Objectives

Closures

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- ▶ Add conditional expressions (if then else) to your language.
- ► Add functions and function application to your interpreter.
- Explain the parts of a closure and why they are necessary.





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Review

- ▶ Last time: made an interpreter with arithmetic, booleans, variables, and let.
- ► This time:
 - Add if expressions.
 - ▶ Add functions and function calls.
- ► Code can be found in the i5 directory.

Variables and Let Expressions

```
1 eval (VarExp var) env =
2   case lookup var env of
3     Just val -> val
4     Nothing -> IntVal 0
5
6 eval (LetExp var e1 e2) env =
7   let v1 = eval e1 env
8   in eval e2 (insert var v1 env)
```

▶ N.B. The variable let creates disappears after the let body is evaluated!!



If Expressions Conclusions Objectives If Expressions Conclusions Objectives 0000 0000000 0000000

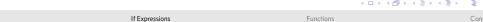
For Example

```
In HASKELL ...
Prelude let z = 10 in z + 1
211
3 Prelude> z
4<interactive>:2:1: error: Variable not in scope: z
In i5...
i5 > let z = 10 in z + 1 end
IntVal 11
i5> z
IntVal 0
```

Adding If Expressions

```
1 data Exp = IfExp Exp Exp Exp
i5>if 5>2 then 10 else 20 fi
IntVal 10
i5> if 5 > 22 then 10 else 20 fi
IntVal 20
```





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Conclusions

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If Expressions

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The Eval

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```
leval (IfExp e1 e2 e3) env =
   let v1 = eval e1 env
    in case v1 of
        BoolVal True -> eval e2 env
                     -> eval e3 env
5
```

Adding Functions to Our Language

► Consider this function application in HASKELL.

$$_{1}(x \rightarrow x + 10) 20$$

- ► We have:
 - ► A parameter
 - ► A function body
 - ► An argument



Adding Functions: Take 1

```
AppExp Exp Exp | ...
data Val = FunVal String Exp | ...

feval (FunExp v body) env = FunVal v body
eval (AppExp e1 e2) env =
let (FunVal v body) = eval e1 env
arg = eval e2 env
in eval body (insert v arg env)
```

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What Could Possibly Go Wrong?

► Consider this function definition and function call.

▶ Now we use a second let to define the increment.

```
1 Main> let f =
2     let delta = 10
3     in \ x -> x + delta
4     in f 20
5 30
```

▶ When we run f 20, is delta still in scope?

If Expressions



Conclusions

The Need for Closures

- ▶ Now consider this one. We have two variables called delta!
- ► How does the function know which one to use?

```
1 Main> let f =
2     let delta = 10 in \ x -> x + delta
3     in
4     let delta = 20 in f 20
5 30 --- Why not 40??
```

Closures

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▶ The "function value" needs to remember the values of free variables in its function body.

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▶ The resulting data structure is called a *closure*.





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An Example Evaluation

► Let's evaluate this expression:

```
let d = 10 in \xspace x -> x + d
```

► Initial call to eval:

▶ Step 1: eval will be called on the IntExp 10 to get the value of d.

```
eval (IntExp 10) [] => IntVal 10
```

Example, Continued

▶ Now d is part of the environment when we evaluate the body of the let.



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Functions
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Now Let's Call the Function!

Objectives

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Now Let's Call the Function! Pt 2

► After the function has been evaluated into a closure ...



Now Let's Call the Function! Pt 3

- ► After the function has been evaluated into a closure ...
- ► And y has been defined ...



Reminder of the Code

▶ Remember what eval says to do with function calls.

```
leval (AppExp e1 e2) env =
let (Closure v body clenv) = eval e1 env
arg = eval e2 env
in eval body (insert v arg clenv)
```



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Now Let's Call the Function! Pt 4

If Expressions

► We unfold the f and y values ...

```
eval (IntOpExp "+" (VarExp "x") (VarExp "d"))
    [("x", eval (VarExp "y") [("y",IntVal 20)), ...]
    ,("d", IntVal 10)]
```

Conclusions

- Some history
 - ▶ The first language to use closures (and call them that) was Peter Landin's SECD machine.
 - ► The first widespread use of closures was in SCHEME, a dialect of LISP.
 - ► Today they are very common!
- ► Things to try
 - ► What if you wanted C-style ifs?
 - ▶ Try some other examples of function calls.
 - ► Try making multi-parameter functions.