An introduction to formal symbolic models

for verifying security protocols

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Verifying security protocols: a difficult task

- testing their resilience against well-known attacks is not sufficient;
- manual security analysis is error-prone.

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Security

Defects in e-passports allow real-time tracking

This threat brought to you by RFID

The register - Jan. 2010

Lifestyle › Tech › News

Contactless card theft: Users warned to watch out for 'digital pickpockets'

Independent - Feb. 2016

A sucessful approach: formal symbolic verification

$\longrightarrow$ provides a rigorous framework and automatic tools to analyse security protocols and find their logical flaws.

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TAMARIN
Tamarin prover interactive mode

ProVerif

AVANTSSAR

Some examples of logical flaws:

- 2008: Authentication flaw in the Single Sign-On protocol used *e.g.* in GMail
  $\longrightarrow$ Armando *et al.* using Avantssar

- 2010: a flaw in the french implementation of the BAC protocol
  $\longrightarrow$ Chothia & Smirnov

Logical flaw on an example

$$\text{aenc}(\text{sign}(k_{AB}, \text{prv}(A)), \text{pub}(B)) \longrightarrow$$

Is the Denning Sacco protocol a good key exchange protocol?

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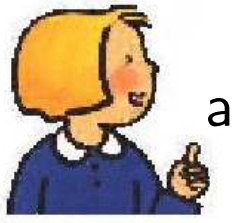

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A possible fix: $\text{aenc}(\text{sign}(\langle B, k_{AB} \rangle, \text{prv}(A)), \text{pub}(B))$

Two major families of models ...

... with some advantages and some drawbacks.

Computational model

- + messages are bitstring, a general and powerful adversary
- − manual proofs, tedious and error-prone

Symbolic model

- − abstract model, e.g. messages are terms
- + automatic proofs

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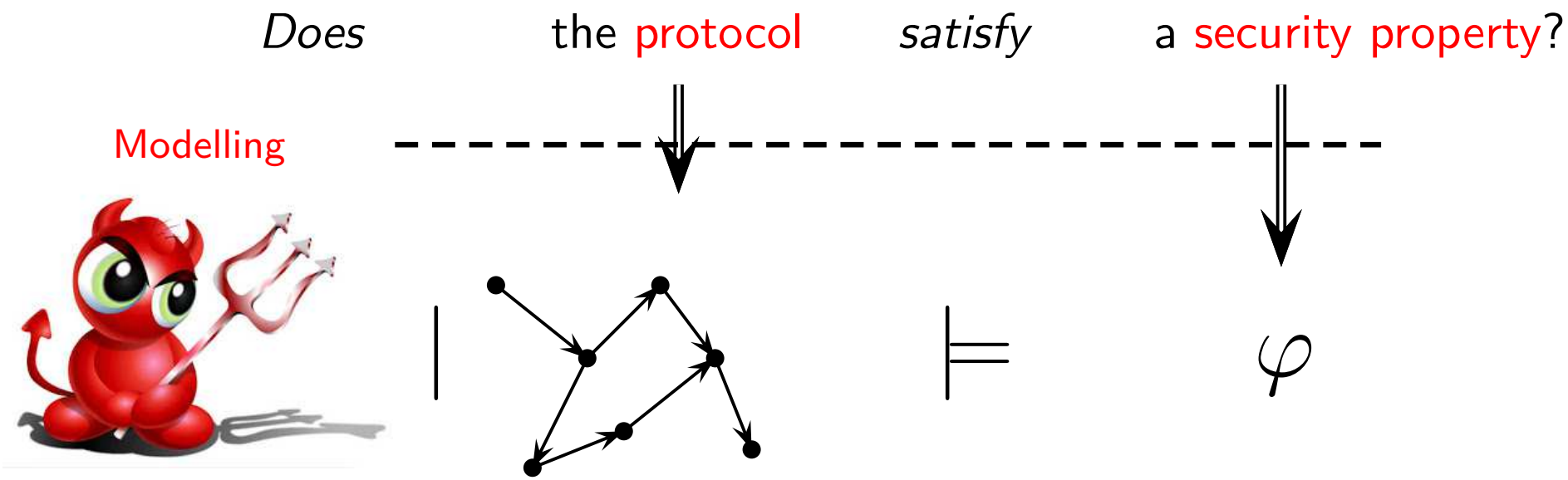
Some results allowed to make a link between these two very different models.

$\longrightarrow$ Abadi & Rogaway 2000

Formal (symbolic) verification in a nutshell



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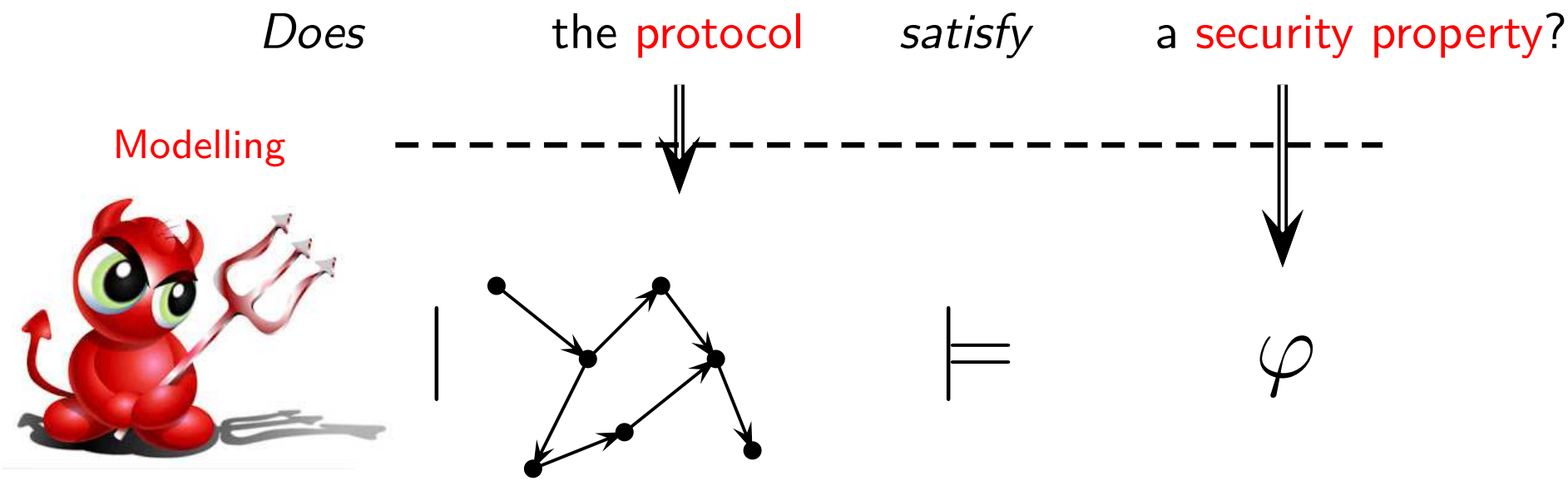

Two main tasks

1. Modelling protocols, security properties, and the attacker
2. Designing verification algorithms and tools

Part I

Modelling protocols, security properties and the attacker

Symbolic models in a nutshell

Some well-known existing models:

- strand spaces [Guttman *et al.*, 99],
- Multiset Rewriting [Durgin *et al.*, 99] - Tamarin tool
- spi-calculus [Abadi & Gordon, 97],
- applied-pi calculus [Abadi & Fournet, 01] - ProVerif tool

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They share some common ingredients:

- messages are abstracted by terms (perfect cryptography)
- the Dolev-Yao attacker who controls the entire network
- language with constructs for concurrency and communication

Messages as first-order terms

Terms are built over a set of names $\mathcal{N}$, and a signature $\mathcal{F}$.

t	::=	n	name n
	$\mid$	$f(t_1, \ldots, t_k)$	application of symbol $f \in \mathcal{F}$

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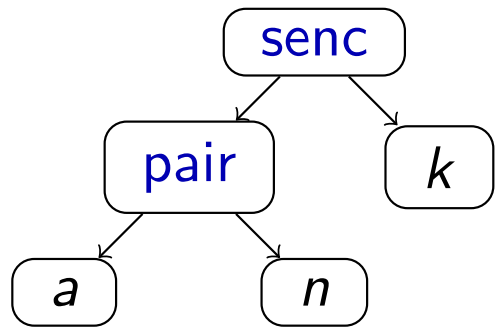

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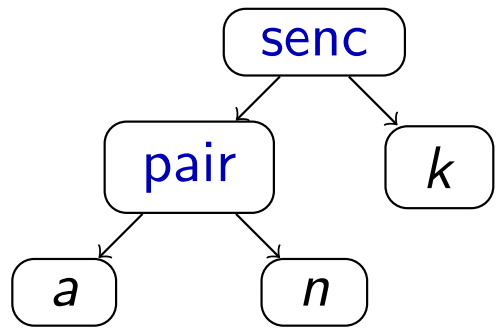
- constructors: senc, pair,
- destructors: sdec, proj_1, proj_2.



The term algebra is equipped with an equational theory E.

$$\mathrm{sdec}(\mathrm{senc}(x, y), y) = x \qquad \begin{array}{rcl} \mathrm{proj}_1(\mathrm{pair}(x, y)) & = & x \\ \mathrm{proj}_2(\mathrm{pair}(x, y)) & = & y \end{array}$$

Example: $\mathrm{proj}_1(\mathrm{sdec}(\mathrm{senc}(\langle a, n\rangle, k), k)) =_{\mathrm{E}} a$.

Protocols as processes

$\longrightarrow$ the applied pi calculus [Abadi & Fournet, 2001]

P, Q	$:=$	0	null process
		$\text{in}(c, x).P$	input
		$\text{out}(c, u).P$	output
		if $u = v$ then P else Q	conditional
		$P \mid Q$	parallel composition
		$!P$	replication
		new $n.P$	fresh name generation

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Semantics $\rightarrow$:

Comm	$\mathsf{out}(c, u).P \mid \mathsf{in}(c, x).Q \rightarrow P \mid Q\{u/x\}$
Then	$\mathsf{if}\ u = v\ \mathsf{then}\ P\ \mathsf{else}\ Q \rightarrow P\ \mathsf{when}\ u =_{\mathsf{E}} v$
Else	$\mathsf{if}\ u = v\ \mathsf{then}\ P\ \mathsf{else}\ Q \rightarrow Q \quad \mathsf{when}\ u \neq_{\mathsf{E}} v$
Repl	$!P \rightarrow P \mid !P$

Going back to the Denning Sacco protocol (1/3)

$$\begin{array}{lcl} A \rightarrow B & : & \mathsf{aenc}(\mathsf{sign}(k, \mathsf{prv}(A)), \mathsf{pub}(B)) \\ B \rightarrow A & : & \mathsf{senc}(s, k) \end{array}$$

What symbols and equations do we need to model this protocol?

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2. asymmetric encryption: aenc, adec, and pk

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3. signature: ok, sign, check, getmsg, and pk

$$\mathsf{check}(\mathsf{sign}(x, y), \mathsf{pk}(y)) = \mathsf{ok} \text{ and } \mathsf{getmsg}(\mathsf{sign}(x, y)) = x$$

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Alice and Bob as processes:

$$\begin{array}{lcl} P_A(sk_a, pk_b) & = & \mathsf{new}\ k. \\ & & \mathsf{out}(c, \mathsf{aenc}(\mathsf{sign}(k, sk_a), pk_b)). \\ & & \mathsf{in}(c, x_a).\ \ldots \end{array}$$

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Example: a simple scenario

$$P_{\mathsf{DS}} = \text{new } sk_a, sk_b.(P_A(sk_a, \mathsf{pk}(sk_b)) \mid P_B(sk_b, \mathsf{pk}(sk_a))$$

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this represents a normal execution between two honest participants

Trace-based security properties

Confidentiality (as non-deducibility)

For all processes A, for all execution $A \mid P \rightarrow^* Q$, we have that Q is not of the form $\mathtt{new}\, \tilde{n}.(\mathrm{out}(c, s).Q' \mid Q'')$ with c public.

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Authentication (as a correspondence property)

1. add events of the form endB(...) or beginA(...) in processes
2. write a query:
   $\forall x_B, x_A, x_K.\text{endB}(x_B, x_A, x_K) \Rightarrow \text{beginA}(x_A, x_B, x_K).$

For all processes A, for all execution $A \mid P \rightarrow^* Q$ that goes through the event $\text{endB}(b, a, k)$, the event $\text{beginA}(a, b, k)$ has been executed before.

Equivalence-based security properties

Vote privacy

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

$$V_A(\mathit{yes}) \mid V_B(\mathit{no}) \stackrel{?}{\approx} V_A(\mathit{no}) \mid V_B(\mathit{yes})$$

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Unlinkability

the fact that a user may make multiple uses of a service or a resource without others being able to link these uses together.

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Testing equivalence $P \approx Q$

$$P \approx Q \quad \text{iff} \quad (P \mid A)\Downarrow_c \;\Leftrightarrow\; (Q \mid A)\Downarrow_c \text{ for any process } A$$

where $R \Downarrow_c$ means that R can evolve and emits on public channel c.

Part II

Designing verification algorithms and tools

State of the art in a nutshell

for analysing confidentiality/authentication properties

Unbounded number of sessions

- undecidable in general [Even & Goldreich, 83; Durgin *et al*, 99]
- decidable for restricted classes [Lowe, 99] [Rammanujam & Suresh, 03] [D'Osualdo *et al.*, 17]

$\longrightarrow$ tools: ProVerif, Tamarin, Maude-NPA, ...

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Bounded number of sessions

- a decidability result (NP-complete) [Rusinowitch & Turuani, 01; Millen & Shmatikov, 01]

$\longrightarrow$ tools: AVANTSSAR platform, ...

ProVerif [Blanchet, 01]

ProVerif is a verifier for cryptographic protocols that may prove that a protocol is secure or exhibit attacks.

`http://proverif.inria.fr`

Advantages

- fully automatic, and quite efficient
- a rich process algebra: replication, else branches, ...
- handles many cryptographic primitives
- various security properties: secrecy, correspondences, equivalences

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No miracle

- the tool can say "can not be proved";
- termination is not guaranteed

ProVerif

ProVerif implements a resolution strategy well-adapted to protocols.

Approximation of the translation in Horn clauses:

- the freshness of nonces is partially modeled;
- the number of times a message appears is ignored, only the fact that is has appeared is taken into account;
- the state of the principals is not fully modeled.

$\longrightarrow$ These approximations are keys for an efficient verification.

Experimental results

$\longrightarrow$ ProVerif works well in practice.

Protocol	Result	ms
Needham-Schroeder shared key	Attack	52
Needham-Schroeder shared key corrected	Secure	109
Denning-Sacco	Attack	6
Denning-Sacco corrected	Secure	7
Otway-Rees	Secure	10
Otway-Rees, variant of Paulson98	Attack	12
Yahalom	Secure	10
Simpler Yahalom	Secure	11
Main mode of Skeme	Secure	23

Pentium III, 1 GHz.

Part III

Main limitations

Dolev-Yao attacker

As any participant, the attacker can intercept, build, and send messages without introducing any delay.
$\longrightarrow$ not suitable to analyse distance bounding protocols

We need a model that takes into account:

- the fact that transmitting a message takes time,
- the location of participants.

How existing symbolic models/tools can be extended/adapted to analyse distance bounding protocols?

$\longrightarrow$ see talks given by T. Chothia, J. Toro-Pozo, and A. Debant

Handling low-level operators

Distance bounding protocols often rely on some low-level operators.

Single bit message: Symbolic models do not allow one to reason at this level.
$\longrightarrow$ this is a problem to model rapid phases in distance bounding.

Algebraic properties of low level operators: A faithful model need to take into account the algebraic properties of those operators:

Example: exclusive-or operator

$$\begin{array}{rclcrcl} (x \oplus y) \oplus z & = & x \oplus (y \oplus z) & \qquad & x \oplus 0 & = & x \\ x \oplus y & = & y \oplus x & & x \oplus x & = & 0 \end{array}$$

$\longrightarrow$ those operators are only partially supported in existing verification tools.

Towards probabilistic models

Existing symbolic verification tools do not allow one to model probabilistic behaviours.

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To say that a bad state is reachable with probability at most p, we need to introduce probability in our modelling
$\longrightarrow$ *e.g.* partially observable Markov decision processes

Some recent works by R. Chadha et al.

- Verification of randomized security protocols LICS, 2017
- Modular Verification of Protocol Equivalence in the Presence of Randomness ESORICS, 2017

Privacy-type properties

In comparison to trace-based security properties

- a more recent research area
- more difficult to analyse (we have to compare sets of traces).

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State-of-the art for traditional protocols

- ProVerif (and Tamarin) consider a strong form of equivalence, namely diff-equivalence.
  $\longrightarrow$ not suitable to analyse *e.g.* unlinkability of the BAC protocol.
- Verification tools for a bounded number of sessions suffer from the well-known state explosion problem
  $\longrightarrow$ only able to analyse very few sessions of the protocol, e.g. 2 or 3 processes in parallel.

Privacy-type properties

In comparison to trace-based security properties

- a more recent research area
- more difficult to analyse (we have to compare sets of traces).

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Open challenge: extending existing verification tools to be able to analyse privacy-type properties on distance bounding protocols.

POPSTAR in a nutshell (2017-2022)

Reasoning about **Physical properties** Of
security Protocols
with an Application To **contactless Systems**

Main issues:

- specificities of contactless systems are not well understood;
- a lack of formal model to reason about these systems.

Main outcomes:

- solid foundations to reason about physical properties;
- new algorithms and tools to analyse the security and privacy of modern protocols;
- make the upcoming generation of nomadic contactless devices more secure.

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Reasoning about **Physical properties** Of
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