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

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Hybrid information flow analysis against web tracking

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Joint work with:
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Nataliia Bielova

Keynote, CRISIS'2017
Overview

1. Web tracking.

2. Knowledge-based information flow analysis.

3. Browser randomisation.
Thanks to EU ePrivacy Directive

Protesters return to Turkey streets

Syrian rebels and Hezbollah 'clash'

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Syrian rebels and Hezbollah 'clash'
A number of people are killed in rare clashes on Lebanese soil between Syrian rebels and the Lebanese militant group Hezbollah, say reports.

Oussain's strategic importance

Hezbollah's role

Syria town

Unwinnable war

Magazine

Watching brief

Eden's marshes

Restoring the wetlands drained by Saddam

Features

The Queen's 'dazzling' coronation - 60 years on

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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.

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

fingerprinter.com

Processing engine

2:52pm: user_fp 9jhlde7fv visited site1.com

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19 Sept 2017
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>

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.

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

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

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

```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

```cpp
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
Domain of knowledge

\[ \kappa : \text{Var} \to \mathbf{K} \]

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

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)

0

1
The hybrid monitor

Defined as an operational reduction semantics:

$$(P, \rho, K) \Downarrow (\rho', K')$$

- $\rho, \rho': \text{Env} \cup \{\cdot\}$
- $\kappa, \kappa': \text{Var} \to K$ labeling of variables with knowledge,
- $\text{Env}: \text{Var} \to \text{Val}$ for dynamic analysis,
- "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

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.

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

The non-interference check is defined as:

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

set of low-equivalent env's
Example analysis

[h1 = 0 , h2 = 1]

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

Knowledge
[low = 0 , x = 0]

Initial

\( K(x) : \)

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

Static analysis of env's with h2 = 0

Static analysis of env's with h1 = 1

Use knowledge in x

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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 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.

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

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

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>

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 $P$

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

<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>

<table>
<thead>
<tr>
<th>P</th>
<th>$o_1$</th>
<th>$o_2$</th>
<th>$o_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Firefox&quot;</td>
<td>$1/2$</td>
<td>$1/3$</td>
<td>$1/6$</td>
</tr>
<tr>
<td>&quot;Opera&quot;</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>
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<tr>
<th>R</th>
<th>&quot;Firefox&quot;</th>
<th>&quot;Opera&quot;</th>
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</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>

\[
\text{max} (x + y) \text{ s.t.} \\
0 \leq x \leq 1 \\
0 \leq y \leq 1 \\
Ax + By + C \leq t
\]
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…

