



Formal methods for software security (invited talk)

Thomas Jensen

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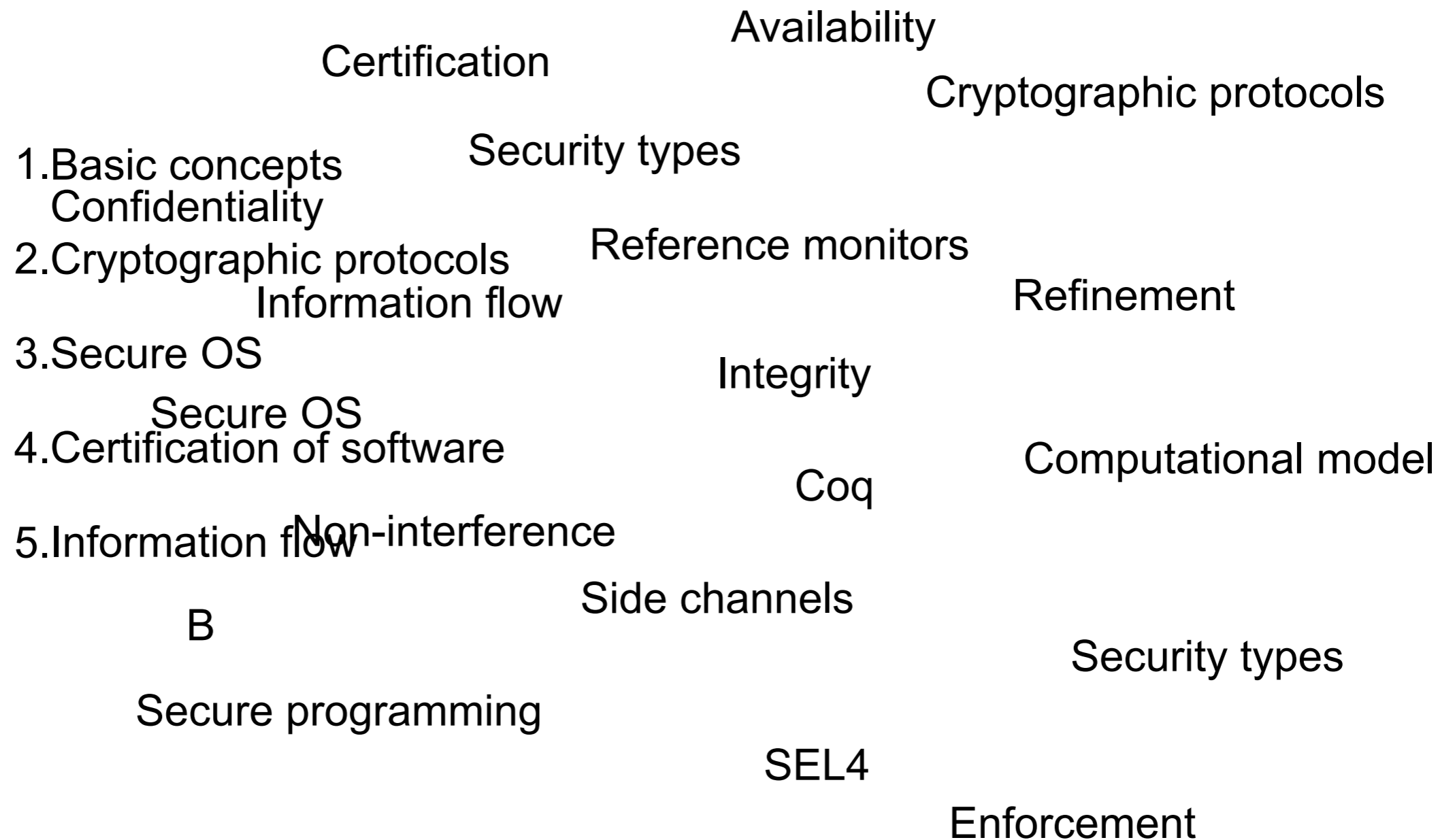
Formal methods for software security

Thomas Jensen, INRIA

GDR Sécurité

Paris, 1 Juin 2017

Formal methods for software security



Basic security concepts

Confidentiality

- the software will not disclose my secrets ... at least not more than I'm willing to accept.

Integrity

- data and decisions are not influenced by intruders.

Availability

- software and services are there when I need them.

Security \neq 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,...)

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. $A \hookrightarrow B : \{N_A, A\}_{K_B}$
2. $B \hookrightarrow A : \{N_A, N_B, B\}_{K_A}$
3. $A \hookrightarrow B : \{N_B\}_{K_B}$

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

$$(\{msg\}_{key}, \dots, key, \dots) \rightarrow (msg, \{msg\}_{key}, \dots, key, \dots)$$

Security properties

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

Tools

A variety of mature tools

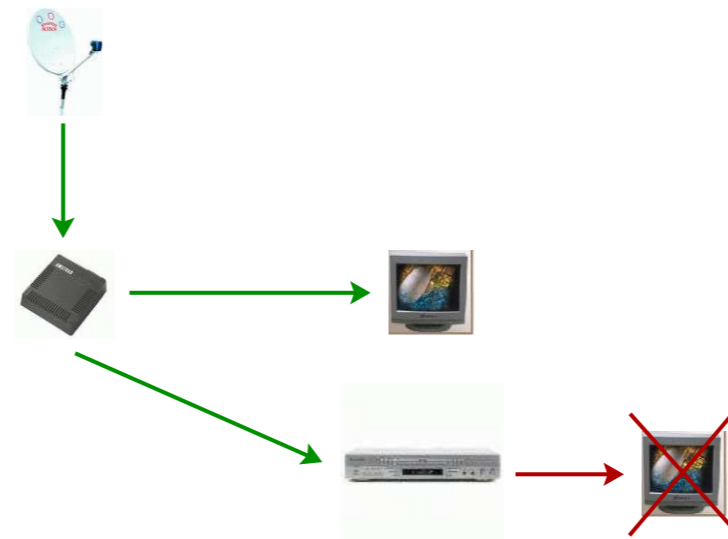
- AVISPA, Tamarin, ProVerif, APTE, ...

based on solid theory

- term and multi-set rewriting, Horn clauses, π -calculus, ...

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 `cryptoverif` tool

Implementations of crypto protocols

Security concerns with **implementations** of protocols and basic operations of cryptography.

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.

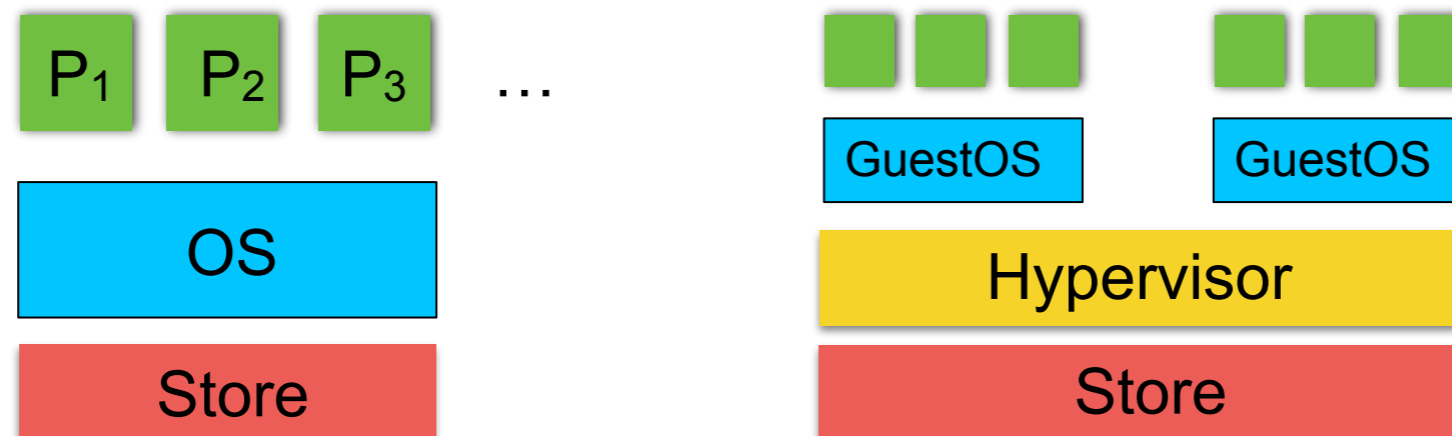
Secure operating systems

Security and OS

Organized Sharing of resources between processes

- using the same memory
- communicating via IPC

and still guarantee **isolation properties**.



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.

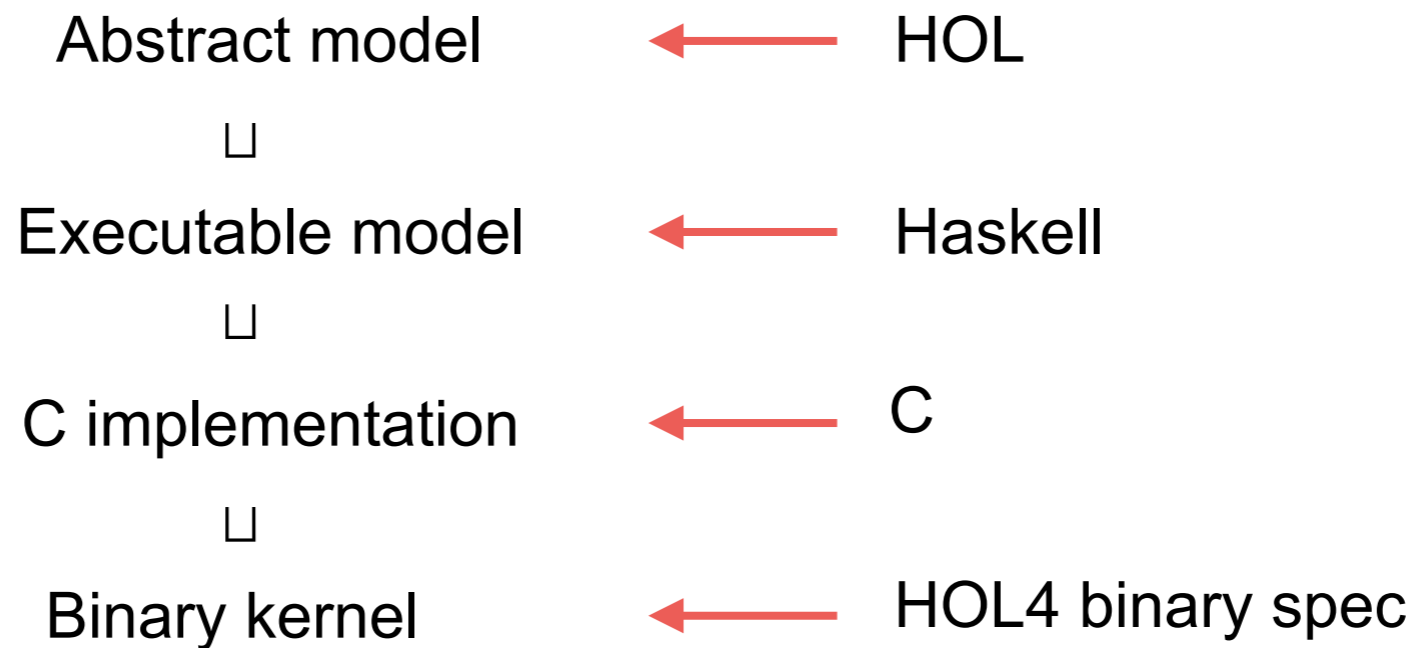
- small code base (9 K Loc),
- threads, memory management, IPC, interrupts, capability-based access control,
- running on ARM,
- verified using the Isabelle/HOL theorem prover.

Prove:

- Functional correctness (and a lot of safety properties)
- Non-interference

SEL4: proof structure

Proof by refinement



On the "Abstract model", build

- access control model,
- integrity and confidentiality proof

200 000 lines of Isabelle/HOL proof

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

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

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

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).

Major challenge: modelling the Java Card API.

Outcome: an abstract model of execution states

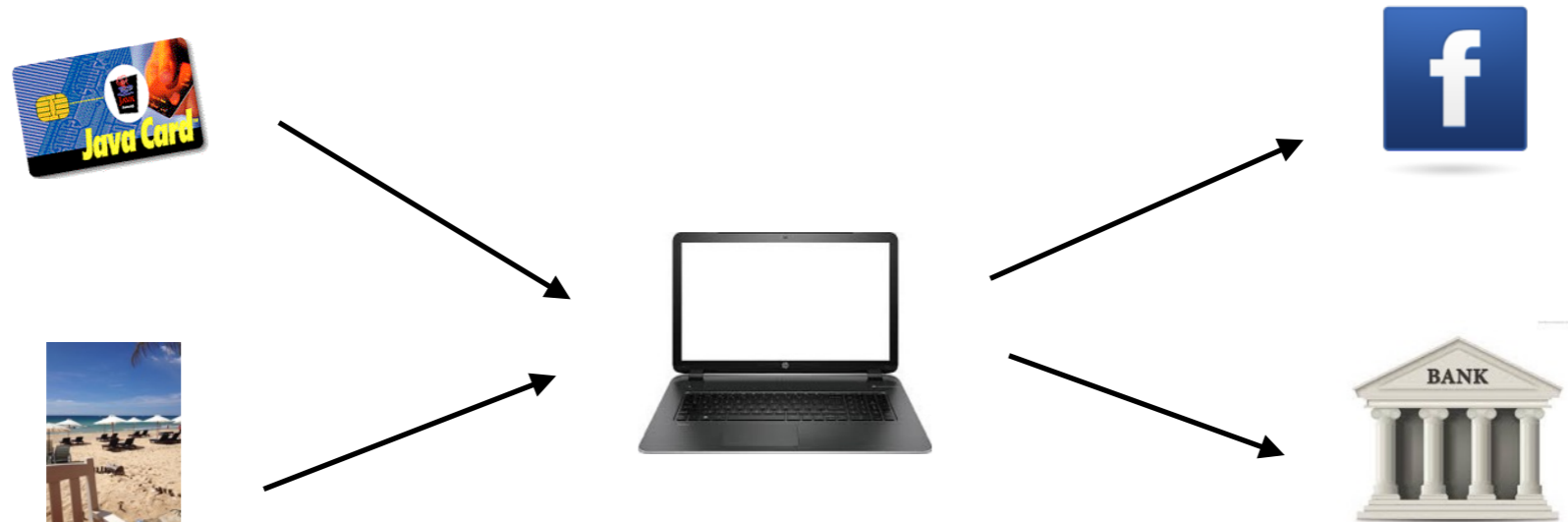
- mined by queries formalising the AFSCM norms.

| | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 |
|----------------------|----|----|----|----|----|----|----|----|
| Alarms | | | | | | | | |
| ClassCastException | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| NegativeArraySize | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| ArrayStoreException | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| SecurityException | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| AppletInStaticFields | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| ArrayConstantSize | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| InitMenuEntries | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

| | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 |
|----------------------|----|----|----|----|----|----|----|----|
| Alarms | | | | | | | | |
| NullPointerException | 94 | 98 | 99 | 99 | 97 | 98 | 97 | 99 |
| ArrayOutOfBounds | 71 | 88 | 92 | 87 | 92 | 98 | 90 | 98 |
| CatchIndividually | 46 | 23 | 82 | 31 | 32 | 67 | 57 | 53 |
| CatchNonISOException | x | x | x | x | x | x | x | x |
| HandlerAccess | x | ✓ | x | x | x | ✓ | ✓ | ✓ |
| AllocSingleton | ✓ | ✓ | ✓ | ✓ | ✓ | x | ✓ | ✓ |
| SDOrGlobalRegPriv | x | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| SWValid | ? | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| ReplyBusy | ? | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

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

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

```
p := s;
```

Direct flow

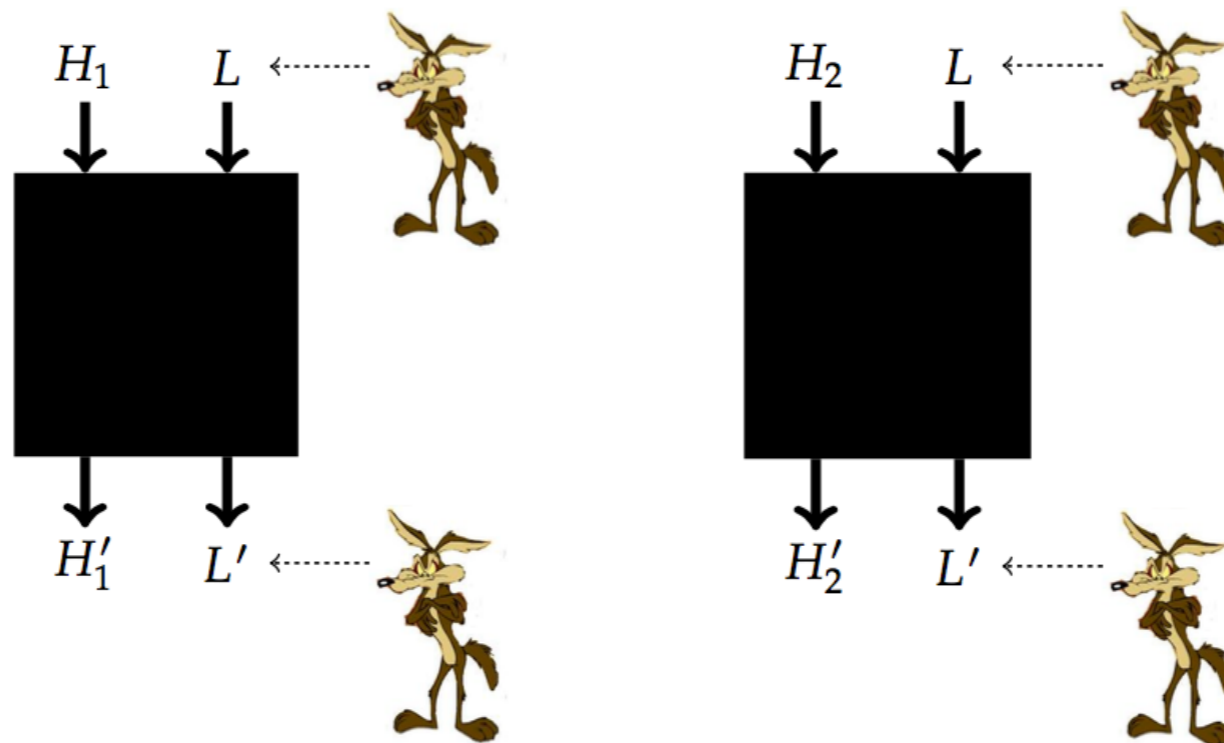
```
if s == 1 then  
  p := 1  
else  
  p := 0
```

Indirect flow

Non-interference

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

Changes in secret values should not be publicly observable



$$\forall s_1, s_2, s'_1, s'_2, \quad s_1 \sim s_2 \wedge (P, s_1) \Downarrow s'_1 \wedge (P, s_2) \Downarrow s'_2 \implies s'_1 \sim s'_2$$

Dynamic enforcement

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

Security levels evolve due to assignments

```
p := s;           // direct flow
```

and when we assign under secret control:

```
if s == 1 then  
  p := 1
```

Secure?

Not enough to enforce confidentiality!

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

| | | |
|----------------------------|---------------------|---------------------|
| <pre>p := 0; q := 1;</pre> | <pre>s=0</pre> | <pre>s=1</pre> |
| <pre>if s == 0 then</pre> | <pre>p=0, q=1</pre> | <pre>p=0, q=1</pre> |
| <pre> q := 0;</pre> | <pre>p=0, q=0</pre> | <pre>skip</pre> |
| <pre>if q == 1 then</pre> | <pre>skip</pre> | <pre>p=1, q=1</pre> |
| <pre> p := 1;</pre> | <pre>p=0</pre> | <pre>p=1</pre> |

Need the "no-sensitive-upgrade" principle

Static information flow control

Information flow types:

$$T, T_{\mathbf{x}}, T_{\text{pc}} \in \{\mathbf{public} \sqsubseteq \mathbf{secret}\}$$

Typing rules:

$$\frac{\vdash \mathbf{e} : T \quad T \sqsubseteq T_{\mathbf{x}} \quad T_{\text{pc}} \sqsubseteq T_{\mathbf{x}}}{T_{\text{pc}} \vdash \mathbf{x} := \mathbf{e}} \quad \textit{assign}$$

$$\frac{\vdash \mathbf{e} : T \quad T_{\text{pc}} \sqcup T \vdash \mathbf{S}_i \quad \mathbf{i} = 1, 2}{T_{\text{pc}} \vdash \mathbf{if} \ \mathbf{e} \ \mathbf{then} \ \mathbf{S}_1 \ \mathbf{else} \ \mathbf{S}_2} \quad \textit{if}$$

Well-typed programs are non-interferent

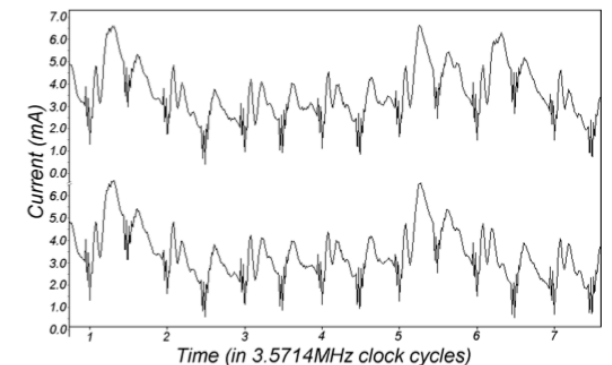
Declassification and side channels

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).

Thank you

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.

Thank you