Semantics

CMPT 379: Compilers

Instructor: Anoop Sarkar

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:
  - Package declaration have the correct structure
  - Expressions 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 {
        var myBin bool;
        func foo() void {
                var x[0] int;
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        func foo() void {
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                return foo() + fibonacci(n-1);
        }

}
```

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 {
        if ( n<=1 )  return 0;
        return fibonacci (n-1) + fibonacci(n-2);
 }
func main() int {
         print_int (fibonacci(40));
}
```

Incorrect! Should be “return n;”

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

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

```
int x =  137;
int z = 42;
int testFunc(int x, int y){
        printf(“%d, %d, %d\n”, x, y, z);
        {
                int x, z;
                z = y;
                x = z;
                {
                        int y = x;
                        {
                                printf(“%d, %d, %d\n”, x, y, z);
                        }
                        printf(“%d, %d, %d\n”, x, y, z);
                }
                printf(“%d, %d, %d\n”, x, y, z);
        }
}
```

Symbol Tables

Symbol Table

```
int x =  137;
int z = 42;
int testFunc(int x, int y){
      printf("%d, %d, %d\n", x, y, z);
      {
            int x, z;
            z = y;
            x = z;
            {
                  int y = x;
                  {
                        printf("%d, %d, %d\n", x, y, z);
                  }
                  printf("%d, %d, %d\n", x, y, z);
            }
            printf("%d, %d, %d\n", x, y, z);
      }
}
```

Symbol Tables

```
int x =  137;
int z = 42;
int testFunc(int x, int y){
        printf("%d, %d, %d\n", x, y, z);
        {
                int x, z;
                z = y;
                x = z;
                {
                        int y = x;
                        {
                                printf("%d, %d, %d\n", x, y, z);
                        }
                        printf("%d, %d, %d\n", x, y, z);
                }
                printf("%d, %d, %d\n", x, y, z);
        }
}
```

Symbol Table	
X	0

Symbol Tables

```
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);
14:             }
15:             printf(“%d, %d, %d\n”, x, y, z);
16:       }
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```

Symbol Table	
X	0
Z	1

Symbol Tables

```
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);
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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);
14:         }
15:         printf("%d, %d, %d\n", x, y, z);
16:     }
17: }
```

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, 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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15:             printf("%d, %d, %d\n", x, y, z);
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```

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, 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);
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```

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) {
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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);
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13:             printf("%d, %d, %d\n", x, y, z);
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```

Symbol Table	
X	0
Z	1
X	2
Y	2

Symbol Tables

```
0:  int x =  137;
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2:  int testFunc(int x, int y) {
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5:              int x, z;
6:              z = y;
7:              x = z;
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11:                         printf("%d, %d, %d\n", x, y, z);
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13:                   printf("%d, %d, %d\n", x, y, z);
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Symbol Table	
X	0
Z	1
X	2
Y	2

Symbol Tables

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

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9:                    int y = x @5;
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8:          {
9:              int y = x @5;
10:             {
11:                 printf("%d, %d, %d\n", x @5, y @9, z @5);
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8:          {
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11:                 printf("%d, %d, %d\n", x @5, y @9, z @5);
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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:                   }
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Symbol Table	
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Y	2
X	5
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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
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);
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Symbol Table	
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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);
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Symbol Table	
X	0
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Symbol Tables

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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);
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```

Symbol Table	
X	0
Z	1
X	2
Y	2

Symbol Tables

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0:   int x =  137;
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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
Y	2

Symbol Tables

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0:  int x =  137;
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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

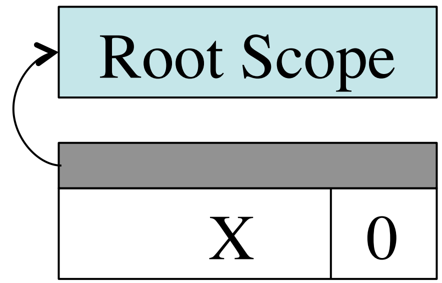
Symbol Tables

- 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

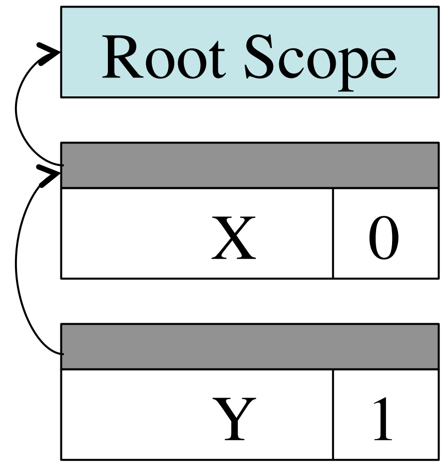
Another View of Symbol Table




```
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: }
```

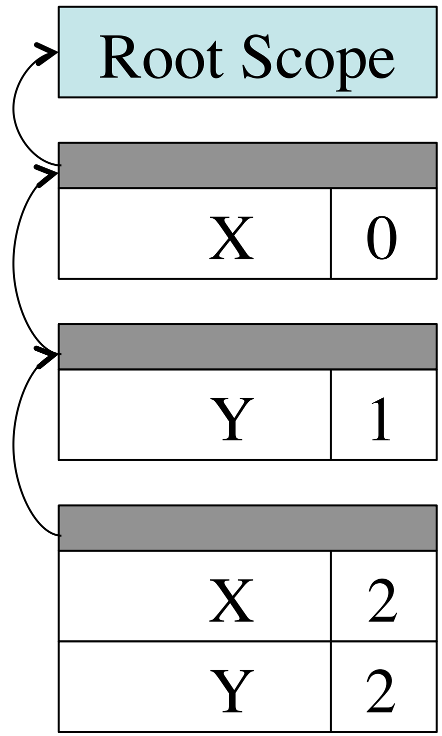
Another View of Symbol Table

```
int x;
int y;
int testFunc(int x, int y)
{
        int w, z;
       {
              int y;
       }
       {
              int w;
       }
}
```



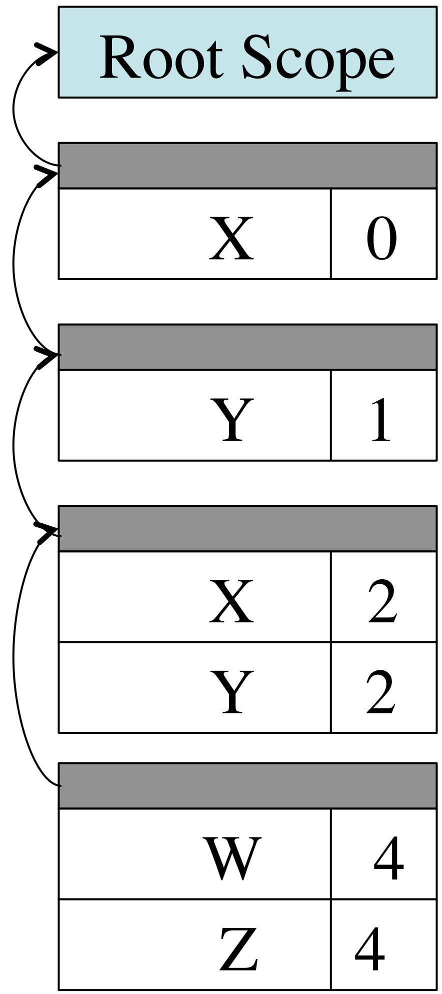
Another View of Symbol Table

```
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: }
```



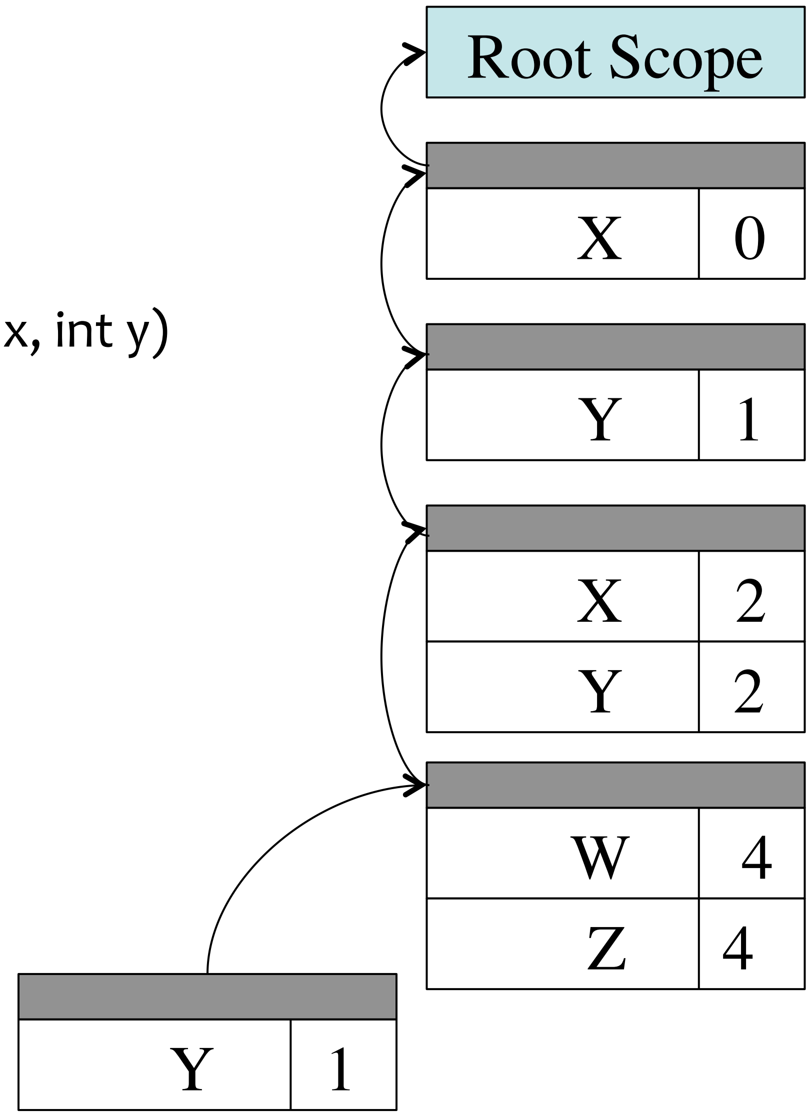
Another View of Symbol Table

```
int x;
int y;
int testFunc(int x, int y)
{
        int w, z;
       {
              int y;
       }
       {
              int w;
       }
}
```



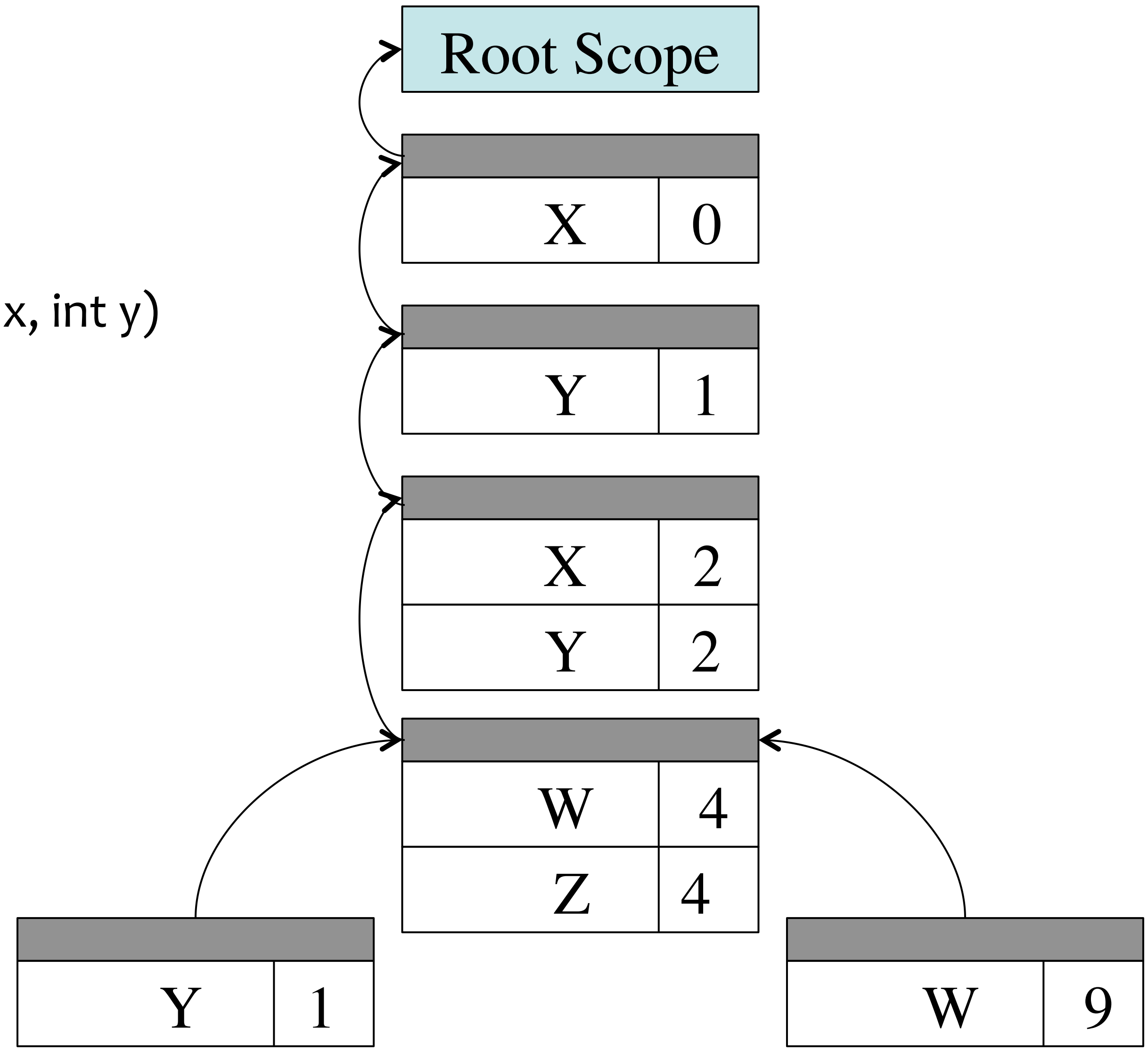
Another View of Symbol Table

```
int x;
int y;
int testFunc(int x, int y)
{
        int w, z;
        {
                int y;
        }
        {
                int w;
        }
}
```



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: }
```



Spaghetti Stacks

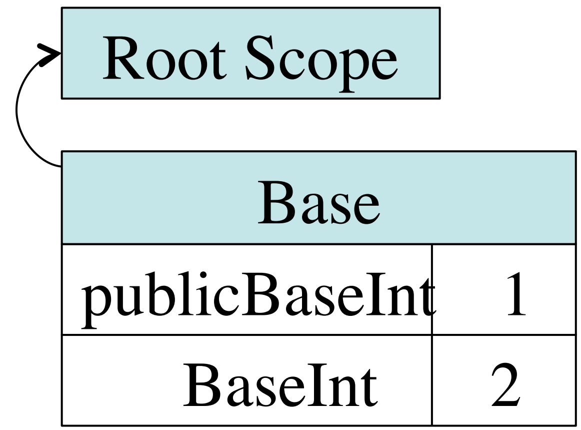
- Treat the symbol table as a linked structure of scopes
- Each scope stores a pointer to its parent, but not vice-versa
- From any point in the program, symbol table appears to be a stack
- This is called a spaghetti stack

Why Two Interpretations?

- Spaghetti stack is a *static structure*; explicit stack is *dynamic structure.*
- Spaghetti stack can be stored in the abstract syntax tree data structure for a program.
- Explicit stack uses less memory and is better for recursive function invocations.

Scoping with Inheritance

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

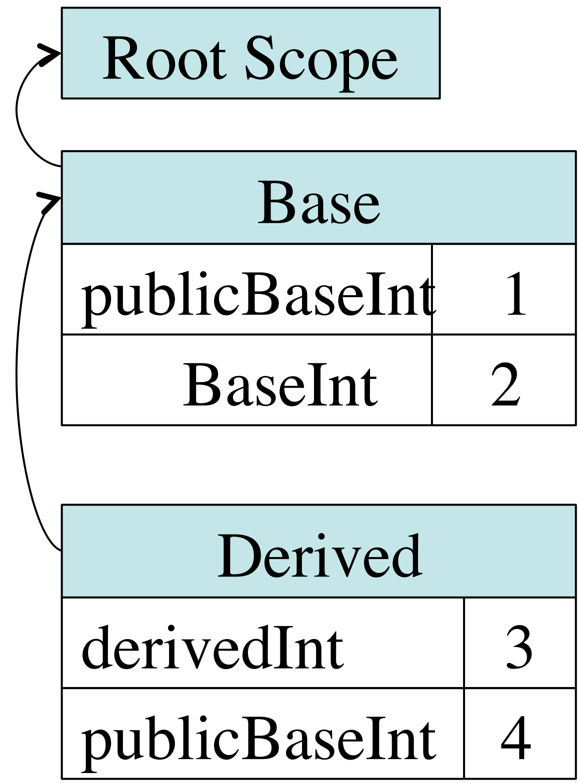


Scoping with Inheritance

```
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);
    }
}
```



Scoping with Inheritance

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public class Base {
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}
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    public void doSomething () {
        System.out.println(publicBaseInt);
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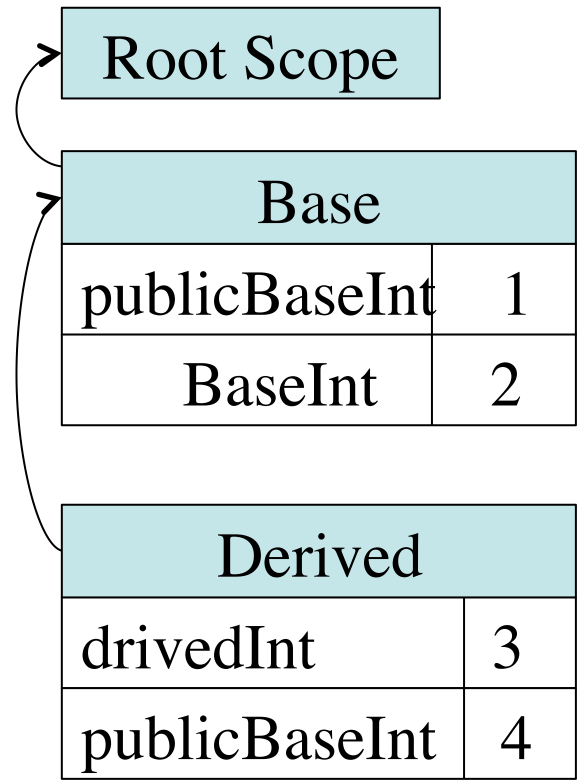
        System.out.println(derivedInt);

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




```
>
```

Scoping with Inheritance

```
public class Base {
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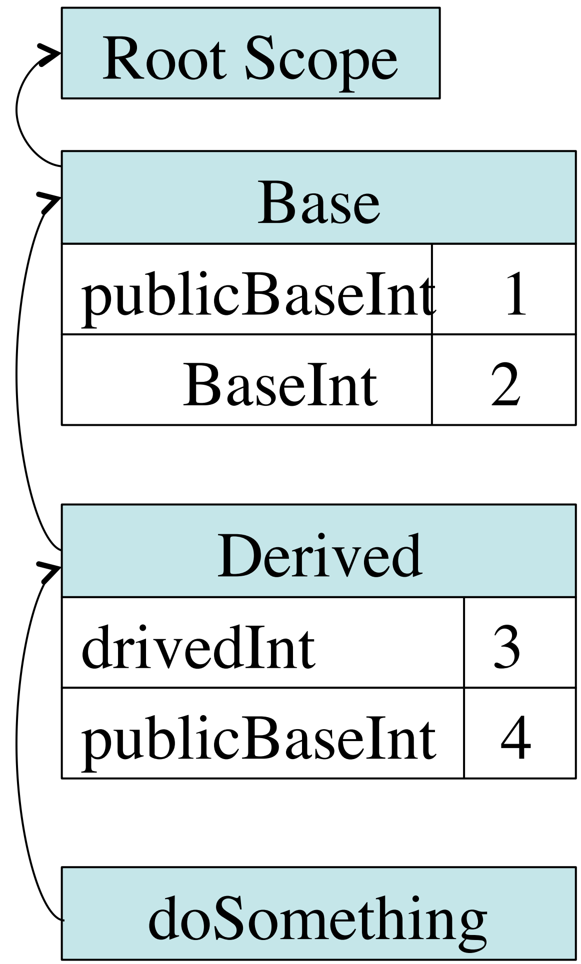
        int publicBaseInt = 6;
        System.out.println(publicBaseInt);
    }
}
```

```
>
```



Scoping with Inheritance

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public class Base {
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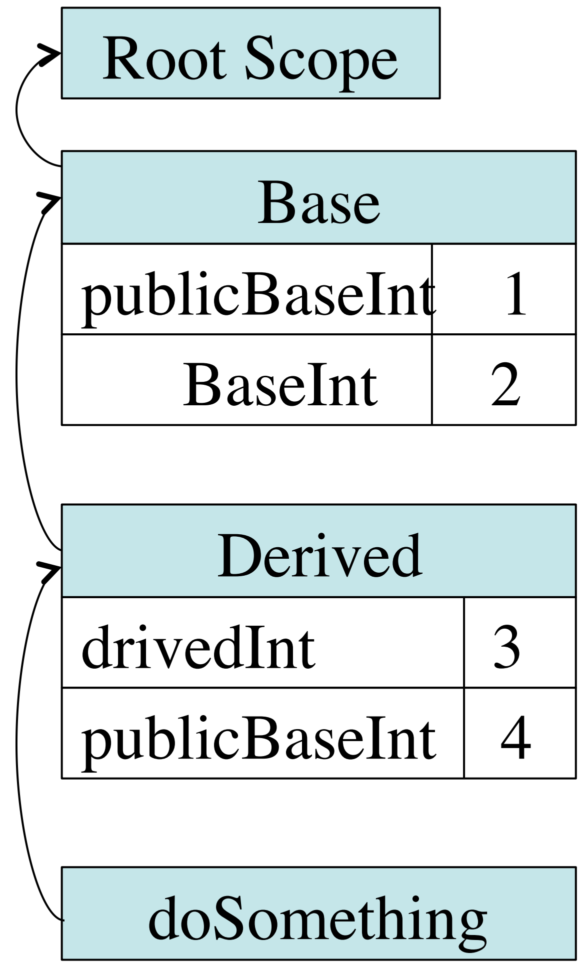
        System.out.println(baseInt);
        System.out.println(derivedInt);

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

```
> 4
```



Scoping with Inheritance

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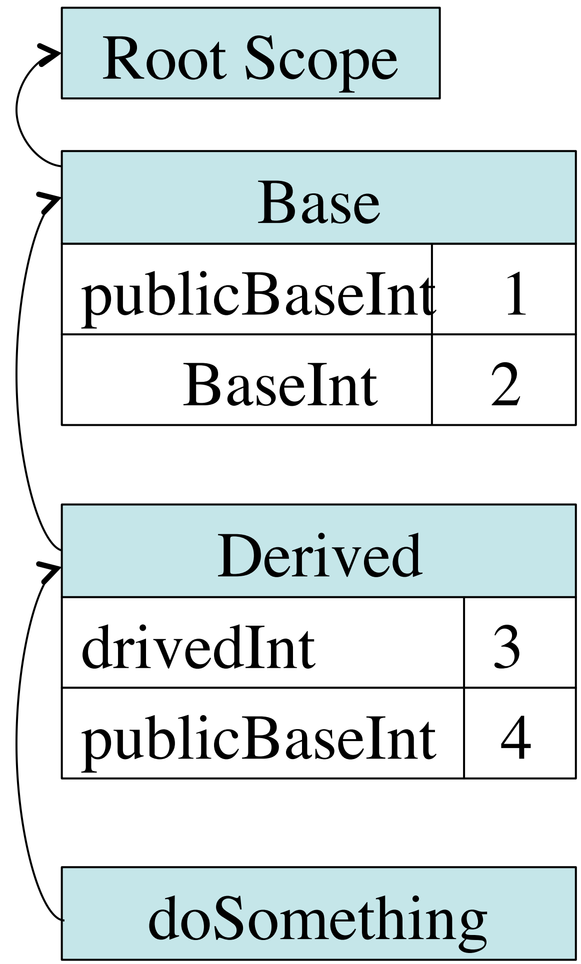
    public void doSomething () {
        System.out.println(publicBaseInt);
        System.out.println(baseInt);
        System.out.println(derivedInt);

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

```
> 4
  2
```



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        System.out.println(baseInt);
        System.out.println(derivedInt);

        int publicBaseInt = 6;
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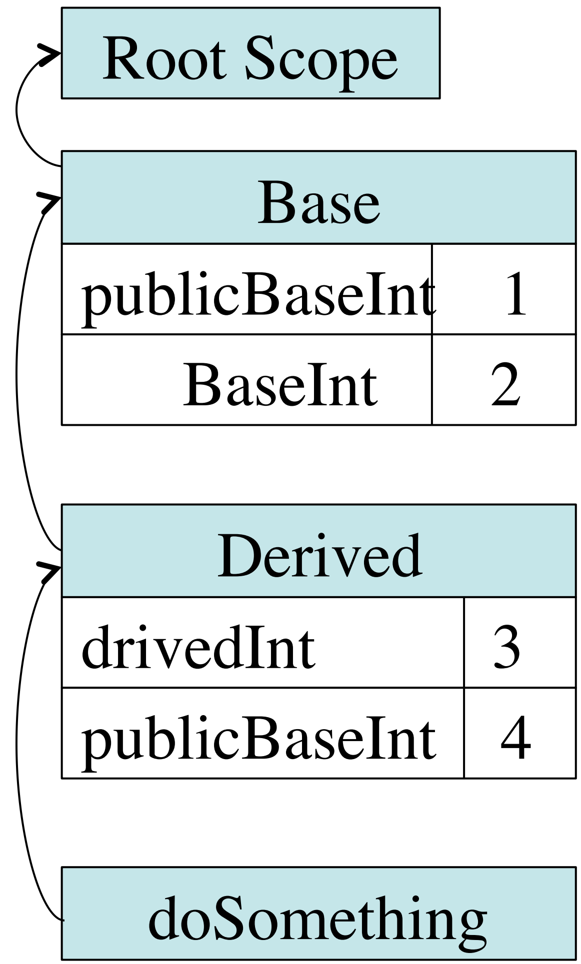
    }
}
```

```
> 4
  2
  3
```



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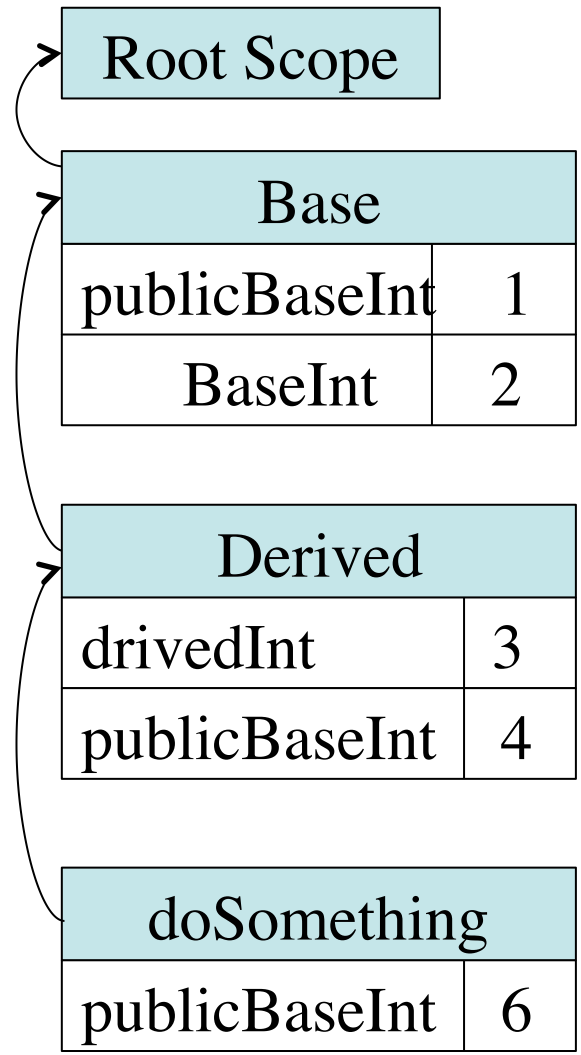
            System.out.println(derivedInt);

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

```
> 4
  2
  3
```



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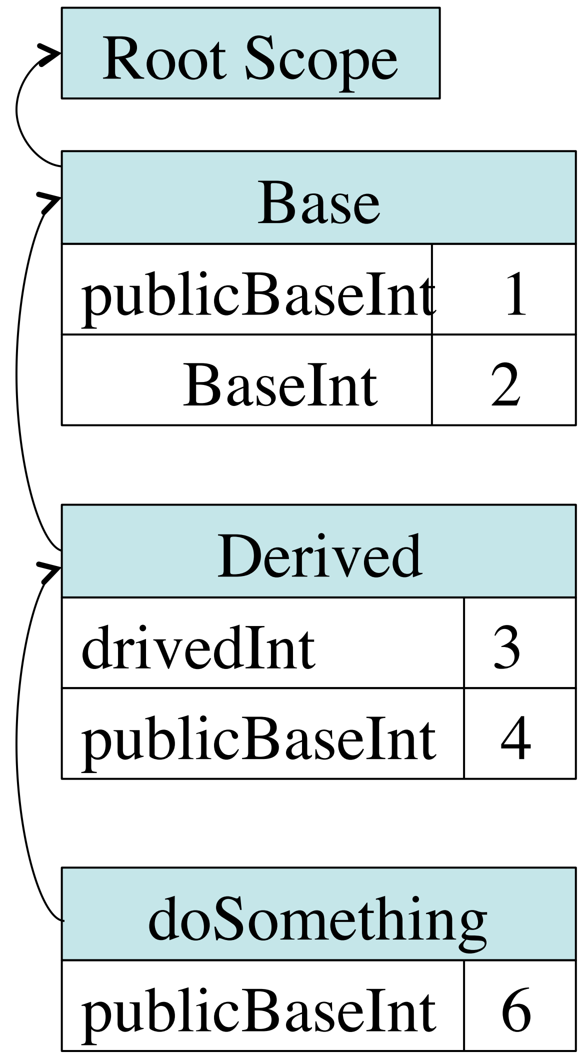
    public void doSomething () {
        System.out.println(publicBaseInt);
        System.out.println(baseInt);
        System.out.println(derivedInt);

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

```
> 4
  2
  3
  6
```



Inheritance and Scoping

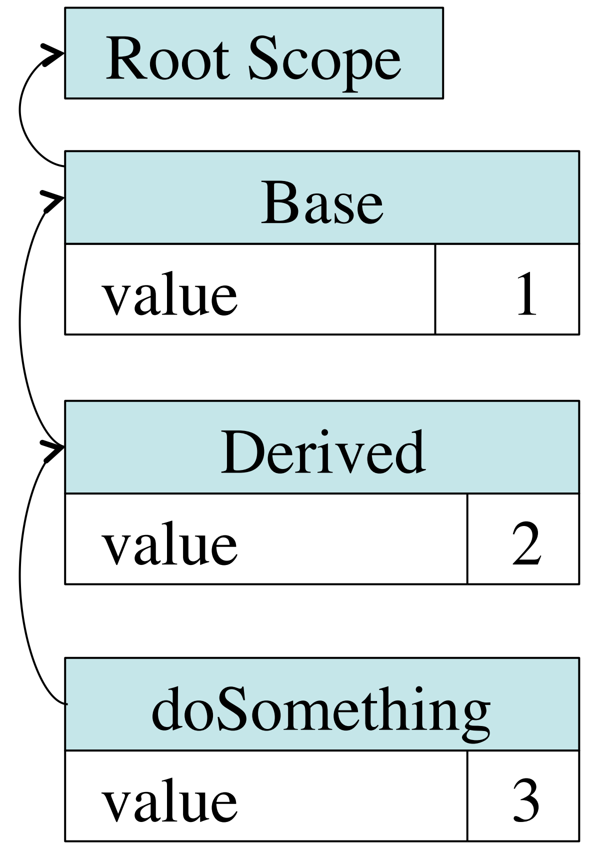
- Typically, the scope for a derived class will store a link to the scope of its base class
- Looking up a field of a class traverses the scope chain until that field is found or a semantic error is found

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);

    }
}
```



Explicit Disambiguation

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}
public class Derived extends Base {
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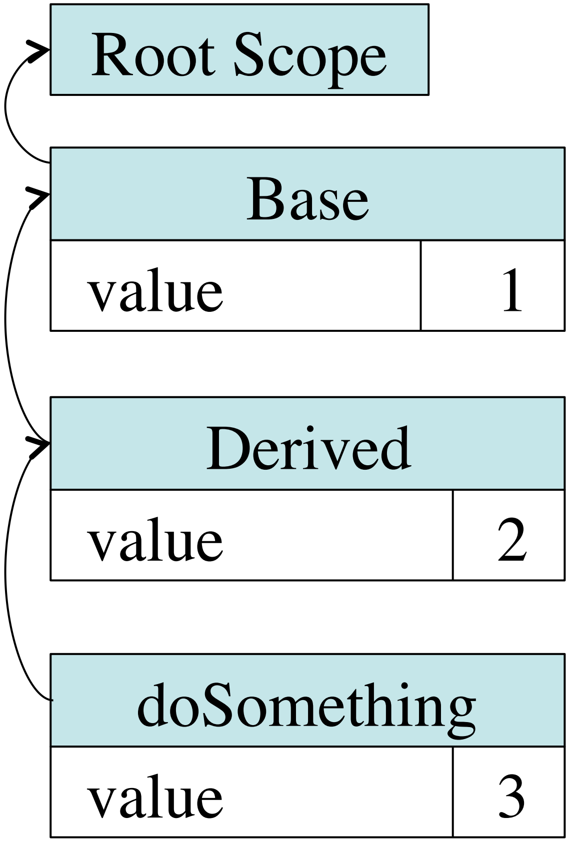
    public void doSomething () {
        int value = 3;
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);

    }
}
```



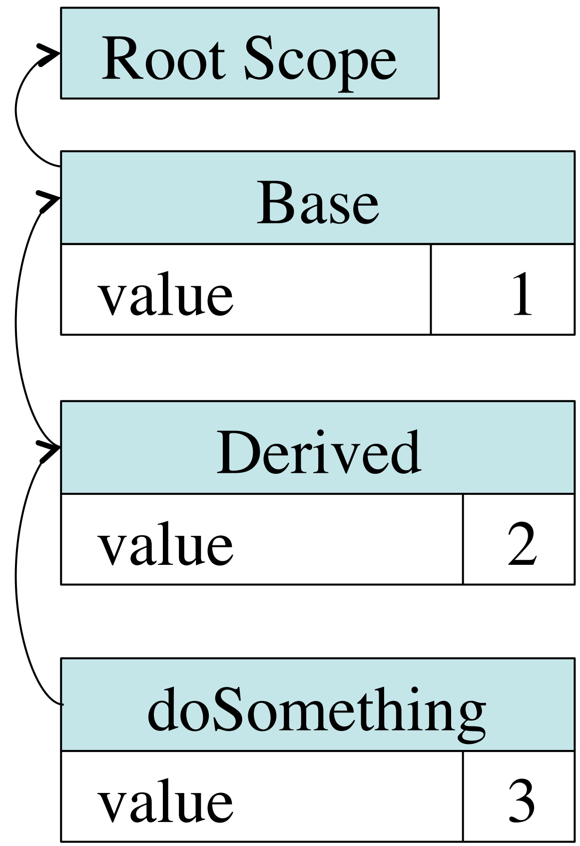
Explicit Disambiguation

```
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
```



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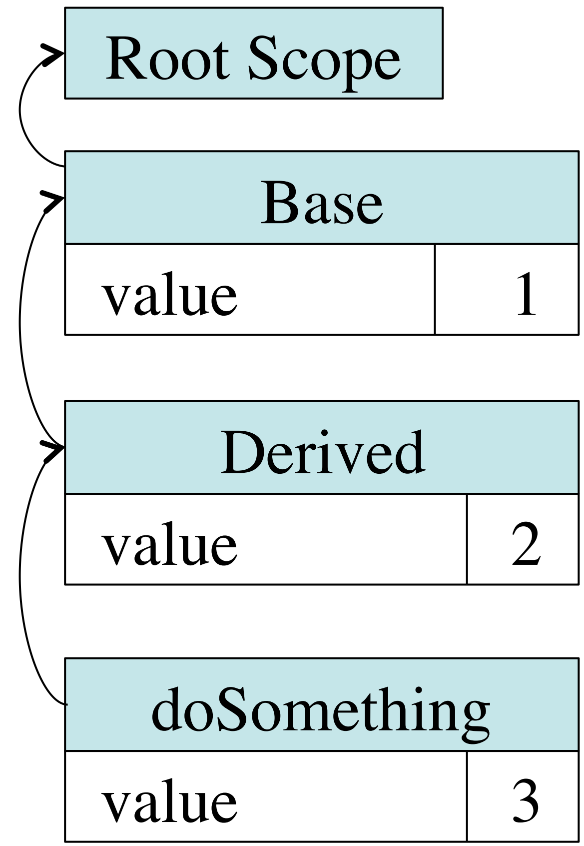
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);

    }
}
```

```
> 3
  2
```



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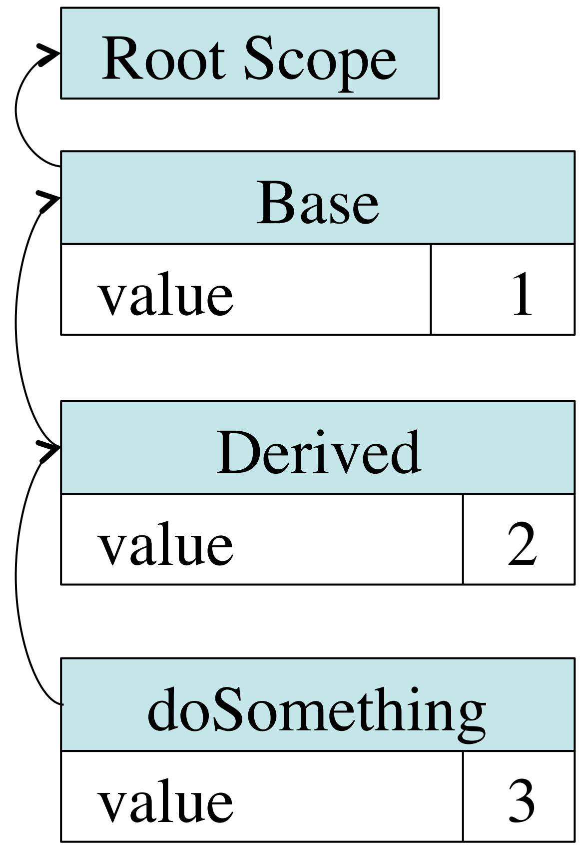
    public void doSomething () {
        int value = 3;
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);

    }
}
```

```
> 3
  2
  1
```



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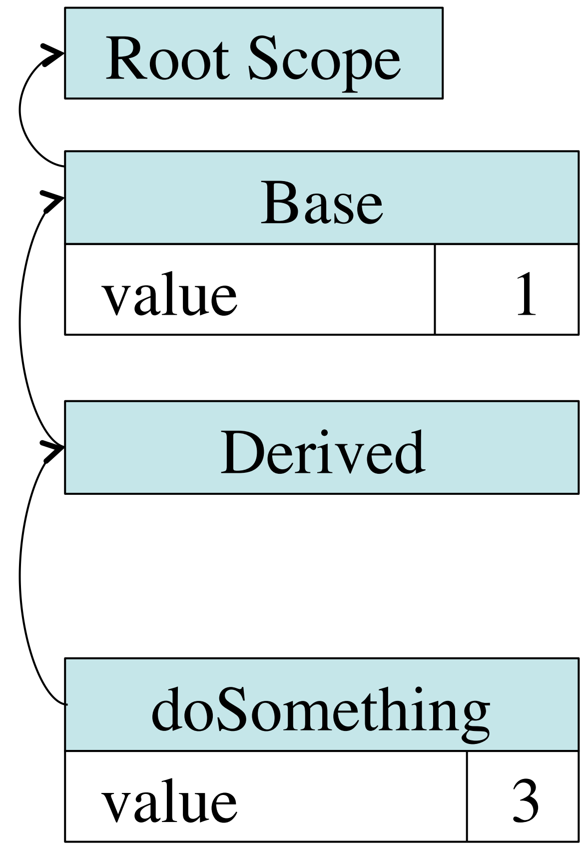
        System.out.println(this.value);
        System.out.println(super.value);

    }
}
```

```
>
```



Explicit Disambiguation

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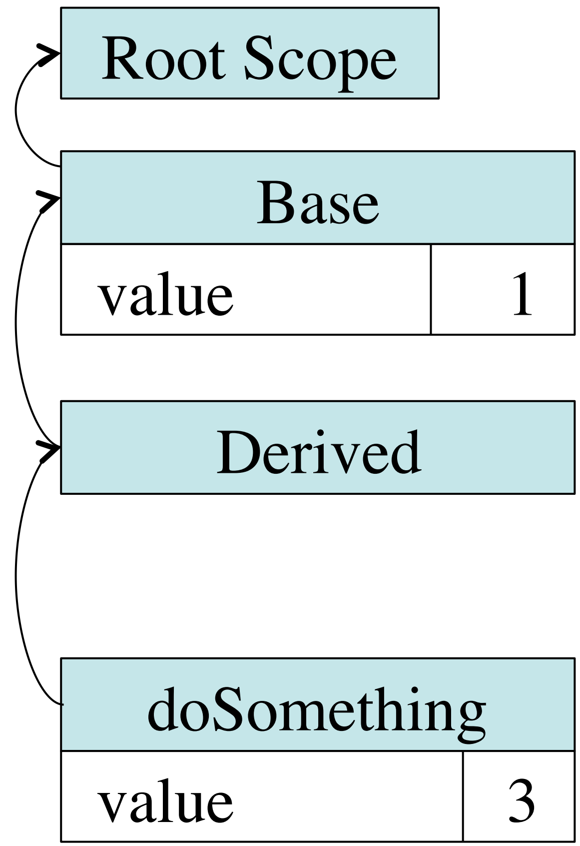
}
public class Derived extends Base {


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

    }
}
```

```
> 3
```



Explicit Disambiguation

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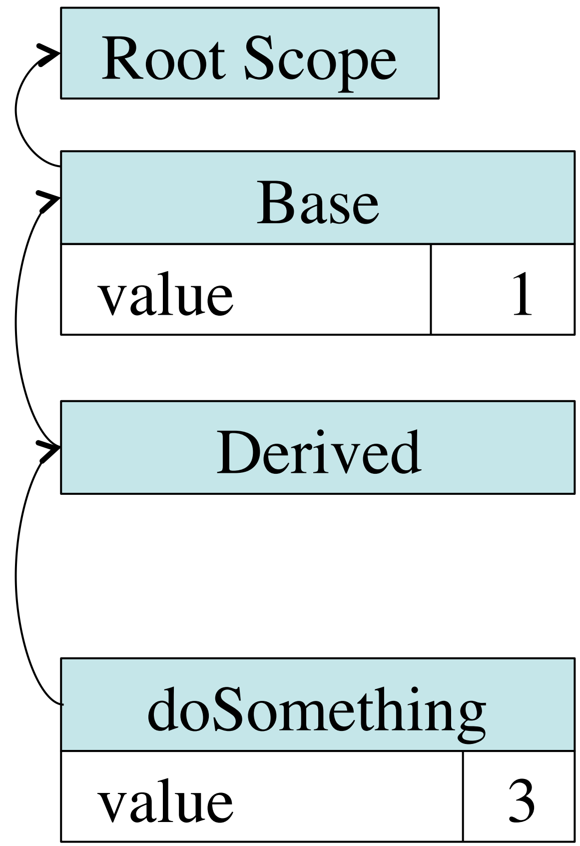
    public void doSomething () {
        int value = 3;
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);

    }
}
```

```
> 3
  1
```



Explicit Disambiguation

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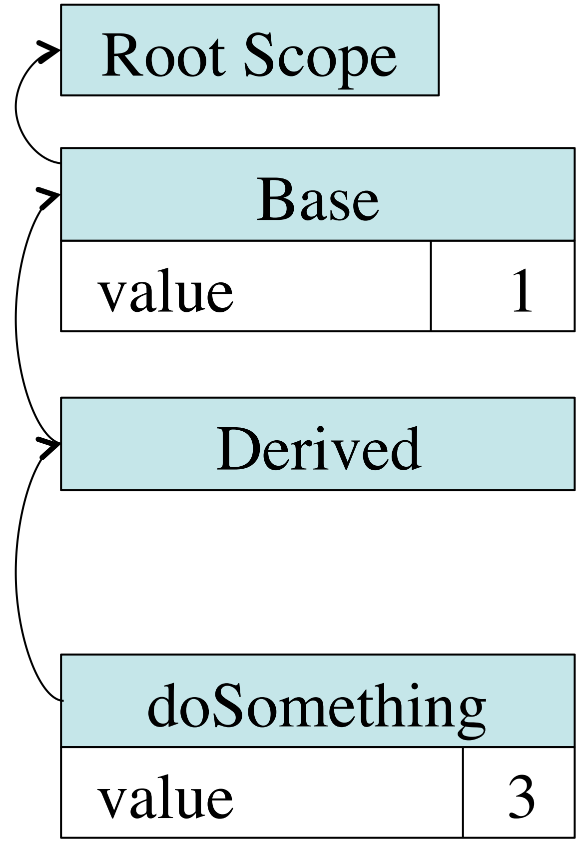
    public void doSomething () {
        int value = 3;
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);

    }
}
```

```
> 3
  1
  1
```



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++)

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

```
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

```
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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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.