# Automated formal analysis of security protocols

# Automated verification

- It is not easy and is error-prone itself to do formal analysis manually;

- Development of methods for automated or semi-automated (interactive) validation and verification is important area, especially in the context of security protocols;

# Different directions

- **Model checking** (state exploration tools);
  - specific (NRL Protocol Analyser,etc)
  - general purpose tools (SMV, SPIN, Mocha, etc)
  - general purpose tools combined with specific translators (Casper/FDR, etc)
  - Unbounded model checking for crypto protocols (ProVerif, Tamarin, etc)
- **Theorem proving**
  - Automated (TAPS, etc)
  - Interactive (Isabell, PVS, etc )
- **Combinations of above techniques**:
  - Athena, etc
- **Others:** decision procedures for specific theories, infinite state model checking,etc

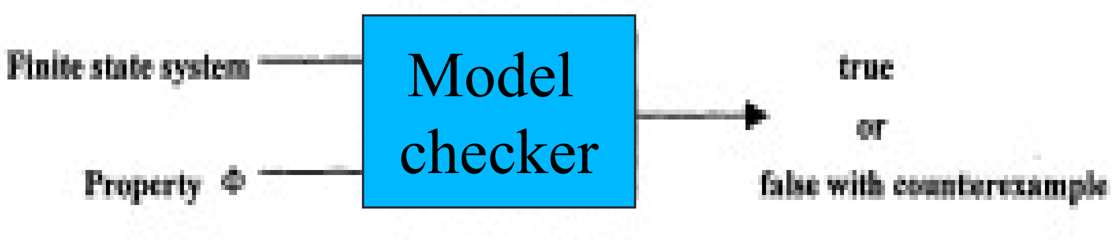
# General questions

- How to represent a protocol (system) to be analysed?
- How to express properties to be verified?

# Model checking

- A protocol (system executing a protocol) is represented as a transition system **M** with **finitely** many states;
- A property to be analysed is expressed by a formula of a logic (temporal, modal, etc) **f;**
- Then verification amounts to checking whether the formula ***f*** *is* true in **M;**
- Model checking is done via efficient state exploration techniques;

# Model checking



**Nice properties**

- Fully automated procedures;
- Very efficient state exploration;

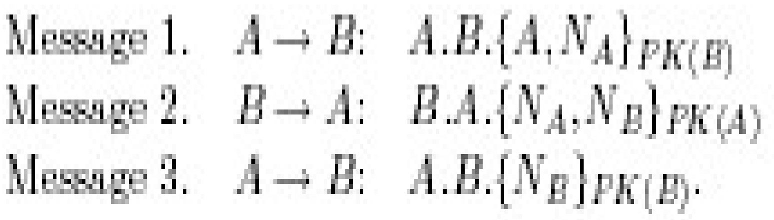
**but**

- Finite state abstraction is not always adequate, especially for protocols with unbounded number of participants or unbounded number of rounds.

# Attack on Needham-Schroeder protocol

- A particular success of model checking methods in security protocol verification was discovery of a flaw in NS protocol based on public key cryptography (Gavin Lowe, 1995-1996);
- **Original protocol**

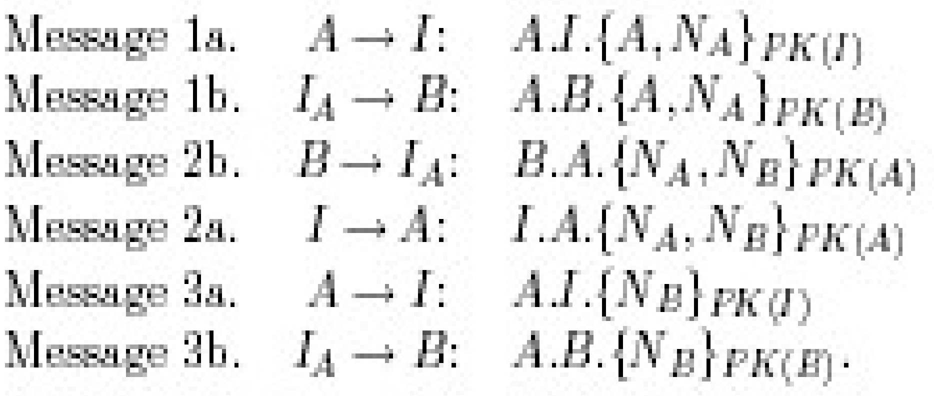
**Attack**



Message 1. $A \to B$: $A.B.\{A, N_A\}_{PK(B)}$

Message 2. $B \to A$: $B.A.\{N_A, N_B\}_{PK(A)}$

Message 3. $A \to B$: $A.B.\{N_B\}_{PK(B)}$.



Message 1a. $A \to I$: $A.I.\{A, N_A\}_{PK(I)}$

Message 1b. $I_A \to B$: $A.B.\{A, N_A\}_{PK(B)}$

Message 2b. $B \to I_A$: $B.A.\{N_A, N_B\}_{PK(A)}$

Message 2a. $I \to A$: $I.A.\{N_A, N_B\}_{PK(A)}$

Message 3a. $A \to I$: $A.I.\{N_B\}_{PK(I)}$

Message 3b. $I_A \to B$: $A.B.\{N_B\}_{PK(B)}$.

Corrupt participant I impersonates A

# Theorem Proving

- A protocol ( a system) to be verified is described by a formula **Fs** of a logic (classical first-order, higher-order, modal, temporal, etc);
- A property to be verified is expressed by a formula **P** of the same logic;
- Then to establish the required property it is enough to prove the theorem **Fs → P;**

# Theorem proving

- **Potential benefits:**
- the systems with *unbounded* (infinite) number
- states can be analysed;
- **But:**
- The problems here are, in general, *undecidable*;
- Procedures are *incomplete* and of high complexity.

# Theorem proving

- What to do?
- Apply automated procedures for fragments of first-order and higher-order logic
  - E.Cohen, TAPS system, Microsoft Research;
- Use interactive theorem proving
  - L.Paulson, Cambridge: using Isabell, higher-order inductive theorem prover for the verification of security protocols;
  - J.Bryans, S. Schenider, using interactive theorem prover PVS;

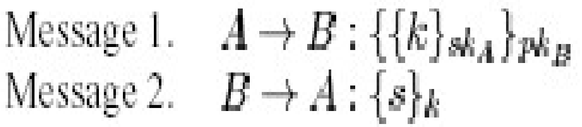
# Other interesting approaches

- Bruno Blanchet, INRIA: approach based on ideas from Logic Programming (ProVerif, available online at http://www.di.ens.fr/~blanchet/crypto-eng.html):

- A protocol is presented as a set of Horn clauses (like a program in Prolog), defining capabilities of all participants);
- Verification then amounts to checking whether a security breaching goal can be reached (derived) from the set of clauses;
- If the system detects the goal is unreachable, then the protocol is correct;
- Standard operational semantics of Prolog is not very useful here due to undesirable looping;
- Novel operational semantics (search strategy) is defined;
- Recent versions use pi-calculus as a language for front-end

# ProVerif system

Denning-Sacco key distribution protocol



Message 1. $A \rightarrow B : \{\{k\}_{sk_A}\}_{pk_B}$

Message 2. $B \rightarrow A : \{s\}_k$

Its representation in ProVerif system

Computation abilities of the attacker:

| | |
|---|---|
| pencrypt | $\mathsf{attacker}(m) \wedge \mathsf{attacker}(pk) \rightarrow \mathsf{attacker}(\mathsf{pencrypt}(m, pk))$ |
| pk | $\mathsf{attacker}(sk) \rightarrow \mathsf{attacker}(\mathsf{pk}(sk))$ |
| pdecrypt | $\mathsf{attacker}(\mathsf{pencrypt}(m, \mathsf{pk}(sk)) \wedge \mathsf{attacker}(sk) \rightarrow \mathsf{attacker}(m)$ |
| sign | $\mathsf{attacker}(m) \wedge \mathsf{attacker}(sk) \rightarrow \mathsf{attacker}(\mathsf{sign}(m, sk))$ |
| getmess | $\mathsf{attacker}(\mathsf{sign}(m, sk)) \rightarrow \mathsf{attacker}(m)$ |
| checksign | removed since implied by getmess |
| sencrypt | $\mathsf{attacker}(m) \wedge \mathsf{attacker}(k) \rightarrow \mathsf{attacker}(\mathsf{sencrypt}(m, k))$ |
| sdecrypt | $\mathsf{attacker}(\mathsf{sencrypt}(m, k)) \wedge \mathsf{attacker}(k) \rightarrow \mathsf{attacker}(m)$ |

Initial knowledge of the attacker:

$\mathsf{attacker}(\mathsf{pk}(sk_A[])), \quad \mathsf{attacker}(\mathsf{pk}(sk_B[])), \quad \mathsf{attacker}(a[])$

Protocol:

First message: $\mathsf{attacker}(\mathsf{pk}(x)) \rightarrow \mathsf{attacker}(\mathsf{pencrypt}(\mathsf{sign}(k[\mathsf{pk}(x)], sk_A[]), \mathsf{pk}(x)))$

Second message: $\mathsf{attacker}(\mathsf{pencrypt}(\mathsf{sign}(k', sk_A[]), \mathsf{pk}(sk_B[]))) \rightarrow \mathsf{attacker}(\mathsf{sencrypt}(s[], k'))$