Formal methods for software security

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Formal methods for software security
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- Certification
- Availability
- Cryptographic protocols

- Security types
- Reference monitors
- Integrity
- Refinement
- Computational model
- Security types
- Enforcement

- Confidentiality
- Information flow
- Sel4

- Secure OS
- Non-interference
- Side channels

- Secure programming
- Coq

Formal methods for software security

1. Basic concepts
2. Cryptographic protocols
3. Secure OS
4. Certification of software
5. Information flow
Basic security concepts

Confidentiality

• my secrets will not be disclosed … at least not more than I'm willing to accept.

Integrity

• my data and decisions are not influenced by intruders.

Availability

• software and services are there when I need them.
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Security ≠ Safety
Basic security concepts

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Security ≠ Safety

... but they are strongly related
Attacker model

Security is open-ended!

The question

**Is my software secure?**

must be complemented by an **attacker model**, stating the threats we are up against.

Specify the attackers

- observational power (output, network messages, time,…)
- actions (code insertion, message injection,…)
- access to machine (physical, through network,…)

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Enforcement mechanisms

Certification of applications
  • Common Criteria
  • Formal methods for reaching upper levels.

Security-enhancing software development
  • secure programming guidelines
  • secure compilation.

Static code analysis
  • eg, Java's byte code verifier, information flow analysis.

Reference monitors and run-time analysis
Cryptographic protocols
Models of cryptographic protocols

Symbolic models

• specified as a series of exchanges of messages
• assuming perfect cryptography

Example: two agents A, B

1. \( A \leftrightarrow B : \{N_A, A\}_{K_B} \)
2. \( B \leftrightarrow A : \{N_A, N_B, B\}_{K_A} \)
3. \( A \leftrightarrow B : \{N_B\}_{K_B} \)

Attackers may

• intercept and re-send messages
• encrypt and decrypt messages (with available keys)
Verification

Model

- state = current message + state of A,B, and attacker
- rewriting rules defining protocol and attacker
  \[
  \{ (msg)_{key}, key \} \rightarrow \{ msg, (msg)_{key}, key \}
  \]

Security properties

- secrecy ("no state where attacker has the secret")
- authentification, re-play, …
- specific properties ("key may not be used on stored content", "vote has been counted")
Tools

A variety of mature tools

- AVISPA, Tamarin, ProVerif, Timbuk, …

based on

- term and multi-set rewriting, Horn clauses, …

Interfaces for writing and animating protocols

- eg as Message Sequence Charts (SPAN).
Computational models

A model closer to reality:

- Messages: bit strings,
- Crypto primitives: functions on bit strings,
- Attacker: any probabilistic poly-time Turing machine.

Properties proved for all traces except for a set of traces of negligible probability.

Secrecy: attacker can distinguish secret from random number with only infinitesimal probability.

Proofs by refinement of models.

See eg. the cryptooverif tool
Implementations of crypto protocols
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Security concerns with implementations of protocols and basic operations of cryptography.
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Implementations of cryptographic primitives are prone to side channel attacks:

- leaking secrets via timing or energy consumption,
- a challenge for implementors
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Implementations of cryptographic primitives are prone to side channel attacks:

• leaking secrets via timing or energy consumption,
• a challenge for implementors

Implementations of entire protocols are prone to programming errors:

• see the Verified TLS project for building a formally verified implementation of TLS.
Secure operating systems
Security and OS

Organized Sharing of resources between processes

- using the same memory
- communicating via IPC

... and still guarantee isolation properties.
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Large, complex software - long history of security alerts.
The SEL4 project

Project run at NICTA 2004-2014.

Formal verification of Liedtke's L4 micro-kernel.

- small code base (9 K Loc),
- threads, memory management, IPC, interrupts, capability-based AC,
- running on ARM,
- verified using the Isabelle/HOL theorem prover.

Prove:

- Functional correctness (and a lot of safety properties)
- Non-interference
SEL4: proof structure

Proof by refinement

Abstract model → HOL

Executable model → Haskell

C implementation → C

Binary kernel → HOL4 binary spec
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On the "Abstract model", build
  • access control model,
  • integrity and confidentiality proof
SEL4: proof structure

Proof by refinement

- Abstract model \(\rightarrow\) HOL
- Executable model \(\rightarrow\) Haskell
- C implementation \(\rightarrow\) C
- Binary kernel \(\rightarrow\) HOL4 binary spec

On the "Abstract model", build
- access control model,
- integrity and confidentiality proof

200 000 lines of Isabelle/HOL proof \(\rightarrow\) 25 person-years
Prove & Run's ProvenCore

SEL4 uses Isabelle/HOL and Haskell

- higher-order logic and lazy functional programming is still not main-stream development tools.

Prove & Run has developed a formally verified microkernel ProvenCore

- refinement proof method
- isolation properties.

using their SMART development framework:

- functional, executable specification
- closer to programmer's intuition
- equipped with a dedicated prover
Certification of Java Card applications
Java Card certification
Java Card certification

Java Card

- reduced dialect of Java for bank cards and SIM,
- no dynamic loading, reflection, floating points, threads,…
- "resource-constrained" programming practice.
Java Card certification

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Industrial context:

- Applications developed by third-parties and put on an app store.
- Must be certified according to industry norms (eg, AFSCM* norms for NFC applications).
- Need "light-weight" certification techniques.

*Association Française du Sans Contact Mobile
AFSCM norms/guidelines

Enforce good programming practice and resource usage

- catch exceptions, call methods with valid args,
- no recursion and almost no dynamic allocation,
- don't call method $xxx$.

Avoid exceptions due to

- null pointers, array indexing, class casts,
- illegal applet interaction through the firewall.
The Java Card analyser
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A combination of numeric and points-to analysis

• tailored to the application domain,
• take advantage of imposed restrictions,
• precise (flow-sensitive, inter-proc, trace partitioning).
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Major challenge: modelling the Java Card API.
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Outcome: an abstract model of execution states

- mined by queries formalising the AFSCM norms.
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<table>
<thead>
<tr>
<th>Alarms</th>
<th>A1</th>
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</tr>
</tbody>
</table>
Information flow analysis
Back to confidentiality

Classify data as either

- private/secret/confidential
- public

A basic security policy:

"Confidential data should not become public"
Breaking confidentiality

```c
int secret s;    // s ∈ \{0,1\}
int public p;
```
Breaking confidentiality

```c
int secret s; // s ∈ \{0,1\}
int public p;

p := s;  \hspace{1cm} \text{Direct flow}
```
Breaking confidentiality

```c
int secret s;       // s \in \{0,1\}
int public p;

p := s;            // Direct flow

if s == 1 then
    p := 1
else
    p := 0

// Indirect flow
```
Non-interference

Confidentiality can be formalised as non-interference:

Changes in secret values should not be publicly observable
Non-interference

Confidentiality can be formalised as **non-interference**:

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Confidentiality can be formalised as non-interference:

Changes in secret values should not be publicly observable

\[ \forall s_1, s_2, s_1', s_2', \quad s_1 \sim s_2 \land (P, s_1) \downarrow s_1' \land (P, s_2) \downarrow s_2' \implies s_1' \sim s_2' \]
Dynamic enforcement

Add a security level ("taint") to all data and variables

Security levels evolve due to assignments
Dynamic enforcement

Add a security level ("taint") to all data and variables

Security levels evolve due to assignments

```plaintext
p := s; // direct flow
```
Dynamic enforcement

Add a security level ("taint") to all data and variables

Security levels evolve due to assignments

\[ p := s; \quad // \quad \text{direct flow} \]
Dynamic enforcement

Add a security level ("taint") to all data and variables

Security levels evolve due to assignments

\[
p := s; \quad \text{\// direct flow}
\]

and when we assign under secret control:

\[
\text{if } s == 1 \text{ then}
\]
\[
p := 1
\]
Dynamic enforcement

Add a security level ("taint") to all data and variables

Security levels evolve due to assignments

\[ p := s ; \]  // direct flow

and when we assign under secret control:

\[ \text{if } s == 1 \text{ then} \]
\[ p := 1 \]
Secure?

Not enough to enforce confidentiality!

```plaintext
int secret s;  // s ∈ {0,1}
int public p,q;

p := 0; q := 1;
if s == 0 then
  q := 0;
if q == 1 then
  p := 1;
```
Secure?

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int secret s; // s ∈ {0,1}
int public p,q;

p := 0; q := 1;
if s == 0 then
  q := 0;
if q == 1 then
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s=0

\[ p=0,q=1 \]

p=0,q=0

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<th>p</th>
<th>q</th>
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<tbody>
<tr>
<td>0</td>
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<td>0</td>
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```c
int secret s;    // s ∈ {0,1}
int public p,q;

s=0
p=0,q=1
skip
p=0,q=0
skip
p=1,q=1

Need the "no-sensitive-upgrade" principle
```
Static information flow control

Information flow types:

\[ T, T_x, T_{pc} \in \{ \text{public} \subseteq \text{secret} \} \]

Typing rules:

\[
\frac{\vdash e : T \quad T \subseteq T_x \quad T_{pc} \subseteq T_x}{T_{pc} \vdash x := e} \text{ assign}
\]

\[
\frac{\vdash e : T \quad T_{pc} \sqcup T \vdash S_i \quad i = 1, 2}{T_{pc} \vdash \text{if } e \text{ then } S_1 \text{ else } S_2} \text{ if}
\]

Well-typed programs are non-interferent
Declassification and side channels

How to declassify confidential data:

• what and when to declassify?
• how much to declassify (passwd, statistics)?

Information leaks due to other channels

• timing
• energy consumption

Challenge: analysis tools to check constant-time properties of (well-crafted) cryptographic computations.
Coda
Many more topics

Malware detection
  • analysis of (obfuscated) binaries.

Access control
  • formal models and enforcement.

Attack trees.

Web security
  • secure web programming with JavaScript et al.

Privacy
  • differential privacy (theory vs. practice),
    • software in coherence with legislation (EU GDPR).
Formal methods for software security

• Formal methods can improve the security of software.
• Come with solid foundations and mature tools.
• More and more industrial applications.
• Technology is becoming main-stream.
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Thank you