CSE 484 / CSE M 584: Computer Security and Privacy

Cryptography: Symmetric Encryption

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Alice and Bob

- Archetypical characters

Eve
(eavesdrops)

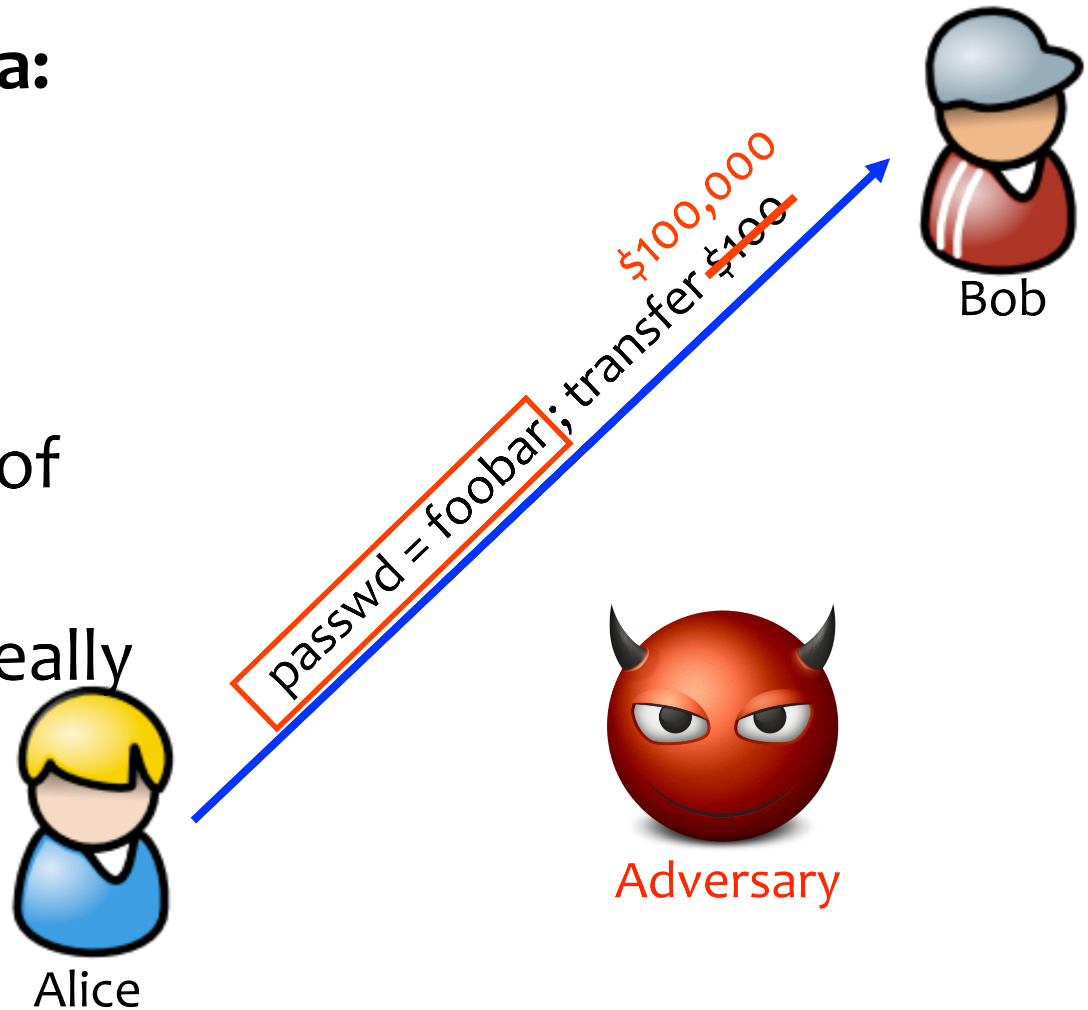
Mallory
(is malicious)

Common Communication Security Goals

Confidentiality of data:
Prevent exposure of information

Integrity of data:
Prevent modification of information

Authenticity : Is this really Bob I'm talking to?



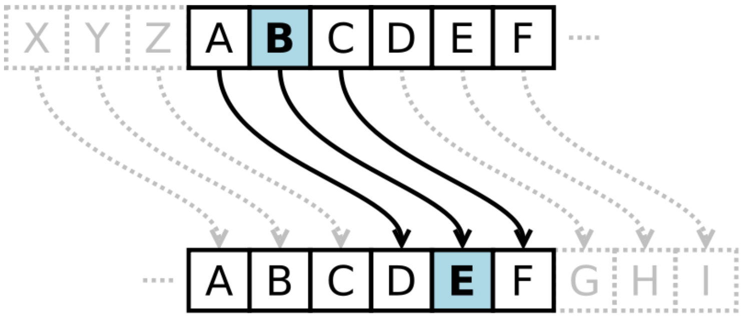
History

- Substitution Ciphers
  - Caesar Cipher
- Transposition Ciphers
- Codebooks
- Machines

- Recommended Reading: **The Codebreakers** by David Kahn and **The Code Book** by Simon Singh.

History: Caesar Cipher (Shift Cipher)

- Plaintext letters are replaced with letters a fixed shift away in the alphabet.



- Example:
  - Plaintext: `The quick brown fox jumps over the lazy dog`
  - Key: Shift 3

    `ABCDEFGHIJKLMNOPQRSTUVWXYZ`

    `DEFGHIJKLMNOPQRSTUVWXYZABC`

  - Ciphertext: `WKHTX LFNEU RZQIR AMXPS VRYHU WKHOD CBGRJ`

History: Caesar Cipher (Shift Cipher)

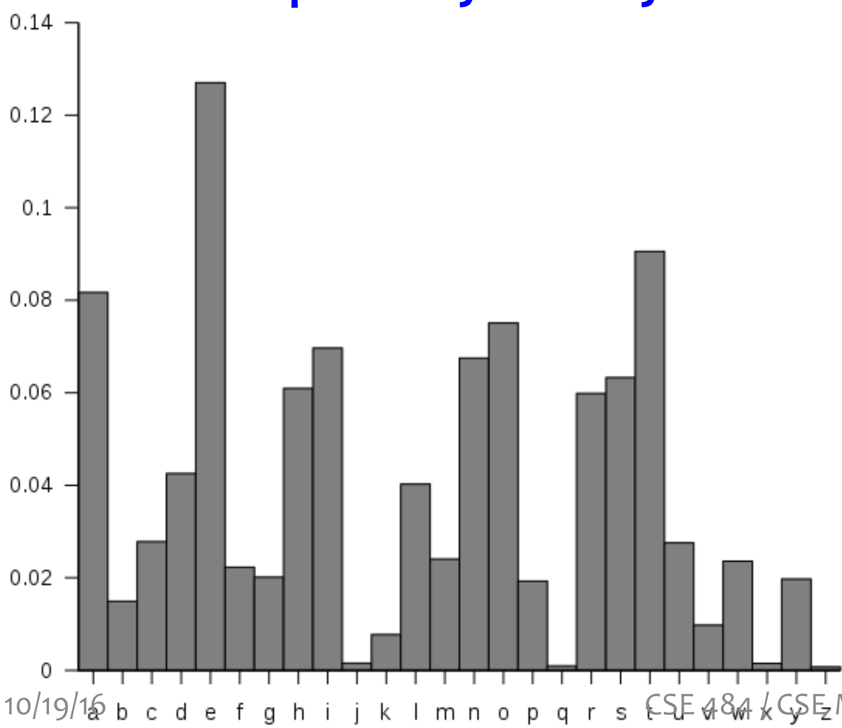
- ROT13: shift 13 (encryption and decryption: same operation)
- What is the key space?
  - 26 possible shifts.
- How to attack shift ciphers?
  - Brute force.

History: Substitution Cipher

- Superset of shift ciphers: each letter is substituted for another one.
- Add a secret key
- Example:
  - Plaintext: `ABCDEFGHIJKLMNOPQRSTUVWXYZ`
  - Cipher: `ZEBRASCDFGHIJKLMNOPQTUVWXY`
- "State of the art" for thousands of years

History: Substitution Cipher

- What is the key space? 26! ~= 2^88
- How to attack?
  - Frequency analysis.



Bigrams:

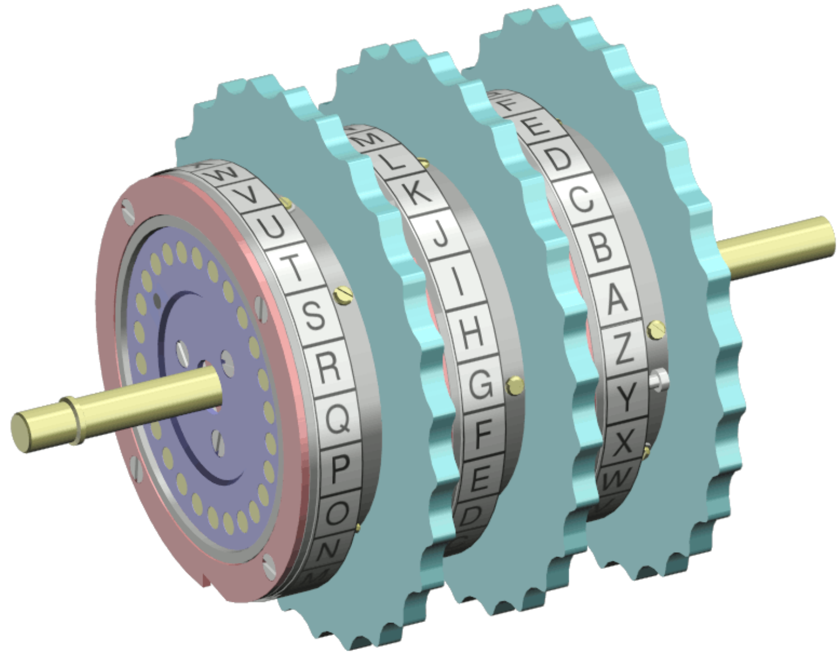
th 1.52%	en 0.55%	ng 0.18%
he 1.28%	ed 0.53%	of 0.16%
in 0.94%	to 0.52%	al 0.09%
er 0.94%	it 0.50%	de 0.09%
an 0.82%	ou 0.50%	se 0.08%
re 0.68%	ea 0.47%	le 0.08%
nd 0.63%	hi 0.46%	sa 0.06%
at 0.59%	is 0.46%	si 0.05%
on 0.57%	or 0.43%	ar 0.04%
nt 0.56%	ti 0.34%	ve 0.04%
ha 0.56%	as 0.33%	ra 0.04%
es 0.56%	te 0.27%	ld 0.02%
st 0.55%	et 0.19%	ur 0.02%

Trigrams:

1. the	6. ion	11. nce
2. and	7. tio	12. edt
3. tha	8. for	13. tis
4. ent	9. nde	14. oft
5. ing	10.has	15. sth

History: Enigma Machine

Uses rotors (substitution cipher) that change position after each key.



Key = initial setting of rotors

Key space?

26^n for n rotors

Kerckhoff’s Principle

- Security of a cryptographic object should depend only on the secrecy of the secret (private) key.
- Security should not depend on the secrecy of the algorithm itself (“security by obscurity”).

How Cryptosystems Work Today

- Public algorithms (Kerckhoff's Principle)
- Security proofs based on assumptions (not this course)

- Don't roll your own!

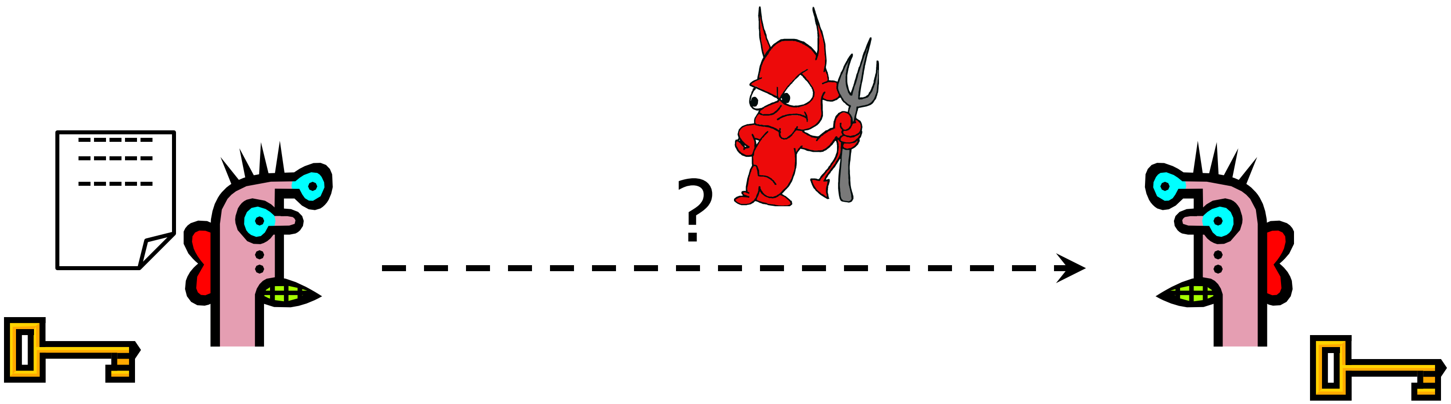
How Cryptosystems Work Today

- Layered approach:
  - Cryptographic primitives, like block ciphers, stream ciphers, hash functions, and one-way trapdoor permutations
  - Cryptographic protocols, like CBC mode encryption, CTR mode encryption, HMAC message authentication

Flavors of Cryptography

- Symmetric cryptography
  - Both communicating parties have access to a shared random string K, called the key.
- Asymmetric cryptography
  - Each party creates a public key pk and a secret key sk.

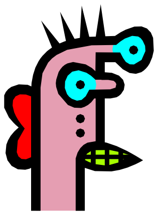
Confidentiality: Basic Problem

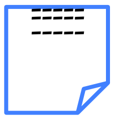


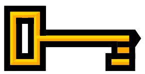
Goal: send a message confidentially.

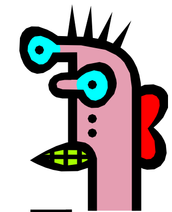
Given: both parties already know the same secret.

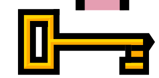
One-Time Pad



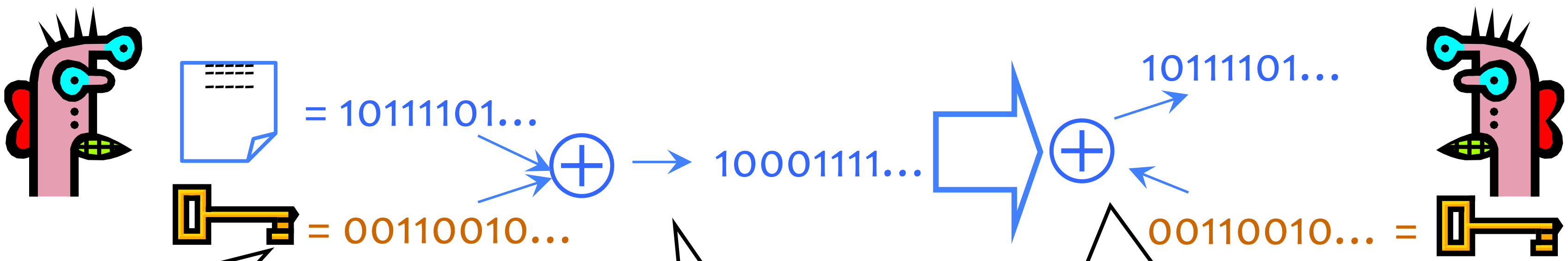
 = 10111101…

 = 00110010…



00110010… = 

One-Time Pad



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

Cipher achieves perfect secrecy if and only if there are as many possible keys as possible plaintexts, and every key is equally likely (Claude Shannon, 1949)

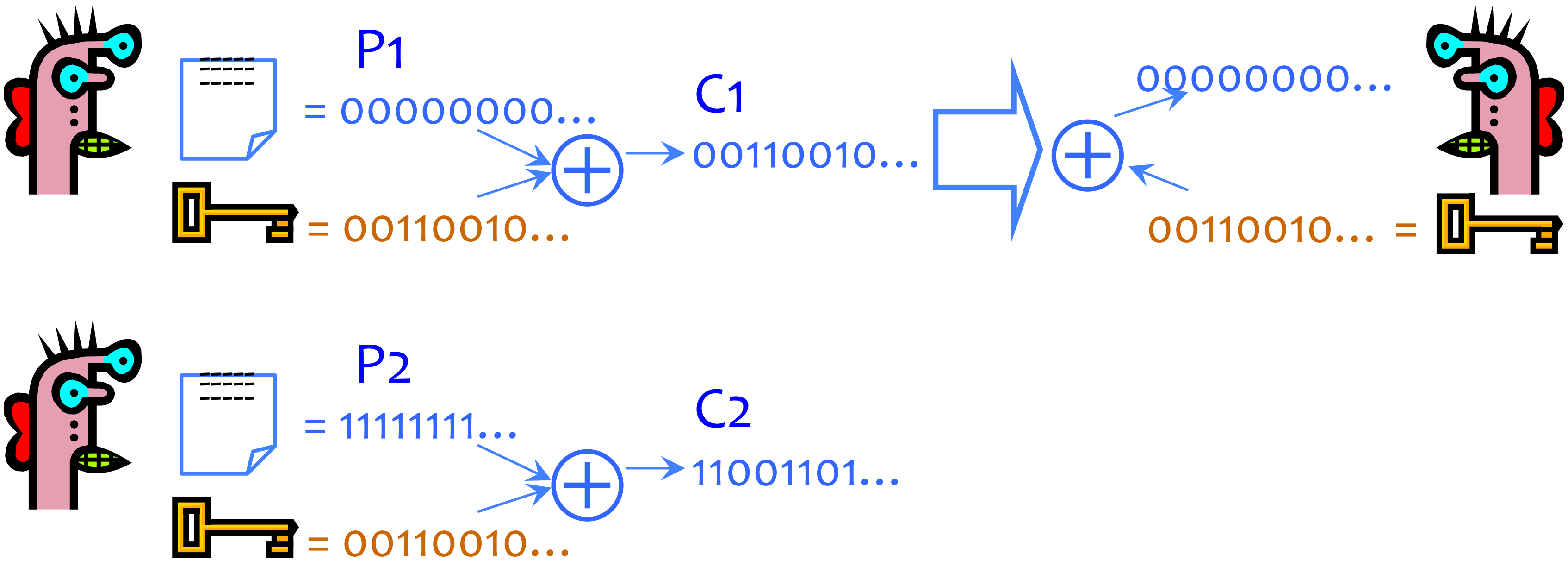
Advantages of One-Time Pad

- 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 sender communicate the key to receiver?

Problems with One-Time Pad

- Key must be as long as the plaintext
  - Impractical in most realistic scenarios
  - Still used for diplomatic and intelligence traffic
- Insecure if keys are reused
  - Attacker can obtain XOR of plaintexts
- Does not guarantee integrity
  - One-time pad only guarantees confidentiality
  - Attacker cannot recover plaintext, but can easily change it to something else

Dangers of Reuse

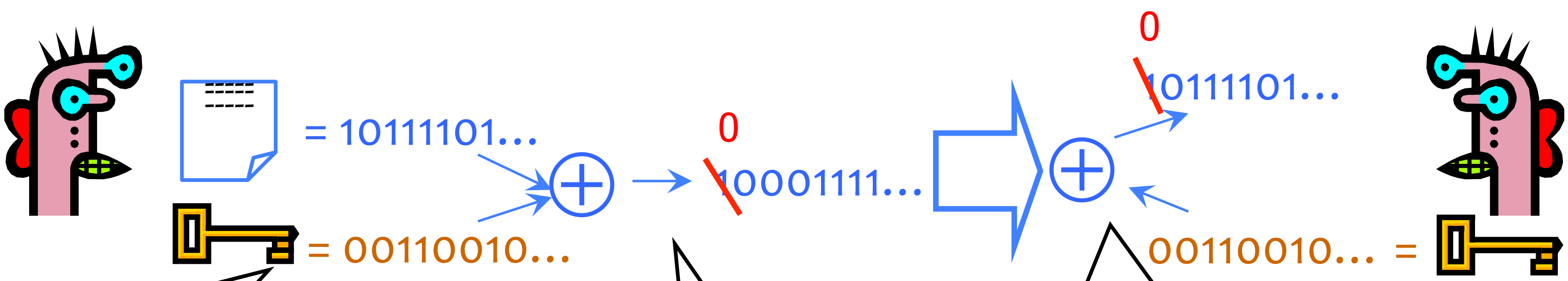


Learn relationship between plaintexts

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

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

No Integrity



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Reducing Key Size

- What to do when it is infeasible to pre-share huge random keys?
  - When one-time pad is unrealistic…
- Use special cryptographic primitives: block ciphers, stream ciphers
  - Single key can be re-used (with some restrictions)
  - Use them in ways that provide integrity

Stream Ciphers

- One-time pad:
  Ciphertext(Key,Message)=Message⊕Key
  – Key must be a random bit sequence as long as message

- Idea: replace "random" with "pseudo-random"

Stream Ciphers

- One-time pad:
  Ciphertext(Key,Message)=Message $\oplus$ Key

- Stream cipher:
  Ciphertext(Key,Message)=
  Message $\oplus$ PRNG(Key)

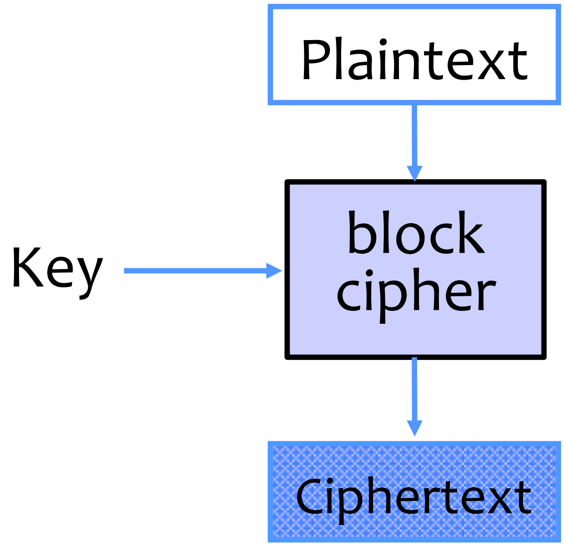
Stream Ciphers

- One time pad, replace "random" with "pseudo-random"
  - Use a pseudo-random number generator (PRNG)
  - PRNG takes a short, truly random secret seed and expands it into a long "random-looking" sequence
    - E.g., 128-bit seed into a 10^6-bit pseudo-random sequence

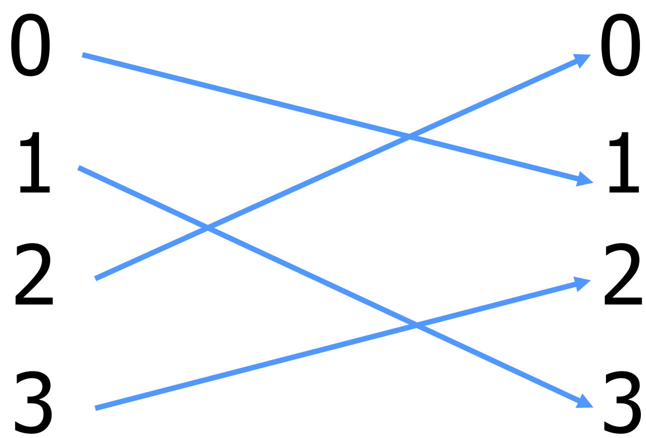
No efficient algorithm can tell this sequence from truly random

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)



Permutations



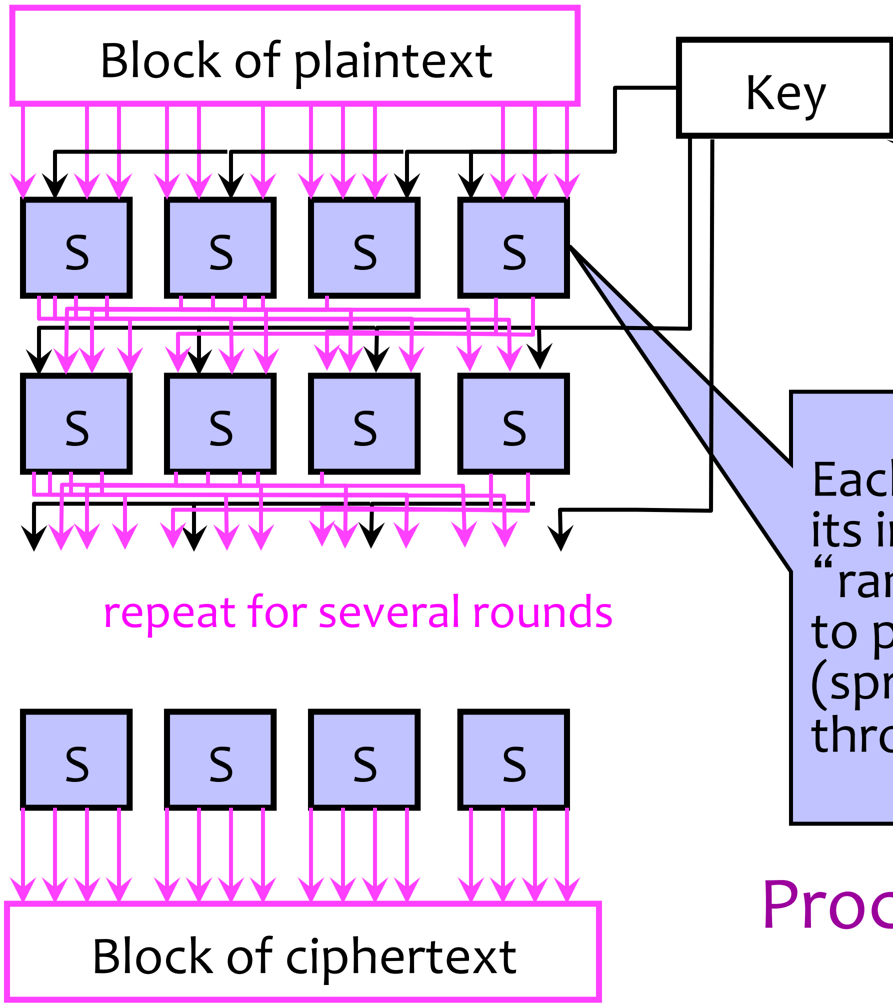
- For N-bit input, $2^N!$ possible permutations
- Idea for how to use a keyed permutation: split plaintext into blocks; for each block use secret key to pick a permutation
  - Without the key, permutation should "look random"

Block 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)



Add some secret key bits to provide confusion

Each S-box transforms its input bits in a "random-looking" way to provide diffusion (spread plaintext bits throughout ciphertext)

Procedure must be reversible (for decryption)

Standard Block Ciphers

- **DES: Data Encryption Standard**
  - Feistel structure: builds invertible function using non-invertible ones
  - Invented by IBM, issued as federal standard in 1977
  - 64-bit blocks, 56-bit key + 8 bits for parity

DES and 56 bit keys

- 56 bit keys are quite short
- 1999: EFF DES Crack + distributed machines
  - < 24 hours to find DES key
- DES ---> 3DES
  - 3DES: DES + inverse DES + DES (with 2 or 3 diff keys)

DES and 56 bit keys

- 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

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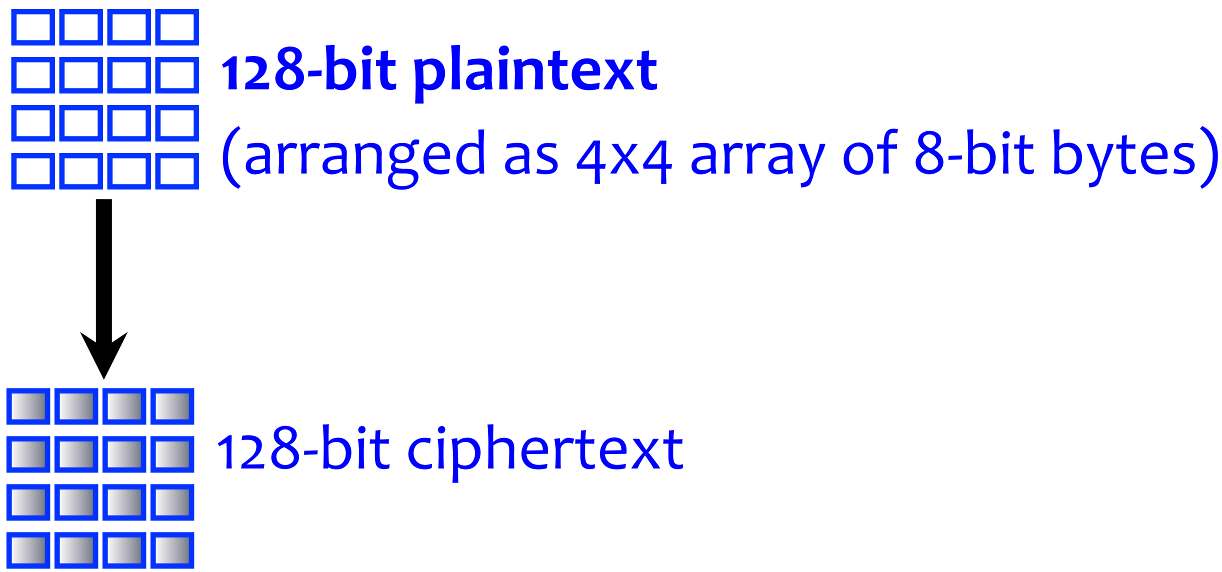
- **AES: Advanced Encryption Standard**
  - New federal standard as of 2001
    - NIST: National Institute of Standards & Technology
  - Based on the Rijndael algorithm
    - Selected via an open process
  - 128-bit blocks, keys can be 128, 192 or 256 bits

Block Ciphers Work on Fixed Length Blocks of Message

- How do you encrypt a short message?

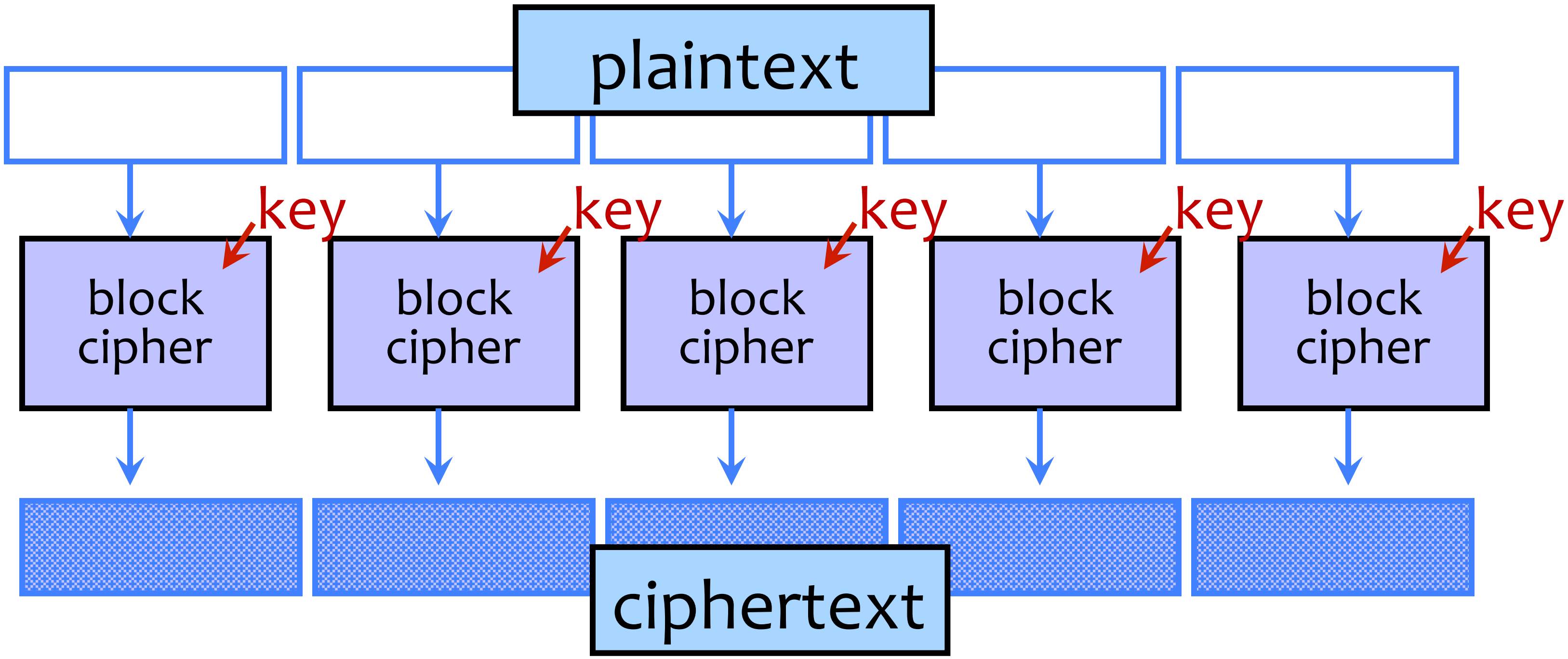
Encrypting a Large Message

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



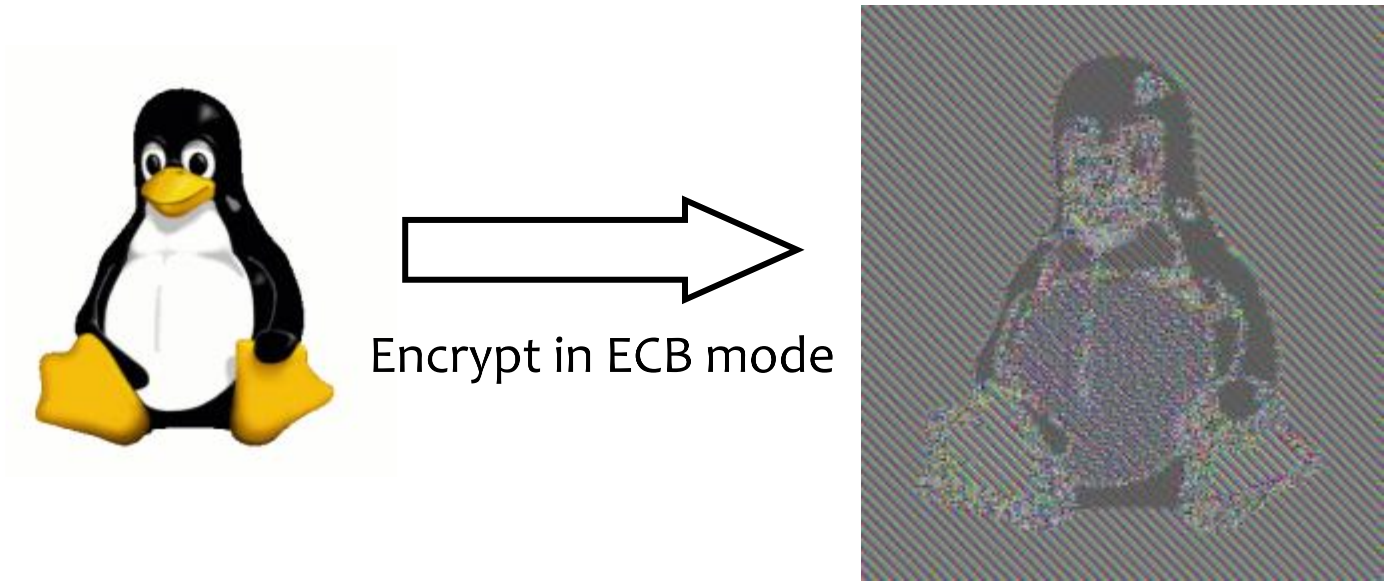
- What should we do?

Electronic Code Book (ECB) Mode



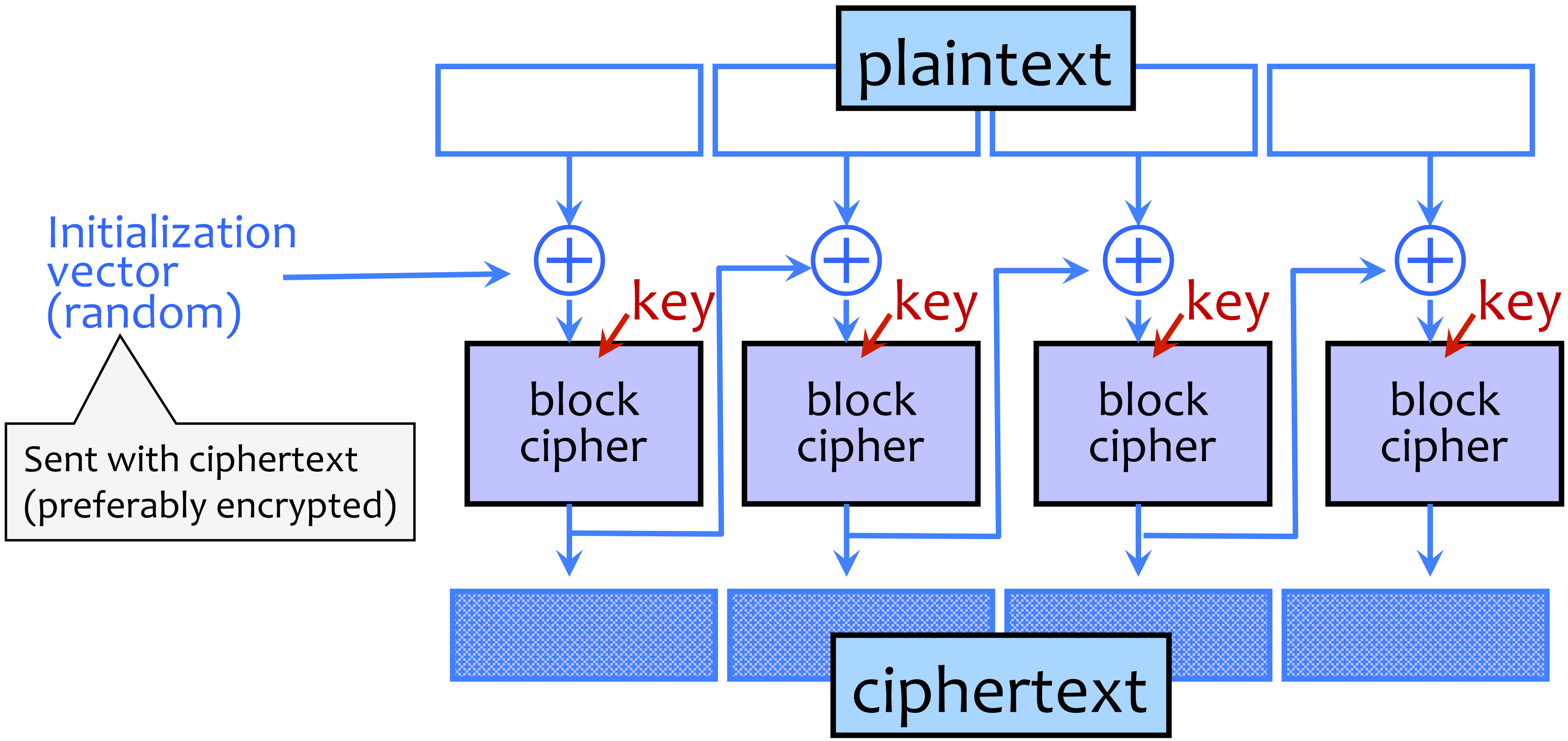
- Identical blocks of plaintext produce identical blocks of ciphertext
- No integrity checks: can mix and match blocks

Information Leakage in ECB Mode



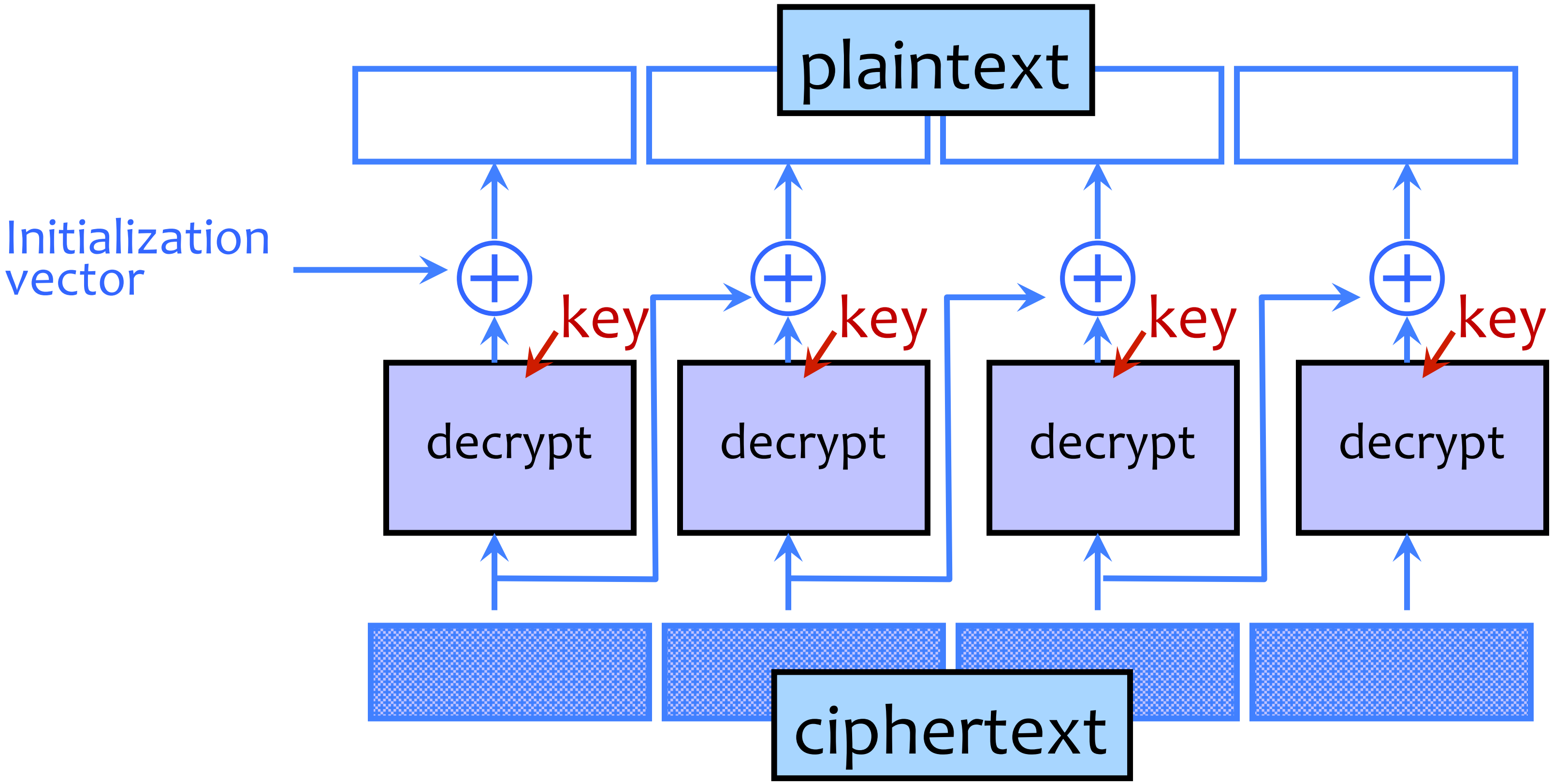
[Wikipedia]

Cipher Block Chaining (CBC) Mode: Encryption

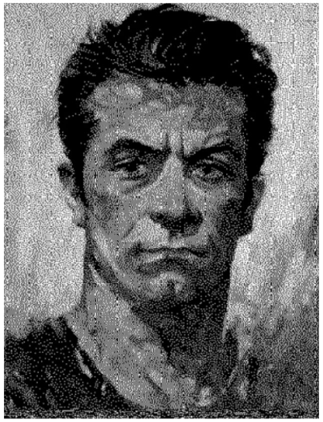


- Identical blocks of plaintext encrypted differently
- Last cipherblock depends on entire plaintext
  - Still does not guarantee integrity

CBC Mode: Decryption

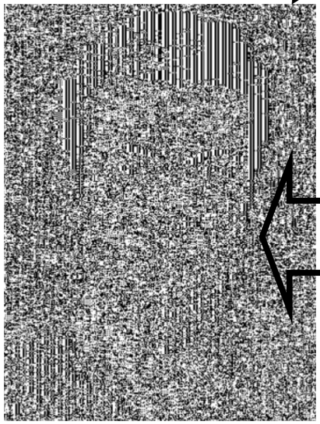


ECB vs. CBC

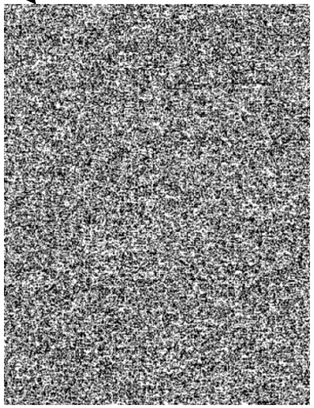


AES in ECB mode

AES in CBC mode

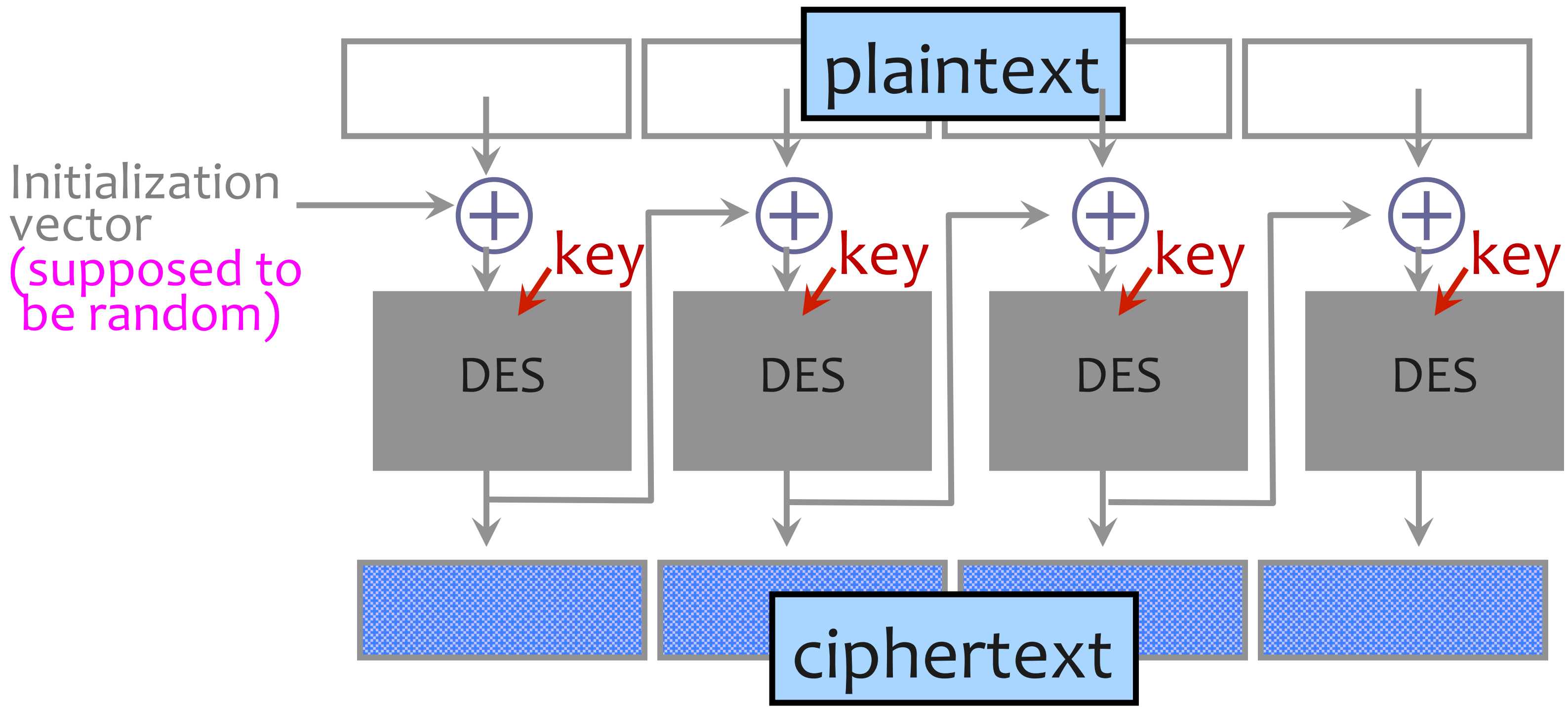


Similar plaintext blocks produce similar ciphertext blocks (not good!)



[Picture due to Bart Preneel]

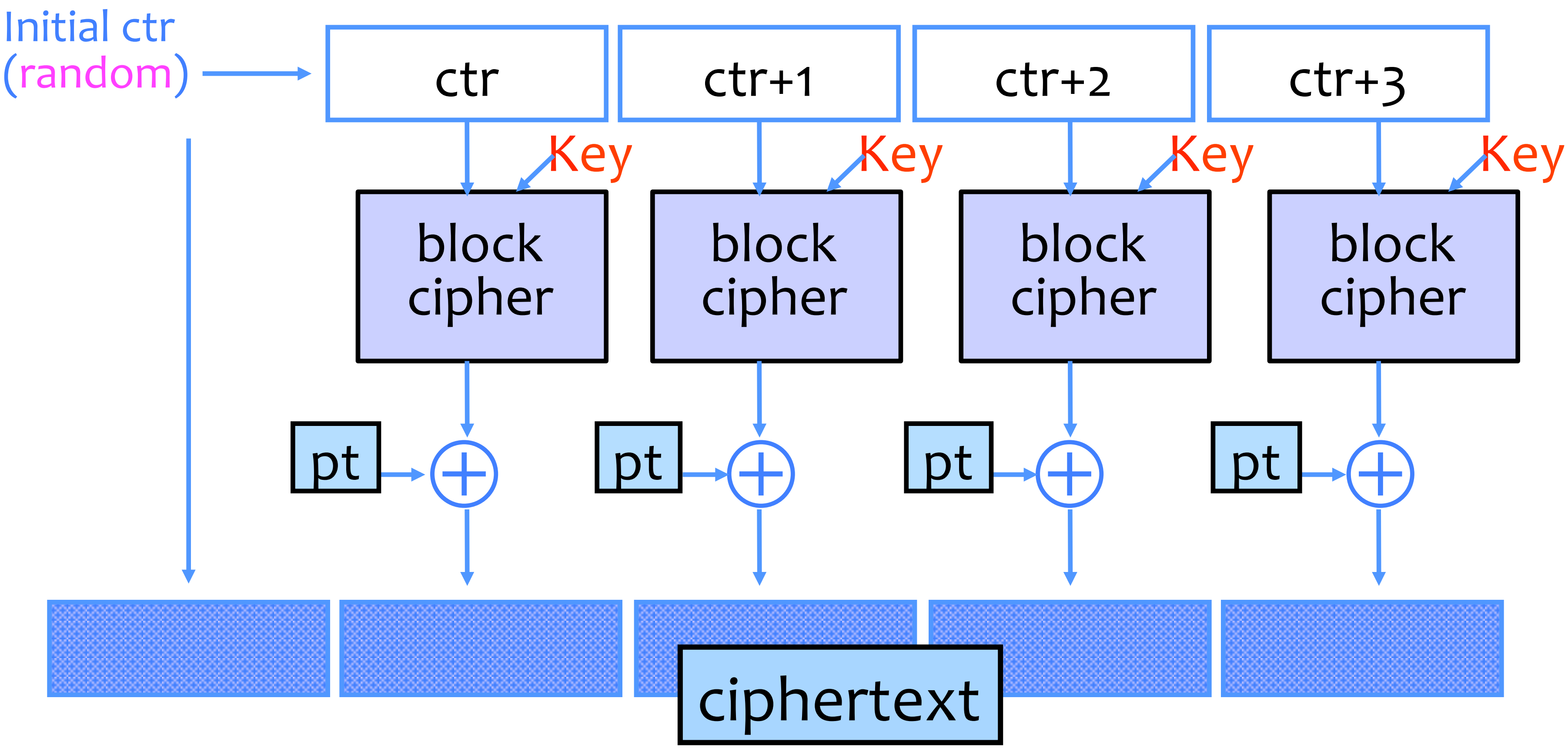
CBC and Electronic Voting



Found in the source code for Diebold voting machines:

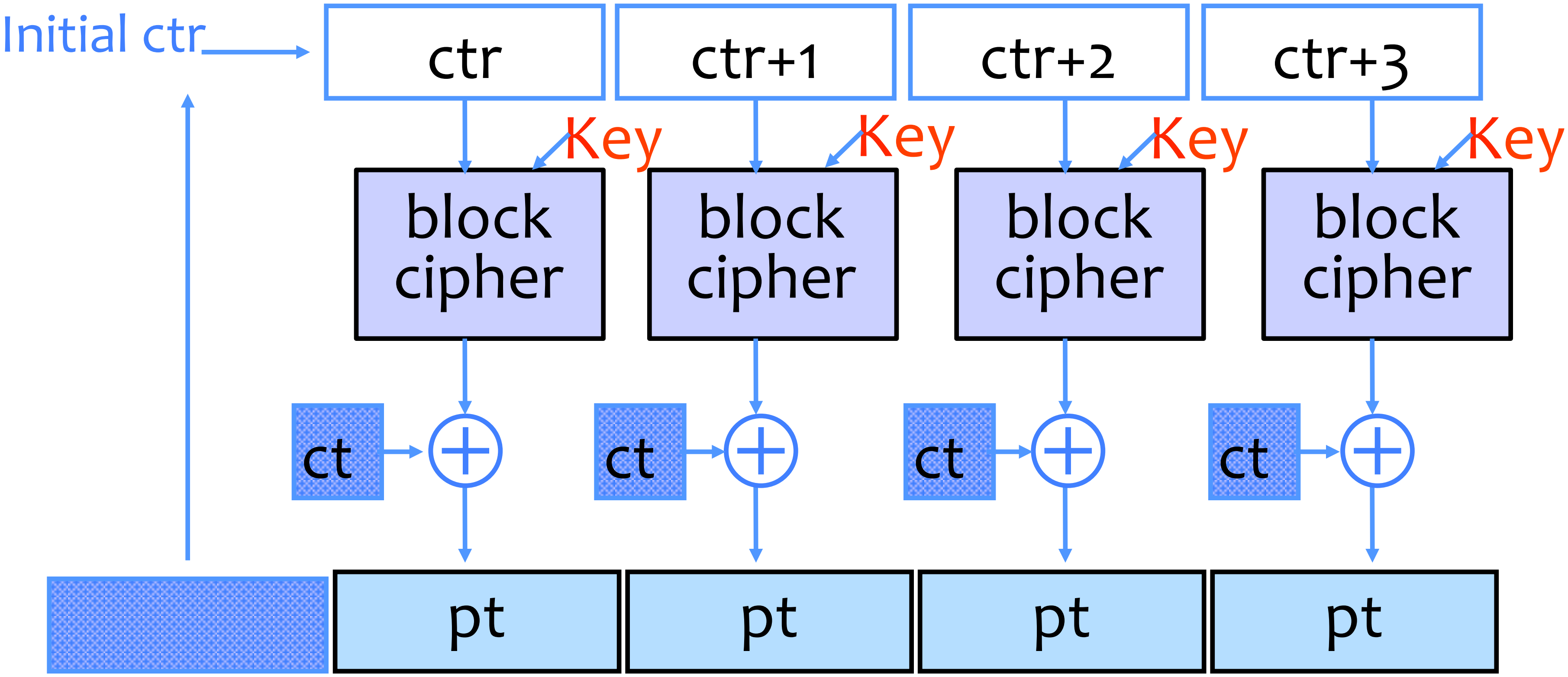
```
DesCBCEncrypt((des_c_block*)tmp, (des_c_block*)record.m_Data,
        totalSize, DESKEY, NULL, DES_ENCRYPT)
```

Counter Mode (CTR): Encryption



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

Counter Mode (CTR): Decryption



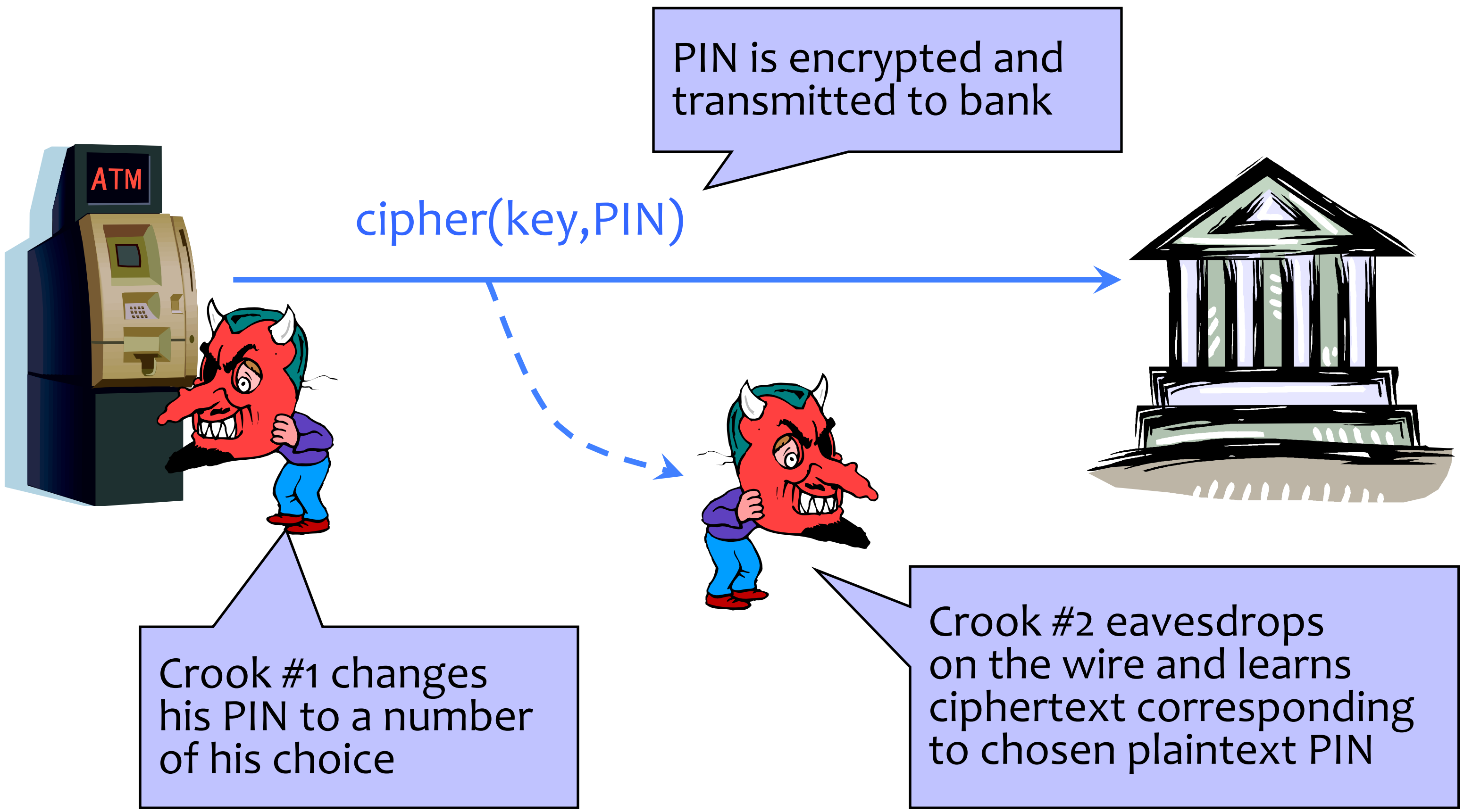
When is an Encryption Scheme "Secure"?

- 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?

- Attackers knows ciphertext and encryption algthm
  - What else does the attacker know? Depends on the application in which the cipher is used!
- Ciphertext-only attack
- KPA: Known-plaintext attack (stronger)
  - Knows some plaintext-ciphertext pairs
- CPA: Chosen-plaintext attack (even stronger)
  - Can obtain ciphertext for any plaintext of his choice
- CCA: Chosen-ciphertext attack (very strong)
  - Can decrypt any ciphertext except the target

Chosen Plaintext Attack



… repeat for any PIN value

Very Informal Intuition

Minimum security requirement for a modern encryption scheme

- Security against chosen-plaintext attack (CPA)
  - Ciphertext leaks no information about the plaintext
  - Even if the attacker correctly guesses the plaintext, he cannot verify his guess
  - Every ciphertext is unique, encrypting same message twice produces completely different ciphertexts
- Security against chosen-ciphertext attack (CCA)
  - Integrity protection – it is not possible to change the plaintext by modifying the ciphertext

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)