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

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Hybrid information flow analysis against web tracking

Thomas Jensen, Inria

Joint work with:

Frédéric Besson
Nataliia Bielova

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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Hezbollah's role

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 efectivemeasure.net

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 pagead2.googlesyndication.com

 js.revsci.net

 b.scorecardresearch.com

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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
Tracking by storing identity

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.
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>
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.

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

Initial values:
- \([\text{low} = 1, \text{x} = 1]\)
- \([\text{low} = 1, \text{x} = 0]\)

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

```plaintext
[secret = 1]
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

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

[secret = 1, public = 1]

Static analysis says public : [1]

[Le Guernic’07, Russo & Sabelfeld’10,…]
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.

Safe approximation of knowledge

Real attacker knowledge

\[ C_1 \rightarrow C_2 \rightarrow C_3 \]


Domain of knowledge

$$\kappa: \text{Var} \rightarrow \mathbb{K}$$

$$\mathbb{K} \triangleq \text{Env} \rightarrow \text{Value} \cup \{T, \perp\}$$

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

which initial environments leads to a particular value of $$x$$?

$\top$ (nothing known about $$x$$ for these envs)
The hybrid monitor

Defined as an operational reduction semantics:

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

- \(\rho, \rho' : Env \cup \{\cdot\}\),
- \(K, K' : Var \rightarrow K\) labeling of variables with knowledge,
- \(Env : Var \rightarrow Val\) 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

\[
\text{IF}_{\text{DYN}} \quad C[e|\rho] = \alpha \quad (c_\alpha, (\rho, \kappa)) \downarrow (\rho', \kappa_\alpha)
\]

(If \( e \) then \( c_{tt} \) else \( c_{ff}, (\rho, \kappa) \)) \( \downarrow (\rho', \mathbb{IF}([e]_\kappa)), \kappa_{tt}, \kappa_{ff}) \)

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

\[
\text{IF}_{\text{STAT}} \quad (c_{tt}, (\cdot, \kappa)) \downarrow (\cdot, \kappa_{tt}) \quad (c_{ff}, (\cdot, \kappa)) \downarrow (\cdot, \kappa_{ff})
\]

(If \( e \) then \( c_{tt} \) else \( c_{ff}, (\cdot, \kappa) \)) \( \downarrow (\cdot, \mathbb{IF}([e]_\kappa), \kappa_{tt}, \kappa_{ff}) \)

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.

\[
\begin{align*}
\text{OUTNI} \quad (c, \text{init}(\rho)) \Downarrow (\rho', \kappa) \quad \rho'(x) = v \quad NI(\rho, \kappa(x), v) \\
(c; \text{output } x, \rho) \Downarrow v
\end{align*}
\]

The non-interference check is defined as:

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

set of low-equivalent env's
Example analysis

\[ h_1 = 0, h_2 = 1 \]

\[
\text{if } h_1 = 1 \text{ then } x = 1 \\
\text{else skip;}
\]

\[
\text{if } h_2 = 1 \text{ then } \text{low} = 1 \\
\text{else } \text{low} = x;
\]

output low

\[ h_1 = 0, h_2 = 1 \]

\[ \text{Initial} \]

\[ \text{Knowledge} \]

\[ \text{Static analysis of env's with } h_2 = 0 \]

\[ \text{Static analysis of env's with } h_1 = 1 \]

\[ \text{Use knowledge in } x \]
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.

\[
p(\text{name}) =
\begin{align*}
&\text{Firefox} & & 0.45 \\
&\text{Chrome} & & 0.45 \\
&\text{Opera} & & 0.10
\end{align*}
\]
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

A priori

<table>
<thead>
<tr>
<th>Browser</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firefox</td>
<td>0.45</td>
</tr>
<tr>
<td>Chrome</td>
<td>0.45</td>
</tr>
<tr>
<td>Opera</td>
<td>0.10</td>
</tr>
</tbody>
</table>

A posteriori

<table>
<thead>
<tr>
<th>Browser</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firefox</td>
<td>0</td>
</tr>
<tr>
<td>Chrome</td>
<td>0</td>
</tr>
<tr>
<td>Opera</td>
<td>1</td>
</tr>
</tbody>
</table>

if (name == “Opera”) x = A;
else x = B;
output x;

A priori

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

Stronger that 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 $P$

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

<table>
<thead>
<tr>
<th>$R$</th>
<th>“Firefox”</th>
<th>“Opera”</th>
</tr>
</thead>
<tbody>
<tr>
<td>$id_1$</td>
<td>$x$</td>
<td>$1-x$</td>
</tr>
<tr>
<td>$id_2$</td>
<td>$1-y$</td>
<td>$y$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$P$</th>
<th>$o_1$</th>
<th>$o_2$</th>
<th>$o_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Firefox”</td>
<td>$1/2$</td>
<td>$1/3$</td>
<td>$1/6$</td>
</tr>
<tr>
<td>“Opera”</td>
<td>$1/6$</td>
<td>$1/2$</td>
<td>$1/3$</td>
</tr>
</tbody>
</table>

$t = 0.6$

$z = \Pr^G ( R \ P ) = Ax + By + C$
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 ≤ x ≤ 1
0 ≤ y ≤ 1
Ax + By + C ≤ 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…

