Providing solutions for more secure exchanges

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Cryptographic protocols

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

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The network is unsecure!

Communications take place over a public network like the Internet.

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

Security properties

- **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?
- Privacy: Alice participate to an election. May a participant learn something about the vote of Alice?
- Non-repudiation: Alice sends a message to Bob. Alice cannot later deny having sent this message. Bob cannot deny having received the message.
- ...

Cryptographic primitives

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Algorithms that are frequently used to build computer security systems. These routines include, but are not limited to, one-way hash functions and encryption functions.

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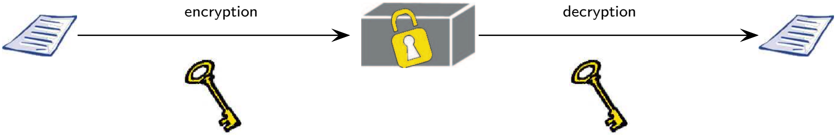
Symmetric encryption



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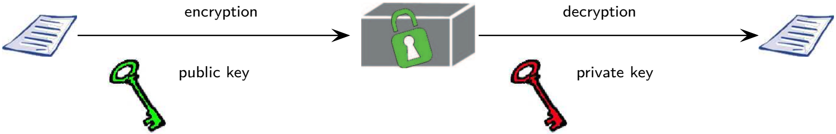
Asymmetric encryption



Symmetric vs. asymmetric encryption

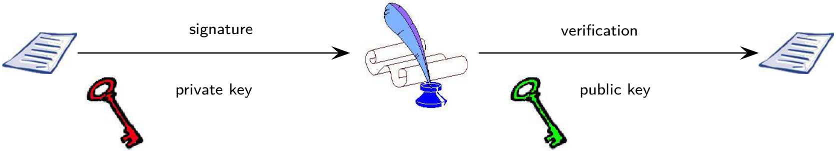
Symmetric encryption

- efficient in practice,
- agents have to share a secret key
  $\longrightarrow$ trusted third party, distribution key protocol

Asymmetric encryption

- not efficient in practice,
- agents do not have to share a secret
  $\longrightarrow$ often used in establishment key protocols
- authentication of public keys (certificate)

Digital signature: How does it work?



- similar to public key encryption
- everyone knows the key to verify the signature (public key)
- the key used to sign a message has to be private (private key)

Properties and applications

Properties

- the signature has to authenticate the signer
- the signature “ belongs to “ one particular document
- the signed document can not be modified afterwards

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Applications

- certificate to authenticate a public key
- contract signing protocols
- E-voting protocols (blind signature)

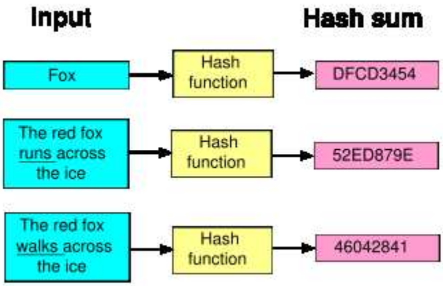
$\longrightarrow$ allows someone to sign without knowing the message he is signing.

Hash function: What is it?

Hash function

It is a reproducible method of turning some kind of data into a (relatively) small number that may serve as a digital "fingerprint" of the data (again substitutions and permutations).

Examples: MD5, SHA-1



Properties and Applications

Properties

- deterministic function
- one-way function: there is no practical way to retrieve m from $hash(m)$
- collision resistant: difficult to find m_1 and m_2 such that $m_1 \neq m_2$ and $hash(m_1) = hash(m_2)$

Some applications

- to improve efficiency: we can sign $hash(m)$ instead of m
- use to guarantee the integrity of a message
- checksum to detect errors

Outline of the talk

1. Introduction

2. Some examples of security protocols
   - Credit Card payment
   - Needham Schroeder protocol

3. How can we verify them?
   - How protocols can be attacked?
   - How protocols can be proved secure?

4. Conclusion

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Carte bancaire

La carte bleue est protégée par un grand nombre public dont on ne connait pas la factorisation.

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Nombre de 96 chiffres

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$\longrightarrow$ Depuis, le nombre utilisé pour sécuriser les cartes bancaires comportent 232 chiffres.

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 banks gives its authorisation.

More details

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

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

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Credit Card

- some *Data*: name of the cardholder, expiry date ...
- a signature of the *Data* – $\{hash(Data)\}_{\mathsf{priv}(B)}$
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More details

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Terminal

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

Payment protocol

the terminal T reads the credit card C:

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

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the terminal T asks the code:

$$2.\quad T \rightarrow CI : \quad code?$$
$$3.\quad CI \rightarrow C : \quad 1234$$
$$4.\quad C \rightarrow T : \quad ok$$

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the terminal T asks the code:

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

the terminal T requests authorisation the bank B:

$$\begin{array}{lcccl} 5. & T & \rightarrow & B : & auth? \\ 6. & B & \rightarrow & T : & 4528965874123 \\ 7. & T & \rightarrow & C : & 4528965874123 \\ 8. & C & \rightarrow & T : & \{4528965874123\}_{K_{CB}} \\ 9. & T & \rightarrow & B : & \{4528965874123\}_{K_{CB}} \\ 10. & B & \rightarrow & T : & ok \end{array}$$

Faille sur la carte bleue

Initialement la sécurité été assurée par :

- cartes difficilement réplicables,
- secret des clefs et du protocole.

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- cartes difficilement réplicables,
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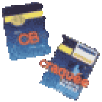
Mais il y a des failles !

- faille cryptographique : les clefs de 320 bits ne sont plus sûres,
- faille logique : pas de lien entre le code secret à 4 chiffres et l'authentification,
- faille matériel : réplicabilité des cartes.



→ "YesCard" fabriquées par Serge Humpich (1997).

La « YesCard »: Comment ca marche ?

Faille logique

$$
\begin{array}{llll}
1. C & \rightarrow T & : \text{Data}, \{\text{hash}(\text{Data})\}_{\text{priv}(B)} \\
2. T & \rightarrow CI & : \mathit{code}? \\
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La « YesCard »: Comment ca marche ?

Faille logique

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2.T & \rightarrow CI & : code? \\
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Remarque : il y a toujours quelqu'un à débiter.
→ ajout d'un faux chiffrement sur une fausse carte (Serge Humpich).

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

Outline of the talk

Needham-Schroeder's Protocol (1978)

- $A \rightarrow B : \{\langle A, N_a \rangle\}_{\mathsf{pub}(B)}$
  $B \rightarrow A : \{\langle N_a, N_b \rangle\}_{\mathsf{pub}(A)}$
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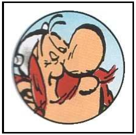

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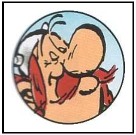

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- When B receives $\{N_b\}_{\text{pub}(B)}$, does this message really comes from A ?

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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.

$$
\begin{array}{lll}
A \rightarrow B & : & \{\langle A, N_a\rangle\}_{\mathsf{pub}(B)} \\
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Example: Man in the middle attack

$\{\langle A, N_a\rangle\}_{\mathsf{pub}(I)}$ → $\{\langle A, N_a\rangle\}_{\mathsf{pub}(B)}$ →

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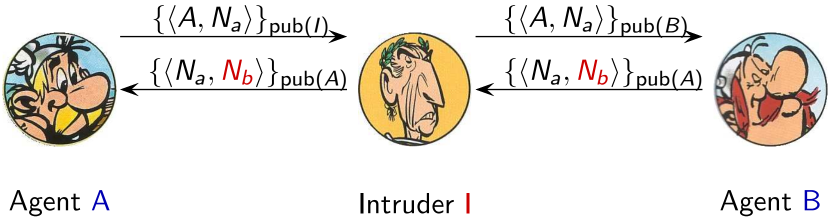

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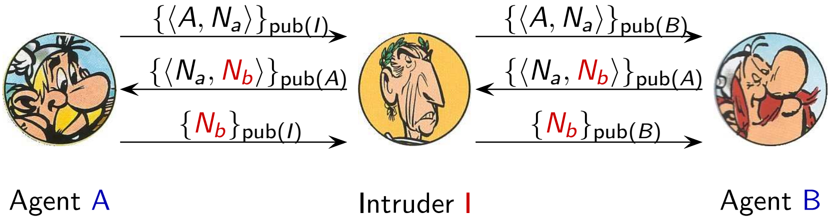

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$\{\langle A, N_a \rangle\}_{\mathsf{pub}(I)} \rightarrow$

$\leftarrow \{\langle N_a, N_b \rangle\}_{\mathsf{pub}(A)}$

$\{N_b\}_{\mathsf{pub}(I)} \rightarrow$

$\{\langle A, N_a \rangle\}_{\mathsf{pub}(B)} \rightarrow$

$\leftarrow \{\langle N_a, N_b \rangle\}_{\mathsf{pub}(A)}$

$\{N_b\}_{\mathsf{pub}(B)} \rightarrow$

Agent A   Intruder I   Agent B

Attack

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

$$
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Outline of the talk

La recherche au LSV

$\longrightarrow$ accroitre notre confiance dans les logiciels critiques

La recherche au LSV

⟶ accroitre notre confiance dans les logiciels critiques

- logiciel: texte relativement long écrit dans un langage spécifique et qui sera exécuté par un ordinateur
- critique: une défaillance peut avoir des conséquences désastreuses en termes humains ou économiques

Difficultés et enjeux de la vérification de programmes

⟶ une petite modification (quelques caractères) peut le transformer complètement.

Un besoin crucial de vérification

- pour des raisons économiques
  ⟶ Ariane 5, carte bancaire, . . .
- mais parfois il y a aussi des vies humaines en jeu
  ⟶ la machine Therac-25 dans les années 80
  ⟶ logiciels embarqués dans les voitures, les avions, . . .
- enjeux démocratiques
  ⟶ vote électronique

Comment fait-on ?

Tests

- à la main ou génération automatique;
- vérification d'un nombre fini de cas.

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Vérification (preuves formelles)

$\longrightarrow$ preuves mathématiques

- à la main ou à l'aide d'ordinateur;
- vérification de tous les cas possibles;
- plus difficile.

Comment vérifier ces programmes ?

Les mathématiques et l'informatique à la rescousse !

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Notre but:

1. faire des preuves mathématiques rigoureuses,
2. d'une façon automatique.

"Construire une machine à détecter les bugs"

Comment vérifier ces programmes ?

Les mathématiques et l'informatique à la rescousse !

Notre but:

1. faire des preuves mathématiques rigoureuses,
2. d'une façon automatique.

"Construire une machine à détecter les bugs"

1936: une telle machine n'existe pas (Alan Turing)

... même dans le cas particulier des protocoles cryptographiques.

Mais alors, que faisons nous ?

Le problème n'a pas de solution ....

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Différentes pistes:

- résoudre le problème dans de nombreux cas intéressants,

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Différentes pistes:

- résoudre le problème dans de nombreux cas intéressants,
- proposer des procédures approchées,

  Exemple: si le vérificateur répond "oui" alors le logiciel est sûr, sinon on ne peut rien dire

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Cryptographic protocols vs (classical) programs

Some specificities:

- protocol are executed in an hostile envrionment

  $\longrightarrow$ a powerful attacker who controls the communication network

- unbounded number of sessions running concurrently

- the cryptographic primitives play an important role

  $\longrightarrow$ we have to take them into account.

How cryptographic protocols can be attacked?

Breaking encryption

- Ciphertext-only attack,
- Known-plaintext attack, . . .

Logical attack

Casser le chiffrement RSA

Les challenges RSA

- défis lancés par le laboratoire RSA Security
- récompenses importantes offertes

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RSA-704	212 chiffres	non résolu – 30 000 dollars	
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⟶ Ces challenges ont été retirés en 2007 !

Logical attack - What is it?

Logical attacks

- can be mounted even assuming perfect cryptography,
  ↪ replay attack, man-in-the middle attack, . . .
- are numerous, see SPORE, Security Protocols Open REpository
  ↪ `http://www.lsv.ens-cachan.fr/spore/`
- subtle and hard to detect by "eyeballing" the protocol

Examples:

- man in the middle attacks: *e.g.* Needham Schroeder protocol;
- replay attacks: electronic passport protocol (French version), electronic voting protocol (*e.g.* Helios).

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Main features:

- Messages are bitstrings
- Protocols are programs that exchange messages
- Real algorithms for cryptographic primitives
- Powerful attacker: any probabilisitic polynomial time Turing machine

$\longrightarrow$ quite realistic model

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- Powerful attacker: any probabilisitic polynomial time Turing machine

$\longrightarrow$ quite realistic model

Advantage: Clear and quite strong security guarantee
Drawback: Proofs are difficult, tedious and error-prone.

Symbolic models

Main features:

- Messages are abstracted by terms (abstract objects)
- Protocols are programs that exchange messages
- Cryptographic primitives are abstracted by function symbols
- Idealized attacker: in particular, we have to describe what he can do.

$\longrightarrow$ very abstract model

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$\longrightarrow$ very abstract model

Advantage: Security proofs are easier to do and they can be mechanized
Drawback: the security guarantees obtained are rather unclear.

Link between the two models

Computational soundness

Computational soundness aims to establish sufficient conditions under which results obtained using symbolic models imply security under computational models.

$\longrightarrow$ Seminal paper: Abadi & Rogaway, 2001

Many other papers have been obtained in this area.

A survey is available [Cortier et al., JAR 2010]

Symbolic model

Messages are abstracted by terms

- pairing $\langle \mathsf{m}_1, \mathsf{m}_2 \rangle$,
- symmetric $\mathsf{senc}(\mathsf{m}, \mathsf{k})$ and public key encryption $\mathsf{aenc}(\mathsf{m}, \mathsf{pub}(\mathsf{A}))$,
- signature $\mathsf{sign}(\mathsf{m}, \mathsf{priv}(\mathsf{A}))$.

Symbolic model

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- symmetric $\mathsf{senc}(m, k)$ and public key encryption $\mathsf{aenc}(m, \mathsf{pub}(A))$,
- signature $\mathsf{sign}(m, \mathsf{priv}(A))$.

Presence of an idealized attacker

- may read, intercept and send messages,
- may build new messages following deduction rules (symbolic manipulation on terms).

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Examples:

$$\frac{m \quad k}{\mathsf{senc}(m, k)} \qquad \frac{\mathsf{senc}(m, k) \quad k}{m} \qquad \frac{\mathsf{aenc}(m, \mathsf{pub}(a)) \quad \mathsf{priv}(a)}{m}$$

Difficulties of the verification

Presence of an attacker ...

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who controls the communication network:

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who controls the communication network:

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who has deduction capabilities

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Presence of an attacker ...

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Secrecy problem for a fixed number of sessions is decidable.

Secrecy problem in presence of a passive attacker

Intruder deduction problem for a fixed inference system $\mathcal{I}$

Input: a finite set of ground terms T (the knowledge of the attacker) and a ground term s (the secret),

Output: Is s deducible from T in $\mathcal{I}$?

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Example: $T = \{\mathsf{senc}(s_1, k_1);\ \mathsf{senc}(s_2, k_2);\ \langle k_1, k_2\rangle\}$ and $s = \langle s_1, s_2\rangle$.

$$\frac{x \quad y}{\langle x, y\rangle} \qquad \frac{\langle x, y\rangle}{x} \qquad \frac{\langle x, y\rangle}{y} \qquad \frac{x \quad y}{\mathsf{senc}(x, y)} \qquad \frac{\mathsf{senc}(x, y) \quad y}{x}$$

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Results

The intruder deduction problem is decidable in PTIME for the inference system given above (and some others)

Secrecy problem via constraint solving

$\longrightarrow$ for a fixed number of sessions

Protocol rules

$\mathsf{in}(u_1);\ \mathsf{out}(v_1)$

$\mathsf{in}(u_2);\ \mathsf{out}(v_2)$

$\ldots$

$\mathsf{in}(u_n);\ \mathsf{out}(v_n)$

Constraint System

$$\mathcal{C} = \begin{cases} T_0 \overset{?}{\vdash} u_1 \\ T_0, v_1 \overset{?}{\vdash} u_2 \\ \quad \ldots \\ T_0, v_1, .., v_n \overset{?}{\vdash} s \end{cases}$$

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Solution of a constraint system in $\mathcal{I}$

A substitution σ such that

for every $T \overset{?}{\vdash} u \in \mathcal{C}$, $u\sigma$ is deducible from $T\sigma$ in $\mathcal{I}$.

Example: Needham-Schroeder's protocol

$A(a, I)$ and $B(b)$ (running in parallel)

$$
\begin{array}{rcl}
 & & \mathsf{out}(\{\langle a, n_a\rangle\}_{\mathsf{pub}(I)}) \\
\mathsf{in}(\{\langle n_a, x_{n_b}\rangle\}_{\mathsf{pub}(a)}) & ; & \mathsf{out}(\{x_{n_b}\}_{\mathsf{pub}(I)}) \\
\\
\mathsf{in}(\{\langle y_a, y_{n_a}\rangle\}_{\mathsf{pub}(b)}) & ; & \mathsf{out}(\{\langle y_{n_a}, n_b\rangle\}_{\mathsf{pub}(y_a)})
\end{array}
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Solution $\sigma = \{y_a \mapsto a,\ \ y_{n_a} \mapsto n_a,\ \ x_{n_b} \mapsto n_b\}$

Decision procedure

There exists an algorithm (actually a set of simplification rules) to decide whether such kind of constraint systems have a solution or not.

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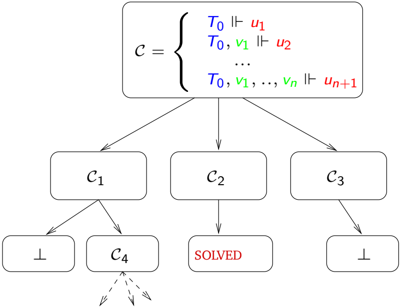
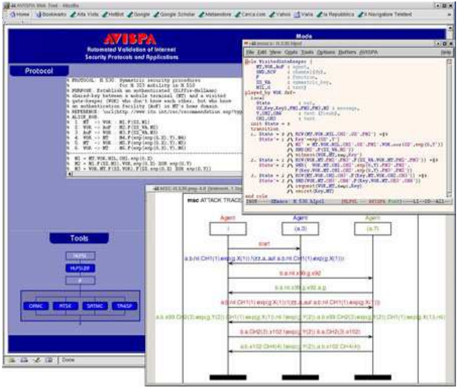
Main idea of the procedure:



Outil de vérification AVISPA

Outil disponible en ligne: `http://www.avispa-project.org/`



$\longrightarrow$ Projet Européen (France, Italie, Allemagne, Suisse)

Outline of the talk

Conclusion

Cryptographic protocols

- numerous, various security goals
- can be attacked even if the primitives are secure
  $\longrightarrow$ `http://www.lsv.ens-cachan.fr/spore/`

How to verify them?

- modelling the protocol, the security properties
- manually /automatically
  $\longrightarrow$ the problem is undecidable in general (some tools exist)

It remains a lot to do

- modelling security properties is a difficult task
- does a suitable E-voting protocol exist?
- take into account the algebraic properties of the primtives
- analyse the source code of the protocol instead of its specification