CSE 127: Computer Security

# Cryptography

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Adopted slides from Kirill Levchenko and Dan Boneh

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  - A tremendous tool
  - The basis for many security mechanisms
- Is not:
  - The solution to all security problems

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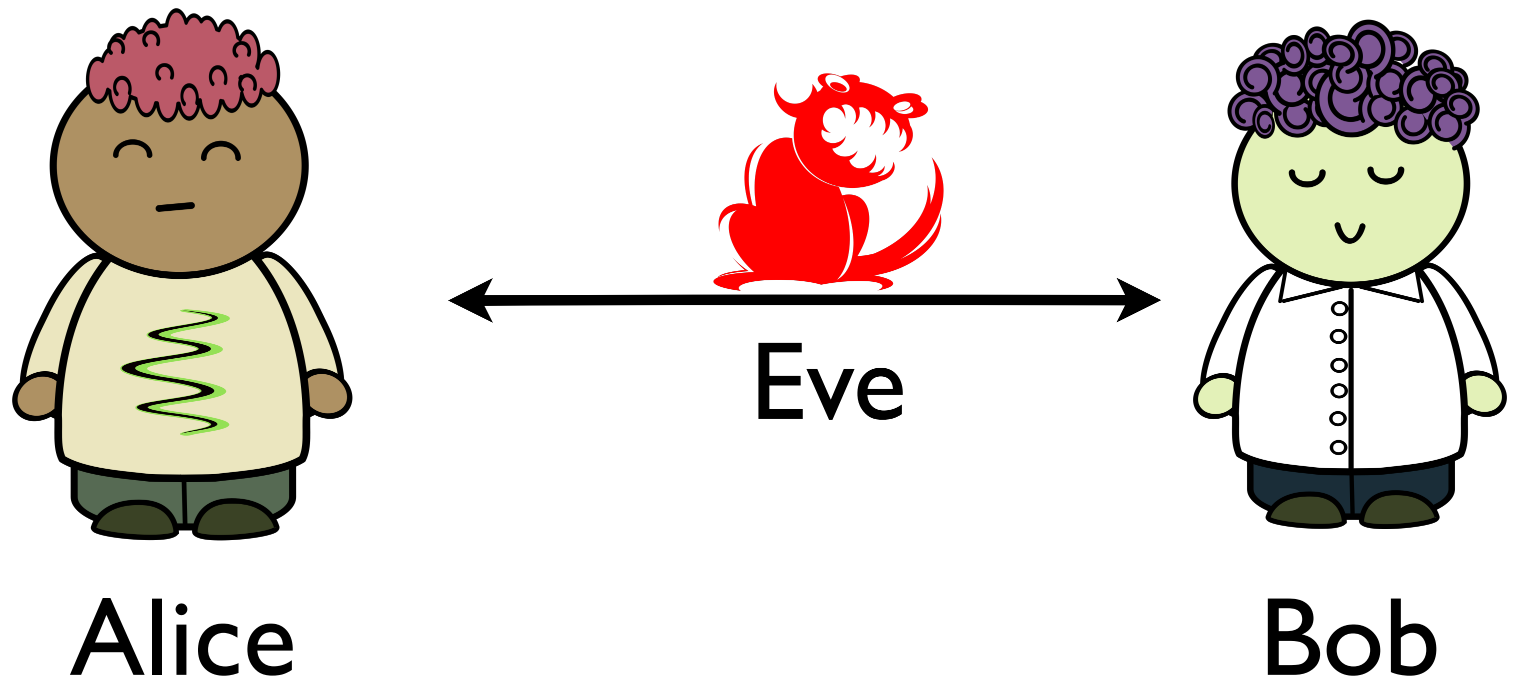
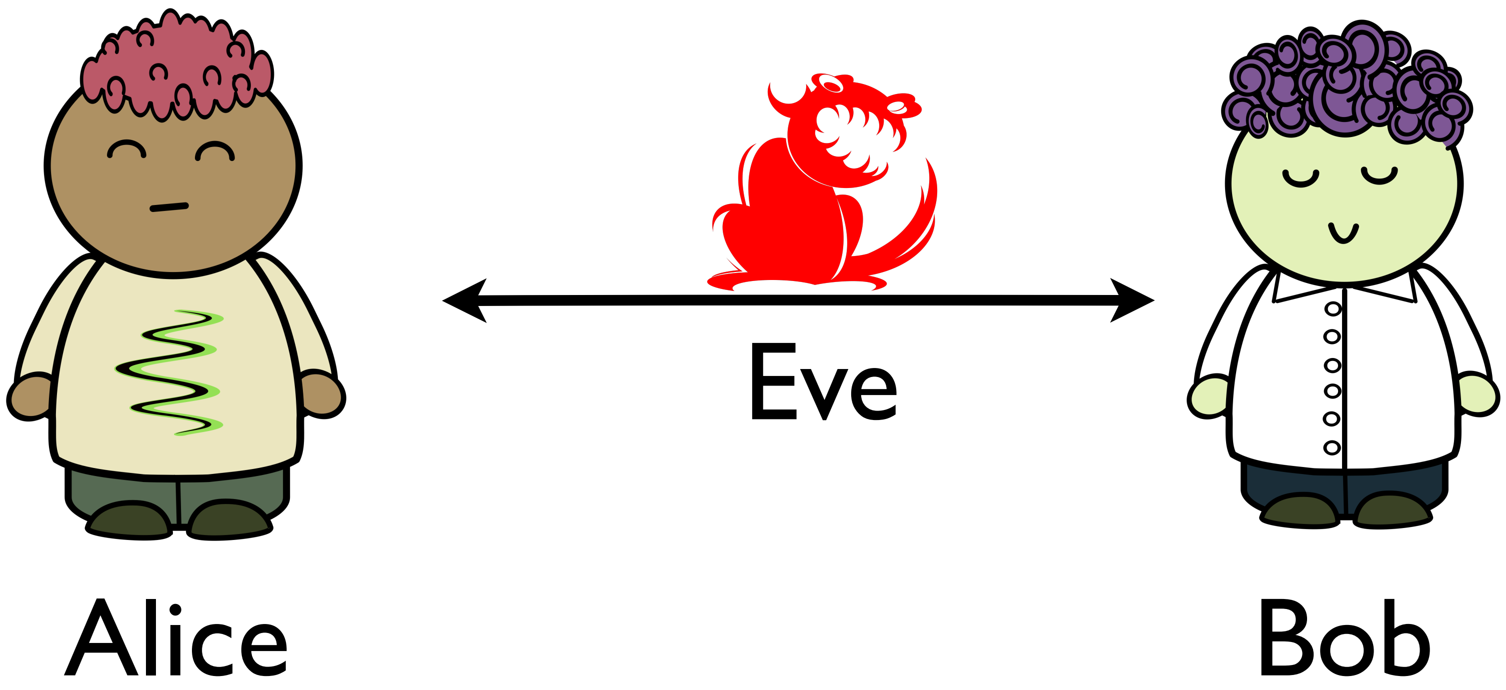
  - Something you should try to invent yourself
  - Blockchain

# This class: secure communication



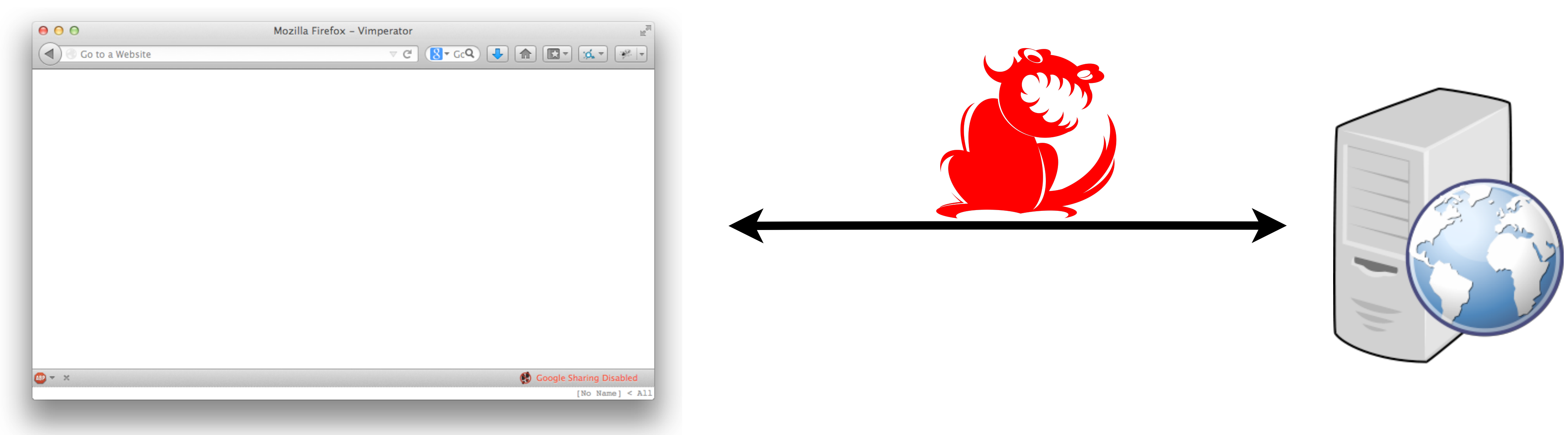

- Authenticity: Parties cannot be impersonated
- Secrecy: No one else can read messages
- Integrity: messages cannot be modified

# Attacker models




- Passive attacker: Eve only snoops on channel
- Active attacker:  Eve can snoop, inject, block, tamper, etc.

# In the real world (SSL/TLS)




- **Handshake Protocol:** Establish shared secret key using public-key cryptography
- **Record Layer:** Transmit data protected by symmetric-key cryptography (using negotiated key)

# Outline

- Symmetric-key crypto
  - Encryption
  - Hash functions
  - Message authentication code
- Asymmetric (public-key) crypto
  - Encryption
  - Digital signatures

# Symmetric-key encryption


- **Encryption:** (key, plaintext) → ciphertext
  - $E_k(m) = c$
- **Decryption:** (key, ciphertext) → plaintext
  - $D_k(c) = m$

# Symmetric-key encryption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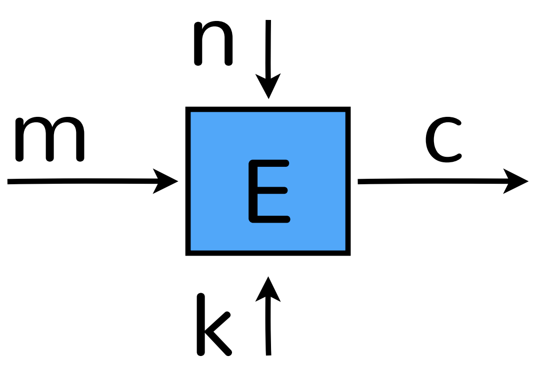


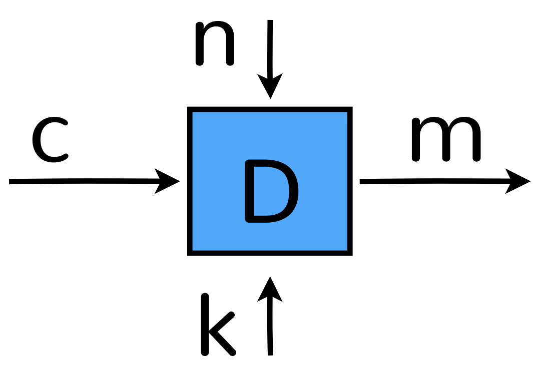


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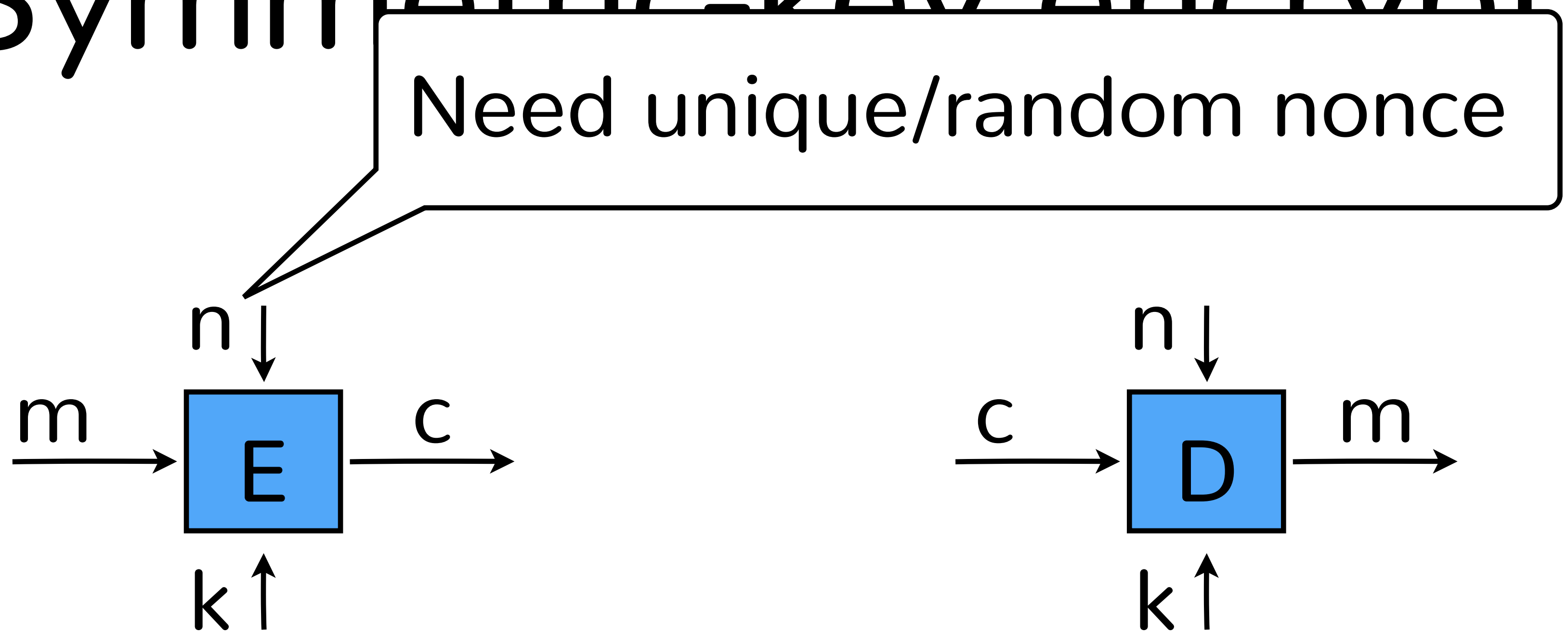


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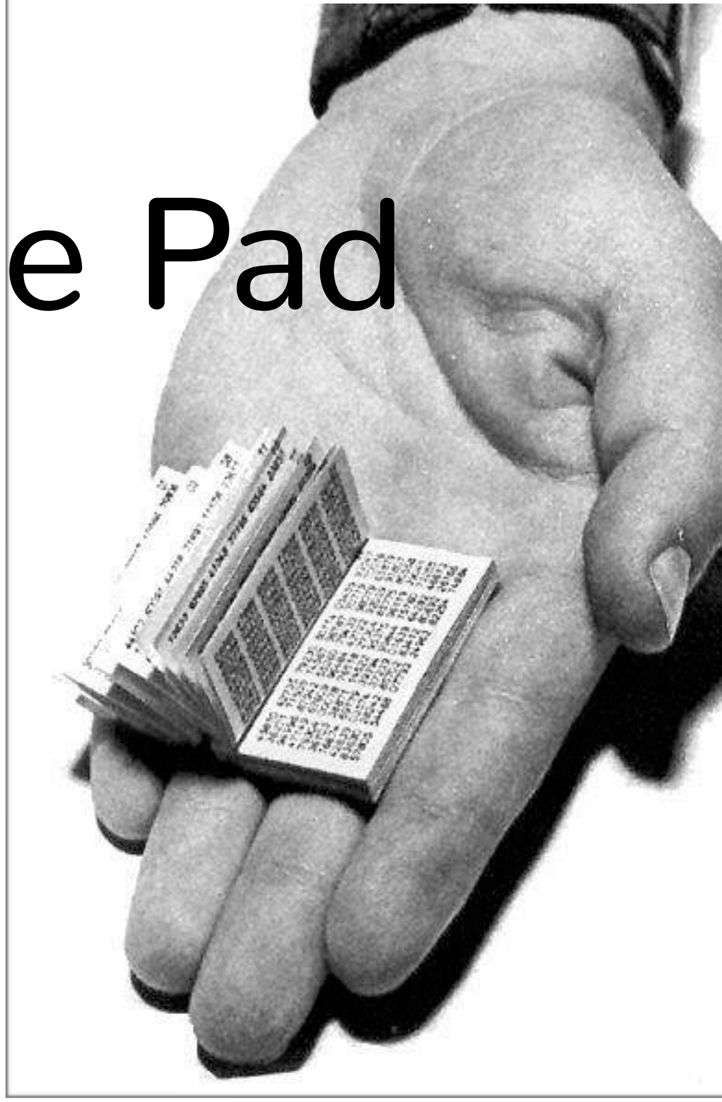
# Encryption properties

- Encryption and decryption are inverse operations
  - $D_k(E_k(m)) = m$
- Secrecy: ciphertext reveals nothing about plaintext
  - More formally: can't distinguish which of two plaintexts were encrypted without key

# First example: One Time Pad



Vernam (1917)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Key: | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| Plaintext: | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| Ciphertext: | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |

$\oplus$

- **Encryption:** $c = E_k(m) = m \oplus k$
- **Decryption:** $D_k(c) =$

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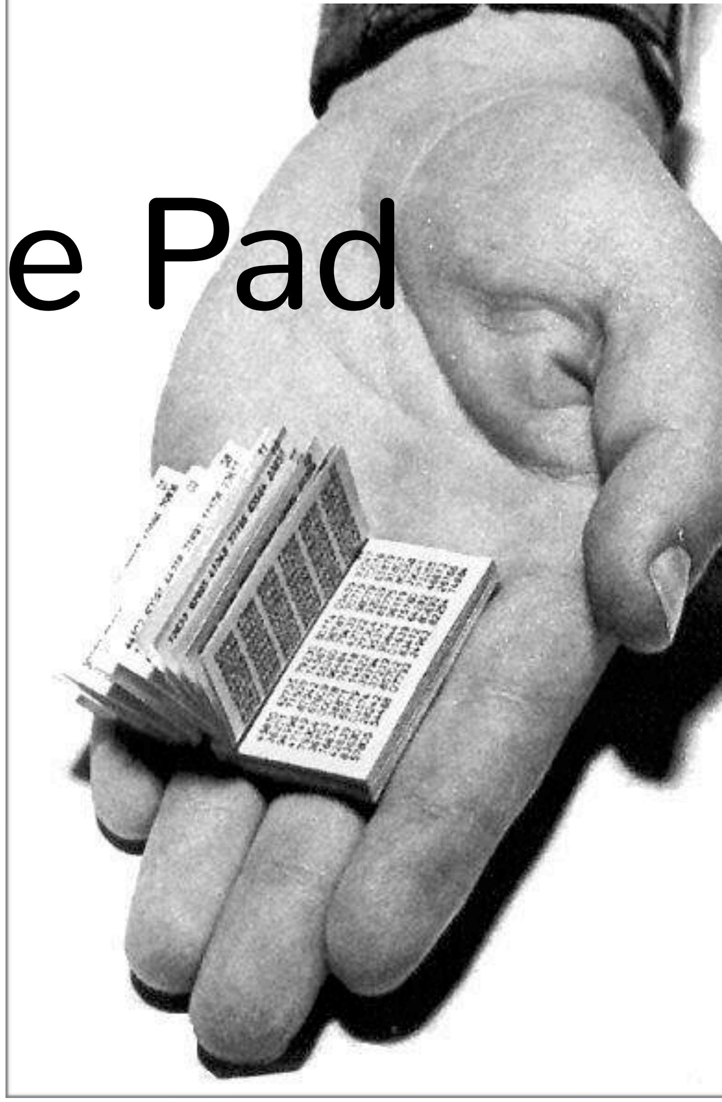

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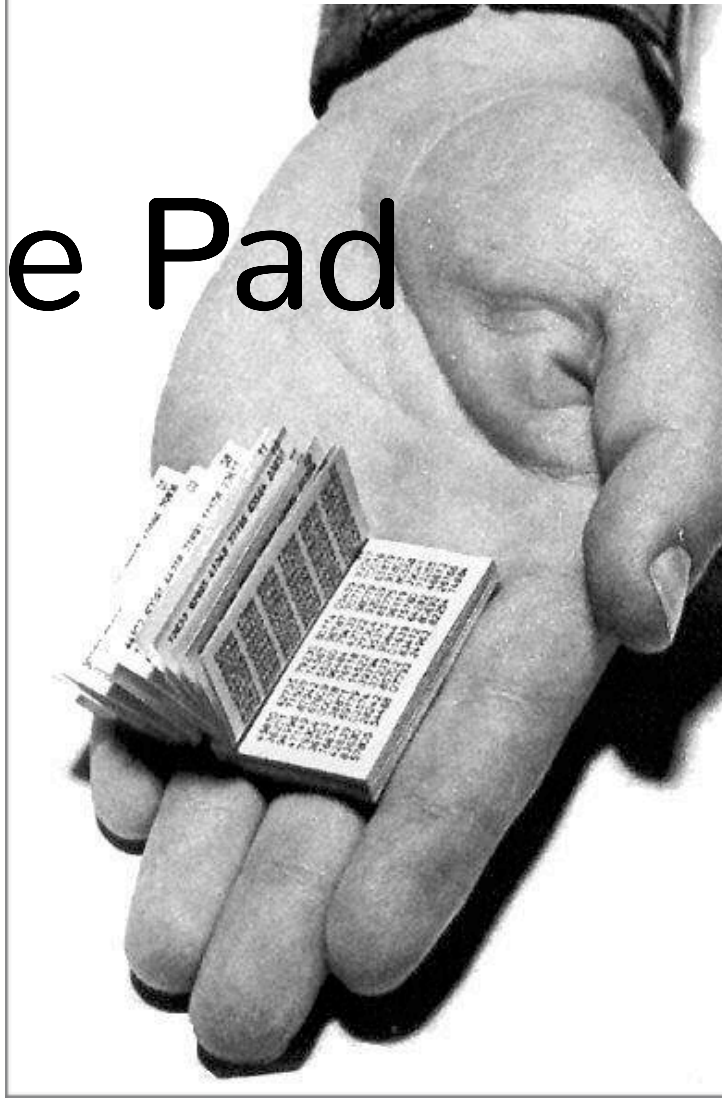

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- **Encryption:** $c = E_k(m) = m \oplus k$
- **Decryption:** $D_k(c) = c \oplus k = (m \oplus k) \oplus k = m$

# OTP security

- Shannon (1949)
  - Information theoretic security: without key, ciphertext reveals no “information” about plaintext
- Problems with OTP
  - Can only use key once
  - Key is as long as the message

# Computational cryptography

- Want the size of the secret to be small
  - If pre-arranged secret smaller than message, not all plaintexts equally probable — ciphertext reveals info about plaintext
- Modern cryptography based on idea that learning anything about plaintext from ciphertext is computationally difficult without secret

# Stream ciphers

- Problem: OTP key is as long as message
- Solution: Pseudo random key

key

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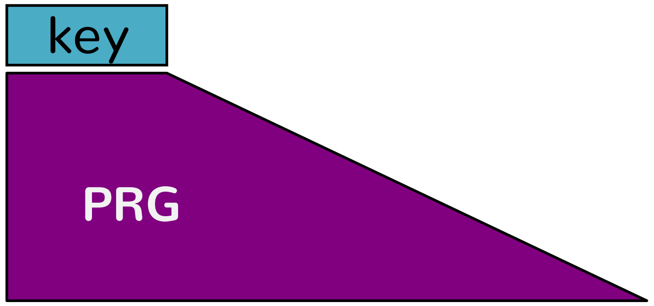

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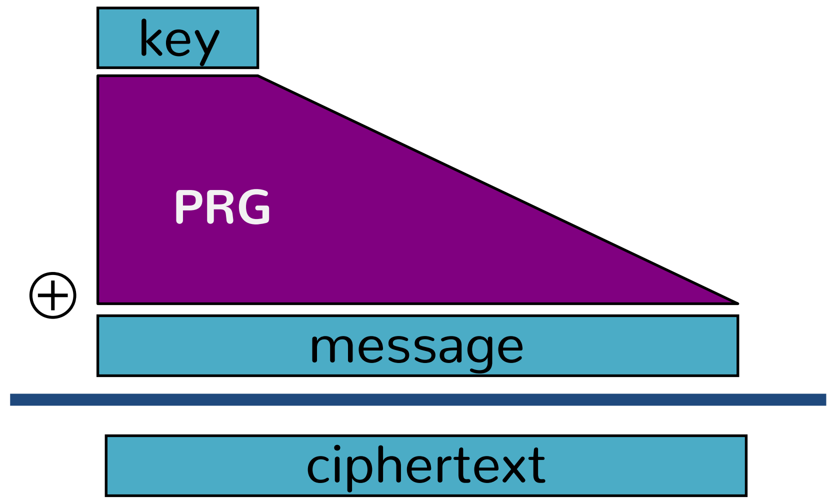


$E_k(m) = \textbf{PRG}(k) \oplus m$

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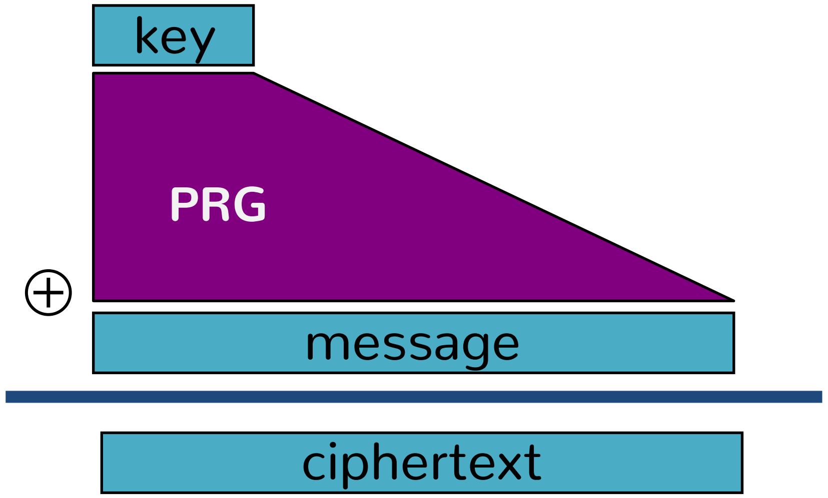


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➤ Examples: ChaCha, Salsa, Sosemanuk, etc.

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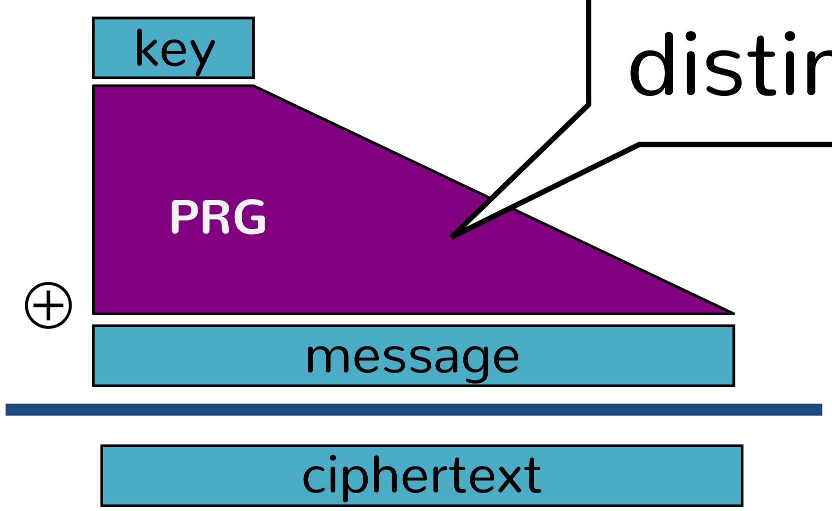
Computationally hard to distinguish from random

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# Dangers in using stream ciphers

- Can we use a key more than once?
  - E.g., $c_1 \leftarrow m_1 \oplus \mathrm{PRG}(k)$

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  - A: yes, B: no

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- Can we use a key more than once?
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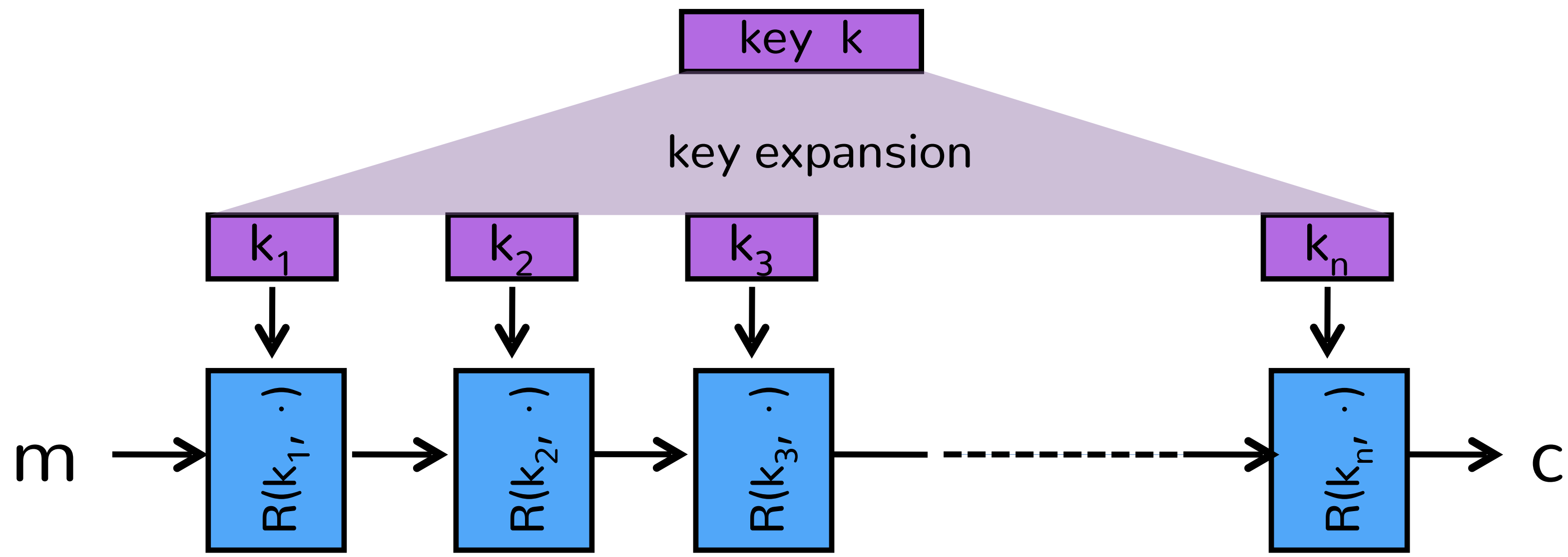
    $c_2 \leftarrow m_2 \oplus \mathrm{PRG}(k)$
  - A: yes, B: no
  - Eavesdropper does: $c_1 \oplus c_2 \rightarrow m_1 \oplus m_2$
  - Enough redundant information in English that:
    $m_1 \oplus m_2 \rightarrow m_1, m_2$

# Block ciphers: crypto work horses


- Block ciphers operate on fixed-size blocks
  - E.g., 3DES: |m| = |c| = 64 bits, |k| = 168 bits
  - E.g., AES: |m| = |c| = 128 bits, |k| = 128, 192, 256
- A block cipher = permutation of fixed-size inputs
  - Each input mapped to exactly one output

# How do they work?




R(k,m): round function

for 3DES (n=48), for AES-128 (n=10)

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# Challenges with block ciphers

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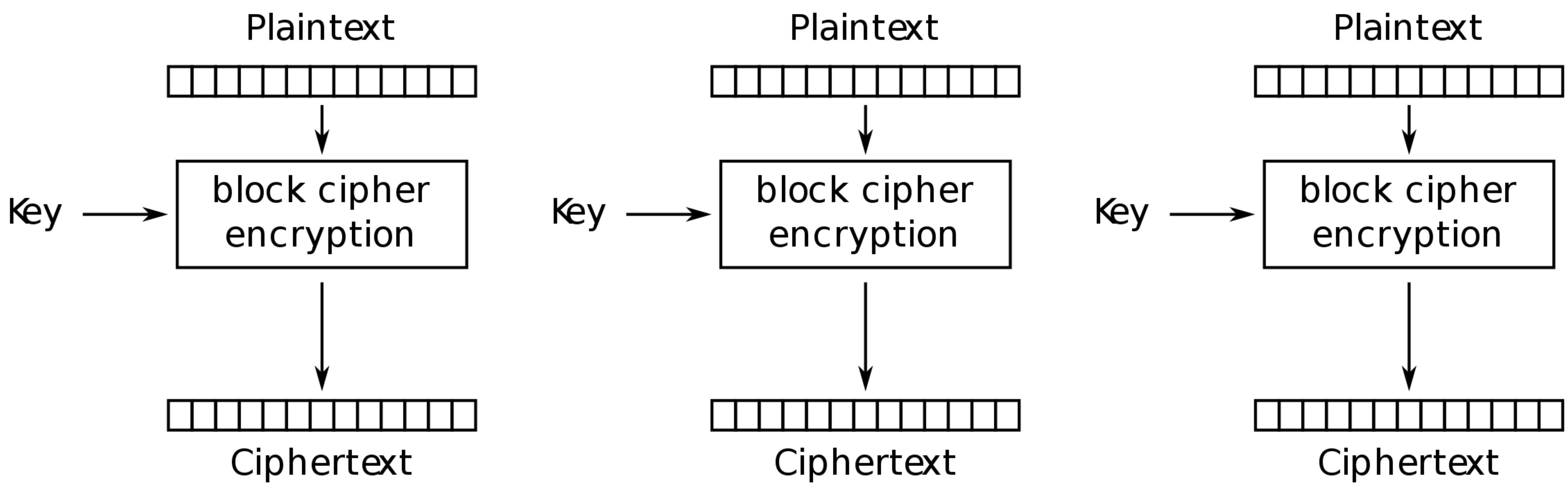
- Block ciphers operate on single fixed-size block
- How do we encrypt longer messages?
  - Several modes of operation for longer messages
- How do we deal with messages that are not block-aligned?
  - Must pad messages in a distinguishable way

# ECB mode




Electronic Codebook (ECB) mode encryption

Source: wikipedia

# Is ECB good? A: yes, **B: no**

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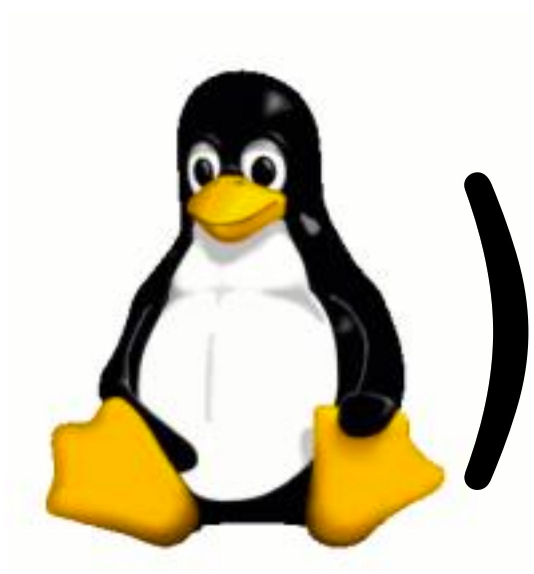
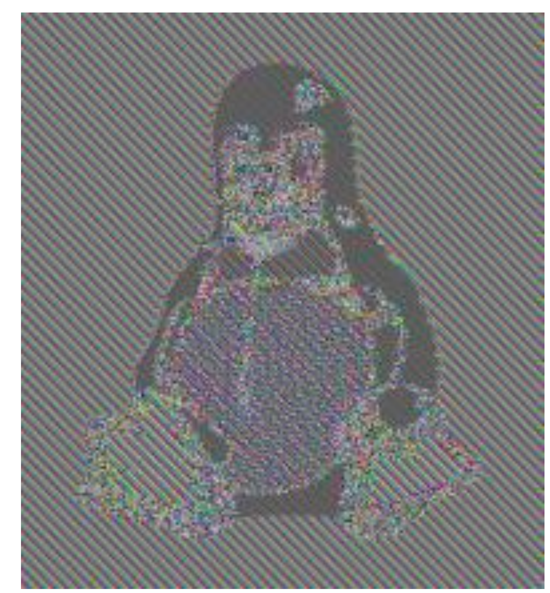
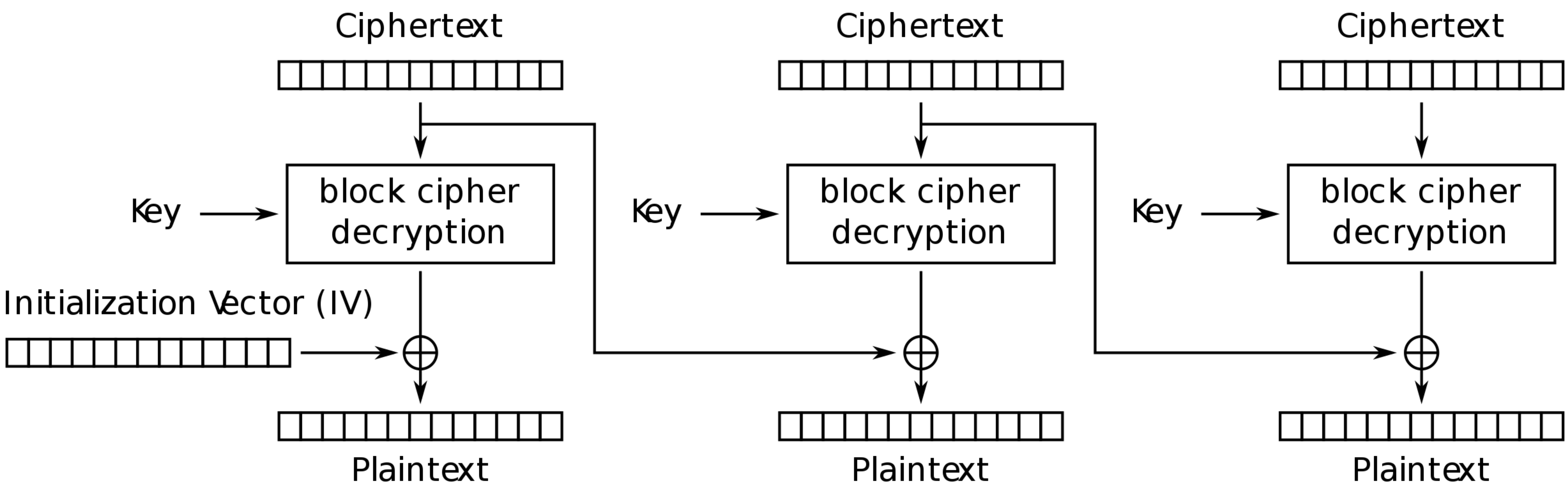
$E_k($  $)=$ 

Source: wikipedia

# CBC mode with random IV




Cipher Block Chaining (CBC) mode decryption

Source: wikipedia

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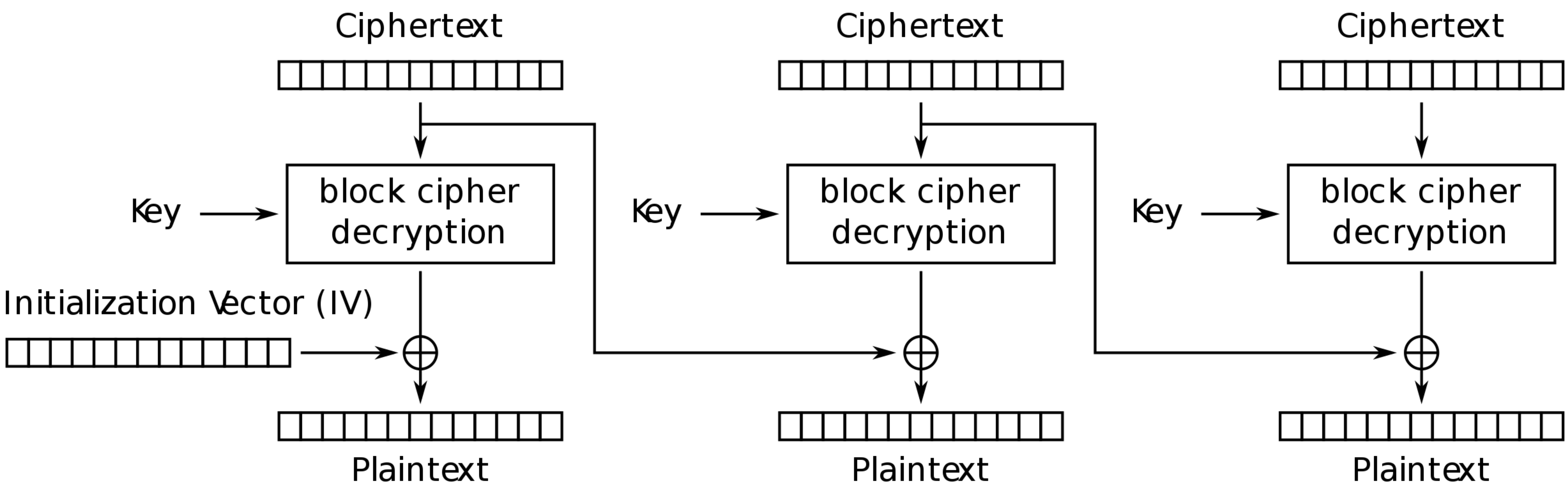
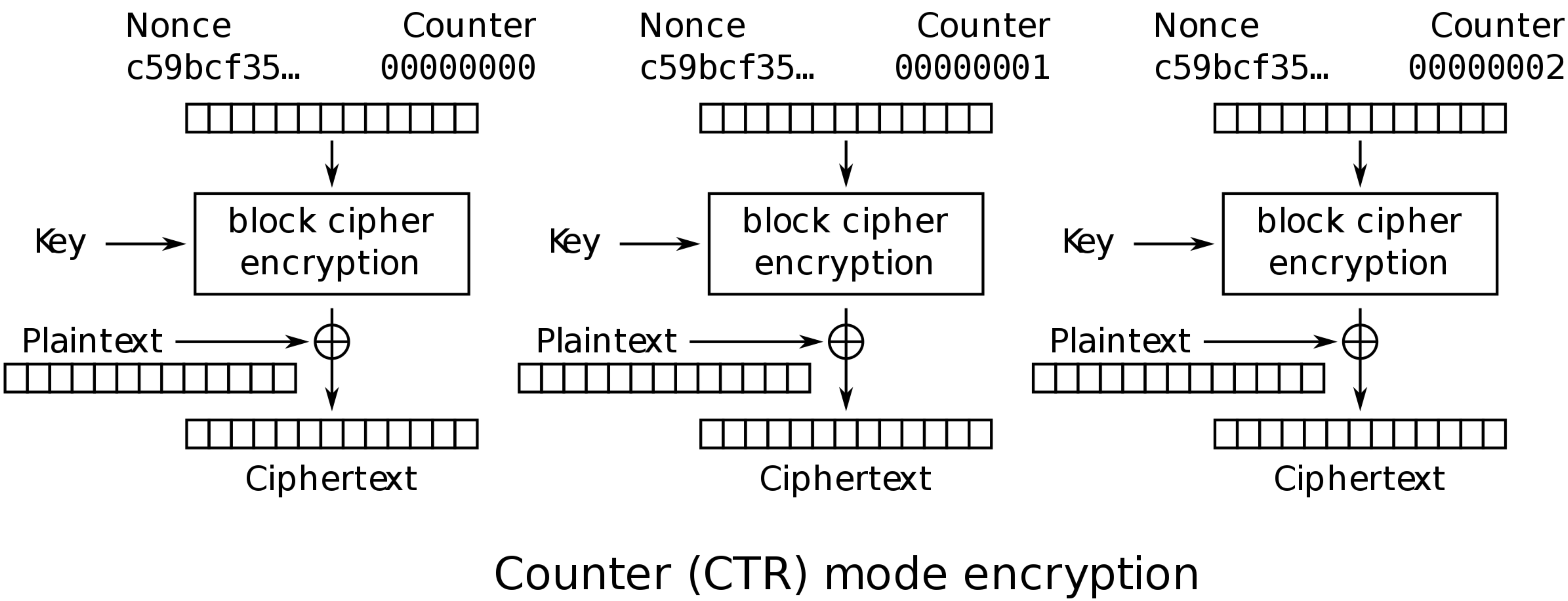



Cipher Block Chaining (CBC) mode decryption

Subtle attacks that abuse padding possible!

Source: wikipedia

# CTR mode with random IV

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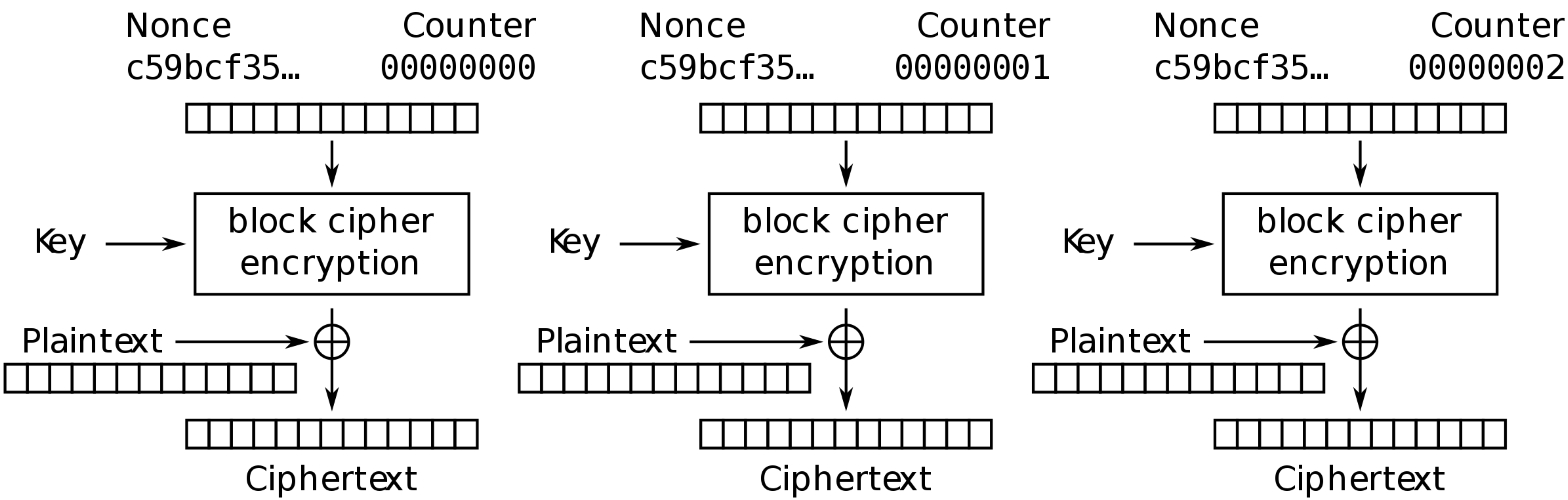
# CTR mode with random IV




Counter (CTR) mode encryption

Essentially use block cipher as stream cipher!

Source: wikipedia

# What security do we actually get?

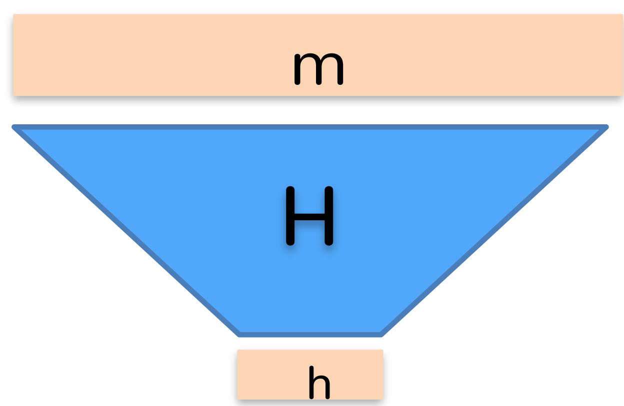
- All encryption breakable by brute force given enough knowledge about plaintext
- Try to decrypt ciphertext with every possible key until a valid plaintext is found
- Attack complexity proportional to size of key space
  - 64-bit key requires $2^{64}$ decryption attempts

# Outline

- Symmetric-key crypto
  - Encryption
  - Hash functions
  - Message authentication code
- Asymmetric (public-key) crypto
  - Encryption
  - Digital signatures

# Hash Functions

- A (cryptographic) hash function maps arbitrary length input into a fixed-size string




$h=H(m)$

  - |m| is arbitrarily large
  - |h| is fixed, usually 128-512 bits

# Hash Function Properties

- Finding a pre-image is hard
  - Given h, find m such that H(m)=h
- Finding a collision is hard
  - Find $m_1$ and $m_2$ such that $H(m_1)=H(m_2)$

# Hash Functions

- MD5: Message Digest
  - Designed by Ron Rivest
  - Very popular hash function
  - Output: 128 bits
  - Broken — **do not use!**

# Hash Functions

- SHA-1: Secure Hash Algorithm 1
  - Designed by NSA
  - Output: 160 bits
  - Broken — **do not use!**
- SHA-2: Secure Hash Algorithm 2
  - Designed by NSA
  - Output: 224, 256, 384, or 512 bits
  - Recommended for use today

# Hash Functions

- SHA-3: Secure Hash Algorithm 3
  - Result of NIST SHA-3 contest
  - Output: arbitrary size
  - Replacement once SHA-2 broken

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# MAC constructions

- HMAC: MAC based on hash function

  $MAC_k(m) = H(\ k \oplus opad \parallel H(\ k \oplus ipad \parallel m\ )\ )$

  - HMAC-SHA1: HMAC construction using SHA-1
  - HMAC-SHA256: HMAC construction using SHA-256

- CMAC: MAC based on block cipher

# MACs

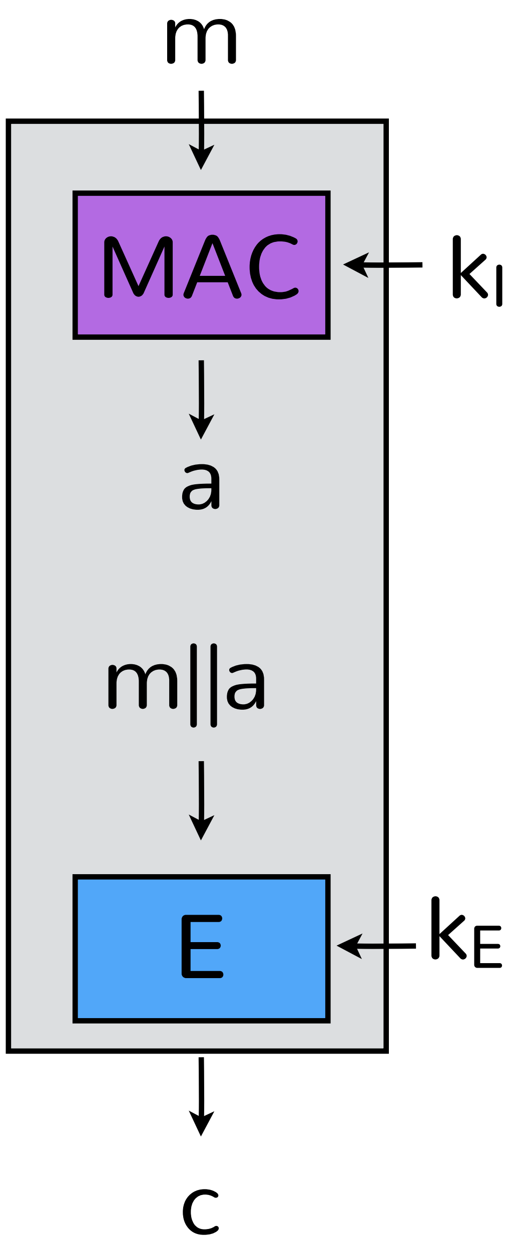
- Validate message integrity based on shared secret
- MAC: Message Authentication Code
  - Keyed hash function using shared secret
  - Hard compute hash without knowing key

$$a = MAC_k(m)$$

# Combining MAC with encryption

MAC then Encrypt (SSL)

- Integrity for plaintext not ciphertext
- Issue: need to decrypt before you can verify integrity
- Hard to get right!



# Combining MAC with encryption

Encrypt and MAC (SSH)

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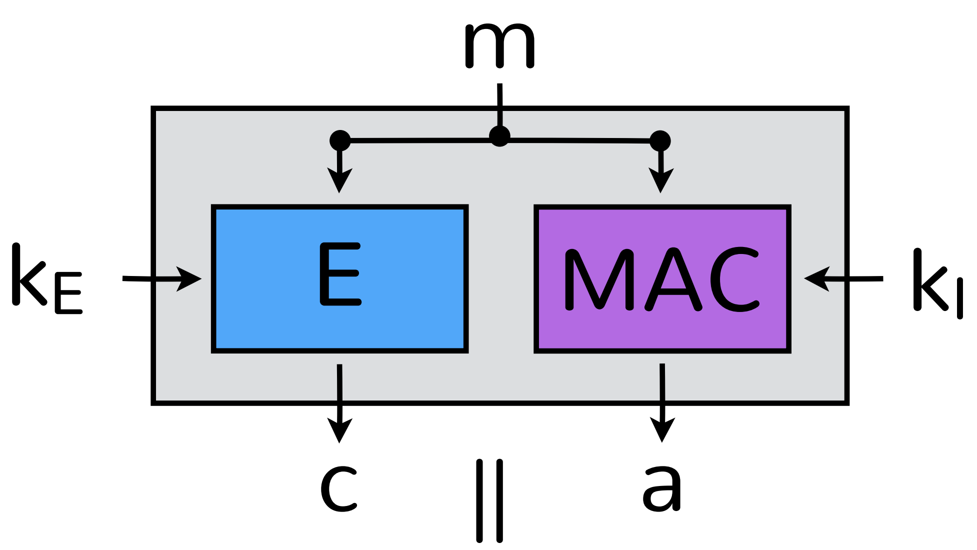
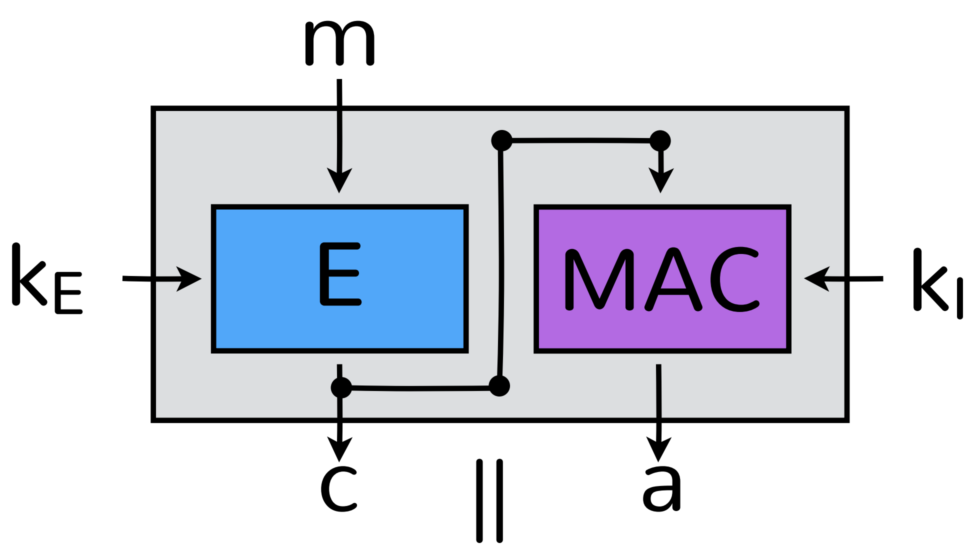


# Combining MAC with encryption

Encrypt then MAC (IPSec)

- Integrity for plaintext and ciphertext
- Always right!



# AEAD construction

- Authenticated Encryption with Associated Data
  - AES-GCM
  - E.g., as used in Google's Tink:

```
import com.google.crypto.tink.Aead;
import com.google.crypto.tink.KeysetHandle;
import com.google.crypto.tink.aead.AeadKeyTemplates;

// 1. Generate the key material.
KeysetHandle keysetHandle = KeysetHandle.generateNew(
    AeadKeyTemplates.AES128_GCM);

// 2. Get the primitive.
Aead aead = keysetHandle.getPrimitive(Aead.class);

// 3. Use the primitive.
byte[] ciphertext = aead.encrypt(plaintext, associatedData);
```