CS450

Structure of Higher Level Languages

Lecture 26: SimpleJS

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Press arrow keys ← → to change slides.

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

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JavaScript `__proto__` deprecated!

- Direct access to attribute `__proto__` is discouraged and deprecated!
- However, getting/setting attribute `__proto__` is syntactic sugar for `GetPrototypeOf` and `SetPrototypeOf` in the JavaScript specification.
- We are using `__proto__` mainly because we are following the Essence of JavaScript.
- Prototypes can be updated dynamically due to mutation

JavaScript function objects

> We can use field `prototype` to declare the prototype of a given class. We can also use field `prototype` to add methods to an object. Operation `new` assigns `Shape.prototype` to `p1.__proto__`.

```javascript
function Shape(x, y) {
  this.x = x;
  this.y = y;
}
// This way we bind the method once
Shape.prototype.translate = function (x, y) {
   this.x += x;
   this.y += y;
}
p1 = new Shape(0, 1);
p1.translate(10, 20);
console.assert(p1.x == 10);
console.assert(p1.y == 21);
```

Desugaring object inheritance

```
var Shape = (obj, x, y) => { // Shape's constructor
  obj.x = x;
  obj.y = y;
  return obj
}
Shape.prototype = {} // Shape extends Object
Shape.prototype.translate = function (x, y) { // Also add method translate
  this.x += x;
  this.y += y;
}
p1 = Shape({"__proto__": Shape.prototype}, 0, 1); // When creating, init prototype
p1.translate(10, 20);
console.assert(p1.x == 10);
console.assert(p1.y == 21);
```

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Desugaring class creation

Version 3

```
class Shape {
  constructor(x, y) {
    this.x = x;
    this.y = y;
  }
  translate(x, y) {
    this.x += x;
    this.y += y;
  }
}
p1 = new Shape(0, 1);
```

Version 2

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

Version 1

```
Shape = (obj, x, y) => {
  obj.x = x;
  obj.y = y;
  return obj
}
Shape.prototype = {}
Shape.prototype.translate =
      function (x, y) {
  this.x += x;
  this.y += y;
}
p1 = Shape(
  {"__proto__": Shape.prototype},
  0, 1);
```

Inheritance desugaring

```
class Rectangle extends Shape {
  constructor(width, height) {
    super(0, 0);
    this.width = width;
    this.height = height;
  }
}
var r1 = new Rectangle(10, 20);
```

```
function Rectangle(width, height)
  Shape.call(this, 0, 0);
  this.width = width;
  this.height = height;
}
Rectangle.prototype =
    {"__proto__": Shape.prototype
var r1 = new Rectangle(10, 20);
```

```
Rectangle = (obj, w, h) => {
  Shape(obj, 0, 0);
  obj.width = w;
  obj.height = h;
  return obj;
}
Rectangle.prototype =
    {"__proto__": Shape.prototype
r1 = Rectangle(
{"__proto__": Rectangle.prototype
  0, 1);
```

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}
```

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).

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

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

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)`.

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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

$$\mathrm{J}[\![x.y]\!] = (\texttt{get-field}\ (\textbf{deref}\ x)\ \texttt{"y"})$$

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.

$$\mathbf{J}[\![x.y := e]\!] = (\texttt{let}\ ([\underline{data}\ \mathbf{J}[\![e]\!]])\ (\texttt{begin}$$
$$(\texttt{set!}\ \underline{x}\ (\texttt{set-field}\ (\text{deref}\ \underline{x})\ \text{"}y\text{"}\ \text{data}))\ \text{data}))$$

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

$$\mathbf{J}[\![x.y := e]\!] = (\texttt{let}\ ([\underline{data}\ \mathbf{J}[\![e]\!]])\ (\texttt{begin}$$
$$(\texttt{set!}\ \underline{x}\ (\texttt{set-field}\ (\text{deref}\ \underline{x})\ \text{"}y\text{"}\ \text{data}))\ \text{data}))$$

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

$$\mathbf{J}[\![x.y := e]\!] = (\texttt{let}\ ([\underline{data}\ \mathbf{J}[\![e]\!]])\ (\texttt{begin}\ (\texttt{set!}\ \underline{x}\ (\texttt{set-field}\ (\text{deref}\ \underline{x})\ \text{"}y\text{"}\ \text{data}))\ \text{data}))$$

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!

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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.

$$J[\![\texttt{function}(x\cdots)\ \{e\}]\!] = (\texttt{alloc}\ (\texttt{object}$$
$$[\texttt{"\$code"}\ (\texttt{lambda}\ (\underline{this}, \underline{x}\cdots)\ J[\![e]\!])][\texttt{"prototype"}\ (\texttt{alloc}\ (\texttt{object}\ ))]))$$

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

$$J[\![\texttt{new}\ e_f(e\cdots)]\!] = \\ (\texttt{let}\ ([\underline{c}\ (\texttt{deref}\ J[\![e_f]\!])]) \\ (\texttt{let}\ ([\underline{o}\ (\texttt{alloc}\ (\texttt{object}\ [\texttt{"\$proto"}(\texttt{get-field}\ \underline{c}\ \texttt{"prototype"})]))]) \\ (\texttt{begin}\ ((\texttt{get-field}\ \underline{c}\ \texttt{"\$code"})\ \underline{o}\ J[\![e]\!]\cdots)\ \underline{o})))$$

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

$$J[\![x.y(e\cdots)]\!] = ((\texttt{get-field}\ (\texttt{deref}\ (\texttt{get-field}\ (\texttt{deref}\ \underline{x})\ \texttt{"y"}))\ \texttt{"\$code"})\ \underline{x}\ J[\![e\cdots]\!])$$

SimpleJS

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

λ-JS

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

Function call

What is the value of `this` when calling a function outside of `new`/method-call?

`this` is initialized to the global variable `window`.

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

$$\mathrm{J}[\![e_f(e\cdots)]\!] = \\ ((\texttt{get-field}\ (\texttt{deref}\ \mathrm{J}[\![e_f]\!])\ \texttt{"\$code"})\ \underline{\textit{window}}\ \mathrm{J}[\![e\cdots]\!])$$

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
```

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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.

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

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

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