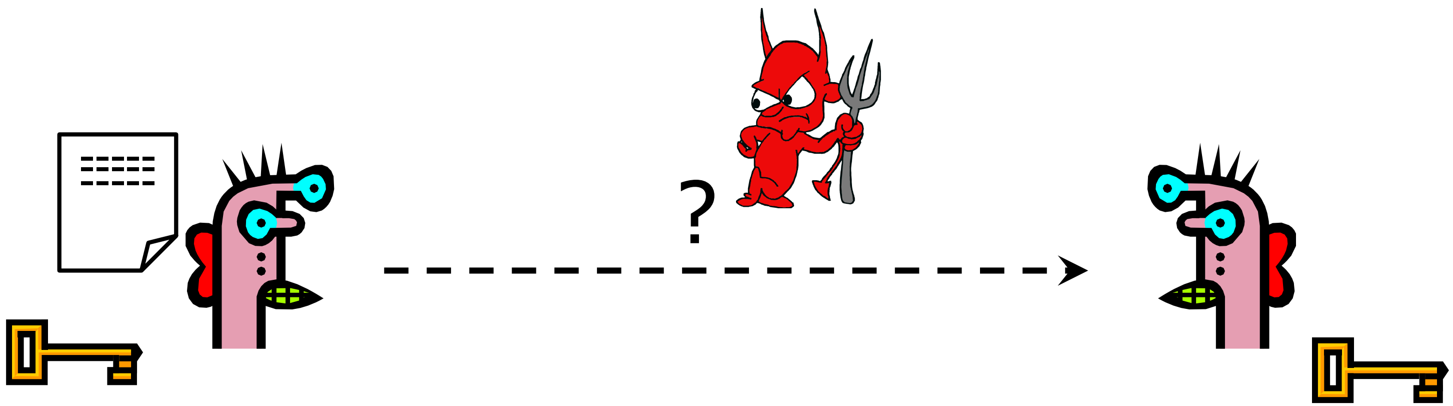
CS 5435

Introduction to Symmetric Cryptography

Vitaly Shmatikov

Basic Problem



Given: both parties already know the same secret

Goal: send a message confidentially

How is this achieved in practice?

Any communication system that aims to guarantee confidentiality must solve this problem

Online Shopping with TLS

https://amazon.com

Enc(K, “Quantity: 1 , CC#: 5415431230123456”)

Step 1:
Key exchange protocol to share secret K

Step 2:
Send data via secure channel

TLS uses many cryptographic primitives:

- **key exchange:** hash functions, digital signatures, public key encryption
- **secure channel:** symmetric encryption, message authentication

Mechanisms to resist replay attacks, man-in-the-middle attacks, truncation attacks, etc…

Kerckhoffs's Principle

An encryption scheme should be secure even if enemy knows everything about it except the key

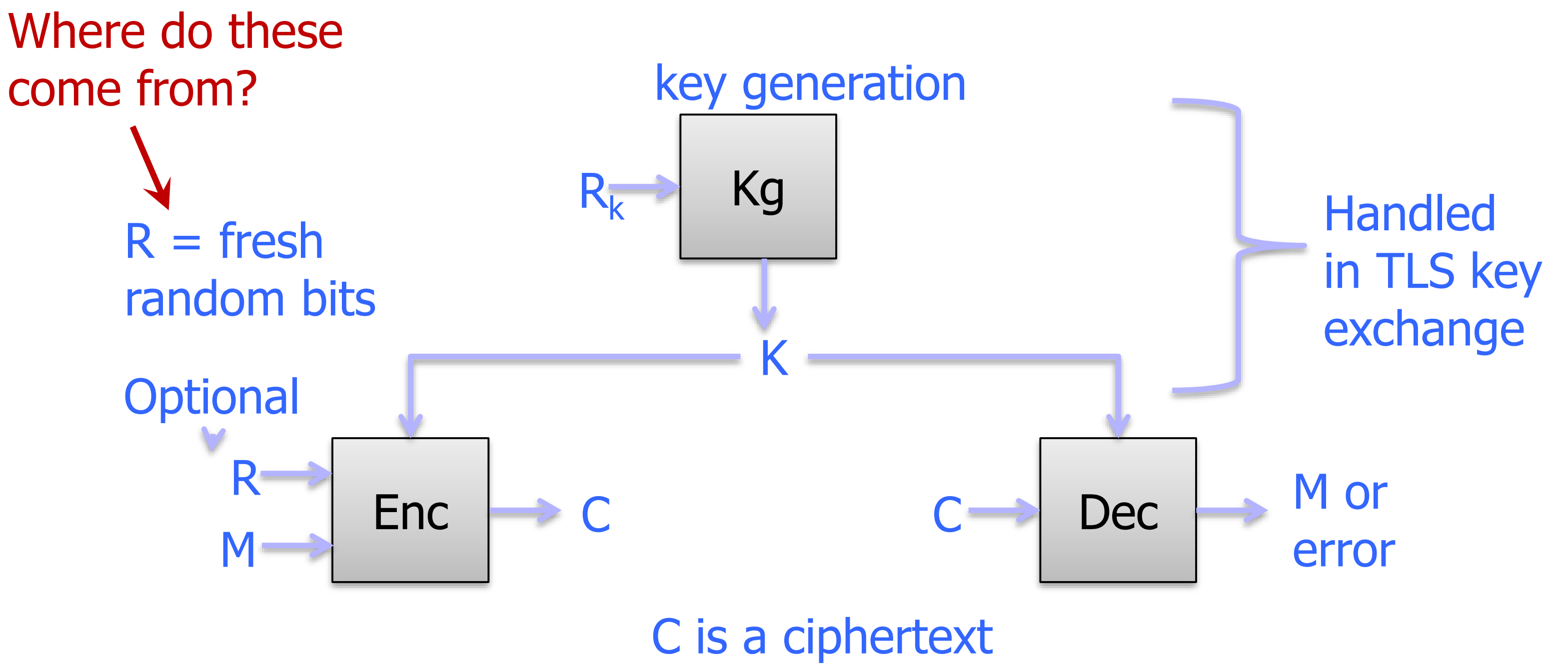
- Attacker knows all algorithms
- Attacker does not know random numbers

Do not rely on secrecy of the algorithms ("security by obscurity")

Easy lesson:
use a good random number generator!

Full name:
Jean-Guillaume-Hubert-Victor-François-Alexandre-Auguste Kerckhoffs von Nieuwenhof

Symmetric encryption



Correctness: Dec(K, Enc(K,R,M)) = M with probability 1 over randomness R used

Kerckhoffs' principle: which parts are public and which are secret?

Randomness Matters!

The New York Times

Business Day

Technology

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS | OPINION | A

Flaw Found in an Online Encryption Method

By JOHN MARKOFF
Published: February 14, 2012

SAN FRANCISCO — A team of European and American mathematicians and cryptographers have discovered an unexpected weakness in the encryption system widely used worldwide for online shopping, banking, e-mail and other Internet services intended to remain private and secure.

The flaw — which involves a small but measurable number of cases — has to do with the way the system generates random numbers, which are used to

m
at
m

Internet users, there is nothing a
sites will need to make changes t
said

RECOMMEND
TWITTER
LINKEDIN
COMMENTS (127)
E-MAIL
PRINT
SINGLE PAGE
REPRINTS

Readers' Comments

Readers shared their thoughts on this article.

Read All Comments (127) »

Uptime | IT and business computing insights

Crypto shocker: four of every 1,000 public keys provide no security (updated)

By Dan Goodin | Published 7 days ago

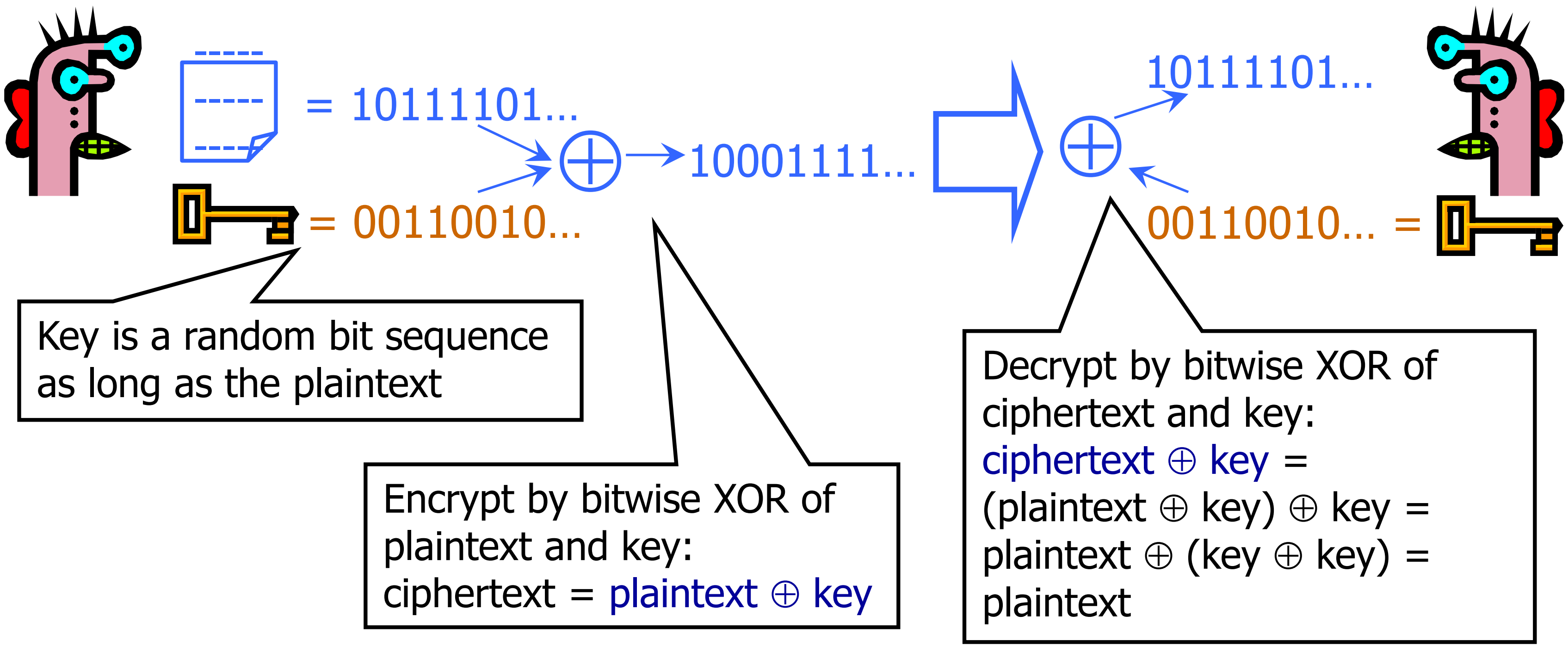
WW2 Enigma machine built by Germans

Polyalphabetic substitution cipher
- Substitution table changes from character to character
- Rotors control substitutions

Allies broke Enigma (even before the war), significant intelligence impact

Computers were built to break WW2 ciphers, by Alan Turing and others

One-Time Pad (Vernam Cipher)



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
- …<u>if and only if</u> the key sequence is truly random
  - True randomness is expensive to obtain in large quantities
- …<u>if and only if</u> each key is as long as the plaintext
  - But how do the sender and the receiver communicate the key to each other? Where do they store the key?

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

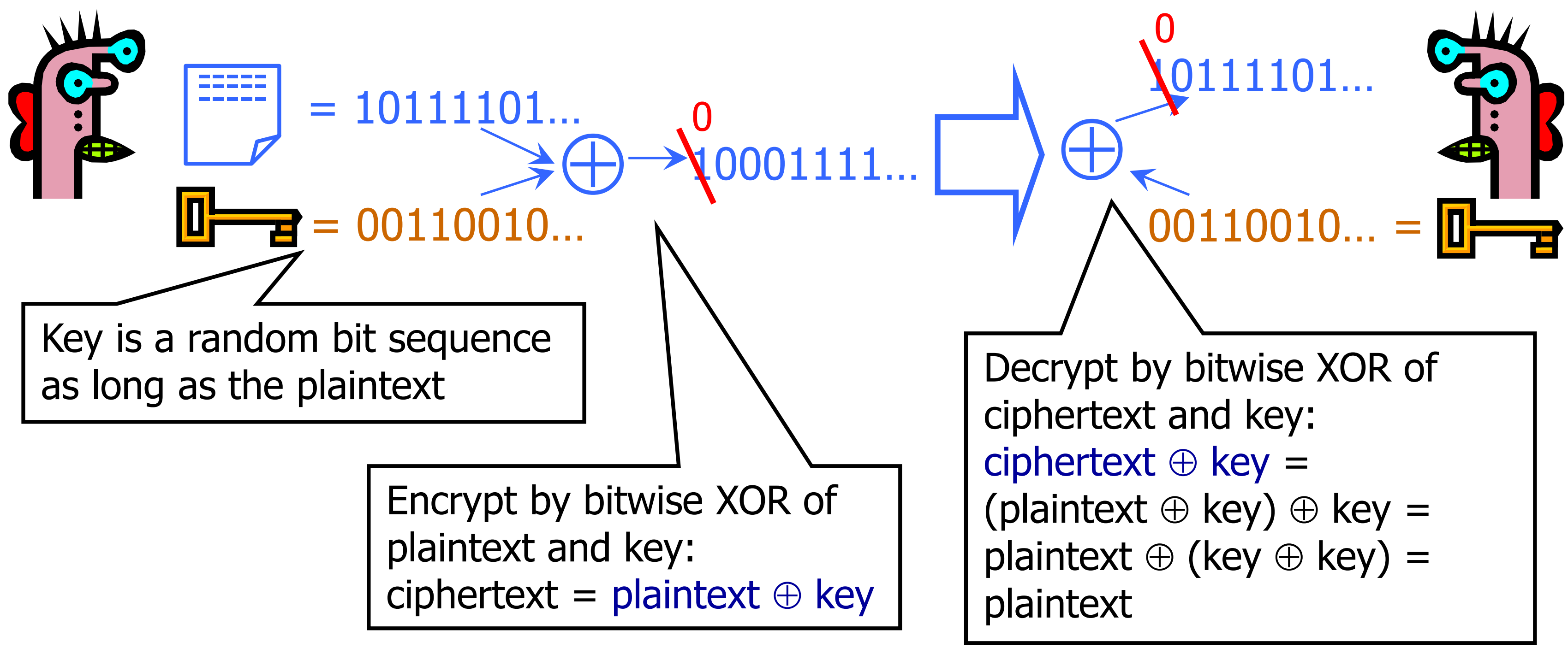
Does not guarantee integrity

- One-time pad only guarantees confidentiality
- Attacker cannot recover plaintext, but can easily change it to something else

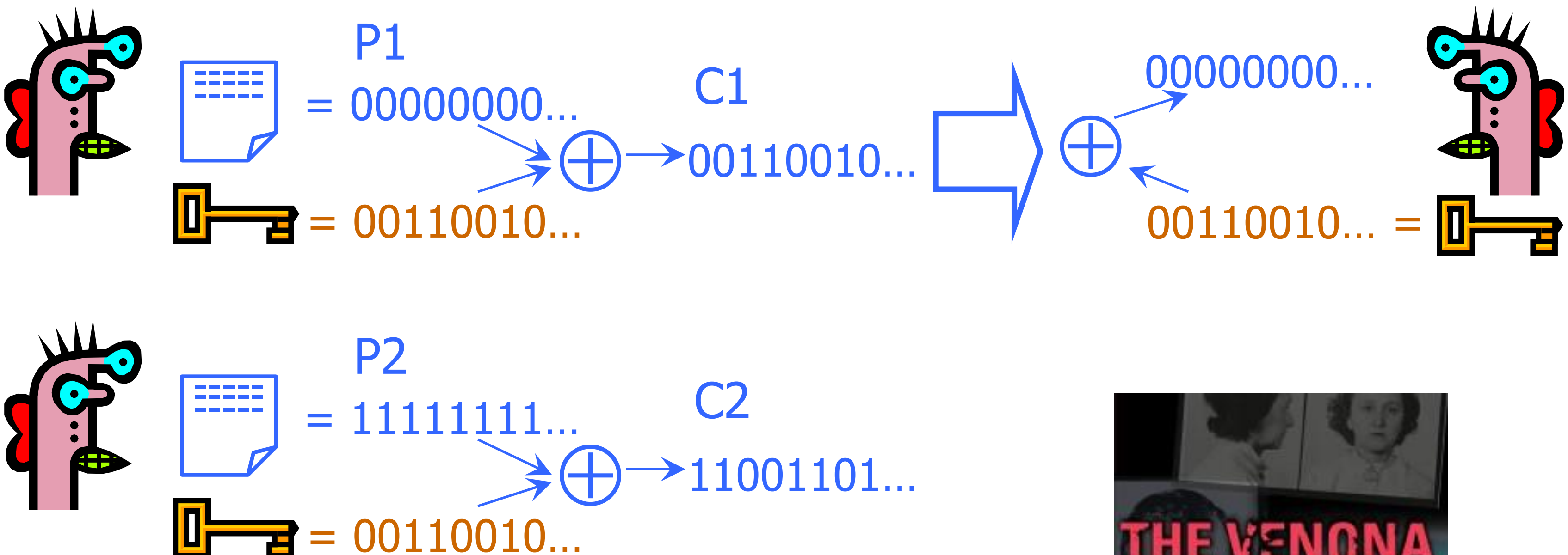
Insecure if keys are reused

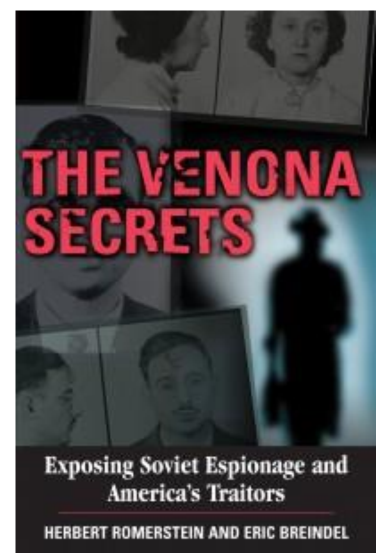
- Attacker can obtain XOR of plaintexts

No Integrity



Dangers of Reuse





Learn relationship between plaintexts

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

Reducing Key Size

What to do when it is infeasible to pre-share huge random keys?

Use special cryptographic primitives:

block ciphers, stream ciphers

- Single key can be re-used (with some restrictions)
- Not as theoretically secure as one-time pad

Block Ciphers

Operates on a single chunk ("block") of plaintext

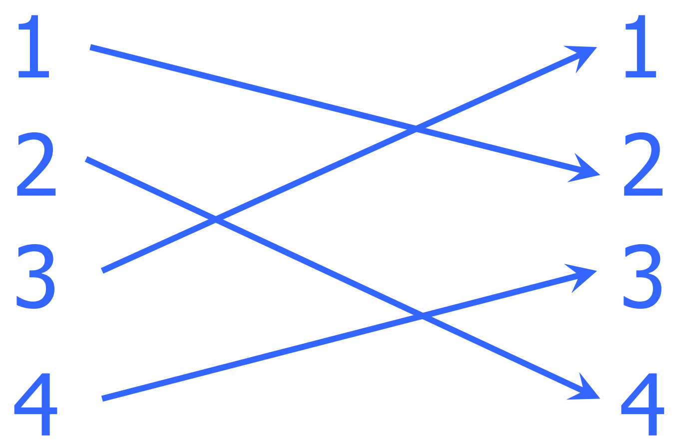
- For example, 64 bits for DES, 128 bits for AES
- Same key is reused for each block (can use short keys)

Result should look like a random permutation

Not impossible to break, just very expensive

- If there is no more efficient algorithm (unproven assumption!), can only break the cipher 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

Permutation



CODE becomes DCEO

For N-bit input, N! possible permutations

Idea: split plaintext into blocks, for each block use secret key to pick a permutation, rinse and repeat

- Without the key, permutation should "look random"

A Bit of Block Cipher History

Playfair and variants (from 1854 until WWII)

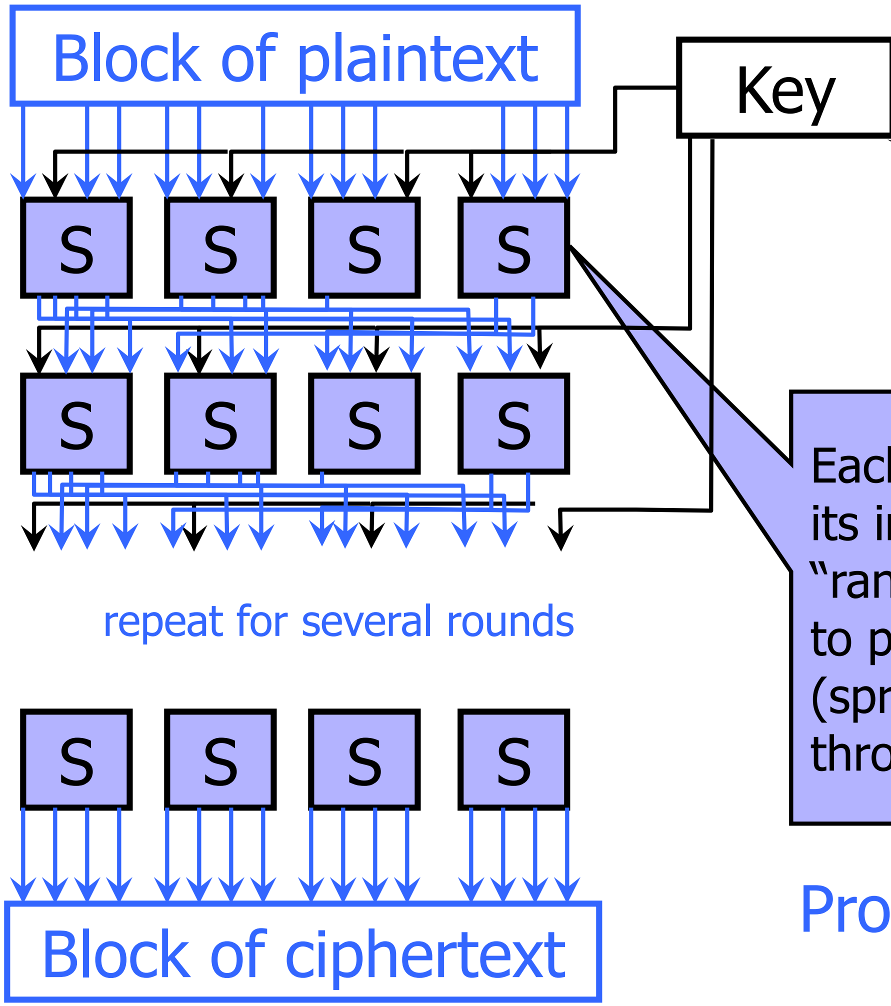
Feistel structure

- "Ladder" structure: split input in half, put one half through the round and XOR with the other half
- After 3 random rounds, ciphertext indistinguishable from a random permutation

DES: Data Encryption Standard

- Invented by IBM, issued as federal standard in 1977
- 64-bit blocks, 56-bit key + 8 bits for parity
- Very widely used (usually as 3DES) until recently
  - 3DES: DES + inverse DES + DES (with 2 or 3 different keys)

DES 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)

Best Attacks Against DES

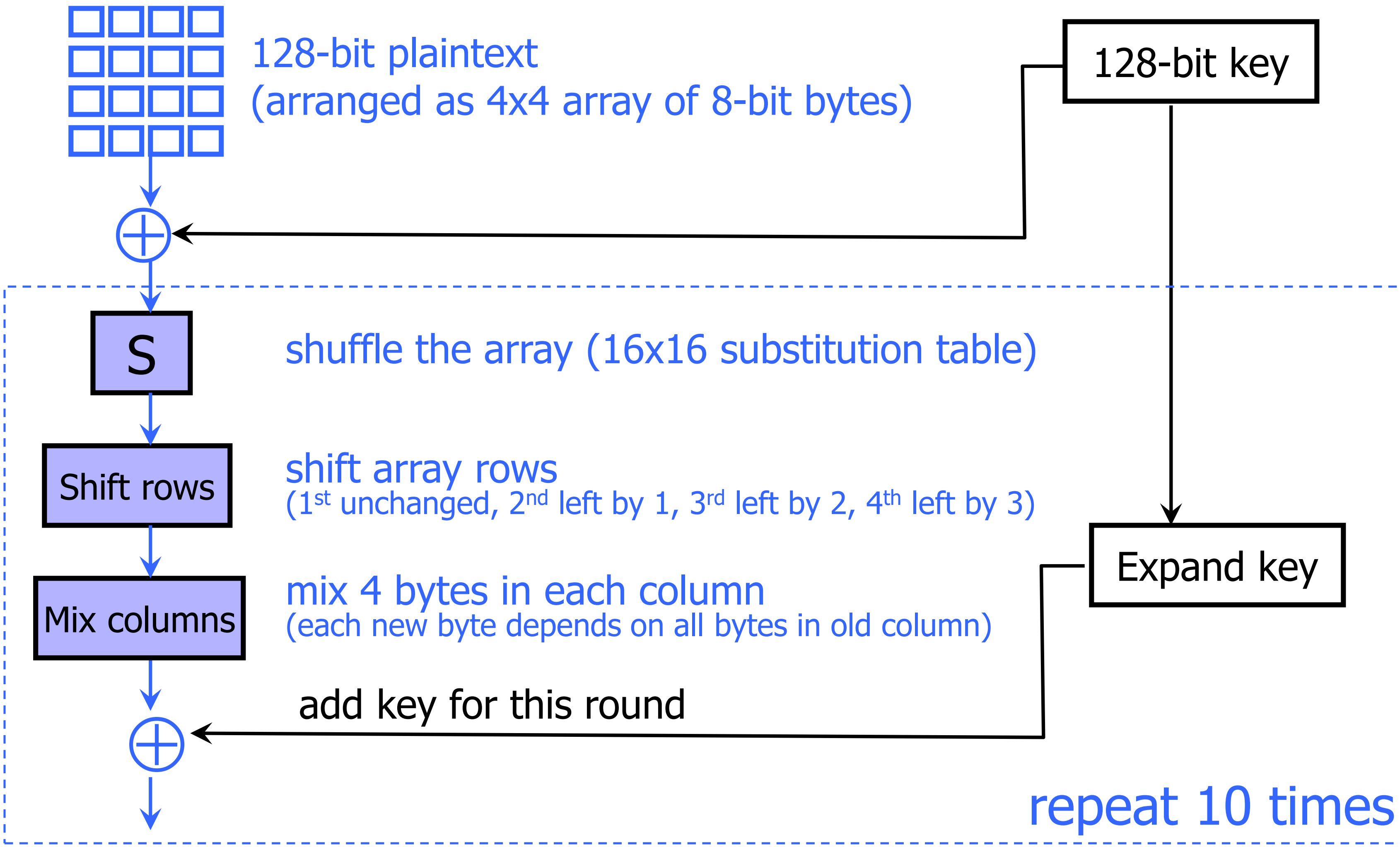
Attack	Attack type	Complexity	Year
Biham, Shamir	Chosen plaintexts, recovers key	2^{47} plaintext, ciphertext pairs	1992
Matsui	Known plaintext, ciphertext pairs, recovers key	2^{42} plaintext, ciphertext pairs, $\sim 2^{41}$ DES computations	1993
DESCHALL	Unknown plaintext, recovers key	$2^{56/4}$ DES computations 41 days	1997
EFF Deepcrack	Unknown plaintext, recovers key	~4.5 days	1998
Deepcrack + DESCHALL	Unknown plaintext, recovers key	22 hours	1999

- DES is still used in some places
- 3DES (use DES 3 times in a row with more keys) expands keyspace and still used widely in practice

Advanced Encryption Standard (AES)

- US 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 clever math

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

Electronic Code Book (ECB) mode

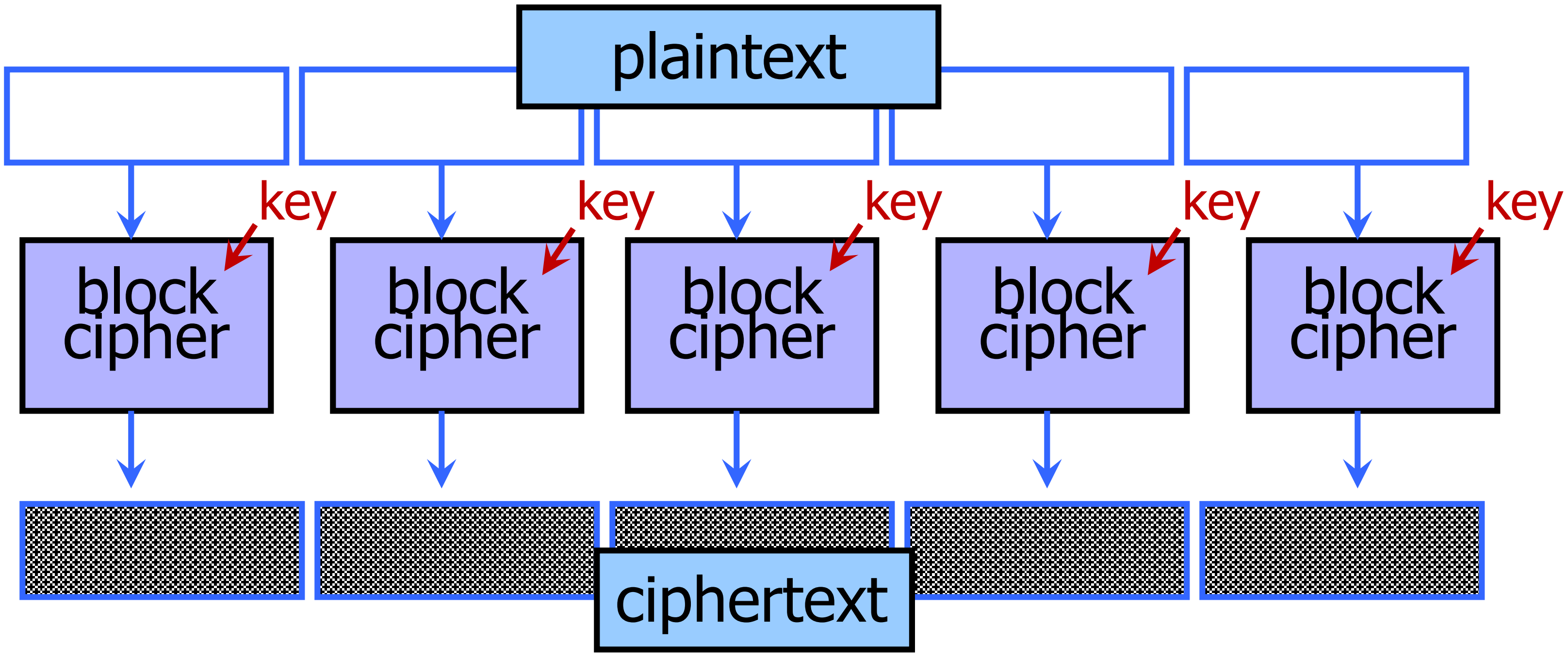
- Split plaintext into blocks, encrypt each one separately using the block cipher

Cipher Block Chaining (CBC) mode

- Split plaintext into blocks, XOR each block with the result of encrypting previous blocks

Also various counter modes, feedback modes, etc.

ECB Mode



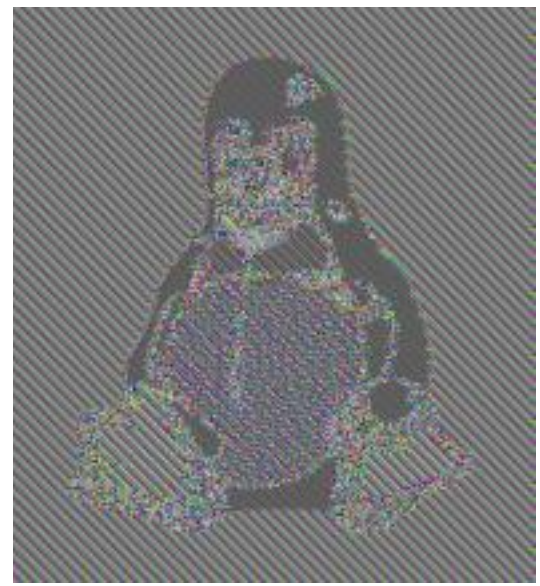
Identical blocks of plaintext produce identical blocks of ciphertext

No integrity checks: can mix and match blocks

Information Leakage in ECB Mode

[Wikipedia]

Encrypt in ECB mode



Adobe Passwords Stolen (2013)

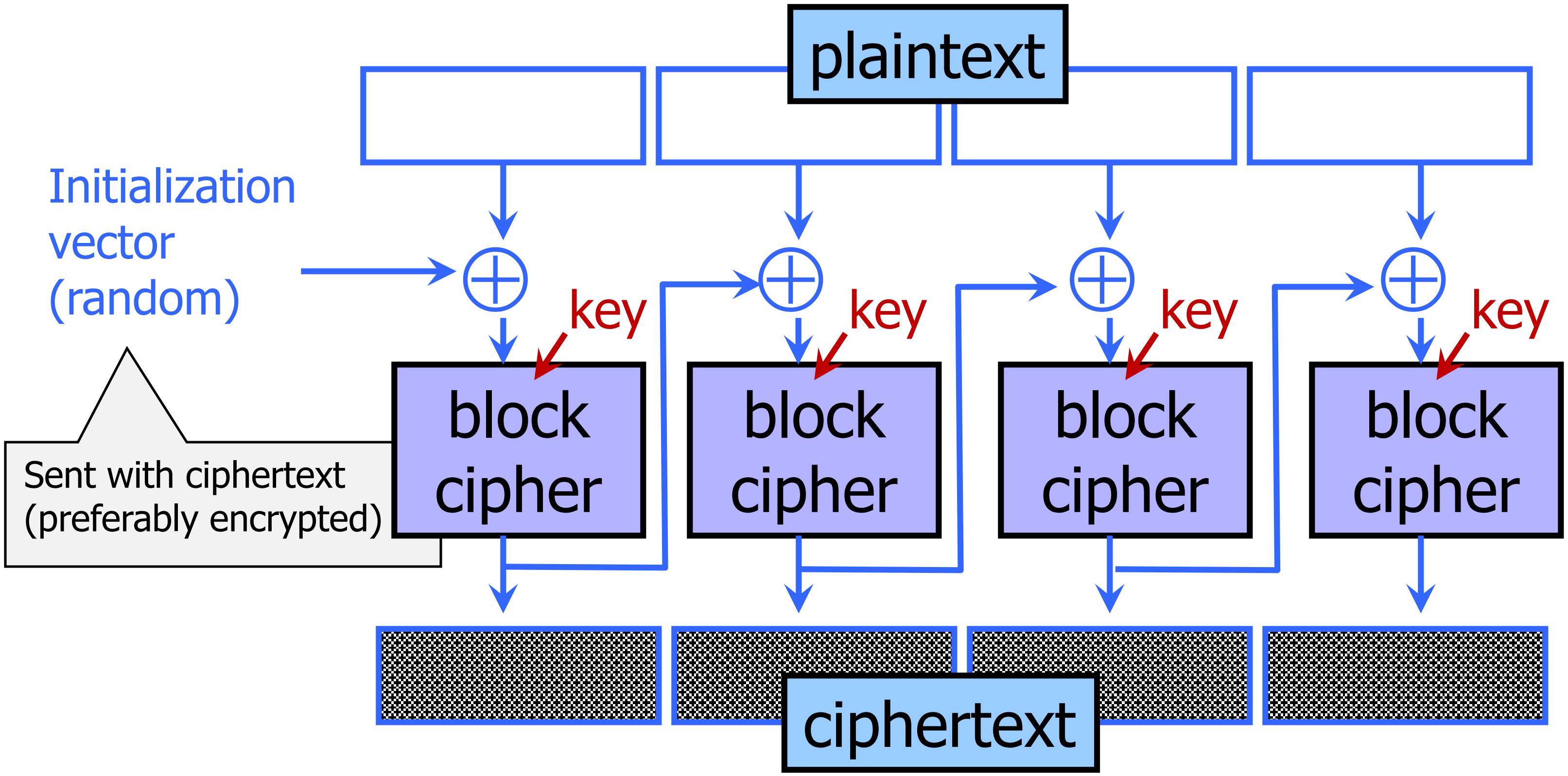
153 million account passwords

- 56 million of them unique

Encrypted using 3DES in ECB mode rather than hashed

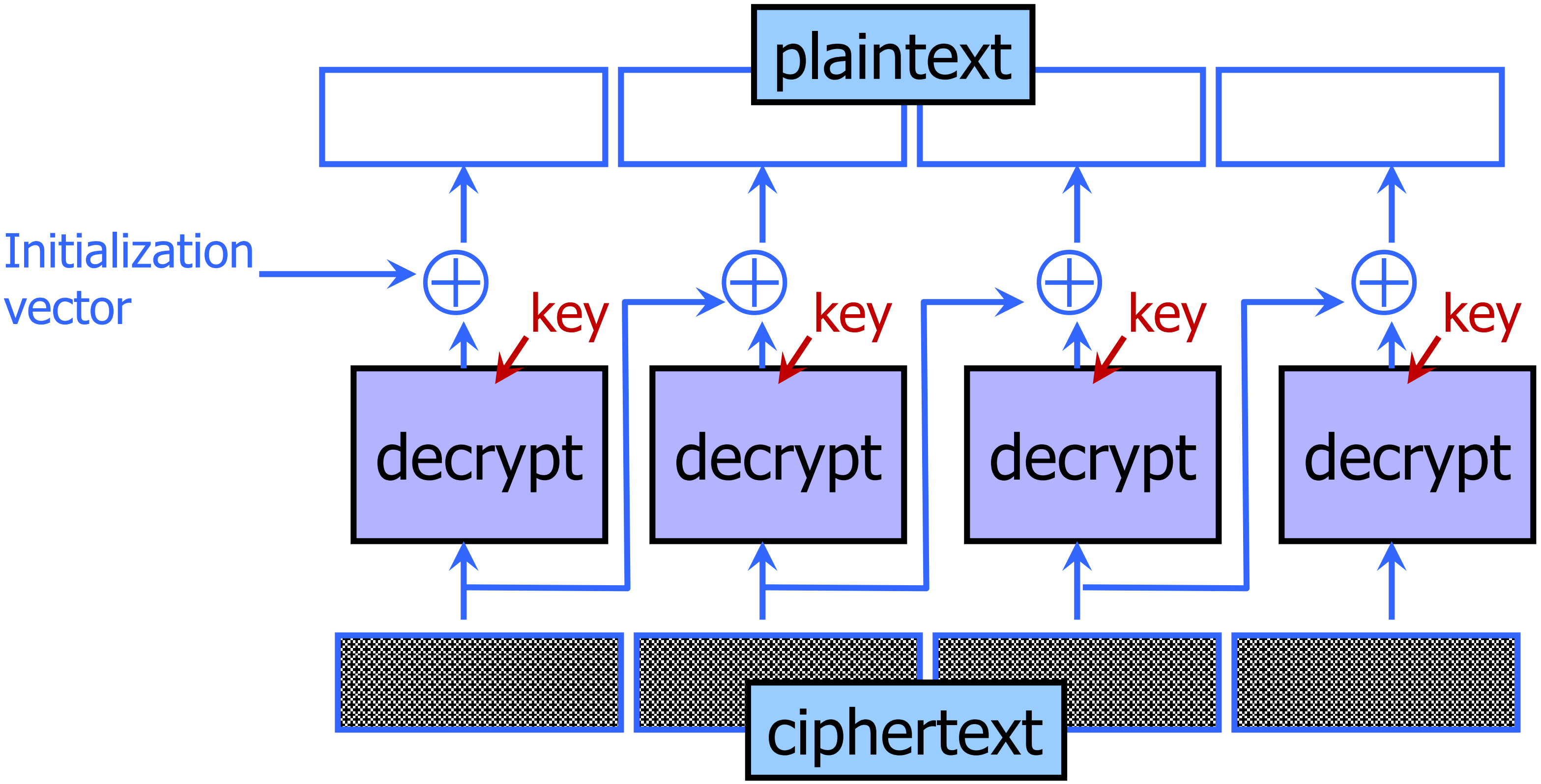
Password hints

CBC Mode: Encryption



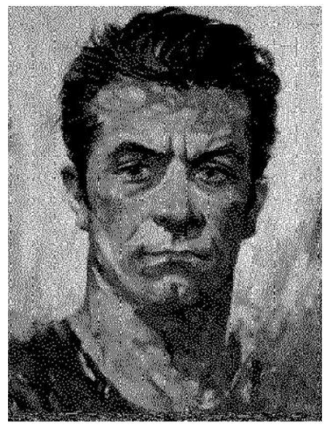
- Identical blocks of plaintext encrypted differently
- Last cipherblock depends on entire plaintext
  - Still does not guarantee integrity

CBC Mode: Decryption



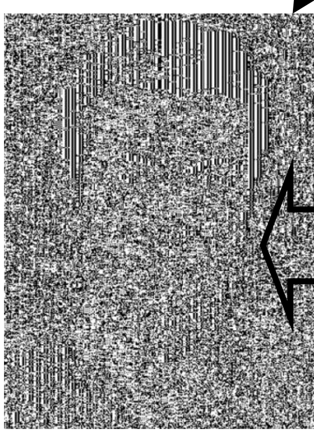
ECB vs. CBC

[Picture due to Bart Preneel]

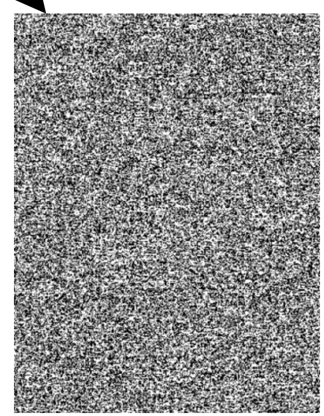


AES in ECB mode

AES in CBC mode



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



Choosing the Initialization Vector

Key used only once

- No IV needed (can use IV=0)

Key used multiple times

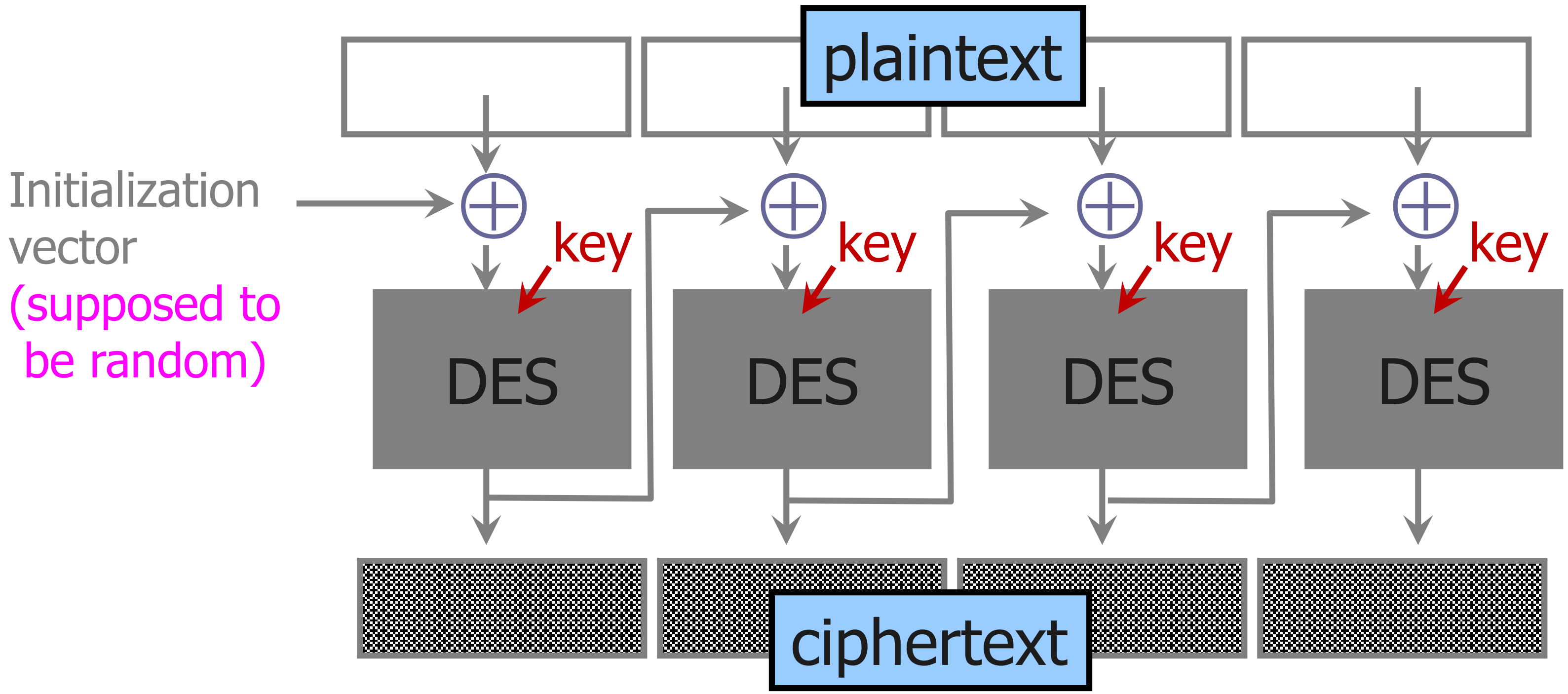
- Best: fresh, random IV for every message
- Can also use unique IV (eg, counter), but then the first step in CBC mode must be IV′ ← E(k, IV)
  - Example: Windows BitLocker
  - May not need to transmit IV with the ciphertext

Multi-use key, unique messages

- Synthetic IV: IV ← F(k′, message)
  - F is a cryptographically secure keyed pseudorandom function

CBC and Electronic Voting

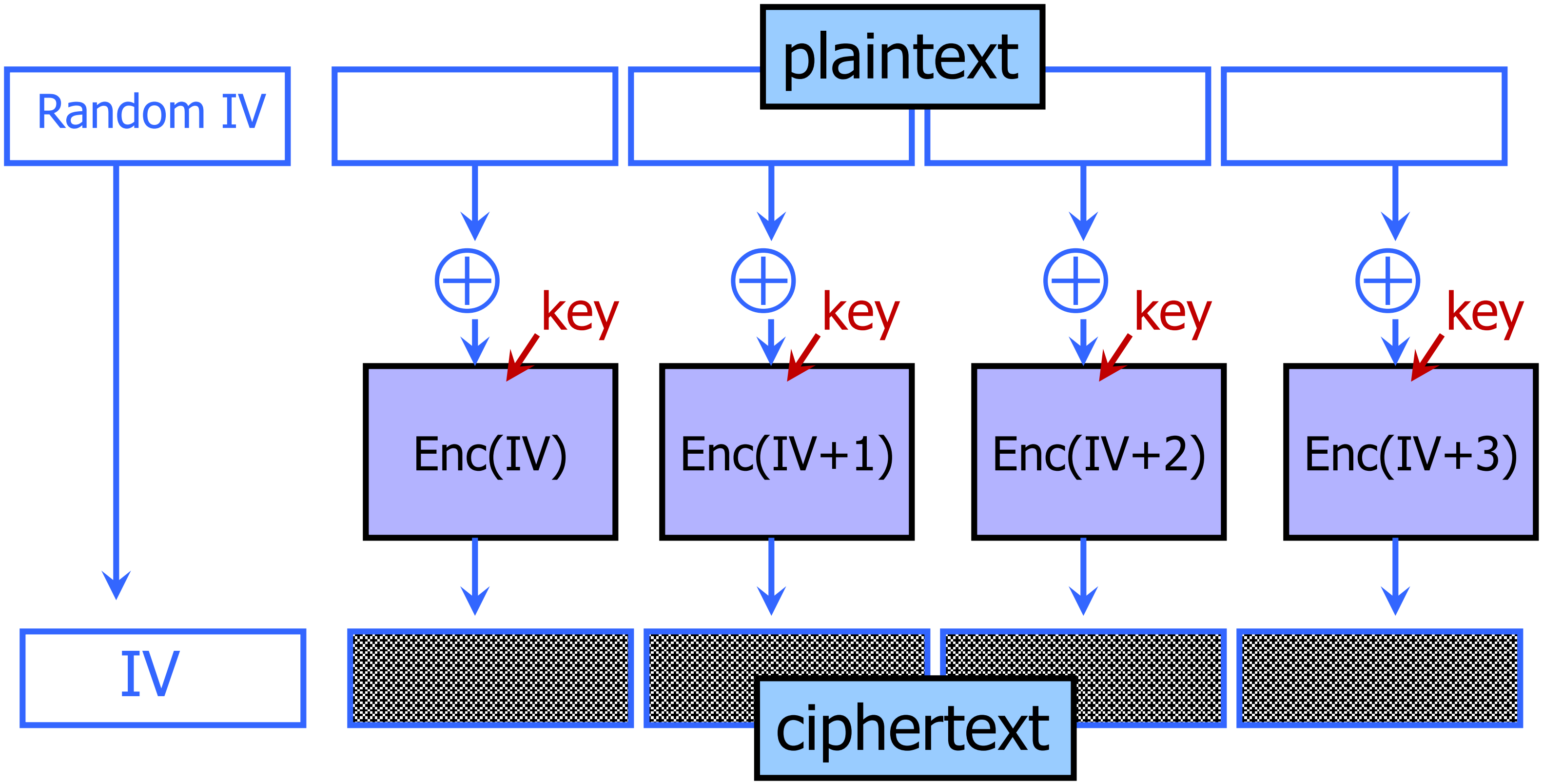
[Kohno, Stubblefield, Rubin, Wallach]



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)
```

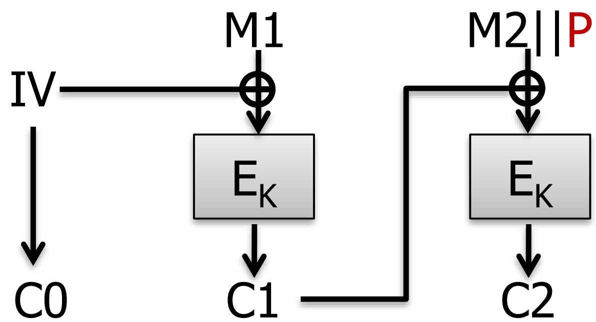
CTR (Counter Mode)



Still does not guarantee integrity

Fragile if counter repeats

Padding Oracle Attack



Assume that M1||M2 has length 2n-8 bits

P is one byte of padding that must equal 0x00

Adversary obtains ciphertext C0,C1,C2

C0, C1, C2

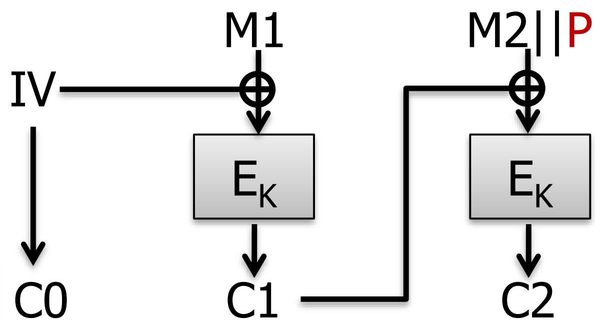
ok

C0, C1 ⊕ 1, C2

error

<u>Dec(K,C′)</u>
M1′||M2′||P′ = CBC-Dec(K,C′)
If P′ ≠ 0x00 then
        Return error
Else
        Return ok

Padding Oracle Attack



Assume that M1||M2 has length 2n-8 bits

P is one byte of padding that must equal 0x00

Low byte of M1 equals i

R, C0, C1 →

← error

R, C0 ⊕ 1, C1 →

← error

R, C0 ⊕ 2, C1 →

← error

…

R, C0 ⊕ i, C1 →

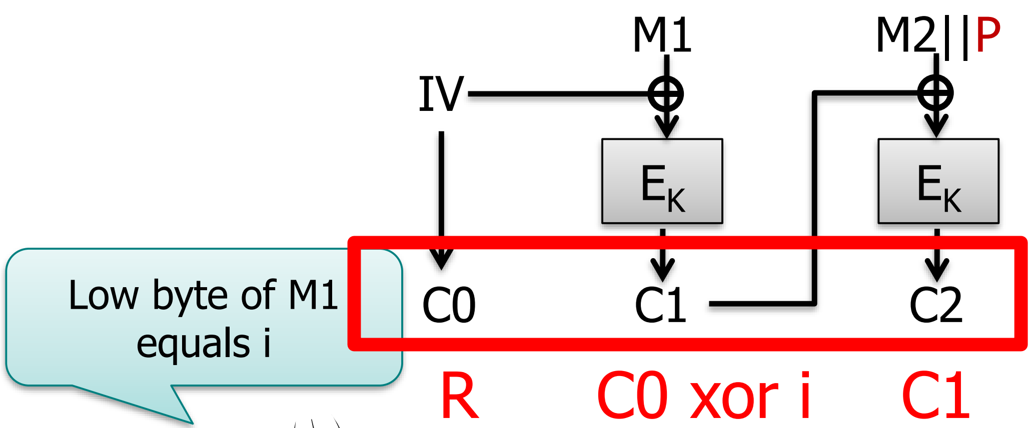
← ok

Adversary obtains ciphertext C0,C1,C2

Let R be arbitrary bits

<u>Dec(K,C′)</u>
M1′||M2′||P′ = CBC-Dec(K,C′)
If P′ ≠ 0x00 then
    Return error
Else
    Return ok

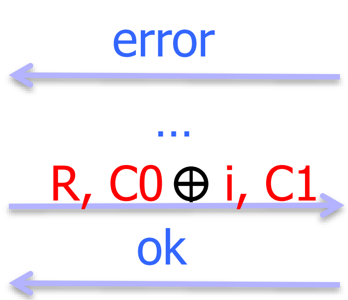
Padding Oracle Attack



<u>Dec(K,C′)</u>
M1′||M2′||P′ = CBC-Dec(K,C′)
If P′ ≠ 0x00 then
Return error
Else
Return ok

Adversary obtains ciphertext C0,C1,C2

Let R be arbitrary bits



Decrypt C1, get M′

M″ = M′ xor C0 xor i

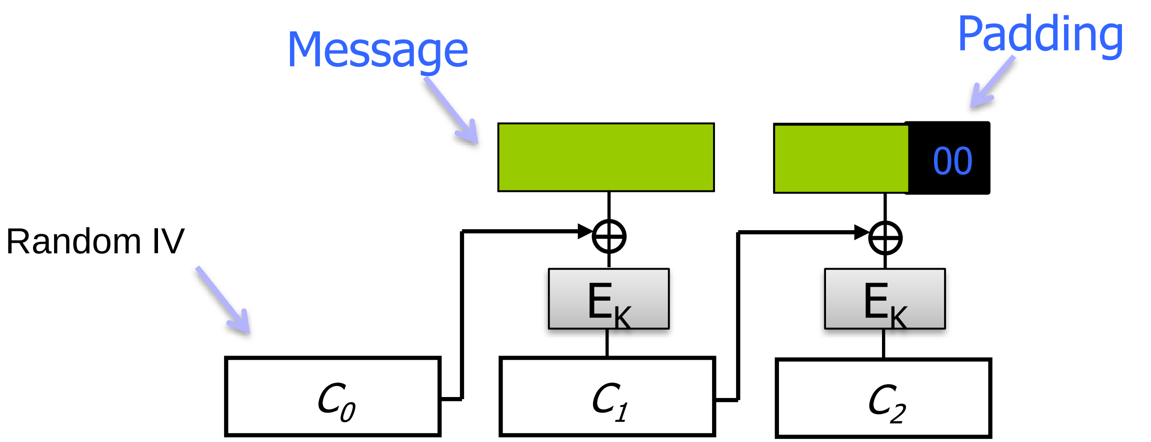
Last byte of M″ is 00 (why?)

M′ = M1 xor C0 (why?)

Therefore, last byte of M1 xor C0 xor C0 xor i is 00

Therefore, last byte of M1 is i

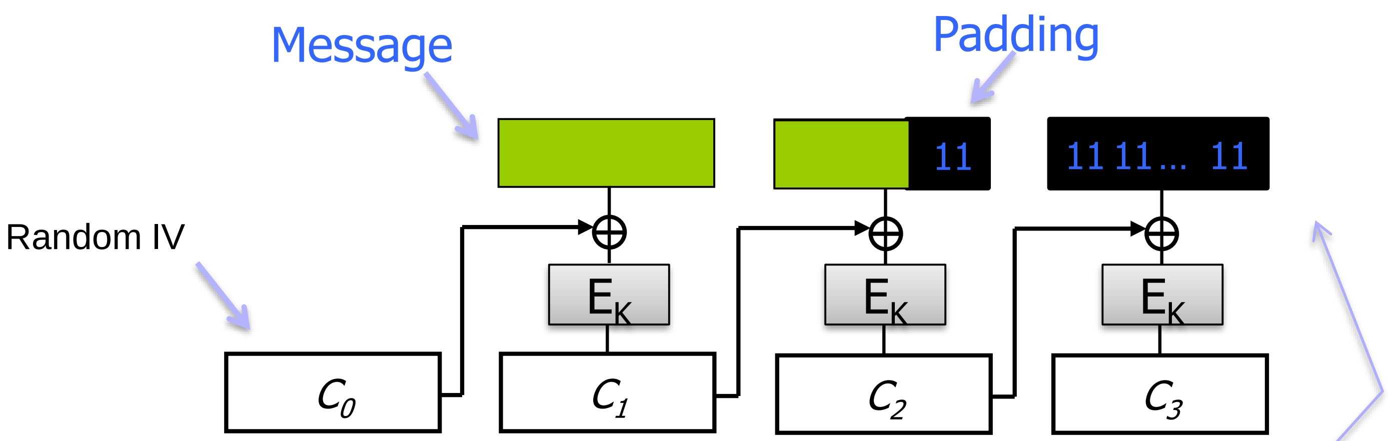
Padding for CBC Mode in TLS



Possible paddings in TLS:

00 01 01 02 02 02 etc.

Padding for CBC Mode in TLS



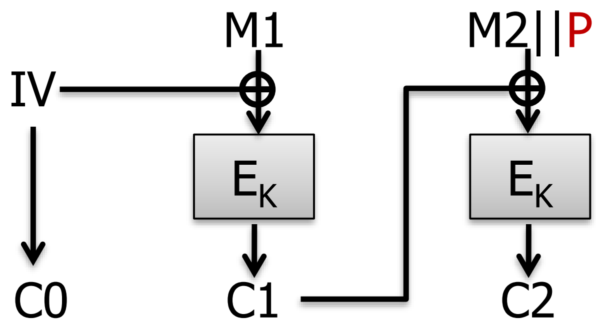
Possible paddings in TLS:

00 01 01 02 02 02 etc.

“Lengths longer than necessary might be desirable to frustrate attacks on a protocol that are based on analysis of the lengths of exchanged messages.”

RFC 5246 Called “traffic analysis attacks”

Vaudenay's Padding Oracle Attack

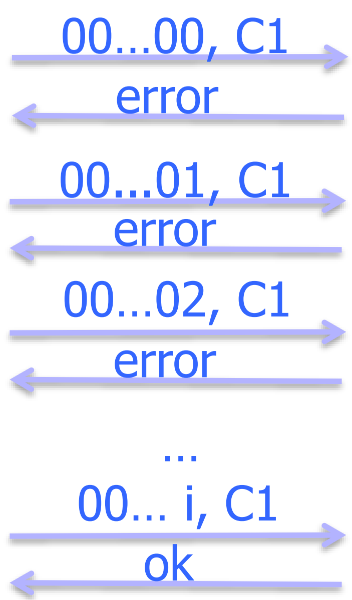


Goal:
decrypt entire plaintext

We know that:
00 = i + IV[n] + M1[n]

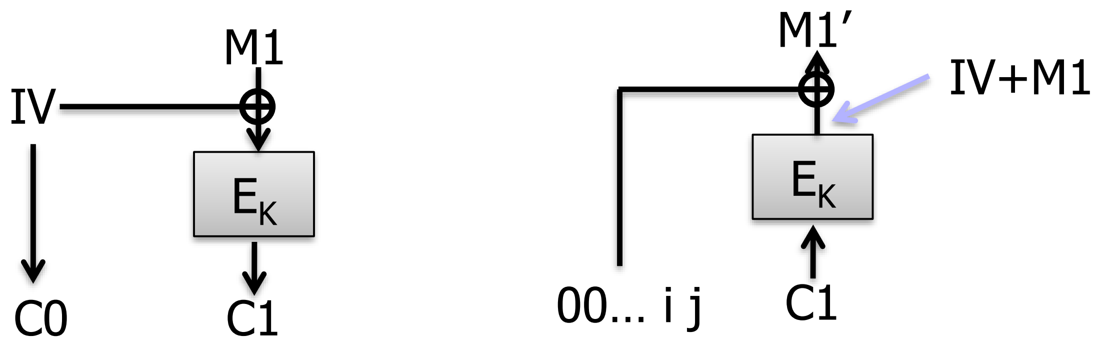
Or do we? Could be:
01 = i + IV[n] + M1[n]
01 = IV[n-1] + M1[n-1]

Easy to exclude other cases




```
Dec(K,C' )
M1' = CBC-Dec(K,C')
(X,plen) <- lastbyte(M1')
For i = 0 to padlen do
    (X,plen') <- lastbyte(X)
    If plen' != plen return Error
Return Ok
```

Vaudenay’s Padding Oracle Attack

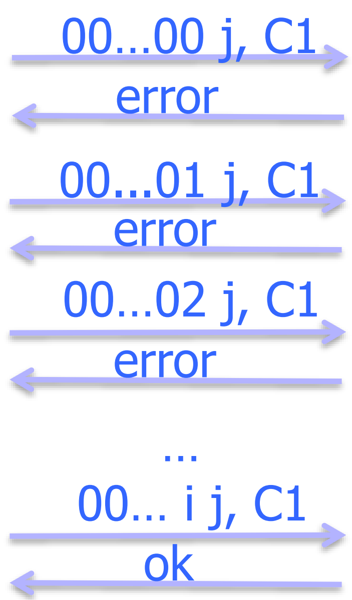


We know M1[n]. Let’s get second to last byte.

Solve j to make M1′[n] = 01
01 = j + IV[n] + M1[n]

Know that:
01 = i + IV[n-1] + M1[n-1]

Repeat for all n bytes



<u>Dec(K,C′)</u>
M1′ = CBC-Dec(K,C′)
(X,plen) <- lastbyte(M1′)
For i = 0 to padlen do
    (X,plen′) <- lastbyte(X)
    If plen′ != plen return Error
Return Ok

Chosen Ciphertext Attacks on CBC

Attack	Description	Year
Vaudenay	10's of chosen ciphertexts, recovers message bits from a ciphertext. Called "padding oracle attack"	2001
Canvel et al.	Shows how to use Vaudenay's ideas against TLS	2003
Degabriele, Paterson	Breaks IPsec encryption-only mode	2006
Albrecht et al.	Plaintext recovery against SSH	2009
Duong, Rizzo	Breaks ASP.net encryption	2011
Jager, Somorovsky	XML encryption standard	2011
Duong, Rizzo	"Beast" attacks against TLS	2011

When Is a Cipher "Secure"?

Hard to recover plaintext from ciphertext?

- What if attacker learns only some bits of the plaintext? Some function of the bits? Some partial information about the plaintext?

Fixed mapping from plaintexts to ciphertexts?

- What if attacker sees two identical ciphertexts and infers that the corresponding plaintexts are identical?
- What if attacker guesses the plaintext – can he verify his guess?
- 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!

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

Known-Plaintext Attack

[From "The Art of Intrusion"]

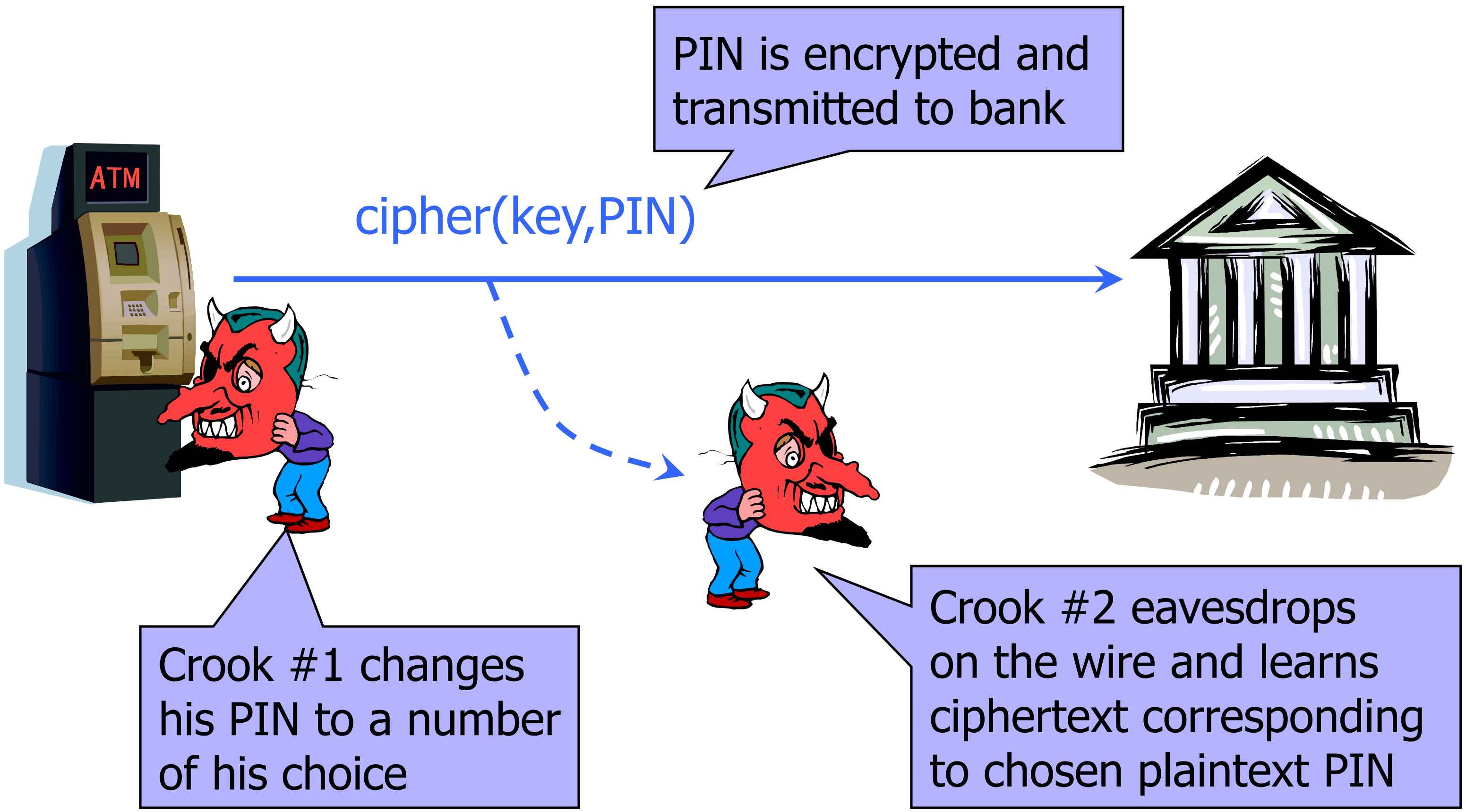
Extracting password from an encrypted PKZIP file …

"… I opened the ZIP file and found a `logo.tif' file, so I went to their main Web site and looked at all the files named `logo.tif.' I downloaded them and zipped them all up and found one that matched the same checksum as the one in the protected ZIP file"

With known plaintext, PkCrack took 5 minutes to extract the key

- Biham-Kocher attack on PKZIP stream cipher

Chosen-Plaintext Attack



… repeat for any PIN value

Very Informal Intuition

Minimum security requirement for a modern encryption scheme

Security against chosen-plaintext attack

- 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

- Integrity protection – it is not possible to change the plaintext by modifying the ciphertext

The Chosen-Plaintext Game

Attacker does not know the key

He chooses as many plaintexts as he wants, and receives 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

Meaning of "Leaks No Information"

Idea: given a ciphertext, attacker should not be able to learn even a single bit of useful information about the plaintext

Let Enc(M_0,M_1,b) be a "magic box" that returns encrypted M_b

0 or 1

- Given two plaintexts, the box always returns the ciphertext of the left plaintext or right plaintext
- Attacker can use this box to obtain the 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 this one bit b

Chosen-Plaintext Security

Consider two experiments (A is the attacker)

Experiment 0
A interacts with Enc(-,-,0)
and outputs his guess of bit b

Experiment 1
A interacts with Enc(-,-,1)
and outputs his guess of bit b

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

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

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

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

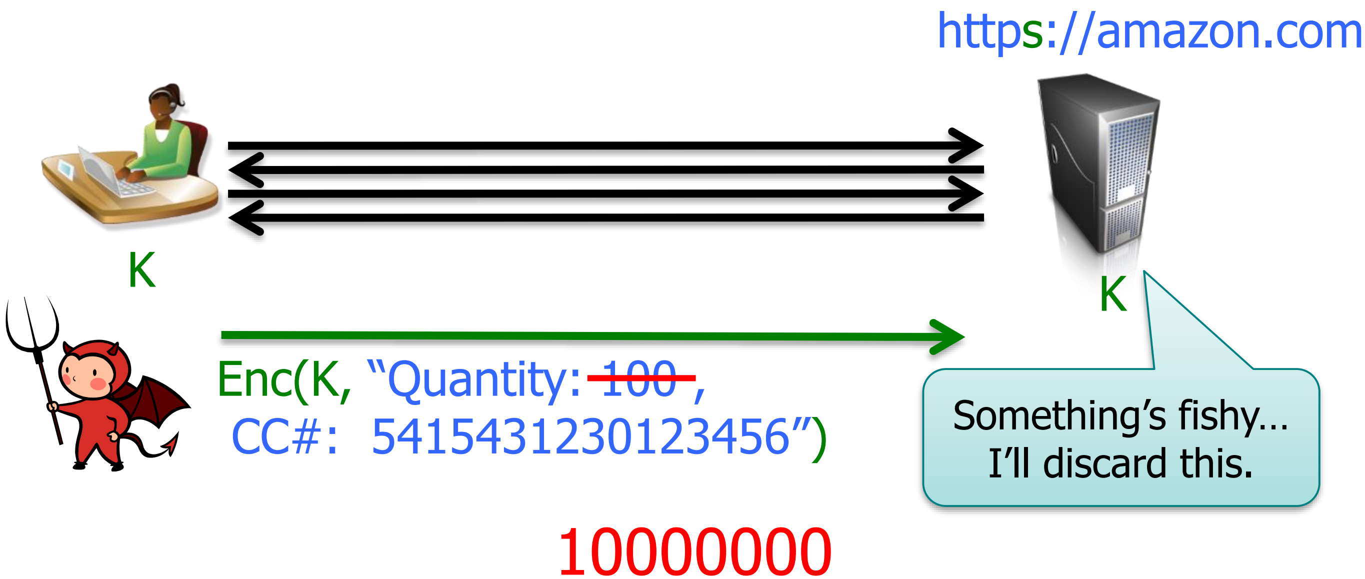
The advantage of this attacker A is 1

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

Authenticated Encryption

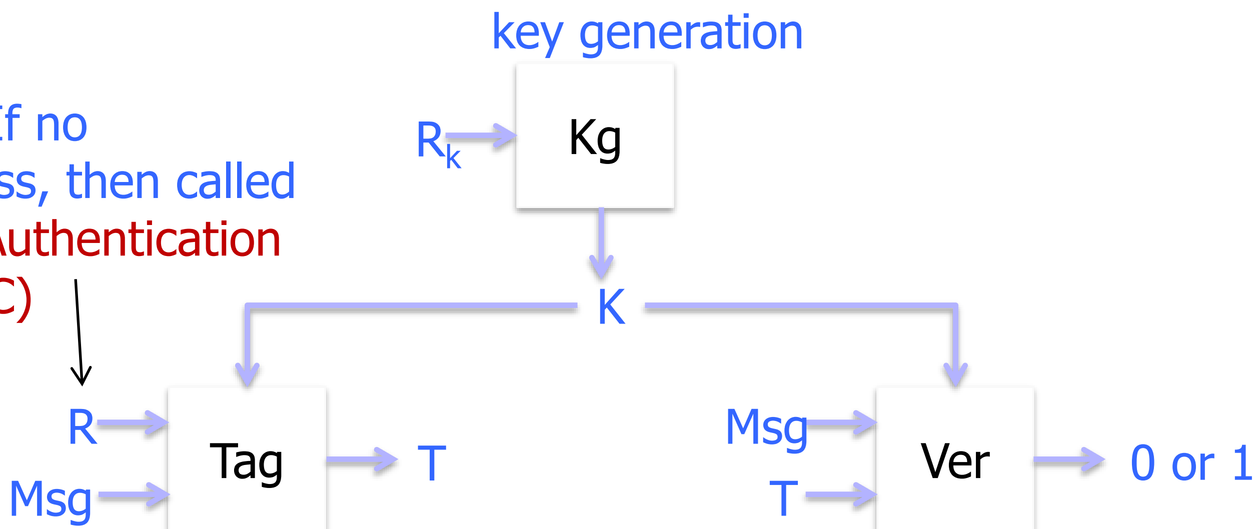
Goal: Hide message and detect tampering

Can build by combining encryption with message authentication scheme



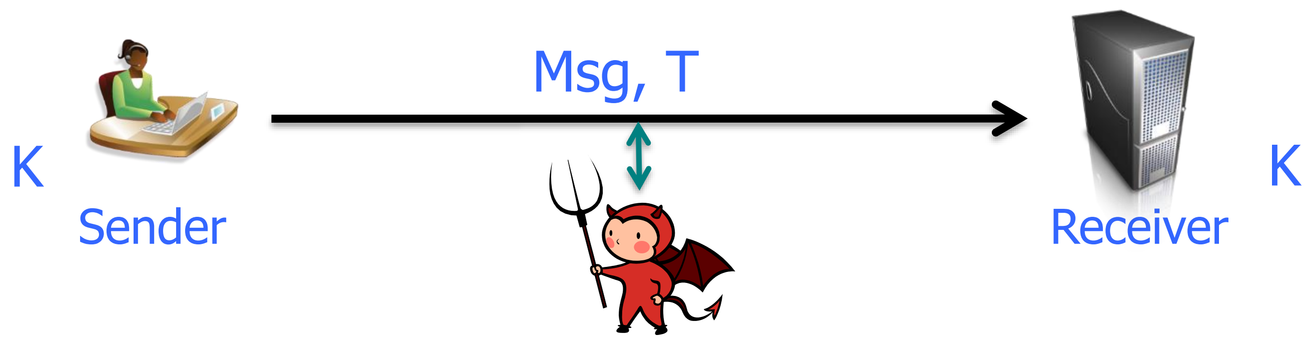
Message Authentication

Optional. If no randomness, then called Message Authentication Code (MAC)



Correctness: Ver(K, Tag(K,Msg,R)) = 1 with probability 1 over randomness R used

Message Authentication



<u>Two algorithms:</u>

Tag(K,Msg) outputs a tag T

Verify(K,Msg,T) outputs 0/1 (invalid / valid)

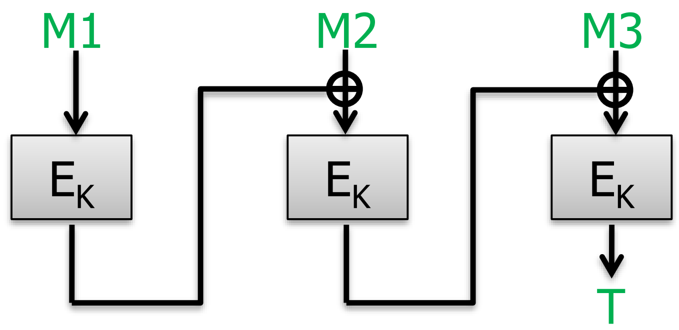
Security: No computationally efficient attacker can forge tags for a new message even when attacker gets

$$(Msg_1, T_1), (Msg_2, T_2), \ldots, (Msg_q, T_q)$$

for messages of his choosing and reasonably large q

CBC-MAC

Split message into blocks M1, M2, M3

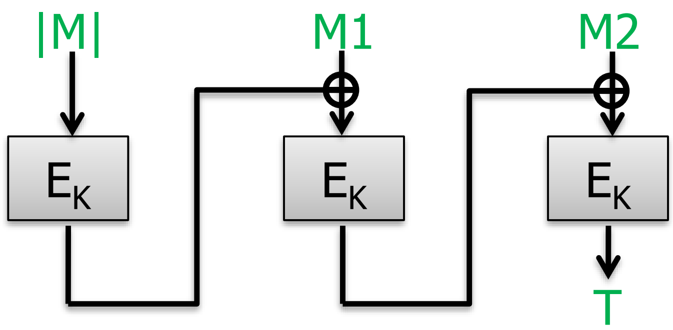


This is a secure MAC

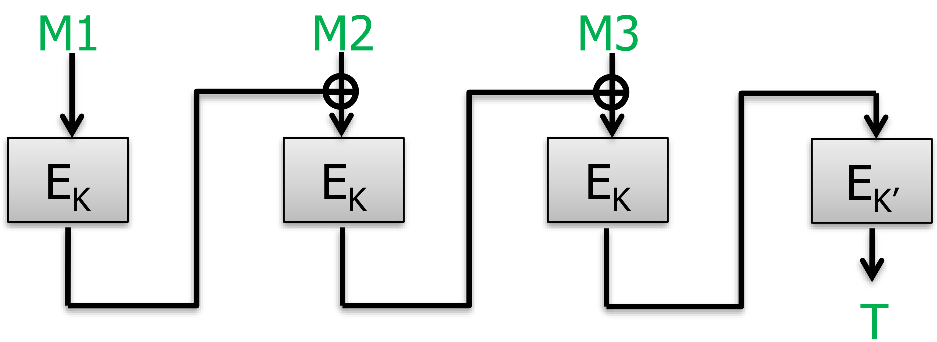
if K used only on same-length messages

Variable Message Length CBC-MAC

Prepend message length



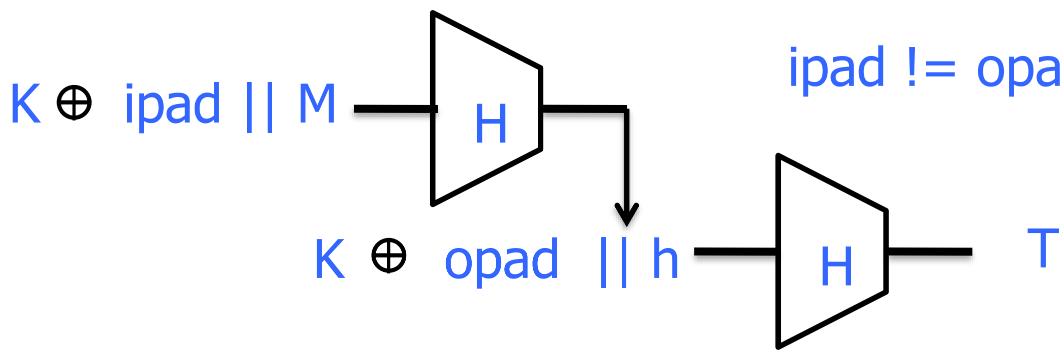
Encrypted CBC-MAC



Message Authentication with HMAC

Use a hash function H to build MAC.
Kg outputs uniform bit string K

Tag(K,M) = HMAC(K,M) defined by:



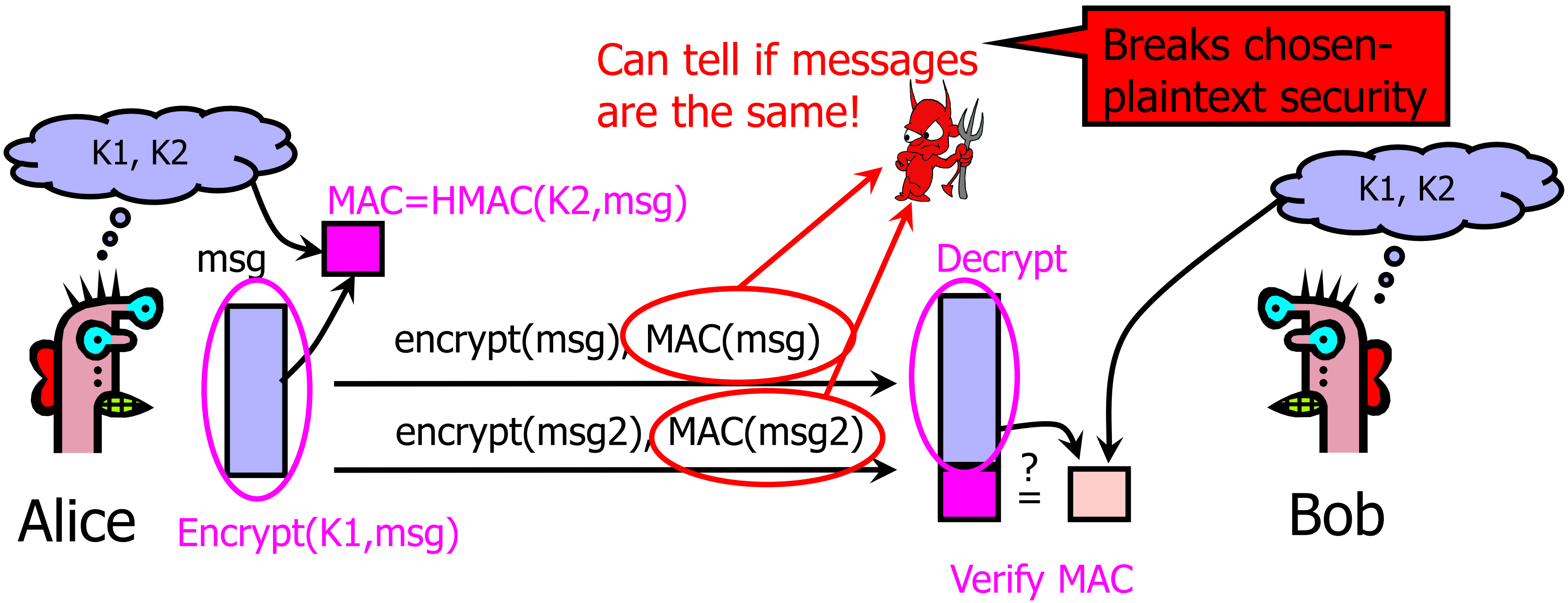
ipad != opad are constants

To verify a M,T pair, check if HMAC(K,M) = T

Unforgeability holds if H behaves like a random function

Encrypt + MAC

Goal: confidentiality + integrity + authentication



MAC is deterministic: messages are equal ⇒ their MACs are equal

Solution: Encrypt, <u>then</u> MAC (or MAC, then encrypt)

Authenticated Encryption Schemes

Attack	Inventor(s)	Notes
OCB (Offset Codebook)	Rogaway	One-pass mode and fastest
AES-GCM (Galois Counter Mode)	McGrew, Viega	CTR mode plus Carter-Wegman MAC
ChaCha20/Poly1305	Bernstein	"essentially" CTR mode plus special Carter-Wegman MAC
CCM	Housley, Ferguson, Whiting	CTR mode plus CBC-MAC
EAX	Wagner, Bellare, Rogaway	CTR mode plus OMAC

Other considerations in authenticated encryption (AE):
robustness & IV misuse, deterministic AE, associated data, …