Distance Bounding Protocols: Computational vs. Symbolic Models

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(joint work with S. Mauw, Z. Smith and R. Trujillo)

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Outline

1. Introduction
2. Probabilistic model based on automata
3. Symbolic model with time and location
4. Symbolic model based on causality
5. Conclusion and Future

Outline

This talk's content

- S. Mauw, J. Toro-Pozo, R. Trujillo-Rasua, "A Class of Precomputation-Based Distance-Bounding Protocols", in *EuroS&P'16*, 2016, pp. 97–111.
- S. Mauw, J. Toro-Pozo, R. Trujillo-Rasua, "Optimality Results on the Security of Lookup-Based Protocols", in *RFIDSec'16*, 2016, pp. 137–150.
- S. Mauw, Z. Smith, J. Toro-Pozo, R. Trujillo-Rasua, "Distance Bounding Protocols: Verification without Time and Location", in *S&P'18*, 2018.

Problem: Relay attack

Source: securepositioning.com

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Definition

A *relay attack* is a man-in-the-middle attack in which an attacker relays verbatim a message from the sender to a valid receiver.

Solution: Distance-bounding protocols

Definition

A *distance-bounding protocol* is an authentication protocol that checks that the distance between verifier and prover is below a given threshold.

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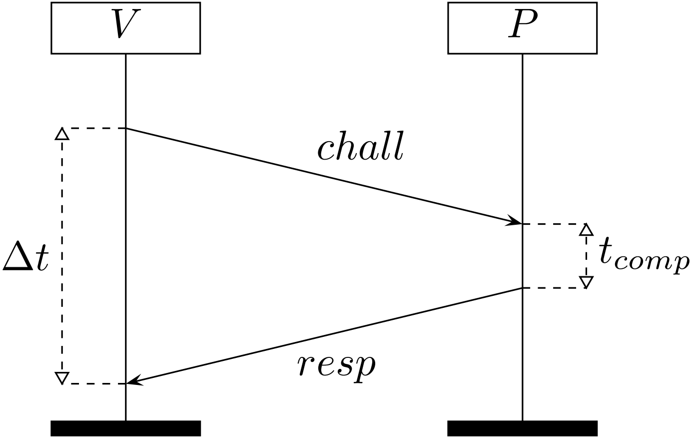
How to measure (or bound) distance?

- Verifier sends a challenge.
- Prover provides corresponding response.
- Verifier measures the round-trip-time.

A challenge/response round



$$dist(V, P) = \frac{1}{2} \cdot c \cdot (\Delta t - t_{comp}) \leq \frac{1}{2} \cdot c \cdot \Delta t$$

Outline

Lookup Protocols: Motivation

- To obtain an accurate upper-bound on the distance, the computational time on the prover's side must be as short as possible.
- Solution: Pre-computing the possible responses and store them in a constant-time-access structure, such as a lookup-table.
- Protocols with a final crypto-verification phase could be outperformed by a precomputation-based protocol with more rounds, with no increase of the computational cost: $\forall n, \exists m\colon \left(\frac{1}{2}\right)^n > \left(\frac{3}{4}\right)^m$.
- Partial information can be given if the protocol gets interrupted before finishing.

Lookup Protocols

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1. In the fast phase, the responses to the challenges are the result of lookup operations from a table.

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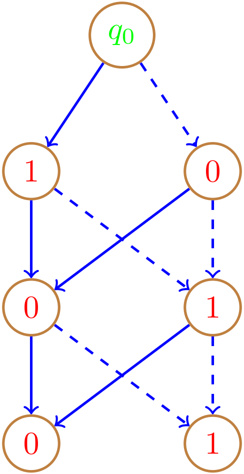
1. In the fast phase, the responses to the challenges are the result of lookup operations from a table.
2. either do NOT have a final verification phase at all or
3. having replied correctly and on time to all challenges is SUFFICIENT to pass the protocol (do not have any crypto-based verification mechanism such as opening commits, keyed hash functions, signatures...).

Protocol Representation: State-Labeled DFA

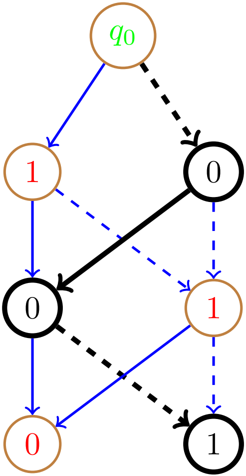


$$A = (\Sigma, \Gamma, Q, q_0, \delta, \ell)$$

Σ is the set of input symbols
Γ is the set of output symbols
Q is the set of states
$q_0 \in Q$ is the initial state
$\delta \colon Q \times \Sigma \to Q$ is the transition function
$\ell \colon Q \to \Gamma$ is the state labeling function

Protocol Representation

State-Labeled DFA



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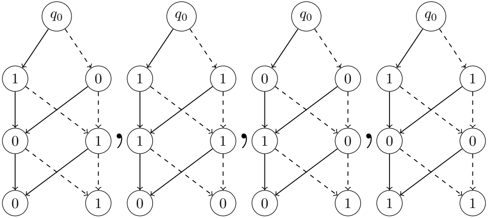
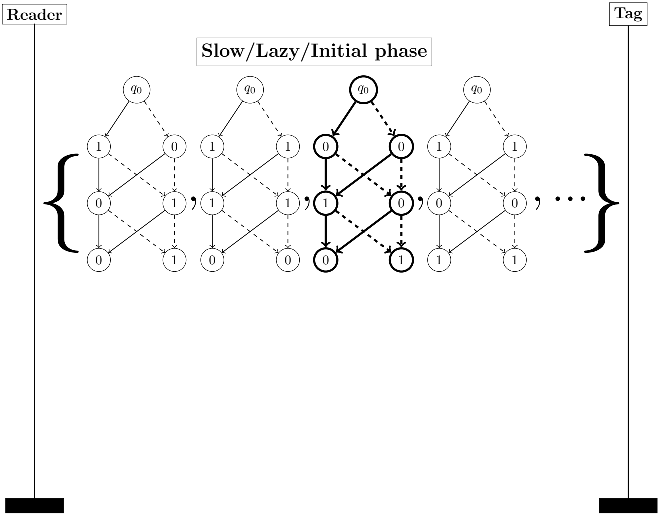
$$\Omega_A\,(101) = 001$$

Protocol Representation

$P = \{$  $, \cdots \}$

Protocol Execution



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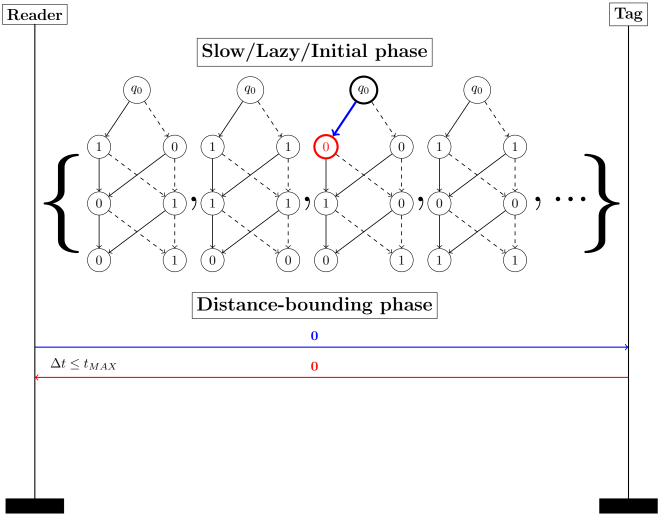

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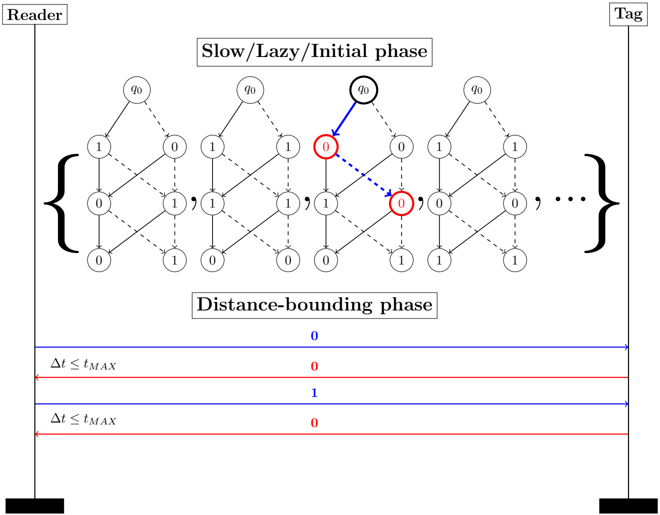

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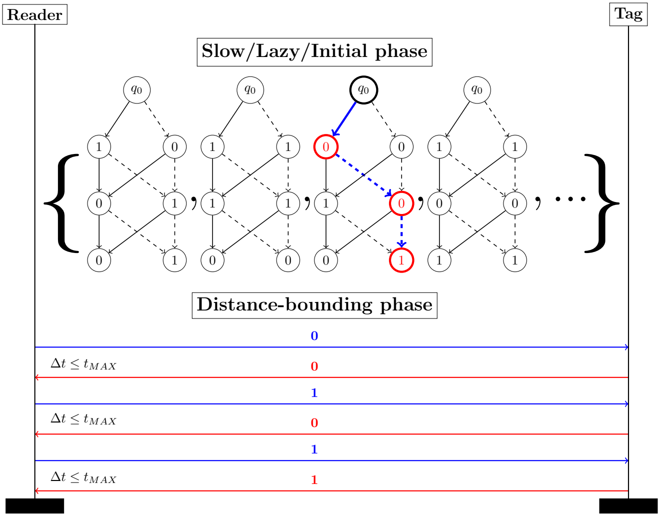
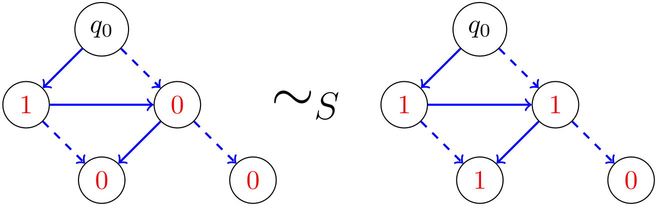


Automata Equivalence Relations

- State-label-insensitive relation ($\sim_S$)

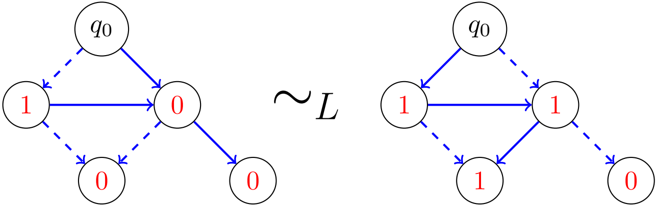
$$(\Sigma, \Gamma, Q, q_0, \delta, \ell) \sim_S (\Sigma, \Gamma, Q, q_0, \delta, \ell')$$



- Label-insensitive relation ($\sim_L$)

$$(\Sigma, \Gamma, Q, q_0, \delta, \ell) \sim_L (\Sigma, \Gamma, Q, q_0, \delta', \ell')$$

such that $\forall q \in Q : \{\delta(q,c) \mid c \in \Sigma\} = \{\delta'(q,c) \mid c \in \Sigma\}$.



Consistency and Closeness

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- The closure of P w.r.t $\sim_R$, denoted by P^R, is the minimal superset of P that is closed under $\sim_R$.

Some formulas

Given a layered automaton A:

$$mafia\left(\{A\}^S\right) = \frac{1}{|\Sigma|^n \cdot |\Gamma|^n} \max_{x \in \Sigma^n} \left\{ \sum_{y \in \Sigma^n} |\Gamma|^{collisions_A(x,y)} \right\}$$

$$mafia\left(\{A\}^L\right) = \frac{1}{|\Sigma|^{2n} \cdot |\Gamma|^n} \sum_{x,y \in \Sigma^n} |\Gamma|^{collisions_A(x,y)}$$

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Trivially, $mafia\left(\{A\}^S\right) \geq mafia\left(\{A\}^L\right)$
because $\max\{u_i\} \geq \frac{1}{N}(u_1 + \cdots + u_N)$

Main theorem

Theorem

For any layered lookup protocol P *the following holds:*

$$mafia(P) \geq mafia\left(P^S\right) \geq mafia\left(\{A\}^L\right) \geq mafia(Tree),$$

for some $A \in P$.

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For any layered lookup protocol P the following holds:

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for some $A \in P$.

Conclusions

- We have formalized relevant structural properties of lookup protocols that have been used in a rather intuitive way.
- We provided simple formulas for computing mafia success probability for all but one lookup protocols.
- We have addressed (partially) the security-memory trade-off problem in layered protocols.

Outline

The basis of our work

Model based on time and location

- P. Schaller, B. Schmidt, D. A. Basin, and S. Capkun, "Modeling and verifying physical properties of security protocols for wireless networks," in *CSF'09*, 2009, pp. 109–123.
- D. A. Basin, S. Capkun, P. Schaller, and B. Schmidt, "Let's get physical: Models and methods for real-world security protocols," in *TPHOLs'09*, 2009, pp. 1–22.
- C. J. F. Cremers, K. B. Rasmussen, B. Schmidt, and S. Capkun, "Distance hijacking attacks on distance bounding protocols," in *S&P'12*, 2012, pp. 113–127.

Specification and Execution

- **Agents**: the set Agent, partitioned into $\{\mathit{Honest}, \mathit{Dishonest}\}$.

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- **Specification**: a set of rules defining the actions of *honest* agents.
- And some other stuff such as **message deduction**.

Specification and Execution

- **Trace**: a sequence $(t_1, e_1) \cdots (t_n, e_n)$ with $t_i \in \mathbb{R}, e_i \in Ev$.

$$\alpha = (1.3, send_{Alice}(m)) \cdot (3, recv_{Bob}(m)) \cdot (5, send_{Bob}(h(m)))$$

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$$dist(Alice, Bob) \leq c \cdot (3 - 1.3)$$

Specification and Execution

- **Specification**: a set of rules defining the actions of *honest* agents.

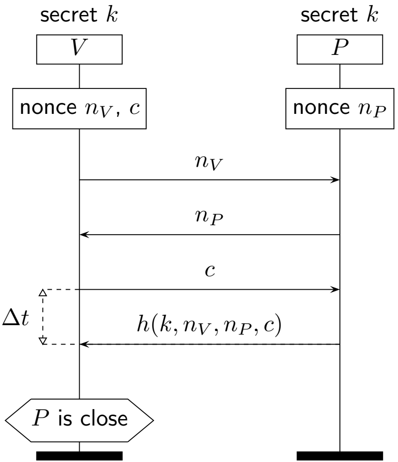
  $\mathcal{P} = \{R_1 \ldots, R_n\}$ where the R_i's have the form:

$$\frac{t \geq maxt(\alpha) \quad A \in Honest \quad cond_1 \quad \cdots \quad cond_n}{(\alpha, (t, e)) \in R_i}$$

  In words: if conditions $cond_j$ are met, then the agent A can execute the event e at time t.

Example

Hancke and Kuhn's 2005



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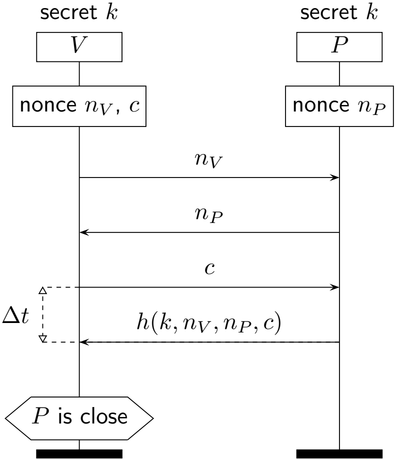


$$\mathcal{P} = \{R_1, R_2, R_3, R_4, R_5\}$$

$$\frac{V \in Hnst \quad t \geq maxt(\alpha) \quad fresh(n_V, \alpha)}{(\alpha, (t, send_V(n_V))) \in R_1}$$

$$\frac{P \in Hnst \quad t \geq maxt(\alpha) \quad (t', recv_P(n_V)) \in \alpha \quad fresh(n_P, \alpha)}{(\alpha, (t, send_P(n_P))) \in R_2}$$

$$\frac{V \in Hnst \quad t \geq maxt(\alpha) \quad (t', send_V(n_V)) \in \alpha \quad (t'', recv_V(n_P)) \in \alpha \quad fresh(c, \alpha)}{(\alpha, (t, send_V(c))) \in R_3}$$

$$\frac{P \in Hnst \quad t \geq maxt(\alpha) \quad (t', recv_P(n_V)) \in \alpha \quad (t'', send_P(n_P)) \in \alpha \quad (t''', recv_P(c)) \in \alpha \quad r = h(sh(V, P), n_V, n_P, c)}{(\alpha, (t, send_P(r))) \in R_4}$$

$$\frac{V \in Hnst \quad t \geq maxt(\alpha) \quad (t', send_V(n_V)) \in \alpha \quad (t'', recv_V(n_P)) \in \alpha \quad u = send_V(c) \quad v = recv_V(r) \quad (tu, u) \in \alpha \quad (tv, v) \in \alpha \quad r = h(sh(V, P), n_V, n_P, c)}{(\alpha, (t, claim_V(P, u, v))) \in R_5}$$

Specification and Execution

- And some other stuff such as **message deduction**.

  The set *infer* (A, α) contains all messages that A can infer from α:

$$\frac{m \in init\,(A)}{m \in infer\,(A,\alpha)} \qquad \frac{(t, recv_A(m)) \in \alpha}{m \in infer\,(A,\alpha)} \qquad \frac{(m_1, m_2) \in infer\,(A,\alpha)}{m_i \in infer\,(A,\alpha)}$$

$$\frac{\begin{array}{c} m_1 \in infer\,(A,\alpha) \\ m_2 \in infer\,(A,\alpha) \end{array}}{(m_1, m_2) \in infer\,(A,\alpha)} \qquad \frac{\begin{array}{c} m \in infer\,(A,\alpha) \\ f \in Func \setminus \{sk, \_^{-1}, sh\} \end{array}}{f(m) \in infer\,(A,\alpha)}$$

$$\frac{\begin{array}{c} m \in infer\,(A,\alpha) \\ k \in infer\,(A,\alpha) \end{array}}{\{m\}_k \in infer\,(A,\alpha)} \qquad \frac{\begin{array}{c} \{m\}_k \in infer\,(A,\alpha) \\ k^{-1} \in infer\,(A,\alpha) \end{array}}{m \in infer\,(A,\alpha)}$$

Execution model

The set of all valid traces $Tr(\mathcal{P})$ is defined by:

$$\alpha \cdot (t, e) \in Tr(\mathcal{P}) \iff \alpha \in Tr(\mathcal{P}) \land \exists R \in \mathcal{P} \cup \{Int, Net\} \colon (\alpha, (t, e)) \in R$$

where:

$$\frac{I \in Dishonest \quad t \geq maxt(\alpha) \quad m \in infer(I, \alpha)}{(\alpha, (t, send_I(m))) \in Int} \qquad \frac{t \geq maxt(\alpha) \quad (t', send_A(m)) \in \alpha \quad t \geq t' + dist(A, B)/c}{(\alpha, (t, recv_B(m))) \in Net}$$

Secure distance-bounding

Definition

A protocol $\mathcal{P}$ satisfies *secure distance-bounding* if and only if:

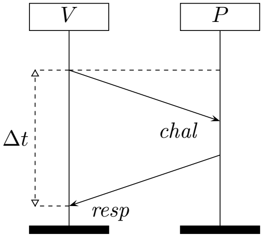
$$\forall \alpha \in Tr\left(\mathcal{P}\right), (t, claim_V(P, u, v)) \in \alpha :$$
$$\exists (tu, u), (tv, v) \in \alpha, P' \approx P : dist(V, P') \leq \frac{c \cdot (tv - tu)}{2}$$

where $\approx = \{(A, A) \mid A \in Honest\} \cup Dishonest \times Dishonest$.

Implemented in Isabelle/HOL, available at
http://www.infsec.ethz.ch/research/software/protoveriphy.html

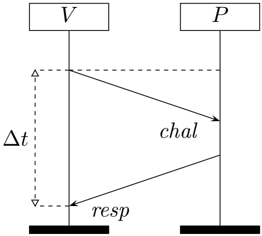
Outline

Three timing scenarios



Correct timing

Three timing scenarios



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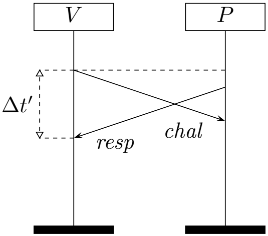
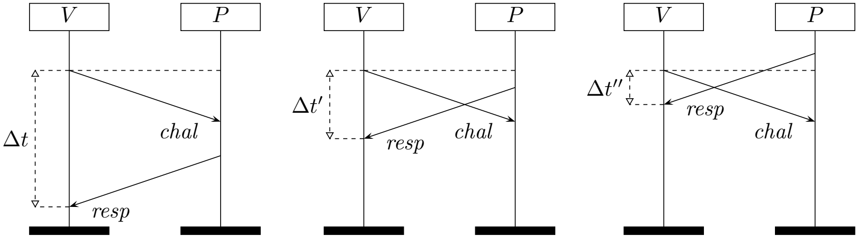


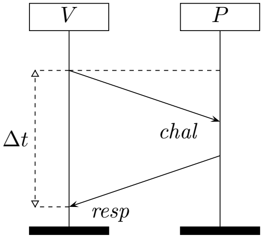
Early timing

Three timing scenarios

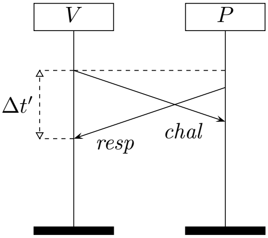


Correct timing Early timing Very early timing

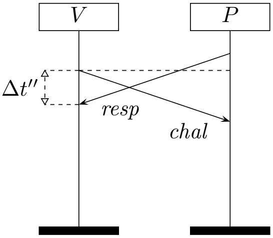
Three timing scenarios



Correct timing



Early timing



Very early timing

Claim: If there is an early timing, then there is a very early timing.

Main theorem

Theorem

A protocol $\mathcal{P}$ satisfies secure distance-bounding if and only if:

$$\forall \sigma \in \pi(Tr(\mathcal{P})), claim_V(P, u, v) \in \sigma:$$
$$\exists u \cdot e \cdot v \sqsubseteq \sigma: actor(e) \approx P$$

where $\pi(T) = \{e_1 \cdots e_n \mid (t_1, e_1) \cdots (t_n, e_n) \in T\}$.

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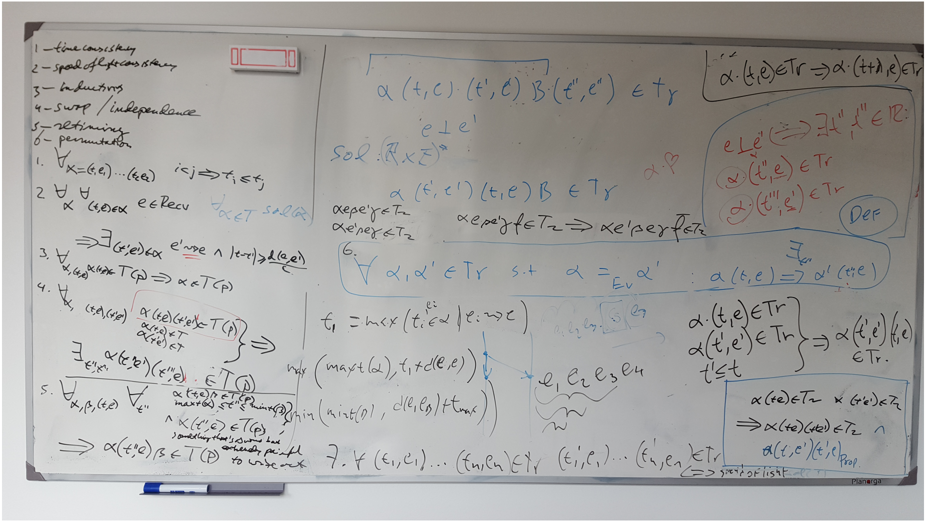
Verified 12+ protocols in Tamarin, available at
http://satoss.uni.lu/software/DBVerify/



1 – time consistency
2 – speed of light consistency
3 – inductions
4 – swap / independence
5 – retiming
6 – permutation
Def

Proof idea

Characterise timed-traces model

For every $(t_1, e_1) \cdots (t_n, e_n) \in Tr(\mathcal{P})$:

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1. $t_1 \leq \cdots \leq t_n$
2. $t_n = recv_A(m)$ implies $i < n$ exists such that $e_i = send_B(m)$ and $t_n - t_i \geq dist(A, B)/c$

Proof idea

Characterise timed-traces model

For every $(t_1, e_1) \cdots (t_n, e_n) \in Tr(\mathcal{P})$:

1. $t_1 \leq \cdots \leq t_n$
2. $t_n = recv_A(m)$ implies $i < n$ exists such that $e_i = send_B(m)$ and $t_n - t_i \geq dist(A, B)/c$
3. if $(t'_1, e_1) \cdots (t'_n, e_n)$ satisfies (1) and (2) then $(t'_1, e_1) \cdots (t'_n, e_n) \in Tr(\mathcal{P})$

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2. $e_n \notin Recv$ and $actor(e_{n-1}) \neq actor(e_n)$ then $e_1 \cdots e_{n-2} \cdot e_n \in \pi(Tr(\mathcal{P}))$

Proof idea

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1. $e_1 \cdots e_{n-1} \in \pi(Tr(\mathcal{P}))$
2. $e_n \notin Recv$ and $actor(e_{n-1}) \neq actor(e_n)$ then $e_1 \cdots e_{n-2} \cdot e_n \in \pi(Tr(\mathcal{P}))$
3. $e_n = send_A(m)$ implies $e_1 \cdots e_n \cdot recv_B(m) \in \pi(Tr(\mathcal{P}))$

Proof idea

Characterise timed-traces model

For every $e_1 \cdots e_n \in \pi(Tr(\mathcal{P}))$:

1. $e_1 \cdots e_{n-1} \in \pi(Tr(\mathcal{P}))$
2. $e_n \notin Recv$ and $actor(e_{n-1}) \neq actor(e_n)$ then $e_1 \cdots e_{n-2} \cdot e_n \in \pi(Tr(\mathcal{P}))$
3. $e_n = send_A(m)$ implies $e_1 \cdots e_n \cdot recv_B(m) \in \pi(Tr(\mathcal{P}))$
4. $\forall A, B \in Honest^2 \cup Dishonest^2$ it holds that $(e_1 \cdots e_n)[A \mapsto B] \in \pi(Tr(\mathcal{P}))$

The Tamarin dbsec lemma

```
lemma dbsec:
"
All P V m n #t. (
VerifierComplete(P, V, m, n)@t ) ==>
(
  Ex #tc.
    Corrupt(V)@tc
)|(
  Ex #t1 #t2 #t3.
    StartFastPhase(V, m)@t1 &
    Action(P)@t2 &
    EndFastPhase(V, m)@t3 &
    (#t1 < #t2) &
    (#t2 < #t3) &
    ( (#t3 < #t ) | (#t3 = #t) )
)|(
  Ex CAgent #t4 #t5 #t6 #t7.
    StartFastPhase(V, m)@t5 &
    EndFastPhase(V, m)@t7 &
    Corrupted(P, V)@t4 &
    CAction(CAgent)@t6 &
    (#t5 < #t6)&
    (#t6 < #t7)&
    ( (#t7 < #t) | (#t7 = #t) )
)
"
```

Verification in Tamarin

Protocol	Satisfies `dbsec`?	Attack found
BC-Signature	No	DH
BC-FiatShamir	No	DH, DF
BC-Schnorr	No	DH, DF
CRCS	No	DH
Meadows et al.	No	DH
Tree-based	Yes	-
Poulidor	Yes	-
Hancke and Kuhn	Yes	-
Uniform	Yes	-
Kim and Avoine	Yes	-
Munilla et al.	Yes	-
Reid et al.	Yes	-
Swiss-Knife	Yes	-
TREAD-PK	No	MF, DH
TREAD-SH	No	DH
PaySafe	No	DF, DH

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What we achieved

- Proved that secure distance-bounding can be formulated through causality.
- Provided a fully-automatic verification framework for DB protocols. (simply specify the protocol and click on "verify `dbsec` lemma").
- Provided computer-verifiable (in)security proofs for a number of state-of-the-art protocols.
- Identified *unreported* vulnerabilities in two published protocols: PaySafe (FC'15) and TREAD (AsiaCCS'17).

Outline

Probabilistic vs. Symbolic

- Where probabilistic models win:
  - More precise results - there's an attach that succeeds w/ prob. p
  - Arithmetic properties can be fairly-well modeled
- Where symbolic models win:
  - No need to consider each attack individually
  - Automated verification - Tamarin, ProVerif, Scyther, Isabelle
  - Computer-verifiable proofs of (in)security

Future

- Terrorist fraud?
  Requires fancy techniques for corruption modeling.

Future

- Terrorist fraud?
  Requires fancy techniques for corruption modeling.

- Automatic probabilistic analysis?
  Seems hard.

Q & A

Thank you

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