Karlsruhe Institute of Technology

Applications of Formal Verification

Verification of Information Flow Properties

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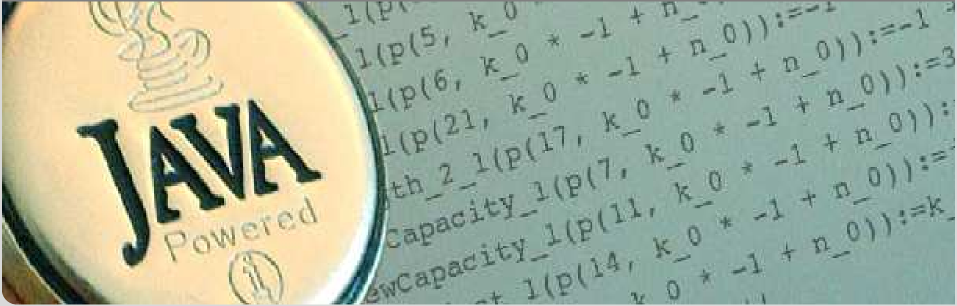


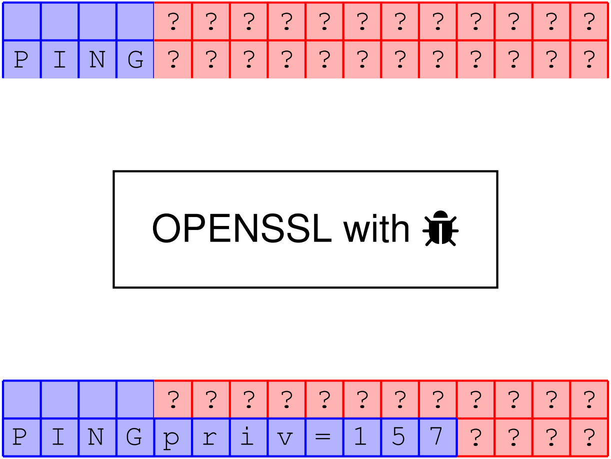
Security is everywhere . . .

Heartbleed Disaster

- published in April 2014
- security bug in the OpenSSL TLS library
- heartbeat protocol (“ping”)
- vulnerability classified as a buffer over-read (read more data than should be allowed.)
- some 17% (around half a million) of certified secure web servers believed vulnerable to the attack
- fixed by adding one `if` statement.
- known data theft: hackers stole security keys from community health systems, compromising the confidentiality of 4.5 million patient records.

Heartbleed – Information Flow

OpenSSL Heartbeat Request `('PING', 12)`

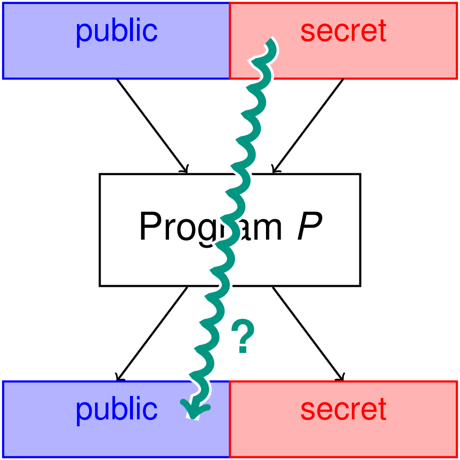


				?	?	?	?	?	?	?	?	?	?	?	?
P	I	N	G	?	?	?	?	?	?	?	?	?	?	?	?

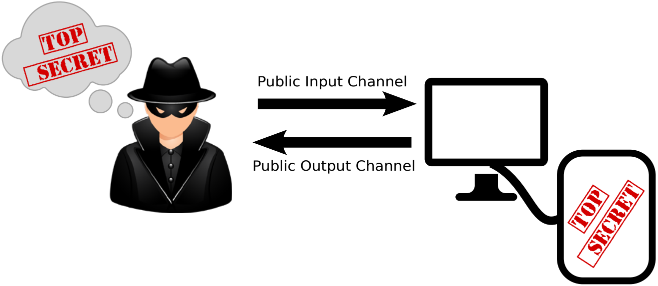
OPENSSL with 🐞

				?	?	?	?	?	?	?	?	?	?	?	?
P	I	N	G	p	r	i	v	=	1	5	7	?	?	?	?

Information Flow Model



Attacker model



- Attacker communicates with system over public channels
- . . . tries to learn the secret which is kept inside the system
- . . . or at least parts of the secret

Attacker scenarios

Attacker is . . .	Public channels are . . .
an agent over the network	network traffic
another application on same device	shared resources (files), interprocess comm.
program using a library	shared memory, method calls

In models:

Attacker's capabilities expressed by the *public channels*.

Mathematical model

Every program is a function

$$P : \mathit{SecretInput} \times \mathit{PublicInput} \rightarrow \mathit{SecretOutput} \times \mathit{PublicOutput}$$

Decomposition into two functions $P = (s, p)$

$$\begin{aligned} s &: \mathit{SecretInput} \times \mathit{PublicInput} \rightarrow \mathit{SecretOutput} \\ p &: \mathit{SecretInput} \times \mathit{PublicInput} \rightarrow \mathit{PublicOutput} \\ P(h, \ell) &= \big(s(h, \ell), p(h, \ell)\big) \end{aligned}$$

We will define security properties for such programs and analyse them.

Convention

Variables with high security status are named h (h_1 etc.) and variables with low (public) security status are named ℓ (ℓ_1 etc.).

Example

Java method

```
private int h;
public int l;
void f() {
   if(h > 5) {
      l ++;
   } else {
      h --;
   }
}
```

`h` and `l` serve as input and output variables.

Model

$$s_f(h,l) = \begin{cases} h & \text{if } h > 5 \\ h - 1 & \text{if } h \leq 5 \end{cases}$$

$$p_f(h,l) = \begin{cases} l + 1 & \text{if } h > 5 \\ l & \text{if } h \leq 5 \end{cases}$$

Attacker model

- Attacker can see `l`.
- Attacker cannot see `h`.
- (e.g. by visibility modifiers)

Secure information flow as a game

Parties: the attacker and the system

Assume: Atacker knows program P

Protocol:

1. Attacker chooses
   $x, y \in \mathit{SecretInput}$,
   $z \in \mathit{PublicInput}$
2. System selects $a \in \{x, y\}$ randomly (i.i.d.).
3. Attacker receives public output $p(a, z)$.
4. Attacker guesses whether $a = x$ or $a = y$.

Winner: Attacker wins this game if they guess a correctly

➜ *Program has **secure information flow** if best guessing strategy has winning probability 0.5.*

Secure information flow as a game (II)

Secure information flow is a hard condition:

- **Attacker may freely choose the secret**
  - even if that value may be unlikely to occur
  - (→ chosen plaintext in crypto)

- **The winning probablity must not deviate from 50%.**
  - 50% are the winning odds for blind guessing.
  - Information gained from public channels still leaves the attacker with same chance.
  - information theoretical security
  - stricter than computational security
    (increasing winning probability within negligible polynomial bounds, → IND-CPA in cryptography)

Noninterference

(Goguen and Meseguer, 1982)

Semantic definition

A program $P = (s, p)$ satisfies **noninterference** if a user cannot learn anything about secret input from inspecting public outputs.

Mathematical condition

$$\forall h_1, h_2, l. \quad p(h_1, l) = p(h_2, l)$$

The public result p of program P is **independent of** the secret input.

Quiz

Have the following programs the noninterference property?

Quiz

```
class MiniExamples {
  public int l;
  private int h;

  void m1() {
    l = h;
  }

  void m2() {
    if (l > 0) {
       h=1;
    } else {
       h=2;
    }
  }

  void m3() {
    if (h>0) {l=1;}
    else {l=2;};
  }

  void m4() {
    h=0; l=h;
  }

  void m5() {
    while(h == 0) { }
  }

  void m6() {
    Thread.sleep(h * 1000);
  }
}
```

Sometimes it is ok to leak a bit …or two

```
private int secretPIN;
int checkPIN(int triedPIN) {
   if(secretPIN == triedPIN) {
      return 1;
   } else {
      return 0;
   }
}
```

1. This method leaks information.
2. How much?
3. Can this be used to learn about the secret?

Information flow control

Noninterference is often too strict.

Relaxations:

Declassification
Allow particular data to flow

Quantitative analysis
Analyse the amount of secret information that flows

Declassification

Situation

The attacker must not learn anything but the value of an expression $ex(h, l)$.
$ex(h, l)$ is called **declassified** and no longer secret.

Mathematical condition

$$\forall h_1, h_2, \ell.\ ex(h_1, \ell) = ex(h_2, \ell) \rightarrow p(h_1, \ell) = p(h_2, \ell)$$

Secure information flow as a game (again)

Parties: the attacker and the system

Assume: Atacker knows pro

Attacker cannot use *ex* to discern *x* and *y*.

Protocol:

1. Attacker choo
   $x, y \in \mathit{SecretInput}$,
   $z \in \mathit{PublicInput}$,
   such that $ex(x, z) = ex(y, z)$
2. System selects $a \in \{x, y\}$ randomly (i.i.d.).
3. Attacker receives public output $p(a, z)$.
4. Attacker guesses whether $a = x$ or $a = y$.

Winner: Attacker wins this game if they guess *a* correctly

➜ *Program has **secure information flow** if best guessing strategy has winning probability 0.5.*

Declassification in the example

Code

```
private int sec;
int checkPIN(int try) {
   if(sec == try) return 1; else return 0;
}
```

Declassification

It is declassified whether PIN is correct: $ex := sec = try$
(Admissible to learn that PIN is correct if the attacker already has the number.)

Proof obligation:

$$\forall sec, sec', try.\ ((sec = try) \leftrightarrow (sec' = try)) \rightarrow \\ p_{\texttt{checkPIN}}(sec, try) = p_{\texttt{checkPIN}}(sec', try)$$

…is valid

Quantitative information flow analysis

Analyse *how much information* flows
not only whether or not it flows.

Examples

`l = h & 0b0111 /*7*/;`	leaks 3 bits (of 32).
`l = h1 ^ h2 ^ h3;`	leaks 32 bits (of 96).

One metric to compute amount of information:
Shannon Entropy H:

$$Pr(r) := \{h \mid p(h) = r\} / SecretSize$$

$$H(L) = \sum_r Pr(r) \cdot \log_2(\mathrm{Pr}(r))$$

(other metrics exist and have use cases)

Verification of Noninterference Properties

Enforcing Noninterference

1. Dynamic checking
2. Static verification
    1. Precise: deductive verification
    2. Approximative: type systems
    3. Approximative: program graph analyses

Dynamic Logic (recap)

Semantics of Dynamic Logic

$$s \models [P]\varphi \quad \Longleftrightarrow \quad s' \models \varphi \text{ for all } s \text{ with } (s, s') \in \rho_P$$

$[P]\varphi$ means "φ holds after the execution of P".

Deductive verification: Self-composition

Variant P' Let P' be a variant of program P in which every occurrence of every variable x is replaced by x'.

Assumption P has one secret variable h and one public variable ℓ (used for input and output).

Noninterference condition

A program P satisfies noninterference if and only if the formula

$$\forall h, h', \ell, \ell'. \quad \ell = \ell' \to [P\,;\,P']\ell = \ell'$$

is valid.

- Different variable sets, executions independent
- *"Self-composition"*: Sequentially composing (;) the same program (modulo variant) twice.

Better self-composition

Loops are difficult to verify: Invariants are needed.

Let P = `beforeLoop; while(c) { body }; afterLoop`.

The self-composition

```
P;P' = beforeLoop; while(c) { body }; afterLoop ;
       beforeLoop'; while(c') { body' }; afterLoop'
```

has *two loops*.

Reorder statements to reduce complexity:

```
beforeLoop; beforeLoop';
while(...) { body'; body' };
afterLoop; afterLoop'
```

is equivalent problem with a single loop.
Coupling invariant (→ Event-B) is easier to find

Alternating Quantifiers

(Darvas, Hähnle, Sands 2005)

An alternative condition

A program *P* satisfies noninterference if and only if the formula

$$\forall \ell . \exists r . \forall h .\ p(h, \ell) = r$$

is valid.

- Equivalent to $\forall h_1, h_2, \ell .\ p(h_1, \ell) = p(h_2, \ell)$
  (→ exercise: prove it!)
- Dynamic Logic Proof Obligation: $\forall \ell . \exists r . \forall h .\ [P](r = \ell)$

\+ Only one program execution, reduce complexity.

– How to instantiate the existential quantifier?
  (→ example)

Security type systems

Goal:

Define programming language in which syntactically correct programs have noninterference property.

Language Grammar:

Variable: $\mathtt{l}_1, \mathtt{l}_2, \ldots, \mathtt{h}_1, \mathtt{h}_2, \ldots$
(fixed security-levels by name)

Expression: Variable | Expression '+' Expression

Command: Variable '`:=`' Expression
| Command '`;`' Command
| `if` Expression = `0` `then` Command
`else` Command `end`
| `while` Expression = `0` `do` Command `end`

Security type system: Explicit flow

Problem:

Assignment can leak information

For instance: $\mathtt{l}_1 := \mathtt{h}_1$

Solution

Assignments to low variables are forbidden if high variables occur in the expression.

Security type system: Implicit flow

Problem:

Conditinal/Loop can leak information

For instance:

```
if h₁ = 0
then l₁ := 0
else l₁ := 1
end
```

Solution

Assignments to low variables are forbidden in a conditional (if) command if a high variable occurs in the branching condition.

(Similar applies to while loops.)

Type rules

$$\frac{}{exp : high}$$

$$\frac{\mathtt{h}_i \notin Vars(exp)}{exp : low}$$

$$\frac{pc \in \{low, high\}}{[pc] \vdash \mathtt{h}_i := exp}$$

forbid explicit flow

$$\frac{exp : low}{[low]\, \mathtt{l}_i := exp}$$

forbid implicit flow

$$\frac{[high] \vdash comm}{[low] \vdash comm}$$

$$\frac{[pc] \vdash comm_1 \quad [pc] \vdash comm_2}{[pc] \vdash comm_1 ; comm_2}$$

$$\frac{exp : pc \quad [pc] \vdash th \quad [pc] \vdash el}{[pc] \vdash \mathtt{if}\ exp = 0\ \mathtt{then}\ th\ \mathtt{else}\ el}$$

$$\frac{exp : pc \quad [pc] \vdash comm}{[pc] \vdash \mathtt{while}\ exp = 0\ \mathtt{do}\ comm}$$

Type rules

A program P is correctly typed if

$$[pc] \vdash P$$

can be inferred for $pc = low$ or $pc = high$.

Theorem

Every correctly typed program has noninterference property.

Incompleteness

There are programs which have noninterference property that cannot be typed.
For instance: $\mathtt{l}_1 := \mathtt{h}_1 - \mathtt{h}_1$

Online Challenge

`http://ifc-challenge.appspot.com`

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Graph-based information flow control

JOANA

`http://pp.ipd.kit.edu/projects/joana/`

Some interesting extensions

- more than 2 security levels
  (e.g., “public” $<$ “internal” $<$ “secret”)
- pointers / objects / records / heap data structures
- exceptions
- reactive systems (more than one input, one output)
- termination / timing analysis
- concurrency

→ All research challenges in their own right!

Summary

Information flow can be analysed and noninterference verified using formal methods.

- Type systems / graph-based systems scale well (up to 100 kLOC)
- Deductive systems are more precise, can prove more cases
- Declassification of expressions in deductive verification
- Declassification of variables in type systems