

Protocol Verification Techniques - Theorem Provers

Design and Verification of Security Protocols and Security
Ceremonies

Programa de Pós-Graduação em Ciências da Computação
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Attention!

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This topic will be divided into two lectures. One will deal with automatic theorem provers using FOL and the second will deal with theorem provers using HOL

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- HOL is any predicate logic that has greater order than Second-Order Logic;

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- Higher-order logic admits quantification over sets that are nested arbitrarily deeply.

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- $\forall P((0 \in P \wedge \forall i(i \in P \rightarrow i + 1 \in P)) \rightarrow \forall n(n \in P))$
- This is the definition of the set of Natural Numbers.

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- Last work published in 2015: "Verifying multicast-based security protocols using the inductive method. Martina, J.E., Paulson, L.C."

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- Out of that we extract:
 - An inductive abstract trace model;
 - Correctness theorem about the traces;
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- We state the goals, theorems and lemmas;
- We prove the theorems inductively to demonstrate correctness.

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 - Checking requires proving that all the traces satisfy the property, by induction on the construction of the traces;
 - Main point: these proofs are big, uninteresting, and better left to machines;
 - Use a theorem prover (Isabelle) to write the proofs.

Isabelle

- Automated support for proof development, which supports:

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- Strong support for inductive definitions.

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 - *Public.thy* which inherits from *Event.thy*, which despite the narrowly chosen name, accounts for the specification of symmetric and asymmetric cryptographic primitives;
 - We also have some other specialised theories for Smart-Cards, Threshold Cryptography and Multicast communication.

Inductive Method Details - Agents

Definition

Agent datatype definition

datatype

```
agent = Friend nat  
      | Server  
      | Spy
```


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- The second category regards the trusted third party;
- Finally we have the attacker, which is categorised separately.

Inductive Method Details - Cryptographic Keys

Definition

shrK function definition

consts

shrK :: "agent => key"

specification (*shrK*)

inj_shrK: "inj *shrK*"

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- A shared key is specified as an injective function taking an agent and returning a key.

Inductive Method Details - Cryptographic Keys

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invKey function definition

consts *invKey* :: "key => key"

specification (*invKey*)

invKey [simp]: "*invKey* (*invKey* *K*) = *K*"

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```

```
specification (invKey)
```

```
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```

```
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 - The first rule is a simplification one that says that the double application of the function brings us back to the original value;
 - The second rule establishes true if the function *invKey* is equal to its identity

Inductive Method Details - Cryptographic Keys

Definition

symKeys set definition

constdefs

symKeys :: "key set"

"symKeys == K. invKey K = K"

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- The symmetric key set is defined as containing all keys where the inverse of the key by the application of the function *invKey* is itself;

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symKeys :: "key set"

"*symKeys* == *K*. *invKey* *K* = *K*"

- By stating $K \in \text{symKeys} \wedge K \notin \text{range shrK}$ we can create a second class of symmetric keys that are not long-term so that it represents sessions keys in our protocols being verified.

Inductive Method Details - Cryptographic Keys

Definition

Axiom for symmetric usage of shared keys

axioms

sym_shrK [iff]: "shrK X \in symKeys"

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- Establishes that our long-term keys are symmetric with an axiom.

Inductive Method Details - Cryptographic Keys

Definition

publicKey definition

datatype

keymode = Signature | Encryption

consts

publicKey :: "[keymode,agent] => key"

specification (*publicKey*)

injective_publicKey:

"publicKey b A = publicKey c A' ==> b=c & A=A' "

Inductive Method Details - Cryptographic Keys

Definition

privateKey axiom definition

axioms

privateKey_neq_publicKey [iff]:

"privateKey b A \neq publicKey c A'"

Inductive Method Details - Cryptographic Keys

Definition

Public Key abbreviations

abbreviation

```
pubEK :: "agent => key" where
  "pubEK == publicKey Encryption"
pubSK :: "agent => key" where
  "pubSK == publicKey Signature"
privateKey :: "[keymode, agent] => key" where
  "privateKey b A == invKey (publicKey b A)"
priEK :: "agent => key" where
  "priEK A == privateKey Encryption A"
priSK :: "agent => key" where
  "priSK A == privateKey Signature A"
```

Inductive Method Details - Compromised Agents

Definition

bad set definition

consts

bad :: "agent set"

specification (*bad*)

Spy_in_bad [iff]: " $Spy \in bad$ "

Server_not_bad [iff]: " $Server \notin bad$ "

Inductive Method Details - Messages

Definition

msg datatype definition

datatype

```
msg = Agent agent  
    | Number nat  
    | Nonce nat  
    | Key key  
    | MPair msg msg  
    | Hash msg  
    | Crypt key msg
```

Inductive Method Details - Events

Definition

event datatype definition

datatype

```
event = Says agent agent msg  
      / Gets agent msg  
      / Notes agent msg
```

Inductive Method Details - Initial Knowledge

Definition

initState definition

consts

```
initState :: "agent => msg set"
```

Inductive Method Details - Initial Knowledge

Definition

Spy agent initial knowledge definition

primrec

```
initState_Spy:  
  "initState Spy =  
    (Key ` invKey ` pubEK ` bad) ∪  
    (Key ` invKey ` pubSK ` bad) ∪  
    (Key ` shrK ` bad) ∪  
    (Key ` range pubEK) ∪ (Key ` range pubSK)"
```


Inductive Method Details - Knows

Definition

knows function definition

```
consts    knows :: "agent => event list => msg set"
```

primrec

```
knows_Nil: "knows A [] = initState A"
```

```
knows_Cons:
```

```
  "knows A (ev # evs) =
```

```
  (if A = Spy then
```

```
  (case ev of
```

```
    Says A' B X => insert X (knows Spy evs)
```

```
    | Gets A' X => knows Spy evs
```

```
    | Notes A' X =>
```

```
      if A' ∈ bad then insert X (knows Spy evs)
```

```
      else knows Spy evs)
```

Inductive Method Details - Knows

Definition

knows function definition

consts

else

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if A'=A then insert X (knows A evs) else

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| Gets A' X =>

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knows A evs)))"

Inductive Method Details - Operators

Definition

parts inductive set definition

inductive_set

parts :: "msg set => msg set"

for *H* :: "msg set"

where

Inj [*intro*]: " $X \in H \implies X \in \text{parts } H$ "

| *Fst*: " $\{|X, Y|\} \in \text{parts } H \implies X \in \text{parts } H$ "

| *Snd*: " $\{|X, Y|\} \in \text{parts } H \implies Y \in \text{parts } H$ "

| *Body*: " $\text{Crypt } K \ X \in \text{parts } H \implies X \in \text{parts } H$ "

Inductive Method Details - Operators

Definition

analz inductive set definition

inductive_set

```
analz :: "msg set => msg set"
```

```
for H :: "msg set"
```

```
where
```

```
  Inj [intro,simp] : "X ∈ H ==> X ∈ analz H"
```

```
  | Fst: "{|X,Y|} ∈ analz H ==> X ∈ analz H"
```

```
  | Snd: "{|X,Y|} ∈ analz H ==> Y ∈ analz H"
```

```
  | Decrypt [dest]:
```

```
    "[|Crypt K X ∈ analz H; Key(invKey K): analz  
H|] ==>
```

```
  X ∈ analz H"
```

Inductive Method Details - Operators

Definition

synth inductive set definition

inductive_set

synth :: "msg set => msg set"

for H :: "msg set"

where

Inj [intro]: "X ∈ H ==> X ∈ synth H"

| Agent [intro]: "Agent agt ∈ synth H"

| Number [intro]: "Number n ∈ synth H"

| Hash [intro]: "X ∈ synth H ==> Hash X ∈

synth H"

| MPair [intro]: "[|X ∈ synth H; Y ∈ synth H|]

==>

{|X,Y|} ∈ synth H"

Inductive Method Details - Operators

Definition

used function definition

consts

`used :: "event list => msg set"`

primrec

`used_Nil: "used [] = (UN B. parts (initState B))"`

`used_Cons: "used (ev # evs) =`

`(case ev of`

`Says A B X => parts {X} \cup used evs`

`| Gets A X => used evs`

`| Notes A X => parts {X} \cup used evs)"`

Dummy Protocol

- | | | | | | |
|----|-----|---------------|-----|---|------------------------------|
| 1. | A | \rightarrow | B | : | $\{ A, B, Na \}_{K_B}$ |
| 2. | B | \rightarrow | A | : | $\{ Na, Nb, K_{AB} \}_{K_A}$ |
| 3. | A | \rightarrow | B | : | $\{ Nb \}_{K_{AB}}$ |

Figure: Example protocol

Dummy Protocol Specification

Definition

inductive definition of example protocol

inductive_set *example* :: "event list set"

where

Nil: "*[]* \in *example*"

|Fake: "*[|evsf* \in *example*; *X* \in *synth*(*analz* (*knows* *Spy evsf*))*]|*"

\Rightarrow *Says Spy B X # evsf* \in *example*"

|EX1: "*[|evs1* \in *example*; *Nonce NA* \notin *used evs1*]*]|*"

\Rightarrow *Says A B* (*Crypt* (*pubK B*) {*|Agent A, Agent B,*
*Nonce NA**|}*) $\#$

evs1 \in *example*"

Dummy Protocol Specification

Definition

```
/EX2: "[|evs2 ∈ example; Nonce NB ∉ used evs2;  
      Key AB ∉ used evs1  
      Says A' B (Crypt (pubK B){|Agent A, Agent B,  
Nonce NA|})  
      ∈ set evs2|]  
⇒ Says B A (Crypt (pubK A) {|Nonce NA, Nonce  
NB, Key AB|})  
# evs2 ∈ example"
```

Dummy Protocol Specification

Definition

```
/EX3: "[|evs3 ∈ example;  
    Says A B (Crypt (pubK B){|Agent A, Agent B,  
Nonce NA|})  
    ∈ set evs3;  
    Says B A (Crypt (pubK A) {|Nonce NA, Nonce  
NB, Key AB|})  
    ∈ set evs3 |]  
⇒Says A B (Crypt (Key AB){|Nonce NB|}) # evs3  
∈ example"
```

Dummy Protocol Specification

Definition

```
/Ops: "[|evso ∈ example;  
  Says B A (Crypt (pubK A) {| Nonce NA, Nonce NB,  
Key AB|})  
  ∈ set evso|]  
  ⇒ Notes Spy {|Nonce NA, Nonce NB, Key AB|}#  
evso ∈ example"
```

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- We describe the protocol goals as Theorems and Lemmas;
- We prove these inductively with the assistance of Isabelle;
- Proof tactics are known for most of the usual goals;
- The problem starts when you want to prove a new goal....

Problems with the Inductive Method

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Discussion

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- What this strategy can not do?

Questions????



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