Hybrid information flow analysis against web tracking  
(invited talk)  
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Hybrid information flow analysis against web tracking

Thomas Jensen, Inria

Keynote, CRISIS'2017
Overview

1. Web tracking.
2. Knowledge-based information flow analysis.
3. Browser randomisation.
Thanks to EU ePrivacy Directive

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Thomas Jensen - Information flow analysis against web tracking

19 Sept 2017
Web tracking

Bigger browsing profiles

= increased value for trackers
= reduced privacy for users

(Hypothetical tracking relationships only.)
Browser extensions to the rescue?

AdBlockPlus: blocks scripts/requests only from known advertisement companies

Ghostery: blocks scripts/requests only from known tracking companies

• No protection from tracking by other companies
• No protection from tracking by the main (first-party) web site
Cookies are used to track repeated visits to a site.
Tracking by finger-printing

Browser and operating system properties are used to track repeated visits to a site.

<script src=fingerprinter.com/script.js>

fingerprinter.com

Processing engine

2:52pm: user_fp 9jhldpe7fv visited site1.com
Panopticlick: an early study on fingerprinting

- A study from 2010 showed that 83.6% of browser fingerprints were unique among the 500,000 browsers tested.

- **Fingerprints**: HTTP headers, browser and OS features, language, plug-ins, fonts, …
Protection mechanisms

Stateful tracking: well-known and being addressed at different levels:

- Third-party cookie blocking
- EU e-Privacy directive
- Non-interference analysis for JavaScript

Stateless tracking: less clear

- IP address tracking
- Web browser finger-printing
2. Knowledge-based information flow analysis
Use information flow to spot web tracking

Scripts can access information about configurations

**Goal**: Estimate the information that a script learns about configurations.

But some information leakage is reasonable!

Scripts may need information about browser and execution environment for optimal user experience.
## Information flow control

<table>
<thead>
<tr>
<th>Non-interference</th>
<th>Attacker knowledge</th>
<th>Quantitative information flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secret input does not flow into public output</td>
<td>What information about the secret flows to output in an execution.</td>
<td>How much information about secrets is leaked?</td>
</tr>
<tr>
<td>Yes/no?</td>
<td>Secret &gt; 42</td>
<td>Leaks 17 bits</td>
</tr>
</tbody>
</table>

- **Non-interference**: Secret input does not flow into public output. The question is "Yes/no?"
- **Attacker knowledge**: What information about the secret flows to output in an execution. The condition is "Secret > 42".
- **Quantitative information flow**: How much information about secrets is leaked? It leaks 17 bits.
Attacker knowledge

```javascript
var x = 0;
if (name == "Firefox") {
    x = 1;
}
else {
    if (fonts == fontsSet1) {
        x = 2;
    }
}
output x;
```

Depending on the browser, different executions leak different amount of information.
Non-interference

A program is termination-insensitive non-interferent if it produces the same output for all low-equivalent input.

Example with two binary secrets $h_1, h_2 \in \{0, 1\}$
Secure and insecure executions

The following program is not secure - but it has secure executions.

```plaintext
if h1 = 1 then x = 1
else skip;
if h2 = 1 then low = 1
else low = x;
output low
```

Initial values:

- `[low = 1, x = 1]`
- `[low = 1, x = 0]`

Secure

Leaks information about secret
Monitoring information flow

Dynamic information flow control

- Label values with security labels.
- Propagate labels during execution.
- Halt execution before outputting secret values.

Non-interference needs "no-sensitive-upgrade" principle:
no assignment to public variables under secret control

\[
\text{[secret} = 1]\]

```plaintext
if secret = 1 then
  output = 1
else
  output = public;
return output
```

[Zdancewic’02, Austin & Flanagan’10]
Hybrid information flow analysis

Combine dynamic IF control with a static analysis

- statically analyse the non-executed branches

- admits more executions but limited by the precision of the static analysis

```
[secret = 1, public = 1]
if secret = 1 then
  output = 1
else output = public;
return output
```

Static analysis says public : [1]
Hybrid monitor of attacker knowledge

Define a hybrid monitor that tracks the knowledge of an attacker.

Use knowledge to

• enforce non-interference,
• accept more secure executions.

Solution:

• A domain for representing attacker knowledge.
• Monitor formalised as an operational semantics.
Attacker knowledge

Knowledge: What does an attacker learn about the input state by seeing a particular output.

Real attacker knowledge

Safe approximation of knowledge
Domain of knowledge

\[ \kappa: \text{Var} \rightarrow \text{K} \]

\[ \text{K} \triangleq \text{Env} \rightarrow \text{Value} \cup \{\top, \bot\} \]

The knowledge in a variable \( \kappa(x) \):

which initial environments lead to a particular value of \( x \)?

\( \top \) (nothing known about \( x \) for these envs)

0

1
The hybrid monitor

Defined as an operational reduction semantics:

\[(P, \rho, K) \Downarrow (\rho', K')\]

- \(\rho, \rho' : \text{Env} \cup \{\cdot\}\),
- \(K, K' : \text{Var} \to K\) labeling of variables with knowledge,
- \(\text{Env} : \text{Var} \to \text{Val}\) for dynamic analysis,
- \(\cdot\) "empty" environment for static analysis.
Semantic rules

Rules come in pairs: one dynamic and one static

Dynamic analysis computes real values and knowledge

Static analysis called on-the-fly and propagates only knowledge

$$\text{IF}_\text{DYN} \quad \frac{C[e]_\rho = \alpha}{(\text{if } e \text{ then } c_{tt} \text{ else } c_{ff}, (\rho, \kappa)) \downarrow (\rho', \Pi F((e)_\kappa, \kappa_{tt}, \kappa_{ff}))}$$

$$\text{IF}_\text{STAT} \quad \frac{(c_{tt}, (\cdot, \kappa)) \downarrow (\cdot, \kappa_{tt}) \quad (c_{ff}, (\cdot, \kappa)) \downarrow (\cdot, \kappa_{ff})}{(\text{if } e \text{ then } c_{tt} \text{ else } c_{ff}, (\cdot, \kappa)) \downarrow (\cdot, \Pi F((e)_\kappa, \kappa_{tt}, \kappa_{ff}))}$$

Operator combining knowledge obtained in branches with knowledge from the condition
Enforcing non-interference

Before any output, the monitor checks non-interference:

- if non-interference then output is not modified.

\[
\text{OUTNI} \quad (c, \text{init}(\rho)) \downarrow (\rho', \kappa) \quad \rho'(x) = v \quad \text{NI}(\rho, \kappa(x), v) \\
(c; \text{output } x, \rho) \downarrow v
\]

The non-interference check is defined as:

\[
\text{NI}(\rho, K, v) \triangleq [\rho]_L \subseteq K^{-1}(v) \cup K^{-1}(\perp).
\]

set of low-equivalent env's
Example analysis

[h1 = 0, h2 = 1]

\[
\text{if } h1 = 1 \text{ then } x = 1 \\
\text{else skip;} \\
\text{if } h2 = 1 \text{ then } \text{low} = 1 \\
\text{else } \text{low} = x; \\
\text{output } \text{low}
\]

Initial

Knowledge

[low = 0, x = 0]

\( K(x): \)

\( K(\text{low}): \)

Use knowledge in x

Static analysis of env's with h2 = 0

Static analysis of env's with h1 = 1

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Stock-taking

Knowledge-based information flow analysis

• computes a correct approximation of attacker knowledge,

• enforces non-interference,

• more permissive than existing hybrid monitors,

• can be combined with other monitors to enhance precision.
3. Browser randomisation against web tracking
How to enforce privacy?

The hybrid monitor monitor evaluates how much a tracker learns about an individual user.

How to react when a script tracks too much?

- With 10 users, our Opera user will be uniquely identified.
- Halting the program or suppress output might still make you identifiable.
- Need collaboration between users.

\[
p(\text{name}) = \\
\text{Firefox} \ 0.45 \\
\text{Chrome} \ 0.45 \\
\text{Opera} \ 0.10
\]
A solution

• Users switch between configurations
• How many configurations are needed to guarantee privacy?
• Usability issue: users want to switch as little as possible

Challenge: find a distribution on configurations for all users such that
• Privacy is guaranteed
• Usability is maximised
Privacy: probability of guessing

\[
\text{if (name == "Opera") } x = A; \\
\text{else } x = B; \\
\text{output } x;
\]

<table>
<thead>
<tr>
<th>Browser</th>
<th>A priori p(name)</th>
<th>A posteriori p(name)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firefox</td>
<td>0.45</td>
<td>Firefox 0</td>
</tr>
<tr>
<td>Chrome</td>
<td>0.45</td>
<td>Chrome 0</td>
</tr>
<tr>
<td>Opera</td>
<td>0.10</td>
<td>Opera 1</td>
</tr>
</tbody>
</table>

Probability \( \Pr^G \): guessing the secret in case of worst observation.

Stronger than definition based on Bayesian risk:

\[
p(A) \max_i p(i|A) + p(B) \max_i p(i|B) = 0.55
\]
Achieving privacy

Find a randomisation $R$ of user state such that when composed with tracking script $P$

$$\Pr^G(R; P) < \text{privacy threshold}.$$
Adding usability

Users don't want to switch configuration:

- choose randomisation so that they get their original configuration as much as possible
- linear constraint on the randomisation matrix.
- problem reduces to linear programming.

<table>
<thead>
<tr>
<th>R</th>
<th>&quot;Firefox&quot;</th>
<th>&quot;Opera&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>id₁</td>
<td>x</td>
<td>1-x</td>
</tr>
<tr>
<td>id₂</td>
<td>1-y</td>
<td>y</td>
</tr>
</tbody>
</table>

max \((x + y)\) s.t.
- \(0 \leq x \leq 1\)
- \(0 \leq y \leq 1\)
- \(Ax + By + C \leq t\)

Usability

Privacy
Wrapping up

Web tracking is done by different techniques

- cookies, other browser storage, fingerprinting

Information flow analysis against fingerprinting

- Hybrid information flow monitoring with static analysis
- Computes tracker knowledge.

Enforcing browser anonymity

- Randomisation of configurations
- Combining privacy and usability
Based on a true story...