CS450

Structure of Higher Level Languages

Lecture 38: SimpleJS; translating LambdaJS to SimpleJS

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My goal with CS450 is to teach you …

1. Fundamental concepts behind most programming languages

- functional programming, delayed evaluation, control flow and exceptions, object oriented systems, monads, macros, pattern matching, variable scoping, immutable data structures

2. A framework to describe language concepts

- λ-calculus and formal systems to specify programming languages
- functional programming and monads to implement specifications

3. A methodology to understand complex systems

- (formally) specify and implement each programming language feature separately
- understand a complex system as a combination of smaller simpler systems
- implement and test features independently

Today we will...

- Revise JavaScript's object system
- Introduce SimpleJS: S-Expression-based syntax and simpler JavaScript rules
- Introduce LambdaJS: λ-calculus + references + immutable objects
- Introduce translation from SimpleJS into LambdaJS

Why are we learning all SimpleJS and LambdaJS?

- You already know λ-calculus with references (heap)
- You already know how objects work (ie, a map with a lookup that work like frames and environments)
- **I want to teach you the fundamentals of JavaScript by building it on top of concepts that you already know!**
- I can introduce another kind of specifying the semantics of a system, by translating it into another system (**denotational semantics**)

Object prototypes

`A.__proto__ = B` links `A` object to `B`, if a field `f` is not available in `A`, then it is looked up in `B` (which works recursively until finding undefined).

```
a = {"x": 10, "y": 20}
b = {"x": 30, "z": 90, "__proto__": a}
b {x: 30, z: 90, *y: 20}
```

Functions are constructors

If we call a function `A` with `new`, then `A` is called as the constructor of a new object.

```
function C(x, y) { this.x = x; this.y = y }
c = new C(10, 20)
c {x: 10, y: 20}
```

Constructor's prototype

If `A` is a function, then `A.prototype` becomes the `__proto__` of every object created using `A` with `new`.

```
C.prototype = {"foo": true, "bar": 100}
d = new C(10, 20)
d {x: 10,  y: 20, *foo: true, *bar: 100}
```

Quiz

What is the name of the paper we are studying?

SimpleJS

Introducing SimpleJS

- SimpleJS is just a simplification of JavaScript with fewer corner case, which is easier to learn.
- SimpleJS was created by your instructor for CS450 (yet close to what you have in The Essence of JavaScript)
- SimpleJS has a formal syntax (below) and also an S-expression syntax (`hw8-util.rkt`)
- Today we will **formally** describe SimpleJS in terms of how we can represent it in LambdaJS (defined in The Essence of JavaScript).

$$
\begin{aligned}
e ::= x \mid \texttt{let}\ x = e\ \texttt{in}\ e \mid x.y \mid x.y := e \mid x.y(e \cdots) \\
\mid \texttt{function}(x \cdots)\{e\} \mid \texttt{new}\ e(e \cdots) \\
\mid \texttt{class}\ \ \texttt{extends}\ e\ \{\texttt{constructor}(x \cdots)\{e\}\ m \cdots\}
\end{aligned}
$$

$$
m ::= x(x \cdots)\{e\}
$$

Writing Shape in SimpleJS

JavaScript

```
function Shape(x, y) {
    this.x = x;
    this.y = y;
}
let p = new Shape(10, 20);
Shape.prototype.translate =
    function(x, y) {
      this.x = this.x + x;
      this.y = this.y + y;
    };
p.translate(1,2);
return p;
```

SimpleJS

```
(let Shape
  (function (x y)
    (begin (set! this.x x)
           (set! this.y y)))
  (let p (new Shape 10 20)
    (let Shape-proto Shape.prototype
      (begin
        (set! Shape-proto.translate
          (function (x y)
            (begin
              (set! this.x (! + this.x x))
              (set! this.y (! + this.y y)))))
        (p.translate 1 2)
        p))))
```

Writing Rectangle in SimpleJS

JavaScript

```
function Rectangle(width, height) {
  this.x = 0;
  this.y = 0;
  this.width = width;
  this.height = height;
}
Rectangle.prototype =
                   Shape.prototype;
let r1 = new Rectangle(10, 20);
return r1;
```

SimpleJS

```
(let Rectangle
  (function (width height)
    (begin
      (set! this.x 0)
      (set! this.y 0)
      (set! this.width width)
      (set! this.height height)))
  (set! Rectangle.prototype Shape.prototype)
  (let r1 (new Rectangle 10 20)
    r1))
```

Writing Rectangle in SimpleJS

JavaScript

```
function Rectangle(width, height) {
  this.x = 0;
  this.y = 0;
  this.width = width;
  this.height = height;
}
Rectangle.prototype =
                   Shape.prototype;
let r1 = new Rectangle(10, 20);
return r1;
```

SimpleJS

```
(let Rectangle
  (function (width height)
    (begin
      (set! this.x 0)
      (set! this.y 0)
      (set! this.width width)
      (set! this.height height)))
  (set! Rectangle.prototype Shape.prototype)
  (let r1 (new Rectangle 10 20)
    r1))
```

What are the possible problems of this form of inheritance?

Writing Rectangle in SimpleJS

JavaScript

```
function Rectangle(width, height) {
  this.x = 0;
  this.y = 0;
  this.width = width;
  this.height = height;
}
Rectangle.prototype =
                   Shape.prototype;
let r1 = new Rectangle(10, 20);
return r1;
```

SimpleJS

```
(let Rectangle
  (function (width height)
    (begin
      (set! this.x 0)
      (set! this.y 0)
      (set! this.width width)
      (set! this.height height)))
  (set! Rectangle.prototype Shape.prototype)
  (let r1 (new Rectangle 10 20)
    r1))
```

What are the possible problems of this form of inheritance?

How can we add a new method to Rectangle?

Writing Rectangle in SimpleJS

> With the highlighted pattern we can safely mutate `Rectangle.prototype`. This is the same as `Rectangle.prototype = {'__proto__': Shape.prototype }`, but we have no syntax for such a pattern in SimpleJS.

JavaScript

```
function Rectangle(width, height) {
  this.x = 0;
  this.y = 0;
  this.width = width;
  this.height = height;
}
let p = function () {}
p.prototype = Shape.prototype;
Rectangle.prototype = new p();
let r1 = new Rectangle(10, 20);
return r1;
```

SimpleJS

```
(let Rectangle
  (function (width height)
    (begin (set! this.x 0) (set! this.y 0)
      (set! this.width width)
      (set! this.height height)))
  (let p (function () 0)
    (begin
      (set! p.prototype = Shape.prototype)
      (set! Rectangle.prototype (new p))
      (let r1 (new Rectangle 10 20)
        r1))))
```

LambdaJS

LambdaJS

Think Racket without `define`, without macros, with objects, and heap operations.

Expressions

$$e ::= v \mid x \mid \lambda x.e \mid e(e) \mid \{s \colon e\} \mid e[e] \mid e[e] \leftarrow e \mid \texttt{alloc}\ e \mid e := e$$

Concrete LambdaJS S-expression syntax

Formal syntax	***S-expression***
$\lambda x.e$	`(lambda (x) e)`
$e_1(e_2)$	`(e1 e2)`
$\{\texttt{"foo"} : 1 + 2, \texttt{"bar"} : x\}$	`(object ["foo" (+ 1 2)] ["bar" x])`
$o[\texttt{"foo"}]$	`(get-field o "foo")`
$\texttt{alloc}\ \{\}$	`(alloc (object))`
$x := \{\}$	`(set! x (object))`
$x := 1; x$	`(begin (set! x 1) x)`
$\text{let}\ x\ =\ 10\ \text{in}\ x + 4$	`(let ([x 10]) (+ x 4))`

> In Racket you can actually allocate a reference with `(box e)`, which is equivalent to LambdaJS`(alloc e)`, and update the contents of that reference with `(set-box! b e)`, which is equivalent to LambdaJS `(set! e)`.

Translating SimpleJS into LambdaJS

Overview

Translating SimpleJS into LambdaJS

1. A SimpleJS object is represented as a reference to an immutable LambdaJS object
2. A SimpleJS function is represented as an object with two fields: (a) a lambda-function that represents the code, a `prototype` field which points to an empty SimpleJS object
3. Create an object with `new` expects a SimpleJS function as argument and must create a new object, initialize its prototype, and call the constructor function (see point 2)
4. Method invocation corresponds to accessing a SimpleJS function and passing the implicit `this` object to it (see 2)

Objectives of the translation

- Explicit `this`
- Functions are not objects: convert `function` into an object+lambda
- Explicit memory manipulation
- No method calls: use function calls

Translating a function

JavaScript

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

Step 1: only objects and lambdas

```
Shape = {
  '$code': (obj, x, y) => {
    obj.x = x;
    obj.y = y;
  },
  'prototype' = {}
};
```

Translating a function

JavaScript

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

Step 1: only objects and lambdas

```
Shape = {
  '$code': (obj, x, y) => {
    obj.x = x;
    obj.y = y;
  },
  'prototype' = {}
};
```

Step 2: explicit references

```
Shape = alloc {'$code': (this, x, y) => {
    this = (deref this)["x"] <- x;   // In LambdaJS we have to replace the whole object
    this = (deref this)["y"] <- y;},
  'prototype': alloc {}};
```

Translating new

JavaScript

```
p1 = new Shape(0, 1);
```

Step 1: only objects and lambdas; no implicit this

```
p1 = {"__proto__": Shape.prototype};
Shape["$code"](p1, 0, 1);
```

Translating new

JavaScript

```
p1 = new Shape(0, 1);
```

Step 1: only objects and lambdas; no implicit this

```
p1 = {"__proto__": Shape.prototype};
Shape["$code"](p1, 0, 1);
```

Step 2: explicit references

```
p1 = alloc {"__proto__": (deref Shape)["prototype"]}};
(deref Shape)["$code"](p1, 0, 1);
```

Translating method invocation

JavaScript

```
p1.translate(10, 20);
```

Step 1: only objects and lambdas; no implicit this

```
m = p1["translate"];     // get object method
m["$code"](p1, 10, 20); // get code for method
```

Translating method invocation

JavaScript

```
p1.translate(10, 20);
```

Step 1: only objects and lambdas; no implicit this

```
m = p1["translate"];    // get object method
m["$code"](p1, 10, 20); // get code for method
```

Step 2: explicit references

Formally

```
m = (deref p1)["translate"];
(deref m)["$code"](p1, 10, 20);
```

SimpleJS

```
(let ([m (get-field (deref p1) "translate")])
  ((get-field (deref m) "$code") p1 10 20))
```

Translating SimpleJS into LambdaJS

Before

```
Shape.prototype.translate = function(x, y)
    this.x += x; this.y += y;
};
p1 = new Shape(0, 1);
p1.translate(10, 20);
```

After

```
// 1. Function declaration
Shape = alloc {
  "$code": (this, x, y) ⇒ { ... },
  "prototype" = alloc {}};
p = (deref Shape)["prototype"];
(deref p)["translate"] = alloc {
  "$code": (this, x, y) ⇒ { ... }
  "prototype": alloc {}};
// 2. new
p1 = alloc {"__proto__":
            (deref Shape)["prototype"]};
(deref Shape)["$code"](p1, 0, 1);
// 3. method call
f = (deref p1)["translate"];
(deref f)["$code"](p1, 10, 20);
```

Translation function

Translation function

- Field lookup
- Field update
- Function declaration
- The new keyword
- Method call
- Class declaration

Field lookup

Field lookup

$$\mathbf{J}[\![x.y]\!] = (\text{deref } x)[\texttt{"y"}]$$

SimpleJS

```
this.x
```

λ-JS

```
(get-field (deref this) "x")
```

Field update

Field update

In JavaScript, assigning an expression e into a field, returns the evaluation of e. However, in LambdaJS assignment returns the reference being mutated.

$$\mathbf{J}[\![x.y := e]\!] = \\ \text{let data} = \mathbf{J}[\![e]\!] \text{ in} \\ x := (\text{deref obj})[\text{"}y\text{"}] \leftarrow \text{data}; \\ \text{data}$$

SimpleJS

```
(set! this.x x)
```

λ-JS

```
(let [(data x)]
  (begin
    (set! this
      (update-field (deref this) "x" data))
    data)))
```

Free variables and bound variables

$$\mathbf{J}[\![x.y := e]\!] = \text{let data} = \mathbf{J}[\![e]\!] \text{ in x} := (\text{deref x})[\text{"}y\text{"}] \leftarrow \text{data; data}$$

SimpleJS

```
(set! data.x 10)
```

λ-JS

```
(let [(data 10)]
  (begin
    (set! data
      (update-field (deref data) "x" data))
    data)))
```

What happened here?

Free variables and bound variables

$$\mathbf{J}[\![x.y := e]\!] = \textsf{let data} = \mathbf{J}[\![e]\!]\ \textsf{in x} := (\textsf{deref x})[\text{"}y\text{"}] \leftarrow \textsf{data; data}$$

SimpleJS

```
(set! data.x 10)
```

λ-JS

```
(let [(data 10)]
  (begin
    (set! data
      (update-field (deref data) "x" data))
    data)))
```

What happened here?

1. Variable data is used in the generated code
2. We must ensure that data is not captured (free) in the generated code!

Quiz

What problem occurs when generating code?

(One sentence is enough.)

Function declaration

Function declaration

> Field `prototype` can be accessed by the user, so we declare it as a reference. Field `$code` does not actually exist in JavaScript, so we prefix it with a dollar sign (`$`) to visually distinguish artifacts of the translation.

$$J[\![\mathtt{function}(x \cdots)\ \{e\}]\!] =$$
$$\text{alloc}\ \{\texttt{"\$code"} : \lambda(\text{this}, \text{x} \cdots).J[\![e]\!], \texttt{"prototype"} : \text{alloc}\ \{\}\}$$

SimpleJS

```
(function (x y)
  (begin
    (set! this.x x)
    (set! this.y y)))
```

λ-JS

```
(let ([js-set!
  (lambda (o f d)
    (begin (set! o (update-field (deref o) f d)) d))
  (alloc (object
      ["$code"
        (lambda (this x y)
          (begin (js-set! this "x" x)
                 (js-set! this "y" y)))]
      ["prototype" (alloc (object))])))
```

The `new` keyword

The new keyword

$$\mathrm{J}[\![\texttt{new}\ e_f(e\cdots)]\!] =$$
$$\text{let ctor} = \text{deref } \mathrm{J}[\![e_f]\!] \text{ in}$$
$$\text{let obj} = \text{alloc } \{\texttt{"\$proto"} : \text{ctor}[\texttt{"prototype"}]\} \text{ in}$$
$$\text{ctor}[\texttt{"\$code"}](\text{obj}, \mathrm{J}[\![e]\!]\cdots);$$
$$\text{obj}$$

SimpleJS

```
(new Shape 0 1)
```

λ-JS

```
(let [(ctor (deref Shape))
      (o (alloc (object "$proto" (get-field ctor "prototype"))))]
  (begin
    ((get-field ctor "$code") o 0 1)
    o))
```

Method invocation

Method invocation

$$\mathbf{J}[\![x.y(e\cdots)]\!] = \Big(\big(\textsf{deref}\ \big((\textsf{deref}\ x)[\texttt{"y"}]\big)\big)[\texttt{"\$code"}]\Big)(x, \mathbf{J}[\![e\cdots]\!])$$

SimpleJS

```
(p1.translate 10 20)
```

λ-JS

```
((get-field
  (deref (get-field (deref p1) "translate"))
  "$code")
  p1 10 20)
;; In Racket pseudo code
(define p1:obj (deref p1)) ; 1. get obj from ref
(define translate:m (get-field p1-obj "translate")) ; 2. get field
(define translate:o (deref translate-m)) ; 3. get object from ref
(define translate:f (get-field translate-obj "$code")) ; 4. get fun
(translate-code p1 10 20) ; 5. call fun pass this (p1)
```

Function call

- We will not be implementing function calls in Homework Assignment 8.

$$\mathrm{J}[\![e_f(e\cdots)]\!] = \\ \text{let obj} = \mathrm{J}[\![e_o]\!] \text{ in} \\ (\text{deref obj})[\texttt{"\$code"}](\text{window}, \mathrm{J}[\![e\cdots]\!])$$

Example 1

```
class Foo {
  constructor() { this.x = 0; }
  bar() { this.x++; }
}
var foo = new Foo();
foo["bar"](); // foo.bar();
// Caveat: foo.bar() ≠ (foo.bar)()
```

Example 2

```
class Foo {
  constructor() { this.x = 0; }
  bar() { this.x++; }
}
var foo = new Foo();
var bar = foo["bar"];
bar(); // TypeError: this is undefined
```

Class declaration

Class declaration

> To allow dynamically dispatching to X's methods, the first four lines instantiate X without calling its constructor. This way, we can safely mutate the **cls**'s prototype without affecting X and any changes to X are visible to **cls** via lookup.

$$
\begin{array}{c}
\mathrm{C}[\![\texttt{class extends } X\ \{body\}]\!] = \\
\textsf{let parent} = \mathrm{C}[\![X]\!]\ \textsf{in} \\
\textsf{let parent}' = \texttt{function}\ ()\{\}\ \textsf{in} \\
\textsf{parent}'\textsf{.prototype} := \textsf{parent.prototype} \\
\textsf{let proto} = \texttt{new}\ \textsf{parent}'\ \textsf{in} \\
\textsf{let cls} = \texttt{function}\ (x \cdots)\{e_c\}\ \textsf{in} \\
\textsf{cls.prototype} := \textsf{proto}; \\
\textsf{proto.m} := \texttt{function}(y \cdots)\{e_m\}; \cdots \\
\textsf{cls}
\end{array}
$$

$$\text{where } body = \texttt{constructor}(x \cdots)\{e_c\}\ m(y \cdots)\{e_m\} \cdots$$