CISPA
HELMHOLTZ CENTER FOR INFORMATION SECURITY

Formal Analysis of Real-World Security Protocols

Lecture 0: Organization and Motivation

Aleksi Peltonen | 2024-10-21

What is a protocol?

- A **protocol** is a set of rules that determine how two or more parties can achieve a common goal by exchanging messages

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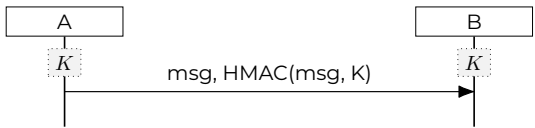
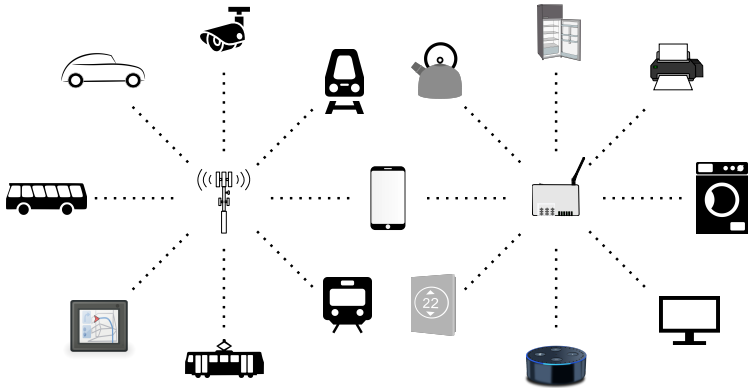
- Protocols that use cryptography to achieve security-related goals are called **security** or **cryptographic** protocols



Why should we care about protocol security?

- New things are constantly connected to the Internet
  - security **protocols** are everywhere



Why should we care about protocol security?

- New things are constantly connected to the Internet
  - security **threats** are everywhere

Nokia Threat Intelligence Report finds malicious IoT botnet activity has sharply increased[1]

Number of IoT devices (bots) engaged in botnet-driven DDoS attacks rose from around 200,000 a year ago to approximately 1 million devices.

Researchers find 36 new security flaws in LTE protocol[2]

South Korean researchers apply fuzzing techniques to LTE protocol and find 51 vulnerabilities, of which 36 were new.

The tech flaw that lets hackers control surveillance cameras[3]

Hackers Can Clone Millions of Toyota, Hyundai, and Kia Keys[4]

Encryption flaws in a common anti-theft feature expose vehicles from major manufacturers.

Massive HTTP DDoS Attack Hits Record High of 71 Million Requests/Second[5]

[1] https://www.nokia.com/about-us/news/releases/2023/06/07/nokia-threat-intelligence-report-finds-malicious-iot-botnet-activity-has-sharply-increased/

[2] https://www.zdnet.com/article/researchers-find-36-new-security-flaws-in-lte-protocol/

[3] https://www.bbc.com/news/technology-65975446

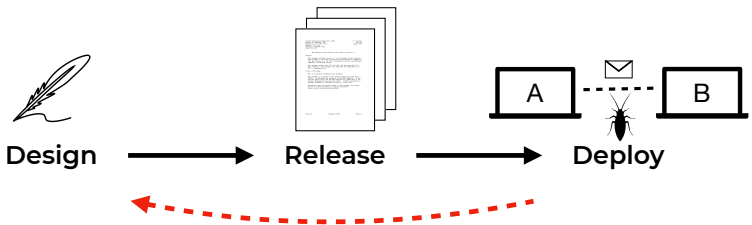
[4] https://www.wired.com/story/hackers-can-clone-millions-of-toyota-hyundai-kia-keys/

[5] https://thehackernews.com/2023/02/massive-http-ddos-attack-hits-record.html

How do we know a protocol is secure?

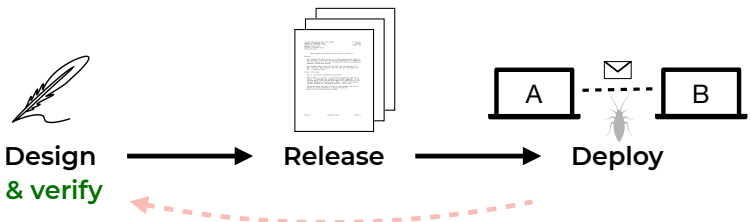
Before 1970

- **No proofs**
- Trial and error – we're not quite sure what a clever attacker could do
- Security: break - patch - repeat



1970-1980

- **Let's prove security** (Goldwasser, Micali, Yao)
- Attacker is any polynomial-time Turing machine
- Reduce security problem to generically solving a hard problem (e.g., discrete logarithm, factoring)



1980-1990

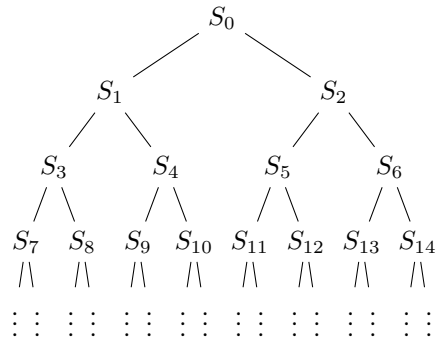
- **Computational proofs**
  - Proofs scale from primitives (“a signature scheme”) to small protocols (“a simple key exchange protocol”)
  - Typically pen-and-paper proofs, very error prone
  - *Not the focus of this lecture*
- **Symbolic proofs**
  - 1983: symbolic attacker model (Dolev-Yao)
  - Reason about abstract terms instead of bitstrings
  - “Perfect cryptography” assumption: Attacker can only decrypt an encrypted message if they know the key
  - Example property: Show that attacker can (not) learn a secret term

1990-2000

- **Model checkers become more widespread**
  - Analyze small finite cases
  - Found many flaws on basic designs
    - 1995: MitM attack on the NSPK protocol discovered with automated verification
- **Proliferation of tools & methods**
  - CSP/FDR, Prolog, NRL Protocol Analyzer, . . .
  - BAN Logic and variants
  - Isabelle (Paulson)

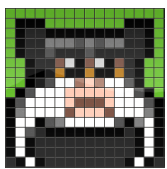
2000-2010

- **Bounded analysis matures**
  - AVISPA/Avantssar (OFMC, SAT-MC, CL-Atse)
  - Hit scaling barrier: State space explosion
- **Unbounded analysis?**
  - Undecidable.. Yet workable in practice?
  - ProVerif, Maude-NPA, Scyther, CPSA, Athena



2010-

- Tool situation stabilizes
  - ProVerif
  - **Tamarin prover**
- Increased expressiveness
  - Equational theories
  - Loops / stateful protocols
- **Real-world analysis**
  - Scaling to real-world protocols
  - Stronger threat models
  - Visibility to security engineers and standards bodies



Course Overview

This lecture

- What is formal analysis of security protocols?
- Learn about one state-of-the-art tool: the **Tamarin prover**
  - Learn how Tamarin works
  - Learn how to use Tamarin
  - Analyze protocols!
- Understand the **guarantees** and **limitations** of such analyses
- How have they been applied to **real-world protocols**?
- What **research** still needs to be done to make protocols secure?

Lecture plan

Lecture	Content
0	Organization and Motivation
1	Terms and Equational Theories
2	Protocols in the Symbolic Model
3	Attacker Model and Trace Properties
4	Verification Theory (Part 1)
5	Verification Theory (Part 2)
6	Using Tamarin in Practice
7	Advanced Security Properties and Threat Models
8	Advanced Features (Part 1)
9	Advanced Features (Part 2)
10	Security Protocol Standards
11	Relation to Cryptography, Scaling, and the Future

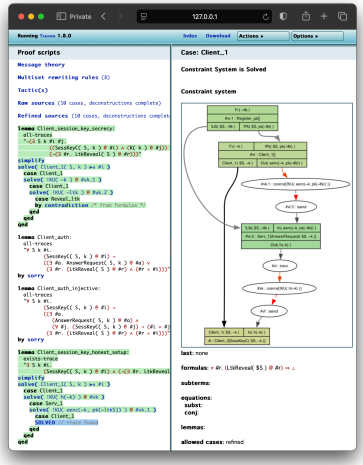
Course book

- David Basin, Cas Cremers, Jannik Dreier, and Ralf Sasse. **Modeling and Analyzing Security Protocols with Tamarin: A Comprehensive Guide**.
  - Available online: `https://tamarin-prover.com/book/index.html`
  - Each lecture will have a list of references to the relevant sections (based on v0.9.5)
- Other references will be included as additional reading when necessary

Analysis of Real-World Protocols

The Tamarin prover

- Symbolic analysis of security protocols
- First released in 2012, still under active development
- Simple protocols: Fully automatic
- Complex protocols: Interactive mode
- Considers an **unbounded number of sessions**, supports advanced features like stateful protocols and loops
- Open source on GitHub: `https://tamarin-prover.com/`



The Tamarin prover

Constraint solver

The Tamarin prover

Theorem prover

Constraint solver

Application domain examples

Key Exchange

- Naxos
- Signed DH
- Station-to-Station
- IKEv2
- Wireguard
- PQ-Wireguard
- Noise protocol family

Large Case Studies

- TLS 1.3
- IEEE 802.11 WPA2
- 5G-AKA
- 5G handover
- SPDM 1.2
- Apple iMessage PQ3

Payment

- EMV

Authentication

- WS-Security
- ACME

E-voting

- Alethea
- Belenios
- Selene

PKI

- ARPKI

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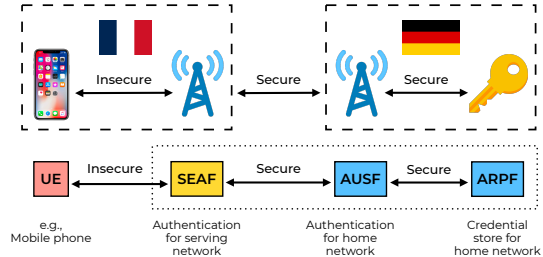
Example 1 - TLS 1.3

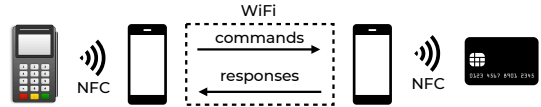
- **What is it?**
  - **T**ransport **L**ayer **S**ecurity, version **1.3**
  - Likely the world's most used security protocol
- **Tamarin analysis**
  - Explicit support for the IETF during the development of TLS 1.3
  - Several person months of work: much of it in just understanding the standard
- **Results**
  - Tamarin finds complete break for the main proposal for Rev 10+'s "delayed authentication"
  - Minimal attack involves 3 modes & 18 messages
  - Motivated change to other mechanism
  - Proven core properties for final version

Example 2 - 5G-AKA



- **What is it?**
  - **5G A**uthentication and **K**ey **A**greement
  - The core key exchange of 5G
- **Tamarin analysis**
  - Analysis of the near-final standard (>1 000 pages)
  - Standard notably harder to parse than TLS 1.3's RFC, yet semi-stable
- **Results**
  - Tamarin finds that privacy is not guaranteed (linkable) – needs redesign
  - Tamarin proves other properties under some assumptions
  - (Prediction: many current wontfix'es will cause trouble later)

Example 3 - EMV



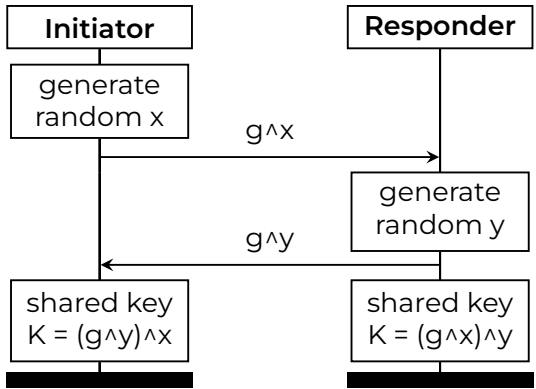
- **What is it?**
  - **E**uropay, **M**astercard, and **V**isa
  - Protocol between your bank, terminal, credit card
  - Modern versions have many different modes: Contactless, PIN, etc.
- **Tamarin analysis**
  - Standard documentation complex
  - Partial reverse engineering
- **Results**
  - Main attacks by researchers from ETH Zürich
    - PIN bypass: use man-in-the-middle to perform arbitrarily large transaction
    - Card mixup attack allow bypassing PIN codes
  - Later refined attacks by researchers from Birmingham and Surrey
    - Relay attacks and attacks on locked iPhones

Back to Basics: Diffie-Hellman

Diffie-Hellman key exchange

One of the first proposals for secure protocols, for which we will see several variants.

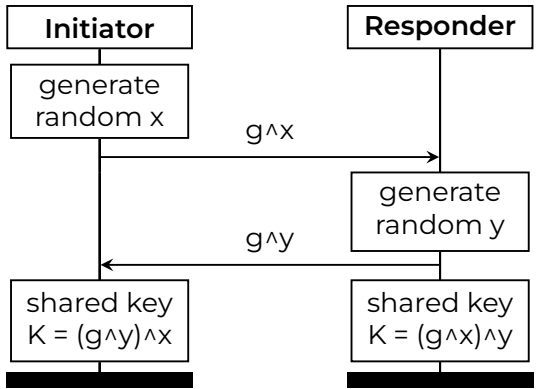
- “g^x” is shorthand for “gx mod P”, where g is the generator of a prime order group of order P. It is **efficient to compute g^x**
- If the group is sufficiently large, it is **infeasible to compute x from g^x**



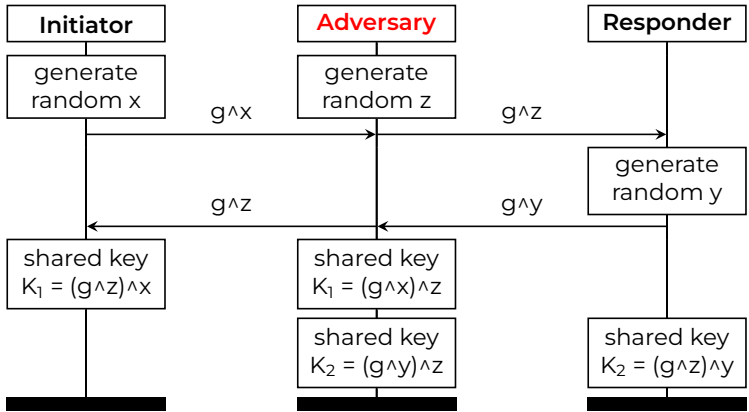
Diffie-Hellman key exchange

What should this protocol achieve?

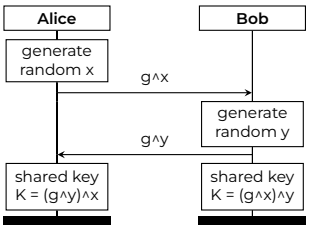
- If an adversary observes the network messages g^x and g^y, they cannot compute the shared key!
- What if the adversary can insert messages too?

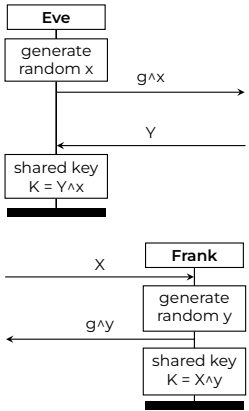


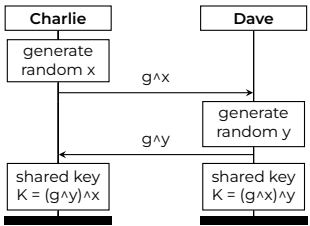
Man-in-the-middle attack



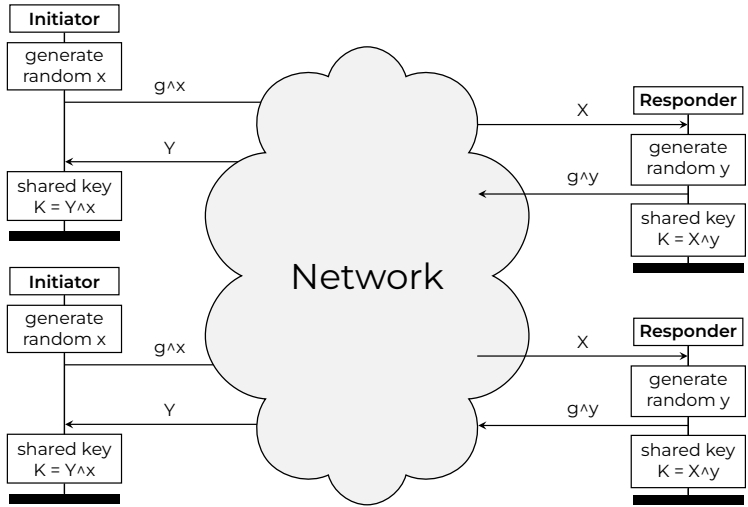
Execution model







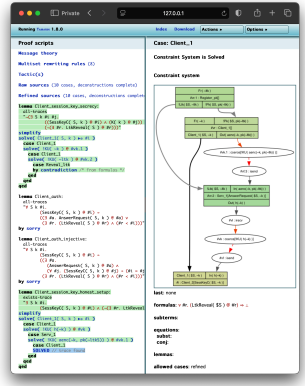
Adversary view



Summary

Summary

- Today, we learned that..
  - ..protocol security can be analyzed computationally or **symbolically**
  - ..we can automate the process using modern tools like **TAMARIN**
- In the next lecture, we will learn more about modeling..
  - *messages* as **terms**, and
  - *cryptographic primitives* as **equations**



Reading material

Recommended reading: [Bas+25, Ch. 1–2]

[Bas+25] D. Basin, C. Cremers, J. Dreier, and R. Sasse. **Modeling and Analyzing Security Protocols with Tamarin: A Comprehensive Guide.** Draft v0.9.5. May 2025.

Case studies i

Case studies:

TLS 1.3 [Cre+16; Cre+17],

5G-AKA [Bas+18; CD19],

EMV [BST21b; BST21a; Rad+22]

[Bas+18] D. Basin, J. Dreier, L. Hirschi, S. Radomirovic, R. Sasse, and V. Stettler. **A Formal Analysis of 5G Authentication.** In: Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security. 2018.

Case studies ii

[BST21a] D. Basin, R. Sasse, and J. Toro-Pozo. **Card Brand Mixup Attack: Bypassing the PIN in non-Visa Cards by Using Them for Visa Transactions.** In: 30th USENIX Security Symposium (USENIX Security 21). 2021.

[BST21b] D. Basin, R. Sasse, and J. Toro-Pozo. **The EMV Standard: Break, Fix, Verify.** In: 2021 IEEE Symposium on Security and Privacy (SP). 2021.

[CD19] C. Cremers and M. Dehnel-Wild. **Component-Based Formal Analysis of 5G-AKA: Channel Assumptions and Session Confusion.** In: 26th Annual Network and Distributed System Security Symposium, NDSS. 2019.

Case studies iii

[Cre+16] C. Cremers, M. Horvat, S. Scott, and T. van der Merwe. **Automated Analysis and Verification of TLS 1.3: 0-RTT, Resumption and Delayed Authentication.** In: 2016 IEEE Symposium on Security and Privacy (SP). 2016.

[Cre+17] C. Cremers, M. Horvat, J. Hoyland, S. Scott, and T. van der Merwe. **A Comprehensive Symbolic Analysis of TLS 1.3.** In: Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security. 2017.

[Rad+22] A.-I. Radu, T. Chothia, C. J. Newton, I. Boureanu, and L. Chen. **Practical EMV Relay Protection.** In: 2022 IEEE Symposium on Security and Privacy (SP). 2022.