Language Based isolation of Untrusted JavaScript

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Joint work with Sergio Maffeis (Imperial College, London) and John C. Mitchell (Stanford University)
1. Web 2.0 and the Isolation Problem

2. Case Study: FBJS
   - Design
   - Attacks and Challenges

3. Formal Semantics of JavaScript

4. Achieving the Isolation goal

5. Ongoing and Future Work
Web 2.0 and the Isolation Problem

Web 2.0: All about mixing and merging content (data and code) from multiple content providers in a user's browser, to provide high-value applications

- Extensive Client-side scripting - lots of JavaScript.
- Systems have complex trust boundaries.
- Security Issues

This work

- Focus on the simple case where content providers are either trusted or untrusted: Third party Advertisements, Widgets, Social Networking site - applications.
- Assume the publisher has access to untrusted content before it adds it to the page.
- Focus on JavaScript content present in untrusted code.
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Web 2.0 and the Isolation Problem

Isolation Problem
Design security mechanisms which allow untrusted code to perform valuable interactions and at the same time prevent intrusion and malicious damage.
Web 2.0 and the Isolation Problem

Isolation Problem

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IIFrames

- Placing all untrusted content in separate IIFrames seems to be a safe solution.
- Social network site applications and Ads: IIFrames are sometimes too restrictive
  - Restricts the ad to a delineated section of the page.
  - Social network applications need more permissive interaction with the host page.
- Some publishers prefer to not use IIFrames
  - Gives better control over untrusted code.
  - Easier to restrict same-origin untrusted code.

This Work

Design isolation mechanisms for untrusted code not placed in separate IIFrames.
Program Analysis Problem

Given an untrusted JavaScript program $P$ and a Heap $H$ (corresponding to the trusted page), design a procedure to either statically or dynamically via run time checks, guarantee that $P$ does not access any security critical portions of the Heap.

- Design static analysis and/or code instrumentation techniques
- Very hard problem to solve for whole of JavaScript as all code that gets executed may not appear textually!

```javascript
var m = "toS"; var n = "tring";
Object.prototype[m + n] = function() { return undefined;};
```

Approach

Solve the above problem for subsets of JavaScript that are more amenable to static analysis.
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Case Study: **FBJS**

- **FBJS** is a *subset* of JavaScript for writing Facebook applications which are placed as a subtree of the page.

**Restrictions Applied**

**Filtering**: Application code must be written in **FBJS**

- Forbid `eval`, `Function` constructs.
- Disallow explicit access to properties (via the dot notation `-o.p) __parent__, constructor, ...`

**Rewriting**

- this is re-written to `ref(this)`
  - `ref(x)` is a function defined by the host (Facebook) in the global object such that `ref(x) = x` if `x ≠ window` else `ref(x) = null`
  - Prevents application code from accessing the global object.
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Case Study: FBJS

Rewriting (contd):

- $o[p]$ is rewritten to $o[idx(p)]$: Controls access to dynamically generated property names.
  
  - $idx(p)$ is a function defined by the host (Facebook) in the global object such that $idx(p) = \text{bad}$ if $p \in \text{Blacklist}$ else $idx(p) = p$.
  
  - **Blacklist** contains sensitive property names like `__parent__`, `constructor`, ...

- Add application specific prefix to all top-level identifiers.
  
  - Example: $o.p$ is renamed to $a1234.o.p$
  
  - Separates effective namespace of an application from others.
  
  - Facebook provides libraries, accessible within the application namespace, to allow safe access to certain parts of the global object.
Case Study: FBJS

Rewriting (contd):

- \( o[p] \) is rewritten to \( o[idx(p)] \): Controls access to dynamically generated property names.
  - \( idx(p) \) is a function defined by the host (Facebook) in the global object such that \( idx(p) = \text{bad} \) if \( p \in \text{Blacklist} \) else \( idx(p) = p \).
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  - Example: \( o.p \) is renamed to \( a1234\_o.p \)
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  - Facebook provides libraries, accessible within the application namespace, to allow safe access to certain parts of the global object.
An attack on FBJS (Nov’08)

Goal of the Attack
Get a handle to the global object in the application code.

Main Idea: Get a handle to the current scope object and shadow the ref method.

1. Getting the current scope: GET SCOPE.
   
   ```javascript
   try {
     throw (function() { return this; });
   }
   catch (f) {
     curr_scp = f();
   }
   ```

   Other tricks: Use named recursive functions (see our CSF’09 paper)

2. Shadow ref: curr_scp.ref = function(x) { return x; }.

3. this will now evaluate to the global object!
Another attack on FBJS (Mar’09)

Goal of the attack
Access a black-listed property name

Main Idea
- The Facebook IDX(e) does the following check:
  1. Evaluate e2.
  2. Convert result(1) to string and check it is blacklisted
  3. If result(2) is false, return result(1) else return “bad”.
- Observe e2 will get converted to string twice.

Almost works

```
e := {toString : function() {this.toString = function() {return ’constructor’}; return ’foo’}}
```

FBJS has a check e instanceof Object ? ”bad”
In Safari, scope objects have a \texttt{null} prototype and hence they escape the \texttt{instanceOf} check.

**Attack !!! (Safari)**

\begin{verbatim}
var obj = GET_SCOPE;

obj.toString = function() {this.toString = function() {return 'constructor'}
 ;return 'foo'};

var f = function() { }; f[obj]('alert(0)')();
\end{verbatim}
Vulnerabilities Disclosed

- To defend against the first attack, Facebook renamed `idx` and `ref` methods to `$FBJS.idx` and `$FBJS.ref`.
- To defend against the second attack, Facebook modified `idx` function to check the browser and decide if the object can escape the "instanceOf" check.
- Does this fix the problem once and for all?
- Are more attacks possible on these lines?
Summary of our analysis of FBJS

We realize the following three fundamental issues:

1. The ultimate goal is to ensure that a piece of untrusted code (that satisfies a certain syntactic criterion), does not access certain global variables.

2. There are a number of subtleties related to the expressiveness and complexity of JavaScript.

3. Finding temporary fixes to the currently known attacks is NOT sufficient.

4. Several million users: Impact value of a single attack is VERY high.

Formal Analysis !!

It is important to do a formal analysis based on traditional programming language foundations to design provable secure isolation techniques.
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3. **Formal Semantics of JavaScript**

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5. **Ongoing and Future Work**
A bit about JavaScript

Key language features

- First class functions, Prototype based language, redefinable object properties.
- Can convert string to code: `eval`, `Function`
- Implicit type conversions

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

- **ECMA262-3**: Standardized for browser compatibility. Does not include DOM and other browser extensions.
- Sufficient for 'understanding' the language but insufficient for rigorously proving properties about it.
- We need a formal semantics for representing the meaning of every possible JavaScript program.
Our Approach

For now, focus on ECMA-262-3rd edition. This is already quite non-trivial!

1. Convert Informal semantics (ECMA262-3) into a Formal semantics. (APLAS’08)
   - Specifies meaning in a **Mathematically rigorous** way.
   - The very act of formalization revealed **subtle aspects** of the language and helped us devise attacks on FBJS.

2. Systematically design subsets of JavaScript to achieve the isolation goal.

3. Use the formal semantics to **rigorously prove** that the isolation goal is attained for all programs within the subset (CSF’09, W2SP’09 and Ongoing).
Structural Operational Semantics

- Meaning of a program $\iff$ sequence of actions that are taken during its execution.
- Specify sequence of actions as transitions of an Abstract State machine

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.
- $l$ : Location of the current scope object (or current activation record).
- $t$ : Term being evaluated.
Semantic Rules

Small step style semantics (Gordon Plotkin)

- Three semantic functions $\rightarrow e$, $\rightarrow s$, $\rightarrow P$ for expressions, statements and programs.
- **Small step transitions**: A semantic function transforms one state to another if certain conditions (premise) are true.
- **General form**: $\langle Premise \rangle$

$$S \xrightarrow{t} S'$$

- **Atomic Transitions**: Rules which do have another transition in their premise (Transition axioms).
- **Context rules**: Rules to apply atomic transitions in presence of certain specific contexts.
- Complete set of rules (in ASCII) span 70 pages.
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Isolation Problem

Ensure that a piece of untrusted code written in a safe subset does not access certain security-critical global variables.

Let $Access(P)$ be the set of property names accessed when program $P$ is executed.

Reduce the isolation problem to the following 2 subproblems.

Problem 1 (Isolation from library code)

Given a blacklist $B$, design a meaningful sublanguage and an enforcement mechanism so that for all enforced programs $P$ in the sublanguage, $Access(P) \cap B \neq \emptyset$

Isolating host library methods: Create a blacklist $B$ of all security-critical methods in the library code.
Isolation Problem

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Reduce the isolation problem to the following 2 sub problems.

Problem 1 (Isolation from library code)

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Isolating host library methods: Create a blacklist $\mathcal{B}$ of all security critical methods in the library code.
Isolation from other untrusted code?

Key Idea: Rename identifiers to separate namespace of untrusted code.

But does this preserve the semantics? Not for \( Jt \).

- **Issue**: Variables are essentially properties of the current scope object (activation object).
  - \( \text{var } x = 42; \text{this}.x \) returns 42 in the global scope.
  - \( \text{var } a123.x = 42; \text{this}.x \) returns "reference error x not defined".
  - Disallow access to scope object!

**Problem 2 (Isolating scope objects)**

Define a meaningful sublanguage so that no program \( P \) in the sublanguage can return a pointer to a scope object.
Isolation from other untrusted code?

**Key Idea:** Rename identifiers to separate namespace of untrusted code.

But does this preserve the semantics? Not for $Jt$.

- **Issue:** Variables are essentially properties of the current scope object (activation object).
  - `var x = 42; this.x` returns 42 in the global scope.
  - `var a123_x = 42; this.x` returns "reference error x not defined".
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**Problem 2 (Isolating scope objects)**

Define a meaningful sublanguage so that no program $P$ in the sublanguage can return a pointer to a scope object.
Plan

<table>
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<tr>
<th>Isolating</th>
<th>Solution 1 (Static)</th>
<th>Solution 2 (Static + Runtime)</th>
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<tr>
<td>Blacklist (Problem 1)</td>
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<tr>
<td>Scope (Problem 2)</td>
<td></td>
<td></td>
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- Solution 1 is a sublanguage with pure static enforcement for achieving the goals in problem 1 and 2.
- Solution 2 is a sublanguage with static and runtime enforcement for achieving the goals in problem 1 and 2.
Isolating blacklist with syntactic enforcement

Design a sublanguage such that for any program $P$, all property names that can potentially be accessed appear textually in the code.

- **Fundamental issue**: Strings (m), Property Names (pn) and Identifiers (x) are implicitly converted to each other.
- Terms whose reduction trace involves conversion from

  $$\text{Strings} \rightarrow \text{Property names} \ (\text{like e[e]})$$
  $$\text{Strings} \rightarrow \text{Code} \ (\text{like eval})$$

are evil. Get rid of them!

**Subset $Jt$**

$Jt$ is defined as ECMA-262 MINUS: all terms containing the identifiers eval, Function, hasOwnProperty, propertyIsEnumerable, constructor and expressions $e[e]$, $e$ in $e$; the statement for $(e$ in $e)$ s;
Isolating blacklist with syntactic enforcement

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  \text{Strings} \rightarrow \text{Code (like eval)}
  \]

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**Subset $J_t$**

$J_t$ is defined as ECMA-262 MINUS: all terms containing the identifiers `eval`, `Function`, `hasOwnProperty`, `propertyIsEnumerable`, `constructor` and expressions `e[e]`, `e in e`; the statement `for (e in e) s;`
## Results

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- $\text{Id}(P)$: Set of identifiers in $P$.
- Some property names are accessed implicitly (Recall type conversions). Denote these property names by $\mathcal{P}_{nat}$. Includes $\{\text{toString, toNumber, valueOf}\}$, Object, Array, RegExp.

### Result

Any property name accessed by a program $P$ in $Jt$ when executed with respect to the initial heap is either contained in $\text{Id}(P)$ or in $\mathcal{P}_{nat}$.

- Can also enforce whitelists!
Isolating scope object with syntactic enforcement

Isolating the scope object

- For initial empty heap state, global object is only accessible via `@scope` and `@this` properties
- Dereferencing `@this` is the only way of returning the current scope object.
- `Object.prototype.valueOf, Array.prototype.sort(concat/reverse` can potentially deference the `@this` property.

Subset $Js$

The subset $Js$ is defined as $Jt$, MINUS: all terms containing the expression `this`; all terms containing the identifiers `valueOf, sort, concat` and `reverse`;

$Js \subset Jt$ : Sufficient for imposing the restriction that properties `valueOf, sort, concat` and `reverse` are never accessed
Isolating scope object with syntactic enforcement

Isolating the scope object

- For initial empty heap state, global object is only accessible via @scope and @this properties
- Dereferencing @this is the only way of returning the current scope object.
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**Subset Js**

The subset $Js$ is defined as $Jt$, MINUS: all terms containing the expression this; all terms containing the identifiers valueOf, sort, concat and reverse;

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<td>Subset $J_s \subseteq J_t$ Filter P if $\text{Id}(P) \cap B \neq \emptyset$</td>
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Result

No program in the language $J_s$ when executed with respect to the initial heap evaluates to the address of a scope object.
Isolating blacklist with runtime enforcement

\( Jt \) is fairly restrictive.

- Disallows \([\] \) operator altogether \( \Rightarrow \) No array access
- In principle, solution to problem 1 should allow \( o[p] \) where \( p \notin B \).

**Runtime Check** : \( e1[e2] \rightarrow e1[IDX(e2)] \) (along the lines of FBJS)

How do we design for \( IDX \) which enforces property that

- No property name from blacklist \( B \) ever gets accessed.
- Semantics is preserved for all programs \( P \) for which \( Access(P) \cap B \neq \emptyset \).
Subset $J_{t^{run}}$

\[ e_1[e_2] \rightarrow \text{va}_1[e_2] \rightarrow \text{va}_1[\text{va}_2] \rightarrow o[\text{va}_2] \rightarrow o[m] \]

- Observe that first $e_1$ and $e_2$ are converted to a value and only then $e_2$ is converted to a string.
- Ideally, $\text{IDX}(e_2)$ should return a value which on being converted to a string, checks if the string obtained from $e_2$ is outside the blacklist and returns it.

```javascript
IDX

($=e_2, \{\text{toString:function()\{return ($=\text{TOSTRING($),FILTER($)}\}}\})$
where TOSTRING($) = (new $String($)).valueOf() FILTER($) = ($blacklist[$]?"bad":$)
```

Subset $J_{t^{run}}$

The subset $J_{t^{run}}$ is defined as as $J_{t^{plus}} e[e]$ minus all terms with identifiers beginning with $\$$
Subset $J_t^{run}$

$e_1[e_2] \rightarrow va_1[e_2] \rightarrow va_1[va_2] \rightarrow o[va_2] \rightarrow o[m]$

- Observe that first $e_1$ and $e_2$ are converted to a value and only then $e_2$ is converted to a string.
- Ideally, $IDX(e_2)$ should return a value which on being converted to a string, checks if the string obtained from $e_2$ is outside the blacklist and returns it.

**IDX**

```
($=e_2, \{toString:function()\{return ($=TOSTRING($),FILTER($))\}\})
```

where $TOSTRING($) = (new $String($)).valueOf()$ FILTER($) = ($blacklist[$]?”bad”:$)

**Subset $J_t^{run}$**

The subset $J_t^{run}$ is defined as as $J_t$ plus $e[e]$ minus all terms with identifiers beginning with $\$$. 

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Language Based isolation of Untrusted JavaScript
### Subset $J^{run}$

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### Result

For all programs $P$ in $J^{run}$ such that $Id(P) \cap B \neq \emptyset$, the program $String = String; \ Rew(P)$ when executed with respect to the initial heap does not access any property from $B$. 
Isolating global object with runtime enforcement

*Js* disallows *this*

- Heavily used in object oriented programming.
- In principle, solution to problem 2 must allow *this* if it does not point to a scope object.

**Runtime check :** \( \text{this} \rightarrow \text{NOSCOPE(this)} \)

- How can we check if a given object is a scope object?
- Not straightforward in general,
  
  Use \( \text{NOGLOBAL(this)} = (\text{this}==?null;\text{this}) \).
- \( \text{NOSCOPE(this)} \) is definable for Firefox, see paper.

**Subset \( J_{run} \)**

Define the subset \( J_{run} \) as \( J_{run} \) plus: all terms containing *this* minus all terms with identifiers beginning with $.
Isolating global object with runtime enforcement

Js disallows this

- Heavily used in object oriented programming.
- In principle, solution to problem 2 must allow this if it does not point to a scope object.

Runtime check: this → NOSCOPE(this)

- How can we check if a given object is a scope object?
- Not straightforward in general,
  Use NOGLOBAL(this) = (this===null;this).
- NOSCOPE(this) is definable for Firefox, see paper.

Subset $Js^\text{run}$

Define the subset $Js^\text{run}$ as Js plus: all terms containing this minus all terms with identifiers beginning with $$. 

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Result

For all programs $P$ in $J_{s}^{run}$ such that $\text{Id}(P) \cap B \neq \emptyset$, the program $\text{Rew}(P)$ when executed with respect to the initial heap, never evaluates to the global object and does not access any blacklisted property.
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|                               |                     | $e_1[e_2] \rightarrow e_1[\text{IDX}(e_2)]$ | $e_1[e_2] \rightarrow e_1[\text{IDX}(e_2)]$
| Global Object (Problem 2 weak)| Subset $J_s$        | Subset $J_s^{run}$             |
|                               | Filter $P$ if $\text{Id}(P) \cap B \neq \emptyset$ | Filter $P$ if $\text{Id}(P) \cap B \neq \emptyset$ |
|                               |                     | $e_1[e_2] \rightarrow e_1[\text{IDX}(e_2)]$ | $e_1[e_2] \rightarrow e_1[\text{IDX}(e_2)]$
|                               |                     | this $\rightarrow \text{NOGLOBAL}(\text{this})$ | this $\rightarrow \text{NOGLOBAL}(\text{this})$

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Solution for FBJS

- Define $FBJS.ref and $FBJS.IDX in a different name-space.
- Use the version of IDX proposed by us.
  - Preserves semantics.
  - Prevents access to blacklisted properties
- Given a library blacklist $B$, use subset $Js^{run}$.
- Appropriately rename all identifiers
- Finally, parse the text of the code to disallow identifier names beginning with "$" or any blacklisted identifiers.
Ongoing and Future Work

- Design suitable run-time checks for `eval`, `Function`.
- Given a set of sensitive property names, design a procedure to analyze the library code and automatically generate the minimal blacklist which will guarantee property isolation.
- Write the semantics in machine readable format so that the proofs can be automated.
- Extend the above results to apply to JavaScript supported by various browsers which include features beyond the ECMA-262 spec, such as `getter`, `setters`, `__proto__` etc.
Thank You!