CSE 484 / CSE M 584 (Winter 2013)

(Continue) Cryptography

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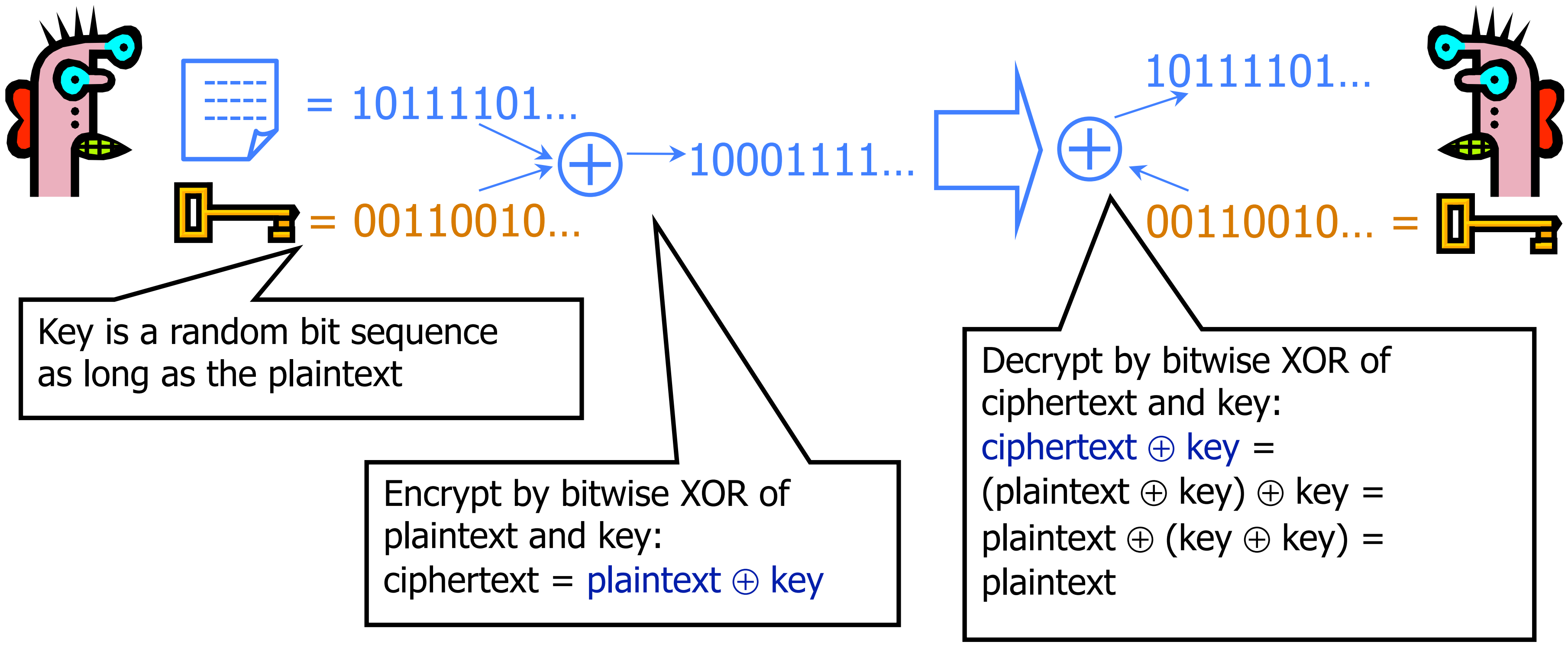
Thanks to Dan Boneh, Dieter Gollmann, Dan Halperin, John Manferdelli, John Mitchell, Vitaly Shmatikov, Bennet Yee, and many others for sample slides and materials ...

Goals for Today

- Cryptography

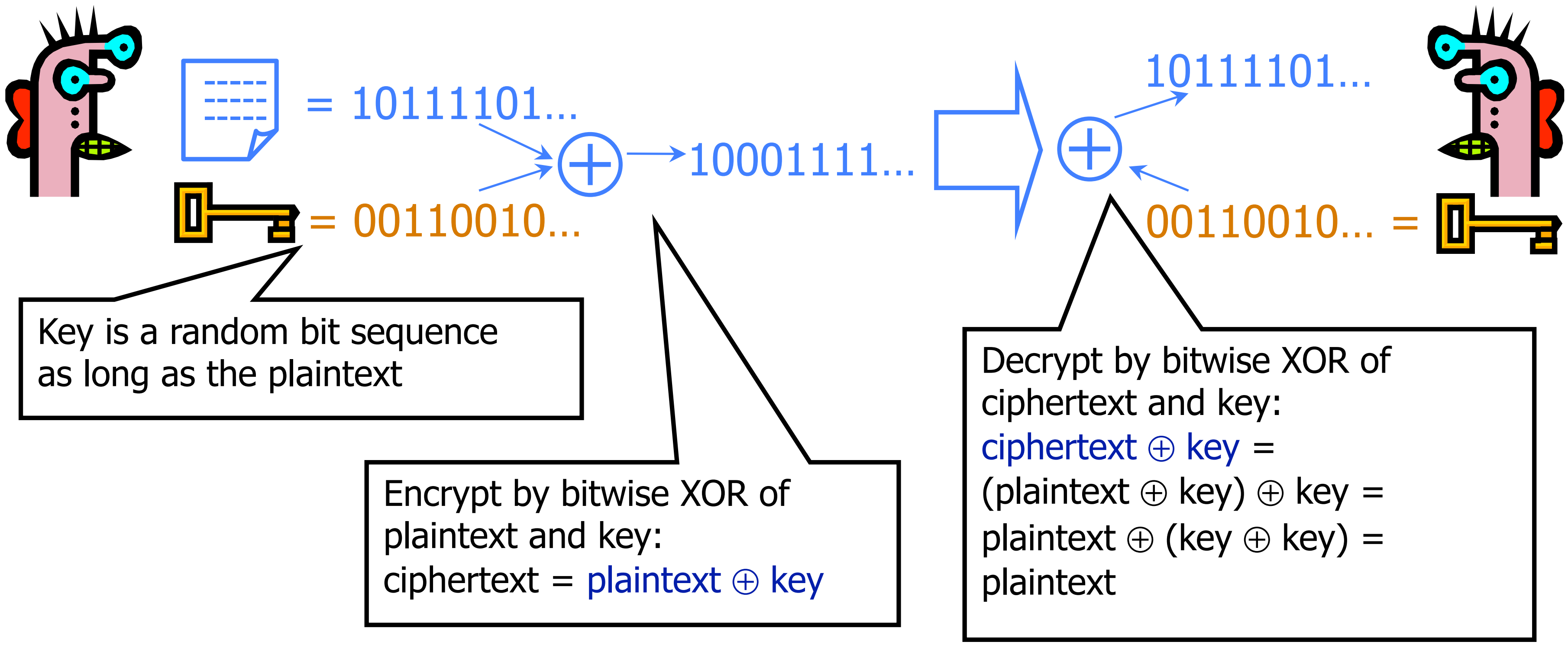
One-Time Pad


= 10111101…
= 00110010…
10001111…
10111101…
00110010… =
Key is a random bit sequence as long as the plaintext
Encrypt by bitwise XOR of plaintext and key:
ciphertext = plaintext ⊕ key
Decrypt by bitwise XOR of ciphertext and key:
ciphertext ⊕ key =
(plaintext ⊕ key) ⊕ key =
plaintext ⊕ (key ⊕ key) =
plaintext

Advantages of One-Time Pad

- Easy to compute
  - Encryption and decryption are the same operation
  - Bitwise XOR is very cheap to compute
- As secure as theoretically possible
  - Given a ciphertext, all plaintexts are equally likely, regardless of attacker's computational resources
  - …as long as the key sequence is truly random
    - True randomness is expensive to obtain in large quantities
  - …as long as each key is same length as plaintext
    - But how does the sender communicate the key to receiver?

Disadvantages

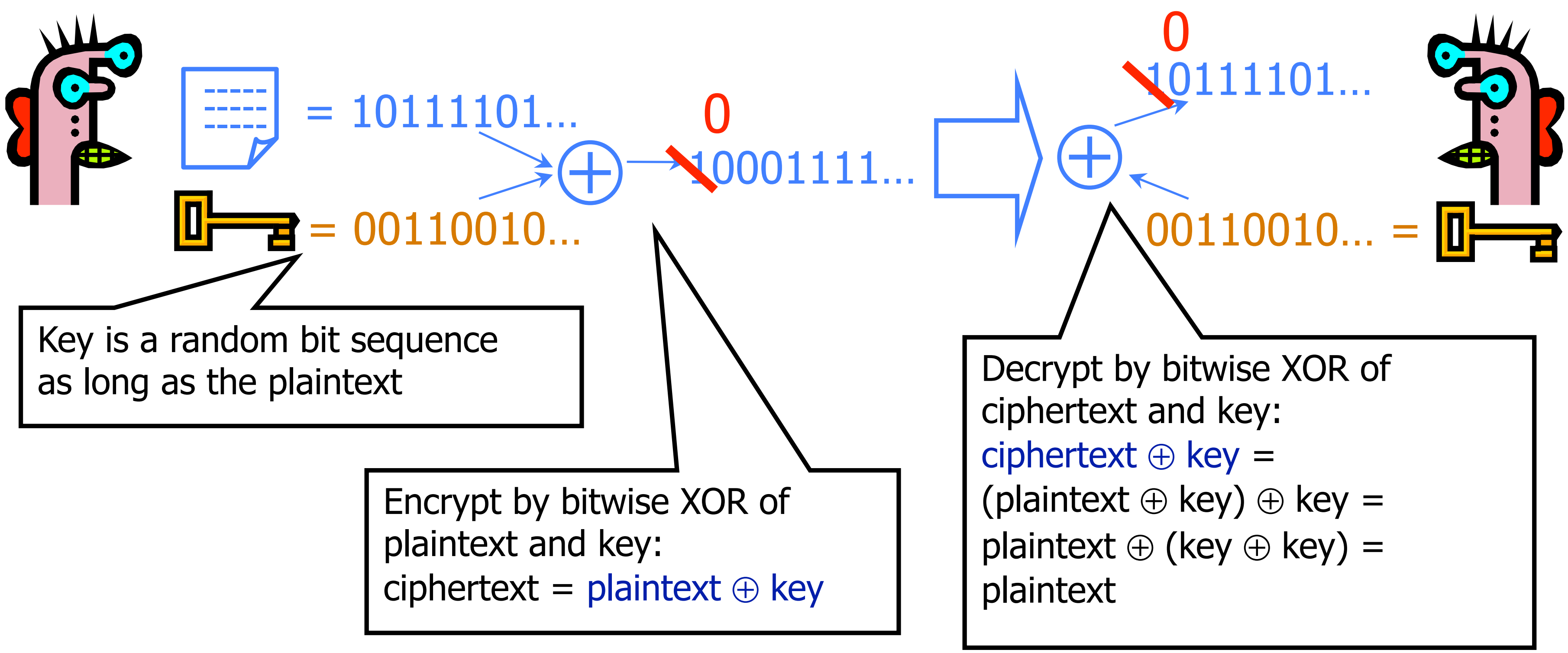


Disadvantage #1: Keys as long as messages.

Impractical in most scenarios

Still used by intelligence communities

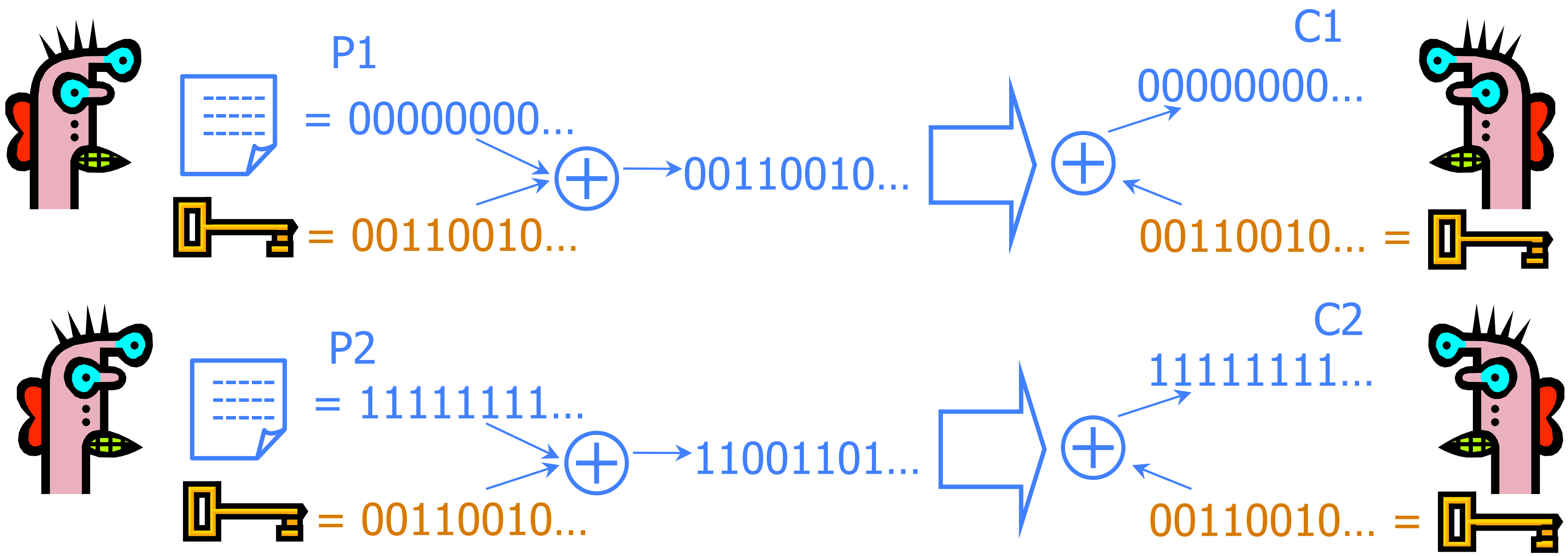
Disadvantages



Disadvantage #2: No integrity protection

Disadvantages

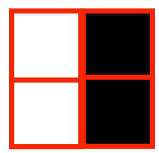
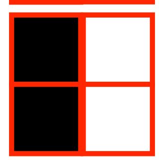
Disadvantage #3: Keys cannot be reused



Learn relationship between plaintexts:

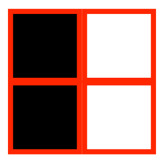
$C1 \oplus C2 = (P1 \oplus K) \oplus (P2 \oplus K) = (P1 \oplus P2) \oplus (K \oplus K) = P1 \oplus P2$

Visual Cryptography

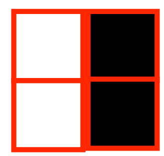
- Generate a random bitmap
- Encode 0 as: 
- Encode 1 as: 

Visual Cryptography

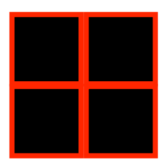
- Take a black and white bitmap image
- For a white pixel, send the same as the mask



or

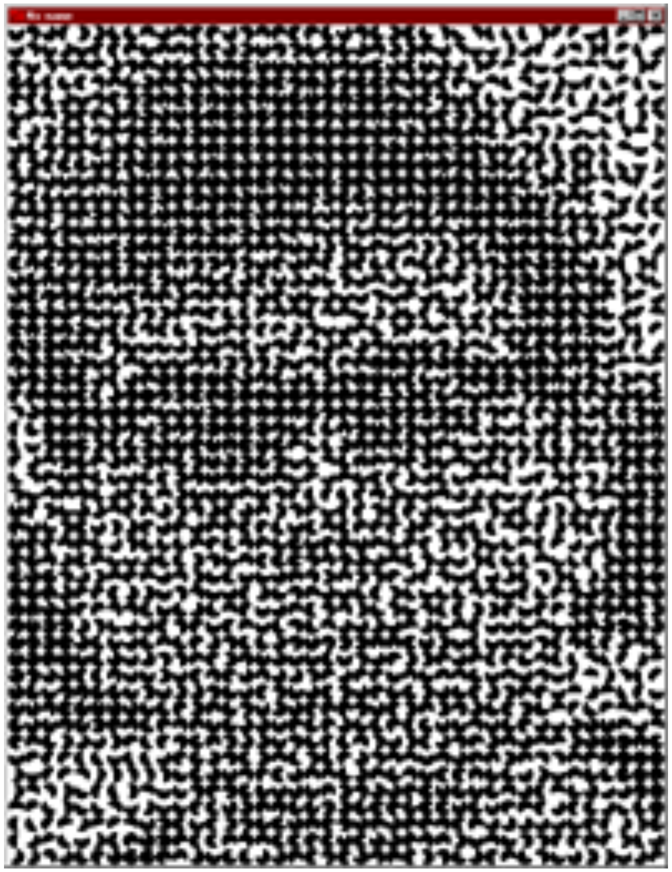


- For a black pixel, send the opposite of the mask



See also http://www.cs.washington.edu/homes/yoshi/cs4hs/cse-vc.html

Visual Cryptography



- http://www.cl.cam.ac.uk/~fms27/vck/face.gif

See also http://www.cs.washington.edu/homes/yoshi/cs4hs/cse-vc.html

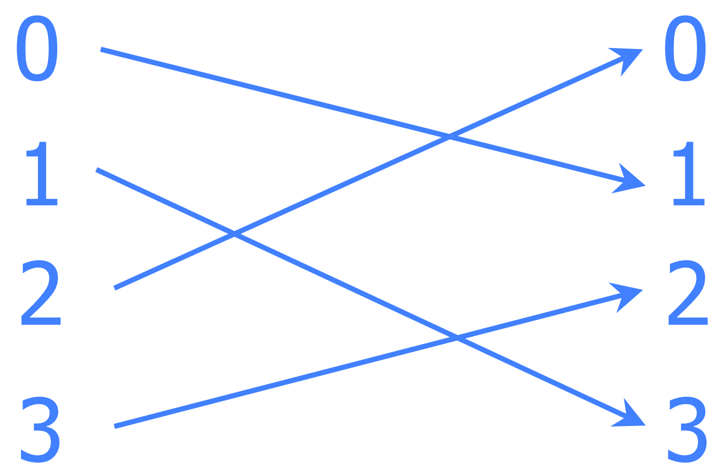
Reducing Keysize

- What do we do when we can’t pre-share huge keys?
  - When OTP is unrealistic

- We use special cryptographic primitives
  - Single key can be reused (with some restrictions)
  - But no longer provable secure (in the sense of the OTP)

- Examples: Block ciphers, stream ciphers

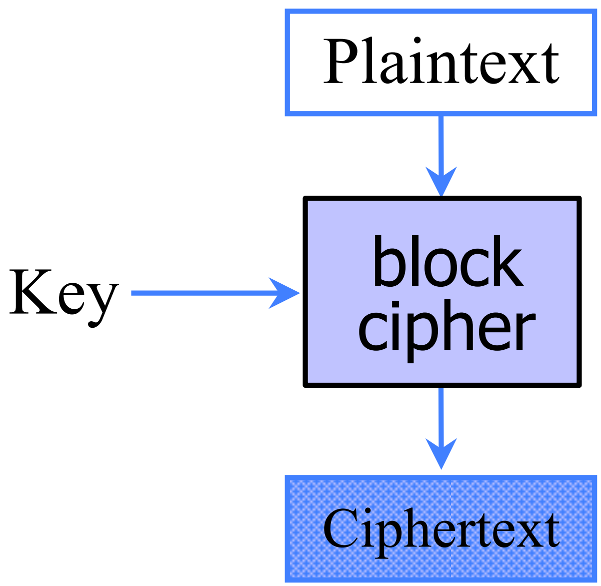
Background: Permutation



- For N-bit input, $2^N!$ possible permutations
- Idea for how to use a keyed permutation: split plaintext into blocks; for each block use secret key to pick a permutation
  - Without the key, permutation should "look random"

Block Ciphers

- Operates on a single chunk ("block") of plaintext
  - For example, 64 bits for DES, 128 bits for AES
  - Each key defines a different permutation
  - Same key is reused for each block (can use short keys)

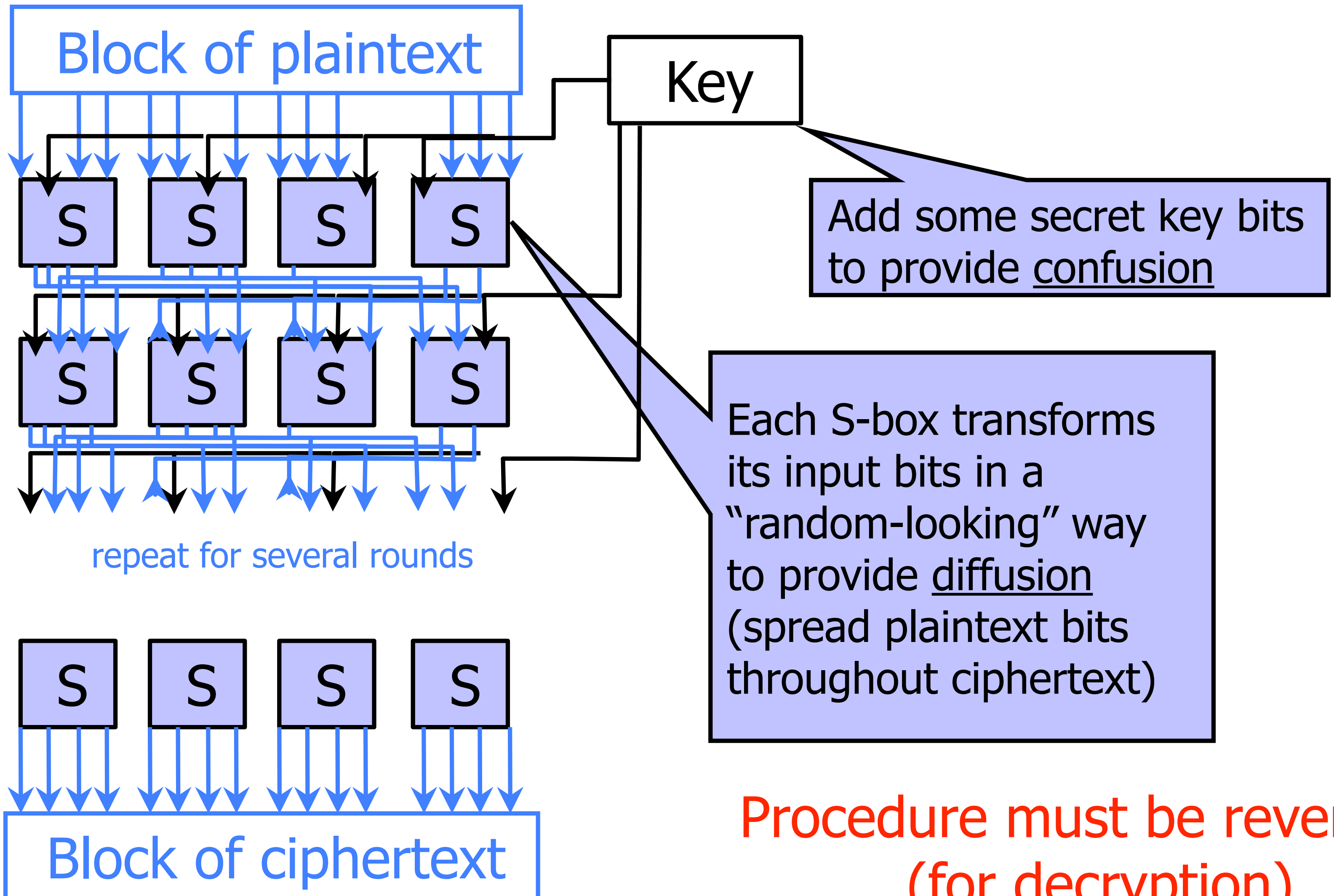


Block Cipher Security

- Result should look like a random permutation on the inputs
  - Recall: not just shuffling bits. N-bit block cipher permutes over 2^N inputs.

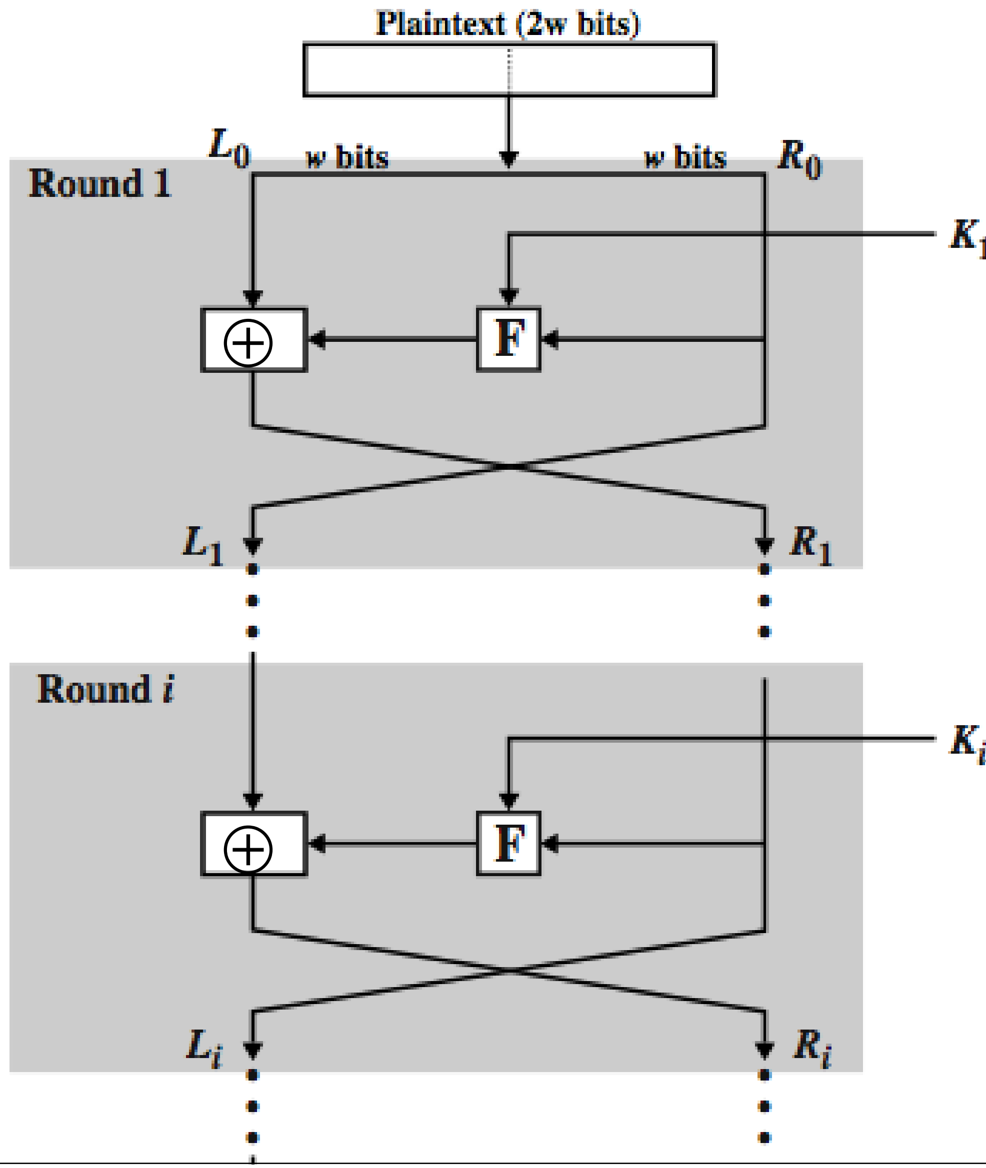
- Only computational guarantee of secrecy
  - Not impossible to break, just very expensive
    - If there is no efficient algorithm (unproven assumption!), then can only break by brute-force, try-every-possible-key search
  - Time and cost of breaking the cipher exceed the value and/or useful lifetime of protected information

Block Cipher Operation (Simplified)



Procedure must be reversible
(for decryption)

Feistel Structure (Stallings Fig 2.2)



DES

- Feistel structure
  - "Ladder" structure: split input in half, put one half through the round and XOR with the other half
  - Theoretical support: After 3 random rounds, ciphertext indistinguishable from a random permutation if internal F function is a pseudorandom function (Luby & Rackoff)
- DES: Data Encryption Standard
  - Feistel structure
  - Invented by IBM, issued as federal standard in 1977
  - 64-bit blocks, 56-bit key + 8 bits for parity

DES and 56 bit keys (Stallings Tab 2.2)

- 56 bit keys are quite short

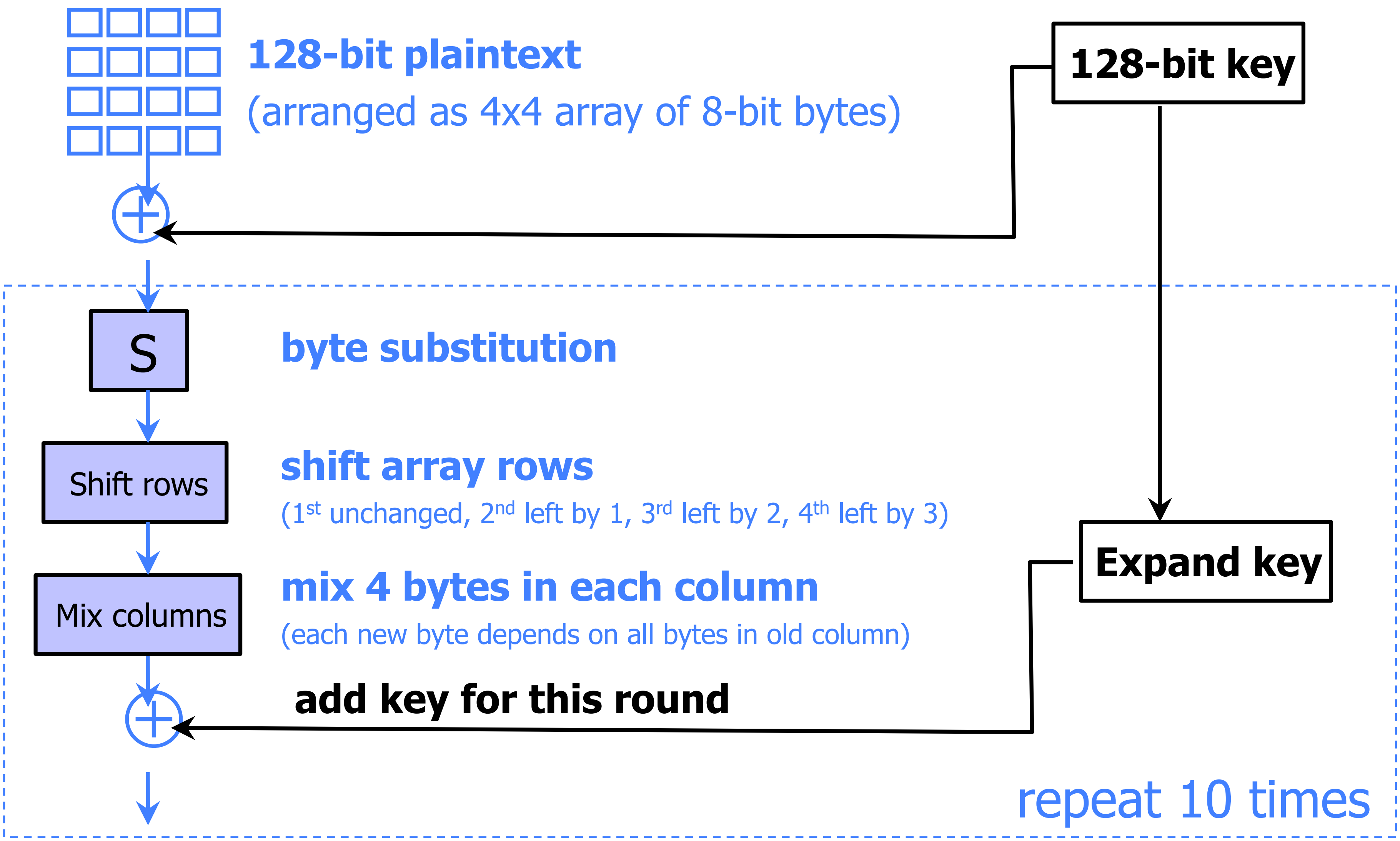
Key Size (bits)	Number of Alternative Keys	Time required at 1 encryption/μs	Time required at 10^6 encryptions/μs
32	$2^{32} = 4.3 \times 10^9$	$2^{31}\ \mu s = 35.8$ minutes	2.15 milliseconds
56	$2^{56} = 7.2 \times 10^{16}$	$2^{55}\ \mu s = 1142$ years	10.01 hours
128	$2^{128} = 3.4 \times 10^{38}$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

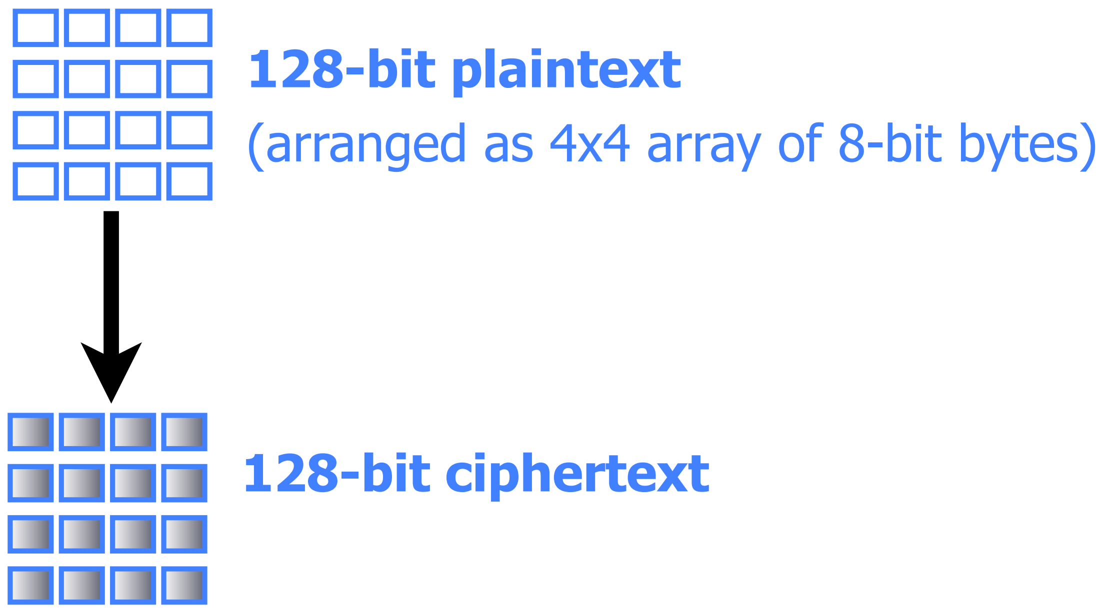
- New federal standard as of 2001
- Based on the Rijndael algorithm
- 128-bit blocks, keys can be 128, 192 or 256 bits
- Unlike DES, does not use Feistel structure
  - The entire block is processed during each round
- Design uses some very nice mathematics

Basic Structure of Rijndael



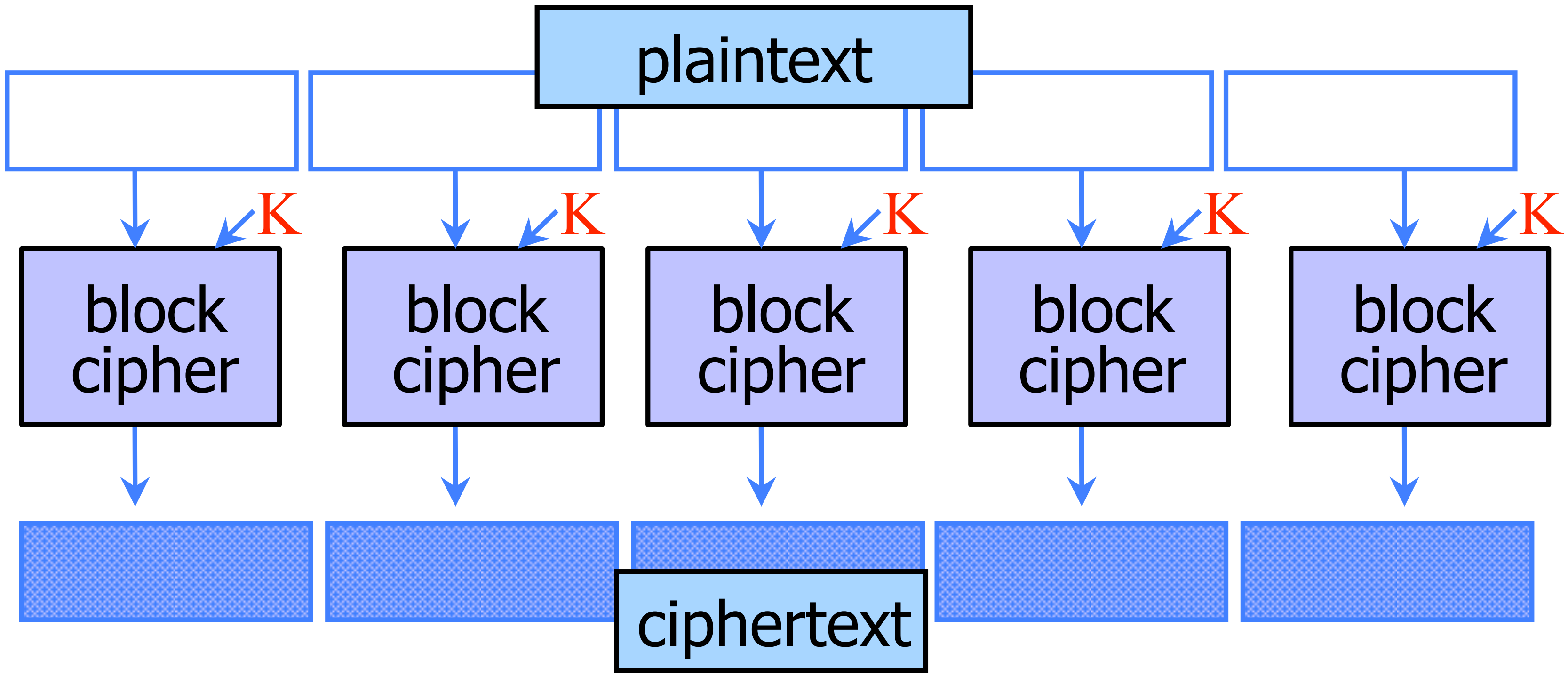
Encrypting a Large Message

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



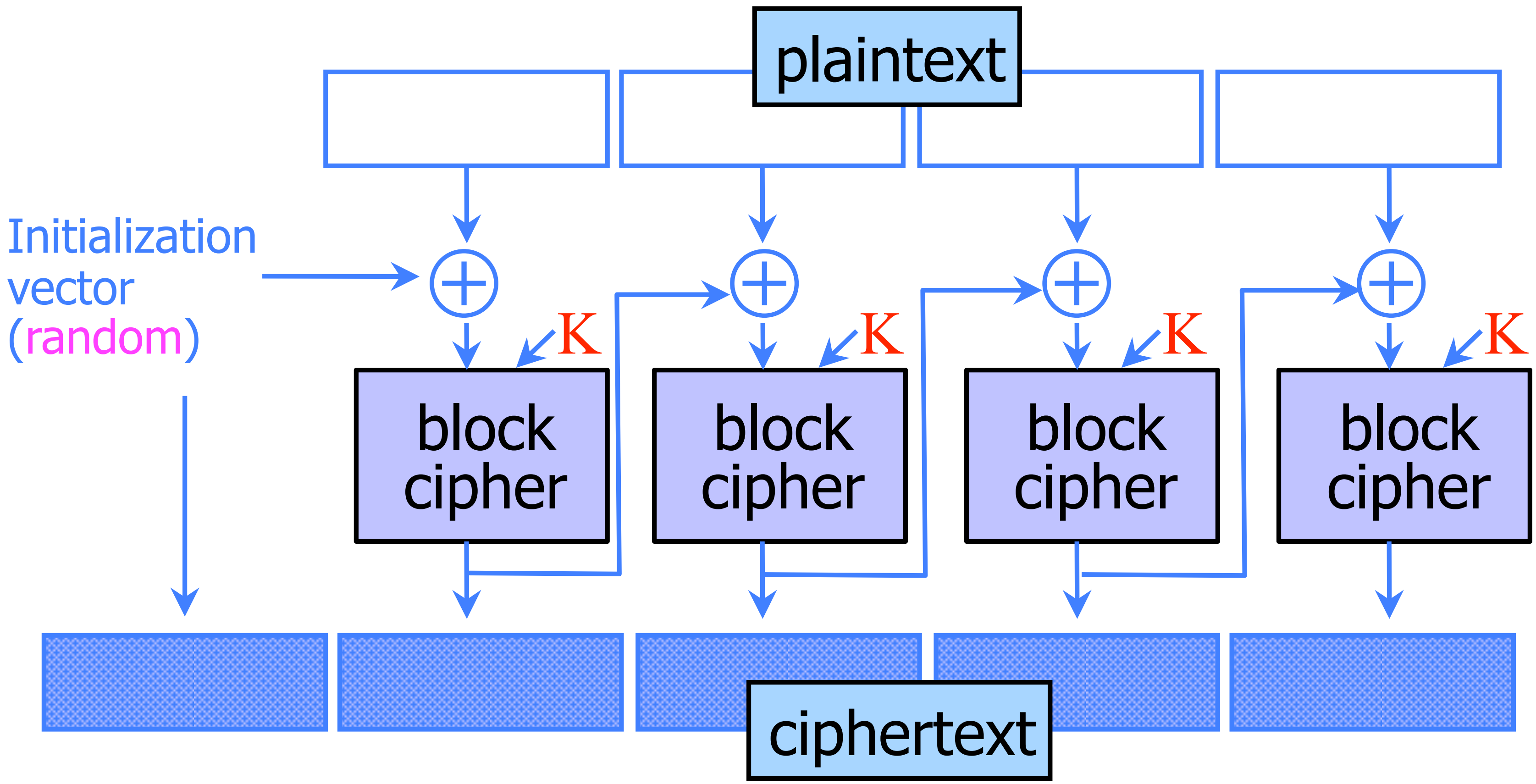
- What should we do?

Electronic Code Book (ECB) Mode



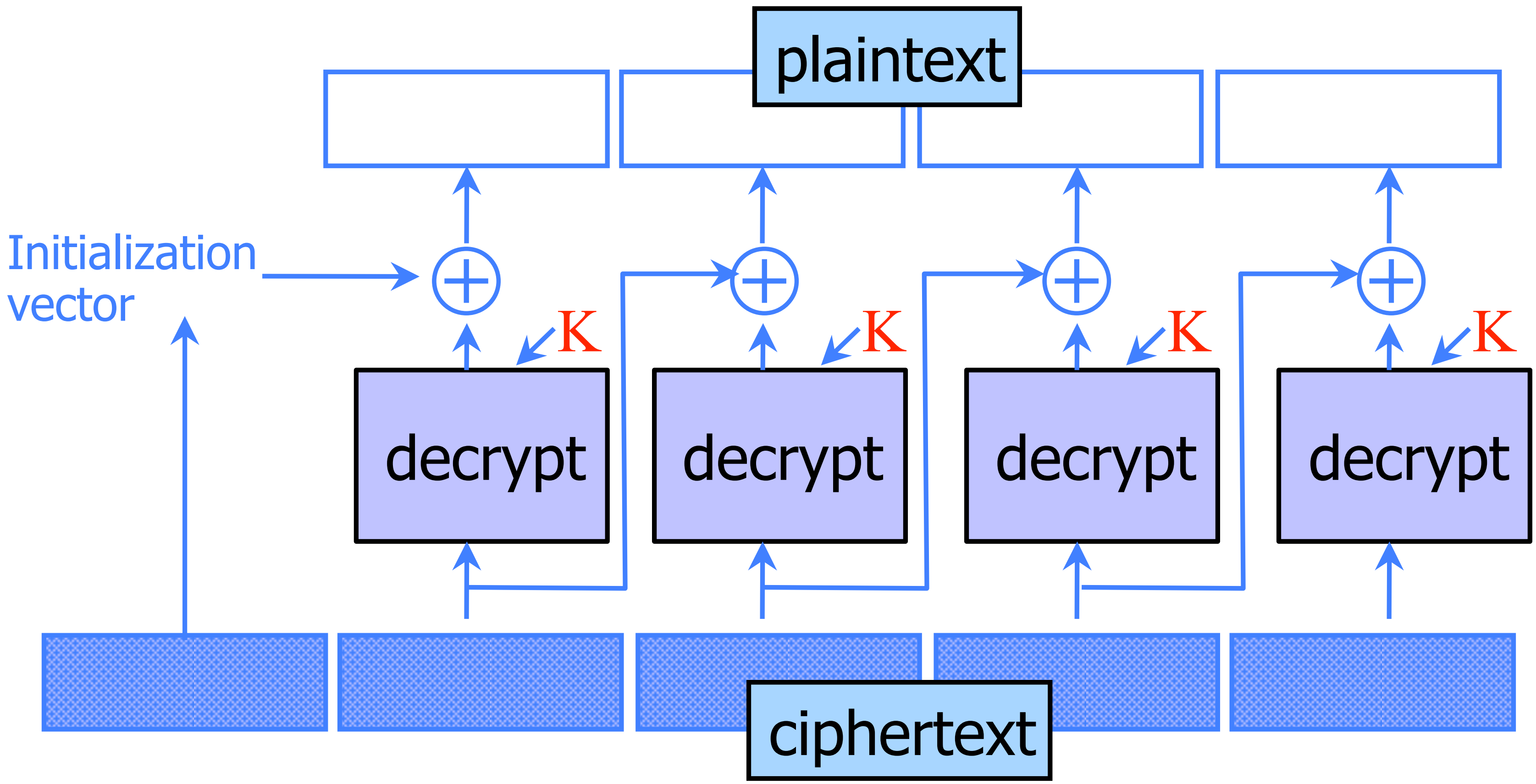
- Identical blocks of plaintext produce identical blocks of ciphertext
- No integrity checks: can mix and match blocks

Cipher Block Chaining (CBC) Mode: Encryption



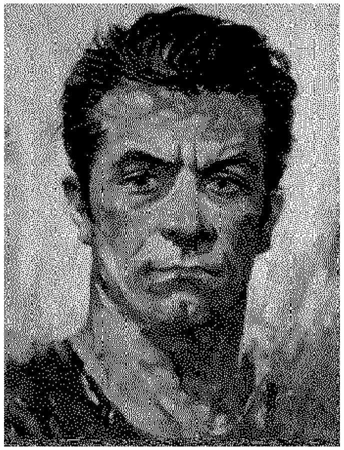
- Identical blocks of plaintext encrypted differently
- Last cipherblock depends on entire plaintext
  - Still does not guarantee integrity

CBC Mode: Decryption



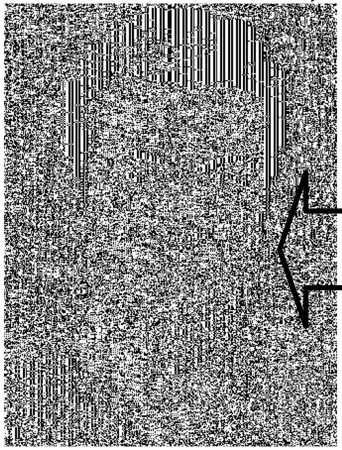
ECB vs. CBC

[Picture due to Bart Preneel]

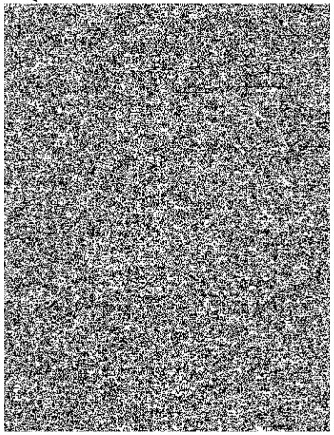


AES in ECB mode

AES in CBC mode

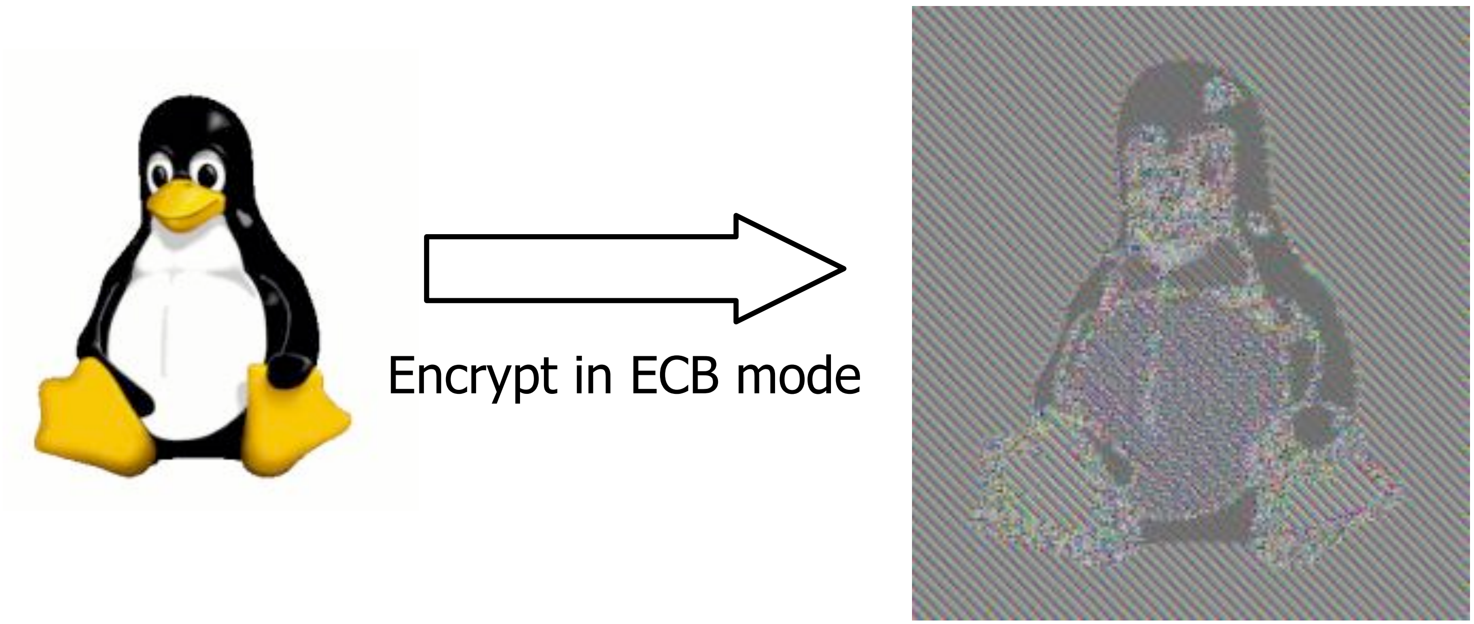


Similar plaintext blocks produce similar ciphertext blocks (not good!)

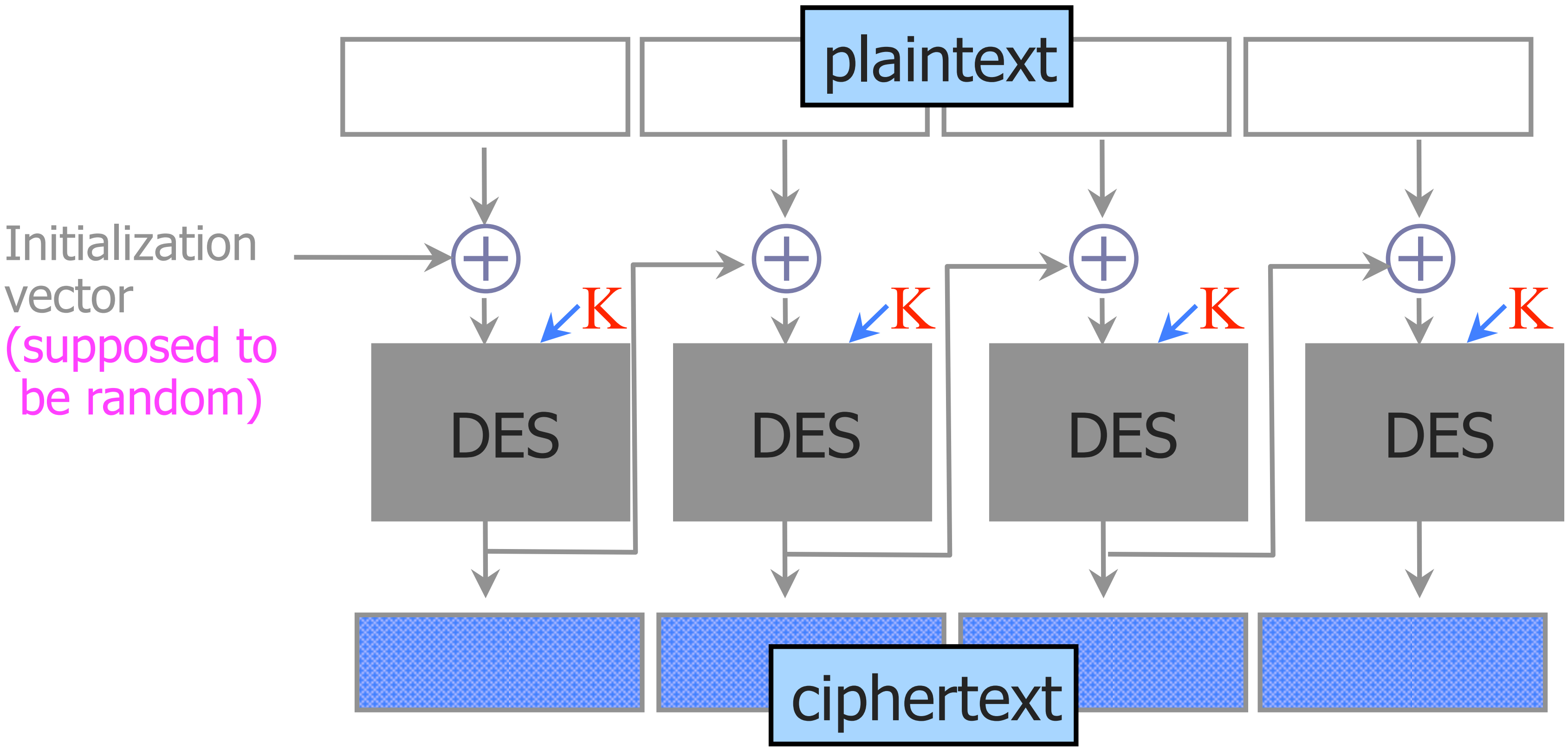


Information Leakage in ECB Mode

[Wikipedia]



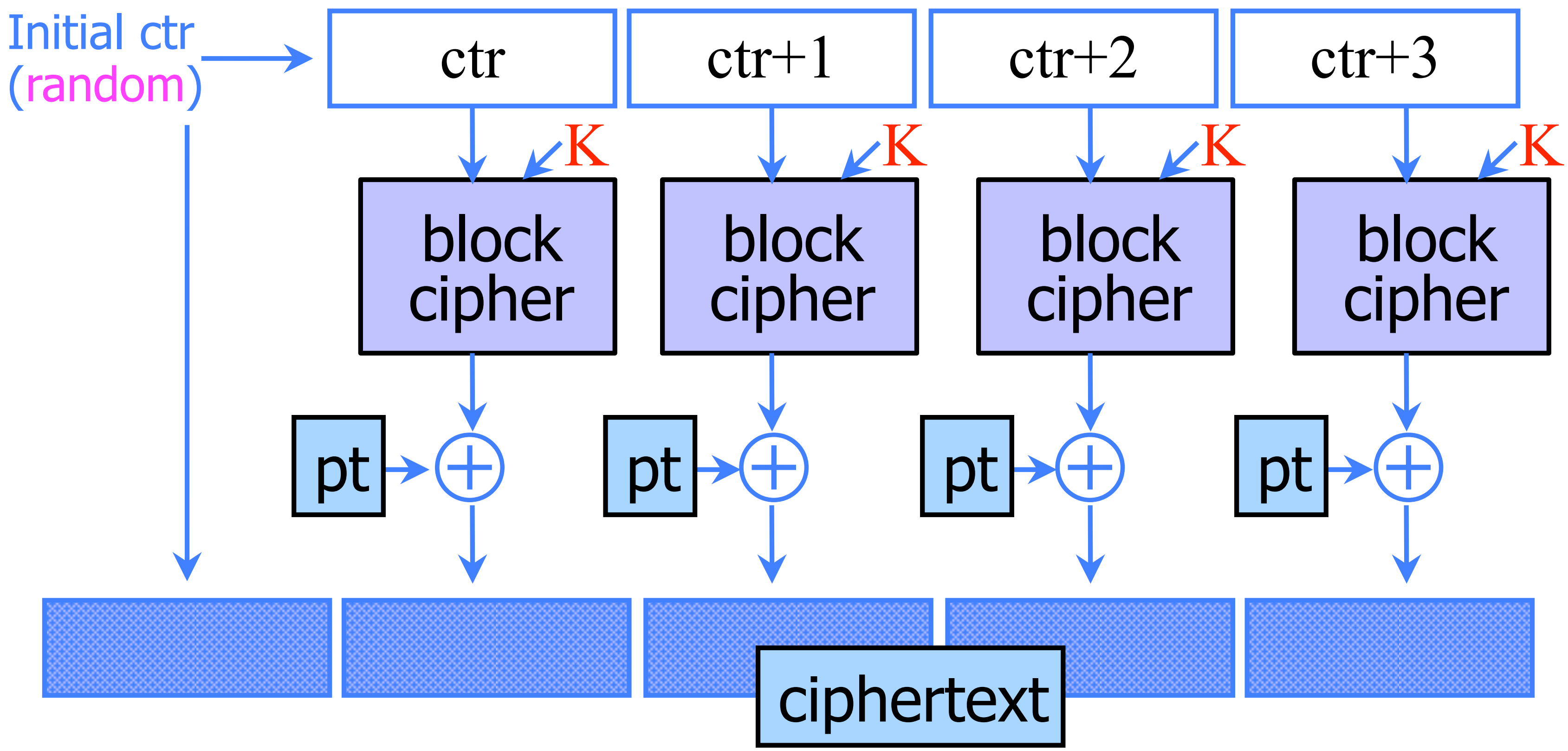
CBC and Electronic Voting



Found in the source code for Diebold voting machines:

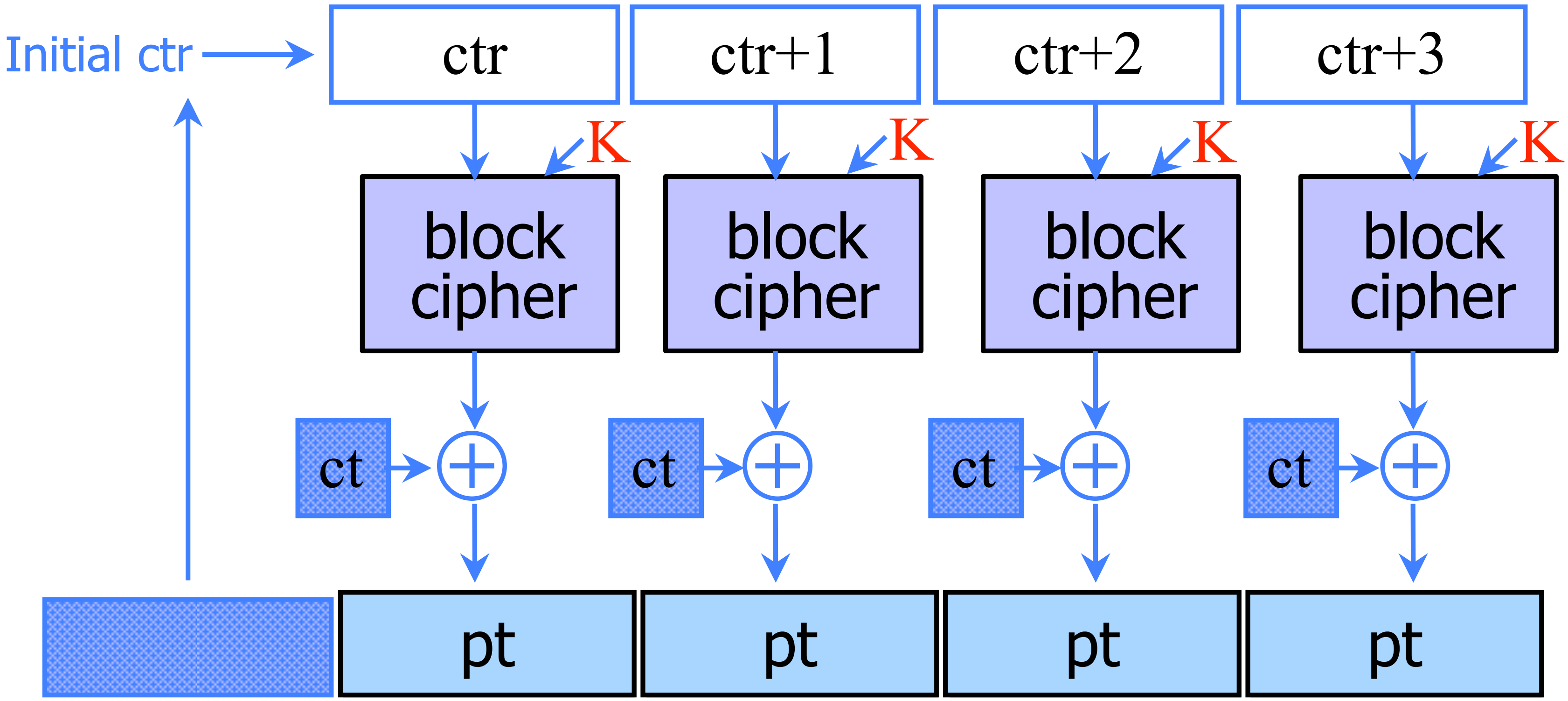
```
DesCBCEncrypt((des_c_block*)tmp, (des_c_block*)record.m_Data,
              totalSize, DESKEY, NULL, DES_ENCRYPT)
```

Counter (CTR) Mode: Encryption



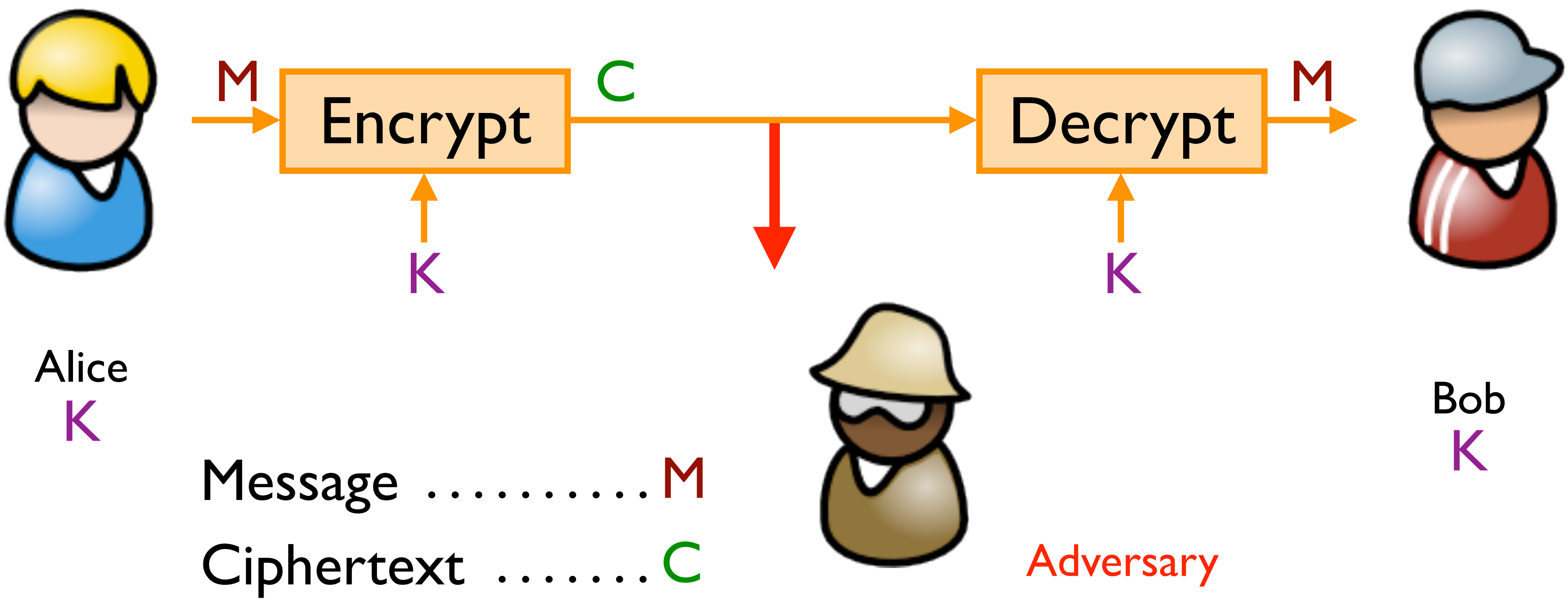
- Identical blocks of plaintext encrypted differently
- Still does not guarantee integrity
- Fragile if ctr repeats

CTR Mode: Decryption



Achieving Privacy (Symmetric)

Encryption schemes: A tool for protecting privacy.



Message . . . . M

Ciphertext C

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 other definitions (like not being able to obtain key)