Hybrid information flow analysis against web tracking
(invited talk)
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To cite this version:
Thomas Jensen. Hybrid information flow analysis against web tracking (invited talk). CRiSIS 2017 - 12th International Conference on Risks and Security of Internet and Systems, Sep 2017, Dinard, France. pp.1-33. hal-01658896

HAL Id: hal-01658896
https://inria.hal.science/hal-01658896
Submitted on 3 Jan 2018

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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
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
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

```
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 execution:

Secure: Low = 1

Leaks information about secret:

h1=0 ∧ h2=0
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
```
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

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

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

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

which initial environments leads to a particular value of \( x \)?
The hybrid monitor

Defined as an operational reduction semantics:

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

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

\[
\begin{align*}
\text{IF}^{\text{Dyn}} & : C[e]_\rho = \alpha \quad (c_\alpha, (\rho, \kappa)) \downarrow (\rho', \kappa_\alpha) \quad (c_\alpha, (\cdot, \kappa)) \downarrow (\cdot, \kappa_\alpha) \\
\text{IF}^{\text{Stat}} & : (c_{tt}, (\cdot, \kappa)) \downarrow (\cdot, \kappa_{tt}) \quad (c_{ff}, (\cdot, \kappa)) \downarrow (\cdot, \kappa_{ff}) \\
& \quad (\text{if} \ e \ \text{then} \ c_{tt} \ \text{else} \ c_{ff}, (\cdot, \kappa)) \downarrow (\cdot, \mathbb{I}(|e|, \kappa_{tt}, \kappa_{ff}))
\end{align*}
\]

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:

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

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

$K(x):$

$K(low):$

Static analysis of env's with h2 = 0

Static analysis of env's with h1 = 1

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.

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

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

A posteriori

\[
p(\text{name}) = \\
\begin{align*}
\text{Firefox} & \quad 0 \\
\text{Chrome} & \quad 0 \\
\text{Opera} & \quad 1
\end{align*}
\]

Probability \( P_{\text{guess}} \): guessing the secret in case of worst observation.

Stronger than definition based on Bayesian risk:

\[
p(\text{A}) \max_i p(\text{i} | \text{A}) + p(\text{B}) \max_i p(\text{i} | \text{B}) = 0.55
\]
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>

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

