Security protocol analysis using the Tamarin Prover

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Overview & Structure

- **Overview**
  - Introduction
  - Tamarin's foundations
  - Modeling a protocol
  - Modeling security properties
  - Algorithm intuition
  - In practice
  - Symbolic vs computational
  - Where do I go from here?

Overview & Structure

- **Mode of operation**
  - No need to use tools during the talk, exercises are for afterwards
  - Short blocks (circa 20 minutes), then answering questions
  - Please write your questions in the Zulip chat channel:

    `”Vericrypt2020 Tamarin Prover”`

    You should have a link in your mail
  - We’ll have a break in the middle (10-15 minutes)

Security Protocols

Problem

- **How do we know if a protocol is secure?**
  - Traditionally: Smart people stare at it

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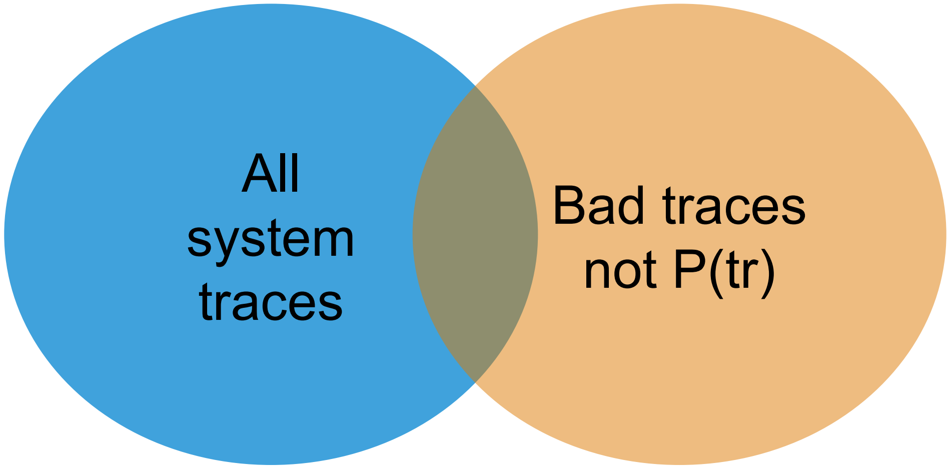
  - Specify threat model & intended property
  - Stare at the protocol, try to find attack
  - Write the proof

Problem

- **How do we know if a protocol is secure?**
  - Traditionally: 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 the 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

- Some highlights:
  - TLS 1.3
  - 5G-AKA
  - EMV (Chip and pin)

What can Tamarin do for you?

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

Selected case studies

- Key exchange protocols
  - Naxos, Signed DH, KEA+, UM, Tsx
- Group protocols
  - GDH, TAK, (Sig)Joux, STR
- Identity-based KE
  - RYY, Scott, Chen-Kudla
- Loops
  - TESLA1 & 2
- Non-monotonic global state
  - Keyserver, Envelope, Exclusive secrets, Contract signing, Security device
- PKI and friends
  - ARPKI, DECIM
- Detailed cryptographic primitives
  - WS-Security, X509, Scuttlebut, Let's Encrypt ACME, Bluetooth handshake, Tendermint

- More complex analyses:
  - TLS 1.3
  - EMV (Chip and pin)
  - 5G-AKA
  - 802.11 WPA2 (Wifi)
  - TPM 2.0 direct anonymous attestation
  - DNP3 SAv5 (power grid)
  - Noise protocols
  - YubiKey/YubiHSM

Demo

Demo

Tamarin

```
cas@Yoga:~/tamarin_ex3_from_slides$ ls
foo_eligibility.spthy  NAXOS_eCK_PFS.spthy  sources-nolemma-load.spthy
loop.spthy             NAXOS_eCK.spthy      sources.spthy
cas@Yoga:~/tamarin_ex3_from_slides$ 
```

Demo

Tamarin

```
cas@Yoga:~/tamarin_ex3_from_slides$ ls
foo_eligibility.spthy  NAXOS_eCK_PFS.spthy  sources-nolemma-load.spthy
loop.spthy             NAXOS_eCK.spthy      sources.spthy
cas@Yoga:~/tamarin_ex3_from_slides$ tamarin-prover interactive .
```

Demo

Tamarin

```
 stdout:  2.7

 stderr:
 checking installation: OK.
The server is starting up on port 3001.
Browse to http://127.0.0.1:3001 once the server is ready.

Loading the security protocol theories './*.spthy' ...
Finished loading theories ... server ready at

    http://127.0.0.1:3001

08/Dec/2020:19:56:06 +0100 [Info#yesod-core] Application launched @(yesod-co
re-1.6.18-Ab7hNtiUzJgGsCLpKcpJyh:Yesod.Core.Dispatch src/Yesod/Core/Dispatch
.hs:163:11)
```

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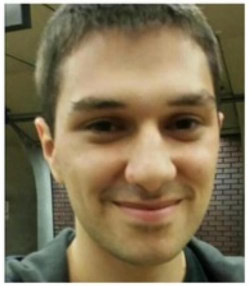

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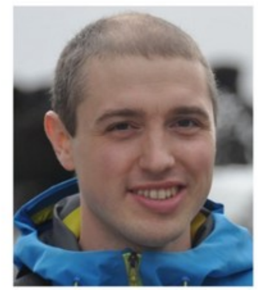

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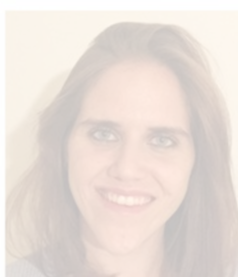


Resources & documentation

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

Tamarin prover

Constraint solver

Tamarin prover

Theorem Prover

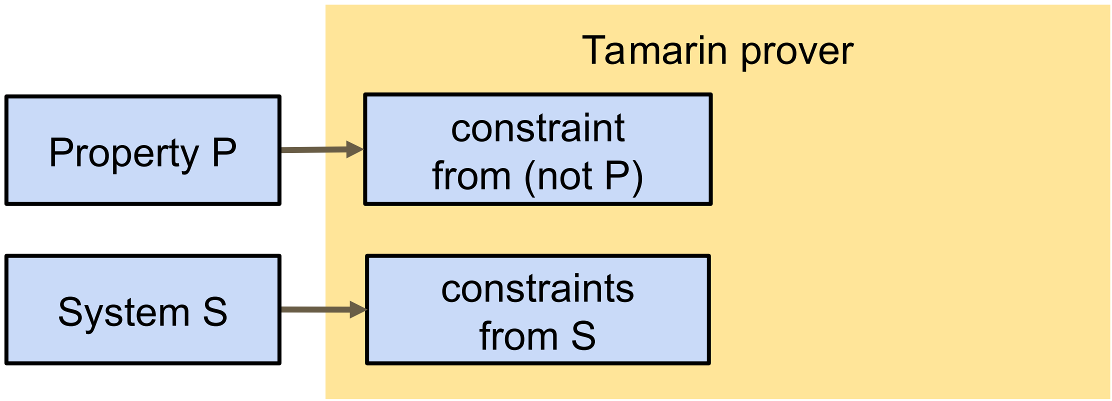
Constraint solver

Tamarin workflow

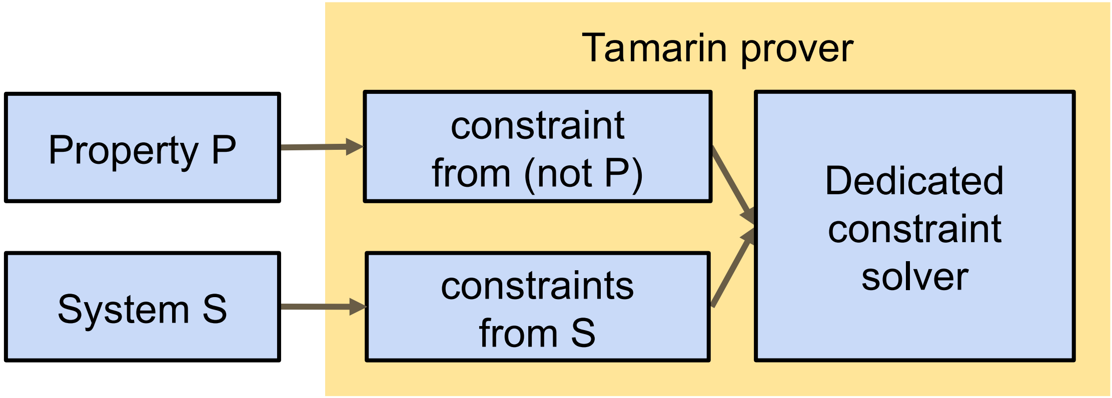
Property P

System S

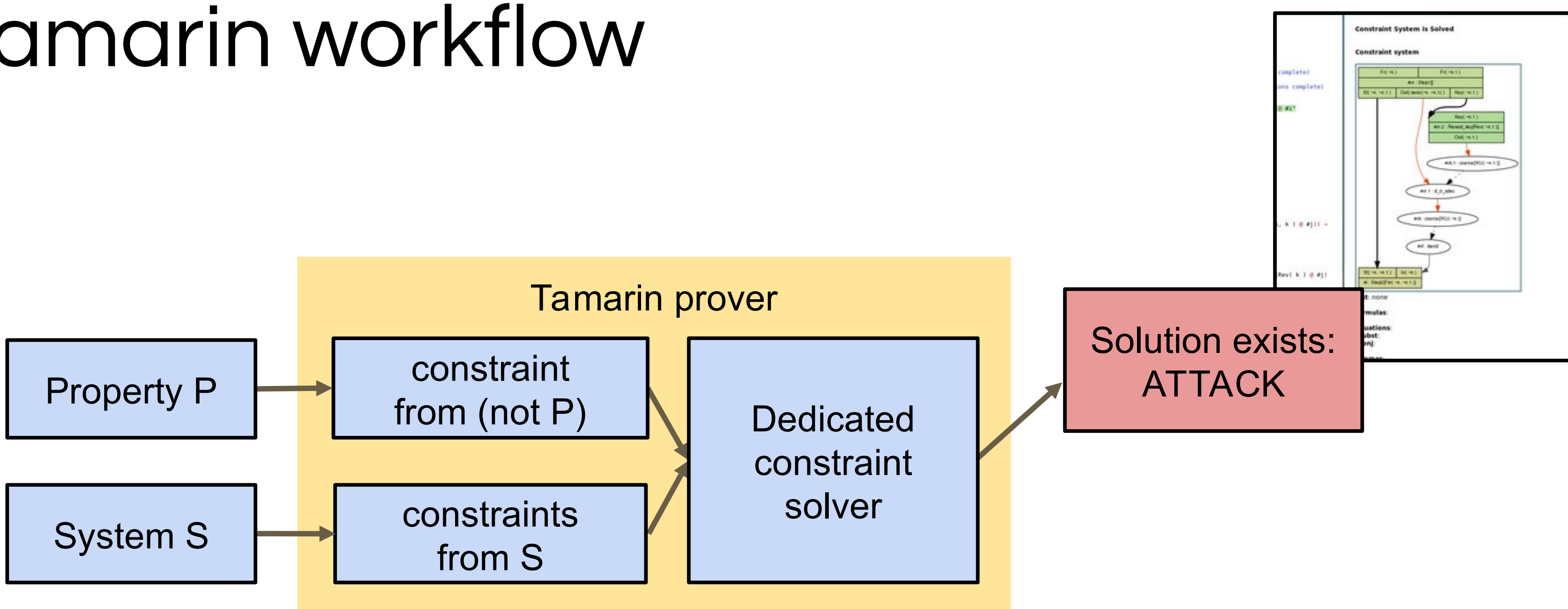
Tamarin workflow



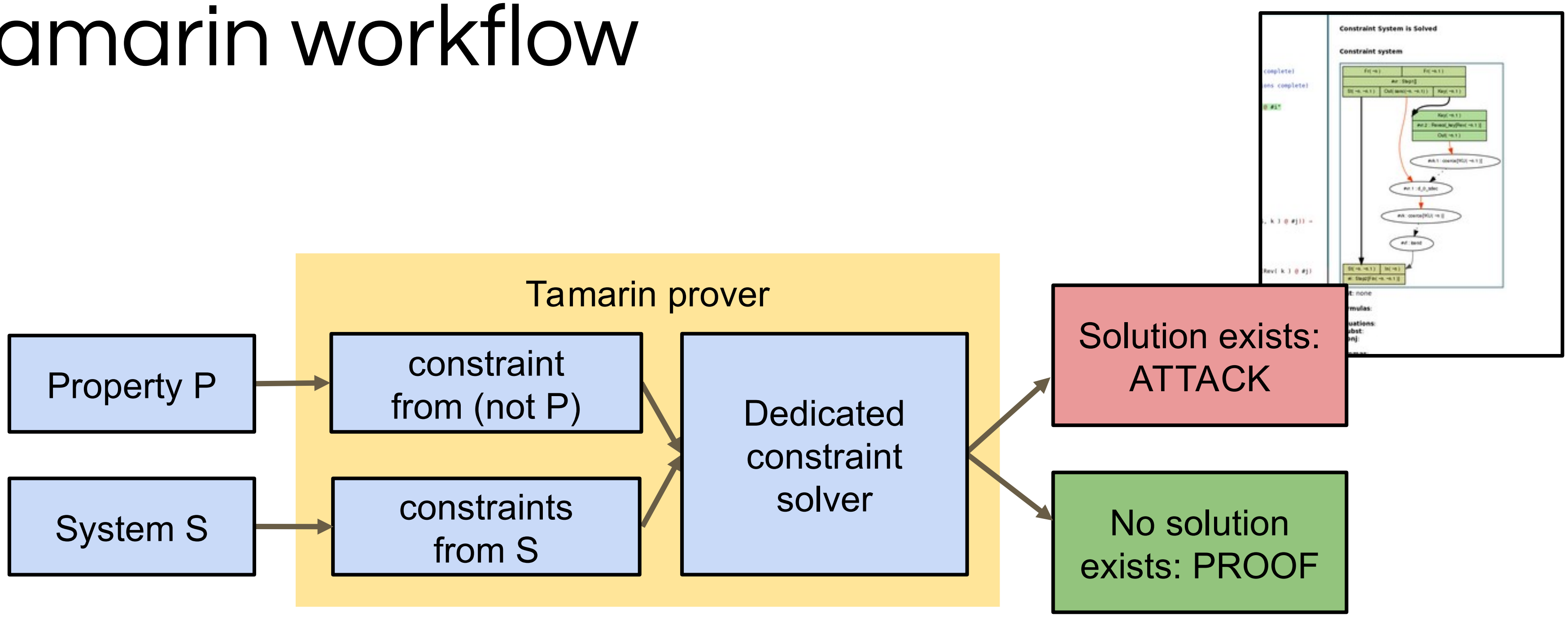
Tamarin workflow



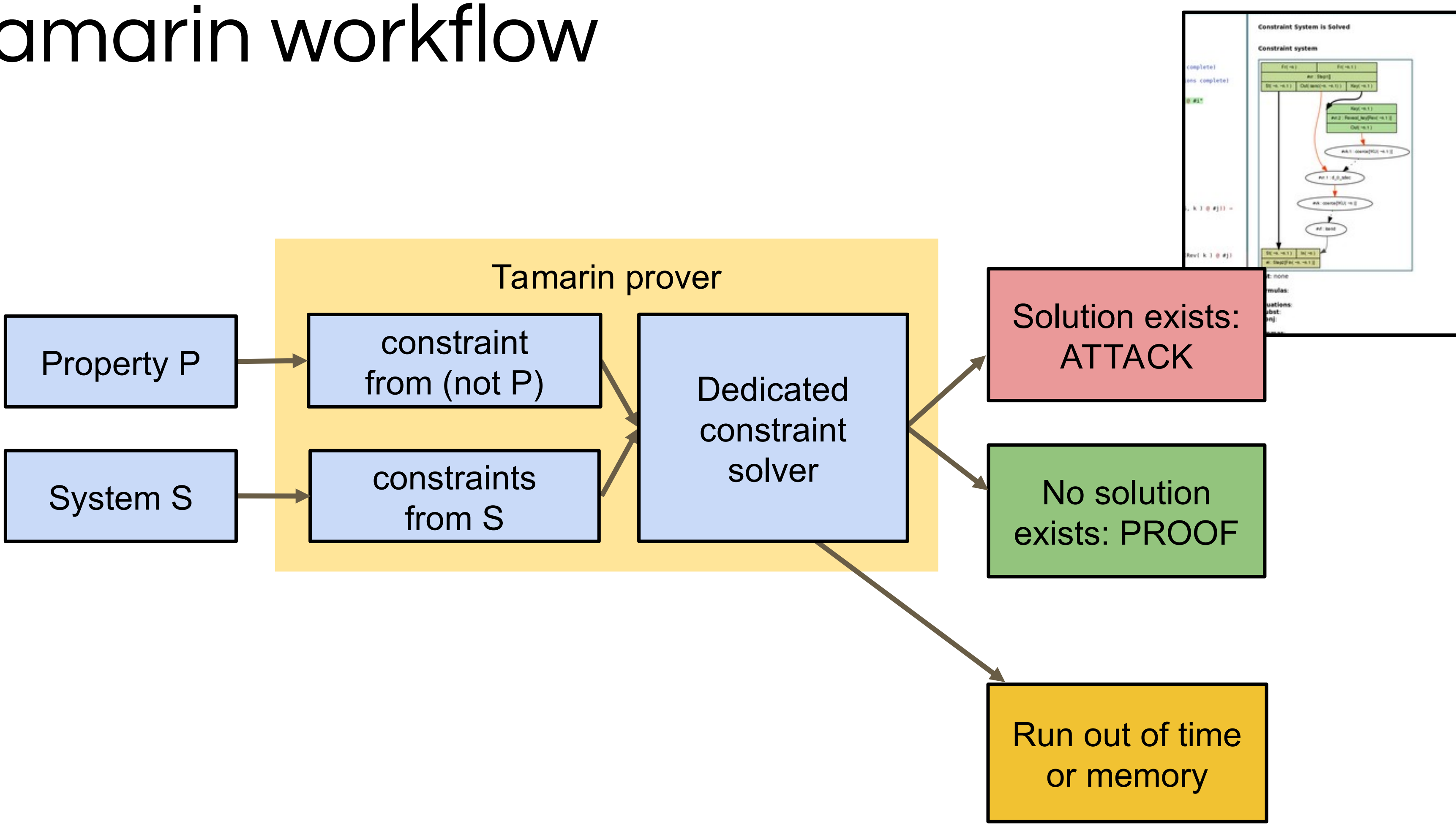
Tamarin workflow



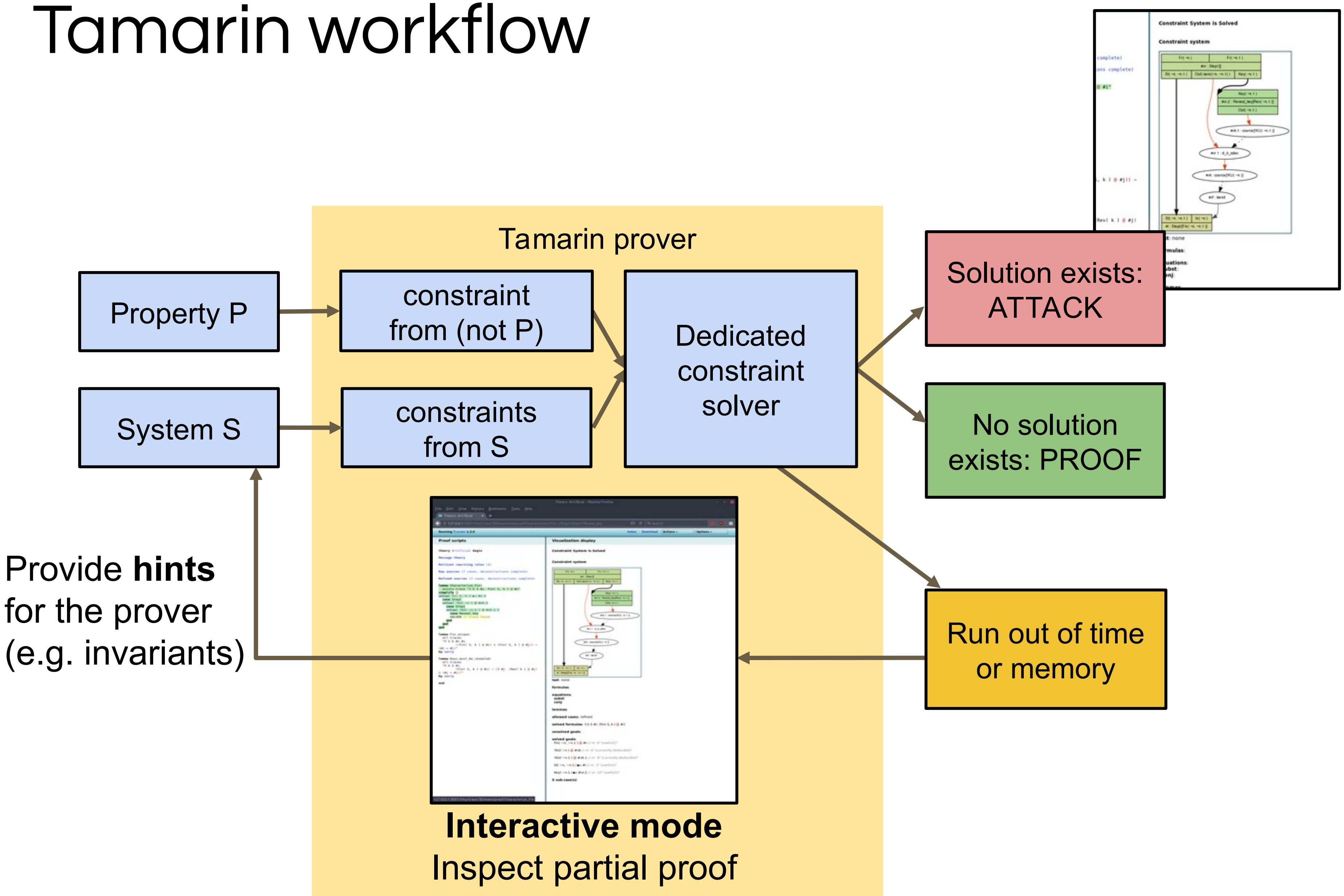
Tamarin workflow



Tamarin workflow



Tamarin workflow



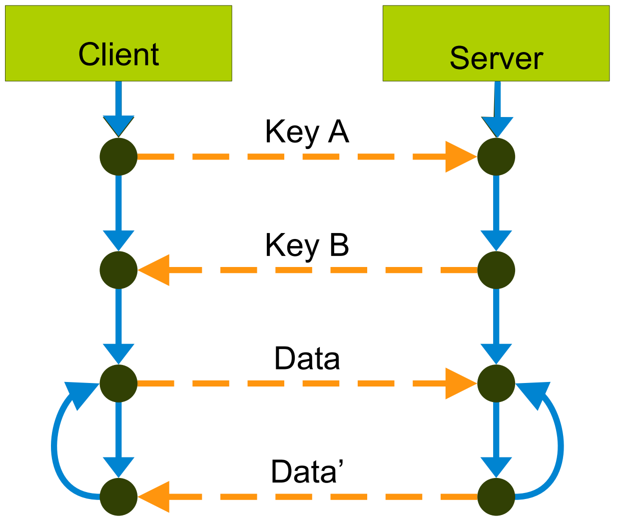
Tamarin: high-level

- **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)

- What we saw:
  - We all use security protocols on a daily basis
  - What Tamarin was built for
  - Who is behind it
  - The main workflow of Tamarin and how users interact with it

Next up: Tamarin’s foundations

Modeling in Tamarin



- **Multiset rewriting**
- 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(_,_), _^_, $\_^{-1}$, _*_, 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**

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

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

- **Executions**

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

- **Traces**

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

‘c’ constant

Example 1: basic

- **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')]

Example 2: fresh & public

‘c’	constant
~t	t has type fresh
$t	t has type public

- **Rules**
  - rule 1: [Fr(~k)] –[GenKey($A)]→ [Key($A, ~k)]

- **Execution example**
  - [ ]
  - –[GenKey(‘alex’)]→ [Key(‘alex’, k.1)]
  - –[GenKey(‘alex’)]→ [Key(‘alex’, k.2)]
  - –[GenKey(‘blake’)]→ [Key(‘blake’, k.3)]

- **Corresponding trace**
  - [GenKey(‘alex’), GenKey(‘alex’), GenKey(‘blake’)]

‘c’	constant
!F	F is persistent

Example 3: 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'))]

- What we saw:
  - What the underlying model of Tamarin is: multiset rewriting
  - Basic elements: *fresh*, *public*, *constant*
  - How rules define a transition system
  - How the transitions define action traces

Next up: modeling NAXOS

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

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$\boxed{\mathrm{I}}$

Fresh esk_I

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

Modeling Naxos

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$\boxed{\mathrm{I}}$

Fresh esk_I

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

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

```
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
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'c'	constant
~t	t has type fresh
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$\boxed{\mathrm{I}}$

Fresh esk_I

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

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

```
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

lkA	A's long-term priv. key
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Fresh esk_I

$ex_I = h1(esk_I, lk_I)$

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

receive Y $\longleftarrow$

```
rule generate_ltk:
   let pkA = 'g'^~lkA
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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
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eskA	A's eph. priv. key
'c'	constant
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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 ) ] --> []
```

- What we saw:
  - The NAXOS protocol
  - How to model it using Tamarin’s rules

Next up: security properties

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
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'c'	constant
~t	t has type fresh
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!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
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!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

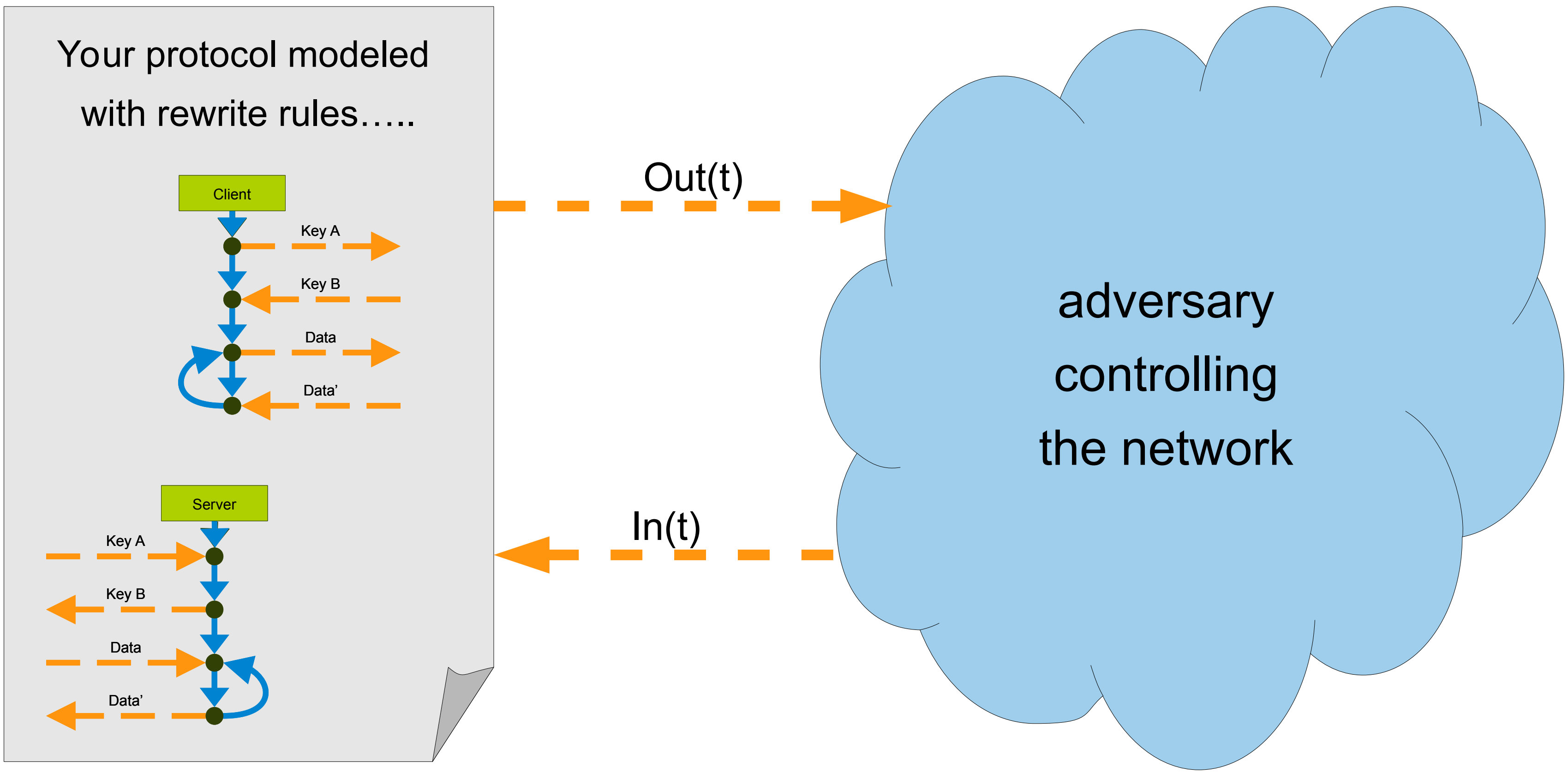
- Adversary can
  - learn **long-term keys**,
  - learn the **randomness** generated in sessions,
  - learn **session keys**
- But only as long as the Test session is *clean*:
  - **No reveal of session key of** Test session or its **matching session**, and
  - No reveal of randomness of Test session 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 ...

Tamarin tackles complex interaction with adversary



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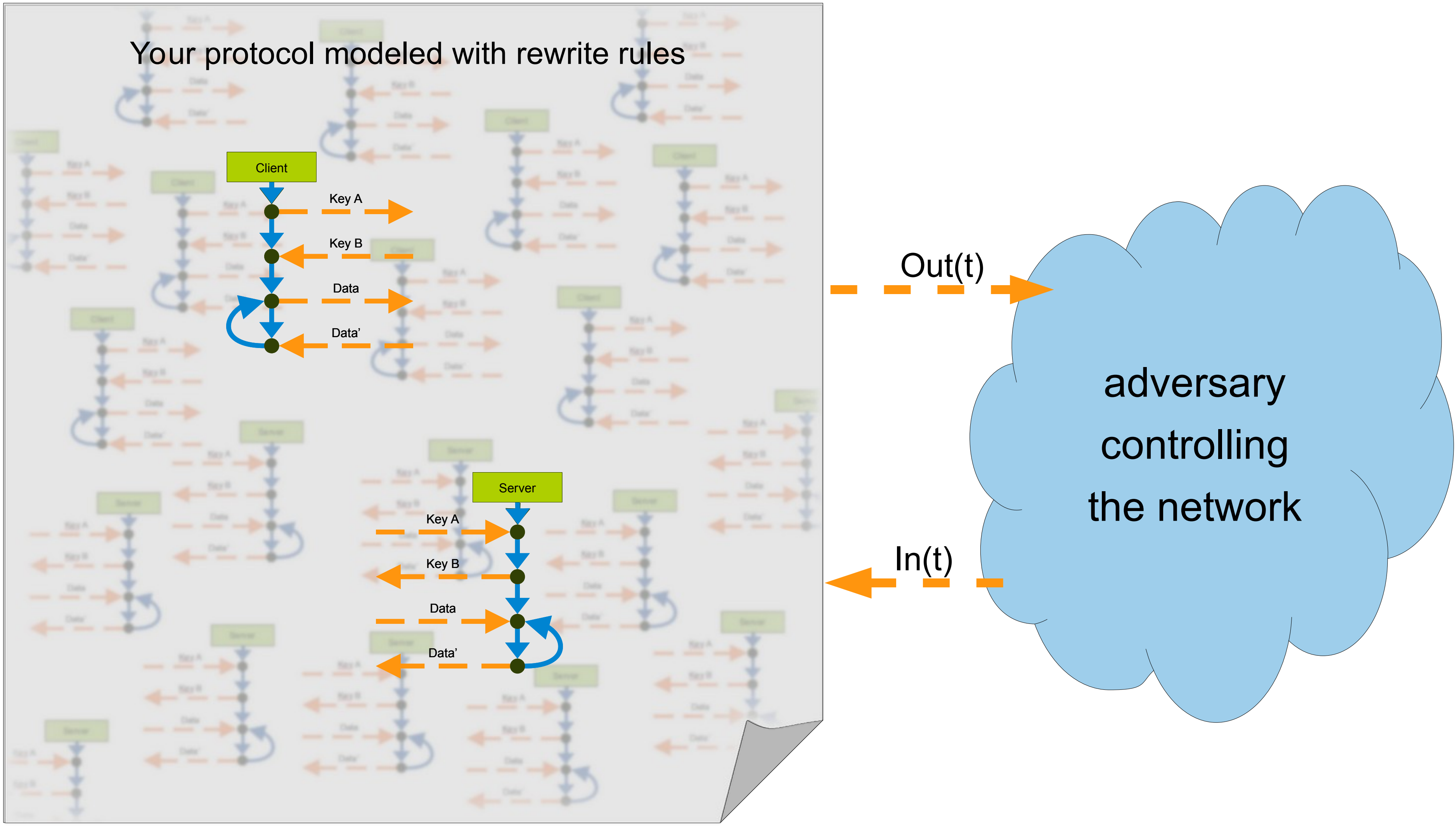
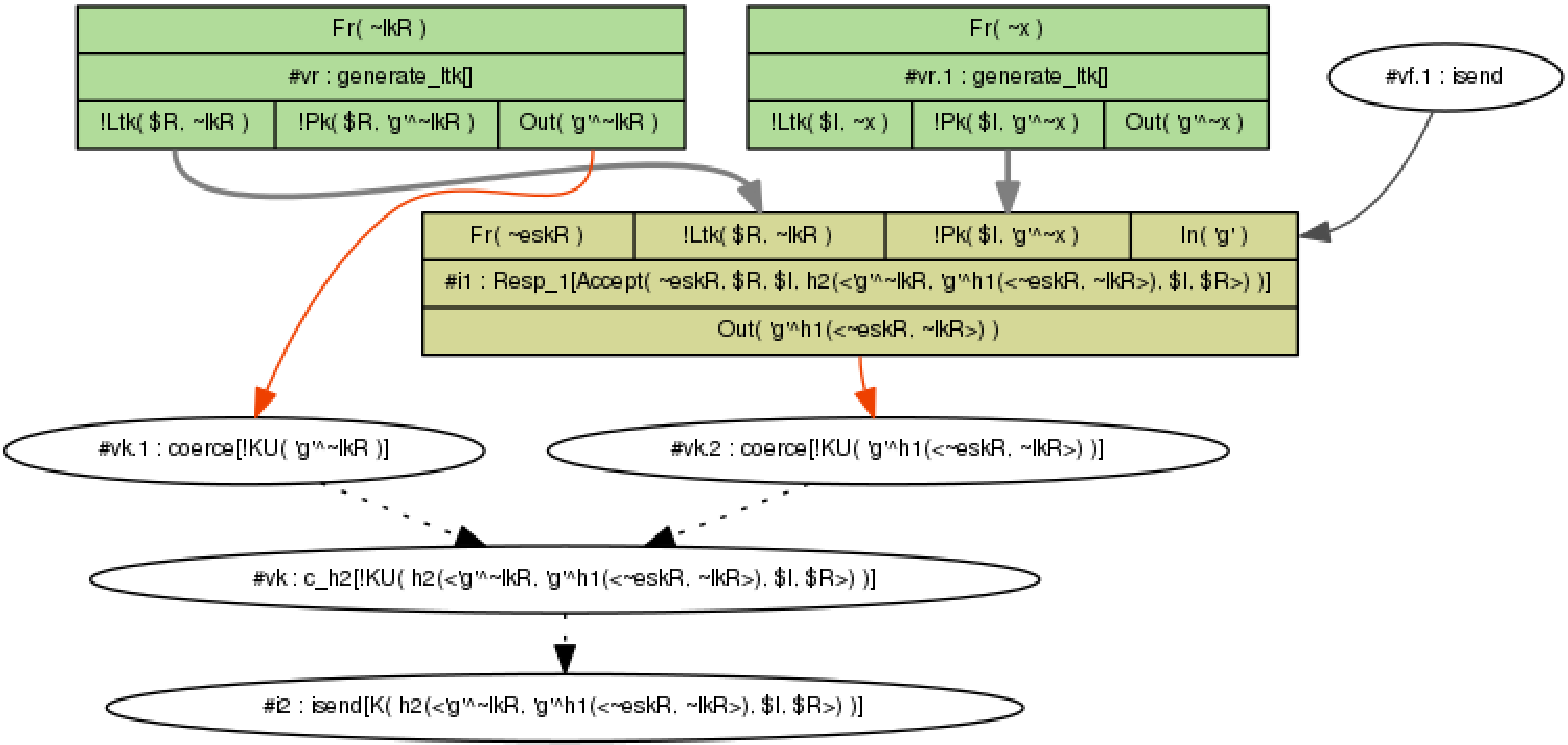


Demo

Reading Tamarin's graphs



- What we saw:
  - How we can write complex security properties in Tamarin
  - How Tamarin deals with counterexamples

Next up: Algorithm intuition

Algorithm intuition

- **Constraint solving algorithm**
- Main ingredients:
  - Dependency graphs
  - Deconstruction (decryption) chains
  - Finite variant property
- **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** (20+)
- 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

- What we saw:
  - Some intuition for Tamarin's algorithm
  - How it resembles constraint solving
  - What this looks like in the graphical user interface

Next up: in practice

How do I know my model is correct?

- **Many ways to model incorrectly**
- Executability
- Break the protocol on purpose
- Look at the chains...
  - (requires an understanding of the algorithm)
- 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

Complexity and termination

- Basic examples
  - Key exchange protocols
  - Signature-based protocols

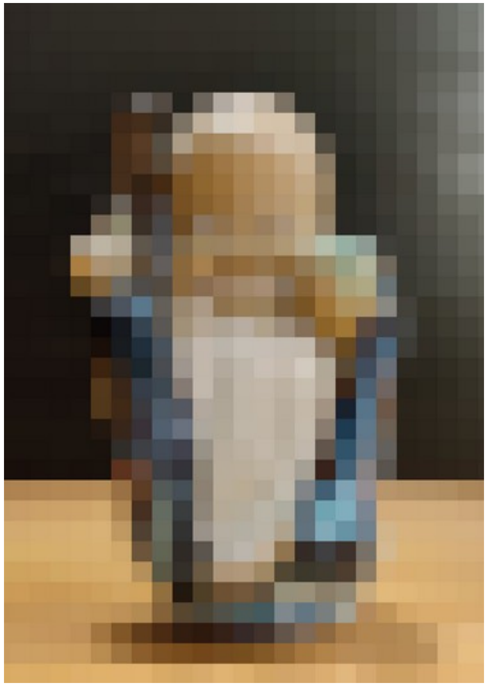
- More complex often needs hints (lemmas)
  - XOR
  - Protocols with complex loops/state machines
  - Diff-equivalence

- What we saw:
  - Challenges in practice include
    - For any formal approach: how and what to model?
    - How do I sanity-check my model?
    - Termination: heuristics & lemmas

Next up: symbolic analysis for cryptographers

Modeling real-world objects

Reality

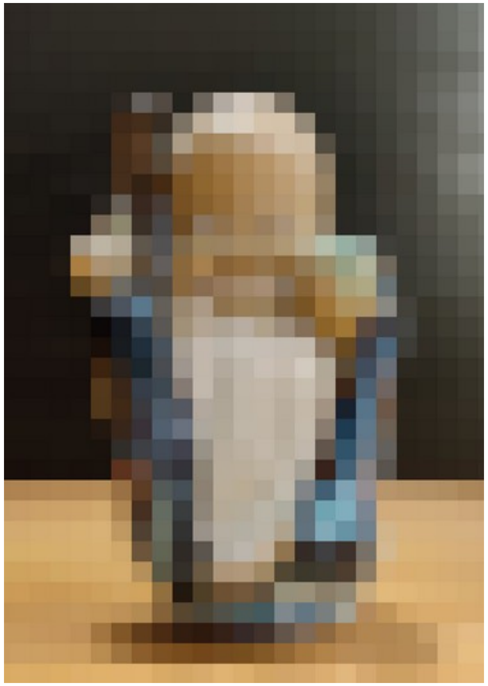


Symbolic

Modeling real-world objects

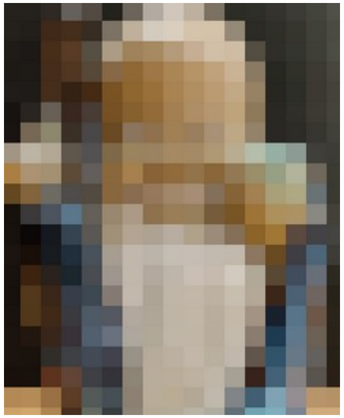
Reality

Computational



Symbolic

Modeling real-world objects



Reality   Computational   Symbolic

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**
  - Restrictions on equational theories, e.g., MQV style exponentiation tricky: we miss Kaliski's UKS attack on MQV.
- **What we *can* do** (some of it recent)
  - Negotiation, weak crypto
  - Non-prime order curves
  - DSKS attacks

- What we saw:
  - Some aspects of the relation between symbolic and computational approaches

Finally: where do I go from here?

Other Tamarin features….

- Advanced equational theory support
  - Diffie-Hellman, XOR, multisets, subterm-convergent and more...
- Construct your own proof interactively, and export it so others can verify
- Program your own heuristic
- Diff-equivalence (observational equivalence)
- Restrictions & conditional rules
- Applied-Pi input (through SAPIC integration)

Some recent results

FRESH

- More accurate modeling of cryptography
  - *Seems Legit: Automated Analysis of Subtle Attacks on Protocols that Use Signatures*
    Jackson, Cremers, Cohn-Gordon, Sasse – ia.cr/2019/779
  - *Prime, Order Please! Revisiting Small Subgroup and Invalid Curve Attacks on Protocols using Diffie-Hellman*
    Cremers, Jackson – ia.cr/2019/526
- Improving automation
  - *Automatic Generation of Sources Lemmas in Tamarin: Towards Automatic Proofs of Security Protocols*
    Cortier, Delaune, Dreier – Springer/HAL report
- EMV Chip and pin → attack to circumvent PIN requirement for VISA contactless
  - *The EMV Standard: Break, Fix, Verify*
    Basin, Sasse, Toro – emvrace.github.io

Starter exercise

- Start from files in `tamarin_ex1_part1.zip`
- Consider `NAXOS_01_simple.spthy`
  - Remove specific elements:
    - Remove the first argument to the `h2` function used to compute the session key, and check with Tamarin what happens if you analyse the properties
      - Note that you need to make the change both at the initiator and the responder
    - Remove the second argument instead, etc. etc.
- Repeat for `NAXOS_08_eCK.spthy`
  - Compare the results to before. Why do they differ?
- Compare `NAXOS_08_eCK.spthy` and `NAXOS_15_eCK_FPS.spthy`
  - Explain the difference (attacks?)

Advanced exercise

- Make sure you have the manual at hand
  - https://tamarin-prover.github.io/manual/index.html
- Try the toy protocol example exercise by Benjamin Kiesl
  - The last questions are challenging and will develop a deeper understanding of Tamarin
  - https://github.com/benjaminkiesl/tamarin_toy_protocol

Which tool should I be using?

- If you are starting out in the domain:
  - Try to find **existing protocol models** that are **close**(ish) to your problem for each tool
    - Pick the tool with the closest existing model, start by adapting that model
- More advanced:
  - Choice can be driven by the **security property** and **threat model** that you are interested in
  - Most approaches give incomparable guarantees; as a consequence they cover different attacks

Tamarin: conclusions

- **Tamarin** offers **many unique features**
  - State machine modeling, flexible properties, equational theories, global state, …
  - Enables automated analysis in areas previously unexplored
  - Many case studies available, from small protocols to large real-world protocols
  - Tamarin *found many new attacks*, impacting several real-world deployments
- Tool and sources are **free**; development on Github
  tamarin-prover.github.io
  - A real team effort!
- **Cas Cremers**


```
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