Security protocol analysis using the Tamarin Prover

Jannik Dreier, Lucca Hirshi

Based on slides by Cas Cremers

Overview & Structure

- **Overview**

1) Advanced Features
   - Heuristics
   - Equational Theories, Observational Equivalence
   - Recent developments
2) Related work
   - Other verification tools
   - Symbolic vs Computation verification
3) Tamarin's Algorithm – some intuitions
4) Some recent research:
   - Partial deconstructions & auto-sources
   - Using Tamarin for real: analzing 5G AKA

Overview & Structure

- **Mode of operation**
  - No need to use tools during the talk.
  - There will be time for questions during the talk and at the end
  - Please raise your hand in zoom or ask questions offline in the discord channel #security-protocols

Outline

Part 1:

Advanced Features

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, choose heuristic or override

Lemmas

- When it doesn’t terminate…
- Guide the proof manually; export
- Write (intermediate) **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

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*
    CCS'19
    Jackson, Cremers, Cohn-Gordon, Sasse – ia.cr/2019/779
  - *Prime, Order Please! Revisiting Small Subgroup and Invalid Curve Attacks on Protocols using Diffie-Hellman*
    CSF'19
    Cremers, Jackson – ia.cr/2019/526
- Improving automation
  - *Automatic Generation of Sources Lemmas in Tamarin: Towards Automatic Proofs of Security Protocols*
    ESORICS'20
    Cortier, Delaune, Dreier – Springer/HAL report
- EMV Chip and pin → attack to circumvent PIN requirement for VISA contactless
  - *The EMV Standard: Break, Fix, Verify*
    SP'21
    Basin, Sasse, Toro – emvrace.github.io
- Spectral analysis of Noise → security hierarchy of protocols from the Noise framework supported by formal analyses
  - *A Spectral Analysis of Noise: A Comprehensive, Automated, Formal Analysis of Diffie-Hellman Protocols*
    Usenix'20
    Girol, Hirschi, Sasse, Jackson, Cremers, Basin – Usenix Paper

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!

- What we saw:
  - Advanced Features
  - Heuristics, Lemmas
  - Equational Theories, Observational Equivalence
  - Recent developments

Next up: Related Work

Outline

Part 2:

Related Work

Other Symbolic Verification Tools

- Two main categories:
  1) Semi-decision procedures for unbounded # sessions
     Tamarin, ProVerif, etc. → Differences: language, automation, modeling features
  2) Decision procedures for bounded # sessions
     DeepSec, Akiss, Spec, etc.
- All tools can check trace properties (reachability)
- Some of them can check equivalence properties (often used to check privacy):
  - Unbounded # sessions: stricter notion of equivalence (diff-equivalence)
    → spurious attacks (sound but incomplete)
  - Bounded # sessions → decision (sound and complete)

Computational Model vs. Symbolic Model

- Computational model:
  - Messages → bitstrings
  - Primitives → probabilistic algorithms
  - Protocol roles → probabilistic polynomial-time Turing machines acting as oracles giving access to data
  - Attacker → any probabilistic polynomial-time Turing machine
  - Security goals often are quantitative and probabilistic (expressed as a probabilistic experiment)

\+ much more precise model

\- less automation and scalability

Modeling real-world objects

Reality

Symbolic

Modeling real-world objects

Reality

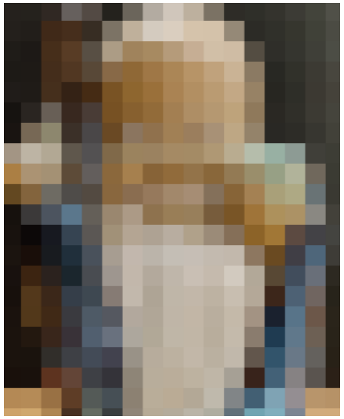
Computational

Symbolic

Modeling real-world objects

Reality

Computational



Symbolic

Survey

- More on the topic, with a comprehensive survey and comparison of the state-of-the-art tools:

SoK: Computer-Aided Cryptography

Manuel Barbosa*, Gilles Barthe†‡, Karthik Bhargavan§, Bruno Blanchet§, Cas Cremers¶, Kevin Liao†||, Bryan Parno**
*University of Porto (FCUP) and INESC TEC, †Max Planck Institute for Security & Privacy, ‡IMDEA Software Institute, §INRIA Paris, ¶CISPA Helmholtz Center for Information Security, ||MIT, **Carnegie Mellon University

***Abstract*—Computer-aided cryptography is an active area of research that develops and applies formal, machine-checkable approaches to the design, analysis, and implementation of cryptography. We present a cross-cutting systematization of the computer-aided cryptography literature, focusing on three main areas: (*i*) design-level security (both symbolic security and computational security), (*ii*) functional correctness and efficiency, and (*iii*) implementation-level security (with a focus on digital side-channel resistance). In each area, we first clarify the role of computer-aided cryptography—how it can help and what the caveats are—in addressing current challenges. We next present a taxonomy of state-of-the-art tools, comparing their accuracy,**

which are difficult to catch by code testing or auditing; ad-hoc constant-time coding recipes for mitigating side-channel attacks are tricky to implement, and yet may not cover the whole gamut of leakage channels exposed in deployment. Unfortunately, the current modus operandi—relying on a select few cryptography experts armed with rudimentary tooling to vouch for security and correctness—simply cannot keep pace with the rate of innovation and development in the field.

Computer-aided cryptography, or *CAC* for short, is an active area of research that aims to address these challenges. It en-

Will appear at SP 2021

ePrint: eprint.iacr.org/2019/1393.pdf

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
  - Also aim for a tool with a formal language that you are most familiar with
    Example: ProVerif & DeepSec→ process calculus (applid-pi)
    Tamarin→ multiset rewriting

- 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

- What we saw:
  - Other symbolic verification tools
  - Symbolic vs Computational Analysis

Next up: Tamarin’s Algorithm

Outline

Part 3:

Tamarin's Algorithm

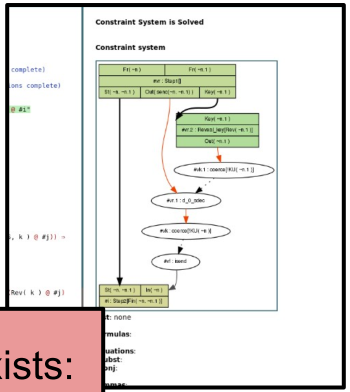
Tamarin: high-level

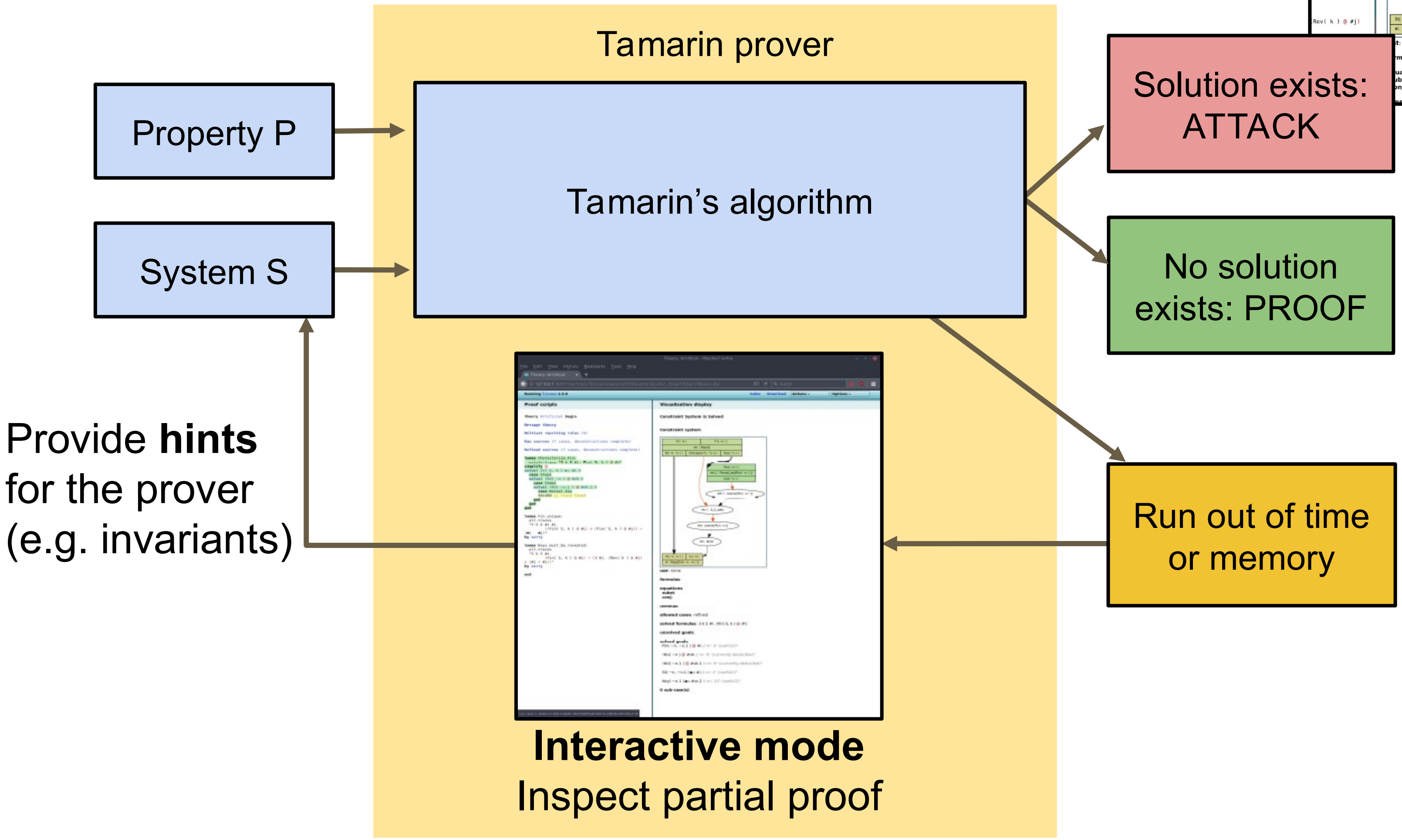
- **Modeling** protocol & adversary done using multiset rewriting
  - Specifies transition system; induces set of traces
- **Property** specification using fragment of first-order logic
  - Specifies “good” traces
- Tamarin tries to
  - provide proof that all system traces are good, or
  - construct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

Basic principles

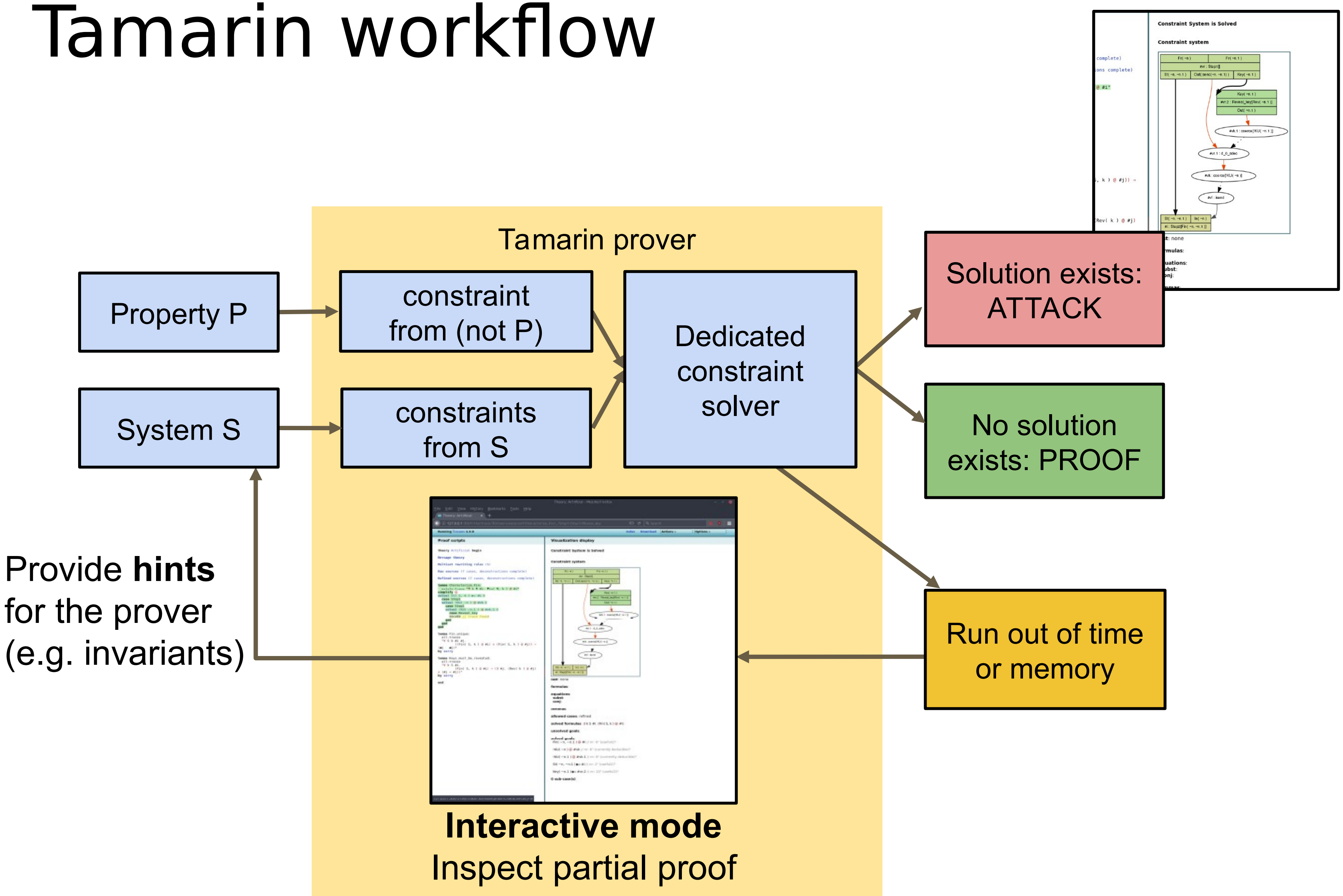
- Backwards search using **constraint reduction rules** (20+)
- Turn negation of formula into set of constraints
- Case distinctions
  - E.g.: Possible sources of a message or fact
- Try to establish:
  - no solutions exist for constraint system, or
  - there exists a „realizable“ execution (trace)
- If multiple rules can be applied: use heuristics

Tamarin workflow





Tamarin workflow



Tamarin prover

Constraint solver

Tamarin prover

Theorem Prover

Constraint solver

Demo

- What we saw:
  - Some intuition on Tamarin's Algorithm

Next up: two recent pieces of research on Tamarin

1) Improving Tamarin with sources lemmas generation (ESORICS'20)
2) Using Tamarin to conduct a security analysis of 5G authentication (CCS'18)

Intermission

Time for some questions