Handout Progress

Interpretation and Compilation
2022

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Handout Phase 0.1

Implement a complete interpreter and compiler for a tiny arithmetic expression language

Use the approach we are developing in the course

- LL(1) parser using JAVACC
- AST Model
- Interpreter
- Compiler

Fully understanding the handout statement is part of the handout as well.

Contact me anytime if you need help.

Handout Phase 0.1

Learning Outcomes

- you learn how to develop a simple parser using JavaCC
    - understand how to specify tokens using regular expressions
    - you understand how to specify a simple non ambiguous LL(1) context free grammar
- you understand the basics of abstract syntax trees (AST)
- you learn how to define the semantics evaluation function over the AST (this provides an interpreter for the language)
- you learn how to define the semantics compilation function over the AST (this provides a compiler for the language, and allows you to meet the Java Virtual Machine (JVM) internals

Handout Phase 0.1

Abstract Syntax (Abstract Constructors)

ADD: Exp x Exp -> Exp

SUB: Exp x Exp -> Exp

MUL: Exp x Exp -> Exp

DIV: Exp x Exp -> Exp

UMINUS: Exp -> Exp

NUM: int -> Exp

Handout Phase 0.1

Concrete Syntax (Examples)

2*3+4

2*(3+4)

4-2/5*2

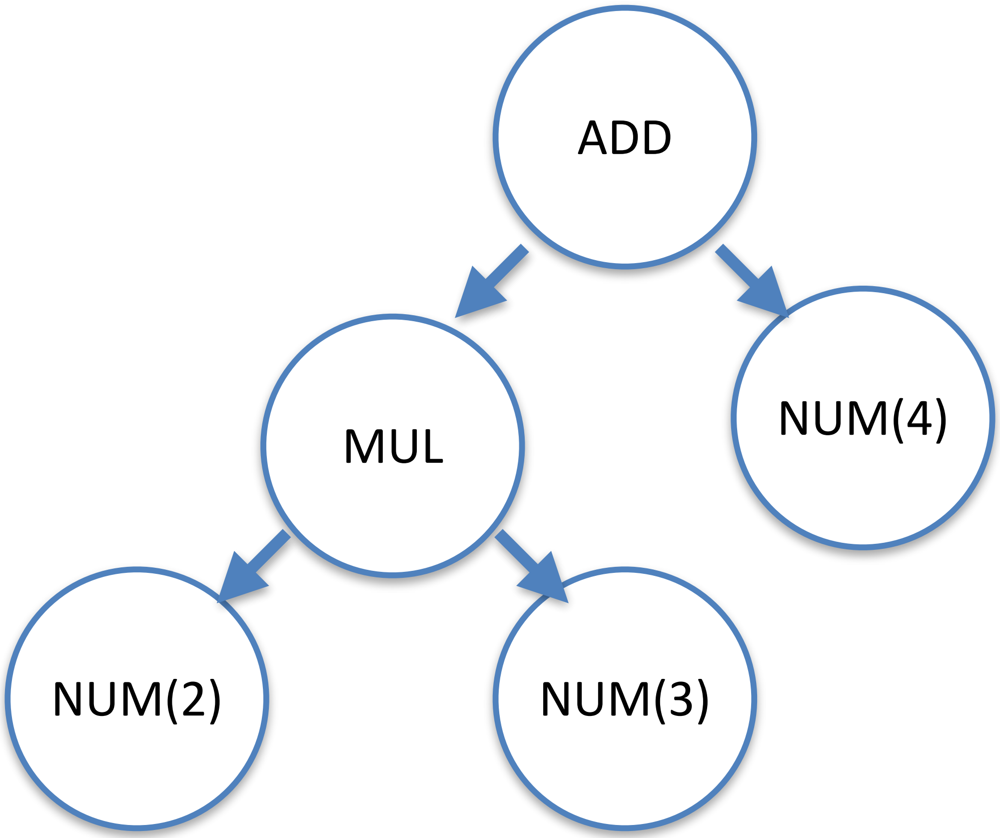
-(2+2-4)

-2

Handout Phase 0.1

Abstract Syntax (Abstract Constructors) **2*3+4**

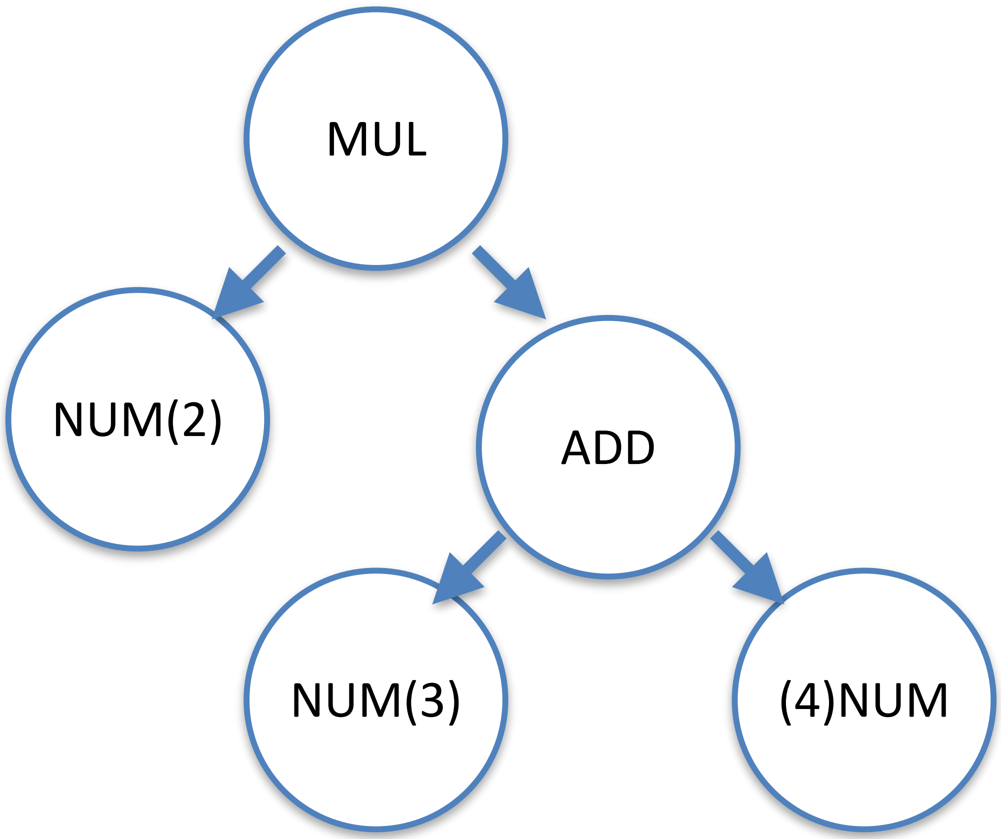
ADD(MUL(NUM(2),NUM(3)), NUM(4))



Handout Phase 0.1

Abstract Syntax (Abstract Constructors) **2*(3+4)**

MUL(NUM(2), ADD(NUM(3),NUM(4))



Handout Phase 0.1

Grammar

Alphabet = { **num**, **+**, **-**, *, **/**, **(**, **)** }

E -> **num**

E -> E **+** E

E -> E **-** E

E -> E ***** E

E -> E **/** E

E -> **-** E

E -> **(** E **)**

Handout Phase 0.1

Grammar (ambiguous)

E ->

| **num**

| E **+** E | E **-** E

| E ***** E | E **/** E | **-**E | **(** E **)**

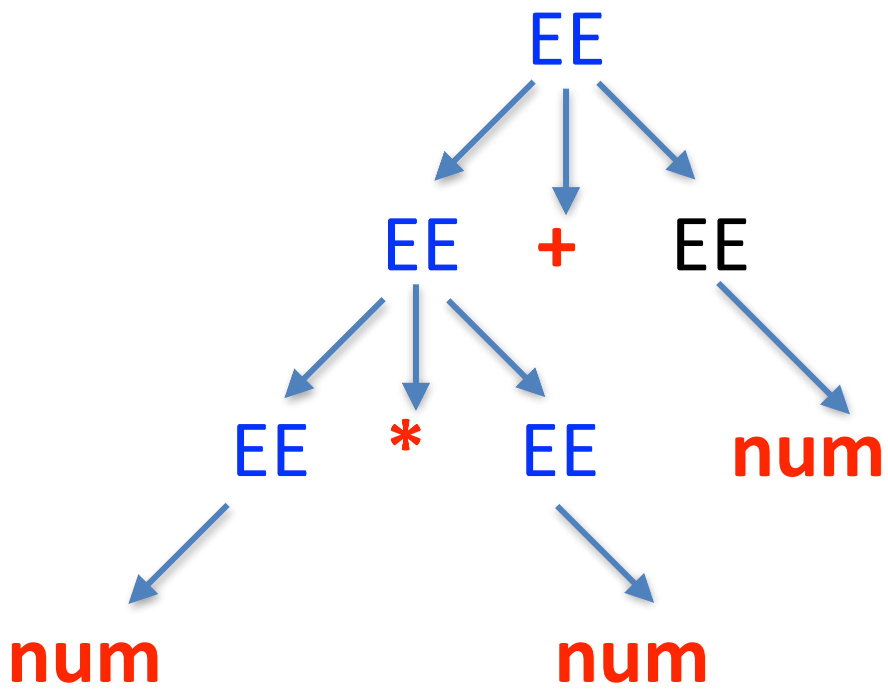
num * num + num has two derivations

EE -> EE + EE -> EE * EE + EE -> **num * num + num**

EE -> EE * EE -> EE * EE + EE -> **num * num + num**

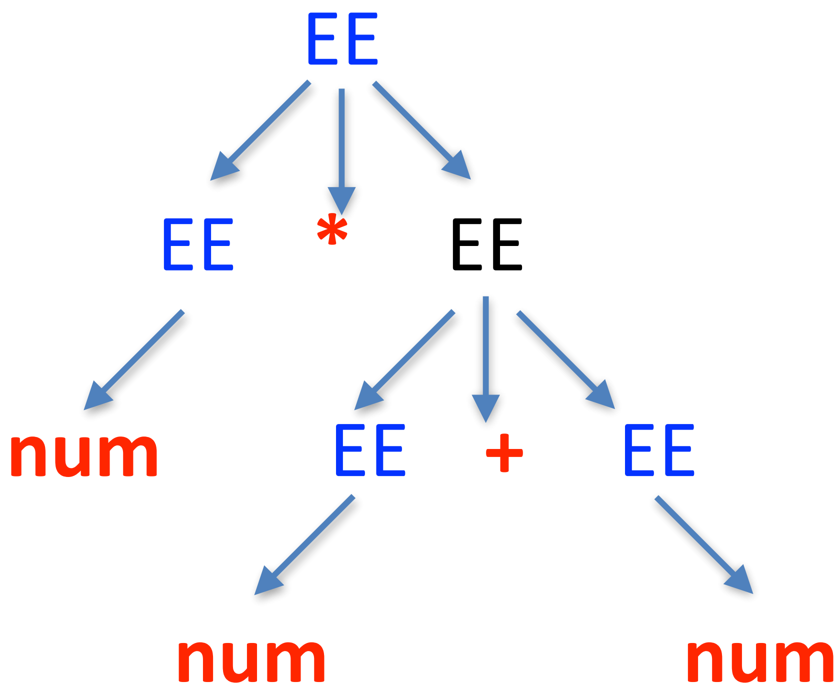
Handout Phase 0.1

EE -> EE **+** EE -> EE ***** EE **+** EE -> **num * num + num**



Handout Phase 0.1

EE -> EE * EE -> EE * EE + EE -> **num * num + num**



Handout Phase 0.1

Grammar (non-ambiguous LL(1))

E -> T

E -> T **+** E

T -> F

T -> F ***** T

F -> **num**

F -> **(** E **)**

F -> **-** F

Handout Phase 0.1

Grammar (non-ambiguous)

E -> T

E -> T **+** E

T -> F

T -> F ***** T

F -> **num**

F -> **(** E **)**

F -> **-** F

Handout Phase 0.1

Grammar (non-ambiguous and LL(1))

E -> TE’

E’ -> ε | **+** E

T -> FT’

T’ -> ε | ***** T

F -> **num**

F -> **(** E **)**

F -> **-** F

E -> TE’ -> T+E -> T+TE’ -> T +T+E -> ... -> T + T + ... + T

Handout Phase 0.1

Grammar (non-ambiguous and LL(1))

E -> TE’

E’ -> ε | **+** E

T -> FT’

T’ -> ε | ***** T

F -> **num**

F -> **(** E **)**

F -> **-** F

num * num + num

E -> TE’ -> FT’E’ -> **num** T’E’ ->

num * T E’ -> **num *** FT’ E’ ->

num * num T’ E’ ->

num * num + E ->

num * num + E ->

num * num + E ->

num * num + TE’ -> **num * num + num**

E -> TE’ -> T+E -> T+TE’ -> T +T+E -> … -> T + T + … + T

Handout Phase 0.1

Grammar (non-ambiguous and LL(1))

EBNF (Extended BNF)

E -> T [(**+** | **-**) T] *

T -> F [(***** | **/**) F] *

F -> **num** | **(** E **)** | **-** **F**

AST (schematic)

```
interface ASTNode {
int eval() ...
}

class AST??? implements ASTNode {


}
```

AST (schematic)

```
class ASTAdd implements ASTNode {
ASTNode lhs;
ASTNode rhs;
public ASTAdd (ASTNode l, ASTNode r) {
        lhs = l;
        rhs = r;
}
}
```

AST (schematic)

```
class ASTAdd implements ASTNode {

public eval() {
        int vl = lhs.eval();
        int rv = rhs.eval();
        return vl + rv;
}

}
```

interpreter main (schematic) (schematic)

```
PARSER_BEGIN(Parser0)

public class Parser0 {

  /** Main entry point. */
  public static void main(String args[]) {
    Parser0 parser = new Parser0(System.in);

    while (true) {
    try {
    System.out.print( "> " );
    ASTNode ast = parser.Start();
    System.out.println( ast.eval() );
    } catch (Exception e) {
      System.out.println ("Syntax Error!");
      parser.ReInit(System.in);
    }
    }
  }

}

PARSER_END(Parser0)
```

(Note) JavaCC installation

Installation

To install JavaCC, navigate to the download directory and type:

```
$ unzip javacc-7.0.10.zip
or
$ tar xvf javacc-7.0.10.tar.gz
```

Then place the binary `javacc-7.0.10.jar` in a new `target/` folder, and rename to `javacc.jar`.

Get the javacc-7.0.10.jar from the Binaries link-
Put in target/ folder under name javacc.jar
Execute using script/javacc

Handout Phase 0.2

Learning Outcomes

- you learn how to develop a simple parser using JavaCC
  - understand how to specify tokens using regular expressions
  - you understand how to specify a simple non-ambiguous LL(1) context free grammar
- you understand the basics of abstract syntax trees (AST)
- you learn how to define the semantics evaluation function over the AST (this provides an interpreter for the language)
- you learn how to define the **semantics compilation** function over the AST (this provides a compiler for the language, and allows you to meet the **Java Virtual Machine** (JVM) internals

AST (schematic)

```
interface ASTNode {
int eval();
void compile(CodeBlock c);
}

class CodeBlock {
String code[];
int pc;
void emit(String opcode){
        code[pc++] = opcode;
}
void dump(PrintStream f) { … // dumps code to f }
}
```

AST (schematic)

```
class ASTAdd implements ASTNode {

public void compile(CodeBlock c) {
        lhs.compile(c);
        rhs.compile(c);
        c.emit(“iadd”);
}

}
```

JVM bytecodes

- sipush *n*
- iadd
- imul
- isub
- idiv
- ineg
- …

- .class public Main
- .super java/lang/Object
- ;
- ; standard initializer
- .method public <init>()V
- aload_0
- invokenonvirtual java/lang/Object/<init>()V
- return
- .end method
- .method public static main([Ljava/lang/String;)V
- .limit locals 10
- .limit stack 256
- ; 1 - the PrintStream object held in java.lang.System.out
- getstatic java/lang/System/out Ljava/io/PrintStream;
- ; place your bytecodes here between START and END
- ; START

- sipush 20
- sipush 20
- iadd
- sipush 2
- imul

- ; END
- ; convert to String;
- invokestatic java/lang/String/valueOf(I)Ljava/lang/String;
- ; call println
- invokevirtual java/io/PrintStream/println(Ljava/lang/String;)V
- return
- .end method

JVM bytecodes

sipush

Operation

Push `short`

Format

```
sipush
byte1
byte2
```

Forms

sipush = 17 (0x11)

Operand Stack

... →

..., *value*

Description

The immediate unsigned *byte1* and *byte2* values are assembled into an intermediate `short`, where the value of the `short` is (*byte1* << 8) | *byte2*. The intermediate value is then sign-extended to an `int` *value*. That *value* is pushed onto the operand stack.

JVM bytecodes

iadd

Operation

Add `int`

Format

`iadd`

Forms

iadd = 96 (0x60)

Operand Stack

..., *value1*, *value2* →

..., *result*

Description

Both *value1* and *value2* must be of type `int`. The values are popped from the operand stack. The `int` *result* is *value1* + *value2*. The *result* is pushed onto the operand stack.

The result is the 32 low-order bits of the true mathematical result in a sufficiently wide two's-complement format, represented as a value of type `int`. If overflow occurs, then the sign of the result may not be the same as the sign of the mathematical sum of the two values.

Despite the fact that overflow may occur, execution of an *iadd* instruction never throws a run-time exception.

compiler main (schematic)

```
PARSER_BEGIN(Parser0C)

  public static void main(String args[]) {
    Parser0C parser = new Parser0C(System.in);
    CodeBlock code = new CodeBlock();
    while (true) {
    try {
    ASTNode ast = parser.Start();
    ast.compile(code);
    code.dump(outfile);
    } catch (Exception e) {
      System.out.println ("Syntax Error!");
      parser.ReInit(System.in);
    }
    }
  }

PARSER_END(Parser0C)
```

Summary of what to know / do

- Install and run javacc
- Write javacc grammars for expression languages
- Define in Java the AST for expression language
- Implement an interpreter method (eval) in the AST for evaluating expressions in read-eval-print loop
- Understand the basic internals of Java Virtual Machine, and the instructions needed to compile expressions
- Install and run jasmin (JVM Assembler)
- Implement the compiler method (compile) in the AST for translating expressions to JVM code and generates JVM code using jasmin (use Main.j as stub).

Summary of what to know / do

- Remove the main() method from Parser0.jj and place it in two different “main” classes
    - ICLInterpreter
    - ICLCompiler
- The interpreter runs a read-eval-print loop as before

```
> ICLInterpreter
> 2+3
5
> 4/2
2
```

Summary of what to know / do

- Remove the main() method from Parser0.jj and place it in two different "main" classes
  - ICLInterpreter
  - ICLCompiler
- Make your compiler accept a source file name in the command line and execute jasmin on the generated assembler file, so that it actually generates the output class file directly.
- So, If text file source.icl contains just the line 2+3, then

  > ICLCompiler source.icl

  > java source

  5

compiler main (schematic)

```
public class ICLCompiler {

 public static void main(String args[]) {
  Parser parser = new Parser(System.in);
  CodeBlock code = new CodeBlock();
  while (true) {
  try {
  ASTNode ast = parser.Start();
  ast.compile(code);
  code.dump(outfile);
  } catch (Exception e) {
   System.out.println ("Syntax Error!");
   parser.ReInit(System.in);
  }
  }
 }
```

Handout Phase 1.0

Interpretation and Compilation
16-OUT–2020

Luis Caires

Language with definition blocks

Abstract Syntax

```
AST ->
    | num | id
    | add( AST, AST) | sub( AST, AST)
    | mul( AST, AST) | div( AST, AST) | neg( AST)
    | def( ( id , AST )+, AST) )
```

Language with definition blocks

Concrete syntax Syntax

Tokens = num id + - * / ( ) { } let = ;

EE ->

| **num** | **id**

| EE **+** EE **|** EE **-** EE

| EE ***** EE **|** EE **/** EE **|** **-**EE **|** **(** EE **)**

| **{** (**let id =** EE **;**)+ EE **}**

Parsing Scheme

```
E -> T ( + T)*

T -> F ( * F) *

F -> <num>
    | <id> | …. |
    | <{>  { l = new List() }
              ( <let> <id> <=> E <;> { l.add (.. ) }  ) +
               E <}>
    { return new ASTDef( l, b ) }
```

Sample programs

```
{ let x = 1;
  let y = x+x;
  x + y
};;

{ let x = 2;
   let y = x+2;
   { let z = 3 ;
     let y = x+1;
     x+y +z
  }
];;

{ let x = 2;
   let y = { let x = x+1; x+x };
    x * y
};;
```

What to do

Implement an interpreter for expression language with definitions

Use the approach developed in the lectures

- Extend your JAVACC LL(1) parser
  - Extend your parser with ids and definitions
- Extend your AST Model
  - ASTId, ASTDef
  - Add actions to the parser so that it will build an AST for correct input expressions
- Define the interpreter (eval method)
- You will need to define an environment based semantics

Fully understanding the handout statement is part of the handout as well. Contact me if you need help.

CALC Interpreter (environment based)

- Algorithm eval( ) that computes the denotation (integer value) of any **open** CALCI expression:

$$\text{eval} : \text{CALCI} \times \text{ENV} \rightarrow \text{Integer}$$

eval(**num**(*n*) , *env*) ≜ *n*

eval(**id**(s) , *env*) ≜ *env*.Find(s)

eval(**add**(E1,E2) , *env*) ≜ **eval**(E1, *env*) + **eval**(E2, *env*)

…

eval(**def**(s, E1, E2), *env*) ≜ **[** v1 = **eval**(E1, *env*);
env = *env*.BeginScope();
env = *env*.Assoc(s, v1);
val = **eval**(E2, *env*);
env = *env*.EndScope();
return val **]**

- Note: Case of id(s) implemented by lookup of the value of s in the current environment

AST

```
interface ASTNode {
int eval(Environment e);
}


class AST??? implements ASTNode {

}
```

AST

```
public class ASTId implements ASTNode {
String id;
ASTId(…) {…}
int eval(Environment e) {
   return e.find(id);
}
}

class AST??? implements ASTNode {


}
```

AST

```
public class ASTMul implements ASTNode {
ASTNode lhs, rhs;
ASTMul(…) {…}
int eval(Environment e) {
   return lhs.eval(e) * rhs.eval(e);
}
}

class AST??? implements ASTNode {

}
```

AST

```
class ASTDef implements ASTNode {
List<Pair<String,ASTNode>> init;
ASTNode body;
int eval(Environment e) {
    ....
}
}
```

AST

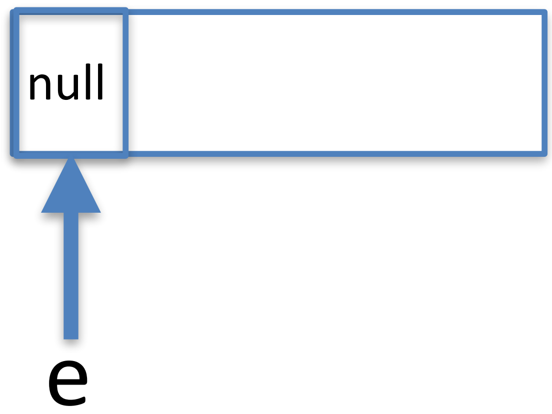
```
class ASTDef implements ASTNode {
Map<String,ASTNode> init;
ASTNode body;
int eval(Environment e) {
    ….
}
}
```

Environment (interpreter)

```
class Environment {
Environment beginScope(); //— push level
Environment endScope(); // - pop top level
void assoc(String id, int val);
int find(String id);
}
```

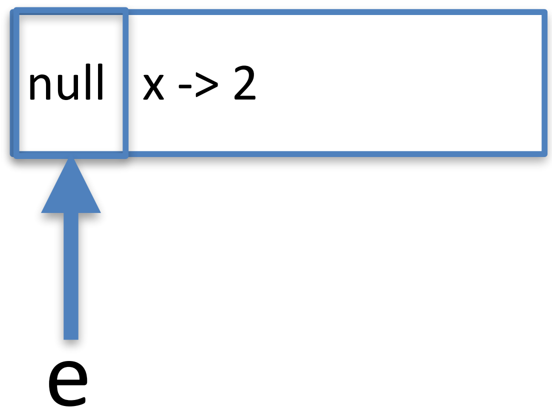
Environment (interpreter)

```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}

e = new Environment()
```



Environment (interpreter)

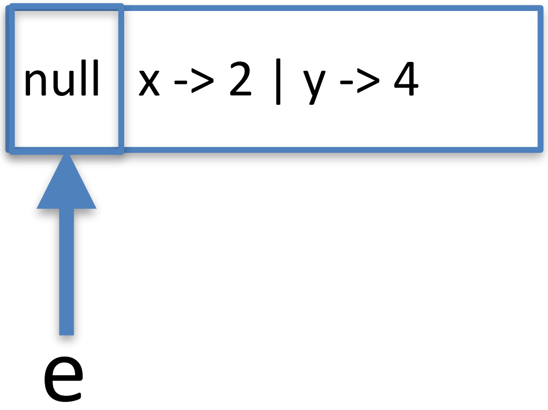
```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}

e.assoc("x",2)
```



Environment (interpreter)

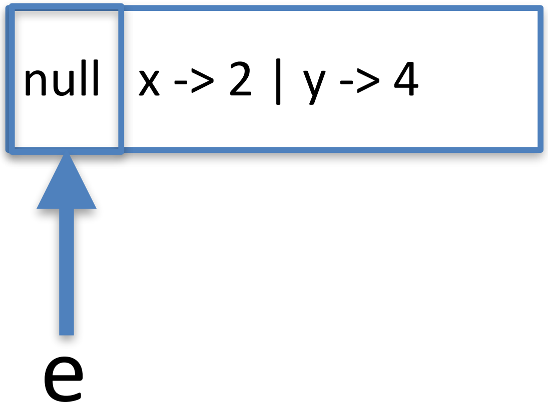
```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}
```

e.assoc(“y”,4)



Environment (interpreter)

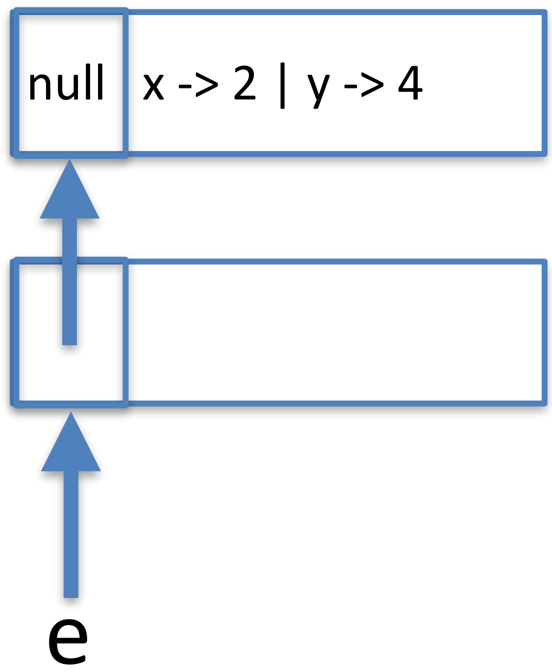
```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}
```



e.assoc("y",5) raise exception IDDeclaredTwice

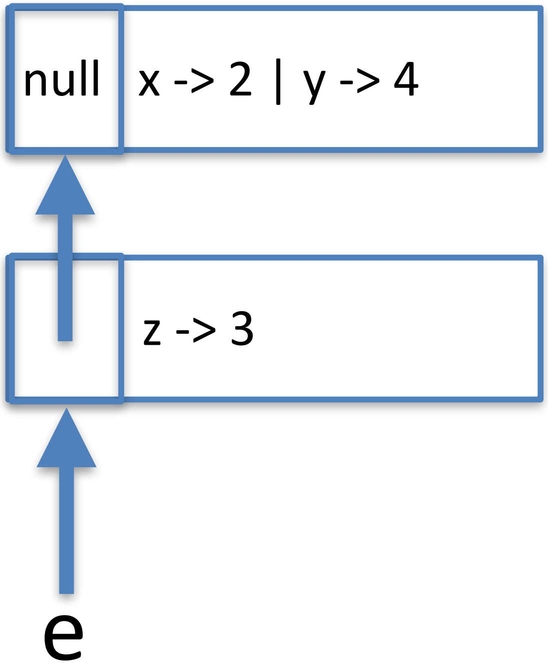
Environment (interpreter)

```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}

e = e.beginScope();
```



Environment (interpreter)

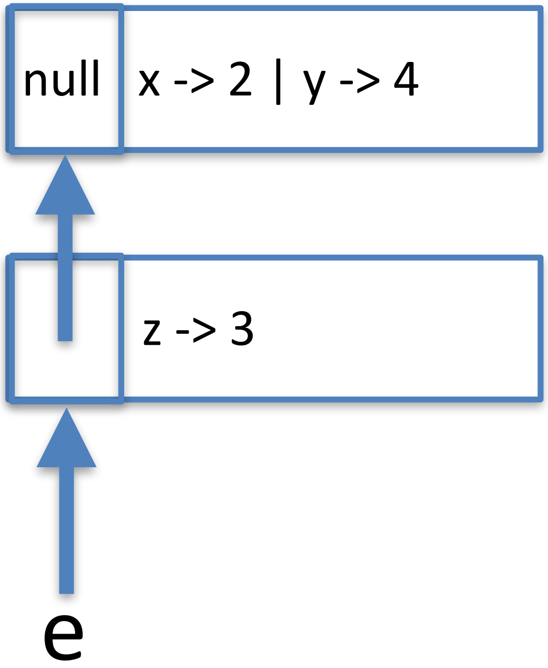
```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}
```



e.assoc("z",3)

Environment (interpreter)

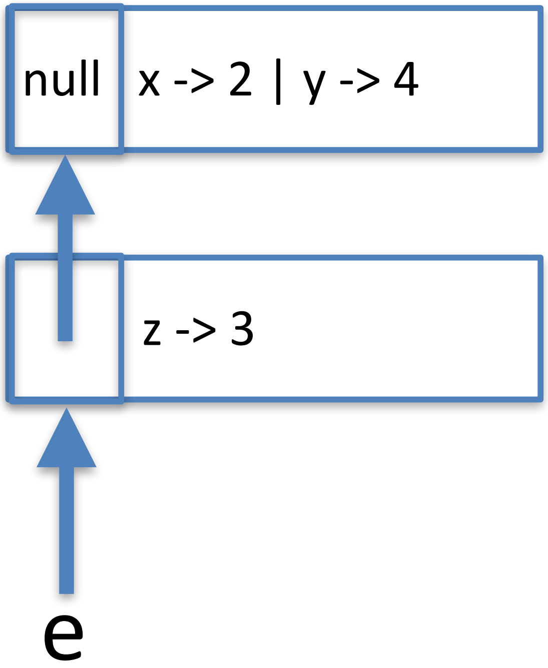
```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}
```



e.find("z") returns 3

Environment (interpreter)

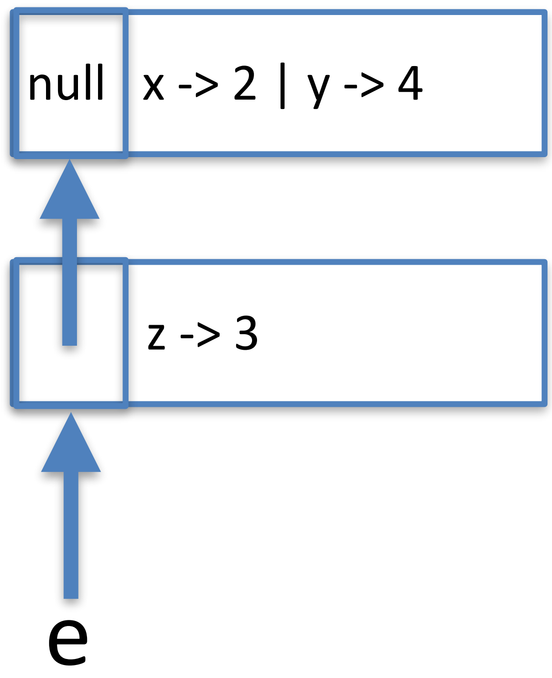
```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}
```



e.find("x") returns 2

Environment (interpreter)

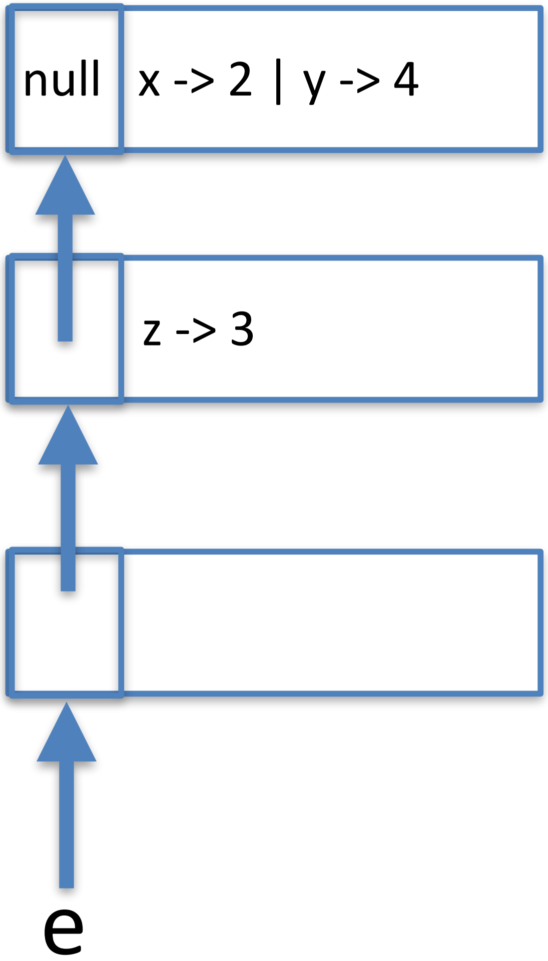
```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}
```



e.find(“a”) raises “Undeclared Identifier”

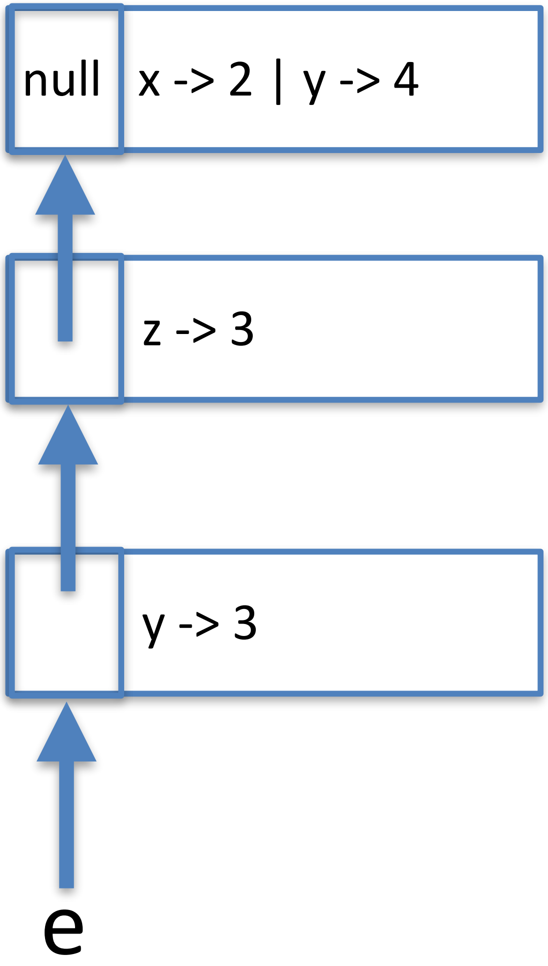
Environment (interpreter)

```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}

e = e.beginScope();
```



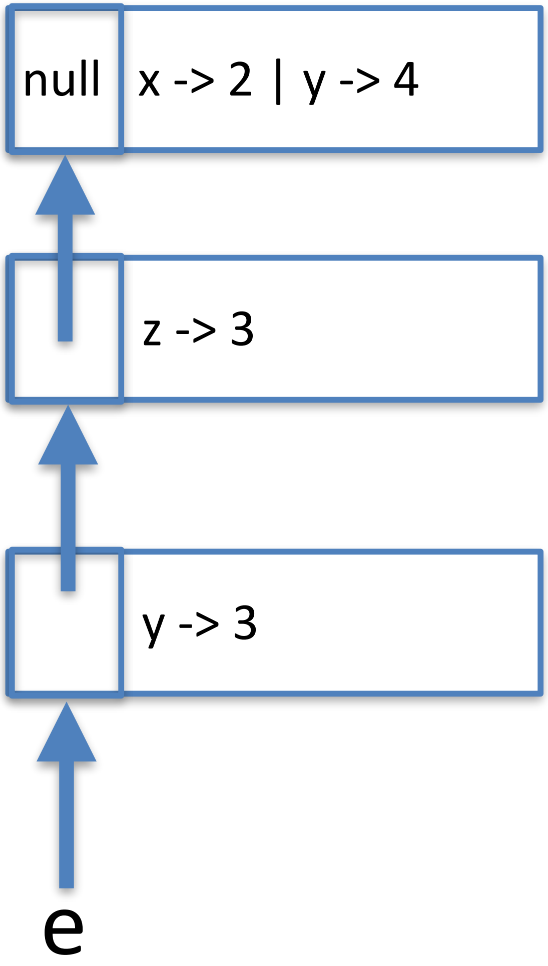
Environment (interpreter)

```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}

e.assoc("y",3);
```



Environment (interpreter)

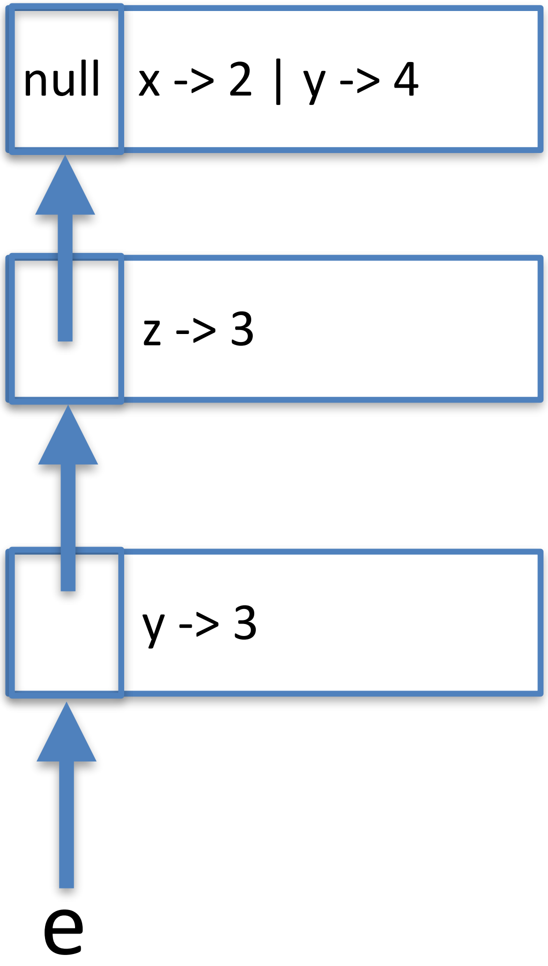
```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}

e.assoc("y",3);
```



Environment (interpreter)

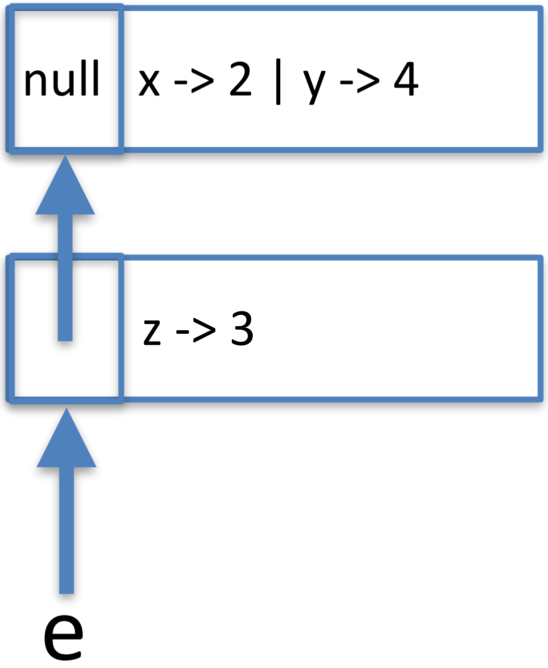
```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}
```

e.find(“y”) returns 3



Environment (interpreter)

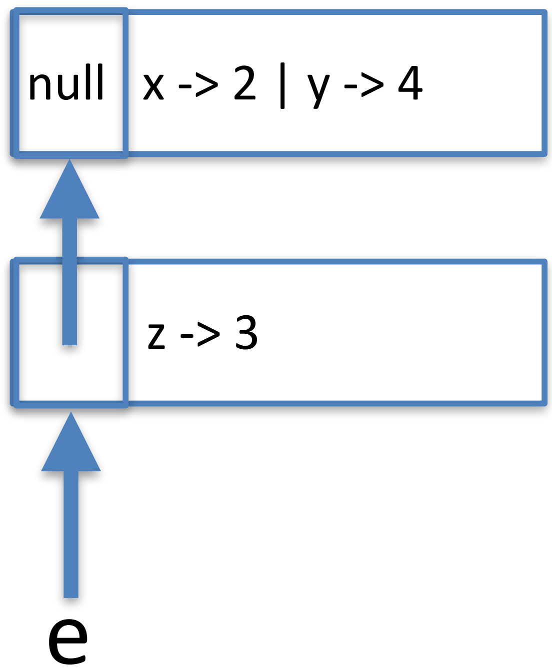
```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}
```



e.endScope()

Environment (interpreter)

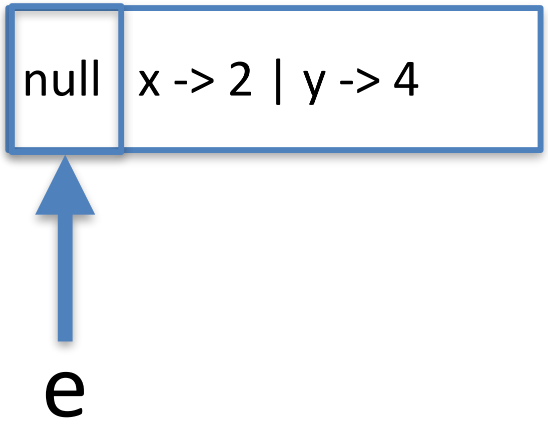
```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}
```



e.find(“y”) returns 4

Environment (interpreter)

```
class Environment {
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}
```




```
e.endScope()
```

Environment (interpreter)

```
class Environment {
Environment ancestor;
Environment beginScope();
Environment endScope();
void assoc(String id, int val);
int find(String id);
}

e = e.endScope()
```

e == null

Sample programs

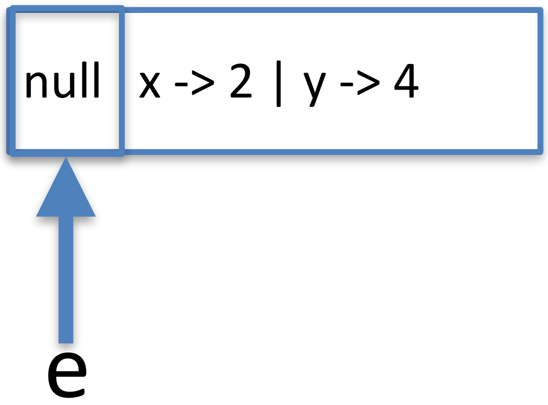
```
{ let x = 1;
  let y = x+x;
  x + y
};;

{ let x = 2;
   let y = x+2;
   { let z = 3 ;
     let y = x+1;
     x+y+z
  }
];;

{ let x = 2;
   let y = { let x = x+1; x+x };
    x * y
};;
```

Sample programs

```
{ let x = 1;
  let y = x+x;
  x + y
};;
```

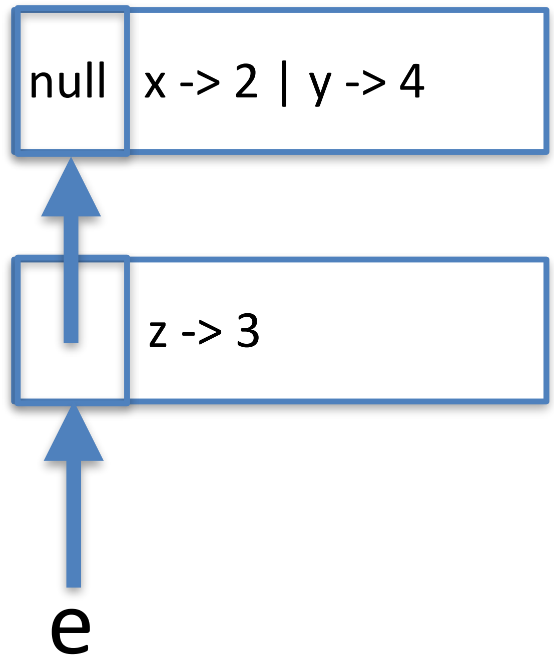
```
{ let x = 2;
  let y = x+2;
  { let z = 3 ;
    let y = x+1;
    x+y+z
  }
];;
```

```
{ let x = 2;
  let y = { let x = x+1; x+x };
   x * y
};;
```



Sample programs

```
{ let x = 1;
  let y = x+x;
  x + y
};;

{ let x = 2;
   let y = x+2;
  { let z = 3 ;
     {
     let y = x+1;
     x+y+z
     }
  }
];;

{ let x = 2;
   let y = { let x = x+1; x+x };
    x * y
};;
```



Sample programs

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  let y = x+x;
  x + y
};;

{ let x = 2;
   let y = x+2;
   { let z = 3 ;
     {
     let y = x+1;
     x+y+z
     }
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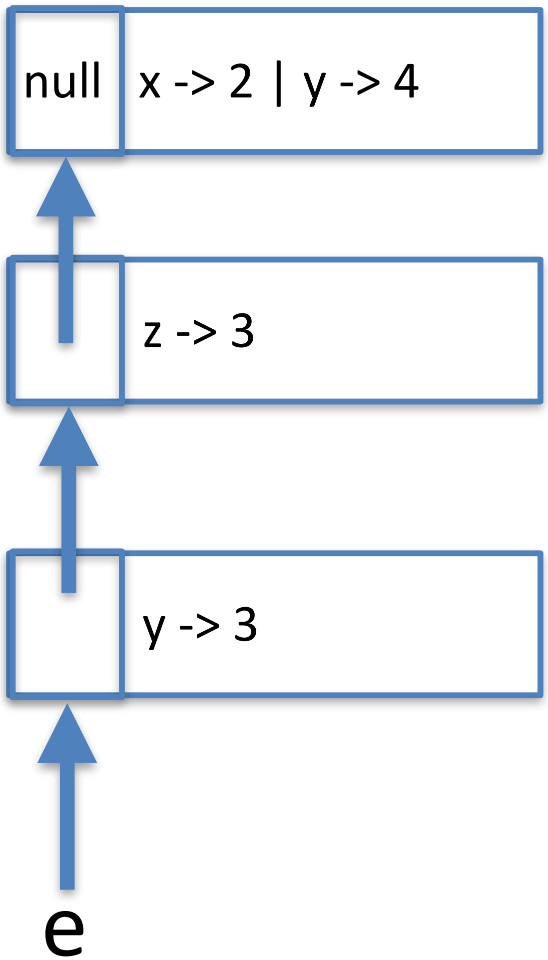

Sample programs

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   { let z = 3 ;
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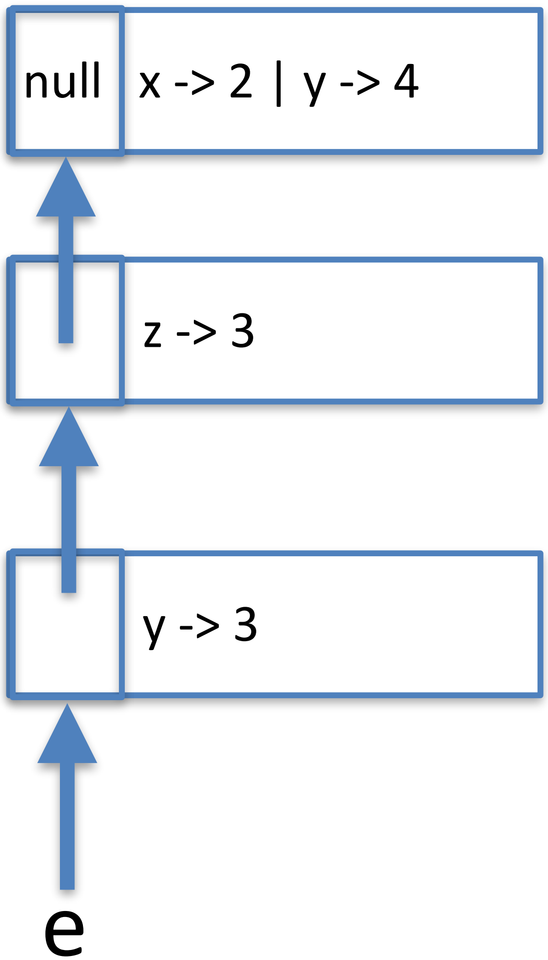

ASTDef eval (sketch)

```
class ASTDef implements ASTNode {

void eval(Environment env) {
     // def x1 = E1 … xn = En in Body end
      env = env.beginScope();
     // for each xi = Ei {
               v = Ei.eval(env);
                env.assoc(xi,v);
   }
   v = Body.eval(env);
   env.endScope();
   return v
}
```

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