Providing solutions for more secure exchanges

Stéphanie Delaune

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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.

Cryptographic protocols

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

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?
- 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.
- ...

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 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)

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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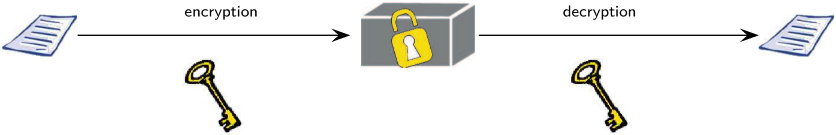
Symmetric encryption



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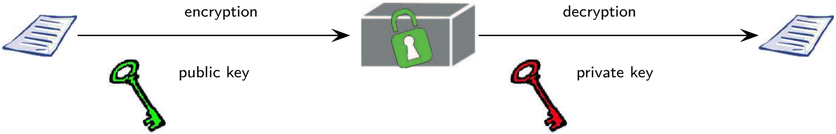
Asymmetric encryption



Symmetric vs. asymmetric encryption

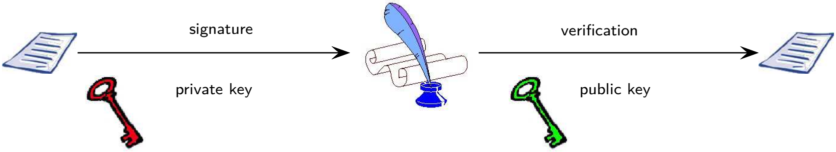
Symmetric encryption

- 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)

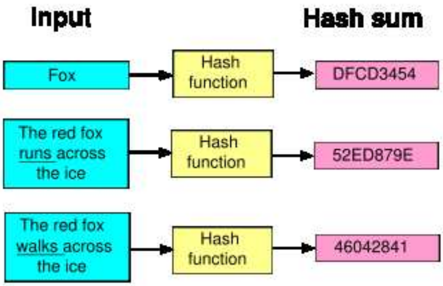
$\longrightarrow$ allows someone to sign without knowing the message he is signing.

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

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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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Affaire Serge Humpich (1997)

il factorise ce nombre de 96 chiffres et conçoit de fausses cartes bleues (les “ YesCard ”).

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il factorise ce nombre de 96 chiffres et conçoit de fausses cartes bleues (les “ YesCard ”).

⟶ 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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Bank

- a private signature key – $\text{priv}(B)$
- a public key to verify a signature – $\text{pub}(B)$
- 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* – $\{hash(Data)\}_{\text{priv}(B)}$
- a secret key shared with the bank – K_{CB}

More details

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

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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:

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

Payment protocol

the terminal T reads the credit card C:

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

the terminal T asks the code:

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

the terminal T requests authorisation the bank B:

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

Faille sur la carte bleue

Initialement la sécurité été assurée par :

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

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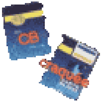
- secret des clefs et du protocole.

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 & : \textit{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).

La « YesCard »: Comment ca marche ?

Faille logique

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1.C & \rightarrow T & : \text{Data}, \{\text{hash}(\text{Data})\}_{\text{priv}(B)} \\
2.T & \rightarrow CI & : code? \\
3.CI & \rightarrow C' & : 2345 \\
4.C' & \rightarrow T & : ok
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$$
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1.C' & \rightarrow T & : \text{XXX}, \{\text{hash}(\text{XXX})\}_{\text{priv}(B)} \\
2.T & \rightarrow CI & : code? \\
3.CI & \rightarrow C' & : 0000 \\
4.C' & \rightarrow T & : ok
\end{array}
$$

Outline of the talk

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

Needham-Schroeder's Protocol (1978)

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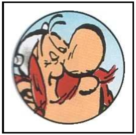

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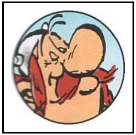

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Questions

- Is N_b secret between A and B ?
- When B receives $\{N_b\}_{\mathrm{pub}(B)}$, 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}{lcl}
A \rightarrow B & : & \{\langle A, N_a \rangle\}_{\mathsf{pub}(B)} \\
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$\{\langle A, N_a \rangle\}_{\mathrm{pub}(I)}$ → $\{\langle A, N_a \rangle\}_{\mathrm{pub}(B)}$ →

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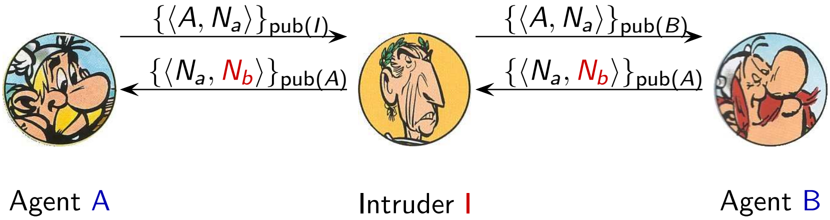

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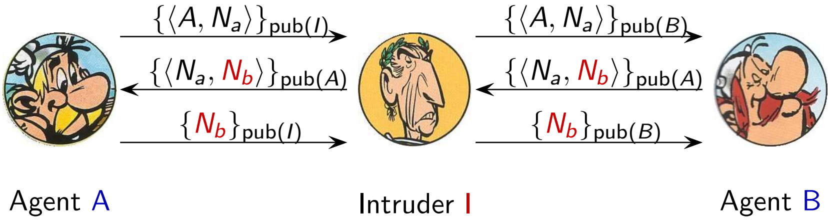

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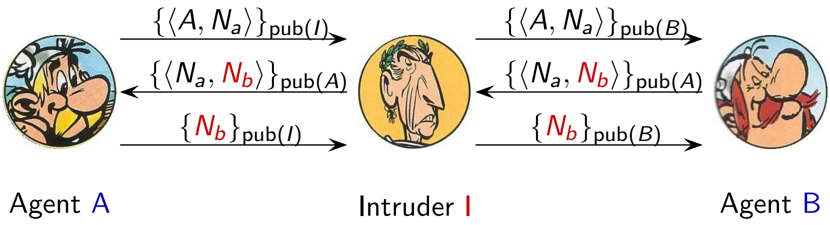

Attack

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

$$
\begin{array}{lll}
A \to B & : & \{\langle A, N_a \rangle\}_{\mathsf{pub}(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

La recherche au LSV

Ennemi public numéro 1: le bug ...

La recherche au LSV

Ennemi public numéro 1: le bug ...

... aussi connu sous le nom de bogue !

Dans la vie quotidienne !

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Ariane V - 4 juin 1996

Un crash après 40 secondes de vol dû

...

Ariane V - 4 juin 1996

Un crash après 40 secondes de vol dû

...

à un bug logiciel !

1. 189 vols réussis pour Ariane IV,
2. réutilisation du logiciel de lancement d'Ariane IV,
3. ajout du nécessaire pour la nouvelle fusée.

⟶ Le logiciel d'Ariane IV contenait un bug !

Sonde Mars Climate Orbiter - 26 septembre 1999

Perte de la sonde due ...

Sonde Mars Climate Orbiter - 26 septembre 1999

Perte de la sonde due ... à un problème d'unité de mesure !

Difficultés et enjeux de la vérification de programmes

$\longrightarrow$ une petite modification (quelques caractères) peut le transformer complètement.

Un besoin crucial de vérification

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

Comment fait-on ?

Tests

- à la main ou génération automatique;
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$\infty \ \infty \ \infty$ Accéder à l'infini: un rêve impossible ? $\infty \ \infty \ \infty$

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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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"

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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mais seulement dans le cas général

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-576	174 chiffres	réussi	2003
RSA-640	193 chiffres	réussi	2005
RSA-704	212 chiffres	non résolu – 30 000 dollars	
...	..	...	
RSA-2048	617 chiffres	non résolu – 200 000 dollars	

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$\longrightarrow$ 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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- 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

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.

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- 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

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 $\langle m_1, m_2 \rangle$,
- symmetric $senc(m, k)$ and public key encryption $aenc(m, pub(A))$,
- signature $sign(m, priv(A))$.

Symbolic model

Messages are abstracted by terms

- pairing $\langle m_1, m_2 \rangle$,
- symmetric $senc(m, k)$ and public key encryption $aenc(m, pub(A))$,
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Presence of an idealized attacker

- may read, intercept and send messages,
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Examples:

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

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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),

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

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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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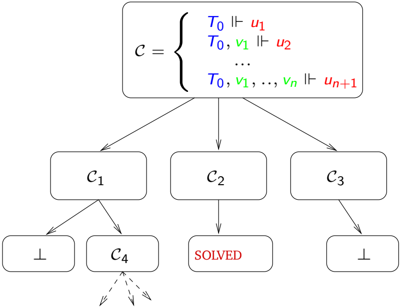
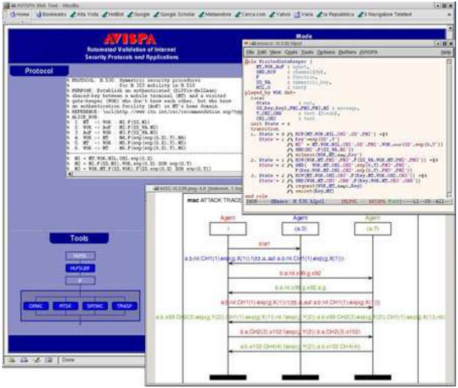
Main idea of the procedure:



Outil de vérification AVISPA

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



⟶ 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