Security protocol analysis using the Tamarin Prover

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Morning overview

- Model checking and verification
- For security protocols:
  The Tamarin Prover
  - Modeling
  - Attacks and proofs
  - Algorithm intuition
  - In practice
- Hands-on session

Afternoon overview

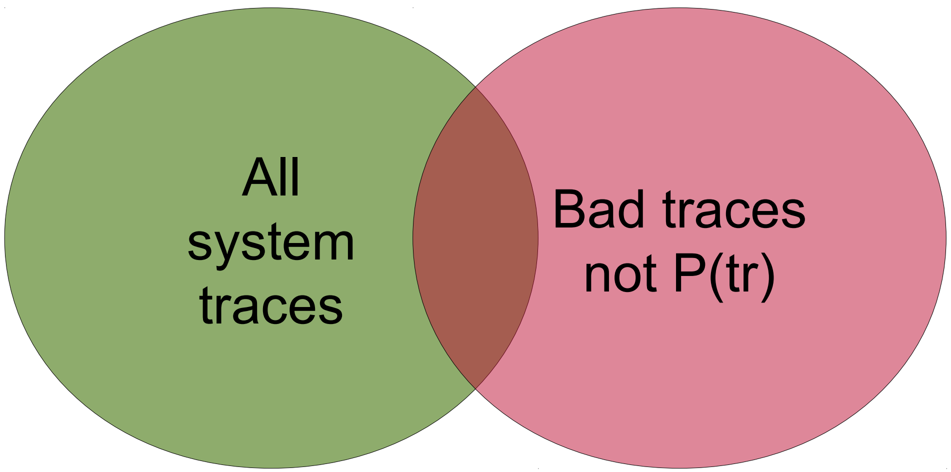
- Recap
- Induction
- State space reduction by sources lemmas
- Equational theories and adversary rules
- Observational equivalence

Problem

- How do we know if a protocol is secure?
  - Traditional: Smart people stare at it
- **More structured approach**:
  Specify threat model & intended property
  - Stare at the protocol, try to find attack.
  - Write the proof
- Can **formal methods** help?
  - Model checking, verification

Trace properties

- For now: trace properties (but more later!):
  - $\forall\, tr \in traces(System)\,.\, P(tr)$



Intersection empty?

Symbolic security analysis

- Idea: make transition system
  - with protocol participants
  - with adversary controlling network
- Encode property
  - **Authentication:**
    In all traces, if an initiator completes, there exists a responder with…
  - **Secrecy:**
    There is no trace in which Adversary learns k
- And check!
- Unfortunately, this turns out to be undecidable

The Tamarin Prover

- Symbolic analysis tool for systems in presence of a Dolev-Yao style network adversary

- Recent highlights:
  - Group key exchange protocols
  - ARPKI
  - TLS 1.3 (See talk tomorrow at TLS:DIV !)

Simon Meier

Benedikt Schmidt

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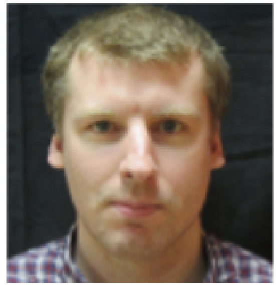

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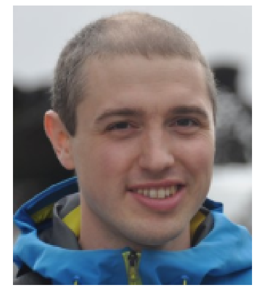
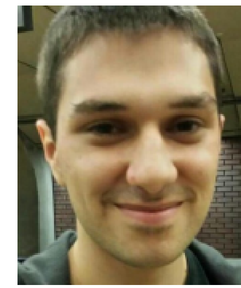


Jannik Dreier



Cedric Staub

Sasa Radomirovic

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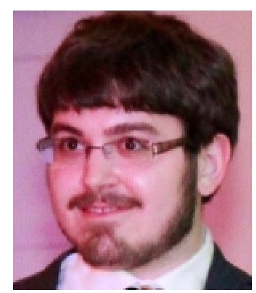


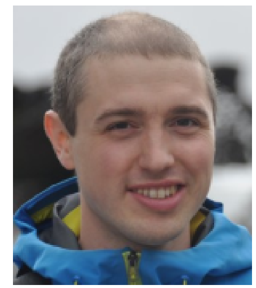
Kevin Milner

and more soon!

Cas Cremers

David Basin

Ralf Sasse



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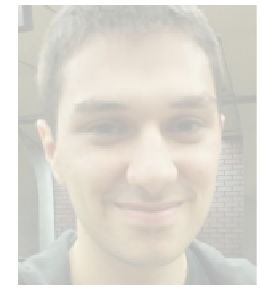
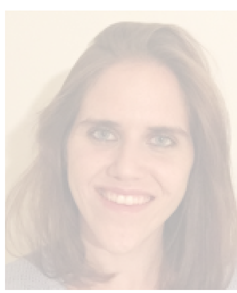
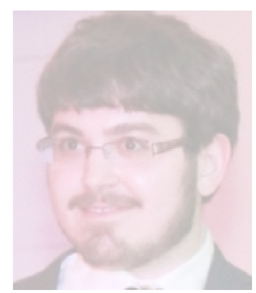






What can Tamarin do for you?

- Rapid prototyping
- Finding attacks before you start a proof effort
- Provide a symbolic proof
- Explore alternative designs/threat models quickly

Selected case studies

- AKE
  - Naxos
  - Signed DH
  - KEA+
  - UM
  - Tsx
- Group protocols
  - GDH
  - TAK
  - (Sig)Joux
  - STR
- ID-based AKE
  - RYY
  - Scott
  - Chen-Kudla
- Loops
  - TESLA1 & 2
- Non-monotonic global state
  - Keyserver
  - Envelope
  - Exclusive secrets
  - Contract signing
  - Security device
  - YubiKey
  - YubiHSM
- PKI with strong guarantees
  - ARPKI (also global state)
- Transparency
  - DECIM (also global state)
- TLS 1.3
  - Rev 10, 10+, and current

Resources & documentation

- Sources on github
- 100+ page manual
- Plenty of examples/case studies
- Algorithm details in theses, papers

Demo

Tamarin: high-level

- **Modeling** protocol & adversary done using multiset rewriting
  - Specifies transition system; induces set of traces
- **Property** specification using fragment of first-order logic
  - Specifies “good” traces
- Tamarin tries to
  - provide proof that all system traces are good, or
  - construct a counterexample trace of the system (attack)

Modeling in Tamarin

- **Multiset rewriting**; surprisingly similar to “oracles”
- Basic ingredients:
  - **Terms** (think “messages”)
  - **Facts** (think “sticky notes on the fridge”)
  - Special facts: **Fr(t)**, **In(t)**, **Out(t)**, **K(t)**
- State of system is a multiset of facts
  - **Initial state** is the empty multiset
  - **Rules** specify the transition rules (“moves”)
- Rules are of the form:
  - `l --> r`
  - `l --[ a ]-> r`

The model

- **Term algebra**
  - enc(_,_), dec(_,_), h(_,_), $\_\hat{}\_$, $\_^{-1}$, _*_, 1, …
- **Equational theory**
  - dec(enc(m,k),k) $=_E$ m,
  - (x^y)^z $=_E$ x^(y*z),
  - $(x^{-1})^{-1} =_E x$, ...
- **Facts**
  - F(t1,...,tn)
- **Transition system**
  - State: multiset of facts
  - Rules: l –[a]→ r
- **Tamarin-specific**
  - Built-in Dolev-Yao attacker rules
    - In( ), Out( ), K( )
  - Special **Fresh** rule:
    - [] --[]--> [Fr(**x**)]
      - With additional constraints on systems such that **x** unique

Semantics

- **Transition relation**

  $S \text{–[a]}\!\rightarrow_R \; ((\, S \setminus^{\#} l \,) \cup^{\#} r \,)$

  where l –[a]→ r is a ground instance of a rule and $l \subseteq^{\#} S$

- **Executions**

  $\text{Exec}(\,R) = \;\{\, [\,] \text{ –}[a_1]\!\rightarrow \ldots \text{–}[a_n]\!\rightarrow S_n$
  $\mid \forall n\,.\, \text{Fr}(n)$ appears only once on rhs $\}$

- **Traces**

  $\text{Traces}(\,R) = \{\, [a_1,\ldots,a_n]$
  $\mid [\,] \text{ –}[a_1]\!\rightarrow \ldots \text{–}[a_n]\!\rightarrow S_n \in \text{Exec}(\,R) \,\}$

‘c’ constant

Semantics: example 1

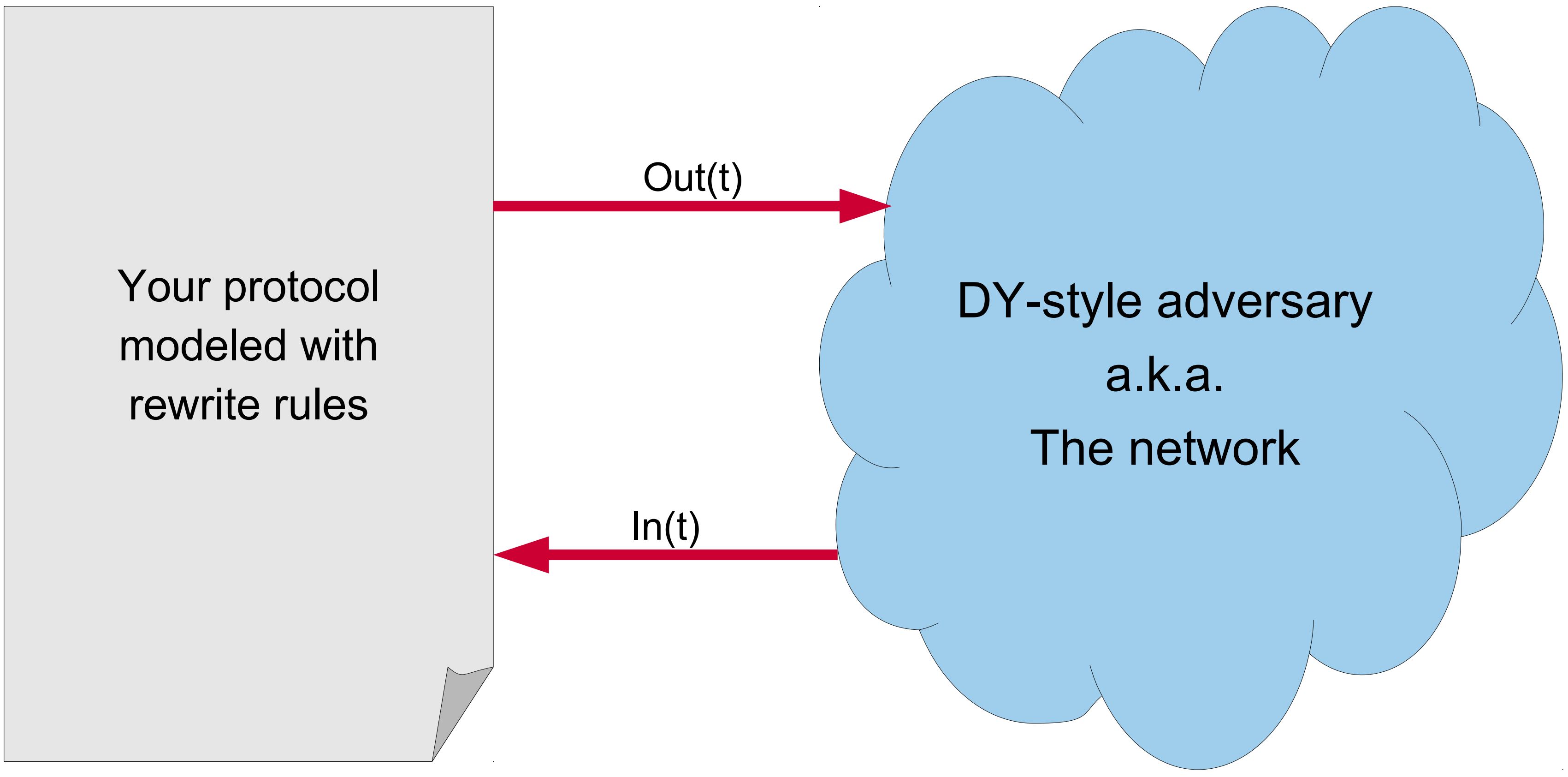
- **Rules**
  - rule 1: [ ] –[Init()]→ [A('5')]
  - rule 2: [A(x)] –[Step(x)]→ [B(x)]
- **Execution example**
  - [ ]
  - –[Init()]→ [A('5')]
  - –[Init()]→ [A('5'), A('5')]
  - –[Step('5')]→ [A('5'), B('5')]
- **Corresponding trace**
  - [Init(), Init(), Step('5')]

‘c’ constant

Semantics: example 2 (persistent facts)

- **Rules**
  - rule1: [ ] –[Init()]→ [!C('ok'), D('1')]
  - rule2: [!C(x), D(y)] –[Step(x,y)]→ [D(h(y))]
- **Execution example**
  - [ ]
  - –[Init()]→ [!C('ok'), D('1')]
  - –[Step('ok','1')]→ [!C('ok'), D(h('1'))]
  - –[Step('ok',h('1'))]→ [!C('ok'), D(h(h('1')))]
- **Corresponding trace**
  - [Init(), Step('ok', '1'), Step('ok', h('1'))]

Tamarin tackles complex interaction with adversary



The Naxos protocol

lkA	A's long-term priv. key
g^lkA	A's long-term pub. key
eskA	A's eph. priv. key

$\boxed{\mathrm{I}}$ $\boxed{\mathrm{R}}$

Fresh esk_I

$ex_I = h1(esk_I, lk_I)$

$hk_I = g^{ex_I}$ $\xrightarrow{hk_I}$ receive X

Fresh esk_R

$ex_R = h1(esk_R, lk_R)$

receive Y $\xleftarrow{hk_R}$ $hk_R = g^{ex_R}$

$$K = h2(g^{(ex_R)(lk_I)}, g^{(ex_I)(lk_R)}, g^{(ex_I)(ex_R)}, I, R)$$

Modeling Naxos

lkA	A's long-term priv. key
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eskA	A's eph. priv. key

$\boxed{\mathrm{I}}$

$$\text{Fresh } esk_I$$

$$ex_I = h1(esk_I, lk_I)$$

$$hk_I = g^{ex_I} \qquad \xrightarrow{hk_I}$$

Modeling Naxos

lkA	A's long-term priv. key
g^lkA	A's long-term pub. key
eskA	A's eph. priv. key
'c'	constant
~t	t has type fresh

$\boxed{\mathrm{I}}$

Fresh esk_I

$$ex_I = h1(esk_I, lk_I)$$

$$hk_I = g^{ex_I} \qquad \xrightarrow{hk_I}$$

```
rule Init_1:
  let exI = h1(<~eskI, ~lkI >)
      hkI = 'g'^exI
  in
   [ Fr( ~eskI ) ] --> [ Out( hkI) ]
```

Modeling Naxos

lkA	A's long-term priv. key
g^lkA	A's long-term pub. key
eskA	A's eph. priv. key
'c'	constant
~t	t has type fresh
$t	t has type public
!F	F is persistent

$\boxed{\mathrm{I}}$

Fresh esk_I

$ex_I = h1(esk_I, lk_I)$

$hk_I = g^{ex_I}$ $\xrightarrow{hk_I}$

```
rule generate_ltk:
   let pkA = 'g'^~lkA
   in
   [ Fr(~lkA) ] --> [ !Ltk( $A, ~lkA ), !PK( $A, pkA), Out(pkA) ]


rule Init_1:
  let exI = h1(<~eskI, ~lkI >)
      hkI = 'g'^exI
  in
   [ Fr( ~eskI ), !Ltk( $I, ~lkI ) ] --> [ Out( hkI) ]
```

Modeling Naxos

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$\boxed{\mathrm{I}}$

Fresh esk_I

$$ex_I = h1(esk_I, lk_I)$$

$$hk_I = g^{ex_I} \qquad \xrightarrow{\quad hk_I \quad}$$

receive Y $\qquad \longleftarrow$

```
rule generate_ltk:
   let pkA = 'g'^~lkA
   in
   [ Fr(~lkA) ] --> [ !Ltk( $A, ~lkA ), !PK( $A, pkA), Out(pkA) ]


rule Init_1:
  let exI = h1(<~eskI, ~lkI >)
      hkI = 'g'^exI
  in
   [ Fr( ~eskI ), !Ltk( $I, ~lkI ) ] --> [ Out( hkI) ]


rule Init_2:
   [ In( Y ) ] --> []
```

Modeling Naxos

lkA	A's long-term priv. key
g^lkA	A's long-term pub. key
eskA	A's eph. priv. key
'c'	constant
~t	t has type fresh
$t	t has type public
!F	F is persistent

$\boxed{\mathrm{I}}$

Fresh esk_I

$ex_I = h1(esk_I, lk_I)$

$hk_I = g^{ex_I}$ $\xrightarrow{hk_I}$

receive Y $\longleftarrow$

```
rule generate_ltk:
   let pkA = 'g'^~lkA
   in
   [ Fr(~lkA) ] --> [ !Ltk( $A, ~lkA ), !PK( $A, pkA), Out(pkA) ]


rule Init_1:
  let exI = h1(<~eskI, ~lkI >)
      hkI = 'g'^exI
  in
   [ Fr( ~eskI ), !Ltk( $I, ~lkI ) ] --> [ Out( hkI),
     Init_1( ~eskI, $I, $R, ~lkI ,hkI) ]

rule Init_2:
   [ Init_1( ~eskI, $I, $R, ~lkI , hkI), In( Y ) ] --> []
```

Property specification

- first order logic interpreted over a trace
  - False — False
  - Equality — $t_1 =_E t_2$
  - Timepoint ordering — $\#i < \#j$
  - Timepoint equality — $\#i = \#j$
  - Action at timepoint #i — $A@\#i$

Property specification

- `l --[ a ]-> r`
- Actions stored as (action) trace

  Additionally:
  adversary knows facts: K()

lkA	A's long-term priv. key
g^lkA	A's long-term pub. key
eskA	A's eph. priv. key
'c'	constant
~t	t has type fresh
$t	t has type public
!F	F is persistent

```
rule Init_2:
  let exI = h1(< ~eskI, ~lkI >),
      kI  = h2(< Y^~lkI, pkR^exI, Y^exI, $I, $R >)
  in
   [ Init_1( ~eskI, $I, $R, ~lkI , hkI), In( Y ), !Pk($R,pkR) ]
   --[ Accept(~eskI, $I, $R, kI) ]-->
   []


Lemma trivial_key_secrecy:
  ''(All #i Test A B k. Accept(Test,A,B,k)@i => Not (Ex #j. K(k)@j ))''
```

Property specification

lkA	A’s long-term priv. key
g^lkA	A’s long-term pub. key
eskA	A’s eph. priv. key
‘c’	constant
~t	t has type fresh
$t	t has type public
!F	F is persistent

```
rule Ltk_reveal:
   [ !Ltk($A, lkA) ] --[ LtkRev($A) ]-> [ Out(lkA) ]


lemma key_secrecy:
  /*
   * If A and B are honest, the adversary doesn't learn the session key
   */
  "(All #i1 Test A B k.
    (
      Accept(Test, A, B, k) @ i1
      &
      not ( (Ex #ia . LtkRev  ( A ) @ ia )
          | (Ex #ib . LtkRev  ( B ) @ ib )
          )
    )
    ==> not (Ex #i2. K( k ) @ i2 )
  )"
```

eCK security model for key exchange

- Adversary can
  - learn **long-term keys**,
  - learn the **randomness** generated in sessions,
  - learn **session keys**
- But only as long as the Test session is *clean*:
  - **No reveal of session key of** Test session or its **matching session**, and
  - No reveal of randomness of Test session as well as the long-term key of the actor, and
  - If there exists a matching session, then something is disallowed
  - If there is no matching session, then something else...

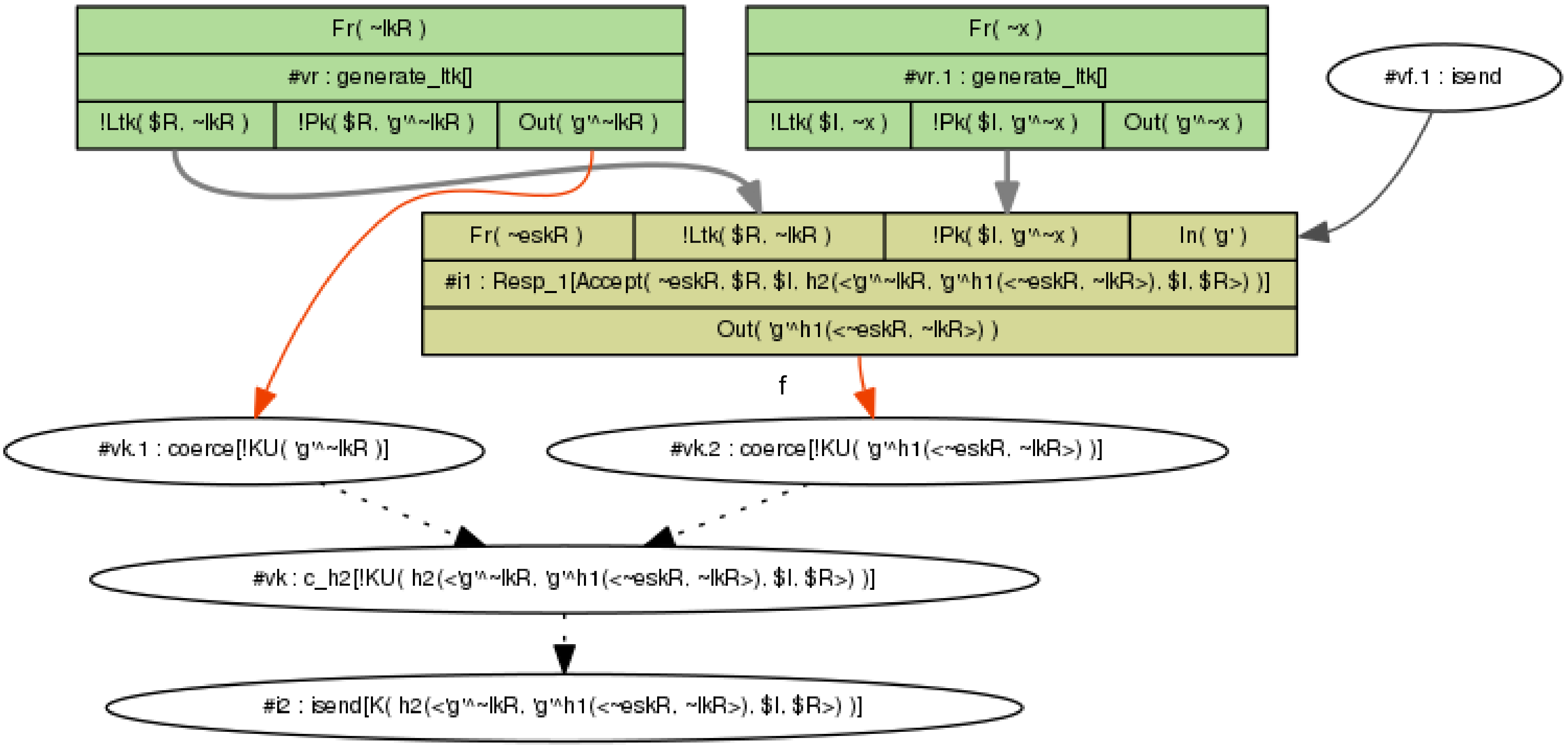
Specifying eCK

```
Lemma eCK_key_secrecy:
  "(All #i1 #i2 Test A B k. Accept(Test, A, B, k) @ i1
                           & K( k ) @ i2 ==>
  (
      (Ex #i3. SesskRev( Test ) @ i3 )
    | (Ex MatchingSession #i3 #i4 ms.
           ( Sid ( MatchingSession, ms ) @ i3
           & Match( Test, ms ) @ i4)
           & (Ex #i5. SesskRev( MatchingSession ) @ i5 ))
    | [ ...andsoforth... ]
  )"
end
```

If Test accepts and the adversary knows k, then the Test must not be fresh, i.e., "... **reveal of session key of Test session** or **its matching session**", or ...

Demo

Reading Tamarin's graphs



Algorithm intuition

- **Constraint solving algorithm**
- Main ingredients:
  - Dependency graphs
  - Deconstruction (decryption) chains
  - Finite variant property (more this afternoon)
- **Invariant**: if adversary knows M then either
  - M was sent in plain
  - Adversary can construct M by knowing subterms
  - Adversary can deconstruct M …. from message sent by protocol rule

Basic principles

- Backwards search using **constraint reduction rules** (27!)
- Turn negation of formula into set of constraints
- Case distinctions
  - E.g.: Possible sources of a message or fact
- Try to establish:
  - no solutions exist for constraint system, or
  - there exists a „realizable“ execution (trace)
- If multiple rules can be applied: use heuristics

Demo

How do I know my model is correct?

- **Lots of ways to cause errors**
- Look at the chains...
  - (requires an understanding of the algorithm)
- Executability
- Break the protocol on purpose
- Much easier to check these things than in manual proofs!

Heuristics?

- If Tamarin terminates, one of two options:
  - **Proof**, or
  - **counterexample** (in this context: attack)
- At each stage in proof, multiple constraint solving rules might be applicable
  - Similar to “how shall I try to prove this?”
  - Choice influences speed & termination, but not the outcome after termination
- Complex **heuristics choose rule**
  - user can give hints or override

Lemmas

- When it doesn’t terminate…
- Guide the proof manually; export
- Write **lemmas**
  - “**Hints**” for the prover
    - They don't change the proof obligation, only help finding a proof
  - Specify lemma that can be used to prune proof trees at multiple points
  - ... more this afternoon and at TLS:DIV

Symbolic analysis for cryptographers

- **Fundamental differences**
  - Dolev-Yao attacker strong abstraction of Probabilistic Polynomial Time Turing Machine
  - Terms are an abstract view of bitstrings
  - No quantitative information (e.g. bounds)
- Current **algorithm limitations**
  - Limited equational theories, e.g., MQV style exponentiation tricky: we miss Kaliski's UKS attack on MQV.
- **What we *could* do** (but often don't; ongoing work)
  - Negotiation, weak crypto
  - Small subgroup attacks
  - DSKS attacks
  - Length extension attacks

Hands-on session!

- Take Naxos-simplified (not full eCK)
- Remove
  - First argument to KDF, check what happens
  - Second etc.
- Load more complex threat model version
  - Do the same for the properties that held before
- Load eCK model version

Discussion & solutions

Tamarin: Conclusions

- **Tamarin** offers **many unique features**
  - Unbounded analysis, flexible properties, equational theories, global state, …
  - Enables automated analysis in areas previously unexplored
- It has many **other features** I didn't touch on now (some this afternoon!)
  - Induction, restrictions, reusable lemmas, heuristics tuning, …
  - Tomorrow at TLS:DIV – TLS 1.3 analysis
  - Many new features planned!
- Tool and sources are **free**; development on Github

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