A Higher-Order Indistinguishability Logic for Cryptographic Reasoning

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New foundation for the Squirrel prover

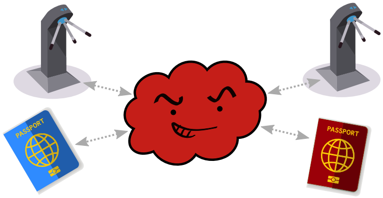
Squirrel is a proof assistant for verifying cryptographic protocols in the computational model.
It is based on the CCSA approach.

Gergei Bana & Hubert Comon. *A Computationally Complete Symbolic Attacker for Equivalence Properties.* CCS 2014.

Outline

- Brief presentation of CCSA base logic, and Squirrel's meta-logic.
- How a higher-order CCSA logic solves several problems.

Example protocol: Basic Hash



Each tag (T_i) owns a secret key k_i.

Reader (R) knows all legitimate keys.

$$\begin{array}{lllll} T_i & \rightarrow & R & : & \langle \mathsf{n}_T, \mathsf{h}(\mathsf{n}_T, k_i) \rangle \\ R & \rightarrow & T_i & : & \mathsf{ok} \end{array}$$

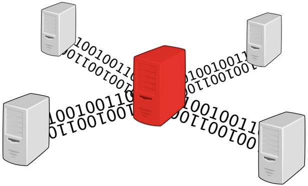
Scenario under consideration:

- Roles R, T_1, ..., T_n with arbitrary number of sessions for each role.
- Attacker can intercept messages, inject new messages.

Security properties:

- Readers must accept only legitimate inputs.
- It must not be possible to track tags.

Cryptographer's model for provable security



Messages	=	bitstrings
Secrets	=	random samplings
Participants	=	PPTIME Turing machines

Rule out unavoidable, unimportant attacks:

- Attacks with negligible probability of success (asymptotically smaller than any η^{-k}).
- Attacks that cannot run in probabilistic polynomial-time.

Cryptographic assumptions

- Keyed hash function may be collision resistant, unforgeable, pseudo-random.
- Encryptions should ensure various forms of indistinguishability.
- Etc.

Outline

Base logic syntax

First-order logic with terms interpreted as probabilistic computations of bitstrings.

- Names n, r, k. . . : special constants represent random samplings.
- Honest function symbols f, enc, ok. . . : represent primitives, public constants, etc.
- Adversarial function symbols $\mathbf{att}_i$ represent attacker computations.

Example

In models where h is an unforgeable hash function,
$\mathbf{att}(\mathsf{h}(\mathsf{true}, \mathsf{k}))$ and $\mathsf{h}(\mathsf{false}, \mathsf{k})$ are unlikely to compute the same bitstring.

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Formulas built from a single predicate $\vec{u} \sim \vec{v}$ expressing indistinguishability.

Example

$\exists x.\ \ (x \sim \mathsf{ok}) \Rightarrow \bot$

Application to Basic Hash protocol

Simple privacy scenario: T_1, T_2 vs. T_1, T'_1.

$$\begin{aligned} \text{Let } u_1, u_2 &= \langle \mathsf{n}_t, \mathsf{h}(\mathsf{n}_t, \mathsf{k}_1)\rangle,\ \langle \mathsf{n}'_t, \mathsf{h}(\mathsf{n}'_t, \boxed{\mathsf{k}_2})\rangle \\ v_1, v_2 &= \langle \mathsf{n}_t, \mathsf{h}(\mathsf{n}_t, \mathsf{k}_1)\rangle,\ \langle \mathsf{n}'_t, \mathsf{h}(\mathsf{n}'_t, \boxed{\mathsf{k}_1})\rangle \end{aligned}$$

Privacy expressed as $u_1, u_2 \sim v_1, v_2$.

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Authentication for T_1, T_2 expressed as $\phi \sim \mathsf{true}$ with ϕ as follows with $input_R = \mathbf{att}(u_1, u_2)$:

$$\begin{aligned} &\big(\mathsf{snd}(input_R) \doteq \mathsf{h}(\mathsf{fst}(input_R), \mathsf{k}_1) \mathbin{\dot\vee} \\ &\ \mathsf{snd}(input_R) \doteq \mathsf{h}(\mathsf{fst}(input_R), \mathsf{k}_2)\big) \\ \dot\Rightarrow\ &\big(input_R \doteq u_1 \mathbin{\dot\vee} input_R \doteq u_2\big) \end{aligned}$$

We assume some builtin connectives with their expected semantics: $\_ \doteq \_$, $\_ \mathbin{\dot\vee} \_$, $\_ \mathbin{\dot\Rightarrow} \_ \ldots$

Semantics of terms

Definition (Semantics in a model $\mathcal{M}$)

For a term t, $[\![t]\!]_{\mathcal{M}}$ is a deterministic polynomial time Turing machine taking as inputs:

- the security parameter η;
- two infinite randomness tapes $\rho = (\rho_h, \rho_a)$ for honest and attacker samplings.

Random samplings can be tracked syntactically:

- Honest randomness only accessed by names.
- Attacker randomness only accessed by $\mathbf{att}_i$ symbols.
- Variables can access anything!

Example

$\Pr[\ [\![\mathsf{n} \doteq t]\!]_{\mathcal{M}}(\eta, \rho) = \mathsf{true}\ ] = 2^{-\eta}$ if t closed, $\mathsf{n} \notin t$

Semantics of formulas

Definition (Computational indistinguishability)

$\mathcal{M} \models \vec{u} \sim \vec{v}$ when, for any polynomial time Turing machine $\mathcal{D}$,

$$|\ \mathsf{Pr}[\mathcal{D}([\![\vec{u}]\!]_{\mathcal{M}}(\eta, \rho_h, \rho_a), \eta, \rho_a)] - \mathsf{Pr}[\mathcal{D}([\![\vec{v}]\!]_{\mathcal{M}}(\eta, \rho_h, \rho_a), \eta, \rho_a)]\ | \text{ is negligible.}$$

The rest is as usual in first-order logic.

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Example

- $u \sim \mathsf{true}$ means that u is true with overwhelming probability.
- $\mathsf{true} \sim \left(t \mathrel{\dot{\neq}} \mathsf{n} \right)$ is valid when t closed and does not contain n.
- $\forall \vec{x}, \vec{y}, \vec{x'}, \vec{y'}. \ (\vec{x}, \vec{y} \sim \vec{x'}, \vec{y'}) \Rightarrow (\vec{x}, \mathsf{f}(\vec{y}) \sim \vec{x'}, \mathsf{f}(\vec{y'}))$ is valid for any function symbol f.

Outline

Basic Hash protocol in the meta-logic

Simple privacy scenario: T_1, T_2 vs. T_1, T_1'.

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Privacy expressed as $u_1, u_2 \sim v_1, v_2$.

Basic Hash protocol in the meta-logic

Privacy expressed as $\text{frame}@\tau \sim_{\mathcal{P},\mathcal{P}'} \text{frame}@\tau$.

- Timestamp τ refers to an arbitrary point in any arbitrary execution trace.
- Macro $\text{frame}@\tau$ stands for the sequence of all protocol outputs before τ.
- Protocol $\mathcal{P}$ = multiple tags playing multiple sessions.
- Protocol $\mathcal{P}'$ = multiple tags playing single sessions.

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Authentication expressed as meta-logic formula:

$$\forall i.\ \ \mathsf{snd}(\mathsf{input}@\tau) = \mathsf{h}(\mathsf{fst}(\mathsf{input}@\tau), \mathsf{k}(i)) \Rightarrow \exists j.\ \ \mathsf{T}(i,j) < \tau\ \wedge\ \mathsf{input}@\tau = \mathsf{output}@\mathsf{T}(i,j)$$

- Macro $\mathsf{input}@\tau$ defined as $\mathbf{att}(\mathsf{frame}@\tau)$. Macro $\mathsf{output}@\tau$ defined depending on τ.
- Indices i, j are elements of an arbitrary finite set.
- Total order $<$ on timestamps corresponds to execution order.

Meta-logic overview

We are now reasoning over all traces (all trace models $\mathbb{T}$)
and all implementations of functions (all computational models $\mathcal{M}$).

$$\begin{array}{rcr} \text{Meta-logic term } t \xrightarrow{\mathbb{T}} & \text{base logic term } (t)^{\mathbb{T}}_{\mathcal{P}} \xrightarrow{\mathcal{M}} & \text{PPTM returning bitstring} \\ \text{Local meta-logic formula } \phi \xrightarrow{\mathbb{T}} & \text{base logic term } (\phi)^{\mathbb{T}}_{\mathcal{P}} \xrightarrow{\mathcal{M}} & \text{PPTM returning boolean} \\ \text{Global meta-logic formula } \Phi \xrightarrow{\mathbb{T}} & \text{base logic formula } (\Phi)^{\mathbb{T}} \xrightarrow{\mathcal{M}} & \text{SAT/UNSAT} \end{array}$$

Important points

- Local formula quantifications only over indices and timestamps: translated to finite disjunctions and conjunctions once $\mathbb{T}$ fixed.
- Translation of macros depends on $\mathcal{P}$: definition of logic tied to a class of protocols.

Proving meta-logic formulas

Custom proof system:

- hides probabilistic reasoning when proving local formulas;
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Freshness in base logic

$(t \dot{\neq} \mathsf{n}) \sim \mathsf{true}$ is valid for any closed term t that doesn't contain n.

Freshness in meta-logic

Local meta-logic formula $\phi \Rightarrow t \neq \mathsf{n}(i)$ is valid if
for any $\mathbb{T}$ such that $(\phi)^{\mathbb{T}} \neq \mathsf{false}$, $(\mathsf{n}(i))^{\mathbb{T}}$ does not occur in $(t)^{\mathbb{T}}$.

Example (Basic Hash)

$\forall i, j, \tau.\ \ \tau < \mathsf{T}(i,j) \Rightarrow \mathsf{n}_t(i,j) \neq \mathsf{fst}(\mathsf{input}@\tau)$

Outline

From machines to random variables

Terms of the old base logic:
probabilistic polynomial-time machines.

$$[\![t]\!]_{\mathcal{M}}(\eta,\rho) \in \{0,1\}^*$$

Terms of the new logic:
η-indexed families of random variables.

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Non-PTIME function symbols

E.g. talking about discrete logarithm is useful in specifications and proofs.

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Arbitrary quantifiers

Easily defined since terms need not be computable:

$$[\![\forall x : \alpha.\ \phi]\!]^{\sigma}_{\mathcal{M}}(\eta, \rho) = \mathsf{true} \quad \text{when} \quad [\![\phi]\!]^{\sigma, x \mapsto a}_{\mathcal{M}}(\eta, \rho) = \mathsf{true} \text{ for all } a \in [\![\alpha]\!]_{\mathcal{M}}.$$

Going higher-order

Quantifications allow to express reasoning steps internally:

$$\forall x, y : \text{message}. \qquad \text{fst}\ \langle x, y\rangle = x$$

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$$\forall p : \text{timestamp} \to \text{bool}. \quad \big(\forall \tau.\ (\forall \tau'.\ \ \tau' < \tau \Rightarrow p\ \tau') \Rightarrow p\ \tau\big) \Rightarrow \forall \tau.\ \ p\ \tau$$

$$\forall p : \alpha \to \text{bool}. \quad \big(\text{not}\ (\exists a : \alpha.\ \ p\ a)\big) = \big(\forall a : \alpha.\ \text{not}\ (p\ a)\big)$$

Generalizing indistinguishability

Global formulas are still first-order formulas, but over higher-order terms.
Arbitrary predicates can be considered:

- $\vec{u} \sim \vec{v}$: distinguisher still polynomial time.
- $\mathsf{adv}(t)$: t can be computed in polynomial time without access to ρ_h.
- ...

Higher-order indistinguishability allows to decompose old axioms:

$$\forall \vec{x}, \vec{y}, \vec{x'}, \vec{y'}. \qquad \mathsf{adv}(\mathsf{f}) \Rightarrow (\vec{x}, \vec{y} \sim \vec{x'}, \vec{y'}) \Rightarrow (\vec{x}, \mathsf{f}(\vec{y}) \sim \vec{x'}, \mathsf{f}(\vec{y'}))$$

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$$\forall f, x, y, f', x', y'. \quad (x, f, y \sim x', f', y') \Rightarrow (x, f\ y \sim x', f'\ y')$$

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Recursive definitions

Equip our λ-calculus with recursive definitions to recover the macros of the old meta-logic.

Example

$\mathsf{frame}_{\mathcal{P}}@\tau \stackrel{def}{=} \mathsf{if}\ \tau = \mathsf{init}\ \mathsf{then}\ \mathsf{empty}\ \mathsf{else}\ \langle \mathsf{output}_{\mathcal{P}}@\tau, \mathsf{frame}_{\mathcal{P}}@(\mathsf{pred}\ \tau)\rangle$

$\mathsf{output}_{\mathcal{P}}@\tau \stackrel{def}{=} \mathsf{match}\ \tau\ \mathsf{with}\ \mathsf{T}(i,j) \mapsto \langle \mathsf{n}_t(i,j), \mathsf{h}(\mathsf{n}_t(i,j), \mathsf{k}(i))\rangle \mid \_ \mapsto \mathsf{default}$

Benefits

- Same term can mix macros for different protocols.
- Same logic can deal with different classes of protocols, different attacker models. . .

Advanced axioms

Axioms cannot be derived as liftings of base logic axioms.

- Recover (adaptations of) previous axioms, justifying them from first principles.
- Opportunity to generalize!

Freshness in higher-order logic

$\phi \Rightarrow t \neq (\mathsf{n}\ i)$ if,

for any $\mathcal{M}, \eta, \rho$ such that $[\![\phi]\!]_{\mathcal{M}}(\eta, \rho) = \mathsf{true}$, $[\![t]\!]_{\mathcal{M}}(\eta, \rho)$ does not sample n at $[\![i]\!]_{\mathcal{M}}(\eta, \rho)$.

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The same can be done for cryptographic axioms, e.g. IND-CCA.

Example

Assume A inputs x and sends back n only if $x = \mathsf{ok}$.

We are now able to prove $\mathsf{input@A} \neq \mathsf{ok} \Rightarrow \mathsf{n} \neq \mathbf{att}(\mathsf{output@A})$.

Relating global and local quantifiers

Theorem

For any local formula ϕ we have:

$$\mathcal{M}, \sigma \models \forall (x : \tau).[\phi] \qquad \textit{iff} \qquad \mathcal{M}, \sigma \models [\dot{\forall} (x : \tau).\phi]$$

- On the left: for any random variable over $[\![\tau]\!]$, ϕ holds with overwhelming probability.
- On the right: it is overwhelmingly true that ϕ holds for any value in $[\![\tau]\!]$.
- Right $\Rightarrow$ left immediate, other direction requires carefulness with probability theory.

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Same result holds for existential quantifier.

Refined version available when types and random variables are constant,
which is the case when we mirror meta-logic reasoning over timestamps and indices.

Conclusion

Theory

- General foundation for Squirrel.
- Conceptually simpler: no more meta-logic, not tied to fixed notion of protocol.
- Complete proof system hiding much of the complexity.

Practice

- Current version of Squirrel implements fragment of new higher-order logic.
- All past case studies carry over.
- New: examples involving corruptions, generic hybrid argument.

Learn more on our website: tech report, tutorials and interactive examples.

`https://squirrel-prover.github.io/`