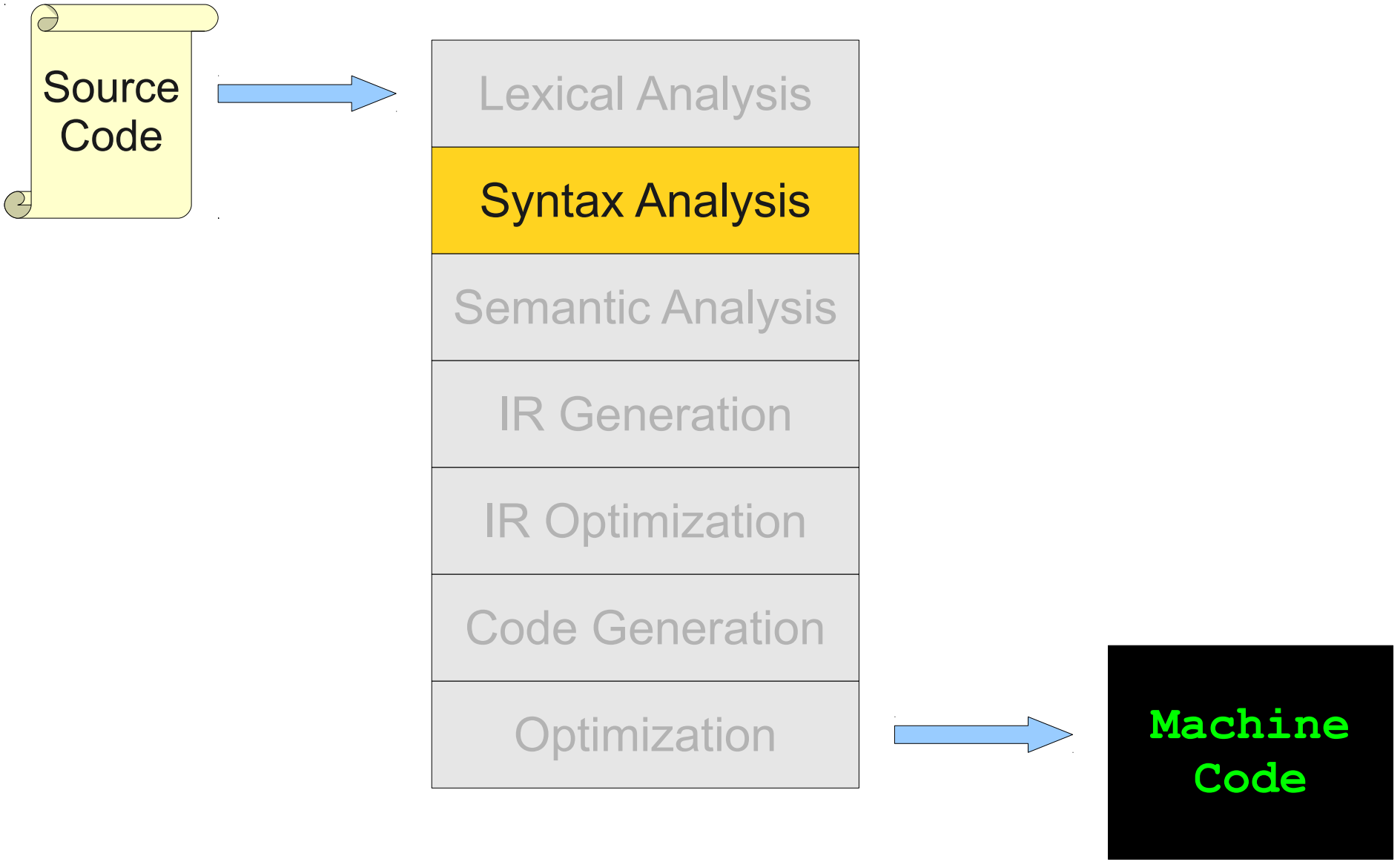
Semantic Analysis

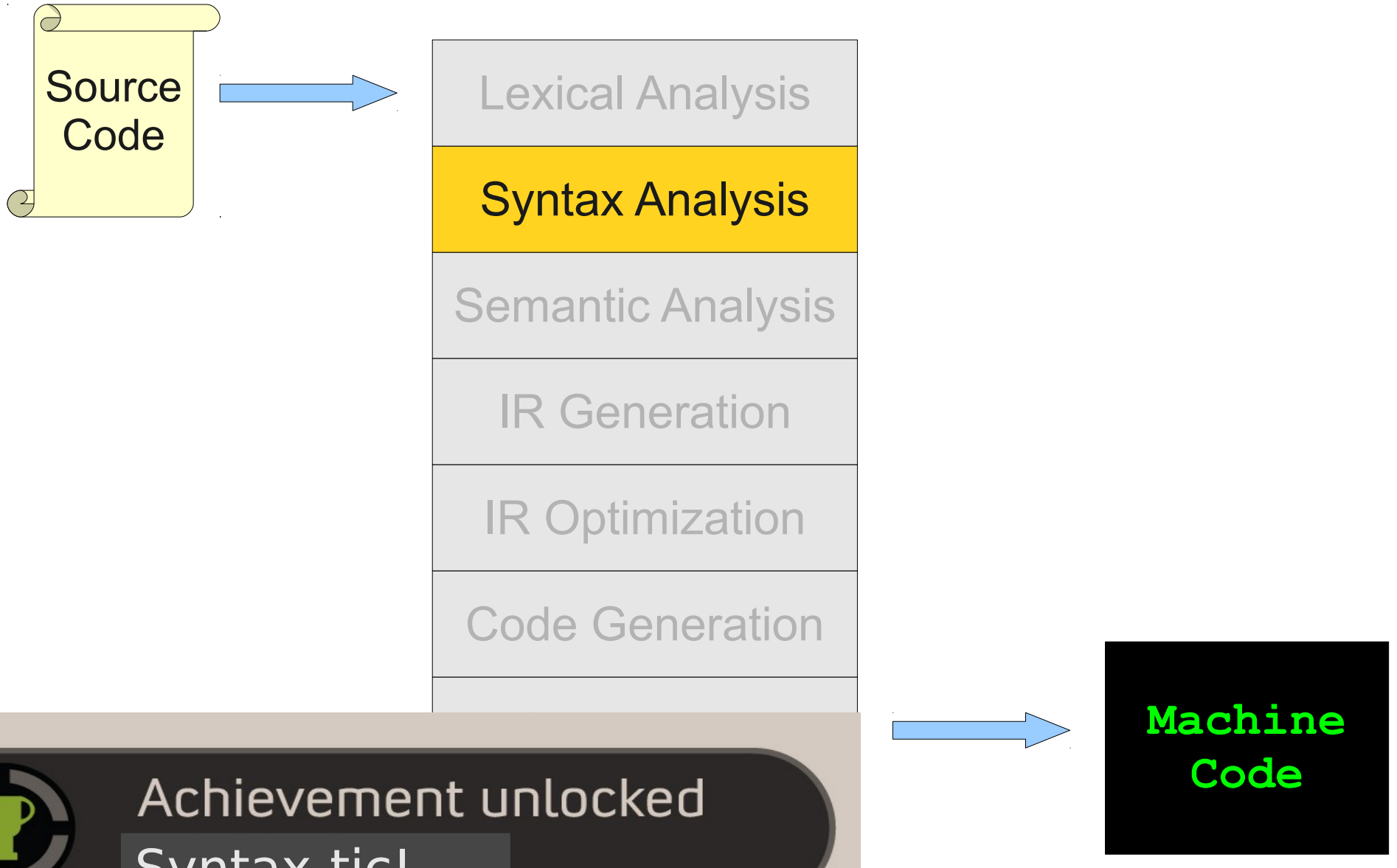
Announcements

- Programming Project 2 due Wednesday at 11:59PM.
  - Office hours every day until then.
  - Ask on Piazzza!
  - Email the course staff!
- Friendly reminder: **Midterm next Wednesday, July 20**.
  - Here, 11:00AM – 1:00PM
  - Please let us know if you have any conflicts!

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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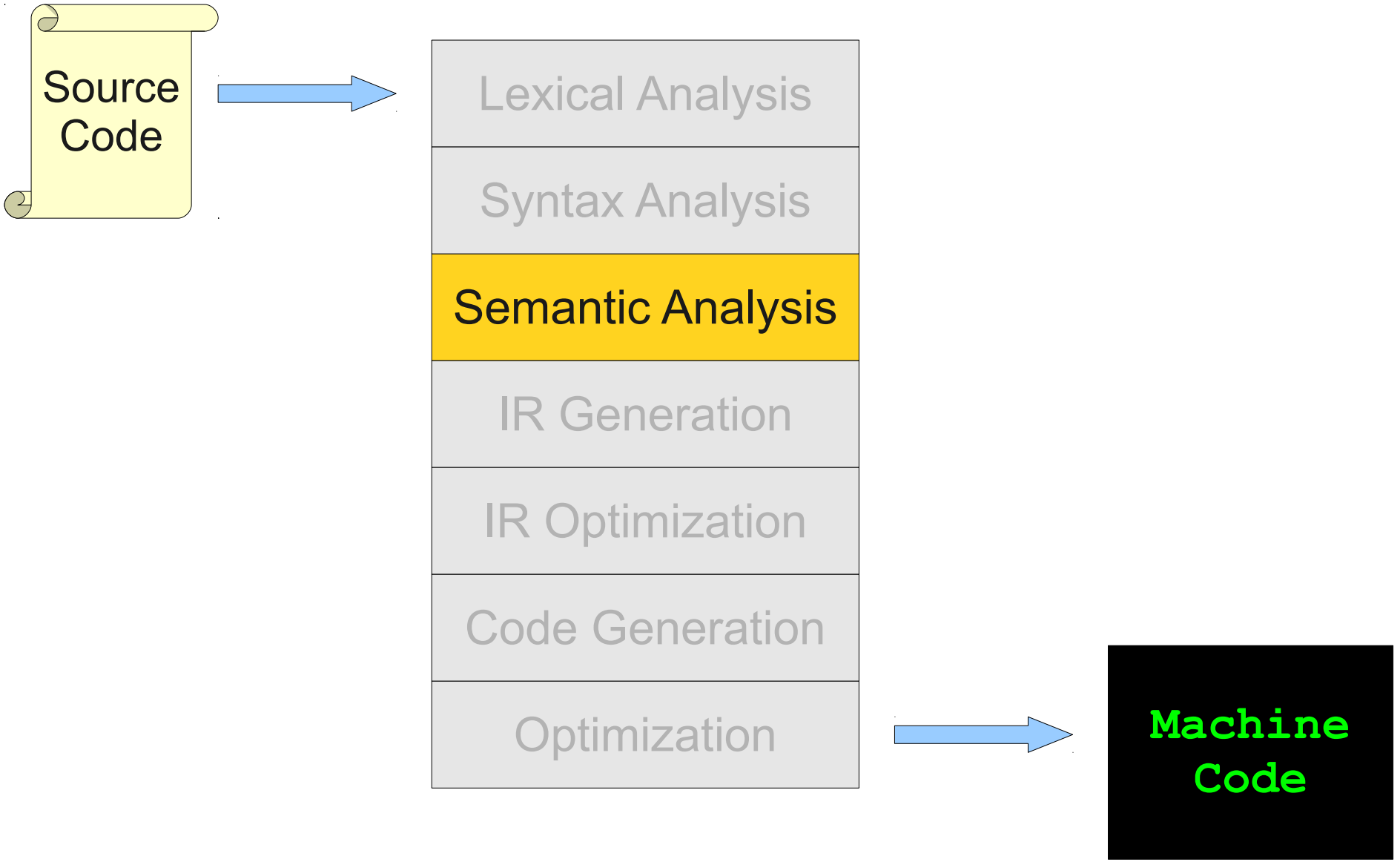
Achievement unlocked
Syntax-tic!

Where We Are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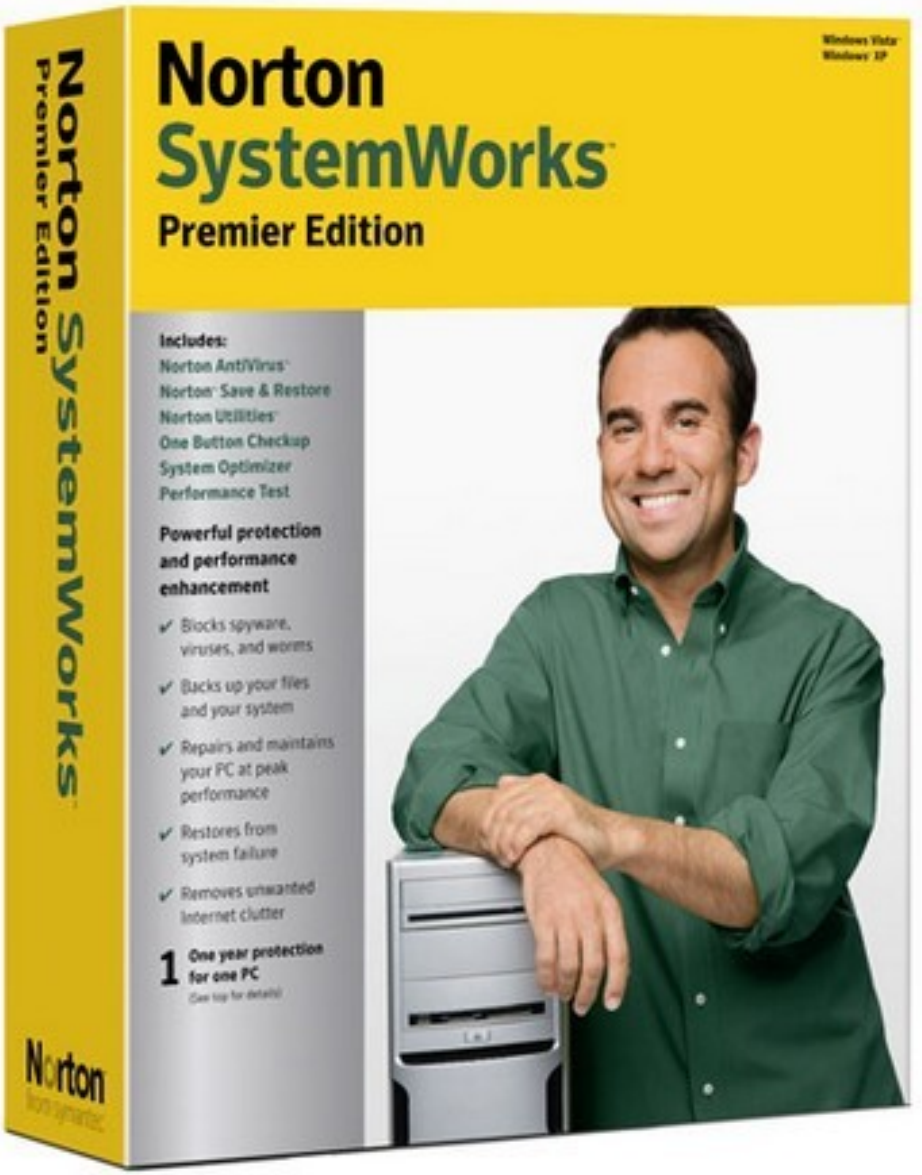
Not Symantec Analysis



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

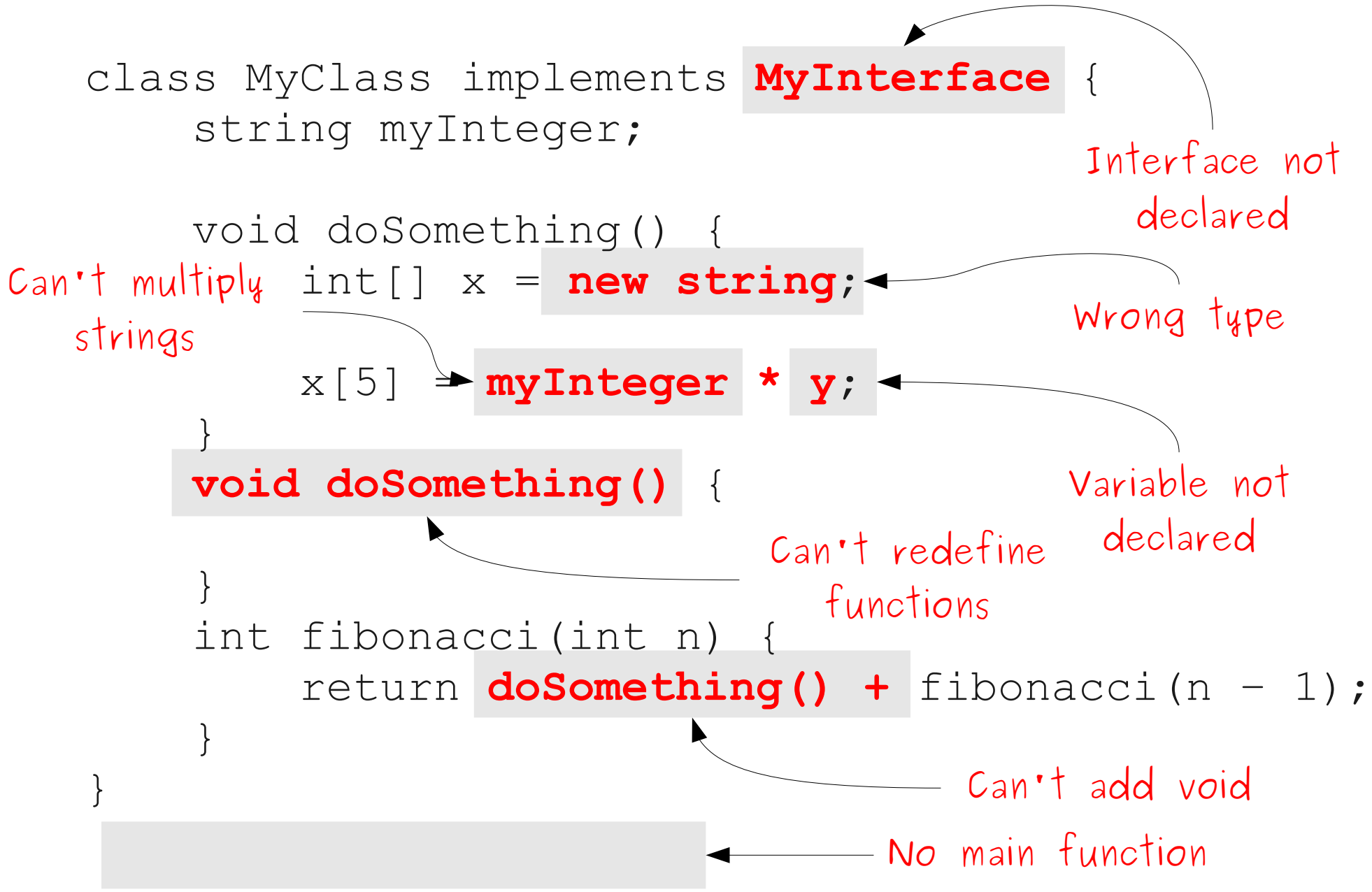
```
class MyClass implements MyInterface {
    string myInteger;

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

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

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

A Short Decaf Program



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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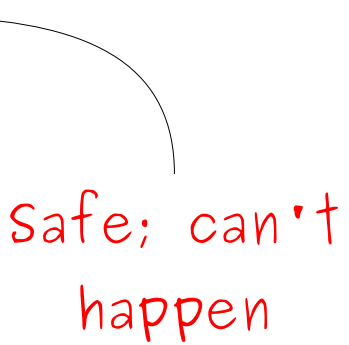

Validity versus Correctness

```
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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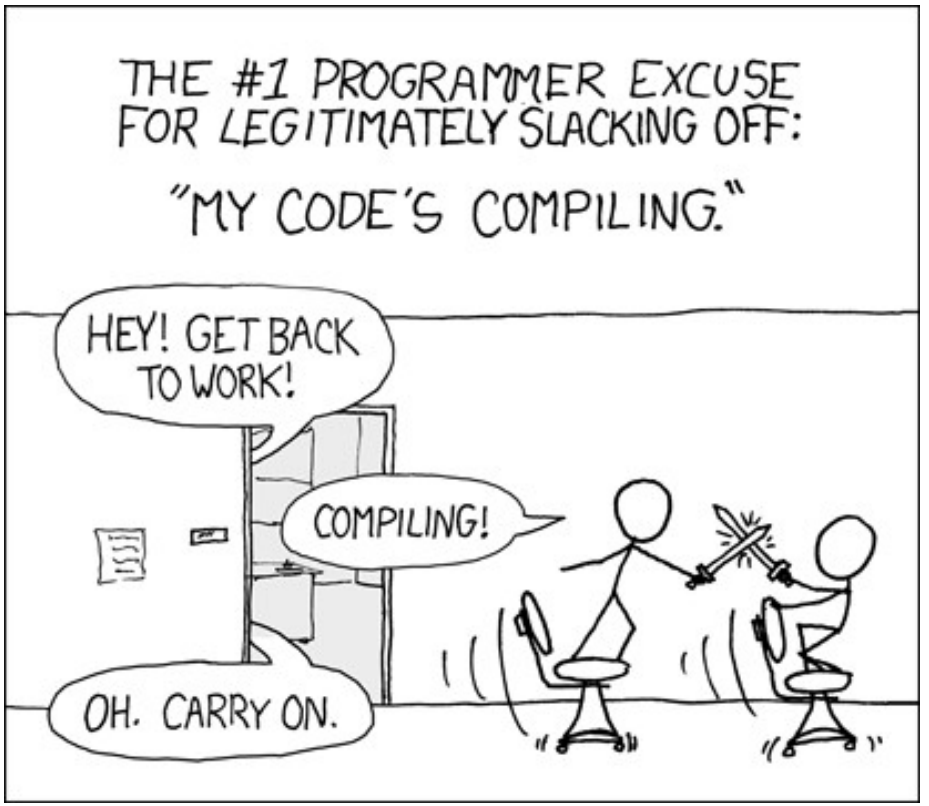

Other Goals of Semantic Analysis

- 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?
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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.

Implementing Semantic Analysis

- **Attribute Grammars**
  - Augment **`bison`** rules to do checking during parsing.
  - A powerful **syntax-directed** translation.
  - Approach suggested in the *Compilers* book.
  - Has its limitations; more on that later.
- **Recursively walk AST**
  - 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 Checking

What's in a Name?

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

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public class Name {
    int Name;
    Name Name(Name Name) {
        Name.Name = 137;
        return Name((Name) Name);
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int Awful() {
    int x = 137;
    {
        string x = "Scope!"
        if (float x = 0)
            double x = x;
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Scope

- The **scope** of an entity is the set of locations in a program where its name refers to itself.
- 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?

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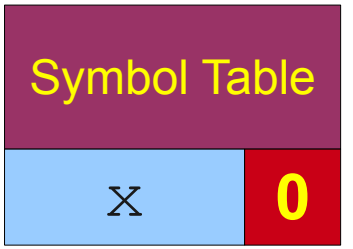

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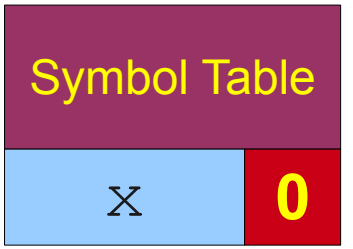

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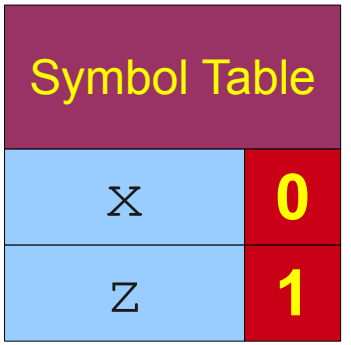

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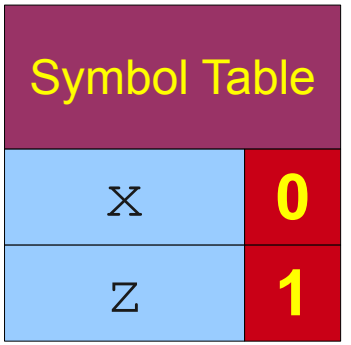

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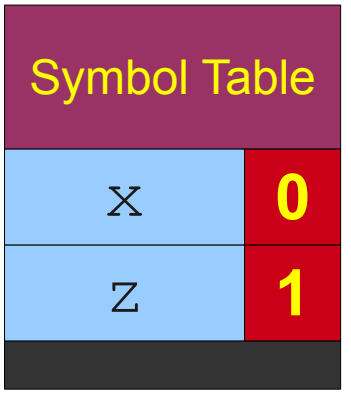

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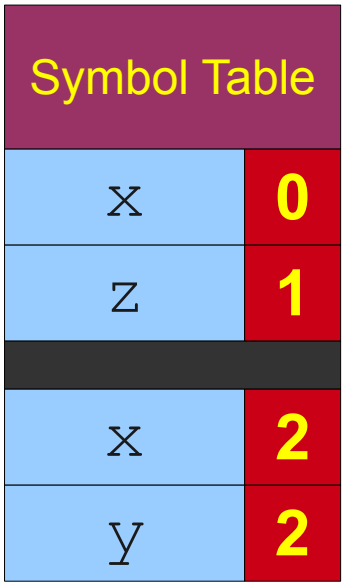

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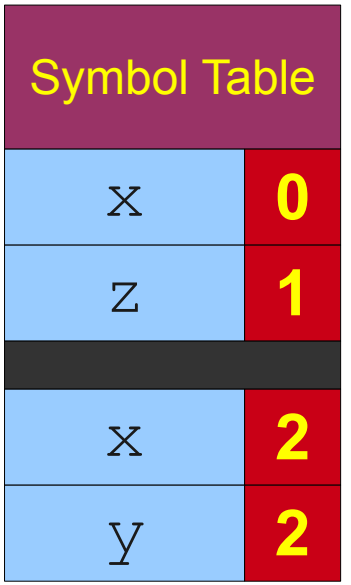

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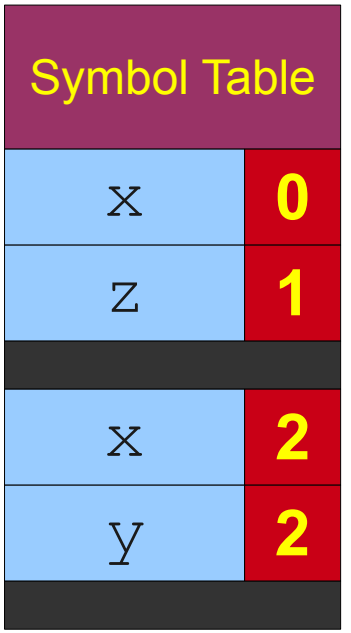

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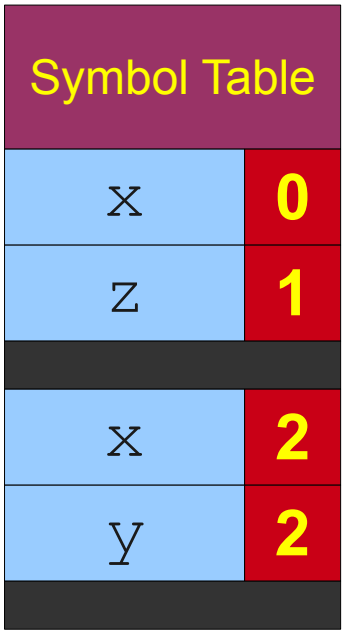

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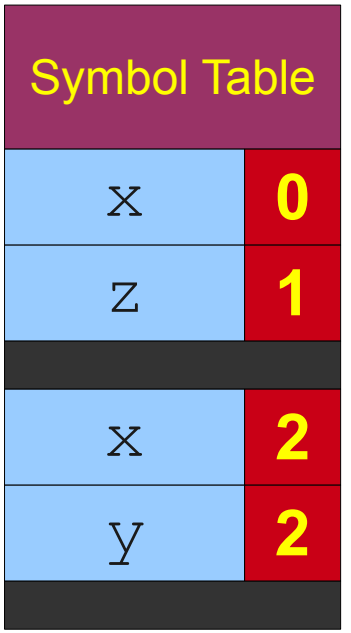

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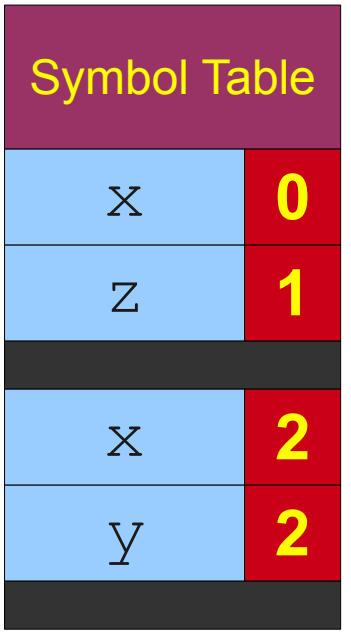

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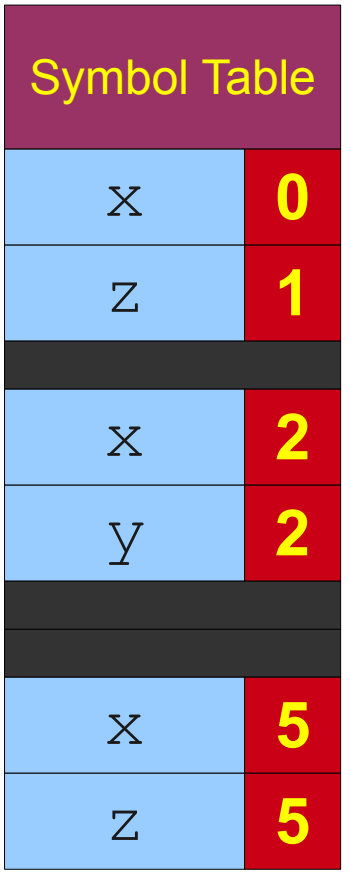

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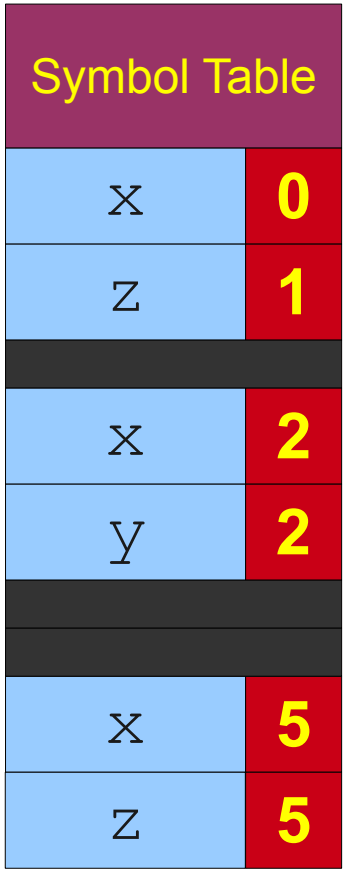

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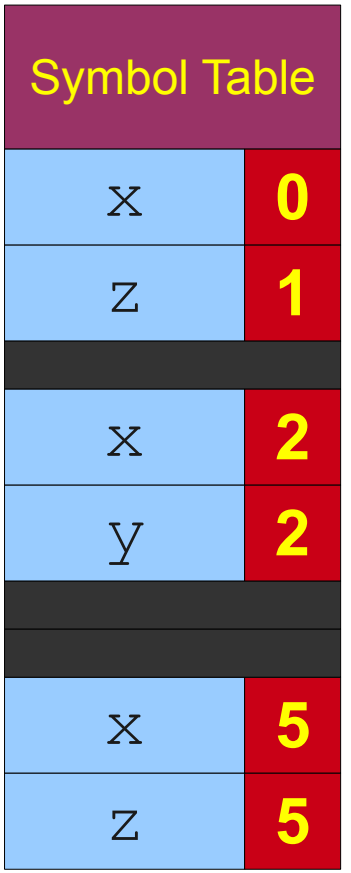

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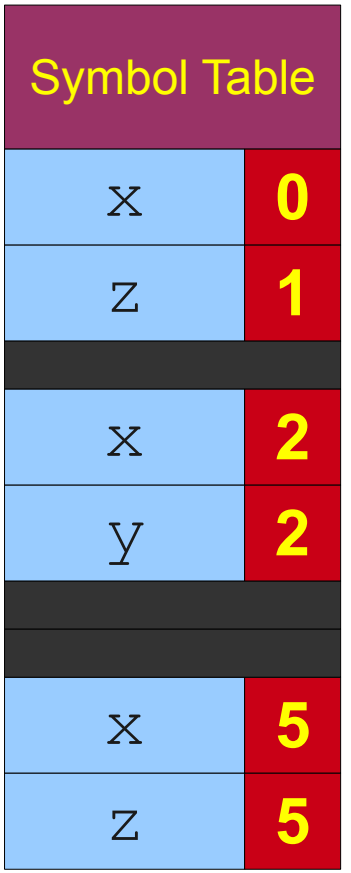

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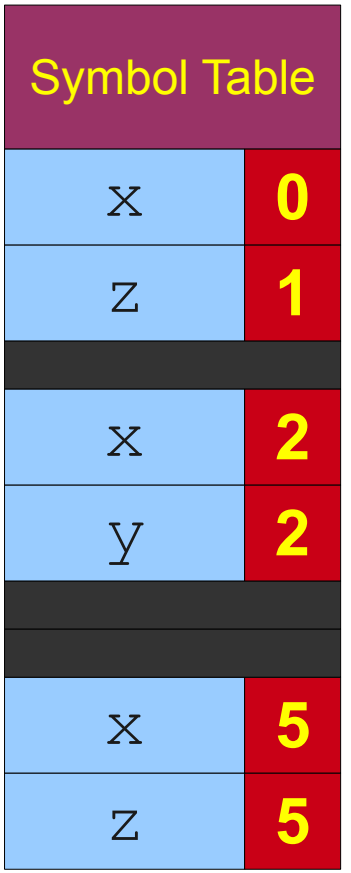

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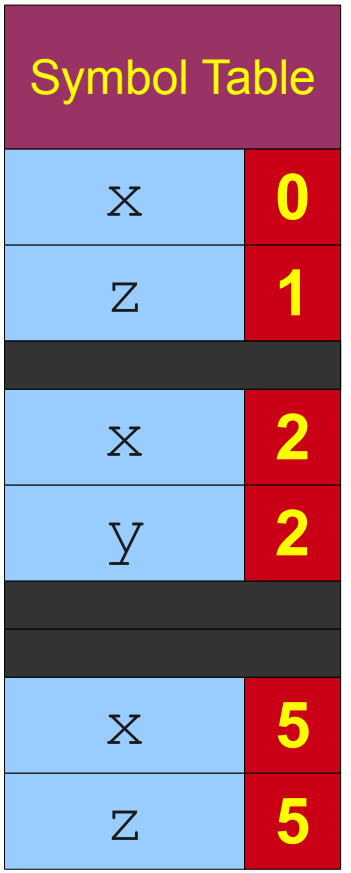

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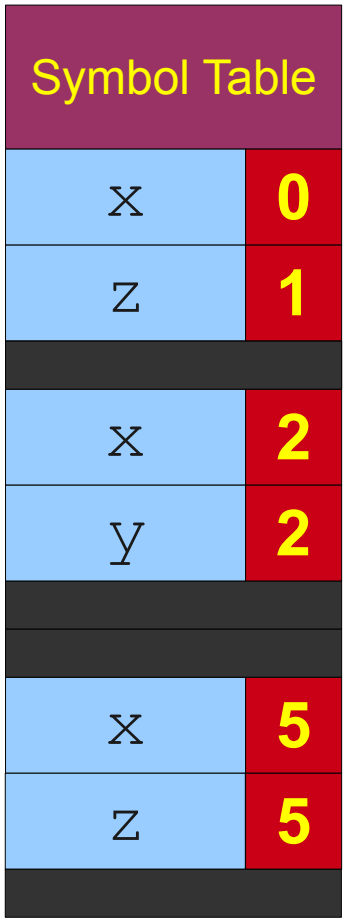

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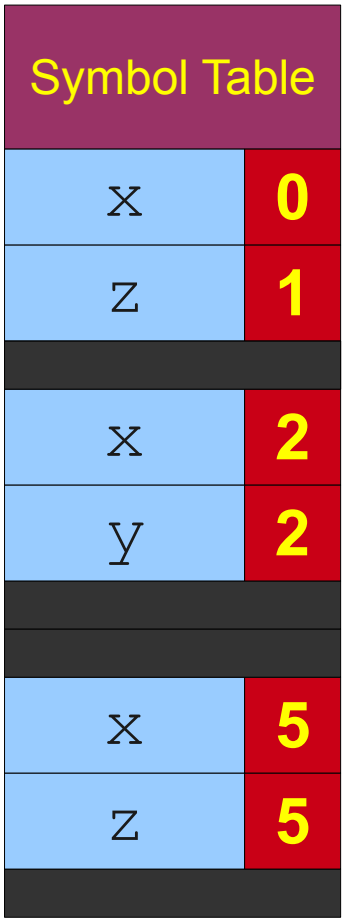

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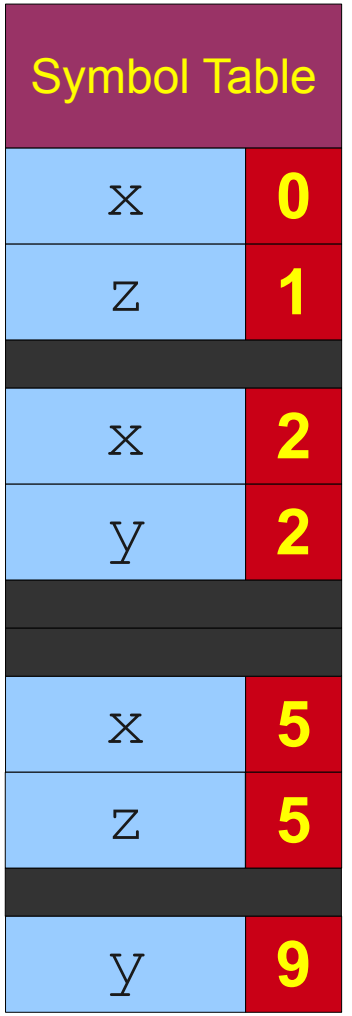

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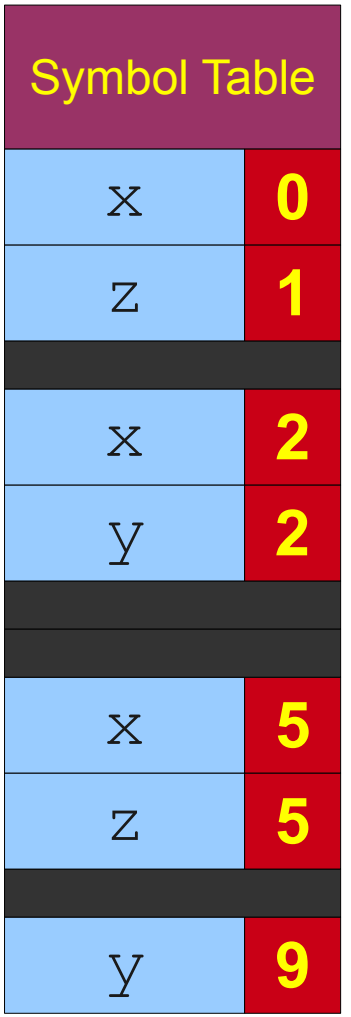

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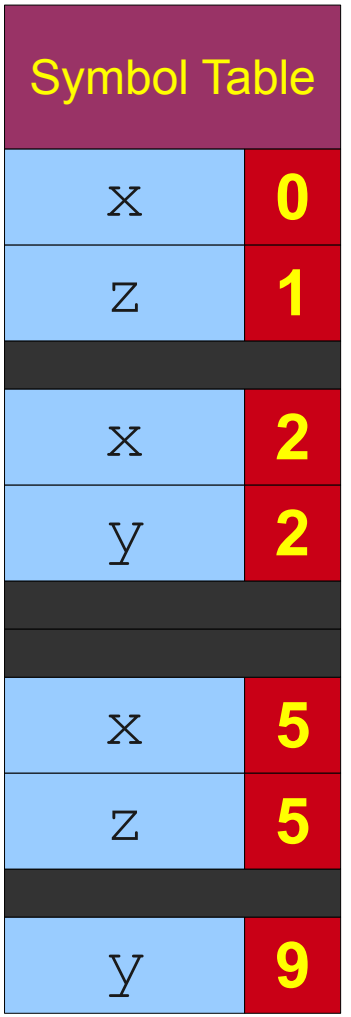

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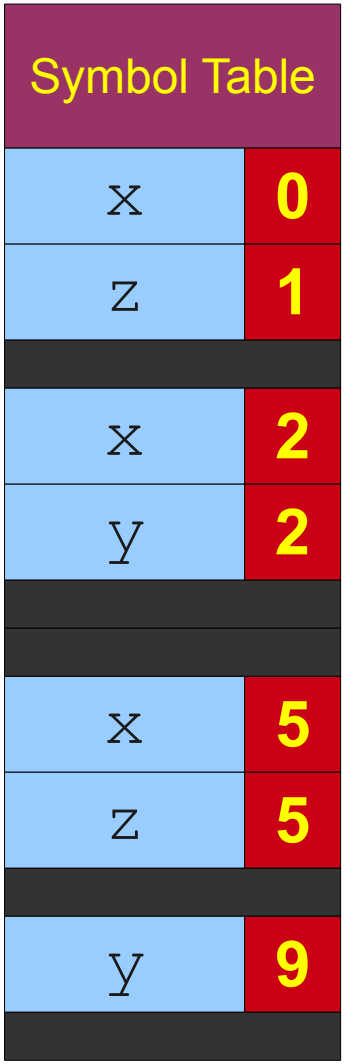

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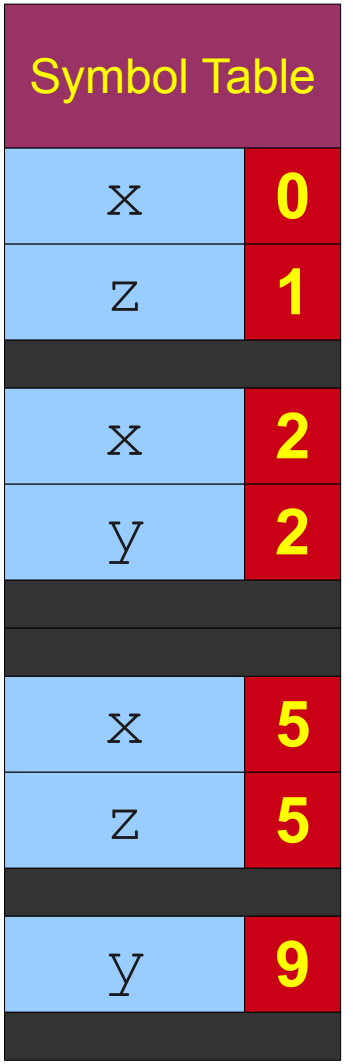

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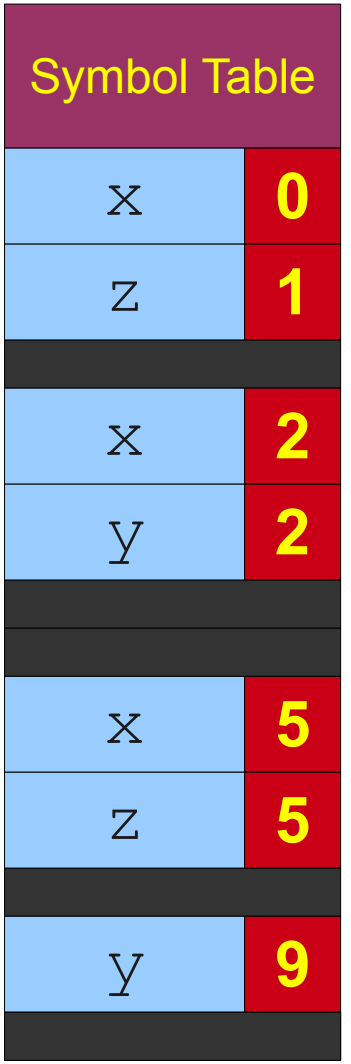

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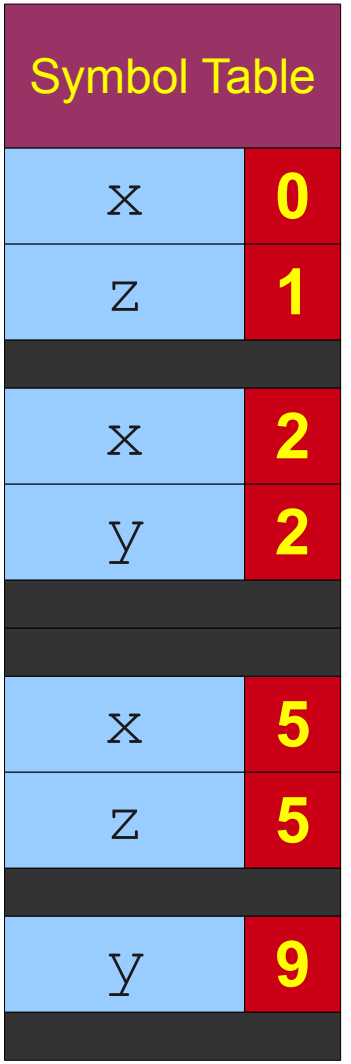

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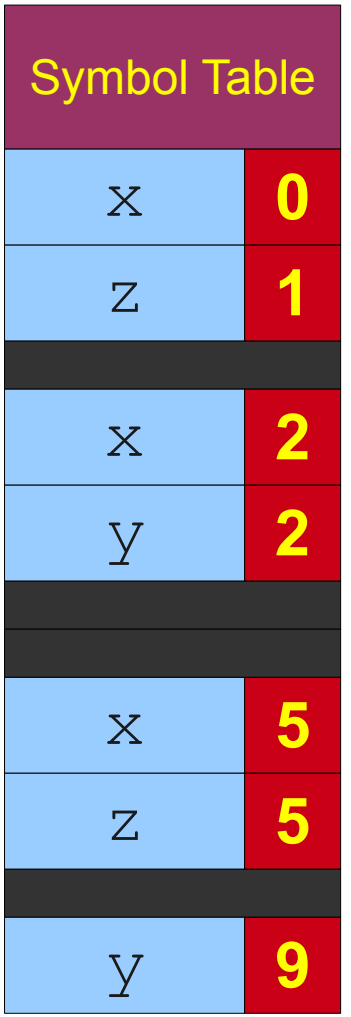

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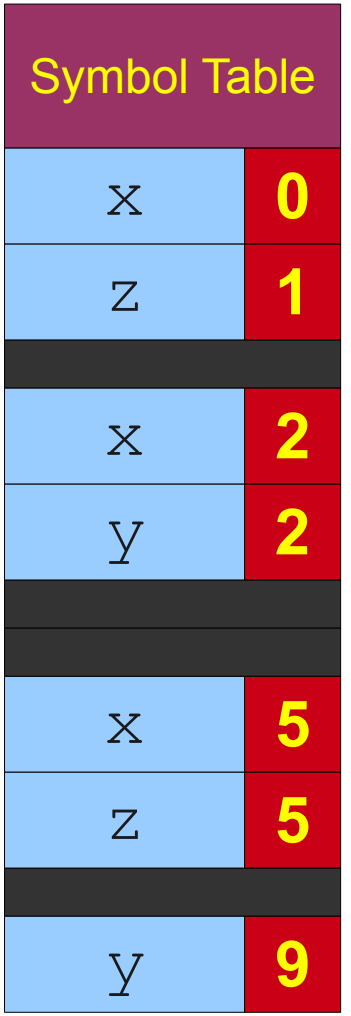

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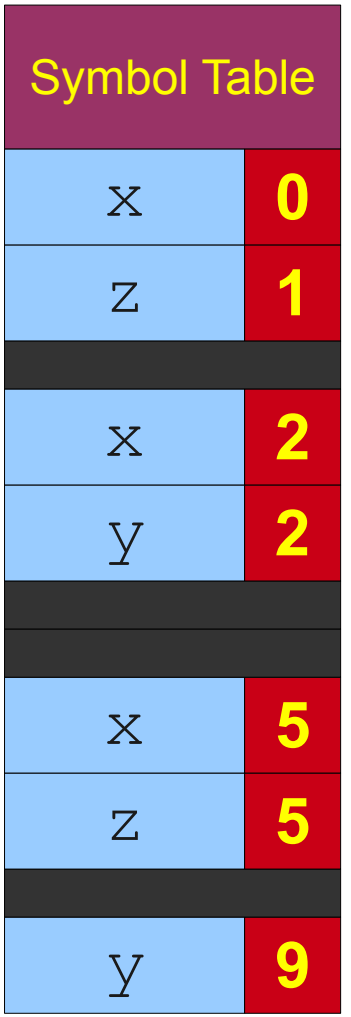

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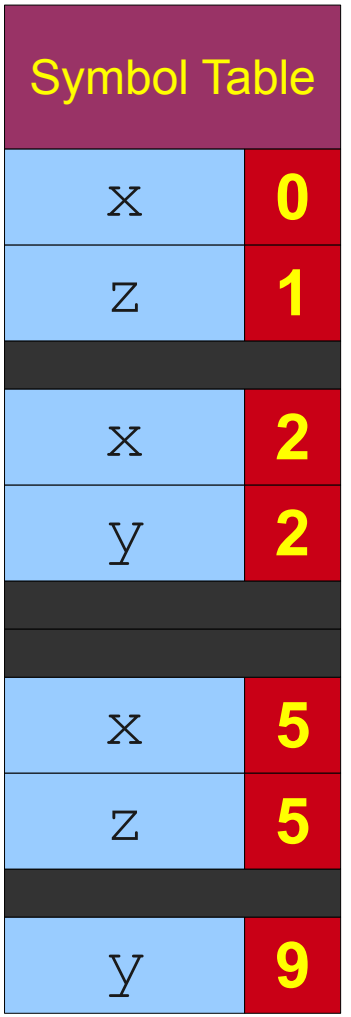

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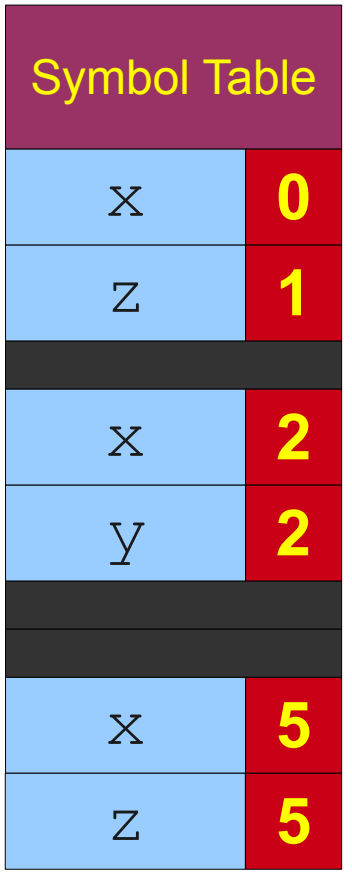

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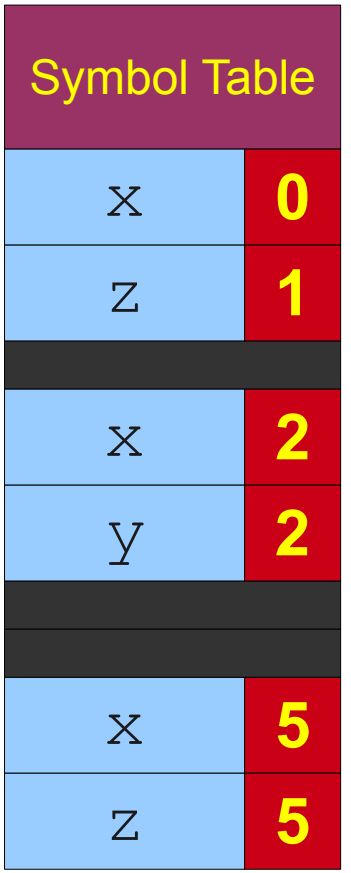

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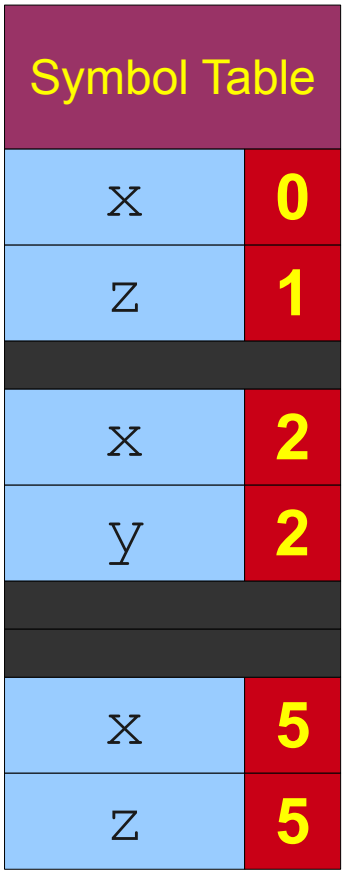

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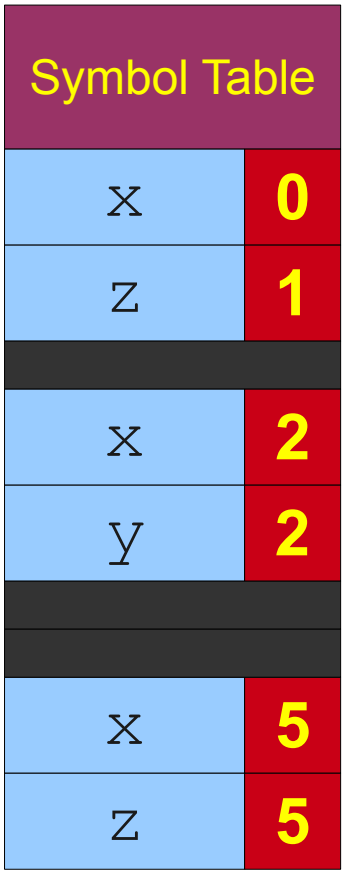

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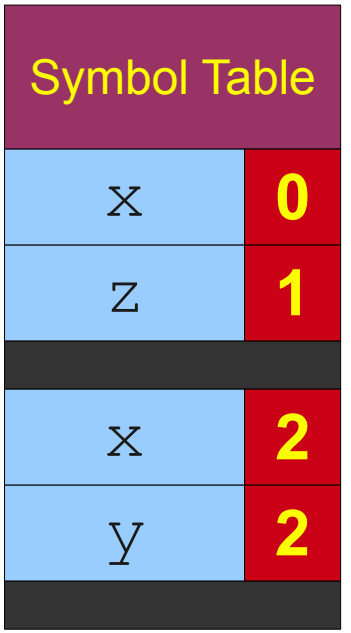

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 8:     {
 9:       int y = x@5;
10:       {
11:         printf("%d,%d,%d\n", x@5, y@9, z@5);
12:       }
13:       printf("%d,%d,%d\n", x@5, y@9, z@5);
14:     }
15:     printf("%d,%d,%d\n", x@5, y@2, z@5);
16:   }
17: }
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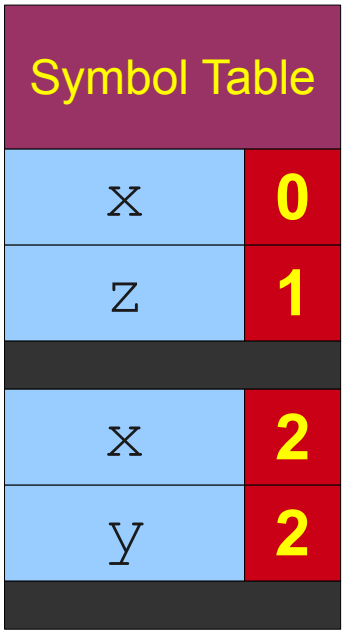

Symbol Tables: The Intuition

```
 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;
 6:     z = y@2;
 7:     x = z@5;
 8:     {
 9:       int y = x@5;
10:       {
11:         printf("%d,%d,%d\n", x@5, y@9, z@5);
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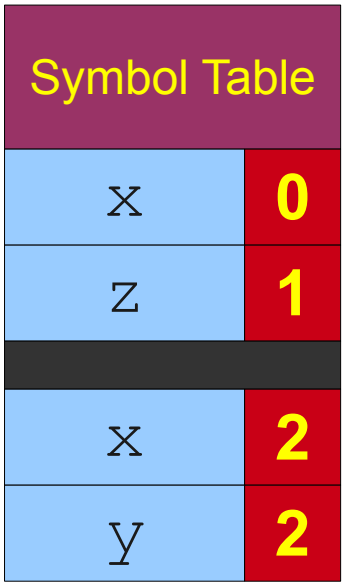

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```

Symbol Table	
x	0
z	1

Symbol Tables: The Intuition

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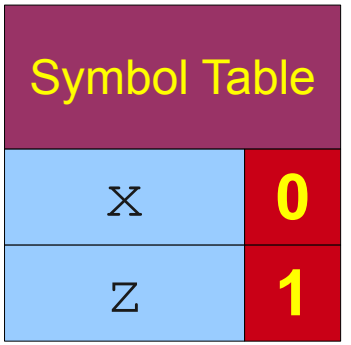

Symbol Table Operations

- Typically implemented as a **stack of tables**.
- Each table 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

```
 0: int x;
 1: int y;
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 3: {
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Another View of Symbol Tables

Root Scope

```
 0: int x;
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Another View of Symbol Tables

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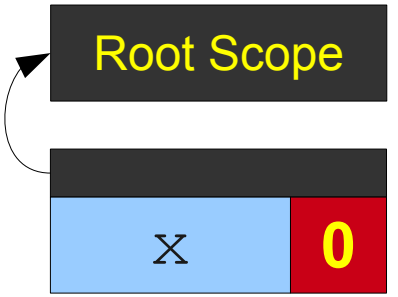
Another View of Symbol Tables

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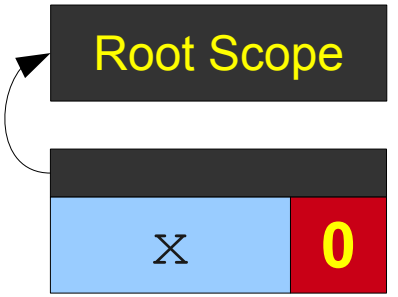


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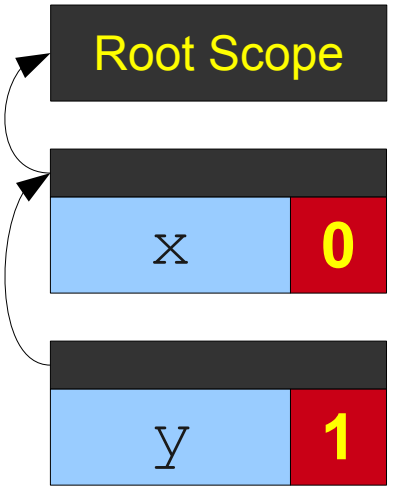

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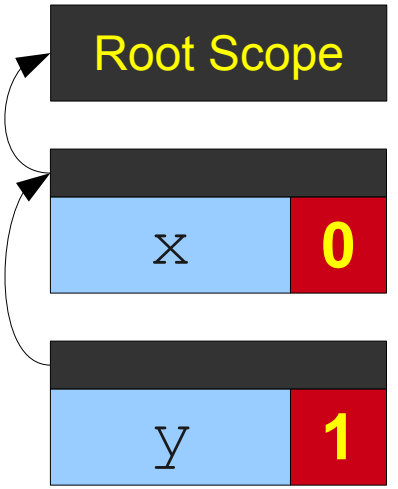

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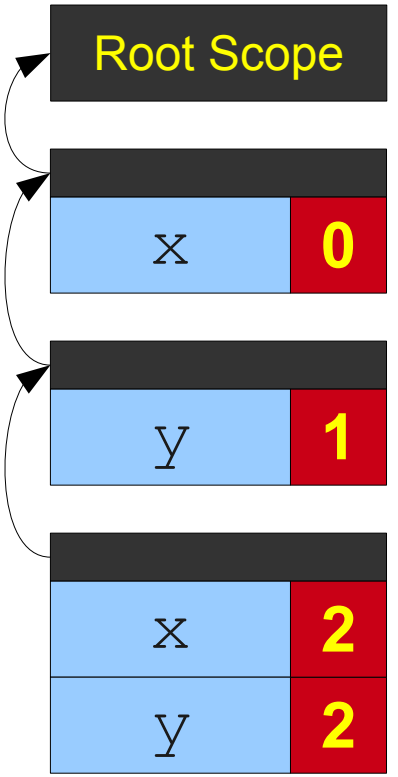

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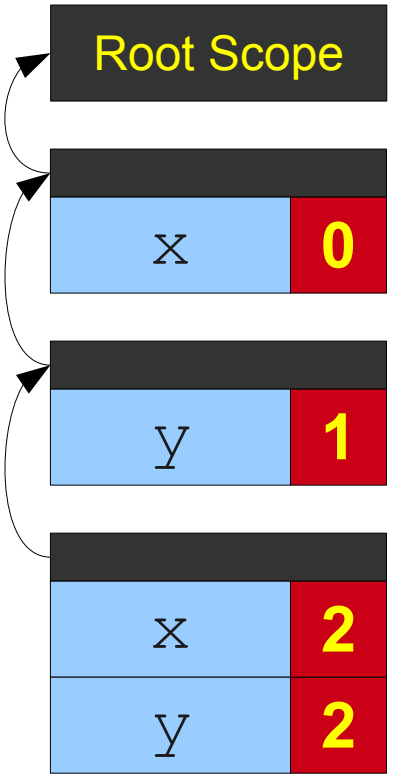

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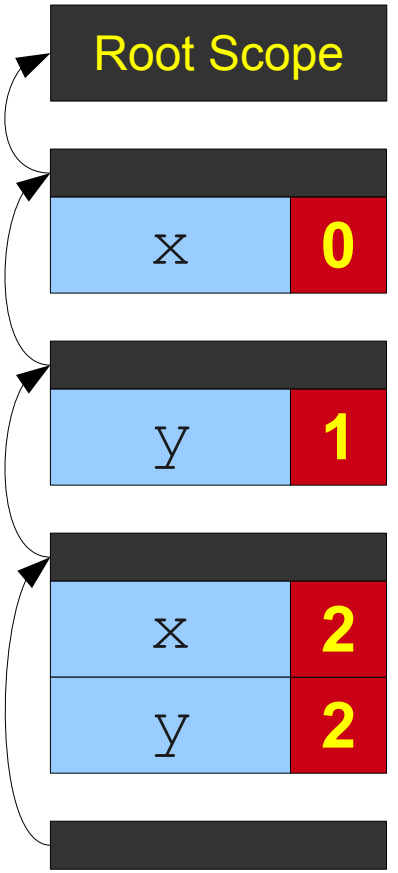

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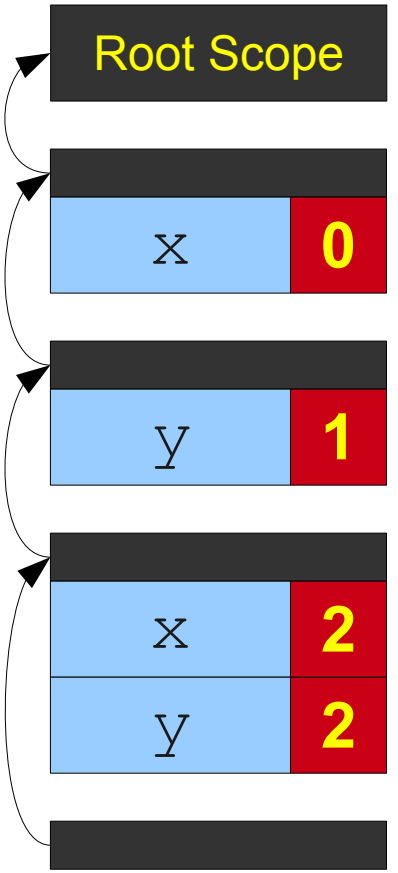

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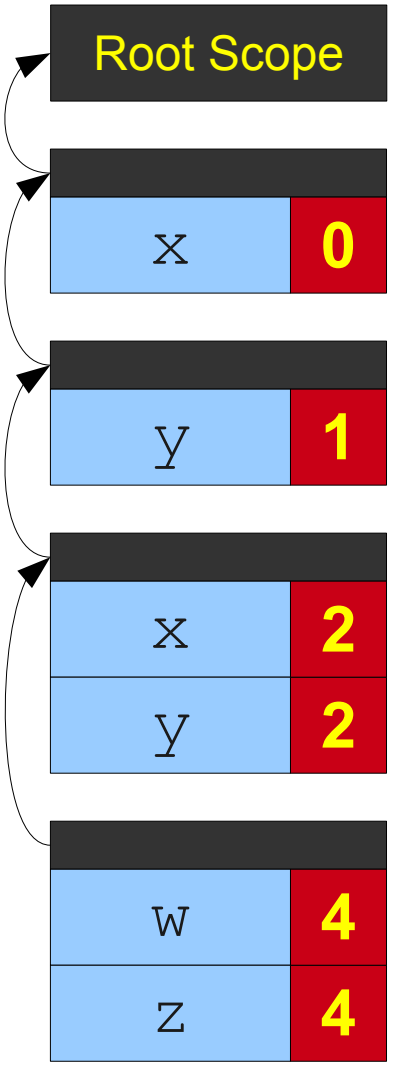

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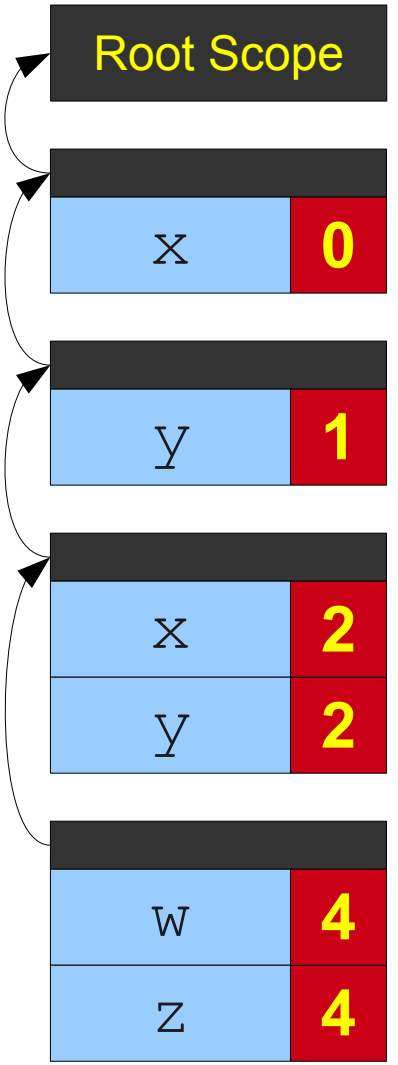

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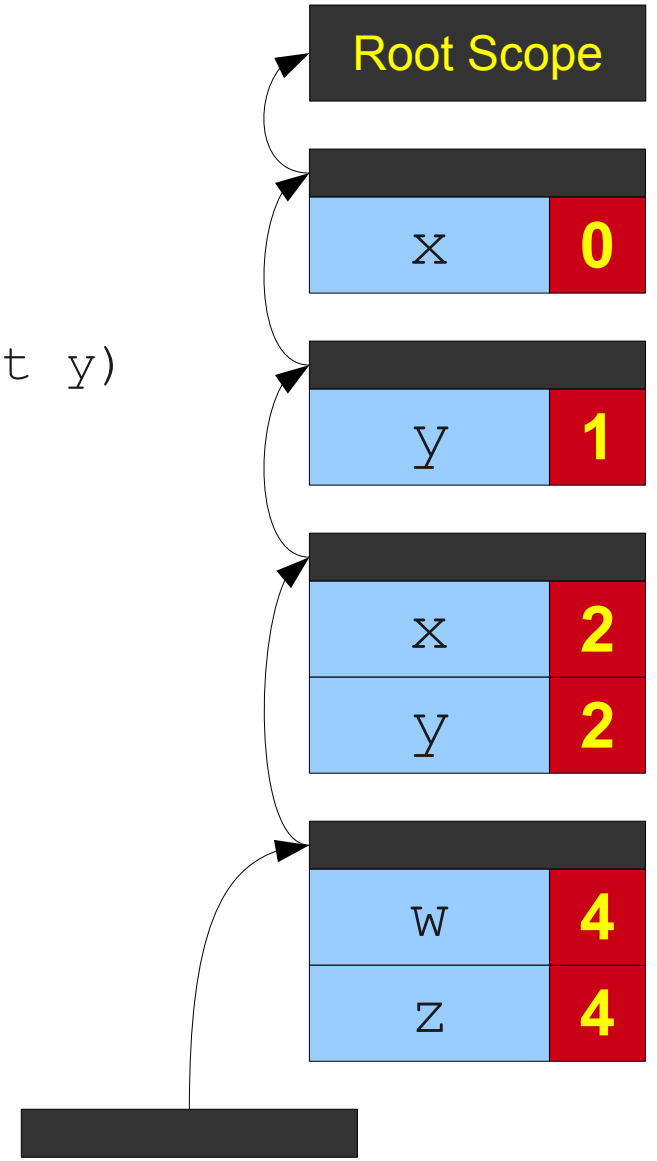

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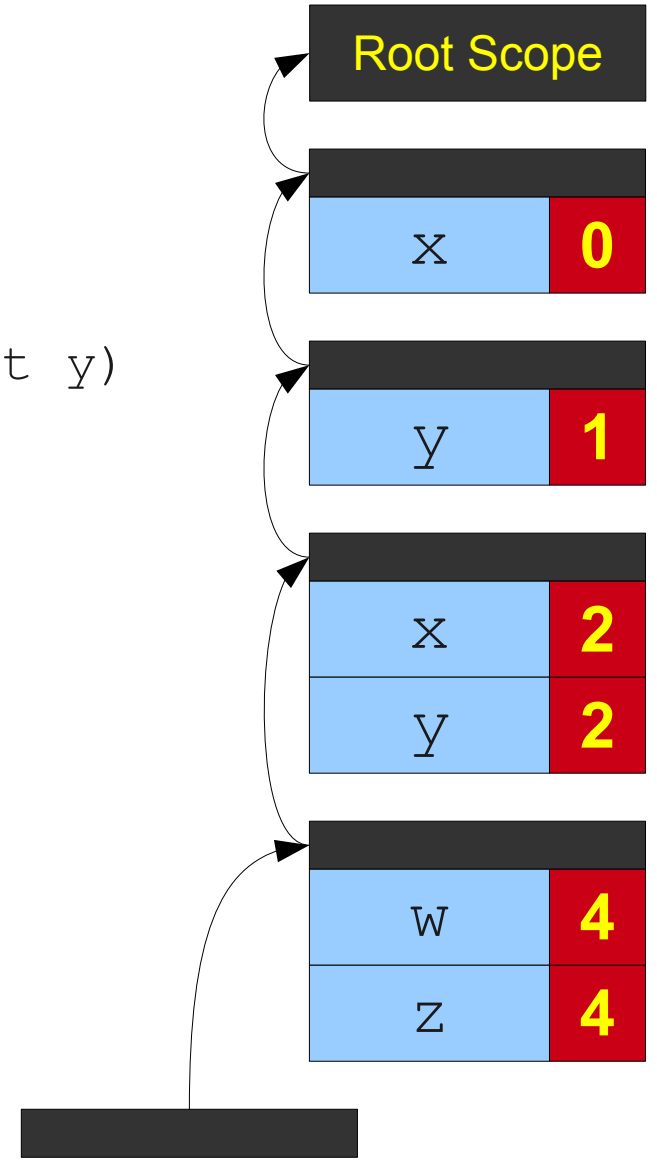

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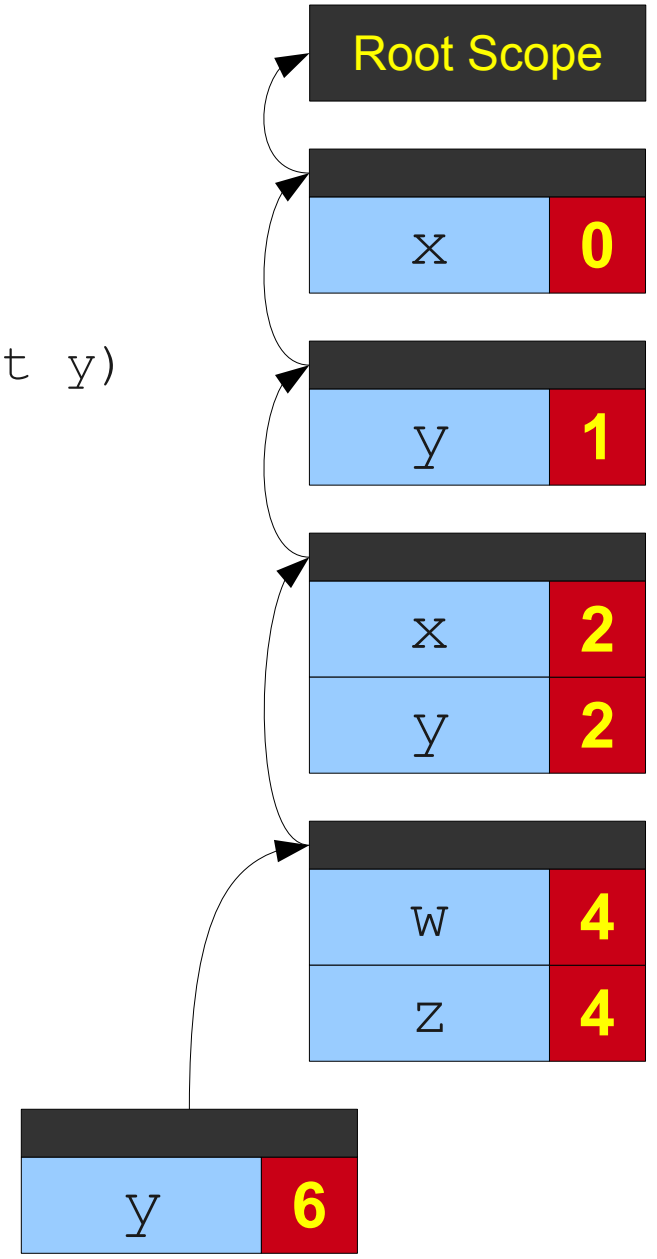

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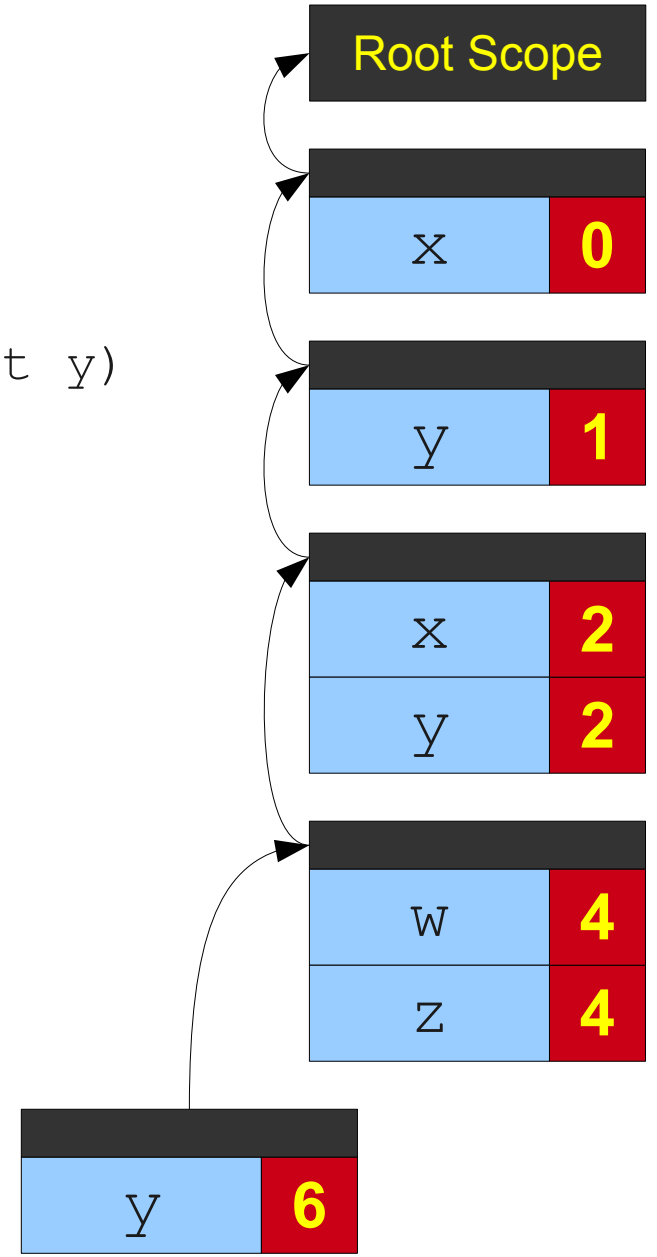

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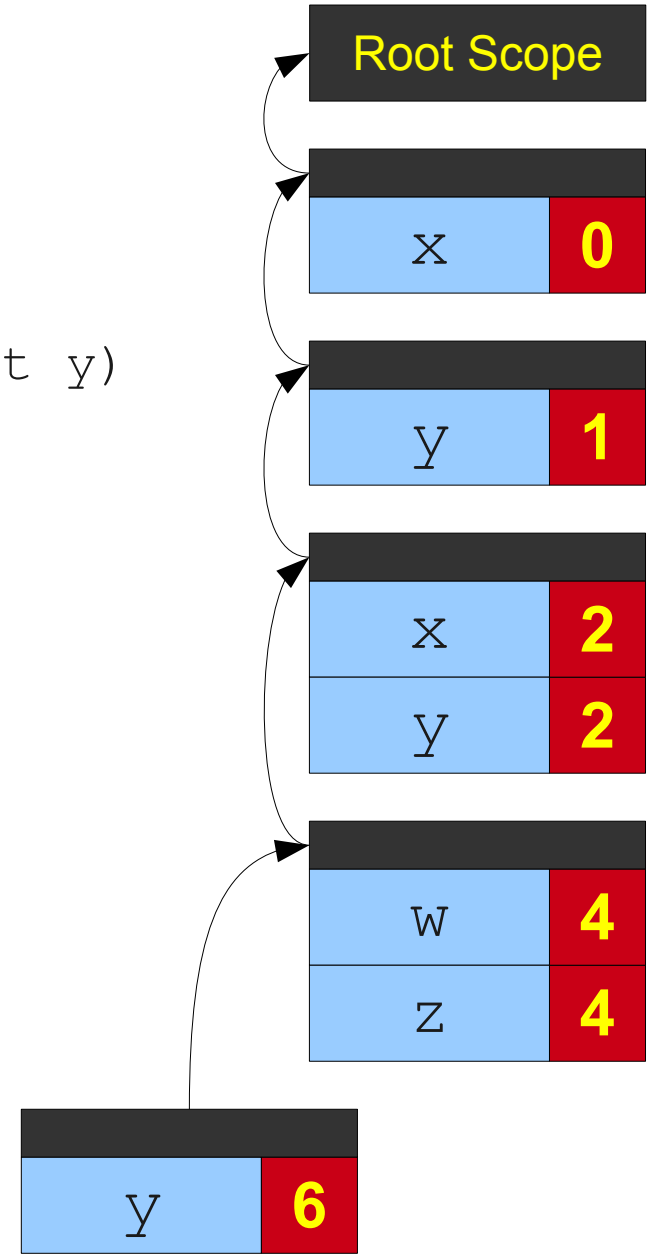

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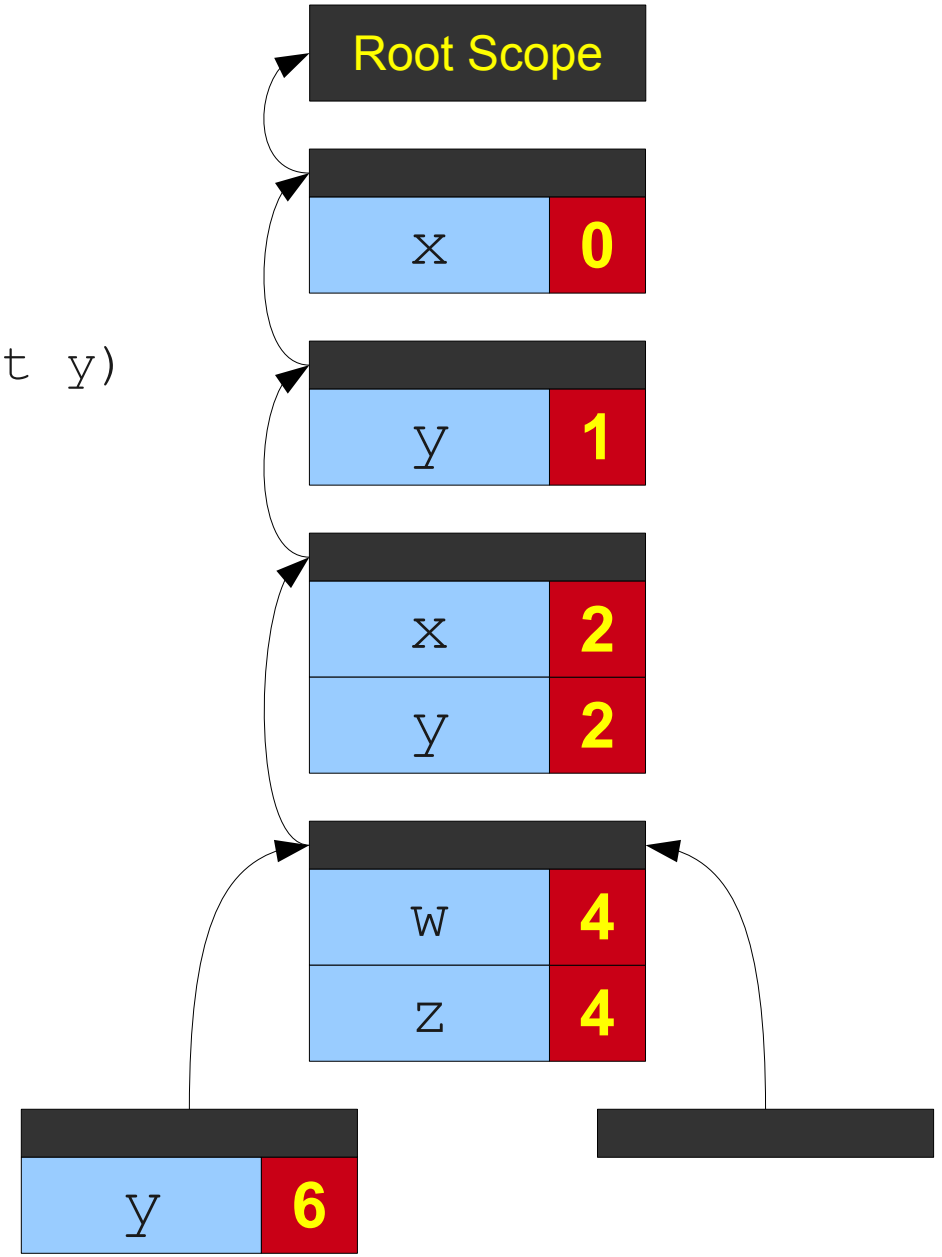

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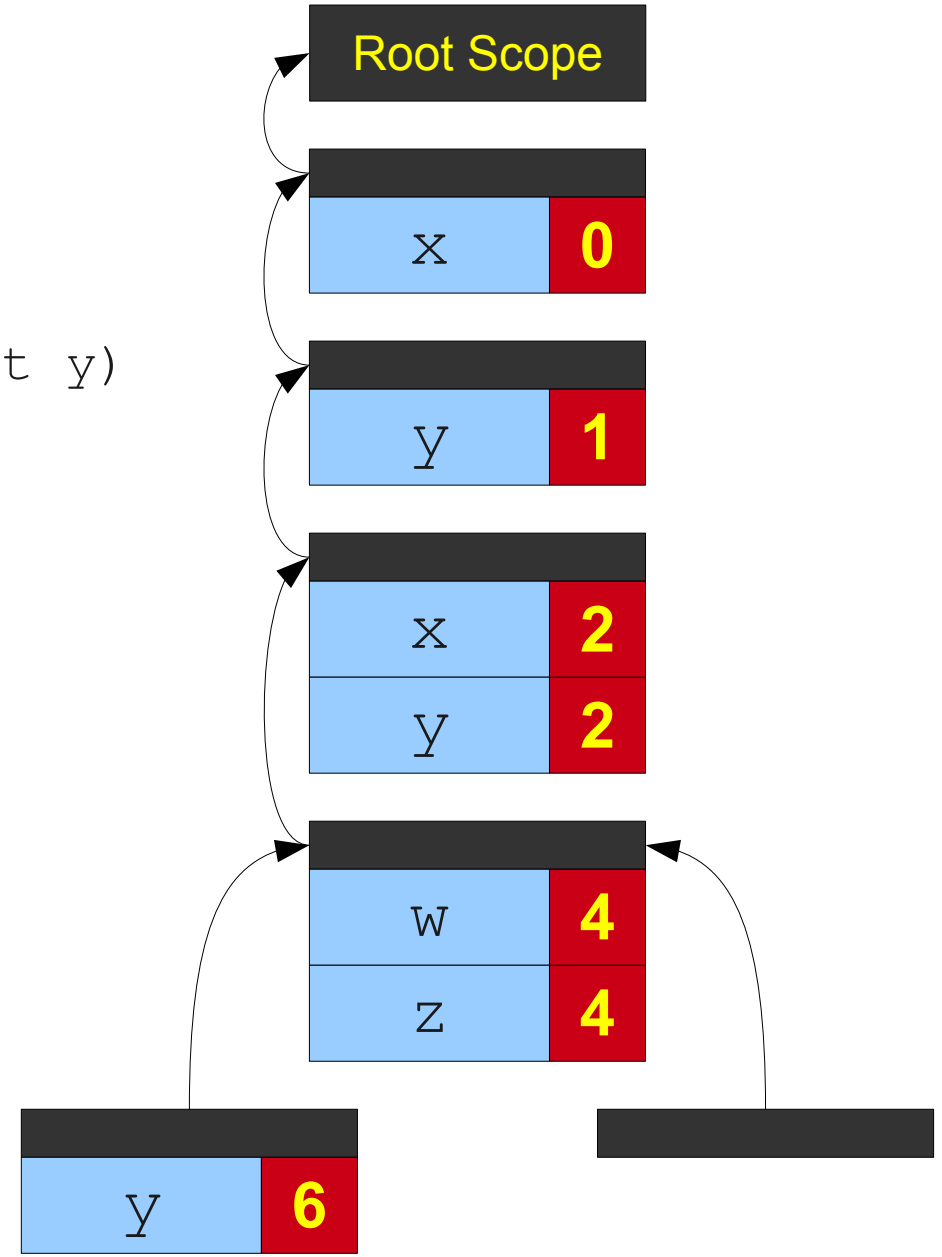

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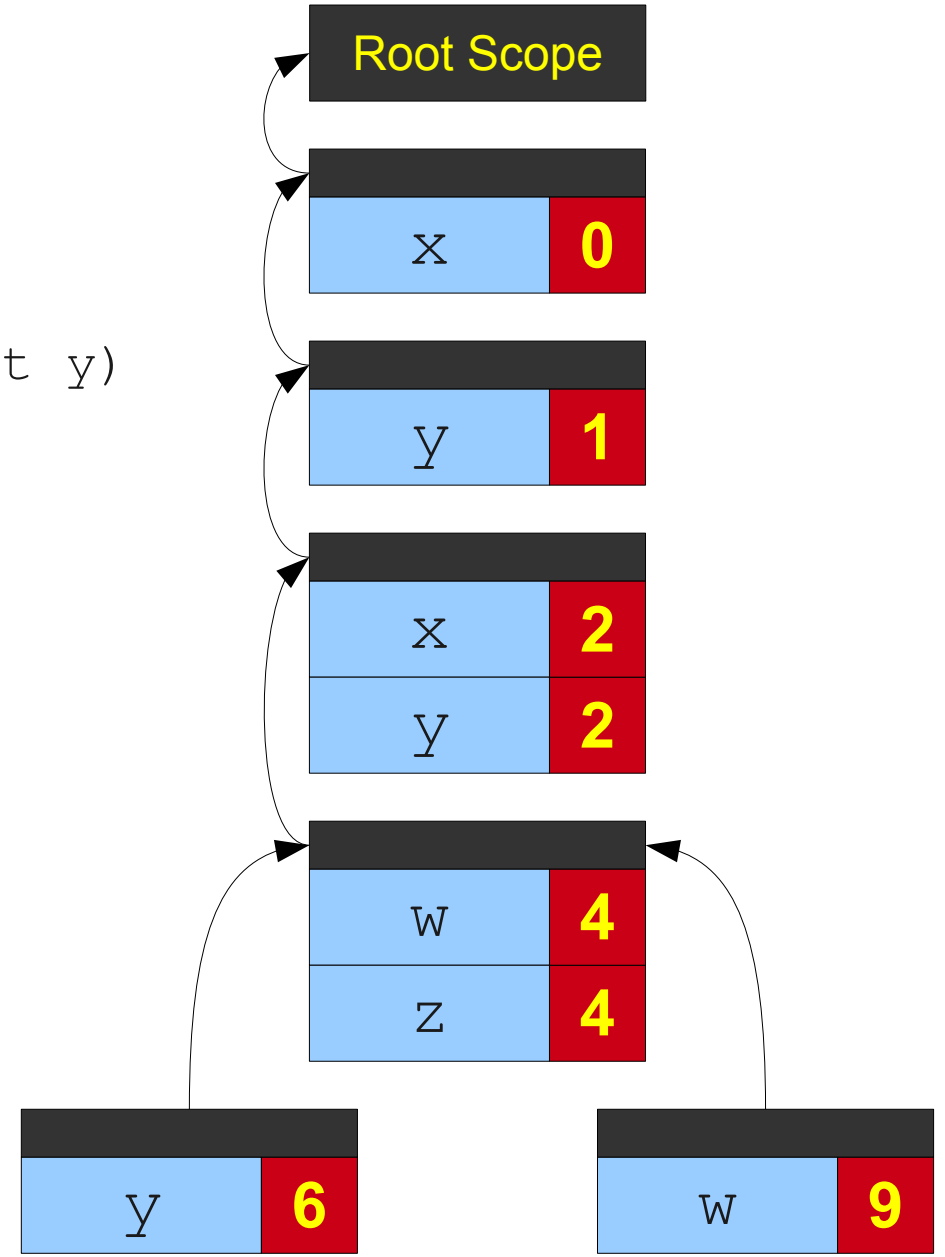

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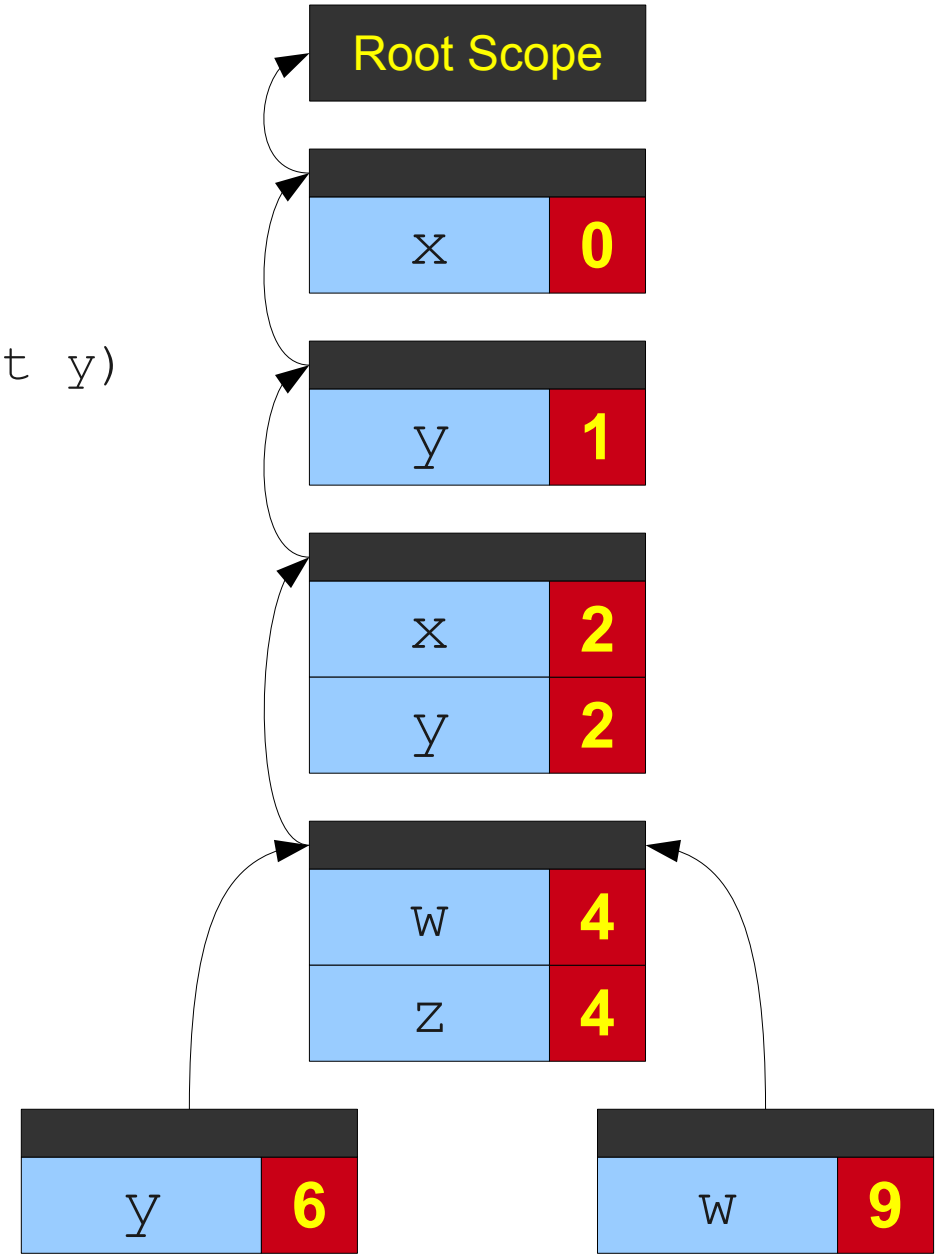

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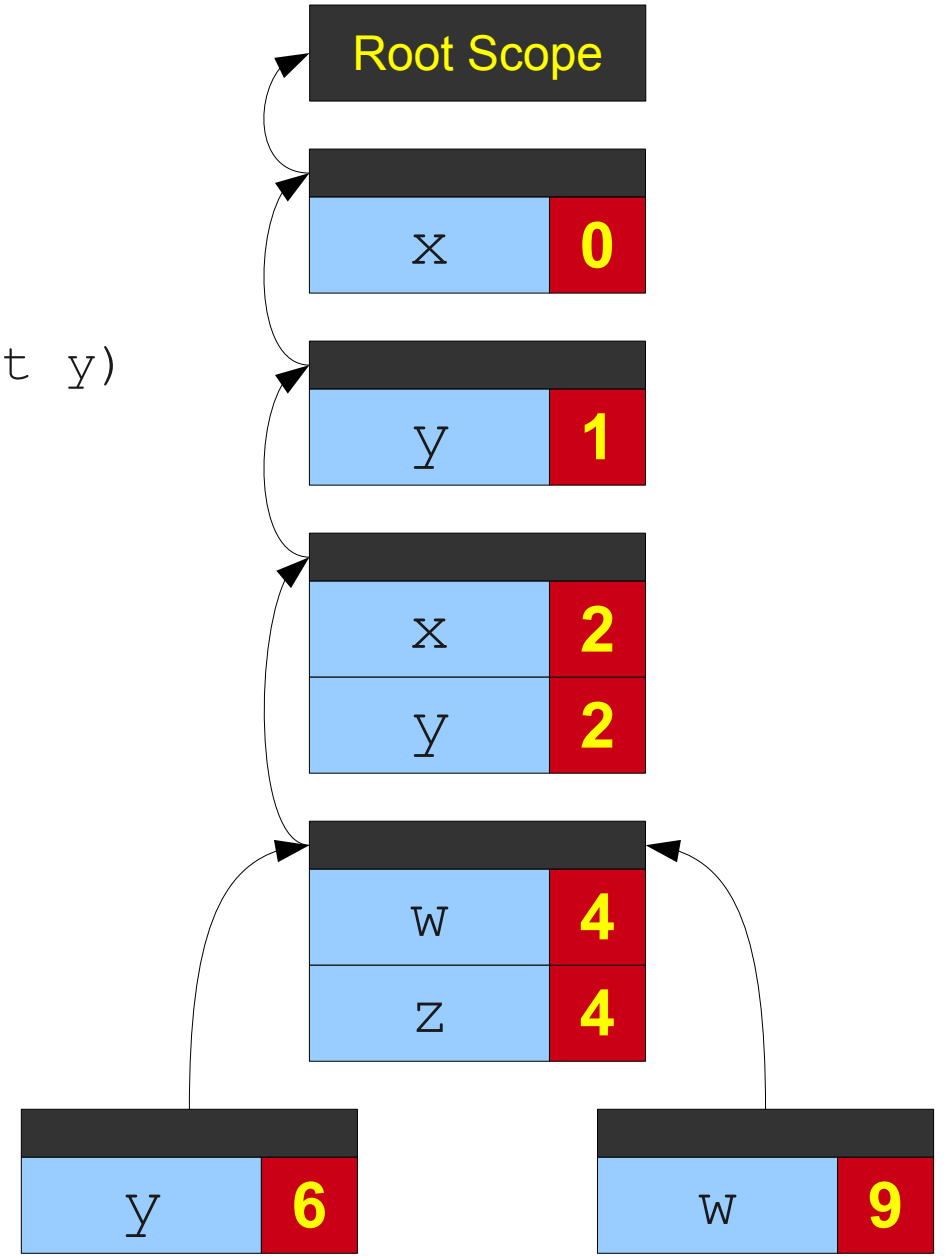

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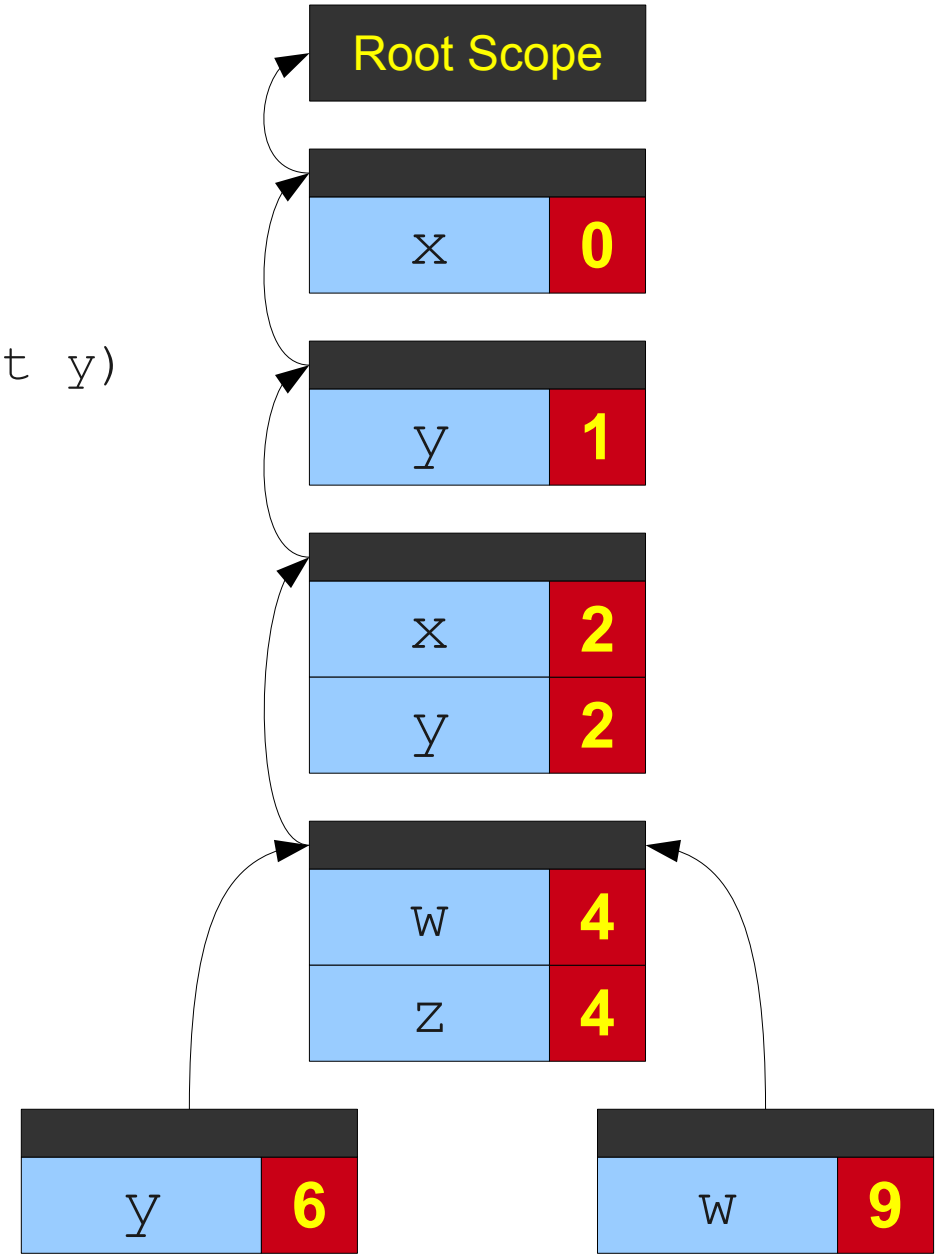

Spaghetti Stacks

- 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

```
public class Base {
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Scoping with Inheritance

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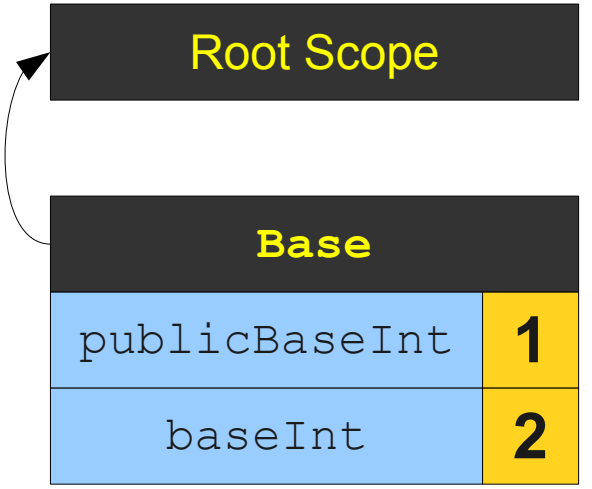


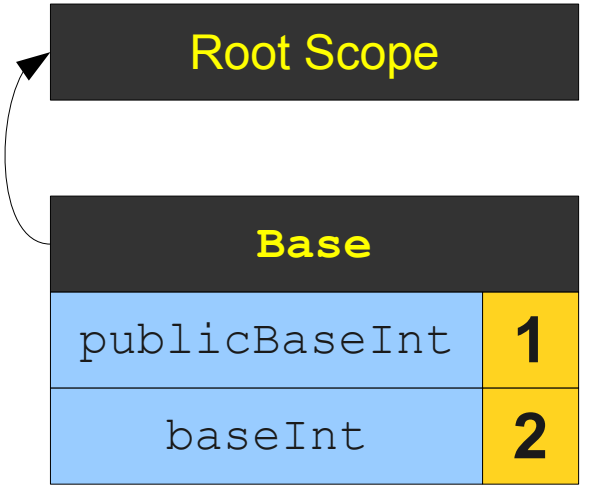
Scoping with Inheritance

```
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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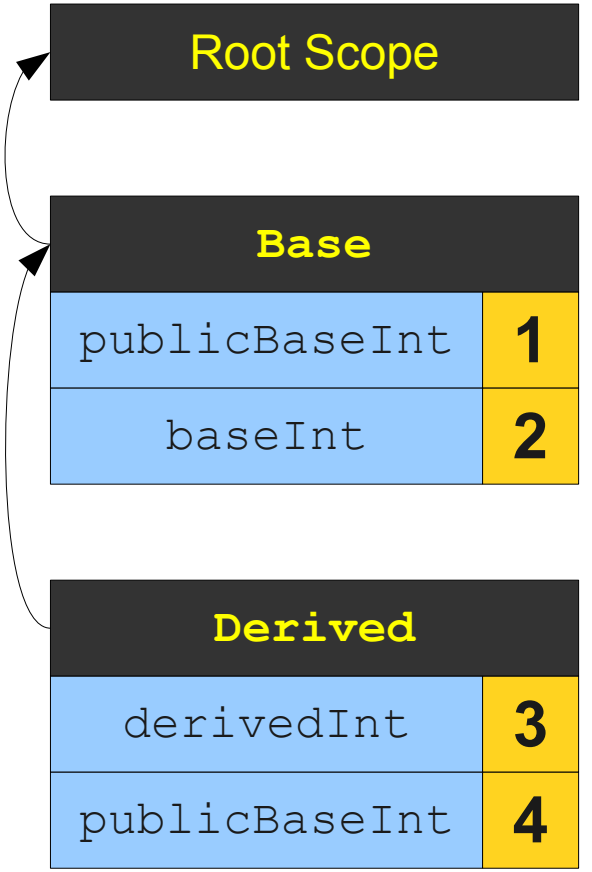

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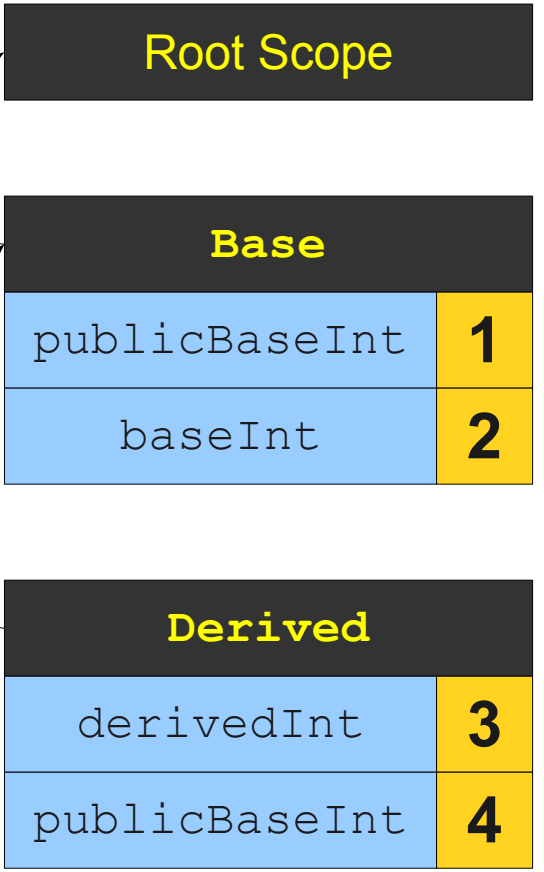

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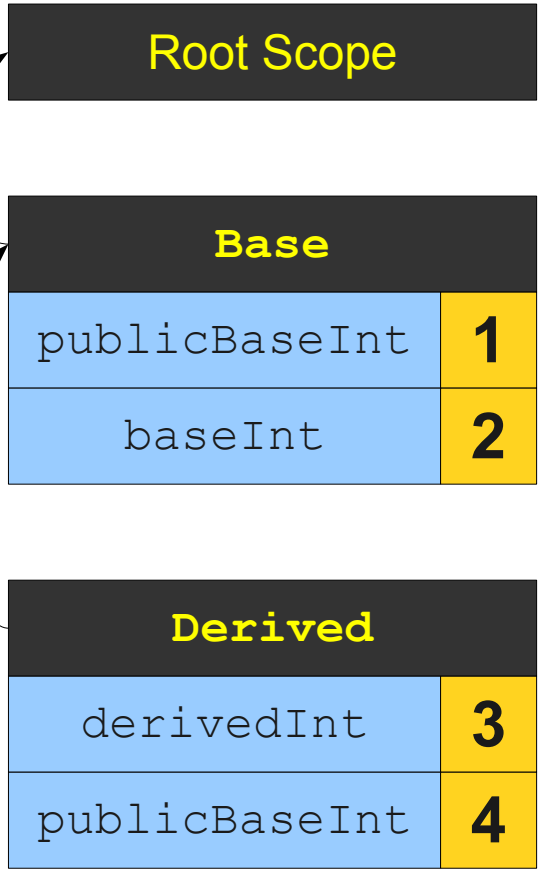

Scoping with Inheritance

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

public class Derived extends Base {
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        int publicBaseInt = 6;
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}
```
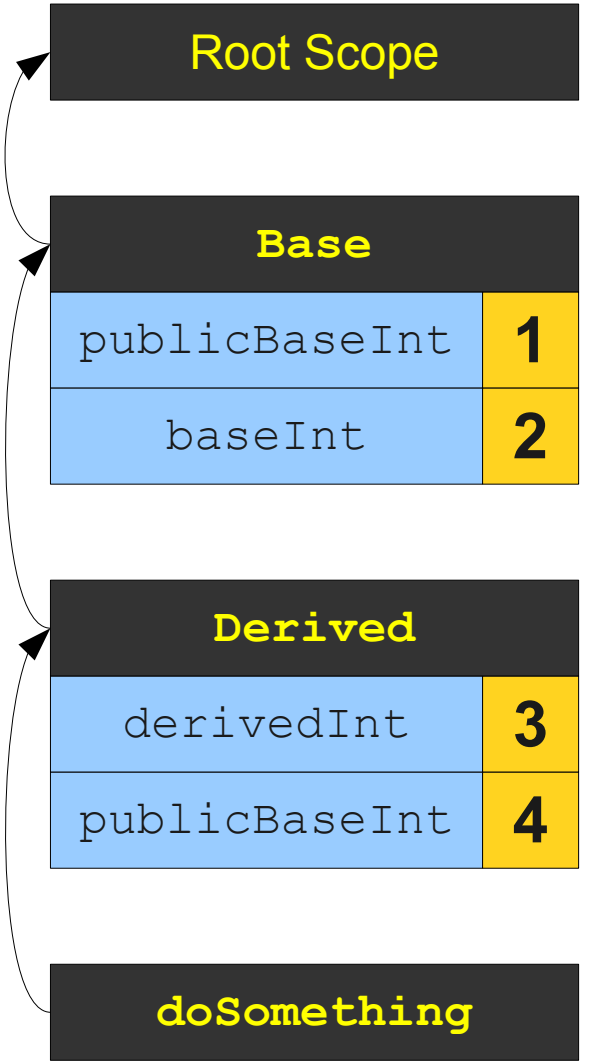

```
>
```



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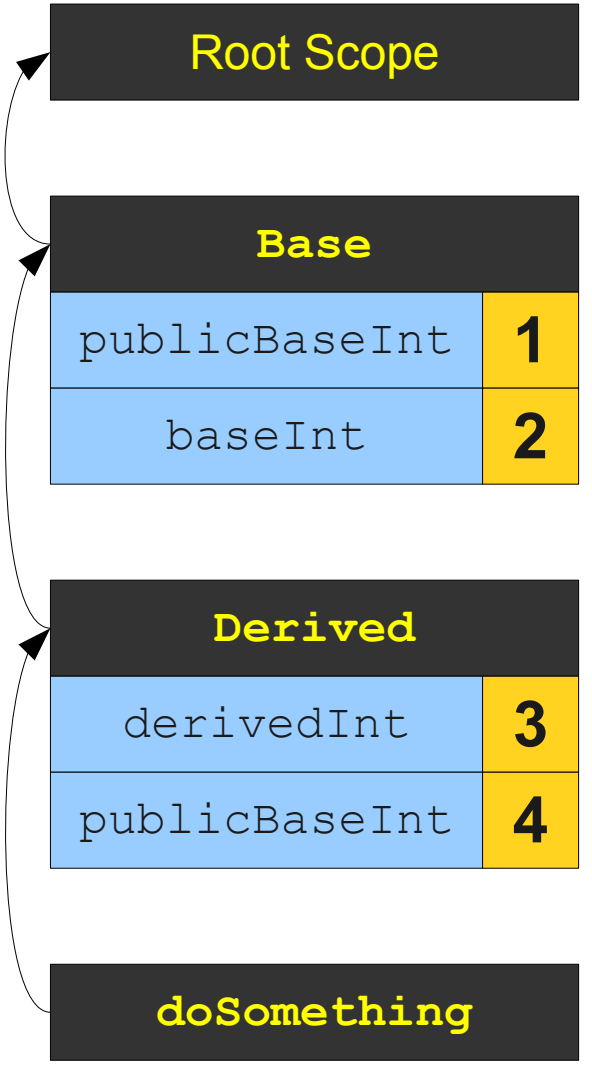
>
```



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```
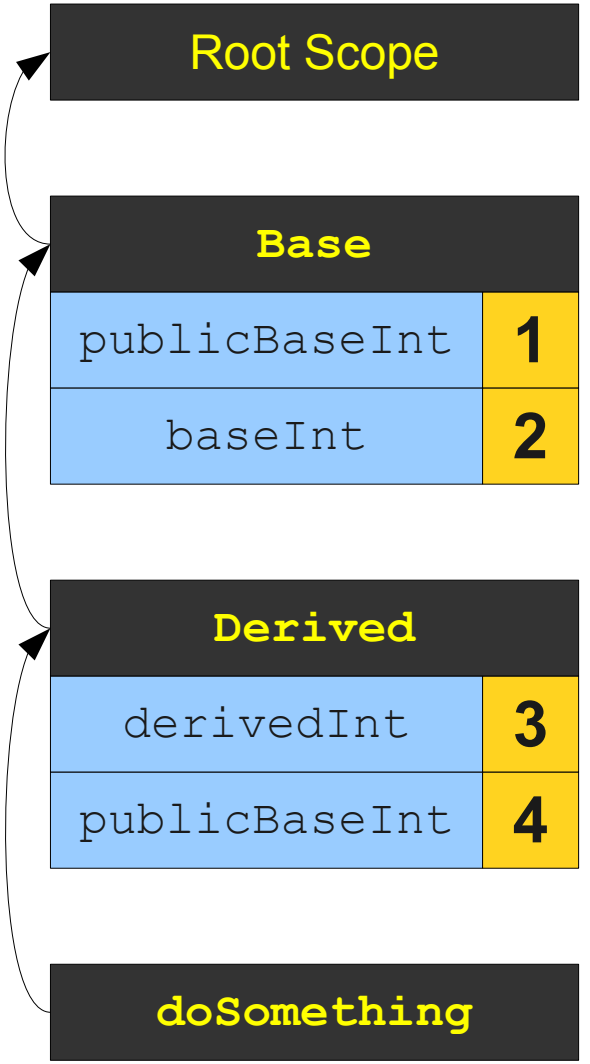

```
> 4
```



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> 4
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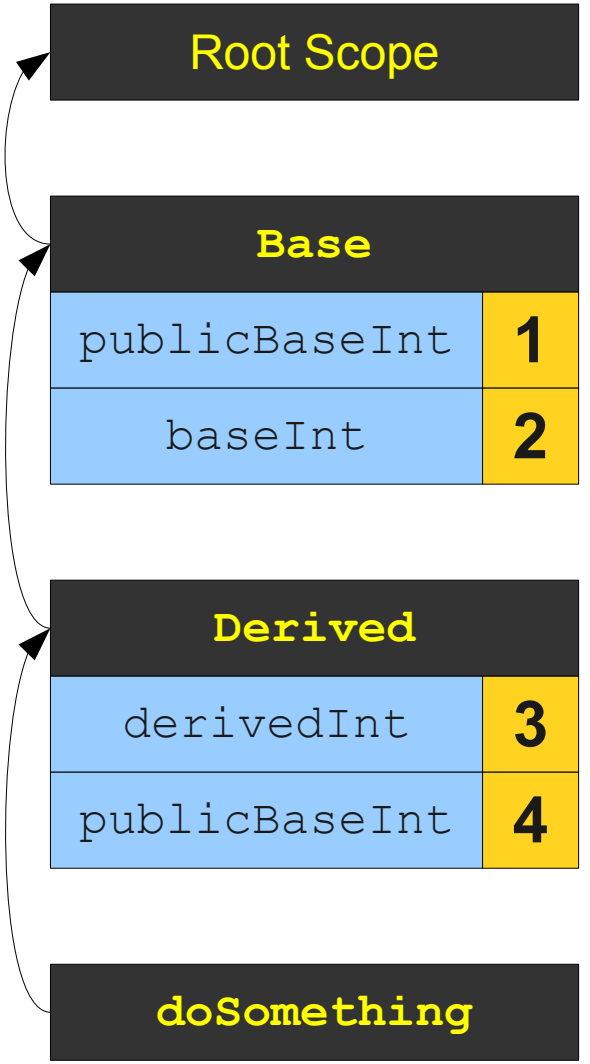

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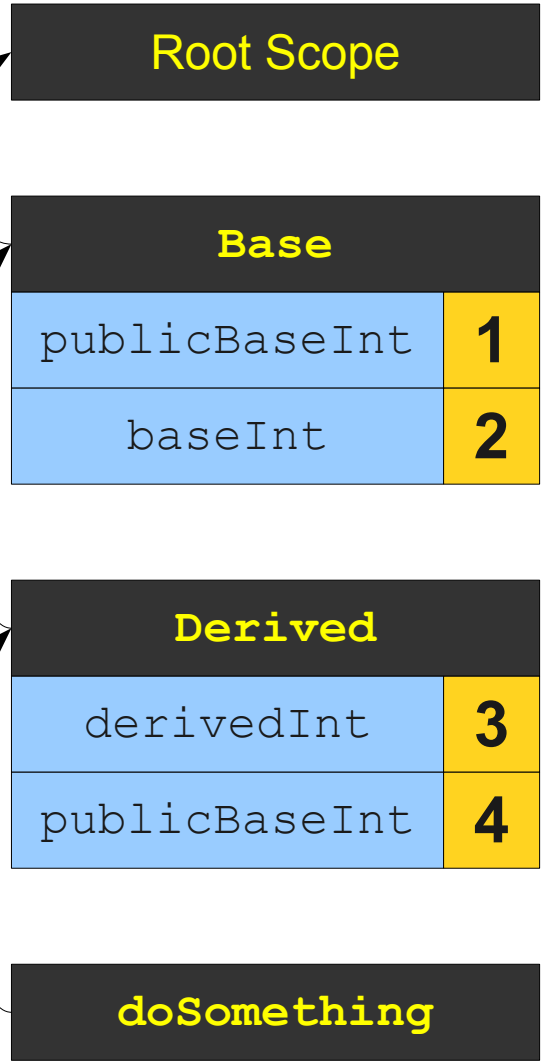
```

```
> 4
  2
```



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```
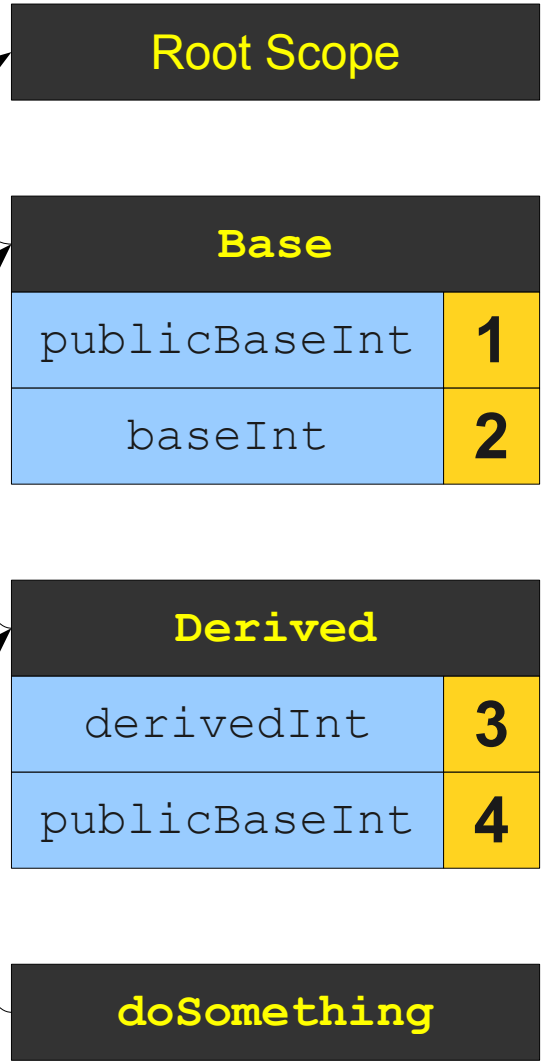

```
> 4
  2
```



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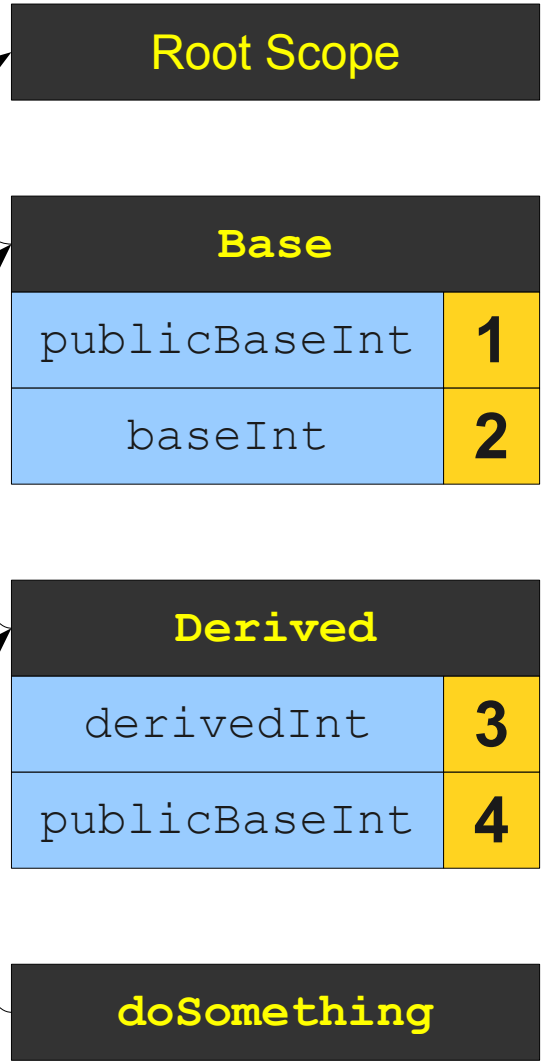
```

```
> 4
  2
  3
```



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    }
}
```
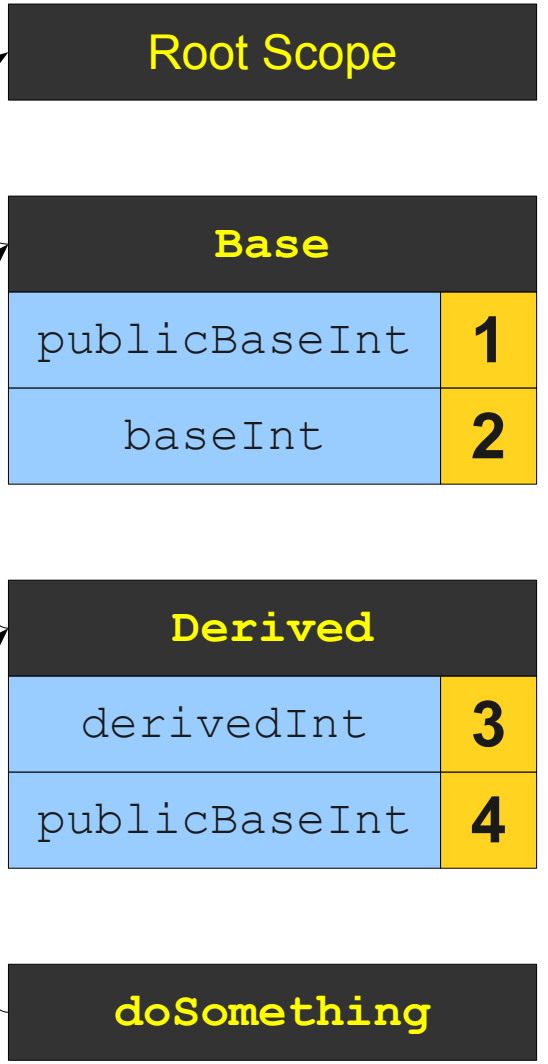

```
> 4
  2
  3
```



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        int publicBaseInt = 6;
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    }
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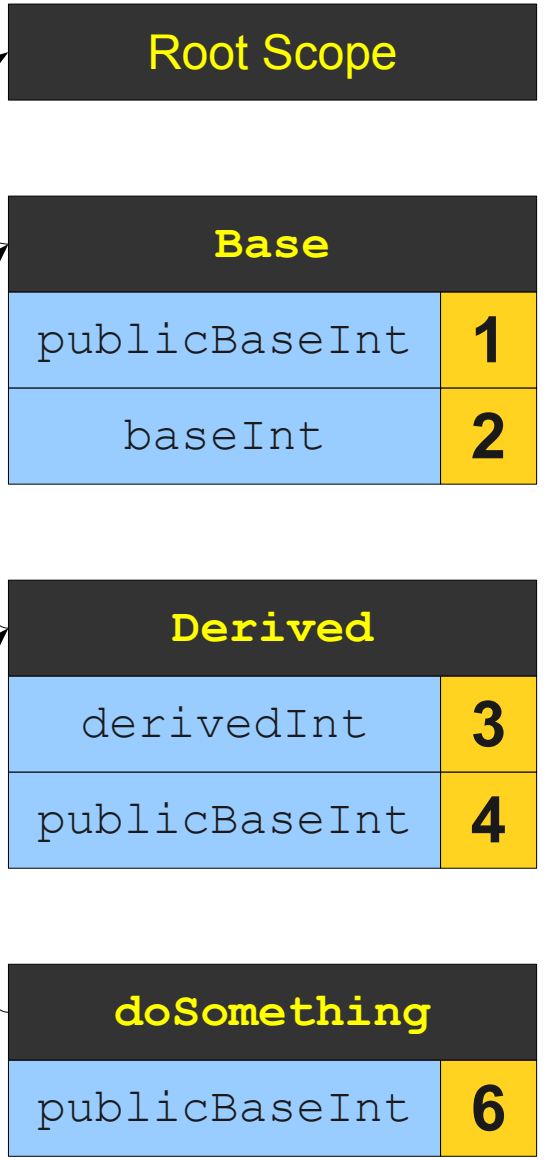
```

```
> 4
  2
  3
```



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```
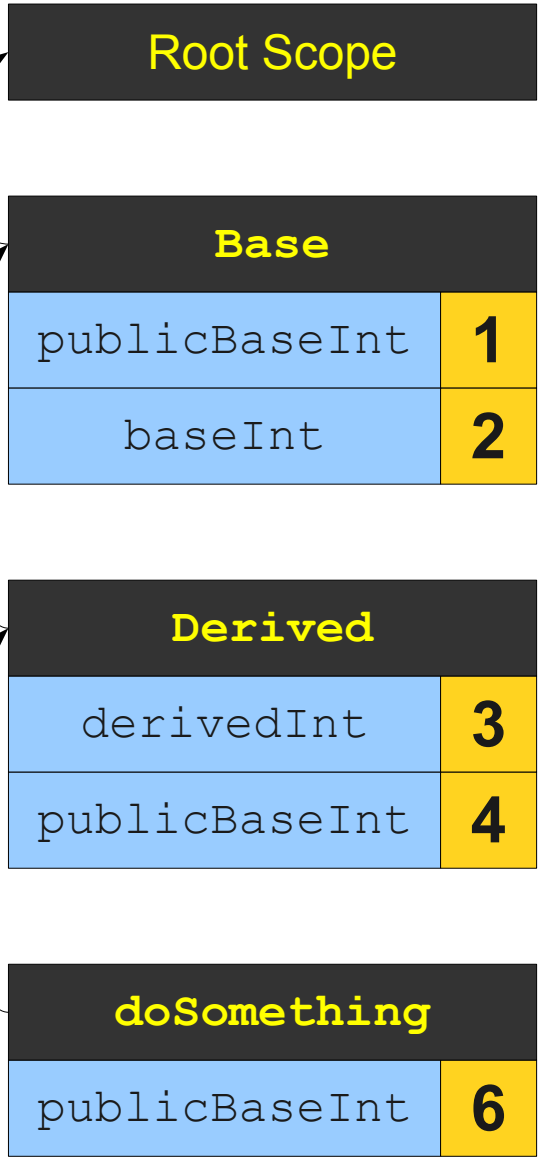

```
> 4
  2
  3
```



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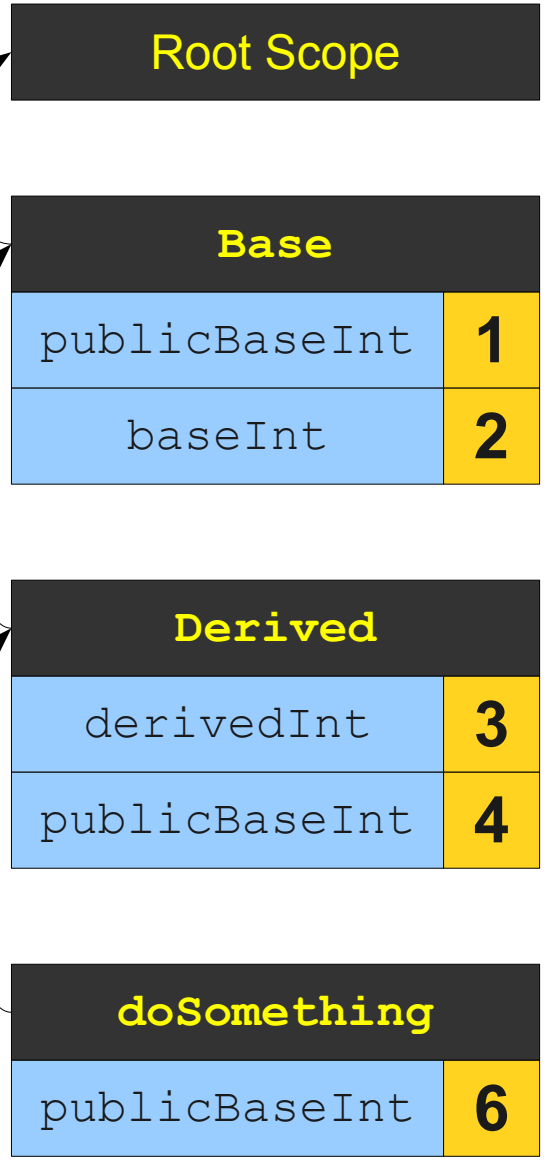
```

```
> 4
  2
  3
  6
```



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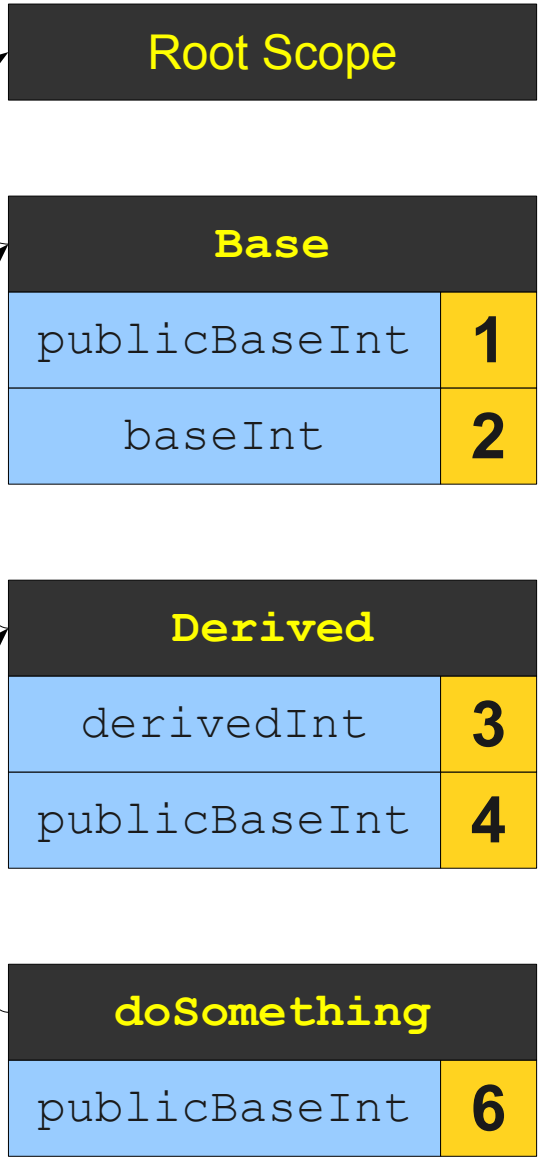
```
> 4
  2
  3
  6
```



Inheritance and Scoping

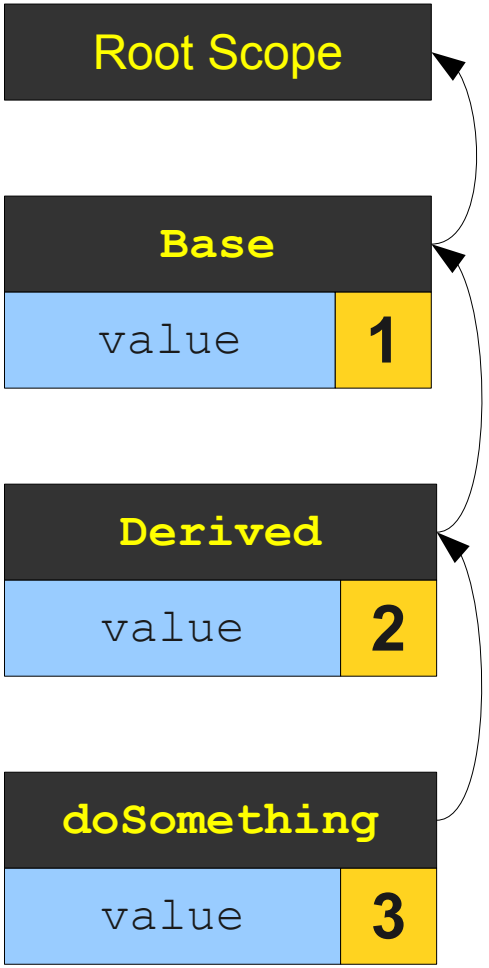
- Typically, the scope for a derived class will store a link to the scope of its base class.
- Looking up a field of a class traverses the scope chain until that field is found or a semantic error is found.

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);
    }
}
```



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}
```

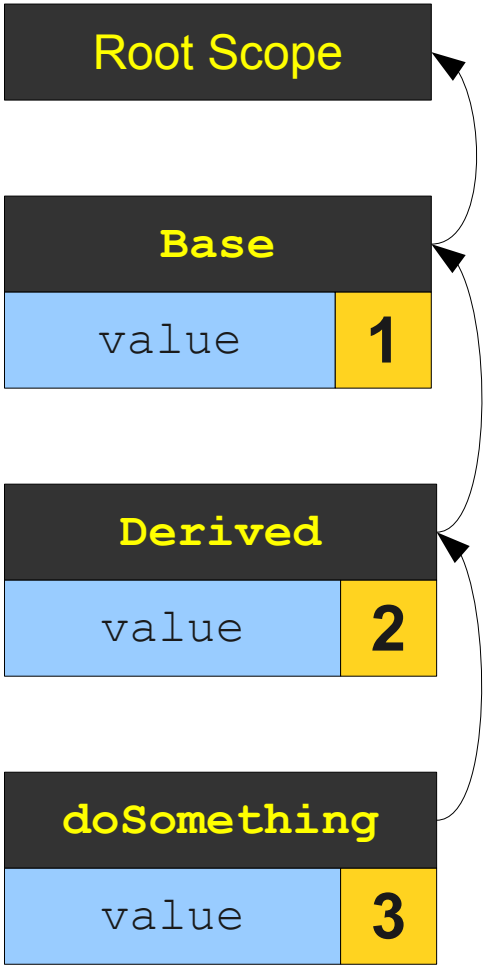

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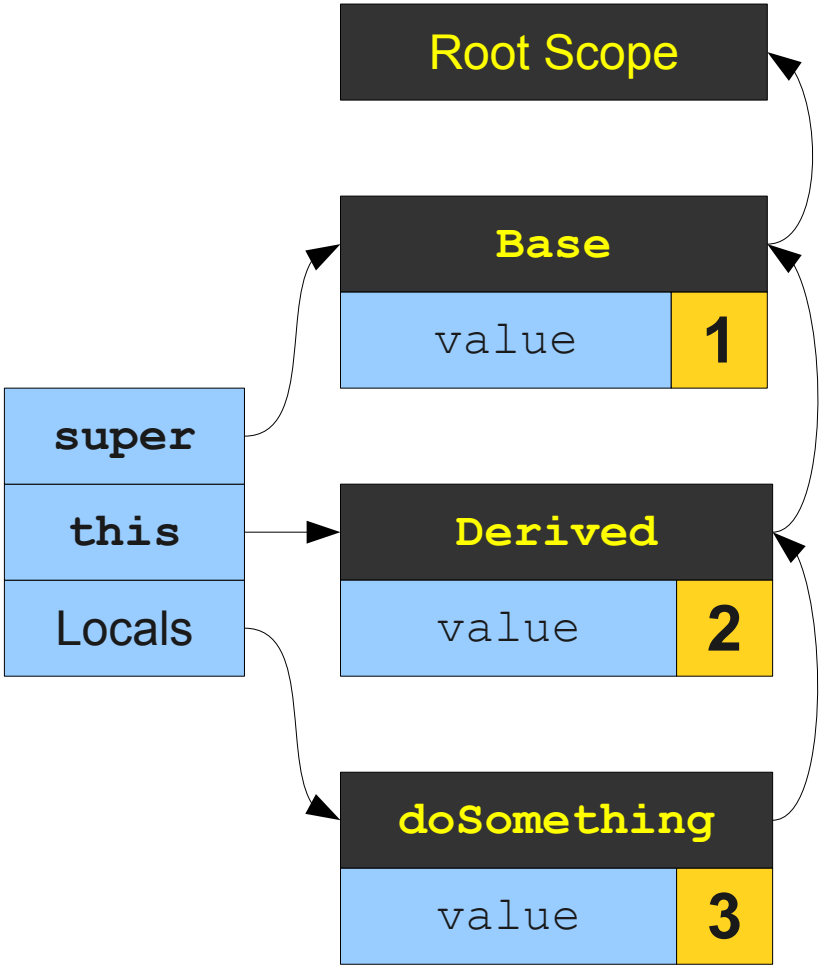

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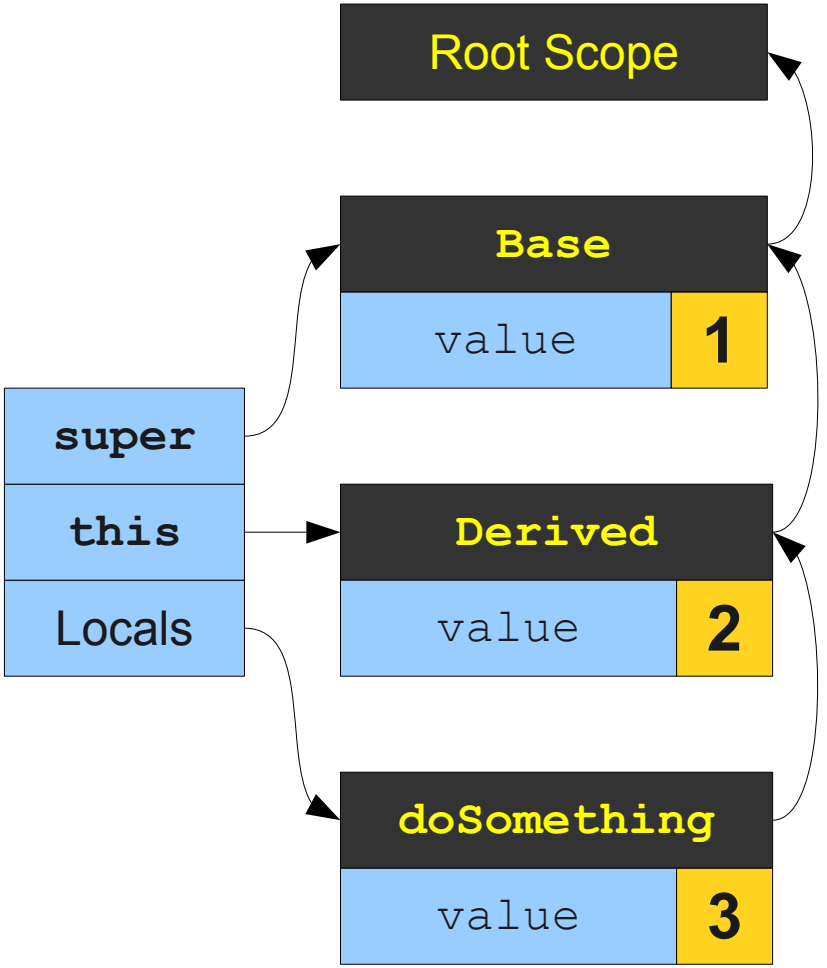

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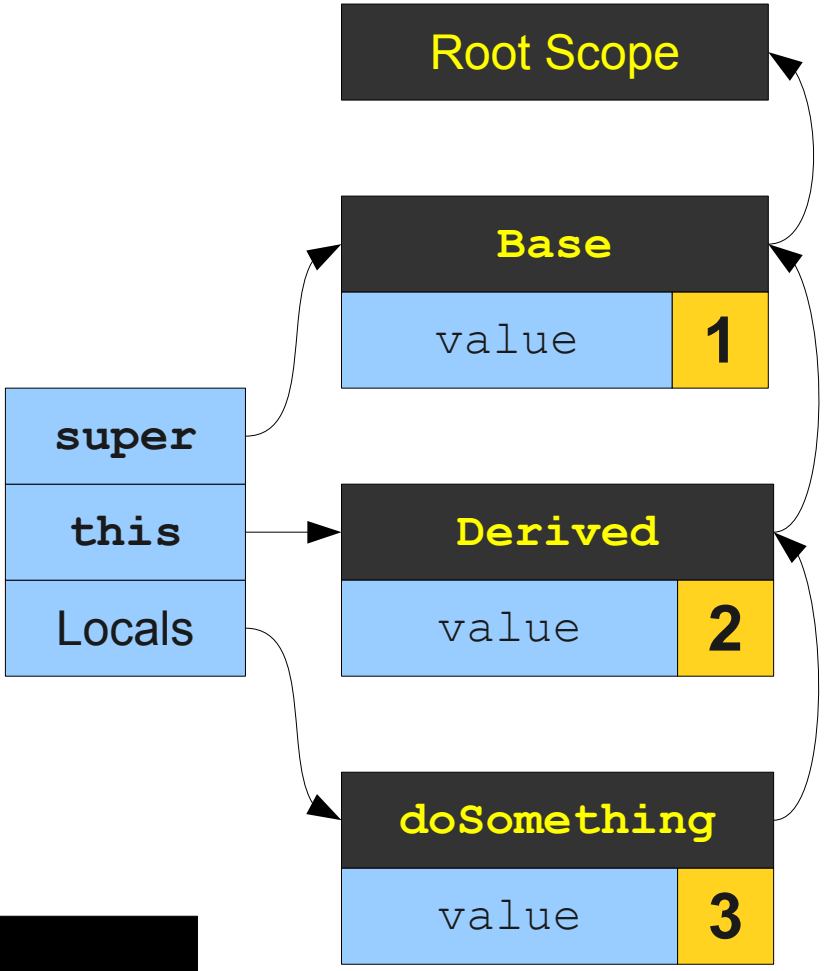

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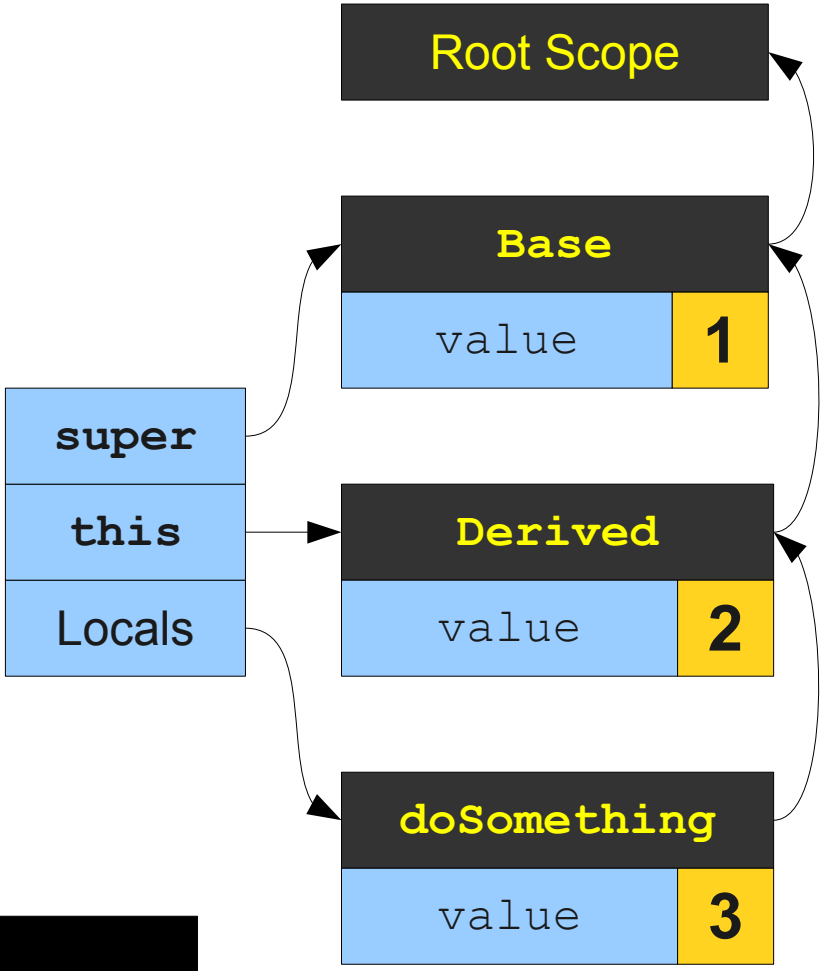

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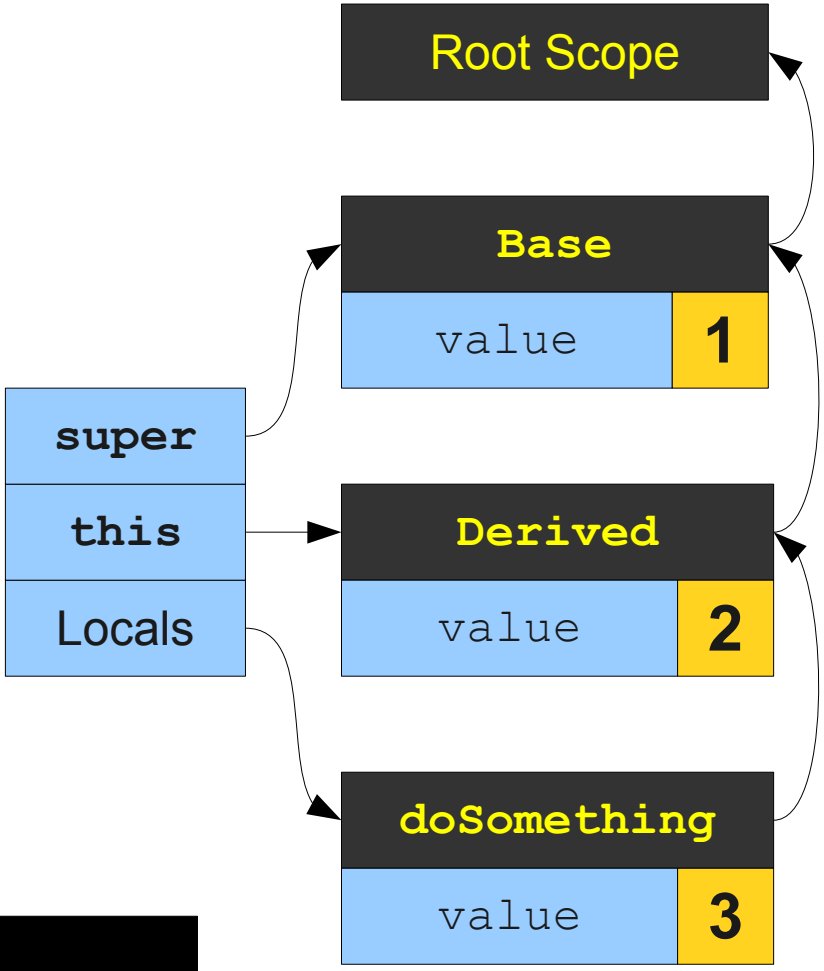
    }
}
```

```
> 3
```



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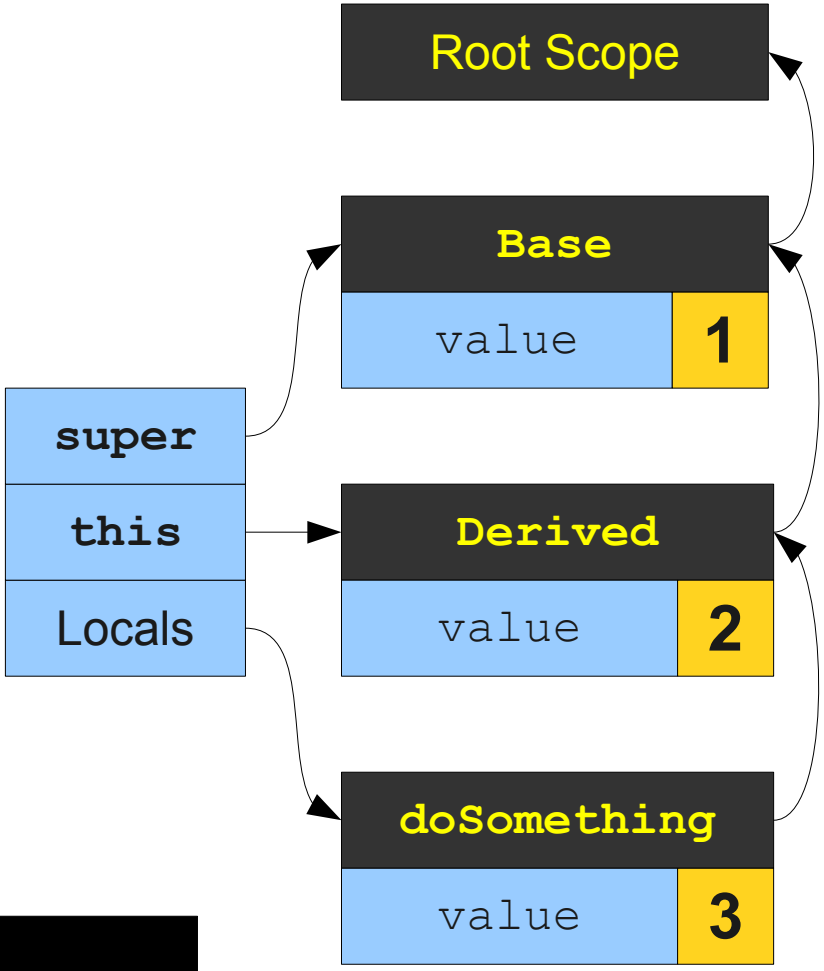
```
> 3
```



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    }
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```
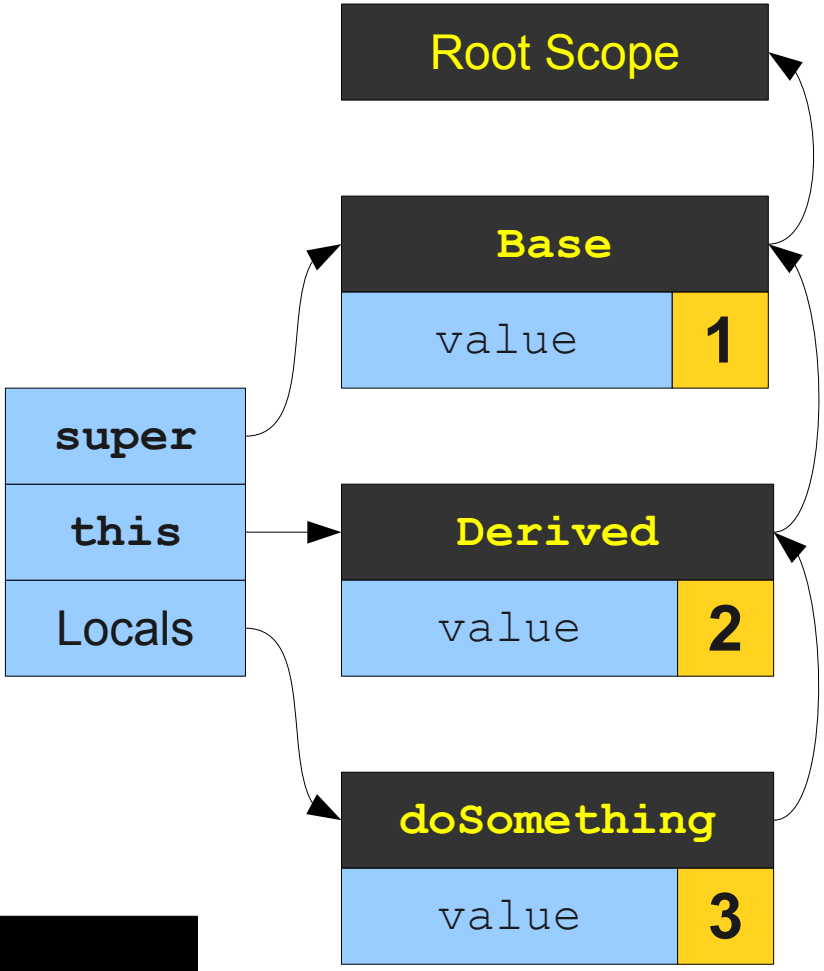

```
> 3
  2
```



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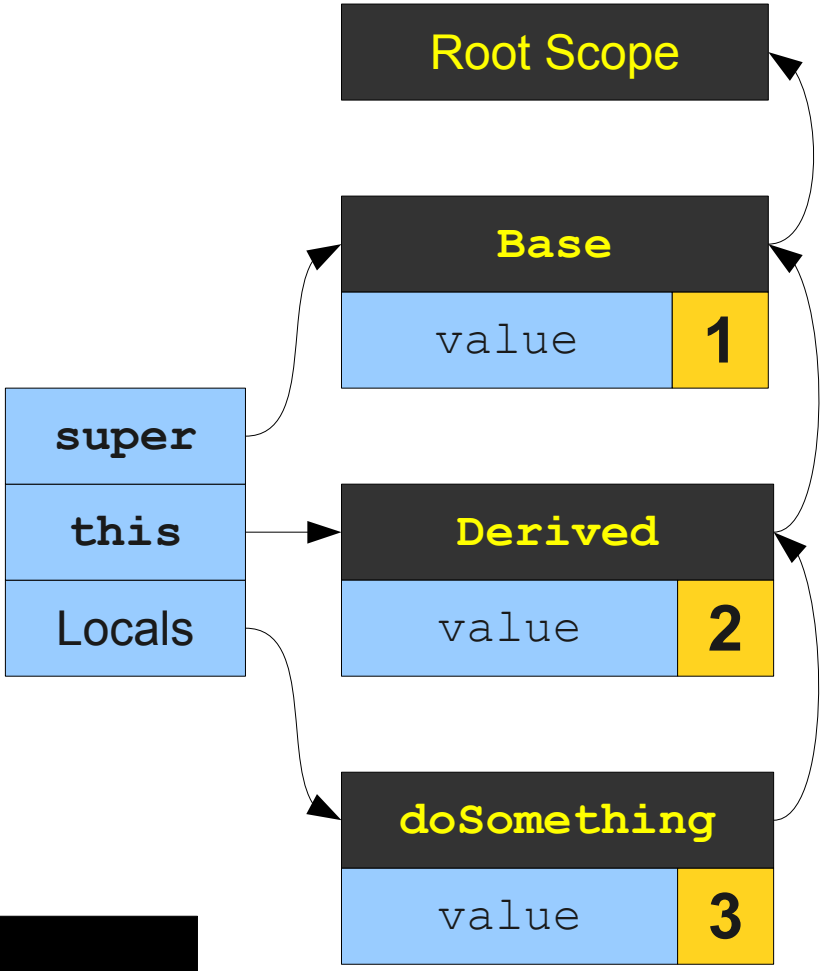
    }
}
```

```
> 3
  2
```



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}
```
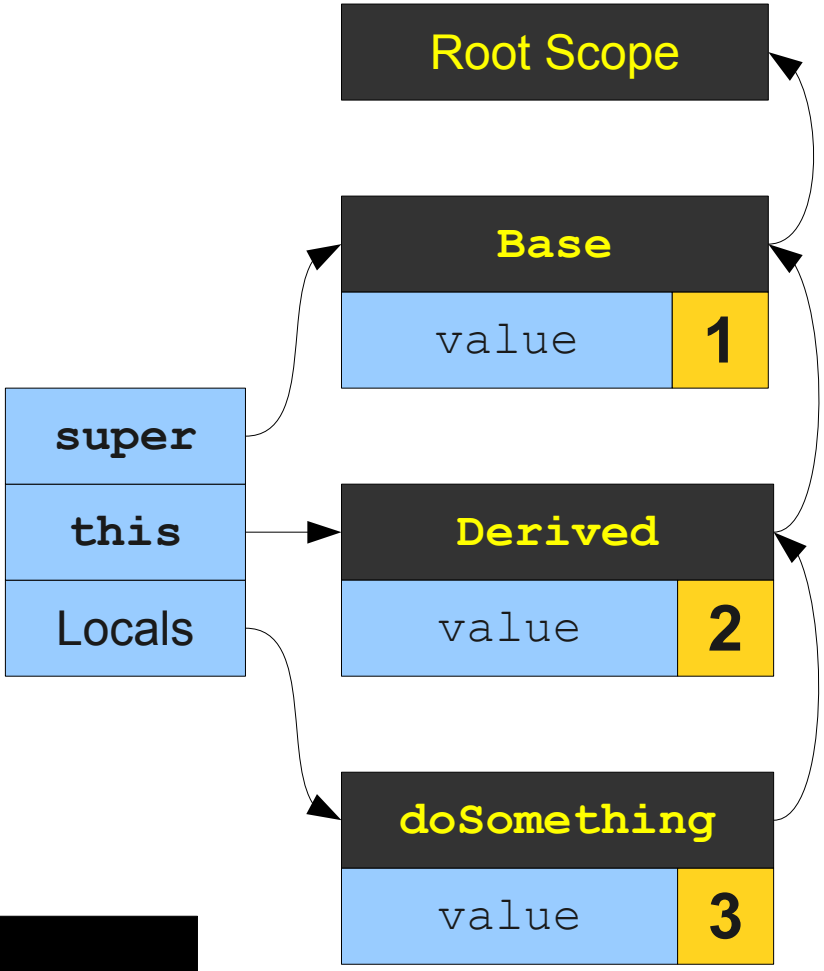

```
> 3
  2
  1
```



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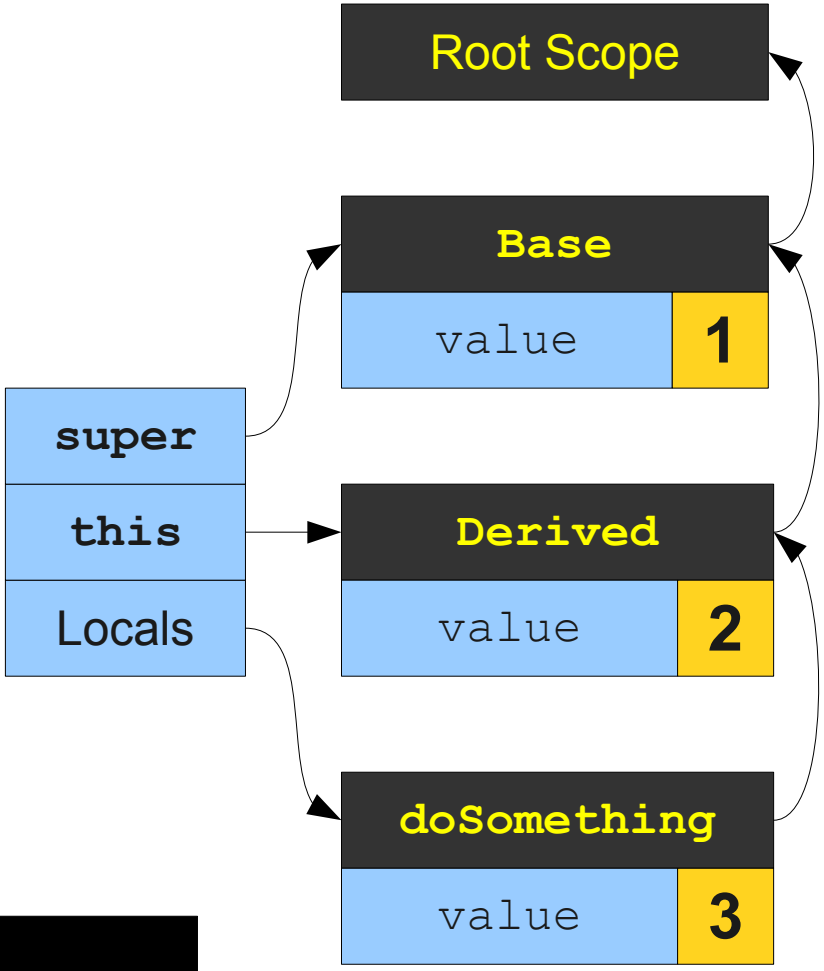
```

```
> 3
  2
  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++).

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 closest 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

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Symbol Table	
x	137
y	42

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Symbol Table	
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```
>
```

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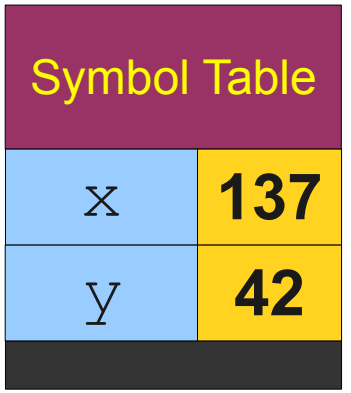

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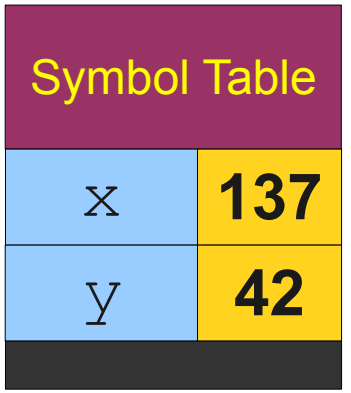

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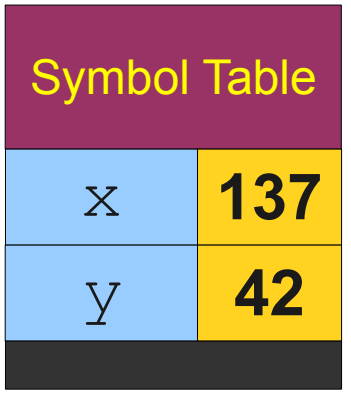


```
> 179
>
```

Dynamic Scoping

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}
Function1();
Function2();
Function3();
```

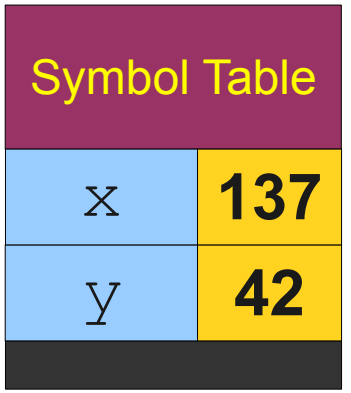


```
> 179
>
```

Dynamic Scoping

```
int x = 137;
int y = 42;
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Symbol Table	
x	137
y	42

```
> 179
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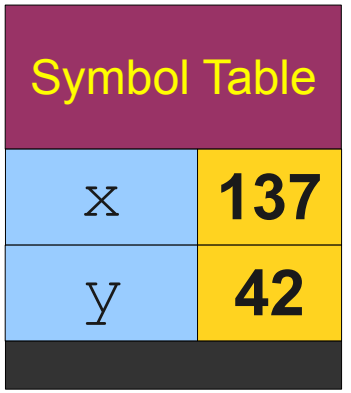


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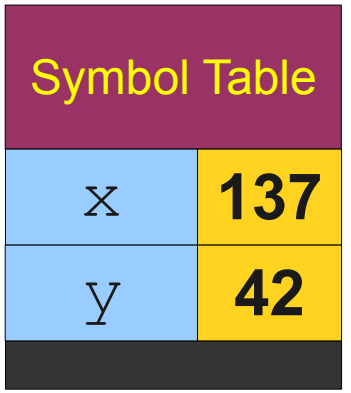


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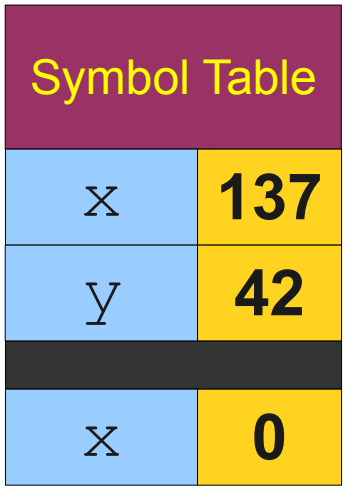


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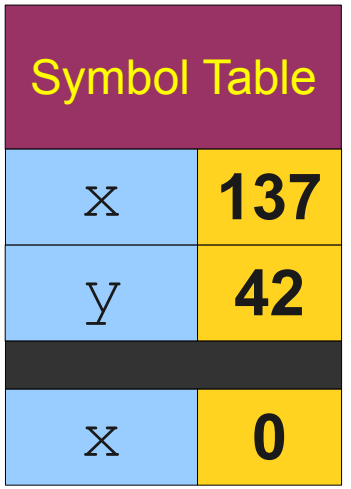


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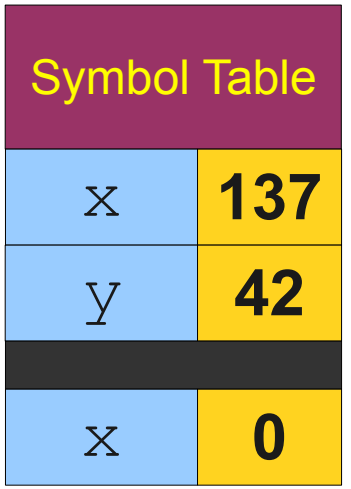


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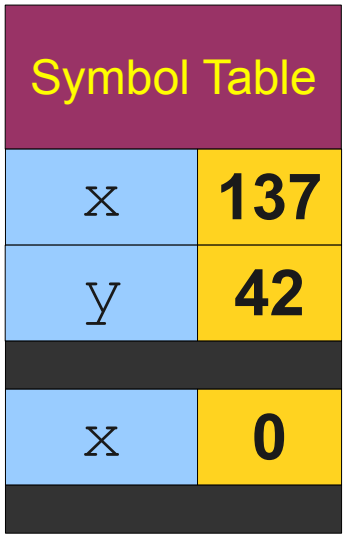


```
> 179
>
```

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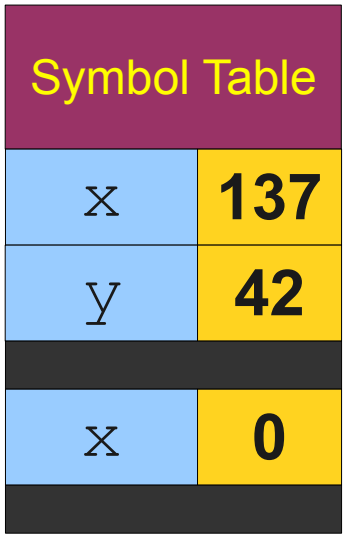


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>
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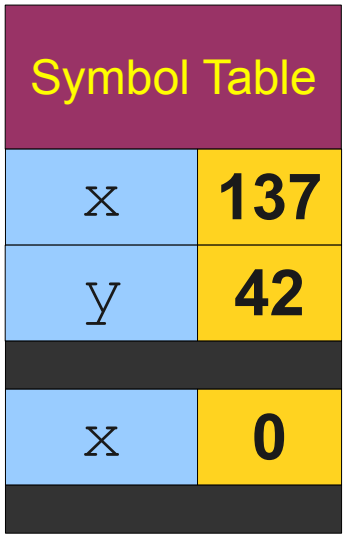


```
> 179
> 42
>
```

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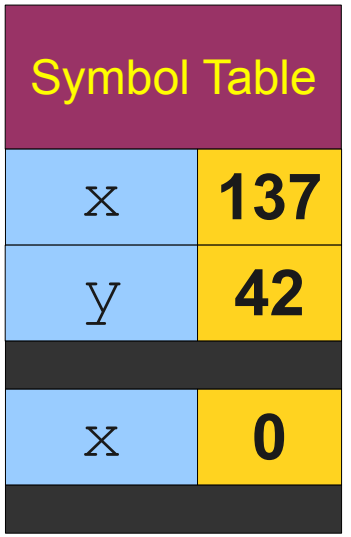


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> 179
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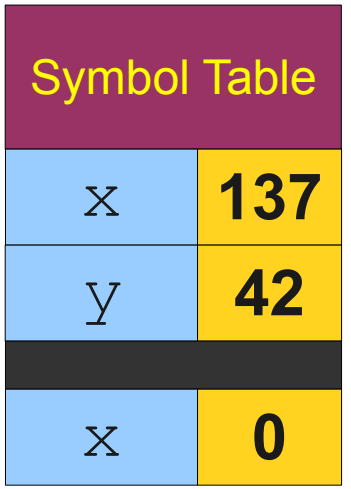


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> 179
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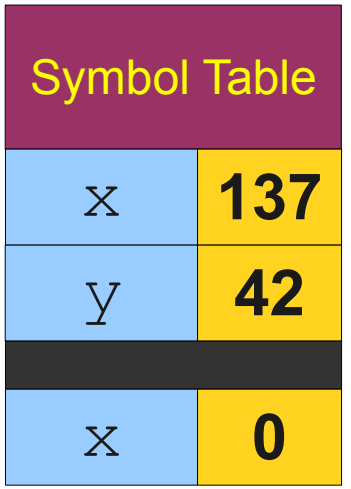


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> 179
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>
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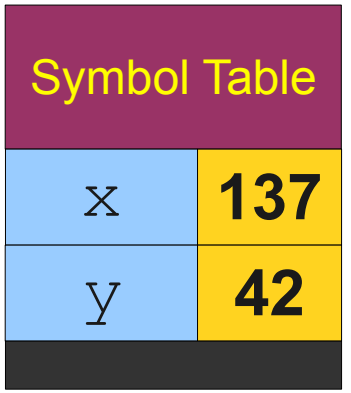


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> 179
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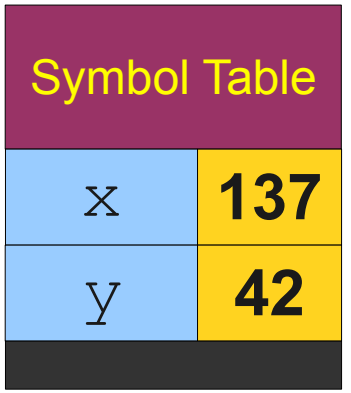


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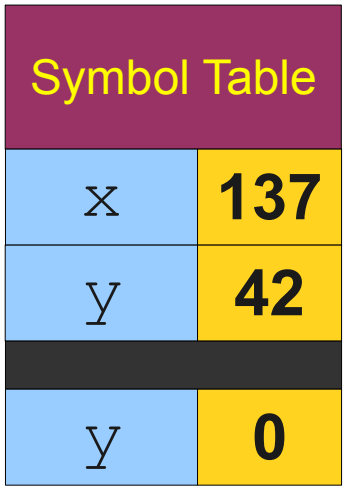


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> 179
> 42
>
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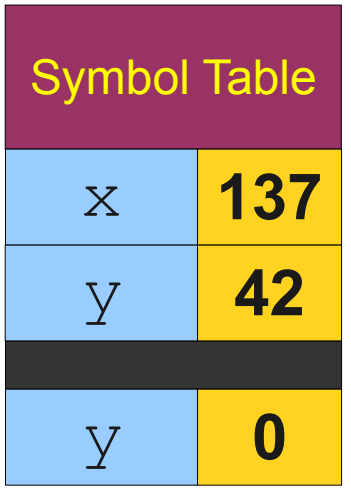


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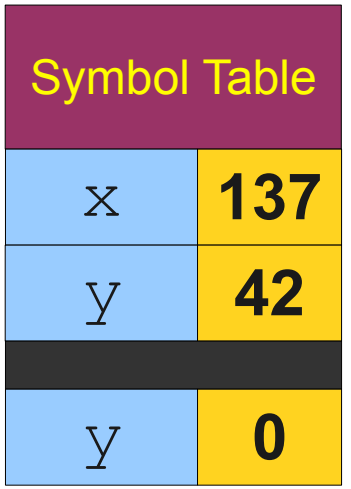


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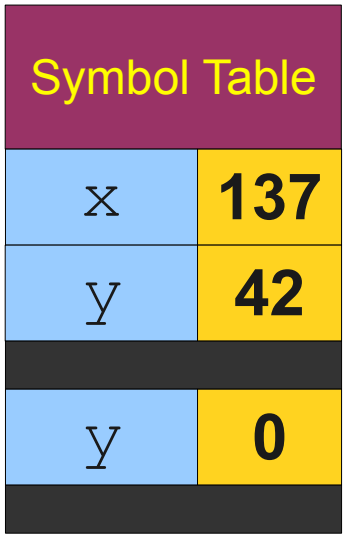


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> 179
> 42
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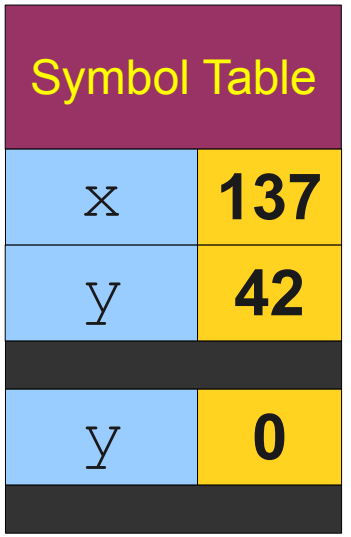


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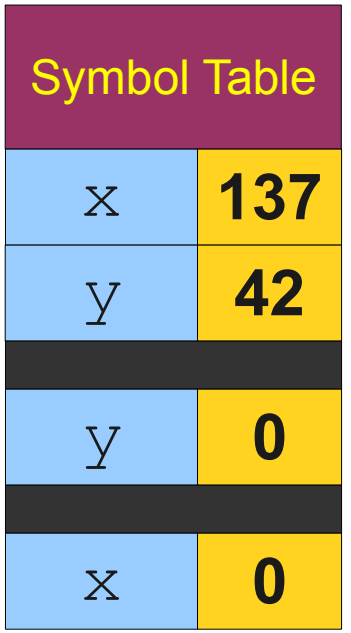


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> 179
> 42
>
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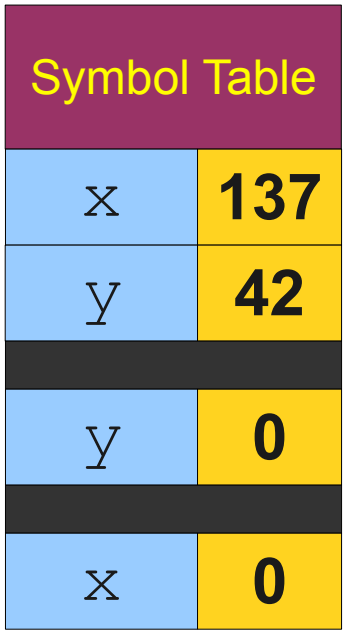


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> 42
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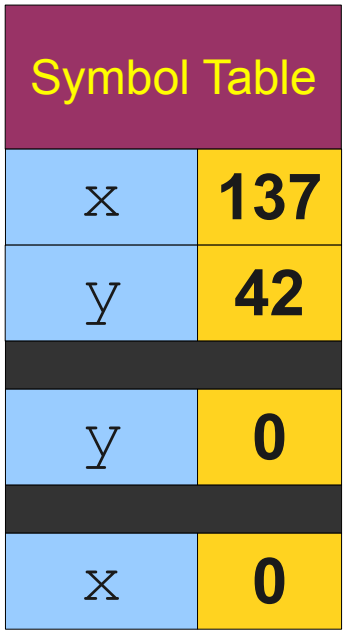


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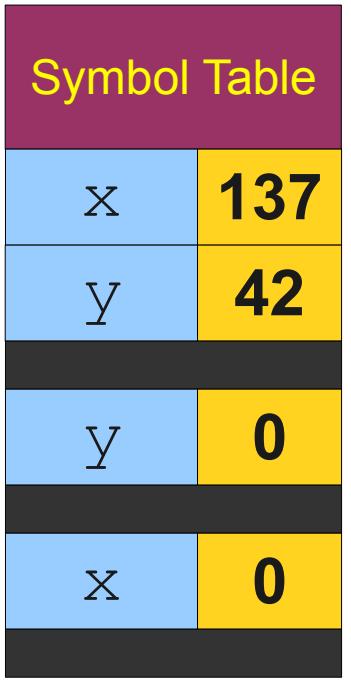


```
> 179
> 42
>
```

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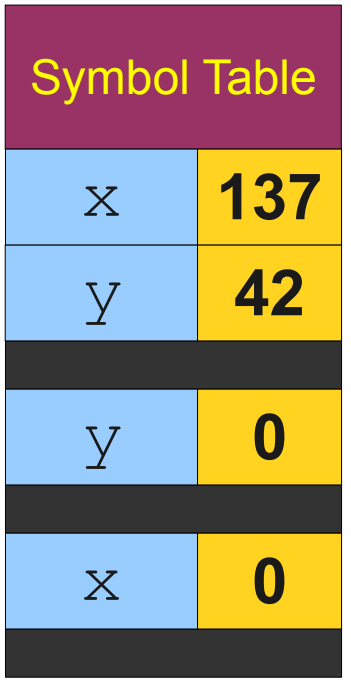


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> 179
> 42
>
```

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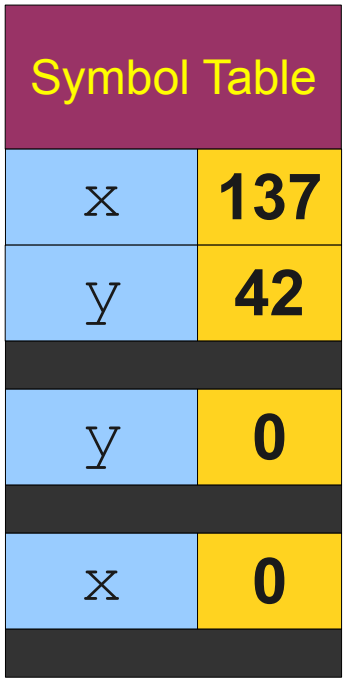


```
> 179
> 42
> 0
>
```

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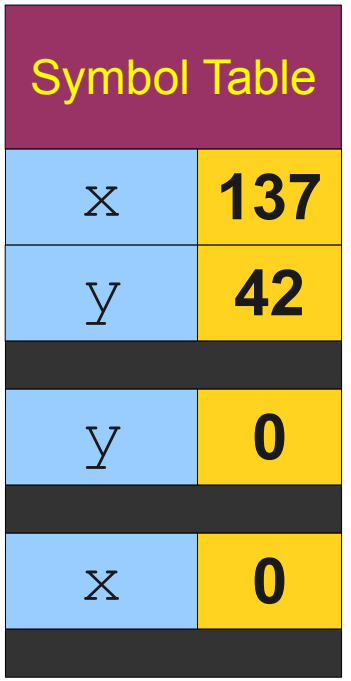


```
> 179
> 42
> 0
>
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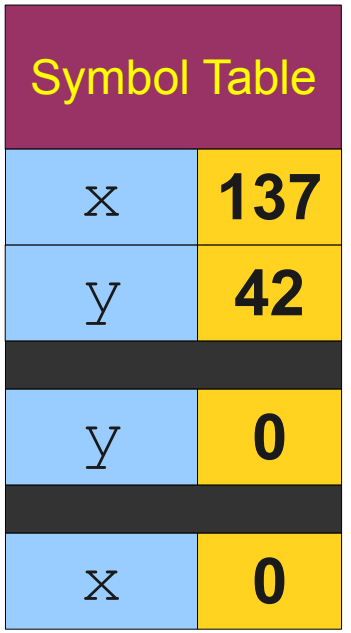


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> 179
> 42
> 0
>
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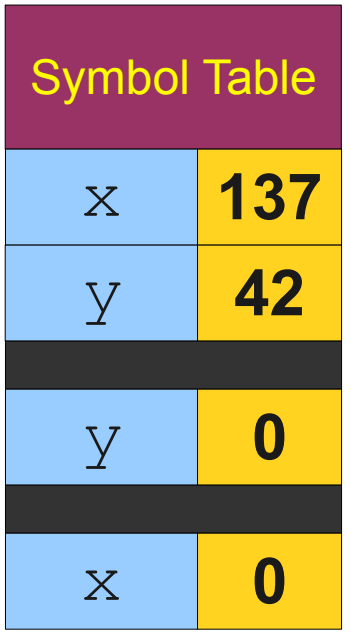


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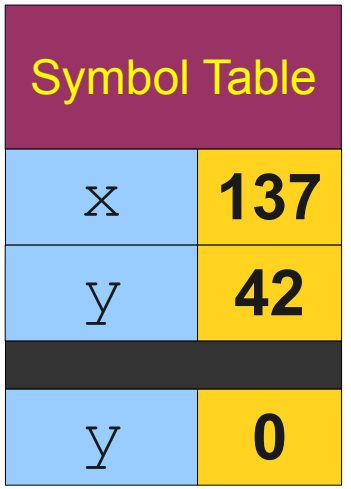


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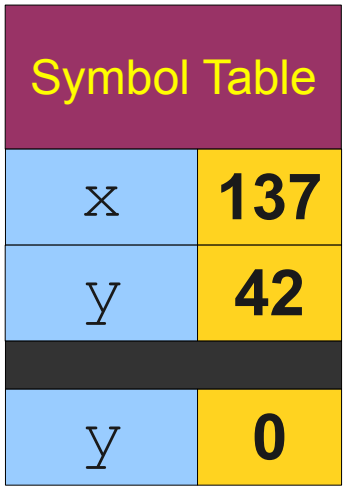
Function3();
```




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

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

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

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}
Function1();
Function2();
Function3();
```

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.

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

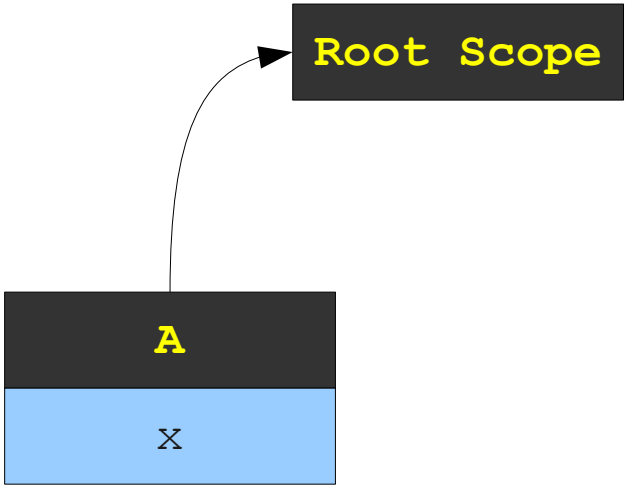
```
class A {
public:
    int x;
};

class B {


};

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

Scoping with Multiple Inheritance

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};

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};

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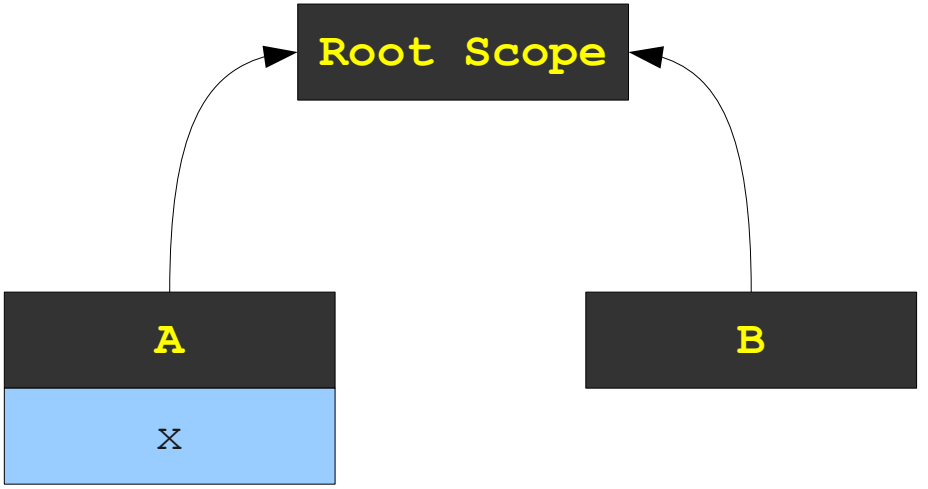
    }
}
```

Scoping with Multiple Inheritance

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};

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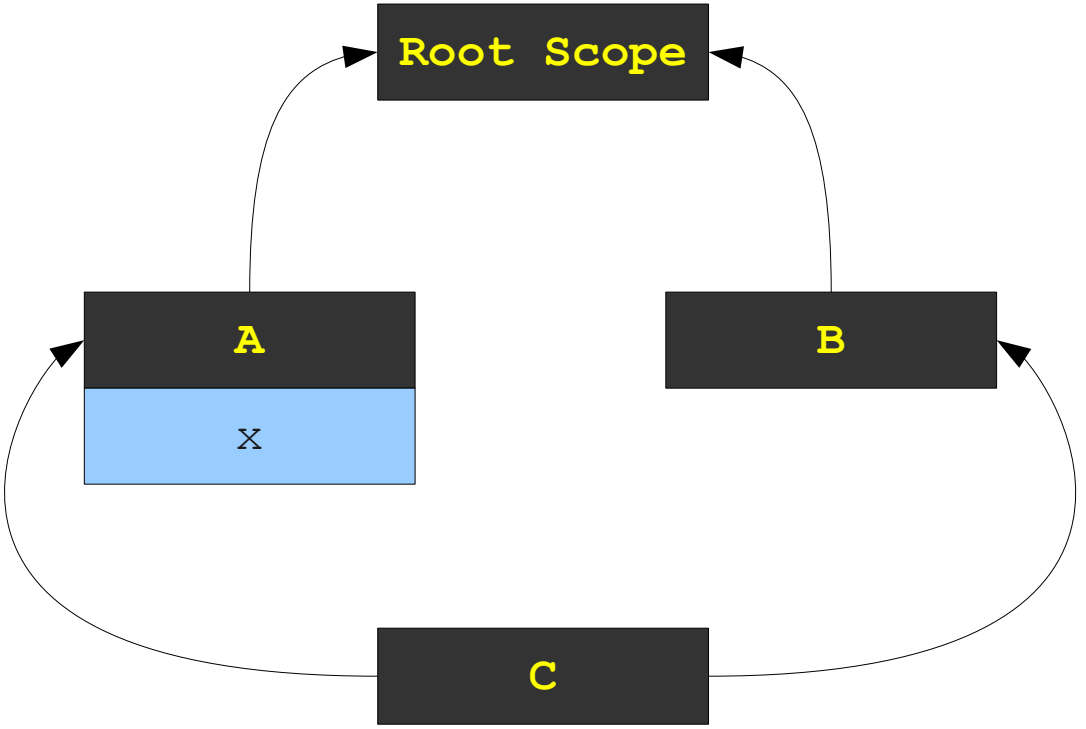

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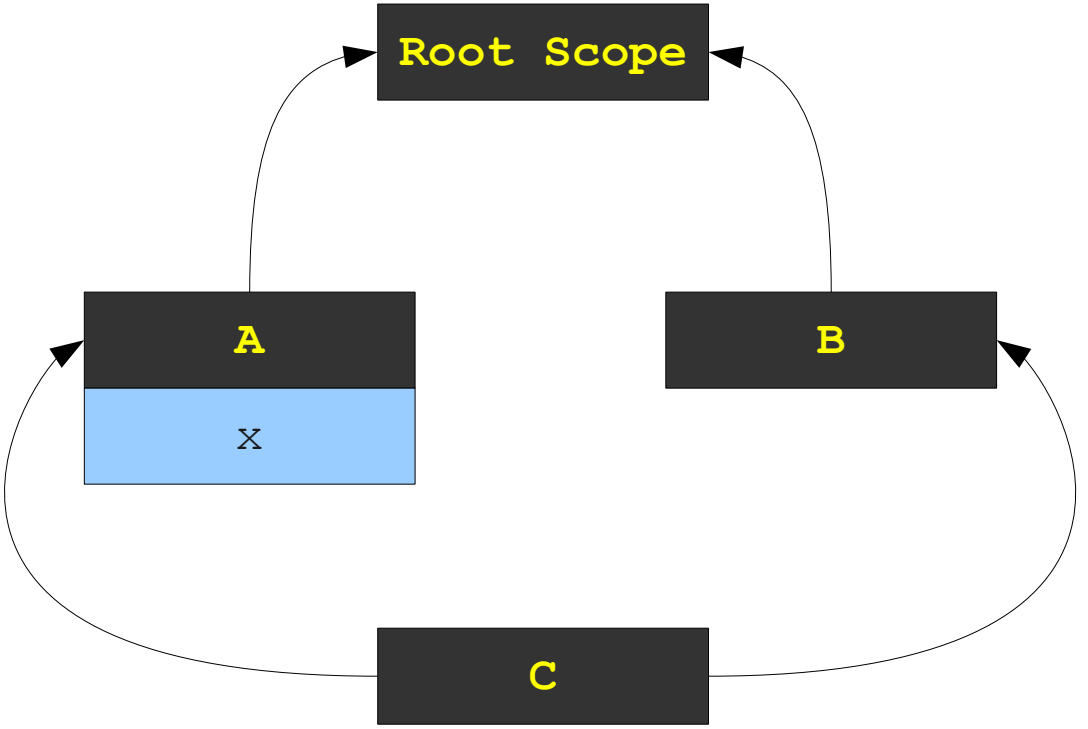

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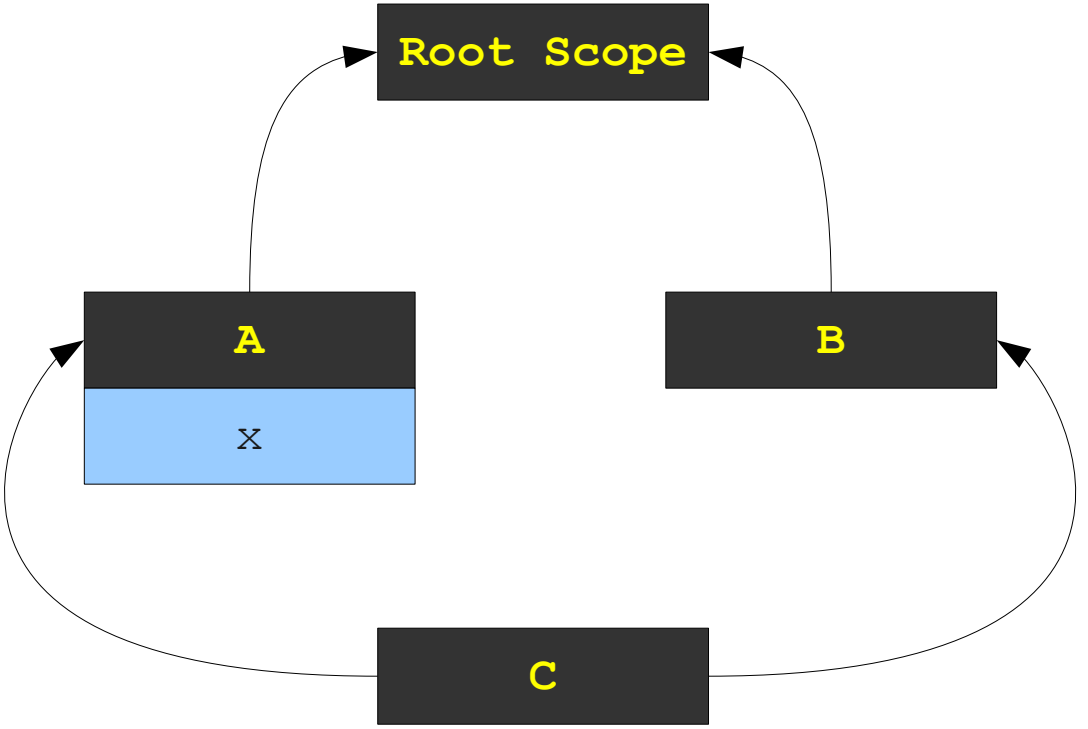

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```

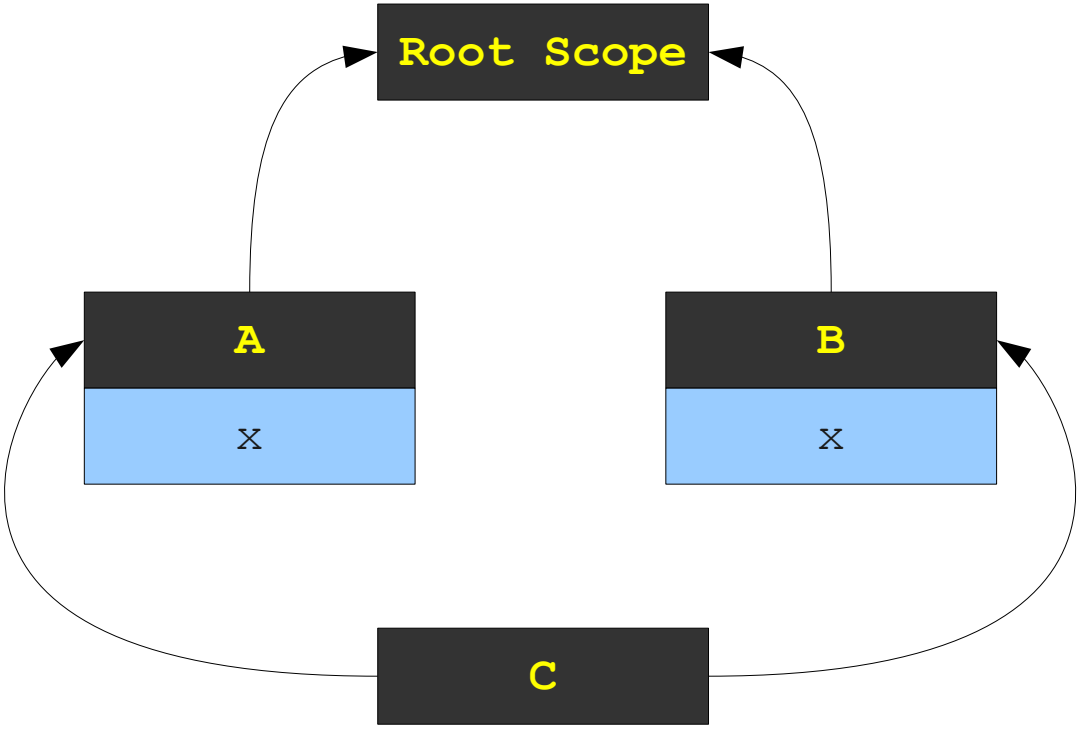

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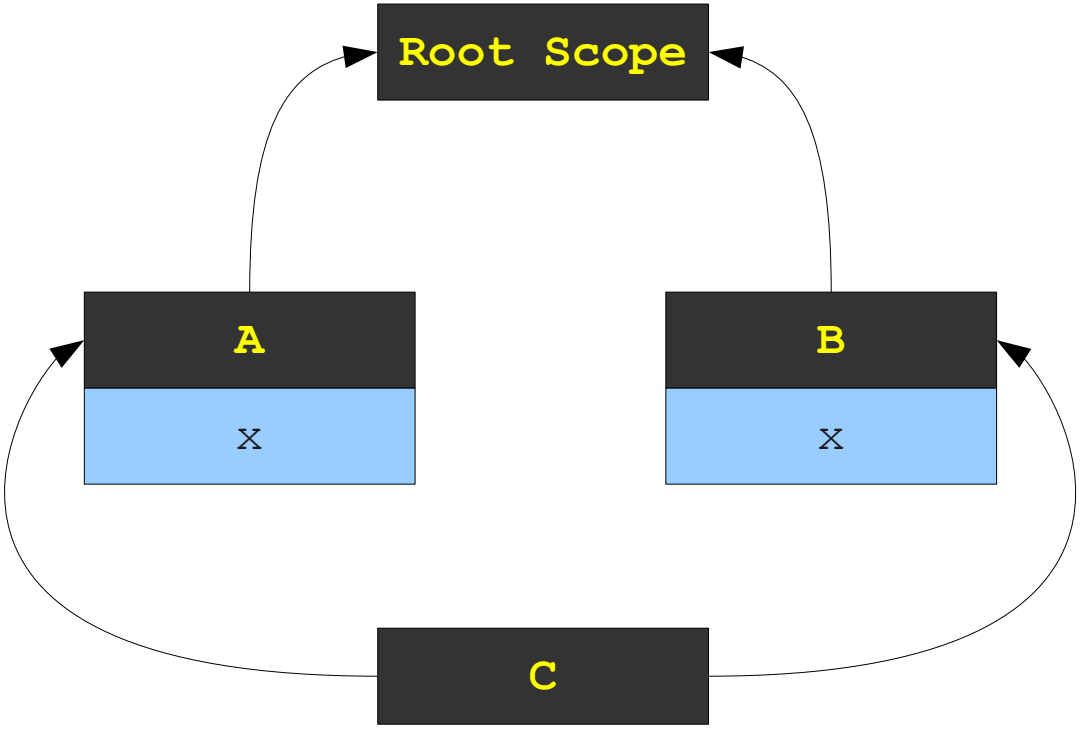

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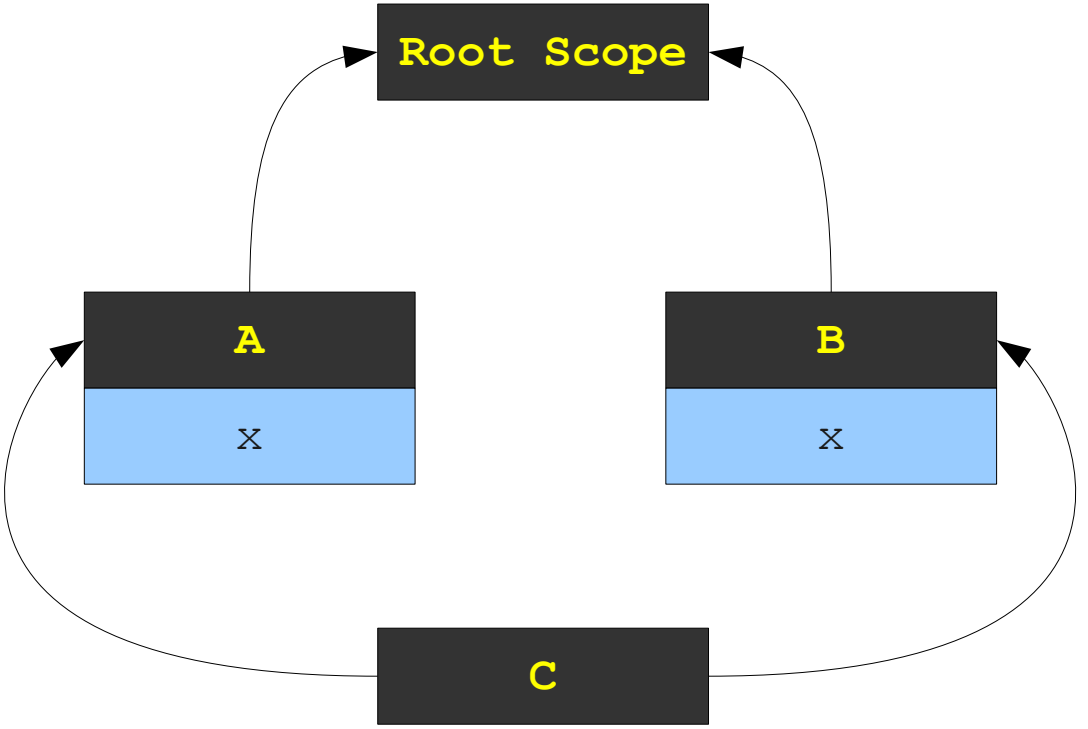


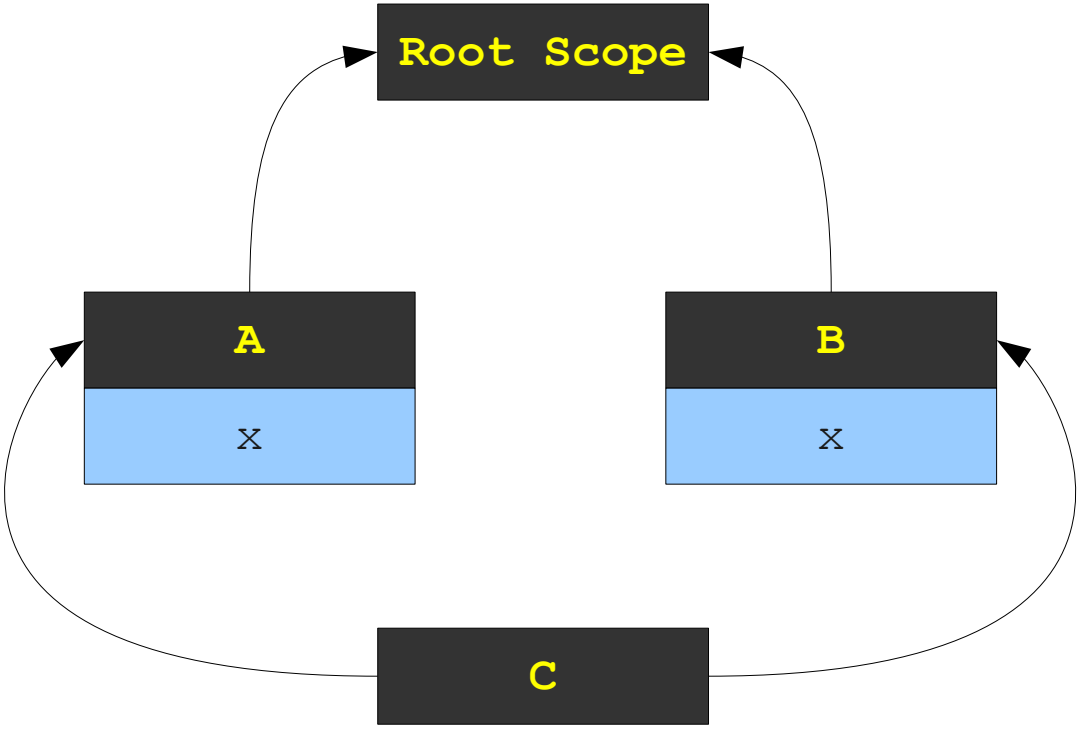
Ambiguous - which x?

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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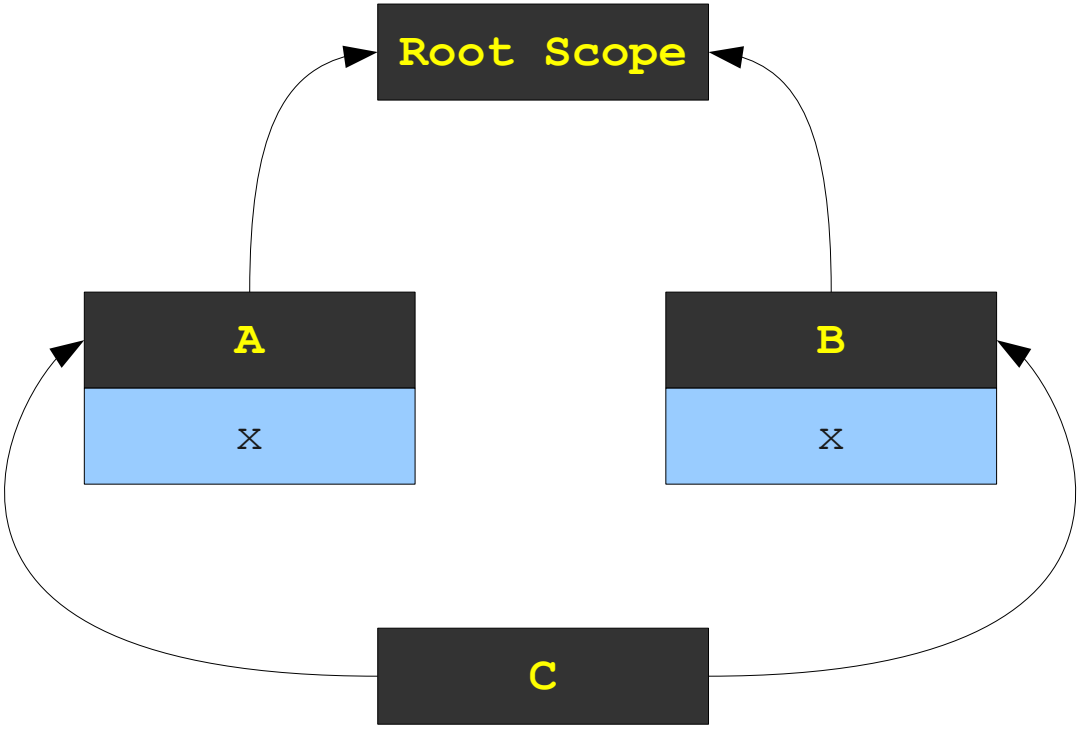

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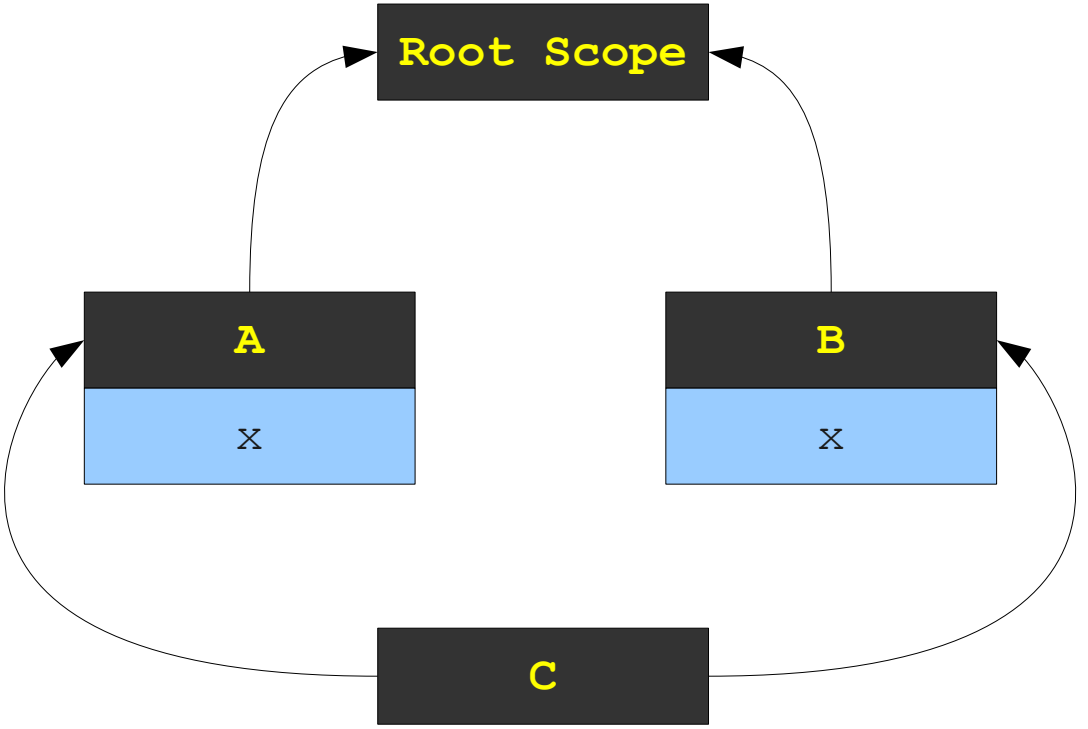

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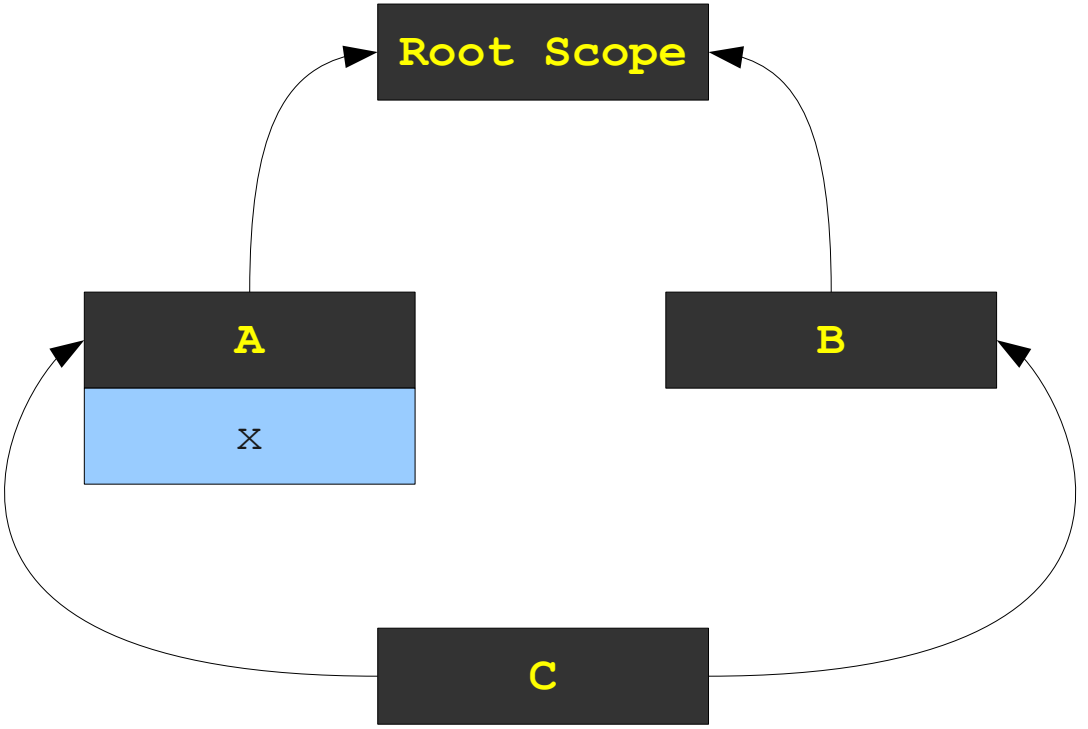

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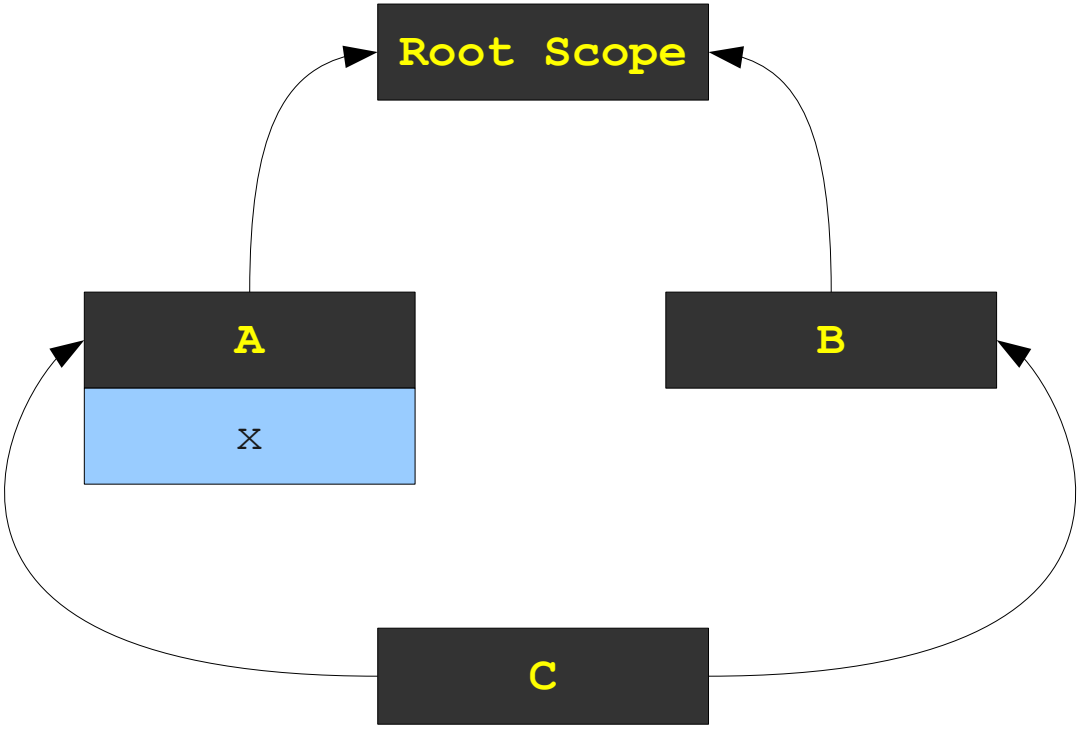

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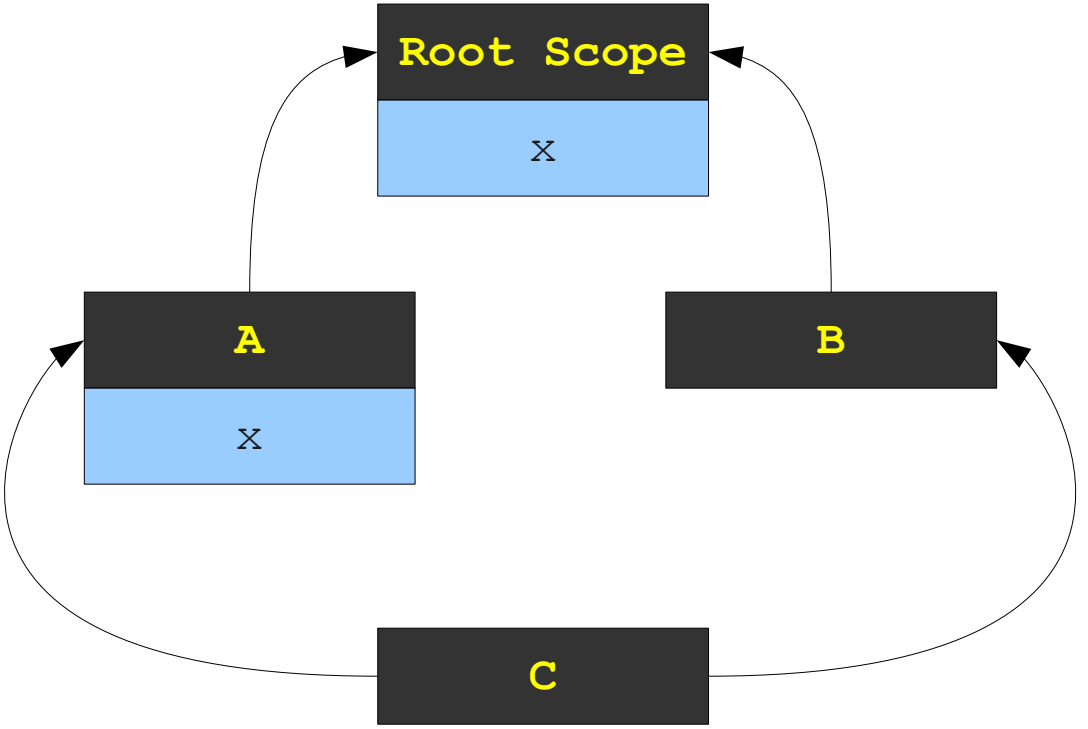

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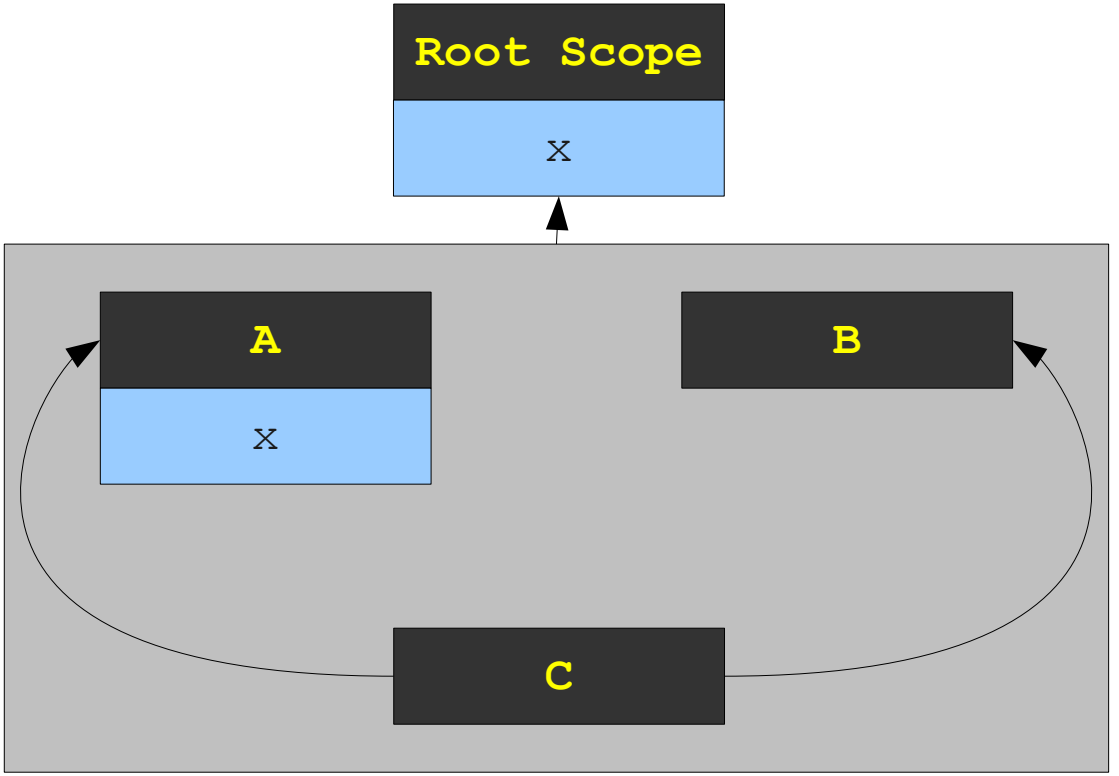


Scoping with Multiple Inheritance

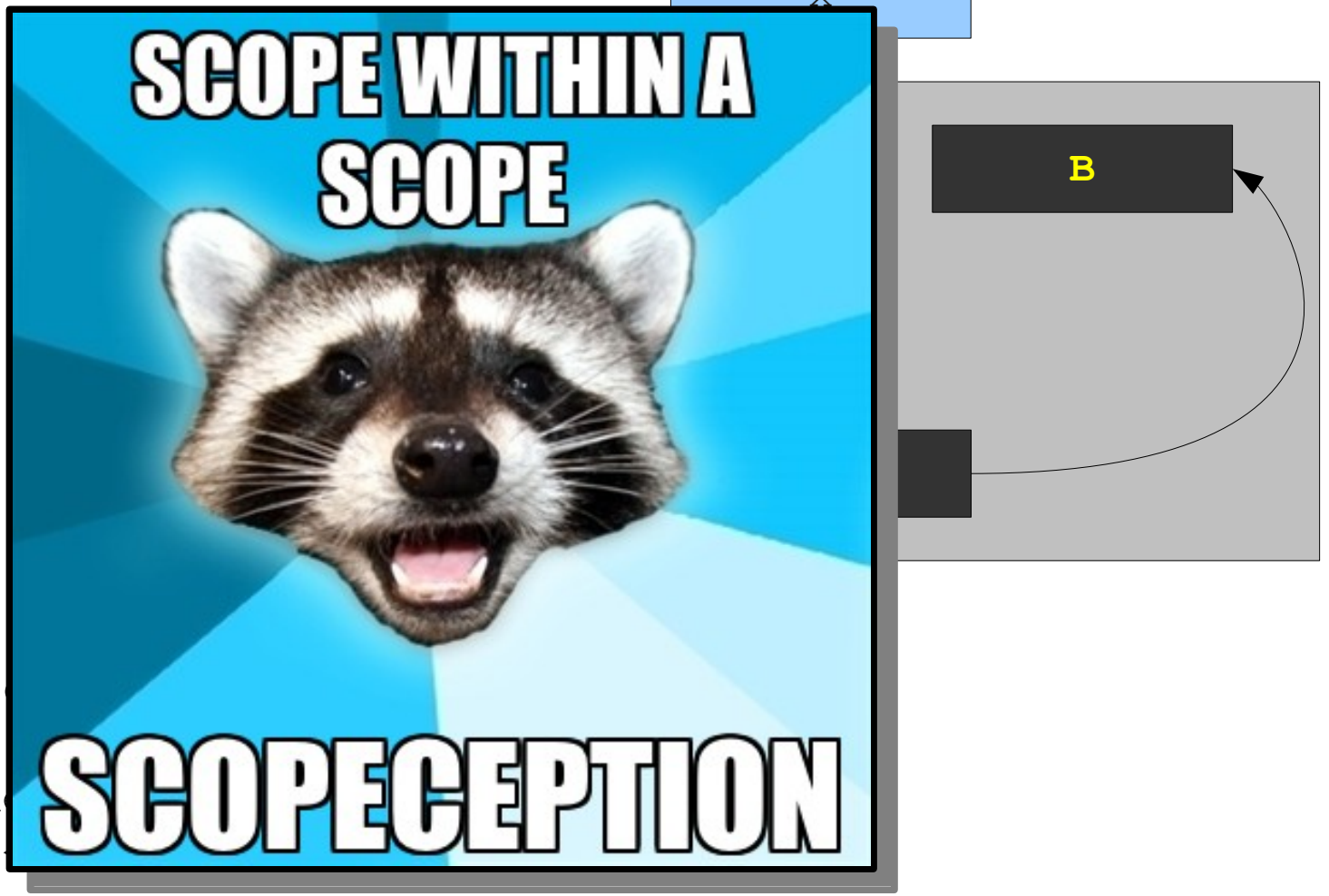
```
int x;

class A {
public:
     int x;
};

class B {


};

class C: publi
public:
     void doSom
          cout <
     }
}
```



(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.

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.