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.*

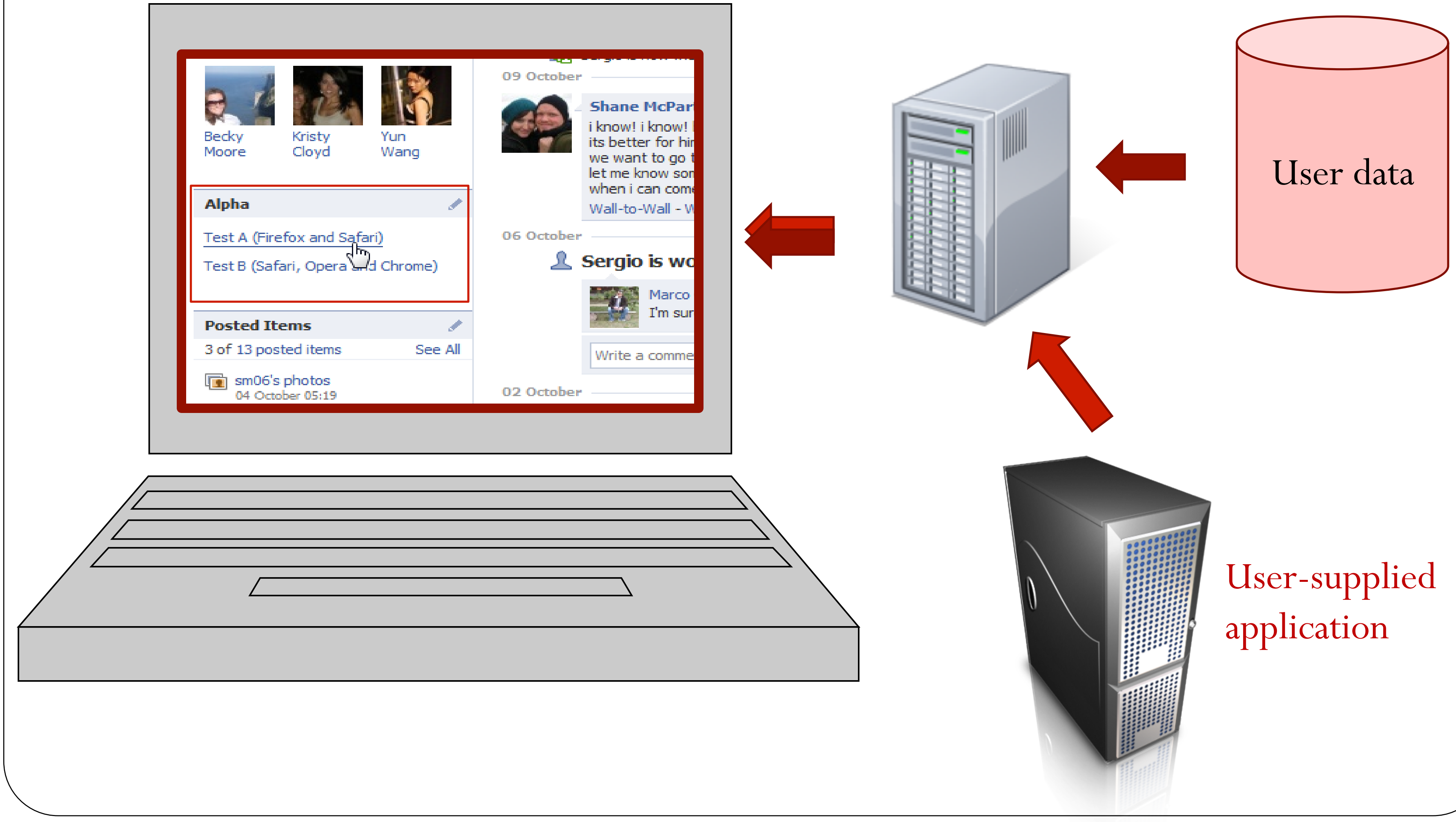
JavaScript: challenges

- Prototype-based object inheritance:
  `Object.prototype.a=“foo”;`
- Objects as mutable records of functions with implicit `this`:
  `o={b:function(){return this.a}};`
- Scope can be a first-class object:
  `this.o === o;`
- Can convert strings into code:
  `eval(“o + o.b()”);`
- Implicit type conversions, that can be redefined.
  `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



User data

User-supplied application

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_{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_{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.

```
var $String=String;
var $B={p1:true;...,pn:true,eval:true,…,$:true,…};
```

- Rewrite `e1[e2]` to `e1[IDX(e2)]`, where

```
IDX(e) =
      ($=e,{toString:function(){
                                return($=$String($),
                                $B[$]?"bad":$)
                                }});
```

- Our rewriting faithfully emulates the semantics.

```
e1[e2] ➔ va1[e2] ➔ va1[va2] ➔ l[va2] ➔ l[m]
```

Evaluation

- Theorem: our JavaScript subset prevents access to the identifiers in B (compatibly with P_{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 `obj.x`.
    - Heavy to separate namespaces of multiple applications.
  - Default blacklisting of `eval`, `Function`.

Preventing scope manipulation

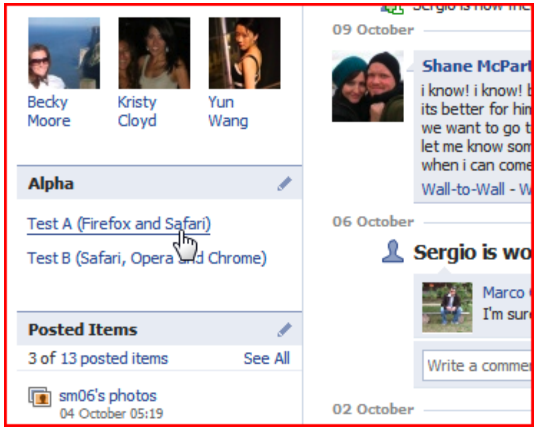
- We want to prevent explicit access to scope objects.

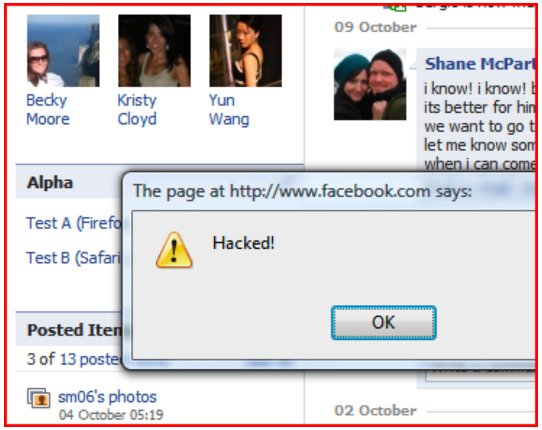
  `this.x=1; var o={y:41}; with (o){x+y};`
- The global scope (in this talk).
  - Evaluate `window` or `this` in the global environment.
  - Evaluate `(function(){return this})()`.
  - Call native functions with same semantics as above {`sort`, `concat`, `reverse`, `valueOf`}.
- Local scope objects (see papers).

Isolating the global scope

- Enforcement mechanism.
  - Save reference to global object in a private (blacklisted) variable.
    `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



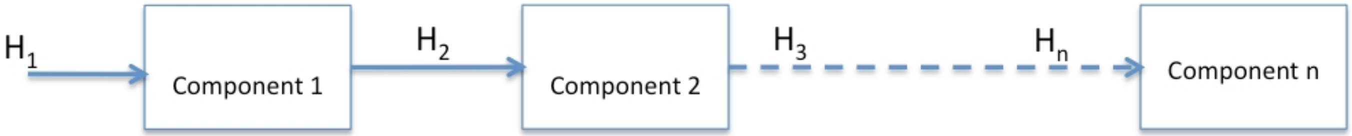


The page at http://www.facebook.com says:

Hacked!

- 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



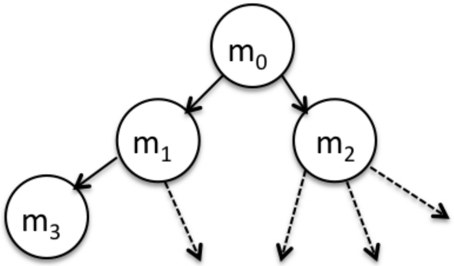
- Components: JavaScript programs $t_1, \ldots t_n$.
- Mashup: sequential composition $t_1; \ldots ; t_n$.
- Shared resources: JavaScript heap locations.
- *Inter-component isolation*:

  Verify/enforce that any two components access disjoint sets of resources.

Capability safe languages

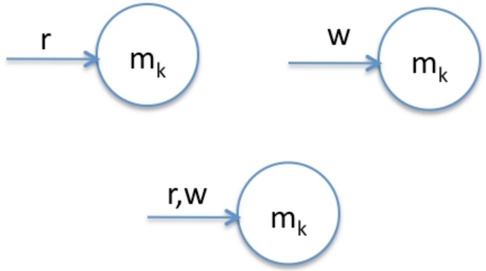
- Each program is endowed with capabilities, which are its only means for designating and accessing resources.
- Our approach.
  - Given a programming language, define formally:
    - *Capability systems*.
    - *Capability safety*.
  - Use *capability safety* to check *inter-component isolation*.

Capability systems: definitions



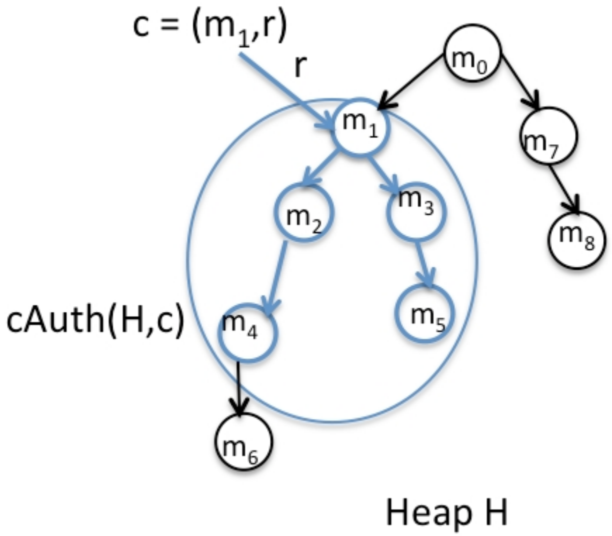
- Resources:
  - Smallest granularity of read/write heap locations m_0, m_1, …
  - Typically organized as a graph.
- Subjects:
  - Entities that access resources.
  - Program expressions t_0, t_1, …

Capability systems: definitions



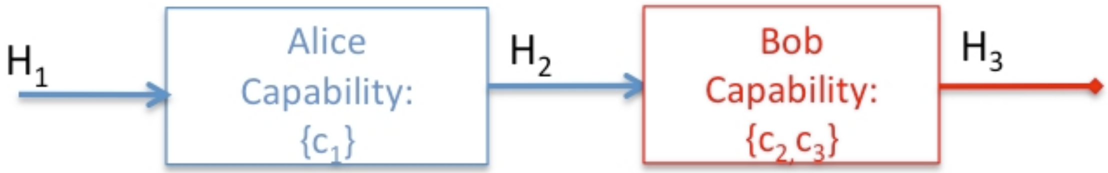
- Capability *C*:
  - Unforgeable entity that designates and provides access to a resource.
  - Pair *(m,p)* of resource *m* and permission *p* in {*r,w*}.
- Subject-capability map *tCap*:
  - Each subject is endowed with certain capabilities.
  - *tCap(t)* is the set of capabilities associated with subject *t*.

Authority



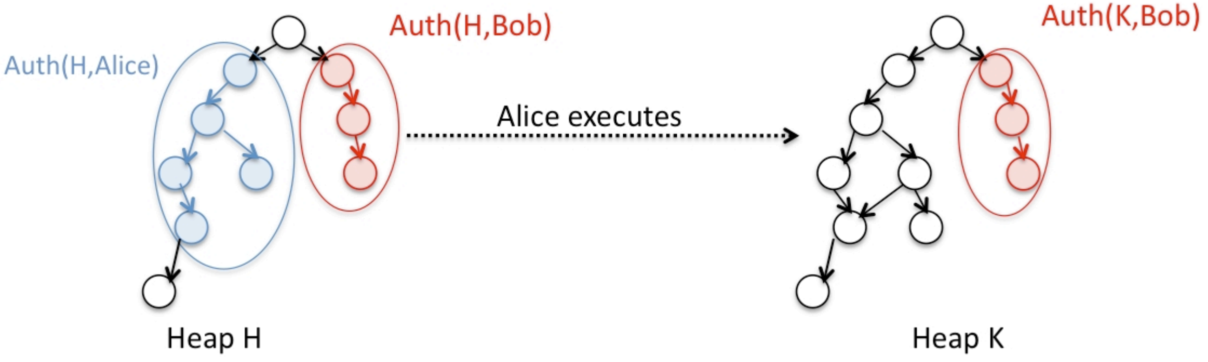
- Authority of a capability *cAuth*:
  - Upper-bound on resources that can be accessed using the capability.
  - *cAuth(H,c)* is the authority of capability *c* in heap *H*.
- Authority of a subject *Auth*:
  - Subjects hold capabilities which provide authority.
  - $Auth(H, t) = \bigcup_{c \text{ in } tCap(t)} cAuth(H,c)$ is the authority of subject *t* in heap *H*.

Capabilities and mashup isolation



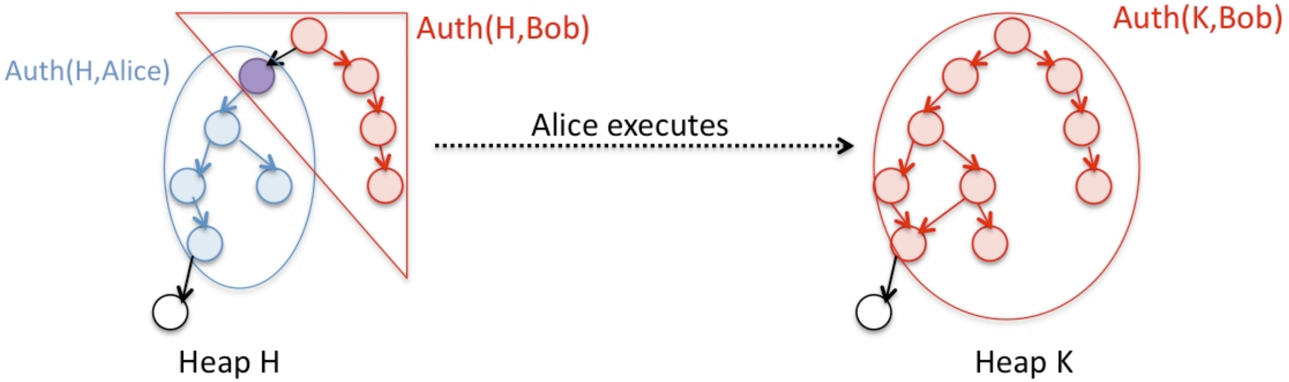
- Idea: allocate capabilities with disjoint authority to Alice and Bob.
  - The authority of a capability depends on the heap.
  - We would like $Auth(H_1, Alice) \cap Auth(H_2, Bob) = \varnothing$.
  - But we know only H_1…
- Strategy:
  - Define a stronger property (*capability safety*) so that it is enough to check $Auth(H_1, Alice) \cap Auth(H_1, Bob) = \varnothing$.

Only connectivity begets connectivity



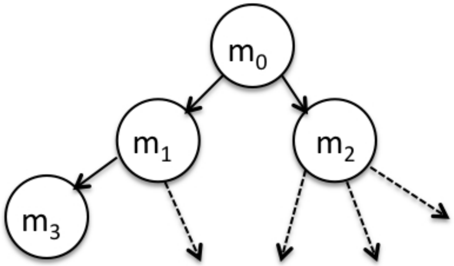
- IF the authority of Alice and Bob in *H* does not overlap THEN Bob's authority does not change.

No authority amplification



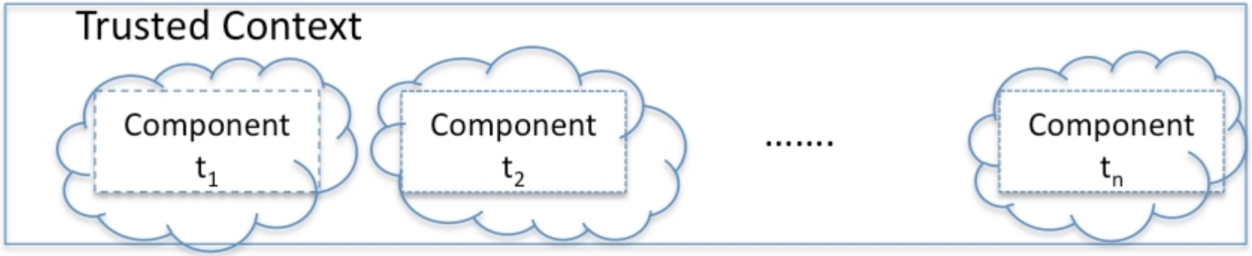
- IF the authority of Alice and Bob in *H* *does* overlap THEN Bob's authority in *K* is at-most:
  - the union of Alice's and Bob's authority in *H*;
  - plus any new authority created by Alice.

Capability safety



- A *capability system* [*C*,*tCap(t)*,*cAuth(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 *cAuth*.
  4. *No authority amplification* holds for *cAuth*.

Isolation Theorem



- *Authority isolation*:
  - Given a heap H and components $t_1, \ldots, t_n$, *authority isolation* holds iff for all $i \neq j$, $Auth(H,t_i)$ and $Auth(H,t_j)$ 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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