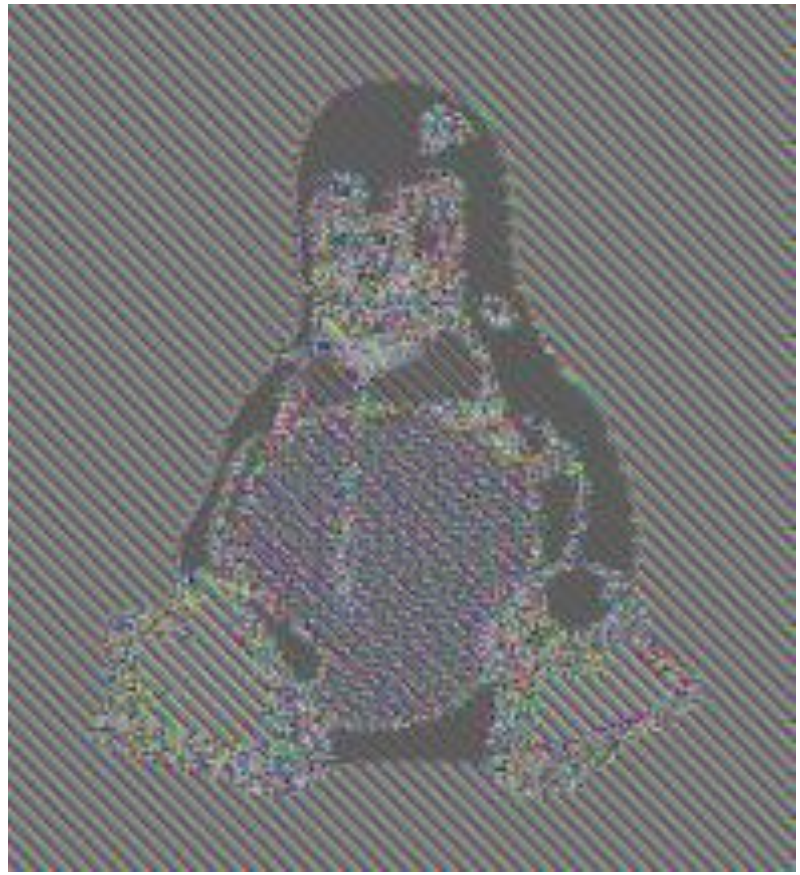
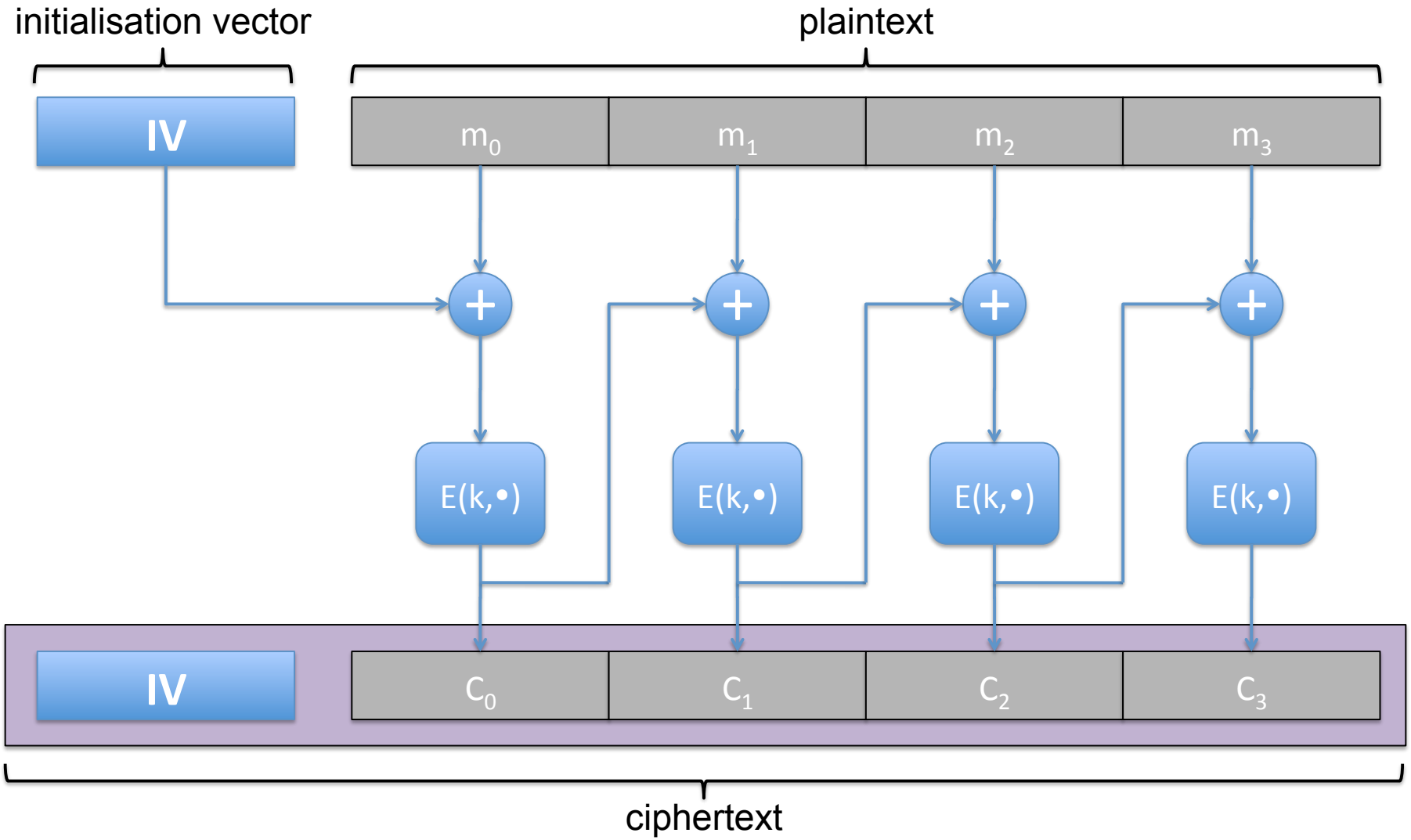


Image encrypted using ECB mode

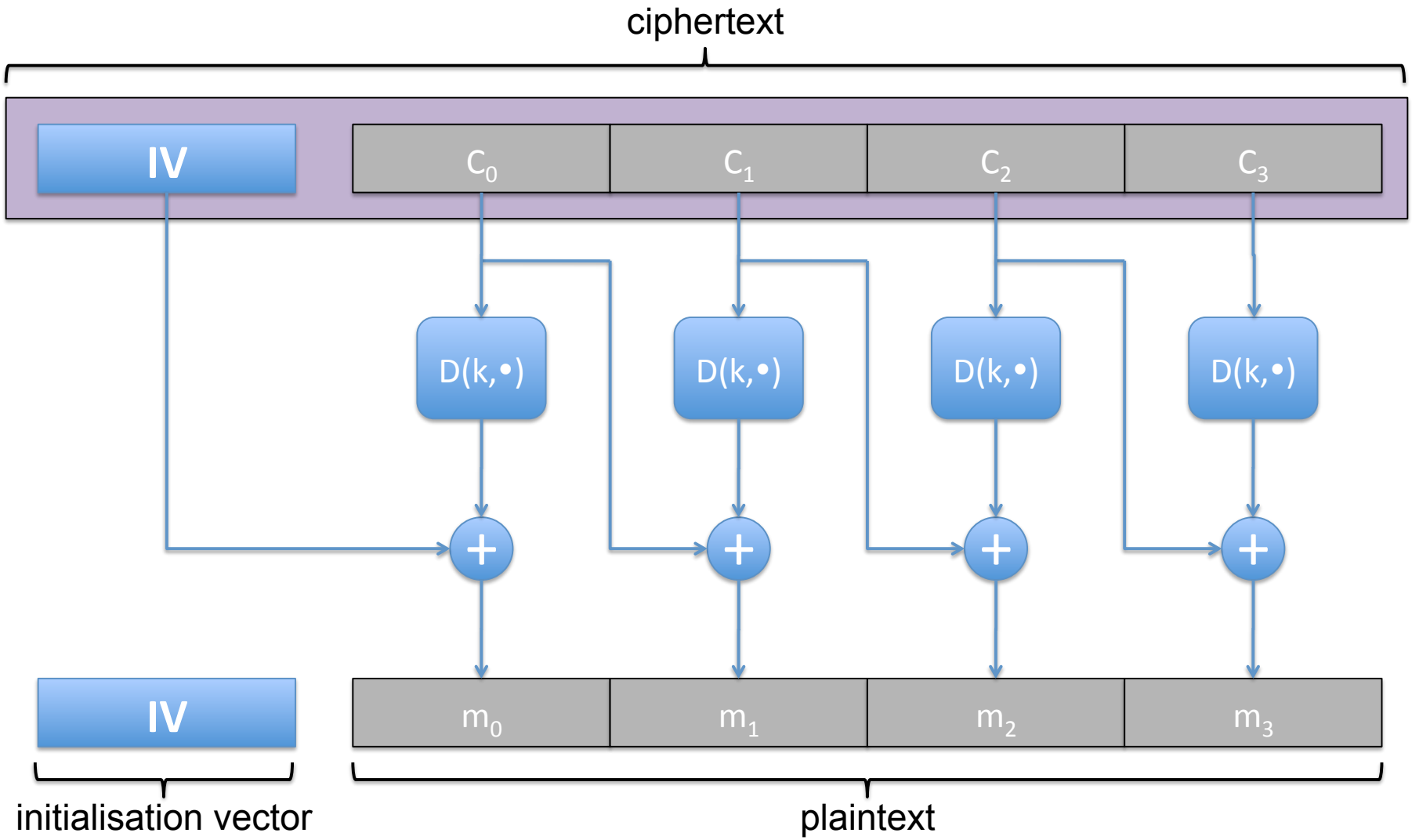
Cipher-block chaining (CBC) mode: encryption

(E, D) a block cipher that manipulates blocks of size ℓ.



IV chosen at random in $\{0,1\}^{\ell}$

Cipher-block chaining (CBC) mode: decryption



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- Hardware controlled user access to data

Sony PlayStation disk encryption attack

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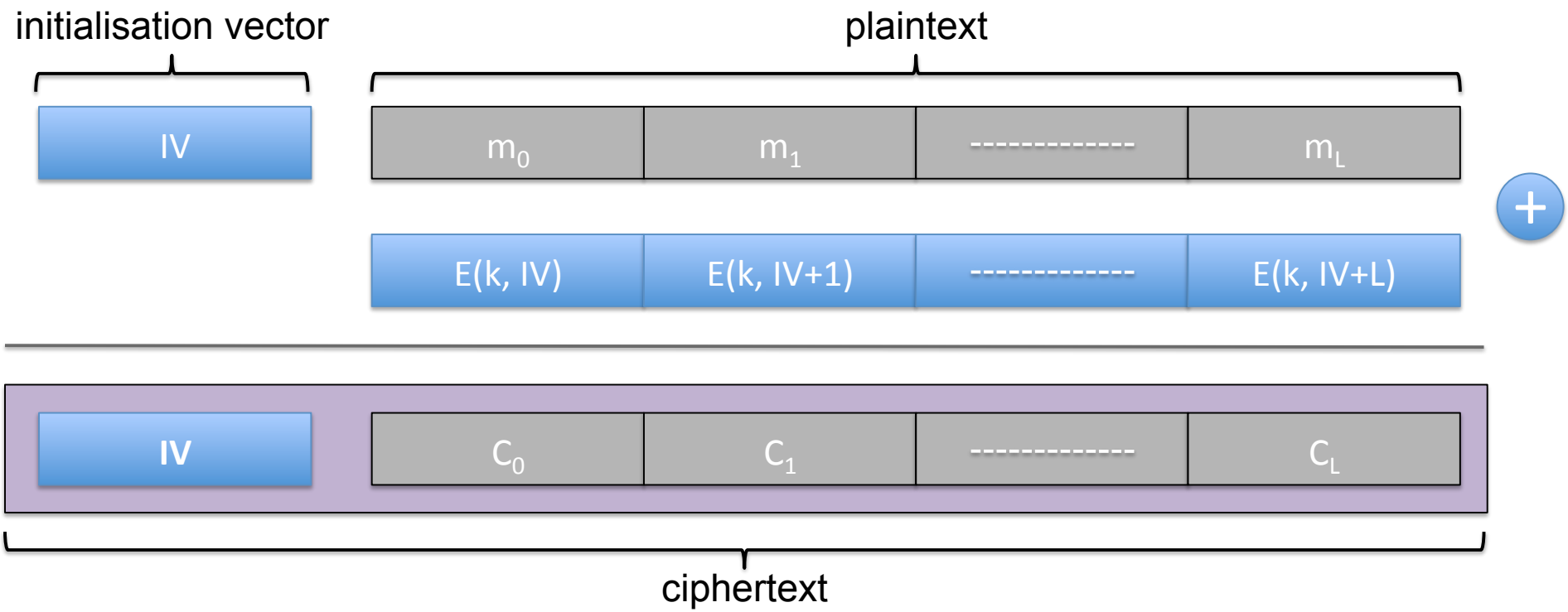
- Put disk back in PlayStation and ask for user data
- PlayStation decrypts the file and gives it to user

Counter (CTR) mode

(E, D) a block cipher that manipulates blocks of size ℓ.



IV chosen at random in $\{0, 1\}^{\ell}$

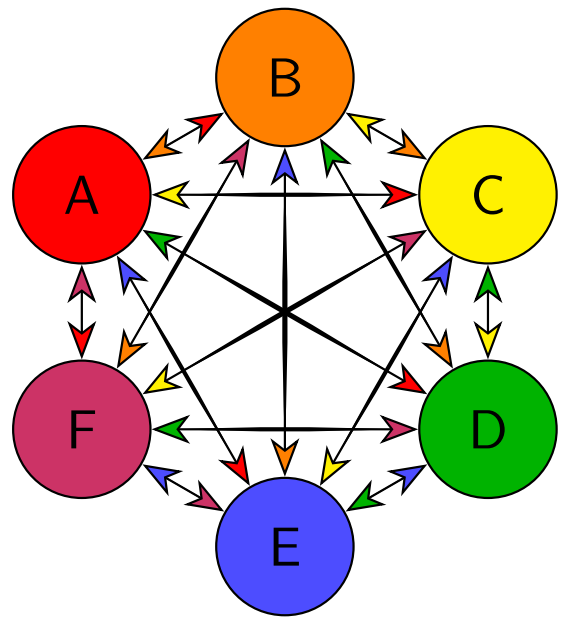
Block-size is also a problem!

- Sweet32 - birthday attacks on 64-bit block ciphers in TLS and openVPN
- Attack due to block-size being too small

The key management problem

The confidentiality problem is now reduced to a key management problem:

- Where are keys generated?
- How are keys generated?
- How are keys shared?
- Where are keys stored?
- Where are the keys actually used?
- How are key revoked and replaced?



One shared secret key per pair of users that want to communicate

What we have learned on Symmetric Encryption

- Frequency analysis as a cryptanalysis attack on classic encryption
- Importance of randomness in cryptography
- Stream ciphers
  - simple and efficient symmetric encryption schemes
  - use a random IV to thwart two-time pad attacks
  - good for random plaintexts otherwise subject to malleability attacks
- Block ciphers - use AES not DES
- CBC mode is more secure that ECB but less resilient to packets loss
- CTR mode more secure than ECB and parallelisable
- Keep up to date with cryptanalysis advances and standards
- Do not implement crypto lightly - use public reference implementations