Language Based Isolation of Untrusted JavaScript

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Outline

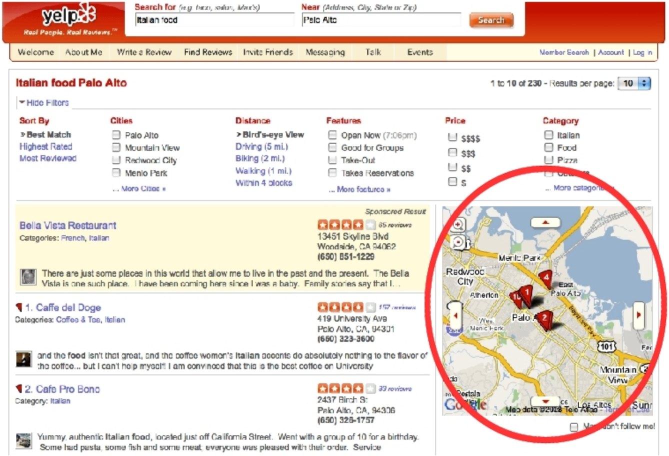
Web 2.0

All about mixing and merging content (data and code) from multiple content providers in the users browser, to provide high-value applications known as mashups

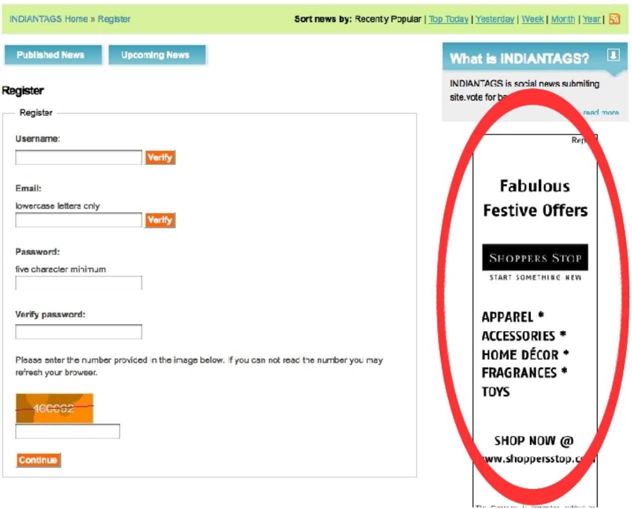
- Terminology:
  - Individual contents being mixed - *Components*.
  - Content Providers - *Principals*.
  - Publisher of the mashup- *Host*.
- Execution environment- Web Browser.
- Web page (DOM) - Shared resource.
- Most common language for mashups- JavaScript.
- Examples:
  - Basic mashups: Any web page with advertisements, iGoogle.
  - More complex mashups: Yelp, Yahoo Newsglobe ...

Example: Basic Mashup (Advertisements)

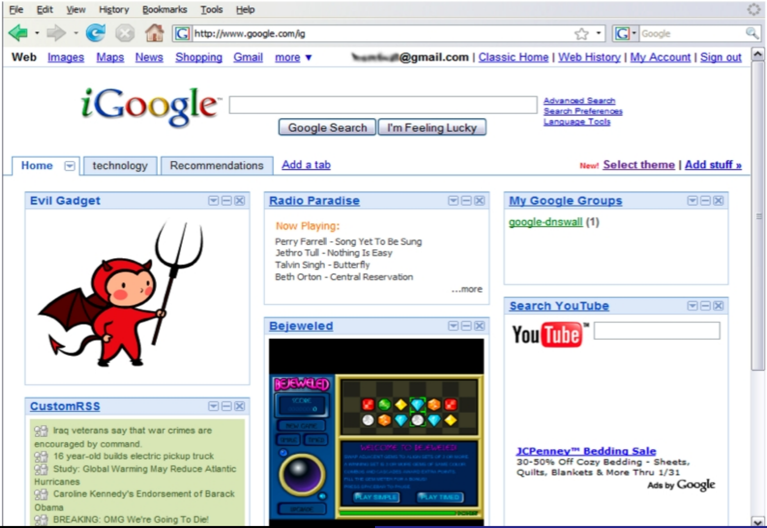
Example: Complex Mashup (Yelp)



Security Issue: Attack Host



Security Issue: Attack other components



Security Issues

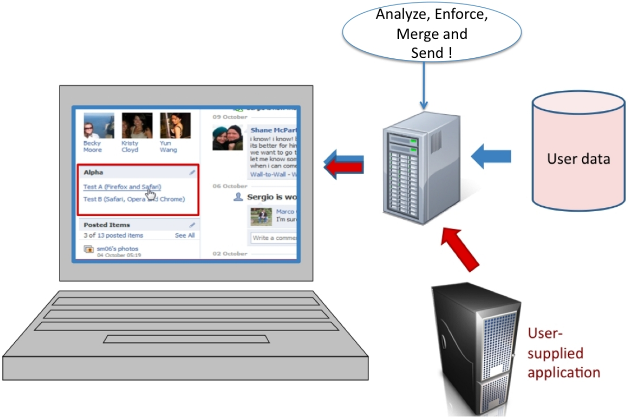
- Each principal owns part of the resources and has *integrity* and *confidentiality* constraints over them.
  - Yelp restrictions: Google map scripts should not tamper with search results.
  - Google Map restrictions: Yelp code should not re-define any functions defined by google maps.
- *Mashups should be designed such that the interests of all principals, including the host are protected.*
- High risk associated: Credit card fraud, identity theft, loss of sensitive information
- Cannot afford to miss a single edge case- Need a definitive proof of correctness.

Our Model: Basic Mashups

Basic JavaScript mashup with non-interacting components.

- Two trust levels: trusted and untrusted.
- Untrusted components are sequentially composed and placed in a trusted context.
- Pages with advertisements, iGoogle, Facebook Apps.
- We consider JavaScript sandboxing as opposed to Iframes.
  - Iframes are restrictive, less control over contents of the frame.
  - Expensive to expose a library to Iframed code.

Design



- Isolation enforced statically at the server.

Isolation Problem

Isolation Problem

Design isolation mechanisms for untrusted components, so that they cannot access security critical resources belonging to the host and also other untrusted components.

Split the Isolation Property.

1. Host Isolation
   - Example: Untrusted component should not read document.cookie or write to window.location.
   - Some existing approaches: ADSafe, FBJS, Caja.
2. Inter-Component Isolation
   - One untrusted component should not write to the variables defined by another untrusted component.
   - Isolation between ads or two untrusted FBJS applications.
   - Tricky! - FBJS, ADsafe and our earlier attempts fail.

A bit about JavaScript

- History :
  - Developed by Brendan Eich at Netscape.
  - Standardized for Browser Compatability : ECMAScript 262-edition 3
- First class functions, Prototype based language, re-definable object properties.
- Scope Objects/Stack frames can be first class JavaScript objects: Variable names ⇔ Property names.
- Implicit type conversions which can trigger user code.

```
var y = "a"; var x = {valueOf: function(){ return y;}}
x = x + 10;
js> "a10"
```

Quick Case study: Facebook *FBJS*

- Basics:
  - Facebook apps are either Iframed or integrated. We are interested in integrated apps.
  - Integrated FaceBook applications are written in FBML/FBJS: Facebook subsets of HTML and JavaScript.
  - FBJS is served from Facebook, after filtering and rewriting.
  - Facebook libraries mediate access to the DOM (Wrapping).
- Security goals:
  - No direct access to the DOM.
  - No tampering with the execution environment
  - No tampering with Facebook libraries.

Isolation Approach

Filtering:

- Blacklist security-critical variable names and disallow them.
- No eval, Function, ...

Rewriting:

- this $\longrightarrow$ ref(this).
  - $\mathit{ref}(x) = x$ if $x \neq \mathit{window}$ else $\mathit{ref}(x) = \mathit{null}$.
- e1[e2] $\longrightarrow$ e1[idx(e2)].
  - $\mathit{idx}(e)$ returns error if e evaluates to a black-listed property name and behaves as identity otherwise.

Wrapping: Facebook provides various wrapped DOM functions to provide controlled access to the DOM.

Quick Casestudy: Yahoo! *ADsafe* (Douglas Crockford)

- Basics:
  - A safe subset of JavaScript to be used by untrusted ad code not placed in an Iframe.
  - Hosting page first places the ADSafe library (*adsafe.js*) on its page.
  - Untrusted ad code must be written in an ADSafe compliant manner. Tool for checking compliance: JSLint.
  - All interaction with the trusted code is mediated by the ADSafe library.
- Security Goals:
  - No direct access to DOM.
  - No tampering with the execution environment
  - No tampering with *ADsafe* libraries.

Isolation Approach

Design

```
<script>
"use strict";
ADSAFE.go("WIDGETNAME_", function (dom) { // Untrusted Code});
</script>
```

- Basic Restrictions
- No this, with, e[e], global variables, ...
- Banned variables:

  arguments, callee, caller, constructor, eval, prototype....
- Some functionality restored via 'ADSAFE' object (provided by the library).
  - ADSAFE.get(o,p): Access property *p* of object *o*.
  - ADSAFE.create(o): Create object that inherits from *o*.
  - . . .

Recent FBJS attack

Attack- Get hold of window object !

```
var f = function(){};
f.bind.apply =
    (function(old){return function(x,y){
                        var getWindow = y[1].setReplay;
                        getWindow(0).alert("Hacked!");
                        return old(x,y)}
      })(f.bind.apply)}
```

- JavaScript offers two ways to call a function: $o.f(v)$ or $f.apply(o, v)$.
- While using $f.apply(o, v)$, we need to make sure that the apply method is non-malicious !
- Reported to Facebook.

Recent ADSafe attack

Attack - Run arbitrary script !

```
var o = {toString:function(){o.toString =
                              function(){return "script"};
                         return "div"}};
dom.append(dom.tag(o).append(dom.text("alert('Hacked!')")));
```

- dom.tag expects a tag-name string, and creates a node if the tag-name is allowed.
- Confuse dom.tag by passing it an object that returns "div" when converted to string first time and "script" the second time.
- Reported to Doug Crockford.

Conclusion

- All attacks found till date are edge cases which the sandboxing technique misses.
- Sandbox designer does not account for all possible future states !
- We need a systematic design followed by a proof of correctness to make sure that we have covered all cases.

Outline

Our previous research: Provably correct sandboxing

Two main contributions:

1. Formal Semantics of JavaScript
2. Sub-language $J_{\mathcal{B}}$ and source-source rewriting $Enf_{\mathcal{B}}$, for enforcing a black-list $\mathcal{B}$.
   - Property: No rewritten program can access properties from the black-list $\mathcal{B}$ or get hold of the global object.
   - Rigorous proof of correctness.
   - As expressive as *FBJS*.
   - Developed in a series of papers - CSF'09, W2SP'09, ESORICS'09.

Rest of this talk:

- Review 1 and 2
- Analyze isolation goals that can and cannot be achieved using the sandbox $J_{\mathcal{B}}$, $Enf_{\mathcal{B}}$.

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Formal Semantics of JavaScript

Formalized all of ECMA-262-3rd edition ($JS_{ecma262}$).

- Small step style operational semantics.
  - Meaning of a program ⇔ sequence of actions that are taken during its execution.
  - Specify sequence of actions as transitions of an Abstract machine
- Developed formal semantics as basis for proofs (APLAS'08)
  - Very long (70 pages of ascii).
  - DOM is just treated as a library object.
  - We experimented with available browsers and shells
  - Defining an operational semantics for a real programming language is hard: sheer size and JavaScript peculiarities.

We are in the process of migrating to ES5 but current semantics is adequate for analyzing *ADsafe* and *FBJS*.

A glimpse of the rules

State

Program state is represented as a triple $\langle H, l, t \rangle$.

- H: Denotes the Heap, mapping from the set of locations($\mathbb{L}$) to objects. H_0 is used to denote the initial heap.
  - Objects are maps from property names ($\mathbb{P}$) to values (v).
- l: Location of the current scope object (or current activation record).
- t: Term being evaluated.

- General form of a rule $\frac{\langle premise \rangle}{H_1, l_1, t_1 \rightarrow H_2, l_2, t_2}$.
- We use H_0 to denote the initial JavaScript heap and l_G to denote the global object.

Language $J_{\mathcal{B}}$, Rewriting $Enf_{\mathcal{B}}$

Goal: Prevent access to property names from blacklist $\mathcal{B}$ and global object.

JavaScript Facts:

- Two kinds of Property Access:
  - Explicit: x, e1.p, e1[e2]
  - Implicit: toString, valueOf . . ..
    We found the complete list -$\mathcal{P}_{nat}$.
- Ways to access global object:
  - this
  - Calling native methods of the form function()(... return this).
- Dynamic Code Generation: eval, Function, constructor.

Design

Controlling e.x and x.

Filter 1

Filter all terms containing an identifier or property name from $\mathcal{B} \cup \{eval, Function, constructor\}$ and also any \$-prefixed property name.

Controlling e1[e2].

- Approach: Rewrite e1[e2] to e1[IDX(e2)]
- Need to avoid "confused IDX" attacks.

Design

Our IDX function.

Init 1

var \$String = String;

var \$BL = {p1:true,...,pn:true, eval:true,...,\$:true,...}

Rewrite 1

Rewrite every occurrence of e1[e2] by e1[IDX(e2)]

```
IDX(e2) = ($=e2,toString:function()return ($=$String($),CHECK_$))
      CHECK_$ = ($BL[$] ? "bad":
                ($ == "constructor" ? "bad": $== "eval" ? "bad":
                ($ == "Function" ? "bad":($[0] == "$" ? "bad":$)))))
```

Preventing access to global object

Taking care of this: Rewrite this with suitable check.

Rewrite 1

Rewrite every occurrence of this to NOGLOBALTHIS.
NOGLOBALTHIS = (this==$g?null;this)

Save global object in $g.

Init 1

```
var $g = this;
```

Other ways of getting hold of global object:

- Method valueOf of Object.prototype and sort, concat, reverse of Array.prototype can potentially return pointer to global object.
- Define wrappers with NOGLOBAL check on return value.

Wrapping native methods

Init 2 (Wrapper)

```
$OPvalueOf = Object.prototype.valueOf;
$OPvalueOf.call = Function.prototype.call;
Object.prototype.valueOf =
function(){var $= $OPvalueOf.call(this); return ($==$g?null:$)}
```

- Similarly *Init*3, 4, 5 for sort, concat, reverse.
- A copy of original call method is saved, motivated by another *FBJS* attack.
- Wrapping eval and Function: doable, but need to define a JavaScript expression that parses, filters and rewrites strings meant to represent JavaScript terms. (constructor will be the only thing left then!)

Result

- Define $J_{\mathcal{B}}$ as JavaScript with *Filter* 1 applied.
- Define $Enf_{\mathcal{B}}$ as the composition of functions *Rewrite* 1, *Rewrite* 2.
- Define H_{wrap} as the heap obtained after executing *Init* 1 and *Init* 2 on the initial JavaScript heap H_0.

Let l_G be the global object.

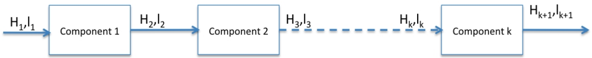
Theorem

For all user terms $t \in J_{\mathcal{B}}$, the following holds for the reduction trace of $Enf_{\mathcal{B}}(t)$ starting from H_{wrap}, l_G

1. Blacklist: No property from the black-list $\mathcal{B}$ is accessed (provided $\mathcal{B} \cap \mathcal{P}_{nat} = \emptyset$).
2. No Global: Final value returned is never the global object.

Outline

Isolation problem



- Let blacklist $\mathcal{B}_{host}$ denote critical elements of hosting page .
- Let $t_1, \ldots, t_n$ be programs running in components $1, \ldots, n$.

Isolation Problem

Define an initial environment H_{mash}, l_{mash} and an enforcement technique for each component such that:

1. Host Isolation: For all i, reduction trace of component i starting from H_i, l_i does not access any property from $\mathcal{B}_{host}$.
2. Inter-Component Isolation: For all i, j, $i < j$, reduction of component i does not write to any heap location that component j reads from.

Isolation technique

We first evaluate the following isolation technique:

- Initial environment H_{wrap}, l_G.
- Enforcement technique Enf_i for component (t_i, id_i):
  1. Check containment in $J_{\mathcal{B}}$
  2. Rewrite program t_i to $Enf_{\mathcal{B}}(t_i)$.
  3. Rewrite every variable x in $Enf_{\mathcal{B}}(t_i)$ to $id_i x$.
- Intuitively this seems correct.
  - 1 and 2 should give host isolation.
  - 3 should give inter-component isolation.

Lets be systematic !

Host Isolation

- From the correctness theorem for sandbox $J_{\mathcal{B}}, Enf_{\mathcal{B}}$ we have:
  - Reduction trace of $Enf_i(t_i)$ starting from H_{wrap}, l_G will never access any property in $\mathcal{B}_{host}$.
  - But what about the trace starting from H_k, l_k ?
  - We do not know H_k, l_k in advance !
- Fortunately, we can formally show that the property holds for starting heap-scope H_i, l_i, provided all other components are also enforced.
- Therefore the isolation technique is sufficient for Host Isolation.

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Inter-Component Isolation

Intuition:

- Global object is the common object shared between components.
- No Global property ensures that no component can get a handle to the global object.
  - Blocks access to global object via e.p and e1[e2].
- Variable renaming separates namespace.
  - Isolates access to global object via x.

Can we conclude each component will access different portion of the global object ?

No, what if component j can reach a function defined by component i which has id_i prefixed variables !

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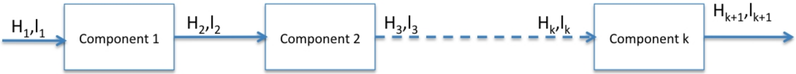
Communication via native objects

Attack

Component i: f.toString.channel = function()(a = 1)
Component j: f.toString.channel()

- f.toString and f.toString will point to the common location Function.prototype.toString even after namespace separation.
- Components i and j can use this location as a communication channel.
- We found a real *FBJS* attack where one app can (maliciously) change the meaning of another app.
- There are other communication channels as well: Array.prototype.push and Array.prototype.pop.

What has gone wrong ?



- Our sandboxing technique restricts execution starting from H_{wrap}, l_G but does not provide any guarantees for H_k, l_k
- Execution of one component can transform the heap such that another component can break out of the sandbox !
- We are caught in the problem of not being able to account for all future states !

Concept: Authority

Authority ($Auth(H, l, t)$)

Authority of a term t for a given heap-scope H, l is some over-approximation of the set of all possible heap actions that can be performed during the reduction of the term.

- Inter-component isolation will hold if for all i, j, $i < j$, we can ensure that
  $Auth(H_i, l_i, t_i)$ does not overlap $Auth(H_j, l_j, t_j)$
- But this check is not useful as we don't know H_i, l_i !
- We can at most know authority of each component for the initial heap-scope.

Authority Safe language

Authority Safety

A language is said to be authority safe if there exists an authority map *Auth* such that

1. Only Connectivity begets Connectivity The execution of a term t_i starting from H, l can only affect the authority of a term t_j if
$Auth(H, l, t_i)$ overlaps with $Auth(H, l, t_j)$
2. No Authority Amplification The execution of a term t_i starting from H, l can at most increase the authority of another term t_j by $Auth(H, l, t_i)$.

Thus non-overlapping authorities ensure no communication is possible.

Result

Authority Isolation

Given an authority safe language, authority isolation holds for terms $t_1, \ldots, t_n$ for heap scope H, l if for all $i, j, i \neq j$ $Auth(H, l, t_i)$ does not overlap with $Auth(H, l, t_j)$

Theorem

Authority Isolation $\implies$ Inter-Component Isolation.

- Authority safety saves us from worrying about the intermediate heap-scopes.
- Reduces the problem to defining an appropriate source-to-source rewriting so that initial authorities are non-overlapping.
- Justifies one time source-to-source rewriting approach.

Solving the mashup isolation problem

- We restrict the language $J_{\mathcal{B}}$ and a derive an authority-safe subset J_{safe}.
  - Make native object properties read-only.
  - Wrap native functions which can act as implicit communication channels.
  - ....
- We define an initial heap-scope H, l and enforcement functions $Enf_1, \ldots, Enf_n$ such that for all $i, j, i \neq j$, $Auth(H, l, t_i)$ does not overlap with $Auth(H, l, t_j)$

Details and rigorous proof of correctness is provided in the paper.

Insight

- Sandbox designers have a mental model of the what code placed in the sandbox can and cannot do - Anticipated Authority
- Sandboxes are calibrated so that anticipated authorities are isolated.
- Reason things break:
  Anticipated Authority $<$ True Authority
- How do we ensure that the mental model captures true authority ?

Prove Authority Safety !

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Prove Authority Safety !

Achieving authority-isolation in general

Object Capabilities

- Capabilities can be viewed as small bags of authority.
  - A pointer can be a capability with set of all reachable locations being its authority.
- The authority of a term is the union of authority arising all capabilities it possesses.
- Authority isolation can be achieved by appropriately distributing capabilities to the various components such that no two components have overlapping authority.
- Approach used by Google Caja.
- This is explained very formally in our Oakland 2010 paper. *Object Capabilities and Isolation of Untrusted Web Applications*

Conclusions and Future Work

- Conclusions:
  - Building correct JavaScript sandboxing mechanism for host isolation is tricky !
  - Sandboxes can protect the host page but may not work for inter-component isolation.
  - Object Capabilities seem like a promising approach for inter-component isolation.
- Ongoing work:
  - Formalized the notion of Object-capability-safety and Authority-safety.
  - First cut at a proof of concept for Google Caja.
- Future work:
  - We plan to write the JavaScript semantics in machine readable format so that the proofs can be automated.
  - Formalize the concept of *Defensive consistency* and its connection with Object-capability-safety .

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Thank You !