Automated and machine-verified security proofs of stateful protocols

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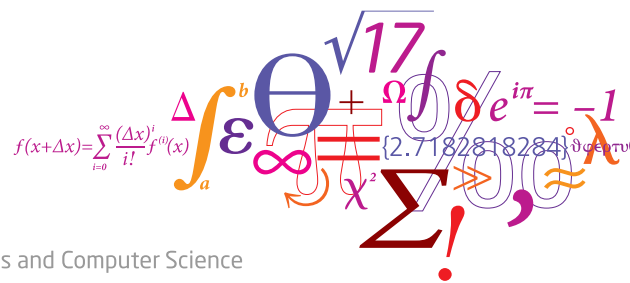

DTU Compute
Department of Applied Mathematics and Computer Science

Overview

1. Stateful protocol verification
2. What we are doing
3. Demo
4. Conclusion

Example: A Keyserver

Stateful protocols:

- Global mutable state spanning multiple sessions

Scenario:

- A server maintains a database of public keys for users
  - Set valid(A) of valid keys of user A
  - Set revoked(A) of revoked keys of user A
- Each user A has a keyring ring(A).

Example: A Keyserver

```
outOfBand(A:honest)
 new PK
 insert PK ring(A)
 insert PK valid(A)
 send PK.
```

Joint transaction between an agent A and the keyserver.

Example: A Keyserver

```
updateKey(A:honest,PK:value)
 PK in ring(A)
 new NPK
 delete PK ring(A)
 insert NPK ring(A)
 send sign(inv(PK),NPK).
```

```
updateKeyServer(A:honest,PK:value,NPK:value)
 receive sign(inv(PK),NPK)
 PK in valid(A)
 NPK notin valid(A)
 NPK notin revoked(A)
 delete PK valid(A)
 insert PK revoked(A)
 insert NPK valid(A).
```

Example: A Keyserver

```
oopsEvent(A:honest,PK:value)
 PK in revoked(A)
 send inv(PK).
```

```
authAttack(A:honest,PK:value)
 receive inv(PK)
 PK in valid(A)
 attack.
```

There is an attack if there exists a run of the protocol in which the `authAttack` transaction fires

Over-Approximation

Popular approach in protocol verification: Ask the question:
"What messages can the intruder ever learn in any reachable state?"

To keep things decidable we over-approximate and restrict the intruder to a typed model

- Not all abstract states are feasible in the real world,
  - but we are on the safe side (it is a sound over-approximation).

$$\begin{aligned}
&\mathsf{pk}_1, \mathsf{pk}_2, \ldots \\
&\mathsf{sign}(\mathsf{inv}(\mathsf{pk}'_1), \mathsf{npk}_1), \mathsf{sign}(\mathsf{inv}(\mathsf{pk}'_2), \mathsf{npk}_2), \ldots \\
&\mathsf{inv}(\mathsf{pk}''_1), \mathsf{inv}(\mathsf{pk}''_2), \ldots \\
&\mathsf{npk}_1, \mathsf{npk}_2, \ldots
\end{aligned}$$

Over-Approximation

Popular approach in protocol verification: Ask the question:
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To keep things decidable we over-approximate and restrict the intruder to a typed model

- Not all abstract states are feasible in the real world,
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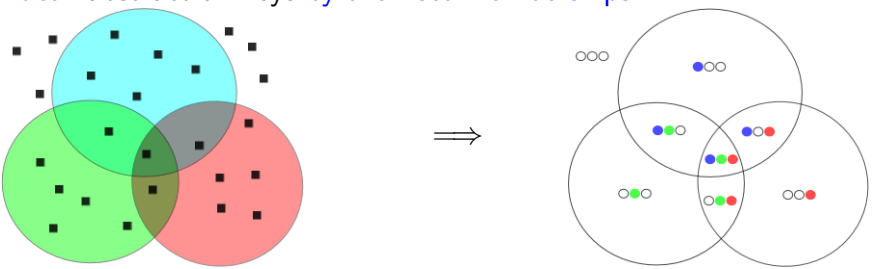
$$PK,$$
$$\mathsf{sign}(\mathsf{inv}(PK'), NPK),$$
$$\mathsf{inv}(PK'')$$

Set-Based Abstraction

How do we handle the databases?

Idea: abstract all keys by their set memberships.



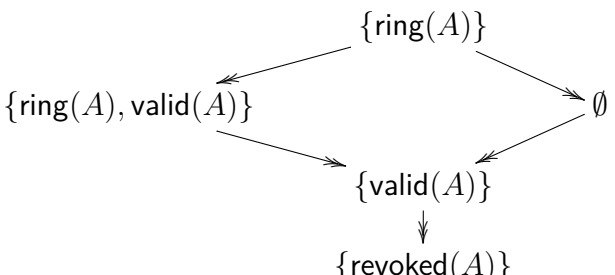
- Implemented in AIF/AIF-ω and Set-π (similar ideas in StatVerif and GSVerif)

Example: The Fixed-Point for the Keyserver

PK,
$\mathsf{sign}(\mathsf{inv}(PK'), NPK)$,
$\mathsf{inv}(PK'')$

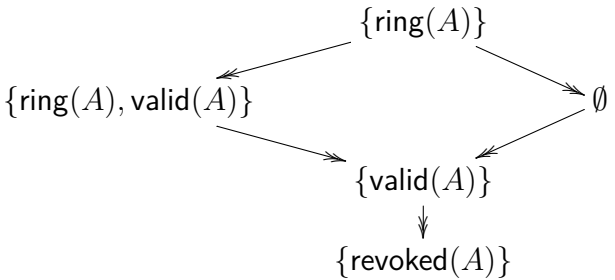
Example: The Fixed-Point for the Keyserver

$\{\mathsf{ring}(A)\}$,
$\mathsf{sign}(\mathsf{inv}(\emptyset), \{\mathsf{ring}(A)\})$,
$\mathsf{inv}(\{\mathsf{revoked}(A)\})$



Example: The Fixed-Point for the Keyserver

$\{\mathsf{ring}(A)\}$,
$\mathsf{sign}(\mathsf{inv}(\emptyset), \{\mathsf{ring}(A)\})$,
$\mathsf{inv}(\{\mathsf{revoked}(A)\})$



- The intruder also knows, e.g.,
  $\mathsf{sign}(\mathsf{inv}(\{\mathsf{valid}(A)\}), \{\mathsf{revoked}(A)\})$
- Since the attack signal does not occur in the fixed-point the keyserver protocol is secure

Should we trust the output of verification tools?

Automatic (OFMC, AIF-ω, GSVerif, ...)	*Interactive* (Isabelle, Coq, Twelf, ...)
May contain bugs $\Rightarrow$ flawed security claims!	Extremely high correctness guarantee
Automated	Requires a lot of expertise
Fast	Time consuming and can be tedious

- Goal: Use automatic methods to obtain a "proof" for proof assistants to check, combining the advantages of both
- Every proof accepted by Isabelle/HOL is machine-verified
  - Every proof argument is verified down to the axioms
  - We only have to trust the small core of Isabelle
  - Subtle assumptions cannot be overlooked

What we are doing

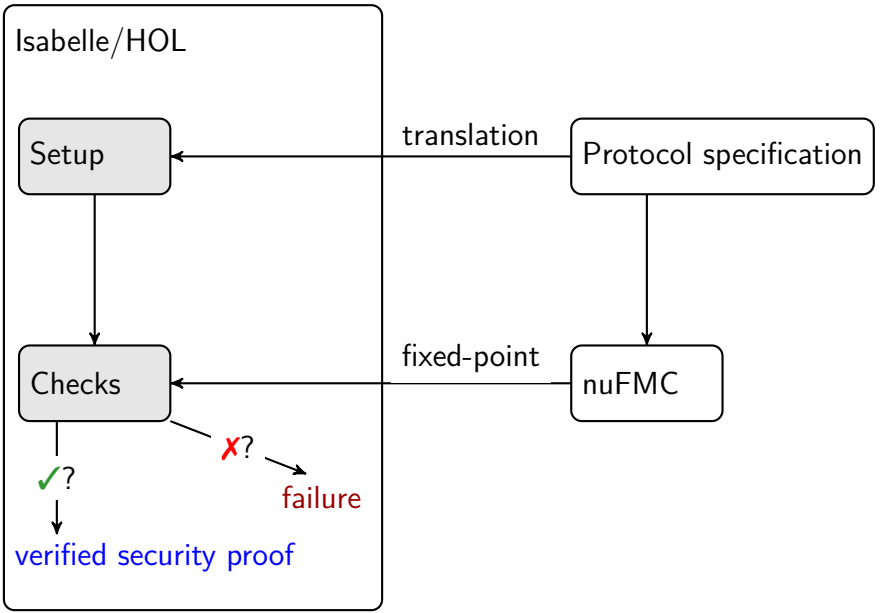
1. Proved a theorem for protocol security in Isabelle. Roughly,

Theorem

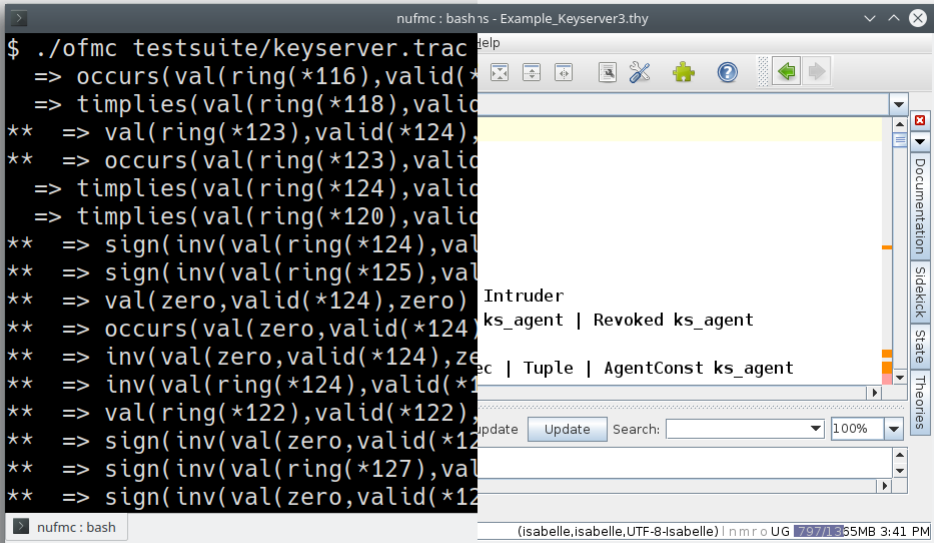
If FP is a fixed-point that covers the protocol $\mathcal{P}$, and the attack *signal does not occur in FP, then $\mathcal{P}$ is secure*

2. The conditions to check falls within the executable fragment of Isabelle
   - They are automatically verifiable
   - The checks terminate (assuming reasonable conditions on the protocol specifications)
3. Extended the OFMC tool to support stateful protocols: nuFMC
4. Connected nuFMC to the Isabelle formalization

Tool Overview



Demo


nufmc : bash
ns - Example_Keyserver3.thy
$ ./ofmc testsuite/keyserver.trac
=> occurs(val(ring(*116),valid(*
=> timplies(val(ring(*118),valid
** => val(ring(*123),valid(*124),
** => occurs(val(ring(*123),valid
=> timplies(val(ring(*124),valid
=> timplies(val(ring(*120),valid
** => sign(inv(val(ring(*124),val
** => sign(inv(val(ring(*125),val
** => val(zero,valid(*124),zero)
** => occurs(val(zero,valid(*124
** => inv(val(zero,valid(*124),ze
** => inv(val(ring(*124),valid(*1
** => val(ring(*122),valid(*122),
** => sign(inv(val(zero,valid(*12
** => sign(inv(val(ring(*127),val
** => sign(inv(val(zero,valid(*12
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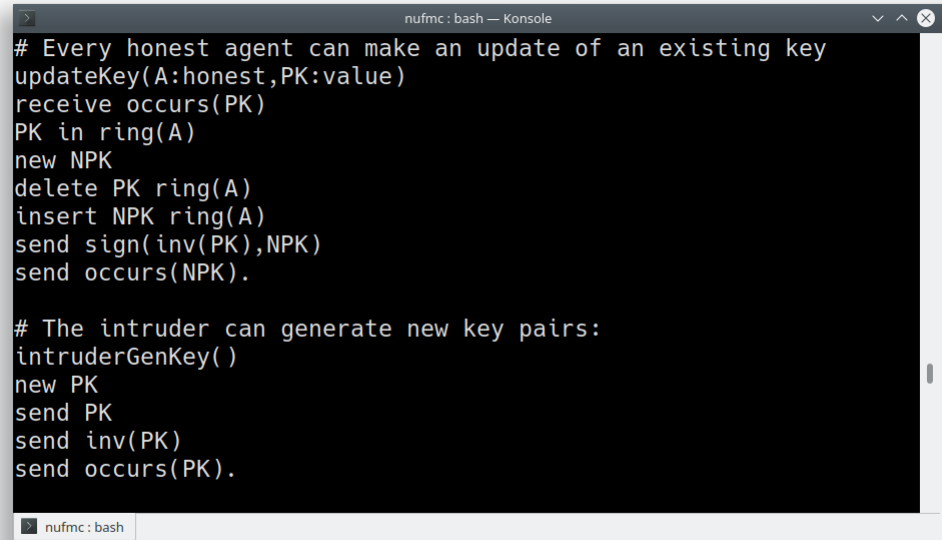
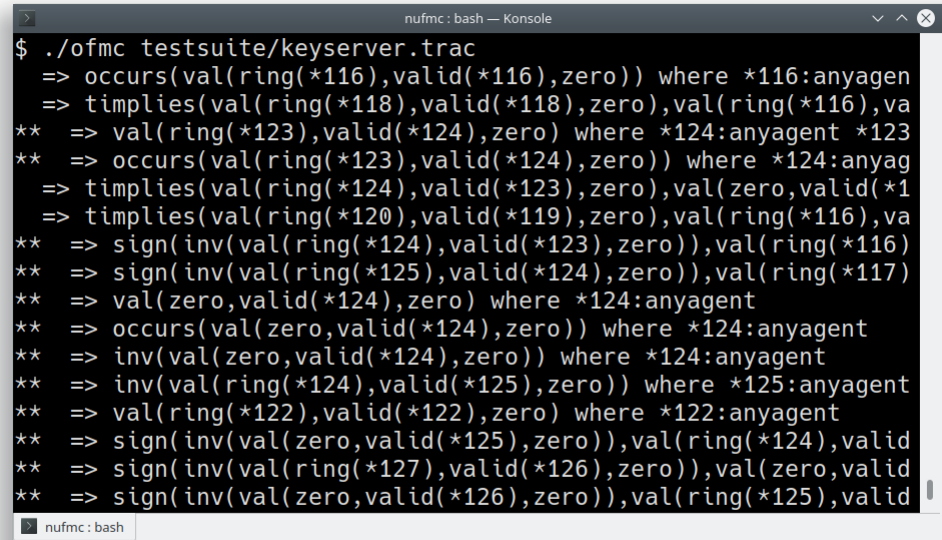
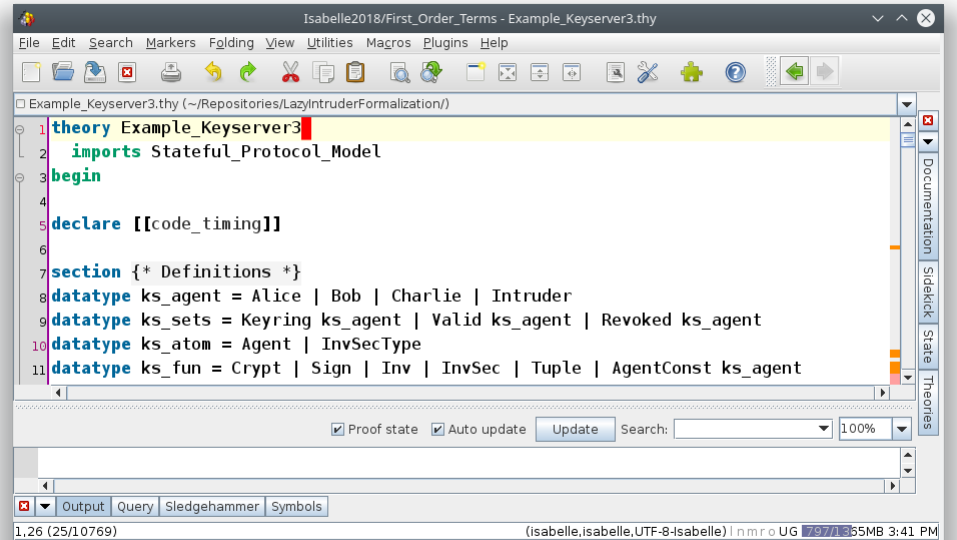
Demo


nufmc : bash — Konsole
# Every honest agent can make an update of an existing key
updateKey(A:honest,PK:value)
receive occurs(PK)
PK in ring(A)
new NPK
delete PK ring(A)
insert NPK ring(A)
send sign(inv(PK),NPK)
send occurs(NPK).
# The intruder can generate new key pairs:
intruderGenKey( )
new PK
send PK
send inv(PK)
send occurs(PK).
nufmc : bash

Demo


nufmc : bash — Konsole
$ ./ofmc testsuite/keyserver.trac
=> occurs(val(ring(*116),valid(*116),zero)) where *116:anyagen
=> timplies(val(ring(*118),valid(*118),zero),val(ring(*116),va
** => val(ring(*123),valid(*124),zero) where *124:anyagent *123
** => occurs(val(ring(*123),valid(*124),zero)) where *124:anyag
=> timplies(val(ring(*124),valid(*123),zero),val(zero,valid(*1
=> timplies(val(ring(*120),valid(*119),zero),val(ring(*116),va
** => sign(inv(val(ring(*124),valid(*123),zero)),val(ring(*116)
** => sign(inv(val(ring(*125),valid(*124),zero)),val(ring(*117)
** => val(zero,valid(*124),zero) where *124:anyagent
** => occurs(val(zero,valid(*124),zero)) where *124:anyagent
** => inv(val(zero,valid(*124),zero)) where *124:anyagent
** => inv(val(ring(*124),valid(*125),zero)) where *125:anyagent
** => val(ring(*122),valid(*122),zero) where *122:anyagent
** => sign(inv(val(zero,valid(*125),zero)),val(ring(*124),valid
** => sign(inv(val(ring(*127),valid(*126),zero)),val(zero,valid
** => sign(inv(val(zero,valid(*126),zero)),val(ring(*125),valid
nufmc : bash

Demo


Isabelle2018/First_Order_Terms - Example_Keyserver3.thy
File Edit Search Markers Folding View Utilities Macros Plugins Help
Example_Keyserver3.thy (~/Repositories/LazyIntruderFormalization/)
theory Example_Keyserver3
imports Stateful_Protocol_Model
begin
declare [[code_timing]]
section {* Definitions *}
datatype ks_agent = Alice | Bob | Charlie | Intruder
datatype ks_sets = Keyring ks_agent | Valid ks_agent | Revoked ks_agent
datatype ks_atom = Agent | InvSecType
datatype ks_fun = Crypt | Sign | Inv | InvSec | Tuple | AgentConst ks_agent
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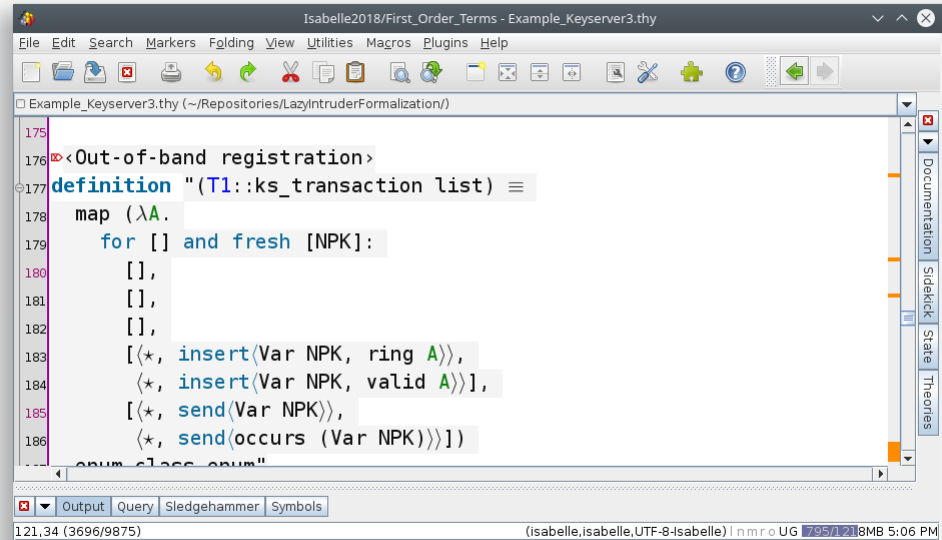
Isabelle2018/First_Order_Terms - Example_Keyserver3.thy
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Example_Keyserver3.thy (~/Repositories/LazyIntruderFormalization/)
175
176 ‹Out-of-band registration›
177 definition "(T1::ks_transaction list) ≡
178 map (λA.
179 for [] and fresh [NPK]:
180 [],
181 [],
182 [],
183 [⟨⋆, insert⟨Var NPK, ring A⟩⟩,
184 ⟨⋆, insert⟨Var NPK, valid A⟩⟩],
185 [⟨⋆, send⟨Var NPK⟩⟩,
186 ⟨⋆, send⟨occurs (Var NPK)⟩⟩])
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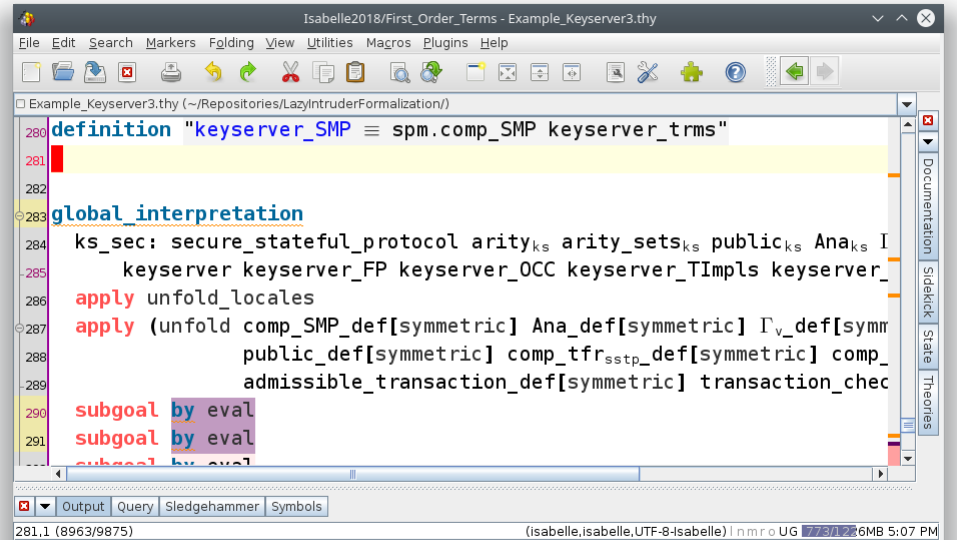
Demo


Isabelle2018/First_Order_Terms - Example_Keyserver3.thy
File Edit Search Markers Folding View Utilities Macros Plugins Help
Example_Keyserver3.thy (~/Repositories/LazyIntruderFormalization/)
280 definition "keyserver_SMP ≡ spm.comp_SMP keyserver_trms"
281
282
283 global_interpretation
284 ks_sec: secure_stateful_protocol arity$_{ks}$ arity_sets$_{ks}$ public$_{ks}$ Ana$_{ks}$ I
285 keyserver keyserver_FP keyserver_OCC keyserver_TImpls keyserver_
286 apply unfold_locales
287 apply (unfold comp_SMP_def[symmetric] Ana_def[symmetric] Γ$_v$_def[symm
288 public_def[symmetric] comp_tfr$_{sstp}$_def[symmetric] comp_
289 admissible_transaction_def[symmetric] transaction_chec
290 subgoal by eval
291 subgoal by eval
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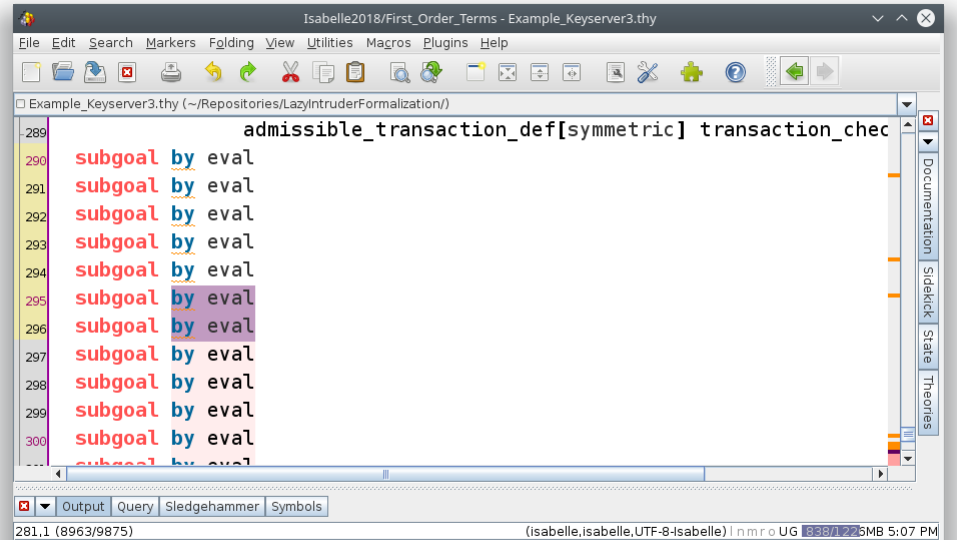
Demo


Isabelle2018/First_Order_Terms - Example_Keyserver3.thy
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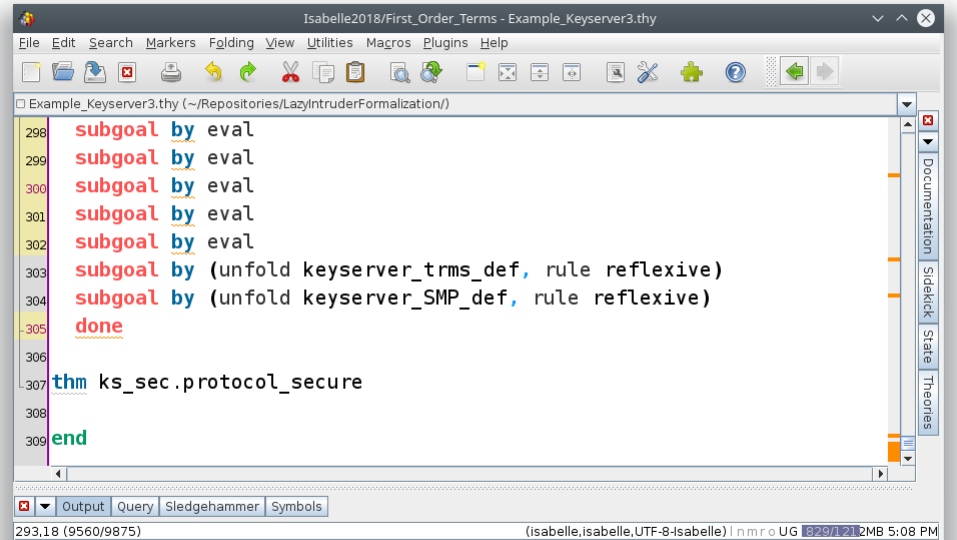
Isabelle2018/First_Order_Terms - Example_Keyserver3.thy
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Example_Keyserver3.thy (~/Repositories/LazyIntruderFormalization/)
298 subgoal by eval
299 subgoal by eval
300 subgoal by eval
301 subgoal by eval
302 subgoal by eval
303 subgoal by (unfold keyserver_trms_def, rule reflexive)
304 subgoal by (unfold keyserver_SMP_def, rule reflexive)
305 done
306
307 thm ks_sec.protocol_secure
308
309 end
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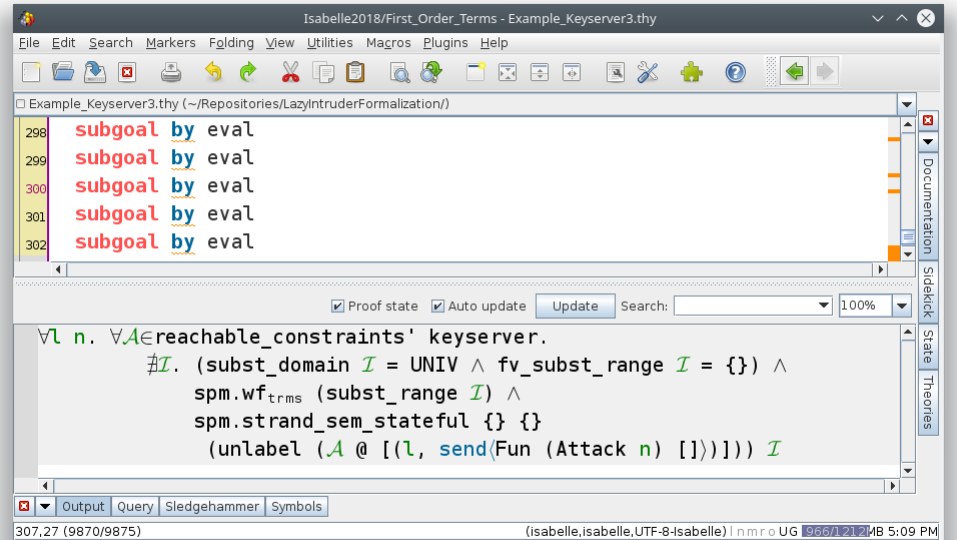
Demo


Isabelle2018/First_Order_Terms - Example_Keyserver3.thy
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Example_Keyserver3.thy (~/Repositories/LazyIntruderFormalization/)
298 subgoal by eval
299 subgoal by eval
300 subgoal by eval
301 subgoal by eval
302 subgoal by eval
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spm.wf_trms (subst_range ℐ) ∧
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Relative Soundness

- Our work is embedded into a whole framework for protocol verification in Isabelle
- nuFMC, like many other tools, assumes a typed model in which the intruder is restricted in what it can construct
- We have previously proven a typing result in Isabelle, namely that the restriction is sound for a large class of protocols: the type-flaw resistant protocols
- Thus, simply proving that the protocol is a member of this class lifts a typed-model proof of nuFMC to a proof for the untyped model as well
- We automatically check for type-flaw resistance
- In the future: automated checking of parallel composition conditions

Conclusion

We integrate an automatic protocol verification tool (nuFMC) with a proof assistant (Isabelle)

- Support for stateful protocols
- Completely automatic
  - Computing the fixed-point with nuFMC is automatic
  - The checks performed in Isabelle are also automatic
- Extremely high correctness guarantee
  - Isabelle verifies the output of nuFMC
- Is embedded into a whole framework for protocol verification in Isabelle
  - Allows us to automatically apply a typing result, lifting the security proofs from a typed model to an untyped one
  - It is possible to manually apply parallel compositionality results