Semantics and Types for Safe Web Programming

by

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Chapter 1

Introduction

Thesis Statement JavaScript programs use prototype-based objects, flow-based type reasoning and other techniques that confound existing type systems. We can design a practical type system that admits the features and idioms of third-party JavaScript programs that were not written with a type-checker in mind. We can integrate a type system with dataflow analysis in a principled manner to account for flow-based type reasoning.

1.1 Why JavaScript?

JavaScript is the *lingua franca* of the Web. Programs written in JavaScript are fundamentally distinct from traditional programs in two key ways. First, applications freely compose code from several sources. Second, the user often cannot control which programs run; Web programs are visited, not installed. Social networks, such as Facebook, are an exemplar of this behavior. Not only do third-party apps and games embed themselves in Facebook, but Facebook embeds itself in many Web pages. For example, to integrate with Facebook, the The New York Times runs an amalgamation of its own code and Facebook’s code (in addition to code from advertising networks). In essence, The New York Times’ readers must visit Facebook.

JavaScript and the DOM—the language and libraries of the Web—lack modularity mechanisms needed to safely compose programs. Moreover, JavaScript has many quirks and mis-features that make it difficult to write and reason about even simple snippets of code. As Web programs grow larger and more complex, programmers need tools to reason about JavaScript.
1.2 Overview of Contributions

This dissertation presents a type system for JavaScript and demonstrates that it allows programmers to reason about Web programs. Specifically, we type-check a collection of third-party programs, making few refactorings and finding various bugs (chapter 7). In addition, we use our type-checker to find bugs in and verify ADsafe, a security-critical JavaScript framework (chapter 8).

This dissertation presents two novel type-checking techniques to tackle idiomatic JavaScript programs that confound existing techniques. First, we observe that JavaScript programmers use control and state to reason about the types of variables. We present flow typing, a method by which a traditional type-checker uses information from a dataflow analysis in a simple and modular way to account for stateful and flow-sensitive reasoning (chapter 4). Second, we observe that objects in JavaScript have arbitrary and dynamically constructed fields. We present fluid object types to account for these dynamic objects (chapter 5).

In the tradition of programming languages research, the type systems and program analyses above are accompanied by proofs of soundness. However, such proofs require a dynamic semantics for JavaScript. This dissertation therefore presents $\lambda_{JS}$, a core calculus for JavaScript (chapter 2). We employ $\lambda_{JS}$ in all our technical work and in our implemented tools. Unlike most core calculi, $\lambda_{JS}$ is accompanied by an implemented desugaring function that translates JavaScript programs to $\lambda_{JS}$ programs. Furthermore, we test our semantics and achieve bug-compatibility with real implementations on a portion of a third-party JavaScript test suite. This gives us confidence that our tools and theorems have some bearing on reality. Testing is particularly important for security; malicious programs attack implementations, not theorems.

This dissertation focuses on JavaScript, but many of the ideas are applicable to other scripting languages, such as Ruby, Python, and Lua. We discuss how the ideas in our semantics and our type systems may be employed to build systems for these other languages (chapter 9).
Chapter 2

Semantics

JavaScript, due to its pervasiveness, is a popular research target. There are many frameworks, tools, and sub-languages of JavaScript (e.g., [15, 18, 25, 37, 38, 51, 66]) that tackle security and other problems in JavaScript-based Web applications. These works do not demonstrate soundness, partly because they lack a tractable semantics of JavaScript. The JavaScript standard [22] is capacious and informal while one major formal semantics [58] is large, not amenable to conventional proof techniques, and inherits the standard’s complexities, as we discuss in section 2.4. These prior semantics leave unanswered some basic questions. (Such as: Is JavaScript lexically scoped?) More significantly, the sheer size of these semantics makes them unsuitable for building tools and doing detailed proofs. We need a tractable semantics for JavaScript.

In this chapter:

- We present a core calculus, $\lambda_{JS}$, that embodies JavaScript’s essential features, excluding $\text{eval}$. $\lambda_{JS}$ fits on three pages and lends itself well to proof techniques such as subject reduction. We exploit these properties in subsequent chapters.

- We show that we can desugar JavaScript to $\lambda_{JS}$. In particular, desugaring handles some of JavaScript’s most notorious features, such as $\text{this}$ and $\text{with}$, so $\lambda_{JS}$ itself remains simple (and thus simplifies proofs that utilize it).

- We mechanize both $\lambda_{JS}$ and desugaring.

---

1This chapter is based on joint work with Claudiu Saftoiu [40].
• To show compliance with reality, we successfully test \( \lambda_{JS} \) and desugaring against a portion of the actual Mozilla JavaScript test suite.

2.1 \( \lambda_{JS} \): A Tractable Semantics for JavaScript

JavaScript is full of surprises. Syntax that may have a conventional interpretation for many readers often has a subtly different semantics in JavaScript. To aid the reader, we introduce \( \lambda_{JS} \) incrementally. We include examples of JavaScript’s quirks and show how \( \lambda_{JS} \) faithfully models them.

Figures 2.1, 2.2, 2.4, 2.8 and 2.9 specify the syntax and semantics of \( \lambda_{JS} \). We use a Felleisen-Hieb small-step operational semantics with evaluation contexts [26]. Throughout this dissertation, we typeset \( \lambda_{JS} \) code in a sans-serif typeface, and JavaScript in a fixed-width typeface.

2.1.1 Functions, Objects and State

We begin with the small subset of \( \lambda_{JS} \) specified in fig. 2.1 that includes just functions and objects. We model operations on objects via functional update. This seemingly trivial fragment already exhibits some of JavaScript’s quirks:

• In field lookup, the name of the field need not be specified statically; instead, field names may be computed at runtime (E-GetField):

\[
\text{let } (\text{obj} = \{ "x" : 500, "y" : 100 \})
\]
\[
\text{let } (\text{select } = \text{func}(\text{name}), \text{obj}[\text{name}])
\]
\[
\text{select}("x") + \text{select}("y")
\]
\[
\rightarrow 600
\]

• A program that looks up a non-existent field does not result in an error; instead, JavaScript returns the value \texttt{undefined} (E-GetField-NotFound):

\[
\{ "x" : 7 \} \Gamma y\} \leftarrow \texttt{undefined}
\]

• Field update in JavaScript is conventional (E-UpdateField)—

\[
\{ "x" : 0 \} \Gamma x\} = 10 \leftrightarrow \{ "x" : 10 \}
\]

—but the same syntax also creates new fields (E-CreateField):

\[
\{ "x" : 0 \} \Gamma z\} = 20 \leftrightarrow \{ "z" : 20, "x" : 10 \}
\]
Figure 2.1: Functions and Objects

- Finally, JavaScript lets us delete fields from objects:

  ```javascript
delete { "x": 7, "y": 13 }["x"] \mapsto \{ "y": 13 \}
  ```

  JavaScript also supports a more conventional dotted-field notation: `obj.x` is valid JavaScript, and is equivalent to `obj["x"]`. To keep \( \lambda_{JS} \) small, we omit the dotted-field notation in favor of the more general computed lookup, and instead explicitly treat dotted fields as syntactic sugar.

Assignment and Imperative Objects

JavaScript has two forms of state: objects are mutable, and variables are assignable. We model both variables and imperative objects with first-class mutable references (fig. 2.2). We desugar

\[ E = \bullet \mid \text{let } (x = E) \mid v(v \cdot E) \mid (str: v_1 \cdots str:E, str: v) \mid v(E) \mid E[v] \mid v[E] = e \mid v[E]
\]

\[ \text{let } (x = v) e \mapsto e[x/v] \]

\[ (\text{func}(x_1 \cdots x_n).e)(v_1 \cdots v_n) \mapsto e[x_1/v_1 \cdots x_n/v_n] \]

\[ \{ \cdots \text{str: } v \cdots \}[\text{str}] \mapsto v \]

\[ \text{str}_x \notin (str_1 \cdots str_n) \]

\[ \{ \text{str}_1: v_1 \cdots \text{str}_n: v_n \} [\text{str}_x] \mapsto \text{undefined} \]

\[ \{ \text{str}_1: v_1 \cdots \text{str}_1: v_1 \cdots \text{str}_n: v_n \} [\text{str}_x] = v \]

\[ \mapsto \{ \text{str}_1: v_1 \cdots \text{str}_1: v \cdots \text{str}_n: v_n \} \]

\[ \text{str}_x \notin (str_1 \cdots) \]

\[ \{ \text{str}_1: v_1 \cdots \}[\text{str}_x] = v_2 \mapsto \{ \text{str}_x: v_2, \text{str}_1: v_1 \cdots \} \]

\[ \text{delete } \{ \text{str}_1: v_1 \cdots \text{str}_x: v_x \cdots \text{str}_n: v_n \} [\text{str}_x] \]

\[ \mapsto \{ \text{str}_1: v_1 \cdots \text{str}_n: v_n \} \]

\[ \text{delete } \{ \text{str}_1: v_1 \cdots \}[\text{str}_x] \mapsto \{ \text{str}_1: v_1 \cdots \} \]

\[ E-\text{GetField} \]

\[ E-\text{GetField-NotFound} \]

\[ E-\text{UpdateField} \]

\[ E-\text{CreateField} \]

\[ E-\text{DeleteField} \]

\[ E-\text{DeleteField-NotFound} \]
\[ l = \ldots \quad \text{Locations} \]
\[ v = \ldots | l \quad \text{Values} \]
\[ \sigma = (l, v) \cdots \quad \text{Stores} \]
\[ e = \ldots | e = e | \text{ref } e | \text{deref } e \quad \text{Expressions} \]
\[ E = \ldots | E = e | v = E | \text{ref } E | \text{deref } E \quad \text{Evaluation Contexts} \]

\[ e_1 \leftrightarrow e_2 \]
\[ \frac{e_1 \rightarrow e_2}{\sigma E(e_1) \rightarrow \sigma E(e_2)} \]
\[ l \not\in \text{dom}(\sigma) \quad \sigma' = \sigma, (l, v) \]
\[ \frac{}{\sigma E(\text{ref } v) \rightarrow \sigma' E(l)} \quad \text{(E-Ref)} \]
\[ \sigma E(\text{deref } l) \rightarrow \sigma E(\sigma(l)) \]
\[ \text{(E-Deref)} \]
\[ \sigma E(l = v) \rightarrow \sigma[l := v]E(v), \text{ if } l \in \text{dom}(\sigma) \]
\[ \text{(E-SetRef)} \]

We use → to denote the reflexive-transitive closure of ↠.

Figure 2.2: Mutable References in \( \lambda_{JS} \)

```
function sum(arr) {
    var r = 0;
    for (var i = 0; i < arr.length; i = i + 1) {
        r = r + arr[i];
    }
    return r;
}

sum([1,2,3]) ↠ 6
var a = [1,2,3,4];
delete a["3"];
sum(a) ↠ NaN
```

Figure 2.3: Array Processing in JavaScript

JavaScript to explicitly allocate and dereference heap-allocated values in \( \lambda_{JS} \).

**Example: JavaScript Arrays** JavaScript has arrays that developers tend to use in a traditional imperative style. However, JavaScript arrays are really objects, and this can lead to unexpected behavior. Figure 2.3 shows a small example of a seemingly conventional use of arrays. Deleting the field \( a["3"] \) (E-DELETEFIELD) does not affect \( a["length"] \) or shift the array elements. Therefore, in the loop body, \( arr["3"] \) evaluates to undefined, via E-GETFIELD-NOTFOUND. Finally, adding undefined to a number yields NaN; we discuss other quirks of addition in section 2.1.6.
2.1.2 Prototype-Based Objects

JavaScript supports *prototype inheritance* [11]. For example, in the following code, `animal` is the prototype of `dog`:

```javascript
var animal = { "length": 13, "width": 7 }
var dog = { "__proto__": animal, "barks": true }
```

Prototypes affect field lookup:

```javascript
dog["length"] -> 13
dog["width"] -> 7
```

```javascript
lab["length"] = 2
lab["width"] = 7
lab["barks"] = true
```

But, prototype inheritance does not affect field update. The code below creates the field `dog["width"]`, but it does not affect `animal["width"]`, which `dog` had previously inherited:

```javascript
dog["width"] = 19
dog["width"] -> 19
animal["width"] -> 7
```

However, `lab` now inherits `dog["width"]`:

```javascript
lab["width"] -> 19
```

Figure 2.4 specifies prototype inheritance. The figure modifies E-GetField-NotFound to only apply when the "__proto__" field is missing.
Prototype inheritance is simple, but it is obfuscated by JavaScript’s syntax. The examples in this section are not standard JavaScript because the "\_proto\_" field is not directly accessible by JavaScript programs\footnote{Some browsers, such as Firefox, can run these examples.} In the next section, we unravel and desugar JavaScript’s syntax for prototypes.

2.1.3 Prototypes

JavaScript programmers can indirectly manipulate prototypes using syntax that is reminiscent of class-based languages like Java. In this section, we explain this syntax and its actual semantics. We
```javascript
var obj = {
  "x": 0,
  "setX": function(val) { this.x = val };
};

// window is the name of the global object in Web browsers
window.x = undefined
obj.setX(10);
obj.x = 10
var f = obj.setX;
f(90);
obj.x = 10 // obj.x was not updated
window.x = 90 // window.x was created
```

Figure 2.6: Implicit this Parameter

account for this class-like syntax by desugaring it to manipulate prototypes directly (section 2.1.2).
Therefore, this section does not grow $\lambda_{JS}$ and only describes desugaring. Figure 2.5 specifies the portion of desugaring that is relevant for the rest of this section.

The this Keyword

JavaScript does not have conventional methods. Function-valued fields are informally called “methods”, and provide an interpretation for a this keyword, but both are quite different from those of, say, Java.

For example, in fig. 2.6 when `obj.setX(10)` is applied, this is bound to `obj` in the body of the function. In the same figure however, although `f` is bound to `obj.setX`, `f(90)` does not behave like a traditional method call. In fact, the function is applied with this bound to the global object [22, Section 10.1.5].

In general, this is an implicit parameter to all JavaScript functions. Its value is determined by the syntactic shape of function applications. Thus, when we desugar functions to $\lambda_{JS}$, we make this an explicit argument. Moreover, we desugar function calls to explicitly supply a value for this.

Functions as Objects

In JavaScript, functions are objects with fields:
```
f = function(x) { return x + 1 }
f.y = 90
f(f.y) → 91
```

We desugar JavaScript’s function to objects in $\lambda_{JS}$ with a distinguished code field that refers to the actual function. Therefore, we also desugar application to lookup the code field.
We could design $\lambda_{JS}$ so that functions truly are objects, making this bit of desugaring unnecessary. In our experience, JavaScript functions are rarely used as objects. Therefore, our design lets us reason about simple functions when possible, and functions as objects only when necessary.

In addition to the code field, which we add by desugaring, and any other fields that may have been created by the programmer, all functions also have a distinguished field called prototype. As fig. 2.5 shows, the prototype field is a reference to an object that eventually leads to the prototype of Object. Unlike the __proto__ field, prototype is accessible and can be updated by programmers. The combination of its mutability and its use in instanceof leads to unpredictable behavior, as we show below.

### Constructors and Prototypes

JavaScript does not have explicit constructors, but it does have a new keyword that invokes a function with this bound to a new object. For example, the following code—

```javascript
function Point(x, y) {
  this.x = x;
  this.y = y
}

pt = new Point(50, 100)
```

—applies the function Point and returns the value of this. Point explicitly sets this.x and this.y. Moreover, new Point implicitly sets this.__proto__ to Point.prototype. We can now observe prototype inheritance:

```javascript
Point.prototype.getX = function() { return this.x }
pt.getX() → pt.__proto__.getX() → 50
```

In standard JavaScript, because the __proto__ field is not exposed, the only way to set up a prototype hierarchy is to update the prototype field of functions that are used as constructors.

### The instanceof Operator

JavaScript’s instanceof operator has an unconventional semantics that reflects the peculiar notion of constructors that we have already discussed. In most languages, a programmer might expect that if x is bound to the value created by new Constr(···), then x instanceof Constr is true. In JavaScript, however, this invariant does not apply.
function Dog() { this.barks = "woof";
function Cat() { this.purrs = "meow";
dog = new Dog();
cat = new Cat();
dog.barks; ↠ "woof"
cat.purrs; ↠ "meow"

function animalThing(obj) {
    if (obj instanceof Cat) { return obj.purrs }
    else if (obj instanceof Dog) { return obj.barks }
    else { return "unknown animal" }
};

animalThing(dog); ↠ "woof"
animalThing(cat); ↠ "meow"
animalThing(4234); ↠ "unknown animal"

Cat.prototype = Dog.prototype;
animalThing(cat); ↠ "unknown animal"
animalThing(dog) ↠ undefined // dog.purrs (E-GetField-NotFound)

Figure 2.7: Using instanceof

For example, in fig. 2.7, animalThing dispatches on the type of its argument using instanceof. However, after we set Cat.prototype = Dog.prototype, the type structure seems to break down. The resulting behavior might appear unintuitive in JavaScript, but it is straightforward when we desugar instanceof into λJS. In essence, cat instanceof Cat is cat._proto_ === Cat.prototype In the figure, before Cat.prototype = Dog.prototype is evaluated, the following are true:

cat._proto_ === Cat.prototype
dog._proto_ === Dog.prototype
Cat.prototype !== Dog.prototype

However, after we update Cat.prototype, we have:

cat._proto_ === the previous value of Cat.prototype
dog._proto_ === Dog.prototype
Cat.prototype === Dog.prototype

Hence, cat instanceof Cat becomes false. Furthermore, since animalThing first tests for Cat, the test dog instanceof Cat succeeds.

2.1.4 Statements and Control Operators

JavaScript has a plethora of control statements. Many map directly to λJS’s control operators (fig. 2.8), while the rest are easily desugared.

4The === operator is the physical equality operator, akin to eq? in Scheme.
\[\begin{align*}
\text{label} & = (\text{Labels}) \\
\text{e} & = \cdots \text{if } (\text{e}) \text{ e } \text{else } e \mid \text{while}(\text{e}) \text{ e } \mid \text{label}: \text{e} \\
& \mid \text{break } \text{label } \text{e} \mid \text{try } \text{e } \text{catch } (x) \text{ e } \mid \text{try } \text{e finally } \text{e} \\
& \mid \text{err } v \mid \text{throw } \text{e} \\
\text{E} & = \cdots \text{if } (\text{E}) \text{ e } \text{else } \text{E}; \text{e} \mid \text{label}: \text{E} \mid \text{break } \text{label } \text{E} \\
& \mid \text{try } \text{E } \text{catch } (x) \text{ e } \mid \text{try } \text{e finally } \text{e} \mid \text{throw } \text{E} \\
\text{E'} & = \bullet \mid \text{let } (x = v \ldots x = E', x = e \ldots) \text{ e } \mid E'(e \ldots) \mid v(v \ldots E', e \ldots) \\
& \mid \text{if } (\text{E'}) \text{ e } \text{else } e \mid \{ \text{str } v \ldots \text{ str } E', \text{ str } e \ldots \} \\
& \mid \text{E'}[x] \mid v[E'] \mid E'[x] = e \mid v[E'] = e \mid v[v] = E' \mid E' = e \mid v = E' \\
& \mid \text{delete } \text{E'}[x] \mid \text{delete } \text{v}[E'] \mid \text{ref } E' \mid \text{deref } E' \mid E' ; e \mid \text{throw } \text{E'} \\
\text{F} & = \text{E'} \mid \text{label}: \text{F} \mid \text{break } \text{label } \text{F} \text{ (Exception Contexts)} \\
\text{G} & = \text{E'} \mid \text{try } \text{G } \text{catch } (x) \text{ e } \text{ (Local Jump Contexts)} \\
& \mid \text{if } (\text{true}) \text{ e } \text{else } \text{e}_2 \leftrightarrow \text{e}_1 \quad (\text{E-IfTrue}) \\
& \mid \text{if } (\text{false}) \text{ e } \text{else } \text{e}_2 \leftrightarrow \text{e}_1 \quad (\text{E-IfFalse}) \\
& \mid \text{v;e } \leftrightarrow \text{e} \quad (\text{E-Begin-Discard}) \\
& \mid \text{while}(\text{e}_1) \text{ e}_2 \leftrightarrow \text{if } (\text{e}_1) \text{ e}_2 ; \text{ while}(\text{e}_1) \text{ e}_2 \text{ else undefined} \quad (\text{E-While}) \\
& \mid \text{throw } v \leftrightarrow \text{err } v \quad (\text{E-Throw}) \\
& \mid \text{try } \text{F}(\text{err } v) \text{ catch } (x) \text{ e } \leftrightarrow \text{e}[x/v] \quad (\text{E-Catch}) \\
& \mid \sigma F'(\text{err } v) \rightarrow \sigma \text{err } v \quad (\text{E-Uncaught-Exception}) \\
& \mid \text{try } \text{F}(\text{err } v) \text{ finally } \text{e } \leftrightarrow \text{e} ; \text{ err } v \quad (\text{E-Finally-Error}) \\
& \mid \text{try } \text{G}(\text{break } \text{label } \text{v}) \text{ finally } \text{e } \leftrightarrow \text{e} ; \text{ break } \text{label } \text{v} \quad (\text{E-Finally-Break}) \\
& \mid \text{try } \text{v } \text{catch } (x) \text{ e } \leftrightarrow \text{v} \quad (\text{E-Catch-Pop}) \\
& \mid \text{try } \text{v } \text{finally } \text{e } \leftrightarrow \text{e} ; \text{ v} \quad (\text{E-Finally-Pop}) \\
& \mid \text{label}: \text{G}(\text{break } \text{label } \text{v}) \leftrightarrow \text{v} \quad (\text{E-Break}) \\
& \mid \text{label}_1 \neq \text{label}_2 \quad (\text{E-Break-Pop}) \\
& \mid \text{label}: \text{G}(\text{break } \text{label}_2 \text{ v}) \leftrightarrow \text{break } \text{label}_2 \text{ v} \quad (\text{E-Label-Pop}) \\
& \mid \text{break } \text{label}_1 \text{ G}(\text{break } \text{label}_2 \text{ v}) \leftrightarrow \text{break } \text{label}_2 \text{ v} \quad (\text{E-Break-Break}) \\
\end{align*}\]

Figure 2.8: Control operators for $\lambda_{JS}$
For example, consider JavaScript’s `return` and `break` statements. A `break` statement transfers control to the local label `l`. A `return` statement transfers control to the end of the local function and produces the value of `e` as the result. Instead of two control operators that are almost identical, `\lambda_{JS}` has a single `break` expression that produces a value.

Concretely, we elaborate JavaScript’s functions to an expression with a label `ret`:

\[
\text{desugar}\left[\text{function}(x \cdots) \{ \text{stmt} \cdots \} \right] = \text{func}(\text{this} \ x \cdots).{(\text{ret}: \text{desugar}[\text{stmt} \cdots])}
\]

Thus, `return` statements are desugared to `break`:

\[
\text{desugar}[\text{return } e] = \text{break } \text{ret } \text{desugar}[e]
\]

while `break` statements are desugared to produce `undefined`:

\[
\text{desugar}[\text{break } \text{label}] = \text{break } \text{label } \text{undefined}
\]

### 2.1.5 Static Scope in JavaScript

The JavaScript standard specifies identifier lookup in an unconventional manner. It uses neither substitution nor environments, but `scope objects` [22, Section 10.1.4]. A scope object is akin to an activation record, but is a conventional JavaScript object. The fields of this object are interpreted as variable bindings.

In addition, a scope object has a distinguished parent-field that references another scope object. (The global scope object’s parent-field is `null`.) This linked list of scope objects is called a `scope chain`. The value of an identifier `x` is the value of the first `x`-field in the `current scope chain`. When a new variable `y` is defined, the field `y` is added to the scope object at the head of the scope chain.

Since scope objects are ordinary JavaScript objects, JavaScript’s `with` statement lets us add arbitrary objects to the scope chain. Given the features discussed below, which include `with`, it is not clear whether JavaScript is lexically scoped. In this section, we describe how JavaScript’s scope-manipulation statements are desugared into `\lambda_{JS}`, which is obviously lexically scoped.

#### Local Variables

In JavaScript, functions close over their current scope chain (intuitively, their static environment). Applying a closure sets the current scope chain to be that in the closure. In addition, an empty
scope object is added to the head of the scope chain. The function’s arguments and local variables (introduced using `var`) are properties of this scope object.

Local variables are automatically lifted to the top of the function. As a result, in a fragment such as this—

```javascript
function foo() {
  if (true) { var x = 10 }
  return x
}
foo() ↠ 10
```

—the `return` statement has access to the variable that appears to be defined inside a branch of the `if`. This can result in somewhat unintuitive answers:

```javascript
function bar(x) {
  return function() {
    var x = x;
    return x
  }
}
bar(200)() ↠ undefined
```

Above, the programmer might expect the `x` on the right-hand side of `var x = x` to reference the argument `x`. However, due to lifting, all bound occurrences of `x` in the nested function reference the local variable `x`. Hence, `var x = x` reads and writes back the initial value of `x`. The initial value of local variables is `undefined`.

We can easily give a lexical account of this behavior. A local variable declaration, `var x = e`, is desugared to an assignment, `x = e`. Furthermore, we add a let-binding at the top of the enclosing function:

```javascript
let (x = ref undefined) ...
```

Global Variables

Global variables are subtle. Global variables are properties of the global scope object (`window`), which has a field that references itself:

```javascript
window.window === window ↠ true
```

Therefore, a program can obtain a reference to the global scope object by simply referencing `window`.

---

5In addition, `this` is bound to `window` in function applications (fig. 2.5).
As a consequence, globals seem to break lexical scope, since we can observe that they are properties of `window`:

```javascript
var x = 0;
window.x = 50;
x = 50
x = 100;
window.x = 100
```

However, `window` is the only scope object that is directly accessible to JavaScript programs [22, Section 10.1.6]. We maintain lexical scope by abandoning global variables. That is, we simply desugar the obtuse code above to the following:

```javascript
window.x = 0;
window.x = 50;
window.x = 50
window.x = 100;
window.x = 100
```

Although global variables observably manipulate `window`, local variables are still lexically scoped. We can thus reason about local variables using substitution, \(\alpha\)-renaming, and other standard techniques.

**With Statements**

The `with` statement is a widely-acknowledged JavaScript wart. A `with` statement adds an arbitrary object to the front of the scope chain:

```javascript
function(x, obj) {
  with(obj) {
    x = 50; // if obj.x exists, then obj.x = 50, else x = 50
    return y }) // similarly, return either obj.y, or window.y
}
```

We can desugar `with` by turning the comments above into code:

```javascript
function(x, obj) {
  if (obj.hasOwnProperty("x")) { obj.x = 50 }
  else { x = 50 }
  if ("y" in obj) { return obj.y }
  else { return window.y }
}
```

---

6Indeed, the latest revision of the JavaScript specification [23] has a strict mode that eliminates some of JavaScript’s most offensive misfeatures, including `with`. 

$e = \cdots | op_n(e_1 \cdots e_n)$
$E = \cdots | op_n(v \cdots E e \cdots)$
$E' = \cdots | op_n(v \cdots E'e \cdots)$
$\delta_n : op_n \times v_1 \cdots v_n \rightarrow c + err$

$op_n(v_1 \cdots v_n) \leftrightarrow \delta_n(op_n, v_1 \cdots v_n) \quad \text{ (E-PRIM)}$

Figure 2.9: Primitive Operators

Nested withs require a little more care, but can be dealt with in the same manner. However, desugaring with is non-compositional. We will return to this point in section 3.4.

**What are Scope Objects?** Various authors (including ourselves) have developed JavaScript tools that work with a subset of JavaScript that is intuitively lexically scoped [5, 18, 25, 38, 43, 66]. We show how JavaScript can be desugared into lexically scoped λJS, validating these assumptions. As a result, we no longer need scope objects in the specification; they may instead be viewed as an implementation strategy.

### 2.1.6 Type Conversions and Primitive Operators

JavaScript is not a pure object language. We can observe the difference between primitive numbers and number objects:

```javascript
x = 10;
y = new Number(7)
typeof x \rightarrow "number"
typeof y \rightarrow "object"
```

Moreover, JavaScript’s operators include implicit type conversions between primitives and corresponding objects:

```javascript
x + y \rightarrow 17
```

We can redefine these type conversions without changing objects’ values:

```javascript
Number.prototype.valueOf = function() { return 0 }
x + y \rightarrow 10
y.toString() \rightarrow "7"
```

---

7 Scope objects are especially well suited for implementing with. Our desugaring strategy for with increases code-size linearly in the number of nested withs, which scope-objects avoid.
Both * and + perform implicit coercions, and * also concatenates strings:

\[ x + y \text{.toString()} \rightarrow ^*107* \text{ // 10 converted to the string } ^*10^* \]
\[ x * y \text{.toString()} \rightarrow 70 \text{ // ^*7^* converted to the number 7} \]

This suggests that JavaScript’s operators are complicated. Indeed, the standard specifies \( x + y \)
with a 15-step algorithm [22, Section 11.6.1] that refers to three pages of metafunctions. Buried in
these details are four primitive operators: primitive addition, string concatenation, and number-to-
string and string-to-number type coercions.

These four primitives are essential and intuitive. We therefore model them with a conventional \( \delta \)
function (fig. 2.9). The remaining details of operators are type-tests and method invocations; as the
examples above suggest, JavaScript internally performs operations such as \( y \text{.valueOf()} \) and \( \text{typeof } x \).
In \( \lambda_{JS} \) we make these type-tests and method calls explicit.

This chapter does not enumerate all the primitives that \( \lambda_{JS} \) needs. Instead, the type of \( \delta \)
constrains their behavior significantly, which often lets us reason without a specific \( \delta \) function. (For
instance, due to the type of \( \delta \), we know that primitives cannot manipulate the heap.)

### 2.2 Soundness and Adequacy of \( \lambda_{JS} \)

**Soundness** We mechanize \( \lambda_{JS} \) with PLT Redex [26]. The process of mechanizing helped us find
errors in our semantics, particularly in the interactions of control operators (fig. 2.8). We use our
mechanized semantics to test \([56] \lambda_{JS} \) for safety. Note that we do not prove this property, since a
progress proof for an untyped language is straightforward. We believe that PLT Redex’s randomized
testing is sufficient.

**Property 1 (Progress)** If \( \sigma e \) is a closed, well-formed configuration, then either:

- \( e \in v \),
- \( e = \text{err } v \), for some \( v \), or
- \( \sigma e \rightarrow \sigma'e' \), where \( \sigma'e' \) is a closed, well-formed configuration.

This property requires additional evaluation rules for runtime type errors, and definitions of well-
formedness. We elide them as they are conventional.
Adequacy  $\lambda_{JS}$ is a semantics for the core of JavaScript. We have described how it models many aspects of the language’s semantics, warts and all. Ultimately, however, a small core language has limited value to those who want to reason about programs written in full JavaScript.

Given our method of handling JavaScript via desugaring, we are obliged to show that desugaring and the semantics enjoy two properties. First, we must show that all JavaScript programs can be desugared to $\lambda_{JS}$.

Claim 1 (Desugaring is Total)  For all eval-free JavaScript programs $e$, $\text{desugar}[e]$ is defined.

Second, we must demonstrate that our semantics corresponds to what JavaScript implementations actually do.

Claim 2 (Desugared Code Produces the Same Output)  For all eval-free JavaScript programs, $e$, $\text{desugar}[\text{eval}_{\text{JavaScript}}(e)]$ produces the same output as $\text{eval}_{\lambda_{JS}}(\text{desugar}[e])$.

We could try to prove these claims, but that just begs the question:

What is $\text{eval}_{\text{JavaScript}}$?

A direct semantics would require evidence of its own adequacy. In practice, JavaScript is truly defined by its major implementations. Open-source Web browsers are accompanied by extensive JavaScript test suites. These test suites help the tacit standardization of JavaScript across major
implementations. We use these test suites to test our semantics.

Figure 2.10 outlines our testing strategy. We first define an interpreter for \( \lambda_{JS} \). This is a straightforward exercise; the interpreter is a mere 100 LOC, and easy to inspect since it is based directly on the semantics. Then, for any JavaScript program, we should be able to run it both directly and in our semantics. For direct execution we employ three JavaScript implementations: SpiderMonkey (used by Firefox), V8 (used by Chrome), and Rhino (an implementation in Java). We desugar the same program into \( \lambda_{JS} \) and run the result through our interpreter. We then check whether our \( \lambda_{JS} \) interpreter produces the same output as each JavaScript implementation.

2.3 Conclusion

Our tests cases are a significant portion of the Mozilla JavaScript test suite. We omit the following tests:

- Those that target Firefox-specific JavaScript extensions.
- Those that use `eval`.
- Those that target library details, such as regular expressions.

The remaining tests are about 5,000 LOC unmodified.

Our \( \lambda_{JS} \) interpreter produces exactly the same output as Rhino, V8, and SpiderMonkey on the entire test suite. Figure 2.11 indicates that these tests employ many interesting syntactic forms, including statements like `with` and `switch` that are considered complicated. We make the following observations:

- No prior semantics for JavaScript accounts for all these forms (e.g., Maffeis et al. [58] do not model `switch`).
- We account for much of JavaScript by desugaring. Therefore, these tests validate both our core semantics and our desugaring strategy.
- These tests give us confidence that our implemented tools are correct.

---

8 For example, the Firefox JavaScript test suite is also found in the Safari source.
9 PLT Redex can evaluate expressions in a mechanized semantics. However, our tests are too large for Redex’s evaluator.
10 To observe output, we add a primitive operator printing operator to the \( \delta \) function.
2.4 Related Work

JavaScript Semantics. JavaScript is specified in 200 pages of prose and pseudocode [22]. This specification is barely amenable to informal study, let alone proofs. Maffeis, Mitchell, and Taly [58] present a 30-page operational semantics, based directly on the JavaScript specification. Their semantics covers most of JavaScript directly, but does omit a few syntactic forms.

Our approach is drastically different. $\lambda_{JS}$ is a semantics for the core of JavaScript, though we desugar the rest of JavaScript into $\lambda_{JS}$. In section 2.2, we present evidence that our strategy is correct. $\lambda_{JS}$ and desugaring together are much smaller and simpler than the semantics presented by Maffeis, et al. Yet, we cover all of JavaScript (other than eval) and account for a substantial portion of the standard libraries as well.

Maffeis, Mitchell, and Taly [58] define an operational semantics for JavaScript that closely follows the JavaScript specification. In contrast, our semantics is factored as a core calculus and a translation to the core. We believe this factoring makes it easier to build tools and proofs for our semantics. An further difference is that we demonstrate faithfulness to implementations by desugaring and running third-party tests in our semantics.

A technical advantage of our semantics is that it is conventional. For example, we use substitution instead of scope objects (section 2.1.5). Therefore, we can use conventional techniques, such as subject reduction, to reason in $\lambda_{JS}$. It is unclear how to build type systems for a semantics that uses scope objects.

David Herman [40] defines a CEKS machine for a small portion of JavaScript. This machine is also based on the standard and inherits some of its complexities, such as implicit type conversions.

CoreScript [93] models an imperative subset of JavaScript, along with portions of the DOM, but omits essentials such as functions and objects. Moreover, their big-step semantics is not easily amenable to typical type safety proofs.

Object Calculi. $\lambda_{JS}$ is an untyped, object-based language with prototype inheritance. However, $\lambda_{JS}$ does not have methods as defined in object calculi. Without methods, most object calculi cease to be interesting. However, we do desugar JavaScript’s method invocation syntax to self-application in $\lambda_{JS}$ [1, Chapter 18].

$\lambda_{JS}$ and JavaScript do not support cloning, which is a crucial element of other prototype-based languages, such as Self [88]. JavaScript does support Self’s prototype inheritance, but the surface
syntax of JavaScript does not permit direct access to an object’s prototype (section 2.1.3). Without cloning, and without direct access to the prototype, JavaScript programmers cannot use techniques such as dynamic inheritance and mode-switching [1].
Chapter 3

Verifying a Simple Web Sandbox

This chapter is a simple application of \( \lambda_{JS} \) (chapter 2) to verify a commonly employed language-based Web sandboxing technique. In chapter 8 we verify an actual third-party Web sandbox and consider its high-level design. This chapter details some of the programming language techniques employed in chapter 8 in a simple setting.

3.1 Isolating Untrusted Code

Web platforms often combine programs from several different sources on the same page. For instance, on a portal like iGoogle, a user can build a page that combines a weather widget with a stock ticker widget; on Facebook, users can run applications. Unfortunately, this means distinct programs can interfere with each other, which creates the possibility that a malicious application may steal data or cause other harm. To prevent both accidents and malice, sites must somehow sandbox widgets.

To this end, platform developers have defined safe sub-languages (often called “safe subsets”) of JavaScript like ADsafe [18], Caja [66], and Facebook JavaScript (FBJS) [25]. These are designed as sub-languages of JavaScript to target developers who already know how to write JavaScript Web applications. These sub-languages disallow blatantly dangerous features such as `eval`. However, they also try to establish more subtle security properties using syntactic restrictions, as well as runtime checks that they insert into untrusted code. Naturally, this raises the question whether these sub-languages function as advertised.

\footnote{This chapter is based on joint work with Claudiu Saftoiu [40].}
Let us consider the following property, which is inspired by FBJS and Caja: we wish to prevent code in the sandbox from communicating with a server. For instance, we intend to block the XMLHttpRequest object:

```javascript
var x = new window.XMLHttpRequest()
x.open("GET", "/get_confidential", false)
x.send("\n");
var result = x.responseText
```

For simplicity, we construct a sub-language that just disallows access to XMLHttpRequest. A complete solution would use our techniques to block other communication mechanisms, such as `document.write` and `Element.innerHTML`.

We begin with short, type-based proofs that exploit the compactness of $\lambda_{JS}$. We then use our tools to migrate from $\lambda_{JS}$ to JavaScript.

### 3.2 Isolating JavaScript

“Disallow access to XMLHttpRequest” is ambiguous and must be precisely defined. In JavaScript, `window.XMLHttpRequest` references the XMLHttpRequest constructor, where `window` names the global object. We make two assumptions:

- In $\lambda_{JS}$, we allocate the global object at location 0. This is a convenient convention that is easily ensured by desugaring.

- The XMLHttpRequest constructor is only accessible as a property of the global object. This assumption is valid as long as we do not use untrusted libraries (or can analyze their code).

Given these two assumptions, we can formally state “disallow access to XMLHttpRequest” as a property of $\lambda_{JS}$ programs:

**Definition 1 (Security)** $e$ is safe if $e \neq E(⟨\text{deref (ref 0)}⟩ \text{ XMLHttpRec quest}\{\})$.

Note that in the definition above, the active expression is $\text{deref (ref 0)}$, and the evaluation context is $E(\text{XMLHttpRec quest}\{\})$.

Intuitively, ensuring safety appears to be easy. Given an untrusted $\lambda_{JS}$ program, we can elaborate property accesses, $e_1[e_2]$, to $\text{lookup}(e_1, e_2)$, where $\text{lookup}$ is defined in fig. 3.1.
lookup = func(obj, field) {
    return if (field === "XMLHttpRequest") { undefined }
    else { (deref obj)[field] }
}

Figure 3.1: Safe Wrapper for \(\lambda_{JS}\)

\[
T = JS
\]

\[
\Gamma \vdash string : JS
\]

\[
\Gamma \vdash x : T
\]

(T-STRING)

\[
\Gamma, x_1 : JS, \cdots, x_n : JS \vdash e : JS
\]

\[
\Gamma \vdash func (x_1 \cdots x_n) \{ \text{return } e \} : JS
\]

(T-FUN)

\[
\Gamma \vdash e_1 : JS \quad \cdots \quad \Gamma \vdash e_n : JS
\]

\[
\Gamma \vdash \delta_n (op_n, e_1 \cdots e_n) : JS
\]

(T-PRIM)

The type judgments for remaining forms are similar to T-Prim and T-Fun: namely, \(\Gamma \vdash e : JS\) if all subexpressions of \(e\) have type \(JS\). However, \(e_1[e_2]\) is not typable.

Figure 3.2: Type System that Disallows Field Lookup

This technique\footnote{Maffeis et al.’s blacklisting \cite{59}, based on techniques used in FBJS, has this form.} has two problems. First, it blocks access to the “XMLHttpRequest” property of any object. Second, although lookup may appear “obviously correct”, the actual wrapping in Caja, FBJS, and other sub-languages occurs in JavaScript, not in a core calculus like \(\lambda_{JS}\). Hence, lookup does not directly correspond to any JavaScript function. We could write a JavaScript function that resembles lookup, but it would be wrought with various implicit type conversions and method calls (section 2.1.6) that could break its intended behavior. Thus, we start with safety for \(\lambda_{JS}\) before tackling JavaScript’s details.

3.3 Types for Securing \(\lambda_{JS}\)

Our goal is to determine whether a \(\lambda_{JS}\) program is safe (definition \[1\]). We wish to do so without making unnecessary assumptions. In particular, we do not assume that lookup (fig. 3.1) is itself safe.

We begin by statically disallowing all field accesses. The trivial type system in fig. 3.2 achieves this, since it excludes a typing rule for \(e_1[e_2]\). This type system does not catch conventional type errors. Instead, it has a single type, \(JS\), of statically safe JavaScript expressions (definition \[1\]).
\[ T = \cdots \mid \text{NotXHR} \]

\[
\text{NotXHR} <: \text{JS} \tag{\text{Sub-Safe}}
\]

\[
\frac{\Gamma \vdash e : S \quad S <: T}{\Gamma \vdash e : T} \tag{\text{T-Sub}}
\]

\[
v \neq \text{"XMLHttpRequest"} \quad \frac{\Gamma \vdash v : \text{NotXHR}}{\Gamma} \tag{\text{T-SafeValue}}
\]

\[
\frac{\Gamma \vdash e_1 : \text{JS} \quad \Gamma \vdash e_2 : \text{NotXHR}}{\Gamma \vdash e_1[e_2] : \text{JS}} \tag{\text{T-GetField}}
\]

\[
x \in \text{dom}(\Gamma) \quad \frac{\Gamma \vdash e_1 : \text{JS} \quad \Gamma[x : \text{NotXHR}] \vdash e_3 : \text{JS}}{\Gamma \vdash \text{if } (x == \text{"XMLHttpRequest"}) \{ e_2 \} \text{ else } \{ e_3 \} : \text{JS}} \tag{\text{T-IfSafe}}
\]

Figure 3.3: Type System for Blocking Access to XMLHttpRequest

\[
\frac{\Gamma \vdash e_2 : \text{JS}}{\Gamma \vdash \text{if } (\text{"XMLHttpRequest"} == \text{"XMLHttpRequest"}) \{ e_2 \} \text{ else } \{ e_3 \} : \text{JS}} \tag{\text{T-IfTrue-XHR}}
\]

\[
\frac{\Gamma \vdash e_2 : \text{JS}}{\Gamma \vdash \text{if } (\text{true}) \{ e_2 \} \text{ else } \{ e_3 \} : \text{JS}} \tag{\text{T-IfTrue}}
\]

Figure 3.4: Auxiliary Typing Rules for Blocking Access to XMLHttpRequest

Following theorem is evidently true:

**Theorem 1** For all \(\lambda_{JS}\) expressions \(e\), if \(\vdash e : T\) and \(e \rightarrow e'\) then \(e'\) is safe.

We need to extend our type system to account for \texttt{lookup}, taking care not to violate theorem\[1\] Note that \texttt{lookup} is currently untypable, since field access is untypable. However, the conditional in \texttt{lookup} seems to ensure safety; our goal is to prove that it does. Our revised type system is shown in fig. 3.3. The new type, \texttt{NotXHR}, is for expressions that provably do not evaluate to the string “XMLHttpRequest”. Since primitives like string concatenation yield values of type \texttt{JS} (T-Prim in fig. 3.2), programs cannot manufacture unsafe strings with type \texttt{NotXHR}. (Of course, trusted primitives could yield values of type \texttt{NotXHR}.)

Note this important peculiarity: These new typing rules are purpose-built for \texttt{lookup}. There are other ways to establish safe access to fields. However, since we will rewrite all expressions \(e_1[e_2]\) to \texttt{lookup}(\(e_1, e_2\)), our type system need only account for the syntactic structure of \texttt{lookup}. 

Our revised type system admits `lookup`, but we must prove theorem [1]. It is sufficient to prove the following lemmas:

**Lemma 1 (Safety)** If $\cdot \vdash e : JS$, then $e \neq E\langle \nu t "XMLHttpRequest" \rangle$, for any value $v$.

The proof of this lemma is by induction on typing derivations, given the typing rules in fig. 3.2 and fig. 3.3. This lemma also holds for the typing rules in fig. 3.4 which we introduce below.

**Lemma 2 (Preservation)** If $\cdot \vdash e : JS$, and $e \rightarrow e'$, then $\cdot \vdash e' : JS$.

**Proof Technique** The typing rules for `lookup` (fig. 3.3) require a technique introduced in *occurrence typing* for Typed Scheme [86].

Although `lookup` is typable, subject reduction requires all expressions in this reduction sequence to be typable:

```javascript
lookup(window, "XMLHttpRequest")
→ if ("XMLHttpRequest" === "XMLHttpRequest") { undefined }
    else { (deref window)["XMLHttpRequest"] }
→ if (true) { undefined }
    else { (deref window)["XMLHttpRequest"] }
→ undefined
```

The intermediate expressions above are not typable, although they are intuitively safe. We can make them typable by extending our type system with the typing rules in fig. 3.4 which let us prove subject reduction.

However, we have to ensure that our new typing rules do not violate safety (lemma [1]). Intuitively, lemma [1] still holds, since our newly-typable expressions are not of the form $e["XMLHttpRequest"]$.

Our type system may appear ad hoc, but it simply reflects the nature of JavaScript security solutions. Note that our type system is merely a means to an end: the main result is the conclusion of theorem [1] which is a property of the runtime semantics.

### 3.4 Scaling to JavaScript

Since we can easily implement a checker for our type system, we might claim we have a result for JavaScript as follows: desugar JavaScript into $\lambda_{JS}$ and type-check the resultant $\lambda_{JS}$ code. This
strategy is, however, unsatisfying because seemingly harmless changes to a typable JavaScript program may result in a program that fails to type-check, due to the effects of desugaring. This would make the language appear whimsical to the widget developer.

Instead, our goal is to define a safe sub-language (just as, say, Caja and FBJS do). This safe sub-language would provide syntactic safety criteria, such as:

• The JavaScript expression $e_1 + e_2$ is safe when its subexpressions are safe.

• $e_1[e_2]$, when rewritten to `lookup(e_1, e_2)`, is safe, but fails if $e_2$ evaluates to "XMLHttpRequest".

Our plan is as follows. We focus on the structure of the desugaring rules and show that a particular kind of compositionality in these rules suffices for showing safety. We illustrate this process by extending the $\lambda_{JS}$ result to include JavaScript’s addition (which, as we explained in section 2.1.6 is non-trivial). We then generalize this process to the rest of the language.

### 3.4.1 Safety for Addition

By theorem 1, it is sufficient to determine whether $\Gamma \vdash \text{desugar}[e_1 + e_2] : JS$. Proving this, however, would benefit from some constraints on $e_1$ and $e_2$. Consider the following proposition:

**Proposition 1** If $\Gamma \vdash \text{desugar}[e_1] : JS$ and $\Gamma \vdash \text{desugar}[e_2] : JS$, then $\Gamma \vdash \text{desugar}[e_1 + e_2] : JS$.

By lemma 1 this proposition entails that if $e_1$ and $e_2$ are safe, then $e_1 + e_2$ is safe. But is the proposition true? desugar$[e_1 + e_2]$ produces an unwieldy $\lambda_{JS}$ expression with explicit type-conversions and method calls. Still, a quick inspection of our implementation shows that:

\[
\text{desugar}[e_1 + e_2] = \text{let } (x = \text{desugar}[e_1]) \text{ let } (y = \text{desugar}[e_2]) \text{ } \ldots
\]

\[
\text{desugar}[e_1 + e_2]
\]

simply recurs on its subexpressions and does not examine the result of desugar$[e_1]$ and desugar$[e_2]$. Moreover, the elided body does not contain additional occurrences of desugar$[e_1]$ and desugar$[e_2]$. Thus, we can write the right-hand side as a two-holed program context:

\[
\text{desugar}[e_1 + e_2] = C_+(\text{desugar}[e_1], \text{desugar}[e_2])
\]

\[
C_+ = \text{let } (x = \_1) \text{ let } (y = \_2) \text{ } \ldots
\]

Therefore, desugaring $e_1 + e_2$ is *compositional*.

A simple replacement lemma [90] holds for our type system:

**Lemma 3 (Replacement)** If:
i. \( D \) is a deduction concluding \( \Gamma \vdash C[e_1, e_2] : JS \),

ii. Subdeductions \( D_1, D_2 \) prove that \( \Gamma_1 \vdash e_1 : JS \) and \( \Gamma_2 \vdash e_2 : JS \) respectively,

iii. \( D_1 \) occurs in \( D \), at the position corresponding to \( \bullet_1 \), and \( D_2 \) at the position corresponding to \( \bullet_2 \), and

iv. \( \Gamma_1 \vdash e'_1 : JS \) and \( \Gamma_2 \vdash e'_2 : JS \).

then \( \Gamma \vdash C(e'_1, e'_2) : JS \).

Replacement, along with weakening of environments, gives us our final lemma:

**Lemma 4** If:

- \( x : JS, y : JS \vdash C_+ [x, y] : JS \), and
- \( \Gamma \vdash \text{desugar}[e_1] : JS \) and \( \Gamma \vdash \text{desugar}[e_2] : JS \),

then \( \Gamma \vdash C_+ \langle \text{desugar}[e_1], \text{desugar}[e_2] \rangle : JS \).

The conclusion of lemma \( 4 \) is the conclusion of proposition \( 1 \). The second hypothesis of lemma \( 4 \) is the only hypothesis of proposition \( 1 \). Therefore, to prove proposition \( 1 \) we simply need to prove \( x : JS, y : JS \vdash C_+ (x, y) : JS \).

We establish this using our tools. We assume \( x \) and \( y \) are safe (i.e., have type \( JS \)), and desugar and type-check the expression \( x \times y \). Because this succeeds, the machinery above—in particular, the replacement lemma—tells us that we may admit \( \times \) into our safe sub-language.

### 3.4.2 A Safe Sub-Language

The proofs of lemma \( 3 \) and \( 4 \) do not rely on the definition of \( C_+ \). For each construct, we must thus ensure that the desugaring rule can be written as a program context, which we easily verify by inspection. We find this true for all syntactic forms other than \( \text{with} \), which we omit from our safe sub-language (as do other sub-language such as Caja and FBJS). If \( \text{with} \) were considered important, we could extend our machinery to determine what circumstances, or with what wrapping, it too could be considered safe.

Having checked the structure of the desugaring rules, we must still establish that their expansion does no harm. We mechanically populate a type environment with placeholder variables, create expressions of each kind, and type-check. All forms pass type-checking, except for the following:
• $x[y]$ and $x.XMLHttpRequest$ do not type—happily, as they are unsafe! This is acceptable because these unsafe forms will be wrapped in $\text{lookup}$.

• However, $x[y]++$, $x[y]--$, $++x[y]$, and $--x[y]$ also fail to type due to the structure of code they generate on desugaring. Yet, we believe these forms are safe; we could account for them with additional typing rules, as employed below for $\text{lookup}$.

### 3.4.3 Safety for $\text{lookup}$

As section 3.3 explained, we designed our type system to account for $\text{lookup}$ (fig. 3.1). However, $\text{lookup}$ is in $\lambda_{JS}$, whereas we need a wrapper in JavaScript. A direct translation of $\text{lookup}$ into JavaScript yields:

$$\text{lookupJS} = \text{function(obj, field) { } if (field === "XMLHttpRequest") { return undefined } else { return obj[field] } }$$

Since $\text{lookupJS}$ is a closed expression that is inserted as-is into untrusted scripts, we can desugar and type-check it in isolation. Doing so, however, reveals a surprise: $\text{desugar[lookupJS]}$ does not type-check.

When we examine the generated $\lambda_{JS}$ code, we see that $\text{obj[field]}$ is desugared into an expression that explicitly converts $\text{field}$ to a string. (Recall that field names are strings.) If, however, $\text{field}$ is itself an object, this conversion includes the method call $\text{field.toString()}$. Working backward, we see that the following exploit would succeed:

$$\text{lookupJS(window, { toString: function() { return "XMLHttpRequest" } })}$$

where the second argument to $\text{lookupJS}$ (i.e., the expression in the field position) is a literal object that has a single method, $\text{toString}$, which returns $"XMLHttpRequest"$. Thus, not only does $\text{lookupJS}$ not type, it truly is unsafe!

Our type system successfully caught a bug in our JavaScript implementation of $\text{lookup}$. The fix is simple: ensure that $\text{field}$ is a primitive string:

$$\text{safeLookup} = \text{function(obj, field) { } if (field === "XMLHttpRequest") { return undefined } else if (typeof field === "string") { return obj[field] } else { return undefined } }$$
This code truly is safe, though to prove it we need to extend our type system. We design the extension by studying the result of desugaring \texttt{safeLookup}.

We have noted that desugaring evinces the unsafe method call. However, \texttt{toString} is called only if \texttt{field} is not a primitive. This conditional is inserted by desugaring:

\begin{verbatim}
if (typeof field === "location") { ... field.toString() ... }
else { field }
\end{verbatim}

Thus, the second \texttt{if} in \texttt{safeLookup} desugars to:

\begin{verbatim}
if (typeof field === "string") {
  obj[if (typeof field === "location") { ... field.toString() ... }
  else { field }]
\end{verbatim}

To now reach \texttt{field.toString()}, both conditions must hold. Since this cannot happen, the unsafe code block is unreachable.

Recall, however, that we designed our type system for $\lambda_J$S around the syntactic structure of the lookup guard. With this more complex guard, we must extend our type system to employ if-splitting—which we already used in section 3.3—a second time. As long as our extension does not violate safety (lemma 1) and subject reduction (lemma 2), the arguments in this section still hold.

\section{3.5 Perspective}

In the preceding sections, we rigorously developed a safe sub-language of JavaScript that disallows access to XMLHttpRequest. In addition, we outlined a proof of correctness for the runtime “wrapper”. To enhance isolation, we have to disallow access to a few other properties, such as \texttt{document.write} and \texttt{Element.innerHTML}. We could do so with simple variants of the proofs in this chapter.

However, verifying a realistic sub-language of JavaScript requires more effort. Chapter 8 presents our verification of ADsafe, a third-party Web sandbox, which use the main ideas from this chapter:

\begin{itemize}
  \item We state the safety properties of ADsafe in the same manner as definition 1.
  \item This chapter used a small, special-purpose type system to verify a safety property. Our ADsafe verification uses a general-purpose JavaScript type system, to tackle the many programming patterns that ADsafe employs.
\end{itemize}

\footnote{Desugaring produces 200 LOC of pretty-printed \texttt{\lambda_J}S (appendix F).}
– The type system in this chapter has a single if-splitting rule. Chapter 4 demonstrates that JavaScript programs, including ADsafe, use many more control and state dependent patterns to reason about types. The ADsafe verification relies on those techniques.

– This chapter’s type system only ensures that an object’s XMLHttpRequest field is inaccessible. ADsafe enforces many more invariants on objects, some of which cannot be expressed in existing object type systems. Chapter 5 presents an object type system that can express these invariants, which we use to verify ADsafe.

• In section 3.4.2 we used types to derive a safe subset of JavaScript. We derive a safe subset for ADsafe in the same manner. However, we also use tests to ensure our derived safe subset corresponds to JSLint, which is ADsafe’s own ad hoc subset.

Our verification of ADsafe also uses λJS. In fact, the primary goal of this chapter is not to define a safe sub-language of JavaScript, but rather to showcase a simple application of λJS:

• λJS is small. It is much smaller than other definitions and semantics for JavaScript. Therefore, our proofs are tractable.

• λJS is adequate and tested. This gives us confidence that our arguments are applicable to real-world JavaScript.

• λJS is conventional, so we are free to use standard type-soundness techniques. In contrast, working with JavaScript’s scope objects would be onerous. This section is littered with statements of the form \( \Gamma \vdash e : \text{JS} \). Heap-allocated scope objects would preclude the straightforward use of \( \Gamma \), thus complicating the proof effort (and perhaps requiring new techniques).

• Finally, desugar is compositional. Although we developed a type system for λJS, we were able to apply our results to most of JavaScript by exploiting the compositionality of desugar.
Chapter 4

Typing Control and State

JavaScript programs employ idioms that confound conventional type systems. In this chapter, we highlight one important set of related idioms: the use of local control and state to reason informally about types. We account for these idioms in two steps. First, we formalize run-time tags and their relationship to types. We then use this relationship to develop a novel strategy that integrates type-checking with flow analysis in a modular way. We demonstrate that in our separation of typing and flow analysis, each component remains conventional, their composition is simple, but the result can handle these idioms better than either one alone.

4.1 Patterns of Control and State

JavaScript (and many other scripting languages) do not support pattern-matching or tagged data constructors. Therefore, programmers have to use reflection to reason about values. For example, the following program uses the `typeof` operator, which returns a string representing the “runtime type” of its argument.

```javascript
/*: Num ∪ {x : Num, y : Num} → Num */
function fromOrigin(p) {
  if (typeof p === "object") {
    return Math.sqrt(p.x * p.x + p.y * p.y);
  }
}
```

1This chapter is based on joint work with Claudiu Saftoiu [41].
2To be precise, `typeof` does not return a (static) type but a (runtime) tag. This distinction becomes significant when we retrofit an actual type system onto JavaScript (section 4.3).
function serialize(val) {
    switch (typeof val) {
    case "undefined":
        return false;
    case "function":
        return false;
    case "boolean":
        return val ? "true" : "false";
    case "number":
        return "" + val;
    case "string":
        return val;
    }
    if (val === null) { return "null"; }

    var fields /*: [Str]*/ = [];
    for (var p in val) {
        var v = serialize(val[p]);
        if (typeof v === "string") {
            fields.push(p + "": " + v);
        }
    }
    return "{ " + fields.join("", ")" + "}";
}

Figure 4.1: Non-local control

Such patterns are pervasive and they suggest we need untagged union types, as written in the comment. If we use union types, then we have to account for the if-statement above, which narrows the type of p to \{x : Num, y : Num\} and Num in the respective branches. However, JavaScript has other control operators that are also used to reason about types. We consider more examples before devising a type-checking strategy.

The function in fig. 4.1 serializes arbitrary values to strings (\(\top\) is the type of all expressions)\(^3\)

Functions and the special value undefined cannot be serialized, so for these it returns false. Let us informally reason about serialize to determine if it is type-safe.

On line 3, the function branches on the result of typeof val:

- For case "undefined", control falls through to line 5.

- On line 6, for case "function", the function returns false.

---

\(^3\)This example is based on toJSON from the popular Prototype library.
• On line 8, for case "boolean", the function branches on val and returns either "true" or "false". Val is a boolean because none of the preceding cases fall through to line 8.

• On line 10, for case "number", the function uses string concatenation to coerce the number val to a string. Val is a number because none of the preceding cases fall through to line 10.

• On line 12, for case "string", the function returns val. Val is a string because none of the preceding cases fall through to here.

This switch is missing a case. If typeof val === "object", then none of the cases above will match and control will fall through. However, since all the explicitly handled cases return, we know that typeof val === "object" holds on lines 15—24.

  JavaScript has a value null and typeof null === "object". Therefore, line 15 tests for null and if the test is true, the program returns "null". However, if the test is false, since the conditional does not have a false-branch, control proceeds to line 17. Since the true-branch returns, val !== null holds on lines 17–24. We can safely use val as an object on these lines. Lines 20—21 also employ flow-directed reasoning, but are relatively trivial. Therefore, we can conclude that serialize is safe.

  We reasoned about serialize by following its convoluted control-flow instead of merely following its syntactic structure. JavaScript forces such reasoning on programmers. The primary culprit is return, which aborts control flow and produces a result. Since serialize uses multiple return statements, our reasoning relies on return aborting its local continuation.

  Can we rewrite this function in a style that enables syntactic reasoning? Using the ternary operator instead of if and switch statements, we might try:

  ```javascript
  function syntactic_serialize(val) {
    return (typeof val === "undefined") ? false :
    ... 
    (val === "null") ? "null" :
    var fields = []; // syntax error: statement
    for (var p in val) // // syntax error: statement
    ... }
  ```

  Unfortunately, variable bindings and loops are statements, which do not compose with expressions. (This syntactic defect is shared by Ruby, Python, and other scripting languages.) This complicates the rewriting (which, in turn, could negatively impact error reporting), and suggests it would be better to tackle serialize directly.
function slice(arr, start, stop) {
  var len = /*: Int */ arr.length;
  if (typeof stop === "undefined") { stop = len - 1; }
  if (start < 0 || stop > len || start > stop) {
    throw "Invalid arguments";
  }
  var r = /*: [a] */ [ ];
  for (var i = 0; i <= stop - start; i++) {
    r[i] = arr[start + i];
  }
  return r;
}

4.1.1 Heap-Sensitive Reasoning

The function slice (fig. 4.2) returns a section of an array:

```
slice([ "A", "B", "C", "D" ], 1, 2) ↠ [ "B", "C" ]
```

However, the third argument (stop) is optional:

```
slice([ "A", "B", "C", "D" ], 1) ↠ [ "B", "C", "D" ]
```

JavaScript does not have optional arguments and default parameters. Instead, elided arguments receive the value `undefined` and extraneous arguments are dropped. `slice` relies on this peculiarity to simulate optional arguments.

If `stop` is `undefined`, then the side-effect `stop = len` ensures that `stop` is an integer in the continuation of the `if`-statement. This function relies not only on control-flow, but on the interaction of control and state to reason about types.

Dynamic Dispatch and Type Tests  We reasoned about the use of `serialize` and `slice` by following their convoluted control-flow and side-effects, instead of merely following their syntactic structure. A reader may argue that these functions are “bad style”, so a type system can legitimately reject them. For example, an easily typable alternative to `serialize` is to extend the builtin prototypes (Object, String, etc.) with a `serialize` method and rely on dynamic dispatch, instead of reflection. Unfortunately, extending builtin classes runs into the fragile base class problem [65] and is thus considered bad practice (e.g., [35]).

---

* `slice` is part of the JavaScript standard, but is not implemented by some older browsers. This definition is from the 4umi compatibility library.
**Perspective**  The examples above make heavy use of local control and state to reason informally about “types”. Section 9.5 shows that such patterns are prevalent in actual JavaScript code (and other scripting languages). A static type system that admits these programs will need to support this style of reasoning and various other features (e.g., objects). The book-keeping needed to account for control and state can pervade the entire type system and occlude its typing of other features.

### 4.2 Semantics and Types

$\lambda_{JS}$, presented in chapter 2 is an adequate model of JavaScript, but contains various details, such as objects, that are orthogonal to our technical presentation. We instead present flow typing using a smaller calculus, $\lambda_S$.

Figure 4.3 specifies the syntax and semantics of $\lambda_S$, which is a core calculus that is sufficient for our exposition of flow typing. $\lambda_S$ includes higher-order functions, mutable references, conditionals, a control operator (break), and basic primitives. Type annotations (discussed below) are ignored during evaluation.

In this chapter, the static types of $\lambda_S$ are much richer than its runtime tags. Therefore, we use a more technically precise name, tagof, to model the typeof operator of real scripting languages. The break operator can model both break and return statements of JavaScript. The break operator aborts the current continuation up to a matching label and returns a value. We specify the semantics of three primitives, of which physical equality (===) and tagof appear extensively in flow-directed reasoning (fig. 4.1). Other expressions, such as tagof x !== "string", are a simple extension of our theory.

Figure 4.3 also specifies the syntax of types, $T$. Types include untagged unions and a top type $\top$, which were motivated in section 4.1. We also include the type of locations, Ref $T$, and a bottom type $\perp$ for control operators that do not return a value. Given these types, subtyping (fig. 4.4) is conventional.

Our typing relation is also mostly conventional. We present select typing judgments in fig. 4.5. Note that the typing environment binds identifiers and labels. By T-SetRef, we can write subtypes to locations. Finally, like JavaScript, $\lambda_S$ programs cannot break across function boundaries, so we statically disallow it by dropping labels when typing functions (T-Abs).

---

5This is a simple restriction of source and sink types [71 Chapter 15.5].
identifiers \( x \)
locations \( l \)
constants \( c = \text{num} \mid \text{str} \mid \text{bool} \mid \text{undefined} \)
values \( v = x \mid c \mid \text{func}(x \cdots ) : T \{ e \} \mid l \)
expressions \( e = \text{let } x = e_1 \text{ in } e_2 \mid e_f(e_1 \cdots e_n) \mid \text{op}_n(e_1 \cdots e_n) \mid \text{if } (e_1) \{ e_2 \} \mid \text{else } \{ e_3 \} \mid \text{break } label \ e \mid \text{label}:T \{ e \} \mid \text{ref } e \mid \text{deref } e \mid \text{setref } e_1 \ e_2 \)
evaluation contexts \( E = \bullet \mid \text{let } x = E \text{ in } e \mid e_f(v \cdots Ee \cdots) \mid \text{op}_n(v \cdots Ee \cdots) \mid \text{break } label \ E \mid \text{if } (E) \{ e_2 \} \mid \text{else } \{ e_3 \} \mid \text{label}:T \{ E \} \mid \text{ref } E \mid \text{deref } E \mid \text{setref } E \ e \mid \text{setref } v \ E \)
stores \( \sigma = \cdot \mid (l,v) \sigma \)
types \( T = \text{Str} \mid \text{Bool} \mid \text{Undef} \mid T_1 \cup T_2 \mid T_1 \cdots \to T \mid \text{Ref } T \mid \bot \mid \top \)

\begin{align*}
\text{(E-Let)} &\quad \sigma E \langle \text{let } x = v \text{ in } e \rangle \to \sigma E \langle e[x/v] \rangle \\
\text{(E-Prim)} &\quad \sigma E \langle \text{op}_n(v \cdots) \rangle \to \sigma E \langle \delta_n(\text{op}_n, v \cdots) \rangle \\
\text{(\(\beta_v\))} &\quad \sigma E \langle \text{func}(x \cdots) \{ e \} \{ v \cdots \} \rangle \to \sigma E \langle e[x/v \cdots] \rangle \\
\text{(E-Break)} &\quad \sigma E \langle \text{break } label \ v \rangle \to \sigma E \langle v \rangle, \text{ when } label \notin E_2 \\
\text{(E-Label-Pop)} &\quad \sigma E \langle \text{label}:\{ \rangle \to \sigma E \langle v \} \rangle \\
\text{(E-Ref)} &\quad \sigma E \langle \text{ref } v \rangle \to (l,v), \sigma E \langle l \rangle \ l \fresh \\
\text{(E-Deref)} &\quad \sigma E \langle \text{deref } l \rangle \to \sigma E \langle \sigma(l) \rangle \\
\text{(E-SetRef)} &\quad \sigma E \langle \text{setref } t \ v \rangle \to \sigma E \langle l/v \rangle E \langle l \rangle \\
\end{align*}

\(\delta_1(\text{tagof, num}) = \text{"number"} \quad \delta_2(\text{+=, v, v}) = \text{true} \)
\(\delta_1(\text{tagof, undefined}) = \text{"undefined"} \quad \delta_2(\text{++, v1, v2}) = \text{false, when } v_1 \neq v_2 \)
\(\delta_1(\text{tagof, str}) = \text{"string"} \quad \delta_2(\text{-, num1, num2}) = \text{num1} - \text{num2} \)
\(\delta_1(\text{tagof, bool}) = \text{"boolean"} \quad \delta_1(\text{tagof, l}) = \text{"location"} \quad \delta_1(\text{tagof, func}(x \cdots) \{ e \} \}) = \text{"function"} \)

Figure 4.3: Syntax and Semantics of \(\lambda_S\)
4.3 Relating Static Types and Runtime Tags

Consider the following JavaScript program:

```javascript
function f(x) {
  if (typeof x === "string") { return 0; }
  else { return (x-1); } }

f(200)
```

We can model this in $\lambda_S$ as follows, with $x$ as a local variable and the `breaks` representing `return` statements and the intended type annotation inserted:

```javascript
let f = ref func(y) : Num ∪ Str → Num {
  return: Num {
    let x = ref y in
    if (tagof (deref x) === "string") { break return 0 }
    else { break return ((deref x) - 1) } }
  }
in (deref f)(200)
```

Both the $\lambda_S$ and original JavaScript programs run without error, returning 199.

This $\lambda_S$ program fails to type in the type checker of the previous section because the - (minus) operator expects its operands to be numbers, but `deref x` has type `Num ∪ Str`. However, the tag-test informs us, the reader, that $x$ has the static type `Str` in the true branch; the type annotation on $y$ bounds its range of values, and thus enables us to conclude that $x$ has type `Num` in the false branch. Thus, the dynamic test and static type annotation collude to demonstrate that this program is

---

Footnote: Chapter X desugars JavaScript to $\lambda_{JS}$ in this form.
\( ty_1(\text{tagof}) = \top \rightarrow \text{Str} \quad ty_2(\text{***}) = \top \times \top \rightarrow \text{Bool} \quad ty_2(\cdot) = \text{Num} \times \text{Num} \rightarrow \text{Num} \)

\[
\Sigma(l) = T \\
\Sigma; \Gamma \vdash l : T
\]  

\((T-\text{LOC})\)

\[
\Sigma; \Gamma \vdash e : S \\
S <: T
\]

\((T-\text{SUB})\)

\[
\Sigma; \Gamma \vdash e : T \\
\Sigma; \Gamma' = \Gamma \text{ with labels removed}
\]

\((T-\text{ABS})\)

\[
\Sigma; \Gamma \vdash \text{func}(x \cdots : S \cdots \rightarrow T \{e\} : S \cdots \rightarrow T)
\]

\((T-\text{ABS})\)

\[
\Sigma; \Gamma \vdash e_1 : \text{Ref} S \\
\Sigma; \Gamma \vdash e_2 : T \\
T <: S
\]

\((T-\text{SetRef})\)

\[
\Sigma; \Gamma \vdash \text{if} (e_1) \{e_2\} \text{ else } \{e_3\} : T
\]

\((T-\text{If})\)

\[
\Sigma; \Gamma \vdash \text{break label } e : \bot
\]

\((T-\text{Break})\)

Figure 4.5: Typing \(\lambda_S\) (Essential Rules)

statically safe. Our goal is to enable the static type checker to arrive at the same conclusion.\(^7\)

To support such reasoning, a retrofitted type system must relate static types and runtime tags. We show this in fig. 4.6. runtime maps types to tag sets (due to the presence of unions), but since types are much richer than tags, we cannot distinguish all static types at runtime, e.g., all arrow types are mapped to the tag “function” (objects would be modeled similarly). static lets us narrow a type based on a known tag. For example, if a value has type \(\text{Str} \cup \text{Num}\) and its tag set is \{“number”\}, then static produces the type \(\text{Num}\). Note that static is partial: for example, static(\{“number”\}, \text{Str}) is undefined.

Since static relates types and tags, our type system can use it to account for runtime tag-tests. We use static by extending \(\lambda_S\) with an auxiliary construct, \text{tagcheck} \(R \ e\) (fig. 4.7), which narrows the type of \(e\) based on the tag set \(R\). By judiciously inserting \text{tagchecks}, we can make our example typable.\(^8\) We thus offer \text{tagcheck} as an appropriate cast-like operator for scripting languages.

\(^7\)Occurrence typing \[\text{\cite{86}}\] is a different approach that can also type-check this example.

\(^8\)Section \[\text{\cite{4.4}}\] presents an efficient technique to insert \text{tagchecks} automatically, so they are hidden from the programmer.
$$r = \{ \text{"string"}, \text{"boolean"}, \text{"number"}, \text{"undefined"}, \text{"function"}, \text{"location"} \}$$

$$R = P(r)$$

<table>
<thead>
<tr>
<th>Function</th>
<th>Type of R</th>
</tr>
</thead>
<tbody>
<tr>
<td>runtime : T → R</td>
<td>{&quot;string&quot;}</td>
</tr>
<tr>
<td>runtime(Str)</td>
<td>{&quot;string&quot;}</td>
</tr>
<tr>
<td>runtime(Bool)</td>
<td>{&quot;boolean&quot;}</td>
</tr>
<tr>
<td>runtime(Num)</td>
<td>{&quot;number&quot;}</td>
</tr>
<tr>
<td>runtime(Undef)</td>
<td>{&quot;undefined&quot;}</td>
</tr>
<tr>
<td>runtime(S ∪ T)</td>
<td>runtime(S) ∪ runtime(T)</td>
</tr>
<tr>
<td>runtime(S → T)</td>
<td>{&quot;function&quot;}</td>
</tr>
<tr>
<td>runtime(⊥)</td>
<td>∅</td>
</tr>
<tr>
<td>runtime(⊤)</td>
<td>r</td>
</tr>
<tr>
<td>runtime(Ref T)</td>
<td>{&quot;location&quot;}</td>
</tr>
</tbody>
</table>

Figure 4.6: Relationship Between Types and Tags

A tagcheck expression can fail in three ways. Two are static: when the tag set R is incompatible with the type of e, static is undefined; even if it is compatible, the resulting type may not be what the context expects. However, the third failure is dynamic: if e reduces to v and tagof(v) /∈ R, then evaluation gets stuck with a tagerr (E-TagCheck-Err). This error condition manifests itself when we try to prove a type soundness theorem.

The preservation lemma is conventional:

**Lemma 5 (Preservation)** If $\Sigma, \cdot ⊢ e : T$, $\Sigma ⊢ σ$, and $σe → σ′e'$, then there exists a $Σ'$, such that:

i. $Σ', \cdot ⊢ e' : T$,

ii. $Σ' ⊢ e'$, and

iii. $Σ ⊆ Σ'$.

However, programs can get stuck on tagerrs:

**Lemma 6 (Progress)** If $\Sigma, \cdot ⊢ e : T$ and $Σ ⊢ σ$, then either:
\( e = \cdots \mid \text{tagcheck } R \ e \mid \text{tagerr} \)
\( E = \cdots \mid \text{tagcheck } R \ E \)

\[
\begin{align*}
\delta_1(\text{tagof}, v) & \in R \\
\sigma E(\text{tagcheck } R \ v) & \rightarrow \sigma E(v) \quad \text{(E-TAGCHECK)}
\end{align*}
\]

\[
\begin{align*}
\delta_1(\text{tagof}, v) & \notin R \\
\sigma E(\text{tagcheck } R \ v) & \rightarrow \sigma E(\text{tagerr}) \quad \text{(E-TAGCHECK-ERR)}
\end{align*}
\]

\[
\begin{align*}
\Sigma; \Gamma \vdash e : S & \quad \text{static}(R, S) = T \\
\Sigma; \Gamma \vdash \text{tagcheck } R \ e : T
\end{align*}
\]

\[
\Sigma; \Gamma \vdash \text{tagerr} : \bot \quad \text{(T-TAGERR)}
\]

Figure 4.7: Typing and Evaluation of Checked Tags

1. \( e \in v \), or

2. there exist \( \sigma' \) and \( e' \), such that \( \sigma e \rightarrow \sigma' e' \), or

3. \( e = E(\text{tagerr}) \), for some \( E \).

Thus, the type soundness theorem is unsatisfying because of (iii.) of the lemma above. We could try to “repair” the type system; indeed, a sufficiently complicated type system might not need \text{tagcheck}s and \text{tagerr}s at all. Our key idea is to admit \text{tagerr}s to keep the type system simple, and then discharge them by other means.

### 4.4 Automatically Inserting Safe \text{tagcheck}s

We need a way to automatically insert \text{tagcheck}s that fail neither statically nor at runtime. The \text{tagcheck}-insertion technique needs to be sound and handle uses of local control and state that we presented in section 4.1. Unlike conventional type systems, flow analyses are well-suited to such reasoning styles, so we consider flow analysis here. Unfortunately, whole-program analysis of functional and object-oriented languages is non-modular and expensive (section 4.6). Moreover, we need to relate abstract heaps produced by flow analysis to types produced by type-checking. We address these problems broadly, before formally presenting one particular analysis (section 4.5).

The goal of the flow analysis is to compute the tag-sets necessary for \text{tagcheck} expressions. Therefore, the domain of the analysis will be tag-sets augmented by some book-keeping information.
Returning to the example from section 4.3, the comments illustrate the kind of information we need from flow analysis:

```plaintext
let f = ref func(y) : Num ∪ Str → Num {
    return:Num {/* tagof(y) ∈ {"number","string"} */
    let x = ref y in /* x = ref y, tagof(y) ∈ {"number","string"} */
    if (tagof (deref x) == "string") {/* same as line 3 */
        break return 0 /* x = ref y, tagof(y) ∈ {"string"} */
    }
    else 
        break return ((deref x) - 1) /* x = ref y, tagof(y) ∈ {"number"} */
} } } in (deref f)(200)
```

The flow analysis should compute that \( x = \text{ref } y \) at all program points, and that on lines 4 and 8, \( \text{tagof}(y) \in \{\text{"number","string"}\} \) and \( \text{tagof}(y) \in \{\text{"number"}\} \), respectively. This information is enough to mechanically transform the program, replacing the \((\text{deref } x)\) expressions with \(\text{tagcheck}\{\text{"number","string"}\} \ (\text{deref } x)\) on line 4 and \(\text{tagcheck}\{\text{"string"}\} \ (\text{deref } x)\) on line 8. Section 4.5 details a control-sensitive, heap-sensitive analysis that produces results such as this.

This analysis, like our type system, is mostly conventional. It is peculiar in populating the initial abstract heap with \( \text{tagof}(y) \in \{\text{"number","string"}\} \). A whole-program analysis might have used the application on line 9 to populate the heap with the argument value of 200. In contrast, our analysis remains local but exploits the type annotation on \( y \), thus determining that \( \text{tagof}(y) \) is in \( \text{runtime}(\text{Num} \cup \text{Str}) = \{\text{"number","string"}\} \).

We thus use types to modularize our flow analysis, so the analysis can remain strictly intra-procedural. The time complexity of flow analysis is therefore a function of the size of individual functions in the program, which does not tend to grow as programs get larger. (Of course, the choice of function calls as modularity boundaries is not essential.) However, this does reduce precision, as we see below.

**Assignment and Aliasing**  Our analysis is locally heap-sensitive and can type-check the following imperative variant of the example function:

```plaintext
let f = ref func(y) : Num ∪ Str → Num {
    let x = ref y in
    let _ = if (tagof (deref x) == "string") { setref x 1 }
```
else { false } in
   (deref x) - 1 /* x = ref y, tagof(y) ∈ \{"number"\} */
end

in (deref f) (200)

However, since we restart the analysis at function applications, we do not track non-local effects.

In the following example, since \texttt{foo(x)} may assign either a number or a string to \texttt{x}, the analysis we present in section \[4.3\] simply restarts on all function applications. Thus we cannot insert a useful \texttt{tagcheck} around the subsequent \texttt{deref x}, so the example is untypable:

\begin{verbatim}
let g = ref func(y) : Num ∪ Str → Num { 
   let x = ref y in
   let _ = setref x 10 in
   let _ = foo(x) in
   (deref x) /* x = ref y, tagof(y) ∈ \{"number","string"\} */
end in (deref g)("test")
\end{verbatim}

More sophisticated analyses that tracked ownership or aliasing could make such examples typable.

\textbf{Soundness} Given that our flow analysis ignores actual arguments, is it sound? To show that a flow analysis is sound, we must define an acceptability relation and prove that statically computed abstract heaps remain acceptable under evaluation. However, here is a trivial variation of our example that violates acceptability:

\begin{verbatim}
let f = ref func(y) : Num ∪ Str → Num { /* ... as before ... */ }
end in (deref f)(true)
\end{verbatim}

The flow analysis ignores the actual argument \texttt{true} (tagged "boolean") and instead assumes that the type annotation is correct. That is, it assumes that at runtime, \texttt{y} is tagged either "number" or "string". Thus, we obtain only a weak preservation of solutions result (lemma \[8\]).

Although flow analysis admits such mis-applied functions, the type system ensures that function applications are well-typed. Conversely, although the type system admits tags at runtime, the flow analysis only inserts \texttt{tagchecks} that provably do not produce \texttt{tagers}. Hence, each component eliminates the other's weakness and in concert they combine to statically check programs that they cannot verify alone.
4.5 Flow Analysis via CPS

A glaring issue with $\lambda_S$ is that it has a single control operator, while real scripting languages support a plethora of control operators (section 2.1.4 and fig. 9.6). To avoid presenting an overly break-specific program analysis, we convert $\lambda_S$ to CPS. CPS has the added advantage of naming intermediate terms, thereby simplifying our analysis. CPS is, however, not a requirement; we only use it for convenience.

4.5.1 CPS Transformation

Figure 4.8 specifies the syntax of CPS-$\lambda_S$, which, with the exception of $V$, is a syntactic restriction of $\lambda_S$. $V$ includes administrative functions (explained shortly). We specify the CPS transformation using a technique developed by Sabry and Felleisen [75]. The transformation is defined by four mutually-recursive functions that respectively map programs, expressions, values, and evaluation contexts from direct-style to CPS:

$$
P_k: \sigma e \rightarrow SM \quad \Phi: v \rightarrow V \quad C_k: e \rightarrow M \quad K_k: E \rightarrow V
$$

For illustration, consider representative cases of these functions:

$$
\mathcal{P}_k[(l, v) \cdots e] = (l, \Phi(v)) \cdots C_k[e] \\
\Phi[\text{func}(x \cdots): S \cdots \rightarrow T \{ e \}] = \text{func}(k, x \cdots):(T \rightarrow \perp) \times S \cdots \rightarrow \perp \{ C_k[e] \} \\
C_k[E(v_f(v \arg \cdots))] = \Phi[v_f](K_k[E], \Phi[v \arg] \cdots) \\
K_k[E(\text{let } x = \bullet \text{ in } e)] = \text{func}(x) \{ C_k[E(e)] \}
$$

In the last case above, the transformation introduces functions not found in the source program to receive the bound value. Since all evaluation contexts are transformed into such “administrative”
functions, all control structures are thus transformed into applications of administrative functions.

For succinctness, we do not introduce continuation-passing operators, and instead let-bind operators’ results. We elide the semantics of CPS-λS, since it is essentially the same as the semantics in fig. 4.3. This style of definition makes it easy to prove that direct-evaluation corresponds to CPS-evaluation, which is necessary to relate typing and flow analysis.

**Lemma 7 (Soundness of CPS Transformation)** If \( σe → σ'e' \) using reduction rule \( R \), then \( \mathcal{P}_k[σe] → \mathcal{P}_k[σ'e'] \) using reduction rules \( R \), \( E\text{-Let} \), and \( \widehat{β}_v \).

In the lemma above, \( \widehat{β}_v \) denotes the reduction rule for administrative functions (defined exactly as \( β_v \)). The lemma roughly states that intermediate redexes in CPS are applications of administrative functions and let-expressions.

### 4.5.2 Modular Flow Analysis

Figure 4.9 specifies our abstract values and the lattice that relates them. Abstract stores (\( \widehat{S} \)) map abstract locations (\( \widehat{l} \)) to tag sets (\( R \)). (Abstract locations are labels on expressions, introduced by CPS.) On the other hand, abstract environments (\( \widehat{Γ} \)) map identifiers to abstract values (\( \widehat{V} \)) that will account for tag-tests.

For example, fig. 4.10 presents our example from the previous section in CPS. The comment on line 2 specifies the initial abstract environment, computed by applying \textit{runtime} to the arguments.
Figure 4.10: tagcheck Insertion

The remaining comments specify how the abstract heap and environment are transformed by each statement. These transformation are acceptable, as specified by our acceptability relation (figs. 4.11 and 4.12).

Note that the user-written identifier \( x \) is bound to a heap-location. However, the CPS-introduced identifiers, which name the subexpressions that reason about \( x \), are not heap-allocated. We exploit this stratification in our analysis domains to simplify the proof of soundness. The abstract heap and environment contain values that locally reason about the heap. For soundness, V-Restart therefore discards the abstract heap and uses \( \text{reset} \) and \( \text{del} \) to widen heap-dependent abstract values to simple tag sets.

**Assignment and Aliasing** In fig. 4.13 we account for the effects of assignments to tag sets. If a program sets an abstract location \( \hat{l} \), then \( \text{F-SetRef} \) simply updates \( \hat{l} \) in the abstract store of its continuation. However, the environment may bind identifiers to abstract values that reason about \( \hat{l} \). Therefore, we use \( \text{del} \) to widen \( \hat{l} \)-dependent values to simple tag sets.

Local variables cannot reference each other. However, we use references to model mutable objects as well. A local variable bound to a mutable object is a reference to a reference, and these objects can be aliased. In these cases, we stop tracking the potentially-aliased abstract location, once again using \( \text{del} \). \( \text{F-Ref-Alias} \) in fig. 4.13 tackles aliasing in \( \text{ref} \) expressions. Similar rules apply to other syntactic forms.
\[ \text{let } r = \text{deref } x \text{ in } M \]

Let \( \hat{\Gamma} \) and \( \hat{S} \) be the computed abstract environment and store at \( \hat{l} \). If \( \hat{\Gamma}(\hat{l}) = \text{Ref } \hat{l}' \), then we transform the expression to:

\[ \text{let } r' = \text{deref } x \text{ in} \]
\[ \text{let } r = \text{tagcheck } \hat{S}(\hat{l}') \text{ in } M \]

For type-checking, this inserted tagcheck is mapped back to the original, direct-style program.

The administrative functions, if applied, can exponentially increase the size of programs. Therefore, we leave certain administrative redexes unapplied (e.g., continuations of if-expressions).
\[ \hat{S}; \hat{\Gamma} \vdash M \]

\[
\begin{align*}
\hat{\Gamma} & \vdash V \leadsto \hat{V} \\
\hat{S}; x : \hat{V}; \hat{\Gamma} & \vdash M \\
\hat{S}; \hat{\Gamma} & \vdash \text{let } x = V \text{ in } M 
\end{align*}
\]  
\[
\text{(F-LetVal)}
\]

\[
\begin{align*}
\hat{\Gamma} & \vdash V \leadsto R \\
\hat{l} : R, \hat{S}; x : \text{Ref } \hat{l}, \hat{\Gamma} & \vdash M \\
\hat{S}; \hat{\Gamma} & \vdash \text{let } x = \text{ref } V \text{ in } M 
\end{align*}
\]  
\[
\text{(F-Alloc)}
\]

\[
\begin{align*}
\hat{\Gamma} & \vdash \text{Ref } \hat{l} \leadsto \hat{S}; x : \text{Deref } \hat{l} R; \hat{\Gamma} \vdash M \\
\hat{S}; \hat{\Gamma} & \vdash \text{let } x = \text{deref } V \text{ in } M 
\end{align*}
\]  
\[
\text{(F-Deref)}
\]

\[
\begin{align*}
\hat{\Gamma} & \vdash \text{LocTagof } \hat{l} \leadsto \hat{S}; x : \text{LocType } \hat{l} \{ \text{"string"} \}, \hat{\Gamma} \vdash M \\
\hat{S}; \hat{\Gamma} & \vdash \text{let } x = \text{tagof } V \text{ in } M 
\end{align*}
\]  
\[
\text{(F-Tagof)}
\]

\[
\begin{align*}
\hat{\Gamma} & \vdash \text{LocTagof } \hat{l} \leadsto \hat{S}; x : \text{LocType } \hat{l} \{ \text{"string"} \}, \hat{\Gamma} \vdash M \\
\hat{S}; \hat{\Gamma} & \vdash \text{let } x = \text{V === "string" in } M 
\end{align*}
\]  
\[
\text{(F-TypeIs-Str)}
\]

\[
\begin{align*}
\hat{\Gamma} & \vdash V \leadsto R \\
\hat{S}; x : \text{R Type}; \hat{\Gamma} & \vdash M \\
\hat{S}; \hat{\Gamma} & \vdash \text{let } x = \text{tagcheck } R \text{ V in } M 
\end{align*}
\]  
\[
\text{(F-TagCheck)}
\]

\[
\begin{align*}
\hat{\Gamma} & \vdash V \leadsto \text{LocType } \hat{l} \leadsto R; \hat{S}; \hat{l} := R; \hat{\Gamma} \vdash M_1 \\
\hat{S}; \hat{l} := \hat{S}(\hat{l}) \setminus R; \hat{\Gamma} & \vdash M_2 \\
\hat{S}; \hat{\Gamma} & \vdash \text{if } \{ V \} \{ M_1 \} \text{ else } \{ M_2 \} 
\end{align*}
\]  
\[
\text{(F-If-Split)}
\]

\[
\begin{align*}
\hat{\Gamma} & \vdash V_f \leadsto \hat{V}_f \\
\hat{\Gamma} & \vdash V \leadsto R \ldots \\
\hat{S}; \hat{\Gamma} & \vdash V_f (V \ldots) 
\end{align*}
\]  
\[
\text{(F-App)}
\]

\[ a \]

\[ F-\text{TypeIsStr is easily generalized to arbitrary tags; we specialize it to strings for presentation only.} \]

Figure 4.12: Acceptability of Flow Analysis (Essential Rules)
CPS transformation is therefore linear time and our flow analysis computes meets through administrative functions.

**Complexity**

Our flow analysis is a monotonic ascent of a lattice of finite height. For a program of \( N \) terms our analysis computes an abstract store and environment at each term. The domain of abstract stores and environments are both of size \( O(N) \). The range of the abstract store is \( R \), and \(|R|\) is a constant. The range of the abstract environment is \( \widehat{V} \), where \( \widehat{V} \) contains the elements of \( R \).

The additional elements of \( \widehat{V} \) are incomparable with each other and are all less than the elements of \( R \). Hence, the height of \( \widehat{V} \) is just 1 greater than the height of \( R \) (i.e., \( O(1) \)). Thus, the analysis needs time quadratic in the program size. In practice, our prototype implementation type-checks real-world JavaScript programs in seconds on modest machines. This is the payoff of using types to modularize the program analysis at function boundaries.

In contrast, a program analysis of untyped, higher-order code, such as 0CFA [78], must compute the set of all functions that may be applied (\( O(N) \) functions) at all call sites (\( O(N) \) call sites). The range of abstract environments in 0CFA thus has size \( O(N) \), which makes the algorithm cubic.

**Soundness**

In addition to fig. 4.12 and fig. 4.13, we require trivial rules for cases where our flow analysis cannot determine useful information. These additional rules admit all other expressions, except `tagerr`s and possibly-faulty `tagcheck`s. Soundness also requires auxiliary rules that reason about the concrete values in the store that are introduced by evaluation. We elided the concrete store from figures 4.12 and 4.13 for clarity; in the following lemmas, we introduce it.

**Lemma 8 (Soundness)** If \( \hat{S}, \cdot \vdash SM \) and \( SM \rightarrow S'M' \) then either:

i. \( \hat{S}', \cdot \vdash S'M' \), or

ii. \( M \) is a \( \beta_v \)-redex of shape \( (\text{func}(x\cdots) : T\cdots \to \bot.N) \ (V\cdots) \), where for some \( V \), \( \delta_1(\text{tagof}, V) \notin \text{runtime}(T) \).

\[
\begin{align*}
\frac{\hat{V} \vdash V_1 \leadsto \text{Ref} \hat{l}}{\hat{V} \vdash V_2 \leadsto R} & \quad \frac{\hat{S}(\hat{l} := R); x : \text{Ref} \hat{l}, \text{del}(\hat{l}, \hat{\Gamma}) = M}{\hat{S}; \hat{\Gamma} \vdash \text{let} x = \text{setref} V_1 V_2 \text{ in } M} & (\text{F-SetRef}) \\
\frac{\hat{V} \vdash V \leadsto \text{Ref} \hat{l}}{\hat{S}; \hat{\Gamma} \vdash \text{let} x = \text{ref} V \text{ in } M} & (\text{F-Ref-Alias}) \\
\end{align*}
\]
4.5.3 Combining Typing and Flow Analysis

We can now prove a stronger progress result that eliminates tags.

Theorem 2 (Strengthened Progress) If:

i. $\Sigma; \cdot \vdash e : T$,

ii. $\Sigma \vdash \sigma$, and

iii. $\tilde{S}; \cdot \models P_k[\sigma e]$,

then either:

i. $e \in v$, or

ii. There exist $\sigma'$ and $e'$, such that $\sigma e \rightarrow \sigma'e'$.

Proof: This follows from lemma [5] with the possibility of tags eliminated by inspection of fig. 4.12—flow analysis does not admit expressions with tags. ■

Theorem 3 requires a corresponding, combined preservation theorem.

Theorem 3 (Combined Preservation) If:

i. $\Sigma; \cdot \vdash e : T$,

ii. $\Sigma \vdash \sigma$,

iii. $\tilde{S}; \cdot \models P_k[\sigma e]$, and

iv. $\sigma e \rightarrow \sigma'e'$,

then there exist $\Sigma'$ and $\tilde{S}'$, such that:

i. $\Sigma'; \cdot \vdash e' : T$,

ii. $\Sigma' \vdash \sigma'$,

iii. $\Sigma \subseteq \Sigma'$, and

iv. $\tilde{S}'; \cdot \models P_k[\sigma'e']$. 
Proof: Conclusions (i.), (ii.), and (iii.) follow immediately from lemma 5. For conclusion (iv.), apply lemma 7 to hypothesis (iv.) to get a reduction sequence, \( P_k[\sigma e] \to P_k[\sigma'e'] \). Apply lemma 8 at each step, eliminating case (ii.) of the lemma as follows. By lemma 7, intermediate expressions are not \( \beta_v \)-redexes, so case (ii.) does not apply. Suppose \( e \) itself has an active \( \beta_v \)-redex:

\[
e = E(\text{func}(x \cdots) : U \cdots \to S \{ e_f \gamma(v \cdots) \})
\]

Once transformed to CPS, \( e \) has the form

\[
\text{func}(k, x \cdots) : (S \to \bot) \times U \cdots \to \bot \{ M_p \}(V \cdots)
\]

where \( V \cdots \) are \( v \cdots \) in CPS. Since \( e \) is typed, there exists a \( \Gamma \) such that:

\[
\Sigma; \Gamma \vdash \text{func}(x \cdots) : U \cdots \to S \{ e_f \gamma(v \cdots) : S \}
\]

For all \( v \), \( \Sigma; \Gamma \vdash v : U \) by inversion. Hence \( \delta_1(\text{tagof}, v) \in \text{runtime}(U) \). Since conversion to CPS does not change tags, \( \delta_1(\text{tagof}, v) = \delta_1(\text{tagof}, V) \), case (ii.) of lemma 8 does not apply. \( \blacksquare \)

4.6 Related Work

Typed Scheme  
Typed Scheme \[6, 7\] is a type system designed to admit Scheme idioms. Typed Scheme uses occurrence typing to account for type tests and type predicates. However, occurrence typing is unsound in the presence of imperative features; thus, it is “turned off” when imperative features are used. Unlike the Scheme programs that Typed Scheme types, programs in mainstream scripting languages make heavy use of imperative features, which we handle.

Technically, we develop a type system and flow analysis that are complementary by design (Lemmas 6 and 8), which combine soundly (Theorems 2 and 3), and which can be enriched independently within the framework of these two lemmas. We conjecture that a similar structure could be extracted from Typed Scheme, as the type system is augmented with meta-functions that update the environment (see Typed Scheme’s use of \( \Gamma^+ \) and \( \Gamma^- \) to affect the environment, and \( \text{combpred} \) to prop type tests to the context in \( \text{if} \) (fig. 4.14)). We believe these are similar to transfer functions for dataflow analyses. However, Typed Scheme is not organized in this manner.
\[ \Gamma \vdash e_1 : \tau_1; \phi_1 \quad \Gamma + \phi_1 \vdash e_2 : \tau_2; \phi_2 \quad \Gamma - \phi_1 \vdash e_3 : \tau_3; \phi_3 \]
\[ \vdash \tau_2 \ll \tau \quad \vdash \tau_3 \ll \tau \quad \phi = \text{combpred}(\phi_1, \phi_2, \phi_3) \]
\[ \Gamma \vdash (\text{if } e_1 \ e_2 \ e_3) : \tau; \phi \]

Figure 4.14: If-splitting in Typed Scheme [86]

**Intensional Polymorphism** Intensional polymorphism [17] provides a `typecase` construct that allows programs to inspect and dispatch on the type of values at runtime. This requires a term-level representation of types at runtime, which is only possible when the static and dynamic semantics of a programming language are co-designed. The present work, Typed Scheme, and other retrofitted type systems (discussed below) do not have access to their types at runtime. Type dispatch in a retrofitted type system happens indirectly. For example, Typed Scheme uses predicates [86], while our work relies on the relationship between static types and runtime tags (section 4.3).

**Other Retrofitted Type Systems** Soft Scheme [91] performs type inference for Scheme programs. It handles the full language of the time, and has a limited form of if-splitting. It does not pay any additional attention to the interaction of types and control flow. This is reasonable because it, like Typed Scheme, is focused on Scheme programs that are mostly functional. However, this means that it too cannot handle the kinds of examples shown in this chapter and found in many scripting languages.

Anderson et al. [5] tackle type inference for JavaScript. However, their language is extremely limited, and their type system cannot tackle the idioms discussed in this chapter (section 4.1).

Heidegger and Thiemann’s [43] recency types account for ad hoc object initialization patterns that are pervasive in JavaScript, but does not address the problems that this chapter does. Our work does not account for objects. Our preliminary investigation suggests that the two approaches are complementary and can fruitfully be combined.

Henglein and Rehof [45] present a translation of Scheme to ML that uses type inference to minimize runtime projections. However, their “type system does not model control flow information” [45, Section 6.5], which is the goal of our work.

Diamondback Ruby [33] is a type system and type inference for Ruby. Although its type language includes union types, it does not account for type-tests to discriminate members of unions, which is the focus of our work. The authors state that “support for occurrence types would be useful future work”.

Types and Flow Analysis  Shivers shows how control-flow can be extended to account for type-tests [78, Chapter 9]. However, whole-program analysis for functional and object-oriented languages is non-modular and expensive [31] or difficult to make effective [30]. Meunier et al. [63] develops a modular analysis for an untyped language by using contracts as sources and sinks for abstract values. We exploit type annotations in the same manner. Since all functions have type annotations, our flow analysis problem is significantly more tractable than in an untyped language with optional contracts.

Jensen et al. [51, 52] and MrSpidey [31] use flow analysis to recover precise type-like information for arbitrary JavaScript and Scheme programs, respectively. A significant advantage of flow analysis is that it does not require type annotations. Our work requires and exploits type annotations to achieve modularity, which leads to quadratic time complexity in theory that appears to translate into practice (section 4.5.2).

There are known equivalences between various type systems and control-flow analyses, e.g., Heintze [44], Nielson and Nielson [68], and Palsberg and O’Keefe [69]. The aforementioned works extend type systems to calculate information that is conventionally calculated by flow analyses. In contrast, our type system is oblivious to control flow information (fig. 4.5). We use a separate flow analysis to account for control-sensitive and heap-sensitive reasoning (section 4.4). We independently prove typing and flow analysis sound, then show that they combine in a simple way (section 4.5.3).

Definite assignment analysis is a commonly used flow analysis that augments typing (e.g., see the Java Language Specification [36, Chapter 16]). Definite assignment analysis conservatively ensures that variables are assigned before they are used. Hence, the analysis rejects programs as untypable when all variables are not definitely assigned. In contrast, our analysis augments the type system to accept programs that would otherwise be untypable.
Chapter 5

Typing Objects

In most statically-typed object-oriented languages, an object’s type or class enumerates its member names and their types. This set of names is finite and the names are first-order, barring cumbersome reflection APIs. In contrast, in JavaScript, reflection is trivial, class hierarchies are fluid, objects’ shapes are amorphous, and member names are first-class strings that can be computed dynamically. These features are difficult to type-check.

This chapter presents fluid object types, a type language for describing the dynamic, reflective idioms employed by JavaScript. Fluid object types have two novel features: they employ string patterns to describe possibly-infinite collections of fields and presence annotations to precisely state the position of inherited fields. We demonstrate that fluid object types account for many programming patterns that are conventionally untypable. Furthermore, chapter 8 demonstrates that fluid object types provide a simple account of language-based Web sandboxes.

5.1 $\lambda^{ob}_S$: A Core Calculus of Lightweight Objects

$\lambda_{JS}$ (chapter 2) is fully capable of modeling JavaScript’s objects. However, $\lambda_{JS}$ also models various other details of JavaScript that are inessential for understanding objects. We thus present fluid object types using a smaller core calculus of lightweight objects.

Figure 5.1 defines the syntax and semantics of $\lambda^{ob}_S$, a calculus of lightweight objects. The objects of $\lambda^{ob}_S$ are extensible records with inheritance and field-deletion. $\lambda^{ob}_S$ distinguishes “parent” as

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1This chapter is based on joint work with Joe Gibbs Politz [39].
$P = \ldots$

$c = \text{num} \mid \text{str} \mid \text{bool}$

$\nu = c \mid \text{func}(x:T).e \mid \Lambda x:\text{<}:T.e \mid \{ \text{str}:v \cdots \}$

$e = x \mid v \mid e(x) \mid \{ \text{str}:v \cdots \} \mid \{ e \mid e \} \mid \text{delete } e \mid e(T)$

$E = \bullet \mid E(e) \mid v(E) \mid \{ \text{str}:v \cdots \} \mid \text{hasfield } e \mid v \text{ hasfield } E \mid E \text{ matches } P$

\[
\begin{align*}
\beta_v & \quad (\text{func}(x:T).e)(v) \mapsto e[x/v] \\
\text{E-Fix} & \quad \text{fix}(f:T).e \mapsto e[f/\text{fix}(f:T).e] \\
\text{E-TApp} & \quad (\Lambda x:\text{<}:S.e)(T) \mapsto e[\alpha/T] \\
\text{E-GetField} & \quad \{ \cdots \text{str}:v \cdots \}[\text{str}] \mapsto v \\
\text{E-Inherit} & \quad \{ \text{str}:v \cdots \text{"parent"}:v_p \}[\text{str}_x] \mapsto v_p[\text{str}_x], \text{if } \text{str}_x \notin (\text{str} \cdots) \\
\text{E-Update} & \quad \{ \cdots \text{str}:v \cdots \}[\text{str} \mapsto v_p] \mapsto \{ \cdots \text{str}:v_x \cdots \} \\
\text{E-Create} & \quad \{ \text{str}:v \cdots \} \{ \text{str}_x = v_x \} \mapsto \{ \text{str}_x \mapsto v_x, \text{str}:v \cdots \}, \text{if } \text{str}_x \notin (\text{str} \cdots) \\
\text{E-Del} & \quad \text{delete} \{ \cdots \text{str}:v_x \cdots \} \{ \text{str}_x \mapsto \{ \cdots \} \\
\text{E-NoDel} & \quad \text{delete} \{ \text{str}:v \cdots \} \{ \text{str}_x \mapsto \{ \text{str}_x \mapsto v_x \} \} \{ \cdots \}, \text{if } \text{str}_x \notin (\text{str} \cdots) \\
\text{E-IfTrue} & \quad \text{if} (\text{true}) \text{ e}_2 \text{ else } \text{ e}_3 \mapsto \text{ e}_2 \\
\text{E-IfFalse} & \quad \text{if} (\text{false}) \text{ e}_2 \text{ else } \text{ e}_3 \mapsto \text{ e}_3 \\
\text{E-Has} & \quad \{ \cdots \text{str}:v \cdots \} \text{ hasfield } \text{str} \mapsto \text{true} \\
\text{E-HasNot} & \quad \{ \text{str}:v \cdots \} \text{ hasfield } \text{str} \mapsto \text{false}, \text{ when } \text{str}' \notin (\text{str} \cdots) \\
\text{E-Match} & \quad \text{str} \text{ matches } P \mapsto \text{true}, \text{ str } \in P \\
\text{E--Match} & \quad \text{str} \text{ matches } P \mapsto \text{false}, \text{ str } \notin P \\
\text{E-String} & \quad \text{str}_1 + \text{str}_2 \mapsto \text{str}_1 \text{ str}_2 \\
\end{align*}
\]

\[
\begin{align*}
\text{E-Cxt} & \quad E(e_1) \mapsto E(e_2), \text{ when } e_1 \mapsto e_2 \\
\text{let } x & \mapsto e_1 \text{ in } e_2 \equiv (\text{func}(x:T).e_2)(e_1) \\
\text{let rec } x & \mapsto e_1 \text{ in } e_2 \equiv (\text{func}(x:T).e_2)(\text{fix } x:T.e_1) \\
\text{func}(x_1:T_1 \cdots x_n:T_n).e & \equiv \text{func}(x_1:T_1) \cdots \text{func}(x_n:T_n).e \\
\text{e}_f(e_1 \cdots e_n) & \equiv e_f(e_1) \cdots (e_n)
\end{align*}
\]

Figure 5.1: Syntax and Semantics of $\lambda_{S}^{ob}$

a reference to the parent object for inheritance (E-Inherit). However, “parent” is otherwise undistinguished; a program can retrieve, update, or even delete “parent”. Field names are first-class strings, not first-order labels. A single program may work with an arbitrary collection of field names, or even dynamically construct names by concatenating strings (E-String+). $\lambda_{S}^{ob}$ programs can use reflection (hasfield) to determine which fields are present on an object. In addition, $\lambda_{S}^{ob}$ programs can use matches to determine if a string matches a particular pattern. We leave the representation of patterns unspecified. (Other languages use a mix of regular expressions and ad hoc testing to achieve the same effect.) Finally, $\lambda_{S}^{ob}$ includes explicit type annotations and instantiations; we introduce types
in section 5.3.

The primary distinction between $\lambda_{ob}^S$ and $\lambda_{JS}$ is that $\lambda_{ob}^S$ lacks mutable state for clarity of presentation. As discussed in section 5.5.1, all our proofs and theorems are over an imperative $\lambda_{JS}$. $\lambda_{ob}^S$ does have additional expressions for string-concatenation and string-matching, but these are trivially expressible as primitives in $\lambda_{JS}$ (section 2.1.6).

5.2 Idiomatic $\lambda_{ob}^S$: Type-Checking Challenges

The examples below demonstrate that $\lambda_{ob}^S$ can model many characteristic uses of objects in scripting languages. (In appendix B, we translate these examples to various scripting languages.) For now, we leave the static types unspecified. We type-check these examples in section 5.3.5 after developing fluid object types.

Example 1: Prototype-based Objects $\lambda_{ob}^S$ can easily encode prototype inheritance:

```plaintext
let Rect = { "area": func(self:?) . self["x"] * self["y"] } in
let Cuboid = { "parent": Rect,
    "vol": func(self) . self["area"](self) * self["z"] } in
let shape = { "x": 2, "y": 5, "z": 10, "parent": Cuboid } in
let vol = shape["vol"](shape) // vol is 100
```

Above, methods are simply function valued-fields that take an explicit self argument. With this encoding, a program can directly access the "parent" field to redefine methods or apply methods to other objects.

Example 2: Extracting Methods Supporting method-extraction promotes code reuse across structurally similar values. For example, arrays may have a collection of utility methods in their common parent:

```plaintext
let ArrParent = { "slice": func(self:?, begin:?, end:?). · · · , · · · } in
let arr1 = { "0": 3, "1": 20, "2": 59, "length": 3, "parent": ArrParent }
```

The implementation of slice may only require that self["len"] be defined; it does not actually need self to be an array. Therefore, this single slice method can be copied and applied to other kinds of collections. This exact scenario occurs frequently in JavaScript programming. Web browsers have
other kinds of collections, such as `HTMLNodeList`, that are not arrays and thus do not have various array methods:

```javascript
let nodeList = {
  "0": htmlElementA,
  "1": htmlElementB,
  "2": htmlElementC,
  "len": 3,
  "parent": HTMLNodeListParent
} in

let eltArray = ArrParent["slice"](nodeList, 0, 1)
// returns an array containing htmlElementA and htmlElementB
```

However, in the code above, `slice` is applied to an `HTMLNodeList` to convert it to an array and make other utility methods (e.g., `map` and `reduce`) available.

**Example 3: Classes** \( \lambda_S^{ob} \) can also encode classes by having methods close over a particular value of `self`. Although explicitly passing `self` to each method is enormously flexible, it is error-prone.\(^2\) We build on the prototypal shapes of Example 1 below:

```javascript
let rec shape2 = {
  "x": 2,
  "y": 5,
  "z": 10,
  "_class_": Cuboid,
  "parent": {
    "vol": func() . shape2["_class_"]["vol"](shape2)
  }
} in

let f = shape2["vol"]
let vol2 = f() // vol2 is still 100, f closes over shape2
```

In this encoding, methods do not require an explicit `self` argument, but the underlying methods are still accessible via the " `_class_` " field.\(^3\) This encoding allows methods themselves to manipulate objects’ structure. However, it also allows other code to freely modify objects. We will use types to hide the `_class_` field from other code.

**Example 4: Ad Hoc Private Fields** All fields are public in \( \lambda_S^{ob} \)’s lightweight objects. In such object systems, it is common to use a convention, such as “field names that begin with an underscore are private.”\(^4\) This convention is easily violated by malicious or buggy code. A module may wish to protect some of the fields in objects in its implementation, and only provide client code with access to a safe lookup function.

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\(^2\)JavaScript suffers exactly this error; `this` is an implicit argument but is supplied at each method call (fig. 2.5).

\(^3\)Python and Ruby have similar encodings; methods close over their `self` argument, but the underlying method is still accessible.

\(^4\)Python and Dart employ such conventions.
For example, a simple dynamic check to ensure that untrusted code does not access fields that begin and end with underscores is as follows:

```plaintext
let safeGetField = Λα <: ?.func(obj:?, fieldName:?, default:?).
  if (fieldName matches "_.*") default
  else if (obj hasfield fieldName) obj[fieldName] else default in
  safeGetField(?)({ "_private": 42, "pub": 23 },
    "_private", 0) // returns 0
```

These checks are notoriously difficult to implement in full-fledged scripting languages. Our type system for $\lambda^{ob}_S$ will demonstrate techniques for statically verifying that such code is correct.

**Example 5: Dictionaries as Dictionaries** There is no need to implement dictionaries in $\lambda^{ob}_S$; objects can be used as dictionaries themselves. Some care must be taken in implementation, however, as a naïve approach may accidentally extract a method from the object’s parent, or the parent itself:

```plaintext
let ObjectParent = { "serialize": func(self:?).···, ··· } in
let dict = { "habitat": "a natural home or environment",
    "park": "a large enclosed piece of ground",
    "parent": ObjectParent } in
  dict["habitat"] // returns "a natural home or environment"
  dict["serialize"] // returns func(self) ... !
  dict["parent"] // returns ObjectParent!
```

To avoid such mishaps, programmers should guard dynamic dictionary accesses:

```plaintext
let safeAssign = Λα ⋲ ?. Λβ ⋲ ?.func(dict:?, word:Str, value:?).
  dict["w_" + word = value]

let safeLookup = Λα ⋲ ?.func(dict:?, word:Str, default:?).
  let lookup = "w_" + word in
    if (dict hasfield lookup) dict[lookup]
    else default
```

This example presents a safe alternative, which prefixes words with "w_" and then uses a dynamic check to ensure only words are accessed. Our type system reasons about field tests to give reasonable static types to dictionaries.

**Type System Features** These examples elicit a baseline feature set to typecheck:

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5A fact the developers of Google Docs know all too well. At the time of this writing, typing `_proto_` JavaScript’s parent, crashes Google Docs: [www.google.com/support/forum/p/Google+Docs/thread?tid=0cd4a00bd6af9e4](http://www.google.com/support/forum/p/Google+Docs/thread?tid=0cd4a00bd6af9e4)
\[
L = P \mid \alpha \mid L_1 \cap L_2 \mid L_1 \cup L_2 \mid L_1L_2 \mid \overline{T} \\
b = \text{Num} \mid \text{Bool} \\
\alpha = \ldots \\
T = b \mid T_1 \to T_2 \mid \mu \alpha.T \mid \top \mid \forall \alpha < : S.T \mid L \mid \{L_{p_1} : T_1 \cdots L_{p_n} : T_n, L_A : \text{abs}\} \\
p = \circ \mid \downarrow \uparrow \\
\Gamma = \cdot \mid \Gamma, x : T \mid \Gamma, \alpha < : T
\]

\[\Gamma \vdash T\]

\[\Gamma \vdash T_1 \cdots \Gamma \vdash T_n \quad \forall i, L_i \cap L_A = \emptyset \text{ and } \forall j \neq i, L_i \cap L_j = \emptyset \]

\[\Gamma \vdash \{L_{p_1} : T_1 \cdots , L_{p_n} : T_n, L_A : \text{abs}\}\]  

(WF-OBJECT)

\[\alpha \in \text{dom}(\Gamma)\]

\[\Gamma \vdash \alpha\]  

(WF-TVAR)

Figure 5.2: Types for \(\lambda_S^{ab}\)

1. Addition and deletion of fields,

2. Prototype-based inheritance with method extraction,

3. Class-like inheritance with bound and unbound method extraction,

4. Invariants on pattern-based field conventions, and

5. Field-presence guards on field access.

5.3 Types for Objects

The preceding examples guide the development of fluid object types in this section. Our full type language is in fig. 5.2 but we motivate and incrementally develop fluid object types in this section. In subsequent sections, we detail the associated type system.

5.3.1 Simple Records

Structural record types are a natural starting point, since \(\lambda_S^{ab}\) does not have classes. Recall that record types are finite maps from field names to field types:

\[T = \cdots \mid \{str_1 : T_1 \cdots str_n : T_n\}\]
Record types can type trivial programs, but not those in section 5.2.

### 5.3.2 Field Patterns

Record types are too simple because they statically enumerate all their fields’ names. Interesting programs use computed field lookups, where the exact field name is not statically known. Consider the type of \( c \) in the following example:

```hs
let getCoord = func(pt: {"x": Num, "y": Num}, c:?) . pt[c]
```

The intended type for \( c \) is not an arbitrary string (\( \text{Str} \)), but a string in the set \( \{"x", "y"\} \). We thus extend our types with precise string types, \( L \)-types, that denote sets of strings:

\[
L = P \\
T = \cdots | L
\]

The exact representation of \( L \)-types is not significant; we only require that the functions and predicates in fig. 5.3 be defined.

Type-checking field lookup with \( L \)-typed strings is straightforward. If \( c \) has type \( \{"x", "y"\} \), then \( \text{pt}[c] \) has type \( \text{Num} \). In general, if \( \text{fld} \) has type \( L \) and \( \text{obj} \) has type \( \{str_1 : T_1, \ldots, str_n : T_n\} \) then at runtime \( \text{obj}[\text{fld}] \) may lookup any \( str_i \in L \). Thus, the type of \( \text{obj}[\text{fld}] \) is the join of the matching fields’ types.

**Patterns Replace Field Names** \( L \)-types allow computed field names, but record types still specify a finite list of fields. They cannot express the type of the dictionary in Example 5, so we reuse \( L \)-types to generalize field names to patterns:

\[
T = \cdots | \{L_1 : T_1, \ldots, L_n : T_n\}
\]

This is the first of the two key features of fluid object types. We can now describe an object with an arbitrary collection of fields. For example, in the following type, all fields that begin with
an underscore have type \texttt{Num} and all other fields have type \texttt{Bool}\footnote{We often use regular expressions to describe patterns. However, regular expressions are not fundamental; any decision procedure over strings is adequate.}.

\[
\{\_.*: \texttt{Num}, \_\_.*: \texttt{Bool}\}
\]

Something odd happened here—this type seems to describe an object with an infinite number of fields. Since objects are finite dictionaries, we could interpret this type as a specification of fields' types if they are present; if a field is absent then indexing that field gets stuck, but typing is preserved. We can do better and address this problem with \textit{presence annotations} in the next section.

In summary, fluid object types use patterns (\textit{L}-types) to describe collections of fields in objects. There are three common classes of \textit{L}-types:

- The \textit{L}-type for the set of all strings is the usual \texttt{Str}-type.

- An \textit{L}-type that represents a singleton set, \{\texttt{str}\}, is the type of the string literal \texttt{str}. In \(e_1[e_2]\), if \(e_2: \{\texttt{str}\}\) then the expression is a conventional, known-label field lookup.

- An \textit{L}-type that represents a possibly-infinite set of strings is useful for typing operations on computed field names. For example, in object update, \(e_1[e_2 = e_3]\), if the type of \(e_2\) is the co-finite set \{\texttt{"parent"}\}, then the operation does not affect \texttt{"parent"} and does not affect the inheritance chain.

\textbf{5.3.3 Presence Annotations}

Conventional structural object types do not expose the position of members on the inheritance chain; types are “flattened” to include inherited members. However, the \texttt{"parent"} field of \(\lambda^a_b\) objects allows programs to distinguish inherited fields. If we flatten object types, all such programs would be untypable.

Fluid object types allow us to expose the precise structure of the inheritance chain with ease. In the following type, \texttt{move} is present on the parent:

\[
\{\texttt{"parent"} : \{\texttt{"move"} : \texttt{Num} \to \texttt{Num}\}\}
\]
This precision unfortunately makes conventional uses of class hierarchies untypable. Functions that consume subtypes of a particular class are agnostic to the position of methods on the inheritance chain; all that matters are methods’ types. However, the type above requires \texttt{move} to be present on precisely the first parent, and does not admit objects that inherit but do not override \texttt{move}.

To remedy this, we introduce the second feature of fluid object types. We add \textit{presence annotations} to fields and a pattern for fields that are \textit{definitely absent}:

\[
p = \downarrow | \uparrow | \circ
\]
\[
T = \cdots | \{L_1^{P_1} : T_1, \cdots, L_n^{P_n} : T_n, L_A : \texttt{abs}\}
\]

We interpret presence annotations as follows:

- \(L^\downarrow : T\) indicates that all fields \(str \in L\) are \textit{definitely present on the object itself} with type \(T\). These fields are not inherited and are not absent.

- \(L^\uparrow : T\) indicates that all fields \(str \in L\) are either \textit{present on the object itself or along the inheritance chain} with type \(T\).

- \(L^\circ : T\) indicates that all fields \(str \in L\) \textit{may be present on the object itself}. If a field \(str\) is present it has type \(T\), but it may be absent.

- The \(L_A : \texttt{abs}\) annotation indicates that all fields \(str \in L_A\) are \textit{definitely absent} on the object; however, they may be present higher up on the inheritance chain. Looking up a definitely absent field therefore does not fail if the field is inherited.

\textbf{Notation} We use two abbreviations to simplify the syntax of fluid objects.

- We elide writing an empty set of absent fields, \(\emptyset : \texttt{abs}\). For example:

\[
\{\texttt{x}^\downarrow : \texttt{Num}, \texttt{y}^\downarrow : \texttt{Num}\} = \{\texttt{x}^\downarrow : \texttt{Num}, \texttt{y}^\downarrow : \texttt{Num}, \emptyset : \texttt{abs}\}
\]

- It is often convenient for the set of absent fields to be the complement of all other fields; we abbreviate this to \(* : \texttt{abs}\). For example, \(*\) represents \{\texttt{x}, \texttt{y}, \texttt{parent}\} in the following type:

\[
\{\texttt{x}^\downarrow : \texttt{Num}, \texttt{y}^\downarrow : \texttt{Num}, \texttt{parent}^\downarrow : P, * : \texttt{abs}\}
\]
Flexibility and Guarantees of Presence Annotations  The $L^\downarrow : T$ and $L^\uparrow : T$ annotations ensure that indexing an $L$-typed field produces a $T$-typed value; programs cannot get stuck indexing fields. They also allow other fields with the same name but different types to exist further up the inheritance chain, but these do not affect the type of object indexing.

The $L^\circ : T$ annotation provides weaker guarantees. For example, if $\text{obj}$ has the type:

$$\{"x"^\circ : \text{Num},"\text{parent}"^\downarrow : \{"x"^\downarrow : \text{Bool}\}\}$$

then $\text{obj}["x"]$ may return either field. For full generality, we present a typing rule that determines that $\text{obj}["x"]$ has type $\text{Num} \sqcup \text{Bool}$. What would be more useful is an operator that narrows the $\circ$ to a $\downarrow$.

5.3.4 Reflection

Consider typing Example 5 from section 5.2. We might give $\text{dict}$ the following type:

$$\{w_.^\ast : \text{Str}\}$$

With this type, the expression $\text{dict}["w\_\text{habitat}"]$ is not typable. The type indicates that "w\_habitat" may not exist on the object, so we must also compute the type of $\text{dict}["\text{parent}"]["w\_\text{habitat}"]$. However, "parent" is not specified.

We must first establish that $\text{dict}["w\_\text{habitat}"]$ is definitely present. In Example 5, the $\text{safeLookup}$ function guards dictionary indexing with a $\text{hasfield}$ check:

$$\text{if} \ (\text{dict hasfield lookup}) \ \text{dict[lookup]} \ \text{else default}$$

The type system can $\text{if-split}$ [86] to account for such guards and narrow the types of $\text{dict}$ and $\text{lookup}$ in the true branch. We present a simple if-splitting rule in section 5.5 here we describe the types in the true-branch after narrowing.

In the true-branch, we have established that the value of $\text{lookup}$ names a member of $\text{dict}$; we can thus narrow a possibly absent member $(\circ)$ to definitely present $(\downarrow)$. However, we do not know exactly which member to narrow. In particular, the following narrowing is wrong:

$$\text{dict} : \{w_.^\ast^\downarrow : \text{Str}\}$$
The type above states that all members are definitely present. However, the program only establishes that a single string is definitely present.

We express this by splitting the pattern \( w_{\cdot \cdot} \) into two components, a type variable \( \alpha \) that represents the string bound to \( \text{lookup} \) and \( w_{\cdot \cdot} \cap \pi \), the remainder of the pattern. Thus in the true-branch, the type-environment, \( \Gamma' \), modifies the enclosing type environment, \( \Gamma \), as follows:

\[
\Gamma' = \Gamma, \alpha <: P, \text{word} : \alpha, \text{dict} : \{\alpha^\downarrow : \text{Str}, P \cap \pi^\circ : \text{Str}\}
\]

where \( P = w_{\cdot \cdot} \).

The patterns used above include type variables and set operators:

\[
L = P \mid \alpha \mid L_1 \cap L_2 \mid L_1 \cup L_2 \mid L_1 L_2 \mid \overline{L}
\]

The final specification of fluid object types and string pattern types is in fig. 5.2. With these types, we can type-check the examples from section 5.2.

### 5.3.5 Type-Checking Examples

With fluid object types introduced, we now revisit the examples from section 5.3.5.

**Example 1** The types for \( \text{Rect} \) and \( \text{Cuboid} \) are as follows:

\[
\text{Rect} : \quad \left\{ \begin{array}{l}
\text{“area”}^\downarrow : \{\text{“x”}^\downarrow : \text{Num}, \text{“y”}^\downarrow : \text{Num}\} \rightarrow \text{Num}
\end{array} \right\}
\]

\[
\text{Cuboid} : \quad \left\{ \begin{array}{l}
\text{“vol”}^\downarrow : \left\{ \begin{array}{l}
\text{“x”}^\downarrow : \text{Num}, \text{“y”}^\downarrow : \text{Num}, \text{“z”}^\downarrow : \text{Num},
\text{“area”}^\uparrow : \{\text{“x”}^\downarrow : \text{Num}, \text{“y”}^\downarrow : \text{Num}\} \rightarrow \text{Num}
\end{array} \right\} \rightarrow \text{Num},
\text{“parent”}^\downarrow : \text{Rect}
\end{array} \right\}
\]

We abuse notation slightly for brevity; in \( \text{Cuboid} \) we use \( \text{Rect} \) as an abbreviation for the whole type. The presence annotations on these types are interesting. On \( \text{Rect} \)'s \( \text{“area”} \) method, the argument omits listing absent fields and only specifies fields the method needs. This allows an object like \( \text{shape} \), which has a \( \text{“z”} \) field, to be freely used with \( \text{“area”} \). \( \text{Cuboid(“vol”)} \) marks \( \text{area} \) as inherited (\( \uparrow \)), since it is agnostic to its position on the inheritance chain.
Example 2  ArrParent requires “slice”’s argument to have a Num-typed “len” field and consistently-typed numeric fields:

\[ \forall \alpha \lt: \top, \mu \beta. \begin{cases} \text{"slice"}^\downarrow &: \{ \text{Dec}^\circ : \alpha, \text{"len"}^\downarrow : \text{Num} \} \\ \rightarrow &: \{ \text{Dec}^\circ : \alpha, \text{"len"}^\downarrow : \text{Num}, \text{"parent"}^\downarrow : \beta \} \\ \ldots & \ldots \end{cases} \]

\[ \text{Dec} = 0 | [1-9][0-9]* \]

Fields that match Dec may be present; if they are, they must have type Num as indicated by the regular expression pattern Dec. If ArrParent is instantiated with the type HTMLElement, then “slice” can be freely used on the object in Example 2.

Example 3  The types of Rect and Cuboid are the same as in Example 1 in this class encoding, but note that shape2["vol"] is closed over its self-argument. We can give shape2 the following type, hiding _class_, to prevent external code from observing its internals:

\[ \{ \text{"x"}^\downarrow : \text{Num}, \text{"y"}^\downarrow : \text{Num}, \text{"z"}^\downarrow : \text{Num}, \text{"vol"}^\uparrow : \rightarrow \text{Num} \} \]

Example 4  The type of safeGetField is:

\[ \forall \alpha \lt: \top, \{ \text{str}^\circ : \alpha \} \rightarrow \text{Str} \rightarrow \alpha \rightarrow \alpha \]

The pattern \( \text{str}^\circ : \alpha \) indicates that all non-underscored fields have type \( \alpha \), if they are present.

Example 5  The types in this example are:

\[ \begin{align*} \text{ObjectParent} &: \{ \text{"serialize"} : \top \rightarrow \text{Str} \} \\ \text{dict} &: \forall \alpha \lt: \top, \{ \text{w..}^\circ : \alpha, \text{"parent"}^\downarrow : \text{ObjectParent}, \text{"serialize"} : \text{abs} \} \\ \text{safeAssign} &: \forall \alpha \lt: \top, \forall \beta \lt: \{ \text{w..}^\circ : \alpha \}, \beta \rightarrow \text{Str} \rightarrow \alpha \rightarrow \beta \\ \text{safeLookup} &: \forall \alpha \lt: \top, \{ \text{w..}^\circ : \alpha \} \rightarrow \text{Str} \rightarrow \alpha \rightarrow \alpha \end{align*} \]

We assume that serialize can serialize arbitrary values. Notably, dict’s type allows serialize to be called, but the types of safeAssign and safeLookup ensure that they cannot access serialize and only manipulate
\[ \Gamma \vdash S <: T \]

\[ \Gamma \vdash T_a <: S_a \quad \Gamma \vdash S_r <: T_r \]

\[ \Gamma \vdash S_a \rightarrow S_r <: T_a \rightarrow T_r \]

\[ \Gamma \vdash b <: b \]

\[ \Gamma \vdash T <: \top \]

\[ \Gamma \vdash S <: T[\alpha/\mu\alpha.T] \]

\[ \Gamma \vdash S <: \mu\alpha.T \]

\[ \Gamma \vdash S[\alpha/\mu\alpha.S] <: T \]

\[ \Gamma \vdash \mu\alpha.S <: T \]

\[ \Gamma \vdash \alpha <: \alpha \]

\[ \alpha <: S \in \Gamma \quad \Gamma \vdash S <: T \]

\[ \Gamma \vdash \alpha <: T \]

\[ \Gamma, \alpha <: U \vdash S <: T \]

\[ \Gamma \vdash (\forall \alpha <: U.S) <: (\forall \alpha <: U.T) \]

\[ L_1 \subseteq L_2 \]

\[ \Gamma \vdash L_1 <: L_2 \]  \hspace{1cm} \text{(S-STR)}

(1)\(\forall i, j.\) if \(L_i \cap M_j \neq \emptyset\) then \(p_i <: q_j\) and \(\Gamma \vdash S_i <: T_j\)

(2) \(\bigcup_{i=1}^{1:n} M_i \subseteq \bigcup_{j=1}^{1:m} L_j \cup L_A\)

(2') \(M_A \subseteq L_A\)

(3) \(\forall j.\) if \(M_j \cap L_A \neq \emptyset\) then \(q_j = \circ\) or \(q_j = \uparrow\)

(4) \(\forall j.\) if \(q_j = \uparrow\) then \(\Gamma \vdash \text{inherit}_{T}(\{L_1^{p_1} : S_1, \ldots, L_n^{p_n} : S_n, L_A : \text{abs}\}, M_j) <: T_j\)

\[ \Gamma \vdash \{L_1^{p_1} : S_1, \ldots, L_n^{p_n} : S_n, L_A : \text{abs}\} <: \{M_1^{q_1} : T_1, \ldots, M_m^{q_m} : T_m, M_A : \text{abs}\} \]  \hspace{1cm} \text{(S-OB)}

\[ p <: q \]

\(\text{p-Refl}\) \hspace{0.5cm} \(\text{p-Maybe}\) \hspace{0.5cm} \(\text{p-Inherit}\) \hspace{0.5cm} \(\text{p-IMaybe}\)

\(p <: p\) \hspace{0.5cm} \(\downarrow <: \circ\) \hspace{0.5cm} \(\downarrow <: \uparrow\) \hspace{0.5cm} \(\downarrow <: \circ\)

Figure 5.4: Algorithmic Subtyping

words in the dictionary.
Figure 5.5: The \( \text{inherit} \) Metafunction

### 5.4 Subtyping

This section presents algorithmic subtyping for \( \lambda^S \). Figure 5.4 is the entire algorithmic subtyping relation. We present fluid object types along with equirecursive \( \mu \)-types and bounded quantification (kernel rule). Some form of recursive type is necessary to type-check objects—we choose equirecursive \( \mu \)-types. Bounded quantification is commonly used to encode data structures; we also employ bounded quantification in our account of reflection. The majority of the algorithmic subtyping relation is conventional. The two interesting rules are S-Str and S-Ob.

Subtyping string types with S-Str uses pattern inclusion. For example, if patterns are defined as regular languages, inclusion is decidable. When patterns include variables, these inclusion constraints can be discharged by existing string solvers [47]. Discharging these patterns may require constraints on \( L \)-bounded type variables in \( \Gamma \). The appropriate \( \Gamma \) is always unambiguous from context, therefore we write \( L_1 \subseteq L_2 \) instead of \( \Gamma \vdash L_1 \subseteq L_2 \).

Algorithmic subtyping for objects, S-Ob, is a generalization of algorithmic subtyping of records. Recall that algorithmic subtyping for records combines the declarative width, depth, and permutation subtyping rules. S-Ob combines generalizations of depth, width, and permutation subtyping, in addition to a flattening rule for inherited fields. For object types, \( \Gamma \vdash S <: T \) if and only if they satisfy the four antecedents of S-Ob:

1. (Permutation and Depth) The types of fields with overlapping names must be subtypes. In addition, \( p <: q \) is a partial order on presence-annotations. Intuitively, \( p <: q \) means that \( T \) can “forget” that a field is definitely present.

2. (Width) The field patterns of \( S \) must include the field patterns of \( T \). Therefore, \( T \) can “hide” fields of \( S \).
3. (Depth) Any field that is absent (abs) in $S$ may be possibly absent (◦) or inherited (↑) in $T$.
This is depth subtyping for absent fields; $T$ can “forget” that a field is absent and introduce it with ◦ or ↑ annotations.

4. (Flattening) For an inherited field (↑) to appear on $T$, subtyping must ensure that the field is defined, with the appropriate type, somewhere on the inheritance chain of $S$. The metafunction $\text{inherit}$ calculates this type on $S$ and the pattern of the ↑-annotated field.

**Flattening**  When $\Gamma \vdash S <: T$, the subtype $S$ can describe the exact position of fields in the inheritance chain, e.g.

$$S = \{x^{↑} : \text{Num}, \text{parent}^{↑} : \{y^{↑} : \text{Str}, y : \text{abs}\}\}$$

However, $T$ may lose this information and flatten the type to

$$T = \{x^{↑} : \text{Num}, y^{↑} : \text{Str}\}$$

The purpose of $\text{inherit}$ (fig. 5.5) is to ensure that ↑-annotated fields are appropriately flattened in the supertype, $T$. For an object type $T$, $\text{inherit}_T(T, L_Q)$ calculates the join of all field on $S$ with patterns that may intersect $L_Q$, given constraints on $L$-bounded type variables in $\Gamma$. This includes all of the fields on the inheritance chain of $S$. Recall that fluid object types allow fields with the same pattern to have different types at different points in the inheritance chain. Consider the following type:

$$T = \{x^{↑} : \text{Num}, z^{↓} : \text{Num}, \text{parent}^{↓} : \{z^{↓} : \text{Bool}\}\}$$

With this definition of $T$, $\text{inherit}(T, x) = \text{Num}$ since indexing a $T$-typed object with “$x$” cannot produce the $\text{Bool}$-valued field in the parent. However, consider the slightly different type:

$$T' = \{x^{↑} : \text{Num}, x^{\circ} : \text{Num}, \text{parent}^{↑} : \{z^{↓} : \text{Bool}\}\}$$

\footnote{An omitted $\Gamma$ argument to $\text{inherit}$ denotes an empty type environment.}
In $T'$, since “$x$” may be absent ($\circ$) indexing may produce either “$x$” field. Therefore, \( \text{inherit}(T', "x") = \text{Num} \sqcup \text{Bool} \). Finally, consider the following type:

$$U = \{ "x^{\circ} : \text{Num} \}$$

In $U$, “$x$” may be absent, but $U$ does not specify the type of “parent”. It is thus unknown if “parent” exists, much less if it has a “$x$” field and what its type might be. Therefore, \( \text{inherit}(U, "x") \) is undefined. We can see this by looking at the definition of \( \text{inherit} \), specifically in defining $T_P$ for $U$ and “$x$”. The first case of $T_P$ does not apply, because the annotation on “$x$” is $\circ$, contradicting the side condition. The second case does not apply either, because there is no “parent” field on $U$.

\( \text{inherit} \) requires a join operator, $\sqcup$, over types. The join operator must satisfy:

$$\left( S \sqcup T = U \right) \Rightarrow (S <: U \land T <: U)$$

We elide the full definition; the interesting case is for object types:

$$\{ L_i^{p_i} : S_i, \cdots, L_A : \text{abs} \} \sqcup \{ M_j^{q_j} : T_j, \cdots, M_A : \text{abs} \}$$

Which is a pairwise intersections of patterns:

$$\left\{ \begin{array}{l}
(L_i \cap M_j)^{p_i\cup q_j} : S_i \sqcup T_j, \cdots, \\
(L_i \cap M_A)^{\circ} : S_i, \cdots, (L_A \cap M_j)^{\circ} : T_j, \cdots, \\
L_A \cap M_A : \text{abs}
\end{array} \right\}$$

For computing the join of the presence annotations $p_i \sqcup q_j$, we use the lattice induced by the $p <: q$ relation in fig. 5.4.

**Lemma 9 (Decidability of Subtyping)** If the functions and predicates on patterns (fig. 5.3) are decidable, then the subtype relation is finite-state.

**Proof:** By coinduction on the subtyping judgments.

---

$^a$The join operator, as presented, may introduce a number of $\emptyset$ field patterns. Inspection of the typing rules shows that empty patterns are inconsequential.
\[
\begin{align*}
ty(num) &= \text{Num} & \nty(bool) &= \text{Bool} \\
\Gamma \vdash e : T
\end{align*}
\]

\[
\begin{array}{c}
\Gamma \vdash e : S \\
\Gamma \vdash S <: T
\end{array}
\quad
\Gamma \vdash e : T
\]

\[
\begin{array}{c}
\Gamma(x) = T \\
\Gamma \vdash x : T
\end{array}
\]

\[
\Gamma \vdash c : ty(c)
\]

\[
\begin{array}{c}
\Gamma, x : S \vdash e : T \\
\Gamma \vdash \text{func} \ (x : S).e : S \to T
\end{array}
\]

\[
\begin{array}{c}
\Gamma \vdash e_f : S \to T \\
\Gamma \vdash e_a : S
\end{array}
\quad
\Gamma \vdash e_f(e_a) : T
\]

\[
\begin{array}{c}
\Gamma, \alpha <: S \vdash e : T
\end{array}
\quad
\Gamma \vdash \Lambda \alpha <: S.e : \forall \alpha <: S.T
\]

\[
\begin{array}{c}
\Gamma \vdash e : \forall \alpha <: U.T \\
\Gamma \vdash S <: U
\end{array}
\quad
\Gamma \vdash e(S) : T[\alpha/S]
\]

\[
\begin{array}{c}
\Gamma \vdash e_1 : \text{Bool} \\
\Gamma \vdash e_2, e_3 : T
\end{array}
\quad
\Gamma \vdash \text{if} \ (e_1) \ e_2 \ \text{else} \ e_3 : T
\]

Figure 5.6: Typing Basics

5.5 Typing

Figure 5.6 presents the basic elements of the typing relation, which includes a conventional account of functions and bounded quantification. The interesting typing rules are in fig. 5.7 and discussed below.

T-Str is the typing rule for string literals, which ascribes a string \(\text{str}\) the singleton \(L\)-type \(\{\text{str}\}\).

T-Str+ concatenates two string patterns.

T-Object is the typing rule for object literals. In an object literal, all fields are definitely present \((\text{str}^+)\) and all field names are statically known. Thus, each field name is a singleton \(L\)-type. In addition, since the object has no more fields, the complement of its fields is definitely absent \((\star : \text{abs})\).
Typing Reflection  T-HasField-Split is a simple if-splitting rule that accounts for the use of reflection in the conditional, and refines the types of \( o \) and \( f \) in the true-branch when the check succeeds. There are various sophisticated if-splitting techniques for typing complex conditionals and
control including flow typing, which is presented in this dissertation (chapter). T-HasField-Split could be adapted to the aforementioned systems.

T-HasField-Split introduces a new type variable $\alpha$ in the true branch, bounded by $\alpha <: L$, as the type of the string $f$. Using $\alpha$, it splits the type of pattern $L$, marking $\alpha$ as definitely present (↓) whereas $L \cap \alpha$ remains possibly absent (◦). Therefore, an $\alpha[f]$ expression in the true branch has exactly the type $S$.

### 5.5.1 Soundness and Mutable State

We prove standard progress and preservation theorems for $\lambda^p_S$. The proofs are over an extended semantics with mutable references, reference types, and store typings. The presentation of fluid object types in this chapter omits references for clarity, but we account for state in our proofs and prototype implementation.

**Theorem 4 (Preservation)** If $\Sigma \vdash \sigma$, $\cdot \vdash e : T$, and $\sigma e \rightarrow \sigma'e'$, then there exists a $\Sigma'$, such that $\Sigma \subseteq \Sigma'$, $\Sigma' \vdash \sigma'$, and $\Sigma'; \cdot \vdash e' : T$.

**Theorem 5 (Progress)** $\Sigma \vdash \sigma$ and $\cdot \vdash e : T$ then either $e \in v$ or there exist $\sigma'$ and $e'$ such that $\sigma e \rightarrow \sigma'e'$.

### 5.6 Implementation

Our type-checker for JavaScript uses fluid object types to type-check objects. The core language of the type-checker is $\lambda^p_S$, which is closely related to $\lambda^p_{ob}$, which is presented in this chapter. Therefore, the implementation is essentially a direct encoding of the material in this chapter.

**Pattern Representations** We use two representations for string patterns: finite sets of strings and finite automata. For finite automata, we use the representation and decision procedure of Hooimeijer and Weimer [48]. Their implementation is fast and based on mechanically proven principles. A thin wrapper transparently converts patterns represented as sets to equivalent finite automata when necessary. The representation of patterns is thus fully abstract to the type-checker.

---

This single typing rule is adequate for type-checking, but the proof of preservation requires auxiliary rules in the style of Typed Scheme [86].
Type-Checking Experiments  We type-check the $\lambda_{SB}^{ab}$ examples in this chapter, various other $\lambda_{SB}^{ab}$ benchmarks, and 7,000 lines of JavaScript code. The JavaScript code we type-check consist of two suites of programs:

- 11 Google Chrome Experiments and Google Gadgets (chapter 7), and
- The ADsafe runtime and various sample ADsafe widgets (chapter 8).

We make two observations about typing objects in JavaScript.

- JavaScript programs heavily manipulate the DOM, which is a massive, object-oriented API with functions and objects for manipulating HTML, CSS, local storage, the canvas, etc. These APIs are specified in various IDL files, which are a type-like interface definitions. We process 4,000 lines of IDL to build a type environment of object types for Web applications.
- In chapter 8, we present a type-based approach for language-based Web sandboxes. Fluid object types are instrumental for this verification; they are needed to describe the interfaces of Web sandboxes.

Performance  Subtyping patterns (fig. 4.4) and type well-formedness (fig. 5.2) suggest two possible performance bottlenecks: both require pairwise pattern intersection checks and subtyping requires pattern inclusion checks, which are reducible to pattern intersection. Finite automata intersection takes exponential time and it is easy to construct synthetic examples that demonstrate the worst-case time complexity of subtyping. Fortunately, we have reason to believe that realistic programs work with a small collection of “interesting” patterns; most patterns are constant strings. The only interesting pattern in the JavaScript standard library is for array indices. ADsafe and Google Caja, discussed above, have two and eight patterns respectively. We test our implementation with patterns from the aforementioned systems. On these patterns, our type-checker is fast; it runs various benchmarks in approximately one second on an Intel Core i5 processor.

5.7 Related Work

Our work builds on the long history of semantics and types for objects and recent work on semantics and types for scripting languages.

[10] www.w3.org/TR/WebIDL
Semantics of Scripting Languages  There are various semantics for scripting languages (chapter 2 and 34, 58, 79) that model each language in detail. This chapter focuses on type-checking a core calculus of objects and elides many features and details of individual scripting languages. Our semantics also abstracts the plethora of string-matching operations available in real scripting languages into a single pattern matching construct, and makes object-reflection manifest for type-checking.

Extensible Records  The representation of objects in $\lambda^b_S$ is derived from extensible records, surveyed by Fisher and Mitchell [28] and Bruce, et al. [13]. Wand presents a type inference algorithm for objects encoded as records [89]. Unlike these languages, field names in $\lambda^b_S$ are first-class strings; $\lambda^b_S$ includes operators to enumerate over fields and test for the presence of fields, since these are typical of scripting languages. Our fluid object types account for these features using presence-annotations and field-name patterns that are related to types for scripting languages, discussed below.

Types and Contracts for Untyped Languages  There are various type systems retrofitted onto untyped languages. We discuss those that support objects.

Strongtalk [12] is a typed dialect of Smalltalk that uses protocols to describe objects. Field patterns can describe more ad hoc objects than the protocols of Strongtalk, which are a finite enumeration of fixed names. Strongtalk protocols may include a brand; they are thus a mix of nominal and structural types. In contrast, fluid object types are purely structural, though we do not anticipate any difficulty incorporating brands.

Our work shares features with various JavaScript type systems. In the type system of Anderson, et al. [5], objects’ fields may be potentially present; it employs strong updates to turn these into definitely present fields. Recency types [43] support field type-changes during initialization. Zhao’s type system [95] also allows unrestricted object extension, but omits prototypes. In contrast to these works, our fluid object types do not support strong updates. We instead allow possible-absent fields to turn into definitely-present fields via reflection, which they do not support. Strong updates would be fruitful to type initialization patterns. In these type systems, field names are first-order labels. Thiemann’s [83] type system for JavaScript allows first-class strings as field names, which we generalize to field patterns. In addition, we allow inheritance chains to be precisely typed by...
distinguishing possibly-inherited fields from fields that are immediately present. These are useful for typing features of scripting languages (section 5.2).

RPython [4] compiles Python programs to efficient byte-code for the CLI and the JVM. Dynamically updating Python objects cannot be compiled. Thus, RPython stages evaluation into an interpreted initialization phase, where dynamic features are permitted, and a compiled running phase, where dynamic features are disallowed. Our types give guarantees without staging restrictions.

DRuby [33] does not account for reflection in general. However, as a special case, An, et al. [3] build a type-checker for Rails-based Web applications that partially-evaluates dynamic operations, producing a program that DRuby can verify. In contrast, our types tackle reflection directly.

System D [16] uses dependent refinements to type dynamic dictionaries. Fluid object types can type-check dictionaries as a special case of objects; we also account for inheritance, recursive objects and imperative state. System D accounts for richer control-dependent type reasoning than the single if-splitting rule presented in this chapter. However, chapter 4 accounts for control and state based type reasoning using other techniques. The authors of System D suggest integrating a string decision procedure to reason about dictionary keys. We use DPRLE [48] to support exactly this style of reasoning.

Heidegger, et al. [42] present dynamically-checked contracts for JavaScript that use regular expressions to describe objects. Our implementation uses regular expressions for static checking.

**Regular Expression Types** Regular tree types and regular expressions can describe the structure of XML documents (e.g., XDuce [49]) and strings (e.g., XPerl [81]). These languages verify XML-manipulating and string-processing programs. Our type system uses patterns not to describe trees of objects like XDuce, but to describe objects’ field names. Our string patterns thus allow individual objects to have semi-determinate shapes. Like XPerl, field names are simply strings, but our strings are used to index objects, which are not modeled by XPerl.
Chapter 6

Assisted Type Refactoring

In the next chapter, we evaluate our JavaScript type-checker on a body of third-part code. However, manually type-refactoring programs is labor-intensive. Therefore, this chapter presents a type-refactoring tool that uses dynamic analysis to infer many annotations\footnote{1}. We employed this tool produce the results in chapter 7.

6.1 Approximating Types by Runtime Instrumentation

Refactoring a large, untyped program to use types is too costly to do at once. Therefore, there are various mechanisms that enable typed and untyped code to interoperate in a single program \cite{29, 85, 92}. We adapt Typed Racket’s mechanisms for interoperability \cite{85}. Since JavaScript does not have modules, we encapsulate typed code in a closure, effectively creating programs with just two modules.

However, merely enabling typed and untyped code to interoperate does not help programmers refactor their code for types. To inject type-annotations into untyped code in any programming language, programmers have to do the following:

- They have to identify the program fragment that they want to make type-safe.
- They have to add type annotations to the fragment, and they have to change code to appease the type-checker.

\footnote{1This chapter is based on joint work with Claudiu Saftoiu \cite{76}.}
Finally, they have to write type annotations for all the untyped free identifiers in the fragment. These tasks can be daunting. They are particularly difficult when the programmer doing the type-refactoring is not the original author. They’re harder still when the program is poorly documented. Because we evaluate our work on various third-party programs found on the Web, we encountered these problems ourselves.

Type inference is a possible solution. For Standard ML, inference is particularly convenient because inference computes principal types. However, principal types aren’t necessary and inference need not even be sound, so long as we type-check after inference.

We have built a tool that infers (possibly unsound) type annotations by runtime instrumentation [67]. From the programmer’s perspective, the tool displays a window with currently computed type annotations. As the program runs and control-paths are exercised, the annotations “grow”. At any point, the programmer can conclude that the program has been exercised enough and stop execution. Our tools insert the computed types into the original source. The programmer can then try to type-check the program. Even when the computed annotations are insufficient, they are never entirely wrong, since they’re based on values observed at runtime. They help a maintenance programmer get started on the task of type-refactoring.

The instrumentation builds an abstract heap, mapping labeled functions to abstract values. The instrumentation records sets of abstract arguments and results of these labeled functions. Constants are abstracted to their runtime tags, objects are abstracted by abstracting their fields, and functions
are abstracted to their labels. We map the abstract heap to a collection of types in a natural way. Runtime tags map to types, abstract objects map to object types, multiple abstract values in a single set map to a union type, and function labels $l$ map to the type annotation of the function $l$.

In chapter 7 we use this tool to automatically generate type annotations for third-party JavaScript programs. Many of these programs are undocumented, and the generated type annotations make type-refactoring much easier.

\footnote{We signal an error on cycles, though self-application does not occur in practice.}
Chapter 7

Evaluation I: Documentation

This and the next chapter evaluate our JavaScript type-checker on a body of third-party code. In this chapter, we present our experience type-refactoring 15 small programs that were authored by different programmers. We demonstrate that some of this code is awful and undocumented. Once typed, the type annotations become a form of provably correct documentation for these programs. This chapter thus demonstrates that our types are an effective way to document JavaScript code.

7.1 Type-Checking Gadgets and Chrome Experiments

We evaluate our work by fully type-refactoring an assortment of Chrome Experiments and Google Desktop Gadgets. These programs are written by several authors and employ many different programming styles. Many are a number of years old and have little or no documentation. Type-refactoring these programs demonstrates that our type-checker admits several programming styles. Note that these are all small programs that one could simply rewrite in a new typed programming language. When programs grows by a few orders of magnitude, rewriting becomes harder and type-refactoring becomes more relevant. Due to a lack of resources, we have not tried to type-refactor larger JavaScript programs.

Figure 7.1 lists these programs and information that we discuss below. In all cases, we first ran our inference tool (section 6.1) to generate annotations. The columns labeled “Type Annotations” state the number of annotations correctly inserted by the tool described in chapter 6 (Auto) and the

---

1This chapter is based on joint work with Claudiu Saftoiu [76].
2www.chromeeperiments.com and desktop.google.com
number that need to be edited or inserted manually (Manual). As the table shows, our 4,500-line codebase requires only 25 manual annotations.

In addition to annotations, a retrofitted type system requires refactorings. Some refactorings expose weaknesses—a static type system cannot account for all legitimate untyped code (the “Problems” column). Other refactorings expose bugs and features that the type system willfully eliminates (the “Fixes” column). Each of these refactorings required approximately one line. Therefore, we changed 6.7% of the lines of code.

The following are a representative sample of programming patterns we willfully eliminate and count as Fixes:

- DOM callbacks that do not use their argument are often written without formal arguments. We signal type errors on arity-mismatches (with the exception of the kinds shown in section 4.1.1).
- We require all identifiers to be statically bound (e.g., 59 of the refactorings in “topten” occur because the program does not use `var` to declare variables).
- Some functions, e.g., `setTimeout`, can take either a string that is eval’d or a function as an argument. To improve program security, we disallow strings as arguments to `setTimeout`.
- It is possible to apply arithmetic operators to arbitrary objects. For example, “watchimer”

<table>
<thead>
<tr>
<th>Program</th>
<th>LOC</th>
<th>Refactorings</th>
<th>Annotations</th>
</tr>
</thead>
<tbody>
<tr>
<td>analogclock</td>
<td>112</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>animation</td>
<td>70</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>burncanvas</td>
<td>157</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>catchit</td>
<td>165</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>countdown</td>
<td>129</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>hashapass</td>
<td>257</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>light</td>
<td>151</td>
<td>8</td>
<td>19</td>
</tr>
<tr>
<td>metronome</td>
<td>106</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>morse</td>
<td>275</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>resistor</td>
<td>591</td>
<td>18</td>
<td>2</td>
</tr>
<tr>
<td>rsi</td>
<td>328</td>
<td>0</td>
<td>27</td>
</tr>
<tr>
<td>text2wav</td>
<td>488</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>topten</td>
<td>443</td>
<td>67</td>
<td>0</td>
</tr>
<tr>
<td>watertype</td>
<td>284</td>
<td>13</td>
<td>36</td>
</tr>
<tr>
<td>watchimer</td>
<td>947</td>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td>TOTAL</td>
<td>4503</td>
<td>156</td>
<td>148</td>
</tr>
</tbody>
</table>

Figure 7.1: Annotation overhead on JavaScript code
subtracts dates, since their `valueOf` method returns a number (UNIX time). We require arithmetic operators (excluding `*`) to receive numeric operands. Therefore, we refactor the program to explicitly call `valueOf`.

We easily account for some of the patterns above. However, by rejecting them, our type-checker makes JavaScript behave more like a “normal” programming language. Furthermore, many of these decisions reflect matters of taste, and can easily be reversed to produce a slightly different type-checker. Indeed, when we type-check ADsafe in chapter 8, we need to disable these checks and admit runtime errors (section 8.8).

The refactorings labeled “Problems” expose some trivial implementation omissions that could be addressed with a little more work, as well as some deeper deficiencies in our type system:

- A pattern seen with callbacks is to declare a variable (e.g., `var x = undefined`) outside and initialize it (e.g., `x = 10`) inside the callback. In such cases, neither typing nor flow-analysis can deduce that `x : Num`. We typically refactor the declaration (e.g., `var x = -1`).
- The `getElementById` function can return arbitrary HTML elements on the page, so its return type is `HTMLElement`, the type of all elements. However, “catchit” uses `getElementById` to access a `<canvas>`, which has drawing methods. In such cases, we insert a downcast (checked by a contract). A richer type system for the DOM could eliminate these refactorings [84].
- “countdown” initializes an empty object literal, then incrementally adds fields. We do not support this pattern, since our flow analysis is agnostic to objects. However, this pattern is addressed by recency types [43].
- There are various syntactic patterns that our type checker does not accommodate. For example, we do not account for functions that are lifted arbitrarily, we require arrays literals instead of supporting `new Array()`, etc. With a little more elbow-grease, we could add support for these features in our type system.

As the table shows, most problems occur in just a few programs. These refactorings could be addressed by enriching the type system. Alternatively, since many of the refactorings are mechanical, a tool could refactor them, keeping the type system simple. Type system simplicity matters when types are used as documentation.
Chapter 8

Evaluation II: Security

This chapter presents a type-based technique for verifying language-based Web sandboxes. In particular, we detail our verification of the ADsafe Web sandbox. In the previous chapter, we used types to document programs. In this chapter types also specify security properties. We use types in two very distinct ways:

- We annotate and type-check the 2.5 KLOC ADsafe runtime library. In contrast, the previous chapter type-checks a collection of programs. Our experience supports folklore that library code is very different from program code. The ADsafe library makes heavier use of type abstraction and reflection. Type-checking revealed several bugs in the ADsafe library.

- We also use types to generate a safe sub-language of JavaScript, following the recipe in section 3.4. Unlike that chapter, the sub-language generated in this chapter is not a toy, but a generalization of ADsafe’s existing, ad hoc JavaScript sub-language. The generated sub-language had one discrepancy, which turned out to be a bug in ADsafe’s sub-language.

We briefly mentioned language-based Web sandboxing chapter 3. This chapter begins detailing what they do and how they work.

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1 This chapter is based on joint work with Spiridon Aristides Eliopoulos and Joe Gibbs Politz [72].
8.1 Mashups

A *mashup* is a Web page that displays content and executes JavaScript code from various untrusted sources. Facebook applications, gadgets on the iGoogle homepage, and various embedded maps are prominent examples of mashups. Moreover, Web pages that display advertisements from ad networks are also mashups; ads often employ JavaScript for animations and interactivity. A survey of popular pages shows that a large percentage of them include scripts from a diverse array of external sources [94]. Unfortunately, these third-party scripts run with the same privileges as trusted, first-party code served directly from the originating site. Hence, the trusted site is susceptible to attacks by maliciously crafted third-party software.

To address this threat, various organizations have developed *language-based Web sandboxes*. These sandboxes all have similar high-level goals and designs, which we outline in section 8.2. In section 8.3 we review the design and implementation of sandboxes and demonstrate the need for tool-supported verification. Section 8.4 provides a detailed plan for the rest of this chapter.

8.2 Language-based Web Sandboxing

The Web browser environment provides references to objects that implement network access, disk storage, geolocation, and other capabilities. Legitimate web applications use them for various reasons, but embedded widgets can exploit them because all JavaScript on a page runs in the same global environment. A Web sandbox thus attenuates or prevents access to these capabilities, allowing
pages to safely embed untrusted widgets. ADsafe [18], Caja [66], FBJS [25], and BrowserShield [73] are language-based sandboxes that employ broadly similar security mechanisms, as explained by Maffeis, et al. [59]:

- A Web sandbox includes a static code checker that filters out certain widgets that are almost certainly unsafe. This checker is run before the widget is delivered to the browser.

- A Web sandbox provides runtime wrappers that attenuate access to the DOM and other capabilities. These wrappers are defined in a trusted runtime library that is linked with the untrusted widget.

- Static checks are necessarily conservative and can reject benign programs. Web sandboxes thus specify how potentially-unsafe programs are rewritten to use dynamic safety checks.

This architecture is illustrated in fig. 8.1, where an untrusted widget from [adnet.com] is embedded in a page from [paper.com]. The untrusted widget is filtered by the static checker. If static checking passes, the widget is rewritten to invoke the runtime library. Both the runtime library and the checked, rewritten widget must be hosted on a site trusted by [paper.com] and are assumed to be free of tampering.

Reference Monitors  A Web sandbox implements a reference monitor between the untrusted widget and the browser’s capabilities. Anderson’s seminal work on reference monitors identifies their certification demands [6, p 10-11]:

The proof of [a reference monitor’s] model security requires a verification that the modeled reference validation mechanism is tamper resistant, is always invoked, and cannot be circumvented.

Therefore, a Web sandbox must come with a precisely stated notion of security, and a proof that its static checks and runtime library correctly maintain security. The end result should be a quantified claim of safety over all possible widgets that execute against the runtime library.

8.3 Code-Reviewing Web Sandboxes

Imagine we are confronted with a Web sandbox and asked to ascertain its quality. One technique we might employ is a code-review. Therefore, we perform an imaginary review of a Web sandbox,
focusing on the details of ADsafe. We then discuss how to (mostly) remove people from the loop.

ADsafe, like all Web sandboxes, consists of two interdependent components:

- a static verifier, called JSLint\(^2\) which filters out widgets not in a safe subset of JavaScript, and
- a runtime library, adsafe.js, which implements DOM wrappers and other runtime checks.

These conspire to make it safe to embed untrusted widgets, though “safe” is not precisely defined. We will return to the definition of safety in section \[8.4\]

**Attenuated Capabilities** Widgets should not be able to directly reference various capabilities in the browser environment. Direct DOM references are particularly dangerous because, from an arbitrary DOM reference, \(elt\), a widget can simply traverse the object graph and obtain references to all capabilities:

```javascript
var myWindow = elt.ownerDocument.defaultView;
myWindow.XMLHttpRequest;
myWindow.localStorage;
myWindow.geolocation;
```

Widgets therefore manipulate wrapped DOM elements instead of direct references. DOM wrappers form the bulk of the runtime library and include many dynamic checks and patterns that need to be verified:

- The runtime manipulates DOM references, but returns them to the widget in wrappers. We must verify that all returned values are in fact wrapped, and that the runtime cannot be tricked into returning a direct DOM reference.

- The runtime calls DOM methods on behalf of the widget. Many methods, such as `appendChild` and `removeChild`, require direct DOM references as arguments. We must verify that the runtime cannot be tricked with a maliciously crafted object that mimics the DOM interface and steals references.

- The runtime attaches DOM callbacks on behalf of the widget. These callbacks are invoked by the browser with event arguments that include direct DOM references. We must verify that the runtime appropriately wraps calls to untrusted callbacks in the widget.

\(^2\)The reader may know that JSLint also performs simple “linting” checks in addition to checks for ADsafe. We only consider JSLint with ADsafe checks enabled.
• The widget has access to a DOM subtree that it is allowed to manipulate. The runtime ensures that the widget only manipulates elements in this subtree. We must verify that various DOM traversal methods, such as `document.getElementById` and `Element.parentNode`, do not allow the widget obtain wrappers to elements outside its subtree.

• The runtime wraps many DOM functions that are only conditionally safe. For example, `document.createElement` is usually safe, unless it is used to create a `<script>` tag, which can load arbitrary code. Similarly, the runtime may allow widgets to set CSS styles, but a CSS URL-value can also load external code. We must verify that the arguments supplied to these DOM functions are safe.

ADsafe’s DOM wrappers are called *Bunches*, which wrap collections of HTML elements. There are twenty Bunch-manipulating functions that are exposed to the widget—in addition to several private helper functions—that face all the issues enumerated above and need to be verified. These functions cannot be verified in isolation, because their correctness is dependent on assumptions about the kinds of values they receive from widgets. These assumptions are discharged by the static checks in JSLint and other runtime checks to avoid loopholes and complexities in JavaScript’s semantics.

**JavaScript Semantics** Web sandboxes also contend with JavaScript features that hinder security:

• Certain JavaScript features are unsafe to use in widgets. For example, a widget can use `this` to obtain `window`, so it is rejected by JSLint:

  ```javascript
  f = function() { return this; };
  var myWindow = f();
  ```

  We must verify that the subset of JavaScript admitted by the static checker does not violate the assumptions of the runtime library.

• Many JavaScript operators and functions include implicit type conversions and method calls that are difficult to reason about. For example, when an operator expects a string but is instead given an object, it does not signal an error. Instead, it calls the object’s `toString` method. It is easy to write a stateful `toString` method that returns different strings on different calls. Such an object can then circumvent dynamic safety checks that are not carefully written to avoid triggering implicit method calls. These implicit calls are avoided by carefully testing
the runtime types of untrusted values, using the `typeof` operator. Such tests are pervasive in ADsafe. As a further precaution, ADsafe tries to ensure that widgets cannot define `toString` and `valueOf` fields in objects.

Chapter 2 catalogs these and other JavaScript quirks that can confound the most experienced programmers. Indeed, the bugs we discover (section 8.9) are not deep design errors, but bugs in code to workaround JavaScript’s semantic quirks.

**JavaScript Encapsulation** JavaScript objects have no notion of private fields. If object operations are not restricted, a widget could access built-in prototypes (via the `__proto__` field) and modify the behavior of the container. Web sandboxes statically reject such expressions:

```
obj.__proto__;
```

There are various other dangerous fields that are also blacklisted and hence rejected by sandboxes. However, syntactic checks alone cannot determine whether computed field names are unsafe:

```
obj["__pro" + "to__"];
```

Widgets are instead rewritten to use runtime checks that restrict access to these fields. Figure 8.2 shows the rewrites employed by various sandboxes. Some sandboxes insert these and other checks automatically, giving the illusion of programming in ordinary JavaScript. ADsafe requires widget authors to insert the dynamic checks themselves, but the principle remains the same.

Web sandboxes use this method to also simulate private fields. For example, ADsafe stores direct DOM references in the `__nodes__` field of Bunches, and blacklists the `__nodes__` field.

**The Reviewability of Web Sandboxes**

We have highlighted a plethora of issues that a Web sandbox must address, with examples from ADsafe. Although ADsafe’s source follows JavaScript “best practices,” the sheer number of checks and abstractions make it difficult to review. There are approximately 50 calls to three kinds of
runtime assertions, 40 type-tests, 5 regular-expression based checks, and 60 DOM method calls in
the 1,800 LOC adsafe.js library. Various ADsafe bugs were found in the past and this chapter
presents a few more (section 8.9). Note that ADsafe is a small Web sandbox relative to larger
systems like Caja.

The Caja project asked an external review team to perform a code review [7]. The findings
describe many low-level details that are similar to those we discussed above. In addition, two
higher-level concerns stand out:

• “[Caja is] hard to review. No map states invariants and points to where they are enforced,
which hurts maintainability and security.”

• “Documentation of TCB is necessary for reviewability and confidence.”

These remarks identify an overarching requirement for any review: the need for specifications.
Specifications tell us if the system intends to meet our needs. In addition, they help us determine if
the implementation is correct.

8.4 Verifying a Sandbox: Our Roadmap

Defining Safety  Because humans are expensive and error-prone, and because the code review
needs to be repeated every time the program changes, it is best to automate the review process.
However, before we begin automating anything, we need some definition of what security means. We
focus on a definition that is specific to ADsafe, though the properties are similar to the goals of other
web sandboxes. From correspondence with ADsafe’s author, we initially obtained the following list
of intended properties (rewritten slightly to use the terminology of this chapter).

Definition 2 (ADsafety)  If the containing page does not augment built-in prototypes, and all em-
bedded widgets pass JSLint, then:

1. widgets cannot load new code at runtime, or cause ADsafe to load new code on their behalf;

2. widgets cannot affect the DOM outside of their designated subtree;

3. widgets cannot obtain direct references to DOM nodes; and

4. multiple widgets on the same page cannot communicate.
Note that the first two properties are common to sandboxes in general—allowing arbitrary JavaScript to load at runtime compromises all sandboxes’ security goals, and all sandboxes provide mediated access to the DOM by preventing direct access.

We also note that the assumption about built-in prototypes is often violated in practice. Nevertheless, like ADsafe, we make this assumption; mitigating it is outside our scope. Given this definition, our goal is to produce a (mostly) automated verification that supports these properties.

**Verifying Safety** We employ the general purpose JavaScript type-system developed for this dissertation to define and verify ADsafety. Type-checking is well-suited for this task for several reasons. We choose a static type system as our tool of choice for several reasons. First, programmers are familiar with type systems, and ours is mostly standard (the novelties are detailed in chapters 4 and 5). This lessens the burden on sandbox developers who need to understand what the verification is saying about their code. Second, our type system is much more efficient than most whole-program analyses or model checkers, leading to a quick procedure for checking ADsafe’s runtime library (20 seconds). Efficacy and understandability allow for incremental use in a tight development loop. Finally, our type system is accompanied by a soundness proof. This property accomplishes the actual verification. Thus, the features of comprehensibility, efficiency, and soundness combine to make type checking an effective tool for verifying some of the properties of web sandboxes.

In order to demonstrate the effectiveness of our type-based verification approach, we use type-based arguments to prove an ADsafety theorem. We mostly achieve this (section 8.8) after fixing bugs exposed by our type checker (section 8.9). The rest of this chapter presents a typed account of untrusted widgets and the ADsafe runtime.

- The ADsafety claim is predicated on widgets passing the JSLint checker. Therefore, we need to model JSLint’s restrictions. We do this in section 8.5.
- Once we know what we can expect from JSLint, we can verify the actual reference monitoring code in `adsafe.js` using type-checking (section 8.7).
- Before we can verify `adsafe.js`, we need to account for the details of JavaScript source and model the browser environment in which this code runs. \( \lambda_{JS} \) (chapter 2) tackles most of these details; we discuss its application in section 8.6.

We discuss extensions to verify other Web sandboxes in section 8.10.
8.5 Modeling Secure Sublanguages

All web sandboxes’ runtime libraries expect to execute against widgets that have been statically checked and rewritten, as shown in fig. 8.1. These checks and rewrites enforce that widgets are written in a sublanguage of JavaScript. This sublanguage ought to be specified explicitly. We focus here on modeling the checks performed by JSLint, ADsafe’s static checker, which presents an interesting challenge: there is no formal specification of the language of JavaScript programs that pass JSLint. Instead, the specification is implicit in the implementation of JSLint itself. In this section, we develop a specification of JSLint-ed widgets.

Only a fraction of JSLint’s static checks are related to ADsafe. The rest are lint-like code-quality checks. JSLint also checks the static HTML of a widget. Verifying this static HTML is beyond the scope of our work; we do not discuss it further. We instead focus on the security-critical static JavaScript checks in JSLint.

How is JSLint used? The ADsafe runtime makes several assumptions about the shape of values it receives from widgets. These assumptions are not documented precisely, but they correspond to various static checks in JSLint. To model JSLint, we reflect these checks in a type, called Widget, which we define below. In section 8.5.2 we discuss how this type relates to the behavior of the JSLint implementation.

8.5.1 A Type for Widgets

We expect that all variables and sub-expressions of widgets are typable as Widget. The ADsafe runtime can thus assume that widgets only manipulate Widget-typed values.

Primitives JSLint admits JavaScript’s primitive values, with trivial types:

\[ \text{Prim} = \text{Num} \cup \text{Str} \cup \text{True} \cup \text{False} \cup \text{Null} \cup \text{Undef} \]

We have separate types for True and False because they are necessary to type-check adsafe.js (section 8.7). Prim is an untagged union type, and our type system accounts for common JavaScript

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3Because we want a strategy that extends to other sandboxes, we do not try to exploit the fact that JSLint is written in JavaScript. The Cajoler of Caja is instead written in Java, and the filters and rewriters for other sandboxes might be written in other languages. The strategy we outline here avoids both getting bogged down in the details of all these languages as well as over-reliance on JavaScript itself.
patterns for discriminating unions. We might initially assume that

\[ \text{Widget} = \text{Prim} \]

**Objects and Blacklisted Fields**  JSLint admits object literals but blacklists certain field names as dangerous. All other fields are allowed to contain widget values. We therefore augment the `Widget` type to include objects. We use *fluid object types* (chapter 5) to describe these objects:

\[ \text{Widget} = \mu x. \text{Prim} \cup \text{Ref} \]

\[
\left\{ \begin{array}{c}
"\text{toString}"","\text{valueOf}" , \\
"\text{arguments}"","\text{caller}"","\text{callee}" , \\
\{"\text{toString}"","\text{valueOf}"\} : \text{abs}
\end{array} \right. \]

The type above states that object literals may not have the fields "toString" and "valueOf". A tlint-typed object may contain any `Widget`-typed field, except those in the explicitly blacklisted: all fields that begin and end with two underscores, and a small, fixed collection of fields.

**Functions** Widgets can create and apply functions, so we must widen our `Widget` type to admit them. Functions in JavaScript are objects with an internal `code` field, which we add to allowed objects:

\[
\ldots \text{Ref} \left\{ \begin{array}{c}
\text{code} : \text{Global} \cup x \times x \cdots \rightarrow x , \\
\ldots
\end{array} \right. \]

The type of the `code` field indicates that widget-functions may have an arbitrary number of `Widget`-typed arguments and return `Widget`-typed results\footnote{The $\alpha \cdots \alpha$ syntax is a literal part of the type, and means the function can be applied to any number of additional $\alpha$-typed arguments. This is *uniform variable-arity polymorphism* \cite{80}.}. It also specifies that the type of the implicit `this`-argument (written inside brackets) may be either `Widget` or `Global`. The type `Global` is not a subtype of `Widget`, which expresses the underlying reason for JSLint’s rejection of all widgets that contain `this` (see Claim 1 below). If the `this`-annotation is omitted, the type of `this` is $\top$.

**Prototypes** JSLint does not allow widgets to explicitly manipulate objects’ prototypes. However, since field lookup in JavaScript implicitly accesses the prototypes, we specify the type of prototypes
Typing Private Fields  Widgets cannot create fields that begin and end with underscores. However, ADsafe uses some of these fields itself as private fields to build the Bunch abstraction:

\[
\ldots \text{Ref}\{\begin{array}{l}
"__proto__" : Object \cup \text{Function} \cup \ldots,
\ldots
\end{array}\}
\]

Notably the type of "__nodes__" Array(HTML) \cup \text{Undef} is not a subtype of Widget, so widgets themselves cannot access it.

The proto field enumerates several safe prototypes, but notably omits DOM prototypes such as HTMLElement, since widgets should not obtain direct references to the DOM.

The full Widget type in fig. 8.3 is a formal specification of the shape of values that adsafe.js receives from and sends to widgets. This type is central to our verification of adsafe.js and of JSLint.

8.5.2 Widget and JSLint Correspondence

Though we have offered intuitive arguments for why Widget corresponds to the checks in JSLint, we would like to gain confidence in its correspondence with the behavior of the actual JSLint program.
that sites use:

**Claim 3 (Linted Widgets Are Typable)** *If JSLint (with ADsafe checks) accepts a widget e, then e and all of its variables and sub-expressions can be Widget-typed.*

We validate this claim by testing. We use ADsafe’s sample widgets as positive tests—widgets that should be typable and lintable—and our own suite of negative test cases (widgets that should be untypable and unlintable).[5] Note the direction of the implication: an unlintable widget may still be typable, since our type checker admits safe widgets that JSLint rejects[6] The type checker could be used as a replacement for JSLint’s ADsafe checks, but these tests give us confidence that checking the Widget type corresponds to what JSLint admits in practice.

### 8.6 Modeling JavaScript and the Browser

Verification of a Web sandbox must account for the idiosyncrasies of JavaScript. It also needs to model the run-time environment—provided by the browser—in which the sandboxed code will execute. Here we discuss how we model the language and the browser.

**JavaScript Semantics** We use $\lambda_{JS}$ (chapter 2), which reduces JavaScript to a core semantics, which omits many of JavaScript’s complexities. As chapter 2 explains, $\lambda_{JS}$ is accompanied by a desugaring function that maps all JavaScript programs (idiosyncrasies included) to behaviorally equivalent $\lambda_{JS}$ programs. The transformation explicates much of JavaScript’s implicit semantics. Hence, we find it easier to build tools that analyze the much smaller $\lambda_{JS}$ language than to directly process JavaScript. Section 2.2 argues that the translation to $\lambda_{JS}$ is adequate by testing it against real world implementations. This testing strategy, and the simplicity of implementation that $\lambda_{JS}$ enables, give us confidence that our tools correctly account for JavaScript.

**Modeling the Browser DOM** ADsafety claims that `window.eval` is not applied. To validate this claim, the environment does not ascribe a type to `eval` and related functions such as `document.write`. Finally, certain functions, such as `setTimeout`, behave like `eval` when given strings as arguments. ADsafe does need to call these functions, but it is careful to never call them with strings. In our type environment, we give them restrictive types that disallow string arguments.

---

[6]Appendix A.1 has examples of the differences.
Figure 8.4: A Fragment of the Type of `window`

```javascript
var dom = {
  append:
    function(bunch)
    /*: [Widget ∪ Global]Widget × Widget ... → Widget */
    { // body of append ... },
  combine:
    function(array)
    /*: [Widget ∪ Global]Widget × Widget ... → Widget */
    { // body of combine... },
  q:
    function (text)
    /*: [Widget ∪ Global]Widget × Widget ... → Widget */
    { // body of q... },
    // ... more dom ...
};
```

Figure 8.5: Annotations on the `dom` object

Figure 8.4 specifies a fragment of the type of `window`, which carefully specifies the type of unsafe functions in the environment. The remaining safe DOM does not need to be fully specified. `adsafe.js` only uses a small subset of the DOM methods. These methods require types. The browser environment is therefore modeled with 500 lines of object types (appendix E). This type environment is essentially the specification of foreign DOM functions imported into JavaScript.

### 8.7 Verifying the Reference Monitor

In section 8.5, we discussed modeling the sublanguage of widgets interacting with the sandboxing runtime. In the case of ADsafe and JSLint, we built up the `Widget` type as a specification of the kinds of values that the reference monitor, `adsafe.js`, can expect at runtime. In this section, we discuss how we use the `Widget` type to model the boundary between reference monitor and widget code, and ensure that the runtime library correctly guards critical behavior.

The `Widget` type specifies the shape of widget values that the ADsafe runtime manipulates. `Widget` is therefore used pervasively in our verification of `adsafe.js`. For example, consider a typical Bunch method:
Bunch.prototype.append = function(child) {
    reject_global(this);
    var elts = child.__nodes__;
    ...
    return this;
}

The Bunch objects that ADsafe passes to the widget have Bunch.prototype as their proto (see fig. 8.3), making these methods accessible. Their use in the widget is constrained only by JSLint, so we must type-check these methods with (only) JSLint’s assumptions in mind.

For example, we might assume that the child argument above should be a Bunch, the implicit this argument should also be a Bunch, and it therefore returns a Bunch. However, JSLint does not provide such strong guarantees. Consider this example, which passes JSLint:

```javascript
var func = someBunch.append;
func(900, true, "junk", -7);
```

Here, this is bound to window, child is a number, and there are additional arguments. Therefore, we cannot assume that append has the type [Bunch]Bunch → Bunch. Instead, the most precise type we can ascribe is:

```javascript
[Widget ∪ Global]Widget ··· → Widget
```

That is, this could be Widget-typed or the type of the global object, Global, and the other arguments may have any subtype of Widget, which includes strings, numbers, and other non-Bunch types. The runtime check in append’s body (namely, reject_global(this)) is responsible for checking that this is not the global object before manipulating it. Our type checker recognizes such checks and narrows the broader type to Widget after appropriate runtime checks are applied. If such checks were missing, the type of this would remain Widget ∪ Global, and return this would signal a type error because Widget ∪ Global is not a subtype of the stated return type Widget.

Ascribing types to functions provided by the ADsafe runtime is therefore trivial. We give all the same type:

```javascript
[Widget ∪ Global]Widget ··· → Widget
```

The type checker we extend is not ADsafe-specific, and requires explicit type annotations. However, since all the annotations are identical, they are trivial to insert. Figure 8.5 shows a small excerpt
of such annotations, which the checker reads from comments, so programs can run unaltered in the browser.

**Types for Private Functions** ADsafe also has a number of private functions, which are not exposed to the widget. These functions have types with capabilities the widget does not have access to, such as HTML. For example, ADsafe specifies a `hunter` object, which contains functions that traverse the DOM and accumulate arrays of DOM nodes. These functions all have the type `HTML → Undef`, and add to an array `result` that has type `Array<HTML>`. ADsafe can freely use these capabilities inside the library as long as it doesn’t hand them over to the widget. Our annotations show that it doesn’t, because these types are not compatible with `Widget`.

**Type-Checking ADsafe** We type-check ADsafe using the JavaScript type-checker developed for this dissertation. ADsafe heavily exercises both flow typing (chapter 4) and fluid object types (chapter 5), the two type-checking innovations that we implement in the type-checker.

The `Widget`-type, which describes the reference monitor’s interface to widgets, evidently uses fluid object types. `Widget` is an untagged union, and within the reference monitor there are a number of runtime checks to discriminate `Widget`-typed values. These runtime checks ensure that protected objects—DOM objects and browser functions in ADsafe’s case—are only manipulated in safe and well-defined ways. For example, when `setTimeout`’s first argument is a string, rather than a function, it exhibits `eval`-like behavior, which violates ADsafety’s constraints. Thus we instead give it the type

$$(\text{Widget} → \text{Widget}) \times \text{Widget} → \text{Num}$$

Doing so forces the first argument to be a function and, in particular, not a string. Now consider its use:

```javascript
later: function (func, timeout)
/*: Widget × Widget → Widget */ {
  if (typeof func === "function") {
    setTimeout(func, timeout || 0);
  } else { error(); }
}
```

Because `ADSAFE.later` is exported to widgets, it can only assume the `Widget` type for its arguments, including `func`. A traditional type checker would thus conclude that `func` has type `Widget` everywhere
in `later`. Because `Widget` includes `Str`, the invocation of `setTimeout` would yield a type error—even though this is precisely what the conditional in `later` is avoiding!

This is an *if-splitting* pattern that we type-checking using flow typing (chapter 4) flow analysis. The analysis informs the type checker that due to the `typeof` check, uses of `func` in the `then`-branch of the conditional can in fact be *refined* from the large `Widget` type of `Str ∪ Num ∪ ...` to the function type that `setTimeout` requires.

### 8.7.1 Required Refactorings

Our type system cannot type check the ADsafe runtime as-is; we need to make some simple refactorings. The need for these refactorings does not reflect a weakness in ADsafe. Rather, they are programming patterns that we cannot verify with our type system. To gain confidence that we didn’t change ADsafe’s behavior, we run ADsafe’s sample widgets against our refactored version of ADsafe, and they behave as expected. We describe these refactorings below:

**Additional *reject_name* Checks**  
ADsafe uses `reject_name` to check accesses and updates to object properties in `adsafe.js`. If-splitting uses these checks to narrow string set types and type-check object property references. However, ADsafe does not use `reject_name` in every case. For example, it uses a regular expression to parse DOM queries, and uses the result to look up object properties. Because our type system makes conservative assumptions about regular expressions, it would erroneously indicate that a blacklisted field may be accessed. Thus, we add calls to `reject_name` so the type system can prove that the accesses and assignments are safe.

**Inlined *reject_global* Checks**  
Most Bunch methods start by asserting `reject_global(this)`, which ensures that `this` is `Widget`-typed in the rest of the method. Our type system cannot account for such non-local side-effects, but once we inline `reject_global`, if-splitting is able to refine types appropriately (for instance, in the `Bunch.prototype.append` example early in this section).

**makeableTagName**  
ADsafe’s whitelist of safe DOM elements is defined as a dictionary:

```javascript
var makeableTagName = {
    "div": true, "p": true, "b": true, ...
};
```
var reject_name = function (name) {
    return
        ((typeof name !== 'number' || name < 0) &&
         (typeof name !== 'string' ||
          name.charAt(0) === '_') ||
         name.slice(-1) === '_' ||
         name.charAt(0) === '-'))
    || banned[name];
};

function F() {} // only used below
ADSAFE.create =
    typeof Object.create === 'function'
? Object.create
: function(o) {
    F.prototype =
        typeof o === 'object' && o
    ? o : Object.prototype;
    return new F();
};

Figure 8.6: The Unverified Portion of ADsafe

This dictionary omits an entry for "script". The document.createElement DOM method creates new nodes. We ensure that <script> tags are not created by typing it as follows:

    document.createElement : ("script") → HTML

ADsafe uses its tag whitelist before calling document.createElement:

    if (makeableTagName[tagName] === true) {
        document.createElement(tagName);
    }

Our type checker cannot account for this check. We instead refactor the whitelist (a trick noted elsewhere [61]):

    var makeableTagName =
        { "div": "div", "p": "p", "b": "b", ... };

The type of these strings are ("div")^+, ("p")^+, ("b")^+, etc., so that makeableTagName[tagName] has type ("div","p","b",...)^+. Since this finite set of strings excludes "script", it now matches the argument type of createElement.
8.7.2 Cheating and Unverifiable Code

A complex body of code like the ADsafe runtime cannot be type-checked from scratch in one sitting. We therefore found it convenient to augment the type system with a cheat construct that ascribes a given type to an expression without descending into it. We could thus use cheat when we encountered an uninteresting type error and wanted to make progress. Our goal, of course, was to ultimately remove every cheat from the program.

We were unable to remove two cheats, leaving eleven unverified source lines in the 1,800 LOC ADsafe runtime. We can, in fact, ascribe interesting types to these functions, but checking them is beyond the power of our type system. Figure 8.6 shows these eleven unverified lines, and we discuss them below.

reject_name The reject_name function returns true if its argument is a blacklisted field and false otherwise. This function is used as a predicate to guard against invalid field accesses, so we ascribe it an intersection type:

\[ \text{UnsafeField} \rightarrow \text{True} \cap \text{UnsafeField} \rightarrow \text{Bool} \]

where UnsafeField is the set of blacklisted field names. Our implemented type-checker does not support checking functions with intersection types, but we type-check applications of intersection-typed functions in the usual way.

ADSAFE.create In the ECMAScript 5 standard, Object.create takes an object o as a parameter and creates a new object whose prototype is o; if o is not an object, the new object’s prototype is Object.prototype. ADsafe provides this same functionality for current browsers through ADSAFE.create. This function is never used by ADsafe; it is only intended for widgets. Therefore, its type must be

\[ [\text{Global} \cup \text{Widget}] \text{Widget} \cdots \rightarrow \text{Widget} \]

JSLint ensures that the actual argument is Widget-typed (section 8.5). However, the return type is problematic. In our Widget type (fig. 8.3), the proto field admits Object but not Widget, which is necessary to type-check the code. Permitting α (which represents Widget) in the type of proto results in a type system that we have not been able to show will terminate.
ADSAFE._intercept  ADsafe allows the hosting Web page to define *interceptors*, which are functions that get direct access to the DOM. Verifying interceptors entails verifying that the trusted container is safe. We can do so using the same technology we use to verify the ADsafe runtime—our typechecker!

8.8 ADsafety Redux

Sections 8.5 and 8.7 gave the details of our strategy for modeling JSLint and verifying `adsafe.js`. In this section, we combine these results and relate it to the original definition of ADsafety (definition 2).

The use of a type system allows us to make straightforward, type-based arguments of safety for the components of ADsafe.

The lemmas below formally reason about type-checked widgets. Claim 3 (section 8.5.2) establishes that linted widgets are in fact typable. Therefore, *we do not need to type-check widgets*. Widget programmers can continue to use JSLint and do not need to know about our type checker. However, given the benefits of uniformity provided by a type checker over ad hoc methods like JSLint (section 8.9 details one exploit that resulted from such an ad hoc approach), programmers may be well served to use our type checker instead.

**Type Soundness**  We type-check ADsafe using the JavaScript type-checker built for this dissertation. However, we disable all checks for runtime errors. Runtime errors are perfectly acceptable (they halt execution before something bad happens).

Since we admit runtime errors, our type soundness theorem is slightly peculiar. As usual, type soundness is composed of two lemmas: progress and preservation. The preservation lemma is conventional, but the progress lemma does not establish the absence of runtime errors. The progress lemma does however establish that the semantics always signals errors instead of getting stuck. Untyped progress was established in section 2.2.

Our assumed environment (section 8.6) provides the abstract heap $\Sigma$ and abstract environment $\Gamma$, which model the initial state of the browser, $\sigma$. We can thus make type-based statements about the combination of widgets and `adsafe.js`:

**Theorem 6 (ADsafety)**  *For all widgets $p$, if*

1. *all subexpressions of $p$ are Widget-typable,*
2. `adsafe.js` is typable,

3. `adsafe.js` runs before `p`, and

4. $\sigma p \rightarrow \sigma' p'$ (single-step reduction),

then at every step $p'$, $p'$ also has the type `Widget`.

**Proof:** Follows from the type preservation of flow typing (theorem 3) and fluid object types (theorem 4).

This theorem says that for all widgets `p` whose subexpressions are `Widget`-typed, if `adsafe.js` type-checks and runs in the browser environment, `p` can take any number of steps and still have the `Widget` type. Since types are preserved, two further key lemmas hold during execution:

**Corollary 1 (Widgets cannot load new code at runtime)** For all widgets `e`, if all variables and sub-expressions of `e` are `Widget`-typed, then `e` does not load new code.

By section 8.6, `eval`-like functions are not ascribed types, hence cannot be referenced by widgets or by the ADsafe runtime. Furthermore, functions that only `eval` when given strings, such as `setTimeout`, have restricted types that disallow `string`-typed arguments. Therefore, neither the widget nor the ADsafe runtime can load new code.

**Corollary 2 (Widgets do not obtain DOM references)** For all widgets `e`, if all variables and sub-expressions of `e` are `Widget`-typed, then `e` does not obtain direct DOM references.

The type of DOM objects is not subsumed by the `Widget` type. All functions in the ADsafe runtime have the type:

$$[\text{Widget } \cup \text{Global}] \text{Widget} \cdots \rightarrow \text{Widget}$$

Thus, functions in the ADsafe runtime do not leak DOM references, as long as they are only applied to `Widget`-typed values. Since all subexpressions of the widget `e` are `Widget`-typed, all values that `e` passes to the ADsafe runtime are `Widget`-typed. By the same argument, `e` cannot directly manipulate DOM references either.

**Widgets can only manipulate their DOM subtree** We cannot prove this claim with our tools. JSLint enforces this property by also verifying the static HTML of widgets; it ensures that all
element IDs are prefixed with the widget’s ID. The wrapper for `document.getElementById` ensures that the widget ID is a prefix of the element ID. Verifying JSLint’s HTML checks is beyond the scope of this work.

In addition, the wrapper for `Element.parentNode` checks to see if the current element is the root of the widget’s DOM subtree. It is not clear if our type checker can express this property without further extensions.

**Widgets cannot communicate** This claim is false; section 8.9.3 presents a counterexample.

### 8.9 Bugs Found in ADsafe

We have implemented the type system presented in this chapter, and applied it to the ADsafe source. The implementation is about 3,000 LOC, and takes 20 seconds to check `adsafe.js` (mainly due to the presence of recursive types). In some cases, type-checking failed due to the weakness of the type checker; these issues are discussed in section 8.7.1. The other failures, however, represent genuine errors in ADsafe that were present in the production system. The same applies to instances where JSLint and our typed model of it failed to conform. All the errors listed below have been reported, acknowledged by the author, and fixed.

#### 8.9.1 Missing Static Checks

JSLint inadvertently allowed widgets to include underscores in quoted field names. In particular, the following expression was deemed safe:

```javascript
fakeBunch = { "__nodes__": [ fakeNode ] };
```

A malicious widget could then create an object with an `appendChild` method, and trick the ADsafe runtime into invoking it with a direct reference to an HTML element, which is enough to obtain `window` and violate ADsafety:

```javascript
fakeNode = {
    appendChild: function(elt) {
        myWindow = elt.ownerDocument.defaultView;
    }
};
```
The full exploit is in fig. 8.7.1

This bug manifested itself as a discrepancy between our model of JSLint as a type checker and the real JSLint. Recall from section 8.5 that all expressions in widgets must have type $\text{Widget}$ (defined in fig. 8.3). For $\{ \text{__nodes__}: [\text{fakeNode}] \}$ to type as $\text{Widget}$, the $\text{__nodes__}$ field must have type $\text{Array}(\text{HTML}) \cup \text{Undef}$. However, $[\text{fakeNode}]$ has type $\text{Widget}$, which signals the error.

JSLint similarly allowed $\text{__proto__}$ and other fields to appear in widgets. We did not investigate whether they can be exploited as above, but setting them causes unanticipated behavior. Fixing JSLint was simple once our type checker found the error. (An alternative solution would be to use our type system as a replacement for JSLint.) We note that when the ADsafe option of JSLint was first announced, its author offered:

If [a malicious client] produces no errors when linted with the ADsafe option, then I will buy you a plate of shrimp.

We have obtained this shrimp bounty (seven plates of shrimp).

8.9.2 Missing Runtime Checks

Many functions in $\text{adsafe.js}$ incorrectly assumed that they were applied to primitive strings. For example, $\text{Bunch.prototype.style}$ began with the following check, to ensure that widgets do not programmatically load external resources via CSS:

\[\text{Figure 8.7: Exploiting JSLint}\]
ADSafe.go("AD_", function (dom, lib) {
    var called = false;
    var obj = {
        "toString": function() {
            if (called) {
                return "url(evil.xml#exp)";
            }
            else {
                called = true;
                return "dummy";
            }
        }
    };
    dom.append(dom.tag("div"));
    dom.q("div").style("MozBinding", o);
});

<!-- evil.xml -->
<?xml version="1.0"?>
<bindings><binding id="exp">
 <implementation><constructor>
  document.write("hacked")
 </constructor></implementation>
</binding></bindings>

Figure 8.8: Firefox-specific Exploit for ADsafe

Bunch.prototype.style = function(name, value) {
    if (/url/i.test(value)) { // regex match?
        error();
    }...
};

Thus, the following widget code would signal an error:

someBunch.style("background",
 "url(http://evil.com/image.jpg)");

The bug is that if value is an object instead of a string, the regular-expression test method will inadvertently invoke value.toString().

A malicious widget can construct an object with a stateful toString method that passes the test when first applied, and subsequently returns a malicious URL. In Firefox, we can use such an object to load an XBL resource\footnote{https://developer.mozilla.org/en/XBL} that contains arbitrary JavaScript (fig. 8.8).

We ascribe types to JavaScript's built-ins to prevent implicit type conversions. Therefore, we require the argument of RegExp.test to have type Str. However, since Bunch.prototype.style can be invoked by widgets, its type is $\text{Widget} \times \text{Widget} \rightarrow \text{Widget}$, and thus the type of value is $\text{Widget}$. 
This bug was fixed by adding a new `string_check` function to ADsafe, which is now called in 18 functions. All these functions are not otherwise exploitable, but a missing check would cause unexpected behavior. The fixed code is typable.

### 8.9.3 Counterexamples to Non-Interference

Finally, a type error in `Bunch.prototype.getStyle` helped us generate a counterexample to ADsafe's claim of widget noninterference (definition 2, part 4). The `getStyle` method is available to widgets, so its type must be `Widget → Widget`. The following code is the essence of `getStyle`:

```javascript
Bunch.prototype.getStyle = function (name) {
  var sty;
  reject_global(this);
  sty = window.getComputedStyle(this.__node__);  
  return sty[name];
}
```

The bug above is that `name` is unchecked, so it may index arbitrary fields, such as `__proto__`:

```javascript
someBunch.getStyle("__proto__");
```

This gives the widget a reference to the prototype of the browser’s `CSSStyleDeclaration` objects. Thus the return type of the body is not `Widget`, yielding a type error.

A widget cannot exploit this bug in isolation. However, it can replace built-in methods of CSS style objects and interfere with the operation of the hosting page and other widgets that manipulate styles in JavaScript.

This bug was fixed by adding a `reject_name` check that is now used in this and other methods. Despite the fix, ADsafe still cannot enforce non-interference, since widgets can reference and affect properties of other shared built-ins:

```javascript
var arr = [ ];
arr.concat.channel = "shared data";
```

The author of ADsafe pointed out the above example and retracted the claim of non-interference.

### Prior Exploits

Before and during our implementation, other exploits were found in ADsafe and reported [59][61]. We have run our type checker on the exploitable code, and our tools catch the bugs and report type errors.
Fixing Bugs and Tolerating Changes Each of our bug reports resulted in several changes to the source, which we tracked. In addition to these changes, adsafe.js also underwent non-security related refactorings during the course of this work. Even though we did not provide our type checker to its author, we easily continued type-checking the code after these changes. One change involved adding a number of new Bunch methods to extend the API. Keeping up-to-date was a simple task, since all the new Bunch methods could be quickly annotated with the Widget type and checked. In short, our type checker has shown robustness in the face of program edits.

8.10 Beyond ADsafe

We employed flow typing (chapter 4) to type-check idiomatic JavaScript, but we could have instead employed some other if-splitting technique. However, fluid object types (chapter 5) are instrumental for describing ADsafe’s interfaces: ADsafe reasons about infinite collections of fields in uniform ways, which is exactly what fluid object types describe.

Our type-based strategy provides a concrete roadmap for sandbox designers:

1. Formally specify the language of widgets using a type system;

2. use this specification to define the interface between the sandbox and untrusted code; and,

3. check that the body of the sandbox adheres to this interface by type-checking.

In particular, developers of new sandboxes should be aware of this strategy. Rather than trying to retrofit the type system’s features onto existing static checks, the sandbox designer can work with the type system to guarantee safety constructively from the start. Tweaks and extensions to the type system are certainly possible—for example, one may want to design a sandboxing framework that forbids applying non-function values and looking up fields of null, which the current type system allows (section 8.8).

ADsafe shares many programming patterns with other Web sandboxes (section 8.3), but doesn’t cover the full range of their features. We outline some of the extensions that could be used to verify them here:

Reasoning About Strings Our type system lets programmers reason about finite sets of strings and use these sets to lookup fields in objects. To verify Caja, we would need to reason about string
patterns. For example, Caja uses the field named \( *foo*\)\_\_\_w\_\_\_ to store a flag that determines if the field \( *foo*\) is writable. We can easily express this and the 8 other patterns used by Caja using fluid object types:

\[
\{ \_\_w_\_^\circ : \text{Bool}, \_\_w_\_T : T \}\]

**Abstracting Runtime Tests**  Our type system accounts for inlined runtime checks, but requires some refactorings when these checks are abstracted into predicates. Larger sandboxes, like Caja, have more predicates, so refactoring them all would be infeasible. We could instead use ideas from occurrence typing [86], which accounts for user-defined predicates.

**Modeling the Browser Environment**  ADsafe wraps a small subset of the DOM API and we manually check that this subset is appropriately typed in the initial type environment. This approach does not scale to a sandbox that wraps more of the DOM. If the type environment were instead derived from the C++ DOM implementation, we would have significantly greater confidence in our environmental assumptions.

### 8.11 Related Work

**JavaScript Web Sandboxes**  ADsafe [18], BrowserShield [73], Caja [66], and FBJS [25] are archetypal Web sandboxes that use static and dynamic checks to safely host untrusted widgets. However, the semantics of JavaScript and the browser environment conspire to make JavaScript sandboxing difficult (chapter 2).

Maffeis et al. [59] use their JavaScript semantics to develop a miniature sandboxing system and prove it correct. Armed with the insight gained by their semantics and proofs, they find bugs in FBJS and ADsafe (which we also catch). However, they do not mechanically verify the JavaScript code in these sandboxes. They also formalize capability safety and prove that a Caja-like subset is capability safe [61]. However, they do not verify the Caja runtime or the actual Caja subset. In contrast, we verify the source code of the ADsafe runtime and account for ADsafe’s static checks.

Taly, et al. [82] develop a flow analysis to find bugs in the ADsafe runtime (that we also catch). They simplify the analysis by modeling ECMAScript 5 strict mode, which is not fully implemented in any current Web browser. In contrast, ADsafe is designed to run on current browsers, and thus supports older and more permissive versions of JavaScript. We use \(\lambda_{JS}\) and associated tools
(chapter 2), which which is not limited to strict mode, so we find new bugs in the ADsafe runtime. In addition, Taly, et al. use a simplified model of JSLint. In contrast, we provide a detailed, type-theoretic account of JSLint, and also test it. We can thus find security bugs in JSLint as well.

Lightweight Self-Protecting JavaScript [62, 70] is a unique sandbox that does not transform or validate widgets. It instead solely uses reference monitors to wrap capabilities. These are modeled as security automata, but the model ignores the semantics of JavaScript. In contrast, this chapter and the aforementioned works are founded on detailed JavaScript semantics.

Yu, et al. [93] use JavaScript sandboxing techniques to enforce various security policies on untrusted code. Their semantic model, CoreScript, simplifies the DOM and scripting language. CoreScript cannot be used to mechanically verify the JavaScript implementation of a Web sandbox, which is what we present in this chapter.

**Modeling the Web Browser** There are formal models of Web browsers that are tailored to model whole-browser security properties [2, 10]. These do not model JavaScript’s semantics in any detail and are therefore orthogonal to semantic models of JavaScript (chapter 2 and [58]) that are used to reason about language-based Web sandboxes. In particular, ADsafe’s stated security goals are limited to statements about JavaScript and the DOM (section 8.4). Therefore, we do not require a comprehensive Web-browser model.

**Static Analysis of JavaScript** GateKeeper [37] uses a combination of program analysis and runtime checks to apply and verify security policies on JavaScript widgets. GateKeeper’s program analysis is designed to model more complex properties of untrusted code than we address by modeling JSLint. However, the soundness of its static analysis is proven relative to only a restricted sub-language of JavaScript, whereas $\lambda_{JS}$ handles the full language. In addition, they do not demonstrate the validity of their run-time checks.

Chugh et al. [15] and VEX [8] use program analysis to detect possibly malicious information flows in JavaScript. Our type system cannot specify information flows, although we do use it to discover that ADsafe fails to enforce a desirable information flow property. VEX’s authors acknowledge that it is unsound, and Chugh et al. do not provide a proof of soundness for their flow analysis. Our type system and analysis are proved sound.

Other static analyses for JavaScript [38, 51, 52] are not specifically designed to encode and check
Language-Based Security  Schneider et al. [77] survey the design and type-based verification of language-based security systems. JavaScript Web sandboxes are inlined reference monitors [24].

Cappos, et al. [14] present a layered approach to building language sandboxes that prevents bugs in higher layers from breaking the abstractions and assurances provided by lower layers. They use this approach to build a new sandbox for Python, whereas we verify an existing, third-party JavaScript sandbox. However, our verification techniques could easily be used from the onset to build a new sandbox that is secure by construction.

IFrames  IFrames are widely used for widget isolation. However, JavaScript that runs in an IFrame can still open windows, communicate with servers, and perform other operations that a Web sandbox disallows. Furthermore, inter-frame communication is difficult when desired; there are proposals to enhance IFrames to make communication easier and more secure [50]. Language-based sandboxing is somewhat orthogonal in scope, is more flexible, and does not require changes to browsers.

Runtime Security Analysis of JavaScript  There are various means to secure widgets that do not employ language-based security. Some systems rely on modified browsers, additional client software, or proxy servers [20, 21, 53, 54, 57, 64, 93]. Some of these propose alternative Web programming APIs that are designed to be secure. Language-based sandboxing has the advantage of working with today’s browsers and deployment methods, but our verification ideas could potentially apply to the design of some of these systems, too.
Chapter 9

Related Scripting Languages

This dissertation focuses on JavaScript; all the software developed to support this dissertation targets JavaScript. This chapter demonstrates that despite syntactic distinctions, the semantics of Python, Ruby, and JavaScript have many common elements. We therefore believe that the type-checking techniques presented in this dissertation (chapters 4 and 5) are more broadly applicable. It is a mere matter of programming to build a core calculus and tested desugaring functions for Python and Ruby, in the style of λJS (chapter 2).

9.1 Objects, Dictionaries, and Inheritance

Untyped scripting languages implement objects as simple dictionaries, mapping member names to values. Inheritance affects member lookup, but does not affect updates and deletion. This semantics is clear in the following JavaScript program:

```javascript
var parent = { "z": 9 };
var obj = { "x": 1, "__proto__": parent };

obj.x // returns 1
obj.z // returns 9
obj.z = 50 // creates new field in obj
obj.z // returns 50, shadowing parent.z
parent.z // returns 9; parent.z not set by obj.z = 50
```

1 This chapter is based on joint work with Claudiu Saftoiu [41] and Joe Gibbs Politz [39].
This program creates two objects, obj and parent, where obj inherits from parent. In Python, we cannot set up inheritance directly; however, the following program creates an equivalent object graph:

```python
class parent(object):
    z = 9  # class member
    def __init__(self): self.x = 1  # instance member

obj = parent()

obj.x  # returns 1
obj.z  # returns 9
obj.z = 50  # creates new field
obj.z  # returns 50, shadowing parent.z
parent.z  # returns 9, just like JavaScript
```

We can delete the parent.z field, returning both programs to their initial state, in JavaScript—

delete obj.z
obj.z  // returns 9

—and in Python—

delattr(obj, "z")
obj.z  # returns 9

Finally, field names are simply strings and do not need to be statically specified in JavaScript—
obj["x " + "yz"] = 99 // creates new field
obj["x y" + "z"] // returns 99

—and in Python—

setattr(obj, "x " + "yz", 99) # creates new field
getattr(obj, "x y" + "z") # returns 99

Figure 9.1 shows that we can translate this sequence to Ruby with only a little more syntactic effort.

**Classes Do Not Shape Objects**   One consequence of exposing the mutable dictionary underlying objects is that a class determines the members of its instances only during initialization. Members can be subsequently added and deleted from individual objects. There is substantial evidence that this occurs in real JavaScript programs [74]. The examples in section 9.5 illustrate that such behavior also occurs in Python and Ruby.

### 9.2 Inheritance in Scripting Languages

A more subtle consequence is that inheritance is brittle in scripting languages. Consider the following Ruby class:

```ruby
class A
  def initialize; @privateFld = 90; end

  def myMethod; return @privateFld * @privateFld; end
end
```

Ostensibly, the interface of class A is only myMethod, and privateFld is part of the implementation. Consider the following subclass:

```ruby
class B < A
  def initialize; super(); @privateFld = "my string"; end
end
```

Both A and B use the name privateFld in their implementations. However, since privateFld is simply a dictionary key, B obliterates assumptions about the implementation of A:

```ruby
obj = B.new
B.myMethod # error: cannot multiply strings
```
class A(object):
    def method(self): return "from class A"

class B(object):
    def method(self): return "from class B"

obj = A()
obj.method() # returns "from class A"
isinstance(obj, A) # returns True

obj.__class__ = B
obj.method() # returns "from class B"
isinstance(obj, B) # returns True: class changed!

Figure 9.2: Fluid Class Hierarchies in Python

It is not safe to subclass A without knowing its internals. Indeed, the principal author of Ruby declares that “it is only safe to extend Ruby classes when you are familiar with (and in control of) the implementation of the superclass” [32, page 240] (emphasis added).

In Python, member names that begin with two underscores are prefixed with the name of the enclosing class. For example, a member named __field__ is renamed to __MyClass_field__ within MyClass. This syntactic trick is supposed to preserve the modularity of classes. However, when used with modules, if A.MyClass extends B.MyClass, the module name is not used in the prefix. Thus the problem demonstrated in Ruby also occurs in Python.

9.3 Classes and Prototypes

The previous examples showed how objects’ shapes can be altered in scripting languages. Since classes are objects themselves, they can be altered as well. Python and JavaScript go further and expose the inheritance hierarchy as mutable members. Assigning to obj.__super__ in Python and obj.__proto__ in JavaScript affects the inheritance chain (fig. 9.2).

9.4 Methods?

JavaScript simply does not have methods. The obj.method(...) syntax binds obj to an implicit argument, this, that is supplied to the function obj.method [23, Section 11.2.3]. However, obj.method is not associated with either obj or its prototype. We can extract the underlying function and call it:
var f = obj.method; f()

Since f() does not use method call syntax, it is treated as a function call; this is not bound to obj, but to a default “global object”.

Unlike JavaScript, Python and Ruby make it harder to extract methods. However, their methods are still unlike methods in other object-oriented languages. For example, consider Python methods, which have an explicit self argument:

class A(object):
    def __init__(self): self.myField = 900

    def method(self): return self.myField

These methods can be extracted from objects and treated as functions that are partially applied to the appropriate self argument:

    obj = A()  # construct
    f1 = obj.method  # extract
    f1()  # apply, returns 900

    Re-extracting a method returns the same reference:

    f2 = obj.method  # the same function?
    f1 == f2  # returns True--same function

    Extracting method from a different instance results in a distinct reference, which is closed over that instance as the self argument:

    obj2 = A()
    obj.method == obj2.method  # returns False

However, we can still obtain the underlying function, called an unbound method in Python, which expects an explicit instance for the self argument:

    f_orig = obj.method.im_func  # im_func is built-in
    f_orig()  # Error: expected 1 argument
    f_orig(obj2)  # returns 900
    obj.method.im_func == obj2.method.im_func  # True

Ruby methods can similarly be extracted and applied.
9.5 Reflection and Pattern Matching

Reflection is not unique to scripting languages; the JVM and the .NET CLI have powerful reflection APIs. However, to use their reflection APIs, programmers must use many explicit downcasts. Reflection is significantly easier to use in untyped scripting languages and thus more prevalent.

Figure 9.3 classifies several common object-related reflective operators found in scripting languages. Programs can reflect on both an object’s class (nominal) and its members (structural), since an object’s class does not fully determine its members. In contrast, Java only supports nominal reflection. Object.getClass does allow Java programs to reflect on the structure of classes. However, because classes fully determine objects’ members, Java does not have operations to examine the structure of individual instances.

Figure 9.3 offers a conservative estimate of the prevalence of type tests and related checks across a broad corpus JavaScript, Python, and Ruby code, by counting occurrences of type testing operators. We believe these numbers undercount, since they do not account for heap-sensitive reasoning and other type testing patterns. For example, we do not try to estimate how often JavaScript programs

---

Table 9.1: Tag Checks and Related Checks

<table>
<thead>
<tr>
<th>Checks For</th>
<th>JS Gadgets</th>
<th>Python stdlib</th>
<th>Ruby stdlib</th>
<th>Django</th>
<th>Rails</th>
</tr>
</thead>
<tbody>
<tr>
<td>undefined/null</td>
<td>3,298</td>
<td>1,686</td>
<td>538</td>
<td>868</td>
<td>712</td>
</tr>
<tr>
<td>instanceof</td>
<td>17</td>
<td>613</td>
<td>1,730</td>
<td>647</td>
<td>764</td>
</tr>
<tr>
<td>typeof</td>
<td>474</td>
<td>381</td>
<td>4</td>
<td>348</td>
<td>719</td>
</tr>
<tr>
<td>field-presence</td>
<td>504</td>
<td>171</td>
<td>4</td>
<td>348</td>
<td>719</td>
</tr>
<tr>
<td>Total Checks</td>
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<td>3,184</td>
<td>2,439</td>
<td>1,867</td>
<td>2,195</td>
</tr>
<tr>
<td>LOC</td>
<td>617,766</td>
<td>313,938</td>
<td>190,002</td>
<td>91,999</td>
<td>294,807</td>
</tr>
</tbody>
</table>

*a* None in Python, and nil in Ruby
*b* isinstance in Python, and .is_a? and .instance_of? in Ruby
*c* type in Python
*d* hasattr in Python, and .respond_to? in Ruby

---

Figure 9.4: Reflection APIs

<table>
<thead>
<tr>
<th></th>
<th>Structural</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruby</td>
<td>o.respond_to?(p)</td>
<td>o.is_a?(c)</td>
</tr>
<tr>
<td>Python</td>
<td>o.methods</td>
<td>is_instance(o, c)</td>
</tr>
<tr>
<td>JavaScript</td>
<td>o.methods</td>
<td>o.instanceof c</td>
</tr>
<tr>
<td></td>
<td>dir(o)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o.hasOwnProperty(p)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>for (x in o)</td>
<td></td>
</tr>
</tbody>
</table>
var banned = { "caller": true, "arguments": true, ... };

function reject_name(name) {
    return ((typeof name !== 'number' || name < 0)
        && (typeof name !== 'string'
            || name.charAt(0) === '_'
            || name.slice(-1) === '_'
            || name.charAt(0) === '-'))
        || banned[name];
}

Figure 9.5: Banned Check from ADsafe

test for the presence of a field, because this operation is syntactically indistinguishable from field lookup.

**Sandbox**s  Reflection in scripting languages is particularly powerful when combined with pattern matching on member names. For example, JavaScript sandboxes like ADsafe and Caja use a combination of static and dynamic checks to ensure that untrusted programs do not access banned fields that may contain dangerous capabilities. To enforce this dynamically, all field-lookup expressions (obj[name]) in untrusted code are rewritten to check whether name is banned. Figure 9.5 is ADsafe's check; it uses a collection of ad hoc tests and also ensures that name is not the name of any field in the banned object, which is effectively used as a set of names.

**Django**  The Python Django ORM dynamically builds classes based on database information. In the following snippet, it adds a field attr_name, that represents a database column, to a class new_class, which it is constructing on-the-fly:

```python
attr_name = '%s_ptr' % base._meta.module_name
field = OneToOneField(base, name=attr_name,
    auto_created=True, parent_link=True)
new_class.add_to_class(attr_name, field)
```

The computed string, attr_name, is not arbitrary; it concatenates "_ptr" onto base._meta.module_name.

**Ruby on Rails**  When setting up a user-defined model, ActiveRecord iterates over the fields of an object and only processes members that match certain patterns:

```ruby
attributes.each do |k, v|
```

---

1. [https://github.com/django/django/blob/master/django/db/models/base.py#L157](https://github.com/django/django/blob/master/django/db/models/base.py#L157)
### 9.6 Control Operators

JavaScript, Python, and Ruby have a diverse set of control operators (fig. 9.6). These are all easily modeled in a Felleisen-Hieb style semantics [26]. For the purpose of analysis, it is easier to pick a

---

uniform representation for all operators, such as continuation-passing style, as we do to type-check JavaScript (section 4.5).

9.7 A Scripting Language Object Calculus

The preceding section presents examples that illustrate the characteristic features of objects in scripting languages. We distill these features into \( \lambda_{Sc} \), a core calculus of functional objects, imperative state, higher-order functions, and reflection. The combination of mutable references and functional objects is sufficient to encode the imperative objects of scripting languages. \( \lambda_{Sc} \) is not, however, intended to be a scripting language itself. It is designed to be a desugaring target for a full scripting language. Its syntax and semantics are in fig. 9.7 and introduced incrementally below.

Objects as Dictionaries \( \lambda_{Sc} \) faithfully models the objects-as-dictionaries design of scripting languages.

- In a field lookup, \( e_1[e_2] \), the field name is not a static string, but an arbitrary expression \( e_2 \), and it is a runtime error if \( e_2 \) does not evaluate to a string.

- Expressions of the form \( e_1[e_2 = e_3] \), are used to both update the value of existing fields (E-Update) and, if the field does not exist, to create new fields (E-Create). This is the behavior of all scripting languages; fields do not need to be declared and different instances of the same class or prototype can have different sets of fields.

- Fields can be deleted with \texttt{delete} \( e_1[e_2] \) (E-Delete). If the specified field does not exist, \( \lambda_{Sc} \) silently continues evaluation. This models JavaScript’s semantics, whereas other languages signal exceptions; it is routine to adapt the semantics to signal exceptions instead.

- When a field is not found, \( \lambda_{Sc} \) looks for the field in the parent object, which is the value of the parent field (E-Inherit). In JavaScript implementations this field is called "_.proto_.", and in Python it is called "_.super_.". In Ruby, the name is not visible to programmers (section 9.3).

Given the lack of syntactic restrictions on object lookup, we can easily write a program that looks up a field that is not defined anywhere on the inheritance chain. In such cases, \( \lambda_{Sc} \) signals an error (E-NotFound). This is a model of Python and Ruby, but not JavaScript. Unusually, JavaScript
\[
\begin{align*}
\sigma & \to \sigma e \\
\text{E-Cxt} & : \quad \sigma E(e_1) \to \sigma E(e_2), \text{when } e_1 \to e_2 \\
\text{E-Ref} & : \quad \sigma E(\text{ref } v) \to \sigma, (l, v)E(l), \text{when } l \notin \text{dom}(\sigma) \\
\text{E-Deref} & : \quad \sigma E(\text{deref } l) \to \sigma E(\sigma(l)) \\
\text{E-SetRef} & : \quad \sigma E(l := v) \to \sigma[l := v]E(v), \text{when } l \in \text{dom}(\sigma)
\end{align*}
\]

The \(wf\) relation is defined recursively over other expressions and lifted to stores in the natural way.

Figure 9.7: Syntax and Semantics of \(\lambda_{SC}\)
does not signal an error, but returns the default value `undefined`. To model JavaScript, we can introduce an `undefined` value and employ the following reduction instead of E-NotFound:

\[
\{ \text{str : v \ldots "parent" : null } \}[\text{str}_x] \mapsto \text{undefined}
\]

if \( \text{str}_x \notin (\text{str}\ldots) \)

The complexity of desugaring a particular scripting language is affected by the chosen reduction relation; desugaring JavaScript is simpler with this alternate reduction. Our formal proofs use E-NotFound, but it is easy to use the JavaScript-like reduction instead.

The fragment of \( \lambda_{Sc} \) presented thus far is sufficient to desugar the examples that do not use reflection.

**Reflection**  Nominal reflection in \( \lambda_{Sc} \) is trivial. An object, \( \text{obj} \), inherits from a parent, \( p \), if \( \text{obj}["parent"] \) \( \equiv \) \( p \). Structural reflection requires additional operators:

- The \( o \text{hasfield} \text{str} \) expression checks whether an object \( o \) has a member \( \text{str} \). This expression is similar to \( \text{hasOwnProperty} \) in JavaScript, \( \text{hasfield} \) does not traverse the inheritance chain to determine if \( o \) inherits \( \text{str} \). The behavior of Python’s \( \text{hasattr} \) and Ruby’s \( \text{respond_to?} \) is easily recovered by desugaring to a loop.

- The \( \text{fieldin} \text{obj} \text{init} \text{init} \text{do} \text{f} \) expression folds the function \( \text{f} \) over the names of the fields of \( \text{obj} \), with \( \text{init} \) as an accumulator. Unlike the \( \text{for in} \) loop of JavaScript or the \( \text{dir} \) function of Python, \( \text{fieldin} \) does not produce names in the inheritance chain. Actual \( \text{for in} \) loops can be desugared to use \( \text{fieldin} \).

**String Pattern Matching**  Section 9.5 shows programs that use a variety of operators to pattern match strings that are then used as field names. To model these programs, we introduce an abstract string-matching operator, \( \text{str matches} \) \( P \). In an actual scripting language, these patterns might be regular expressions. The precise encoding of patterns is irrelevant to our core calculus. We thus abstract \( P \) to be an arbitrary class of string-sets with decidable membership.

**Classes and Prototypes**  The classes and prototypes of scripting languages can be desugared to the records of \( \lambda_{Sc} \). Desugaring JavaScript’s prototype inheritance is natural; section 2.1.2 describe
how `new`, `this`, and other keywords are easily desugared to their semantics; the same strategy applies to $\lambda_{Sc}$.

To encode Ruby and Python’s classes, one could add primitive classes to $\lambda_{Sc}$ and model them directly. These primitive classes would need to admit the introspective operations and observations employed by our examples, such as extracting methods, affecting the inheritance hierarchy, and modifying classes. Because the objects of $\lambda_{Sc}$ naturally admit these observations and effects, we instead study classes by desugaring them. For example, the Python code in fig. 9.8 can be desugared to a $\lambda_{Sc}$ program that produces the object graph in the same figure.

Each Python object instance is desugared into a collection of $\lambda_{Sc}$ objects—an object containing the instance’s fields (`self`) and auxiliary objects containing the “bound methods” for each inherited class. This desugaring admits the observations and operations on Python objects made in section 9.4:

- Since bound methods are closed over `self`, programs can extract them and correctly use them as functions.
- A program can distinguish inherited fields from instance fields.
• A program can redefine a method on a class and have references to existing bound methods call the new method.

The desugaring function that produces the object graph in fig. 9.8 is straightforward: constructor invocation creates the self object, then walks the inheritance chain to create the auxiliary objects containing bound methods, closed over self. Finally, the programmer-written constructor (_init_ in Python) is applied to self.

9.8 Limitations

\(\lambda_{Sc}\) models the essential features of objects that are common to Ruby, Python, and JavaScript, but omits the following features:

• Python’s multiple-inheritance,

• Getters and setters, and

• Object proxies and proxy-like traps in Python and Ruby [19].

These features could be desugared into \(\lambda_{Sc}\), but it would be clearer to support them directly. We also elide other features that are not directly related to objects, such as eval, concurrency, control operators, and implicit type conversions, as they are not directly related to our goal of studying objects and reflection.

9.9 Soundness

We mechanize \(\lambda_{Sc}\) with PLT Redex [26]. We use our mechanized semantics to test \([56]\) \(\lambda_{Sc}\) for safety.

**Theorem 7 (Progress)** If \(\sigma e\) is a closed, well-formed configuration, then either:

- \(e \in v\),

- \(e = E(\text{err})\), or

- \(\sigma e \rightarrow \sigma'e'\), where \(\sigma'e'\) is a closed, well-formed configuration.

This property requires additional evaluation rules for runtime errors, which we elide for clarity.
Chapter 10

Conclusions and Future Work

This dissertation demonstrates that semantics engineering \[26\] works in practice. We develop $\lambda_{JS}$, which is a Felleisen-Hieb style core calculus for the essentials of JavaScript—a language without any formal specification. We engineer a translation from the full language to the core calculus. Finally, we test that the semantics and translation faithfully model implementations. This process could be repeated for any other programming language.

We use $\lambda_{JS}$ as the basis of our proofs and our implementations. As of this writing, $\lambda_{JS}$ is used by research groups at several other institutions, including Microsoft Research, Fujistu Laboratories, Northeastern University, University of Utah, KAIST, and University of Chile.

This dissertation presents two novel type-checking principles:

- **Flow typing** combines type-checking and flow analysis to type-check programs that use local control and state to affect types. We present a principled technique to combine the type-checker and flow analysis in a simple and modular way.

- **Fluid object types** are a natural generalization of record types and row type variables. They give a static account of object systems that support reflection and dynamic field names.

We implement flow typing and fluid object types in a JavaScript type-checker. Using this type-checker, we demonstrate that:

- Types are an effective way to document JavaScript code,

- Types can verify security properties of JavaScript programs, and
• Types can be employed to mechanically generate safe sub-languages of JavaScript.

We also give evidence that our techniques are applicable to other scripting languages.

Future Work

There are various immediate avenues of research that could build on this dissertation.

Semantics \(\lambda_{JS}\) is approximately a semantics for ECMA-262, 3rd edition, which is presently the most widely-used version of JavaScript. JavaScript is evolving rapidly and \(\lambda_{JS}\) needs to keep up with new standards and experimental features. The S5 project at Brown University grows \(\lambda_{JS}\) to support ECMA-262, 5th edition. S5 is better tested than \(\lambda_{JS}\), using the new standardized test suite for JavaScript, test262. S5 tackles addition features, such as `eval`, that \(\lambda_{JS}\) omits.

The testing strategy we use to demonstrate \(\lambda_{JS}\)’s adequacy can also be used to develop semantics for other scripting languages. As a rule, scripting languages do not bother with formal semantics. But, the languages that matter have canonical implementations and extensive test suites. These two components—an oracle and a set of valid inputs—are all that a good semanticist needs to reverse-engineer a formal semantics. A more interesting problem might be to automate the semantics reverse-engineering process.

Types We use our tools to type-check approximately 7,000 lines of code. What would it take to increase this number by a few orders of magnitude? Can we do it without compromising type soundness? Do we have to weaken the guarantees our type-checker provides? (e.g., must we admit Java-like `NullPointerException`?) We cannot manually annotate and type-refactor millions of lines of code. We need some form of tool support, but it does not have to be ML-style type inference. In section 6.1 we discuss a simple tool that uses instrumentation to infer types that are might be incorrect; such techniques could be pushed further. Future work should be guided by studying type-checking failures with an existing type-checker, such as ours.

Security We verify ADsafe, which is the simplest of the major Web sandboxes. Verifying a more sophisticated sandbox such as Google Caja, which is used to isolate untrusted code by Yahoo! and

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1 http://www.cs.brown.edu/research/plt/dl/S5
2 http://test262.ecma.script.org
Google, seems to be the obvious next step. Such a verification would be useful, but it is not clear if it would produce new research results. Types could instead be used to develop a different kind of Web sandbox that addresses some limitations of current approaches:

- The runtime checks in Web sandboxes have an overhead that impedes adoption. Google Caja presently reports 2x or higher slowdowns on various benchmarks. A type-checker can determine that untrusted code does not violate the sandbox’s safety properties, and thus safely bypass runtime checks. Crucially, statically unverifiable code would continue to use runtime checks.

Indeed, in chapter 8, the safe sub-language we generate from types is already less restrictive than ADsafe’s own sub-language. A Web sandbox could allow “safe type annotations” in untrusted widgets. Note that such a pay-for-performance model is similar to Thorn’s [92].

- We tried and failed to prove a basic non-interference property for ADsafe widgets. The property turned out to be false; it is violated in several ways by JavaScript’s semantics and no Web sandbox can establish such a property. Developing and verifying that such a property holds is also an open problem.

---

Appendix A

Further Details of ADsafe Verification

Chapter 8 presents a type-based verification of ADsafe’s original source code. The chapter documents the few refactorings necessary to satisfy the type-checker (section 8.7.1) and the bugs that we found (section 8.9). This chapter details the discrepancies between ADsafe’s static checker, JSLint, and our type-checker, and details the few lines of code that remain unverified.

A.1 Differences Between JSLint and Typed Widgets

In section 8.5.2 we argue that if a widget passes JSLint, then it is also Widget-typable. However, Widget-typability does not imply that the widget passes JSLint. JSLint is a “code quality tool” that was retrofitted to perform security checks. Some of these code quality checks are irrelevant for safety, thus they reject safe code that the Widget-type admits. We give some examples below.

**Banned Names**  The Widget-type states that prototype, arguments, and several other strings cannot be used as field names. However, it is safe to use them as identifiers:

```javascript
ADSAFE.lib("Widget_", function() {
    var prototype, arguments;
});
```

However, JSLint rejects this program because it simply scans for “banned names”.

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Unused Identifiers  JSLint requires identifiers to be used and hence rejects this program:

```
ADSAFE.lib("Widget_", function() {
    var unusedVariable;
});
```

However, this program is perfectly safe and Widget-typable.

Pascal-style Declarations  JSLint requires all variable declarations to be at the head of a function, so it rejects this program:

```
ADSAFE.lib("test_", function () {
    var x = 34;
    x = x + 1;
    var y = 45;
});
```

However, this program is Widget-typable.
Appendix B

Characteristic Uses of Objects

This appendix translates the \( \lambda^S \) examples in section 5.2 to various actual scripting languages.

Example 1

Prototype inheritance:

```javascript
let Rect = { "area": func(self:?).self["x"] * self["y"], "parent": null } in
let Cuboid = { "parent": Rect,
    "vol": func(self).self["area"][self] * self["z"] } in
let shape = { "x": 2, "y": 5, "z": 10: "parent": Cuboid } in
let vol = shape["vol"](shape) // vol is 100
```

**JavaScript**  Here is the equivalent program in JavaScript. Note that the this argument is implicit:

```javascript
var Rect = { area: function() { return this.x * this.y; },
    __proto__: null };
var Cuboid = { __proto__: Rect,
    vol: function() { return this.area() * this.z; } };
var shape = { x: 2, y: 5, z: 10: "parent": Cuboid };
var vol = shape.vol(); // vol is 100
var f = vol;
var vol = f(); // ERROR: this.area is undefined
```

**Lua**  This program can be written in Lua using metatables, which allow assigning a parent-like field:

```lua
Rect = { area = function(self) return self.x * self.y end }
Cuboid = { vol = function(self) return self.area(self) * self.z end }
```
setmetatable(Cuboid, {__index = Rect})
shape = { x=2, y=5, z=10 }
setmetatable(shape, {__index = Cuboid})
vol = shape.vol(shape)
f = shape.vol
vol2 = f()  // ERROR: attempt to index local self (a nil value)

Example 2

Extracting methods:

let ArrParent = { "slice": func(self?:?,begin?:?,end:?). ···, ··· } in
let arr1 = { "0": 3, "1": 20, "2": 59, "length": 3, "parent": ArrParent }
let nodeList = { "0": htmlElementA, "1": htmlElementB, "2": htmlElementC,
"len": 3, "parent": HTMLNodeListParent } in
let eltArray = ArrParent["slice"](nodeList, 0, 1)
// returns an array containing htmlElementA and htmlElementB

JavaScript  This version of slice is built-in. We use DOM-manipulation functions to fetch array-like objects.

var ArrParent = Array.prototype;
var arr1 = [3, 20, 59]; // JavaScript desugars to an Array object
// Get all the links on a page:
var nodeList = document.getElementsByTagName("a");
// Using .call on a function allows us to provide the this arg
var eltArray = ArrParent.slice.call(nodeList, 0, 1)
// eltArray contains the first two elements in the list

Lua  Lua objects allow trivial method extraction—Lua has similar array behavior to JavaScript as well, and any number-indexed dictionary can be used by library methods.

arr = {123, 45, 6}
table.sort(arr)
-- arr is now {1 = 6, 2 = 45, 3 = 123}
not_arr = {foo = "bar"}
not_arr[1] = 6
not_arr[2] = 5
not_arr[3] = 4
table.sort(not_arr)
-- not_arr is now {1 = 4, 2 = 5, 3 = 6, foo = "bar"}

Example 3

Bound methods:
let Rect = { "area": func(self?) . self["x"] * self["y"], "parent": null } in
let Cuboid = { "parent": Rect,
    "vol": func(self) . self["area"][self] * self["z"] } in
let rec shape2 = {
    "x": 2, "y": 5, "z": 10,
    "_class_": Cuboid,
    "parent": {
        "vol": func() . shape2["_class_"]["vol"][shape2]
    }
} in
let f = shape2["vol"]
let vol2 = f() // vol2 is still 100, f closes over shape2

Python  In Python, we can see this effect with classes:

class Rect(object):
    def area(self): return self.x * self.y
class Cuboid(Rect):
    def vol(self): return self.area() * self.z
shape2 = Cuboid()
shape2.x = 2; shape2.y = 5; shape2.z = 10
f = shape2.vol
vol2 = f() # vol2 is 100

Ruby  In Ruby, we use obj.method(:methname) to access the method, and method.call to invoke it:

class Rect
  def area; self.x * self.y; end
end
class Cuboid < Rect
  def vol; self.area() * self.z; end
end
shape2 = Cuboid.new
def shape2.x; 2; end
def shape2.y; 5; end
def shape2.z; 10; end
f = shape2.method(:vol)
vol2 = f.call() # vol2 is 100

Example 4

Ad hoc private fields:
let safeGetField = Λα <: ?.func(obj:?, fieldName:?, default:?).
if (fieldName matches "_.+_.") default
else if (obj hasfield fieldName) obj[fieldName] else default in
safeGetField({ "_private_": 42, "pub": 23, "parent": null },
 "_private_", 0) // returns 0

JavaScript  In JavaScript, this check could be performed with a regex. For a real-world example, see reject._name in ADsafe.

function safeGetField(obj, field, default) {
    if(/_(.*)_/.test(field)) return default
    else {
        if(obj.hasOwnProperty(field)) return obj[field];
        else return default;
    }
}

Python  A similar check works in Python. Note that variations on this pattern are found in production code inside Django.

def safeGetField(obj, field, default):
    rx = re.compile(r"_(.*)._")
    if rx.match(field) is not None: return default
    else:
        if hasattr(obj, field): return getattr(obj, field)
        else: return default

Ruby  Note that several variations on this pattern are found in production code inside Ruby on Rails.

def safeGetField(obj, field, default)
    return default unless /_(.*)._/.match(field).nil?
    return default unless obj.respond_to?(field)
    return obj.send(field.intern)
end

Example 5

Safe dictionary lookup:

2. https://github.com/django/django/blob/master/django/db/models/base.py#L157
let safeAssign = \( \alpha \leftarrow ?.func(dict?:?,word:Str,value:?).dict["w_" + word = value] \)

let safeLookup = \( \alpha \leftarrow ?.func(dict?:?,world:Str,default:?). \)

let lookup = "w_" + word in
  if (dict hasfield lookup) dict[lookup]
  else default

**JavaScript**  While JavaScript does not have type abstraction, implementation of the core functionality is trivial:

```javascript
function safeAssign(dict, word, value) { dict["w_" + word] = value; }
function safeLookup(dict, word, default) {
  var lookup = "w_" + word;
  if(dict.hasOwnProperty(word)) return dict[lookup];
  return default;
}
```

Such an implementation is necessary in JavaScript when objects are used as dictionaries, because of the presence of the `_proto_` field in major browsers.

**Python**  Python and Ruby both support dictionary-like objects natively, and don’t need to use this pattern.
Appendix C

Proofs: Flow Typing

C.1 Full Typing Relation

\[
\begin{align*}
\text{ty}_1(\text{typeof}) &= \top \rightarrow \text{Str} \\
\text{ty}_2(\text{===}) &= \top \times \top \rightarrow \text{Bool} \\
\text{ty}_2(-) &= \text{Num} \times \text{Num} \rightarrow \text{Bool}
\end{align*}
\]

\[
\frac{\Sigma; \Gamma \vdash e : S \cdots \quad \text{ty}_n(\text{op}_n) = S \cdots \rightarrow T}
{\Sigma; \Gamma \vdash \text{op}_n(e \cdots) : T} \quad \text{(T-PrimApp)}
\]

\[
\begin{align*}
\Sigma; \Gamma \vdash \text{num} : \text{Num} \quad \text{(T-Num)} \\
\Sigma; \Gamma \vdash \text{str} : \text{Str} \quad \text{(T-Str)} \\
\Sigma; \Gamma \vdash \text{bool} : \text{Bool} \quad \text{(T-Bool)} \\
\Sigma; \Gamma \vdash \text{undefined} : \text{Undef} \quad \text{(T-Undef)}
\end{align*}
\]

\[
\frac{\Sigma(l) = T}
{\Sigma; \Gamma \vdash l : T} \quad \text{(T-Loc)}
\]

\[
\frac{\Gamma(x) = T}
{\Sigma; \Gamma \vdash x : T} \quad \text{(T-Id)}
\]
\( \Sigma; \Gamma, x : S, \cdots \vdash e : T \quad \Gamma' = \Gamma \) with labels removed

(T-Abs)

\( \Sigma; \Gamma \vdash \text{func}(x : S \cdots \rightarrow T \ e : S \cdots \rightarrow T) \)

(T-App)

\( \Sigma; \Gamma \vdash e : S \cdots \quad \Sigma; \Gamma \vdash f : S \cdots \rightarrow T \)

\( \Sigma; \Gamma \vdash f(e : \cdots) : T \)

(T-Let)

\( \Sigma; \Gamma \vdash \text{let } x = e_1 \text{ in } e_2 : T \)

\( \Sigma; \Gamma \vdash e : T \)

(T-Ref)

\( \Sigma; \Gamma \vdash \text{ref } e : \text{Ref } T \)

(T-Deref)

\( \Sigma; \Gamma \vdash \text{deref } e : T \)

\( \Sigma; \Gamma \vdash e_1 : \text{Ref } S \quad \Sigma; \Gamma \vdash e_2 : T \quad T < S \)

\( \Sigma; \Gamma \vdash \text{setref } e_1 e_2 : \text{Ref } T \)

(T-SetRef)

\( \Sigma; \Gamma \vdash \text{if } (e_1) \lbrace e_2 \rbrace \text{ else } \lbrace e_3 \rbrace : T \)

(T-If)

\( \Sigma; \Gamma, \text{label} : T \vdash e : T \)

(T-Label)

\( \Gamma(\text{label}) = T \quad \Sigma, \Gamma \vdash e : T \)

(T-Break)

\( \Sigma; \Gamma \vdash \text{break } \text{label } e : \bot \)

\( \Sigma; \Gamma \vdash e : S \quad S < T \)

\( \Sigma; \Gamma \vdash e : T \)

(T-Sub)

\( \forall l \in \text{dom}(\Sigma). \Sigma; \vdash \sigma(l) : \Sigma(l) \quad \text{dom}(\Sigma) = \text{dom}(\sigma) \)

(T-\(\sigma\))

\( \Sigma \vdash \sigma \)
C.2 Type Safety

Lemma 10 (Progress) If $\Sigma; \cdot \vdash e : T$ and $\Sigma \vdash \sigma$ then either:

i. $e \in v$, or

ii. There exists $\sigma', e'$, such that $\sigma e \rightarrow \sigma' e'$, or

iii. There exists an $E$, such that $e = E\langle \text{tagerr} \rangle$.

Proof: By lemma [12], cases (i.) and (iii.) are immediate, leaving only the case where $e = E\langle \text{ae} \rangle$. By lemma [13], there exist $S$ and $\Gamma$, such that $\Sigma; \Gamma \vdash \text{ae} : S$. By case-analysis on $\text{ae}$, applying inversion (lemma 17) and canonical forms (lemma 18) where indicated:

- Case $\text{ae} = \text{ref } v$. By E-Ref, $\sigma E\langle \text{ref } e \rangle \rightarrow \sigma, (l, v)(l)$ where $l \notin \text{dom}(\sigma)$.

- Case $\text{ae} = \text{deref } v$. By inversion, $\Sigma; \Gamma \vdash v : \text{Ref } S'$. By canonical forms, $v = l$ and $l \in \text{dom}(\Sigma)$. By T-$\sigma$, $l \in \text{dom}(\sigma)$. By E-Deref, $\sigma E\langle \text{deref } l \rangle \rightarrow \sigma E\langle \sigma(l) \rangle$.

- Case $\text{ae} = \text{setref } v_1 v_2$. By inversion, $\Sigma; \Gamma \vdash v_1 : \text{Ref } S_1$. By canonical forms, $v_1 = l$, hence $l \in \text{dom}(\sigma)$. By E-SetRef, $\sigma E\langle \text{setref } l v_2 \rangle \rightarrow \sigma[l := v_2]E(l)$.

- Case $\text{ae} = \text{label } : T \{ E_1 \langle \text{break label } v \rangle \}$. By E-Break, $\sigma E\langle \text{label } : T \{ E_1 \langle \text{break label } v \rangle \} \rangle \rightarrow \sigma E\langle v \rangle$.

- Case $\text{ae} = \text{label } : T \{ v \}$. By E-Label-Pop, $\sigma E\langle \text{label } : T \{ v \} \rangle \rightarrow \sigma E\langle v \rangle$.

- Case $\text{ae} = \text{let } x = v \text{ in } e$. By E-Let, $\sigma E\langle \text{let } x = v \text{ in } e \rangle \rightarrow \sigma E\langle e[x/v] \rangle$.

- Case $\text{ae} = v_f(v \cdots)$. By canonical forms, $\Sigma; \Gamma \vdash v_f : S' \cdots \rightarrow S$. By inversion (lemma 17), $v_f = \text{func}(x \cdots) \{ e \}$. By E-Abs, $\sigma E\langle \text{func}(x \cdots) \{ e \}(v \cdots) \rangle \rightarrow \sigma E\langle e'[x/v] \cdots \rangle$.

- Case $\text{ae} = \text{op}_n(v \cdots)$ is similar to the case above.

- Case $\text{ae} = \text{tagcheck } R v$. If $\delta_1(\text{typeof}, v) \in R$, then $\sigma E\langle \text{tagcheck } R v \rangle \rightarrow \sigma E\langle v \rangle$ by E-TagCheck.

If not, then $\sigma E\langle \text{tagcheck } R v \rangle \rightarrow \sigma E\langle \text{tagerr} \rangle$ by E-TagCheck-Err.

Lemma 11 (Preservation) If $\Sigma_1; \cdot \vdash e_1 : T$, $\Sigma_1 \vdash \sigma_1$, and $\sigma_1 e_1 \rightarrow \sigma_2 e_2$, then there exists a $\Sigma_2$, such that:
i. $\Sigma_2; \cdot \vdash e_2 : T,$

ii. $\Sigma_2 \vdash \sigma_2,$ and

iii. $\Sigma_1 \subseteq \Sigma_2.$

**Proof:** By case-analysis of the reduction rules, there exists an evaluation context $(E),$ an active expression $(ae),$ and an expression $(e'),$ such that $e_1 = E\langle ae \rangle$ and $e_2 = E\langle e' \rangle.$ Hence,

$$\sigma_1 E\langle ae \rangle \rightarrow \sigma_2 E\langle e' \rangle$$

By lemma 13, there exist $\Gamma$ and $S,$ such that $\Sigma_1; \Gamma \vdash ae : S$ and $\Gamma$ only contains labels. We will prove that $\Sigma_2; \Gamma \vdash e' : S$, so that $\Sigma_2; \Gamma \vdash E\langle e' \rangle : T.$

We proceed by case-analysis on $ae$, using inversion (lemma 17) where specified:

- **let** $x = v$ in $e$. By inversion, $\Sigma_1; \Gamma \vdash v : U$ and $\Sigma_1; x : U, \Gamma \vdash e : S$. By E-Let, $ae \rightarrow e[x/v].$ By substitution (lemma 16), $\Sigma; \Gamma \vdash e[x/v] : S$.

- **(func (x⋯) ( e ))(v⋯).** By inversion and canonical forms, $\Sigma_1; \Gamma \vdash v : U ⋯$ and $\Sigma_1; x : U ⋯ \vdash e : S$. By E-App, $\sigma(\text{func}(x⋯) ( e ))(v⋯) \rightarrow \sigma e[x/v] ⋯$. By substitution (lemma 16), $\Sigma_1; \cdot \vdash e[x/v] ⋯ : S$.

- **label : S′ { v }.** By inversion, $\Sigma_1; \text{label} : S′, \Gamma \vdash v : S′$ and $S′ <: S$. By E-Label-Pop, $\sigma\text{label} : S{ v } \rightarrow \sigma v$. Typing values does not require labels in the environment (lemma 15), hence $\Sigma_1; \Gamma \vdash v : S′$. The conclusion follows by T-Sub.

- **label : S′ { E′(break label v) }.** By inversion, $\Sigma_1; \text{label} : S′, \Gamma \vdash E′(\text{break label v}) : S′$ and $S′ <: S$. By E-Break, $\sigma E′(\text{break label v}) \rightarrow \sigma v$. Since the evaluation context, $E′$ cannot bind identifiers and values can be typed without labels (lemma 15), $\Sigma_1; \Gamma \vdash v : S′$.

- **ref v.** By inversion, $\Sigma_1; \Gamma \vdash v : U$ and Ref $U <: S$. By E-Ref, for an $l \notin \text{dom}(\sigma_1),$ $\sigma_2 = \sigma_1, (l, v)$ and $\sigma_1\text{ref } v \rightarrow \sigma_2 l$. Let $\Sigma_2 = l : U, \Sigma_1$. By T-Loc, $\Sigma_2; \cdot \vdash l : \text{Ref } U,$ followed by T-Sub with Ref $U <: S$.

- **deref l.** By inversion, $\Sigma_1; \Gamma \vdash l : \text{Ref } U$ with $U <: S$. By hypothesis and T-Loc, $\Sigma_1(l) = U$. By $\Sigma_1 \vdash \sigma_1,$ there exists a $v$ such that $\sigma_1(l) = v$ and $\Sigma; \Gamma \vdash v : U$. By E-Deref, $\sigma_1\text{deref } l \rightarrow \sigma_1 v$. By T-Sub, $\Sigma_1; \Gamma \vdash v : S.$
• setref $l\ v$. By inversion, $\Sigma_1; \Gamma \vdash l : \text{Ref } S'$, $\Sigma_1; \Gamma \vdash v : U$, $U <: S'$, and $\text{Ref } S' <: S$. By T-Loc, $\Sigma_1(l) = S'$. By E-SetRef, $\sigma_1 \text{setref } l\ v \rightarrow \sigma_1[l/v]$. Since $\Gamma$ does not bind identifiers and by lemma 15, $\Sigma_1; \cdot \vdash v : U$. By T-Sub, $\Sigma; \cdot \vdash v : S'$. Hence, $\Sigma_1 \vdash \sigma_1[l/v]$.

• tagcheck $R\ v$.

$- \sigma_1E(\text{tagcheck } R\ v) \rightarrow \sigma_1E(v)$, and $\delta_1(\text{typeof}, v) \in R$. By inversion, $\Sigma_1; \Gamma \vdash v : U$ and $S' = \text{static}(R, U)$ for $S' <: S$. By definition of static, $S' <: U$. By case-analysis of $v$:

* $v = \text{func } (x\ldots) : T_a\ldots \rightarrow T_r \{ e \}$, hence $\Sigma_1; \cdot \vdash v : T_a \ldots \rightarrow T_r$, and $T_a \ldots \rightarrow T_r <: U$.

By lemma 19, static$(R, T_a \ldots \rightarrow T_r) <: \text{static}(R, U) <: S$. By lemma 20, “function” $\in \text{runtime}(U)$. Hence, static$(R, T_a \ldots \rightarrow T_r) = T_a \ldots \rightarrow T_r$.

* Constants are symmetric to functions.

$- \sigma_1E(\text{tagcheck } R\ v) \rightarrow \sigma_1E(\text{tagerr})$. Apply T-TagErr and T-Sub.

Definition 1 (Active Expressions) An active expression, $ae$ is one of:

$ae \quad = \quad \text{let } x = v \text{ in } e$

$\quad \mid v_f(v\ldots)$

$\quad \mid op_n(v\ldots)$

$\quad \mid \text{label}:T \{ v \}$

$\quad \mid \text{ref } v$

$\quad \mid \text{deref } v$

$\quad \mid \text{setref } v_1\ v_2$

$\quad \mid \text{label}:T \{ E(\text{break } v) \} \text{ where label } \notin E$

$\quad \mid \text{tagcheck } R\ v$

Lemma 12 For all closed expressions $e$, either:

i. $e \in v$,

ii. there exist $e$ and $ae$ such that $e = E(\text{ae})$, or

iii. $e = E(\text{tagerr})$, for some $E$. 
Proof: By definition of $e$, $v$, and $E$. ■

Lemma 13 (Closed Active Expressions) For all $\Sigma, T, E, ae$, if $\Sigma; \cdot \vdash E(\langle ae \rangle) : T$, then there exist $S$ and $\Gamma$, where $\Gamma$ only contains labels, such that $\Sigma; \Gamma \vdash ae : S$.

Proof: there exists a subdeduction of the typing derivation, such that $\Sigma; \Gamma \vdash \langle ae \rangle : S$. Suppose an identifier, $x \in dom(\Gamma)$. Then, $ae$ is in a program context $\langle let \ x = e_1 \ in \ \cdot \rangle$ or $\langle func(x \cdots) \{ \ \cdot \} \rangle$. However, this cannot occur since $ae$ is in an evaluation context. ■

Lemma 14 For all $E$, if $\sigma_1 e_1 \rightarrow \sigma_2 e_2$, then $\sigma_1 E(\langle e_1 \rangle) \rightarrow \sigma_2 E(\langle e_2 \rangle)$.

Proof: by case-analysis of the reduction rules, there exist $E', e'_1, e'_2$, such that $e_1 = E'(\langle e'_1 \rangle)$, $e_2 = E'(\langle e'_2 \rangle)$, and $\sigma_1 E'(\langle e'_1 \rangle) \rightarrow \sigma_2 E'(\langle e'_2 \rangle)$. By the same reduction rule, $\sigma_1 E(\langle e'_1 \rangle) \rightarrow \sigma_2 E(\langle e'_2 \rangle)$.

Lemma 15 If $\Sigma; \Gamma \vdash v : T$ then $\Sigma; \Gamma' \vdash v : T$, where $\Gamma' = \Gamma$ with labels removed.

Proof: the only interesting case is $v = \langle func(x \cdots) \{ \ e \} \rangle$, where $e$ is typed in an extension of $\Gamma$ with labels removed, i.e., $\Gamma'$. ■

Lemma 16 (Substitution) If $\Sigma; x : S, \Gamma \vdash e : T$ and $\Sigma; \Gamma \vdash v : S$, then $\Sigma; \Gamma \vdash e[x/v] : T$.

Proof: by induction on the typing derivation. ■

Lemma 17 (Inversion) If:

- $\Sigma; \Gamma \vdash \text{ref} \ e : T$, then $\text{Ref} S <: T$ and $\Sigma; \Gamma \vdash e : S$,
- $\Sigma; \Gamma \vdash \text{deref} \ e : T$, then $\Sigma; \Gamma \vdash e : \text{Ref} S$ with $S <: T$,
- $\Sigma; \Gamma \vdash \text{setref} e_1 e_2 : T$, then $\Sigma; \Gamma \vdash e_1 : \text{Ref} S$, $\Sigma; \Gamma \vdash e_2 : U$, $U <: S$, and $\text{Ref} S <: T$,
- $\Sigma; \Gamma \vdash e_f (e \cdots) : T$, then $\Sigma; \Gamma \vdash e_f : S \cdots \rightarrow T'$, $\Sigma; \Gamma \vdash e : S \cdots$, and $T' <: T$.
- $\Sigma; \Gamma \vdash \text{label} : S \{ e \} : T$, then $S <: T$ and $\sigma; \text{label} : S, \Gamma \vdash e : S$.
- $\Sigma; \Gamma \vdash \text{let} x = e_1 \ in \ e_2 : T$, then $\Sigma; \Gamma \vdash e_1 : S$ and $\Sigma; x : S, \Gamma \vdash e_2 : T$.
- $\Sigma; \Gamma \vdash \text{tagcheck} R e : T$, then $\Sigma; \Gamma \vdash e = S$ and $\text{static}(R,S) = T'$, where $T' <: T$. 

**Proof:** by induction on the typing derivation. In all cases, only T-Sub and one other typing rule apply. T-Sub requires induction and the other latter is immediate.

- Only T-Ref and T-Sub apply. T-Ref is immediate with $\text{Ref } S = T$. For T-Sub, by inversion, $\Sigma; \Gamma \vdash \text{ref } e : T'$ and $T' <: T$. By induction, $T' = \text{Ref } S$ and $\Sigma; \Gamma \vdash e : S$.

- Only T-Deref and T-Sub apply. T-Deref is immediate with $T <: T$. For case T-Sub, by inversion $\Sigma; \Gamma \vdash \text{deref } e : S$ and $S <: T$. By induction, $\Sigma; \Gamma \vdash e : S'$ with $S' <: S$. By S-Trans, $S' <: T$.

- Only T-SetRef and T-Sub apply. T-SetRef is immediate, with $\text{Ref } S = T$. For T-Sub, by inversion, $\Sigma; \Gamma \vdash \text{setref } e_1 e_2 : T'$ and $T' <: T$. By induction, $\Sigma; \Gamma \vdash e_1 : \text{Ref } S$, $\Sigma; \Gamma \vdash e_2 : U$, $U <: S$, and $\text{Ref } S <: T'$. By S-Trans, $\text{Ref } S <: T$.

- Only cases T-App and T-Sub apply. T-App is immediate. For T-Sub, the conclusion follows by induction and S-Arr.

- Only cases T-Sub and T-Label apply. T-Label follows immediately with $S = T$ and S-Ref.

- Only T-Let and T-Sub apply. T-Let is immediate. For T-Sub, by induction, $\Sigma; \Gamma \vdash e_1 : S$, $\Sigma; x : S, \Gamma \vdash e_2 : T'$, and $T' <: T$. Apply T-Sub.

- Only T-TagCheck and T-Sub apply. T-TagCheck is immediate. For T-Sub, by induction, it holds for a $T' <: T$.

\[ \blacksquare \]

**Lemma 18 (Canonical Forms)** For $\Sigma; \Gamma \vdash v : T$:

i. If $T = \text{Ref } S$ then $v = \text{loc}$ and $\Sigma(\text{loc}) <: S$.

ii. If $T = U \cdots \rightarrow S$ then $v = \text{func}(x \cdots) \{ e \}$.

**Proof:** By induction on the typing derivation.

i. Only T-Loc and T-Sub apply. T-Loc is immediate. For T-Sub, $\Sigma; \Gamma \vdash v : T'$ with $T' <: T$. By induction, $v = \text{loc}$, $T' = \text{Ref } S'$, and $\Sigma(\text{loc}) <: S'$. 
ii. Only T-Abs and T-Sub apply. T-Abs is immediate, and T-Sub follows by induction.

Lemma 19 (static commutes with subtyping) If $S <: T$, then $\text{static}(R, S) <: \text{static}(R, T)$.

Proof: by induction on $S <: T$.

Lemma 20 If $\Sigma; \Gamma \vdash v : T$, then $\delta_1(\text{typeof}, v) \in \text{runtime}(T)$.

Proof: by case analysis of $v$.

C.3 CPS Transformation

The following four mutually-recursive functions define our CPS transformation: $C_k$ transforms expressions, $\Phi$ transforms values, $K_k$ transforms evaluation contexts, and $P_k$ transforms program states (expressions with stores). This style of transformation is due to Sabry and Felleisen [75]. Our presentation has a few minor distinctions:

- The semantics of our source language directly specifies the evaluation of `break`, which is a very restricted form of `call/cc`. Hence, `break` is an expression transformed by $C_k$, instead of a value transformed by $\Phi$.

- We use a global store instead of a syntactic store, hence the need for $P_k$.

- We use `let`-expressions to avoid continuation-passing operators.

- We do not employ a fully-compacting transformation. For example, we do not have a special-case for $C_k[E[(\text{func}(x\ldots):T \{ e \}) (v\ldots)]]$, as it would introduce interprocedural flows in the source language. (In contrast, see [75] Definition 5.)
\[ C_k : e \to M \]

\[
C_k[v] = k(\Phi[v])
\]

\[
C_k[E(let \ (x = v) \ e)] = let \ (x = \Phi[v])C_k[E(e)]
\]

\[
C_k[E(v_f(v_1 \cdots))] = \Phi[v_f](K_k[E], \Phi[v] \cdots)
\]

\[
C_k[E(op_n(v_1 \cdots))] = let \ x = op_n(\Phi[v] \cdots) \ in \ K_k[E](x)
\]

\[
C_k[E(if \ (v) \ { e_2 } \ else \ { e_3 } )] = (func \ (k) \ { if \ (\Phi[v]) \ C_k[e_2] \ else \ { C_k[e_3] } \ })(K_k[E])
\]

\[
C_k[E_1(label: \ { E_2(break \ label \ v) } )] = K_k[E_1](\Phi[v]), \ when \ label \not\in \ E_2
\]

\[
C_k[E(label: \ { v \ i } )] = C_k[E(v)]
\]

\[
C_k[E(ref \ v)] = let \ x = ref \ \Phi[v] \ in \ K_k[E](x)
\]

\[
C_k[E(deref \ v)] = let \ x = deref \ \Phi[v] \ in \ K_k[E](x)
\]

\[
C_k[E(setref \ l \ v)] = let \ x = setref \ l \ \Phi[v] \ in \ K_k[E](l)
\]

\[
C_k[E(tagcheck \ R \ v)] = let \ x = tagcheck \ R \ \Phi[v] \ in \ K_k[E](x)
\]

\[ \Phi : v \to V \]

\[
\Phi[x] = x
\]

\[
\Phi[func(x \cdots):S \to T \ \{e\}] = func(k, x \cdots): (T \to \bot) \times S \to \bot \ \{ C_k[e] \}
\]

\[
\Phi[c] = c
\]

\[
\Phi[l] = l
\]
\[ K_k : E \rightarrow V \]

\[
K_k[\bullet] = k \\
K_k[E(\text{let } (x = \bullet) e)] = \text{func}(x) \{ C_k[E(e)] \} \\
K_k[E(\text{setref } e)] = \text{func}(x) \{ C_k[E(x = e)] \} \\
K_k[E(\text{break label } \bullet)] = \text{func}(x) \{ C_k[E(\text{break label } x)] \} \\
K_k[E(\text{tagcheck } R \bullet)] = \text{func}(x) \{ C_k[E(\text{tagcheck } R x)] \}
\]

\[ P_k : \sigma e \rightarrow SM \]

\[ P_k[(l, v) \cdots e] = (l, \Phi(v)) \cdots C_k[e] \]

**Lemma 21 (Soundness of \( P_k \))** If \( \sigma e \rightarrow R \sigma' e' \), then \( P_k[\sigma e] \rightarrow (P_{R,E-Let,\beta}) P_k[\sigma' e'] \).

**Proof:** The proof is by induction on the size of \( \sigma e \) and proceeds by case-analysis of the definition of \( \rightarrow \). To prove that only R, E-Let, and \( \beta \) are applied, we simply examine the reduction sequences below. Note that the auxiliary lemma 22 only employs \( \beta \).

- **Case E-Let.**

  \[
  S C_k[E(\text{let } (x = v) e)] \\
  = S \text{let } (x = \Phi[v]) C_k[E(e)] \\
  \rightarrow S C_k[E(e)][x/\Phi[v]] \quad \text{E-Let} \\
  = S C_k[E(e)[x/v]] \quad \text{lemma 23}
  \]

  which is \( C_k \), applied to the the RHS of E-Let.
• Case E-Break.

\[
S \cdot C_k[\{\text{label}: T \langle \text{break label v} \rangle}\}]
\]
\[
= S \cdot K_k[E_1(\Phi[v])]
\]
\[
\rightarrow S \cdot C_k[E_1(v)] \quad \text{lemma 22}
\]

• Case E-Label-Pop.

\[
S \cdot C_k[E \langle \text{label} \{v\} \rangle]
\]
\[
= S \cdot C_k[E \langle v \rangle]
\]

• Case E-Ref.

\[
S \cdot C_k[E \langle \text{ref v} \rangle]
\]
\[
= S \cdot \text{let } x = \text{ref } \Phi[v] \text{ in } K_k[E](x)
\]
\[
\rightarrow S, (l, \Phi[v]) \text{ let } x = l \text{ in } K_k[E](x) \quad \text{E-Ref}
\]
\[
\rightarrow S, (l, \Phi[v]) \cdot K_k[E](l) \quad \text{E-Let}
\]
\[
= S, (l, \Phi[v]) \cdot K_k[E](\Phi(l))
\]
\[
\rightarrow S, (l, \Phi[v]) \cdot C_k[E \langle l \rangle] \quad \text{lemma 22}
\]

• Case E-Deref.

\[
S \cdot C_k[E \langle \text{deref l} \rangle]
\]
\[
= S \cdot \text{let } x = \text{deref } l \text{ in } K_k[E](x)
\]
\[
\rightarrow S \cdot \text{let } x = S(l) \text{ in } K_k[E](x) \quad \text{E-Deref and } \text{dom}(S) = \text{dom}(\sigma)
\]
\[
\rightarrow S \cdot K_k[E](S(l)) \quad \text{E-Let}
\]
\[
\rightarrow S \cdot C_k[E \langle l \rangle] \quad \text{lemma 22} \text{ where } S(l) = \Phi(v)
\]

• Case E-SetRef.

\[
S \cdot C_k[E \langle \text{setref l v} \rangle]
\]
\[
= S \cdot \text{let } x = \text{setref } l \Phi[v] \text{ in } K_k[E](l)
\]
\[
\rightarrow (l, \Phi[v]) \cdot S \text{ let } x = l \text{ in } K_k[E](l)
\]
\[
\rightarrow (l, \Phi[v]) \cdot S \cdot K_k[E](l) \quad \text{since } x \text{ is unused}
\]
\[
\rightarrow (l, \Phi[v]) \cdot S \cdot C_k[E \langle l \rangle] \quad \text{by lemma 22} \text{ since } \phi(l) = l
\]
• Case E-TagCheck.

\[ S \ C_k[E[\text{tagcheck } R v]] \]
\[ = S \text{ let } x = \text{tagcheck } R \Phi[v] \text{ in } K_k[E](x) \]
\[ \rightarrow S K_k[E](\Phi[v]) \quad \text{since } \text{typeof}(v) = \text{typeof}(\Phi[v]) \]
\[ \rightarrow S C_k[E(v)] \]

lemma 22

\[ S \leftarrow S \]

Lemma 22 \[ SK_k[E]\Phi[v)] \rightarrow \beta SC_k[E(v)]. \]

Proof: The proof is by case analysis of \( E \). We elide \( S \) in the steps below as it remains constant.

• Case \( E(\text{ref } \cdot) \).

\[ K_k[E(\text{ref } \cdot)](\Phi[v]) \]
\[ = (\text{func}(x) \ (C_k[E(\text{ref } x)])(\Phi[v])) \]
\[ \rightarrow C_k[E(\text{ref } x)][x/\Phi[v]] \]
\[ = C_k[E(\text{ref } x)] \]

\[ \rightarrow \]

by lemma 23

• Case \( E(\text{break label } \cdot) \).

\[ K_k[E(\text{break label } \cdot)](\Phi[v]) \]
\[ = (\text{func}(x) \ (C_k[E(\text{break label } x)])(\Phi[v])) \]
\[ \rightarrow C_k[E(\text{break label } x)][x/\Phi[v]] \]
\[ = C_k[E(\text{break label } x)] \]

by lemma 23

• Case \( E(\text{if } \cdot) \ (e_1) \text{ else } \ (e_2) \).

\[ K_k[E(\text{if } \cdot) (e_1) \text{ else } (e_2)](\Phi[v]) \]
\[ = \text{func}(x) \ (C_k[E(\text{if } x) (e_1) \text{ else } (e_2)])(\Phi[v]) \]
\[ \rightarrow C_k[E(\text{if } x) (e_1) \text{ else } (e_2)][x/\Phi[v]] \]
\[ = C_k[E(\text{if } x) (e_1) \text{ else } (e_2)][x/v] \]

by lemma 23

\[ = C_k[E(\text{if } v) (e_1) \text{ else } (e_2)] \]
• Case \( E\langle •(e\ldots) \rangle \).

\[
K_k[E\langle •(e\ldots) \rangle ](\Phi[v]) = \text{func}(f) \{ C_k[E\langle f(e\ldots) \rangle ](\Phi[v]) \}
\]

\[
\rightarrow C_k[E\langle f(e\ldots) \rangle ][f/\Phi[v]] = C_k[E\langle v(e\ldots) \rangle ]
\]

Cases \( E\langle v_f(v\ldots e\ldots) \rangle \) and \( E\langle op_a(v\ldots e\ldots) \rangle \) are similar.

• Case \( E\langle label: \{ • \} \rangle \).

\[
K_k[E\langle label: \{ • \} \rangle ](\Phi[v]) = \text{func}(x) \{ C_k[E\langle label: \{ x \} \rangle ](\Phi[v]) \}
\]

\[
\rightarrow C_k[E\langle label: \{ x \} \rangle ][x/\Phi[v]] = C_k[E\langle label: \{ v \} \rangle ]
\]

by lemma 23

• Case \( E\langle deref • \rangle \).

\[
K_k[E\langle deref • \rangle ](\Phi[v]) = \text{func}(x) \{ C_k[E\langle deref x \rangle ](\Phi[v]) \}
\]

\[
\rightarrow C_k[E\langle deref x \rangle ][x/\Phi[v]] = C_k[E\langle deref v \rangle ]
\]

by lemma 23

• Case \( E\langle setref • e \rangle \).

\[
K_k[E\langle setref • e \rangle ](\Phi[v]) = \text{func}(x) \{ C_k[E\langle setref x e \rangle ](\Phi[v]) \}
\]

\[
\rightarrow C_k[E\langle setref x e \rangle ][x/\Phi[v]] = C_k[E\langle setref v e \rangle ]
\]

by lemma 23

Case \( E\langle setref v • e \rangle \) is similar.
• Case $E\langle \text{tagcheck } R \rangle$.

$$
\begin{align*}
\mathcal{K}_k[E\langle \text{tagcheck } R \rangle](\Phi[v]) & = (\func(x) \{ C_k[E\langle \text{tagcheck } R \rangle x \} \})(\Phi[v]) \\
& \to C_k[E\langle \text{tagcheck } R \rangle x](x/\Phi[v]) \quad \beta_v \\
& = C_k[E\langle \text{tagcheck } R \rangle x][x/v] \\
& = C_k[E\langle \text{tagcheck } R \rangle v]
\end{align*}
$$

\[\square\]

Lemma 23 (Substitution Commutes with $C_k$) $C_k[e][x/\Phi(v)] = C_k[e[x/v]]$.

**Proof:** by induction on the structure of $e$. For each inductive case of $C_k$, expand the definitions of $\Phi$ and $\mathcal{K}_k$ on the RHS to get a term with $C_k$ applied to subterms of $e$. The inductive hypotheses now trivially apply. \[\square\]

### C.4 Additional Rules for Flow Analysis

For soundness of flow analysis, we need to reason about intermediate terms with concrete locations, $l$. Hence, we extend abstract heaps to the type:

\[\begin{align*}
\hat{S} & : \hat{l} + l \to R \\
\hat{S}; \hat{\Gamma} \triangleright V \rightsquigarrow \hat{V}
\end{align*}\]

\[
\begin{align*}
\hat{S}(\hat{l}) & = R & \text{runtime}(V) & = R \\
\hat{S}; \hat{\Gamma} \triangleright V \rightsquigarrow \text{Deref } \hat{l} \ R & \quad \text{(V-DEREF)} \\
\hat{S}; \hat{\Gamma} \triangleright V \rightsquigarrow \text{Deref } \hat{l} \\
\hat{S}; \hat{\Gamma} \triangleright \delta_1(\text{typeof}, V) \rightsquigarrow \text{LocTypeof } \hat{l} & \quad \text{(V-TYPEOF)} \\
\hat{S}; \hat{\Gamma} \triangleright V_1 \rightsquigarrow \text{LocType } \hat{l} & \quad V_2 \in \hat{S}(\hat{l}) \\
\hat{S}; \hat{\Gamma} \triangleright \delta_2(\text{==}, V_1, V_2) \rightsquigarrow \text{LocType } \hat{l} \ R & \quad \text{(V-TYPEIS)} \\
\hat{S}; \hat{\Gamma} \triangleright SM
\end{align*}\]
Furthermore, flow analysis is sound:

**Lemma 24 (Soundness of Flow Analysis)** If $\hat{S} \cdot \models SM$ and $SM \rightarrow S'M'$, then either:

- $\hat{S}' \cdot \models S'M'$, or

\[
\begin{align*}
\text{C.5 Flow Analysis} & \\

\frac{\hat{S}; \hat{\Gamma} \triangleright V \leadsto \hat{V}}{} & (\text{F-DEREF-UNK}) \\
\frac{\hat{S}; \hat{\Gamma} \triangleright x \mapsto r, \hat{\Gamma} \models SM}{} & (\text{F-DEREF-UNK}) \\
\frac{\hat{S}; \hat{\Gamma} \triangleright \{\text{"string"}\}, \hat{\Gamma} \models SM}{} & (\text{F-TYPEOF-UNK}) \\
\frac{\hat{S}; \hat{\Gamma} \triangleright V_1 \leadsto \hat{V}_1 \quad \hat{S}; \hat{\Gamma} \triangleright V_2 \leadsto \hat{V}_2}{\hat{S}; \hat{\Gamma} \models S \text{ let } (x = \text{typeof } V) \ M} & (\text{F-EQ}) \\
\frac{\hat{S}; \hat{\Gamma} \triangleright V_1 \leadsto \text{Ref } \hat{l}_1 \quad \hat{S}; \hat{\Gamma} \triangleright V_2 \leadsto \text{Ref } \hat{l}_2 \quad \hat{l} : R, \hat{S}; \hat{x} : r, \text{del}(\hat{l}_1, \text{del}(\hat{l}_2, \hat{\Gamma})) \models SM}{} & (\text{F-SETREF-ALIAS1}) \\
\frac{\hat{S}; \hat{\Gamma} \triangleright V_1 \leadsto \hat{V}_1 \quad \hat{S}; \hat{\Gamma} \triangleright V_2 \leadsto \text{Ref } \hat{l}_2 \quad \hat{l} : R, \hat{S}; \hat{x} : r, \text{del}(\hat{l}_2, \hat{\Gamma}) \models SM}{} & (\text{F-SETREF-ALIAS2}) \\
\frac{\hat{S}; \hat{\Gamma} \triangleright V \leadsto \hat{V}}{} & (\text{F-IF}) \\
\frac{\hat{S}; \hat{\Gamma} \models M_1 \quad \hat{S}; \hat{\Gamma} \models M_2}{\hat{S}; \hat{\Gamma} \models \text{if (V) } \{ M_1 \} \ \text{else } \{ M_2 \}} & (\text{F-IF-TRUE}) \\
\frac{\hat{S}; \hat{\Gamma} \models \text{if (true) } \{ M_1 \} \ \text{else } \{ M_2 \}}{} & (\text{F-IF-TRUE}) \\
\frac{\hat{S}; \hat{\Gamma} \models \text{if (false) } \{ M_1 \} \ \text{else } \{ M_2 \}}{} & (\text{F-IF-TRUE}) \\
\end{align*}
\]
• $M$ is a $\beta_v$ redex, $\text{func}(x\cdots) : T\cdots \vdash (N:\!(V\cdots))$, and for some $V$, $\delta_1(\text{typeof}, V) \notin \text{runtime}(T)$.

**Proof:** by case-analysis on $M$.

• Case $S \text{func}(x\cdots) : T\cdots \vdash (N:\!(V\cdots)) \rightarrow SN[x/V]\cdots$.

By inversion, $\vdash x : \text{runtime}(T)\cdots \vdash N$ (V-Restart) and there exist $R\cdots$, such that $\vdash V \rightsquigarrow R\cdots$. Since $V\cdots$ are all closed, $\delta_1(\text{typeof}, V)\cdots$ is defined. By case analysis on $V$, $\vdash ; ; ; V \rightsquigarrow \{\delta_1(\text{typeof}, V)\}\cdots$. There are two cases:

- If $\{\delta_1(\text{typeof}, V)\}\subseteq \text{runtime}(T)\cdots$, then by substitution (lemma 25), $\vdash \cdot ; \cdot \vdash N[x/V\cdots]$.

- Otherwise, for some $V, T$, $\delta_1(\text{typeof}, V) \notin \text{runtime}(T)$.

• Case $S \text{let}\ x = \text{vin} M \rightarrow SM[x/V]$.

By F-LetVal, $\widehat{S}; \vdash S \text{let} x = \text{vin} M$. By hypothesis, $\widehat{S}; x : \widehat{V} \equiv SM$ and $\widehat{S}; \vdash V \rightsquigarrow \widehat{V}$. By substitution (lemma 25), $\widehat{S}; \vdash SM[x/V]$.

• Case $S \text{let}\ x = \text{ref} \text{vin} M \rightarrow (l, V)S \text{let} x = l\in M$.

There are two applicable rules.

- By F-Allok, $\widehat{S}; \vdash V \rightsquigarrow R$ and $\hat{l} : R, \widehat{S}; x : \text{Ref} \hat{l} \equiv SM$. By V-Loc, $(l, V), \widehat{S}; \vdash l \rightsquigarrow \text{Ref} l$.

  Renaming $\hat{l}$ to $l$ (lemma 26), $l : R, \widehat{S}; x : \text{Ref} l \equiv SM$. Hence by F-LetVal, $l : R; \widehat{S}; \vdash (l, V), S \text{let} x = l\in M$.

- By F-Ref-Alias, $\widehat{S}; \vdash V \rightsquigarrow \text{Ref} \hat{l}$ and $\widehat{S}; x : r \equiv SM$. By V-Loc, followed by V-Sub, $(l, v), \widehat{S}; \vdash \hat{l} \rightsquigarrow r$. Hence by F-LetVal, $l : r, \widehat{S}; \vdash (l, V), S \text{let} x = l\in M$.

• Case $S \text{let}\ x = \text{deref} l \text{in} M \rightarrow S \text{let} x = S(l) \text{in} M$.

- By F-Deref, $\widehat{S}; \vdash l \rightsquigarrow \text{Ref} l$, $\widehat{S}(l) = R$, and $\widehat{S}; x : \text{Deref} l R \equiv SM$. By V-Deref, $\widehat{S}; \vdash S(l) \rightsquigarrow \text{Deref} l R$. Apply F-LetVal to the RHS.

- By F-Deref-Unk, $\widehat{S}; x : r \equiv SM$ and $\widehat{S}; \vdash S(l) \rightsquigarrow \widehat{V}$. By V-Sub and F-LetVal, the conclusion follows.

• Case $S \text{let}\ x = \text{typeof} V \text{in} M \rightarrow S \text{let} x = \delta_1(\text{typeof}, V) \text{in} M$.

- By F-Typeof, $\vdash V \rightsquigarrow \text{Deref} \hat{l} R$ and $\widehat{S}; x : \text{LocTypeof} \hat{l} \equiv M$. By V-Typeof, $\widehat{S}; \vdash \delta_1(\text{typeof}, V) \rightsquigarrow \text{LocTypeof} \hat{l}$. Apply F-LetVal to the RHS.
Lemma 25 (Substitution) If \( \hat{\delta} \cdot \hat{\delta}(\text{typeof}, V) \leadsto \tilde{V} \). By definition of \( \delta_1(\text{typeof}) \), \( \hat{\delta} \cdot \hat{\delta}(\text{typeof}, V) \leadsto \{\text{"string"}\} \). Apply F-LetVal.

- Case \( S \) let \( x = V \) in \( M \rightarrow S \) S let \( x = \delta_2(\text{===}, V_1, V_2) \) in \( M \).
  - By F-TypeIs-Unk, \( \hat{\delta} \cdot \hat{\delta}(\text{typeof}, V_1) \leadsto \tilde{V}_1 \). By definition of \( \delta_2(\text{===}) \), \( \hat{\delta}(\text{typeof}, V_1, V_2) \leadsto \{\text{"string"}\} \). Apply F-LetVal.
  - By F-TypeIs-Str, \( \hat{\delta} \cdot \hat{\delta}(\text{===}, V_1, V_2) \leadsto \{\text{"string"}\} \). Apply F-LetVal to the RHS.
  - By F-Eq, \( \hat{\delta} \cdot \hat{\delta}(\text{===}, V_1, V_2) \leadsto \{\text{"string"}\} \). Apply F-LetVal.

- Case \( S \) if \( (\text{true}) \{ M_1 \} \) else \( \{ M_2 \} \rightarrow S \) M_1.
  - By F-True, \( \hat{\delta} \cdot \hat{\delta}(\text{typeof}, V) \leadsto \text{LocType} \hat{l} \), \( R \sqsubseteq \hat{\delta}(\hat{l}) \), and \( \hat{\delta} \cdot \hat{\delta}(\text{typeof}, V) \leadsto M_1 \).

- Case \( S \) if \( (\text{false}) \{ M_1 \} \) else \( \{ M_2 \} \rightarrow S \) M_2.
  - By F-False, \( \hat{\delta} \cdot \hat{\delta}(\text{typeof}, V) \leadsto \text{LocType} \hat{l} \), \( R \sqsubseteq \hat{\delta}(\hat{l}) \), and \( \hat{\delta} \cdot \hat{\delta}(\text{typeof}, V) \leadsto M_2 \).

**Lemma 25 (Substitution)** If \( \hat{\delta} \cdot \hat{\delta}(\text{typeof}, V) \leadsto \tilde{V} \), with \( \tilde{V} \sqsubseteq \hat{\delta} \cdot \hat{\delta}(\text{typeof}, V) \leadsto \). The key to this proof is substituting values \( \hat{\delta} \cdot \hat{\delta}(\text{typeof}, V) \leadsto \tilde{V} \), with \( \tilde{V} \sqsubseteq \hat{\delta} \cdot \hat{\delta}(\text{typeof}, V) \leadsto \). So, by V-Restart:

\[
\vdash \cdot; y : \text{runtime}(T) \cdots, \text{reset}(x : \hat{V}:\tilde{\Gamma}) = M'
\]

By definition of \( \text{reset}, \hat{V} \sqsubseteq \hat{\delta}(\text{typeof}, V) \leadsto \). Since \( M' \) is smaller than \( M \), the inductive hypothesis applies.
Lemma 26 (Renaming Locations) If $\tilde{l} : \tilde{V}, \tilde{S}; \tilde{\Gamma} \models SM$ and $l \notin \text{dom}(S)$, then $l : \tilde{V}, \tilde{S}; \tilde{\Gamma}[\tilde{l}/l] \models SM$.

Proof by induction on the size of $\tilde{\Gamma}$.

C.6 Combined Soundness Theorems

Theorem 8 (Strengthened Progress) If:

i. $\Sigma; \cdot \vdash e : T$,

ii. $\Sigma \vdash \sigma$, and

iii. $\tilde{S}; \cdot \models \mathcal{P}_k[\sigma e]$, 

then either:

i. $e \in v$, or

ii. There exist $\sigma'$ and $e'$, such that $\sigma e \rightarrow \sigma'e'$.

Proof: This follows from lemma 6, with the possibility of tags eliminated by inspection of the acceptability relation—flow analysis does not admit expressions with tags.

Theorem 9 (Combined Preservation) If:

i. $\Sigma; \cdot \vdash e : T$,

ii. $\Sigma \vdash \sigma$,

ii. $\tilde{S}; \cdot \models \mathcal{P}_k[\sigma e]$, and

iv. $\sigma e \rightarrow \sigma'e'$,

then there exist $\Sigma'$ and $\tilde{S}'$, such that:

i. $\Sigma'; \cdot \vdash e' : T$,

ii. $\Sigma' \vdash \sigma'$,

iii. $\Sigma \subseteq \Sigma'$, and
iv. \( S' ; = P_k[\sigma'e'] \).

**Proof:** Conclusions (i.), (ii.), and (iii.) follow immediately from lemma 5. For conclusion (iv.), apply lemma 7 to hypothesis (iv.) to get a reduction sequence, \( P_k[\sigma e] \rightarrow P_k[\sigma'e'] \). Apply lemma 8 at each step, eliminating case (ii.) of the lemma as follows. By lemma 7, intermediate expressions are not \( \beta_v \)-redexes, so case (ii.) does not apply. Suppose \( e \) itself has an active \( \beta_v \)-redex:

\[
e = E\langle \text{func}(x \cdots) : U \cdots \rightarrow S \{ e_f \, y(v \cdots) \rangle
\]

Transform \( e \) to CPS:

\[
C_k[e] = \Phi J\langle \text{func}(x \cdots) : U \cdots \rightarrow S \{ e_f \, y(\Phi[v]) \rangle
\]

Since \( e \) is typable, there exists a \( \Gamma \) such that:

\[
\Sigma; \Gamma \vdash \text{func}(x \cdots) : U \cdots \rightarrow S \{ e_f \, y(v \cdots) : S
\]

Furthermore, by inversion (lemma 17), \( \Sigma; \Gamma \vdash v : U \cdots \). For all \( v \), \( \delta_1(\text{typeof}, v) \in \text{runtime}(U) \) (lemma 20). By inspection of \( \Phi \), \( \delta_1(\text{typeof}, v) = \delta_1(\text{typeof}, \Phi[v]) \), case (ii.) of lemma 8 does not apply.

\[\blacksquare\]
Appendix D

Proofs: Fluid Object Types

D.1 Definitions

Definition 3 (Type Equivalence) We define a relation on types $=_T$.

$$
\forall i,j. L_i \cap M_j \neq \emptyset \Rightarrow S_i =_T T_j \land p_i = q_j
$$

$$
\forall i. \exists (j_1, \ldots, j_k). L_i \subseteq \bigcup_{j \in (j_1, \ldots, j_k)} M_j
$$

$$
\forall j. \exists (i_1, \ldots, i_k). M_i \subseteq \bigcup_{i \in (i_1, \ldots, i_k)} L_i
$$

$\{L_1^{p_1} : S_1, \ldots, L_n^{p_n} : S_n, L_A : \text{abs}\} =_T \{M_1^{q_1} : T_1, \ldots, M_m^{q_m} : T_m, M_A : \text{abs}\}$ \hspace{1cm} (EQUIV-OBJ)

The other cases of $=_T$ are trivial; to define them we lift Equiv-Obj in the natural way over the other types. $=_T$ describes an equivalence class of types—we use $T_1 =_T T_2$ and $T_1 = T_2$ interchangeably in this document, and types represented by the same letter are assumed to be related by $=_T$.

Definition 4 (Subtyping) The generating function,

$$
ST : \mathcal{P}(\Gamma \times T \times T + p \times p) \to \mathcal{P}(\Gamma \times T \times T + p \times p)
$$

is defined co-inductively by the subtyping judgments. We define subtyping as $\Gamma \vdash S <: T$, iff $(\Gamma, S, T) \in \nu ST$ and $p <: q$, iff $(p, q) \in \nu ST$. 

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Definition 5 (Transitivity) For $R \subseteq P(\Gamma \times T \times T + p \times p)$

$$TR(R) = \{(\Gamma, x, z) \mid \forall x, z \in T, \exists y \in T, (\Gamma, x, y), (\Gamma, y, z) \in R\}$$

$\cup \{(x, z) \mid \forall x, z \in p, \exists y \in p, (x, y), (y, z) \in R\}$

Definition 6 (Top-down Subexpressions) $S$ is a top-down subexpression of $T$, written $S \sqsubseteq T$, if $(S, T)$ is in $\mu TD$, defined as follows:

$$TD(R) = \{(T, T) \mid T \text{ is a finite type } \}$$

$\cup \{(S, \{L^p : T, \text{rest} \ldots \}) \mid (S, T) \in R\}$

$\cup \{(S, \{L^p : T, \text{rest} \ldots \}) \mid (S, \{\text{rest}\}) \in R\}$

$\cup \{(S, \{L^p : T\}) \mid (S, T) \in R\}$

$\cup \{(S, \text{Ref } T) \mid (S, T) \in R\}$

$\cup \{(S, \mu x. T) \mid (S, T[x/\mu x. T]) \in R\}$

$\cup \{(S, T_1 \rightarrow T_2) \mid (S, T_1) \in R\}$

$\cup \{(S, T_1 \rightarrow T_2) \mid (S, T_2) \in R\}$

$\cup \{(S, \forall x <: U. T) \mid (S, U) \in R\}$

$\cup \{(S, \forall x <: U. T) \mid (S, T) \in R\}$

Definition 7 (Bottom-Up Subexpressions) $S$ is a bottom-up subexpression of $T$, written $S \trianglelefteq T$, if $(S, T)$ is in $\mu BU$, defined as follows:

$$BU(R) = \{(T, T) \mid T \text{ is a finite type } \}$$

$\cup \{(S, \{L^p : T, \text{rest} \ldots \}) \mid (S, T) \in R\}$

$\cup \{(S, \{L^p : T, \text{rest} \ldots \}) \mid (S, \{\text{rest}\}) \in R\}$

$\cup \{(S, \{L^p : T\}) \mid (S, T) \in R\}$

$\cup \{(S, \text{Ref } T) \mid (S, T) \in R\}$

$\cup \{(S, T_1 \rightarrow T_2) \mid (S, T_1) \in R\}$

$\cup \{(S, T_1 \rightarrow T_2) \mid (S, T_2) \in R\}$

$\cup \{(S, \forall x <: U. T) \mid (S, U) \in R\}$

$\cup \{(S, \forall x <: U. T) \mid (S, T) \in R\}$

$\cup \{(S[x/\mu x. T], \mu x. T) \mid (S, T) \in R\}$
Definition 8 (Active Expressions) Active expressions, $ae$, are defined as follows:

$$ae = v_1(v_2) | \text{ref } v | \text{deref } v | v_1 = v_2 | v_1[v_2] | v_1[v_2] = v_3 | \text{delete } v_1[v_2] | \text{if } (v_1) \{ e_2 \} \text{ else } \{ e_3 \} | v_1 \text{ hasfield } v_2 | v_1 \text{ matches } v_2 | \text{fieldin } \{ s_1 : v_1, s_2 : v_2, \ldots \} \text{ init } v_{acc} \text{ do } v_f$$

D.2 Auxiliary Lemmas

Lemma 27 For all $T$, $\mathcal{T}_T^\downarrow \subseteq \mathcal{T}_T^\uparrow$

Proof This is exactly the same argument as Pierce [71].

Lemma 28 The set of top-down subexpressions, $\mathcal{T}_T^\downarrow = \{ S \mid (S,T) \in \mu TD \}$, is finite for all $T$.

Proof By lemma 27, $\mathcal{T}_T^\downarrow \subseteq \mathcal{T}_T^\uparrow$ for all $T$, and by lemma 29, $\mathcal{T}_T^\uparrow$ is finite for all $T$, so $\mathcal{T}_T^\downarrow$ is finite for all $T$.

Lemma 29 The set of bottom-up subexpressions, $\mathcal{T}_T^\uparrow = \{ S \mid (S,T) \in \mu BU \}$ is finite for all $T$.

Proof The second position in the each right-hand clause in $BU$ is smaller than the left.

Lemma 30 If $(S,T[x/U]) \in \mathcal{T}_{T[x/U]}^\downarrow$, then either $(S,U) \in \mathcal{T}_U^\downarrow$ or $S = S'[x/U]$ for some $(S',T) \in \mathcal{T}_T^\downarrow$.

Proof By case analysis on $T$. 
D.3 Subtyping

Lemma 31 If:

\[ S : \mathcal{P}(\Gamma \times \mathcal{T} \times \mathcal{T} + p \times p) \rightarrow \mathcal{P}(\Gamma \times \mathcal{T} \times \mathcal{T} + p \times p) \]

is a monotone function, and for all \( R \), \( TR(S(R)) \subseteq S(TR(R)) \), then \( \nu S \) is transitive.

Proof: This definition is from Gapayev, et al., and reproduced in Pierce’s text. Its relation to transitivity is discussed there—we use it as a goal and defer to their explanation to complete the proof [71, Lemma 21.3.6].

Lemma 32 (Subtyping is Transitive) \( TR(\nu ST) \subseteq \nu ST \)

Proof:

For arbitrary \( R \), we consider both field annotations in \((p, q)\), and subtyping judgments \((\Gamma, S, T)\):

Let \((p, q) \in TR(ST(R))\). By definition of \( TR \), there exists a \( p' \) such that \((p, p'), (p', q) \in ST(R)\).

By case analysis of the \( p <: p \) rules, it follows trivially that \((p, q) \in ST(TR(R))\).

Let \((\Gamma, S, T) \in TR(ST(R))\). By definition of \( TR \), there exists a \( U \) such that \((\Gamma, S, U), (\Gamma, U, T) \in ST(R)\). We will show that \((\Gamma, S, T) \in ST(TR(R))\), so that by lemma [31] \( \nu ST \) is transitive.

By case-analysis on the possible shapes of \( U \) (eliding the trivial cases where \( T = \top \)):

- \( U = \{L_{p1}^{p1} : U_1, \cdots, L_{pn}^{pn} : U_n, L_A : \text{abs}\}. \)

Since \((\Gamma, S, U), (\Gamma, U, T) \in ST(R)\), by cases of \( ST \),

\( S = \{K_1^n : S_1, \cdots, K_m^n : S_i, K_A : \text{abs}\}, \) and

\( T = \{M_1^n : T_1, \cdots, M_m^n : T_m, M_A : \text{abs}\}. \)

By hypothesis, \((\Gamma, S, U) \in ST(R)\), which must be by S-Object. By hypothesis of S-Object:

\( \forall i, j: \text{if } K_i \cap L_j \neq \emptyset \text{ then } (S_i, U_j) \in R \) and \((o_i, p_j) \in R, \)

\( \bigcup_1^{n-i} L_i \subseteq \bigcup_1^{n-i} K_h \cup K_A, \)

\( L_A \subseteq K_A, \)

\( \forall i: \text{if } L_i \cap K_A \neq \emptyset \text{ then } (p_j = o \text{ or } p_j = \uparrow), \)

\( \forall i: \text{if } p_i = \uparrow \text{ then } (\Gamma, \text{inherit}(S, L_i), U_i) \in R. \)

Similarly,
∀i,j. if \( L_i \cap M_j \neq \emptyset \) then \((U_i, T_j) \in R\) and \((p_i, q_j) \in R\),

(8) \( \bigcup_{j=1}^{m} M_j \subseteq \bigcup_{i=1}^{n} L_i \cup L_A \),

(8’) \( M_A \subseteq L_A \),

(9) ∀j. if \( M_j \cap L_A \neq \emptyset \) then \( q_j = \circ \) or \( q_j = \uparrow \),

(10) ∀j. if \( q_j = \uparrow \) then \((\Gamma, \text{inherit}(U, M_j), T_j) \in R\).

Our goal is to show that \((\Gamma, S, T) \in ST(TR(R))\), by constructing a proof of S-Object using the above hypotheses and the definition of \( ST \) and \( TR \). Informally, we need to find support for the hypotheses of S-Object for \( S \) and \( T \) among the elements of \( TR(R) \). In particular, we show that:

a. \( \bigcup_{j=1}^{m} M_j \subseteq \bigcup_{h=1}^{l} K_h \cup K_A \).

**Proof:** By (4), (4’), (8), (8’), and transitivity of subset inclusion.

b. ∀h, j. if \( K_h \cap M_j \neq \emptyset \) then \((o_h, q_j) \in TR(R)\) and \((\Gamma, S, T) \in TR(R)\)

**Proof:** Let \( x \in K_h \cap M_j \), thus \( x \in K_h \) and \( x \in M_j \). By (8), there are two cases:

i. \( x \in L_A \) — In this case, \( M_j \cap L_A \neq \emptyset \). Since \( L_A \subseteq K_A \) by (8’), \( x \in K_A \). But by the well-formedness of object types, object types’ fields are partitioned, and this is a contradiction, since \( x \in K_h \). This case cannot occur.

ii. \( x \in L_i \) for some \( i \) — In this case, we have that \( x \in L_i \) and \( x \in M_j \), so by (7), \((U_i, T_j) \in R\) and \((p_i, q_j) \in R\). We also have that \( x \in L_i \) and \( x \in K_h \), so by (3), \((S_h, U_i) \in R\) and \((o_h, p_i) \in R\). This completes item b., as by definition of \( TR \), \((o_h, p_i) \in R\), \((p_i, q_j) \in R \Rightarrow (o_h, q_j) \in TR(R)\), and \((S_h, U_i) \in R\), \((U_i, T_j) \in R \Rightarrow (S_h, T_j) \in TR(R)\).

c. ∀j. \( M_j \cap K_A \neq \emptyset \) \( \Rightarrow (q_j = \circ \) or \( q_j = \uparrow)\)

**Proof:** For each non-vacuous case of \( j \), there is some \( x \) with \( x \in M_j \) and \( x \in K_A \). By (8), there are two cases:

i. \( x \in M_j \cap L_i \) for some \( i \) — In this case, \( L_i \cap K_A \neq \emptyset \), so by (5) \( p_i = \circ \) or \( p_i = \uparrow \). Only \( p-\text{Refl} \) applies, so item c. is complete.

ii. \( x \in M_j \cap L_A \) — This case follows directly from (9).
d. \( \forall j. \text{if } q_j \uparrow \text{ then } (\Gamma, \text{inherit}(S,M_j),T_j) \in TR(R) \).

**Proof:** By (10), \( \forall j. \text{if } q_j \uparrow \text{ then } (\Gamma, \text{inherit}(U,M_j),T_j) \in R \). By assumption, we have that \((\Gamma, S, U) \in R \) (or, equivalently, \( \Gamma \vdash S <: U \)). Recall from (1) that \( S = \{K_{1}^n : S_1, \ldots, K_{m}^n : S_n, K_A : \text{abs}\} \). By lemma 38, since \( \Gamma \vdash S <: U, M_j \subseteq M_j \), it must be that \( \Gamma \vdash \text{inherit}(S,M_j) <: \text{inherit}(U,M_j) \) for each \( j \). Now we have that \((\Gamma, \text{inherit}(S,M_j), \text{inherit}(U,M_j)) \in R \) and \((\Gamma, \text{inherit}(U,M_j), T_j) \in R \) for each \( j \), which is sufficient to show that \((\Gamma, \text{inherit}(S,M_j), T_j) \in TR(R) \) for each \( j \), which completes the proof.

- **Case** \( U = b \). Only S-b applies, so \( S \) and \( T \) must both be \( b \), and are therefore in \( R \).
- **Case** \( U = L_u \). Only case S-Str applies for \( S <: U \) and \( U <: T \). Thus, \( S = L_s \) and \( T = L_T \), with \( L_s \subseteq L_u \subseteq L_T \). Thus \( S <: T \) follows by transitivity of the subset relation.
- **Case** \( U = \text{Ref } U' \). Only case S-Ref applies, thus \( S = \text{Ref } S' \) and \( T = \text{Ref } T' \), with

\[
(S',U'),(U',S'),(U',T'),(T',U') \in R
\]

By definition of \( TR \),

\[
(S',T'),(T',S') \in TR(R)
\]

Thus,

\[
(\text{Ref } S', \text{Ref } T') \in ST(TR(R))
\]

- **Case** \( U = \alpha \). There are three possibilities, depending on uses of S-VR and S-VTR:
  - \( S = \alpha \) and \( T = \alpha \), so \((\Gamma, S, T) \in TR(R) \) by S-VR.
  - \( S = \beta, \beta \neq \alpha, (\beta <: \alpha) \in \Gamma, \) and \((\alpha <: T) \in \Gamma \). In this case, \((\Gamma, S, T) \in TR(R) \) by S-VTR.
  - \( S = \alpha \) and \((\alpha <: T) \in \Gamma \). In this case, \((\Gamma, S, T) \in TR(R) \) by S-VTR.
- **Case** \( U = \forall \alpha <: U_1.U_2 \). The only rule that applies is S-Kern, so it must be that:
  - \( S = \forall \alpha <: U_1.S_2 \),
  - \((\Gamma, \alpha <: U_1), S_2, U_2) \in ST(R),\)
- \( T = \forall \alpha <: U_1, T_2, \)
- \( ((\Gamma, \alpha <: U_1), U_2, T_2) \in ST(R). \)

By the definition of \( TR, ((\Gamma, \alpha <: U_1), S, T) \in TR(R). \)

- \( U = \mu \alpha. T \) This case is addressed in [71, chapter 21].
- \( U = U_1 \rightarrow U_2 \) See [71, page 288]

\[ \]

**Lemma 33 (Subtyping is Reflexive)** For all \( T \in \mathcal{T}, (T, T) \in \nu ST, \) and for all \( F \in \mathcal{F}, (F, F) \in \nu ST. \)

**Proof:** By case analysis on the subtyping rules.

**Lemma 34** \( ST \) is Invertible

**Proof:** The corresponding support function is well-defined. By inspection of the subtyping rules, for a given pair of expressions, only one typing rule applies.

**Lemma 35** For all types \( S \) and \( T, S <: T \) is decidable.

**Proof:** Since \( S \) and \( T \) are finite \( \mu \)-types, the set \( reachables_{ST}(S, T) \) is finite [71, Proposition 21.9.11]. Thus, the algorithm \( gfp_{ST} \) [71, Definition 21.5.5] terminates [71, Theorem 21.5.12].

**Lemma 36** For all \( \Gamma, T, L, M, inherit_\Gamma(T, L) \sqcup inherit_\Gamma(T, M) = inherit_\Gamma(T, L \sqcup M). \)

**Proof:** By induction on the syntactic size of \( T \) and by definition of the join operator.

Note that in the definition of \( inherit \), the condition in both cases requires that for some \( L_C, L_Q \subseteq L_C \). \( L \subseteq L_C \) and \( M \subseteq L_C \) hold if the left-hand side of the equality are defined. However, \( L \sqcup M \subseteq L_C \) holds only because \( L \sqcup M = L \sqcup M \).

**Lemma 37** If \( L_Q \subseteq M_Q \subseteq \bigcup_{j=1}^{m} M_j \) and \( \forall i, j. L_i \cap M_j \neq \emptyset \Rightarrow \Gamma \vdash S'_i <: T'_j \) then

\[
\Gamma \vdash \bigcup_{i} \{ S'_i \mid \Gamma \vdash L_Q \cap L_i \neq \emptyset \} <: \bigcup_{j} \{ T'_j \mid \Gamma \vdash M_Q \cap M_j \neq \emptyset \}
\]
**Proof:** It is sufficient to show that for all $S'_i$ on the left-hand side, there exists a $T'_j$ such that $\Gamma \vdash S'_i <: T'_j$.

For any $S'_i$, since $L_i \cap L_Q \neq \emptyset$, $\exists \text{str. str} \in L_i \cap L_Q$. Since $L_Q \subseteq \bigcup M_j$, intersecting on the left-hand side we have $L_i \cap L_Q \subseteq \bigcup M_j$. Thus $\text{str} \in \bigcup\{M_j | q_j \neq ^\circ\}$. Therefore, $\exists M_j, \text{str} \in M_j$, hence $L_i \cap M_j \neq \emptyset$ and so $\Gamma \vdash S'_i <: T'_j$. ■

**Lemma 38** For all $\Gamma, S, T, L_Q, M_Q$, if:

- $H1.$ $\Gamma \vdash S <: T$,
- $H2.$ $\Gamma \vdash L_Q \subseteq M_Q$,
- $H3.$ $\text{inherit}_F(S, L_Q) = S'$, and
- $H4.$ $\text{inherit}_F(T, M_Q) = T'$,

then $\Gamma \vdash S' <: T'$.

**Proof:** By double induction on syntactic size of $S'$ and $T'$, followed by case analysis of $\text{inherit}$ in $H3$ and $H4$. We thus have four cases. In all cases, by inversion of $(H1)$ and the definition of $\text{inherit}$, we have:

$$S = \{L_1^p : S_1'^{i_1} \cdots L_n^p : S_n'^{i_n}, L_A : \text{abs}\}$$

$$T = \{M_1^p : T_1'^{i_1} \cdots M_m^p : T_m'^{i_m}, M_A : \text{abs}\}$$

We thus have available the hypotheses of S-Object:

- $I1.$ $\forall i, j. L_i \cap M_j \neq \emptyset \Rightarrow p_i <: q_j \land \Gamma \vdash S'_i <: T'_j$,
- $I2.$ $\bigcup_{i=1}^{\cdots m} M_i \subseteq \bigcup_{j=1}^{\cdots n} L_j \cup L_A$,
- $I3.$ $M_A \subseteq L_A$,
- $I4.$ $\forall j. \text{if } q_j = ^\uparrow \text{ then } q_j = ^\uparrow \land \Gamma \vdash \text{inherit}(S, M_j) <: T'_j$, and
- $I5.$ $\forall j. \text{if } M_j \cap L_A \neq \emptyset \text{ then } q_j = ^\circ \text{ or } q_j = ^\uparrow$
Case 1. Base case, where "parent" of both S and T are Null or elided.

By definition of inherit, the goal is:

\[ \Gamma \vdash L^\prime_i \cap L_i \neq \emptyset \prec \left( \bigcup_i \{ S'_i | \Gamma \vdash L^\prime_i \cap L_i \neq \emptyset \} \cup \text{inherit}(S_p, L) \right) \]

The condition on both applications of inherit are \( L_Q \subseteq \bigcup_i \{ L_i \mid p_i \neq \circ \} \) and \( M_Q \subseteq \bigcup_j \{ M_j \mid q_j \neq \circ \} \). Therefore, \( M_Q \subseteq \bigcup M_j \) and lemma 37 applies.

Case 2. Inductive case, where "parent" of both S and T are references to objects.

H5. \( \exists L_i. \) "parent" \( \in L_i \land S'_i = \text{Ref } S_p \),

H5'. \( L_Q \subseteq \bigcup_i \{ L_i \} \cup L_A \),

H6. \( \exists M_i. \) "parent" \( \in M_i \land T'_i = \text{Ref } T_p \), and

H6'. \( M_Q \subseteq \bigcup_i \{ M_i \} \cup M_A \).

HInd. \( \forall L'_Q, M'_Q, S_P, T_P. |S_p| < |S| \land |T_p| < |T| \land \Gamma \vdash L'_Q \subseteq M'_Q \land \Gamma \vdash S_P <: T_P \) implies that

\( \text{inherit}_L(S_P, L'_Q) = S'_P \land \text{inherit}_L(T_P, M'_Q) = T'_P \Rightarrow \Gamma \vdash S'_P <: T'_P \).

The goal thus reduces to:

\[ \Gamma \vdash \bigcup_i \{ S'_i \mid \Gamma \vdash L^\prime_i \cap L_i \neq \emptyset \} \cup \text{inherit}(S_p, L) \prec \bigcup_i \{ T'_i \mid \Gamma \vdash M^\prime_i \cap M_i \neq \emptyset \} \cup \text{inherit}(T_p, M) \]

where \( L = L_Q \cap (L_A \cup \bigcup \{ L_i \mid p_i = \circ \}) \) and \( M = M_Q \cap (M_A \cup \bigcup \{ M_j \mid q_j = \circ \}) \).

We define the set of inherited fields of T that are looked up by \( M_Q \) and are absent on S:

\[ N = \{ M_j \mid M_Q \cap M_j \cap L_A \neq \emptyset \land q_j = \uparrow \} \]

\[ L^+ = L \cap \bigcup N \]

\[ L^- = L \cap \overline{\bigcup N} \]

Using lemma 36, we rewrite the goal to:

\[ \Gamma \vdash \bigcup_i \{ S'_i \mid \Gamma \vdash L^\prime_i \cap L_i \neq \emptyset \} \cup \text{inherit}(S_p, L \cap \overline{\bigcup N}) \cup \text{inherit}(S_p, L \cap \bigcup N) \]

\[ <: \bigcup_i \{ T'_i \mid \Gamma \vdash M^\prime_i \cap M_i \neq \emptyset \} \cup \text{inherit}(T_p, M) \]

We prove the goal by breaking it into the following subcases:
a. \( \Gamma \vdash \bigcup \{ S'_i \mid \Gamma \vdash \text{L} \cap \text{L}_i \neq \emptyset \} <: \bigcup \{ T'_j \mid \Gamma \vdash \text{M} \cap \text{M}_j \neq \emptyset \} \)

We cannot apply lemma \(^{37}\) directly because \( \text{M} \subseteq \bigcup \text{M}_j \cup \text{M}_A \), whereas the hypothesis of the lemma requires \( \text{M} \subseteq \bigcup \text{M}_j \).

However, note that since \( \text{L}_A \cap \text{L}_i = \emptyset \) (by well-formedness of types), we have \( \text{L} \cap \text{L}_i \neq \emptyset \) iff \( \text{L}_A \cap \text{L}_i \neq \emptyset \). Similarly, \( \text{M} \cap \text{M}_j \neq \emptyset \) iff \( \text{M}_A \cap \text{M}_j \). We can therefore rewrite the subgoal to \( \Gamma \vdash \bigcup \{ S'_i \mid \Gamma \vdash \text{L} \cap \text{L}_A \cap \text{L}_i \neq \emptyset \} <: \bigcup \{ T'_j \mid \Gamma \vdash \text{M} \cap \text{M}_A \cap \text{M}_j \neq \emptyset \} \). Lemma \(^{37}\) now applies.

b. \( \Gamma \vdash \text{inherit}(S_p, \text{L} \cap \bigcup \text{N}) <: \text{inherit}(T_p, \text{M}) \)

By induction (\text{HInd}). The following cases allow us to apply \text{HInd}.

- \(|S_p| < |S|\) and \(|T_p| < |T|\) are trivial.

- We show that \( \Gamma \vdash S_p <: T_p \). By \text{H5} and \text{H6}, "\text{parent}" \( \in \text{L}_P, \text{M}_P \) thus \( \text{L}_P \cap \text{M}_P \neq \emptyset \).

  Therefore, \( \Gamma \vdash \text{Ref} S_p <: \text{Ref} T_p \) by \text{H1}. By (S-Ref), it follows that \( \Gamma \vdash S_p <: T_p \).

- We show that \( \Gamma \vdash \text{L} \cap \bigcup \text{N} \subseteq \text{M} \). It is sufficient to show that \( \forall x. \Gamma \vdash x \in \text{L} \cap \bigcup \text{N} \Rightarrow \Gamma \vdash x \in \text{M} \).

  By definition of \( \text{L} \), \( x \in \text{L} \) such that (H2), \( x \in \text{M} \).

  By (H6'), \( x \in \text{M}_A \cup \bigcup_j \text{M}_j \). If \( x \in \text{M}_A \), we are done. So, consider the case where \( \exists j. x \in \text{M}_j \).

  By definition of \( \text{L} \), either \( x \in \text{L}_A \) or \( x \in \bigcup \{ \text{L}_i \mid p_i = o \} \). If \( x \in \text{L}_A \), then by \text{H5} \( q_j = o \). If \( x \in \bigcup \{ \text{L}_i \mid p_i = o \} \), since \( x \in \text{L}_i \cap \text{M}_j, p_i <: q_j \), and by \text{p-Refl}, \( q_j = o \).

  Therefore, \( x \in \text{M} \) since it is in both sets.

c. \( \Gamma \vdash \text{inherit}(S_p, \text{L} \cap \bigcup \text{N}) <: \bigcup \{ T'_j \mid \Gamma \vdash \text{M} \cap \text{M}_j \neq \emptyset \} \)

Rewrite the left-hand side by expanding the definition of \( \text{N} \), distributing the intersection over the union, and applying lemma \(^{36}\).

\[ \Gamma \vdash \bigcup \{ \text{inherit}(S_p, \text{L} \cap \text{M}_j) \mid \text{M} \cap \text{M}_j \cap \text{L}_A \neq \emptyset \wedge q_j = \top \} <: \bigcup \{ T'_j \mid \Gamma \vdash \text{M} \cap \text{M}_j \neq \emptyset \} \]

It is sufficient to show that for all elements of the left-hand side, there exists a supertype on the right-hand side. For each \( \text{inherit}(S_p, \text{L} \cap \text{M}_j) \) on the left-hand side, the associated \( T'_j \) is on
the right-hand side by definition of \(N\). We now show that

\[
\Gamma \vdash inherit(S_p, L \cap M_j) <: T_j'
\]

Since \(M_j \cap L_A \neq \emptyset\) and \(q_j = \uparrow\), I4 applies and \(\Gamma \vdash inherit(S, M_j) <: T_j'\). By lemma 36, \(inherit(S, M_j) = inherit(S, L \cap M_j) \sqcup inherit(S, L \cap M_j)\), so \(\Gamma \vdash inherit(S, L \cap M_j) <: T_j\) by the definition of joins. Further, by the definition of \(inherit\),

\[
\Gamma \vdash inherit(S, L \cap M_j) = inherit(S, L \cap M_j) \sqcup inherit(S, L \cap M_j)
\]

and by the definition of \(L\), \(L \cap M_j \cap L_A \cup \{L_i \mid p_i = \circ\}\) is the same as \(L \cap M_j\). By the definition of joins:

\[
\Gamma \vdash inherit(V(S_p, L \cap M_j)) <: T_j
\]

which, when applied for each \(j\), completes Case 2.

**Case 3.** Impossible case, where the "parent" field is on the right-hand side type, but is elided on the left-hand side type.

By well-formedness of types, if \(\exists i. \text{"parent"} \in M_i\) then \(q_i = \uparrow\). But by I2, "parent" \(\in \bigcup_{j=1}^{n} L_j \cup L_A\)

which is a contradiction.

**Case 4.** Inductive case, where the "parent" field is on the left-hand side type, but is elided or null on the right-hand side type.

**HLP.** \(\exists L_P. \text{"parent"} \in L_P \land S'_i = \text{Ref} S_P,\)

**H6.** \(L_Q \subseteq \bigcup_{i=1}^{n} L_i \cup L_A\),

**HRP.** If \(\exists M_P. \text{"parent"} \in M_P\) then \(T'_P = \text{Null}\), and

**H8.** \(M_Q \subseteq \bigcup_{i=1}^{n} \{M_i \mid q_i \neq \circ\}\).

There are two cases of HRP. First, if \(\exists M_P. \text{"parent"} \in M_P\) holds, then \(L_P \cap M_P \neq \emptyset\). Thus by I1, it must be that \(\Gamma \vdash \text{Ref} S_P <: \text{Null}\), which is a contradiction. Therefore, we consider the second case, where \(\neg \exists M_P. \text{"parent"} \in M_P\). The goal is therefore:

\[
\bigcup_{i=1}^{n} \{S'_i \mid \Gamma \vdash L_Q \cap L_i \neq \emptyset\} \sqcup inherit(S_P, L_Q \cap (L_A \cup \{L_i \mid p_i = \circ\})) <: \bigcup_{j=1}^{m} \{T'_j \mid \Gamma \vdash M_Q \cap M_j \neq \emptyset\}
\]
The first part of the join is satisfied by lemma 37. For part 2, using lemma 36 rewrite:

$$\Gamma \vdash \text{inherit}(S_P, L_Q \cap (L_A \cup \bigcup \{L_i | p_i = \circ\})) \triangleleft \bigcup_{j}^{1 \cdots m} \{T_j' | \Gamma \vdash M_Q \cap M_j \neq \emptyset\}$$

to:

$$\Gamma \vdash \text{inherit}(S_P, L_Q \cap L_A) \sqcup \text{inherit}(S_P, L_Q \cap \bigcup \{L_i | p_i = \circ\}) \triangleleft \bigcup_{j}^{1 \cdots m} \{T_j' | \Gamma \vdash M_Q \cap M_j \neq \emptyset\}$$

There are two cases.

- Consider \(\text{str} \in L_Q \cap L_A\). This case follows by the same argument as in item c. of Case 2.

- Consider \(\text{str} \in L_Q \cap L_i\), where \(p_i = \circ\). By H2, \(\text{str} \in M_Q\). By H8, there exists an \(M_j\), such that \(\text{str} \in M_j\) and \(q_j \neq \circ\). By I1, since \(\text{str} \in L_i, M_j\), it must be that \(p_i < q_j\). By inspection of the definition of the \(p < q\) relation, we have a contradiction.

\[\blacksquare\]

**Lemma 39** If \(\{L_1 : F_1 \cdots L_n : F_n\} \triangleleft \{M_1 : G_1 \cdots M_m : G_m\}\), then \(\bigcup_{i}^{1 \cdots m} \{M_j | G_j = T^i\} \subseteq \bigcup_{i}^{1 \cdots n} \{L_i | F_i = T^i\}\).

**Proof:** By contradiction.

Assume there exists some string \(x\) with \(x \in \bigcup_{j}^{1 \cdots m} \{M_j | G_j = T^i\}\) and \(x \notin \bigcup_{i}^{1 \cdots n} \{L_i | F_i = T^i\}\).

By assumption of S-Object, \(\bigcup_{j}^{1 \cdots m} M_j \subseteq \bigcup_{i}^{1 \cdots n} L_i\), so it must be that there is some \(L_i\) that contains \(x\), but either has type \(T^o\) or \(\text{abs}\). That is, there must be an \(M_j\) with \(x \in M_j\) and an \(L_i\) with \(x \in L_i\) with \(G_j = T^i\) and either \(F_i = \text{abs}\) or \(F_i = T^o\). This violates S-Object, which asserts that since \(L_i \cap M_j \neq \emptyset\), it must be that \(F_i \triangleleft G_j\), which cannot happen since possibly absent and definitely absent fields cannot subtype definitely present fields.

\[\blacksquare\]

## D.4 Typing

**Lemma 40 (Canonical Forms)** If \(\Sigma; \Gamma \vdash v : T\) and if \(T\) is:
\[
\Gamma \vdash v : S \quad \Gamma(f) = L \quad \Sigma; \Gamma, \alpha <: L, f : \alpha \vdash e_2 : T
\]
\[
\frac{L' = L \cap \alpha}{\Sigma; \Gamma \vdash \text{if } \{\text{str} : v \cdots\} \text{ hasfield } f \text{ else } e_2 \text{ else } e_3 : T}
\] (T-IfHasField1)

\[
\Gamma(o) = \{\cdots L^o : S \cdots\} \quad \Sigma; \Gamma, o : \{\cdots \text{str}^{i} : S, L^o : S \cdots\} \vdash e_2 : T
\]
\[
\frac{L' = L \cap \{\text{str}\}}{\Sigma; \Gamma \vdash \text{if } (o \text{ hasfield } \text{str}) \text{ else } e_2 \text{ else } e_3 : T}
\] (T-IfHasField2)

\[
\Gamma \vdash v : S \cdots \quad \Sigma; \Gamma \vdash e_3 : T \quad \text{str}_2 \notin \text{str} \cdots
\]
\[
\Sigma; \Gamma \vdash \text{if } \{\text{str} : v \cdots\} \text{ hasfield } \text{str}_2 \text{ else } e_2 \text{ else } e_3 : T
\] (T-IfHasFieldFalse)

\[
\Sigma; \Gamma \vdash e_3 : T
\]
\[
\frac{\Sigma; \Gamma \vdash \text{if } (\text{false}) \text{ else } e_2 \text{ else } e_3 : T}{\Sigma; \Gamma \vdash \text{if } (\text{false}) \text{ else } e_2 \text{ else } e_3 : T}
\] (T-IfFalse)

Figure D.1: Auxiliary Typing Rules for If-Splitting

Figure D.2: Usage of Auxiliary Typing Rules by Substitution
Lemma 41 (Inversion) If:

- \{L_1^{p_1} : S_1 \cdots L_m^{p_m} : S_m\} then \(v = \text{str} v_1 \cdots v_n\), \(\Sigma; \Gamma \vdash v_1 \cdots v_n : U_1 \cdots U_n\), \(\Sigma; \Gamma \vdash v : \{\text{str}^k : U_1 \cdots \text{str}^k_n : U_n, \{\text{str}^k_1 \cdots \text{str}^k_n\} : \text{abs}\}\) and \(\{\text{str}^k_1 : U_1 \cdots \text{str}^k_n : U_n, \{\text{str}^k_1 \cdots \text{str}^k_n\} : \text{abs}\}\) <:
  \{L_1^{p_1} : S_1 \cdots L_m^{p_m} : S_m\},

- \(\text{Ref} \ S\), then \(v = \text{loc} \ \text{and} \ \Sigma(\text{loc}) <: S\),

- \(S \rightarrow T\), then \(v = \text{func}(x) \ {\ell} \ e\),

- \(L\) then \(v = \text{str} \ \text{and} \ \Gamma \vdash \text{str} <: L\)

Proof: By induction on the typing derivation.

Lemma 41 (Inversion) If:

- \(\Sigma; \Gamma \vdash \text{str} \ v \cdots \text{str} \ v_n : T\) then \(\Sigma; \Gamma \vdash v : S \cdots \text{and} \ \Gamma \vdash \{\text{str}^k : S \cdots\} <: T\)

- \(\Sigma; \Gamma \vdash \text{ref} \ e : T\) then \(\Sigma; \Gamma \vdash e : S\) and \(\text{Ref} \ S = T\)

- \(\Sigma; \Gamma \vdash l : T\) then \(\Sigma(l) = T\)

- \(\Sigma; \Gamma \vdash \text{deref} \ e : T,\) then \(\Sigma; \Gamma \vdash e : \text{Ref} \ S\) with \(S <: T\),

- \(\Sigma; \Gamma \vdash e_1 = e_2 : T,\) then \(\Sigma; \Gamma \vdash e_1 : \text{Ref} \ S,\ \Sigma; \Gamma \vdash e_2 : U, \ U <: S,\ \text{and} \ \text{Ref} \ S <: T\),

- \(\Sigma; \Gamma \vdash e_f(e \cdots) : T,\) then \(\Sigma; \Gamma \vdash e_f : S \cdots \rightarrow T',\ \Sigma; \Gamma \vdash e : S \cdots, \text{and} \ T' <: T\).

- \(\Sigma; \Gamma \vdash e_o(e_f) : T,\) then \(\Sigma; \Gamma \vdash e_o : \{L_1^{p_1} : S_1 \cdots\}, \ \Sigma; \Gamma \vdash e_f : L, \in\text{herit}((L_1^{p_1} : S_1 \cdots), L) = T', \text{and} \ T' <: T\).

- \(\Sigma; \Gamma \vdash e_o(e_f) = e_o, e_f : T \ \text{then} \ \Sigma; \Gamma \vdash e_o : \{L^p : S \cdots, L_A : \text{abs}\}, \ \Sigma; \Gamma \vdash e_f : L', \ \Sigma; \Gamma \vdash e_o : U, \ \forall L. \text{if} \ L \cap L' \neq \emptyset \ \text{then} \ U <: S, \ \text{and} \ \Gamma \vdash \{L^p : S \cdots, L_A : \text{abs}\} <: T\).

- \(\Sigma; \Gamma \vdash \text{delete} \ e_o(e_f) : T,\) then \(\Sigma; \Gamma \vdash e_o : \{L_1^{p_1} : S_1 \cdots\}, \ \Sigma; \Gamma \vdash e_f : L, \ \forall L \cap L_i \neq \emptyset. \ F_i \neq T^k, \ \Gamma \vdash \{L_1^{p_1} : S_1 \cdots\} <: T\)

- \(\Sigma; \Gamma \vdash e_1 \ \text{hasfield} \ e_2 : \text{Bool}, \) then \(\Sigma; \Gamma \vdash e_1 : \{L_1 : F_1 \cdots L_n : F_n\}, \ \Sigma; \Gamma \vdash e_2 : L\).

- \(\Sigma; \Gamma \vdash e \ \text{matches} \ P : \text{Bool}, \) then \(\Sigma; \Gamma \vdash e : L\).

- \(\Sigma; \Gamma \vdash \text{if} \ (v_1) \ {\ell} \ e_2 \ {\ell} \ e_3 \ : T,\) then \(\Sigma; \Gamma \vdash v_1 : \text{Bool}, \ \Sigma; \Gamma \vdash e_2 : T, \text{and} \ \Sigma; \Gamma \vdash e_3 : T\).
• \( \Sigma; \Gamma \vdash \textbf{fieldin} v_{\text{obj}} \init v_{\text{acc}} \textbf{do} v_f : T \), then \( \Sigma; \Gamma \vdash v_{\text{obj}} : \{L^p : S \cdots \} \), \( \Sigma; \Gamma \vdash v_{\text{acc}} : T \), and
\( \Sigma; \Gamma \vdash v_f : (\text{Str} \rightarrow T) \rightarrow T \)

**Lemma 42 (Type Substitution)** If \( \Sigma; \alpha <: S, \Gamma \vdash e : T \) and \( \Gamma \vdash U <: S \) then \( \Sigma; \Gamma[\alpha/U] \vdash e[\alpha/U] : T[\alpha/U] \).

**Proof:** By induction on the typing derivation.

**Lemma 43 (Substitution)** If \( \Sigma; x : S, \Gamma \vdash e : T \) and \( \Sigma; \Gamma \vdash v : S \), then \( \Sigma; \Gamma \vdash e[x/v] : T \).

**Proof:** By induction on the typing derivation. The only interesting case is substituting the identifiers in \( \textbf{if} \ (o \ \textbf{hasfield} \ f) \ e_2 \ \textbf{else} \ e_3 \) when it is typed by \( \text{T-IfHasField} \). The resulting expressions require the auxiliary typing rules in fig. \[D.1\]

- The expression is typed by \( \text{T-HasField} \) and \( x = o \). The resulting expression is typable by \( \text{T-IfHasField1} \) as follows. By canonical forms, \( v = \{str : v \cdots \} \) and \( \Sigma; \Gamma \vdash v' : T' \). By induction, \( \Sigma; \Gamma, \alpha <: L, f : \alpha e_2[x/v] \) and \( \Sigma; \Gamma \vdash e_3[x/v] \). The remaining antecents of \( \text{T-IfHasField1} \) are those of \( \text{T-HasField} \).

- The expression is typed by \( \text{T-HasField} \) and \( x = f \). The resulting expression is typable by \( \text{T-IfHasField2} \) as follows. By canonical forms, \( v = str, \Sigma; \Gamma \vdash v : str \), and \( \Gamma \vdash str <: L \). By type substitution followed by induction, \( \Sigma; \Gamma, o : \{\cdots str^k : S, L^o : S \cdots \} \vdash e_2 : T \). The remaining antecedents of \( \text{T-IfHasField2} \) are those of \( \text{T-HasField} \).

- The expression is typed by \( \text{T-IfHasField1} \) and \( x = f \). The resulting expression has the form:

\[
\text{if} \ \{\langle str: v' \cdots \rangle \ \textbf{hasfield} \ str'\} \ e_2 \ \textbf{else} \ e_3
\]

There are two cases.

- If \( str' \in str \cdots \) then by type substitution and induction, \( \Sigma; \Gamma, \alpha <: L, f : \alpha \vdash e_2 : T[\alpha/str][f/v] = \Sigma; \Gamma \vdash e_2[f/v] : T \). By induction, \( \Sigma; \Gamma \vdash e_3[f/v] : T \). Finally, the conditional has type \( \text{Bool} \). Thus the expression is typable by \( \text{T-If} \).

- If \( str' \notin str \cdots \) then the term is trivally typable by \( \text{T-IfHasFieldFalse} \).

- The expression is typed by \( \text{T-IfHasField2} \) and \( x = o \). The resulting expression has the form:

\[
\text{if} \ \{\langle str: v' \cdots \rangle \ \textbf{hasfield} \ str'\} \ e_2 \ \textbf{else} \ e_3
\]
There are two cases.

- If \(str' \in str\cdots\) then the result is trivially typable by T-If.
- If \(str' \notin str\cdots\) then the term is trivially typable by T-IfHasFieldFalse.

\[\square\]

**Lemma 44 (Main Preservation)** If \(\Sigma_1; \cdot \vdash ae : T, \Sigma_1 \vdash \sigma_1,\) and \(\sigma_1 E(ae) \rightarrow \sigma_2 E(e_2)\) then there exists a \(\Sigma_2,\) such that:

\[
i. \, \Sigma_2 \supseteq \Sigma_1,

\[
ii. \, \Sigma_2 \vdash \sigma_2, \text{ and}

\[
iii. \, \Sigma_2; \cdot \vdash e_2 : T.
\]

**Proof:** By case-analysis on \(ae\), using inversion (lemma 41) where specified:

- \(\sigma_1 E((\text{func } (x : S') \{ e \} (v)) \rightarrow \sigma_1 E(e[x/v])).\)
  By inversion, \(\Sigma_1; \cdot \vdash v : S, \cdot \vdash S <; S', \Sigma_1; x : S \vdash e : T',\) and \(\cdot \vdash T' <; T.\) By substitution (lemma 43), \(\Sigma_1; \cdot \vdash e[x/v] : T.\)

- \(\sigma E((\lambda \alpha <; S.e)(U)) \rightarrow \sigma E(e[\alpha/U])\)
  By type substitution (lemma 42).

- \(\sigma E(\text{ref } v) \rightarrow \sigma, l, v E(\ell)\) where \(l \notin \text{dom}(\sigma).\) By inversion, \(\Sigma_1; \cdot \vdash v : S\) and \(\text{Ref } S <; T.\) Let \(\Sigma_2 = l : S, \Sigma_1.\) By T-Loc, \(\Sigma_2; \cdot \vdash l : \text{Ref } S.\)

- \(\sigma E(\text{deref } l) \rightarrow \sigma E(\sigma(l))\)
  By inversion, \(\Sigma; \Gamma \vdash l : \text{Ref } S\) and \(\Gamma \vdash S <; T.\) By inversion, \(\Sigma(l) = S.\) Thus by T-Loc and T-Sub \(\Sigma; \Gamma \vdash l : T.\)

- \(\sigma E(\text{setref } l v) \rightarrow \sigma[l := v] E(l)\) where \(l \in \text{dom}(\sigma).\)
  By inversion (T-SetRef), \(\Sigma; \Gamma \vdash l : \text{Ref } S, \Sigma; \Gamma \vdash v : S,\) and \(\text{Ref } S = T.\) By inversion (T-Loc), \(\Sigma(l) = T\) thus \(\Sigma \vdash \sigma[l := v].\) by T-Loc, \(\Sigma; \Gamma \vdash l : T.\)
\( \sigma E(\{ \cdots \text{str}: v \cdots \})[\text{str}] \rightarrow \sigma E(v) \). By inversion, \( \Sigma_1; \cdot \vdash \text{str} : L, \Sigma_1; \cdot \vdash \{ \cdots \text{str}_1 : v_1 \cdots \} : S \), \( \Sigma_1; \cdot \vdash v : T', T' <: \text{inherit}.(S, L) \), and \( \text{inherit}.(S, L) <: T \). By inversion, \( \{ \cdots \text{str}' : T' \cdots \} <: S \). Thus \( \cdot \vdash T' <: T \).

By lemma 38, \( \text{inherit}.(\{ \cdots \text{str}' : T' \cdots \}, \text{str}) <: \text{inherit}.(S, L) \), and finally \( \text{inherit}.(\{ \cdots \text{str}' : T' \cdots \}, \text{str}) = T' \).

\( \sigma E(\{ \cdots \text{str}: l \cdot \text{str} \}) \rightarrow \sigma E(\{ \text{deref} \ l \}[\text{str}]) \), where \( \text{str} \notin \cdots \).

By inversion of the LHS, \( \Sigma_1; \cdot \vdash \text{str} : L, \Sigma_1; \cdot \vdash \{ \cdots \text{parent} : T_P \} : S \), and \( \text{inherit}.(S, L) <: T \). By lemma 38, \( \text{inherit}.(\{ \cdots \text{parent} : T_P \}, \text{str}) <: \text{inherit}.(S, L) \). By inversion, \( \Sigma_1; \cdot \vdash l : \text{Ref} \ S_P = T_P \). Since \( \text{str} \notin \cdots \) and by definition of \( \text{inherit} \), \( \text{inherit}.(\{ \cdots \text{parent} : \text{Ref} \ S_P \}, \text{str}) = \text{inherit} \cdot \text{inherit} \cdot \text{inherit} \cdot \text{inherit} \cdot (S_P, \text{str}) \), which is a subtype of \( T \).

Type right-hand side with T-Sub and T-GetField, using \( \Sigma_1; \cdot \vdash \text{str} : \text{str}, \text{inherit} \cdot \text{inherit} \cdot \text{inherit} \cdot \text{inherit} \cdot (S_P, \text{str}) <: T \), and \( \Sigma_1; \cdot \vdash \text{deref} \ l \vdash \text{Ref} \ S_P \) above.

\( \sigma E(\{ \cdots \text{str}: v \cdots \})[\text{str} = v'] \rightarrow \sigma E(\{ \cdots \text{str}: v' \cdots \}) \)

By inversion \( \text{(T-Update)} \), \( \Sigma; \Gamma \vdash \{ \cdots \} : \{ L : S \cdots \}, \Gamma \vdash \{ L : S \cdots \} <: T \), and \( \Sigma; \Gamma \vdash v' : U' \).

By inversion \( \text{(T-Object)} \), \( \Sigma; \Gamma \vdash \{ \cdots \text{str}: v \cdots \} : \{ \cdots \text{str}: U \cdots \} \) and \( \Gamma \vdash \{ \cdots \text{str}: U \cdots \} <: \{ L : S \cdots \} \). Thus by inversion \( \text{(T-Update)} \), \( \Gamma \vdash U' <: U \). The resulting expression is typable by S-Object, thus by S-Sub, \( \Gamma \vdash \{ \cdots \text{str}: U' \cdots \} <: \{ \cdots \text{str}: U \cdots \} <: T \).

\( \sigma E(\{ \cdots \})[\text{str} = v'] \rightarrow \sigma E(\{ \cdots \}) \) where \( \text{str} \notin \cdots \)

By inversion of T-Update, \( \Sigma; \Gamma \vdash \{ \cdots \text{str}: v \cdots \} : S \) and \( \Gamma \vdash S <: T \).

\( \sigma E(\text{delete} \ t \{ \cdots \text{str}: v \cdots \}) \rightarrow \sigma E(t \cdots) \)

Similar to to E-UpdateField case above.

\( \sigma E(\text{delete} \ t \{ \cdots \}) \rightarrow \sigma E(\text{delete} \ t \{ \cdots \}) \) where \( \text{str} \notin \cdots \)

Similar to to E-UpdateField case above.

\( \sigma E(\text{fieldin} \ t \{ \text{size}, \text{rest} \cdots \} \text{init} \ v_{\text{acc}} \text{ do} \ v_f) \rightarrow \sigma E(\text{fieldin} \ t \{ \text{str}_2 : v_2 \cdots \} \text{init} \ v_f(\text{str}_1)(v_{\text{acc}}) \text{ do} \ v_f) \)

By inversion, \( \Sigma; \Gamma \vdash v_{\text{acc}} : T \) and \( \Sigma; \Gamma \vdash v_f : (\text{Str} \rightarrow T) \rightarrow T \). The double application can by typed by T-App, and the resulting expression will by typable by T-FieldIn.
• $\sigma E\langle \text{fieldin } \{ \; s : v \} \ \text{init } v_{\text{acc}} \ \text{do } v_f \rangle \rightarrow \sigma E\langle v_f(s)(v_{\text{acc}}) \rangle$

Similar to E-FieldIn above.

The remaining cases are conventional and straightforward. (if is standard, and in the rest, both the left-hand side and the right-hand side have type $\text{Bool}$.)

• $\sigma E\langle \text{if}(\text{true}) \{ e_1 \} \ \text{else } \{ e_2 \} \rangle \rightarrow \sigma E\langle e_1 \rangle$

• $\sigma E\langle \text{if}(\text{false}) \{ e_1 \} \ \text{else } \{ e_2 \} \rangle \rightarrow \sigma E\langle e_2 \rangle$

• $\sigma E\langle \{ \cdots \; \text{str : } v \cdots \} \ \text{hasfield } \text{str} \rangle \rightarrow \sigma E\langle \text{true} \rangle$

• $\sigma E\langle \{ \cdots \} \ \text{hasfield } \text{str} \rangle \rightarrow \sigma E\langle \text{false} \rangle$ where $\text{str} \notin \cdots$

• $\sigma E\langle \text{str matches } P \rangle \rightarrow \sigma E\langle \text{true} \rangle$

• $\sigma E\langle \text{str matches } P \rangle \rightarrow \sigma E\langle \text{false} \rangle$

\[ \blacksquare \]

**Theorem 10 (Preservation)** If $\Sigma_1 \vdash e_1 : T$, $\Sigma_1 \vdash \sigma_1$, and $\sigma_1 e_1 \rightarrow \sigma_1 e_2$, then there exists a $\Sigma_2$, such that:

i. $\Sigma_2; \cdot \vdash e_2 : T$,

ii. $\Sigma_2 \vdash \sigma_2$, and

iii. $\Sigma_1 \subseteq \Sigma_2$.

**Proof:** By case-analysis of the reduction rules, there exists an evaluation context, $E$, an active expression, $ae$, and an expression, $e'$, such that $e_1 = E(ae)$ and $e_2 = E(e')$. There thus exists a subdeduction $\Sigma_1; \cdot \vdash ae : S$ of the original typing derivation. Lemma 44 now applies, so we have $\Sigma_2 \subseteq \Sigma_1$, $\Sigma_2 \vdash \sigma_2$, and $\Sigma_2; \cdot \vdash e' : S$. Replacing the original subdeduction, we have $\Sigma_2; \cdot \vdash E(e') : T$.

\[ \blacksquare \]

**Theorem 11 (Typed Progress)** If $\Sigma \vdash \sigma$ and $\Sigma ; \cdot \vdash e : T$ then either $e \in v$ or there exist $\sigma'$ and $e'$ such that $\sigma e \rightarrow \sigma' e'$. 

\[ \blacksquare \]
Proof: By case-analysis of the reduction rules, either \( e \in v \), \( e = E(\text{ae}) \), or \( e = E(\text{err}) \). By inspection of the typing relation, \( \text{err} \) is untypeable. We therefore consider the case where \( e = E(\text{ae}) \) by case-analysis on the definition of active expressions.

- The cases where \( \text{ae} \) is of the form \( v_1(v_2) \), \( \text{ref} v \), \( \text{deref} v \), \( v_1 \ast v_2 \), and \( \text{if} \langle v_1 \rangle \{ e_2 \} \text{ else } \{ e_3 \} \) are routine.

- Consider \( \text{ae} = v_1(v_2) \). By inversion, \( \Sigma; \vdash v_1 : \{L_1^{p_1} : T_1 \cdots L_m^{p_m} : T_m\} \) and \( \Sigma; \vdash v_2 : L_Q \). By canonical forms, \( v_1 = \{\text{str}_1 : w_1 \cdots \text{str}_m : w_m\} \) and \( \{\text{str}_1 : S_1 \cdots \text{str}_m : S_m, \text{str}_1 \cdots \text{str}_m\} <: \{L_1^{p_1} : T_1 \cdots L_m^{p_m} : T_m\} \). Also by canonical forms, \( v_2 = \text{str}_Q \) and \( \text{str}_Q <: L_Q \).

Therefore, we must only demonstrate that the E-NotFound reduction is not applicable in the case where “parent” is \text{null}. It is sufficient to show that \( \text{str}_Q \in \{\text{str}_1 \cdots \text{str}_m\} \), which we do by the following sequence of inclusions:

By S-Str, \( \text{str}_Q \in L_Q \). By definition of \text{inherit}, when “parent” is \text{null}, \( L_Q \subseteq \bigcup\{L_i \mid p_i \neq \circ\} \).

Evidently, \( \bigcup\{L_i \mid p_i \neq \circ\} \subseteq \bigcup L_i \). By antecedent (2) of S-Object, we have that \( \bigcup L_i \subseteq \{\text{str}_1 \cdots \text{str}_m\} \).

- Consider \( \text{ae} = v_1[v_2 \ast v_3] \). By inversion, \( \Sigma; \vdash v_1 : \{L^p : S \cdots \} \) and \( \Sigma; \vdash v_2 : L_Q \). By canonical forms, \( v_1 = \{\text{str} : w \cdots\} \) and \( v_2 = \text{str}_Q \). Thus either E-Create or E-Update apply.

- Consider \( \text{ae} = \text{delete} \ v_1(v_2) \). By inversion, \( \Sigma; \vdash v_1 : \{L^p : S \cdots \} \) and \( \Sigma; \vdash v_2 : L_Q \). By canonical forms, \( v_1 = \{\text{str} : w \cdots\} \) and \( v_2 = \text{str}_Q \). Thus either E-Delete or E-Delete-None apply.

- Consider \( \text{ae} = v_1 \text{ hasfield} \ v_2 \). By inversion, \( \Sigma; \vdash v_1 : \{L^p : S \cdots \} \) and \( \Sigma; \vdash v_2 : L_Q \). By canonical forms, \( v_1 = \{\text{str} : w \cdots\} \) and \( v_2 = \text{str}_Q \). Thus either E-HasField or E-HasNotField apply.

- Consider \( \text{ae} = v \text{ matches} \ P \). By inversion and canonical forms, \( v = \text{str} \). Thus either E-Matches or E-NoMatch apply.

- Consider \( \text{ae} = \text{fieldin} \ (s_1 : v_1, \ s_2 : v_2 \ \cdots) \text{ init} \ v_{\text{acc}} \text{ do} \ v_f \). By inversion, \( \Sigma; \vdash v_1 : \{L^p : S \cdots\} \).

By canonical forms, \( v_1 = \{\text{str} : w \cdots\} \). Thus either E-FieldIn or E-FieldIn-End apply.
 Appendix E

The ADsafe Environment

This appendix contains the type environment we use to type-check ADsafe. Widget is the recursively
type of values that untrusted widgets can manipulate. In the concrete syntax below, the field name
* is shorthand for all fields, except those explicitly marked BAD or given a type.

type Widget = trec t .
  Undef
  + Null
  + Num
  + Int
  + Str
  + Bool
  + { "prototype" : BAD,
      ___nodes___ : Array<HTMLElement + Undef> + Undef,
      ___star___ : Bool + Undef,
      ___proto___ : BAD,
      ___parent___ : BAD,
      valueOf : _,
      hasOwnProperty : _,
      toString : _,
      arguments : BAD,
      "constructor" : BAD,
      watch : BAD,
      unwatch : BAD,
      #proto : Object+Function+Array+Bunch_proto+Str+Num+Bool+RegExp,
      * : 't,
      #code : ['t + HTMLWindow] 't ... -> 't
    }

The WidgetObj type is the object portion of the Widget type. It makes it easier to write some types
below.
type WidgetObj =
  { "prototype" : BAD,
    ___nodes___ : Array<HTMLElement + Undef> + Undef,
    ___star___ : Bool + Undef,
    ___proto___ : BAD,
    ___parent___ : BAD,
    valueOf : _,
    hasOwnProperty : _,
    toString : _,
    arguments : BAD,
    "constructor" : BAD,
    watch : BAD,
    unwatch : BAD,
    #proto : Object+Function+Array+Bunch_proto+Str+Num+Bool+RegExp,
    * : 'Widget,
    #code : ['Widget + HTMLWindow] 'Widget ... -> 'Widget }

Selector is the type we ascribe to CSS selectors for ADsafe. CSS selectors have several other fields, but these are the only ones that ADsafe requires.

type Selector =
  { op: Str + Undef,
    name: Str + Undef,
    value: Str + Undef,
    #proto: Object,
    *: Bot,
    #code: Bot }

The reject_name function is a key check in ADsafe that returns true on strings in banned and false otherwise.

type not_banned =
  "$^{"arguments", "caller", "callee", "constructor", "eval", "stack",
    "watch", "unwatch", "valueOf", "toString", "hasOwnProperty",
    "prototype", "___nodes___", "___star___", "___proto___", "___parent___",
    "__defineGetter__", "__defineSetter__"}

type banned =
  "${"arguments", "caller", "callee", "constructor", "eval", "stack",
    "watch", "unwatch", "valueOf", "toString", "hasOwnProperty",
    "prototype", "___nodes___", "___star___", "___proto___", "___parent___",
    "__defineGetter__", "__defineSetter__"} +
  Bool + Null + Undef + 'WidgetObj + Num

reject_name : (('banned -> True) + ('not_banned -> Bool))

A Pecker is an ADsafe abstraction for selecting elements.
type Pecker =

{"." : HTMLElement + Undef -> Bool,
"&" : HTMLElement + Undef -> Bool,
"_" : HTMLElement + Undef -> Bool,
"[" : HTMLElement + Undef -> Bool,
"[=" : HTMLElement + Undef -> Bool,
"[!=" : HTMLElement + Undef -> Bool,
"[=" : HTMLElement + Undef -> Bool,
"[$" : HTMLElement + Undef -> Bool,
"[*=" : HTMLElement + Undef -> Bool,
"[~=" : HTMLElement + Undef -> Bool,
"[^=" : HTMLElement + Undef -> Bool,
":blur" : HTMLElement + Undef -> Bool,
":checked" : HTMLElement + Undef -> Bool,
":disabled" : HTMLElement + Undef -> Bool,
":even" : HTMLElement + Undef -> Bool,
":focus" : HTMLElement + Undef -> Bool,
":hidden" : HTMLElement + Undef -> Bool,
":odd" : HTMLElement + Undef -> Bool,
":tag" : HTMLElement + Undef -> Str,
":text" : HTMLElement + Undef -> Bool,
":trim" : HTMLElement + Undef -> Bool,
":unchecked" : HTMLElement + Undef -> Bool,
":visible" : HTMLElement + Undef -> Bool,
#proto: Object, *: _, #code: _
}

Makeable is ADsafe's whitelist of safe DOM elements.

type Makeable =

{a : "a",
abbr : "abbr",
acronym : "acronym",
address : "address",
area : "area",
b : "b",
bdo : "bdo",
big : "big",
blockquote: "blockquote",
br : "br",
button : "button",
canvas : "canvas",
caption : "caption",
center : "center",
cite : "cite",
code : "code",
col : "col",
colgroup : "colgroup",
dd : "dd",
del : "del",
 dfn : "dfn"};
dir : "dir",
div : "div",
dl : "dl",
dt : "dt",
em : "em",
fieldset : "fieldset",
font : "font",
form : "form",
h1 : "h1",
h2 : "h2",
h3 : "h3",
h4 : "h4",
h5 : "h5",
h6 : "h6",
hr : "hr",
i : "i",
img : "img",
input : "input",
ins : "ins",
kbd : "kbd",
label : "label",
legend : "legend",
li : "li",
map : "map",
menu : "menu",
object : "object",
ol : "ol",
optgroup : "optgroup",
option : "option",
p : "p",
pre : "pre",
q : "q",
samp : "samp",
select : "select",
small : "small",
span : "span",
strong : "strong",
sub : "sub",
sup : "sup",
table : "table",
tbody : "tbody",
td : "td",
textarea : "textarea",
tfoot : "tfoot",
th : "th",
thead : "thead",
tr : "tr",
tt : "tt",
u : "u",
ul : "ul",
"var" : "var"
#proto : Object,
*     : Bot,
#code : Bot
}

Appendix F

Desugared Lookup Function

This appendix shows the result of desugaring the following snippet of JavaScript to $\lambda_{JS}$:

```javascript
function(obj, field) {
    if (field === "XMLHttpRequest") {
        return undefined;
    } else {
        return obj[field];
    }
}
```

For brevity, we do not show the object that wraps the function, but just the function below. We use the concrete syntax of $\lambda_{JS}$ that is parsed by PLT Redex.

```lambda
(lambda (this arguments)
  (let
    ((obj (get-field
           (deref (deref arguments))
           "0")))
    (let
      ((field (get-field
                (deref (deref arguments))
                "1")))
      (let
       ()
       (label $return
       (begin
       (begin
       (if (=== field "XMLHttpRequest")
       (begin
       (break $return
       (get-field
       (deref $global)
       "undefined")))
       undefined)
       (if (=== (typeof field) "string")
       (begin
```
(break $return
;;;; The expression below (desugar 'obj[field])
(get-field
;;;; The expression below is (deref (desugar 'obj)). If 'obj is
;;;; not an object, it is converted to an object. This is perfectly safe,
;;;; since we just need it to have type JS.
(deref (let
  (($2
    obj))
  (if (=== (typeof $2) "undefined")
    (throw ($makeException "TypeError" ":toObject received undefined"))
  (if (=== $2 null)
    (throw ($makeException "TypeError" ":toObject received null"))
  (if (=== (typeof $2) "boolean")
    (alloc (object ($"proto" $Boolean.prototype)
      ($"class" "Boolean")
      ($"value" $2)))
  (if (=== (typeof $2) "number")
    (alloc (object ($"proto" $Number.prototype)
      ($"class" "Number")
      ($"value" $2)))
  (if (=== (typeof $2) "string")
    (alloc (object ($"proto" $String.prototype)
      ($"class" "String")
      ($"value" $2)
      ($"length" (str-length $2))))
  $2)))))
;;;; The expression below is (toString (desugar 'field)), where toString
;;;; is the metafunction defined in ECMA262-3, Section 9.8.1. Of course,
;;;; here we have toString written in JS. In ECMA262-3, toString uses
;;;; other metafunctions. Here, they are all inlined.
(let
  (($str field))
  (if (=== (typeof $str) "location")
    ;; The true branch below is unreachable.
    (if (if (=== (typeof (deref $str)) "object")
      #f
      #t)
      (throw "Catastrophe - toStr given a ref of a not-obj")
    (prim->string
      (let
        (($x $str))
        (if (=== (typeof $x) "location")
          (if (if (=== (typeof (deref $x)) "object")
            #f
            #t)
            (throw "Catastrophe - toPrim given a ref of a not-obj")
          (let
            (($v$0f (get-field
              (deref $x)
              "value0f")))
            (if (if (=== (typeof $v$0f) "location")
              (let
                (($isF (deref $v$0f)))
                (if (=== (typeof $isF) "object")
                  (=== (typeof (get-field
                    $isF
                    "$code")) "lambda")
                #f))
              #f))
            #f)
          )
        )))
    )))
  )))
)
 Below, field.valueOf() is called. It may produce an arbitrary result, so it has type JS (not type NoXHR)

\[
\begin{align*}
\text{(get-field} \\
\text{(deref $3)} \\
\text{"$code"}) \text{x (alloc (alloc (object ("length" 0.0) \
\text{("callee" $3)} \\
\text{("$class" "Object")) \
\text{("proto" $Object.prototype)}) \
\text{("$isArgs" #t))))})
\end{align*}
\]

(if (prim? $vRes)
$vRes
(let

\[
\begin{align*}
\text{(($toStr (get-field} \\
\text{(deref $x)} \\
\text{"toString")))}
\end{align*}
\]

(if (if (=== (typeof $toStr) "location")
(let
\[
\begin{align*}
\text{(($isF (deref $toStr)))}
\end{align*}
\]

(if (=== (typeof $isF) "object")
(let
\[
\begin{align*}
\text{((get-field} \\
\text{(deref $4)} \\
\text{"$code"}) \text{x (alloc (alloc (object ("length" 0.0) \
\text{("callee" $4)} \\
\text{("$class" "Object")) \
\text{("proto" $Object.prototype)}) \
\text{("$isArgs" #t))))})
\end{align*}
\]

(if (prim? $tRes)
$tRes
(let

\[
\begin{align*}
\text{(($toStr (get-field} \\
\text{(deref $x)} \\
\text{"toString")))}
\end{align*}
\]

(if (if (=== (typeof $toStr) "location")
(let
\[
\begin{align*}
\text{(($isF (deref $toStr)))}
\end{align*}
\]

(if (=== (typeof $isF) "object")
(let
\[
\begin{align*}
\text{((get-field} \\
\text{(deref $5)} \\
\text{"$code"}) \\
\text{"toString"})}
\end{align*}
\]

(if (prim? $tRes)
$tRes
(let

\[
\begin{align*}
\text{(($toStr (get-field} \\
\text{(deref $x)} \\
\text{"toString")))}
\end{align*}
\]
"$code") $x (alloc (alloc (object ("length" 0.0) 
("callee" $5) 
("$class" "Object") 
("$proto" $Object.prototype) 
("$isArgs" #t)))))))

(if (prim? $tRes) $tRes
  (throw ($makeException "TypeError" ":apply expects array")))
  (throw ($makeException "TypeError" ":apply expects array")))
  (if (=== (typeof $x) "object") 
    (throw "Catastrophe - toPrim given plain object") 
    $x))))))

;; The expression below is the false branch of the conditional. The 
;; type-test is unnecessary; it's inserted naively by desugaring.
(if (=== (typeof $toStr) "object") 
  (throw "Catastrophe - toStr given plain object")
;; Here, we know that $toStr (i.e. field) has type NoXHR. The operator 
;; prim->string is the identity on strings, and doesn't convert booleans or numbers to the 
;; string "XMLHttpRequest"!
(prim->string $toStr))))))))

undefined
(begin
  (break $return
    (get-field
      (deref $global)
      "undefined"))
  undefined))

undefined)
undefined))))
Bibliography


