Using Interpolation for the Verification of Security Protocols

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Outline

1. The idea
2. SPiM
   - Method description
   - Example
3. SPiM Java prototype
4. Future work

The idea behind SPiM

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Interpolation

- Successfully applied in formal methods for model checking and test-case generation for sequential programs

Security protocols

- Unsuitable to the direct application of such methods:
  - sequential programs only
  - no intruder logic

The idea behind SPiM

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Security protocols

- Unsuitable to the direct application of such methods:
  - sequential programs only
  - no intruder logic

SPiM (Security Protocol interpolation Method)

- Given a formal protocol specification, it combines
  - Craig interpolation,
  - symbolic execution,
  - standard Dolev-Yao intruder model

  to search for goals (i.e., possible attacks on the protocol)
- **Interpolants**: generated as a response to search failure in order to prune possible useless traces and speed up exploration

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General overview of SPiM

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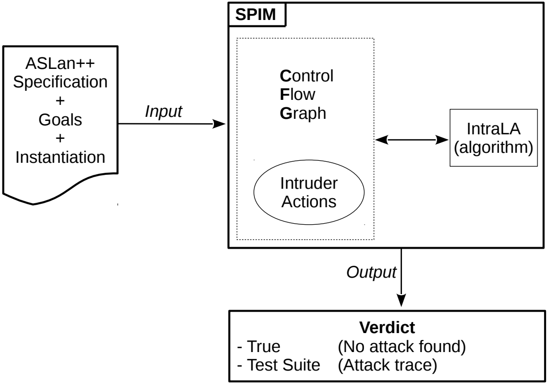
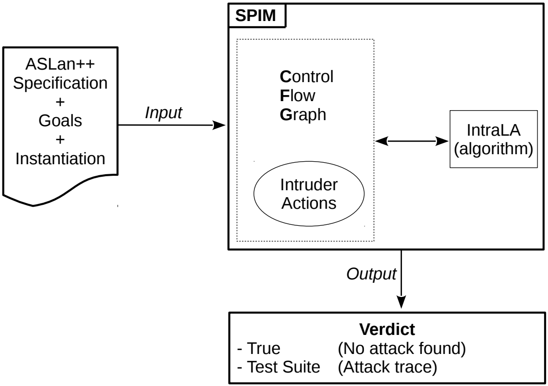


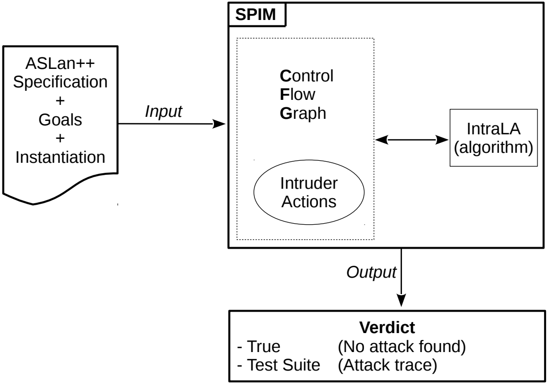
Starts from a specification of security protocol and property, and a scenario

General overview of SPiM



Creates and symbolically executes a sequential program (**control flow graph**) searching for set of goals (i.e., attacks)

General overview of SPiM



When a goal is reached

extracts attack trace (test case) from set of constraints produced in execution path

General overview of SPiM

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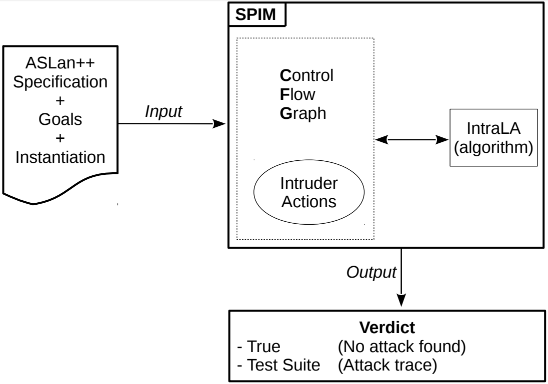

When search fails to reach a goal

starts backtrack phase, during which nodes of graph are annotated (à la McMillan) with formulas obtained by using Craig interpolation

Interpolants: generated as a response to search failure in order to prune possible useless traces and speed up exploration

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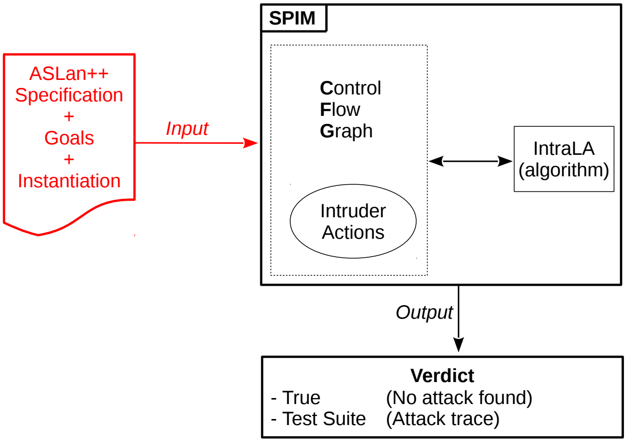
Input


ASLan++
Specification
+
Goals
+
Instantiation
Input
SPIM
Control
Flow
Graph
Intruder
Actions
IntraLA
(algorithm)
Output
Verdict
- True (No attack found)
- Test Suite (Attack trace)

An example

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Needham-Schroeder Public Key (NSPK) protocol

$$A \rightarrow B \quad : \quad \{N_A, A\}_{pk(B)}$$
$$B \rightarrow A \quad : \quad \{N_A, N_B\}_{pk(A)}$$
$$A \rightarrow B \quad : \quad \{N_B\}_{pk(B)}$$

Man-in-the-middle attack

$$A \rightarrow i \quad : \quad \{N_A, A\}_{pk(i)}$$
$$i(A) \rightarrow B \quad : \quad \{N_A, A\}_{pk(B)}$$
$$B \rightarrow i(A) \quad : \quad \{N_A, N_B\}_{pk(A)}$$
$$i \rightarrow A \quad : \quad \{N_A, N_B\}_{pk(A)}$$
$$A \rightarrow i \quad : \quad \{N_B\}_{pk(i)}$$
$$i(A) \rightarrow B \quad : \quad \{N_B\}_{pk(B)}$$

An example

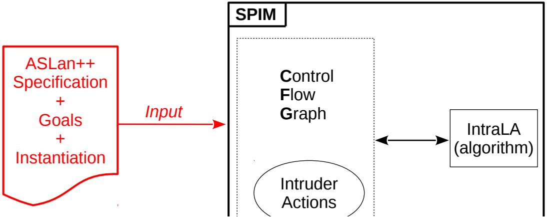
Needham-Schroeder with Lowe's fix (NSL) protocol

$$A \rightarrow B \quad : \quad \{N_A, A\}_{pk(B)}$$
$$B \rightarrow A \quad : \quad \{N_A, N_B, B\}_{pk(A)}$$
$$A \rightarrow B \quad : \quad \{N_B\}_{pk(B)}$$

Man-in-the-middle attack

Attack does not work anymore (other attacks do).

Input



ASLan++ NSL Code example

```
Alice(Actor,B:agent){

 Na:=fresh();
 Actor->B:{Actor.Na}_pk(B);
 B->Actor:{Na.?Nb.B}_pk(Actor);
 Actor->B:{Nb}_pk(B);

}
```

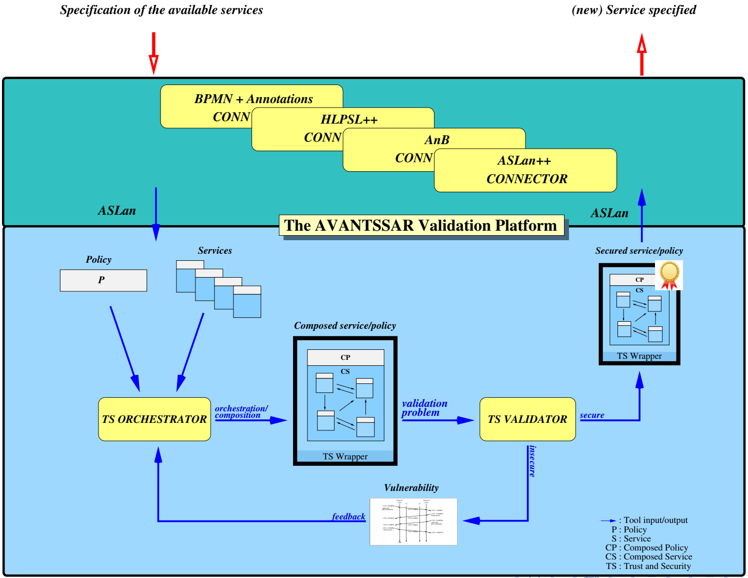
```
Bob(Actor,A:agent){

 ?->Actor:{?A.?Na}_pk(Actor);
 Nb:=fresh();
 Actor->A:{Na.Nb.B}_pk(A);
 A->Actor:{Nb}_pk(Actor);

}
```

Goal:
Bob authenticates Alice

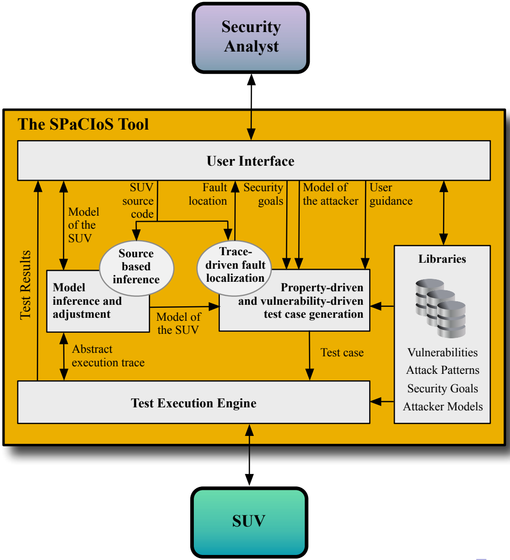
Instantiation:

	Alice	Bob
(1)	a	i
(2)	i	b

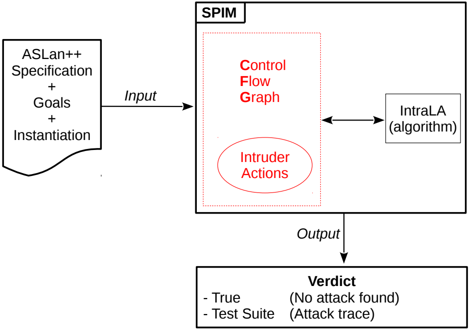
The AVANTSSAR Platform



The SPaCIoS Tool



Control Flow Graph and Intruder Actions



- IntraLA algorithm designed for sequential programs

  (K. McMillan. *Lazy annotation for program testing and verification*. CAV'10)

- To apply (a modified version of) IntraLA to security protocols, we define a translation of a specification of a protocol P for a given scenario into a sequential non-deterministic program

From parallel to sequential

$Alice := a, Bob := i$

```
1.1)  Alice.Actor := a;
1.2)  Alice.B := Y_1;
1.3)  IK := {a,b,i,pk_a,pk_b,pk_i,pk_i^-1};
1.4)
1.5)  Alice.Na := c_1;
1.6)  IK := IK + {Alice.Na,Alice.Actor}_pk(Alice.B);
1.7)
1.8)  if (IK |- {Alice.Na,?Alice.Nb,Alice.B}_pk(Alice.Actor))
1.9)    then
1.10)     Alice.Nb = Y_2;
1.11)    else
1.12)     end
1.13)
1.14)  IK := IK + {Alice.Nb}_pk(Alice.B);
```

```
Alice(Actor,B:agent){

 Na:=fresh();
 Actor->B:{Actor.Na}_pk(B);
 B->Actor:{Na.?Nb.B}_pk(Actor);
 Actor->B:{Nb}_pk(B);

}

Bob(Actor,A:agent){

 ?->Actor:{?A.?Na}_pk(Actor);
 Nb:=fresh();
 Actor->A:{Na.Nb.B}_pk(A);
 A->Actor:{Nb}_pk(Actor);

}
```

From parallel to sequential

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$Alice := i, Bob := b$

```
Bob.Actor := b;
IK := {a,b,i,pk_a,pk_b,pk_i,pk_i^-1};

if (IK |- {?Bob.Na,?Bob.A}_pk(Bob.Actor))
  then
    Bob.Na = Y_1;
    Bob.A = Y_2;
  else
    end

Bob.Nb := c_1;
IK := IK + {Bob.Na,Bob.Nb,Bob.Actor}_pk(Bob.A);

if (IK |- {Bob.Nb}_pk(Bob.Actor))
  then
    do nothing
  else
    end
```

```
Alice(Actor,B:agent){

 Na:=fresh();
 Actor->B:{Actor.Na}_pk(B);
 B->Actor:{Na.?Nb.B}_pk(Actor);
 Actor->B:{Nb}_pk(B);

}

Bob(Actor,A:agent){

 ?->Actor:{?A.?Na}_pk(Actor);
 Nb:=fresh();
 Actor->A:{Na.Nb.B}_pk(A);
 A->Actor:{Nb}_pk(Actor);

}
```

Control Flow Graph - NSL

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- Combining sessions
- Input variables X_i to switch between sessions

```
1.1)  Alice.Actor := a;
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1.3)  IK := {a,b,i,pk_a,pk_b,pk_i,pk_i^-1};
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 {Alice.Na,?Alice.Nb,Alice.B}_pk(Alice.Actor))
1.9)    then
1.10)      Alice.Nb = Y_2;
1.11)     else
1.12)      end
1.13)
1.14)  IK := IK + {Alice.Nb}_pk(Alice.B);
```
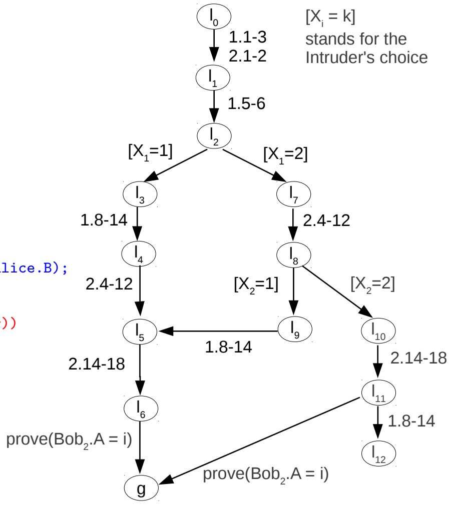



Correctness of the translation

Summing up

- Each ASLan++ statement is translated into a fragment of code in a pseudo programming language (SiL).
- The session interleaving is simulated in SiL by using conditionals with respect to input parameters.
- A (quite standard) notion of equivalence between ASLan++ and SiL states is defined.

Equivalence Theorem

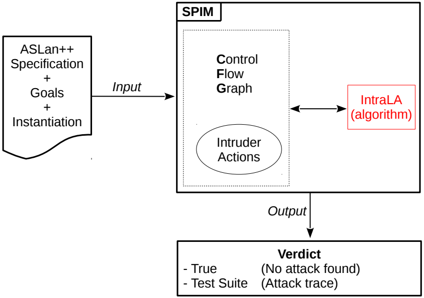
The original ASLan++ specification and its translation into SiL are "**equivalent**".

Proof By standard bisimulation techniques. In particular, we show that for each sequence of steps in ASLan++, there exists a path in the control flow graph of its SiL translation that passes through equivalent states.

Corollary

An **attack state** is found in an ASLan++ specification iff a **goal location** is reachable in its SiL translation.

IntraLA algorithm



Modified IntraLA algorithm executes symbolically a program graph searching for goal locations (attacks)

- If we fail to reach a goal, an **annotation** (condition under which no goal can be reached) produced by Craig interpolation
- Annotation (backtrack) propagated to other nodes to block a later phase of symbolic execution along an uninteresting run (that will not reach goal)

IntraLA [McMillan, CAV2010]

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Init $\dfrac{}{\{l_0, s_0\},\ A_0,\ G_0}$

Decide $\dfrac{Q,\ A,\ G}{Q + (l_2, s_2),\ A,\ G}$

$$q = (l_1, s_1) \in Q$$
$$e = (l_1, a, l_2) \in \Delta$$
$$\neg B(q, A(e))$$
$$s_2 \in SI(a)(s_1)$$
$$\neg B((l_2, s_2), A(l_2))$$

Learn $\dfrac{Q,\ A,\ G}{Q,\ A + e\colon \phi,\ G}$

$$q = (l_1, s_1) \in Q$$
$$e = (l_1, a, l_2) \in \Delta$$
$$B(q, \phi)$$
$$J(e : \phi, A)$$

Conjoin $\dfrac{Q,\ A,\ G}{Q - q,\ A + l\colon \phi,\ G - l}$

$$q = (l, s) \in Q$$
$$\neg B(q, A(l))$$
$$\forall e \in Out(l), e :\ \phi_e \in A \wedge B(q, \phi_e)$$
$$\phi = \wedge\{\phi_e \mid e \in Out(l)\}$$

- Decide: symbolically executes one program action and generates a new **query** (keeps track of which symbolic states still need to be considered) from an existing one
- Learn used to generate annotations in backtrack phase
- Conjoin used to backtrack and merge annotations coming from different branches

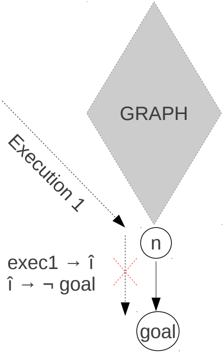
Interpolants as annotations

Craig's Interpolation

In FOL, if $\alpha \wedge \beta$ is inconsistent, then there exists $\hat{\imath}$ s.t.

- α implies $\hat{\imath}$
- $\hat{\imath}$ implies $\neg\beta$
- $\mathcal{L}(\hat{\imath}) \in \mathcal{L}(\alpha) \cap \mathcal{L}(\beta)$

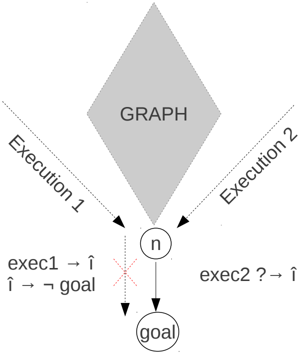
Interpolants as annotations



An example

After an "unsuccessful" execution 1, we calculate an interpolant î as a condition that prevents us to reach the goal, and **annotate** the location *n* with it.

Interpolants as annotations



An example

If execution 2 reaches in the same location a state where î is implied, then we can **ignore** that path (as we know that no goal will ever be reached).

Interpolants as annotations

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- α implies $\hat{\imath}$
- $\hat{\imath}$ implies $\neg\beta$
- $\mathcal{L}(\hat{\imath}) \in \mathcal{L}(\alpha) \cap \mathcal{L}(\beta)$

We can define α and β as follows:

- $\alpha = PC \bigwedge_{v \in Var} v = Env(v)$
- $\beta = Sem(a) \wedge \neg ann'$

where:

- *PC* is a conjunction of *path constraints*
- *Var* is the set of *program variables*
- *Env* is the *environment*
- *Sem*(*a*) is the *semantics* (expressed as a transition formula) of the last *action a*
- *ann* is the current *annotation* of the node

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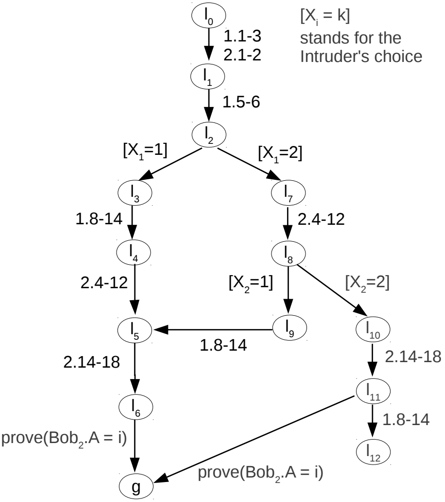
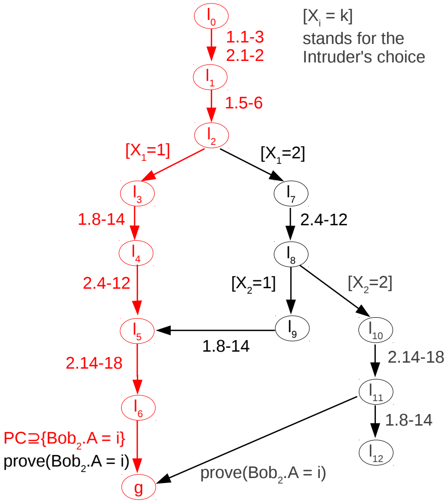
NSL example



[X_i = k] stands for the Intruder's choice

NSL example



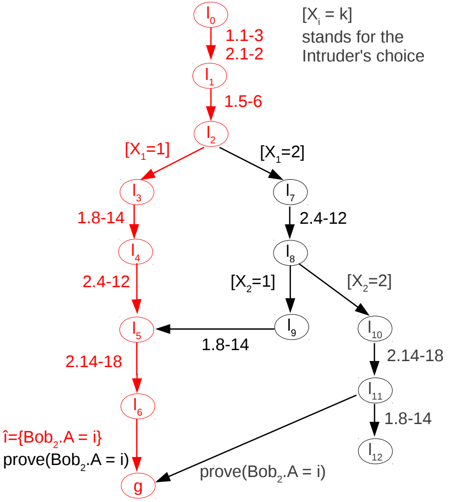
[X_i = k] stands for the Intruder's choice

NSL example

Learn on (I_6, g)

$\alpha \Rightarrow \hat{\imath} \Rightarrow \neg\beta$

$\hat{\imath} = \{Bob_2.A = i\}$



NSL example

Learn on (I_5, I_6)

$\alpha \Rightarrow \hat{\imath} \Rightarrow \neg\beta$

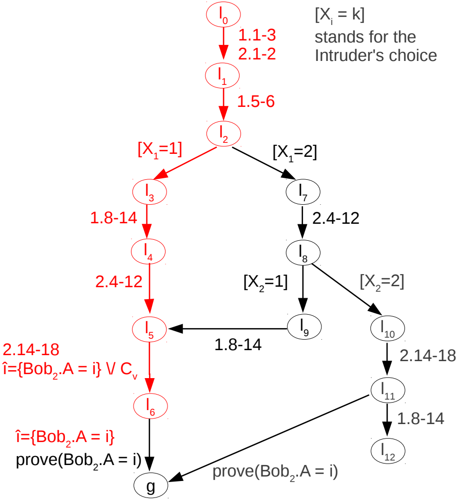
$\hat{\imath} = \{Bob_2.A = i\} \vee C_V$

$C_V \in \mathcal{L}(Var)$

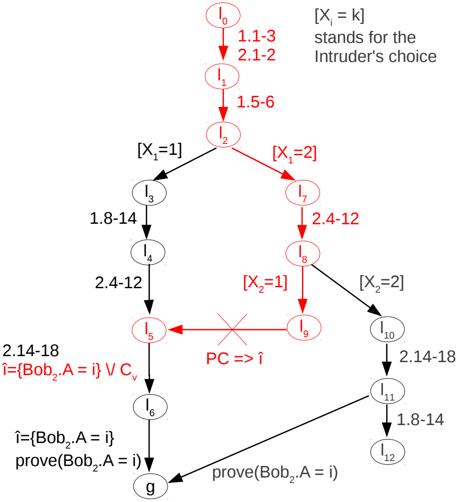
is a constraint

over Var s.t. C_V entails

$IK \nvdash \{Bob_2.Nb\}_{pk\{Bob2.Actor\}}$

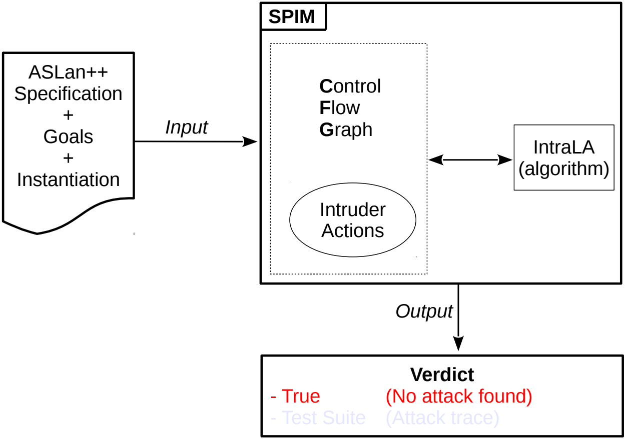


NSL example



[X_i = k]
stands for the
Intruder's choice

Verdict NSL


ASLan++
Specification
+
Goals
+
Instantiation
Input
SPIM
Control
Flow
Graph
Intruder
Actions
IntraLA
(algorithm)
Output
Verdict
- True
(No attack found)
- Test Suite
(Attack trace)

Verdict NSPK

Without Lowe's fix we obtain a MITM attack:

$$
\begin{array}{rcl}
Alice_1.Actor \rightarrow Alice_1.B & : & \{Alice_1.Na, Alice_1.Actor\}_{pk(Alice_1.B)} \\
? \rightarrow Bob_2.Actor & : & \{Bob_2.Na, Bob_2.A\}_{pk(Bob_2.Actor)} \\
Bob_2.Actor \rightarrow Bob_2.A & : & \{Bob_2.Na, Bob_2.Nb\}_{pk(Bob_2.A)} \\
Alice_1.B \rightarrow Alice_1.Actor & : & \{Alice_1.Na, Alice_1.Nb\}_{pk(Alice_1.Actor)} \\
Alice_1.Actor \rightarrow Alice_1.B & : & \{Alice_1.Nb\}_{pk(Alice_1.B)} \\
Bob_2.A \rightarrow Bob_2.Actor & : & \{Bob_2.Nb\}_{pk(Bob_2.Actor)}
\end{array}
$$

Verdict NSPK

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Bob_2.Actor \rightarrow Bob_2.A & : & \{Bob_2.Na, Bob_2.Nb\}_{pk(Bob_2.A)} \\
Alice_1.B \rightarrow Alice_1.Actor & : & \{Alice_1.Na, Alice_1.Nb\}_{pk(Alice_1.Actor)} \\
Alice_1.Actor \rightarrow Alice_1.B & : & \{Alice_1.Nb\}_{pk(Alice_1.B)} \\
Bob_2.A \rightarrow Bob_2.Actor & : & \{Bob_2.Nb\}_{pk(Bob_2.Actor)}
\end{array}
$$

The instantiation of the obtained attack is:

$$
\begin{array}{rcl}
a \rightarrow i & : & \{c_1, a\}_{pk(i)} \\
i(a) \rightarrow b & : & \{c_1, a\}_{pk(b)} \\
b \rightarrow i(a) & : & \{c_1, c_2\}_{pk(i(a))} \\
i \rightarrow a & : & \{c_1, c_2\}_{pk(a)} \\
a \rightarrow i & : & \{c_2\}_{pk(i)} \\
i(a) \rightarrow b & : & \{c_2\}_{pk(b)}
\end{array}
$$

Verdict NSPK

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i \rightarrow a & : & \{c_1, c_2\}_{pk(a)} \\
a \rightarrow i & : & \{c_2\}_{pk(i)} \\
i(a) \rightarrow b & : & \{c_2\}_{pk(b)}
\end{array}
$$

That is the usual MITM attack on NSPK protocol:

$$
\begin{array}{rcl}
A \rightarrow i & : & \{N_A, A\}_{pk(i)} \\
i(A) \rightarrow B & : & \{N_A, A\}_{pk(B)} \\
B \rightarrow i(A) & : & \{N_A, N_b\}_{pk(A)} \\
i \rightarrow A & : & \{N_A, N_B\}_{pk(A)} \\
A \rightarrow i & : & \{N_B\}_{pk(i)} \\
i(A) \rightarrow B & : & \{N_B\}_{pk(B)}
\end{array}
$$

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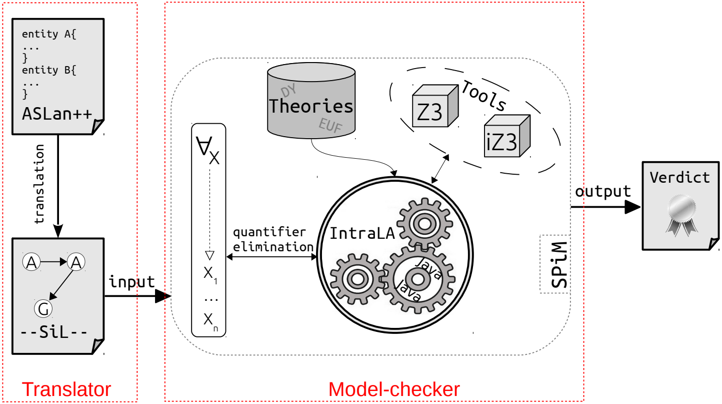
SPiM

Details

- based on Z3 (sat check) and iZ3 (interpolant generation)
- uses a modified version of IntraLA



Results

A comparison

In order to show the **effectiveness** of our interpolation-based technique, we let the tool run in two different modalities on a few case studies:

1. **IntraLA**: annotation-driven symbolic execution;
2. **Full-explore**: standard symbolic execution (i.e., full exploration of the graph).

Specification (sessions)	IntraLA (# Decide+Learn)	Full-explore (# Decide)	attack
NSL (ab,ab)	125m22s (327+218)	419m15s (587)	no
NSL (ai,ab)	3m15s (81+20)	4m4s (109)	no
NSPK (ab,ab)	54m13s (237+218)	131m53s (587)	no
NSPK (ai,ab)	1m49s (92+20)	1m55s (113)	yes
Helsinki (ab,ab)	224m21s (291+258)	549m38s (681)	no
Yahalom (abs)	22m56s (31)	23m10s (31)	no

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Future work

- **Full implementation (and more case studies)**
- ASLan++ full coverage
- More complex protocols and goals (LTL)
- **Test case generation and integration in testing phase**

Thank you

Inference rules for a Dolev-Yao intruder

$$\frac{M \in IK}{M \in \mathcal{DY}(IK)}\ G_{\mathrm{axiom}}$$

$$\frac{M_1 \in \mathcal{DY}(IK) \quad M_2 \in \mathcal{DY}(IK)}{[M_1, M_2] \in \mathcal{DY}(IK)}\ G_{\mathrm{pair}} \qquad \frac{[M_1, M_2] \in \mathcal{DY}(IK)}{M_i \in \mathcal{DY}(IK)}\ A_{\mathrm{pair}_i}$$

$$\frac{M_1 \in \mathcal{DY}(IK) \quad M_2 \in \mathcal{DY}(IK)}{\{M_1\}_{M_2} \in \mathcal{DY}(IK)}\ G_{\mathrm{crypt}}$$

$$\frac{\{M_1\}_{M_2} \in \mathcal{DY}(IK) \quad inv(M_2) \in \mathcal{DY}(IK)}{M_1 \in \mathcal{DY}(IK)}\ A_{\mathrm{crypt}}$$

$$\frac{\{M_1\}_{inv(M_2)} \in \mathcal{DY}(IK) \quad M_2 \in \mathcal{DY}(IK)}{M_1 \in \mathcal{DY}(IK)}\ A^{-1}_{\mathrm{crypt}}$$

We convert such a deduction system into a formula (over a finite number of inference steps) and use Z3/iZ3 for performing symbolic execution and calculating annotations.

How we model Dolev-Yao intruder inference

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$$
\begin{aligned}
\varphi_j = \quad & \forall M. (\mathcal{DY}_{IK}^{j+1}(M) \leftrightarrow (\mathcal{DY}_{IK}^{j}(M) \\
& \vee (\exists M'. \mathcal{DY}_{IK}^{j}([M, M']) \vee \mathcal{DY}_{IK}^{j}([M', M])) \\
& \vee (\exists M_1, M_2. M = [M_1, M_2] \wedge \mathcal{DY}_{IK}^{j}(M_1) \wedge \mathcal{DY}_{IK}^{j}(M_2)) \\
& \vee (\exists M_1, M_2. M = \{M_1\}_{M_2} \wedge \mathcal{DY}_{IK}^{j}(M_1) \wedge \mathcal{DY}_{IK}^{j}(M_2))) \\
& \vee (\exists M'. \mathcal{DY}_{IK}^{j}(\{M\}_{M'}) \wedge \mathcal{DY}_{IK}^{j}(inv(M'))) \\
& \vee (\exists M'. \mathcal{DY}_{IK}^{j}(\{M\}_{inv(M')}) \wedge \mathcal{DY}_{IK}^{j}(M'))
\end{aligned}
$$