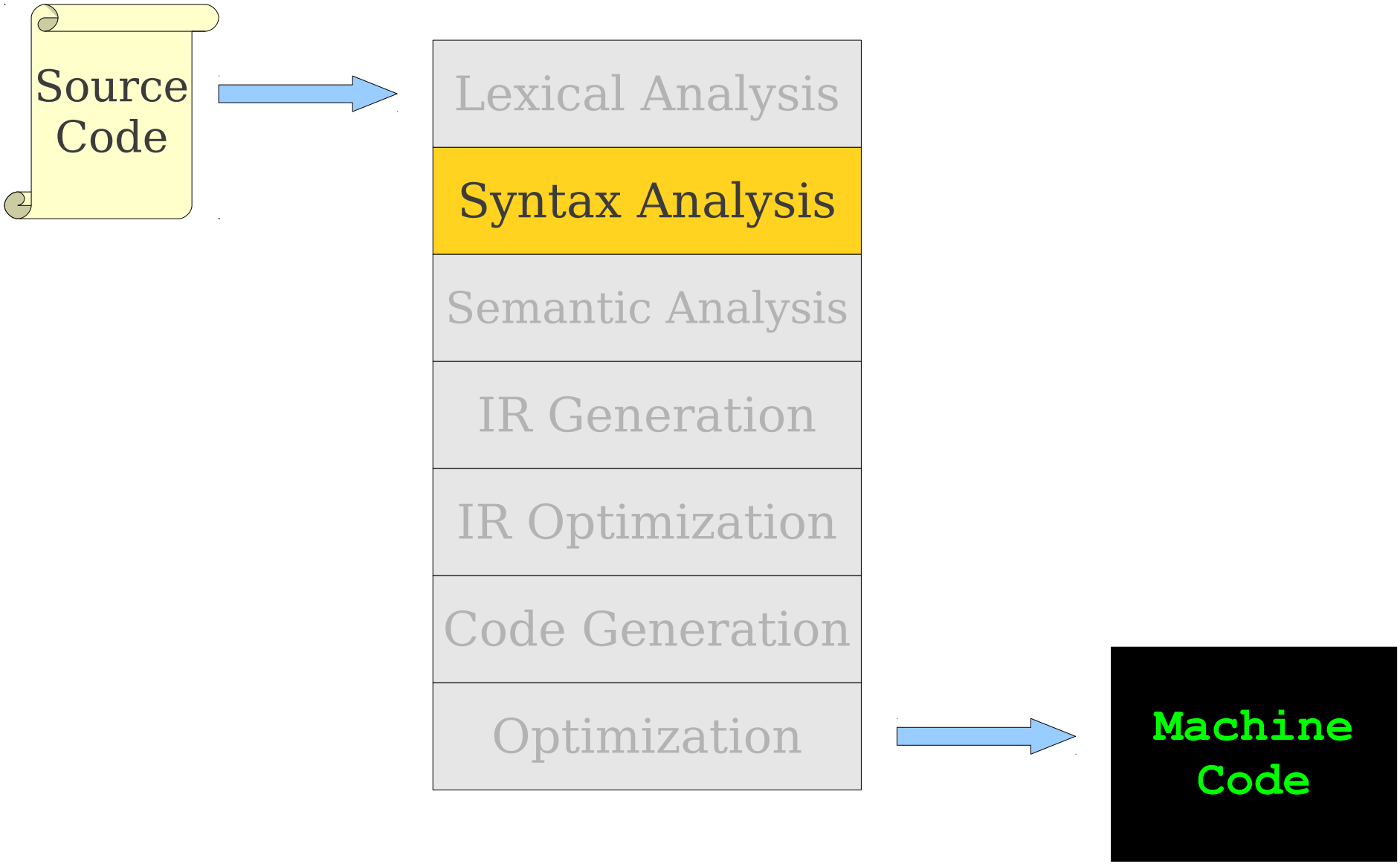
Semantic Analysis

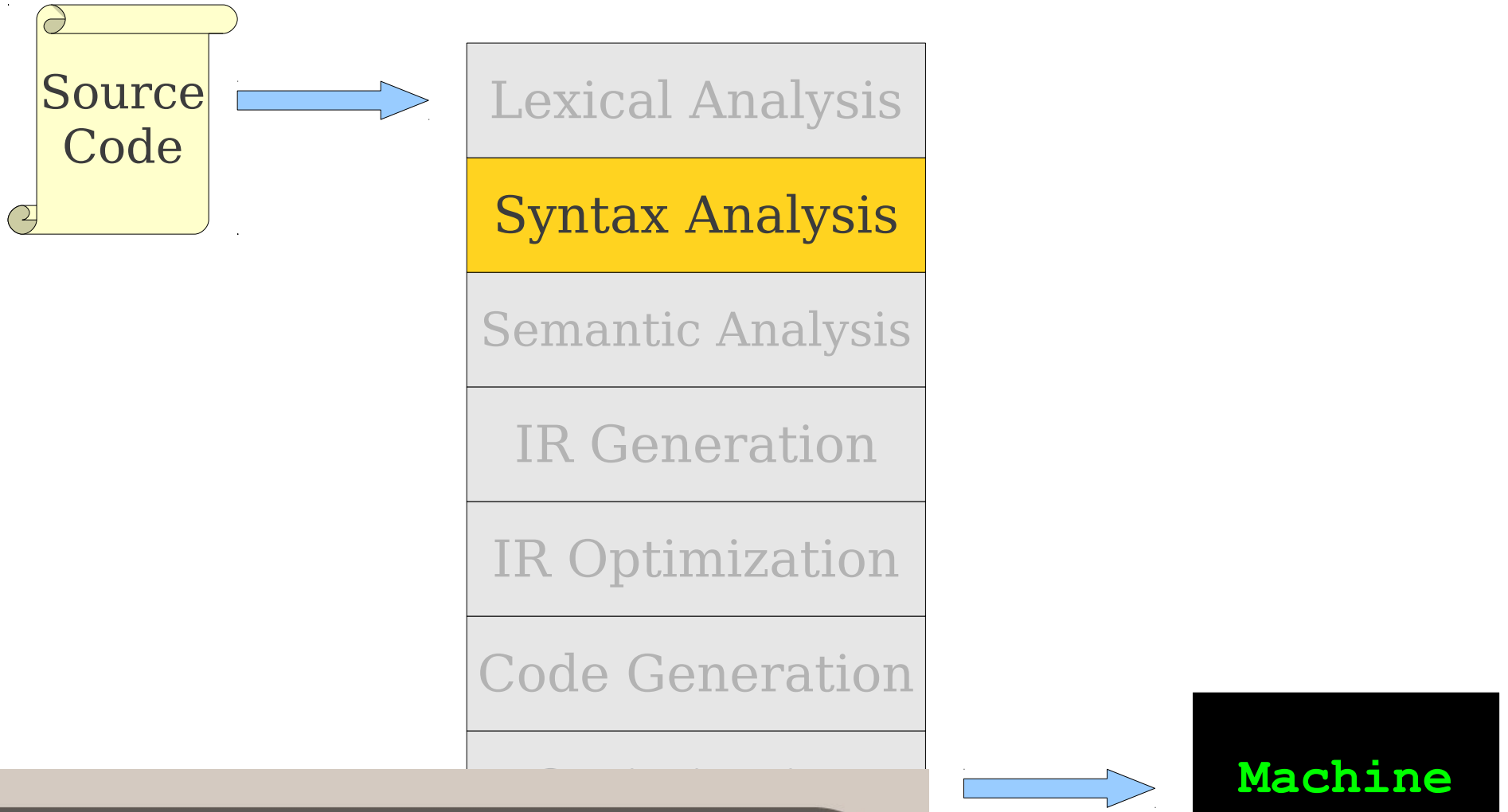
Announcements

- Programming Project 2 due Friday at 11:59PM.
- Written Assignment 2 due Wednesday at 5:00PM.
- Questions?
  - Stop by office hours!
  - Ask on Piazza!
  - Email the course staff!

Where We Are


Source Code
Lexical Analysis
Syntax Analysis
Semantic Analysis
IR Generation
IR Optimization
Code Generation
Optimization
Machine Code

Where We Are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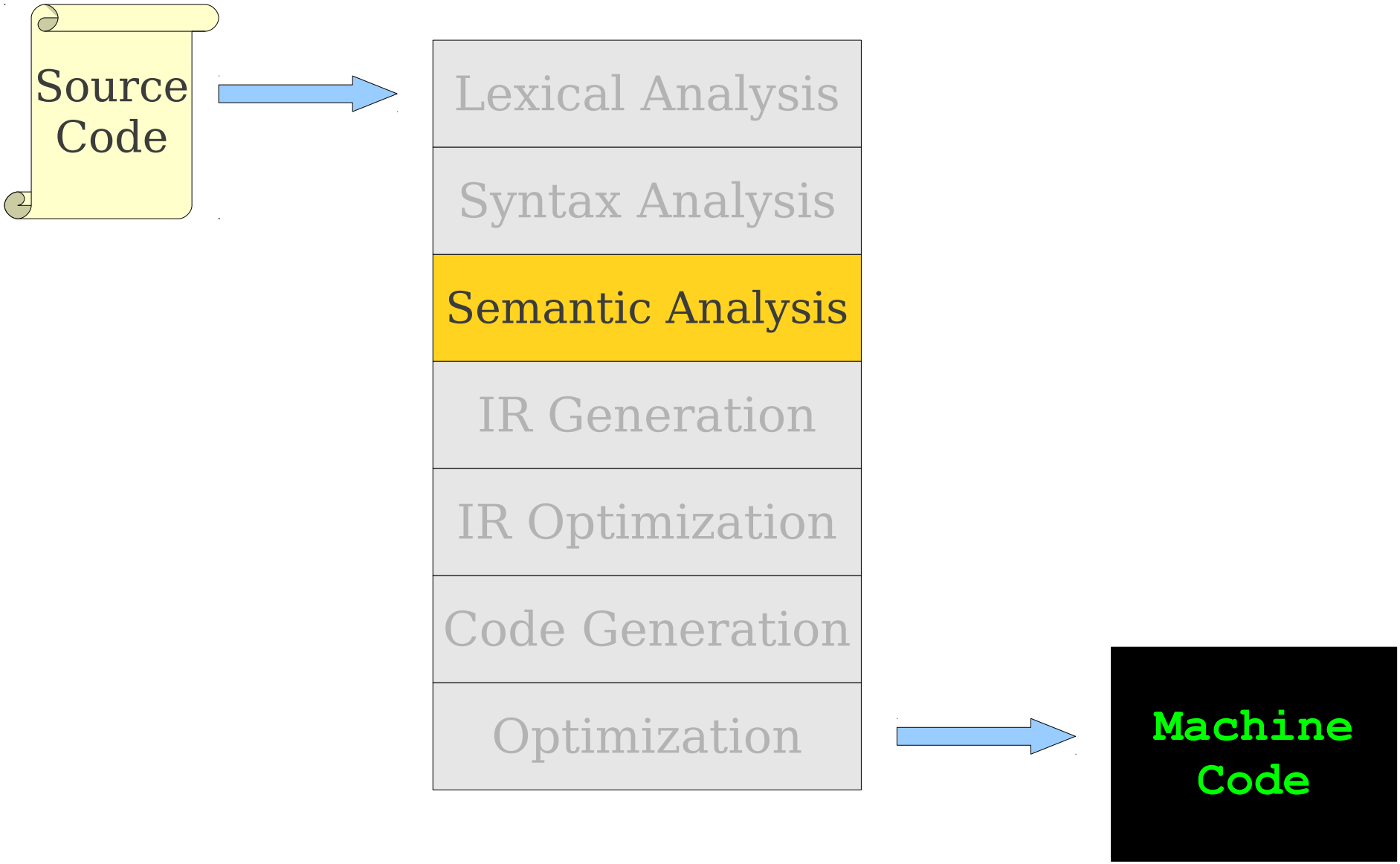
Achievement unlocked
Syntax-tic!

Where We Are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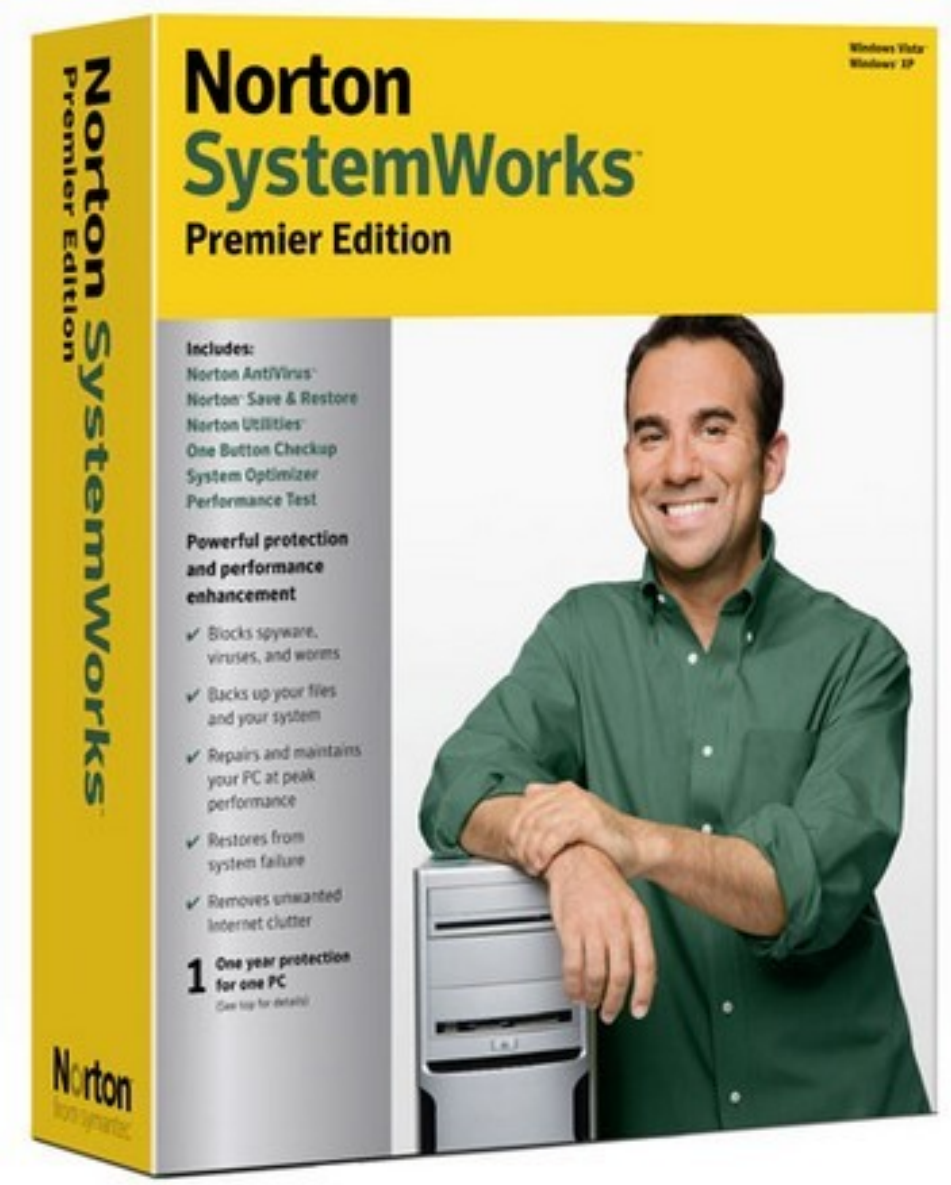
Not Symantec Analysis



Where We Are

- Program is *lexically* well-formed:
  - Identifiers have valid names.
  - Strings are properly terminated.
  - No stray characters.
- Program is *syntactically* well-formed:
  - Class declarations have the correct structure.
  - Expressions are syntactically valid.
- Does this mean that the program is legal?

A Short Decaf Program

```
class MyClass implements MyInterface {
    string myInteger;

    void doSomething() {
        int[] x = new string;

        x[5] = myInteger * y;
    }
    void doSomething() {

    }
    int fibonacci(int n) {
        return doSomething() + fibonacci(n - 1);
    }
}
```

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```

Interface not declared

Wrong type

Can't multiply strings

Variable not declared

Can't redefine functions

Can't add void

No main function

Semantic Analysis

- Ensure that the program has a well-defined **meaning**.
- Verify properties of the program that aren't caught during the earlier phases:
  - Variables are declared before they're used.
  - Expressions have the right types.
  - Arrays can only be instantiated with `NewArray`.
  - Classes don't inherit from nonexistent base classes
  - ...
- Once we finish semantic analysis, we know that the user's input program is legal.

Challenges in Semantic Analysis

- Reject the largest number of incorrect programs.
- Accept the largest number of correct programs.

Validity versus Correctness

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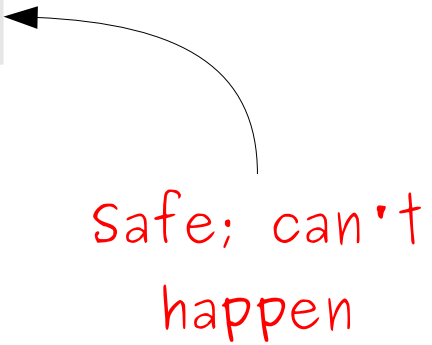

Validity versus Correctness

```
int Fibonacci(int n) {
    if (n <= 1) return 0;

    return Fibonacci(n - 1) + Fibonacci(n - 2);
}

int main() {
    Print(Fibonacci(40));
}
```

Validity versus Correctness

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int Fibonacci(int n) {
    if (n <= 1) return 0;

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}

int main() {
    Print(Fibonacci(40));
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Incorrect, should be "return n;"

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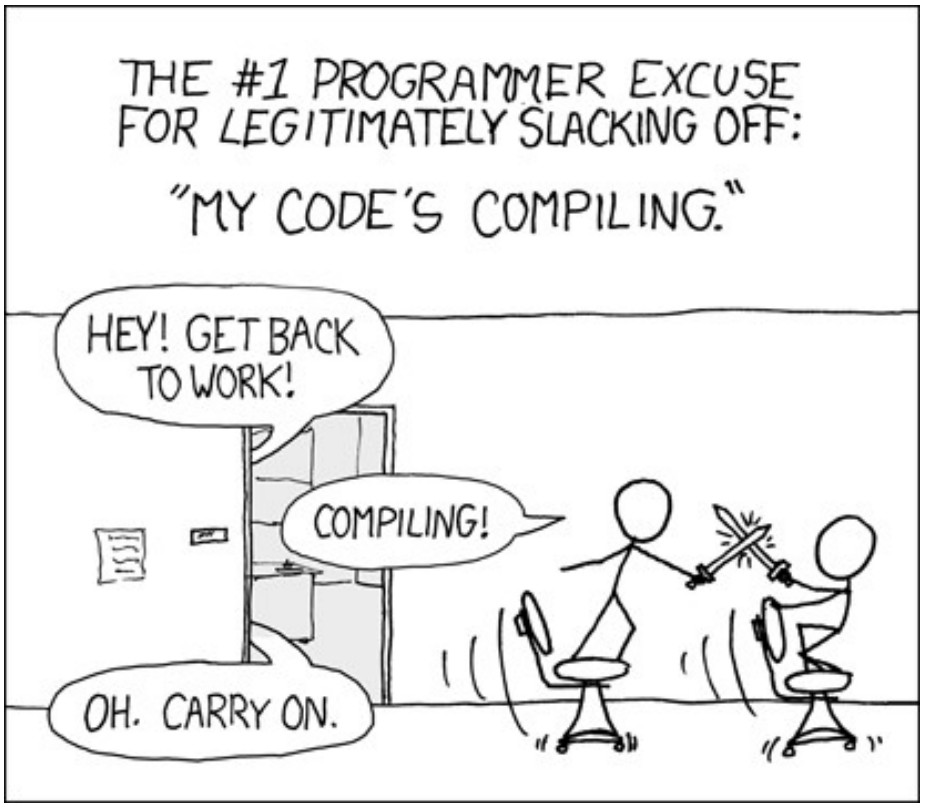

Other Goals of Semantic Analysis

- Gather useful information about program for later phases:
  - Determine what variables are meant by each identifier.
  - Build an internal representation of inheritance hierarchies.
  - Count how many variables are in scope at each point.

Why can't we just do this during parsing?

Limitations of CFGs

- Using CFGs:
  - How would you prevent duplicate class definitions?
  - How would you differentiate variables of one type from variables of another type?
  - How would you ensure classes implement all interface methods?

Limitations of CFGs

- Using CFGs:
  - How would you prevent duplicate class definitions?
  - How would you differentiate variables of one type from variables of another type?
  - How would you ensure classes implement all interface methods?
- For most programming languages, these are *provably impossible*.
  - Use the pumping lemma for context-free languages, or Ogden's lemma.

Implementing Semantic Analysis

- **Attribute Grammars**
  - Augment **`bison`** rules to do checking during parsing.
  - Approach suggested in the *Compilers* book.
  - Has its limitations; more on that later.
- **Recursive AST Walk**
  - Construct the AST, then use virtual functions and recursion to explore the tree.
  - The approach we'll take in this class.

Overview for this Week

- **Scope-Checking** (Today)
  - How can we tell what object a particular identifier refers to?
  - How do we store this information?
- **Type-Checking** (Wednesday / Friday)
  - How can we tell whether expressions have valid types?
  - How do we know all function calls have valid arguments?

Scope

Not This

What's in a Name?

- The same name 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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- 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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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

- A **symbol table** is a mapping from a name to the thing that name refers to.
- As we run our semantic analysis, continuously update the symbol table with information about what is in scope.
- Questions:
  - What does this look like in practice?
  - What operations need to be defined on it?
  - How do we implement it?

Symbol Tables: The Intuition

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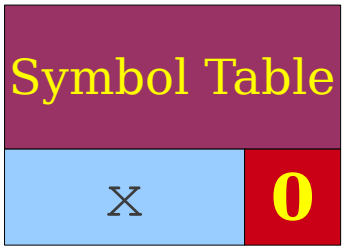

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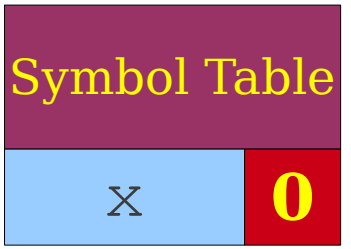

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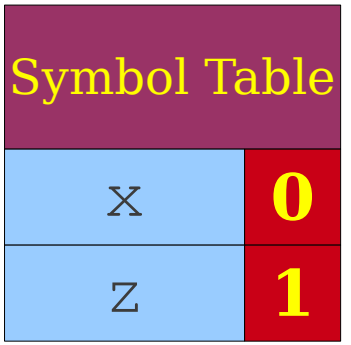

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Symbol Table	
x	0
z	1

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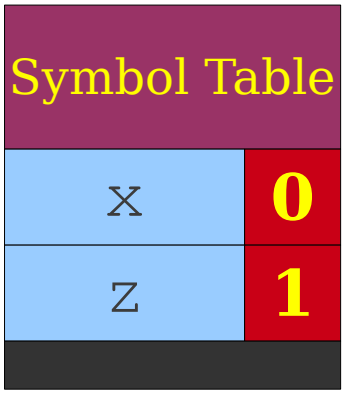

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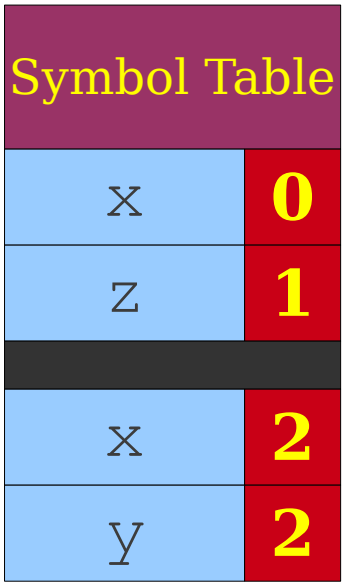

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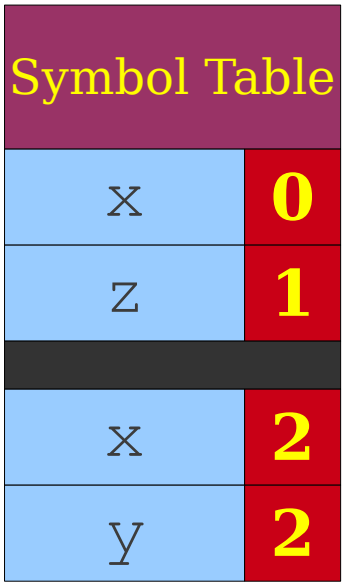

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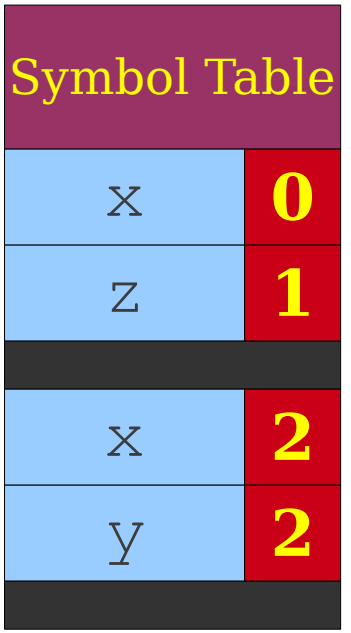

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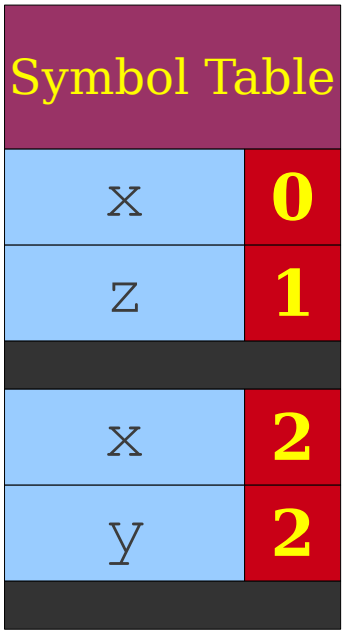

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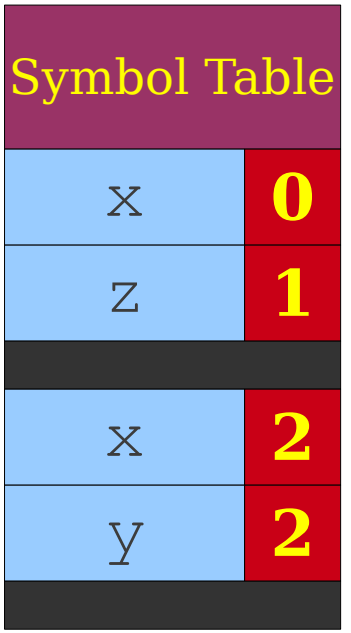

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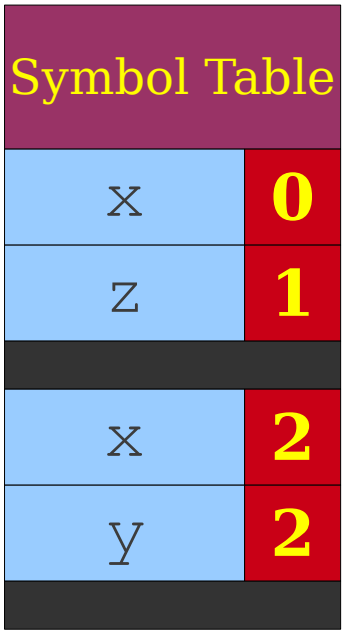

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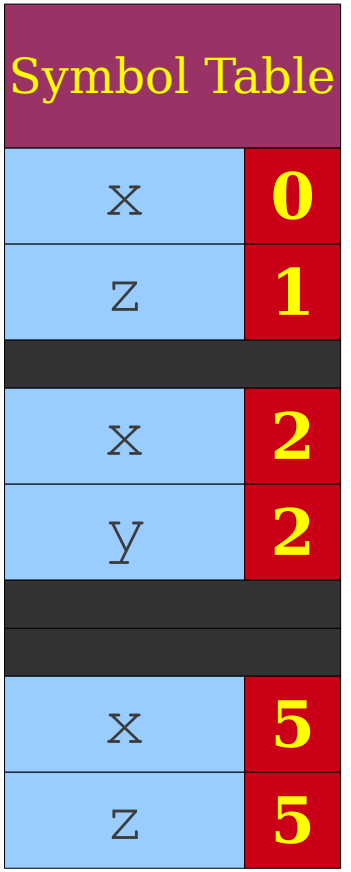

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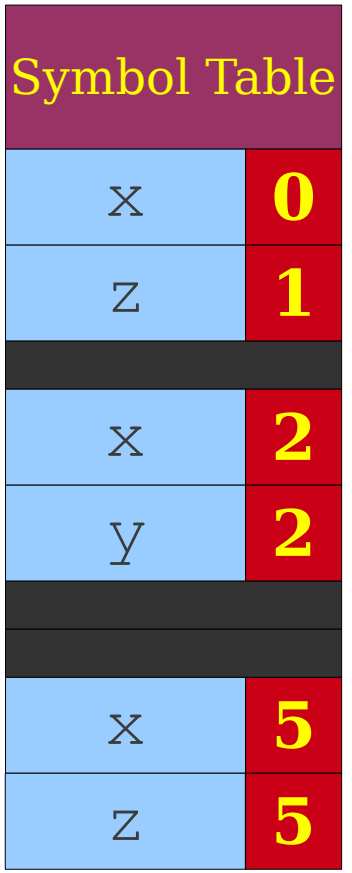

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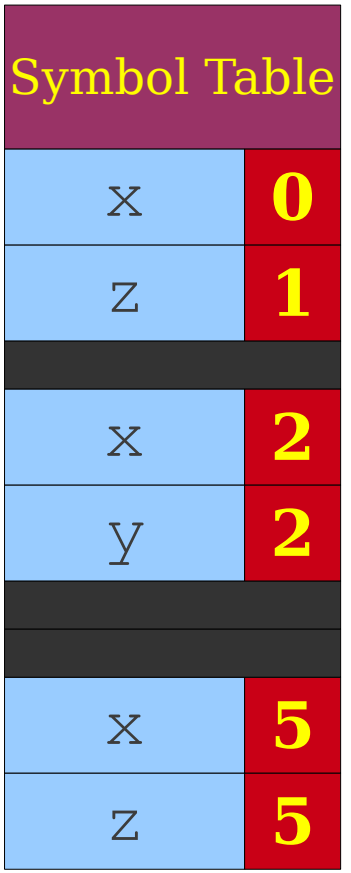

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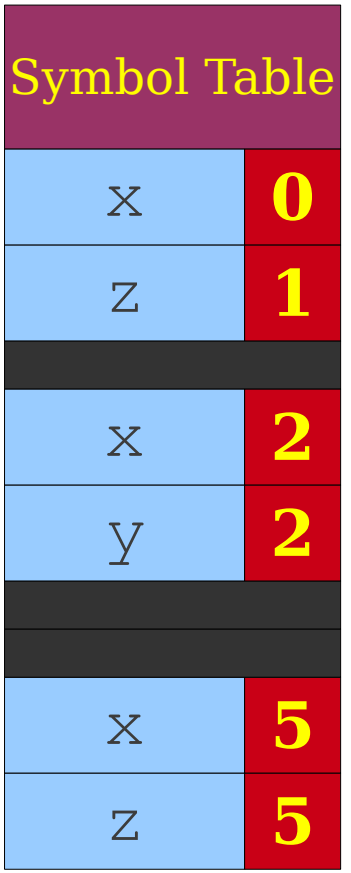

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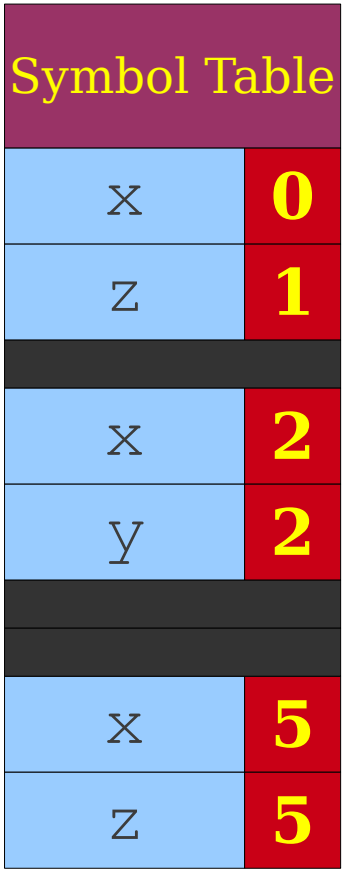

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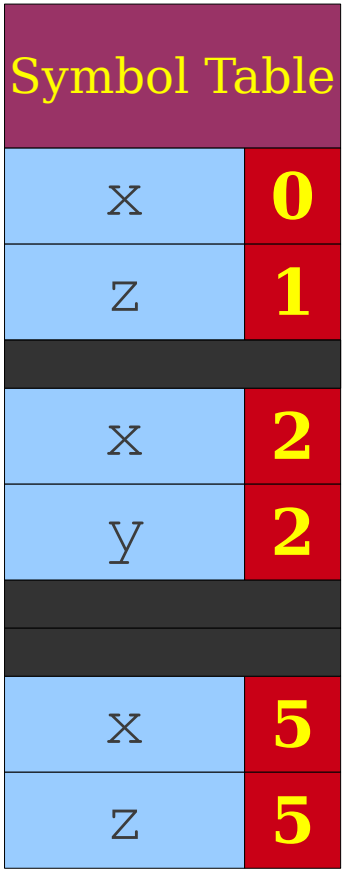

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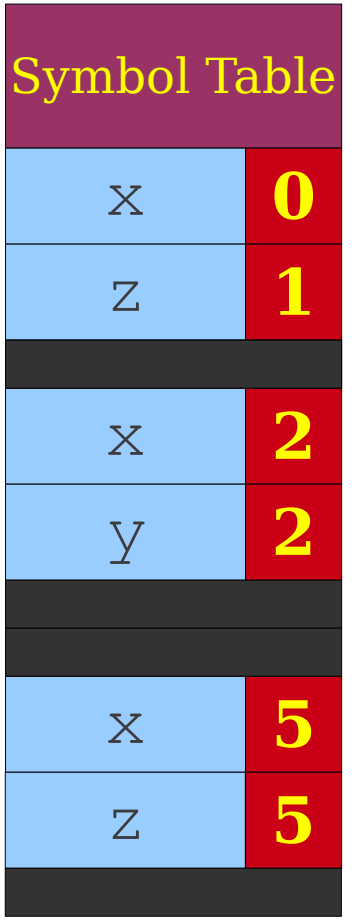

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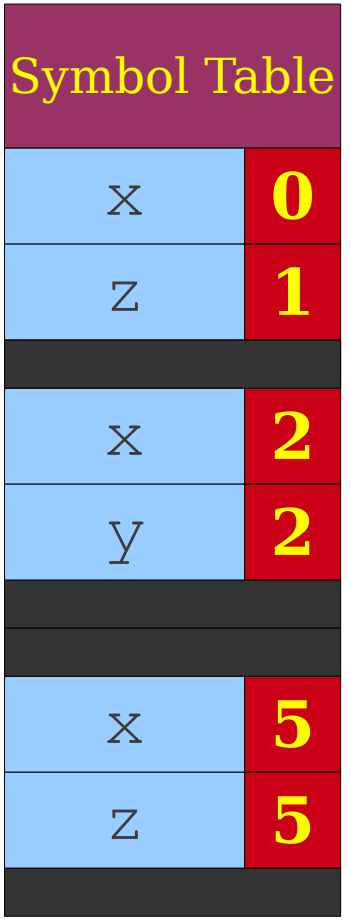

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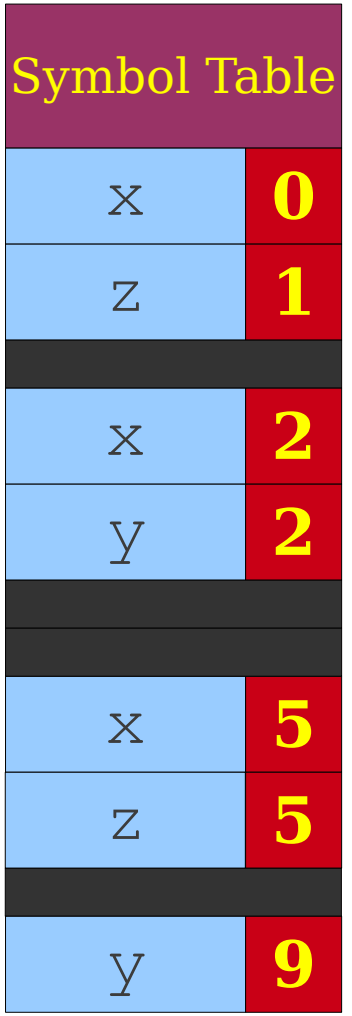

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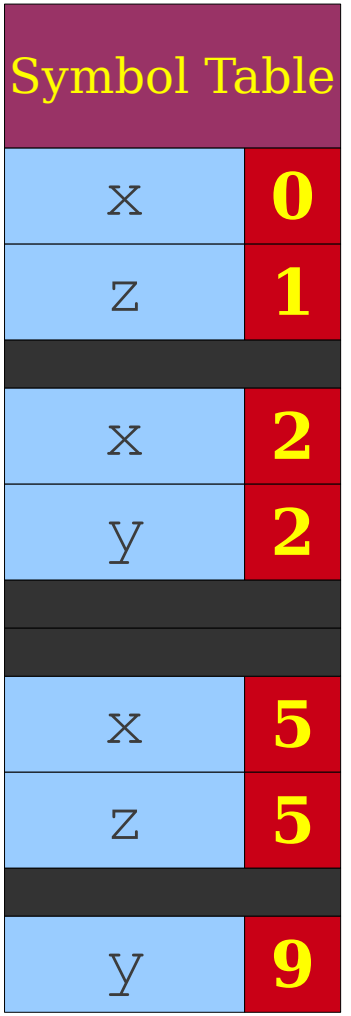

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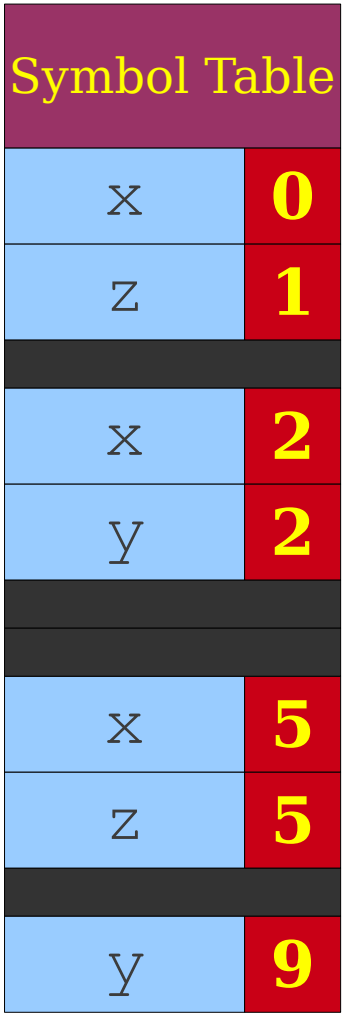

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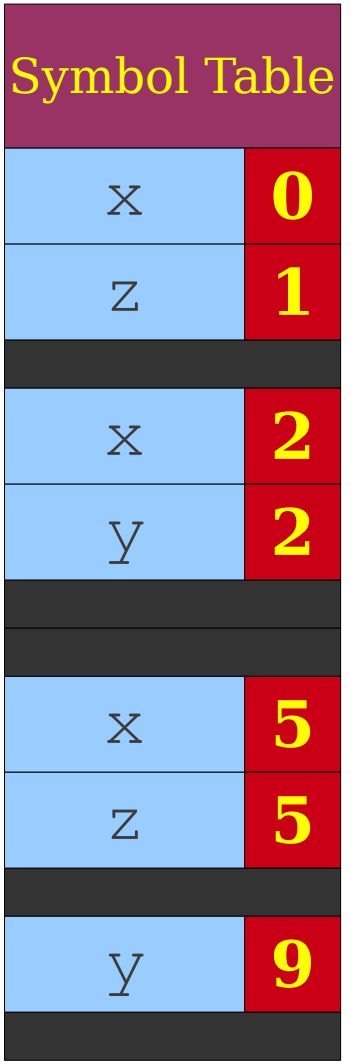

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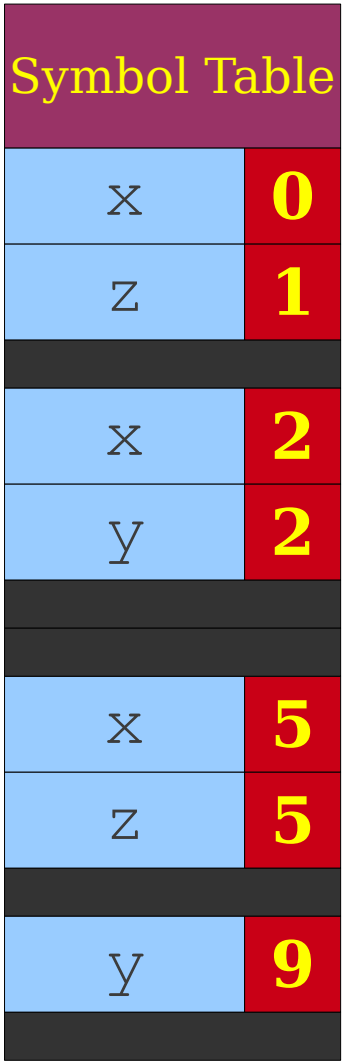

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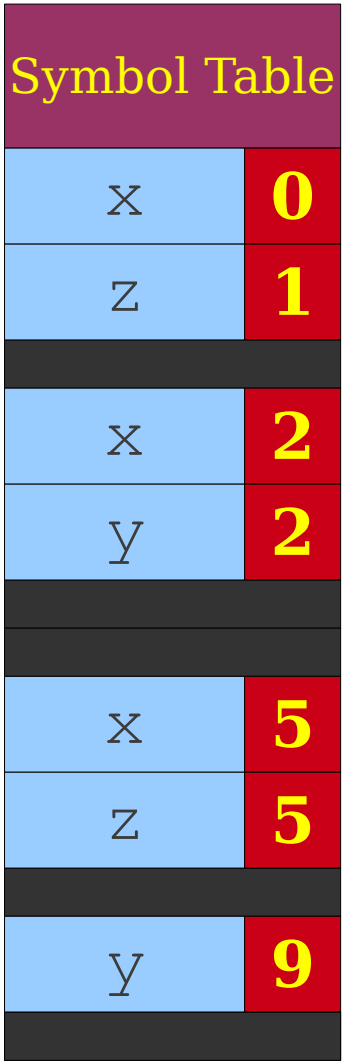

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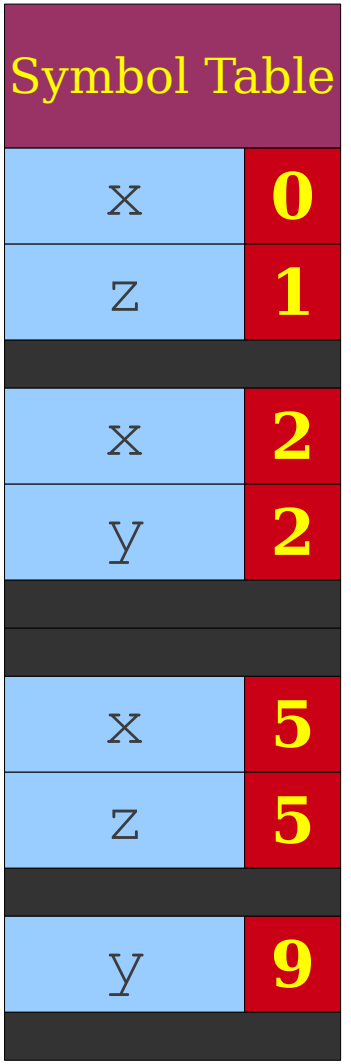

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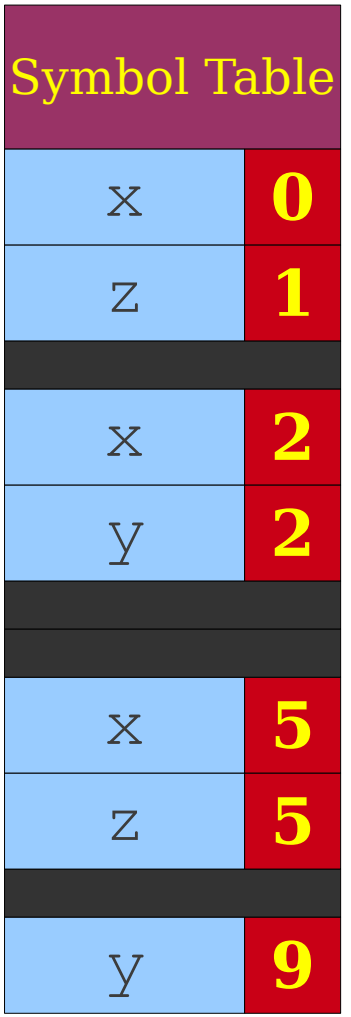

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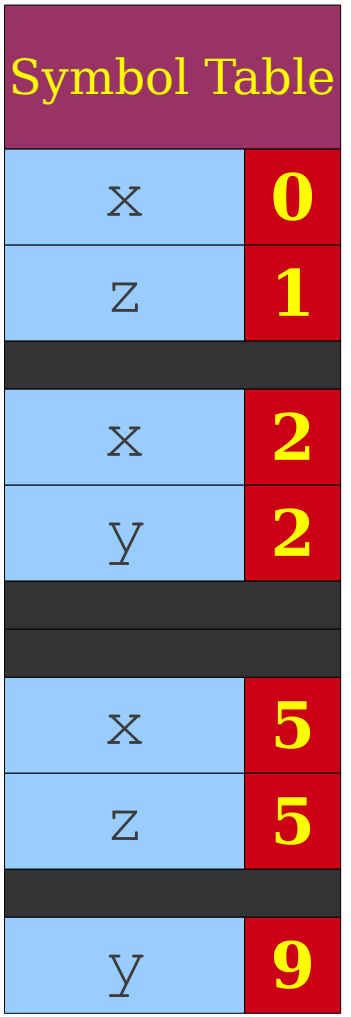

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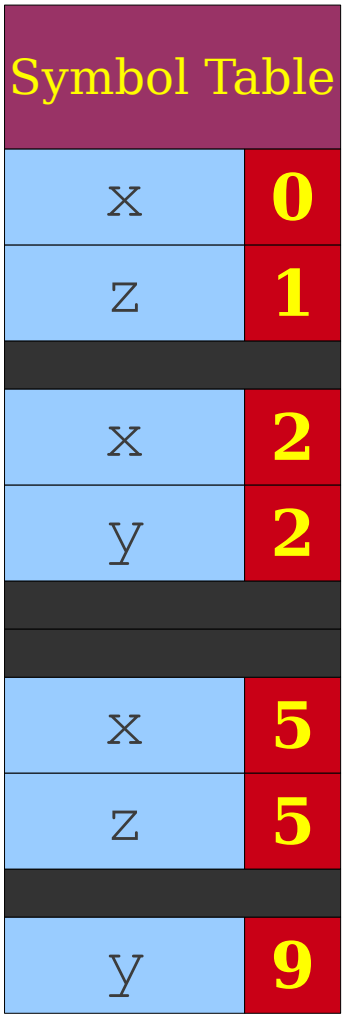

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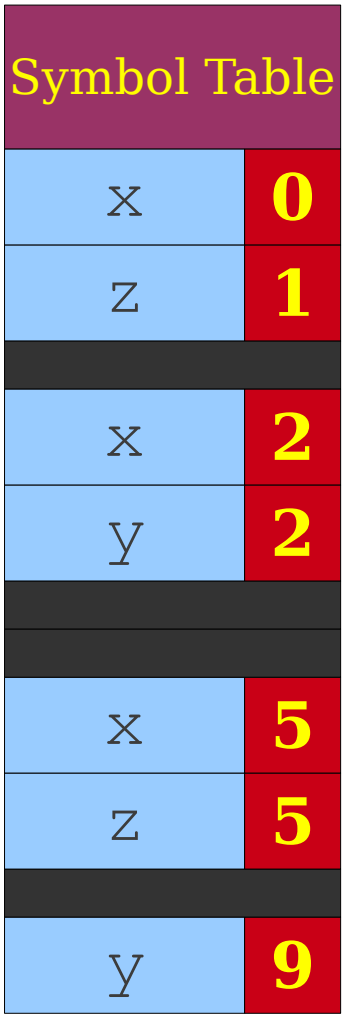

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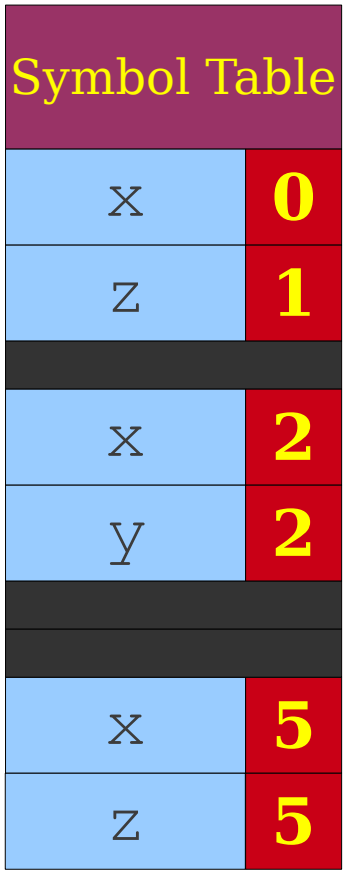

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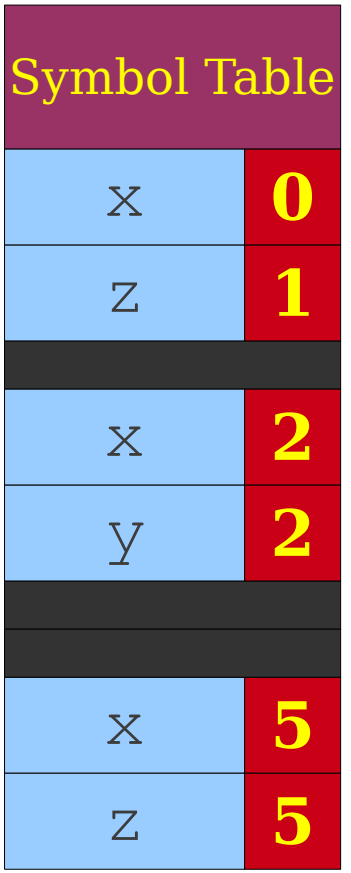

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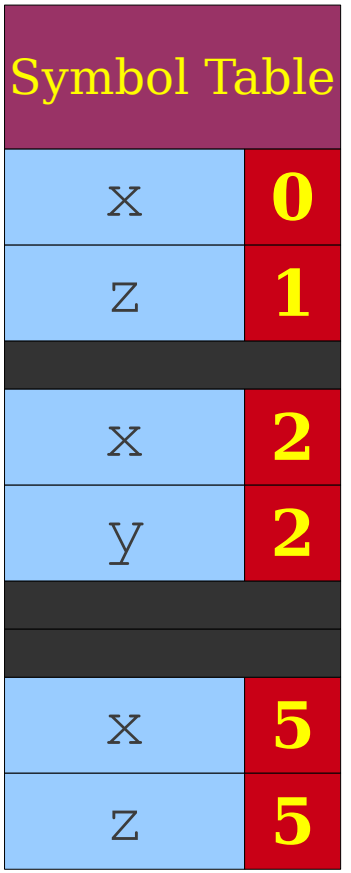

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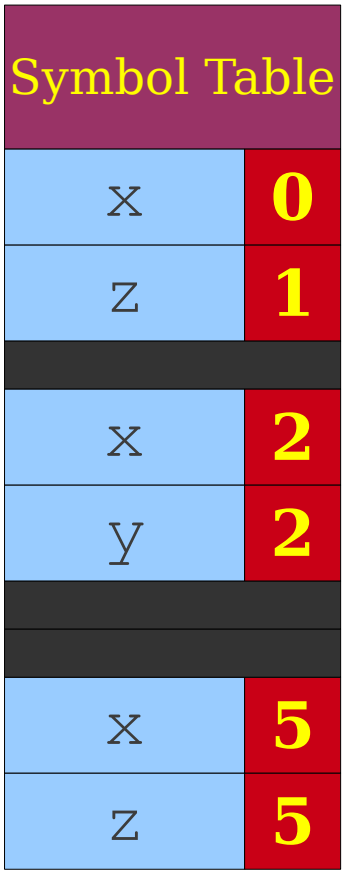

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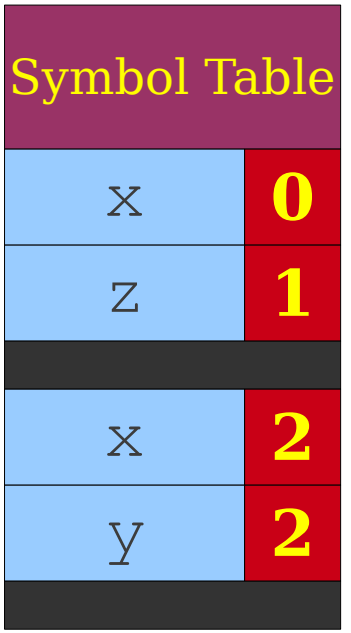

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 9:       int y = x@5;
10:       {
11:         printf("%d,%d,%d\n", x@5, y@9, z@5);
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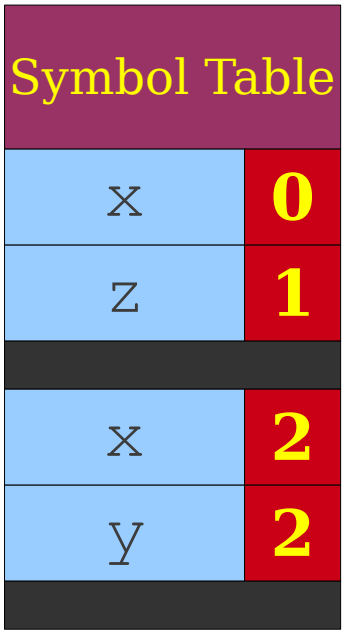

Symbol Tables: The Intuition

```
 0: int x = 137;
 1: int z = 42;
 2: int MyFunction(int x, int y) {
 3:   printf("%d,%d,%d\n", x@2, y@2, z@1);
 4:   {
 5:     int x, z;
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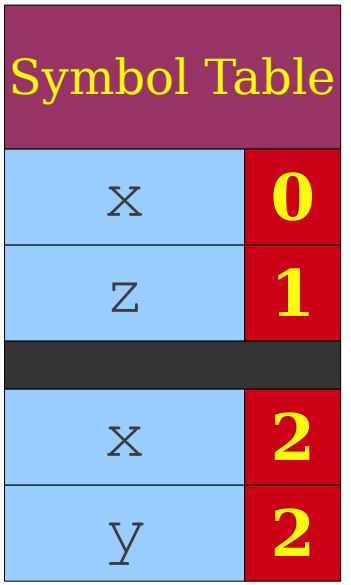

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Symbol Table	
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Symbol Table	
x	0
z	1

Symbol Table Operations

- Typically implemented as a **stack of maps**.
- Each map corresponds to a particular scope.
- Stack allows for easy “enter” and “exit” operations.
- Symbol table operations are
  - **Push scope**: Enter a new scope.
  - **Pop scope**: Leave a scope, discarding all declarations in it.
  - **Insert symbol**: Add a new entry to the current scope.
  - **Lookup symbol**: Find what a name corresponds to.

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 in terms of recursive AST traversals like this.

Another View of Symbol Tables

Another View of Symbol Tables

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Another View of Symbol Tables

Root Scope

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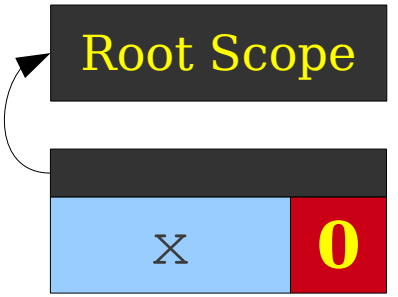


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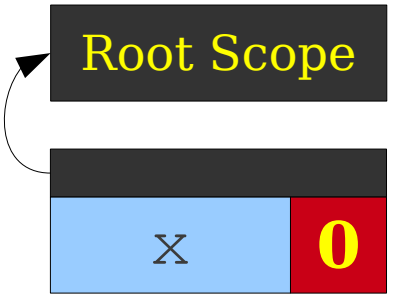


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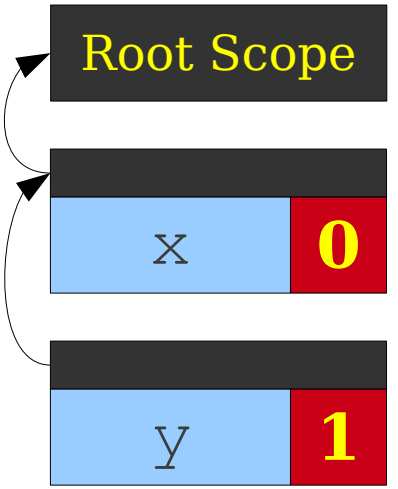

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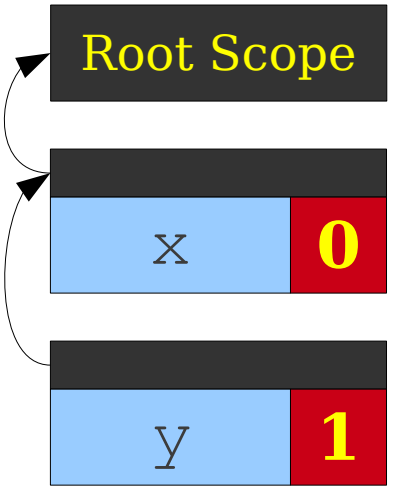

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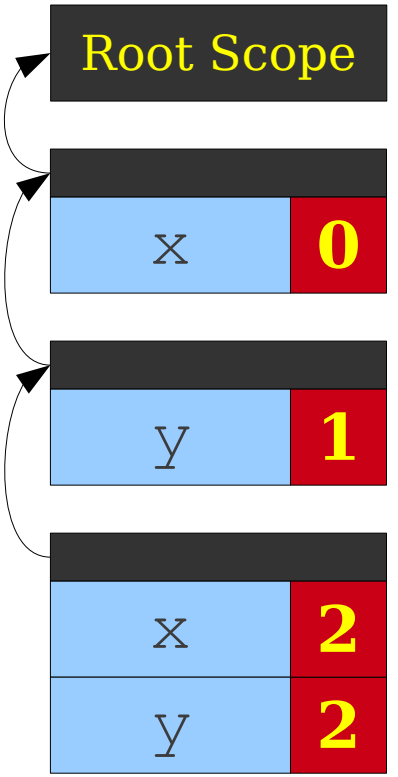

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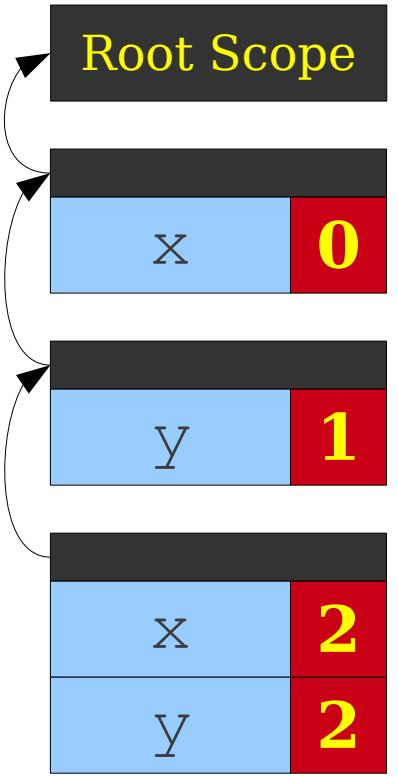

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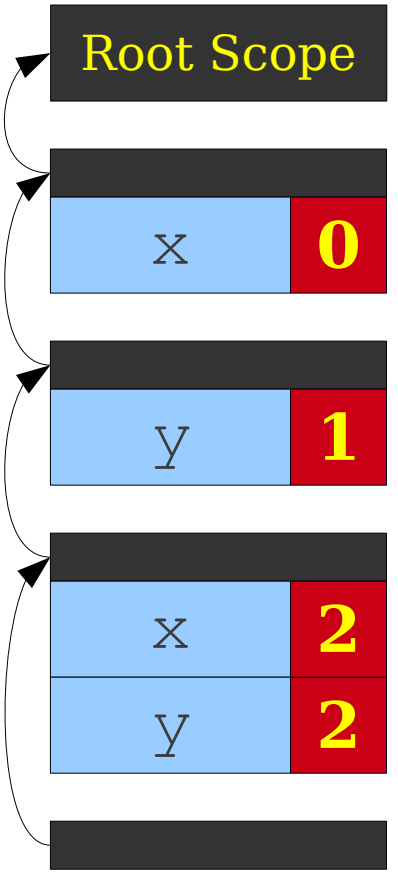

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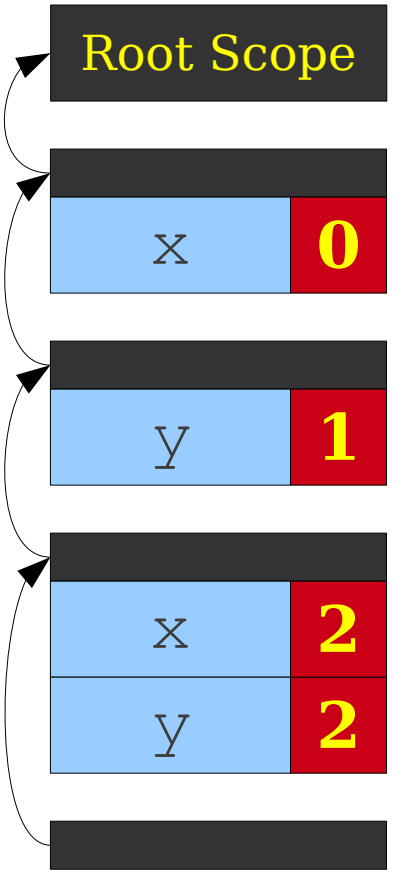

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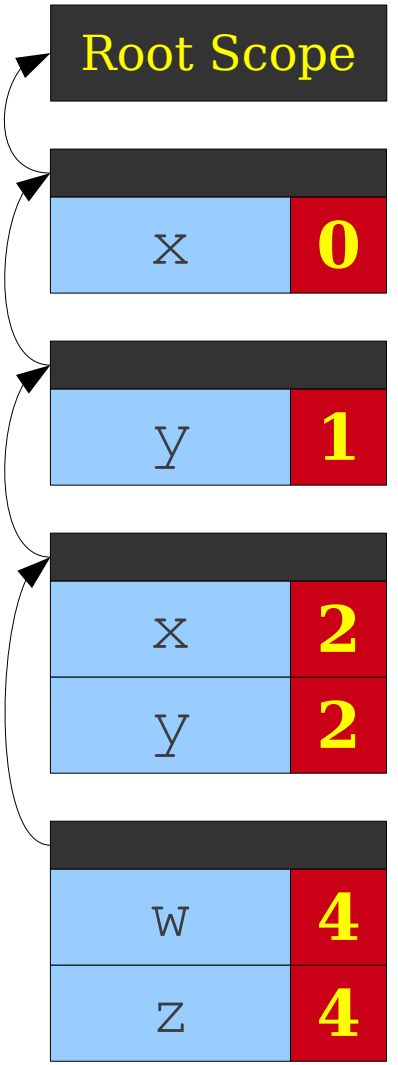

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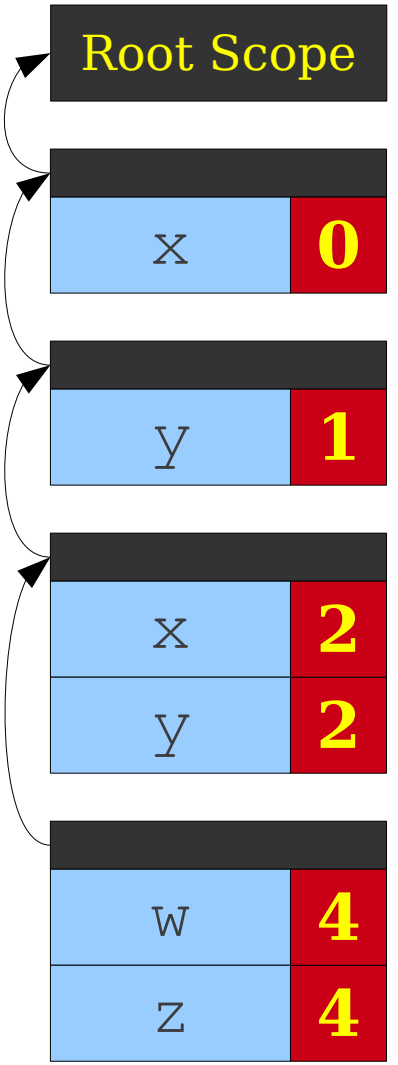

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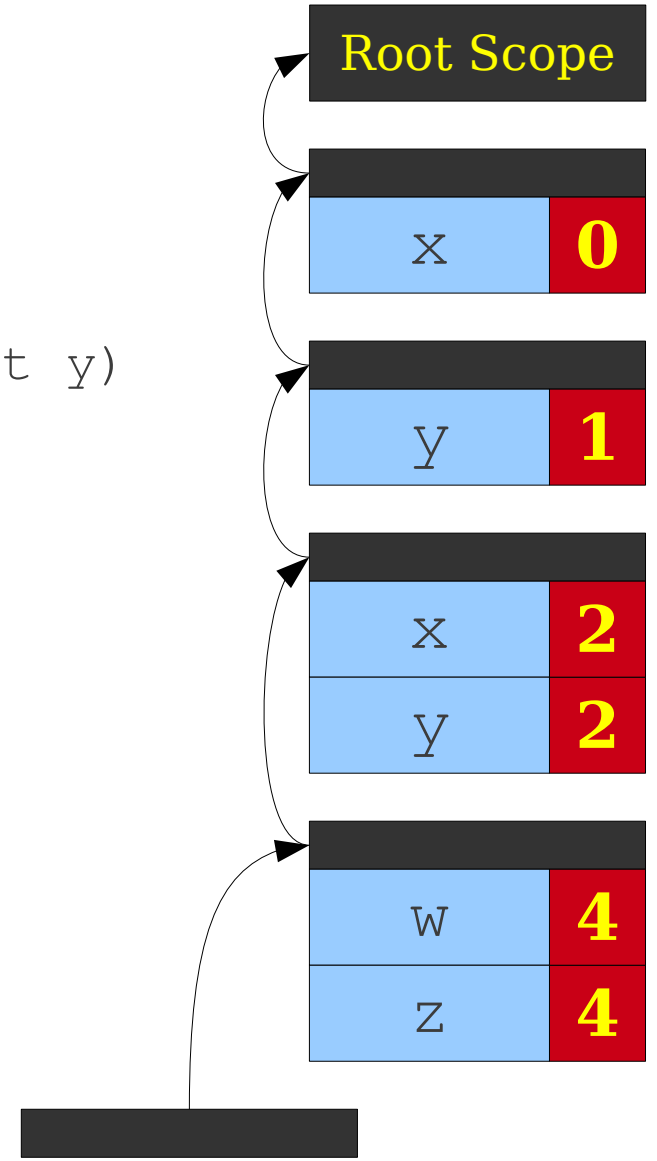

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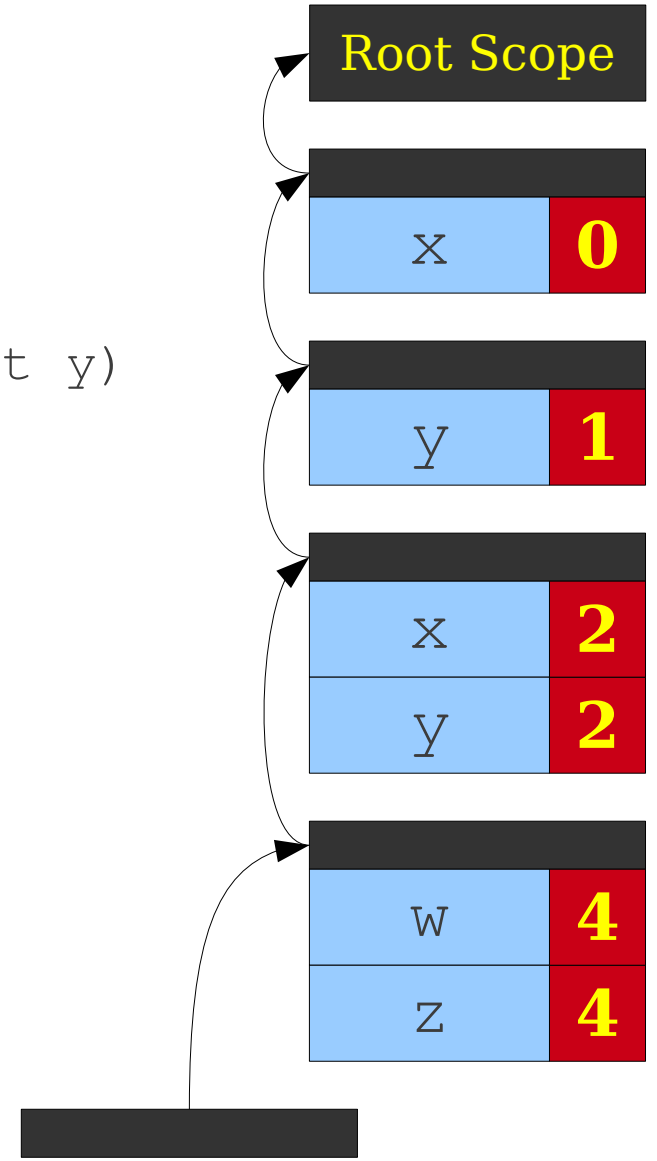

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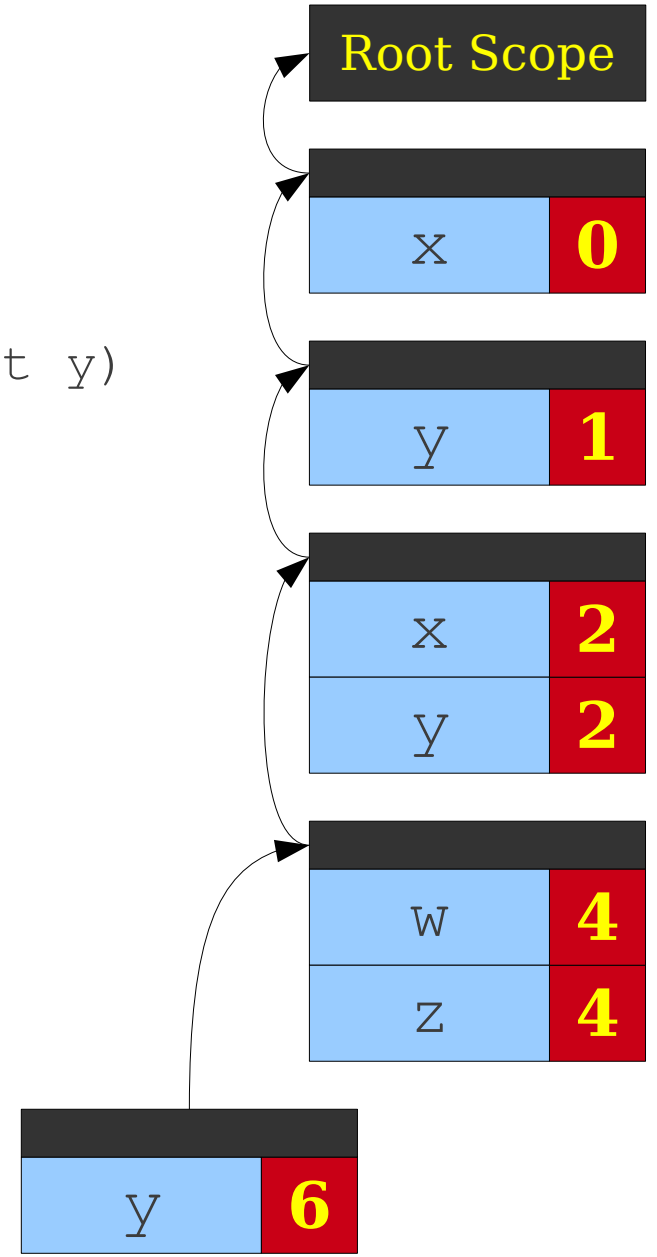

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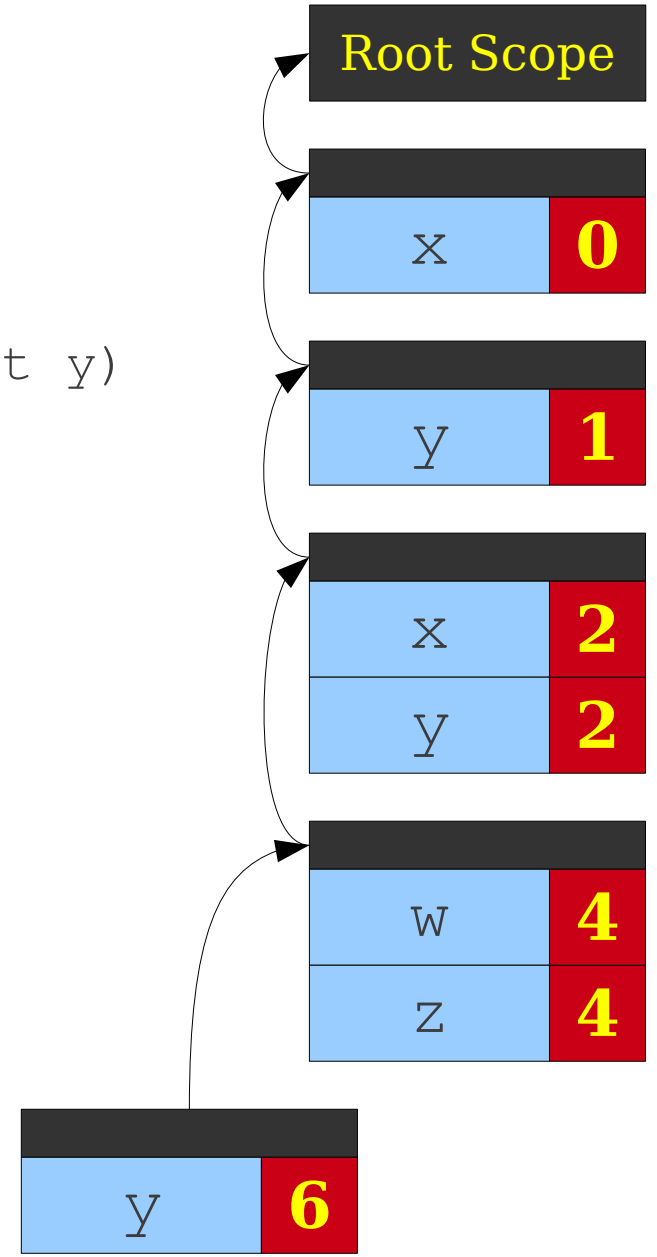

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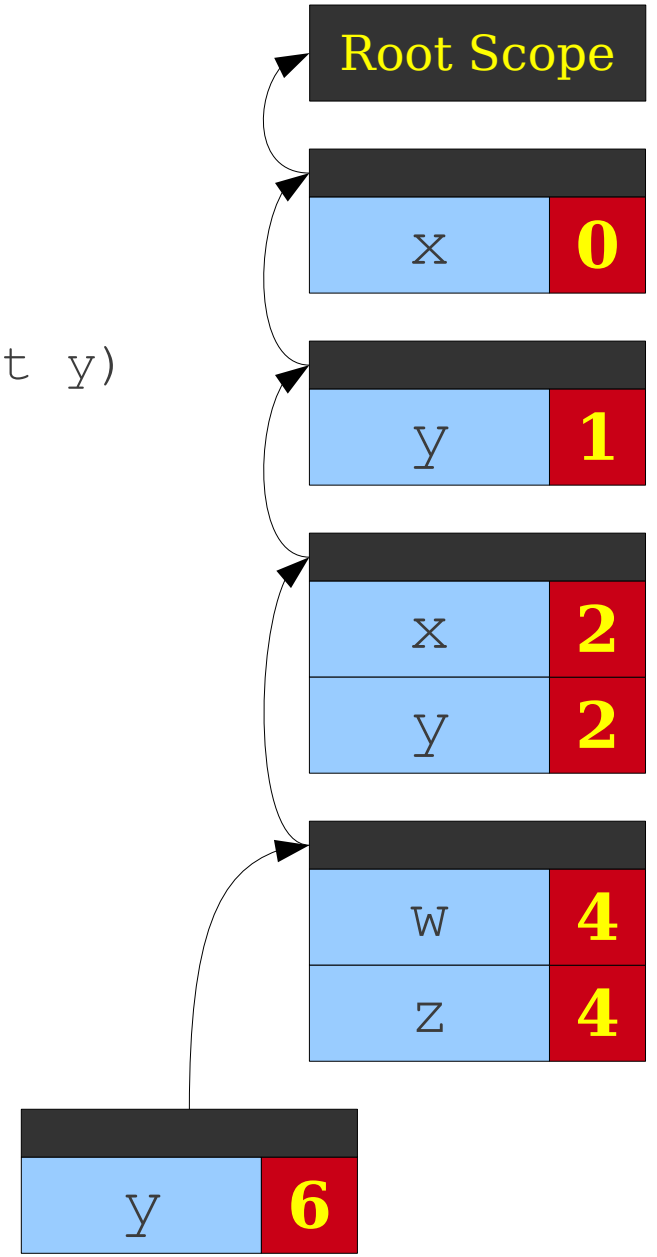

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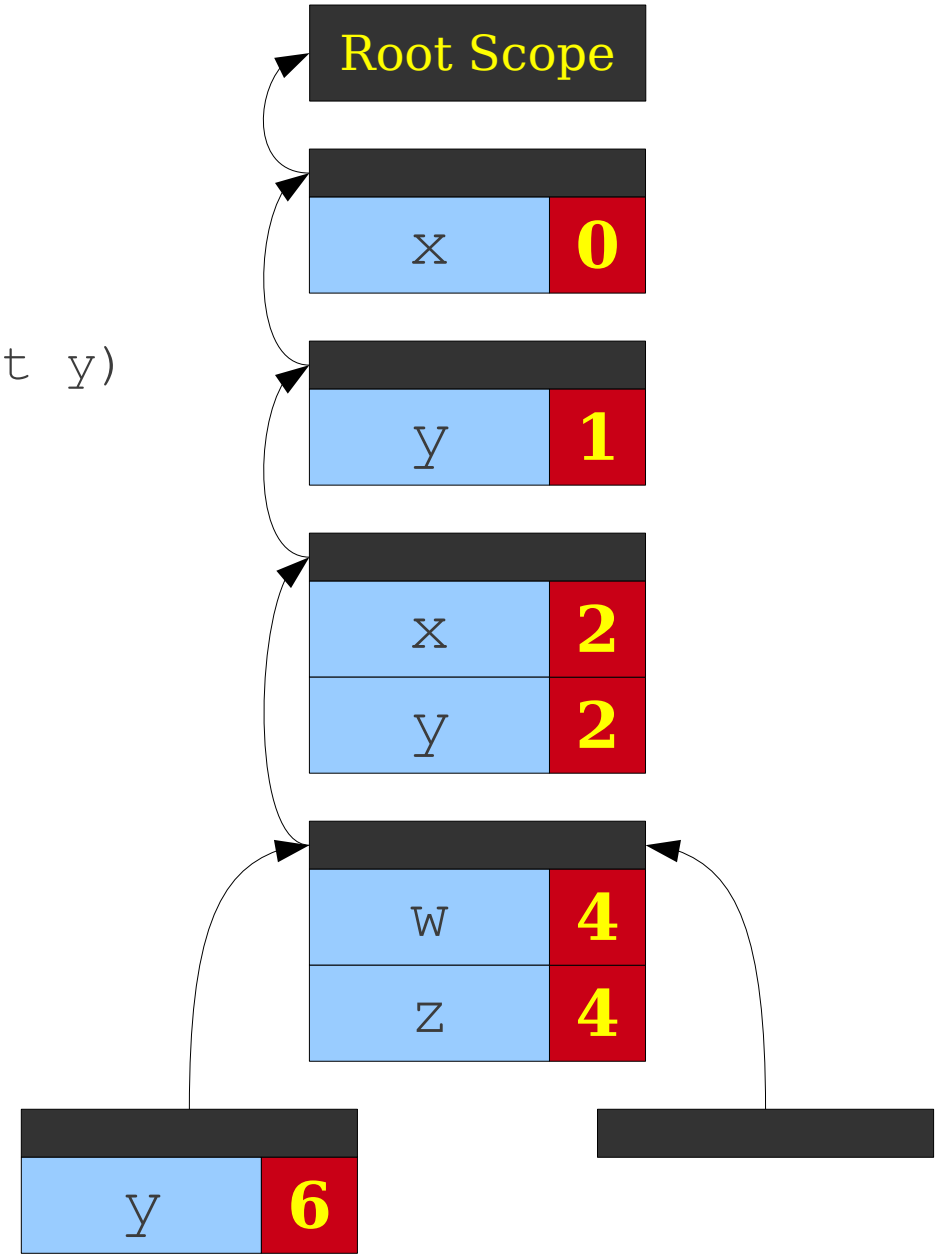

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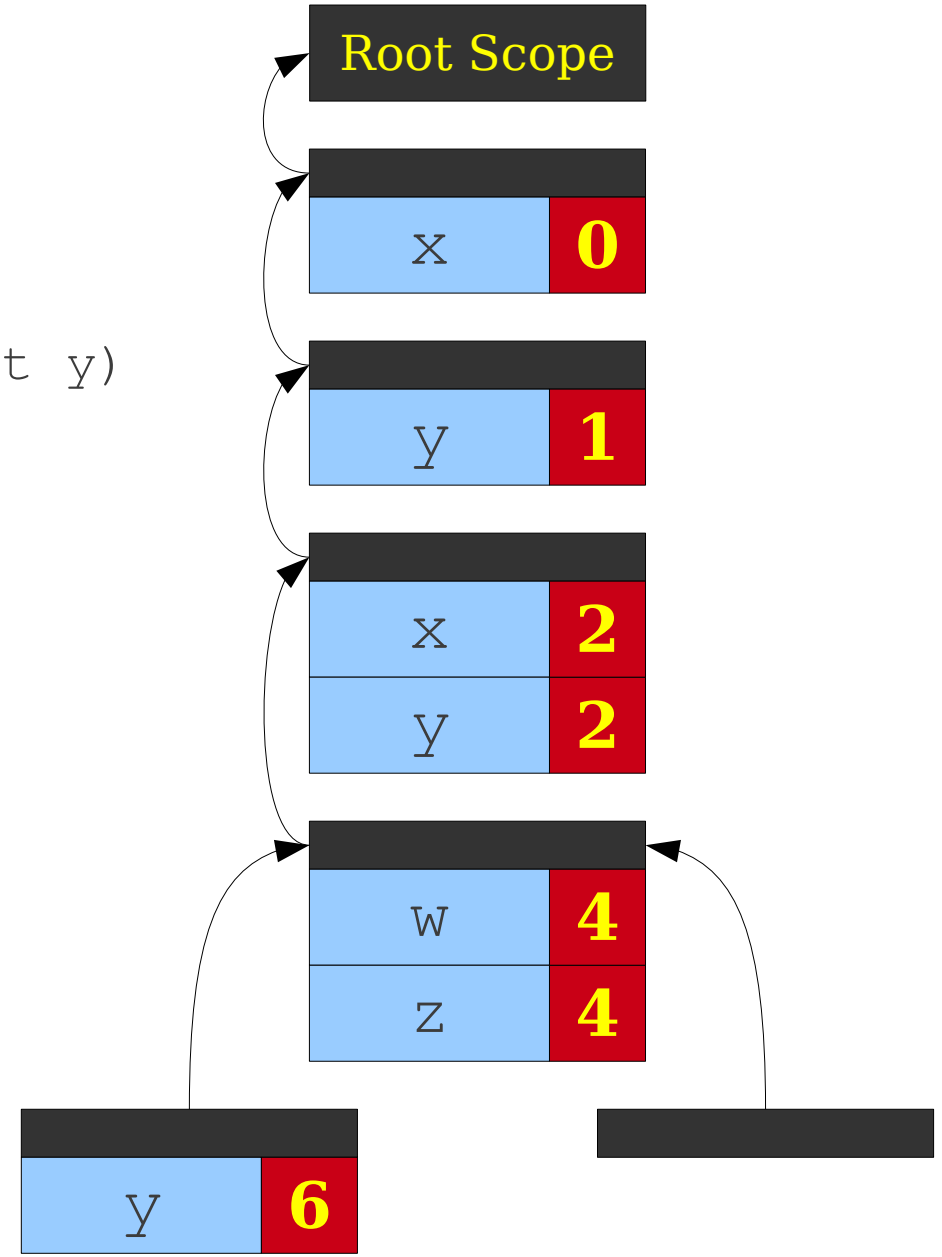

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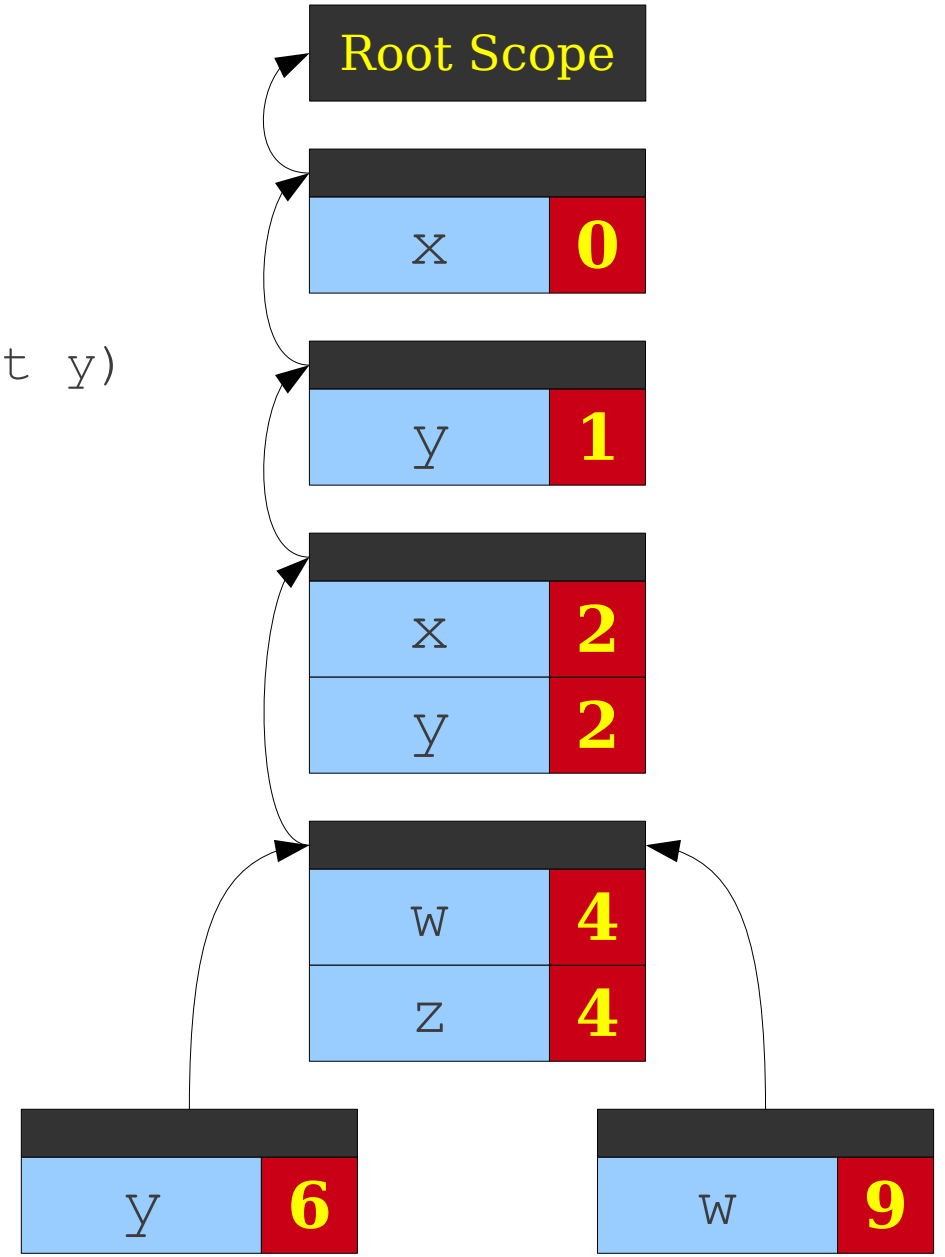

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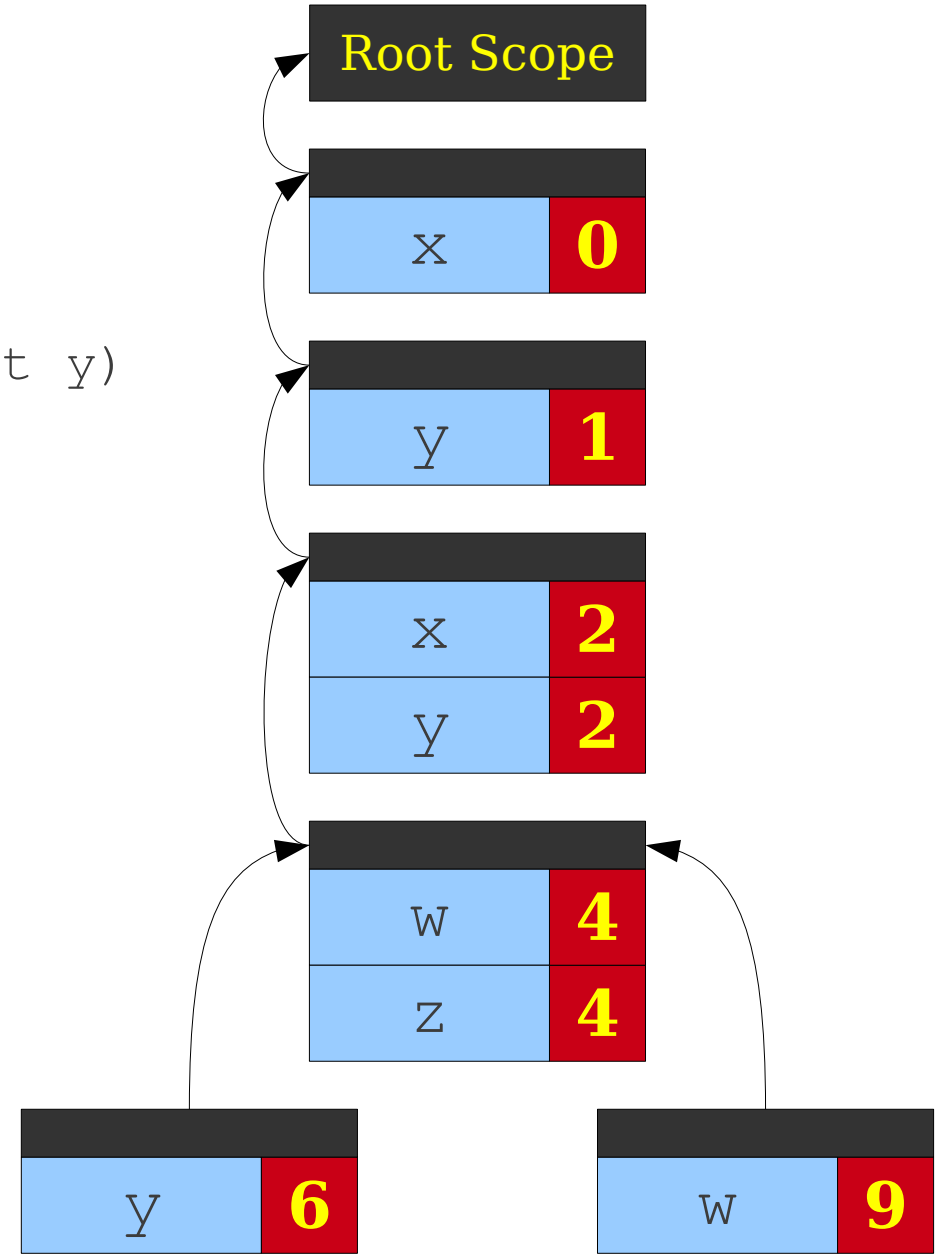

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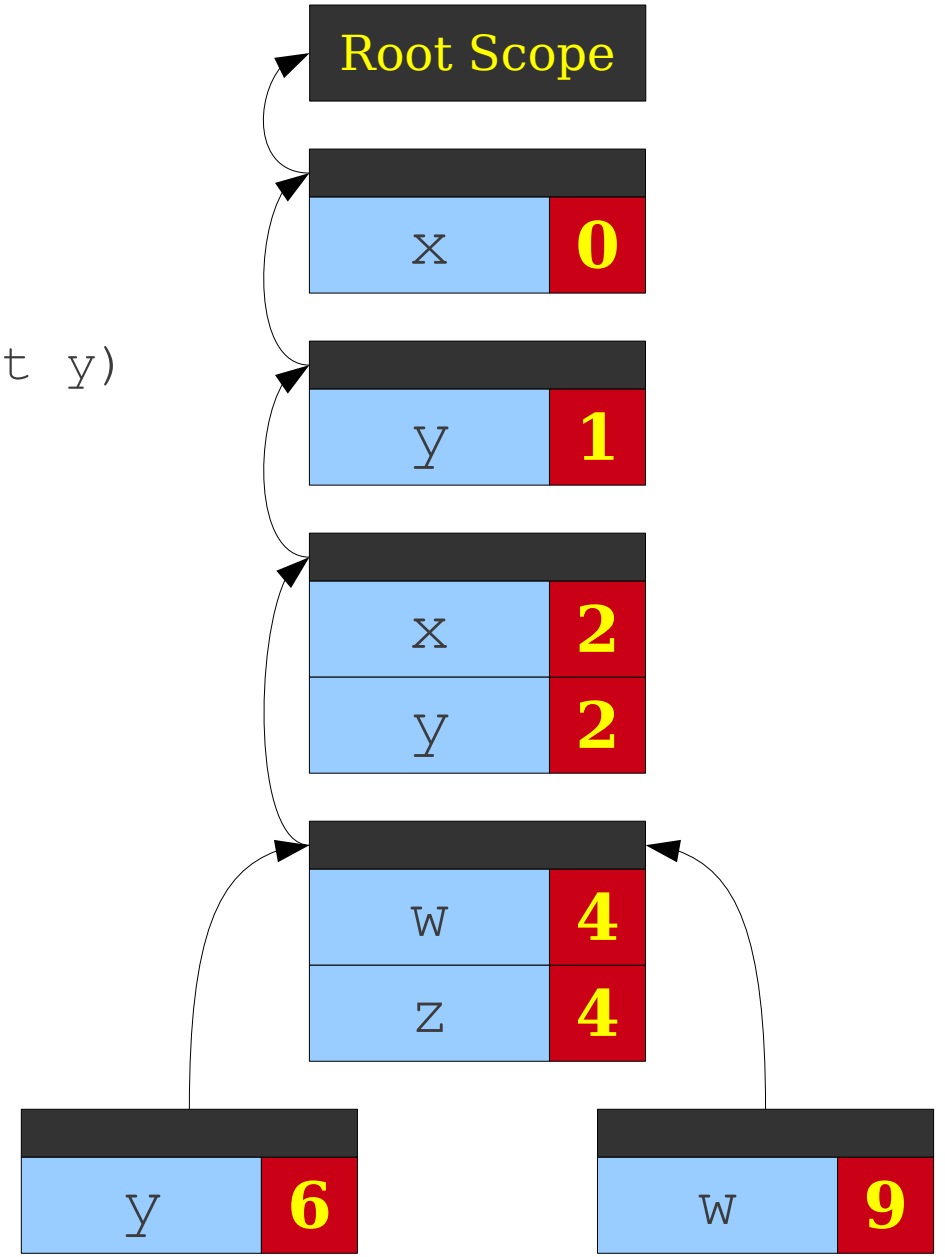

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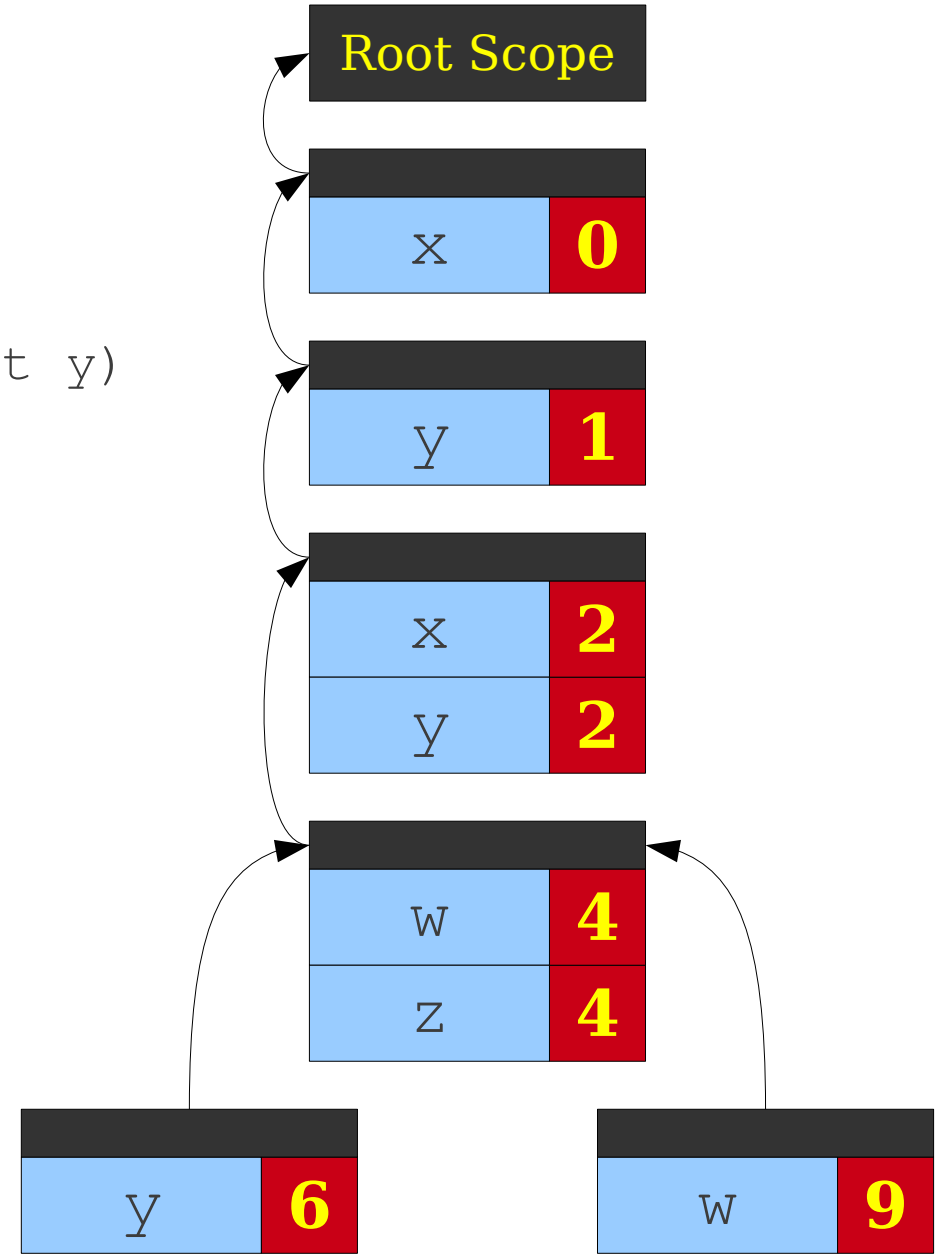

Spaghetti Stacks

- Treat the symbol table as a linked structure of scopes.
- Each scope stores a pointer to its parents, 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 a *dynamic* structure.
- Explicit stack is an optimization of a spaghetti stack; more on that later.

Scoping in Object-Oriented Languages

Scoping with Inheritance

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

Scoping with Inheritance

Root Scope

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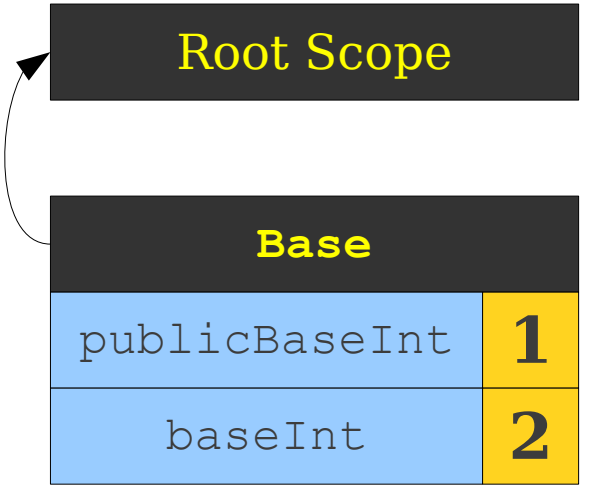

Scoping with Inheritance

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public class Base {
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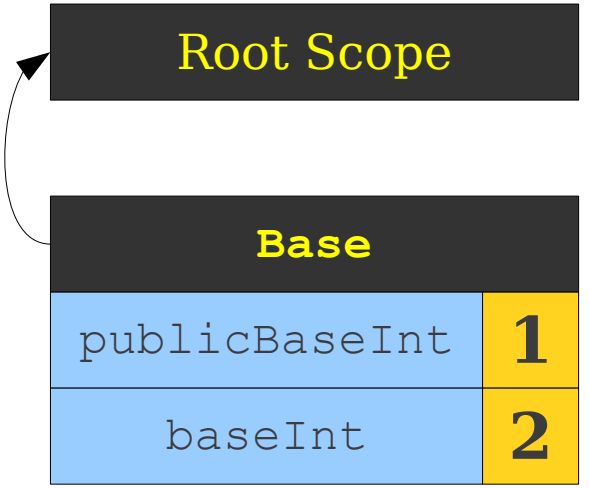
public class Derived extends Base {
    public int derivedInt = 3;
    public int publicBaseInt = 4;

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

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



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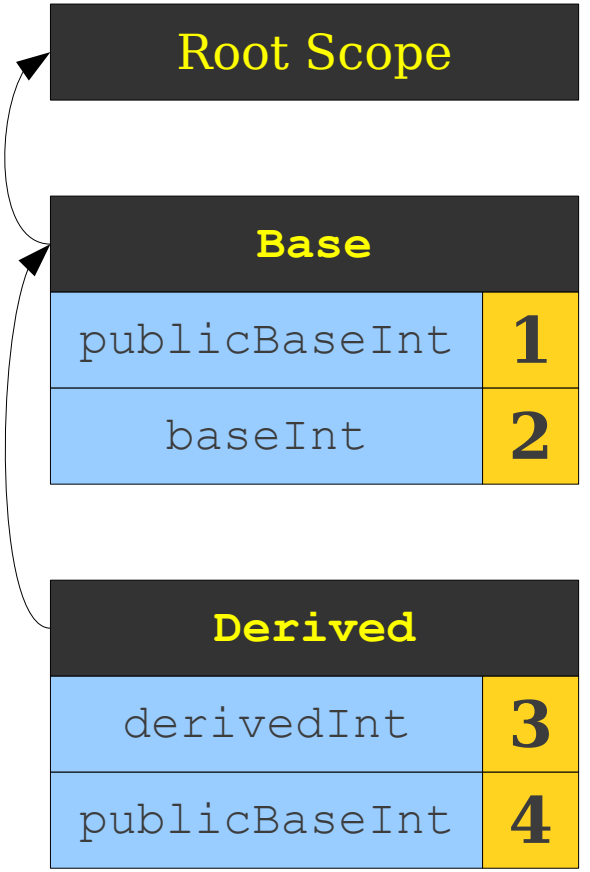

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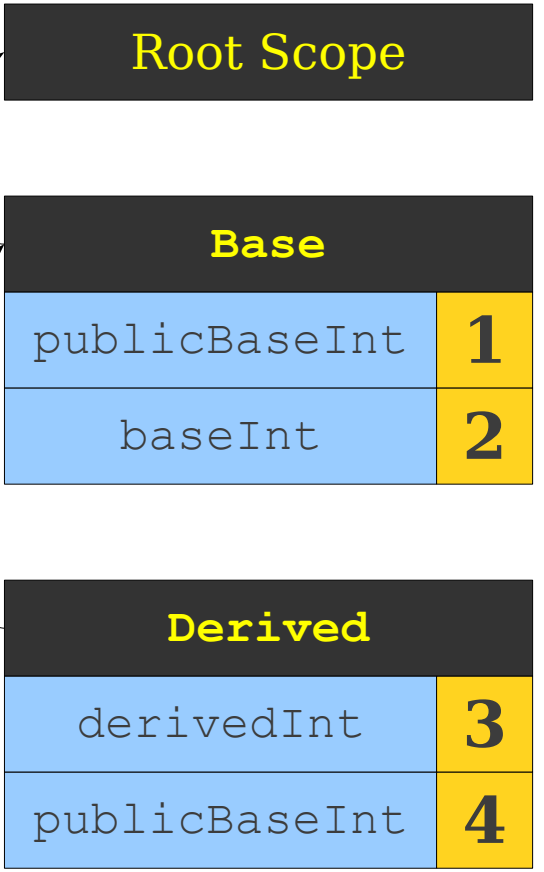

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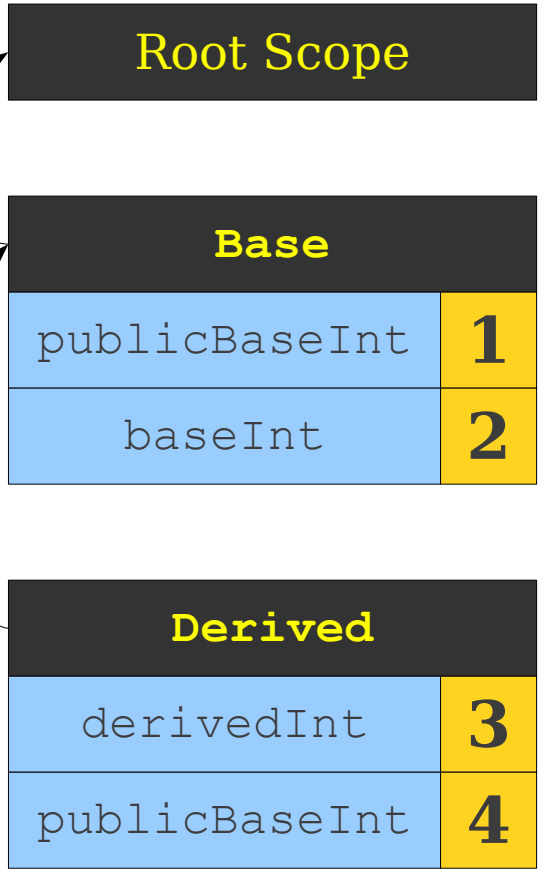

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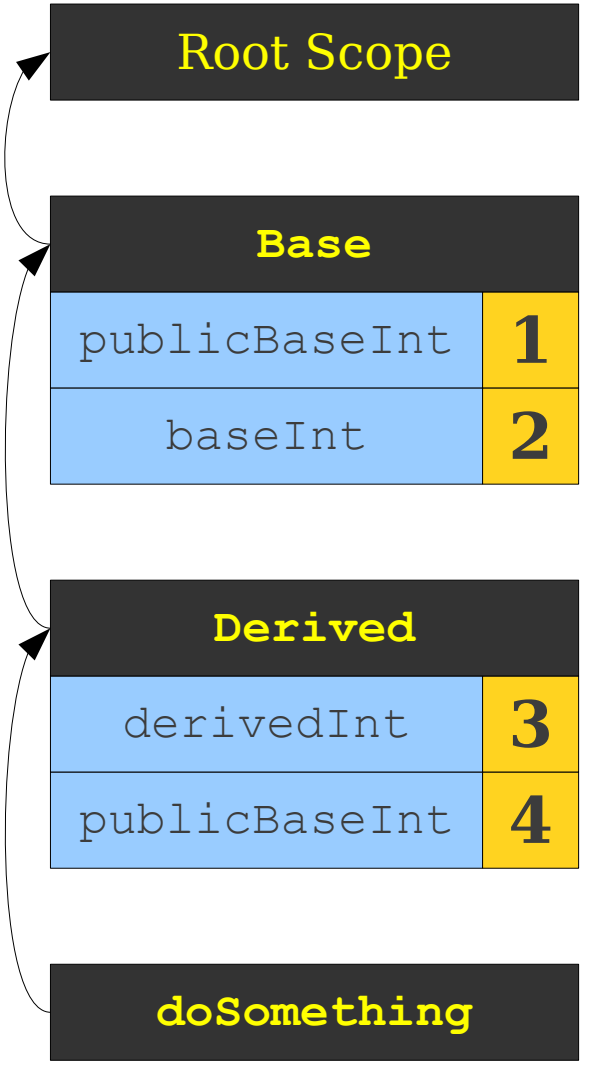
        System.out.println(publicBaseInt);
        System.out.println(baseInt);
        System.out.println(derivedInt);

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

```
>
```



Scoping with Inheritance

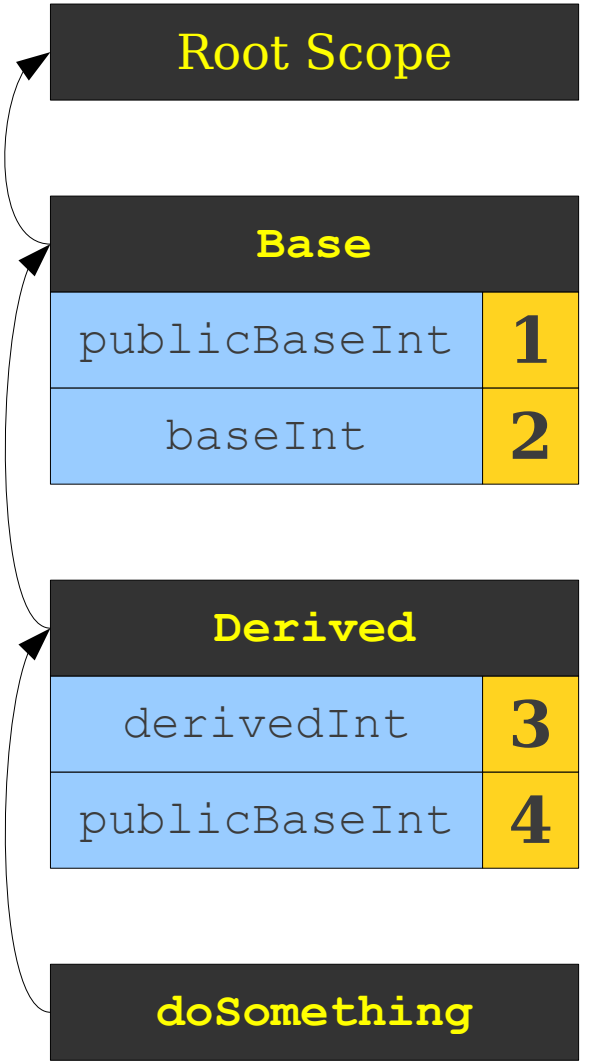
```
public class Base {
    public int publicBaseInt = 1;
    protected int baseInt = 2;
}

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);
    }
}
```

```
>
```



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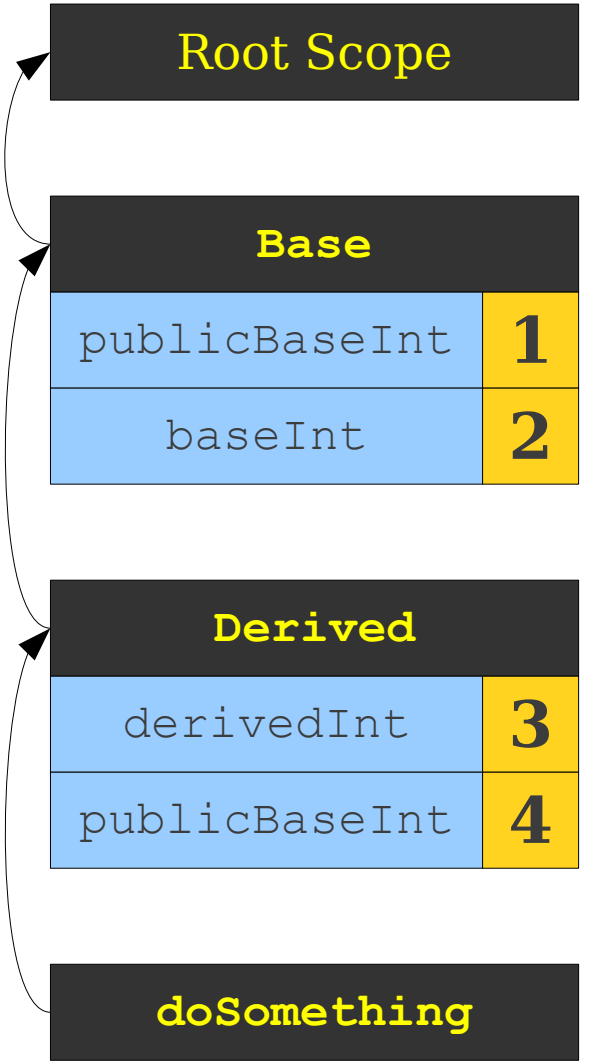
        int publicBaseInt = 6;
        System.out.println(publicBaseInt);
    }
}
```

```
> 4
```



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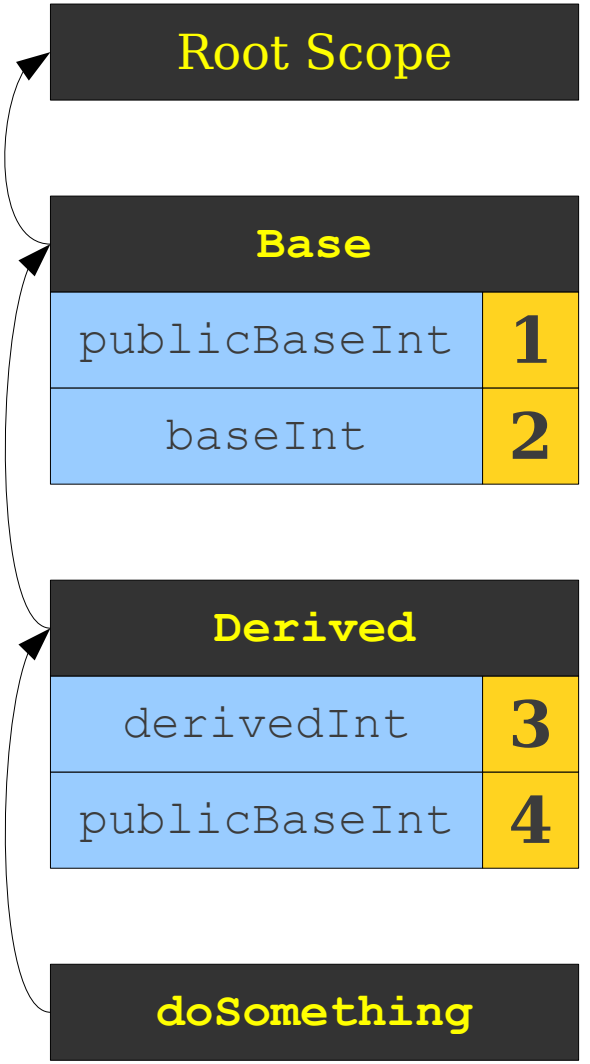
```
> 4
```



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        System.out.println(publicBaseInt);
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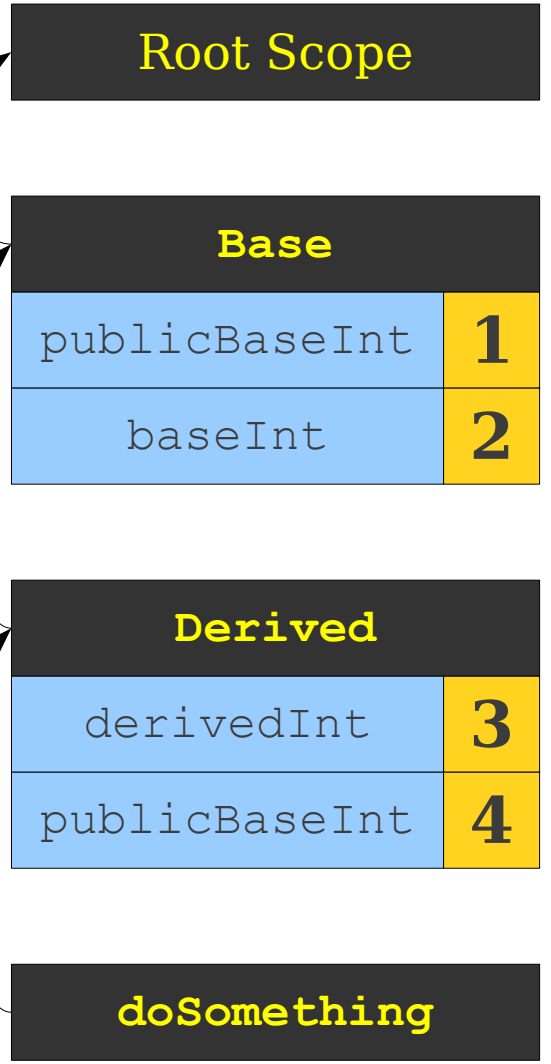
```

```
> 4
  2
```



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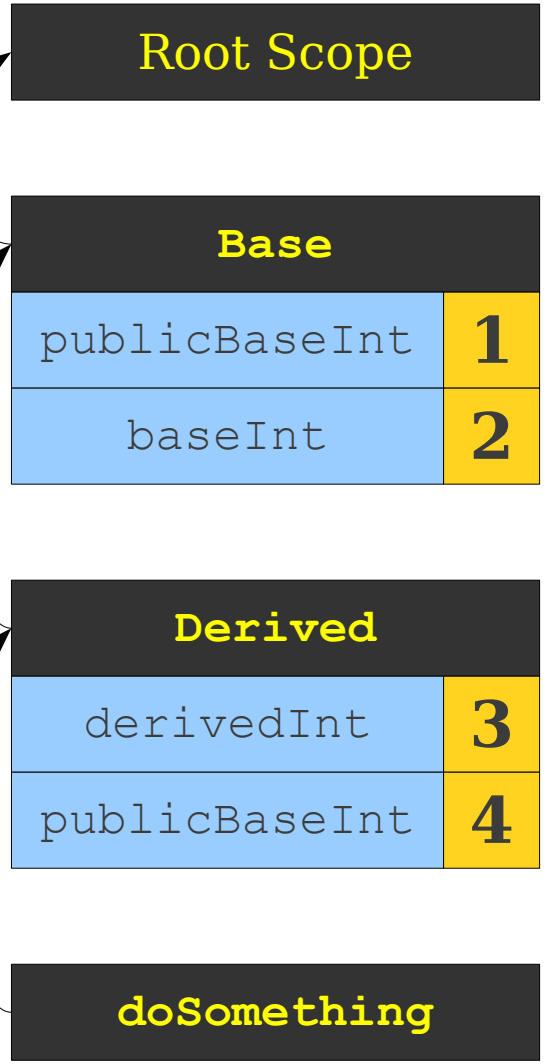
```
> 4
  2
```



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    }
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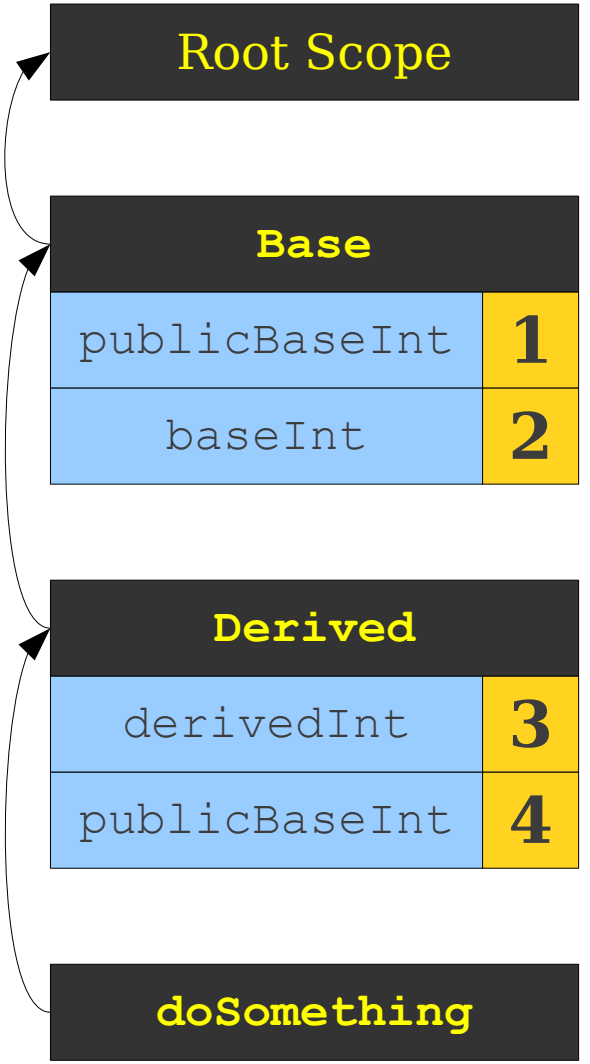
```
> 4
  2
  3
```



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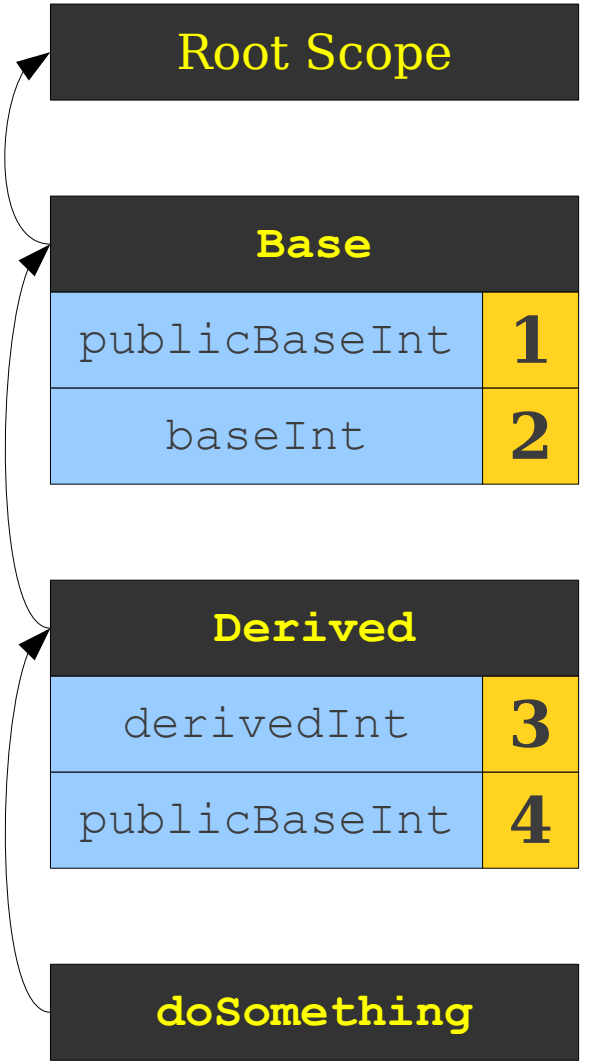
```
> 4
  2
  3
```



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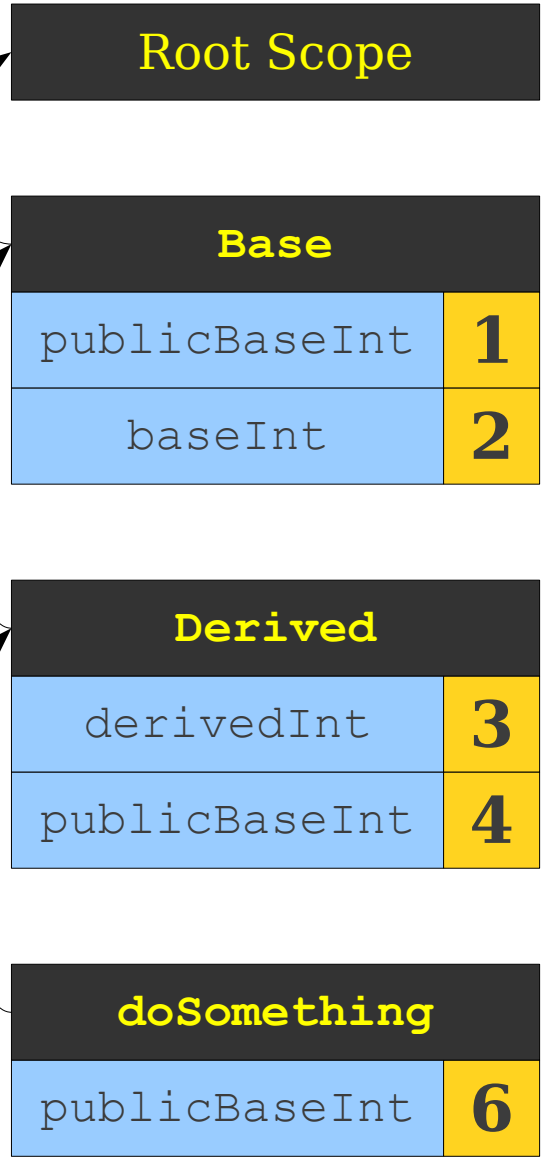
    }
}
```

```
> 4
  2
  3
```



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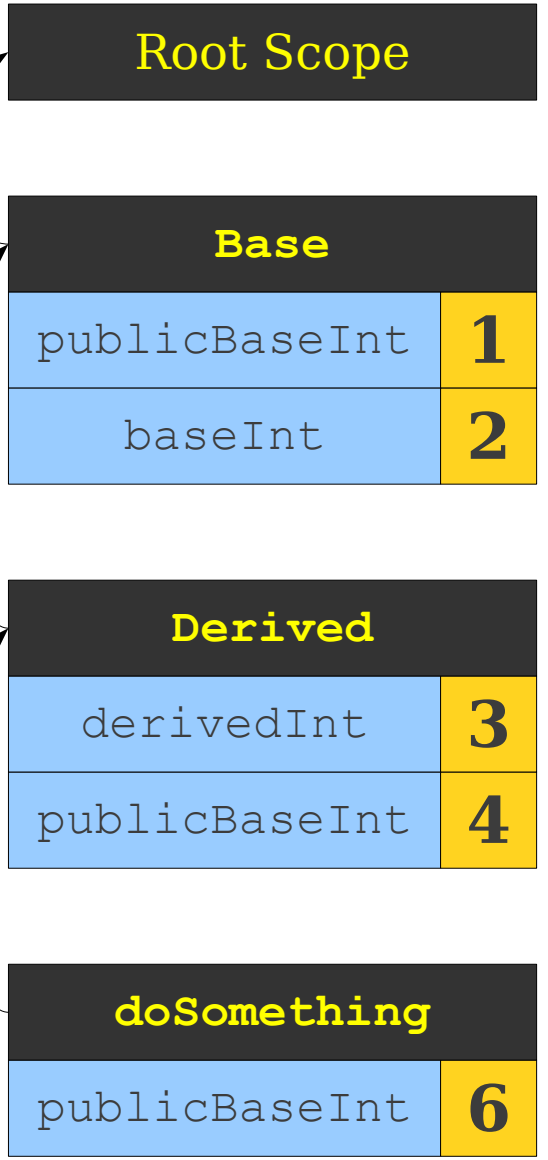
    }
}
```

```
> 4
  2
  3
```



Scoping with Inheritance

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public class Base {
    public int publicBaseInt = 1;
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}

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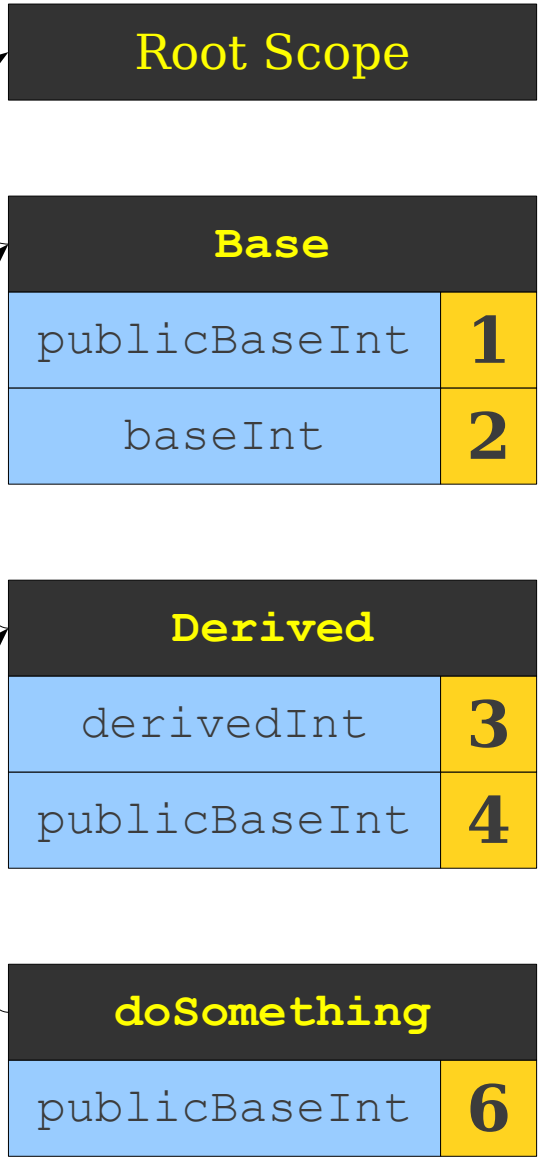
        int publicBaseInt = 6;
        System.out.println(publicBaseInt);
    }
}
```

```
> 4
  2
  3
  6
```



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    }
}
```

```
> 4
  2
  3
  6
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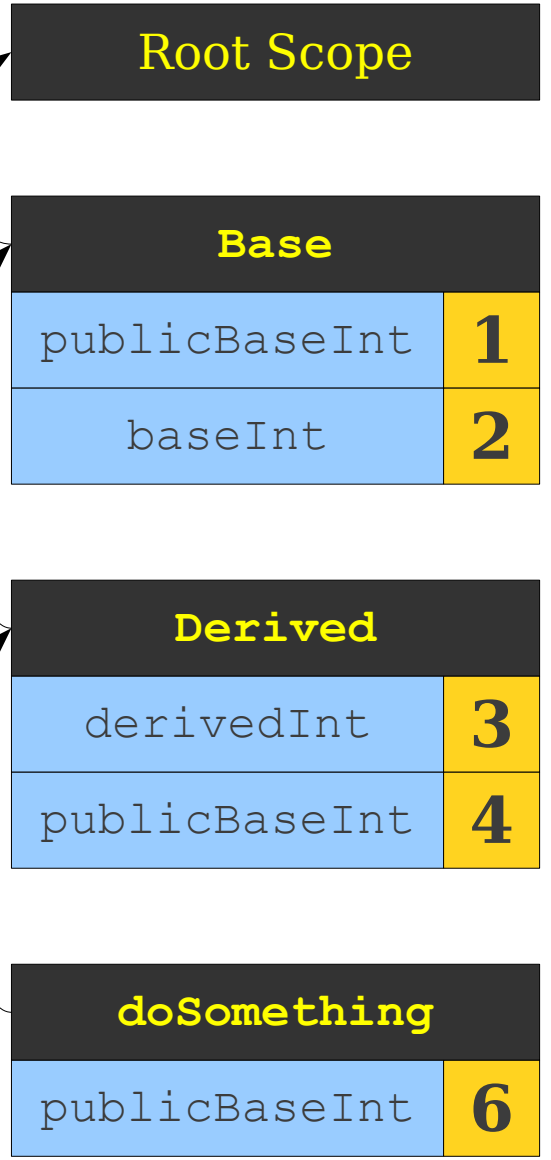


Scoping with Inheritance

```
public class Base {
    public int publicBaseInt = 1;
    protect
}

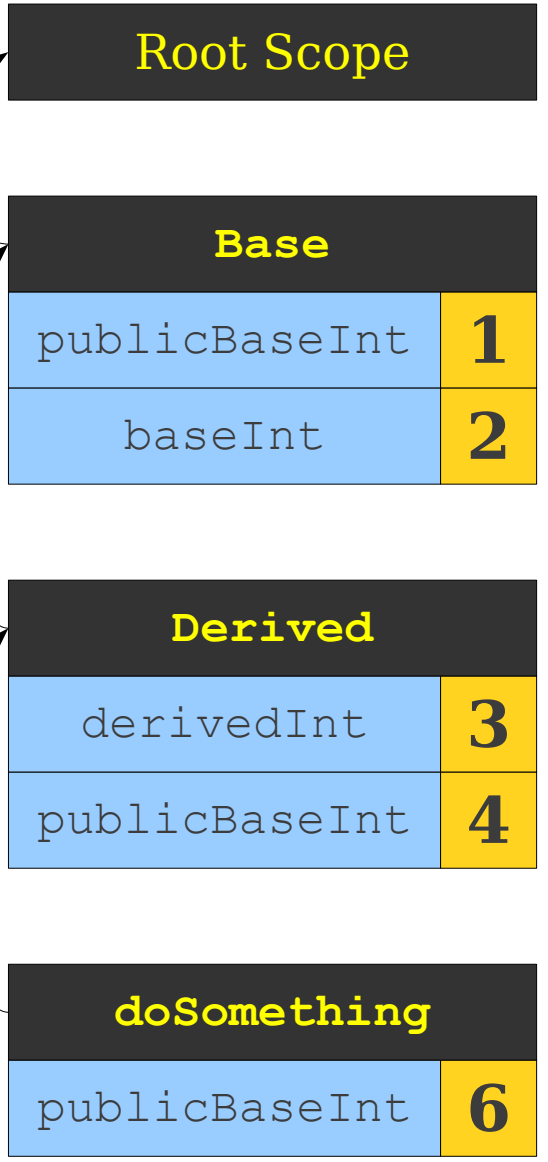
public clas
    public
    public

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

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

Typically the scope would also contain the names "**Base**" and "**Derived**," along with the function name "**doSomething.**" For simplicity, I've left these out.

```
> 4
  2
  3
  6
```



Inheritance and Scoping

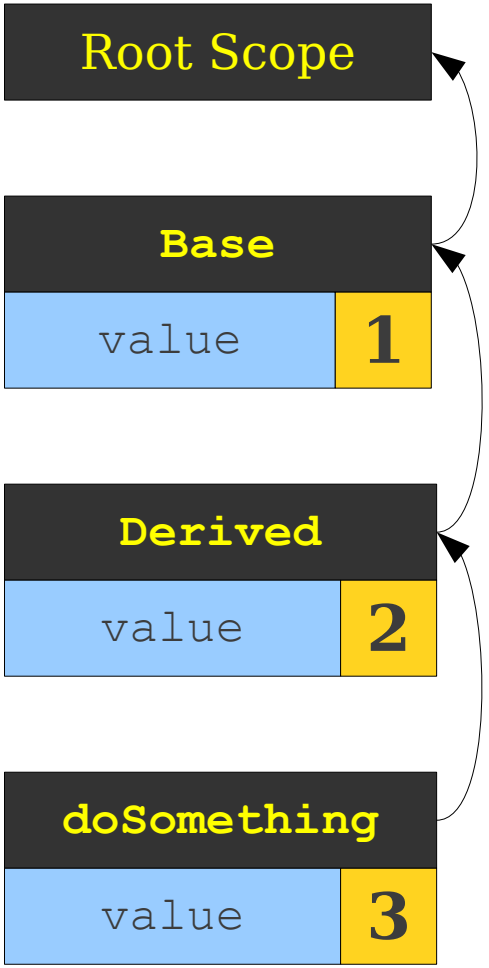
- Typically, the scope for a derived class will store a link to the scope of its base class.
- Looking up a field of a class traverses the scope chain until that field is found or a semantic error is found.

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

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

public class Derived extends Base {
    public int value = 2;

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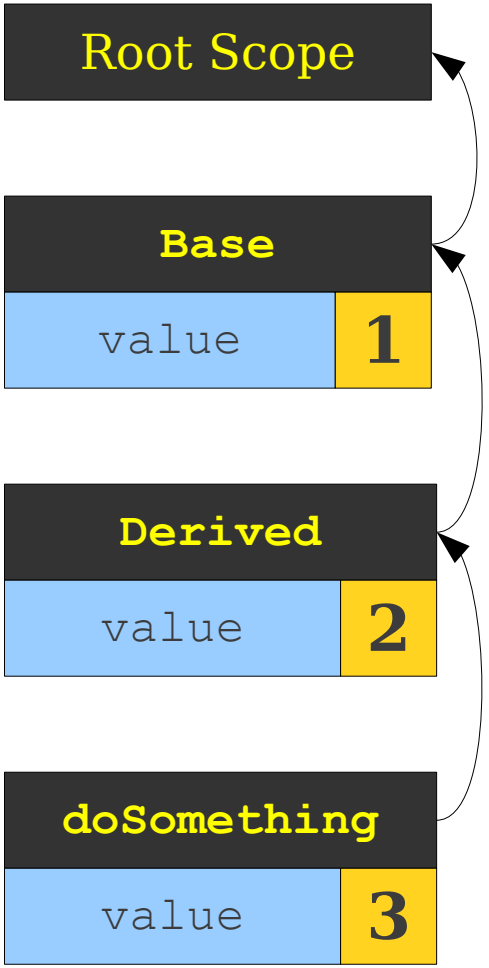
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);
    }
}
```



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public class Base {
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        System.out.println(value);
        System.out.println(this.value);
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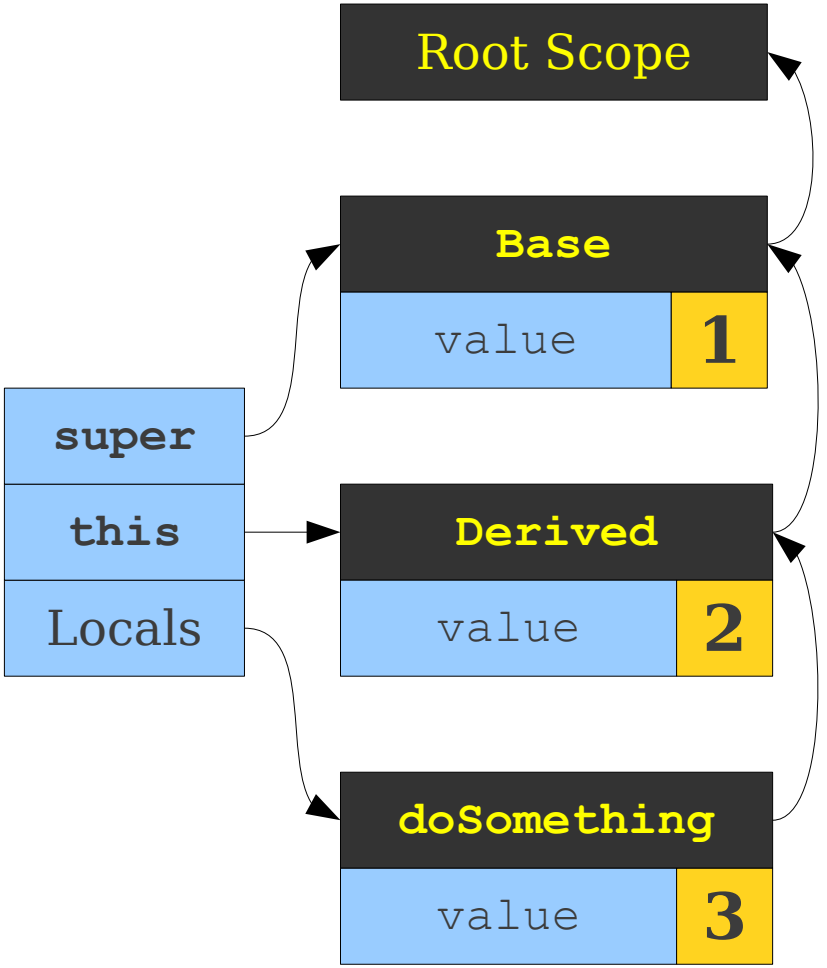
```



Explicit Disambiguation

```
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public class Derived extends Base {
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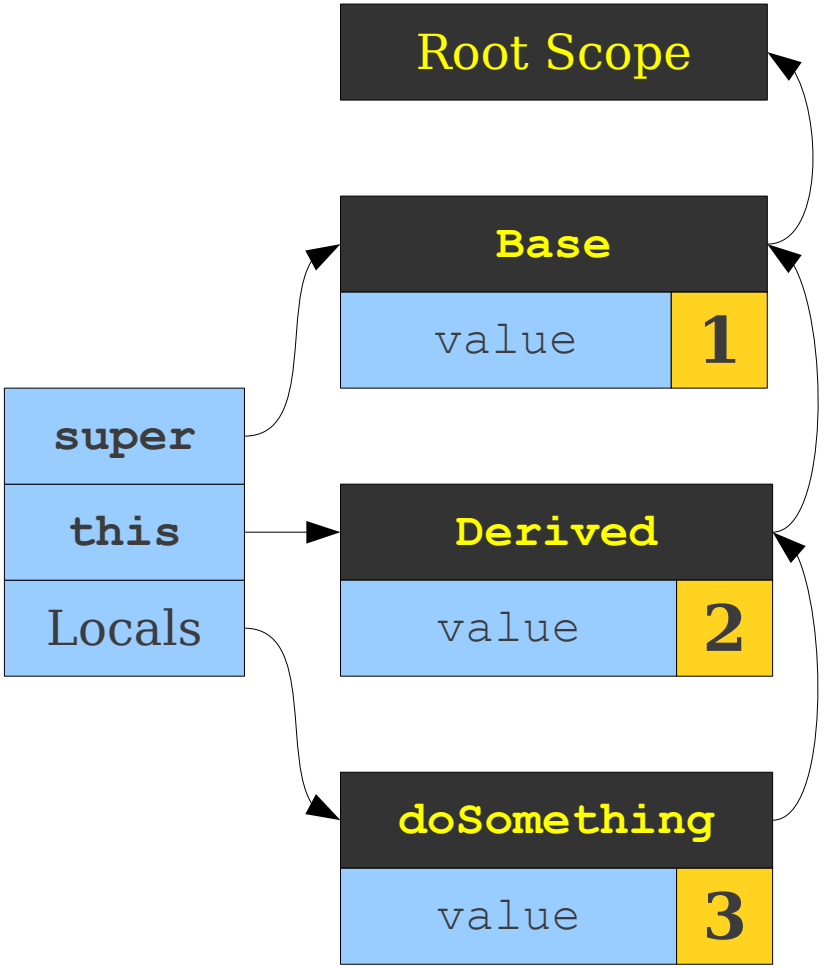

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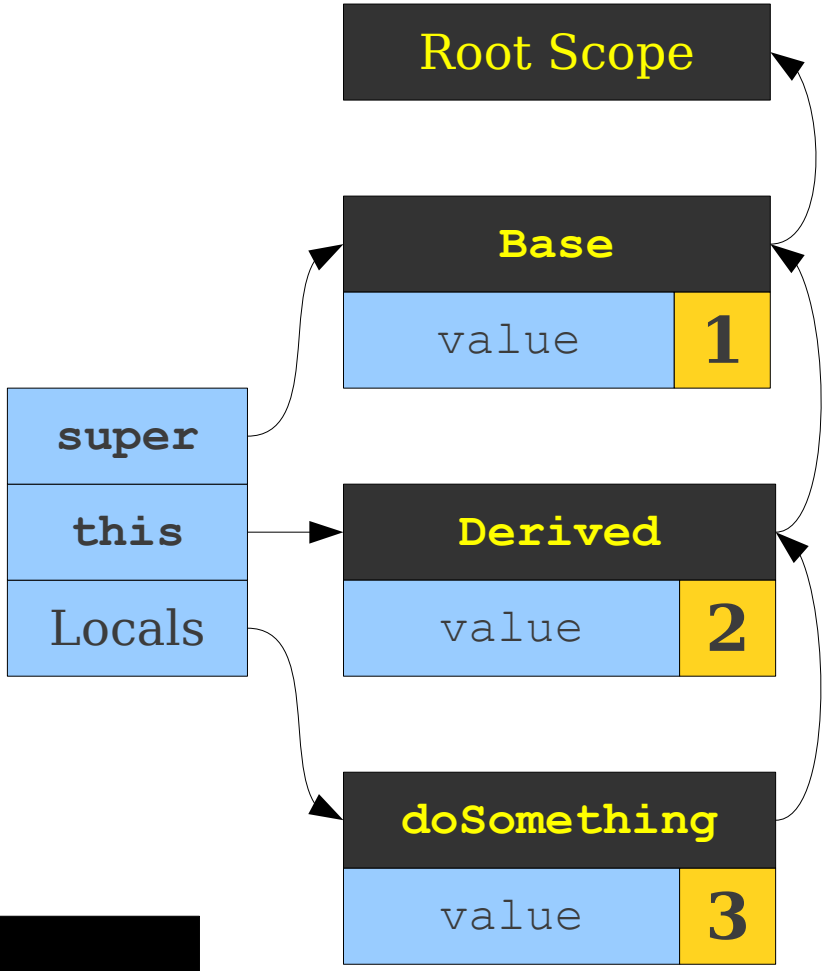

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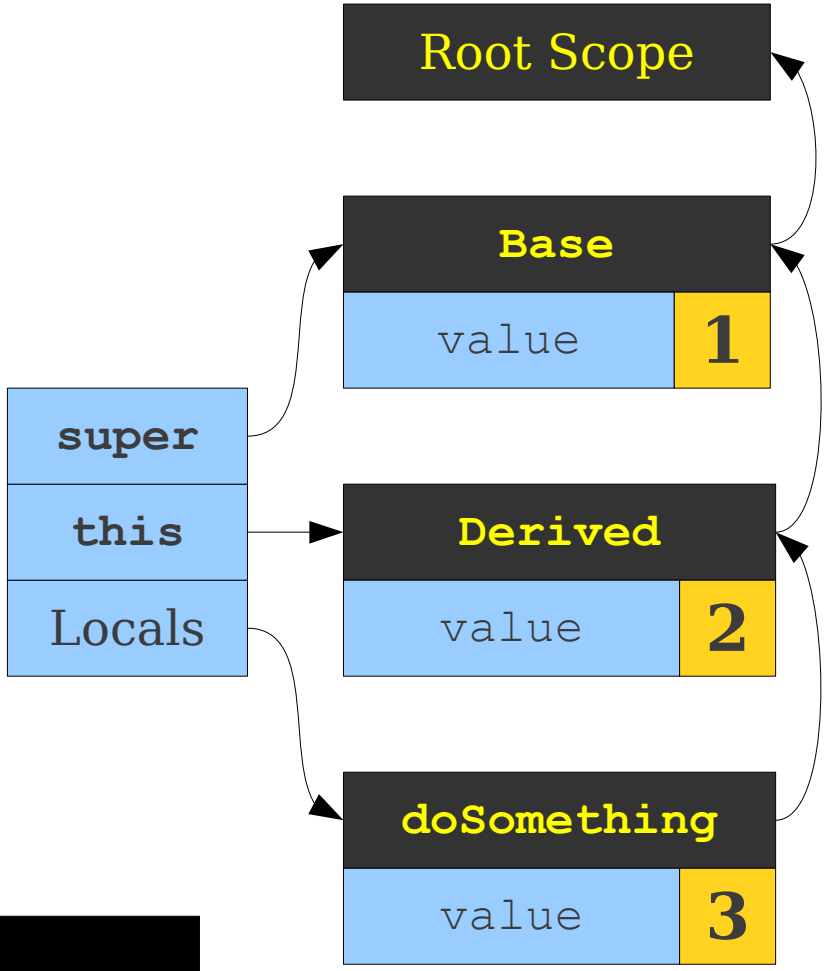
```

```
>
```



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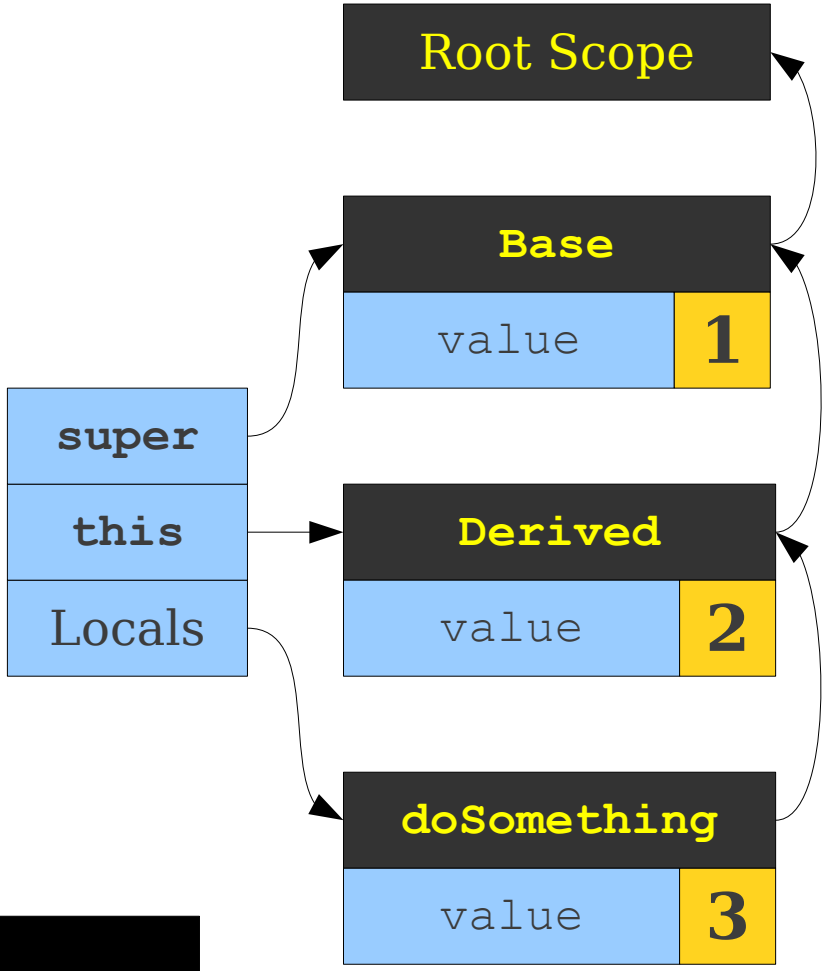
    public void doSomething() {
        int value = 3;
        System.out.println(value);
        System.out.println(this.value);
        System.out.println(super.value);
    }
}
```

```
> 3
```



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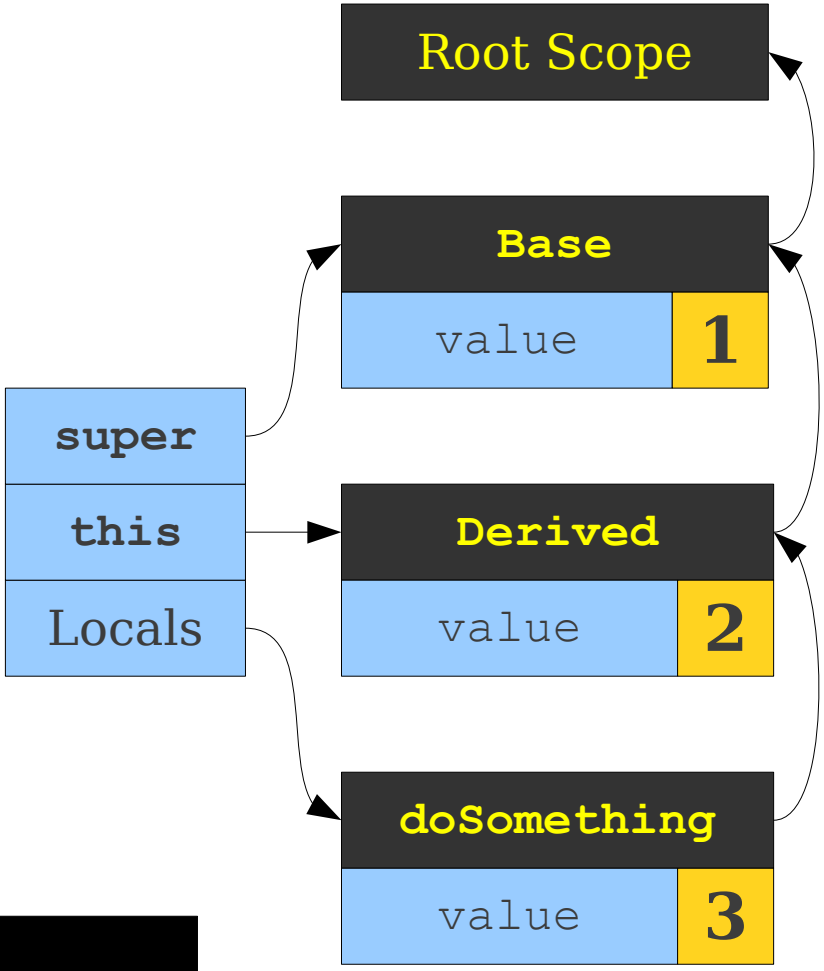
```
> 3
```



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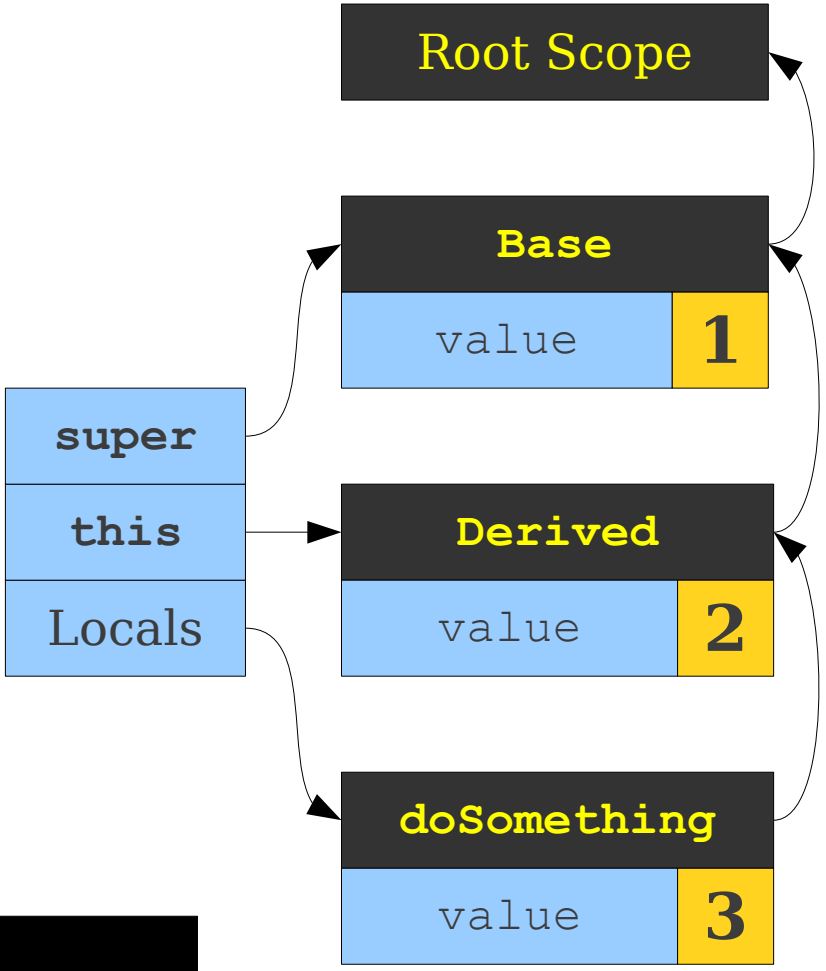
        System.out.println(this.value);
        System.out.println(super.value);
    }
}
```

```
> 3
  2
```



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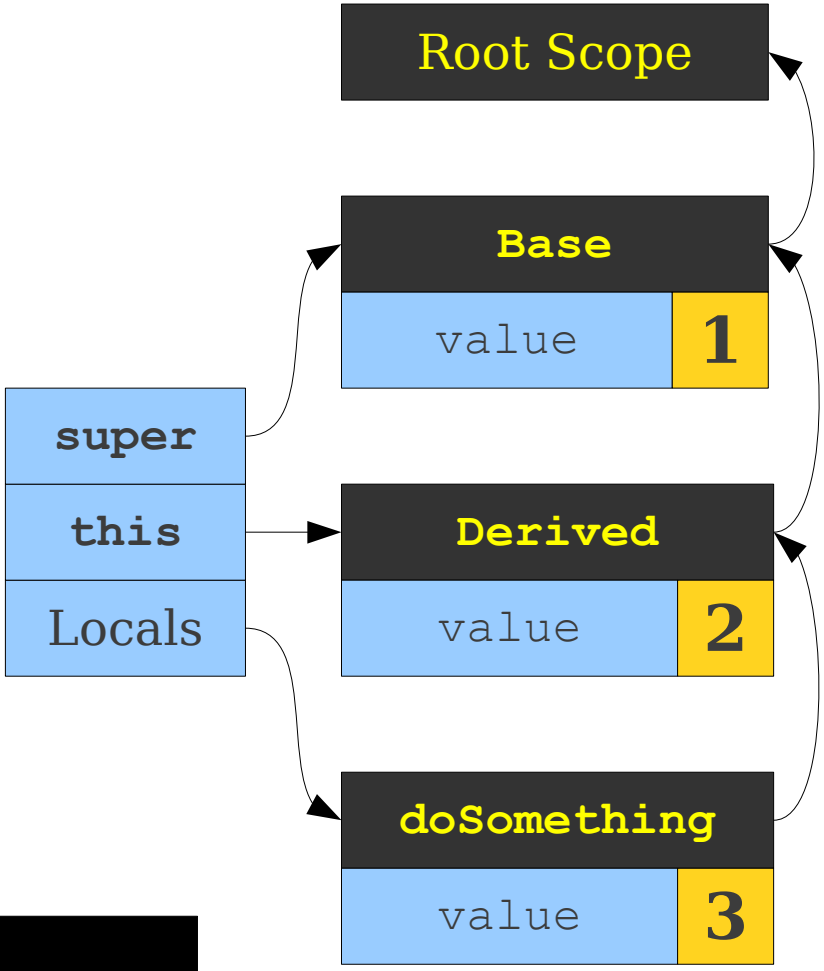
```

```
> 3
  2
```



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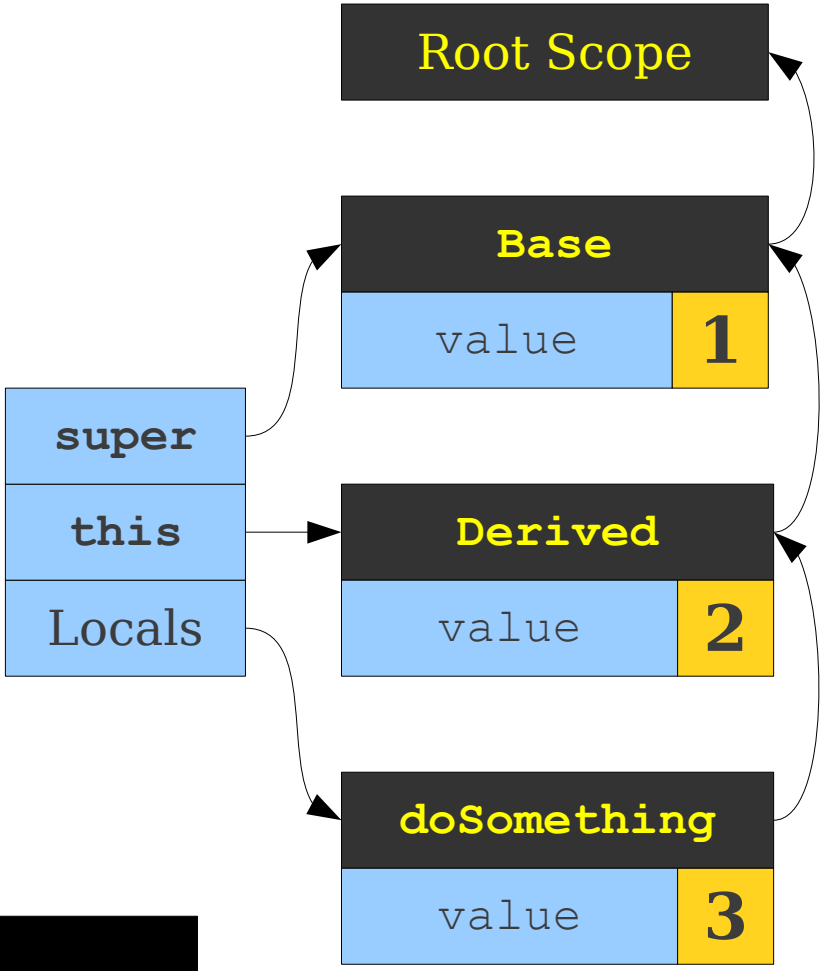
```

```
> 3
  2
  1
```



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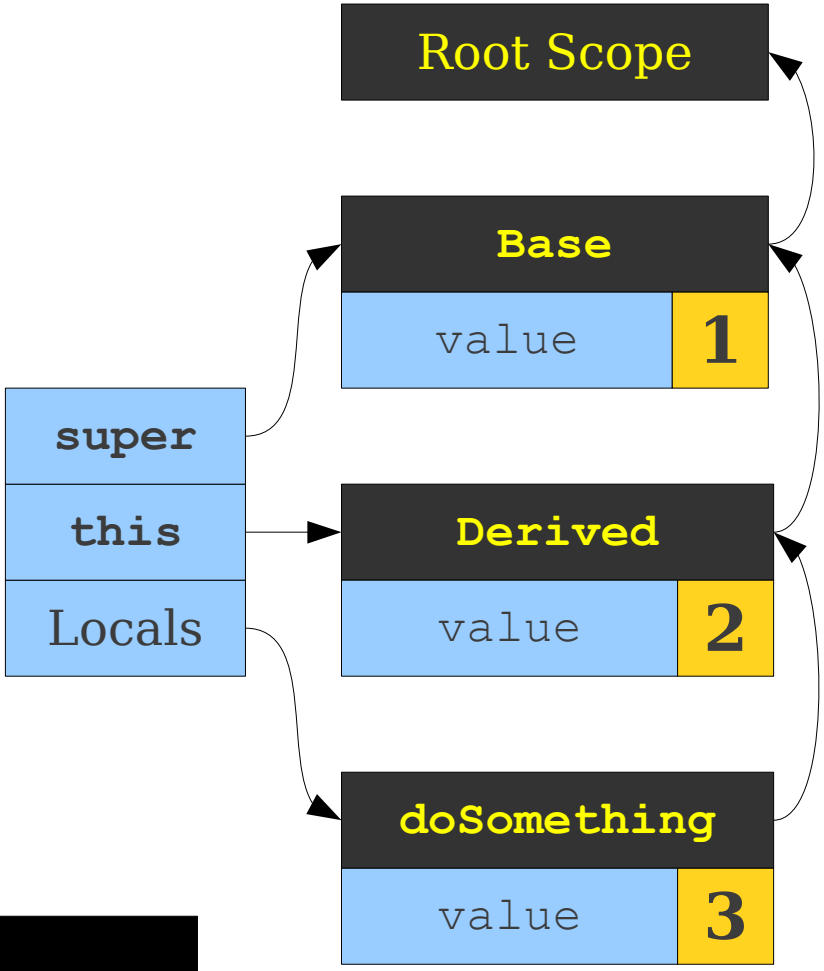
```
> 3
  2
  1
```



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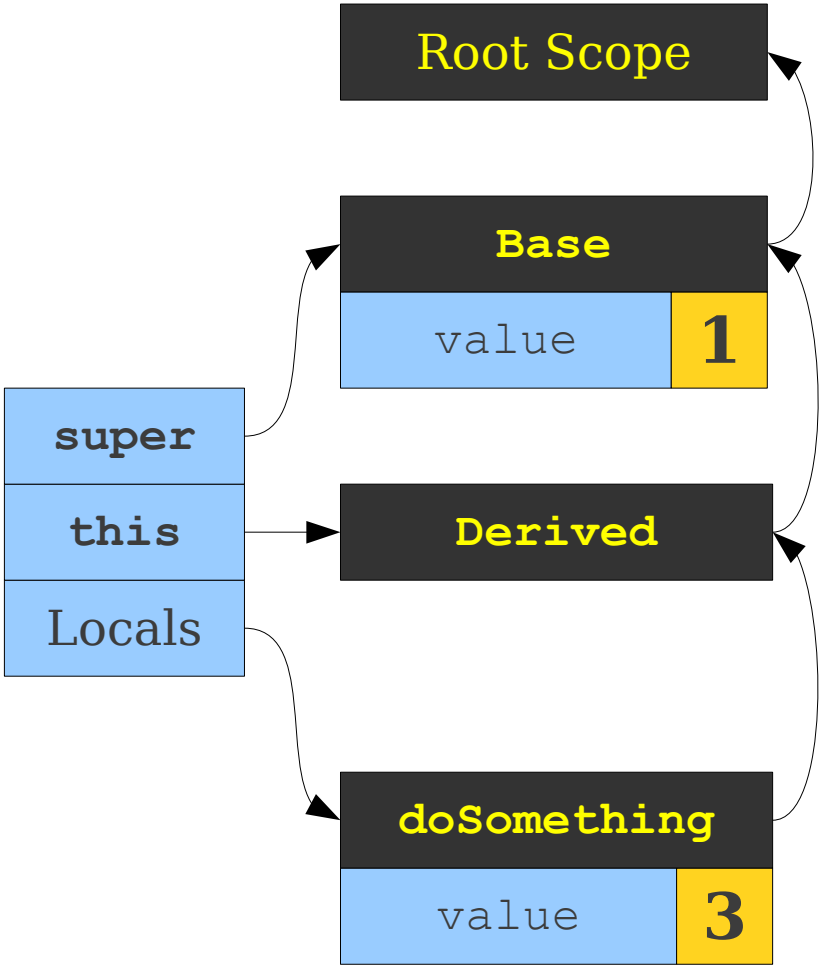

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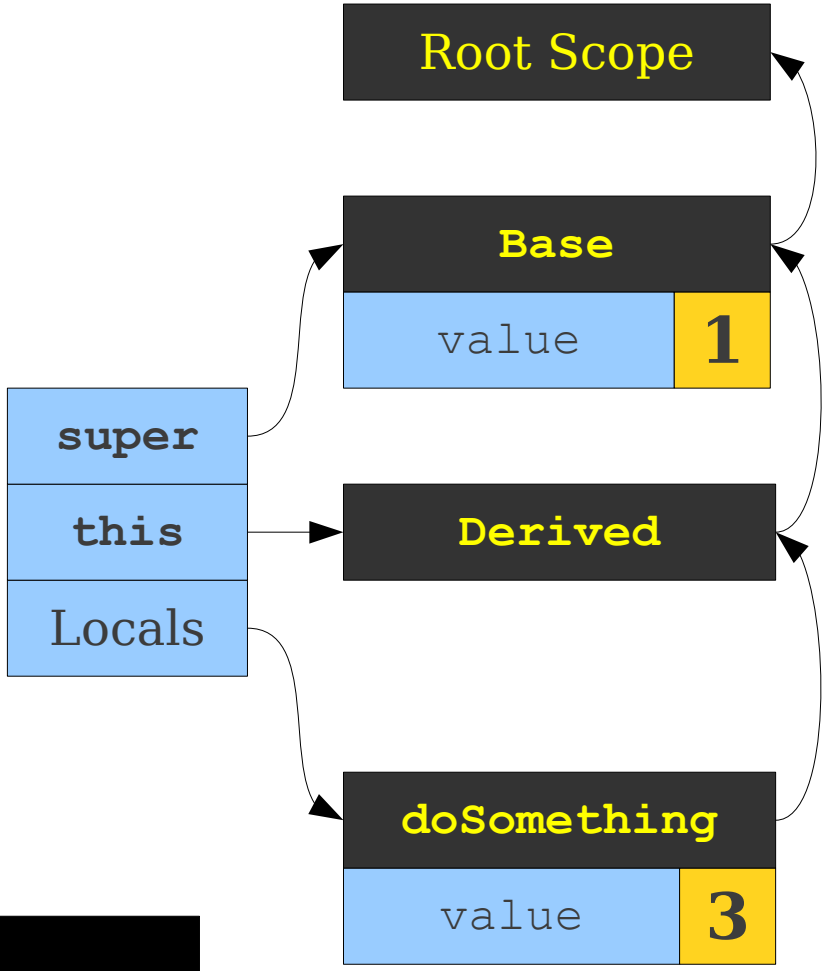

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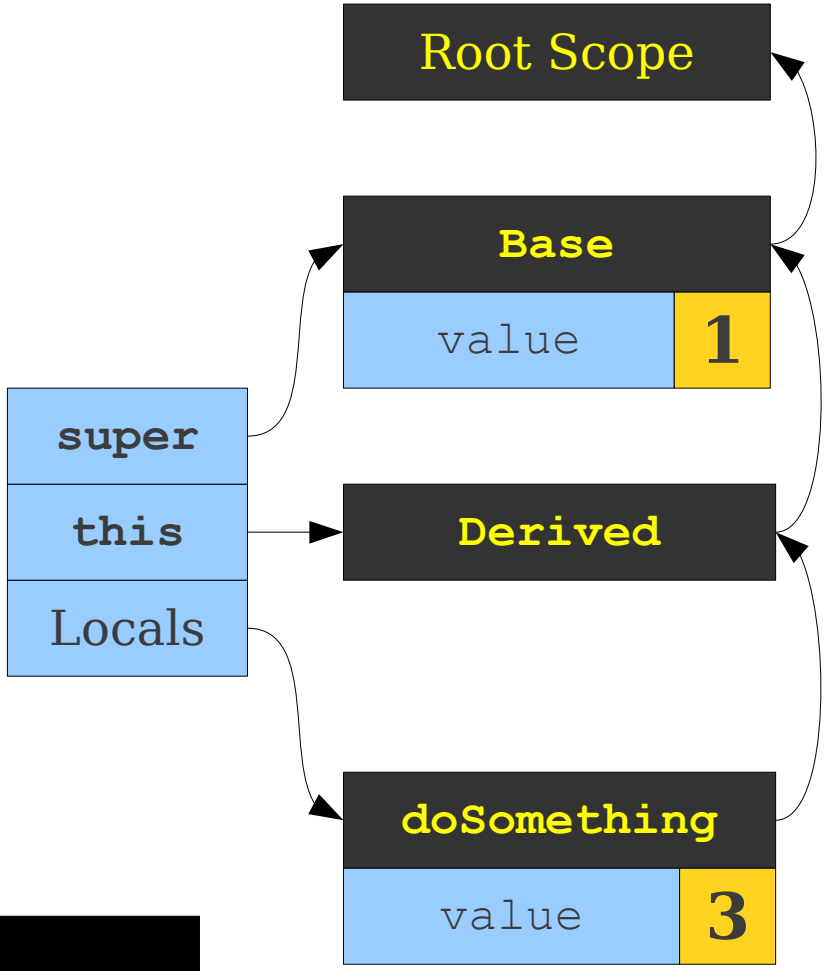
>
```



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        System.out.println(super.value);
    }
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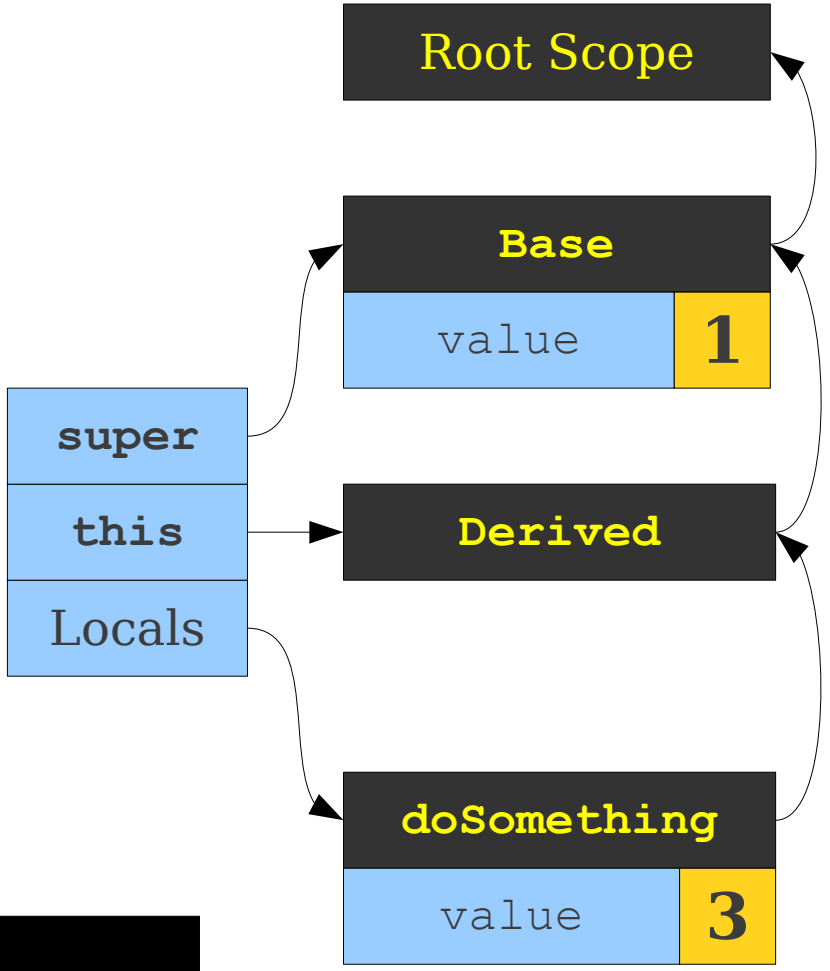
```

```
> 3
```



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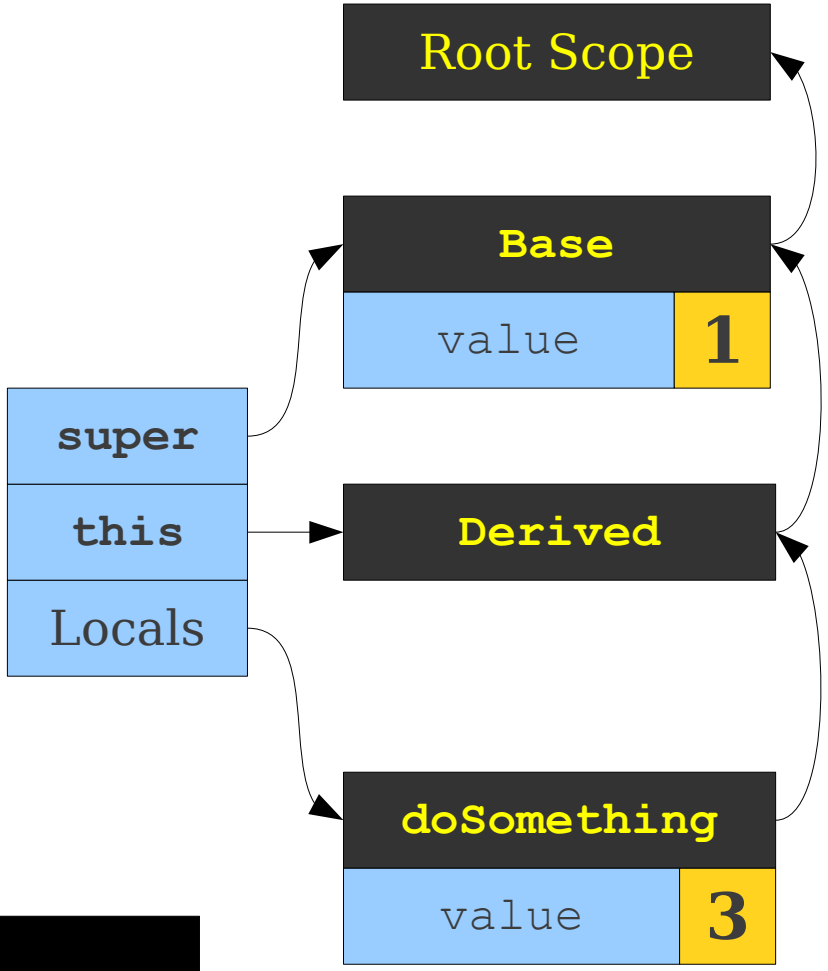
    }
}
```

```
> 3
```



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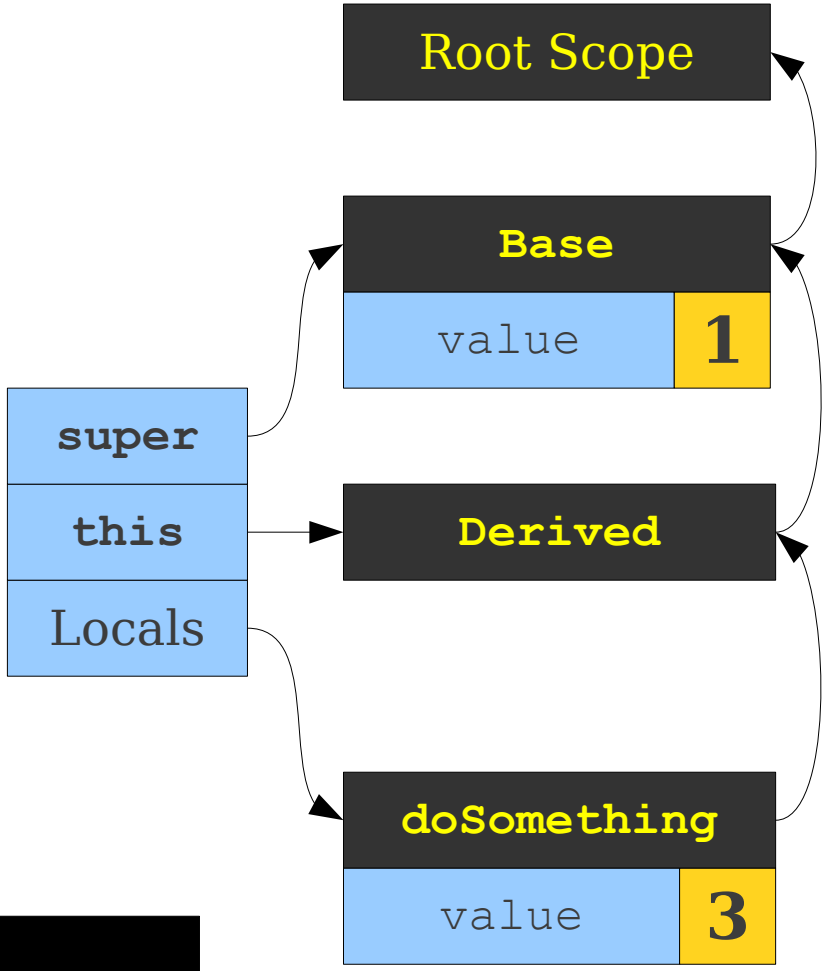
    }
}
```

```
> 3
  1
```



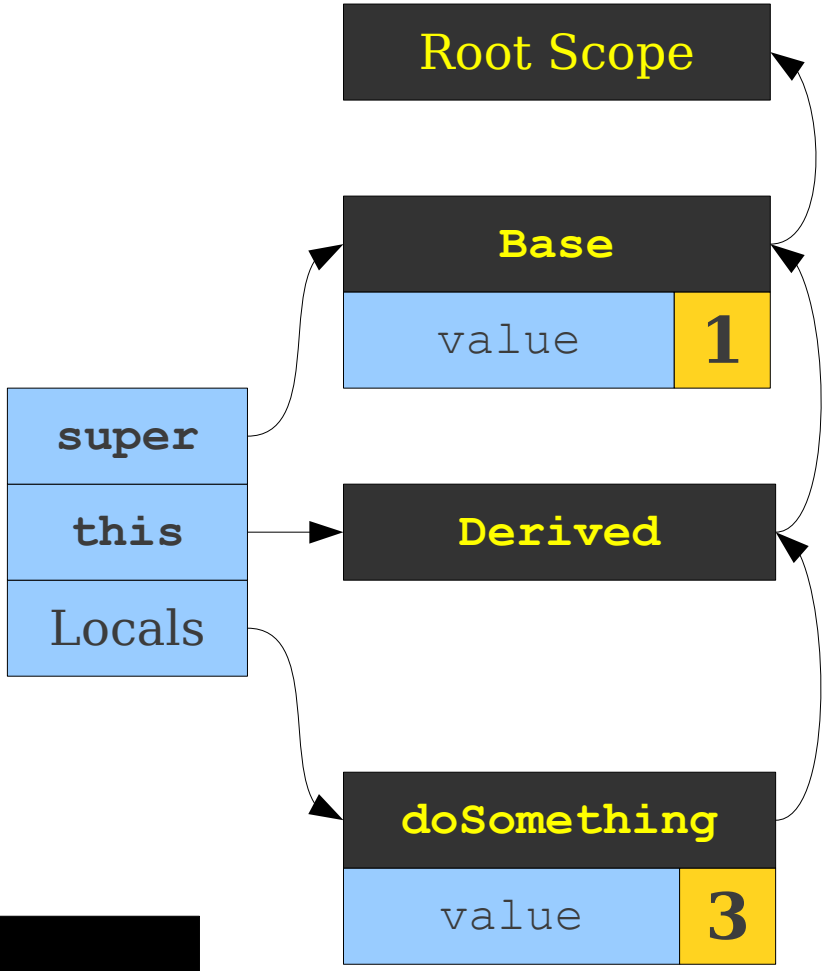
Explicit Disambiguation

```
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
```



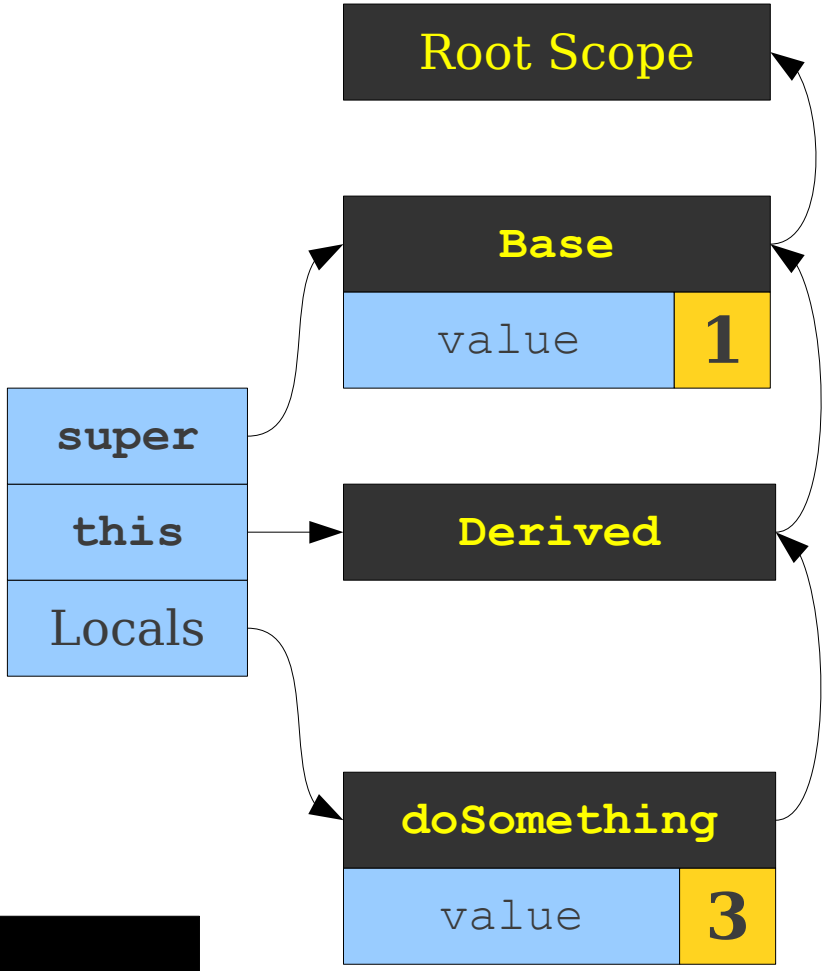
Explicit Disambiguation

```
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
```



Explicit Disambiguation

```
public class Base {
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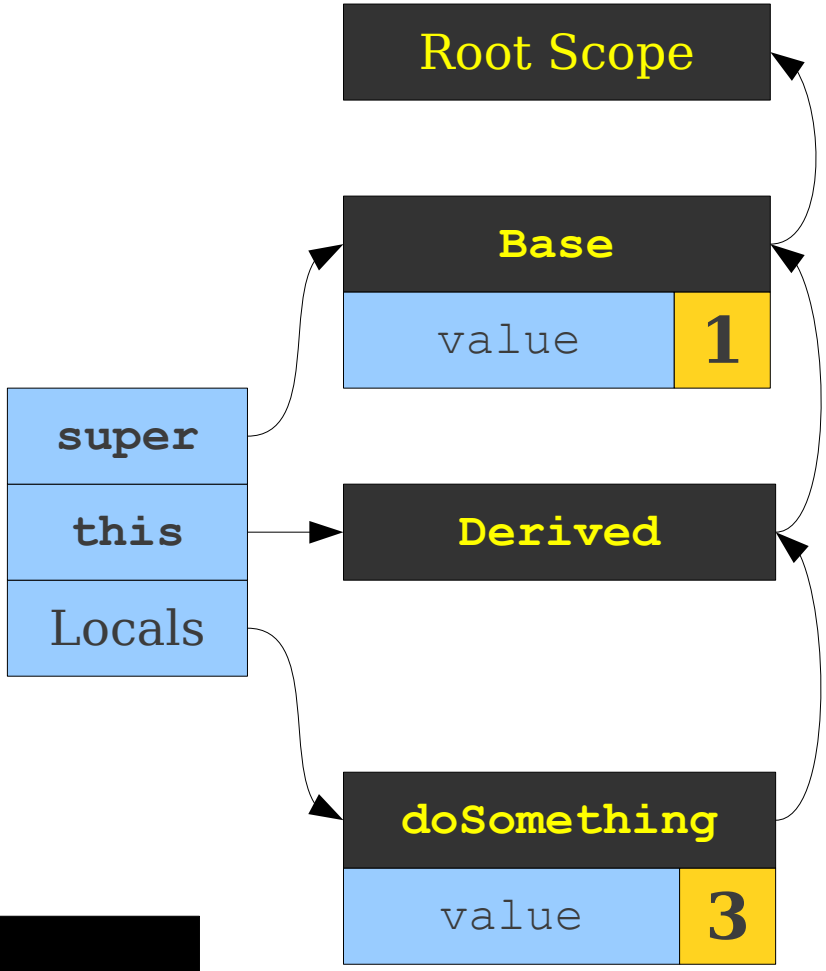
    }
}
```

```
> 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++).

Scoping in Practice

Scoping in C++ and Java

```
class A {
public:
    /* … */

private:
    B* myB
};

class B {
public:
    /* … */

private:
    A* myA;
};
```

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

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

Scoping in C++ and Java

```
class A {
public:
    /* … */

private:
    B* myB
};

class B {
public:
    /* … */

private:
    A* myA;
};
```

Error: B not declared

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

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

Perfectly fine!

Single- and Multi-Pass Compilers

- Our predictive parsing methods always scan the input from left-to-right.
  - **L**L(1), **L**R(0), LA**L**R(1), etc.
- Since we only need one token of lookahead, we can do scanning and parsing simultaneously in one pass over the file.
- Some compilers can combine scanning, parsing, semantic analysis, and code generation into the same pass.
  - These are called **single-pass compilers**.
- Other compilers rescan the input multiple times.
  - These are called **multi-pass compilers**.

Single- and Multi-Pass Compilers

- Some languages are designed to support single-pass compilers.
  - e.g. C, C++.
- Some languages *require* multiple passes.
  - e.g. Java, **Decaf**.
- Most modern compilers use a huge number of passes over the input.

Scoping in Multi-Pass Compilers

- Completely parse the input file 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, though they are logically distinct.

Scoping with Multiple Inheritance

```
class A {
public:
    int x;
};

class B {


};

class C: public A, public B {
public:
    void doSomething() {
        cout << x << endl;
    }
}
```

Scoping with Multiple Inheritance

Root Scope

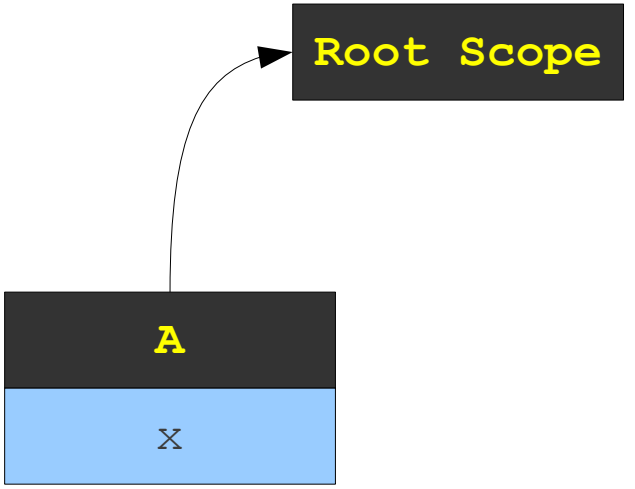
```
class A {
public:
    int x;
};

class B {


};

class C: public A, public B {
public:
    void doSomething() {
        cout << x << endl;
    }
}
```

Scoping with Multiple Inheritance




```
class A {
public:
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};

class C: public A, public B {
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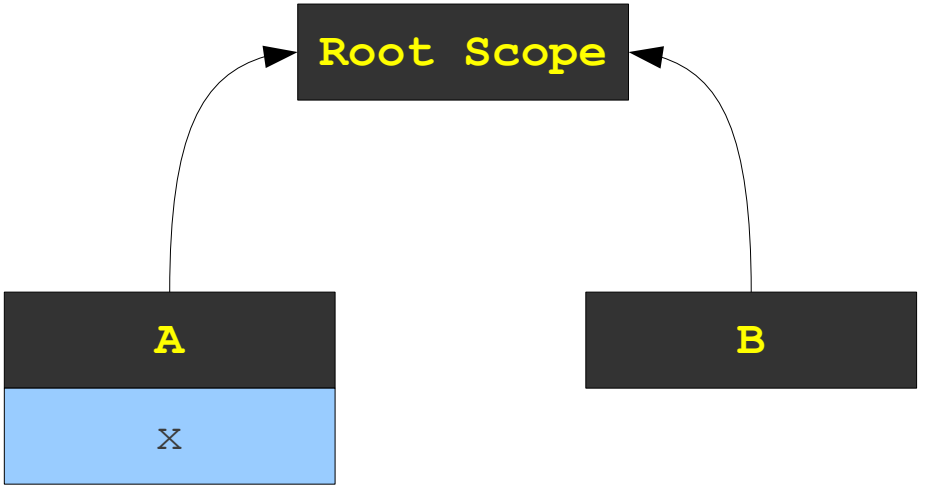
    }
}
```

Scoping with Multiple Inheritance

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public:
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};

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```

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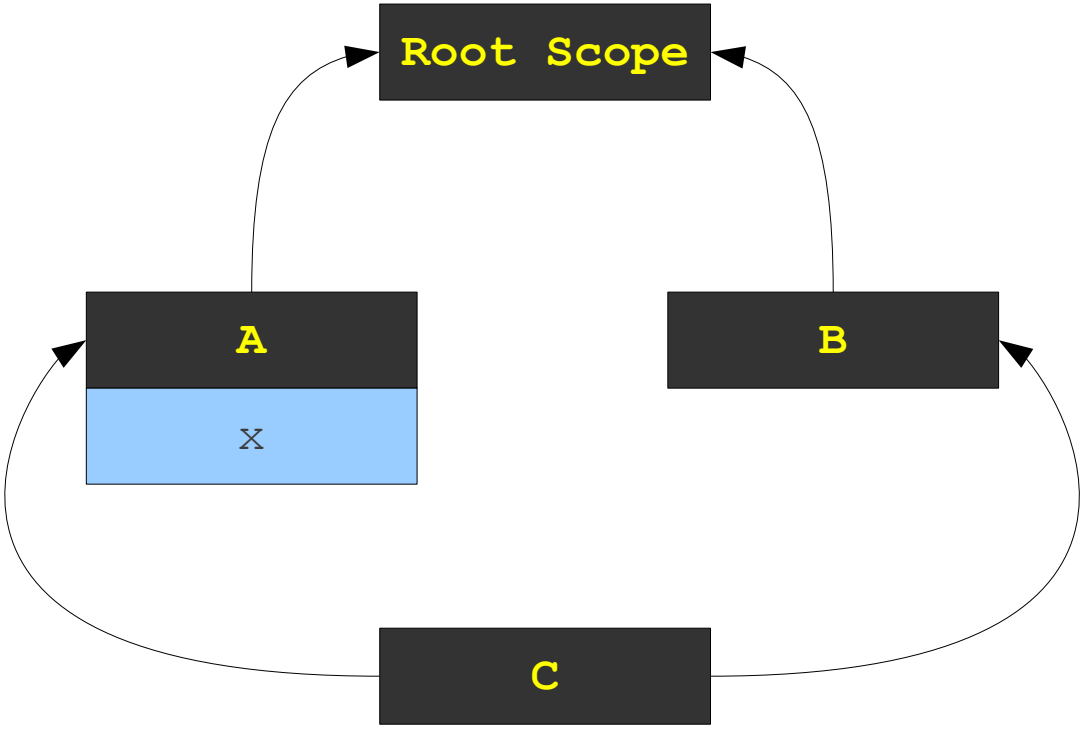
}
```



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};

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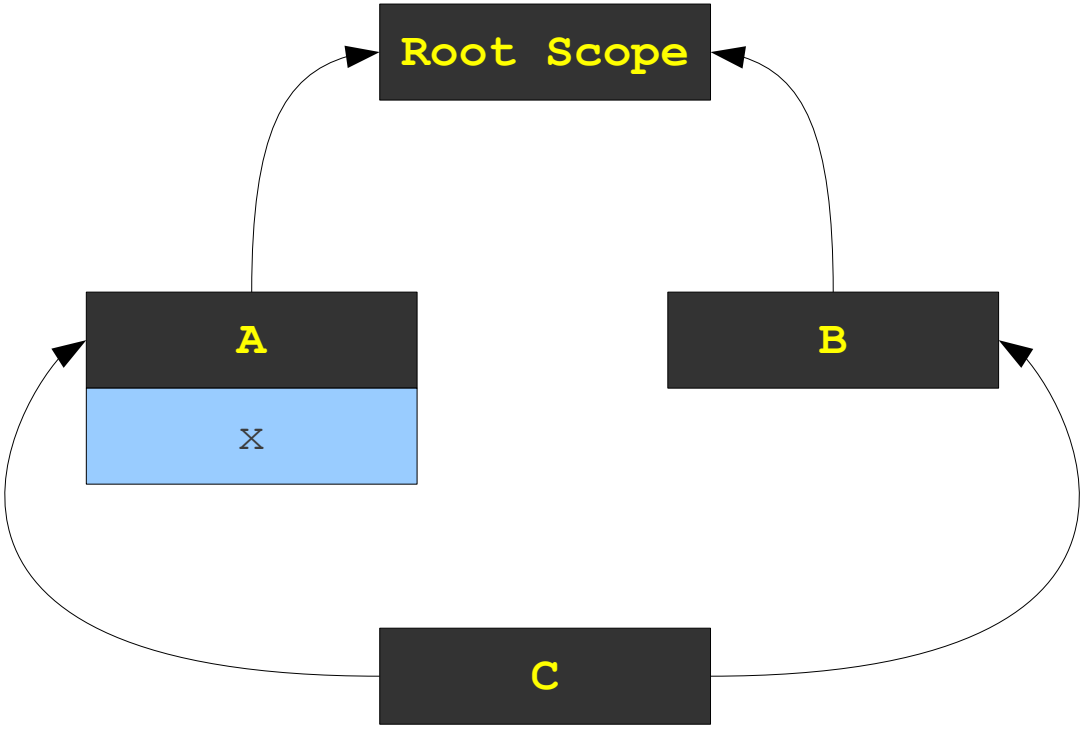
```



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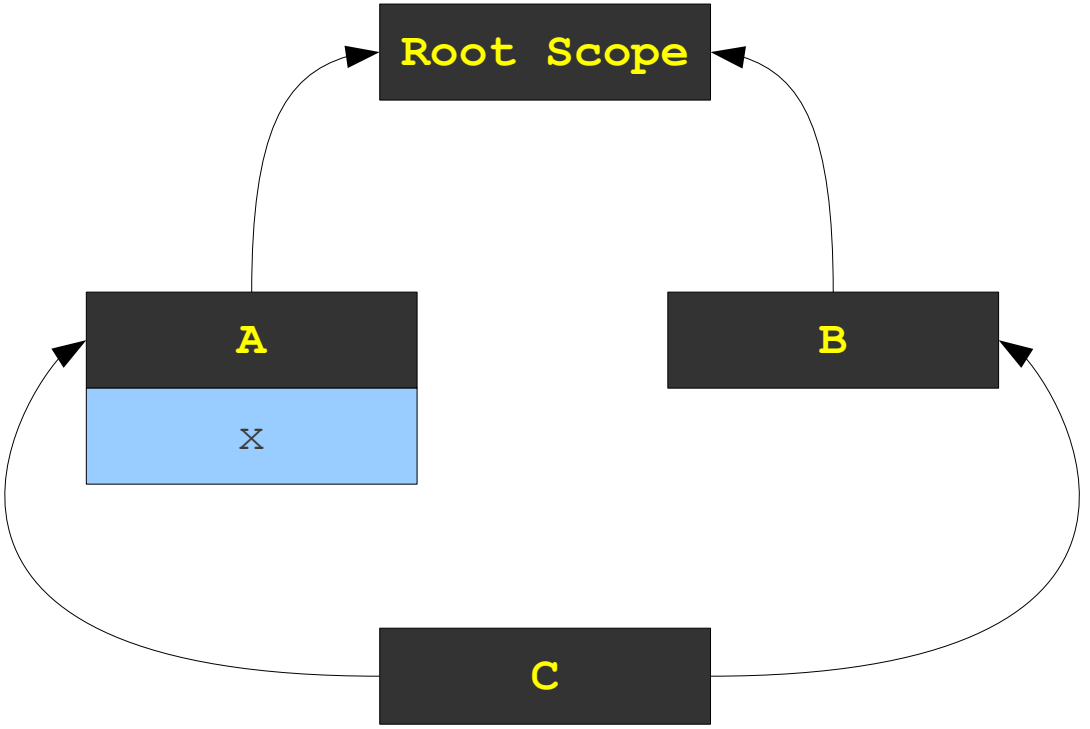
```



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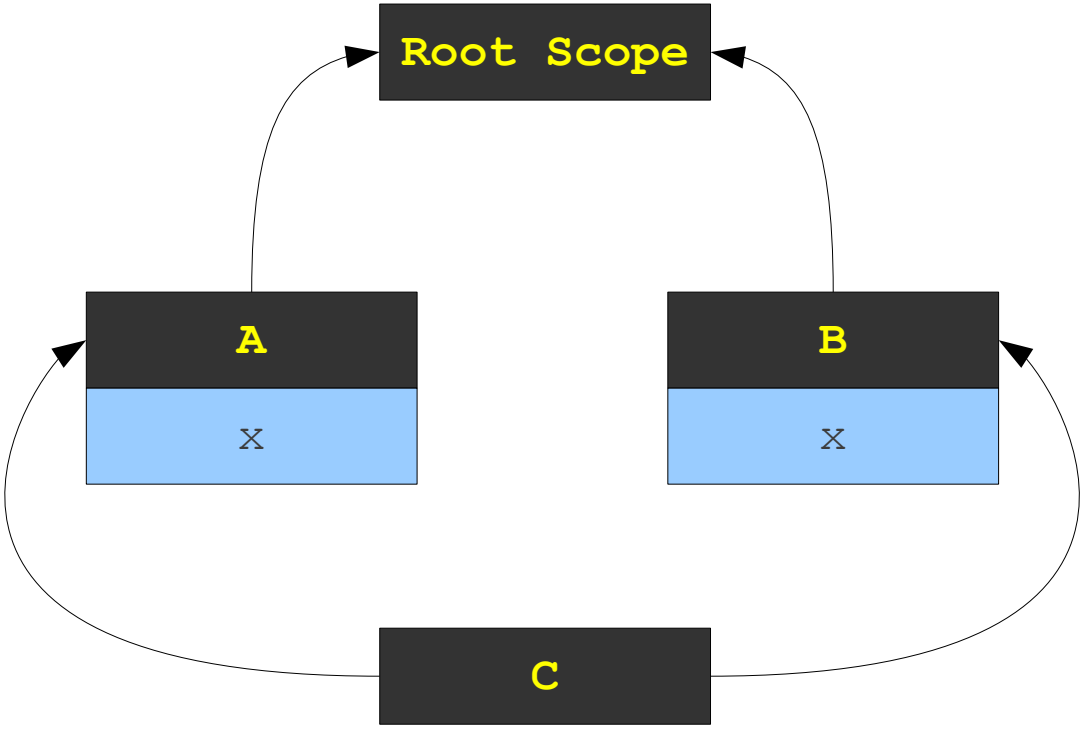
```



Scoping with Multiple Inheritance

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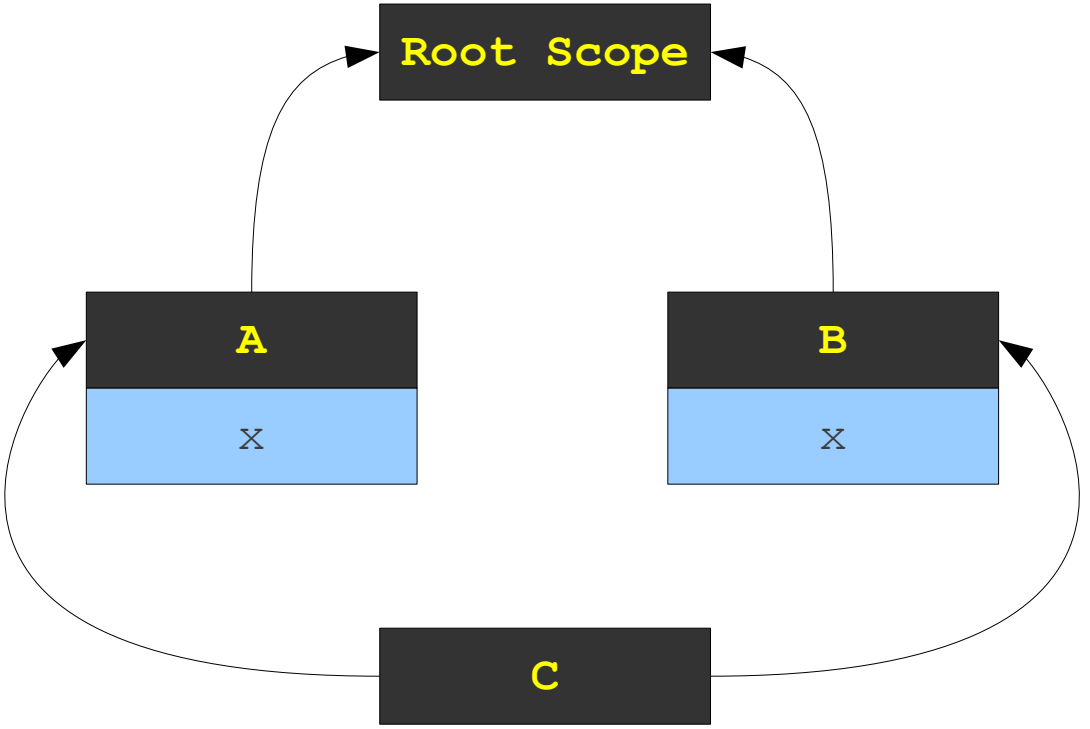

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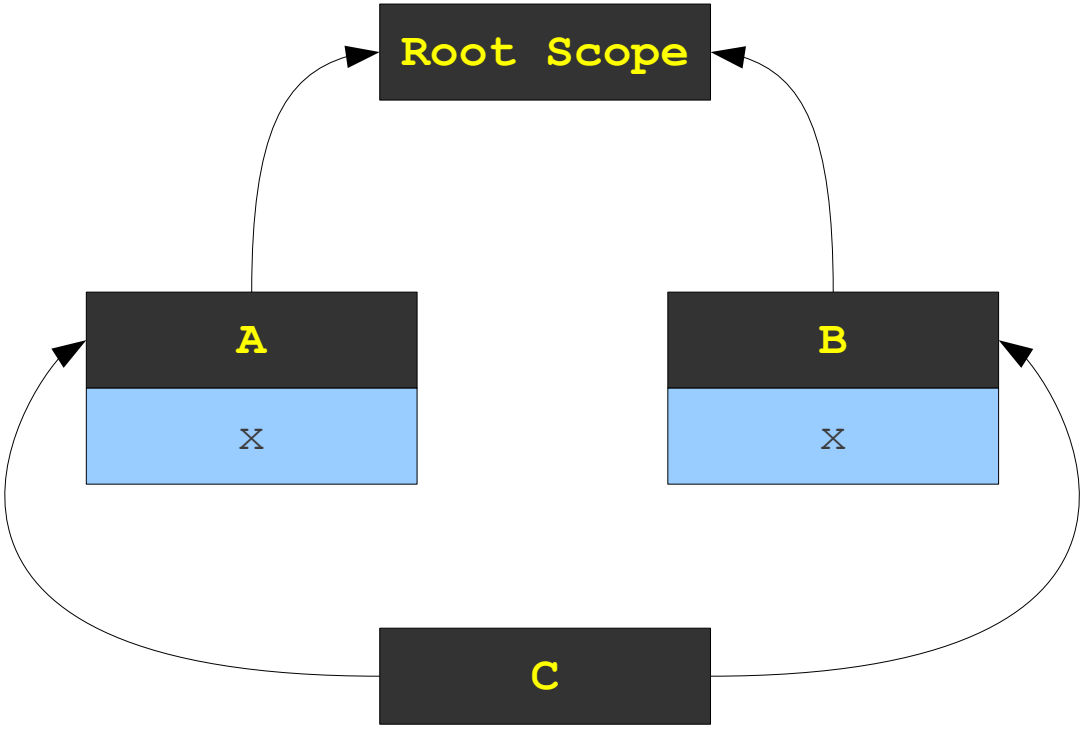


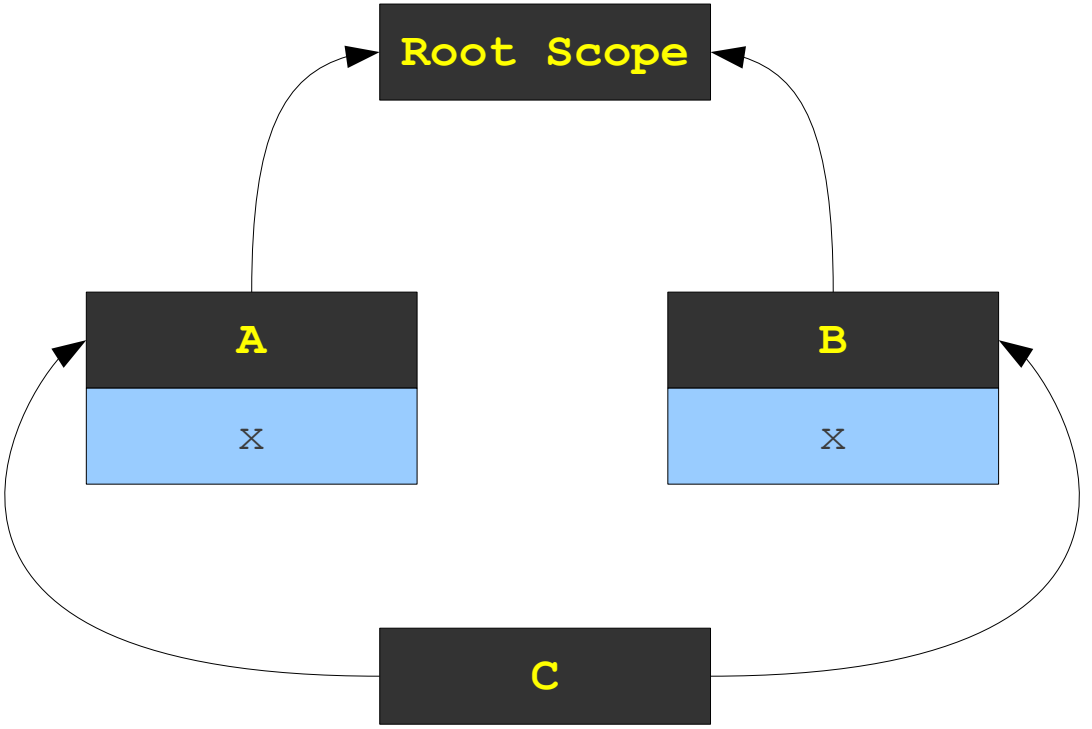
Ambiguous - which x?

Scoping with Multiple Inheritance

```
class A {
public:
    int x;
};

class B {
public:
    int x;
};

class C: public A, public B {
public:
    void doSomething() {
        cout << A::x << endl;
    }
}
```



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};

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public:
    int x;
};

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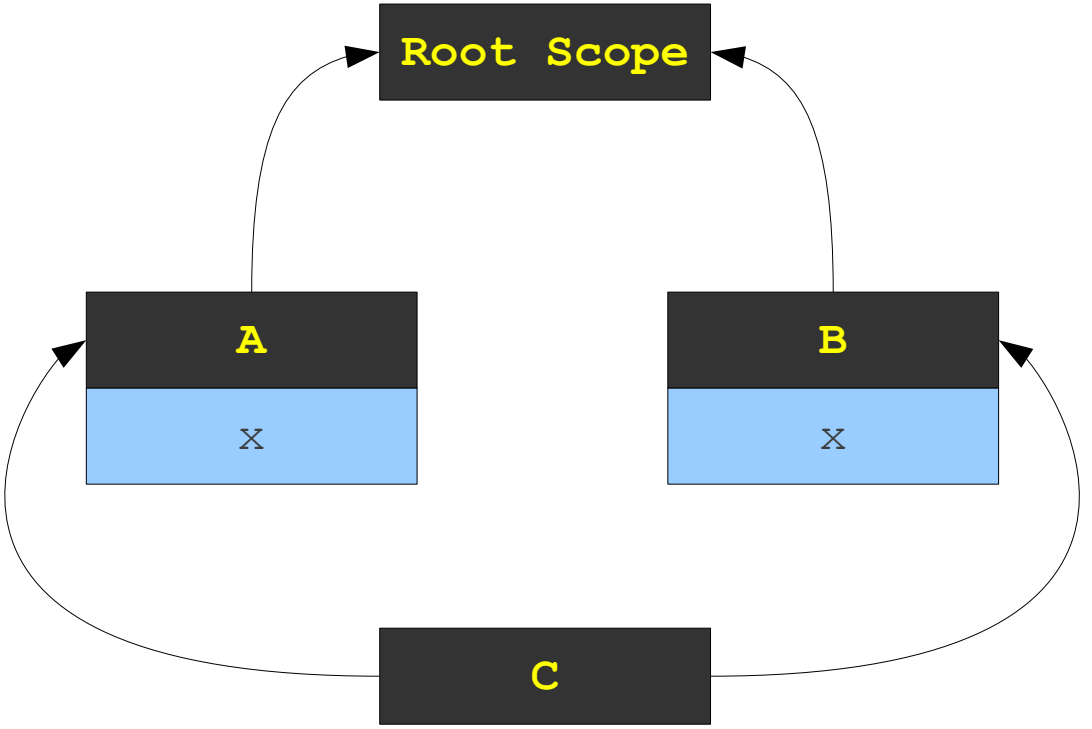
    void doSomething() {
        cout << x << endl;
    }
}
```



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```
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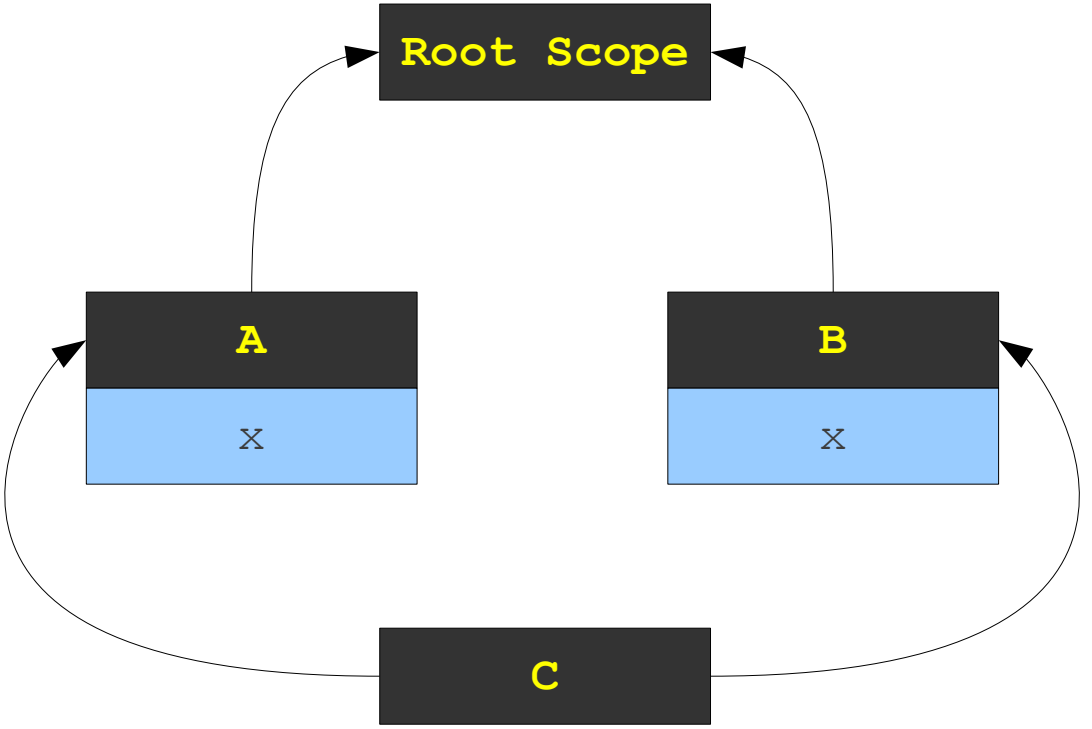
public:
    int x;
};

class B {


};

class C: public A, public B {
public:
    void doSomething() {
        cout << x << endl;
    }
}
```



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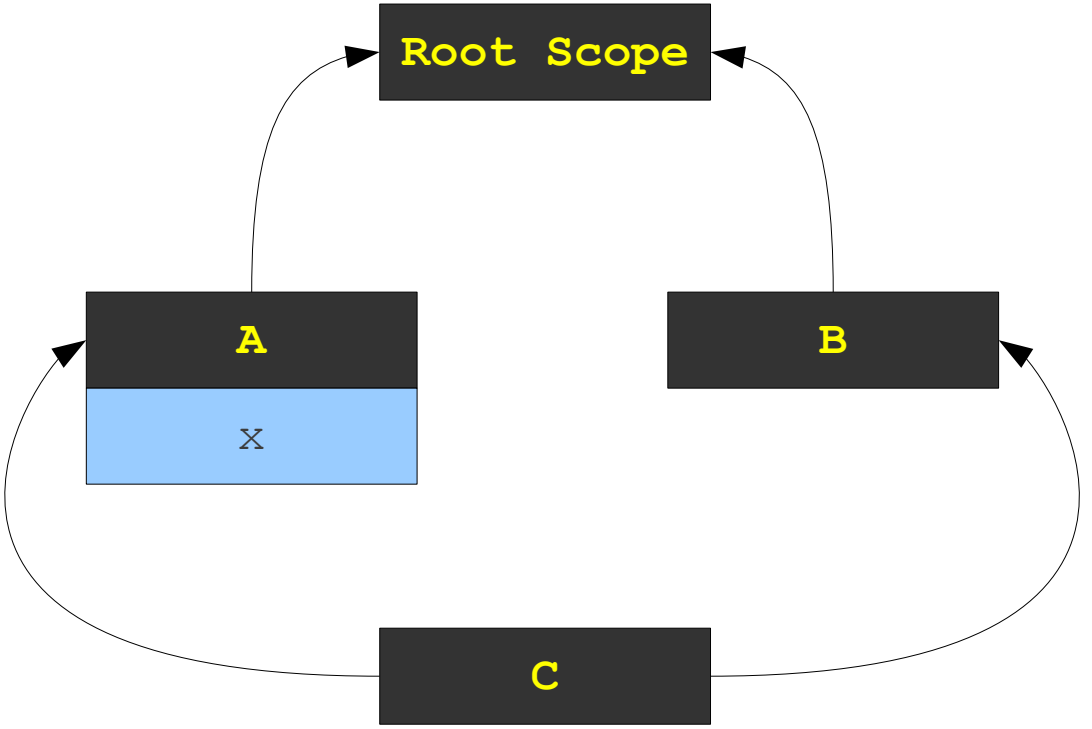

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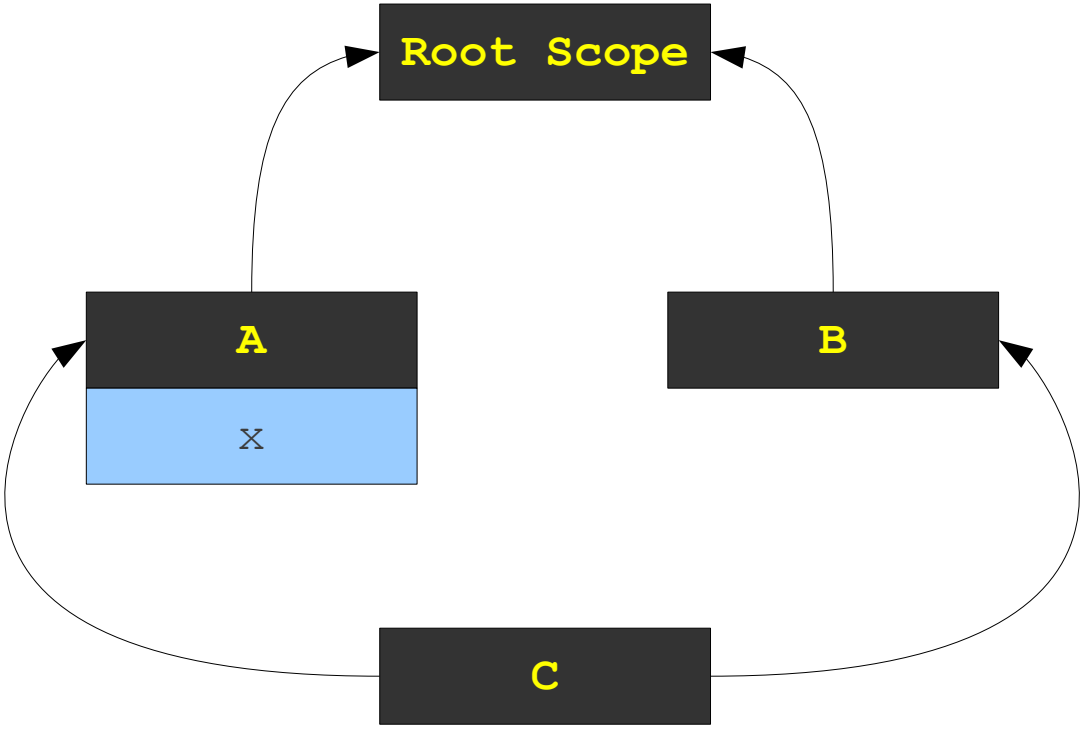

Scoping with Multiple Inheritance

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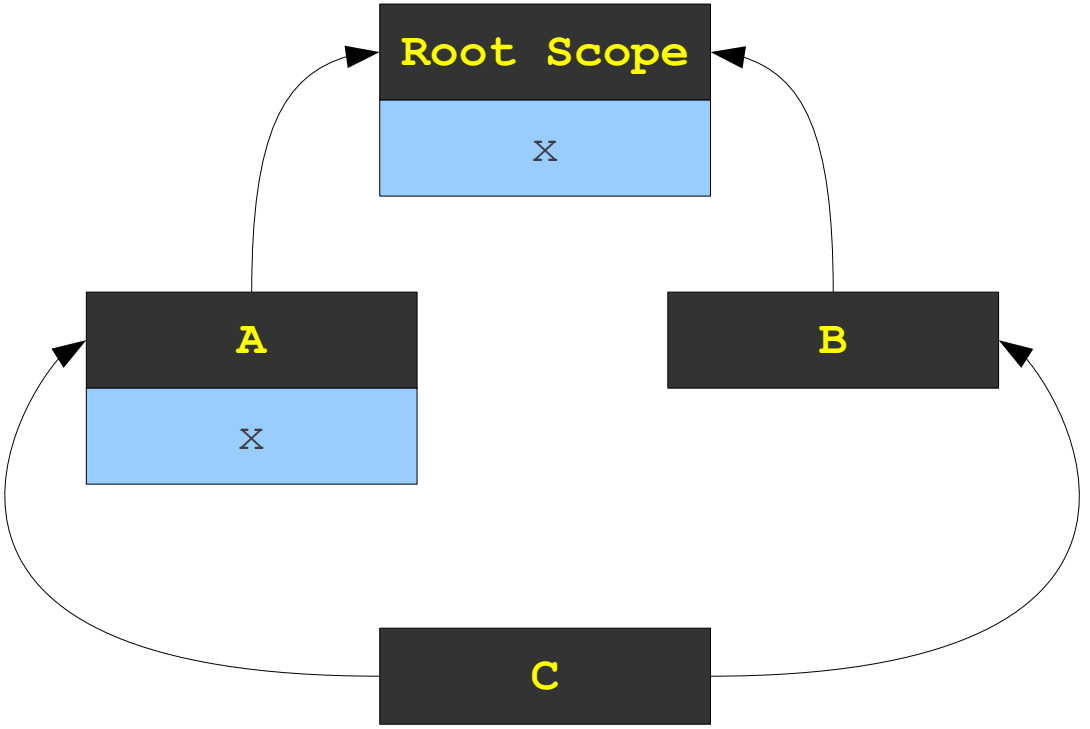

Scoping with Multiple Inheritance

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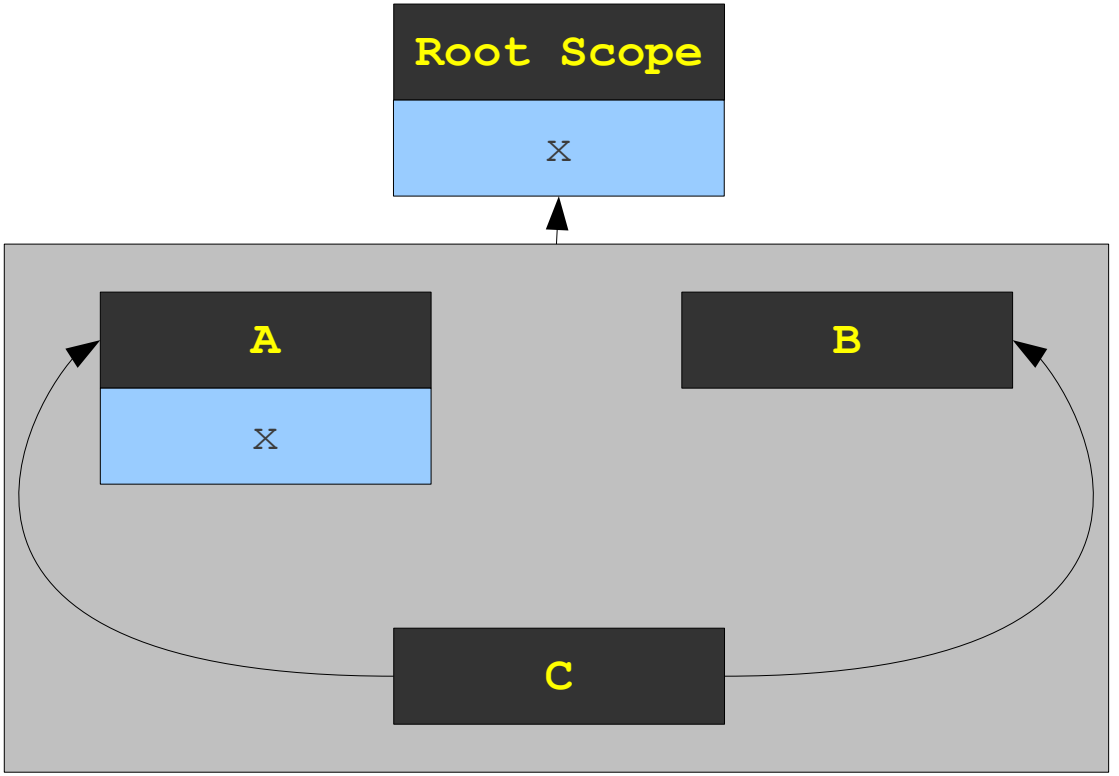

(Simplified) C++ Scoping Rules

- Inside of a class, search the entire class hierarchy to see the set of names that can be found.
  - This uses the standard scoping lookup.
- If only one name is found, the lookup succeeds unambiguously.
- If more than one name is found, the lookup is ambiguous and requires disambiguation.
- Otherwise, restart the search from outside the class.

Dynamic Scoping

Static and Dynamic Scoping

- The scoping we've seen so far is called **static scoping** and is done at compile-time.
  - Names refer to lexically related variables.
- Some languages use **dynamic scoping**, which is done at runtime.
  - Names refer to the variable with that name that is most 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();
```

Dynamic Scoping

```
int x = 137;
int y = 42;
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    int y = 0;
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}
Function1();
Function2();
Function3();
```

Symbol Table	
x	**137**
y	**42**

```
>
```

Dynamic Scoping

```
int x = 137;
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Function1();
Function2();
Function3();
```

Symbol Table	
x	**137**
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```
>
```

Dynamic Scoping

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}
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    int y = 0;
    Function2();
}
Function1();
Function2();
Function3();
```

Symbol Table	
x	137
y	42

```
>
```

Dynamic Scoping

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int x = 137;
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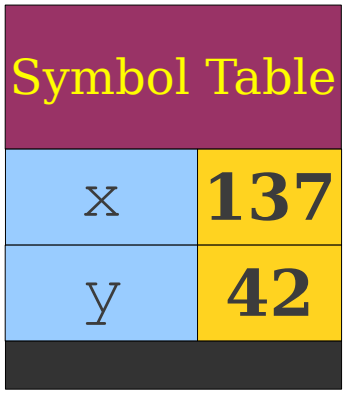
    Function2();
}
Function1();
Function2();
Function3();
```



Dynamic Scoping

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}
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    Function1();
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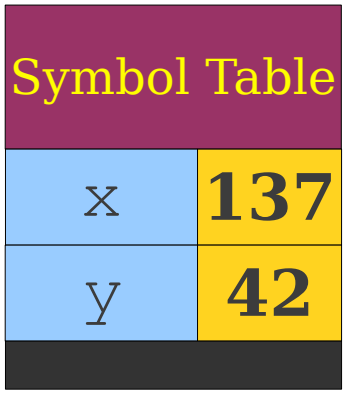
void Function3() {
    int y = 0;
    Function2();
}
Function1();
Function2();
Function3();
```



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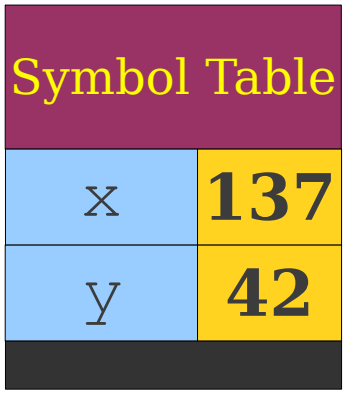


```
> 179
>
```

Dynamic Scoping

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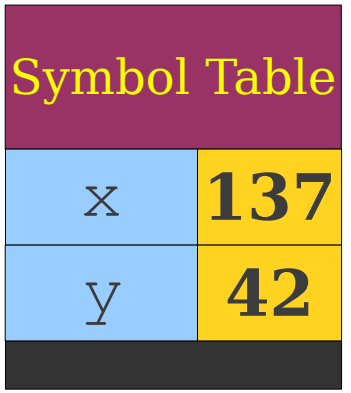


```
> 179
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```

Symbol Table	
x	**137**
y	**42**

```
> 179
>
```

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> 179
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Symbol Table	
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```
> 179
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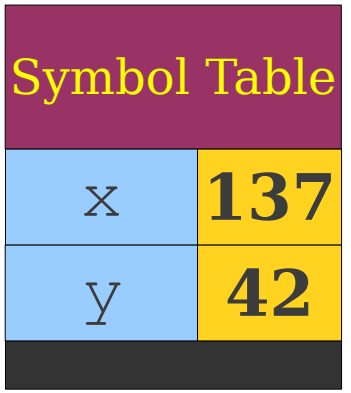


```
> 179
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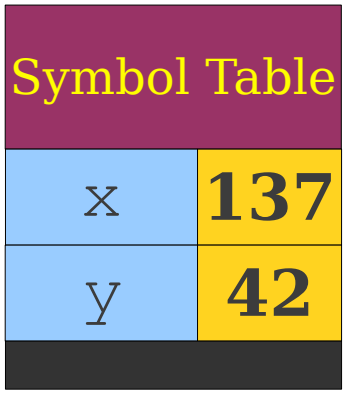


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> 179
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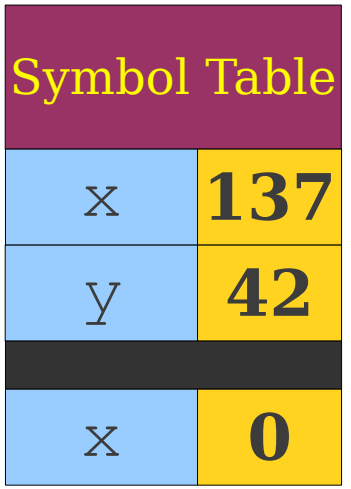


```
> 179
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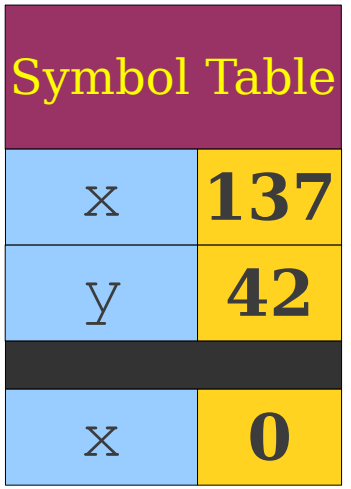


```
> 179
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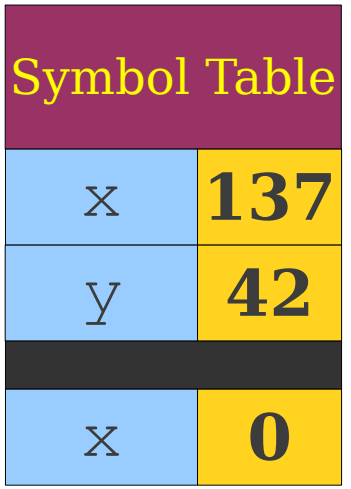


```
> 179
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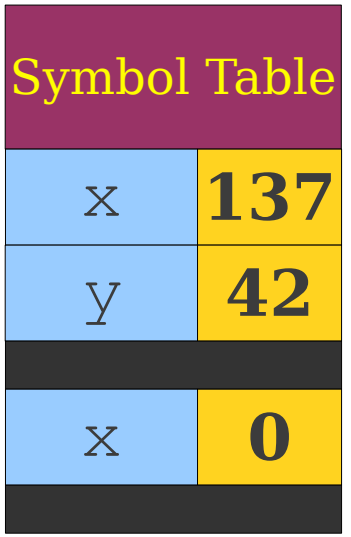


```
> 179
>
```

Dynamic Scoping

```
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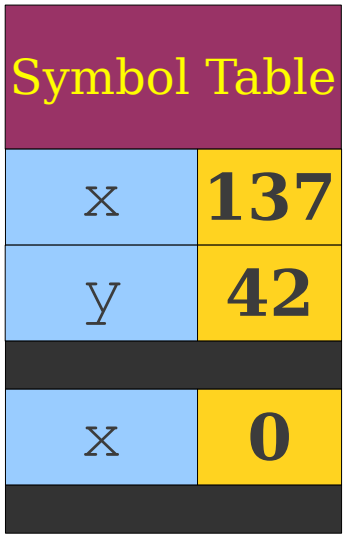


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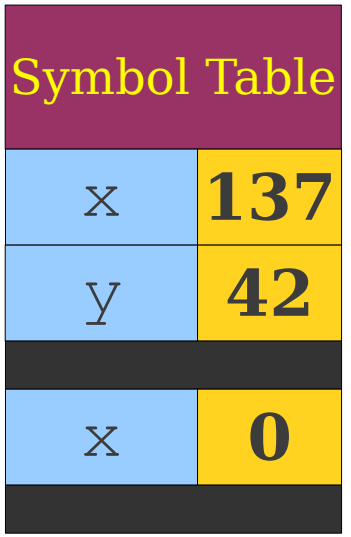


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> 179
> 42
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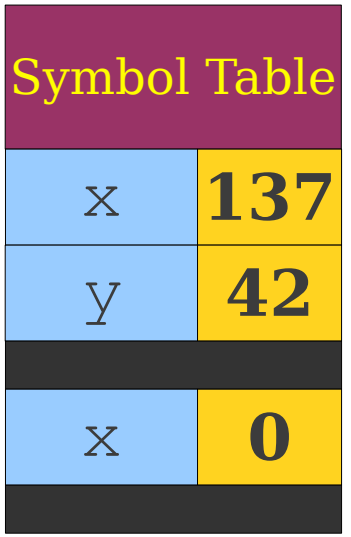


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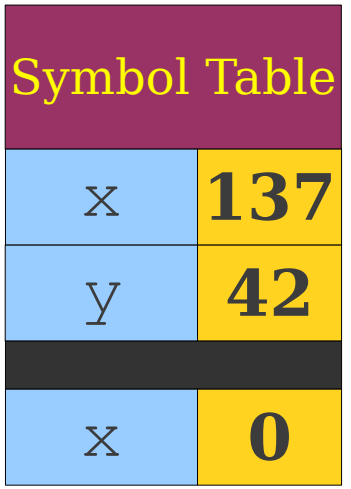


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> 179
> 42
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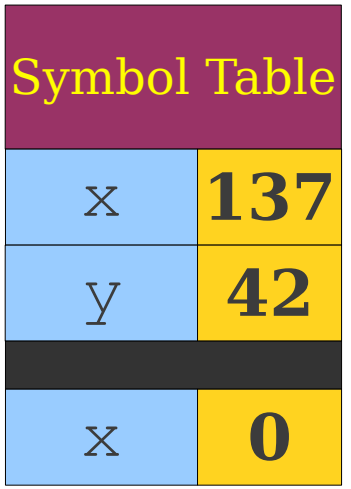


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Symbol Table	
x	137
y	42

```
> 179
> 42
>
```

Dynamic Scoping

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int x = 137;
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```

Symbol Table	
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```
> 179
> 42
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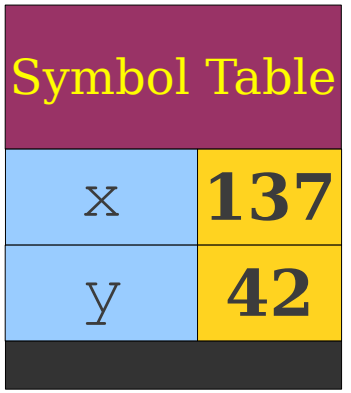


```
> 179
> 42
>
```

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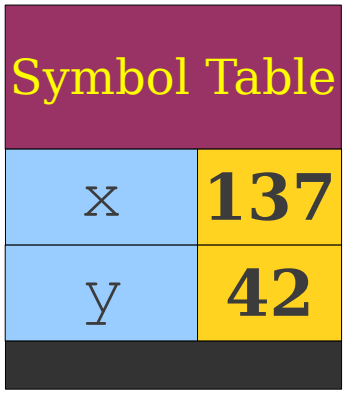


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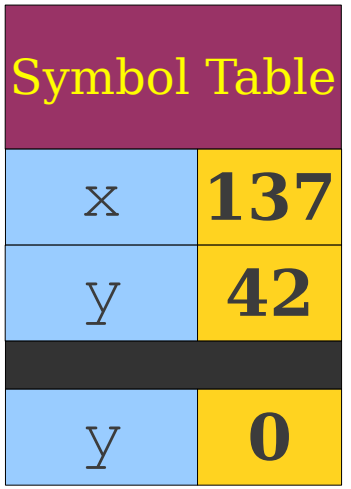


```
> 179
> 42
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```

Dynamic Scoping

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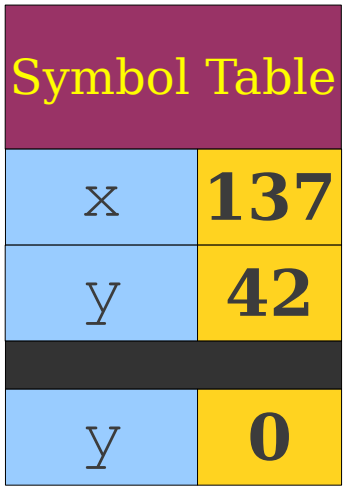


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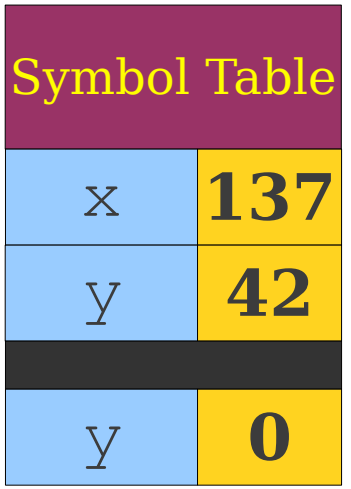


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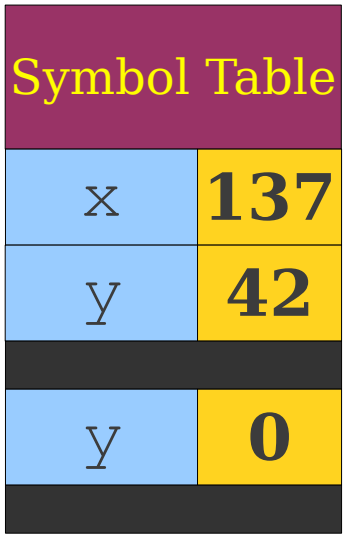


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> 179
> 42
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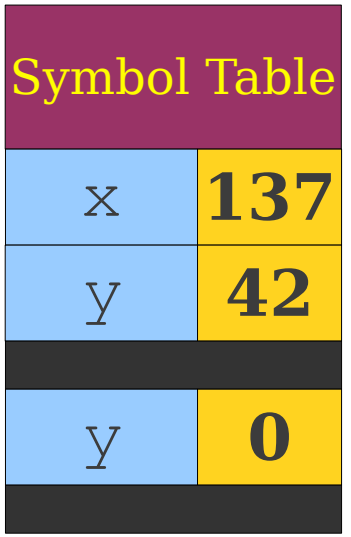


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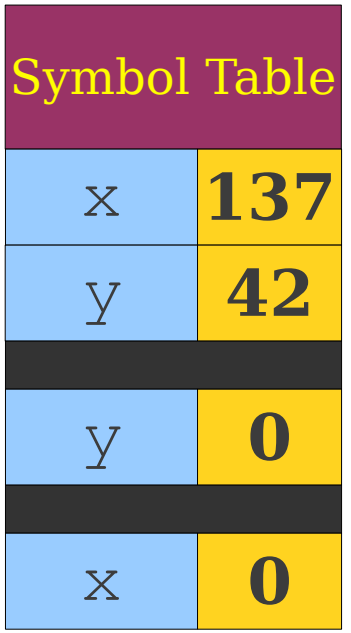


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> 179
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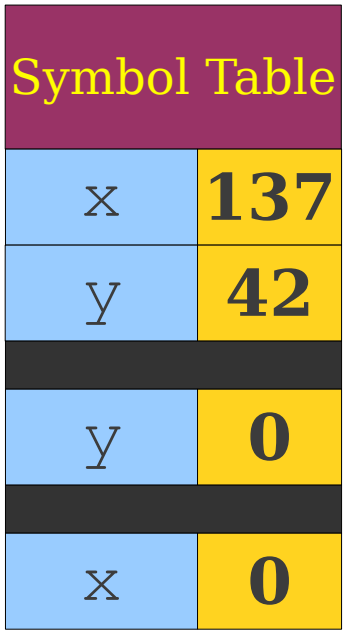


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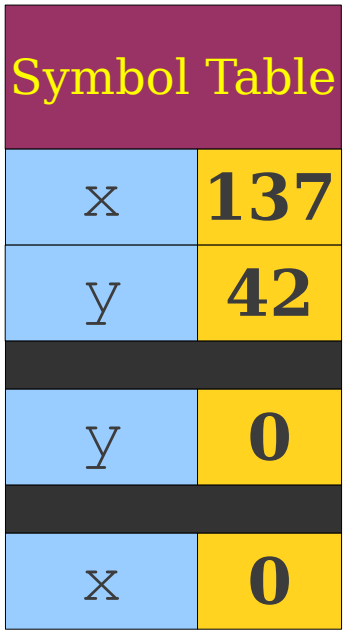


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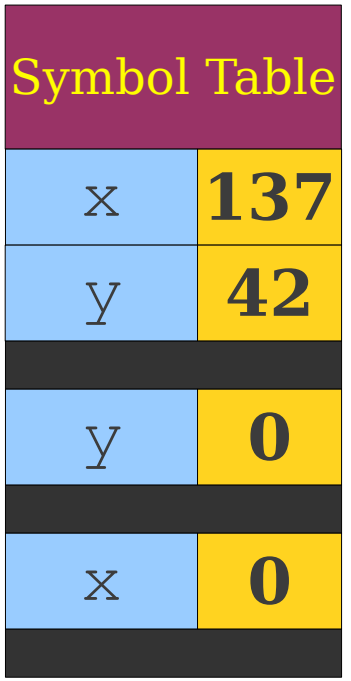


```
> 179
> 42
>
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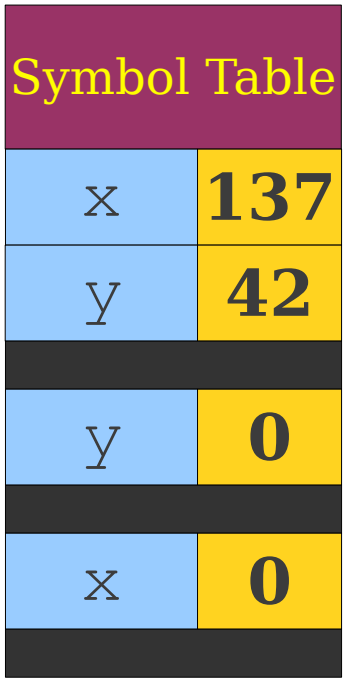


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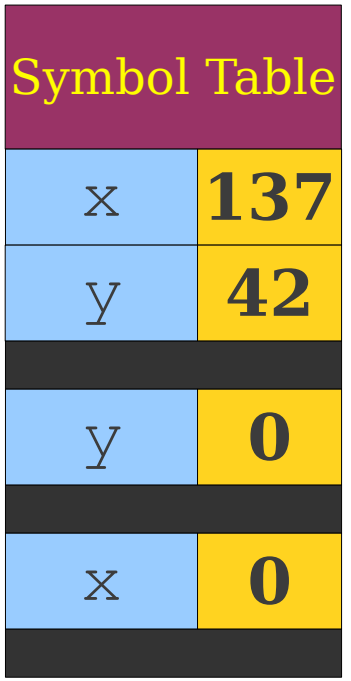


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> 179
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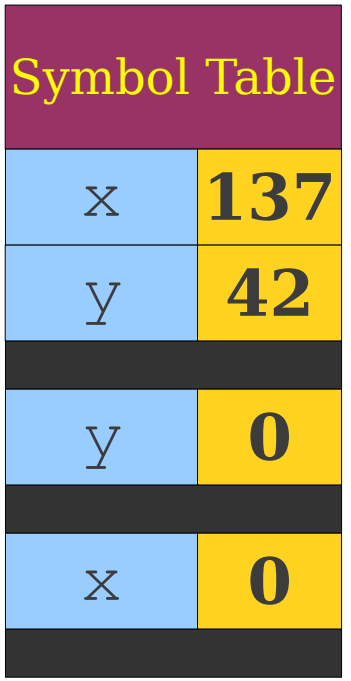


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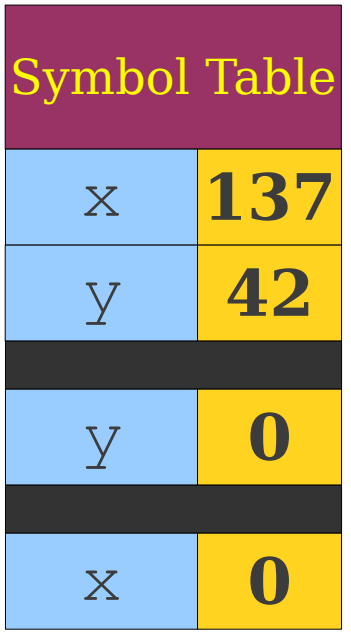


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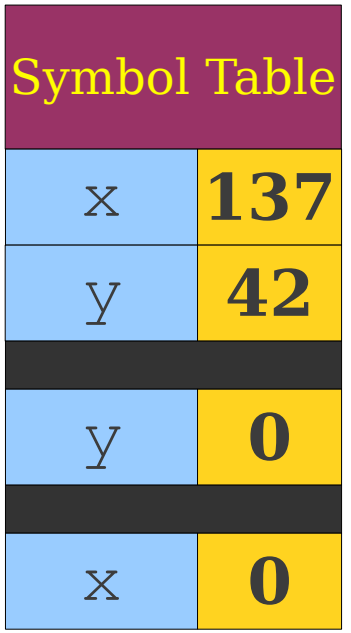


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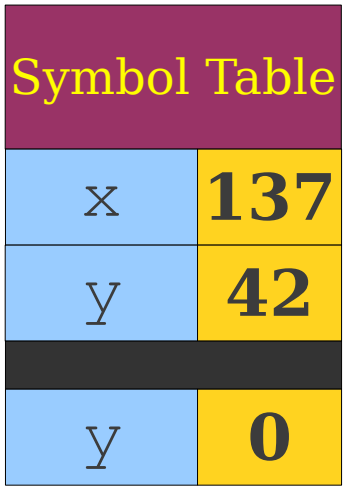


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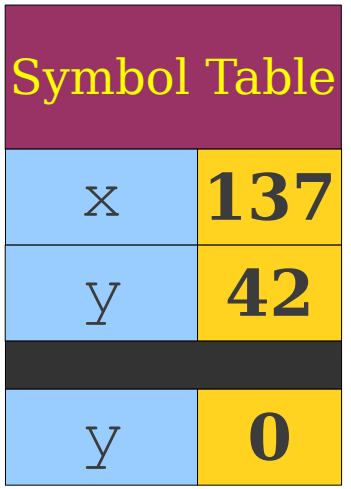


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```

Symbol Table	
x	**137**
y	**42**

```
> 179
> 42
> 0
>
```

Dynamic Scoping

```
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Symbol Table	
x	**137**
y	**42**

```
> 179
> 42
> 0
>
```

Dynamic Scoping in Practice

- Examples: Perl, Common LISP.
- Often implemented by preserving symbol table at runtime.
- Often less efficient than static scoping.
  - Compiler cannot “hardcode” locations 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.

Next Time

- **Type Checking**
  - Types as a proof system.
  - Static and dynamic types.
  - Types as a partial order.