# Introduction to cryptographic protocols

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(Partly based on slides by Stéphanie Delaune)

# Cryptographic protocols

Paiement
Internet

## Cryptographic protocols

- small programs designed to secure communication (various security goals)
- use cryptographic primitives (e.g. encryption, hash functions, . . . )

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# Security properties (1)

- **Secrecy**: May an intruder learn some secret message between two honest participants?
- Authentication: Is the agent Alice really talking to Bob?
- Fairness: Alice and Bob want to sign a contract. Alice initiates the protocol. May Bob obtain some advantage?
- Non-repudiation: Alice sends a message to Bob. Alice cannot later deny having sent this message. Bob cannot deny having received the message.
- ...

# Security properties: E-voting (2)

**Eligibility:** only legitimate voters can vote, and only once

**Fairness:** no early results can be obtained which could influence the remaining voters

**Individual verifiability:**
a voter can verify that her vote was really counted

**Universal verifiability:**
the published outcome really is the sum of all the votes

Belgique - Election 2004 - http://www.poureva.be/ - (C) Kanar

# Security properties: E-voting (3)

Privacy: the fact that a particular voter voted in a particular way is not revealed to anyone

Receipt-freeness: a voter cannot prove that she voted in a certain way (this is important to protect voters from coercion)

Coercion-resistance: same as receipt-freeness, but the coercer interacts with the voter during the protocol, (e.g. by preparing messages)

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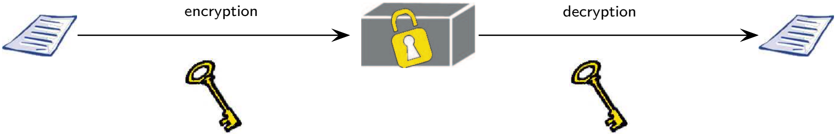
### Symmetric encryption



⟶ Examples: Caesar encryption, DES, AES, . . .

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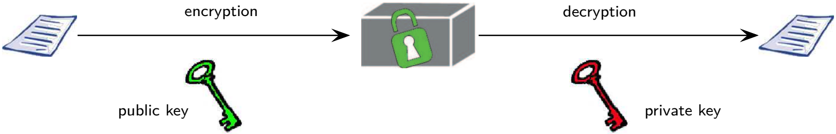
### Asymmetric encryption



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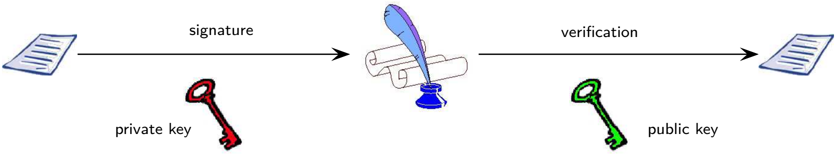
### Signature



# Why verify security protocols ?

The verification of security protocols has been and is still a very active research area.

- Their design is error prone.
- Security errors are not detected by testing:
  they appear only in the presence of an adversary.
- Errors can have serious consequences.

# Models of protocols

Active attacker:

- the attacker can intercept all messages sent on the network
- he can compute messages
- he can send messages on the network

# Models of protocols: the symbolic model

The symbolic model or "Dolev-Yao model" is due to Needham and Schroeder [1978] and Dolev and Yao [1983].

- The cryptographic primitives are blackboxes.
- The messages are terms on these primitives.
  $\hookrightarrow$ $\{m\}_k$ encryption of the message $m$ with key $k$,
  $\hookrightarrow$ $(m_1, m_2)$ pairing of messages $m_1$ and $m_2$, ...
- The attacker is restricted to compute only using these primitives.
  $\Rightarrow$ perfect cryptography assumption
  - So the definitions of primitives specify what the attacker can do.
    One can add equations between primitives.
    Hypothesis: the only equalities are those given by these equations.

This model makes automatic proofs relatively easy (AVISPA, ProVerif, Scyther, Tamarin, ...).

# Models of protocols: the computational model

The computational model has been developed at the beginning of the 1980's by Goldwasser, Micali, Rivest, Yao, and others.

- The messages are bitstrings. 01100100
- The cryptographic primitives are functions on bitstrings. $\mathcal{E}(011, 100100) = 111$
- The attacker is any probabilistic (polynomial-time) Turing machine.
  - The security assumptions on primitives specify what the attacker cannot do.

This model is much more realistic than the symbolic model, but until recently proofs were only manual.

# Models of protocols: side channels

The computational model is still just a model, which does not exactly match reality.

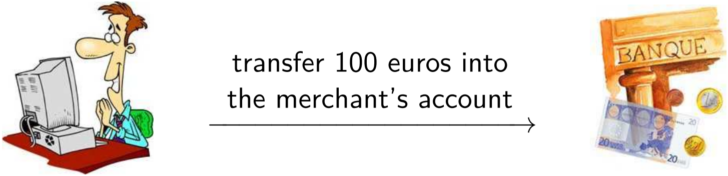
In particular, it ignores side channels:

- timing
- power consumption
- noise
- physical attacks against smart cards

which can give additional information.

In this course, we will ignore side channels.

# Symbolic model: example of attacks, replay attacks



transfer 100 euros into the merchant's account

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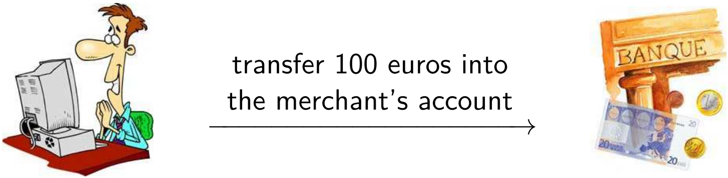

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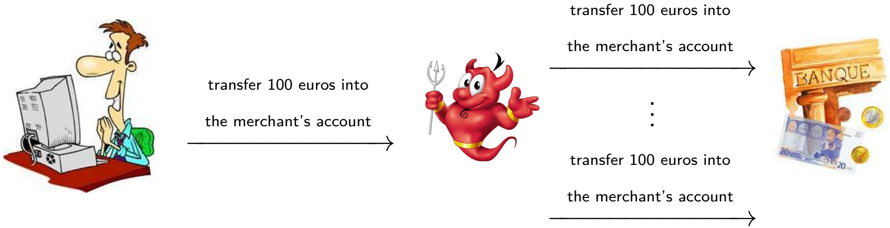

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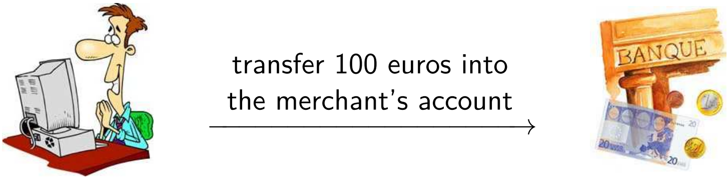

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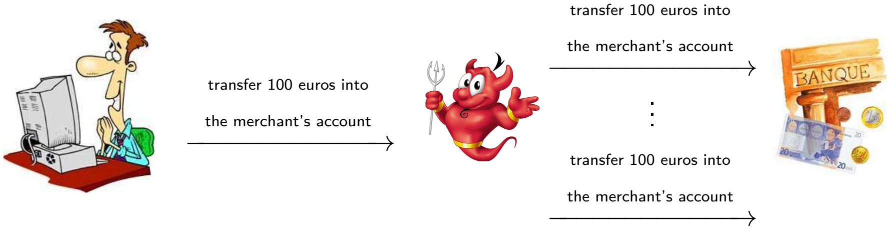

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Example: attack on the decoders (TV)

⟶ block the message that cancels the subscription

# Verifying protocols in the symbolic model

- Compute the set of all terms that the attacker can obtain.
- This set is infinite:
  - The attacker can generate messages of unbounded size.
  - The number of sessions of the protocol is unbounded.

# Complexity

- Bounded messages and number of sessions
  - ⇒ finite state
  - Model checking: FDR [Lowe, TACAS'96]
- Bounded number of sessions but unbounded messages
  - ⇒ insecurity is typically NP-complete
  - Constraint solving: Cl-AtSe, integrated in AVISPA
    Extensions of model checking: OFMC, integrated in AVISPA
- Unbounded messages and number of sessions
  - ⇒ the problem is undecidable

# Solutions to undecidability

- Rely on user interaction
  - Interactive theorem proving, Isabelle [Paulson, JCS'98]
- Use approximations
  - Abstract interpretation [Monniaux, SCP'03], TA4SP integrated in AVISPA
  - Typing [Abadi, JACM'99], [Gordon, Jeffrey, CSFW'02] (Sometimes also relies on type annotations by the user.)
- Allow non-termination

ProVerif uses approximations and allows non-termination.

# Relevance of the symbolic model

- Numerous attacks have already been obtained.
- An attack in the symbolic model immediately implies an in the computational model (and a practical attack).
  - A proof in the symbolic model does not always imply a proof in the computational model (see next).
- Allows us to perform automatic verification.

# Proofs in the computational model

- Manual proofs by cryptographers:
    - proofs by sequences of games [Shoup, Bellare&Rogaway]
- Automation:
    - CryptoVerif
    - CertiCrypt/EasyCrypt, relies on Coq
    - Typing

# Link between the two models

- Computational soundness theorems:

  Proof in the symbolic model ⇒ proof in the computational model

  modulo additional assumptions.

  Approach pioneered by Abadi&Rogaway [2000]; many works since then.

# Link between the two models: application

- Indirect approach to automating computational proofs:

1. Automatic symbolic protocol verifier

↓

proof in the symbolic model

2. Computational soundness

⟶

proof in the computational model

# Credit Card Payment Protocol

# Example: credit card payment

- The client $Cl$ puts his credit card $C$ in the terminal $T$.
- The merchant enters the amount $M$ of the sale.

- The terminal authenticates the credit card.
- The client enters his PIN.
  If $M \geq 100$ €, then in 20% of cases,
  - The terminal contacts the bank $B$.
  - The bank gives its authorisation.

# More details

the Bank $B$ , the Client $Cl$, the Credit Card $C$ and the Terminal $T$

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**Bank**

- a private signature key – $\mathrm{priv}(B)$
- a public key to verify a signature – $\mathrm{pub}(B)$
- a secret key shared with the credit card – $K_{CB}$

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- some *Data*: name of the cardholder, expiry date ...
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**Terminal**

- the public key of the bank – $\mathrm{pub}(B)$

# Payment protocol

the terminal $T$ reads the credit card $C$:

$$1. \quad C \quad \rightarrow \quad T : \quad \mathit{Data}, \{\mathit{hash}(\mathit{Data})\}_{\mathrm{priv}(B)}$$

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the terminal $T$ reads the credit card $C$:

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the terminal $T$ asks the code:

$$\begin{array}{lcccl} 2. & T & \rightarrow & Cl : & code? \\ 3. & Cl & \rightarrow & C : & 1234 \\ 4. & C & \rightarrow & T : & ok \end{array}$$

# Payment protocol

the terminal $T$ reads the credit card $C$:

1. $C \rightarrow T : \mathit{Data}, \{\mathit{hash}(\mathit{Data})\}_{\mathsf{priv}(B)}$

the terminal $T$ asks the code:

2. $T \rightarrow CI : \mathit{code?}$
3. $CI \rightarrow C : 1234$
4. $C \rightarrow T : \mathit{ok}$

the terminal $T$ requests authorisation from the bank $B$:

5. $T \rightarrow B : \mathit{auth?}$
6. $B \rightarrow T : 4528965874123$
7. $T \rightarrow C : 4528965874123$
8. $C \rightarrow T : \{4528965874123\}_{K_{CB}}$
9. $T \rightarrow B : \{4528965874123\}_{K_{CB}}$
10. $B \rightarrow T : \mathit{ok}$

# Attack against credit cards

Initially, security was guaranteed by:

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Initially, security was guaranteed by:

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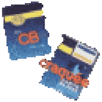
However, there are attacks!

- cryptographic attack: 320-bit keys are no longer secure,
- logical attack: no link between the 4-digit PIN code and the authentication,
- hardware attack: replication of cards.



→ “YesCard” made by Serge Humpich (1997).

# The « YesCard »: how does it work?

## Logical attack

$$\begin{aligned}
1. C &\rightarrow T &&: \text{Data}, \{\text{hash}(\text{Data})\}_{\text{priv}(B)} \\
2. T &\rightarrow CI &&: PIN? \\
3. CI &\rightarrow C &&: 1234 \\
4. C &\rightarrow T &&: ok
\end{aligned}$$

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2. T & \rightarrow Cl & : PIN? \\
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Remark: there is always somebody to debit.
→ add a fake ciphertext on a fake card (Serge Humpich).

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$$\begin{array}{llll} 1. C' & \rightarrow T & : \mathsf{XXX}, \{\mathsf{hash}(\mathsf{XXX})\}_{\mathsf{priv}(B)} \\ 2. T & \rightarrow CI & : PIN? \\ 3. CI & \rightarrow C' & : 0000 \\ 4. C' & \rightarrow T & : ok \end{array}$$

# Needham-Schroeder (public-key) Protocol

# Needham-Schroeder's Protocol (1978)

- $$\begin{array}{rcrr} A & \rightarrow & B: & \{A, N_a\}_{\text{pub}(B)} \\ B & \rightarrow & A: & \{N_a, N_b\}_{\text{pub}(A)} \\ A & \rightarrow & B: & \{N_b\}_{\text{pub}(B)} \end{array}$$

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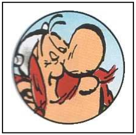

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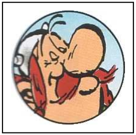

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Questions

- Is $N_b$ secret between $A$ and $B$ ?
- When $B$ receives $\{N_b\}_{\text{pub}(B)}$, does this message really comes from $A$ ?

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**Attack**

An attack was found 17 years after its publication! [Lowe 96]

# Example: Man in the middle attack

Agent A

Intruder I

Agent B

**Attack**

- involving 2 sessions in parallel,
- an honest agent has to initiate a session with I.

A → B : $\{A, N_a\}_{\mathrm{pub}(B)}$
B → A : $\{N_a, N_b\}_{\mathrm{pub}(A)}$
A → B : $\{N_b\}_{\mathrm{pub}(B)}$

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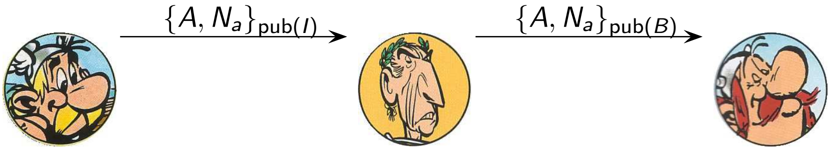

$\{A, N_a\}_{\mathrm{pub}(I)}$

$\{A, N_a\}_{\mathrm{pub}(B)}$

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$\mathrm{A} \rightarrow \mathrm{B} \quad : \{A, N_a\}_{\mathrm{pub}(B)}$

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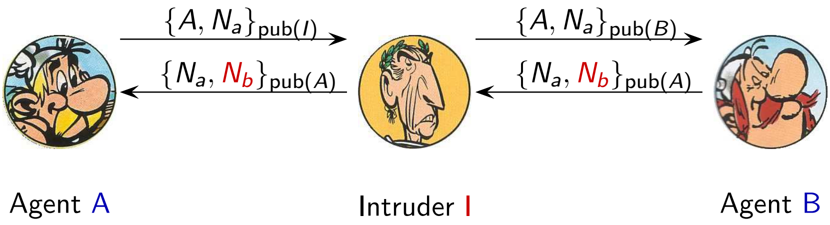

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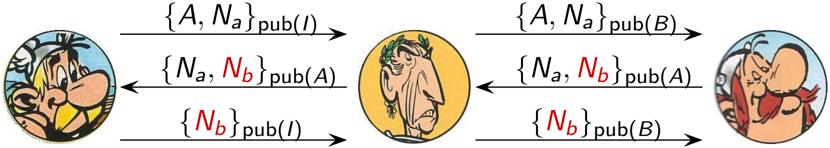

$\{A, N_a\}_{\text{pub}(I)}$ →

← $\{N_a, N_b\}_{\text{pub}(A)}$

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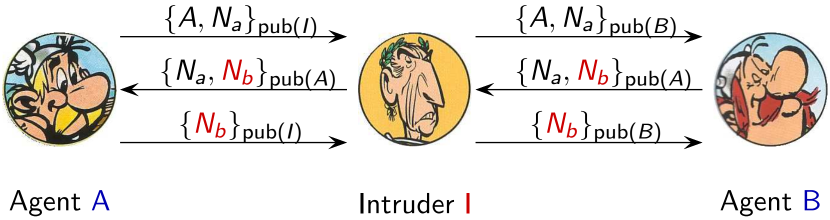

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**Attack**

- the intruder knows $N_b$,
- When B finishes his session (apparently with A), A has never talked with B.

$$
\begin{array}{lll}
A \rightarrow B & : & \{A, N_a\}_{\text{pub}(B)} \\
B \rightarrow A & : & \{N_a, N_b\}_{\text{pub}(A)} \\
A \rightarrow B & : & \{N_b\}_{\text{pub}(B)}
\end{array}
$$

# Exercise

$$\begin{array}{lll} \text{A} \rightarrow \text{B} & : & \{A, N_a\}_{\text{pub}(B)} \\ \text{B} \rightarrow \text{A} & : & \{N_a, N_b\}_{\text{pub}(A)} \\ \text{A} \rightarrow \text{B} & : & \{N_b\}_{\text{pub}(B)} \end{array}$$

## Exercise

Propose a fix for the Needham-Schroeder protocol.