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## 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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### Protesters return to Turkey streets

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892

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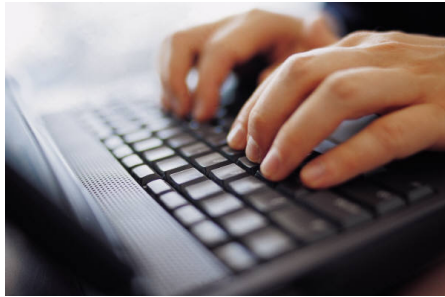
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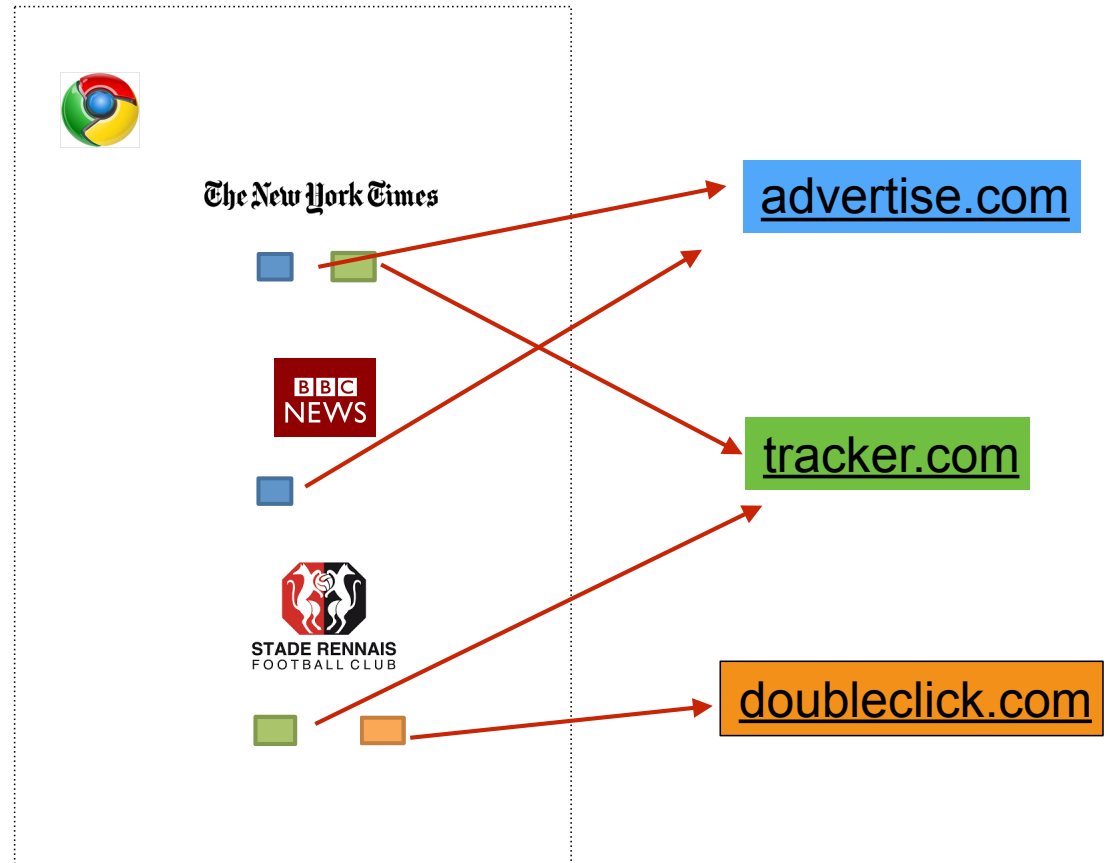
# Web tracking



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**

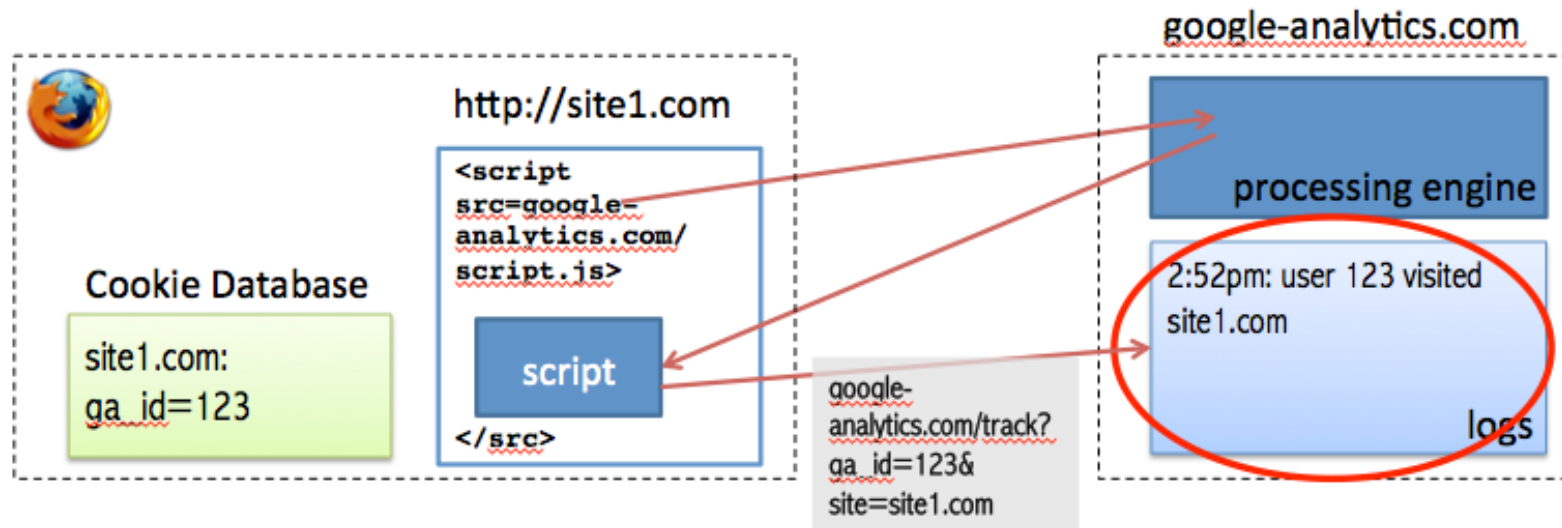


Ghostery: blocks scripts/requests **only from known tracking companies**

- No protection from tracking by other companies
- No protection from tracking by the main (first-party) web site

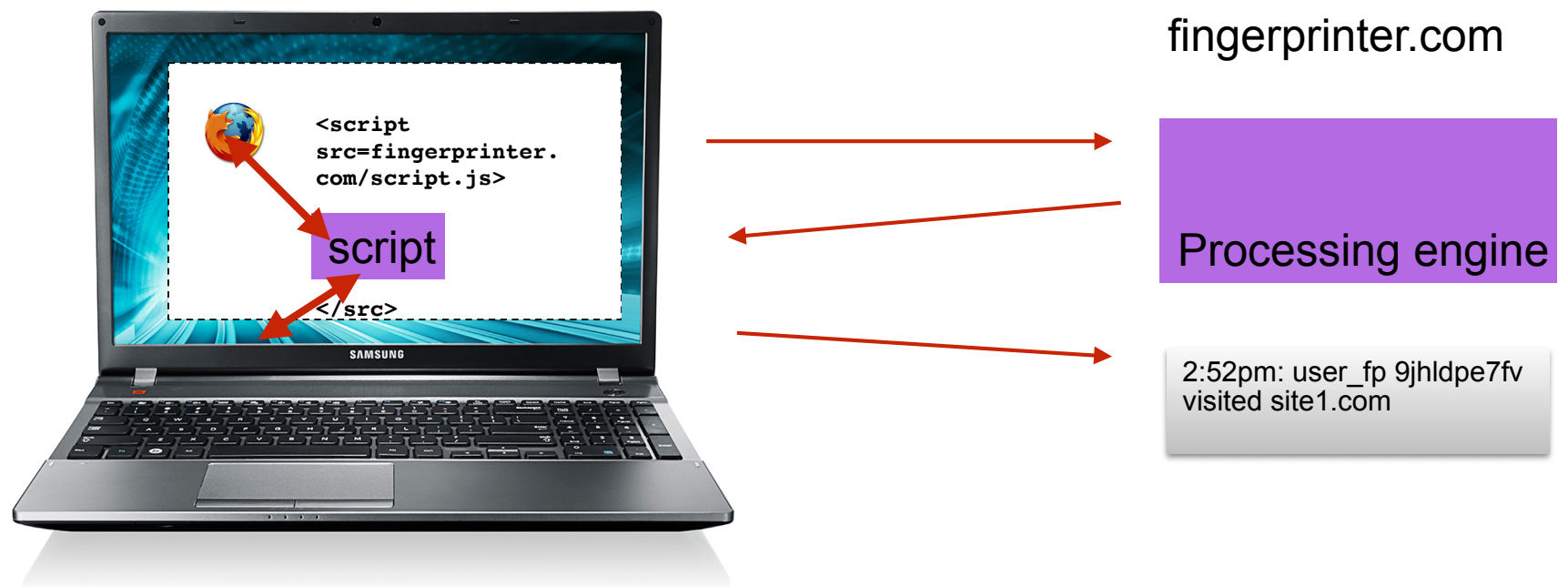
# Tracking by storing identity

Cookies are used to track repeated visits to a site.



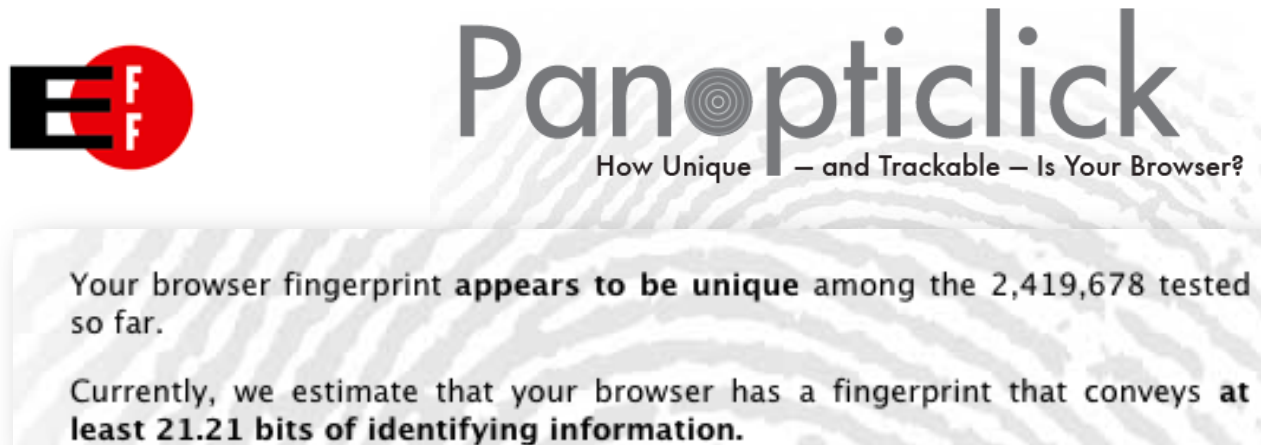
# Tracking by finger-printing

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, ...

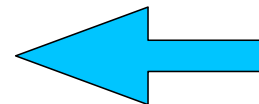
# Protection mechanisms

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

## Non-interference

Secret input does not flow into public output

Yes/no ?

## Attacker knowledge

What information about the secret flows to output in an execution.

Secret > 42

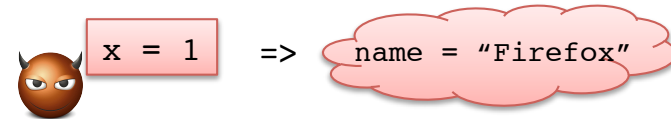
## Quantitative information flow

How much information about secrets is leaked?

Leaks 17 bits

# 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  $h1, h2 \in \{0,1\}$

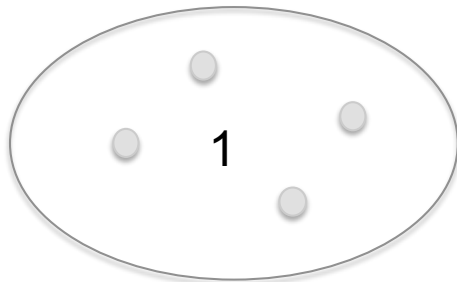
# Secure and insecure executions

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
```

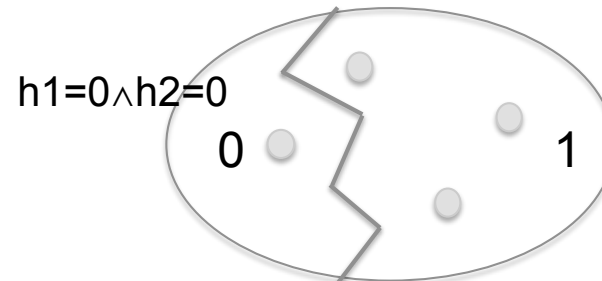
Initial values:

[low = 1, x = 1]



Secure

[low = 1, x = 0]



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

```
[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

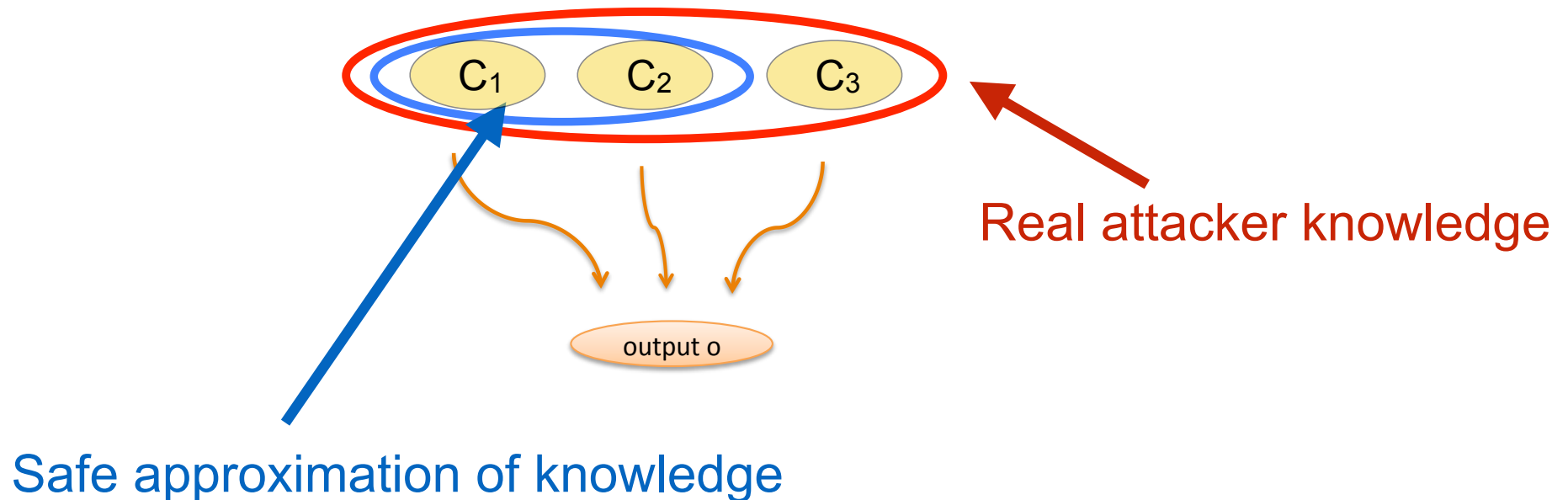
- enforce non-interference,
- accept more secure executions.

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.



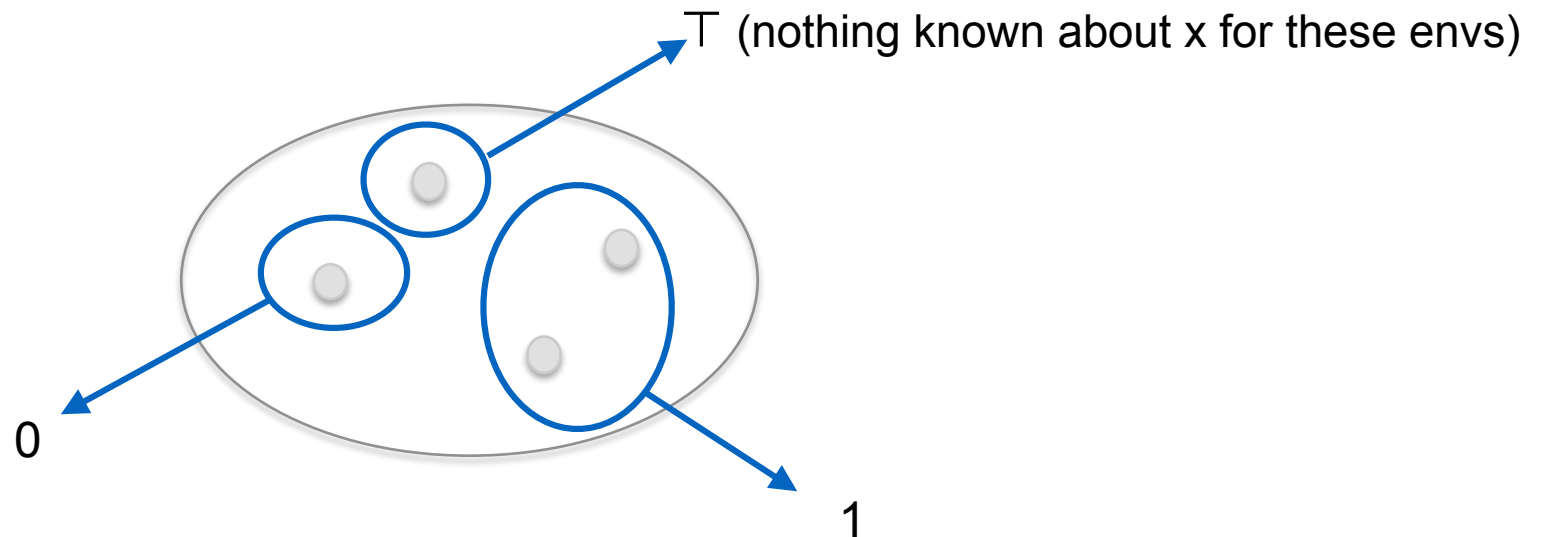
# Domain of knowledge

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

$$\mathbf{K} \triangleq \text{Env} \rightarrow \text{Value} \cup \{\top, \perp\}$$

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:

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

- $\rho, \rho' : \text{Env} \cup \{\cdot\}$ ,
- $\kappa, \kappa' : \text{Var} \rightarrow \mathbf{K}$  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

$$\text{IFDYN} \frac{C[e]_{\rho} = \alpha \quad (c_{\alpha}, (\rho, \kappa)) \Downarrow (\rho', \kappa_{\alpha}) \quad (c_{\bar{\alpha}}, (\cdot, \kappa)) \Downarrow (\cdot, \kappa_{\bar{\alpha}})}{(\text{if } e \text{ then } c_{tt} \text{ else } c_{ff}, (\rho, \kappa)) \Downarrow (\rho', \text{IFF}(\llbracket e \rrbracket_{\kappa}, \kappa_{tt}, \kappa_{ff}))}$$

$$\text{IFSTAT} \frac{(c_{tt}, (\cdot, \kappa)) \Downarrow (\cdot, \kappa_{tt}) \quad (c_{ff}, (\cdot, \kappa)) \Downarrow (\cdot, \kappa_{ff})}{(\text{if } e \text{ then } c_{tt} \text{ else } c_{ff}, (\cdot, \kappa)) \Downarrow (\cdot, \text{IFF}(\llbracket e \rrbracket_{\kappa}, \kappa_{tt}, \kappa_{ff}))}$$

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.

$$\text{OUTNI} \frac{(c, \text{init}(\rho)) \Downarrow (\rho', \kappa) \quad \rho'(x) = v \quad \text{NI}(\rho, \kappa(x), v)}{(c; \text{output } x, \rho) \Downarrow v}$$

The non-interference check is defined as:

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

set of low-equivalent env's



# Example analysis

[h1 = 0 , h2 = 1]

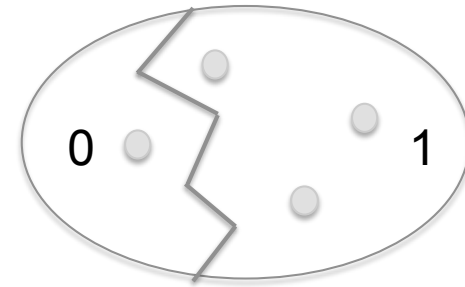
Static analysis

```

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

Knowledge

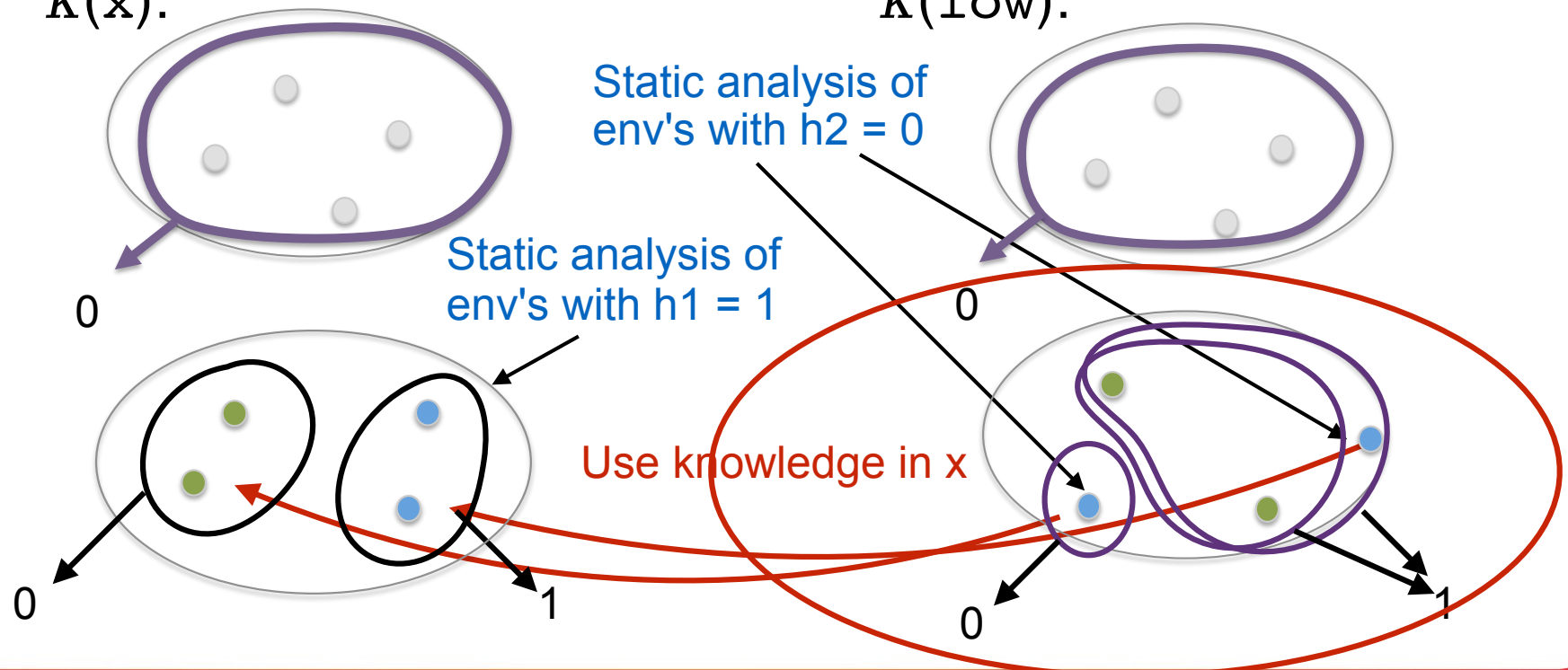
[low = 0 , x = 0]



$K(x)$ :

$K(low)$ :

Initial



# 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.

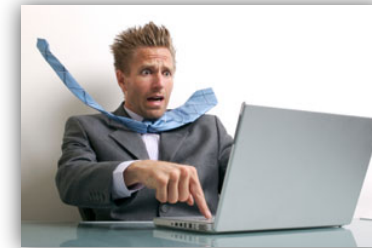
## How to react when a script tracks too much?

p(name) =	
Firefox	0.45
Chrome	0.45
Opera	0.10

- 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.

# 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(name) =	
Firefox	0.45
Chrome	0.45
Opera	0.10

x = A

A posteriori

p(name) =	
Firefox	0
Chrome	0
Opera	1

Probability  $\text{Pr}^G$ : guessing the secret in case of worst observation.

Stronger than definition based on Bayesian risk:

$$p(A) \max_i p(i|A) + p(B) \max_i p(i|B) = 0.55$$

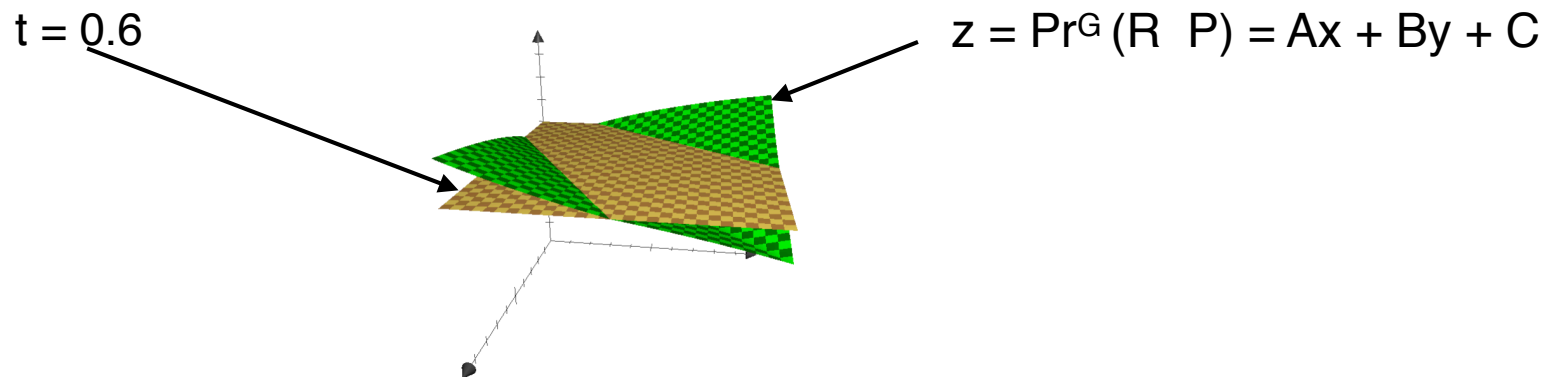
# Achieving privacy

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

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

R	"Firefox"	"Opera"
id <sub>1</sub>	x	1-x
id <sub>2</sub>	1-y	y

P	o1	o2	o3
"Firefox"	1/2	1/3	1/6
"Opera"	1/6	1/2	1/3



# 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.

R	"Firefox"	"Opera"
id <sub>1</sub>	x	1-x
id <sub>2</sub>	1-y	y

$$\begin{aligned} \max (x + y) \text{ s.t.} \\ 0 \leq x \leq 1 \\ 0 \leq y \leq 1 \\ Ax + By + C \leq t \end{aligned}$$

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...

- F. Besson, N. Bielova, T. Jensen: Hybrid Information Flow monitoring against web tracking, CSF 2013.
- F. Besson, N. Bielova, T. Jensen: Browser randomization against fingerprinting: A Quantitative information flow approach, NordSec 2014.
- F. Besson, N. Bielova, T. Jensen: Hybrid monitoring of attacker knowledge, CSF 2016.