Implementing Lambdas with Environments: Closures

CS 350

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Broad Goals

Overview

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- Implement an interpreter for a Curly variant with functions

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  - Add a Lambda feature

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- Replicate the behaviour of the substitution-based interpreter

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Key Concepts

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Key Concepts

- Definition of a closure

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Key Concepts

- Definition of a closure
- Static and Dynamic Scope for first-class functions

The Details

Substitution to Environmenst, Review

- Interpreter takes environment argument

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Substitution to Environmenst, Review

- Interpreter takes environment argument

```
(define (interp [env : Env]
                [expr : Expr])
        : Value ;; Was Number
  ....)
```

- Function-calls evaluate body in environment containing argument

Core and Abstract Syntax

- Exact same as Curly-Lambda substitution version

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Core and Abstract Syntax

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```
(define-type Expr
  ....
  (Fun [arg : Symbol]
       [body : Expr]))
```

- Goal is to interpret the same language, but with environments

A (Wrong) First Attempt: Values

- Define `Value` just like in substitution version

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```
(define-type Value
  (NumV [num : Number])
  (FunV [arg : Symbol]
        [body : Expr]))
```

A Wrong First Attempt: Functions Interp

- As a first attempt, try building functions just like in substitition version

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(define (interp env expr)
  (type-case Expr interp
     ....
     [(Fun x body)
       (FunV x body)] ))
```

A Wrong First Attempt: Calls Interp

- Just like before

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- Interpret function body in the environment with the parameter bound to the argument's value

```
(define (interp env expr)
  (type-case Expr interp
  ....
    [(Call funExpr argExpr)
      (let* ([argVal (interp argExpr)]
             [funVal (checkAndGetFun (interp funExpr))]
             [funParam (fst funVal)]
             [funBody (snd funVal)]))
        (interp (extendEnv (bind funParam argVal)
                           env) ;;<------
                funBody))] ))
```

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- When we actually go to interpret the body, we don't have the environment that the function was created in

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The problem

- With a lambda, there could have been many substitutions that were applied to its free variables
  - With substitutions, the variables get replaced in the lambda
  - With environments, the variables aren't replaced *until we interpret the body*
- When we actually go to interpret the body, we don't have the environment that the function was created in
  - Just the environment from the time of the call
- We've implemented **dynamic scoping** by accident!

The Solution: Closures

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    - The combination of a function variable+body and an environment is called a **closure**

The Solution: Closures

- A function should be *closed* over its environment at the point it's created (interpreted)
- So we add an extra piece of data to the `Value` variant for functions: the environment at the time of creation
    - The combination of a function variable+body and an environment is called a **closure**
- Closures give environment interpreters the same behavior as substitution interpreters

Terminology

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- *Static scope* means a function never changes once it has been **defined**
  - We can still create functions dynamically
  - But once created they're static

The New Value Type

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```
(define-type Value
  (NumV [num : Number])
  ;; Like FunV but with an environment
  (ClosureV [arg : Symbol]
            [body : Expr]
            [env : Env]))
```

A New Dynamic Type Checker

- Same idea as `checkAndGetFun`, just has an extra piece of data to retrieve

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```
(define (checkAndGetClosure [v : Value]) : ((Symbol * Expr) * Env)
  (type-case Value v
     [(ClosureV x body env)
      (pair (pair x body) env)]
     [else
     (error 'curlyTypeError
            (string-append "Expected Function, got number:"
                           (to-string v)))]))
```

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(define (interp env expr)
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```
(define (interp env expr)
  (type-case Expr interp
  ....
    [(Call funExpr argExpr)
      (let* ([argVal (interp argExpr)]
             [funVal (checkAndGetClosure (interp funExpr))]
             [funParam (fst (fst funVal))]
             [funBody (snd (fst funVal))]
             [funEnv (snd funVal)]))
       (interp (extendEnv (bind funParam argVal)
                          funEnv);;<------
               funBody))] )
```

Summary: Dynamic vs. Static Scope

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- Free variables in a function body are variables that are not defined/bound in that function body
- Static scope gives free variables values from the environment when the function was *constructed*
- Dynamic scope gives variables values from the environment when the function was *called*

Example: Static Scope

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```
{letvar double {fun {x} {* x 2}}
  {letvar quadruple {fun {y} {double {double y}}}
    {letvar double 2
      {quadruple 3}}}}
```

- `{fun {y} {double {double x}}}` has one free variable, `double`

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  - Functions and variables are in *the same namespace* in Curly-Lambda

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  - Functions and variables are in *the same namespace* in Curly-Lambda
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  - Env is `double := {fun {x} {* x 2}}`

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  - Env is `double := {fun {x} {* x 2}}`
- Env at call:

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  - Env is `double := {fun {x} {* x 2}}`
- Env at call:
  - `double := 2`

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- `{fun {y} {double {double x}}}` evaluates to closure
  - Body is `{double {double x}}`
  - Env is `double := {fun {x} {* x 2}}`
- Env at call:
  - `double := 2`
  - `quadruple := {fun {y} {double {double x}}}`

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  - Functions and variables are in *the same namespace* in Curly-Lambda
- `{fun {y} {double {double x}}}` evaluates to closure
  - Body is `{double {double x}}`
  - Env is `double := {fun {x} {* x 2}}`
- Env at call:
  - `double := 2`
  - `quadruple := {fun {y} {double {double x}}}`
  - `double := {fun {x} {* x 2}}`

Example: Static Scope ctd

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```
{letvar double {fun {x} {* x 2}}
  {letvar quadruple {fun {y} {double {double x}}}
    {letvar double 2
      {quadruple 3}}}}
```

- Call evaluates `quadruple` to closure

Example: Static Scope ctd

```
{letvar double {fun {x} {* x 2}}
  {letvar quadruple {fun {y} {double {double x}}}
    {letvar double 2
      {quadruple 3}}}}
```

- Call evaluates `quadruple` to closure
- Finally evaluates `{double {double x}}`

Example: Static Scope ctd

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{letvar double {fun {x} {* x 2}}
  {letvar quadruple {fun {y} {double {double x}}}
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- Call evaluates `quadruple` to closure
- Finally evaluates `{double {double x}}`
  - In extended closure environment:

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- Call evaluates `quadruple` to closure
- Finally evaluates `{double {double x}}`
  - In extended closure environment:
    - `x := 3`

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- Call evaluates `quadruple` to closure
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  - In extended closure environment:
    - `x := 3`
    - `double := {fun {x} {* x 2}}`

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```

- Call evaluates `quadruple` to closure
- Finally evaluates `{double {double x}}`
  - In extended closure environment:
    - `x := 3`
    - `double := {fun {x} {* x 2}}`
- Result is 12

Example: Dynamic Scope

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  - Doesn't save environment

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  - In extended *call site* environment:

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- Dynamic type error

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    - `double := 2`
    - `quadruple := {fun {y} {double {double x}}}`
    - `double := {fun {x} {* x 2}}`
- Dynamic type error
  - Can't call 2 as a function

But Professor, When Will I Ever Use This?

Static Scoping in the Wild

Python:

Static Scoping in the Wild

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Static Scoping in the Wild

Python:

```
timesTwo = lambda x : 2 * x
quadruple = lambda y : timesTwo(timesTwo(y))
def mainFun(x):
    timesTwo = 2.0
    return quadruple(x)
return mainFun(3)
```

```
12
```

Result:

```
12
```

Static Scoping in the Wild

JavaScript:

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Static Scoping in the Wild

JavaScript:

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var timesTwo = function (x) { return x * 2 };
var quadruple =
    function (x) {return timesTwo(timesTwo(x)) };
function mainFun(x){
    var timesTwo = 2.0;
    return quadruple(x)}
return mainFun(3)
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Result:

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Async in JavaScript

- From the w3schools async tutorial

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```
async function myFunction() {
  return "Hello";
}
myFunction().then(
  function(value) {myDisplayer(value);}
);
```

- `myFunction.then` is a higher order function

Async in JavaScript

- From the w3schools async tutorial

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  return "Hello";
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- They call the function argument the *callback*

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- `myFunction.then` is a higher order function
  - Takes in another function as an argument
- They call the function argument the *callback*
- `function(value)` is just the Javascript syntax for lambda

Async in JavaScript

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- `myFunction.then` is a higher order function
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- `function(value)` is just the Javascript syntax for lambda
  - Dynamically creates the function that is run when `myFunction` actually runs

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- `myFunction.then` is a higher order function
  - Takes in another function as an argument
- They call the function argument the *callback*
- `function(value)` is just the Javascript syntax for lambda
  - Dynamically creates the function that is run when `myFunction` actually runs
- Concurrency in JS is mostly just syntactic sugar for lambda/higher-order functions

And More

- Swift “Closures” are just lambdas

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- Swift “Closures” are just lambdas

```
names.sorted(by:
  { (s1: String, s2: String) -> Bool
      in return s1 > s2
  } )
```

- C++11 added anonymous functions

And More

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names.sorted(by:
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names.sorted(by:
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  } )
```

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```
sort(V.begin(), V.end(), [](auto& a, auto& b)
{
   return a > b;
});
```

- Java 8 added anonymous functions

And More

- Swift “Closures” are just lambdas

```
names.sorted(by:
  { (s1: String, s2: String) -> Bool
      in return s1 > s2
  } )
```

- C++11 added anonymous functions

```
sort(V.begin(), V.end(), [](auto& a, auto& b)
{
   return a > b;
});
```

- Java 8 added anonymous functions

And More

- Swift “Closures” are just lambdas

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```
Arrays.sort(arr,
  (String a, String b) ->
              a.length() - b.length());
```

- This is all just lambda with different syntax