Language-Based Isolation of Untrusted JavaScript

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Motivation

• We want to improve the security of web applications using programming-language techniques.
• We focus on the client-side (more standardized).
  • JavaScript is the language of the browser.
• Examples: web advertising and social networking.
  • Benefit from embedding third-party code.
• Problem: let trusted and untrusted JavaScript code interact safely in the same execution environment.
JavaScript: challenges

- Prototype-based object inheritance:
  
  ```javascript
  Object.prototype.a = "foo";
  ```

- Objects as mutable records of functions with implicit `this`:
  
  ```javascript
  o = {b: function() { return this.a }};
  ```

- Scope can be a first-class object:
  
  ```javascript
  this.o === o;
  ```

- Can convert strings into code:
  
  ```javascript
  eval("o + o.b()");
  ```

- Implicit type conversions, that can be redefined.
  
  ```javascript
  Object.prototype.toString = o.b;
  ```
JavaScript: operational semantics

- We built a small-step semantics amenable to formal proofs.
  - Focus on the standardized ECMA 3 (hence, no DOM).
  - Model validated experimentally with browsers and shells.
  - Theorems about sanity-check properties.
- Operational semantics for *real* programming languages is hard.
  - Sheer size.
  - JavaScript challenges.
  - Established techniques do not work.
    - `while(e){s} ≠ if(e){s;while(e){s}};`
    - `var x={}; x+1;` depends on `Object.prototype.valueOf;`
Third-party content: Apps
Browser-based JavaScript sandbox

- Same Origin Policy and inline frames can sandbox untrusted code in an isolated execution environment.
- There is a considerable price to pay.
  - Full JavaScript can be too powerful.
  - Interactions with other applications are severely limited.
  - Framed applications are restricted to a confined region of the screen.
JavaScript sandboxing JavaScript

• A different approach.
  • Trusted and untrusted JavaScript run in the same execution environment.
  • Trusted code enforces a software sandbox on the untrusted code.
  • Fine grained control on the interaction between applications.

• We singled out three instances:
  • Facebook FBJS (viral social network).
  • Yahoo’s ADsafe (high value advertising).
  • Google Caja (web gadget platform).
Security goal

- Concrete security goals.
  - No direct access to the DOM.
  - No tampering with the execution environment.
- Idea: blacklist global variables (document, Object, ... & host libraries).
- Not easy to enforce in JavaScript.
  - Reflection
  - Semantics oddities
  - Implicit accesses, ...
- A solution must be compatible with running multiple untrusted apps.
Our blacklisting subset

- B is a list of identifiers not to be accessed by untrusted code.
- \( P_{\text{nat}} \) is the set of identifiers that can be accessed implicitly.
  - For example reading `Object` or writing `length`.
- Solution: we can enforce B (compatibly with \( P_{\text{nat}} \)) by filtering and rewriting untrusted code.
  - Disallowing all terms containing an identifier from B.
  - Including `eval`, `Function` and `constructor` in B by default.
  - Rewriting `e1[e2]` to `e1[IDX(e2)]`. 
The run time monitor IDX

- We need auxiliary variables, prefixed with $ and included in B.
  
  ```javascript
  var $String=String;
  var $B={p1:true;...,pn:true,eval:true,...,$:true,...};
  ```

- Rewrite $e_1[e_2]$ to $e_1[IDX(e_2)]$, where
  
  ```javascript
  IDX(e) =
  ($=e,{toString:function(){
  return($=$String($),
  $B[$]?"bad":$)
  }});
  ```

- Our rewriting faithfully emulates the semantics.
  
  $e_1[e_2] \Rightarrow val[e_2] \Rightarrow val[val[va_2]] \Rightarrow l[va_2] \Rightarrow l[m]$
Evaluation

- **Theorem:** our JavaScript subset prevents access to the identifiers in B (compatibly with $P_{\text{nat}}$).
- **Our enforcement does not alter the semantics of good code.**
- **Two main limitations.**
  - Variables are blacklisted together with property names.
  - If $x$ is blacklisted, we must blacklist also $\text{obj.}x$.
  - Heavy to separate namespaces of multiple applications.
  - Default blacklisting of $\text{eval, Function}$. 
Preventing scope manipulation

- We want to prevent explicit access to scope objects.
  
  ```javascript
  this.x=1; var o={y:41}; with (o){x+y};
  ```

- The global scope (in this talk).
  
  - Evaluate `window` or `this` in the global environment.
  - Evaluate `(function(){return this})()`.
  - Call native functions with same semantics as above
    ```javascript
    {sort, concat, reverse, valueOf}.
    ```

- Local scope objects (see papers).
Isolating the global scope

- Enforcement mechanism.
  - Save reference to global object in a private (blacklisted) variable.
    ```javascript
    var $Global=window;
    ```
  - Rewrite `this` to `(this===Global?null,this)`.

- No need to blacklist `sort, concat, reverse, valueOf`.
  - We can wrap them and sanitize returned values in a similar fashion.

- Benefits of isolating the global scope.
  - Statically filter out the global variables to be protected, no need to include them in the runtime blacklist used by IDX.
  - Multiple apps can coexist easily (only global variables need to be disjoint).
Comparison with Facebook

- Our subsets are similar to FBJS but:
  - Preserve original semantics more closely.
  - Proofs increase confidence in the correctness.
- Differences pointed to vulnerabilities in FBJS (and Yahoo! ADsafe).
  - Exploits: we built FBJS applications able to reach the DOM.
  - We proposed fixes to Facebook.
  - Considerable potential for damage (popular apps have 20M+ users).
Inter-component isolation

- Components: JavaScript programs $t_1, \ldots t_n$.
- Mashup: sequential composition $t_1; \ldots; t_n$.
- Shared resources: JavaScript heap locations.
- Inter-component isolation:
  Verify/enforce that any two components access disjoint sets of resources.
Capability safe languages

- Each program is endowed with capabilities, which are its only means for designating and accessing resources.

- Our approach.
  - Given a programming language, define formally:
    - Capability systems.
    - Capability safety.
  - Use capability safety to check inter-component isolation.
Capability systems: definitions

- **Resources:**
  - Smallest granularity of read/write heap locations $m_0, m_1, \ldots$
  - Typically organized as a graph.

- **Subjects:**
  - Entities that access resources.
  - Program expressions $t_0, t_1, \ldots$
• Capability $C$:
  • Unforgeable entity that designates and provides access to a resource.
  • Pair $(m,p)$ of resource $m$ and permission $p$ in $\{r,w\}$.

• Subject-capability map $tCap$:
  • Each subject is endowed with certain capabilities.
  • $tCap(t)$ is the set of capabilities associated with subject $t$. 
Authority

- Authority of a capability \( cAuth \):
  - Upper-bound on resources that can be accessed using the capability.
  - \( cAuth(H, c) \) is the authority of capability \( c \) in heap \( H \).

- Authority of a subject \( Auth \):
  - Subjects hold capabilities which provide authority.
  - \( Auth(H, t) = \bigcup_{c \in tCap(t)} cAuth(H, c) \) is the authority of subject \( t \) in heap \( H \).
Capabilities and mashup isolation

- Idea: allocate capabilities with disjoint authority to Alice and Bob.
  - The authority of a capability depends on the heap.
  - We would like $\text{Auth}(H_1, Alice) \cap \text{Auth}(H_2, Bob) = \emptyset$.
  - But we know only $H_1$...

- Strategy:
  - Define a stronger property (capability safety) so that it is enough to check $\text{Auth}(H_1, Alice) \cap \text{Auth}(H_1, Bob) = \emptyset$. 
Only connectivity begets connectivity

- IF the authority of Alice and Bob in \( H \) does not overlap THEN Bob’s authority does not change.
No authority amplification

- IF the authority of Alice and Bob in $H$ does overlap
  THEN Bob’s authority in $K$ is at-most:
  - the union of Alice’s and Bob’s authority in $H$;
  - plus any new authority created by Alice.
A capability system $[C, t\text{Cap}(t), c\text{Auth}(H, c)]$ is safe iff

1. All access derives from capabilities.
2. The authority of a capability satisfies topology-only bounds.
3. Only connectivity begets connectivity holds for $c\text{Auth}$.
4. No authority amplification holds for $c\text{Auth}$. 
Isolation Theorem

- Authority isolation:
  - Given a heap $H$ and components $t_1, \ldots, t_n$, authority isolation holds iff for all $i \neq j$, $\text{Auth}(H, t_i)$ and $\text{Auth}(H, t_j)$ do not overlap.
- Theorem: authority isolation implies inter-component isolation.
- The result holds for any sequential imperative language.
Applications of the Isolation Theorem

- **JavaScript mashups:**
  - We proved that a variant of our JavaScript subset for host isolation is *capability safe*.
  - We derived an enforcement function that guarantees *authority isolation*.
    - Make native function objects read-only.
    - Wrap native functions so they never receive the global object as `this`.

- **Google Caja:**
  - We formalized the core of the Cajita subset of JavaScript.
  - We proved that our model of Cajita is *capability safe*. 
Concluding remarks

- We used programming language techniques to study safe JavaScript subsets.
  - Provably correct solutions.
  - Validated by experiment.
  - Impact on real applications.
- Limitations.
  - Proofs by hand are long and error-prone.
  - We separate components. What about controlled interaction?
- Future work.
  - Mechanization of semantics in a proof assistant.
  - Tool to enforce subsets and scan libraries.
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