Cryptographic Protocols

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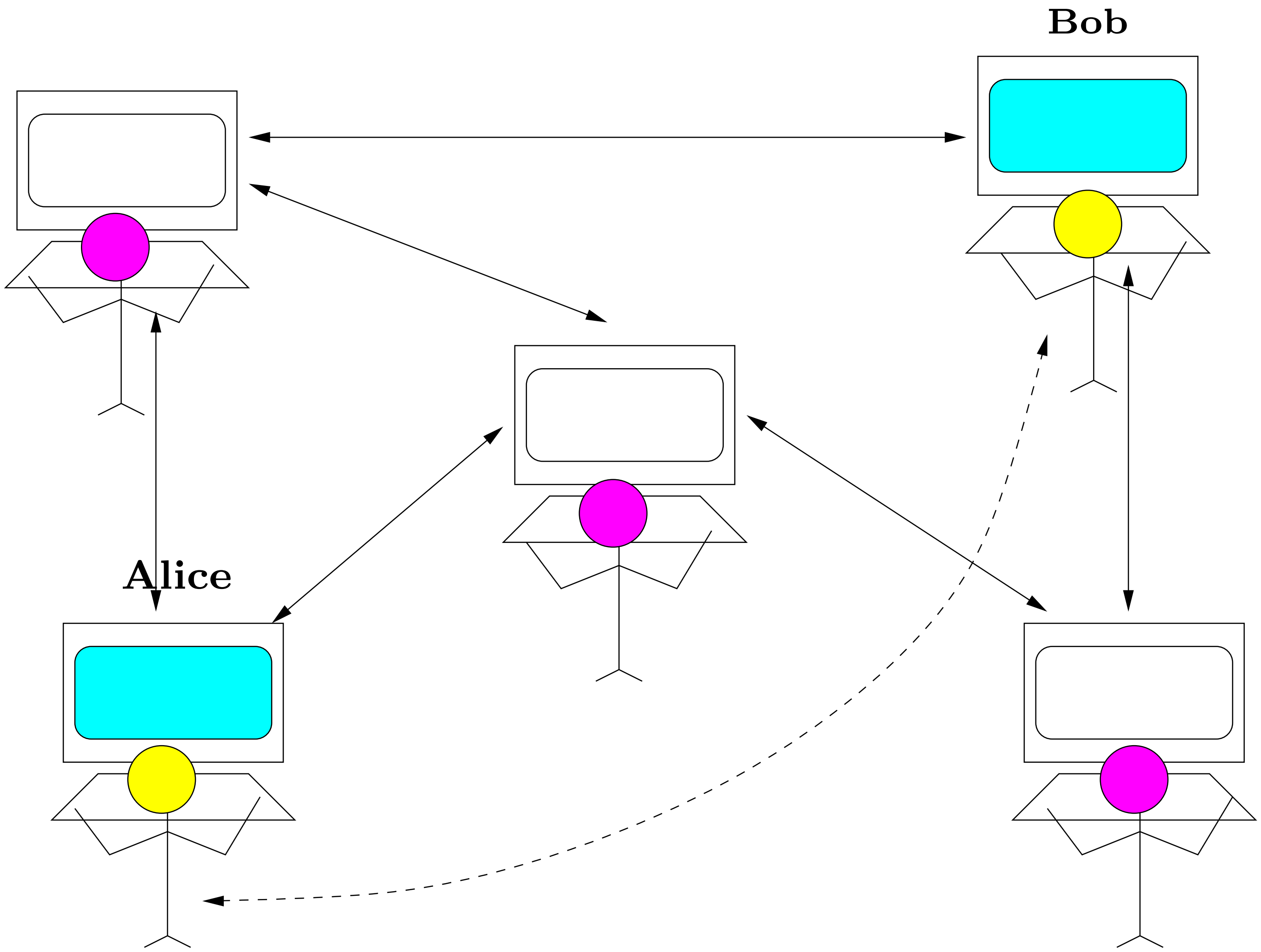
Communication over computer networks



Security problems

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- delete messages,
- modify messages,
- impersonate as Alice to Bob,
- deny having sent or received a message
- ...

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How to secure communication over an insecure network ?

Cryptography and cryptographic protocols to the rescue ...

Encrypting and decrypting messages

. . . the naive way:

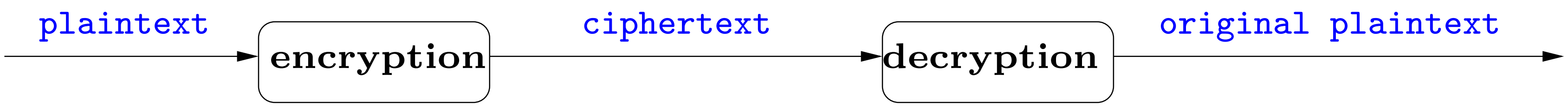
Instead of Alice $\longrightarrow$ Bob:

`This is Alice.  My credit card number is 1234567890123456`

We have Alice $\longrightarrow$ Bob:

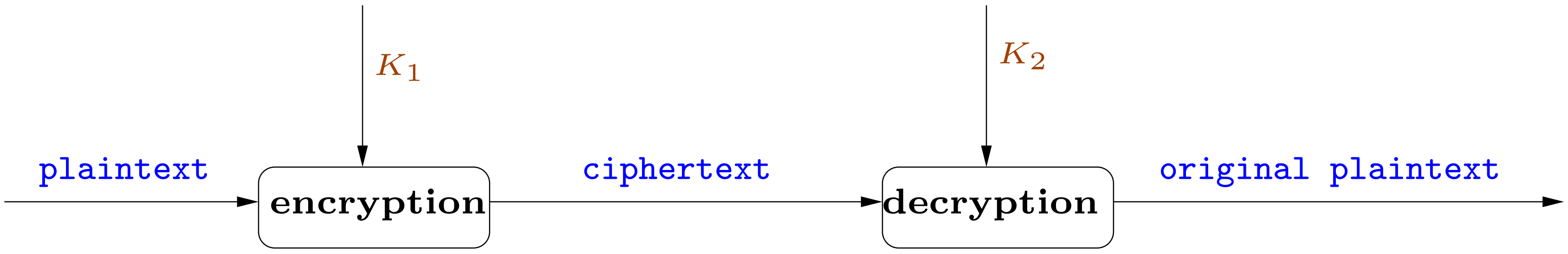
`6543210987654321 si rebmun drac tiderc yM .ecilA si sihT`

Alice and Bob agree on the method of encryption and decryption.



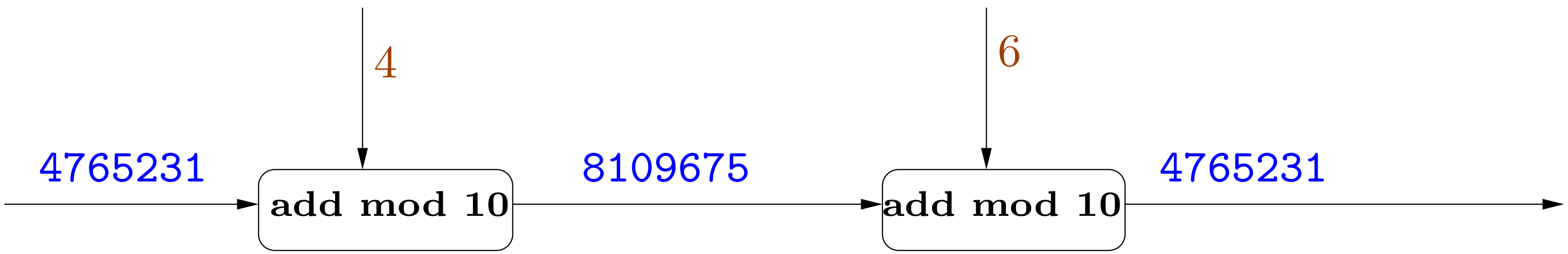
Cryptography with keys

Today we instead have the following picture:



The encryption and decryption algorithms are assumed to be publicly known.

The security lies in the (secret) keys.



Cryptography of the pre-computer age

Substitution ciphers: each character is mapped to the another character. The famous Caesar cipher: A $\rightarrow$ D, B $\rightarrow$ E, $\ldots$, Z $\rightarrow$ C.

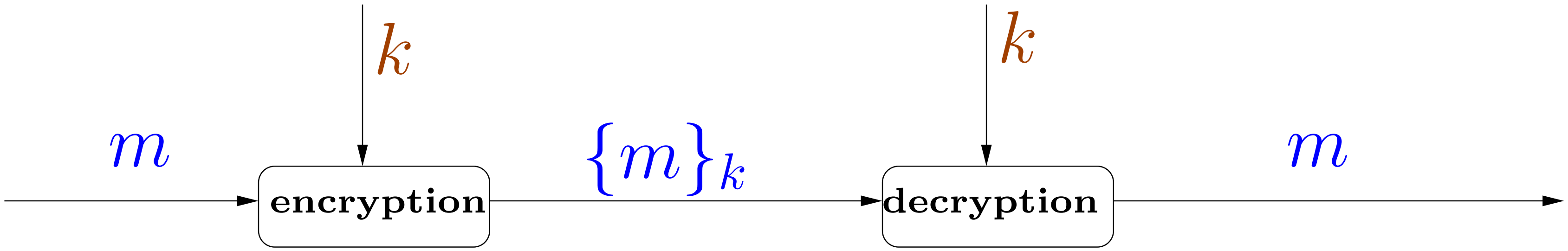
transposition cipher: shuffling around of characters.

Plaintext: `this is alice my credit card number is 1234567890123456`

```
thisisalic
emycreditc
ardnumberi
s123456789
0123456
```

Ciphertext: `teas0 hmr11 iyd22 scn33 iru44 sem55 adb66 lie7i tr8cc i9`

Private key cryptography



- The same key k is used for encryption and decryption
- Given message m and key k, we can compute the encrypted message $\{m\}_k$
- Given the encrypted message $\{m\}_k$ and the key k, we can compute the original message m

Private key cryptography

Suppose K_{ab} is a private key shared between A and B.

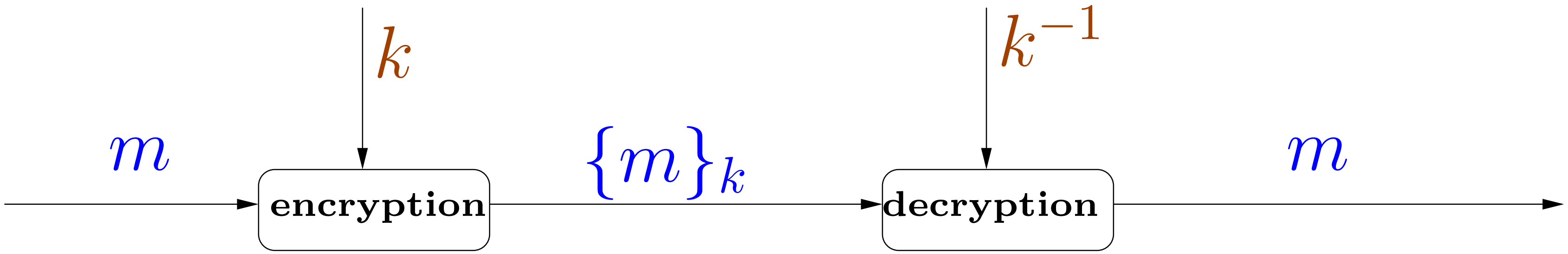
A can send a message m to B using private key cryptography:

$$A \longrightarrow B : \{m\}_{K_{ab}}$$

Only B can get back the message m.

A and B need to agree beforehand on a key K_{ab} which should not be disclosed to any one else

Public key cryptography



- A chooses pair (K_a, K_a^{-1}) of keys such that
  - messages encrypted with K_a can be decrypted with K_a^{-1}
  - K_a^{-1} cannot be calculated from K_a
- A makes K_a public: this is the public key of A
- A keeps K_a^{-1} secret: this is the private key of A

Public key cryptography

Then any B can send a message to A which only A can read:

$$B \longrightarrow A : \{m\}_{K_a}$$

Sometimes we have the additional property: messages encrypted with K_a^{-1} can be decrypted with K_a

Then A can send a message m to B

$$A \longrightarrow B : \{m\}_{K_a^{-1}}$$

and B is sure that the message m was encrypted by A. Hence we have authentication

One way hash functions

Properties of a one way hash function H:

– Given M, it is easy to compute $H(M)$ (called message digest).
– Given $H(M)$ is is difficult to find M' such that $H(M) = H(M')$.

A sends to B the message M together with the encrypted hash value $\{H(M)\}_{K_{ab}}$.

Efficient means of demonstrating authenticity, since $H(M)$ is of a fixed size.

Public key cryptography in practice

[user1@host1] `ssh user2@host2`

```
The authenticity of host 'host2 (xyz.xyz.xy.xy)' can't be
established.
RSA key fingerprint is
**:**:**:**:**:**:**:**:**:**:**:**:**:**:**:**.
Are you sure you want to continue connecting (yesno)? yes
Warning: Permanently added 'host2,xyz.xyz.xy.xy' (RSA)
to the list of known hosts.
Password:********

Welcome to host2
```

[user2@host2]

Cryptography is not enough!

Intruder is more clever. He can attack even if the cryptographic algorithms are perfect.

Alice tells Bank to transfer $\pounds 5000$ to Charlie's (intruder) account:

$$A \longrightarrow B : \{A, B, \text{ transfer 5000 euros } \ldots\}_{K_{ab}}$$

- B believes that message comes from A
- Charlie has no way to decrypt the message

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- B believes that message comes from A
- Charlie has no way to decrypt the message
- But: Charlie can send the same message again to the bank

Intruder can replay known messages (freshness attack)

Solution: use session key

Generate fresh random value (nonce) for each new session and use it as a key for that session.

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Doesn't work. What about

$$A \longrightarrow B : \{K_{ab}\}_{K_{long}}$$

Using a long term key to agree on a session key.

A more complex solution

A and B both choose a nonce each.

1. $A \longrightarrow B : \{A, N_a\}_{K_b}$
2. $B \longrightarrow A : \{N_a, N_b\}_{K_a}$
3. $A \longrightarrow B : \{N_b\}_{K_b}$

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The second message is to assure A that B is active and N_b is fresh.

The third message is to assure B that A is active and N_a is fresh.

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Expected security property: N_a and N_b are known only to A and B.
Expected authentication property: A and B are assured that they are talking to each other.

$$A \longrightarrow B : \{A, B, N_a, N_b \text{ transfer 5000 euros } \ldots\}_{K_b}$$

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How secure is this ? How to guarantee security ?

Cryptography and cryptographic protocols

- Cryptography deals with algorithms for encryption, decryption, random number generation, etc. Cryptographic protocols use cryptography for exchanging messages.

- Attacks against cryptographic primitives involves breaking the algorithm for encryption, etc. Attacks against cryptographic protocols may be of completely logical nature.

- Cryptographic protocols may be insecure even if the underlying cryptographic primitives are completely secure.

- Hence we often separate the study of cryptographic protocols from that of cryptographic primitives.

Difficulty in ensuring correctness of cryptographic protocols

- Infinitely many sessions
- Infinitely many participants
- Infinitely many nonces
- Sessions are interleaved
- Adversary can replace messages by any arbitrary message: infinitely branching system

Back to our example

1. $A \longrightarrow B : \{A, N_a\}_{K_b}$
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Back to our example

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This is the well-known Needham-Schroeder public-key protocol.

Published in 1978. Attack found after 17 years in 1995 by Lowe.

Man in the middle attack

$$A \xrightarrow{\{A, N_a\}_{K_c}} C\ (A) \xrightarrow{\{A, N_a\}_{K_b}} B$$

$$A \xleftarrow{\{N_a, N_b\}_{K_a}} C\ (A) \xleftarrow{\{N_a, N_b\}_{K_a}} B$$

$$A \xrightarrow{\{N_b\}_{K_c}} C\ (A) \xrightarrow{\{N_b\}_{K_b}} B$$

Man in the middle attack

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$$\text{A} \xrightarrow{\{N_b\}_{K_c}} \text{C (A)} \xrightarrow{\{N_b\}_{K_b}} \text{B}$$

Even very simple protocols may have subtle flaws

Consequences

Suppose B is the server of a bank.

C, who can now pretend to be A:

$$C \longrightarrow B : \{N_a, N_b, \text{ transfer £5000 from account of } A \text{ to account of } C\}_{K_b}$$

A fix: the Needham-Schroeder-Lowe protocol [Lowe,1985]

B includes his identity in the message he sends:

$$
\begin{array}{ll}
1. & A \longrightarrow B : \{A, Na\}_{K_b} \\
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Is it secure?

A variant of the Needham-Schroeder-Lowe protocol

Suppose now we change the place of B in the second message:

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\end{array}
$$

Does this affect security?

Type flaw

An attack on the variant of the Needham-Schroeder-Lowe protocol [Millen]:

$$\mathsf{C} \xrightarrow{\{A, C\}_{K_b}} \mathsf{B}$$

$$\mathsf{B} \xrightarrow{\{C, \underbrace{N_b, B}_{N_c}\}_{K_a}} \mathsf{A}$$

$$\mathsf{C} \xleftarrow{\{N_b, B, N_a, A\}_{K_c}} \mathsf{A}$$

Security properties

Secrecy:

- some data M is unknown to the intruder (reachability property).
- global secrecy: a message is secret all the time.
- local secrecy: a message is secret till the corresponding session has not ended.

Security properties

Authentification:

- If A accepts a message M as coming from B then B actually sent M.
- If A received a message of form M_1 then B sent a message of form M_2.
- If A got a message of form M then B was active

Security properties

Anonymity: an external person should not be able to know about the sender of a message. E.g. for electronic voting, mobile telephony.

Non-repudiation: an agent should not be able to deny that he sent some message. E.g. for electronic contract signing

Fairness: E.g. in electronic contract signing no party should have an advantage over the other. The following electronic contract signing protocol is not fair for A:

$$A \rightarrow B : Sig_A(m)$$

$$B \rightarrow A : Sig_B(m)$$

An overview of cryptography

RSA

Proposed by Ron Rivest, Adi Shamir and Leonard Adleman in 1978.

One of the most well-known public-key algorithms.

Its security is believed to derive from the difficulty of the integer factorization problem: decomposing an integer into its prime factors.

Based on modular arithmetic:

$$
\begin{aligned}
0 = 15 = 30 = 45 &\pmod{15} \\
4 = 19 = 34 = 49 &\pmod{15} \\
10 + 70 = 80 = 5 &\pmod{15} \\
6 \times 8 = 48 = 3 &\pmod{15} \\
11^2 = 121 = 1 &\pmod{15}
\end{aligned}
$$

Numbers x and y are relatively prime if $gcd(x, y) = 1$.

Euler phi function $\phi(n)$ is the number of positive integers smaller than n and relatively prime to n.

$$\text{If } gcd(a, n) = 1 \text{ then } a^{\phi(n)} = 1 \pmod{n}$$

Now suppose p and q are two distinct prime numbers and $n = pq$.

The set of positive integers smaller than n and relatively prime to n are $\{1, \ldots, pq - 1\} \setminus \{p, 2p, \ldots, (q - 1)p, q, 2q, \ldots, (p - 1)q\}$.

Hence $\phi(n) = pq - 1 - p - q + 2 = (p - 1)(q - 1)$.

Randomly choose two large distinct prime numbers p and q. $n = pq$.

Choose e such that e and $\phi(n)$ are relatively prime.

Compute d such that $ed = 1 \pmod{\phi(n)}$

I.e. $d = e^{-1} \pmod{\phi(n)}$ (use Euclid's algorithm)

Public key $= (n, e)$, encryption: $C = M^e \pmod{n}$

Private key $= d$, decryption: $M = C^d \pmod{n}$

We have $M^{ed} = M^{k\phi(n)+1} = (M^{\phi(n)})^k M = M \pmod{n}$.

The whole message is first divided into smaller portions $< n$.

Also works if M is not relatively prime to n.

$M = ap$ where $0 < a < q$.

$M^{ed} = (M^{\phi(n)})^k M = (a^{q-1}p^{q-1})^{p-1}M = 1^{p-1}M = M \pmod{q}$

$M^{ed} = 0 = M \pmod{p}$

Hence $M^{ed} = M \pmod{n}$

We use the fact that if $a = b \pmod{p}$ and $a = b \pmod{q}$ where p, q are primes then $a = b \pmod{pq}$.

Block algorithms

Given encryption and decryption algorithms that work on blocks of fixed sizes (e.g. 64 bits), how to deal with messages of arbitrary sizes.

Electronic Codebook Mode (ECB): encrypt each block independently.

$\{P_1 \ldots P_n\}_k = \{P_1\}_k \ldots \{P_n\}_k$

This is similar to looking up in a dictionary with 2^{64} entries.

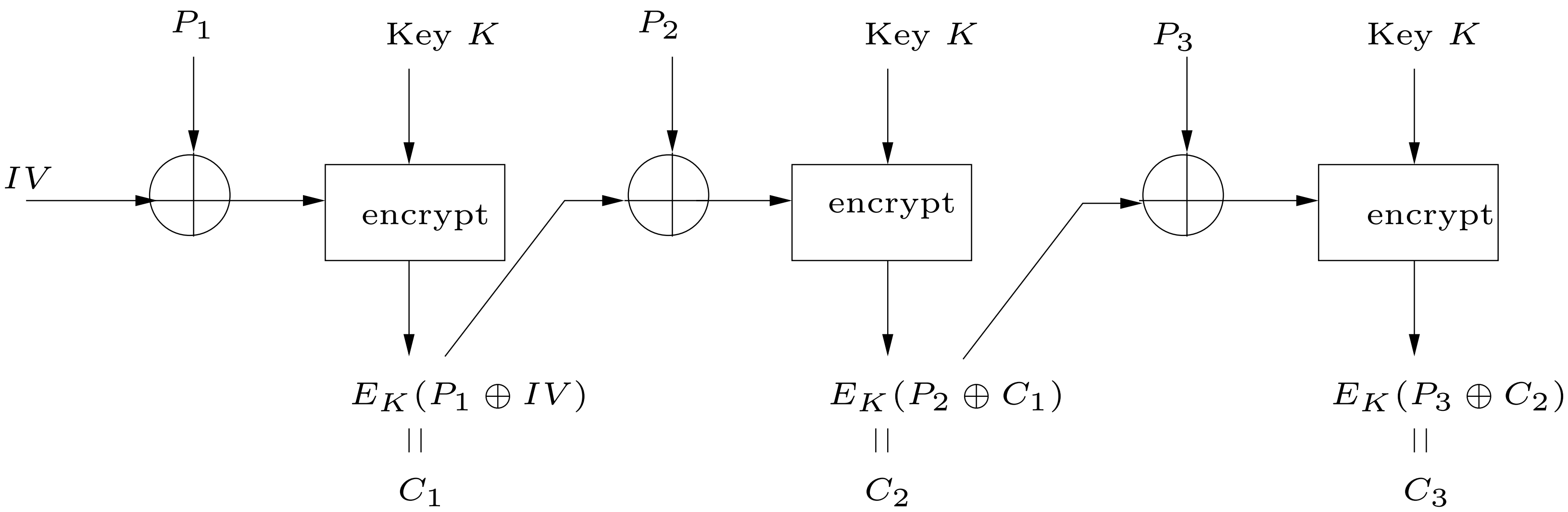
Subject to block replay attacks.

Example of block replay attack.

Interbank money transfers:

Date/Timestamp	1 block
Sending bank name	1 block
Receiving bank name	1 block
Depositor's Name	6 blocks
Depositor's Account	2 blocks
Amount of deposit	1 block

Cipher Block Chaining Mode (CBC)



Encryption	Decryption
$C_1 = E_K(IV \oplus P_1)$	$P_1 = D_K(C_1) \oplus IV$
$C_2 = E_K(C_1 \oplus P_2)$	$P_2 = D_K(C_2) \oplus C_1$
$C_3 = E_K(C_2 \oplus P_3)$	$P_3 = D_K(C_3) \oplus C_2$

Choose a random initialization vector (IV) for each message.