Semantics

CMPT 379: Compilers

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anoopsarkar.github.io/compilers-class

Program Errors

- Program is lexically well-formed
  - Identifiers have valid names
  - Strings are properly terminated
  - No unknown characters
- Program is syntactically well-formed:
  - Class declaration have the correct structure
  - Experssions are syntactically valid
- Does this mean that the program is legal?

Example (decaf program)

```
package test {
        var myBin bool;
        func foo() void {
                var x[0] int;
                var k int = myBin * y;

        }
        func foo() void {
        }
        func fibonacci(n int) int  {
                return foo() + fibonacci(n-1);

        }
}
```

Example (decaf program)

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package test {
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}
```

Cannot define Array type as local variable
Cannot define Array of size 0

Variable not declared

Cannot redefine functions

Cannot multiply boolean

Cannot add void

No main function

Goal of Semantic Analysis

- Ensure that the program has a well-defined meaning

- Verifies properties of the program that are not caught during the earlier phases

  - All variables are declared before use

  - Types are used correctly in expressions

  - Method calls have correct number and types of parameters and return value

Challenges in Semantic Analysis

- Reject all/most of the incorrect programs

- Accept all correct programs

Validity vs Correctness

```
func main () int {
        var x string;
        if (false) {
                x = 137;
        }
}
```

Safe! cannot happen!

Validity vs Correctness

```
func fibonacci (n int) int {                    Incorrect! Should
                                                be "return n;"
        if ( n<=1 )   return 0;

        return fibonacci (n-1) + fibonacci(n-2)

 }
func main() int {

        print_int (fibonacci(40));

}
```

Challenges in Semantic Analysis

- Reject the largest number of incorrect programs

- Accept all correct programs

- Work fast!

Other Goals of Semantic Analysis

- Gather useful information about the program for code generation:
  - Determine what variables are meant by each identifier
  - Build an internal representation of inheritance hierarchies
  - Keep track of variables which are in scope at each program point

Limitation of CFGs

- Using CFGs
  - How would you prevent duplicate package definitions?
  - How would you differentiate variables of one type from variables of another type?
  - How would you ensure all called methods are defined?

- For most programming languages, these are *provably impossible* in a CFG

Implementing Semantic Analysis

- Attribute Grammars
  - Augment parsing rules to do checking during parsing
  - Has its limitations

- Recursive AST Walk
  - Construct the AST, then use recursion to explore the tree

Scoping

What's in a Name?

- The same name (identifier) in a program may refer to fundamentally different things:
- This is perfectly legal Java code:

```
public class A {
     char A;
     A   A (A  A) {
               A.A = 'A';
               return A ( (A)  A);
     }
  }
```

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What's in a Name?

- The same name (identifier) in a program may refer to completely different objects:

- This is perfectly legal C++ code:

```
int Awful () {
    int x = 137;
    {
            string x = "Scope!"
            if (float x = 0)
                    double x = x;
    }
    if (x == 137)  cout << "Y";
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            if (float x = 0)
                    double x = x;
    }
    if (x == 137)  cout << "Y";
}
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Scope

- The scope of an entity is the set of locations in a program where that entity's name refers to that entity.

- The introduction of new variables into scope may hide older variables

- How do we keep track of what's visible?

Symbol Tables

- Symbol tables map **names** (string format) to **descriptors** (information about identifiers)

- As we run our semantic analysis, continuously update the symbol table with information about what is in scope

Symbol Tables

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0:   int x =  137;
1:   int z = 42;
2:   int testFunc(int x, int y){
3:       printf("%d, %d, %d\n", x, y, z);
4:       {
5:            int x, z;
6:            z = y;
7:            x = z;
8:            {
9:                 int y = x;
10:                {
11:                     printf("%d, %d, %d\n", x, y, z);
12:                }
13:                 printf("%d, %d, %d\n", x, y, z);
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Symbol Table	
X	0

Symbol Tables

Symbol Table	
X	0
Z	1

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Symbol Table	
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X	2
Y	2

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Symbol Table	
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Symbol Table	
X	0
Z	1
X	2
Y	2
X	5
Z	5

Symbol Tables

```
0:   int x = 137;
1:   int z = 42;
2:   int testFunc(int x, int y) {
3:       printf("%d, %d, %d\n", x @2, y @2, z @1);
4:       {
5:           int x, z;
6:           z @5 = y @2;
7:           x @5 = z @5;
8:           {
9:               int y = x @5;
10:              {
11:                  printf("%d, %d, %d\n", x @5, y @9, z @5);
12:              }
13:              printf("%d, %d, %d\n", x @5, y @9, z @5);
14:          }
15:          printf("%d, %d, %d\n", x @5, y @2, z @5);
16:      }
17:  }
```

16-07-05

Symbol Table	
X	0
Z	1
X	2
Y	2
X	5
Z	5

Symbol Tables

```
0:   int x = 137;
1:   int z = 42;
2:   int testFunc(int x, int y) {
3:       printf("%d, %d, %d\n", x @2, y @2, z @1);
4:       {
5:           int x, z;
6:           z @5 = y @2;
7:           x @5 = z @5;
8:           {
9:               int y = x @5;
10:              {
11:                  printf("%d, %d, %d\n", x @5, y @9, z @5);
12:              }
13:              printf("%d, %d, %d\n", x @5, y @9, z @5);
14:          }
15:          printf("%d, %d, %d\n", x @5, y @2, z @5);
16:      }
17: }
```

Symbol Table	
X	0
Z	1
X	2
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Symbol Tables

```
0:   int x =  137;
1:   int z = 42;
2:   int testFunc(int x, int y) {
3:       printf("%d, %d, %d\n", x @2, y @2, z @1);
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5:           int x, z;
6:           z @5 = y @2;
7:           x @5 = z @5;
8:           {
9:               int y = x @5;
10:              {
11:                   printf("%d, %d, %d\n", x @5, y @9, z @5);
12:              }
13:              printf("%d, %d, %d\n", x @5, y @9, z @5);
14:          }
15:          printf("%d, %d, %d\n", x @5, y @2, z @5);
16:      }
17: }  16-07-05
```

Symbol Table	
X	0
Z	1
X	2
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Symbol Tables

```
0:   int x = 137;
1:   int z = 42;
2:   int testFunc(int x, int y) {
3:       printf("%d, %d, %d\n", x @2, y @2, z @1);
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5:           int x, z;
6:           z @5 = y @2;
7:           x @5 = z @5;
8:           {
9:               int y = x @5;
10:              {
11:                  printf("%d, %d, %d\n", x @5, y @9, z @5);
12:              }
13:              printf("%d, %d, %d\n", x @5, y @9, z @5);
14:          }
15:          printf("%d, %d, %d\n", x @5, y @2, z @5);
16:      }
17:  }   16-07-05
```
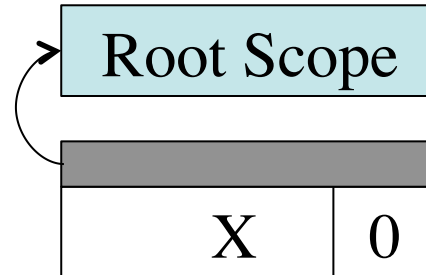
Symbol Table	
X	0
Z	1
X	2
Y	2

Symbol Tables

```
0:   int x = 137;
1:   int z = 42;
2:   int testFunc(int x, int y) {
3:       printf("%d, %d, %d\n", x @2, y @2, z @1);
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5:           int x, z;
6:           z @5 = y @2;
7:           x @5 = z @5;
8:           {
9:               int y = x @5;
10:              {
11:                  printf("%d, %d, %d\n", x @5, y @9, z @5);
12:              }
13:              printf("%d, %d, %d\n", x @5, y @9, z @5);
14:          }
15:          printf("%d, %d, %d\n", x @5, y @2, z @5);
16:      }
17: }   16-07-05
```

Symbol Table	
X	0
Z	1
X	2
Y	2

Symbol Tables

```
 0:  int x = 137;
 1:  int z = 42;
 2:  int testFunc(int x, int y) {
 3:      printf("%d, %d, %d\n", x @2, y @2, z @1);
 4:      {
 5:          int x, z;
 6:          z @5 = y @2;
 7:          x @5 = z @5;
 8:          {
 9:              int y = x @5;
10:              {
11:                  printf("%d, %d, %d\n", x @5, y @9, z @5);
12:              }
13:              printf("%d, %d, %d\n", x @5, y @9, z @5);
14:          }
15:          printf("%d, %d, %d\n", x @5, y @2, z @5);
16:      }
17:  }
```

Symbol Table	
X	0
Z	1

16-07-05

Symbol Tables

- Symbol tables map **names** (string format) to **descriptors** (information about identifiers)

- As we run our semantic analysis, continuously update the symbol table with information about what is in scope

- Typical implementation: stack

- Basic Operations:
  - Push scope: Enter a new scope
  - Pop scope: Leave a scope, discarding all declarations
  - Insert symbol: add a new identifier to the current scope
  - Lookup symbol: Given an identifier, find a descriptor

Using a Symbol Table

- To process a portion of the program that creates a scope (block statements, function calls, classes, etc.)

  - Enter a new scope

  - Add all variable declarations to the symbol table

  - Process the body of the block/function/class

  - Exit the scope

- Much of semantic analysis is defined over the parse tree using symbol tables

Another View of Symbol Table

Root Scope

X	0

➡️ 0: int x;
  1: int y;
  2: int testFunc(int x, int y)
  3: {
  4:        int w, z;
  5:        {
  6:              int y;
  7:        }
  8:        {
  9:              int w;
 10:   }
 11: }

Another View of Symbol Table
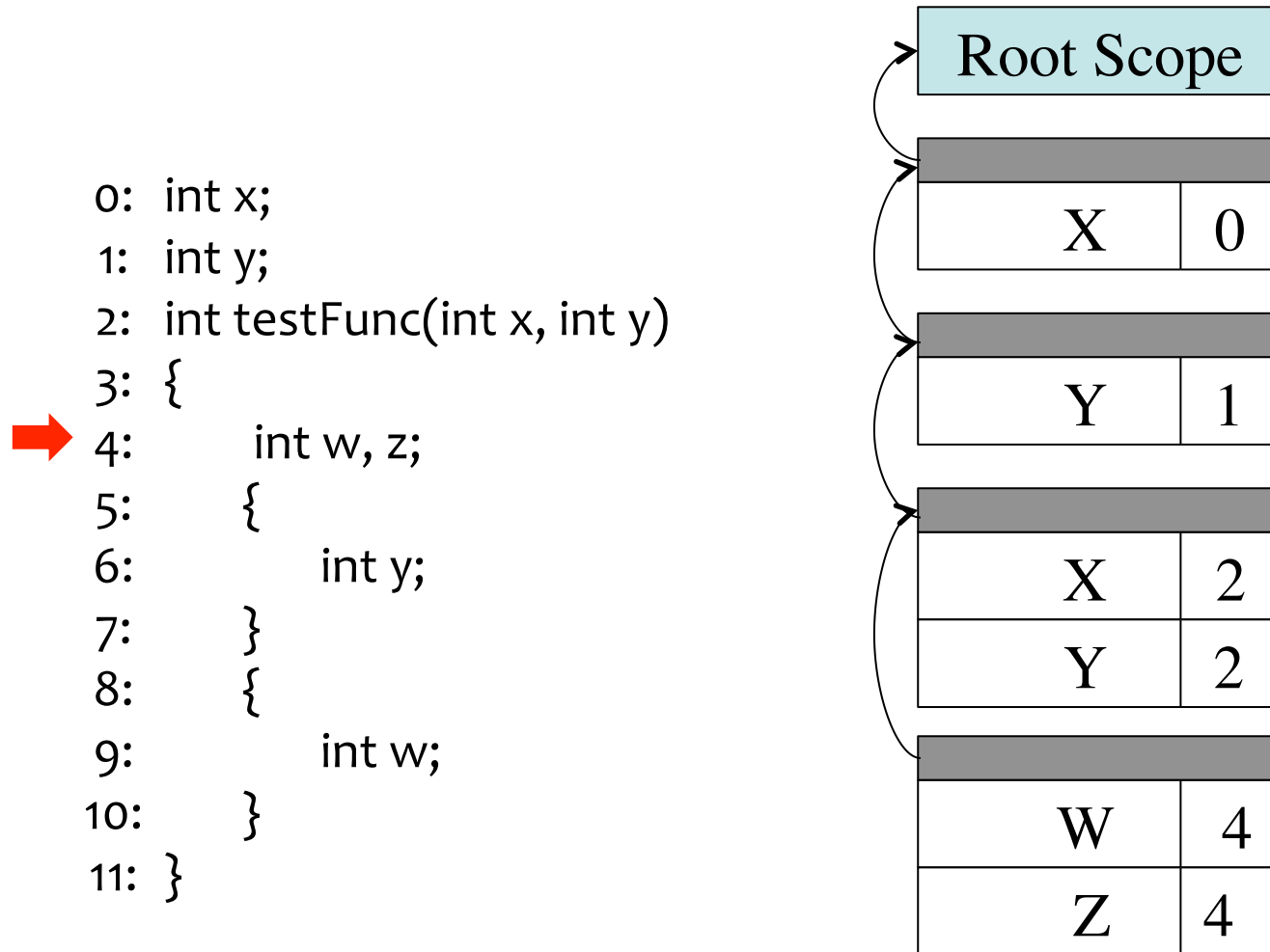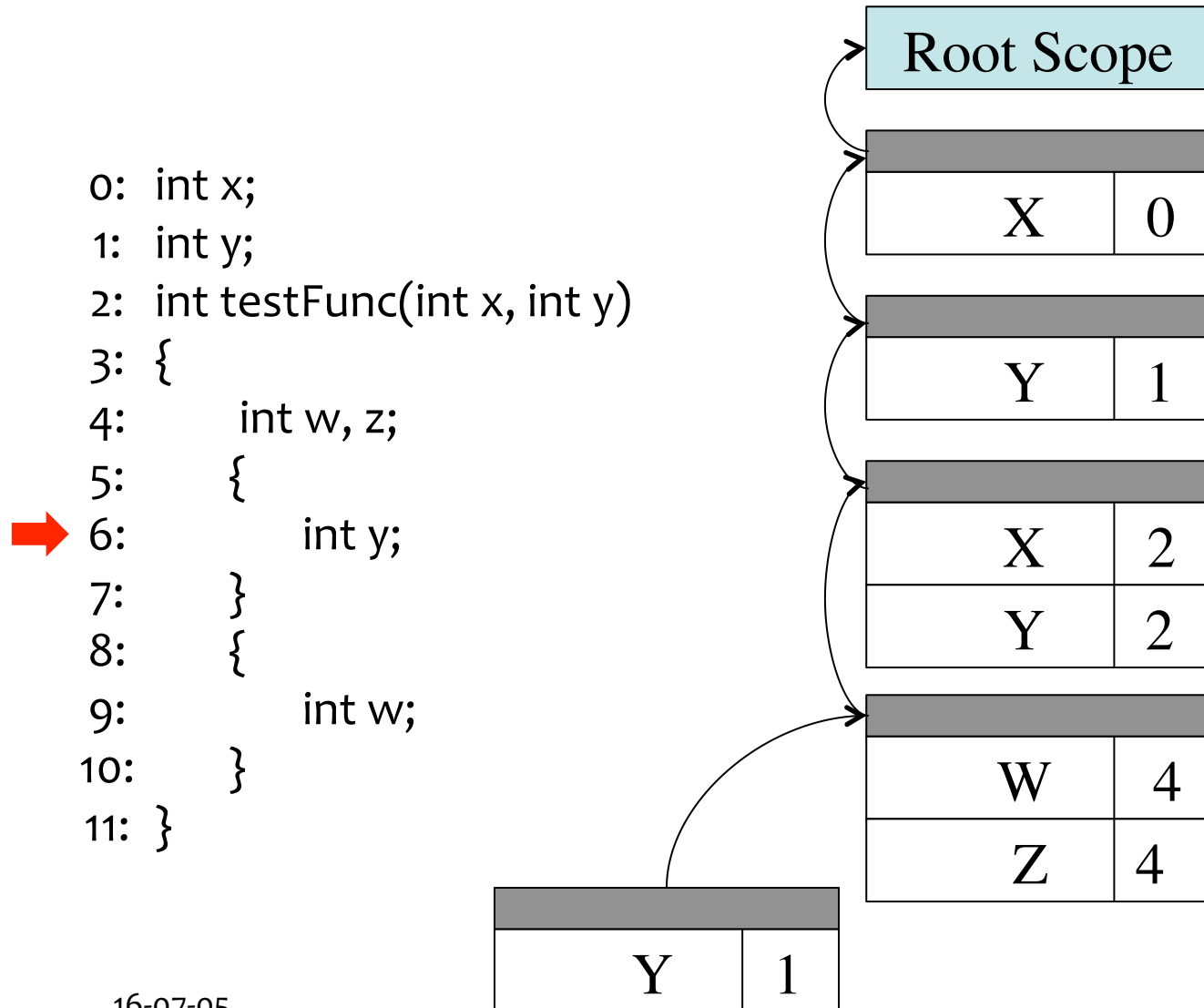
```
 0:  int x;
 1:  int y;
 2:  int testFunc(int x, int y)
 3:  {
 4:       int w, z;
 5:       {
 6:            int y;
 7:       }
 8:       {
 9:            int w;
10:       }
11: }
```
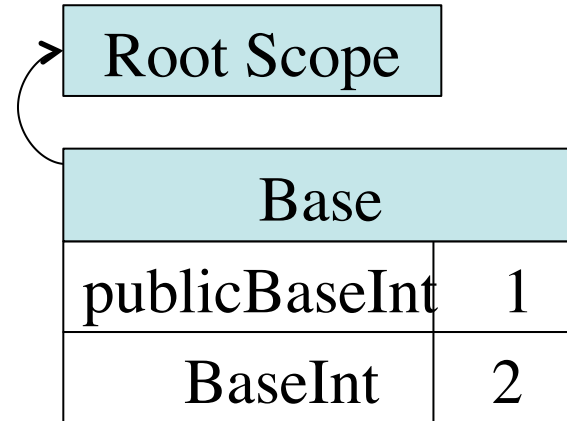
Root Scope

X	0

Y	1

Another View of Symbol Table

```
 0:  int x;
 1:  int y;
 2:  int testFunc(int x, int y)
 3:  {
 4:       int w, z;
 5:       {
 6:            int y;
 7:       }
 8:       {
 9:            int w;
10:       }
11:  }
```

Root Scope	
X	0

Y	1

X	2
Y	2

Another View of Symbol Table

0: int x;
1: int y;
2: int testFunc(int x, int y)
3: {
4:     int w, z;
5:     {
6:         int y;
7:     }
8:     {
9:         int w;
10:     }
11: }

Root Scope	

X	0

Y	1

X	2
Y	2

W	4
Z	4

Another View of Symbol Table

```
 0:  int x;
 1:  int y;
 2:  int testFunc(int x, int y)
 3:  {
 4:       int w, z;
 5:       {
 6:           int y;
 7:       }
 8:       {
 9:           int w;
10:       }
11: }
```

Root Scope	

X	0

Y	1

X	2
Y	2

W	4
Z	4

Y	1

Another View of Symbol Table

```
0:  int x;
1:  int y;
2:  int testFunc(int x, int y)
3:  {
4:      int w, z;
5:      {
6:          int y;
7:      }
8:      {
9:          int w;
10:     }
11: }
```

Root Scope	

X	0

Y	1

X	2
Y	2

W	4
Z	4

Y	1

W	9
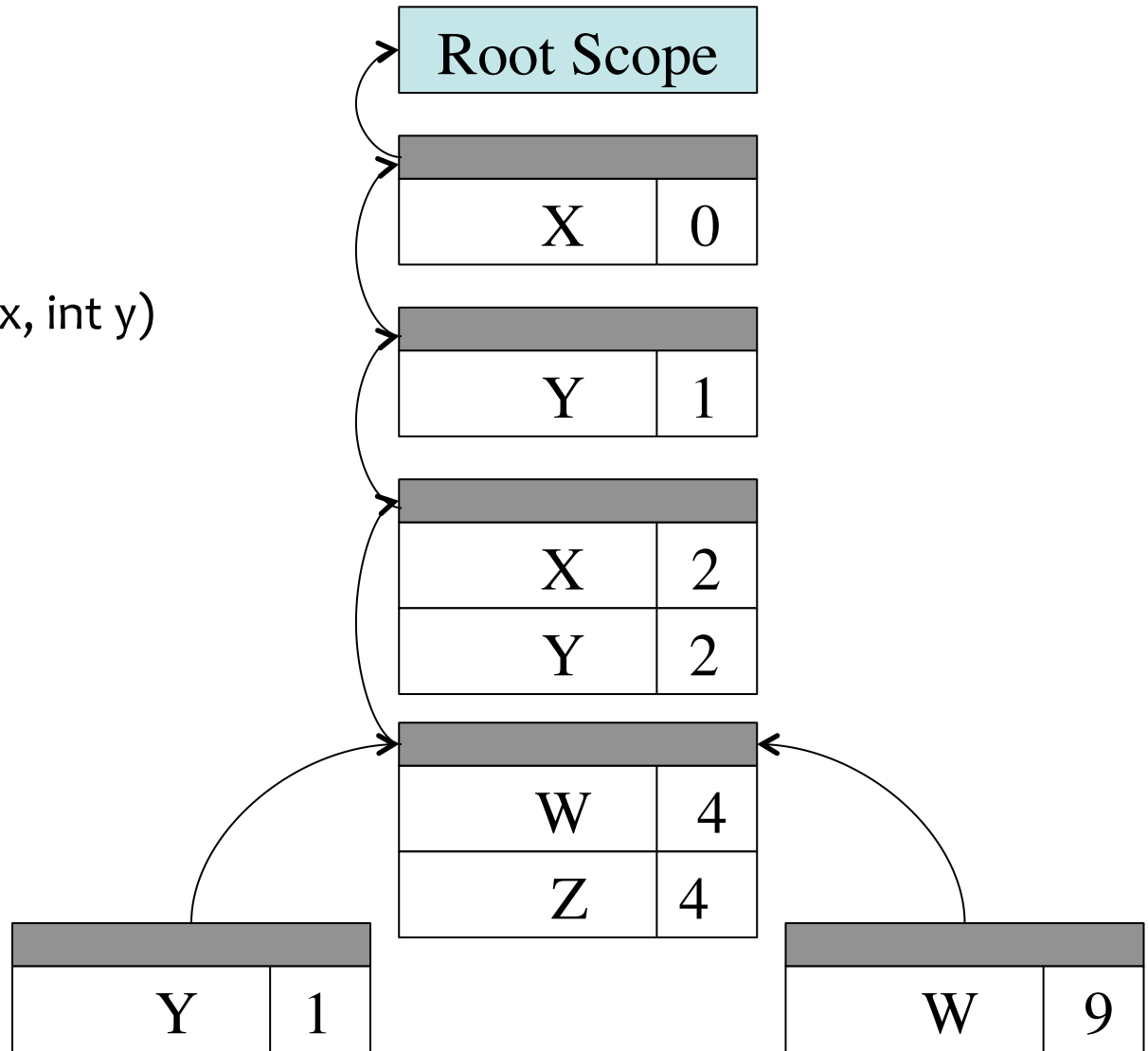
Spaghetti Stacks

- Treat the symbol table as a linked structure of scopes

- Each scope stores a pointer to its parent, but not vice-versa

- From any point in the program, symbol table appears to be a stack

- This is called a spaghetti stack

Why Two Interpretations?

- Spaghetti stack more accurately captures the scoping structure

- Spaghetti stack is a *static structure*; explicit stack is *dynamic structure*

- Explicit stack is an optimization of a spaghetti stack

Scoping with Inheritance

```
public class Base {
    public int publicBaseInt = 1;
    protected int baseInt = 2;
}
```

Root Scope	

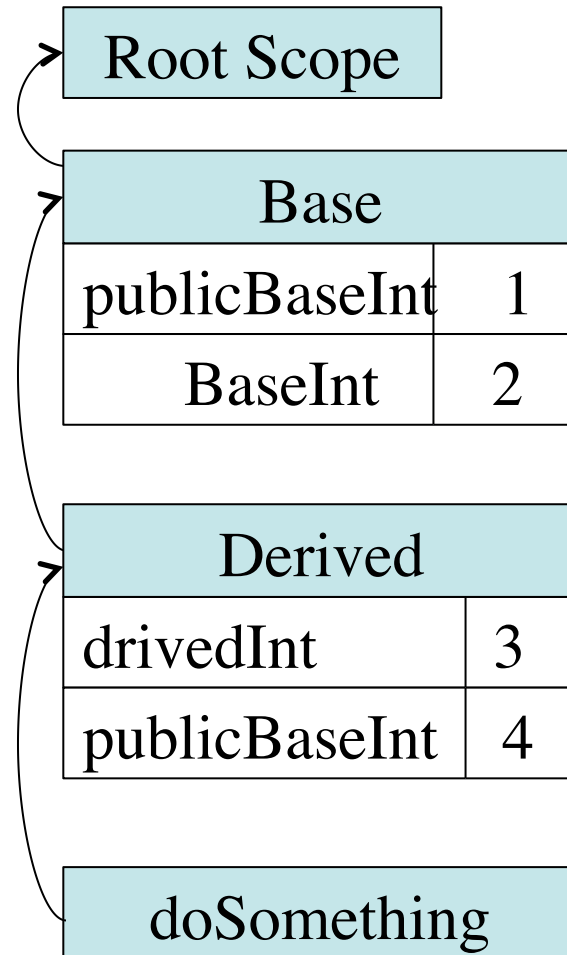| Base	
publicBaseInt	1
BaseInt	2

Scoping with Inheritance

```
public class Base {
    public int publicBaseInt = 1;
    protected int baseInt = 2;
}
public class Derived extends Base {
    public int derivedInt = 3;
    public int publicBaseInt = 4;

    public void doSomething () {
        System.out.println(publicBaseInt);
        System.out.println(baseInt);
        System.out.println(derivedInt);

        int publicBaseInt = 6;
        System.out.println(publicBaseInt);
    }
}
```

Root Scope	

Base	
publicBaseInt	1
BaseInt	2

Derived	
derivedInt	3
publicBaseInt	4

Scoping with Inheritance

```
public class Base {
    public int publicBaseInt = 1;
    protected int baseInt = 2;
}
public class Derived extends Base {
    public int derivedInt = 3;
    public int publicBaseInt = 4;

    public void doSomething () {
        System.out.println(publicBaseInt);
        System.out.println(baseInt);
        System.out.println(derivedInt);

        int publicBaseInt = 6;
        System.out.println(publicBaseInt);
    }
}
```

Root Scope	

Base	
publicBaseInt	1
BaseInt	2

Derived	
drivedInt	3
publicBaseInt	4

>

Scoping with Inheritance

```java
public class Base {
    public int publicBaseInt = 1;
    protected int baseInt = 2;
}
public class Derived extends Base {
    public int derivedInt = 3;
    public int publicBaseInt = 4;

    public void doSomething () {
        System.out.println(publicBaseInt);
        System.out.println(baseInt);
        System.out.println(derivedInt);

        int publicBaseInt = 6;
        System.out.println(publicBaseInt);
    }
}
```
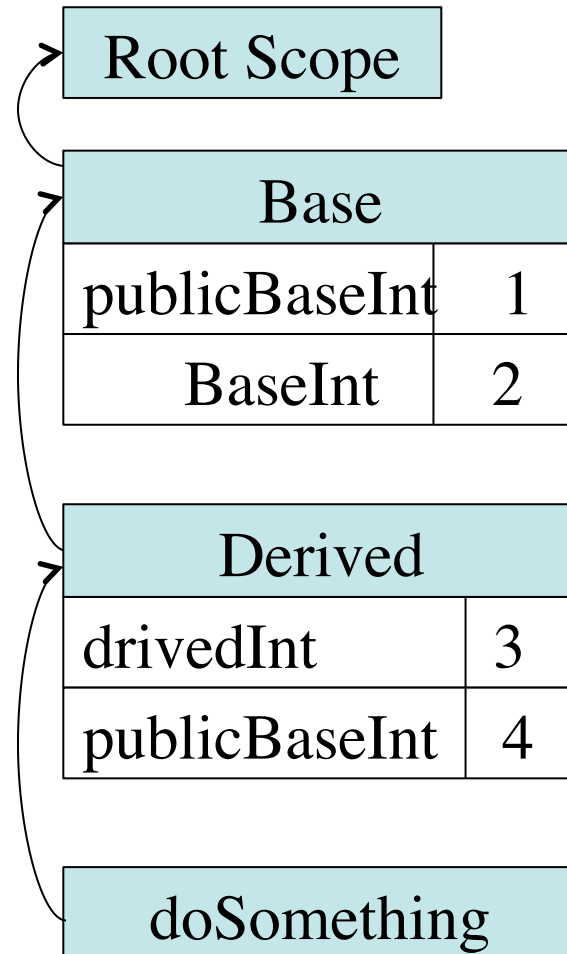
Root Scope	

Base	
publicBaseInt	1
BaseInt	2

Derived	
drivedInt	3
publicBaseInt	4

doSomething

`>`

Scoping with Inheritance

```
public class Base {
    public int publicBaseInt = 1;
    protected int baseInt = 2;
}
public class Derived extends Base {
    public int derivedInt = 3;
    public int publicBaseInt = 4;

    public void doSomething () {
        System.out.println(publicBaseInt);
        System.out.println(baseInt);
        System.out.println(derivedInt);

        int publicBaseInt = 6;
        System.out.println(publicBaseInt);
    }
}
```
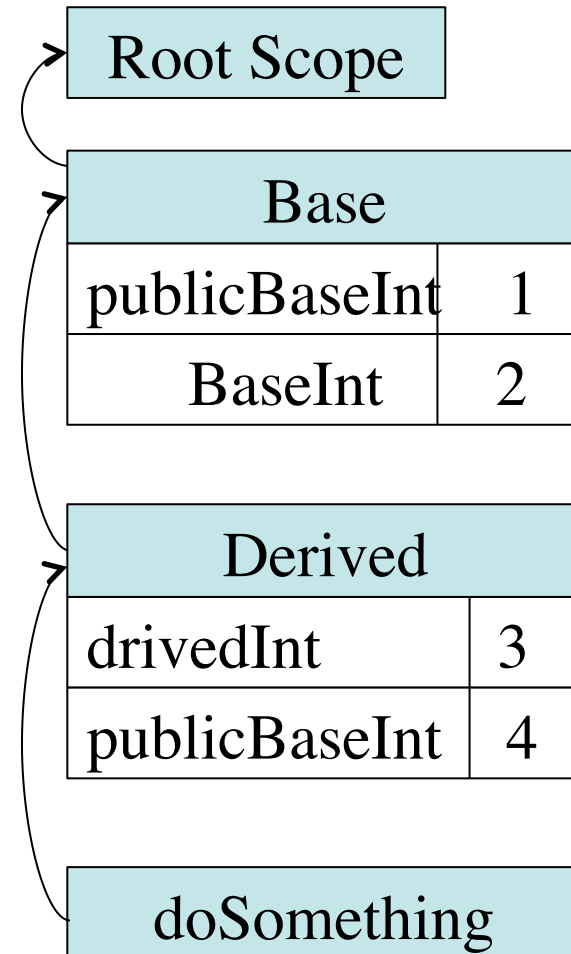
> 4

Root Scope	

Base	
publicBaseInt	1
BaseInt	2

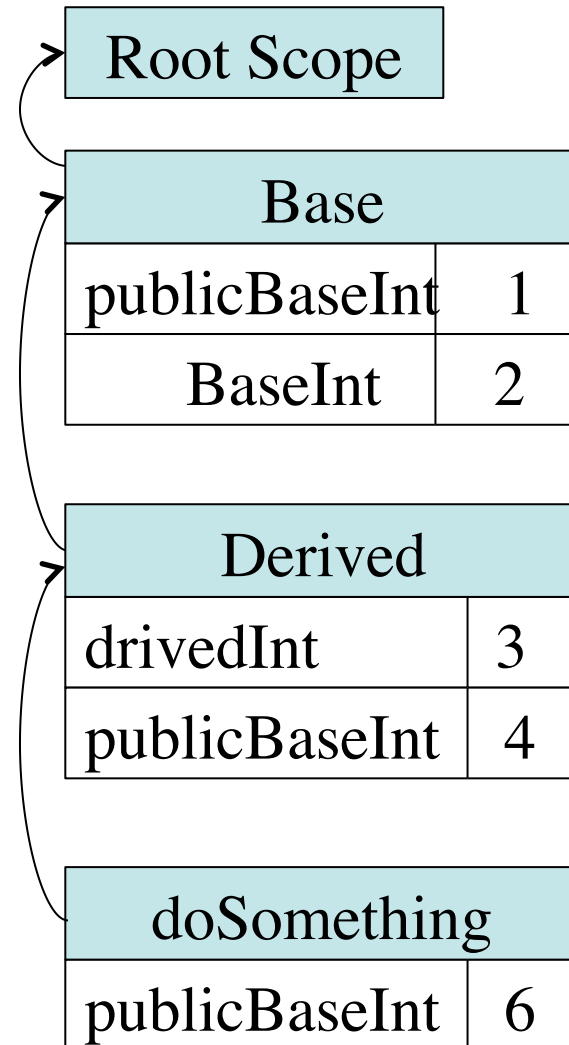| Derived	
drivedInt	3
publicBaseInt	4

doSomething	

Scoping with Inheritance

```
public class Base {
    public int publicBaseInt = 1;
    protected int baseInt = 2;
}
public class Derived extends Base {
    public int derivedInt = 3;
    public int publicBaseInt = 4;

    public void doSomething () {
        System.out.println(publicBaseInt);
        System.out.println(baseInt);
        System.out.println(derivedInt);

        int publicBaseInt = 6;
        System.out.println(publicBaseInt);
    }
}
```

Root Scope	

Base	
publicBaseInt	1
BaseInt	2

Derived	
drivedInt	3
publicBaseInt	4

doSomething	

```
> 4
  2
```

Scoping with Inheritance

```
public class Base {
    public int publicBaseInt = 1;
    protected int baseInt = 2;
}
public class Derived extends Base {
    public int derivedInt = 3;
    public int publicBaseInt = 4;

    public void doSomething () {
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        System.out.println(baseInt);
        System.out.println(derivedInt);

        int publicBaseInt = 6;
        System.out.println(publicBaseInt);
    }
}
```

Root Scope	

Base	
publicBaseInt	1
BaseInt	2

Derived	
drivedInt	3
publicBaseInt	4

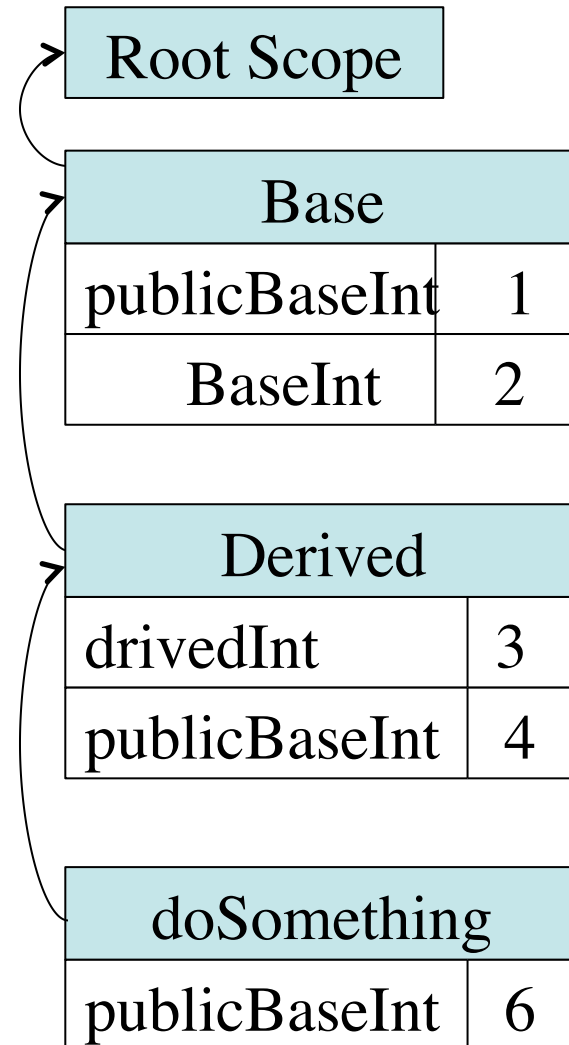| doSomething	

```
> 4
  2
  3
```

Scoping with Inheritance

```
public class Base {
    public int publicBaseInt = 1;
    protected int baseInt = 2;
}
public class Derived extends Base {
    public int derivedInt = 3;
    public int publicBaseInt = 4;

    public void doSomething () {
        System.out.println(publicBaseInt);
        System.out.println(baseInt);
        System.out.println(derivedInt);

        int publicBaseInt = 6;
        System.out.println(publicBaseInt);
    }
}
```
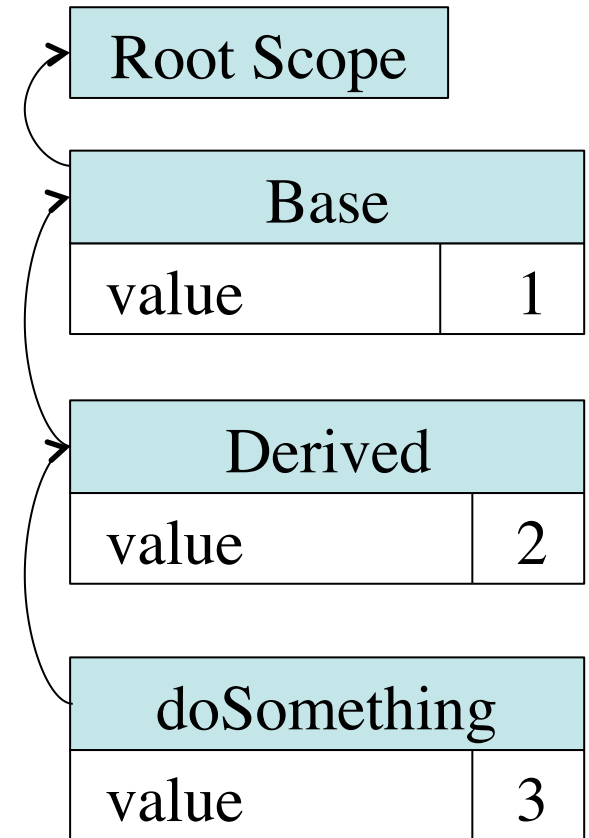
```
> 4
  2
  3
```

Root Scope

Base	
publicBaseInt	1
BaseInt	2

Derived	
drivedInt	3
publicBaseInt	4

doSomething	
publicBaseInt	6

Scoping with Inheritance

```
public class Base {
    public int publicBaseInt = 1;
    protected int baseInt = 2;
}
public class Derived extends Base {
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    public int publicBaseInt = 4;

    public void doSomething () {
        System.out.println(publicBaseInt);
        System.out.println(baseInt);
        System.out.println(derivedInt);

        int publicBaseInt = 6;
        System.out.println(publicBaseInt);
    }
}
```

```
> 4
  2
  3
  6
```

Root Scope	

Base	
publicBaseInt	1
BaseInt	2

Derived	
drivedInt	3
publicBaseInt	4

doSomething	
publicBaseInt	6

Inheritance and Scoping

- Typically, the scope for a derived class will store a link to the scope of its base class

- Looking up a field of a class traverses the scope chain until that field is found or a semantic error is found
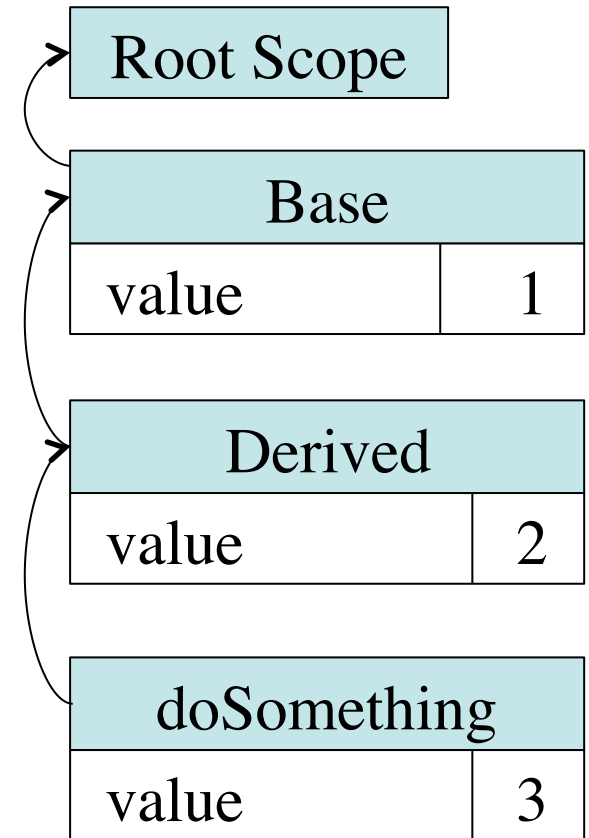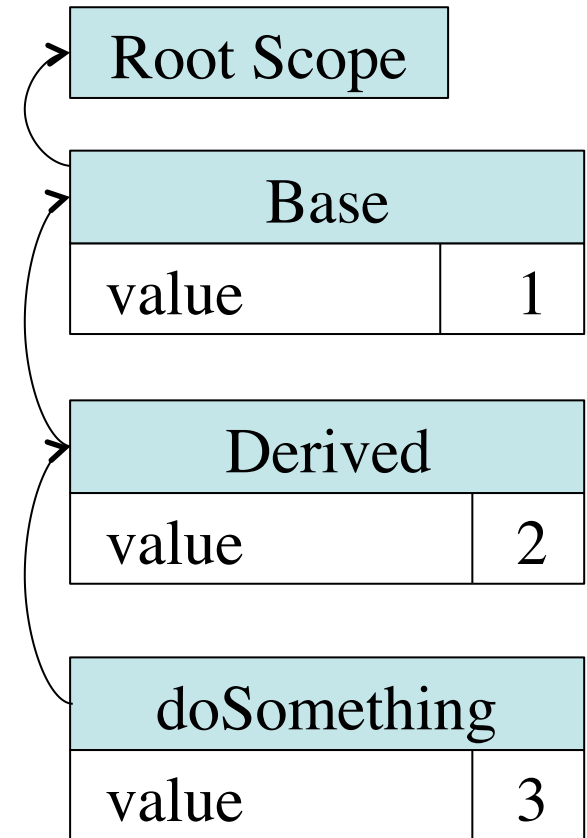
Explicit Disambiguation

```
public class Base {
    public int value = 1;
}
public class Derived extends Base {
    public int value = 2;

    public void doSomething () {
         int value = 3;
         System.out.println(value);
         System.out.println(this.value);
         System.out.println(super.value);

    }
}
```

Root Scope	

Base	
value	1

Derived	
value	2

doSomething	
value	3

Explicit Disambiguation

```java
public class Base {
    public int value = 1;
}
public class Derived extends Base {
    public int value = 2;

    public void doSomething () {
        int value = 3;
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);

    }
}
```
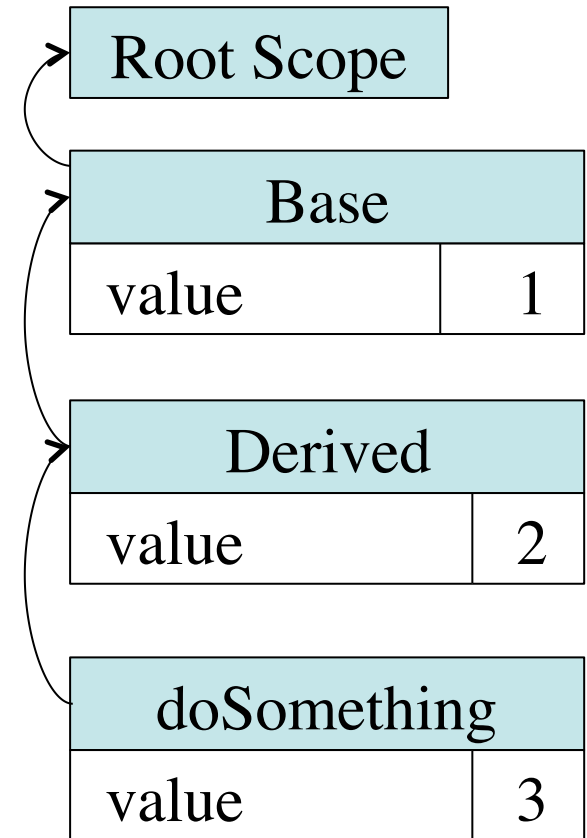
Root Scope	

Base	
value	1

Derived	
value	2

doSomething	
value	3

Explicit Disambiguation

```
public class Base {
    public int value = 1;
}
public class Derived extends Base {
    public int value = 2;

    public void doSomething () {
        int value = 3;
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);

    }
}
```
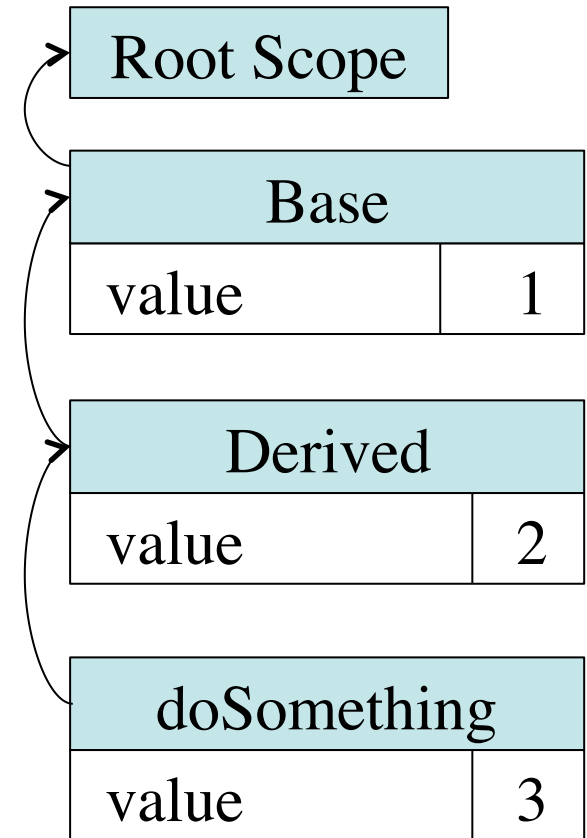
> 3

Root Scope	

Base	
value	1

Derived	
value	2

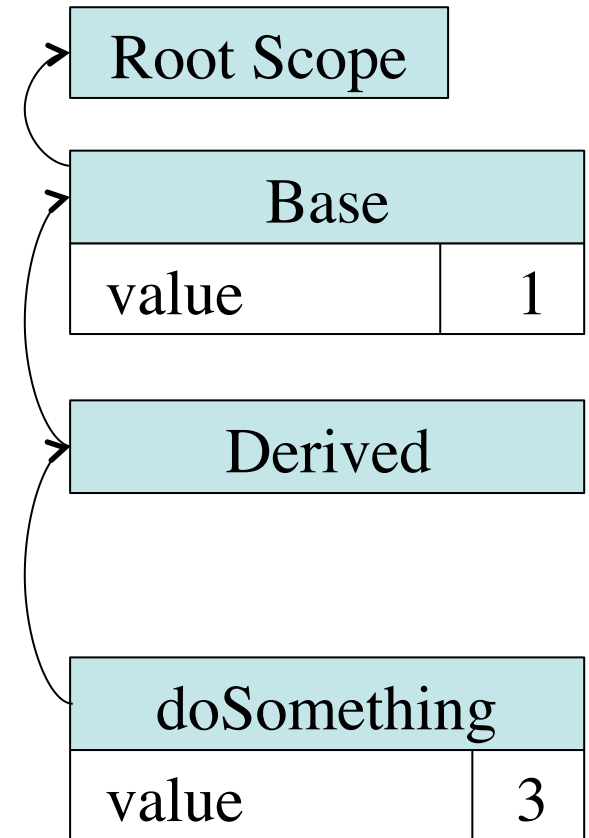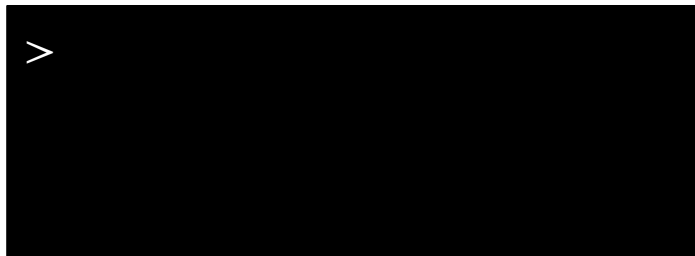| doSomething	
value	3

Explicit Disambiguation

```java
public class Base {
    public int value = 1;
}
public class Derived extends Base {
    public int value = 2;

    public void doSomething () {
        int value = 3;
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);

    }
}
```

```
> 3
  2
```

Root Scope	

Base	
value	1

Derived	
value	2

doSomething	
value	3

Explicit Disambiguation

```
public class Base {
    public int value = 1;
}
public class Derived extends Base {
    public int value = 2;

    public void doSomething () {
        int value = 3;
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);

    }
}
```

```
> 3
  2
  1
```

Root Scope	

Base	
value	1

Derived	
value	2

doSomething	
value	3

Explicit Disambiguation

```java
public class Base {
    public int value = 1;
}
public class Derived extends Base {


    public void doSomething () {
         int value = 3;
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);

    }
}
```
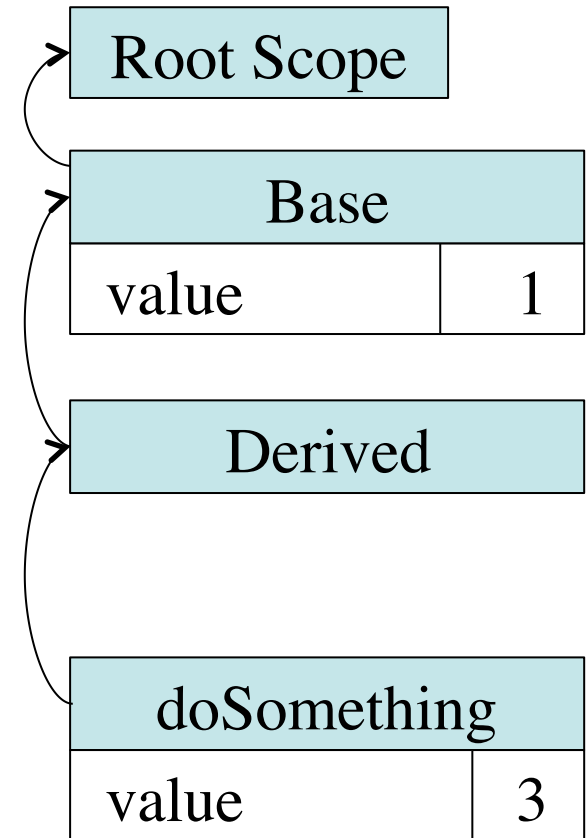
Root Scope

Base	
value	1

Derived

doSomething	
value	3

>

Explicit Disambiguation

```
public class Base {
    public int value = 1;
}
public class Derived extends Base {


    public void doSomething () {
        int value = 3;
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);

    }
}
```
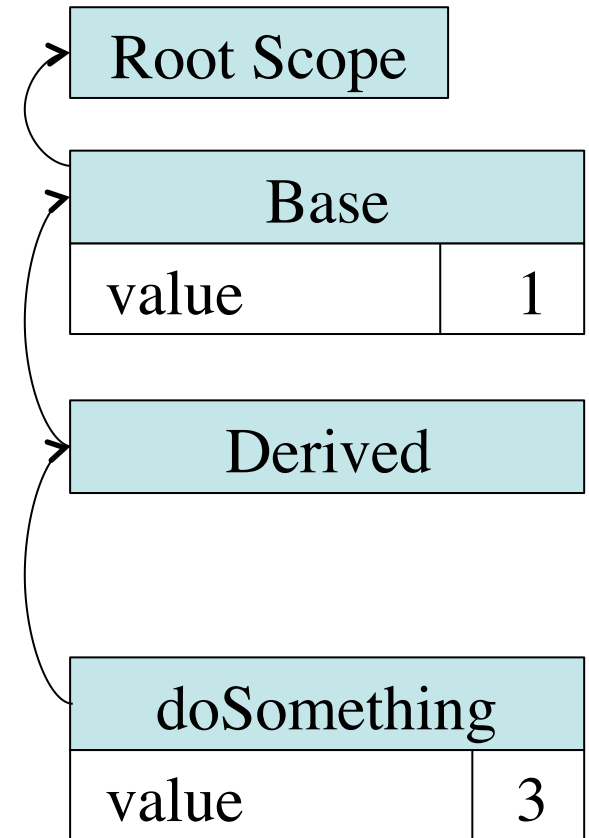
> 3

Root Scope	

Base	
value	1

Derived	

doSomething	
value	3

Explicit Disambiguation

```
public class Base {
    public int value = 1;
}
public class Derived extends Base {


    public void doSomething () {
        int value = 3;
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);

    }
}
```
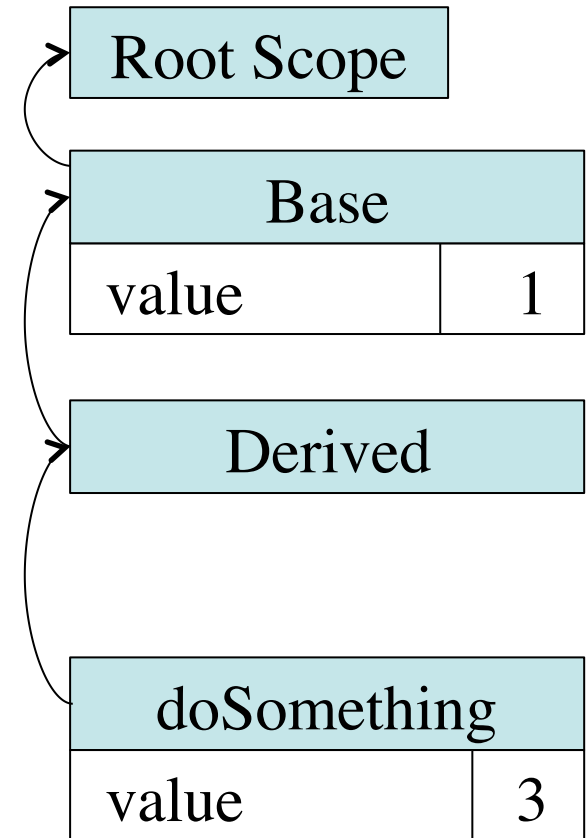
```
> 3
  1
```

Root Scope	

Base	
value	1

Derived	

doSomething	
value	3

Explicit Disambiguation

```
public class Base {
    public int value = 1;
}
public class Derived extends Base {


    public void doSomething () {
         int value = 3;
         System.out.println(value);
         System.out.println(this.value);
         System.out.println(super.value);

    }
}
```

```
> 3
  1
  1
```

Root Scope	

Base	
value	1

Derived	

doSomething	
value	3

Disambiguating Scopes

- Maintain a second table of pointers into the scope stack

- When looking up a value in a specific scope, begin the search from that scope

- Some languages allow you to jump up to any arbitrary base class (for example, C++)

Scoping in C++ and Java

```
class A {
    public:
        /*....*/
    private:
        B* myB;
};
```

Error: B not declared

```
class B {
    public:
        /*....*/
    private:
        A* myA;
};
```

```
class A {
    private B* myB;
};
```

Perfectly fine!

```
class B {
    private A* myA;
};
```

Single and Multi-pass Compilers

- Our predictive parsing methods always scan the input from left-to-right
  - LL(1), LR(0), SLR(1), LALR(1),..
- Since we only need one token of lookahead, we can do lexical analysis and parsing simultaneously in one pass over the file
- Some compilers can combine lexical analysis, parsing, semantic analysis, and code generation into same pass
  - Single pass compilers
- Other compilers rescan the input multiple times
  - Multi-pass compilers

Single and Multi-pass Compilers

- Some languages are defined to support single-pass compilers
  - C, C++

- Some languages require multi-passes
  - Java

- Most modern compilers uses many passes over the input program

Scoping in Multi-pass Compilers

- Completely parse the input into an abstract syntax tree (first pass)

- Walk the AST, gathering information about classes (second pass)

- Walk the AST checking other properties (third pass)
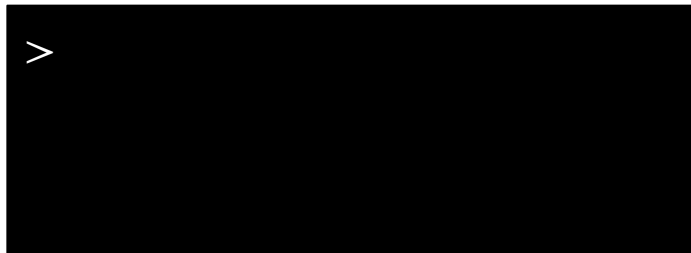
- Could combine some of these

Static and Dynamic Scoping

- The scoping we've seen so far is called static scoping and is done at compile time
  - Identifiers refer to logically related variables
- Some languages uses dynamic scoping, which is done at runtime
  - Identifiers refer to the variable with that name that is closely nested at runtime

Dynamic Scoping

```
int x = 137;
int y = 42;
void function1 () {
    print(x + y);
}
void function2 () {
    int x = 0;
    function1();
}
void function3 () {
    int y = 0;
    function2();
}
function1();
function2();
function3();
```

Symbol Table	
X	137
Y	42

>

Dynamic Scoping

```
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int y = 42;
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```
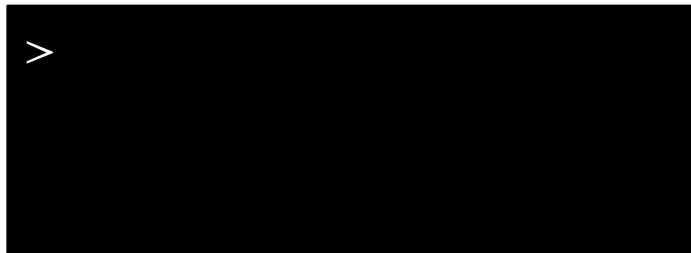
Symbol Table	
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Dynamic Scoping

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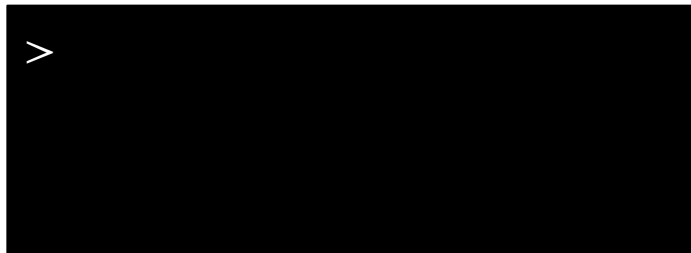
Symbol Table	
X	137
Y	42

> 179

Dynamic Scoping

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int x = 137;
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Symbol Table	
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> 179

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Symbol Table	
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Symbol Table	
X	137
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> 179
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Symbol Table	
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> 179

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function3();
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Symbol Table	
X	137
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X	0

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> 179
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Symbol Table	
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> 179
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> 179
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> 179
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Symbol Table	
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> 179
  42
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function1();
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function3();
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Symbol Table	
X	137
Y	42
Y	0

> 179
 42

Dynamic Scoping

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function1();
function2();
function3();
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Symbol Table	
X	137
Y	42
Y	0

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> 179
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int x = 137;
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> 179
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> 179
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> 179
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X	0

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X	0

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Symbol Table	
X	137
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```
> 179
  42
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```

Dynamic Scoping in Practice

- Examples: Perl
- Often implemented by preserving symbol table at runtime
- Often less efficient than static scoping
  - Compiler cannot hardcode location of variables
  - Names must be resolved at runtime

Summary

- **Semantic analysis** verifies that a syntactically valid program is correctly-formed and computes additional information about the meaning of the program

- **Scope checking** determines what objects or classes are referred to by each name in the program.

- Scope checking is usually done with a **symbol table** implemented either as a stack or **spaghetti stack**.

- In object-oriented programs, the scope for a derived class is often placed inside of the scope of a base class.

- Some semantic analyzers operate in multiple passes in order to gain more information about the program.

- In dynamic scoping, the actual execution of a program determines what each name refers to.

- With multiple inheritance, a name may need to be searched for along multiple paths.