Security protocols

For secure communication over an insecure network.

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

Encrypting and decrypting messages

. . . the naive way:

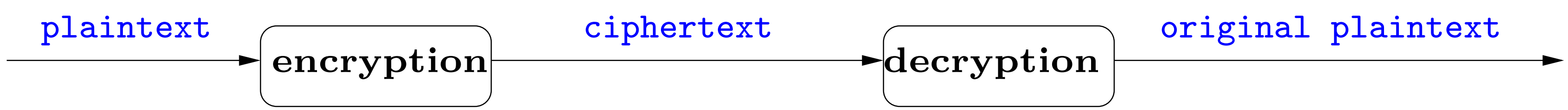
Instead of Alice $\longrightarrow$ Bob:

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

We have Alice $\longrightarrow$ Bob:

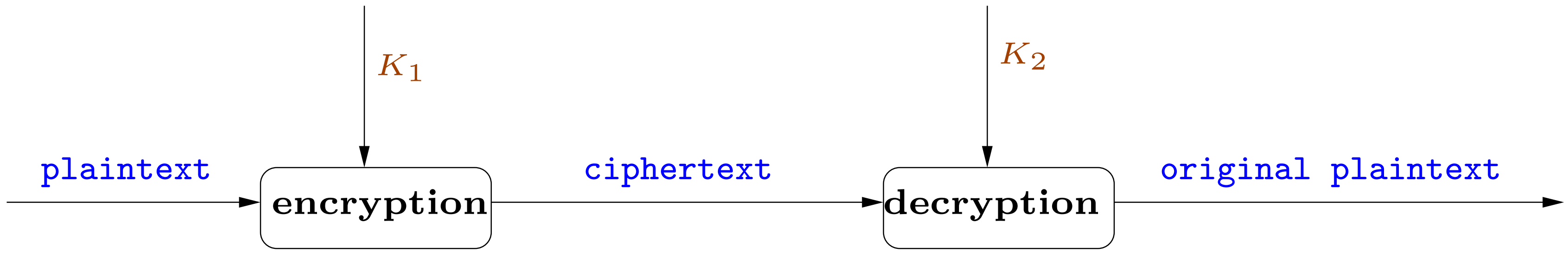
`6543210987654321 si rebmun drac tiderc yM .ecilA si sihT`

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



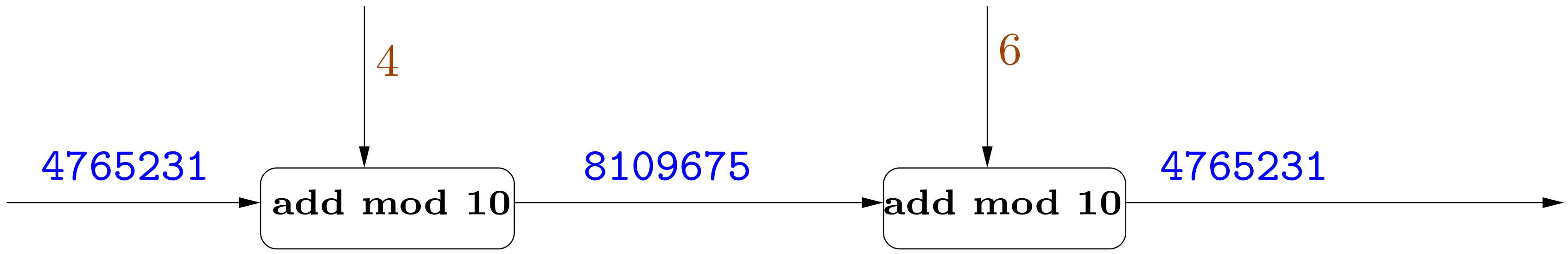
Cryptography with keys

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, ..., Z $\rightarrow$ C.

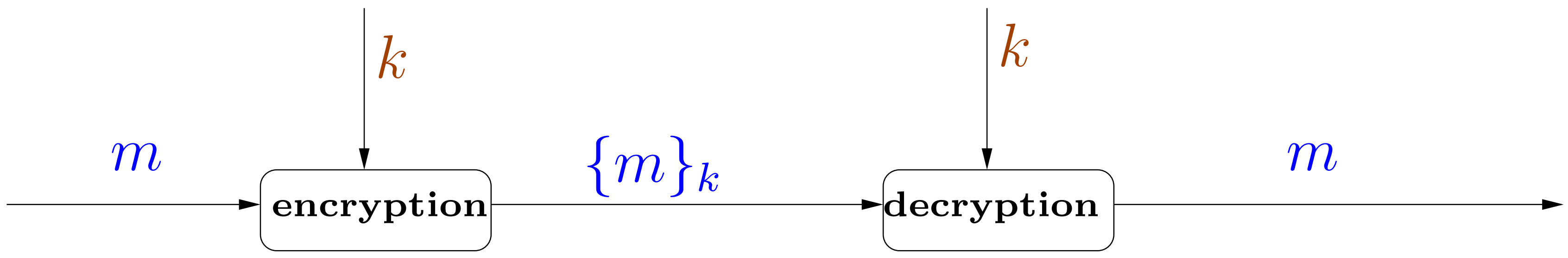
transposition cipher: shuffling around of characters.

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.

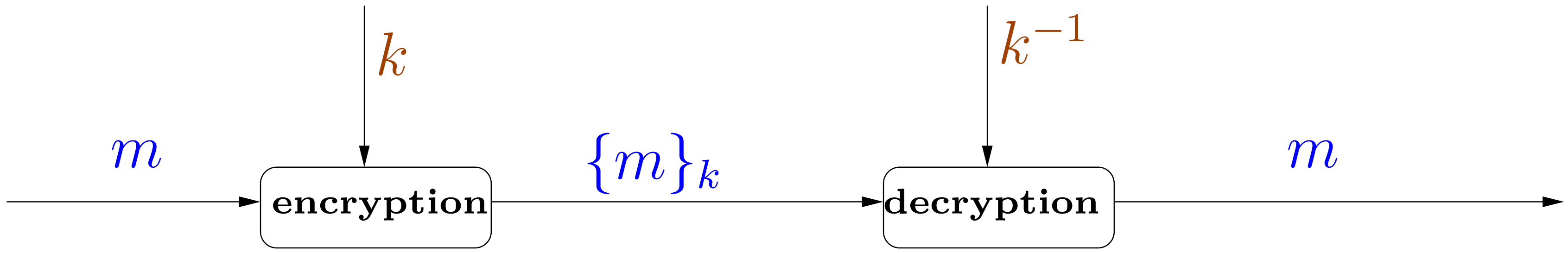
A can send a message m to B using private key cryptography:

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

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.

Cryptography is not enough!

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

Alice tells Bank to transfer £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.

$$
\begin{array}{ll}
1. & A \longrightarrow B : \{A, N_a\}_{K_b} \\
2. & B \longrightarrow A : \{N_a, N_b\}_{K_a} \\
3. & A \longrightarrow B : \{N_b\}_{K_b}
\end{array}
$$

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

Back to our example

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

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

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

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

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

Man in the middle attack

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

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

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:

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

1. $A \longrightarrow B : \{A, Na\}_{K_b}$
2. $B \longrightarrow A : \{N_a, N_b, B\}_{K_a}$
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Does this affect security?

Type flaw

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

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

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

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

The Spi calculus

Abadi, Gordon, 1997

- Extends pi calculus which provides a language for describing processes.
- We treat protocols as processes, where messages sent and received by processes may involve encryption.
- Security is defined as equivalence between processes in the eyes of an arbitrary environment.
- Environment is also a spi calculus process.
- We study information flow to check whether secrets are leaked.

- A process may involve sequences of actions for sending and receiving messages on channels.
- A Processes may contain smaller processes running in parallel.

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Use halt to denote a finished process: it does nothing.

We write $\mathsf{send}_c\langle M\rangle; P$ to denote a process that sends the message M on channel c after which it executes the process P.

$\mathsf{recv}_c(x); Q$ denotes a process that is listening on the channel c.

On receiving some message M on this channel then it executes process $Q[M/x]$.

The process

$$P_1 \triangleq \mathsf{recv}_c(x); \mathsf{send}_d\langle x\rangle; \mathsf{halt}$$

on receiving message M on channel c, sends M on channel d and then halts.

The process

$$P_2 \triangleq \mathsf{send}_c\langle M\rangle; \mathsf{halt}$$

sends M on channel c and halts.

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sends M on channel c and halts.

Putting them in parallel gives the process

$$P_3 \triangleq P_1 \mid P_2$$

The message sent by P_2 is received by P_1. Hence P_3 as a whole can make a "silent" transition to the process $\mathsf{send}_d\langle M\rangle; \mathsf{halt}$.

Further the process

$$P_5 \triangleq P_3 \mid P_4$$

where

$$P_4 \triangleq \mathsf{recv}_d(x); \mathsf{halt}$$

can halt after making only silent transitions.

Intuitively P_5 represents the protocol

$$P_2 \longrightarrow P_1 : \quad M \quad \text{(on channel } c\text{)}$$

$$P_1 \longrightarrow P_4 : \quad M \quad \text{(on channel } d\text{)}$$

We can restrict access to channels.

The process $\mathsf{new}\ c; P$ creates a fresh channel c and can be used inside process P. No outside process can access c.

(c is like a bound variable whose scope is inside P)

We consider processes to be the same after renaming of bound names.

Consider the process

$$(\mathsf{new}\ c; \mathsf{send}_c\langle M\rangle; \mathsf{halt}) \mid (\mathsf{recv}_c(x); \mathsf{halt})$$

No communication happens between the two smaller processes.

The above process is the same as the following one.

$$(\mathsf{new}\ d; \mathsf{send}_d\langle M\rangle; \mathsf{halt}) \mid (\mathsf{recv}_c(x); \mathsf{halt})$$

Hence new allows us to create channels for secure communication.

Consider the process

$$\mathsf{new}\ c; (\mathsf{send}_c\langle M\rangle; \mathsf{halt} \mid \mathsf{recv}_c(x); P \mid \mathsf{recv}_c(x); Q)$$

Communication can take place between first and second subprocess to create the process $\mathsf{new}\ c; (P[M/x] \mid \mathsf{recv}_c(x); Q)$

Or communication can take place between first and third subprocess to create the process $\mathsf{new}\ c; (\mathsf{recv}_c(x); P \mid Q[M/x])$

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Or communication can take place between first and third subprocess to create the process $\mathsf{new}\ c; (\mathsf{recv}_c(x); P \mid Q[M/x])$

However the process

$$(\mathsf{new}\ c; (\mathsf{send}_c\langle M\rangle; \mathsf{halt} \mid \mathsf{recv}_c(x); P)) \mid \mathsf{recv}_c(x); Q$$

can only lead to the process $(\mathsf{new}\ c; P[M/x]) \mid \mathsf{recv}_c(x); Q$

Channels can also be sent as messages. Consider the following protocol where c_{AB} is a freshly created channel whereas c_{AS} and c_{SB} are long term channels.

$$A \longrightarrow S : c_{AB} \text{ on } c_{AS}$$

$$S \longrightarrow B : c_{AB} \text{ on } c_{SB}$$

$$A \longrightarrow B : M \text{ on } c_{AB}$$

can be represented as follows where $F(y)$ is a process involving variable y.

$$\begin{aligned}
A &\triangleq \mathsf{new}\ c_{AB}; \mathsf{send}_{c_{AS}}\langle c_{AB}\rangle; \mathsf{send}_{c_{AB}}\langle M\rangle; \mathsf{halt} \\
S &\triangleq \mathsf{recv}_{c_{AS}}(x); \mathsf{send}_{c_{SB}}\langle x\rangle; \mathsf{halt} \\
B &\triangleq \mathsf{recv}_{c_{SB}}(x); \mathsf{recv}_{x}(y); F(y) \\
P &\triangleq \mathsf{new}\ c_{AS}; \mathsf{new}\ c_{SB}; (A \mid S \mid B)
\end{aligned}$$

P makes silent transitions to $\mathsf{new}\ c_{AS}; \mathsf{new}\ c_{SB}; F(M)$.

Processes can perform computations like

- encryption, decryption (we will deal with only symmetric key encryption)
- pairing, unpairing
- increments, decrements
- checking equality of messages

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The process

$\mathsf{recv}_c(x_1, x_2, x_3); \mathsf{case}\ x_1\ \mathsf{of}$
$\quad \{y_1\}_K : \mathsf{check}\ (y_1 == x_2); \mathsf{send}_c\langle y_1, \mathsf{succ}\ (x_3)\rangle; \mathsf{halt}$

receives an input of the form $\{M\}_K, M, N$ on channel c and sends out $y_1, \mathsf{succ}\ (x_3)$ on channel c.

The syntax

$M ::=$		term
	n	name
	(M, N)	pair
	0	zero
	$\mathsf{succ}\ (M)$	successor
	$\{M_1, \ldots, M_k\}_N$	encryption
	x	variable

$P ::=$	process
$\mathsf{send}_M \langle N_1, \ldots, N_k \rangle; P$	output
$\mathsf{recv}_M (x_1, \ldots, x_k); P$	input
halt	halt
$P \mid Q$	parallel composition
$\mathsf{repeat}\ P$	replication
$\mathsf{new}\ n; P$	restriction
$\mathsf{check}\ (M == N); P$	comparison
$\mathsf{let}\ (x, y) = M; P$	unpairing
$\mathsf{case}\ M\ \mathsf{of}\ 0 : P,\ \mathsf{succ}\ (x) : Q$	integer case analysis
$\mathsf{case}\ M\ \mathsf{of}\ \{x_1, \ldots, x_k\}_N : P$	decryption

Intuitively, $\mathsf{repeat}\ P$ represents infinitely many copies of P running in parallel.

In other words we can consider $\mathsf{repeat}\ P$ to represent $P \mid P \mid P \mid \ldots$

Consider

$$\begin{aligned} P &\triangleq \mathsf{recv}_c(x); \mathsf{halt} \\ P_1 &\triangleq \mathsf{send}_c(M_1); \mathsf{halt} \\ P_2 &\triangleq \mathsf{send}_c(M_2); \mathsf{halt} \end{aligned}$$

The process

$$P_1 \mid P_2 \mid \mathsf{repeat}\ P$$

can make silent transitions (internal communication) to create the process

$$\mathsf{repeat}\ P$$

A one message protocol using cryptography, where K_{AB} is a symmetric key shared between A and B for private communication.

$$A \longrightarrow B : \{M\}_{K_{AB}} \text{ on } c_{AB}$$

This can be represented as

$$
\begin{aligned}
A &\triangleq \mathsf{send}_{c_{AB}}\langle\{M\}_{K_{AB}}\rangle; \mathsf{halt} \\
B &\triangleq \mathsf{recv}_{c_{AB}}(x); \mathsf{case}\ x\ \mathsf{of}\ \{y\}_{K_{AB}} : F(y) \\
P &\triangleq \mathsf{new}\ K_{AB}; (A \mid B)
\end{aligned}
$$

The key K_{AB} is restricted, only A and B can use it.

The channel c_{AB} is public. Other principals may send messages on it or listen on it.

P can make silent transitions to $\mathsf{new}\ K_{AB}; F(M)$.