To Dream the Impossible Dream: Toward Security Analysis for JavaScript

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Based on [ECOOP12], [PLDI13], [ICSE13], ongoing work

Many Colleagues

Satish Chandra (Samsung)
Asger Feldhaus (Aarhus)
Salvatore Guarneri (Google)
Manu Sridharan (Samsung)
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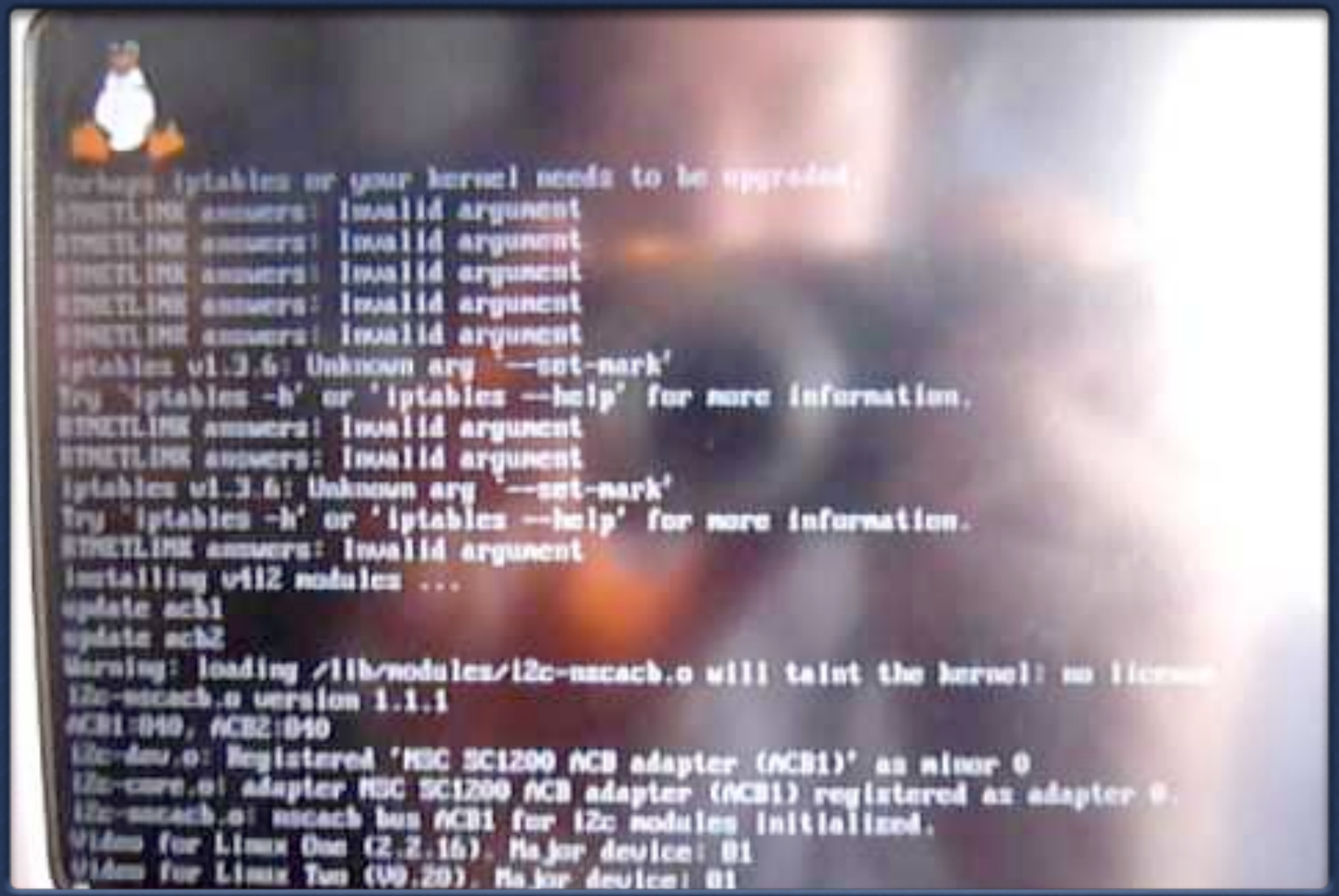
Frank Tip (Samsung)

Work done at IBM Thomas J. Watson Research Center

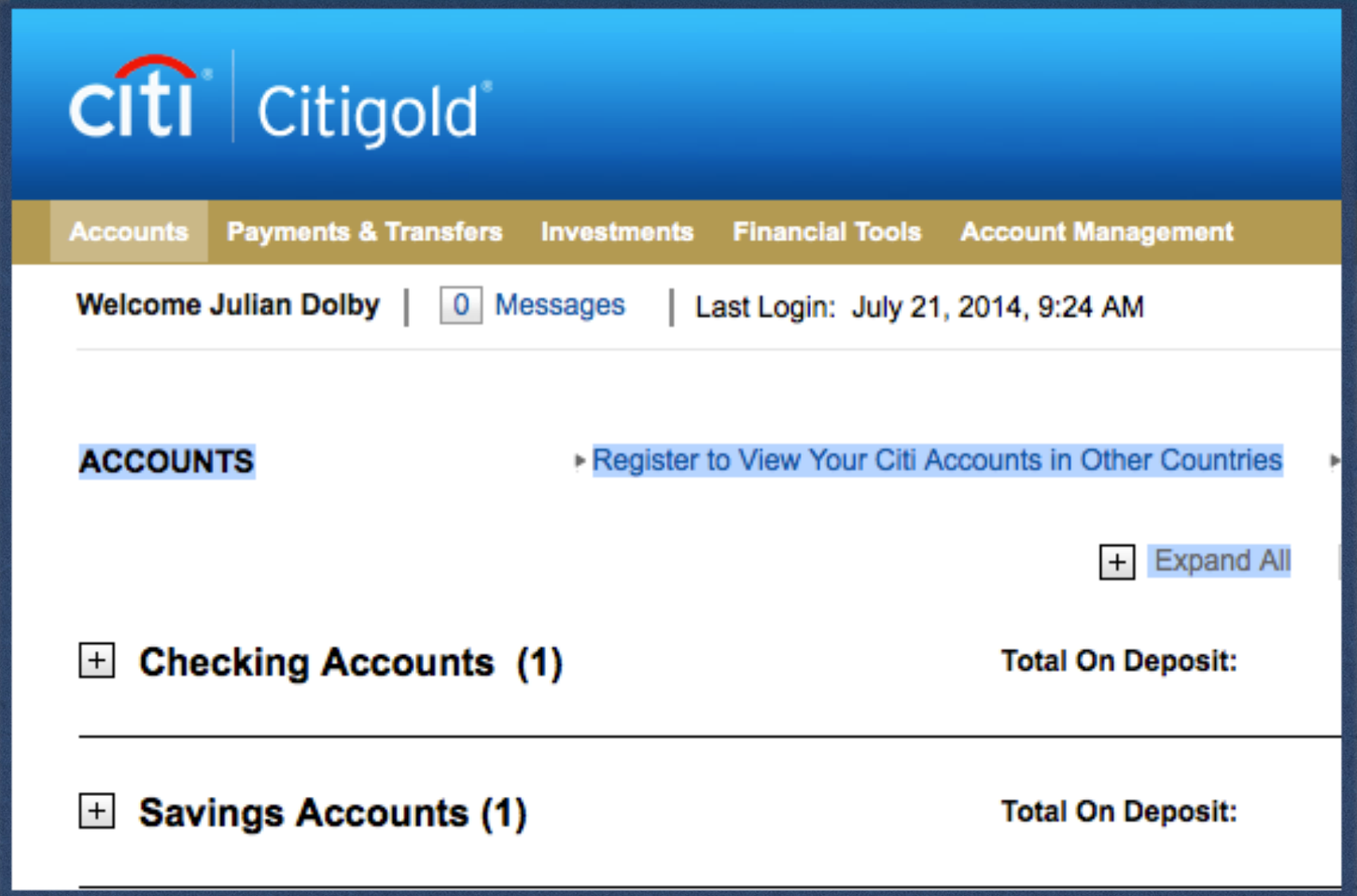
Some software works...



...and some does not

Two Classes of Software

- *"Important" software*
  - *Avionics, Antilock brakes, Medical, Financial*
    - *Deaths or major losses when it breaks*
- *Other software*
  - *Inflight entertainment, Social media*
  - *Mostly just causes annoyance*



"Important" software...

```
var f = function(){
          $jq(function($){
        if($jq("#InterdictionOverlayContent").jfpwidget() === undefined){
            $jq("#InterdictionOverlayContent").jfpwidget(new CJW.jfp.widget.Overlay(
{
        wrapperSet: "#InterdictionOverlayContent",
        hideTitleBar: false,
        dialog: true
    },
{
        draggable: false,
        resizable: false,
        position: ["center", 140],
        width: 550,
        height: 420,
        shadowOffset: 20,
        hideTitleBar: false,
        shadow:true,
        modal: true,
        beforeClose: checkStatusCsq
    },
{}));
        }
     }
      );
};
if (window.$RDY){
    $RDY('CJW.jfp.widget.Overlay',f);
}
else{
    f();
}
```

...has changed

JavaScript is "Important"

- *Web sites dominate life*
  - *banking, healthcare, shopping, communication...*
    - *important data and transactions*
- *Modern Web sites are implemented in JavaScript*
  - *rich client applications embody business logic*
  - *heavy use of rich frameworks, notably* `jQuery`

Improve Software Quality

program analysis based on call graphs

Traditional Call Graphs

- *Approximates targets at all call sites*
- *Type-based graphs simple but imprecise*

```
class Foo { void fun(); }
class Bar extends Foo { void fun(); }
Foo x = new Bar(); x.fun();
```
Foo.fun, Bar.fun

- *Dataflow-based graphs more precise, complex*

```
class Foo { void fun(); }
class Bar extends Foo { void fun(); }
Foo x = new Bar(); x.fun();
```
Bar.fun

Traditional Call Graphs

- *Dynamic languages complicate analysis*
- *Type-based graphs not applicable without static types*

```
x.fun = function foo {… }
var fun = x.f;
fun();
```

- *Dataflow-based graphs can track function objects*

```
x.fun = function foo {… }
var fun = x.f;
fun();
```

Traditional Call Graphs

- *JavaScript further challenges program analysis*
  - *heavy use of reflection, i.e. eval*
  - *first-class property names*

`x.s = y`

$$\frac{o \in pt(x)}{pt(y) \subseteq pt(o.\texttt{s})} \quad [\textsc{StoreField}]$$

`x[v] = y`

$$\frac{o \in pt(x) \qquad \texttt{s} \in pt(v)}{pt(y) \subseteq pt(o.\texttt{s})} \quad [\textsc{StoreField}]$$

- *Dynamism worsens asymptotic complexity*

Traditional Call Graphs

- *Much first-class property access in frameworks*

```
jQuery.fn = {
 extend: function ext(obj) {
  for(var p in obj)
    jQuery.fn[p] = obj[p];
 }
};
```

`p`: *fields of obj, e.g.* `"x","y", "z"`

`obj[p]`: *values of field, e.g.* `obj[x]=4,obj[y]="a"`

`jQuery.fn[p] = obj[p]` *assigns to all fields in* `p`

Correlation Tracking

- *Correlated first-class property reads and writes*

```
jQuery.fn = {
 extend: function ext(obj) {
  for(var p in obj)
    jQuery.fn[p] = obj[p];
 }
};
```

Same value per iteration

- *Need separate analysis per loop iteration*
  - *apply context sensitivity*
  - *extract loop body into separate function*

Correlation Tracking

```
jQuery.fn = {
 extend: function ext(obj) {
  for(var p in obj)
   jQuery.fn[p] = obj[p];
 }
};
```

```
if (p == "x") {
 jQuery["x"] = obj["x"]
} else if (p == "y" ) {
 jQuery["x"] = obj["x"]
}
```

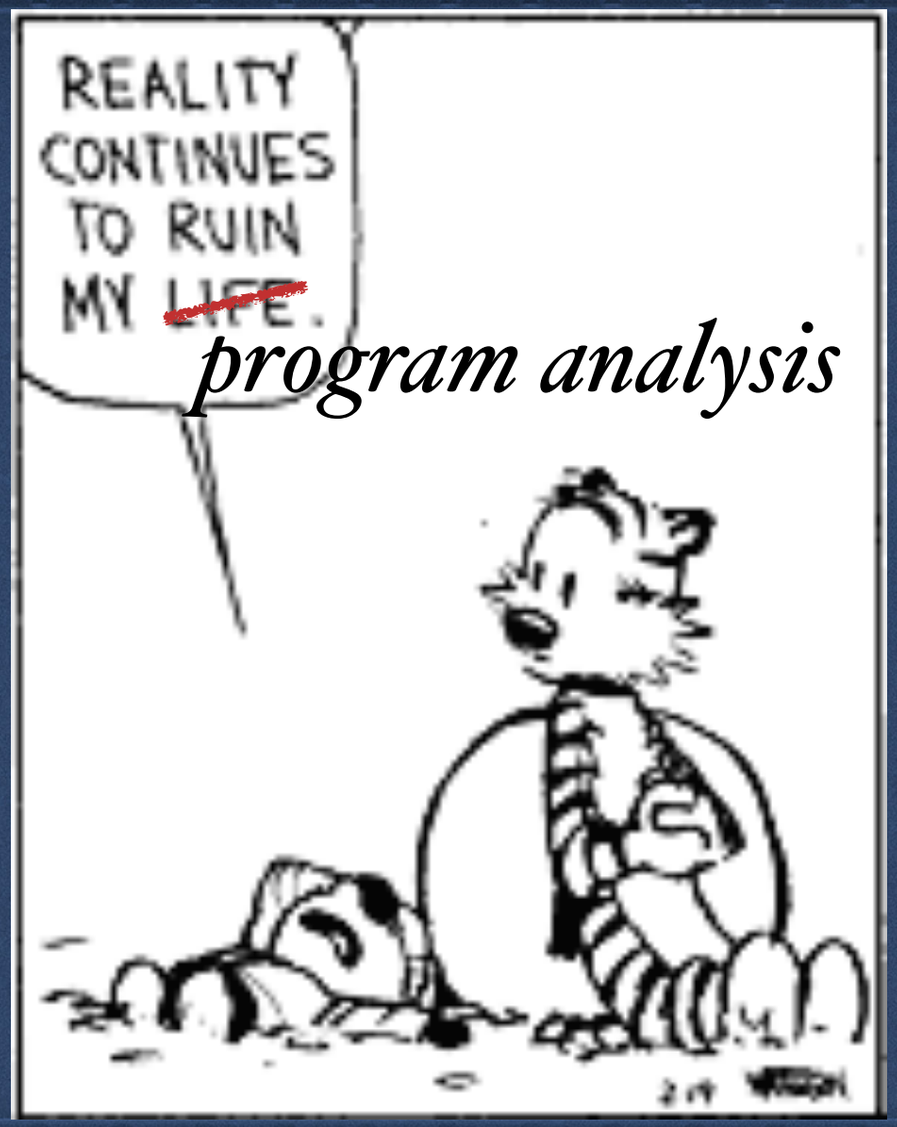
Implemented using context-sensitivity

Traditional Call Graphs

Framework	Baseline$^-$	Baseline$^+$	Correlations$^-$	Correlations$^+$
dojo	* (*)	* (*)	3.1 (30.4)	6.7 (*)
jquery	*	*	78.5	*
mootools	0.7	*	3.1	*
prototype.js	*	*	4.4	4.5
yui	*	*	2.2	2.1

+/- means with/without modeling of call and apply

- *Correlation tracking greatly aids analysis*
- *Other JavaScript dynamism still problematic*
- *Framework-based code beyond state of the art*



program analysis

Dynamic Determinacy

Runtime information to aid static analysis

Actual JQuery Code

```
var e = ("blur,focus,load,resize,scroll,unload," +
 "click,dblclick,mousedown,mouseup,mousemove," +
"mouseover,mouseout,change,reset,select,submit," +
“keydown,keypress,keyup,error").split(",");

for(var i=0;i<e.length;i++) new function(){
      var o = e[i];
      jQuery.fn[o] = function(f){
            return f ? this.bind(o, f) : this.trigger(o); };
      jQuery.fn["un"+o] = function(f){
            return this.unbind(o, f); };
      jQuery.fn["one"+o] = function(f){
            return this.each(function(){
                  var count = 0;
                  jQuery.event.add(this, o, function(e){
                        if(count++) return;
                        return f.apply(this, [e]); }); }); }; };
```

Dynamic Behavior

```
jQuery.fn.blur = function () { ... };
jQuery.fn.unblur = function () { ... };
jQuery.fn.oneblur = function () { ... };
jQuery.fn.focus = function () { ... };
jQuery.fn.unfocus = function () { ... };
jQuery.fn.onefocus = function () { ... };
jQuery.fn.load = function () { ... };
jQuery.fn.unload = function () { ... };
jQuery.fn.oneload = function () { ... };
```

- *Dynamic code is completely constant at runtime*
- *Values must be the same in every execution*

Determinacy Facts

- *Record values known at runtime to be constant*
- *Record as determinacy facts*

$$[\![e]\!]_{f \to g \to \ldots \to k} = c$$

expression

context

value

Determinacy Examples

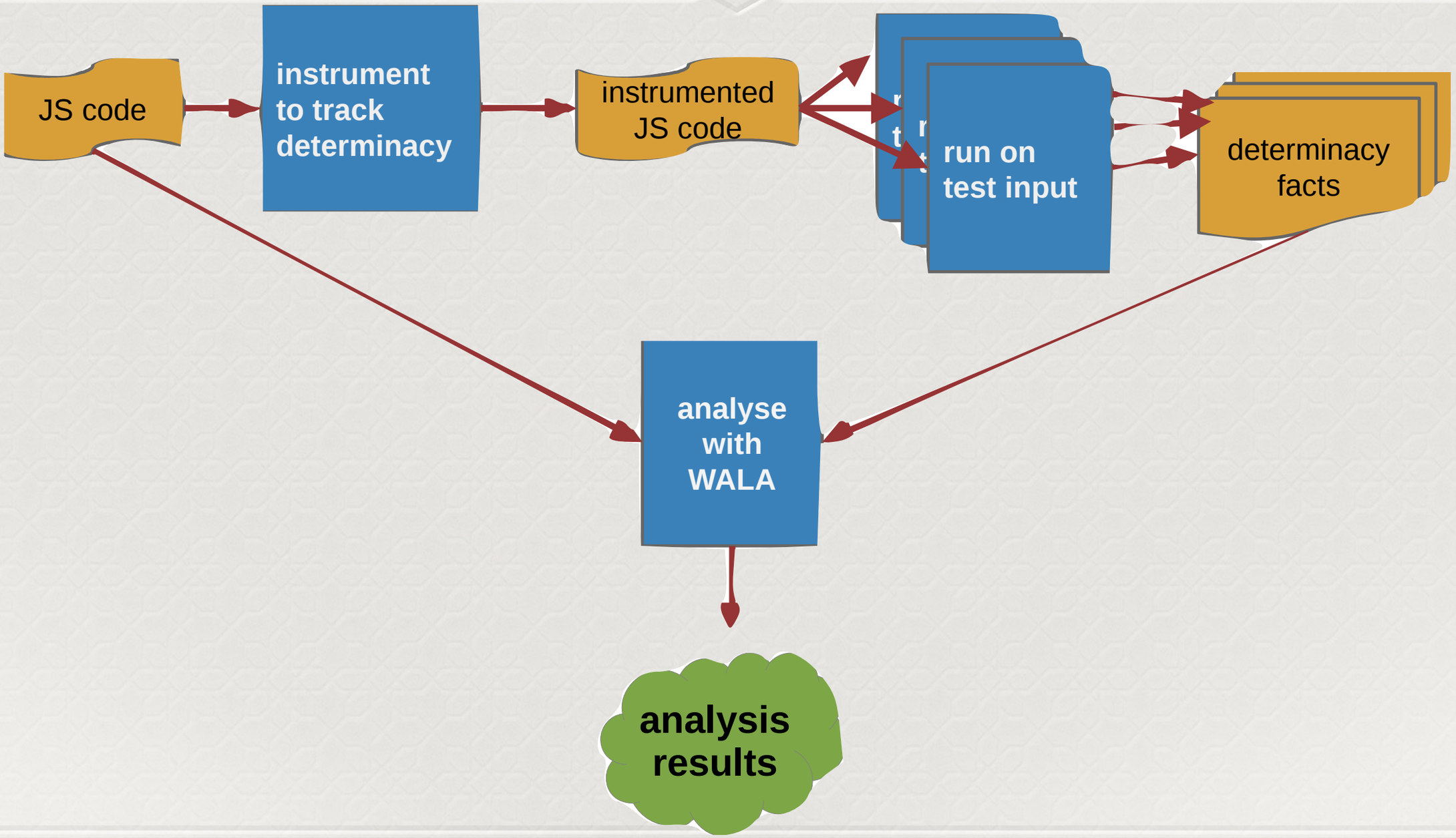
```
var e = ("blur,focus,load,resize,scroll,unload," +
 "click,dblclick,mousedown,mouseup,mousemove," +
"mouseover,mouseout,change,reset,select,submit," +
“keydown,keypress,keyup,error").split(",");

for(var i=0;i<e.length;i++) new function(){
    var o = e[i];
     …
    jQuery.fn["un"+o] = …
```

$$[\![\ \texttt{e[i]}\ ]\!]_{\perp \to 5} = \text{“}unload\text{”}$$

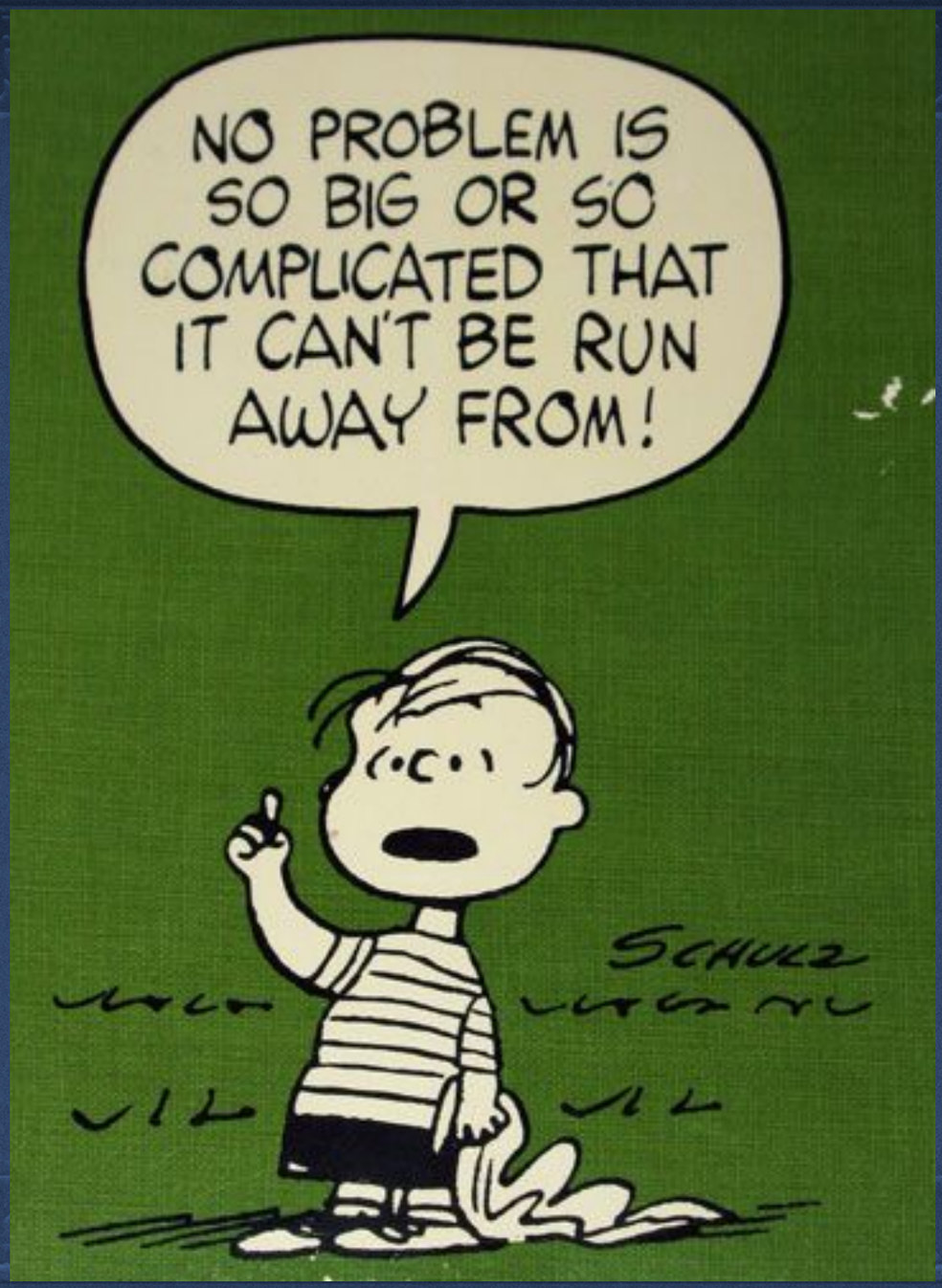
$$[\![\ \text{“}\texttt{un}\text{”} + \texttt{o}\ ]\!]_{\perp \to 5} = \text{“}ununload\text{”}$$

Implementation



Does it work?

- *Determinacy greatly aids static analysis*
- *See OOPSLA13 paper from Aarhus for a static version*
- *Allows analysis of more jQuery versions*
- *Still not sufficient for real jQuery applications*



Approximate Callgraphs

Let's not solve the impossible problems

Field-Sensitive Approach

```
jQuery.fn = {
 extend: function ext(obj) {
  for(var p in obj)
   jQuery.fn[p] = obj[p];
 }
};
```

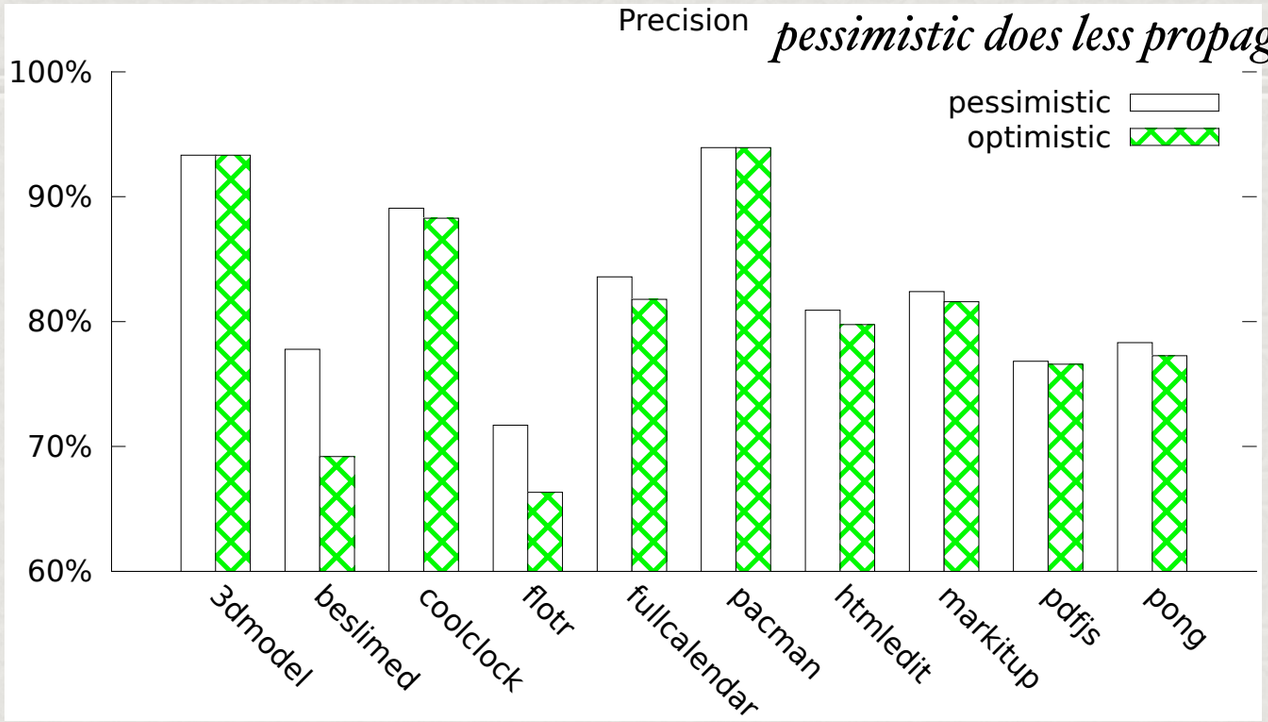
- *Field-based means one location per property*
  - *imprecisely merge properties for each name*
  - *makes copying fields a no-op to analysis*
- *No full pointer analysis*

Unsoundness

```
arr = ["Width","Height"];
for (var i=0;i<arr.length;++i)
 $.fn["outer"+arr[i]] = function() { ... };
$.fn.outerWidth();
```

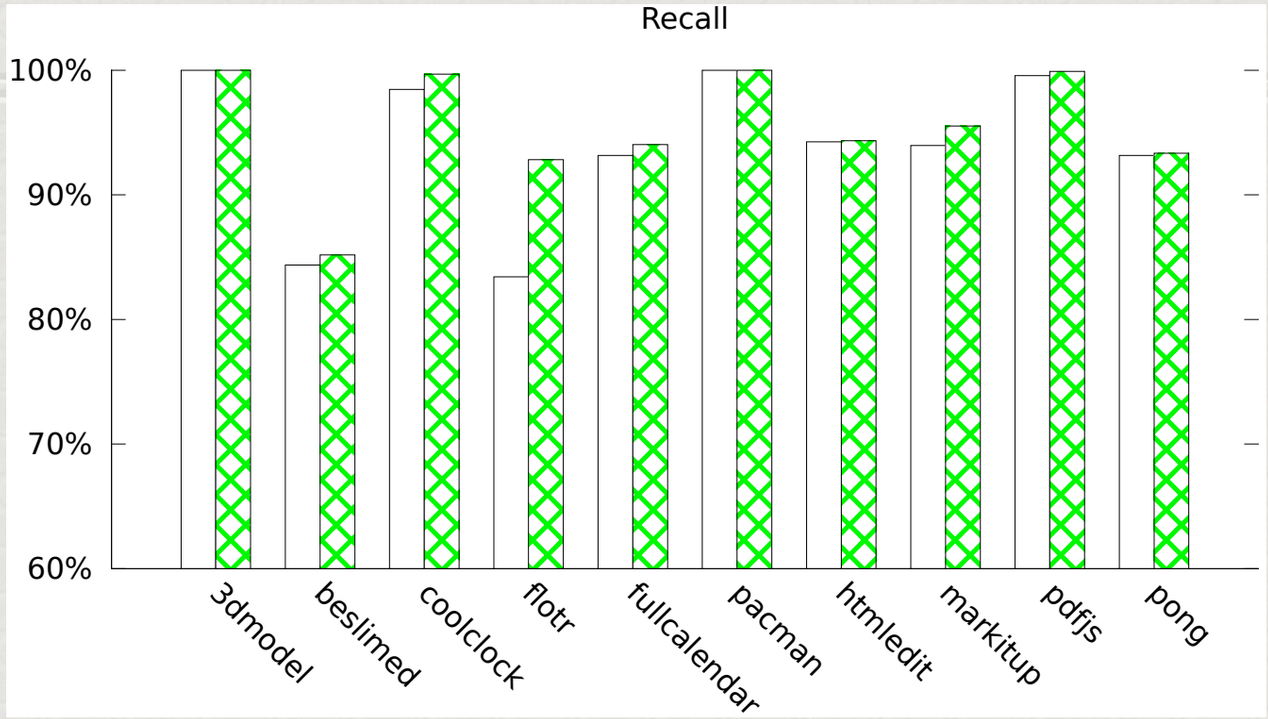
- *Ignoring dynamic accesses can be unsound*
  - *some functions only written in such accesses*
- *Field based analysis imprecise for some idioms*
  - *inheritance and overriding not distinguished*
  - *less common in JavaScript than Java*

Call Graph Precision



- *Fraction of static edges found in dynamic call graph*
- *Variable noise, like most static call graphs*
  - *>= 90% real edges in a few cases, always > 50%*
  - *Pessimistic reduces extraneous propagation*

Call Graph Recall



- *Fraction of dynamic edges found in static call graph*
- *Unsoundness limited*
  - *>= 80% of the call graph usually found*
  - *Optimistic helps callback-heavy code*

Taint Analysis Client

Adapt taint analysis to approximate call graphs

Taint Example

```
<head>
<TITLE>Welcome!</TITLE>
<script src="script.js">
</script>
</head>
<body>
<br>
Welcome to our system
<form>
  <input type="button"
         onClick="doit();"/>
  <br>
  <input type="textarea"
         id="fd"
         value="enter text"/>
</form>
</body>
</HTML>
```

```
function copy(a, b) {
  for(t in a) {
    b[t] = a[t]; } }

var Facade = {
  open: function open(obj) {
    window.open(obj.url); },
  url: function url() {
    var obj = { };
    var elt = document.getElementById("fd");
    obj.url = elt.value;
    return obj;
} };

function doit() {
  var x = Facade.url();
  var y = { url: "http://cnn.com/" };
  Facade.open(y);
  copy(x,y);
  Facade.open(y); }
```

taint rule: document.getElementById.value > window.open

Taint Example

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<head>
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how to identify tainted source?

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  copy(x,y);
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```

don't taint all 'url' properties

Taint Example

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function doit() {
  var x = Facade.url();
  var y = { url: "http://cnn.com/" };
  Facade.open(y);
  copy(x,y);
  Facade.open(y); }
```

first-class property accesses

Taint Example

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  Facade.open(y);
  copy(x,y);
  Facade.open(y); }
```

only open after copy is bad

Taint Example

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function doit() {
  var x = Facade.url();
  var y = { url: "http://cnn.com/" };
  Facade.open(y);
  copy(x,y);
  Facade.open(y); }
```

only some 'url' tainted

Flow-Sensitive Propagation

- *No pointer analysis*
  - *No explicit aliasing*
    - *Rely on local queries*
- *Use access paths*
  - *Globals, e.g. document*
  - *But must handle methods*

```
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```

Identifying Tainted Sources

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} };
```

variable	path
document	document

taint rule: document.getElementById.value > window.open

Identifying Tainted Sources

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```

variable	path
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elt	document.getElementById

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Identifying Tainted Sources

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} };
```

variable	path
document	document
elt	document.getElementById
_	document.getElementById.value

taint rule: document.getElementById.value > window.open

Distinguishing Objects

variable	path
obj	url

```
function copy(a, b) {
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variable	path
obj	url
x	url

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```

taint rule: document.getElementById.value > window.open

First-Class Properties

variable	path
obj	url
x	url
a	url
b	*

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First-Class Properties

variable	path
obj	url
x	url
a	url
b	*
obj	*
_	_

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```

taint rule: document.getElementById.value > window.open

Taint Analysis

- *Flow-sensitive approach promising*
  - *tolerates imprecisions from field-based analysis*
  - *initial scalability results promising*
- *Evaluation so far against existing analyses*
  - *better scalability of underlying analysis*
  - *equally precise results*

The Impossible Dream

- *Approximate analysis seems inevitable*
  - *traditional approaches do not scale yet*
  - *dynamism of JavaScript challenging*
- *Approximate security analysis promising*
  - *shows good coverage compared to existing approaches*
  - *scalability benefits of approximate techniques*