# Cryptography (cont.)

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Thanks to Dan Boneh, Dieter Gollmann, John Manferdelli, John Mitchell, Vitaly Shmatikov, Bennet Yee, and many others for sample slides and materials ...

# Updates Oct. 17th

- **Lab 1** is due *Friday*
  - TA office hours Fri before class (12-2:20, CSE 002)
  - My office hours today, Wed after class (CSE 210)
- 584 paper reviews
- What are you doing to Emacs?

# Today

- Today's symmetric algorithm: ***AES block cipher***
- ***Cryptographic primitives***: how to use a block cipher
- Evaluating privacy and integrity

# DES and 56 bit keys (Stallings Tab 2.2)

- 56 bit keys are quite short

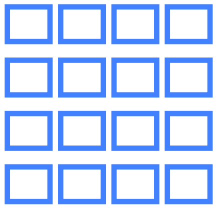
| Key Size (bits) | Number of Alternative Keys | Time required at 1 encryption/$\mu s$ | Time required at $10^6$ encryptions/$\mu s$ |
|---|---|---|---|
| 32 | $2^{32} = 4.3 \times 10^9$ | $2^{31}\ \mu s = 35.8$ minutes | 2.15 milliseconds |
| 56 | $2^{56} = 7.2 \times 10^{16}$ | $2^{55}\ \mu s = 1142$ years | 10.01 hours |
| 128 | $2^{128} = 3.4 \times 10^{38}$ | $2^{127}\ \mu s = 5.4 \times 10^{24}$ years | $5.4 \times 10^{18}$ years |
| 168 | $2^{168} = 3.7 \times 10^{50}$ | $2^{167}\ \mu s = 5.9 \times 10^{36}$ years | $5.9 \times 10^{30}$ years |
| 26 characters (permutation) | $26! = 4 \times 10^{26}$ | $2 \times 10^{26}\ \mu s = 6.4 \times 10^{12}$ years | $6.4 \times 10^6$ years |

- 1999: EFF DES Crack + distibuted machines
  - < 24 hours to find DES key
- DES ---> 3DES
  - 3DES: DES + inverse DES + DES (with 2 or 3 diff keys)

# Advanced Encryption Standard (AES)

- New federal standard as of 2001
- Based on the Rijndael algorithm
- 128-bit blocks, keys can be 128, 192 or 256 bits
- Unlike DES, does <u>not</u> use Feistel structure
  - The entire block is processed during each round
- Design uses some very nice mathematics

# Basic Structure of Rijndael



**128-bit plaintext**

(arranged as 4x4 array of 8-bit bytes)

**128-bit key**

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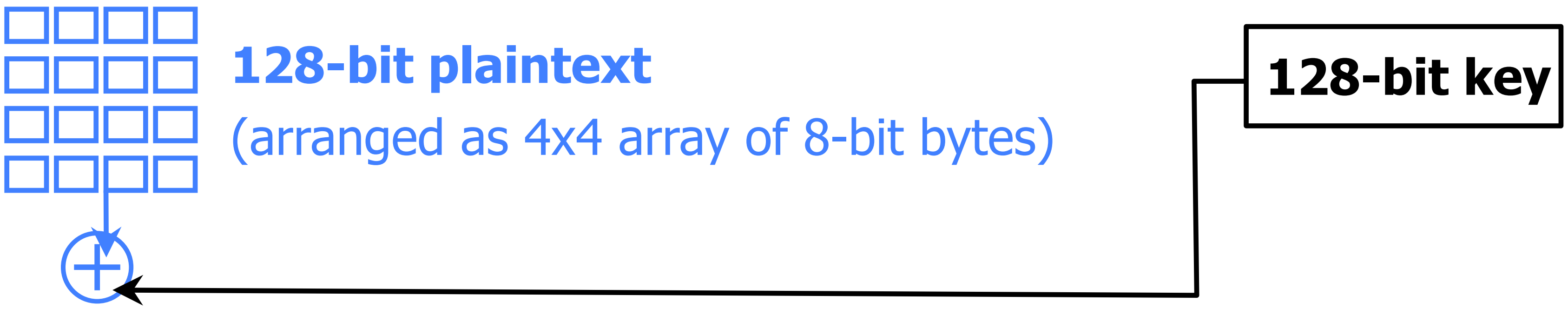

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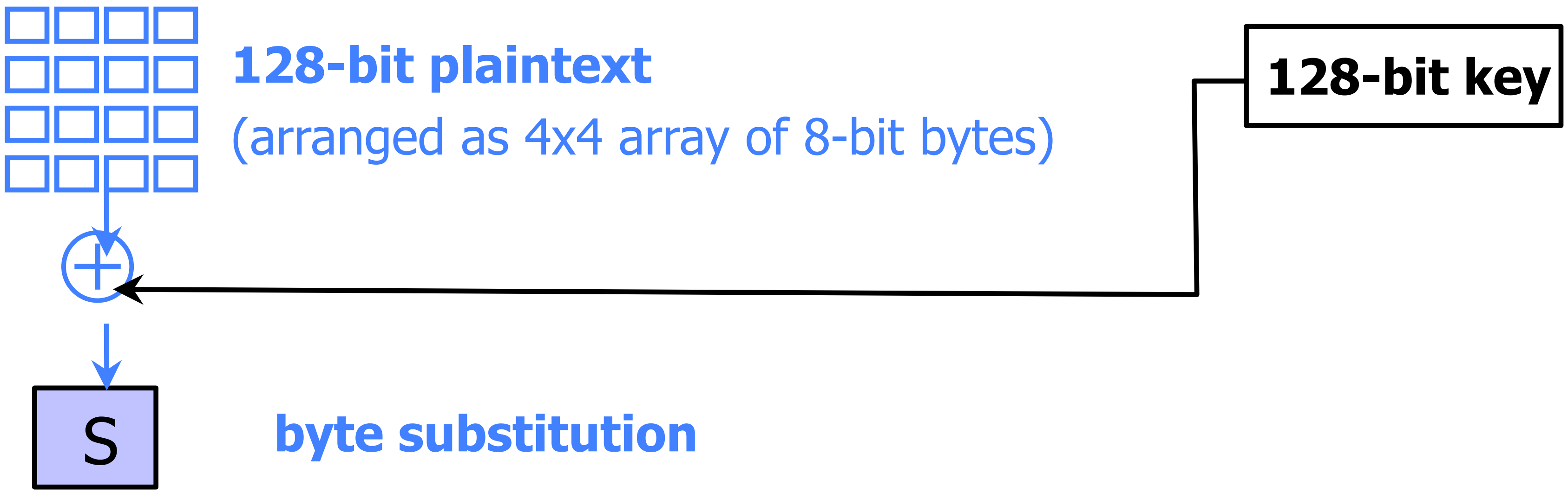

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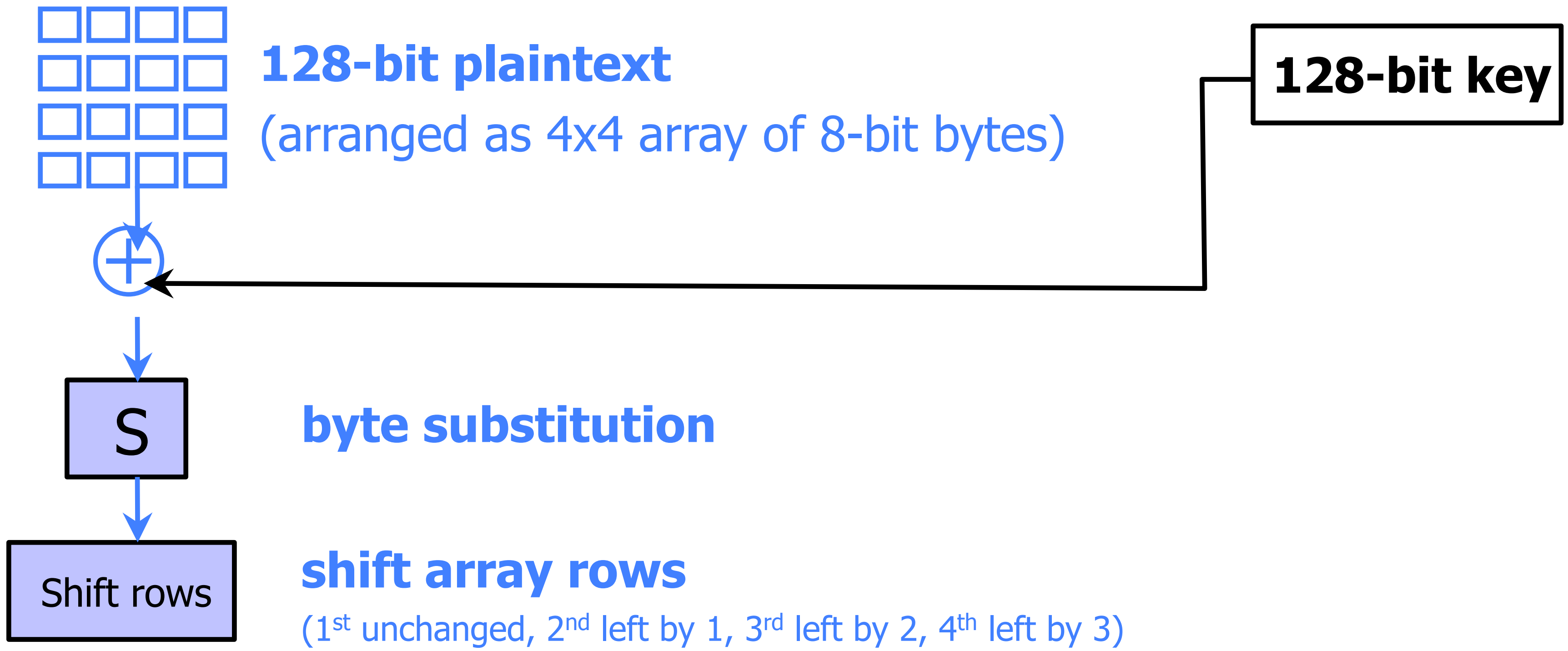

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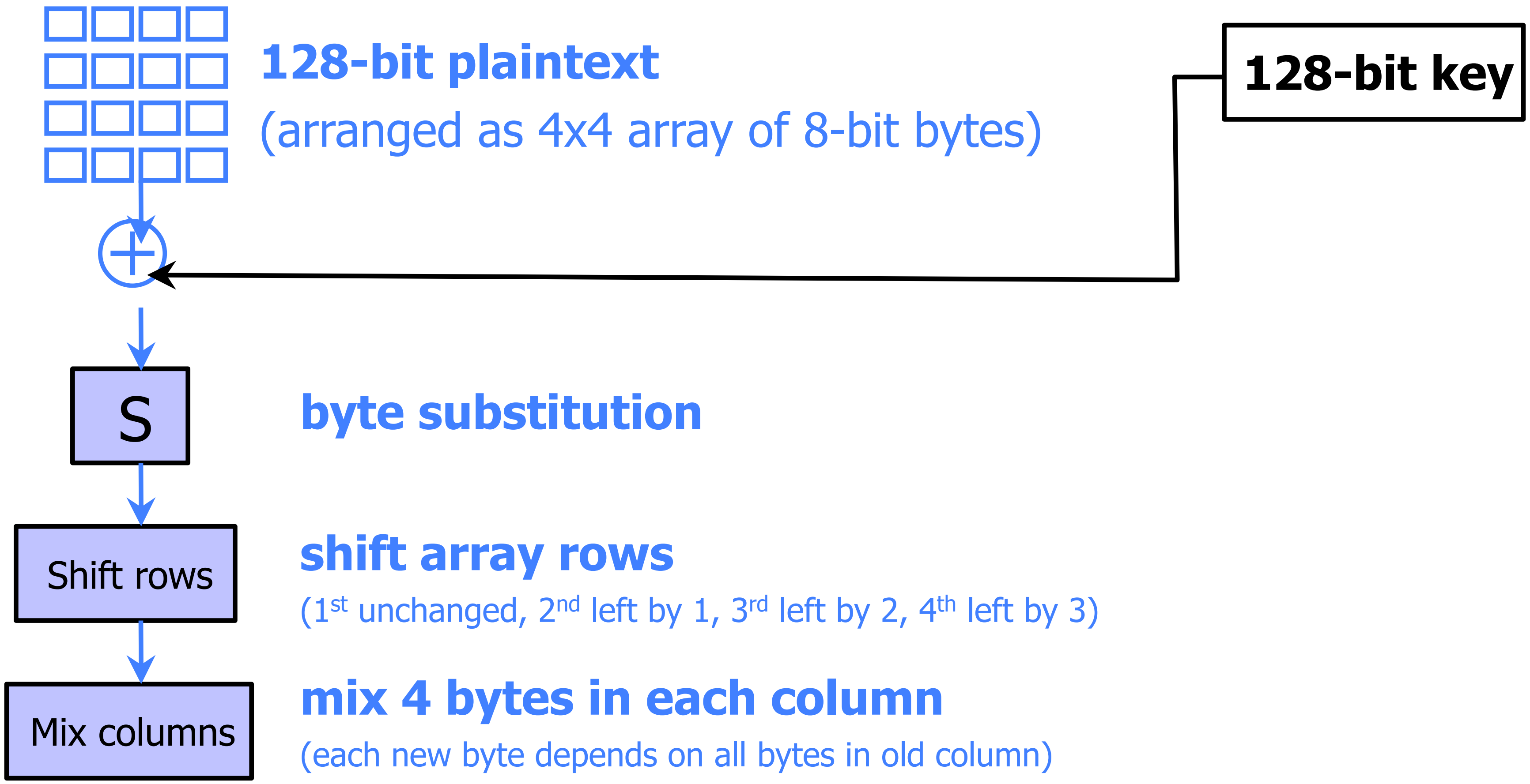

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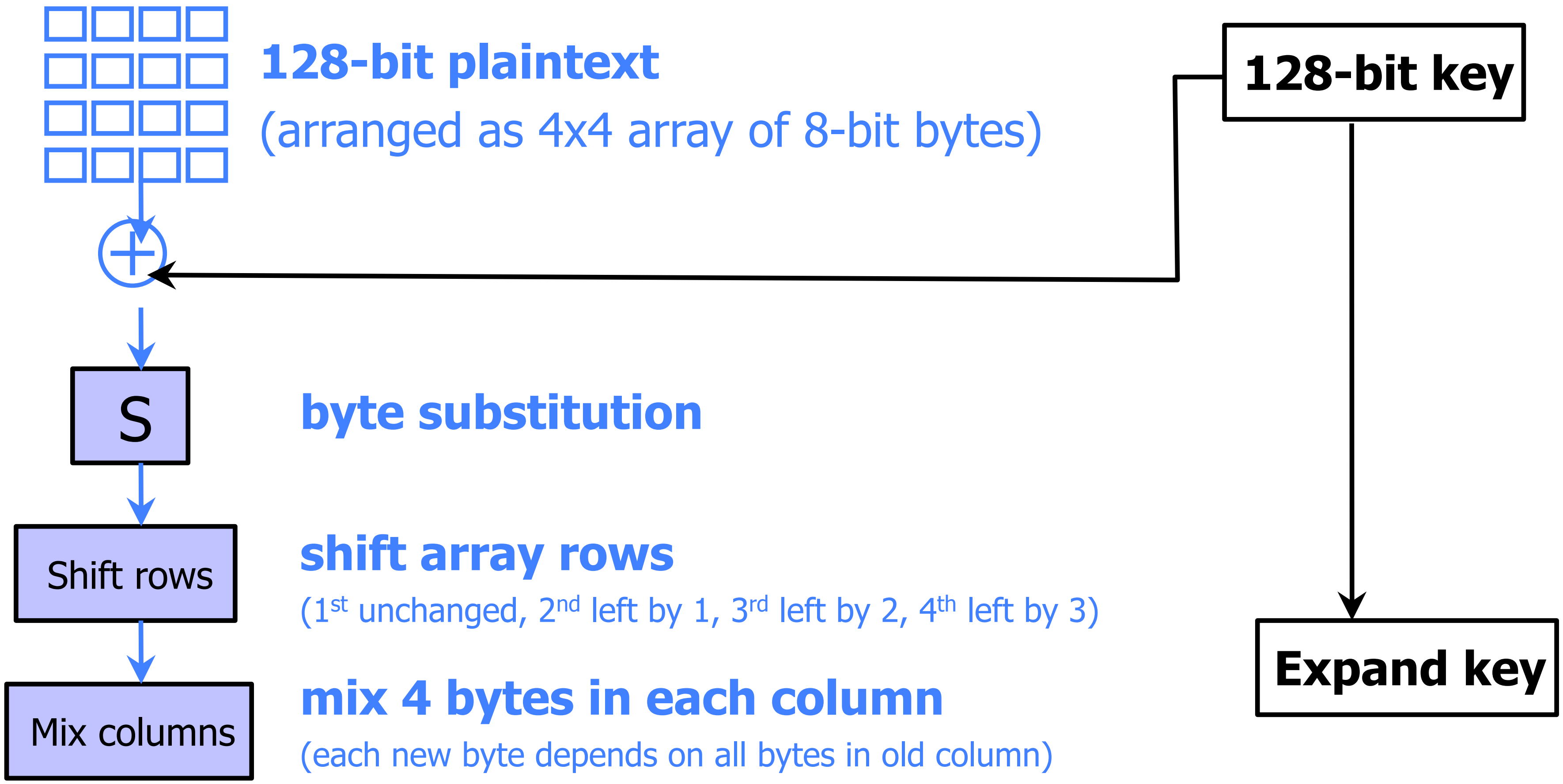

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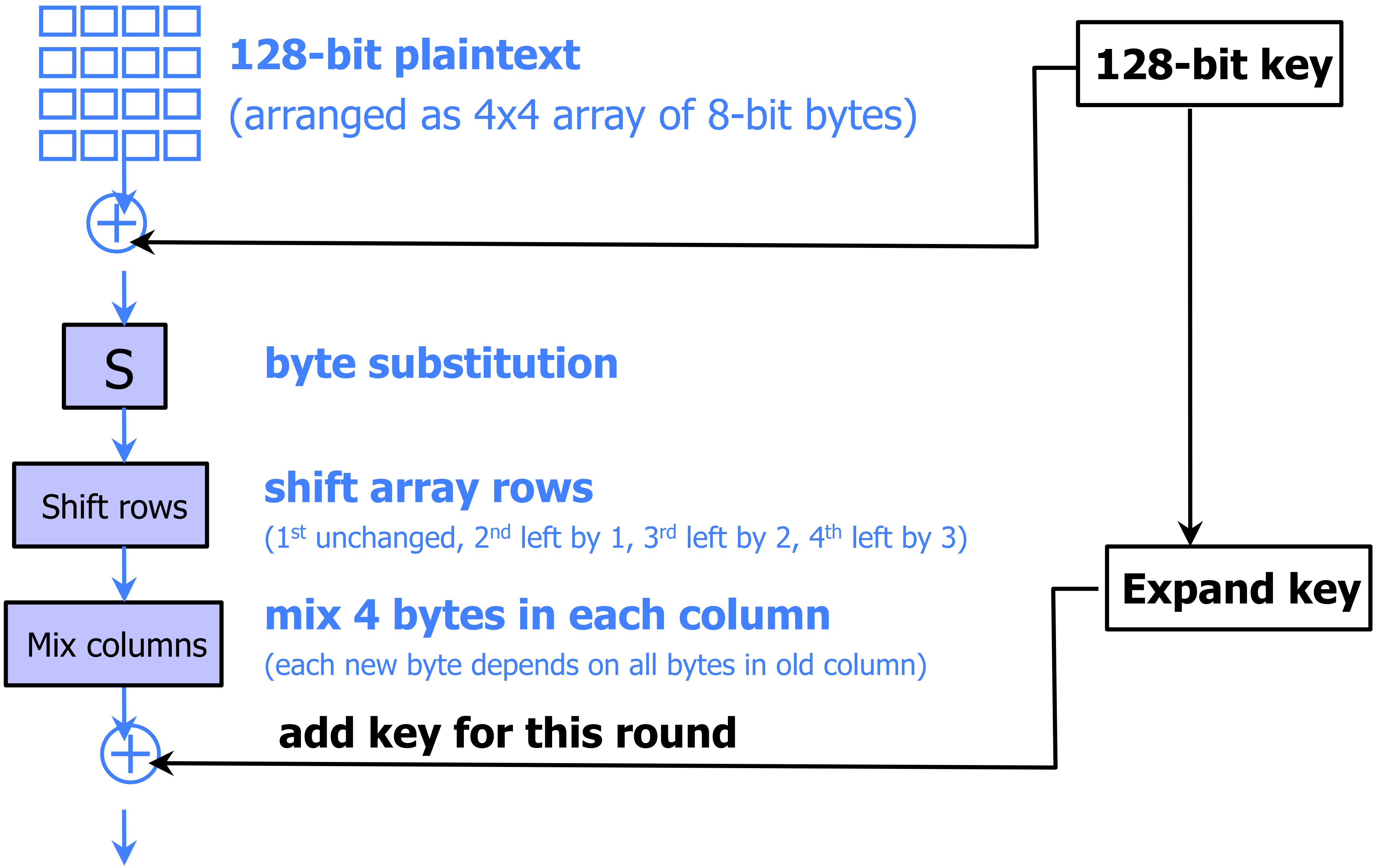

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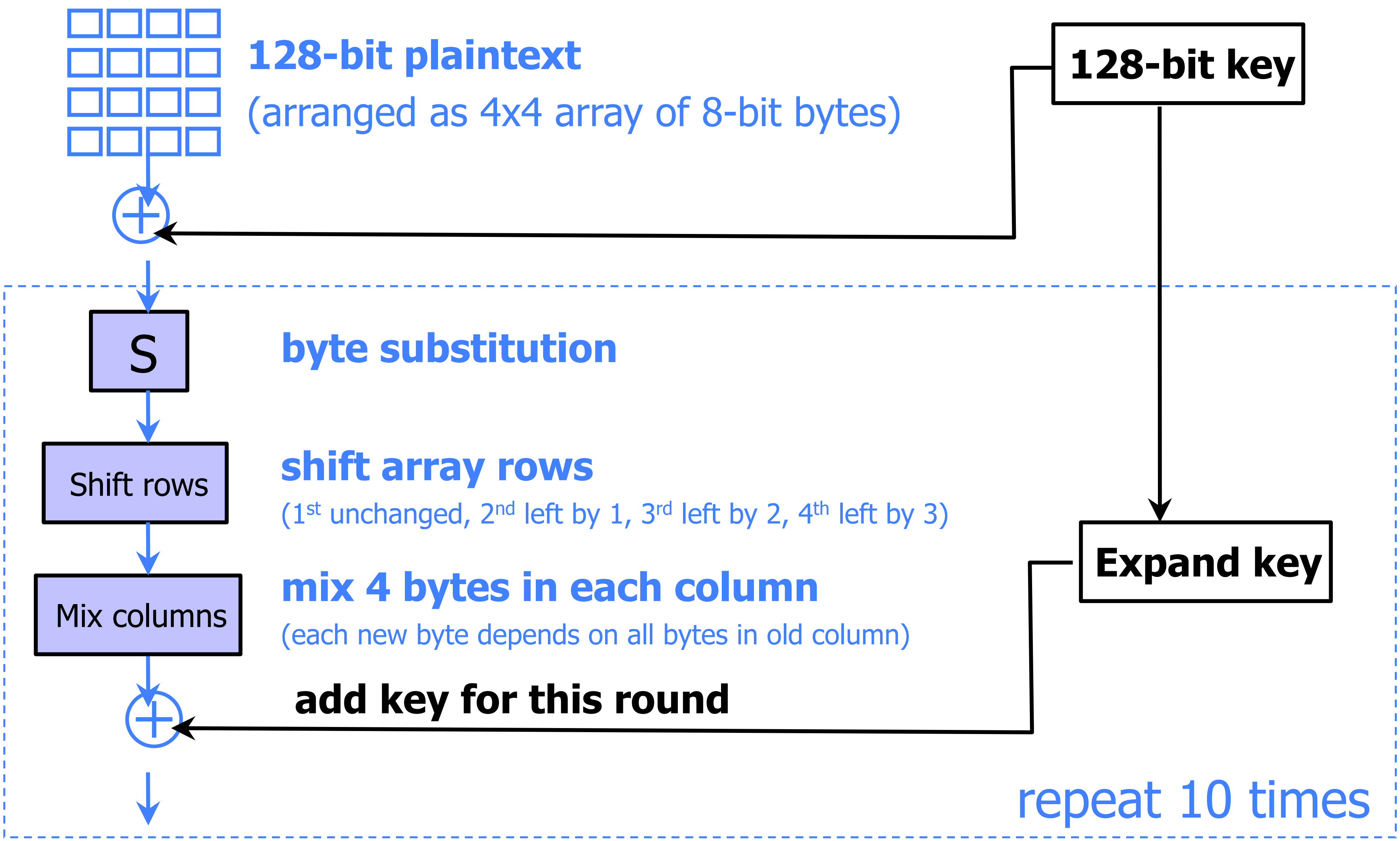
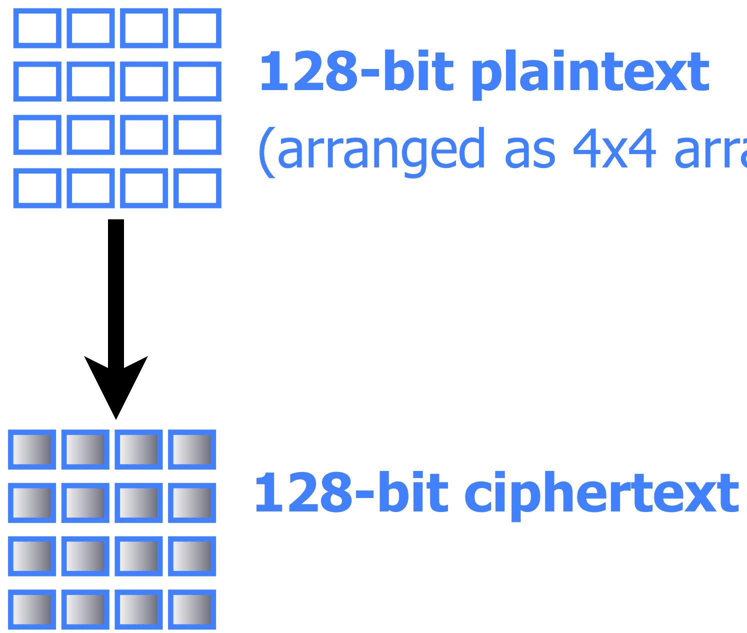


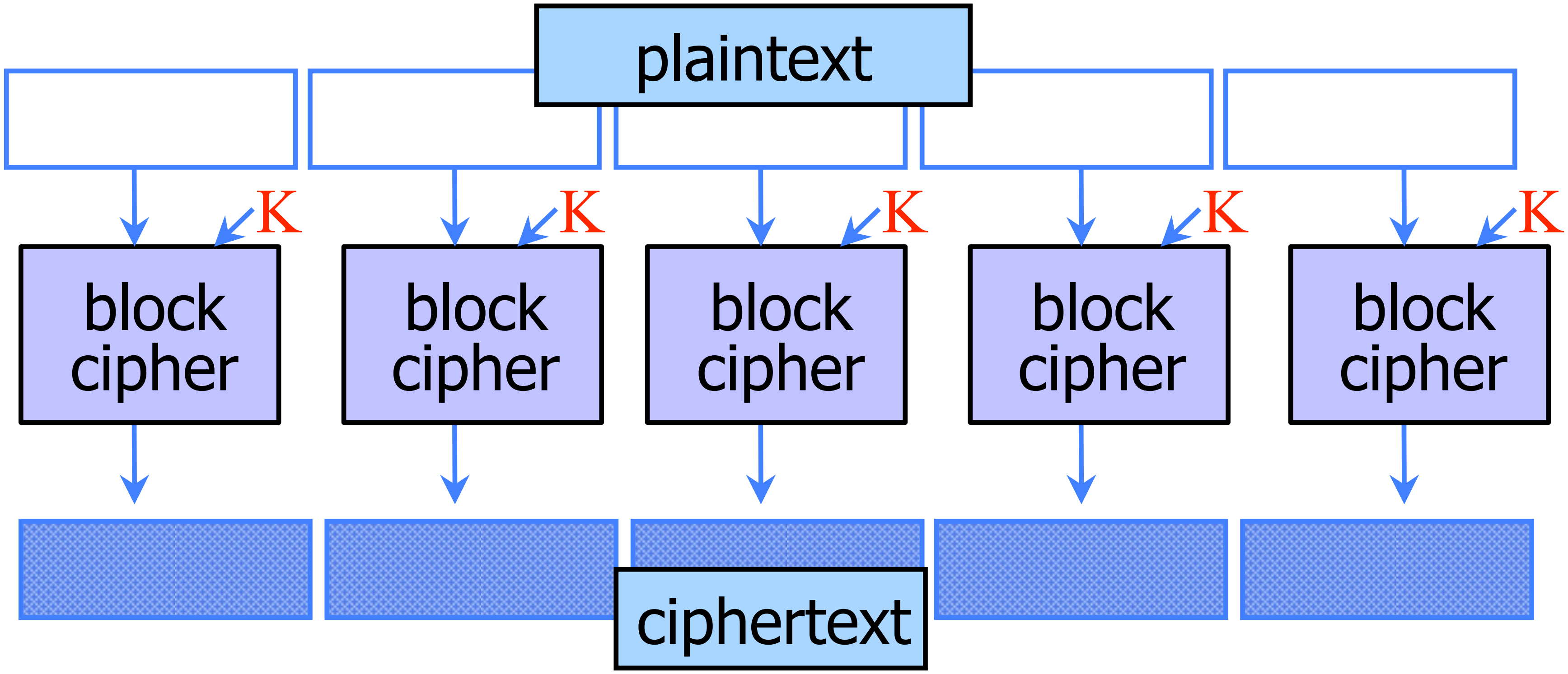
# Encrypting a Large Message

- So, we've got a good block cipher, but our plaintext is larger than 128-bit block size




- What should we do?

# Electronic Code Book (ECB) Mode



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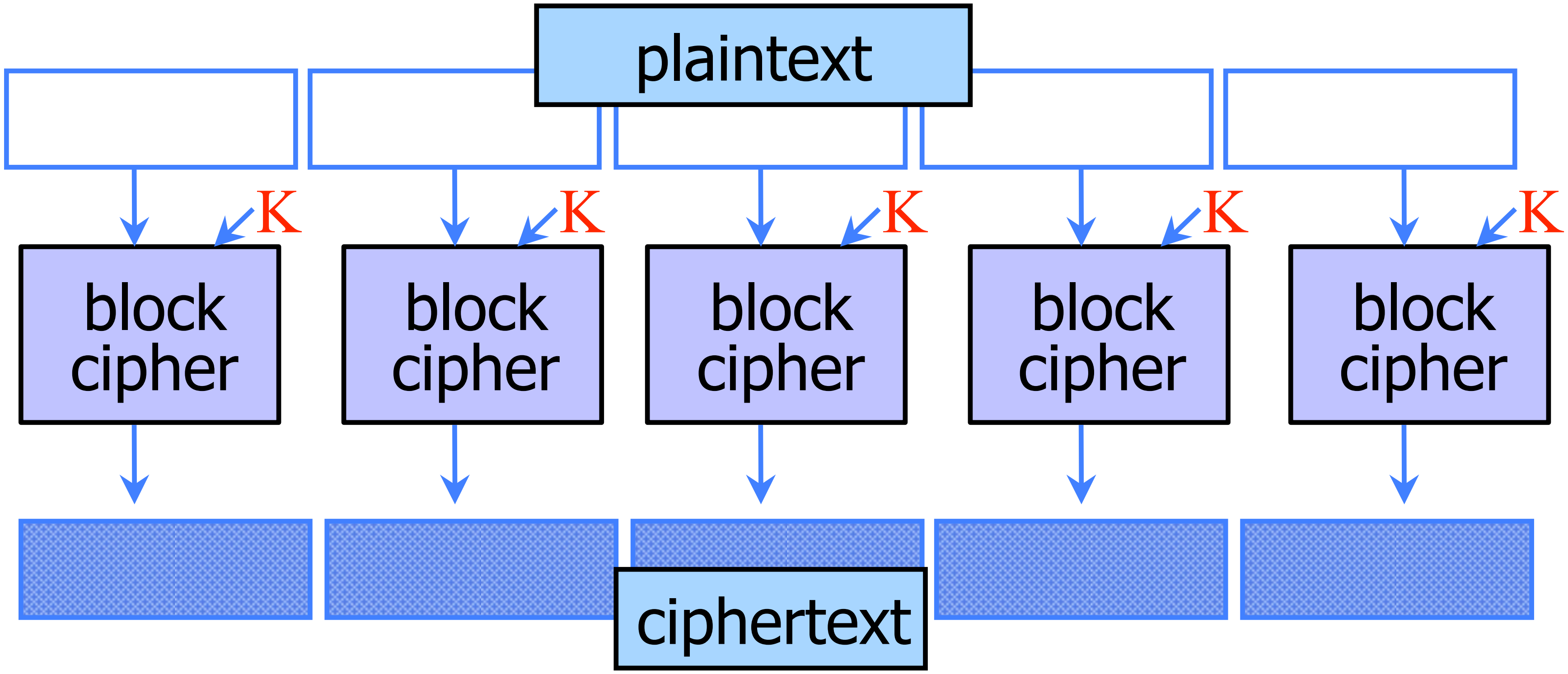
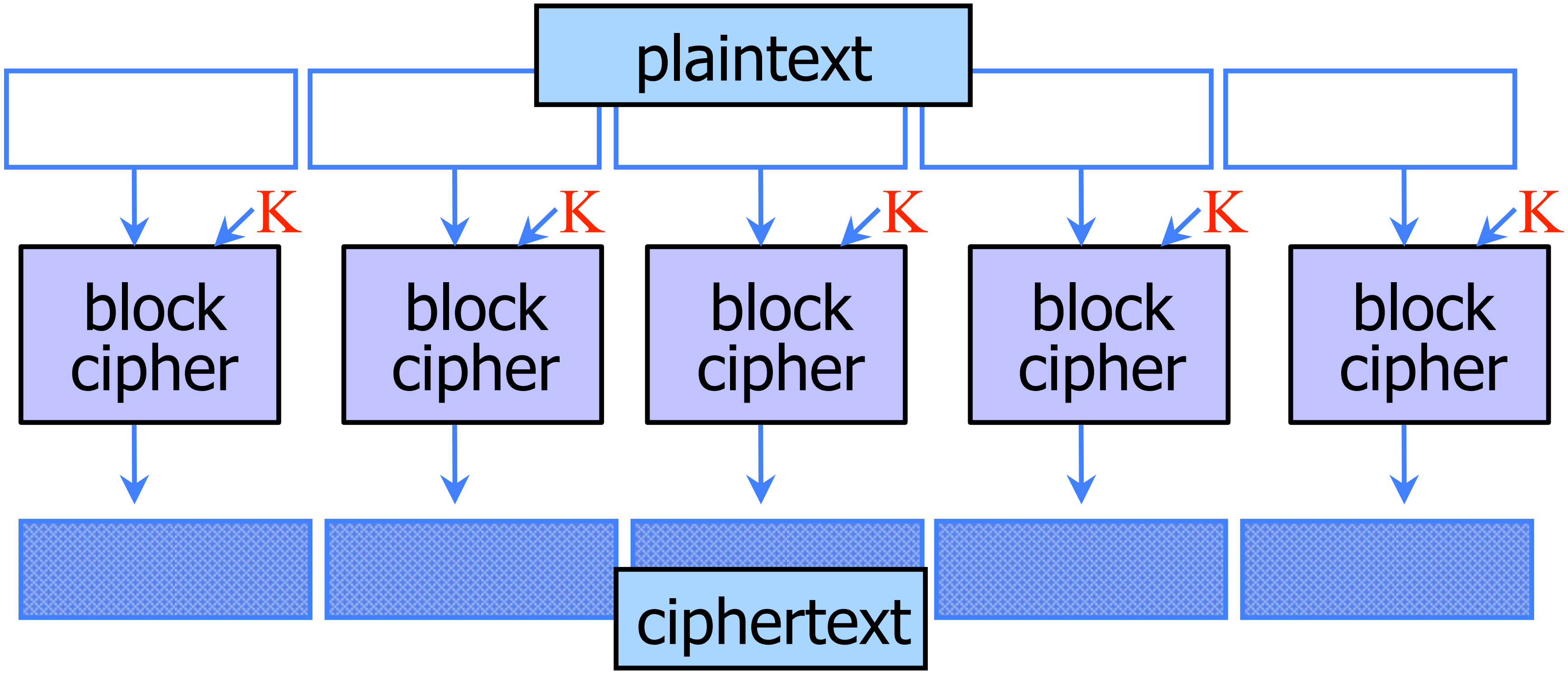


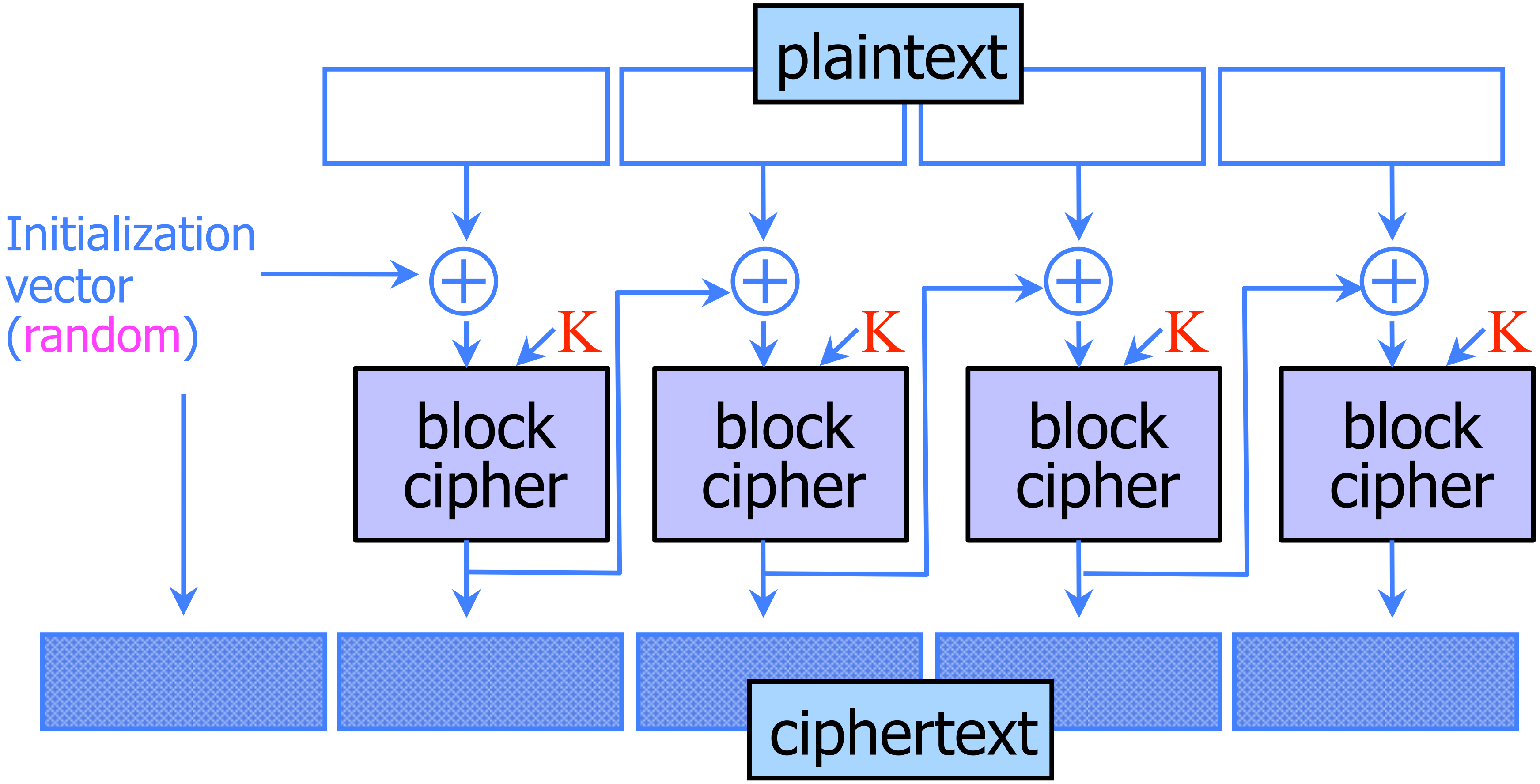

- Identical blocks of plaintext produce identical blocks of ciphertext

# Electronic Code Book (ECB) Mode



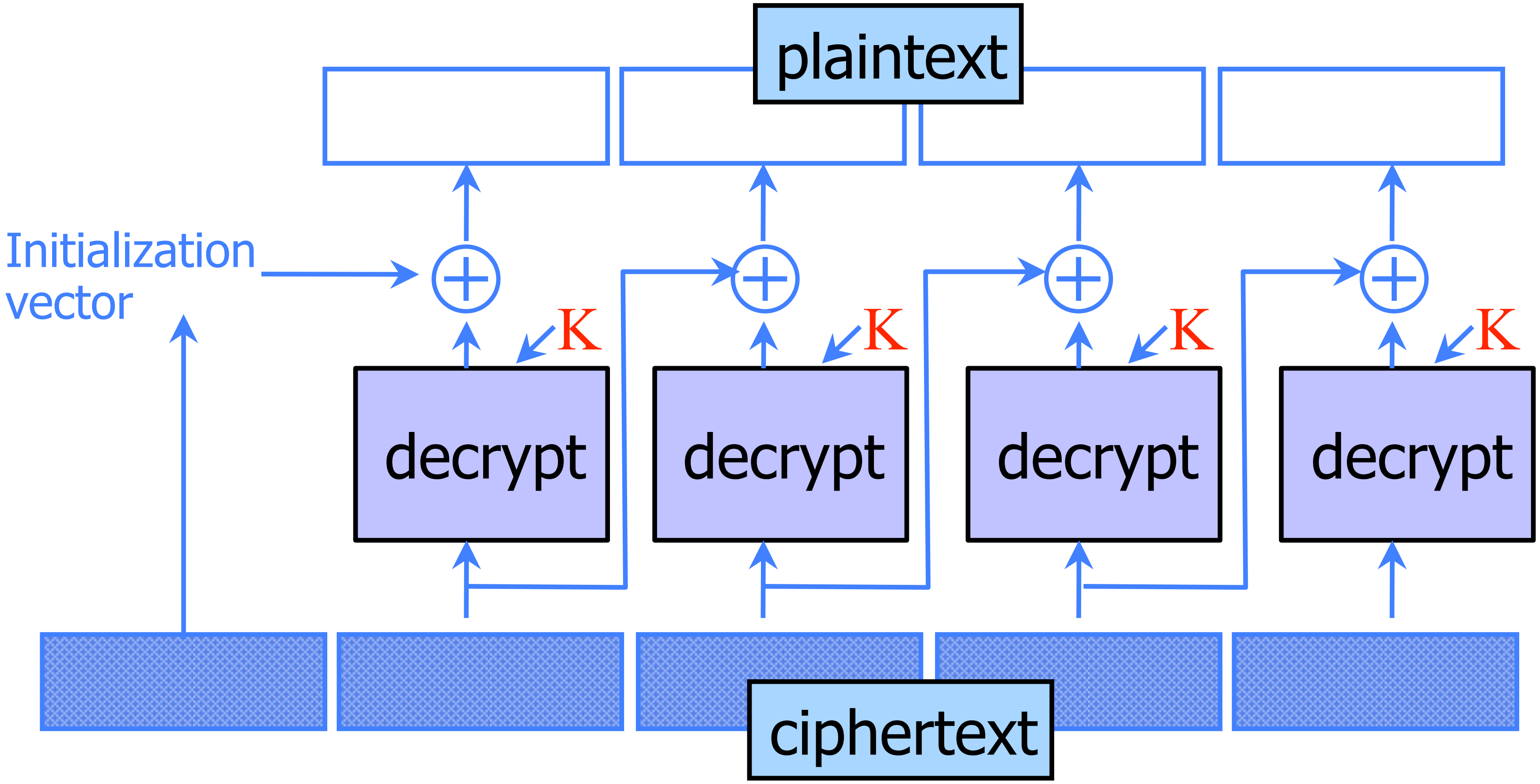

- Identical blocks of plaintext produce identical blocks of ciphertext
- No integrity checks: can mix and match blocks

# Cipher Block Chaining (CBC) Mode: Encryption




- Identical blocks of plaintext encrypted differently
- Last cipherblock depends on entire plaintext
  - Still does not guarantee integrity

# CBC Mode: Decryption

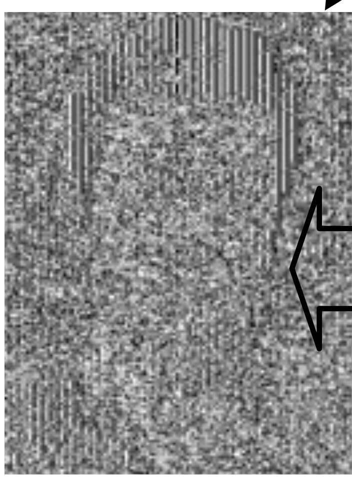


# ECB vs. CBC

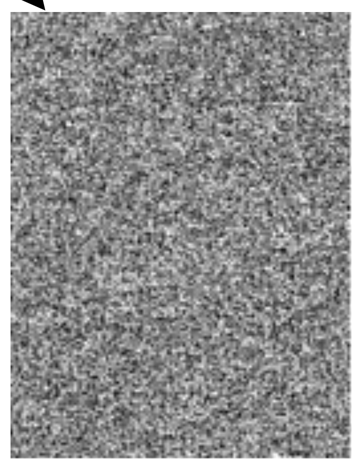
[Picture due to Bart Preneel]

AES in ECB mode

AES in CBC mode

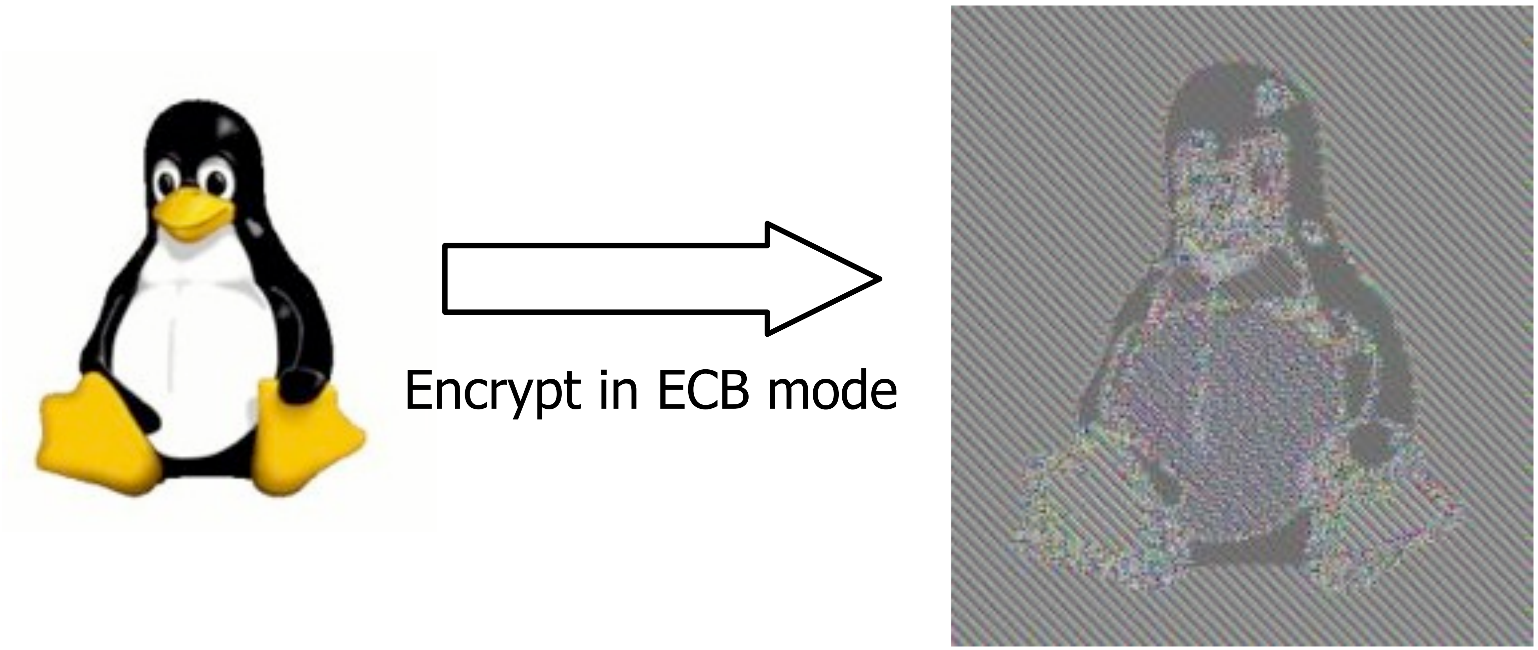


Similar plaintext blocks produce similar ciphertext blocks (not good!)

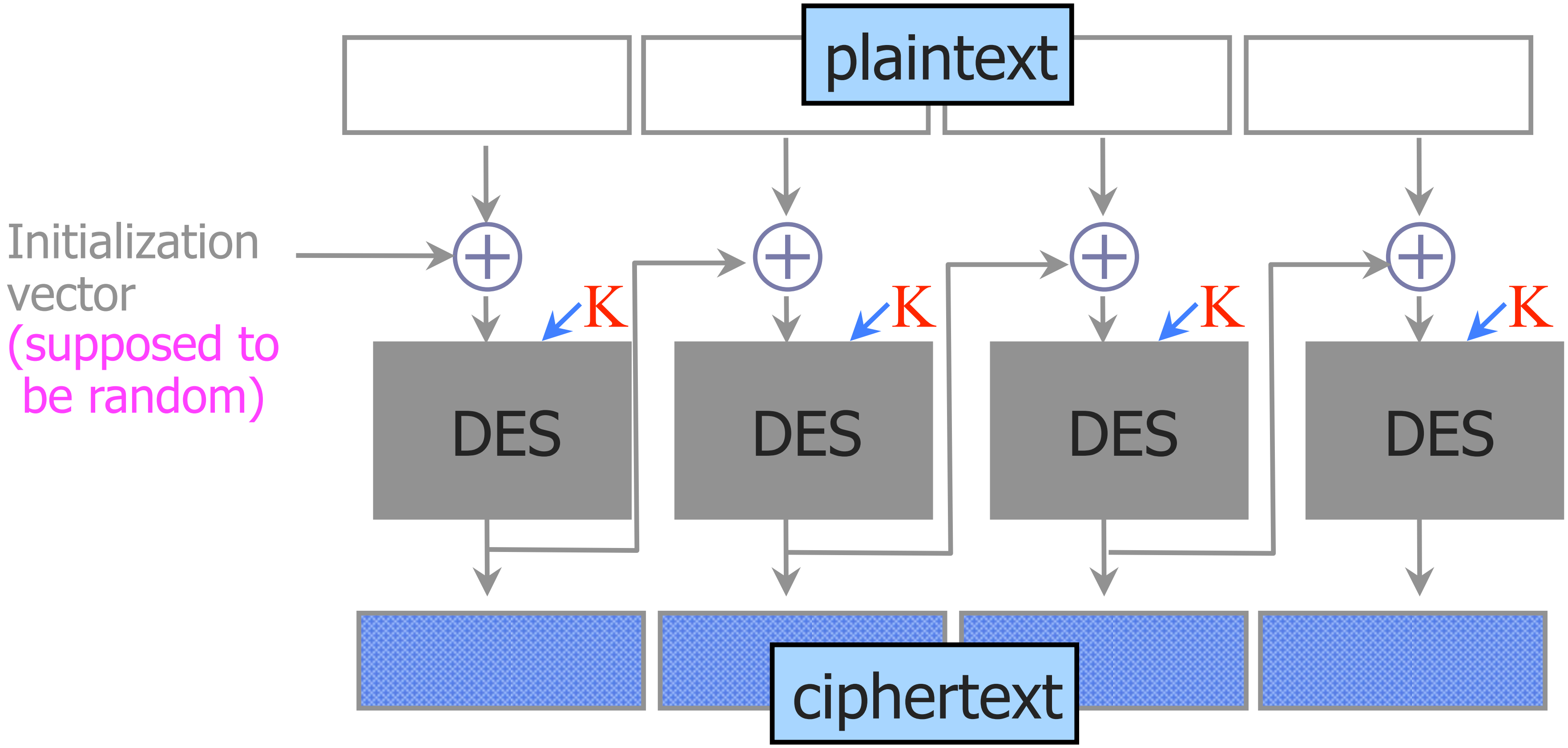


# Information Leakage in ECB Mode

[Wikipedia]



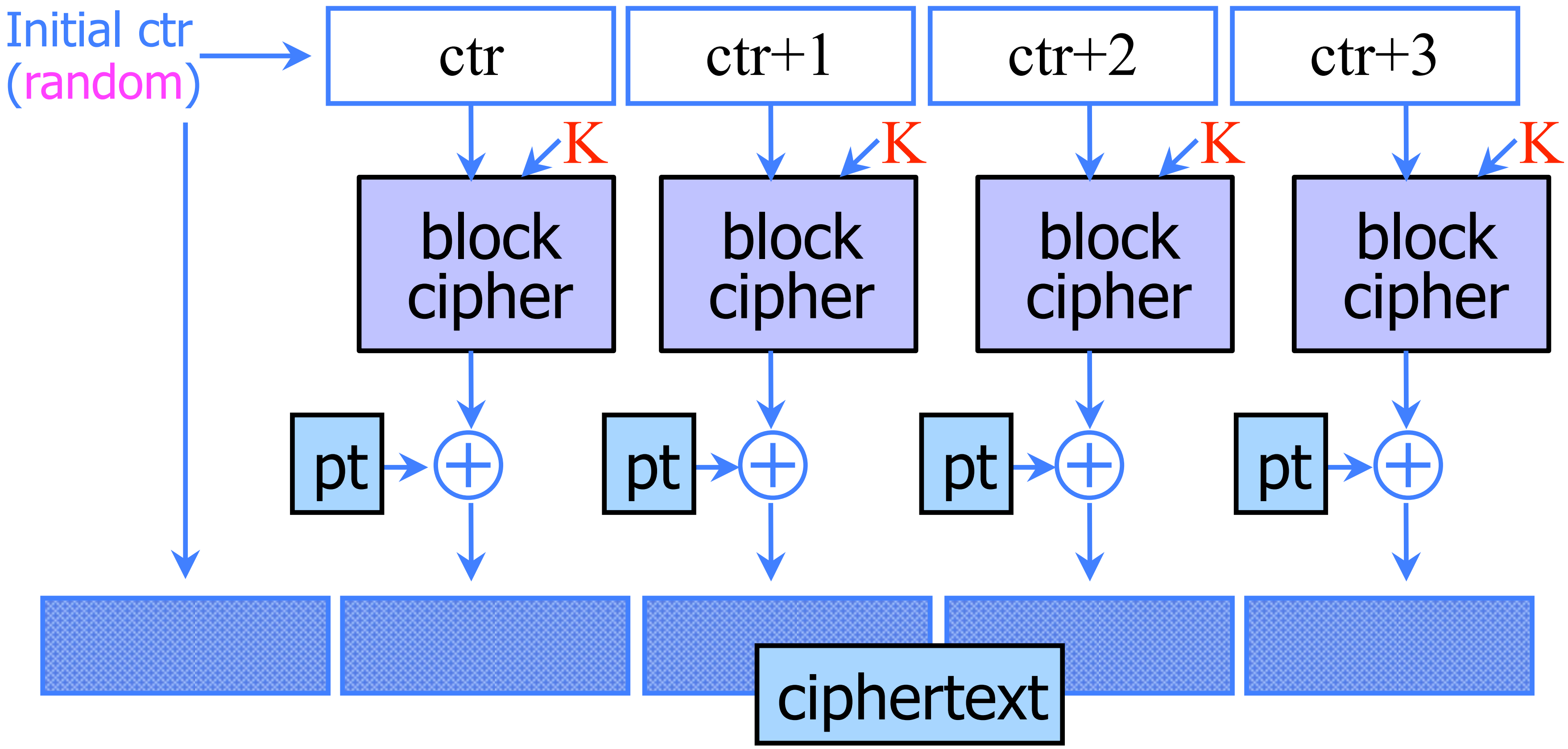
# CBC and Electronic Voting




Found in the source code for Diebold voting machines:

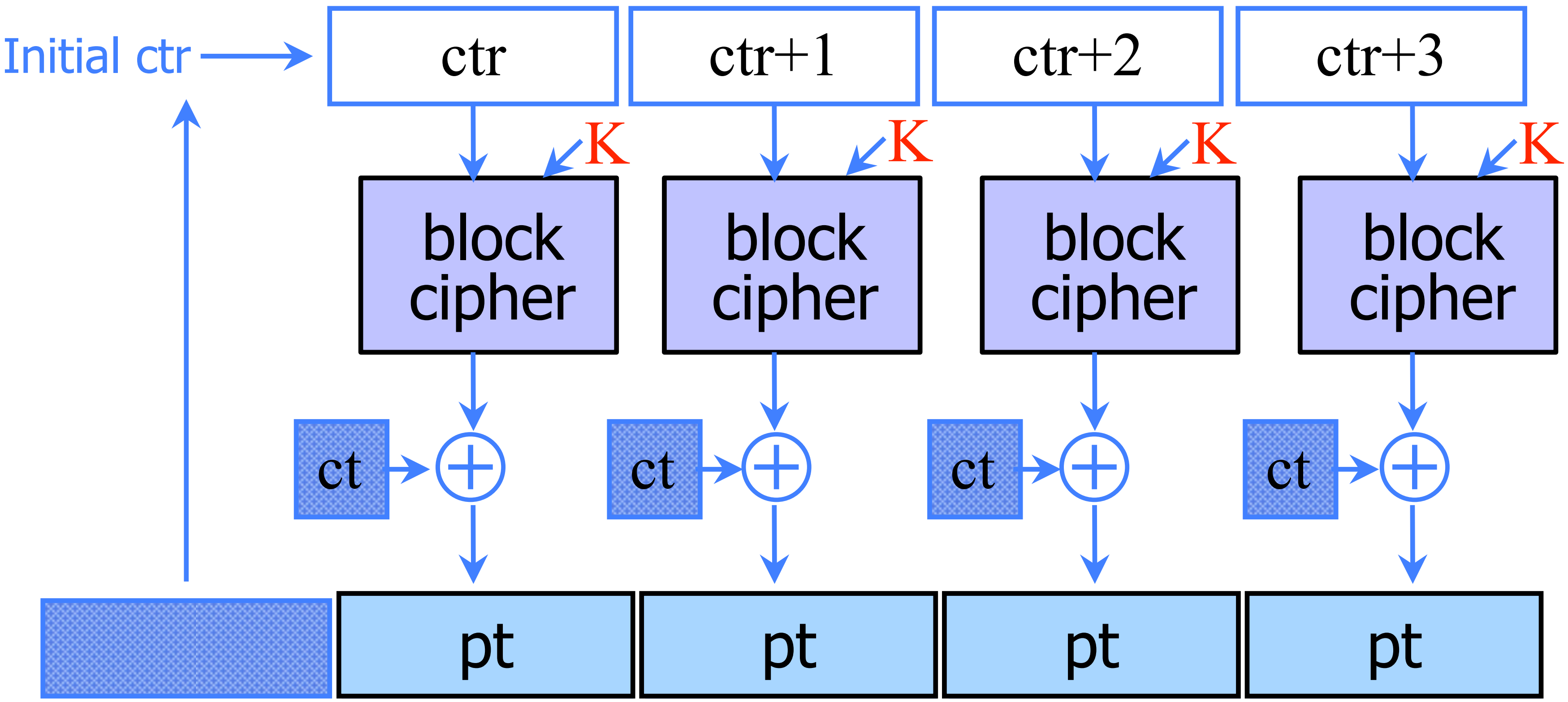
```
DesCBCEncrypt((des_c_block*)tmp, (des_c_block*)record.m_Data,
    totalSize, DESKEY, NULL, DES_ENCRYPT)
```

# Counter (CTR) Mode: Encryption



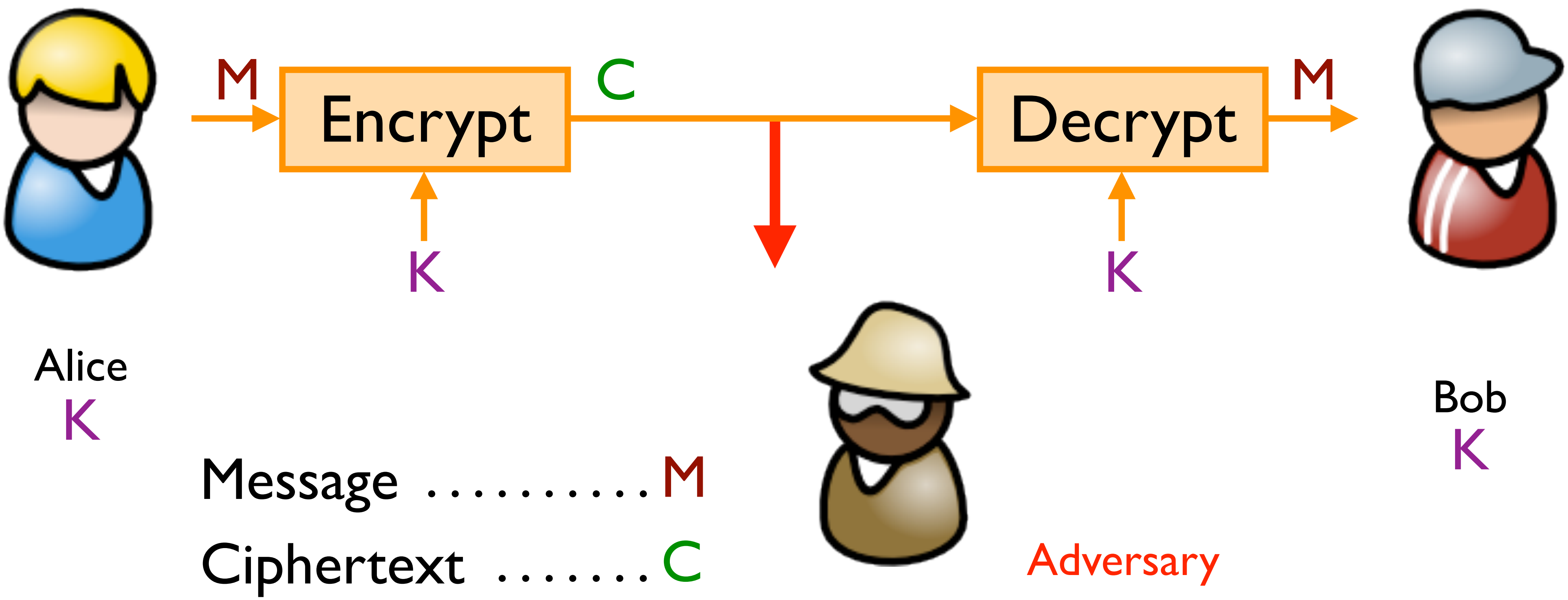

- Identical blocks of plaintext encrypted differently
- Still does not guarantee integrity
- Fragile if ctr repeats

# CTR Mode: Decryption



# Achieving Privacy (Symmetric)

Encryption schemes: A tool for protecting privacy.



# When Is an Encryption Scheme "Secure"?

- Hard to recover the key?
  - What if attacker can learn plaintext without learning the key?
- Hard to recover plaintext from ciphertext?
  - What if attacker learns some bits or some function of bits?
- Fixed mapping from plaintexts to ciphertexts?
  - What if attacker sees two identical ciphertexts and infers that the corresponding plaintexts are identical?
  - Implication: encryption must be randomized or stateful

# How Can a Cipher Be Attacked?

- Assume that the attacker knows the encryption algorithm and wants to learn information about some ciphertext
- Main question: what else does attacker know?
  - Depends on the application in which cipher is used!
- Ciphertext-only attack
- Known-plaintext attack (stronger)
  - Knows some plaintext-ciphertext pairs
- Chosen-plaintext attack (even stronger)
  - Can obtain ciphertext for any plaintext of his choice
- Chosen-ciphertext attack (very strong)
  - Can decrypt any ciphertext <u>except</u> the target
  - Sometimes very realistic model

# Defining Security (Not Required)

- Attacker does not know the key
- He chooses as many plaintexts as he wants, and learns the corresponding ciphertexts
- When ready, he picks two plaintexts $M_0$ and $M_1$
  - He is even allowed to pick plaintexts for which he previously learned ciphertexts!
- He receives either a ciphertext of $M_0$, or a ciphertext of $M_1$
- He wins if he guesses correctly which one it is

# Defining Security (Not Required)

- Idea: attacker should not be able to learn even a single bit of the encrypted plaintext
- Define Enc($M_0$,$M_1$,b) to be a function that returns encrypted $M_b$

  0 or 1

  - Given two plaintexts, Enc returns a ciphertext of one or the other depending on the value of bit b
  - Think of Enc as a magic box that computes ciphertexts on attacker's demand. He can obtain a ciphertext of any plaintext M by submitting $M_0=M_1=M$, or he can try to learn even more by submitting $M_0 \neq M_1$.
- Attacker's goal is to learn just one bit b

# Chosen-Plaintext Security (Not Required)

- Consider two experiments (A is the attacker)

Experiment 0

A interacts with Enc(-,-,0)
and outputs bit d

Experiment 1

A interacts with Enc(-,-,1)
and outputs bit d

  - Identical except for the value of the secret bit
  - d is attacker's guess of the secret bit

If A "knows" secret bit, he should be able to make his output depend on it

- Attacker's advantage is defined as

| Prob(A outputs 1 in Exp0) - Prob(A outputs 1 in Exp1)) |

- Encryption scheme is chosen-plaintext secure if this advantage is negligible for any efficient A

# "Simple" Example (Not Required)

- Any deterministic, stateless symmetric encryption scheme is insecure
  - Attacker can easily distinguish encryptions of different plaintexts from encryptions of identical plaintexts
  - This includes ECB mode of common block ciphers!

Attacker A interacts with Enc(-,-,b)

Let X,Y be any two different plaintexts

$C_1 \leftarrow Enc(X,Y,b)$; $C_2 \leftarrow Enc(Y,Y,b)$;

If $C_1=C_2$ then b=1 else say b=0

- The advantage of this attacker A is 1

Prob(A outputs 1 if b=0)=0 Prob(A outputs 1 if b=1)=1

# Why Hide Everything?

- Leaking even a little bit of information about the plaintext can be disastrous
- Electronic voting
  - 2 candidates on the ballot (1 bit to encode the vote)
  - If ciphertext leaks the parity bit of the encrypted plaintext, eavesdropper learns the entire vote
- Also, want a strong definition, that implies others

# Birthday attacks

- Are there two people in the first 1/3 of this classroom that have the same birthday?
  - Yes?
  - No?

# Birthday attacks

- Why is this important for cryptography?
  - 365 days in a year (366 some years)
    - Pick one person. To find another person with same birthday would take on the order of 365/2 = 182.5 people
    - Expect "collision" -- two people with same birthday -- with a room of only 23 people
    - For simplicity, approximate when we expect a collision as the square root of 365.
  - $2^{128}$ different 128-bit keys
    - Pick one key at random. To exhaustively search for this key requires trying on average $2^{127}$ keys.
    - Expect a "collision" after selecting approximately $2^{64}$ random keys.
    - 64 bits of security against collision attacks, not 128 bits.