Habilitation Defense

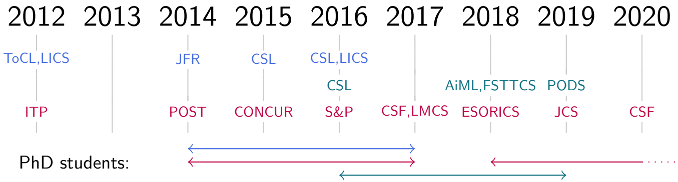
Contributions to the Verification of Cryptographic Protocols

David Baelde

Université Paris-Saclay

February 10, 2021

Research & supervision since 2012



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- Proof systems for data logics
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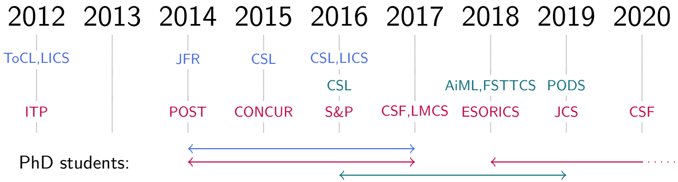

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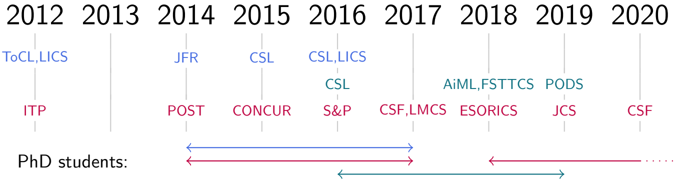

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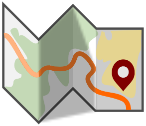
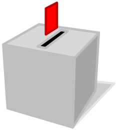
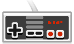
  🔊 MPRI M2 course in 2017–2019

Increasingly many activities are becoming digitalized.





Security & Privacy

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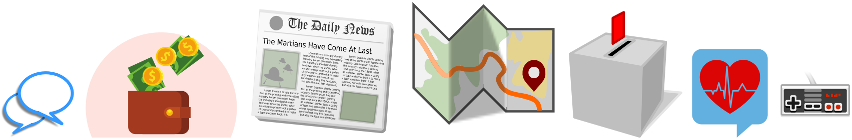
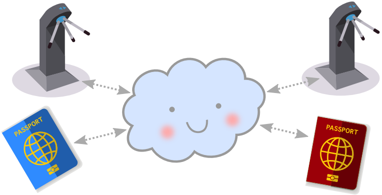


These systems must ensure important properties:

- security: secrecy, authenticity, no double-spending...
- privacy: anonymity, absence of tracking...

Frequent flaws at the hardware, software and specification levels.

Cryptographic protocols: a naive example



Each tag (T_i) owns a secret key k_i.

Reader (R) knows all legitimate keys.

$$\begin{array}{cccl} R & \rightarrow & T_i & : \; n_R \\ T_i & \rightarrow & R & : \; \mathsf{h}(n_R, k_i) \end{array}$$

Scenario under consideration:

- roles R, T_1, ..., T_n; arbitrary number of sessions for each role

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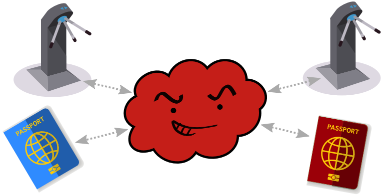

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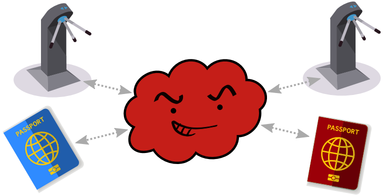

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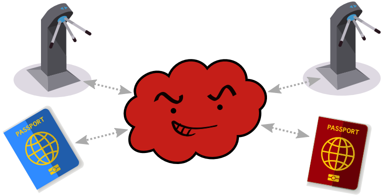

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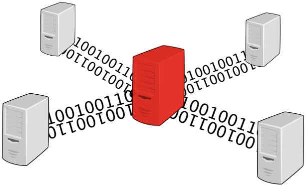
Readers correctly authenticate tags.

Tags can be tracked: the protocol is not unlinkable.

- The attacker can obtain the pseudonym $\mathsf{h}(0, k_i)$ from a tag.

The computational model



Messages = bitstrings

Secrets = random samplings

Participants = PPTIME Turing machines

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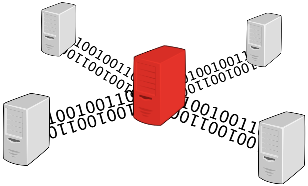

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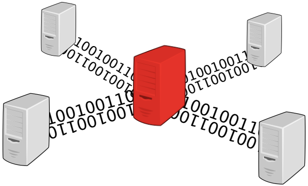

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Example (Unforgeability, EUF-CMA)

There is a negligible probability of success for the following game, for any attacker $\mathcal{A}$:

- Draw k uniformly at random.
- $\langle u, v \rangle := \mathcal{A}^{\mathcal{O}}$ where $\mathcal{O}$ is the oracle $x \mapsto \mathsf{h}(x, k)$.
- Succeed if $u = \mathsf{h}(v, k)$ and $\mathcal{O}$ has not been called on v.

Naive protocol in the computational model

Authentication

Attacker can interact with tags and readers,
wins if some reader accepts a message that has not been emitted by a tag.

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- Impossible if h is unforgeable.

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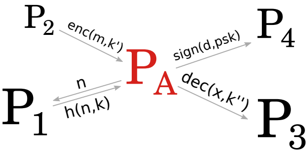
Privacy

Attacker interacts with either T_A, T_B or T_A, T_A
wins if he guesses in which situation he is.

- Success with probability almost 1 thanks to pseudonyms.

A symbolic model



Messages = terms modulo equations

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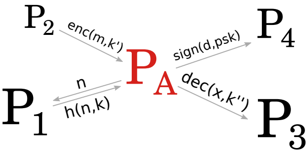

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Example (Equational theory for symmetric encryption)

$$\mathsf{sdec}(\mathsf{senc}(x, y), y) =_{\mathsf{E}} x$$

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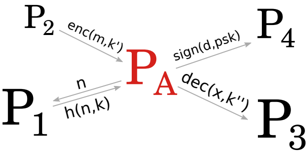

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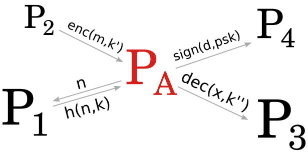
Example (Processes)

$$T_i \stackrel{def}{=} \mathbf{in}(c, x).\mathbf{out}(c, \mathsf{h}(x, k_i)) \qquad S \stackrel{def}{=} T_i \mid T_j \mid P_A$$

$$P_A \stackrel{def}{=} \mathbf{out}(c, 0).\mathbf{in}(c, x).\mathbf{out}(c, 0).\mathbf{in}(c, y).\mathsf{if}\ x = y\ \mathsf{then}\ \mathbf{success}$$

A symbolic model



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Analyze system through LTS rather than explicit adversarial environment:

- Security properties modelled as reachability problems in the LTS.
- Privacy properties modelled as equivalence problems, e.g. may testing, trace equivalence.

Verification in the symbolic model

Trace properties

Undecidable in general, some restrictions decidable.
Mature automated tools borrowing, e.g., from rewriting and logic.

- Casper, Proverif, AVISPA, Scyther, Tamarin
  (Oxford, Inria Paris & Nancy, ETH Zürich, CISPA)
- Breaking/fixing/proving Google SSO, 3G/5G authentication, Neuchatel & Belenios e-voting, WPA2, Signal, TLS 1.3, etc.

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Equivalence properties

- Bounded sessions: several tools and some decision procedures
  SPEC, Apte, Akiss, DeepSec, SAT-Equiv (ANU, LSV, Inria Nancy)
- Unbounded sessions: diff-equivalence in Proverif and Tamarin

Contributions to the verification of cryptographic protocols

Unlinkability [SP'16, JCS'19, CSF'20 distinguished paper]

- Modelling: importance of chosen equivalence and reader model
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Trace equivalence verification for bounded sessions

- Support for exclusive or in Akiss [CSF'17]
- Partial order reductions [POST'14, CONCUR'15, LMCS'17, ESORICS'18]

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Proofs in the computational model [submitted]

- A meta-logic for proving trace and equivalence properties in the computational model

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Focus 1/2

Partial Order Reductions for Protocol Equivalence Verification

joint work with Delaune & Hirschi

A classic problem

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$\mathbf{out}(a, c_1).$ $\mathbf{in}(c_1, R_1).$ $\mathbf{in}(c_1, w_2)$

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- A classic problem in the verification of concurrent systems, which has been tackled using many partial order reduction (POR) techniques.
- Some POR used for verifying trace properties of crypto protocols.
- A new problem for equivalences of crypto protocols.

Compression

A first technique, directly inspired by focusing from proof theory.

Execution strategy in two alternating phases

- Output phase: eagerly execute outputs
- Focus on some process, initiating a session if possible
- Input phase: execute inputs of the process under focus

Parallel compositions processed only in output phase,
conditionals executed transparently in both phases.

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Lifting POR to equivalence

Compression preserves enough reachable states e.g. to verify secrecy, but it is unsound to verify trace equivalence only along compressed traces.

Example

$\mathbf{out}(c, n).\mathbf{out}(c, \mathsf{h}(n, k))$ vs. $\mathbf{out}(c, n) \mid \mathbf{out}(c, \mathsf{h}(n, k))$

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Definition (Action-determinism)

There is never two inputs (resp. outputs) in parallel on the same channel.

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Solution: annotate processes & actions with info. about process structure.

Lemma

Two action-deterministic processes are trace equivalent iff they can execute the same annotated traces, resulting in statically equivalent configurations.

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Corollary

Regular and compressed trace equiv. coincide for action-det. processes.

Full POR technique

Reduced strategy further constrains compressed executions, only allowing lexicographically minimal representatives of each partial order.

Data dependencies now taken into account.

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Verification algorithms rely on symbolic semantics and constraint solving.

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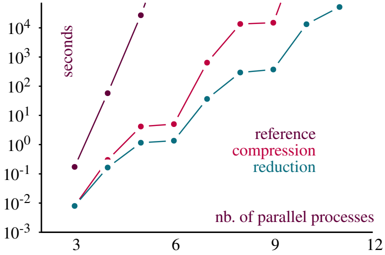

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Conclusion

Success

Our techniques are used in all relevant tools:

- SPEC and Apte [B., Delaune & Hirschi, 2014, 2015 & 2017]
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Further work on symmetry reductions [Cheval et al., 2019].

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Discussion

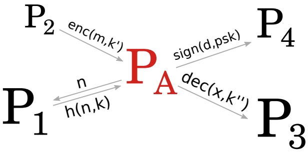
- Soundness result applies to LTS without internal communication.
  Holds for a reasonable subclass of action-deterministic processes; status yet unknown for standard assumption.
- More general technique [B., Delaune & Hirschi, 2018]
  builds on standard POR concepts but yields mixed results so far.

Focus 2/2

A Meta-Logic for Proving Protocols in the Computational Model

joint work with Delaune, Jacomme, Koutsos & Moreau

Limitations of the symbolic models



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- A proof holds because some capabilities have *not* been included: implicit assumptions.

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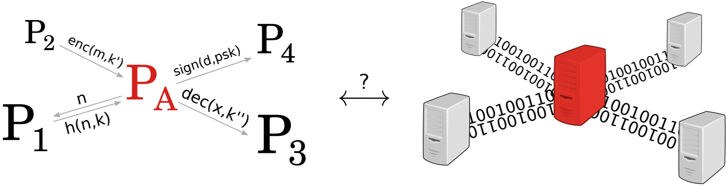

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- Limited support for primitives with algebraic properties, e.g. xor.
- A proof holds because some capabilities have *not* been included: implicit assumptions.
- Symbolic proofs are generally not computationally sound.

First-order logic over computational models

The computationally complete symbolic attacker [Bana & Comon, 2012 & 2014]

Terms interpreted as PPTIME machines

- Names = constants n, k interpreted as uniform samplings
- Primitives = function symbols interpreted as deterministic machines
- Attacker computations = *adversarial* function symbols $\mathbf{att}_i$ interpreted as PPTIME machines

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Indistinguishability

Predicate $\sim$ interpreted as computational indistinguishability.

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$$\mathsf{n} \sim \mathsf{m} \qquad \mathsf{false} \sim^{?} \varphi_{\mathrm{accept}}$$

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Cryptographic assumptions

Restrict interpretations of primitives to satisfy some crypto assumptions.

Example (Collision-resistance axiom)

$$\mathsf{true} \ \sim \ \mathsf{EQ}(\mathsf{h}(u, \mathsf{k}), \mathsf{h}(v, \mathsf{k})) \dot{\Rightarrow} \mathsf{EQ}(u, v)$$

where u and v are ground and k is only used as $\mathsf{h}(\_, \mathsf{k})$

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Restrict interpretations of primitives to satisfy some crypto assumptions.

Example (Collision-resistance axiom)

$$\mathtt{true} \sim \mathsf{EQ}(\mathsf{h}(u, \mathsf{k}), \mathsf{h}(v, \mathsf{k})) \dot{\Rightarrow} \mathsf{EQ}(u, v)$$

where u and v are ground and k is only used as $\mathsf{h}(\_, \mathsf{k})$

Full methodology

Given processes P and P' with bounded traces
and axiom schemes Ax including crypto assumptions,

First-order logic over computational models

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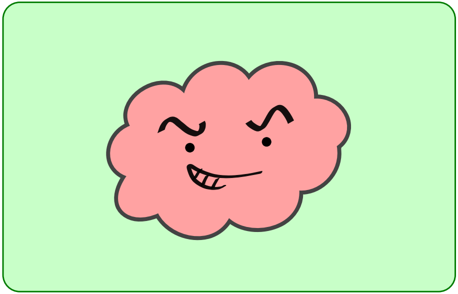
Full methodology

Given processes P and P' with bounded traces
and axiom schemes Ax including crypto assumptions,

- generate for each trace t_i a goal $\varphi_{t_i} := \vec{u}_{t_i} \sim \vec{u'}_{t_i}$;
- verify that $\mathrm{Ax} \models \varphi_{t_i}$ using some proof system for first-order logic.

Contrasting the Dolev-Yao and Bana-Comon approaches



In summary:

- We are still dealing with symbolic expressions.

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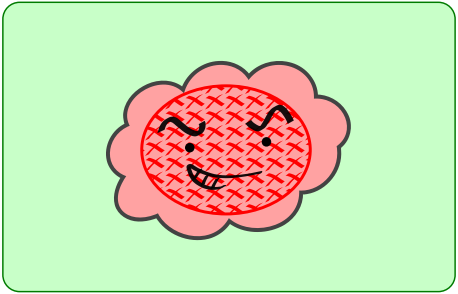

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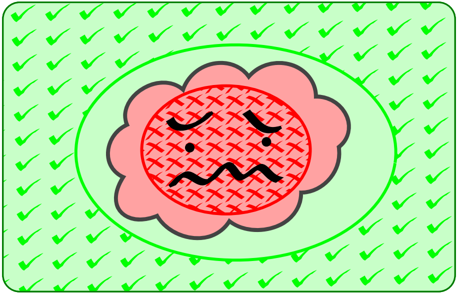

In summary:

- We are still dealing with symbolic expressions.
- Instead of specifying what the attacker can do, specify what is safe.

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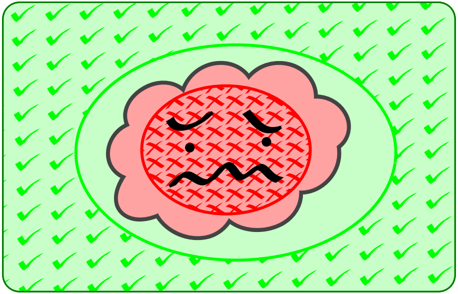

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Example (Information-hiding axiom for xor)

$$\vec{u}, t \oplus \mathsf{n} \sim \vec{u}, \mathsf{m} \quad \text{when} \quad \mathsf{n}, \mathsf{m} \not\sqsubseteq \vec{u}, t \quad \text{and} \quad \mathsf{len}(t) = \mathsf{len}(\mathsf{n})$$

A meta-logic over the Bana-Comon logic

The Bana-Comon approach has some practical limitations:

- So far, automatically verifying $\mathsf{Ax} \models \varphi_t$ remains infeasible.
- The methodology assumes a fixed bound b on protocol traces.

base logic $\quad \varphi_{t_1},\ \varphi_{t_2},\ \ldots \quad + \quad \dfrac{\psi' \quad \psi''}{\psi} \quad = \quad \pi_{t_1},\ \pi_{t_2},\ \ldots$

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$\rightsquigarrow$ Develop a meta-logic

meta-logic $\qquad \Phi$

$$\Downarrow$$

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$\rightsquigarrow$ Develop a meta-logic suitable for interactive proofs, independent of b.

$$
\begin{array}{lccccccc}
\text{meta-logic} & \Phi & + & \dfrac{\Psi' \quad \Psi''}{\Psi} & = & \Pi \\[2ex]
 & \Downarrow & & \Downarrow & & \Downarrow \\[2ex]
\text{base logic} & \varphi_{t_1},\ \varphi_{t_2},\ \ldots & + & \dfrac{\psi' \quad \psi''}{\psi} & = & \pi_{t_1},\ \pi_{t_2},\ \ldots
\end{array}
$$

Meta-logic terms and formulas

Example (Authentication for arbitrary traces of naive protocol)

$$\forall k.\ \ \mathsf{cond}@\mathsf{R}'(k) \Rightarrow\ \exists i,j.\ \ \mathsf{T}(i,j) < \mathsf{R}'(k) \wedge \mathsf{input}@\mathsf{T}(i,j) = \mathsf{output}@\mathsf{R}(k)$$

- $\mathsf{T}(i,j)$ = action of session j of T_i
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Syntax

Meta-formulas Φ feature indices, timestamps, macros, quantifications over timestamp and index variables.

Semantics

Given protocol $\mathcal{P}$ and trace model $\mathbb{T}$, interpret Φ as base logic *term* $(\Phi)^{\mathbb{T}}_{\mathcal{P}}$. Meta-formula Φ is valid wrt. $\mathcal{P}$ when $\mathcal{M} \models (\Phi)^{\mathbb{T}}_{\mathcal{P}} \sim \mathsf{true}$ for all $\mathbb{T}$ and $\mathcal{M}$.

Meta-logic sequents and proof systems

Trace properties

Sequents $\Gamma \vdash_{\mathcal{P}} \Phi$ where Γ is a multiset of meta-formulas, $\mathcal{P}$ a protocol.

- Inference rules of standard classical first-order logic.
- Reasoning about ordering on timestamps, e.g. induction.
- Liftings of Bana-Comon axioms, in particular crypto. assumptions.

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Equivalence properties

Sequents $\ldots \vdash_{\mathcal{P},\mathcal{P}'} \vec{u} \sim \vec{v}$ for protocols $\mathcal{P}$ and $\mathcal{P}'$.

Valid when, for all $\mathbb{T}$, the base logic formula $(\vec{u})^{\mathbb{T}}_{\mathcal{P}} \sim (\vec{v})^{\mathbb{T}}_{\mathcal{P}'}$ is valid.

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- Liftings of Bana-Comon rules + induction +
  ability to leverage trace properties.

The Squirrel prover 

emacs@khaima

File Edit Options Buffers Tools squirrel Proof-General Help

Goal Retract Undo Next Use Goto Qed Home Command Interrupt Restart Help

```
hash h

abstract ok : message
abstract ko : message

name key : index->message
name n : index->message

channel cT
channel cR

process tag(i:index,j:index) =
  in(cR,x); out(cT,h(x,key(i)))

process reader(k:index) =
  out(cR,n(k));
  in(cT,x);
  if exists (i:index), x = h(n(k),key(i)) then
    R': out(cR,ok)
  else
    R'': out(cR,ko)

system ((!_k R: reader(k)) | (!_i !_j T: tag(i,j))).

goal authentication_R1 :
  forall k:index, cond@R'(k) =>
    exists (i,j:index), T(i,j) < R'(k) && input@T(i,j
Proof.
  intros.
  expand cond@R'(k).
  euf M0.
  exists i,j.
Qed.
```

-:--- naive-hash.sp Bot L36 (squirrel script +2 Scripting)

```
[goal> Focused goal (1/1):
System: default/both
----------------------------------------
forall (k:index),
(cond@R'(k) =>
 exists (i,j:index), (T(i,j) < R'(k) && input@T(i,j) = output@R(k)))
```

A proof assistant for our meta-logic

- About 15k lines of OCaml code, Proof General integration.
- Protocol specification in π-calculus style.
- Trace and equivalence properties.
- Basic automated reasoning, tactics and proof-search combinators.

Conclusion

Success

Mechanized proofs for arbitrary traces using Bana-Comon approach:

- Authentication, strong secrecy, unlinkability for various protocols using hashes, signatures, encryptions, xor & Diffie-Hellman

Unlinkability of some RFID protocol with xor could not be proved using Tamarin [B., Delaune & Moreau, 2020].

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Challenges

- Tackle more complex case studies, random oracle model, forward and post-compromise privacy, etc.
  Preliminary successes on protocols with mutable state.
- Improve automation: combining decision procedures à la SMT.
- Provide true unbounded guarantees:
  validity of meta-logic formulas only means security for each trace.

Perspectives

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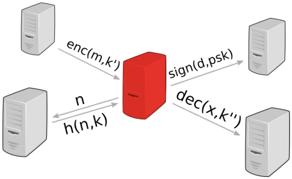
Computational model

- Active and impactful field of research
- Cryptoverif & Easycrypt very successful; Bana-Comon in Coq closely related
- Finding interesting targets for Squirrel, e.g. protocols with mutable state
- Cooperation thanks to standard semantics



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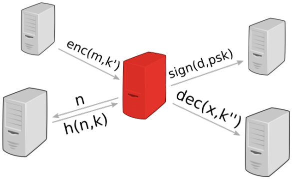

Symbolic models

- Will remain king in automation and attack finding
- A future where partial orders are considered from the beginning: already SAT-Equiv, soon Akiss
- Need to better understand the range of equivalences between trace and diff-equivalences, and the corresponding threat models