On Contracts and Sandboxes for JavaScript

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Motivation

89.8 %

of all web sites use JavaScript[1]

- Most important client-side language for web sites
- Web-developers rely on third-party libraries
  - e.g. for calendars, maps, social networks

[1] according to `http://w3techs.com/`, status of July 2015

Situation of a Web-developer

JavaScript issues

- Dynamic programming language
  - Code is accumulated by dynamic loading
  - e.g. eval, mashups
- JavaScript has no security awareness
  - No namespace or encapsulation management
  - Global scope for variables/ functions
  - All scripts have the same authority

Problems

1. Side effects may cause unexpected behavior
2. Program understanding and maintenance is difficult
3. Libraries may get access to sensitive data
4. User code may be prone to injection attacks

Key challenges of present research

- All-or-nothing choice when including code
- Isolation guarantees noninterference
- Some scripts must have access the application state or are allowed to change it

Goals

1. Manage untrusted JavaScript Code
2. Control the use of data by included scripts
3. Reason about effects of included scripts

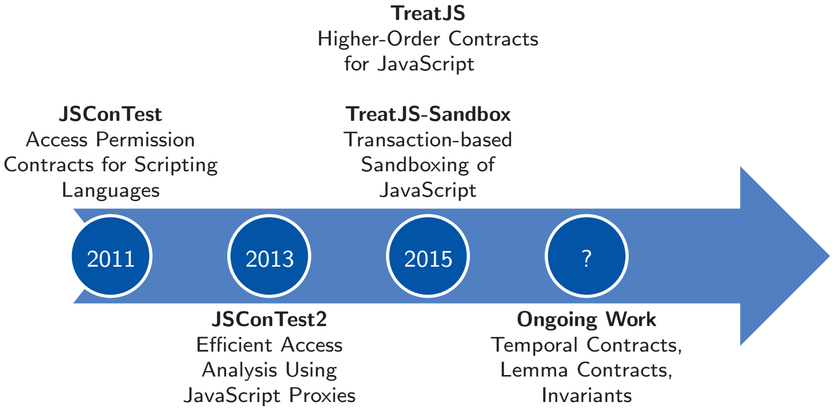
Language-embedded Systems

Shortcomings

- Static verifiers are imprecise because of JavaScript's dynamic features or need to restrict JavaScript's dynamic features
- Interpreter modifications guarantee full observability but need to be implemented in all existing engines

- Implemented as a library in JavaScript
- Library can easily be included in existing projects
- All aspects are accessible thought an API
- No source code transformation or change in the JavaScript run-time system is required

Timeline



TreatJS
Higher-Order Contracts for JavaScript
JSConTest
Access Permission Contracts for Scripting Languages
TreatJS-Sandbox
Transaction-based Sandboxing of JavaScript
2011
2013
2015
?
JSConTest2
Efficient Access Analysis Using JavaScript Proxies
Ongoing Work
Temporal Contracts, Lemma Contracts, Invariants

JSConTest

Access Permission Contracts for Scripting Languages

JSConTest

- Investigate effects of unfamiliar function
- Type and effect contracts with run-time checking
- Summarizes observed access traces to a concise description
- Effect contracts specifying allowed access paths

Type and effect contracts

```
/*c (obj, obj) -> any with [x.b,y.a] */
function f(x, y) {
  y.a = 1;
  y.b = 2; ✗ violation
}
```

Shortcomings of JSConTest

- Implemented by an offline code transformation
  - Partial interposition (dynamic code, *eval*, **with**, ...)
  - Tied to a particular version of JavaScript
  - Transformation hard to maintain
- Special contract syntax
  - Requires a special JavaScript parser
- Efficiency issues
  - Naive representation of access paths
  - Wastes memory and impedes scalability

JSConTest2

Efficient Access Analysis Using JavaScript Proxies

JSConTest2

Redesign and reimplementation of JSConTest based on JavaScript proxies

Advantages

- Full interposition for the full language
  - Including dynamically loaded code and `eval`
- Safe for future language extensions
  - No transformation to maintain
- Runs faster in less memory
  - Efficient representation of access paths
  - Incremental path matching
- Maintenance is simplified
  - No custom syntax for contracts

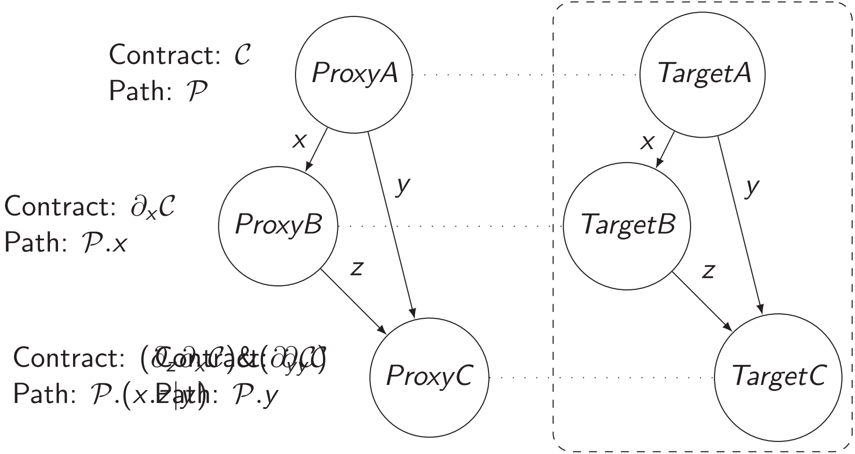
JSConTest2

Contracts on Objects

```
var obj = APC.permit('(a.?+b*)', {a:{b:5},b:{b:11}});
a = obj.a; // APC.permit('?', {b:5});
a.b = 3;
```

- *APC* encapsulates JSConTest2
- *permit* wraps an object with a permission. Arguments:
  1. Permission encoded in a string
  2. Object that is protected by the permission
- Contract specifies permitted access paths
  - Last property is readable/ writeable
  - Prefix is read-only
  - Not addressed properties are neither readable nor writeable
  - Read-only paths possible (@ denotes a non-existing property)

Proxy Membrane



The JSConTest2 Approach

- Implementation based on the JavaScript Proxy API
- Shortcomings of previous, translation-based implementation avoided

- Full interposition of contracted objects
  - Proxy intercepts all operations
  - Proxy-handler contains a contract and a path set
  - Forwards the operation or signals a violation
- Returned object contains the remaining contract (*Membrane*)

- Access contracts are regular expressions on literals
  - Each literal defines a property access
  - The language defines a set of permitted access paths

TreatJS

Higher-Order Contracts for JavaScript

Introduction

- Language embedded contract system for JavaScript
- Enforced by run-time monitoring

- Specifies the interface of a software component
- Pre- and postconditions

- Standard abstractions for higher-order-contracts (base, function, and dependent contracts) [Findler,Felleisen'02]
- Systematic blame calculation
- Side-effect free contract execution
- Contract constructors generalize dependent contracts

Base Contract [Findler,Felleisen'02]

- *Base Contracts* are built from predicates
- Specified by a plain JavaScript function

```
function isNumber (arg) {
  return (typeof arg) === 'number';
};
var _Number_ = Contract.Base(isNumber);

assert(1, _Number_); ✓
assert('a', _Number_); ✗ blame the subject
```

- Subject v *gets blamed* for *Base Contract* $\mathcal{B}$ iff:
  $\mathcal{B}(v) \neq true$

Function Contract [Findler,Felleisen'02]

```
// Number × Number → Number
function plus (x, y) {
  return (x + y);
}

var plus = assert(plus, Contract.Function([_Number_,
    _Number_], _Number_));
```

Function Contract [Findler,Felleisen'02]

```
// Number × Number → Number
function plus (x, y) {
  return (x + y);
}

plus('a', 'a'); ✗ blame the context
```

- Context gets *blamed* for $\mathcal{C} \rightarrow \mathcal{C}'$ iff:
  Argument x gets *blamed* for $\mathcal{C}$ (as subject)

Function Contract [Findler,Felleisen'02]

```
// Number × Number → Number
function plusBroken (x, y) {
  return (x>0 && y>0) ? (x + y) : 'Error';
}
```

plusBroken(0, 1); ✗ *blame the subject*

- Subject f gets *blamed* for $\mathcal{C} \to \mathcal{C}'$ iff:
  $\neg$ (Context gets *blamed* $\mathcal{C}$) $\wedge$ ($f(x)$ gets *blamed* $\mathcal{C}'$)

New!

Overloaded Operator

- Function *plus* works for strings, too
- Requires to model overloading and multiple inheritances

```
// Number × Number → Number
function plus (x, y) {
  return (x + y);
}

plus('a', 'a'); ✗ blame the context
```

Combinations of Contracts

- No support for arbitrary combination of contracts
- Racket supports `and/c` and `or/c`
- Attempt to extend conjunction and disjunction to higher-oder contracts

Combinations of Contracts
and/c

- and/c tests any contract
- no value fulfills Number and String at the same time

$(\mathit{and/c}\ (\mathit{Number} \times \mathit{Number} \rightarrow \mathit{Number})\ (\mathit{String} \times \mathit{String} \rightarrow \mathit{String}))$

```
function plus (x, y) {
  return (x + y);
}
```

plus('a', 'a'); ✗ *blame the context*

Combinations of Contracts

or/c

- or/c checks first-order parts and fails unless exactly one (range) contract remains
- Work for disjoint base contracts
- No combination of higher-oder contracts
- No support for arbitrary combinations of contracts

```
(or/c (Number × Number → Number) (String × String → String))
function plus (x, y) {
  return (x + y);
}
```

```
plus('a', 'a'); ✓
```

Combinations of Contracts

TreatJS

- Support for arbitrary combination of contracts
  - Combination of base and function contracts
  - Combination of function contracts with a different arity
- Intersection and union contracts
- Boolean combination of contracts

Intersection Contract

```
// (Number × Number → Number) ∩ (String × String → String)
function plus (x, y) {
  return (x + y);
}

var plus = assert(plus, Contract.Intersection(
  Contract.Function([_Number_, _Number_], _Number_)
  Contract.Function([_String_, _String_], _String_));
```

Intersection Contract

```
// (Number × Number → Number) ∩ (String × String → String)
function plus (x, y) {
  return (x + y);
}

plus(true, true); ✗ blame the context
```

- Context gets *blamed* for $\mathcal{C} \cap \mathcal{C}'$ iff:
  (Context gets *blamed* for $\mathcal{C}$) $\wedge$ (Context gets *blamed* for $\mathcal{C}'$)

Intersection Contract

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```
// (Number × Number → Number) ∩ (String × String → String)
function plusBroken (x, y) {
  return (x>0 && y>0) ? (x + y) : 'Error';
}
```

plusBroken(0, 1); ✗ *blame the subject*

- Subject f gets *blamed* for $\mathcal{C} \cap \mathcal{C}'$ iff:
  (f gets *blamed* for $\mathcal{C}$) $\vee$ (f gets *blamed* for $\mathcal{C}'$)

Contract Assertion

- A failing contract must not signal a violation immediately
- Violation depends on combinations of failures in different sub-contracts

```
// (Number → Number) ∩ (String → String)
function addOne (x) {
  return (x + 1);
}

addOne('a');
```

Contract Assertion

- A failing contract must not signal a violation immediately
- Violation depends on combinations of failures in different sub-contracts

```
// (Number → Number) ∩ (String → String)
function addOne (x) {
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addOne('a');
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Contract Assertion

- A failing contract must not signal a violation immediately
- Violation depends on combinations of failures in different sub-contracts

```
// (Number → Number) ∩ (String → String)
function addOne (x) {
  return (x + 1);
}

addOne('a'); ✓
```

Blame Calculation

- Contract assertion must connect each contract with the enclosing operations
- *Callback* implements a constraint and links each contracts to its next enclosing operation
- Reports a record containing two fields, *context* and *subject*
- Fields range over $\mathbb{B}_4 = \{\bot, \mathsf{f}, \mathsf{t}, \top\}$ [Belnap'1977]

Non-Interference

- No syntactic restrictions on predicates
- Problem: Contract may interfere with program execution
- Solution: Predicate evaluation takes place in a sandbox

```
function isNumber (arg) {
  type = (typeof arg);
  return type === 'number';
};

var _Number_ = Contract.Base(isNumber);
```

Non-Interference

- No syntactic restrictions on predicates
- Problem: Contract may interfere with program execution
- Solution: Predicate evaluation takes place in a sandbox

```
function isNumber (arg) {
  type = (typeof arg); ✗ access forbidden
  return type === 'number';
};

var _Number_ = Contract.Base(isNumber);

assert(1, _Number_);
```

Sandbox

- All contracts guarantee noninterference
- Read-only access is safe

```
var _Array_ = Contract.Base(function (arg) {
  return (arg instanceof Array); ✗ access forbidden
});
```

Sandbox

- All contracts guarantee noninterference
- Read-only access is safe

```
var _Array_ = Contract.Base(function (arg) {
  return (arg instanceof OutsideArray); ✓
});

var _Array_ = Contract.With({OutsideArray:Array}, _Array_);
```

Contract Constructor

- Building block for dependent, parameterized, abstract, and recursive contracts
- Constructor gets evaluated in a sandbox, like a predicate
- Returns a contract
- No further sandboxing for predicates

```
var __Type__ = Contract.Constructor(function (type) {
  return Contract.Base(function (arg) {
    return (typeof arg) === type;
  });
});

var _Number_ = __Type__('number');
```

TreatJS-Sandbox

Transaction-based Sandboxing of JavaScript

TreatJS-Sandbox

- Language-embedded sandbox for full JavaScript
- Inspired by JSConTest2 and Revocable References
- Adapts SpiderMonkey's compartment concept to run code in isolation to the application state
- Provides features known from transaction processing in database systems and transactional memory

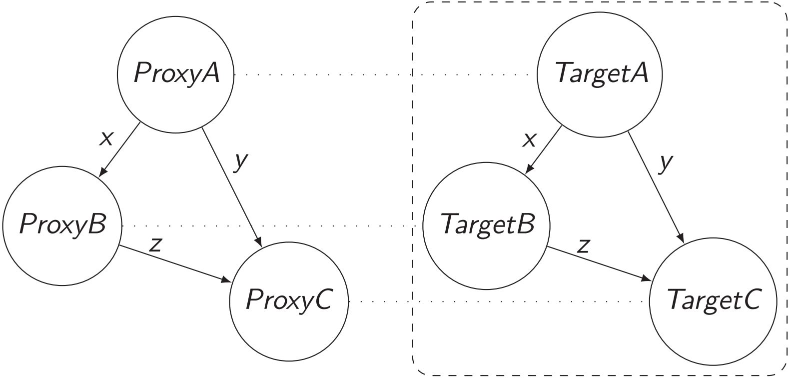
Sandbox Encapsulation

- A reference is the right to access an object
- Requires to control property read and property write

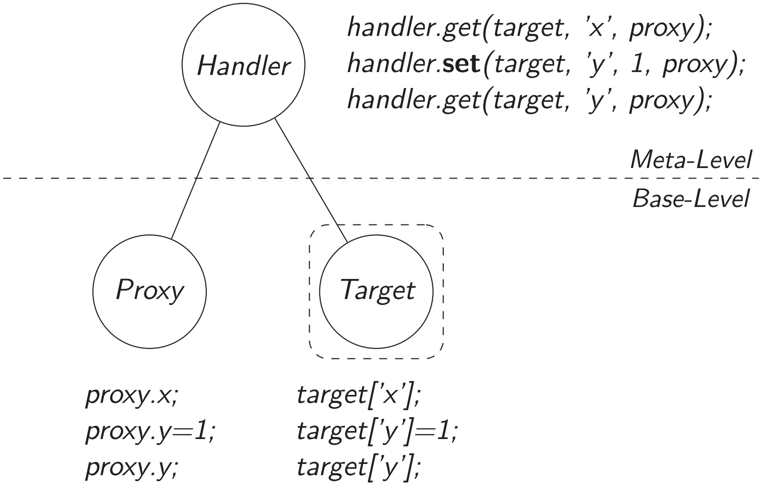
Sandbox Encapsulation

1. Place a write protection on objects
2. Remove external bindings of functions

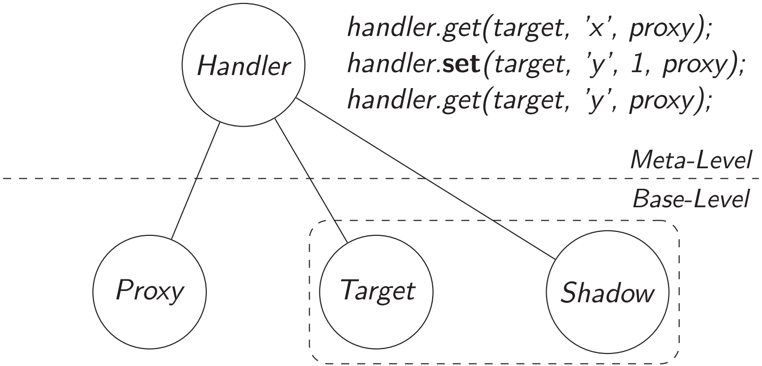
Identity Preserving Membrane



JavaScript Proxies



Shadow Objects



proxy.x;
proxy.y=1;
proxy.y;

target['x'];

shadow['y']=1;
shadow['y'];

Function Recompilation

- Function decompilation uses the **Function**.*prototype.toString* method to return a string that contains the source code of that function
- Applying *eval* to the string creates a fresh variant
- A **with** statement places a proxy in top of the scope chain
- The *hasOwnProperty* trap always returns true

JavaScript Scope Chain

```
var x = 1;

function f (y){

  function g () {
    var z = 1;
    return x+y+z;
  }

}
```

Sandbox Scope Chain

```
var x = 1;

  with(sbxglobal){

    function g () {
      var z = 1;
      return x+y+z;
    }

  }
```

Conclusion

- JSConTest/ JSConTest2: Effect monitoring for JavaScript
- Enables to specify effects using access permission contracts

- TreatJS: Language embedded, dynamic, higher-order contract system for full JavaScript
- Support for intersection and union contracts
- Contract constructors with local scope

- Sandbox: Language embedded sandbox for full JavaScript
- Runs code in a configurable degree of isolation
- Provides a transactional scope

Ongoing Work

- Temporal/ Computation Contracts
- Lemma Contracts
- Invariants
- Different blaming semantics (Lax, Picky, Indy)

Further Challenges

Limitations

- Dynamic contract checking impacts the execution time
- Arbitrary combinations of contracts lead to unprecise error messages

1. Hybrid contract checking
2. Static pre-checking of contracts
3. Optimization, contract rewriting