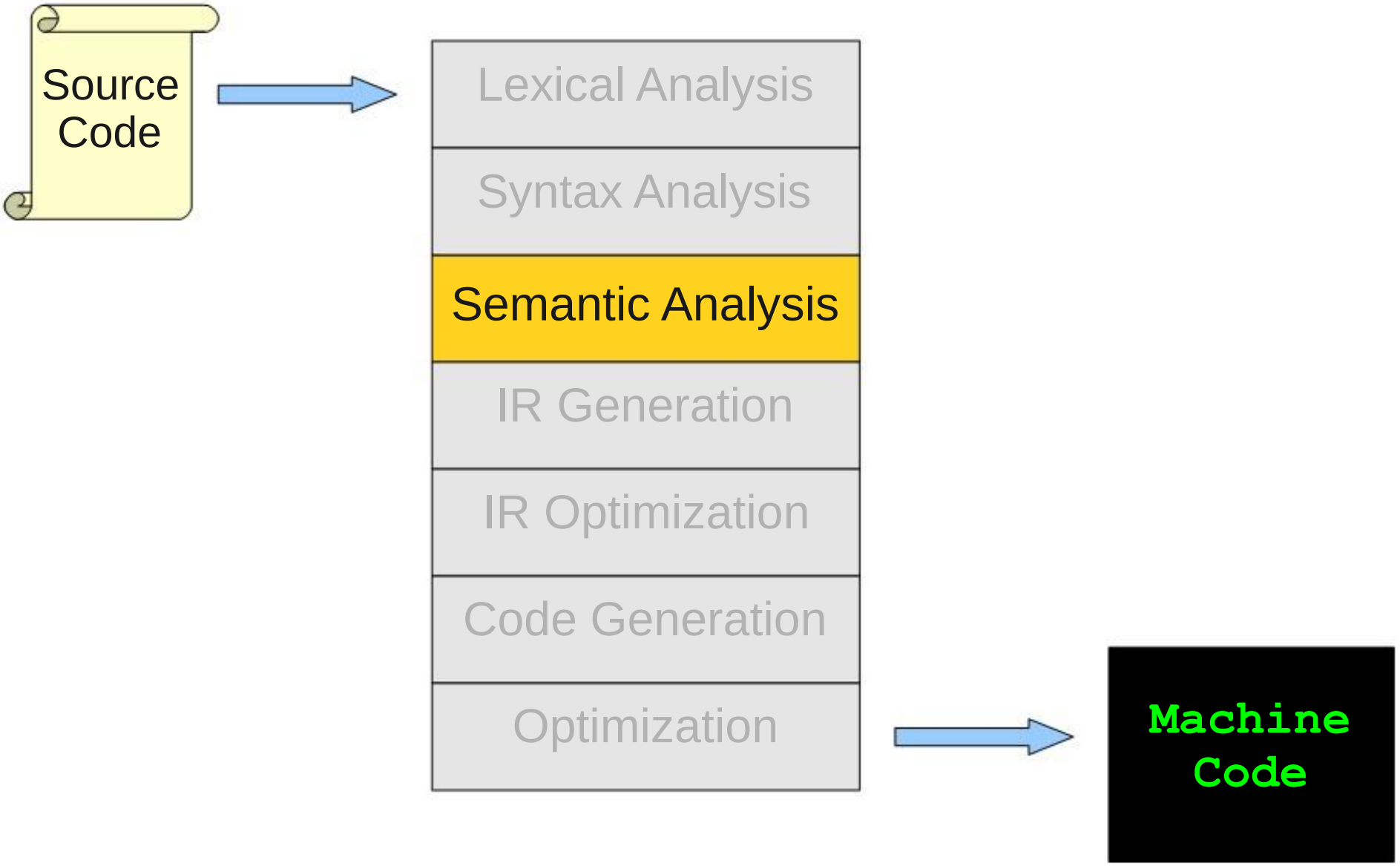
Semantic Analysis

Where We Are


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

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.
  - Etc.
- Once we finish semantic analysis, we know that the user's input program is legal.

Validity versus Correctness

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

Not Valid (String cannot be assigned by integer)

Validity versus Correctness

Valid but **Incorrect!**

should be "return n;"

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

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

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

Correctness is far beyond the ability of compiler.

Why can't we just do this during parsing?

- Limitation of CFGs:
  - How would you prevent duplicate variable definitions?
  - How would you prevent variable assignment with different types?
  - How would you ensure classes implement all interface methods?

For most programming languages, these are **provably impossible**.

Overview of Semantic Analysis

- **Scope-Checking**
  - How can we tell which object a particular identifier refers to?
- **Type-Checking**
  - 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:

```
public class Name {
    int Name;
    Name Name(Name Name) {
        Name.Name = 137;
        return Name((Name) Name);
    }
}
```

We need to properly maintain scopes of ‘Name’ variables because each ‘Name’ has it’s own scope.

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?

Symbol Tables: The Intuition

(Explicit stack)

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 1: int z = 42;
 2:  int MyFunction(int x, int y) {
 3:     printf("%d,%d,%d\n", x, y, z);
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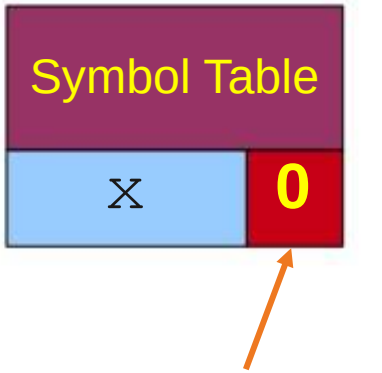

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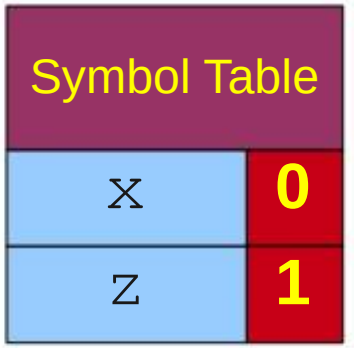

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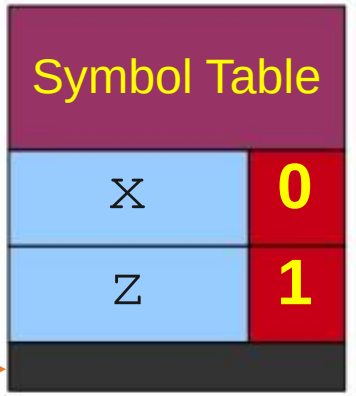
Scope separator →



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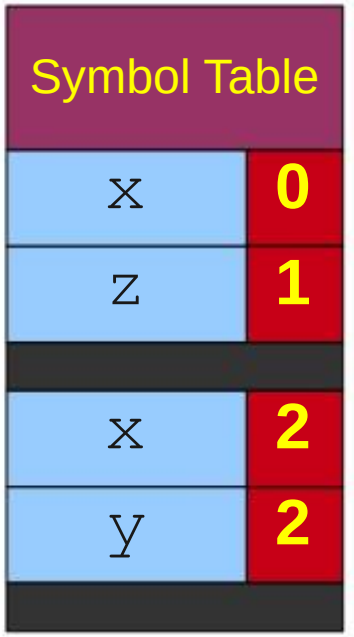

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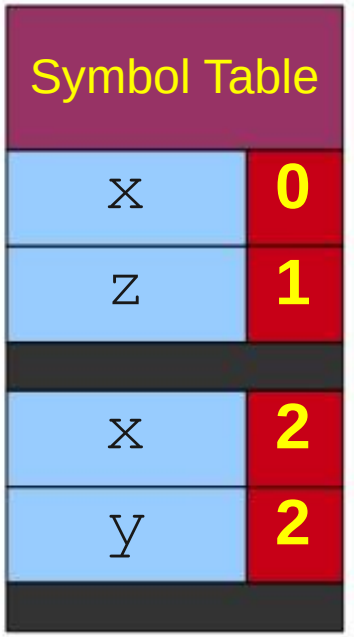

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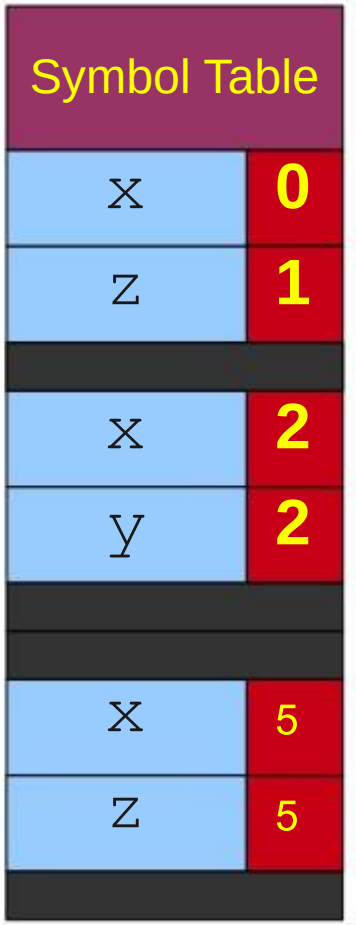

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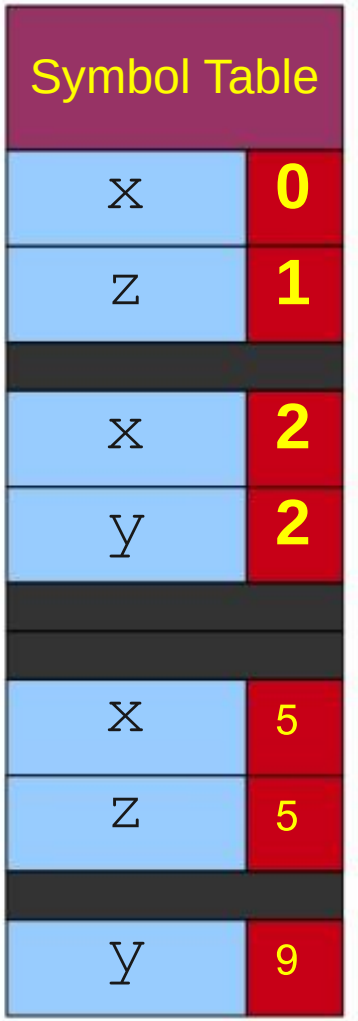

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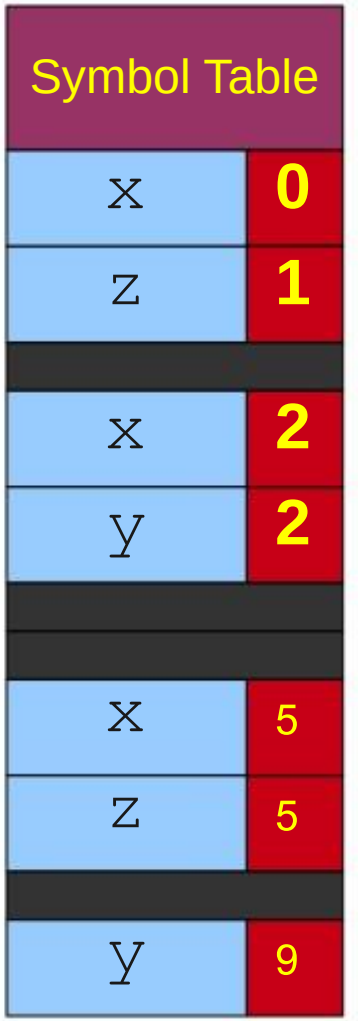

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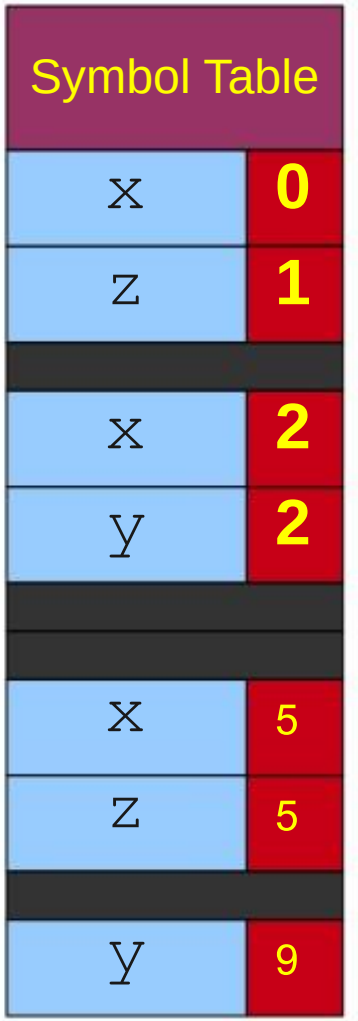

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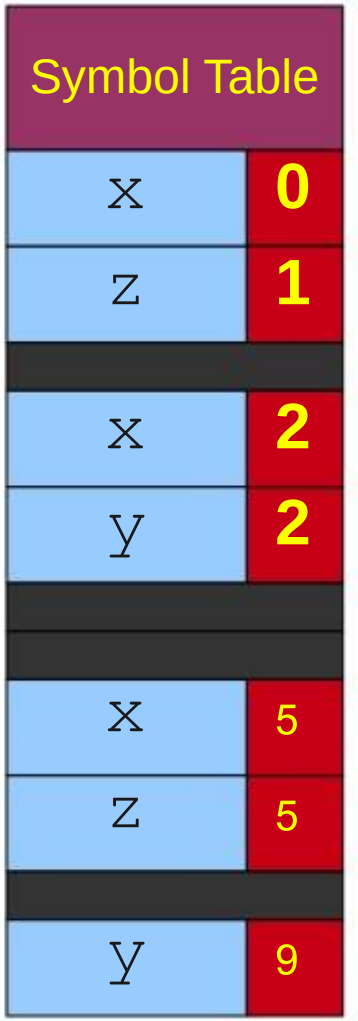

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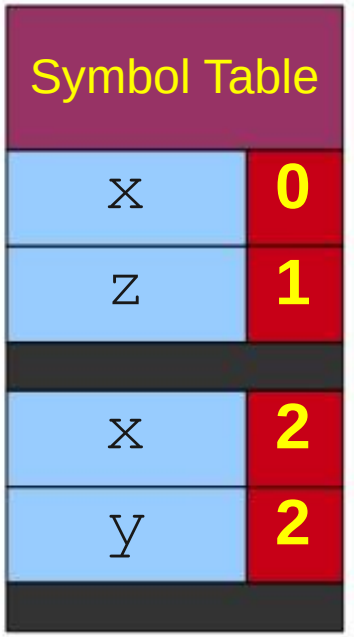

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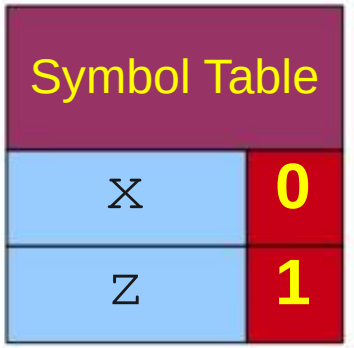

Symbol Table Operations

- Typically implemented as a **stack of tables**.
  (We just have seen it.)
- Each table corresponds to a particular scope.
- 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.

- Another view of Symbol Table: (**Spaghetti Stacks**)

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.

Another View of Symbol Tables

(Spaghetti Stacks)

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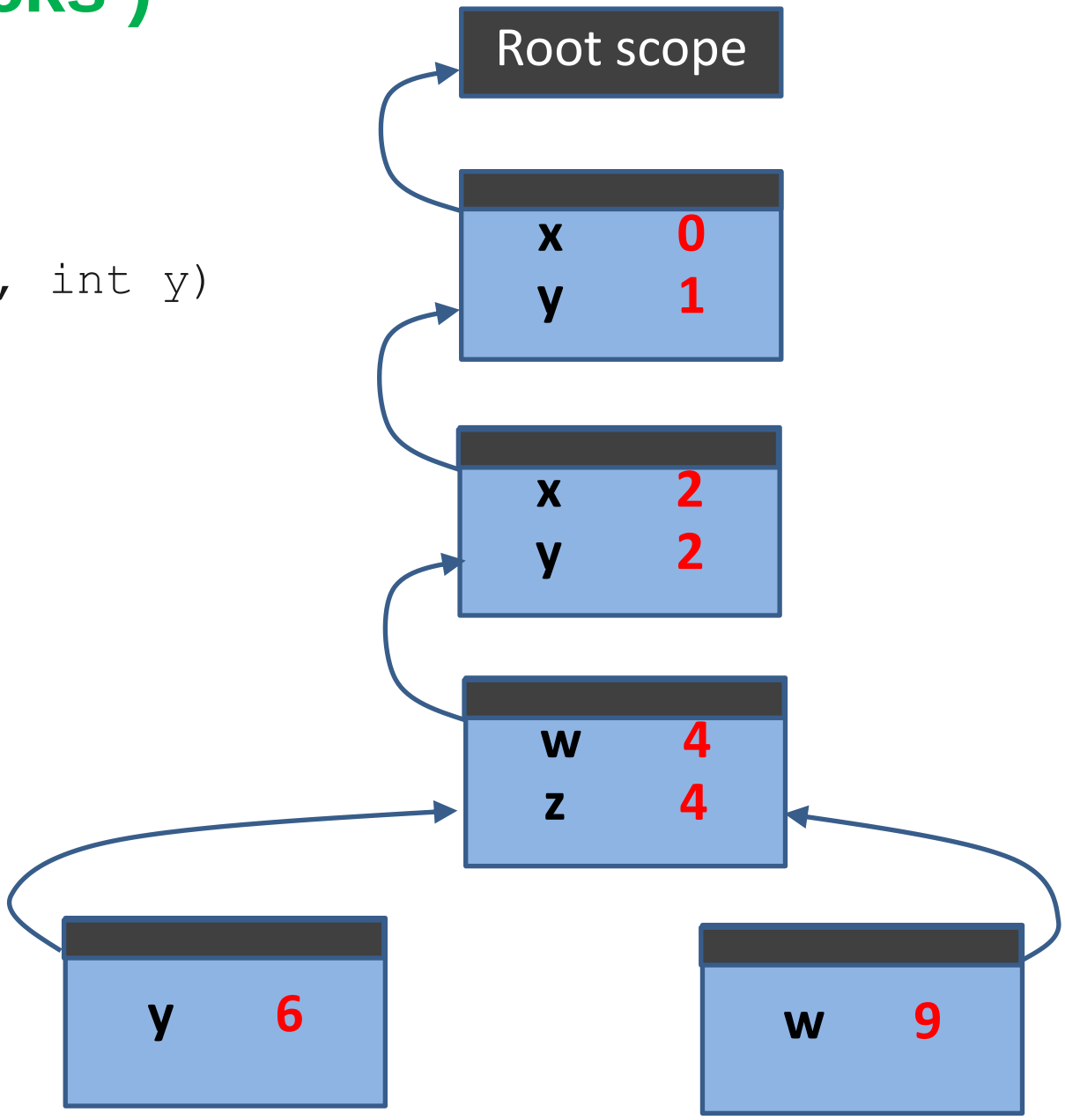


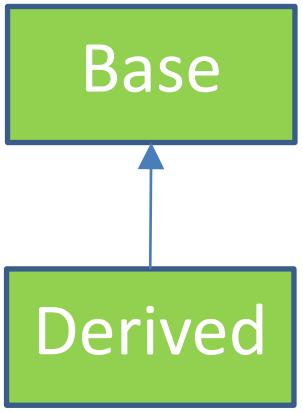
Why Two Interpretations?

- Spaghetti stack is a **static** structure while Explicit stack is a **dynamic** structure.
- Explicit stack is an optimization of a spaghetti stack.

Scoping in Object-Oriented Languages

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.

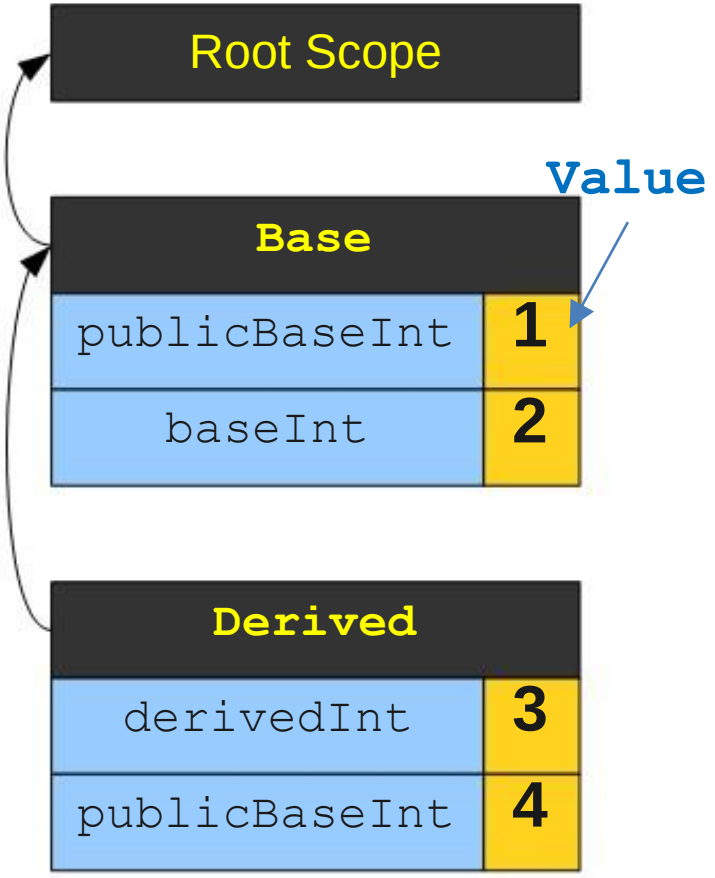
Scoping with Inheritance

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

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

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

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



Scoping with Inheritance

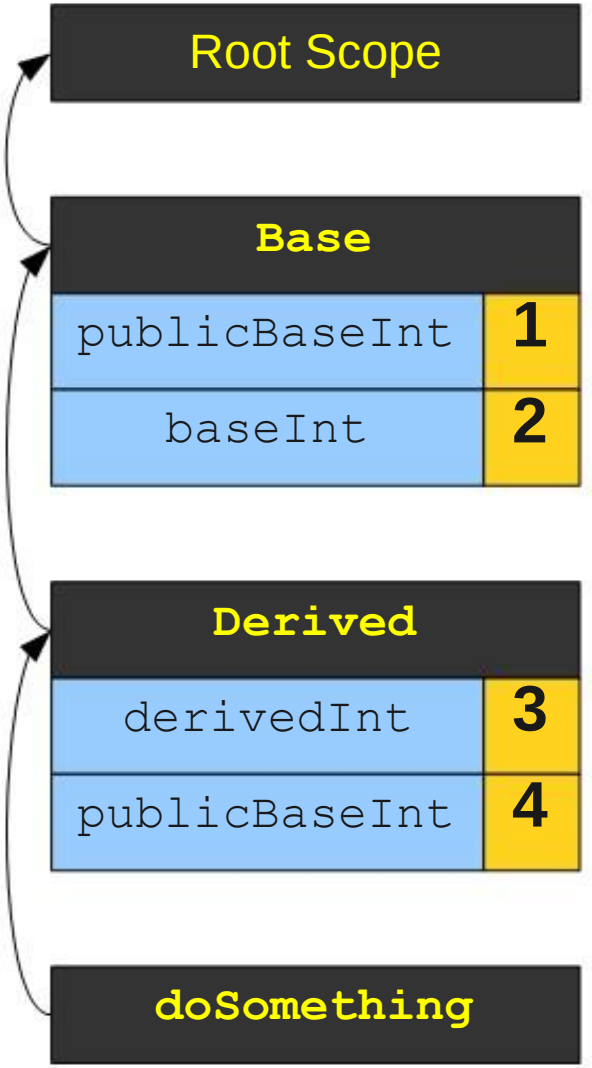
```
public class Base {
    public int publicBaseInt = 1;
    protected int baseInt = 2;
}

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

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

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

```
>
```



Scoping with Inheritance

```
public class Base {
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}

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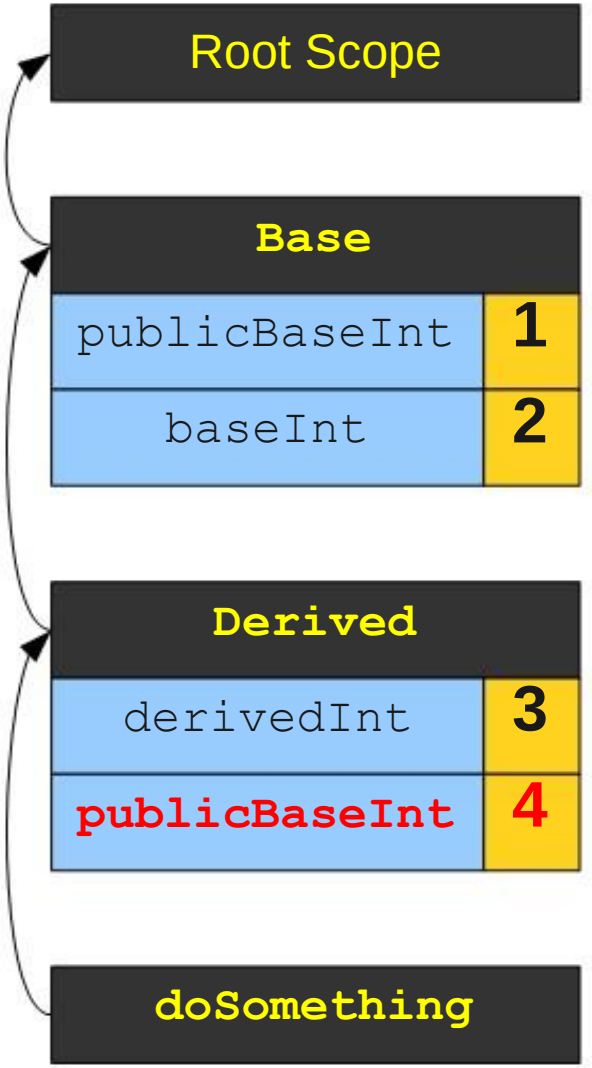
        System.out.println(publicBaseInt);
        System.out.println(baseInt);
        System.out.println(derivedInt);

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

```
> 4
```



Scoping with Inheritance

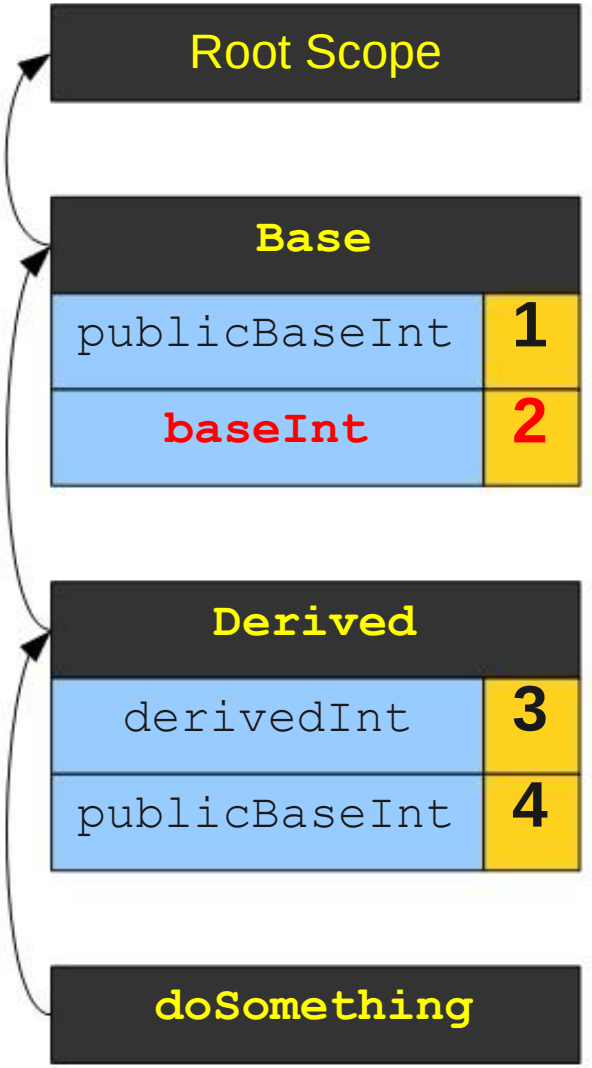
```
public class Base {
    public int publicBaseInt = 1;
    protected int baseInt = 2;
}

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

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

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

```
> 4
  2
```



Scoping with Inheritance

```
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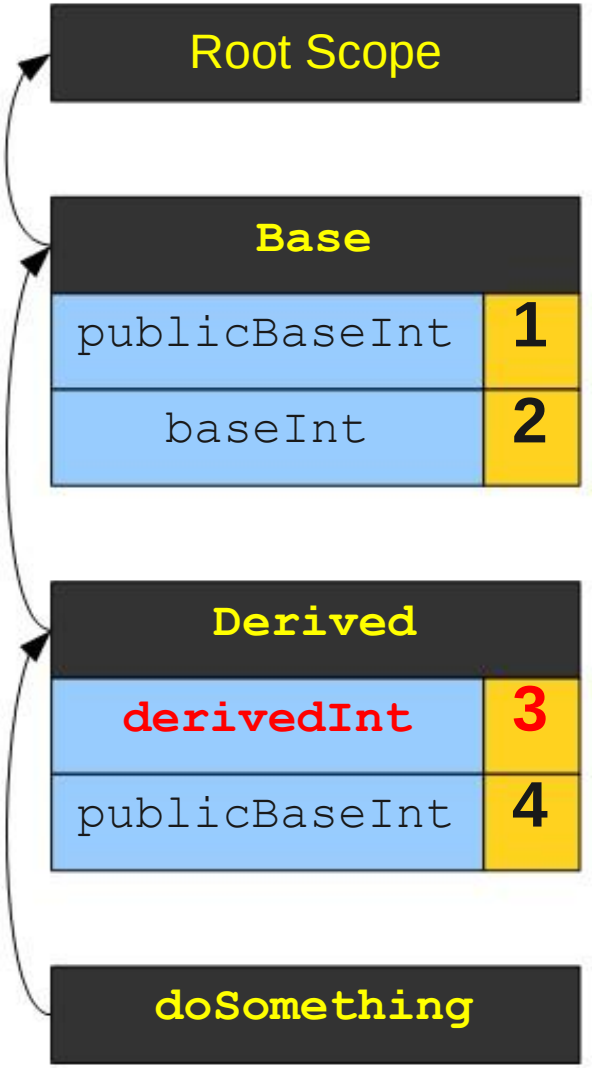
    protected int baseInt = 2;
}

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

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

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

```
> 4
  2
  3
```



Scoping with Inheritance

```
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}

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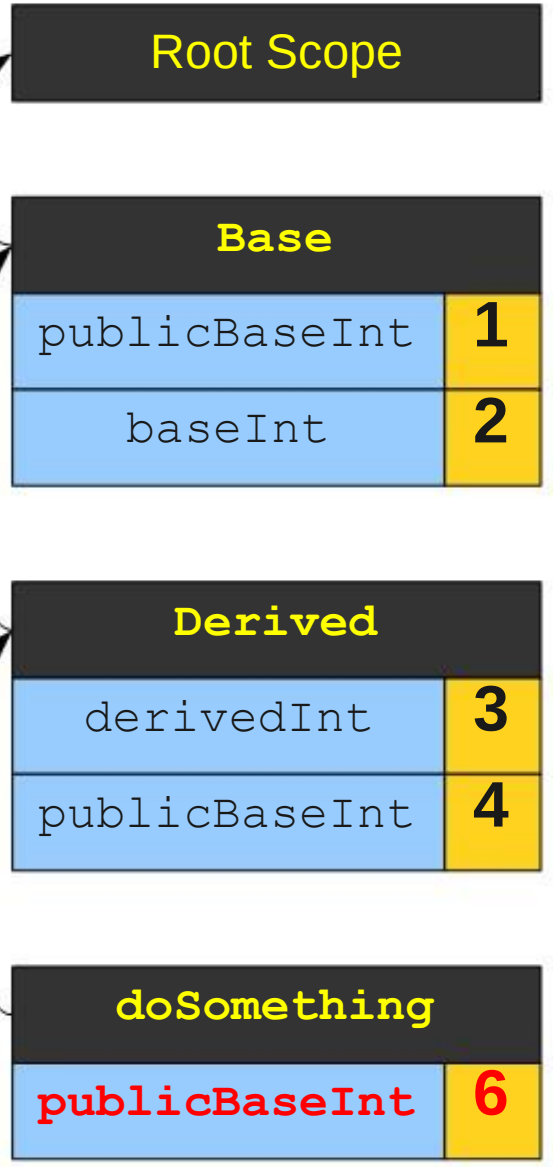
    public int publicBaseInt = 4;

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

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

```
> 4
  2
  3
```



Scoping with Inheritance

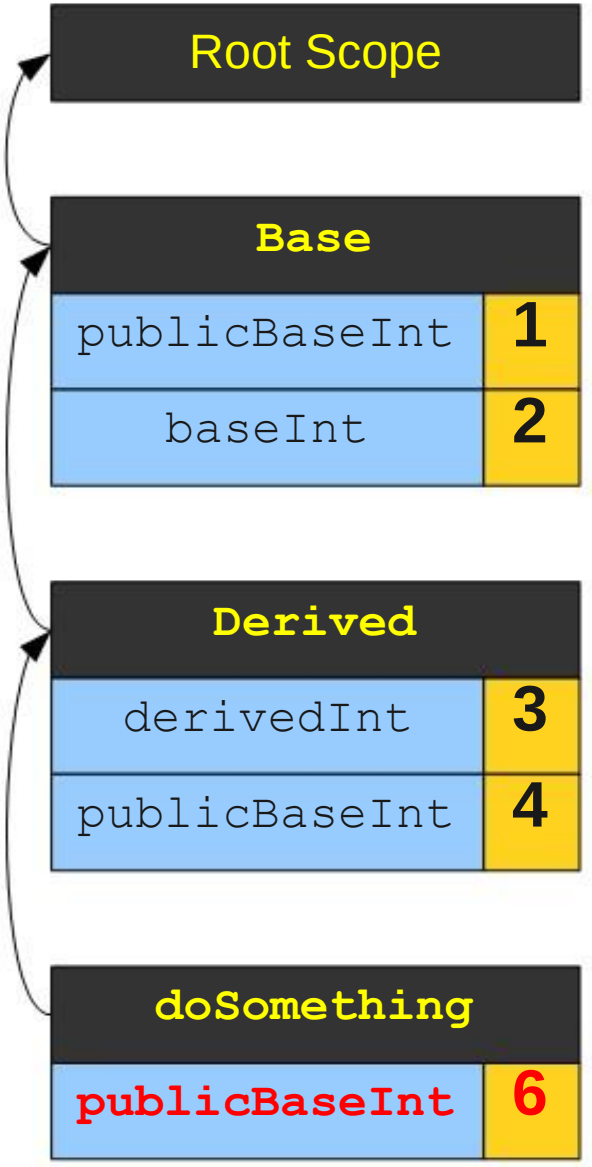
```
public class Base {
    public int publicBaseInt = 1;
    protected int baseInt = 2;
}

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

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

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

```
> 4
  2
  3
  6
```



Dynamic Scoping

Static and Dynamic Scoping

- The scoping we've seen so far is called **static scoping** and is done at **compile-time**.

- Some languages use **dynamic scoping**, which is done at **runtime**.
  - Allows variables in different scopes to have the same name.
  - Names refer to the variable that is closest at runtime.

Dynamic Scoping

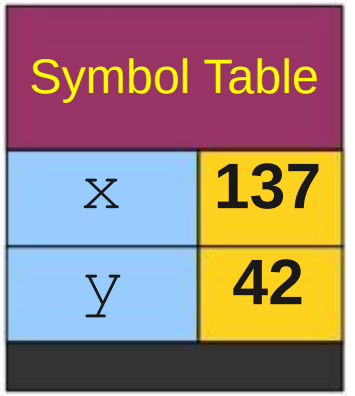
```
int x = 137;
int y = 42;
void Function1() {
    Print(x + y);
}
void Function2() {
    int x = 0;
    Function1();
}
void Function3() {
    int y = 0;
    Function2();
}
Function1();
Function2();
Function3();
```

Symbol Table	
x	137
y	42

```
>
```

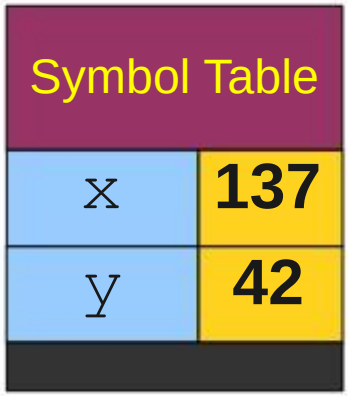
Dynamic Scoping

```
int x = 137;
int y = 42;
void Function1() {
    Print(x + y);
}
void Function2() {
    int x = 0;
    Function1();
}
void Function3() {
    int y = 0;
    Function2();
}
Function1();
Function2();
Function3();
```



Dynamic Scoping

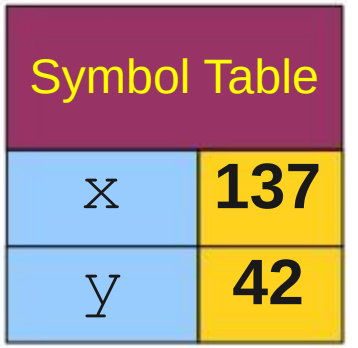
```
int x = 137;
int y = 42;
void Function1() {
    Print(x + y);
}
void Function2() {
    int x = 0;
    Function1();
}
void Function3() {
    int y = 0;
    Function2();
}
Function1();
Function2();
Function3();
```




```
> 179
>
```

Dynamic Scoping

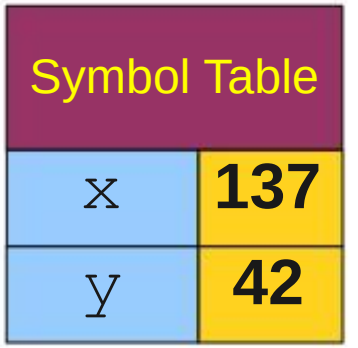
```
int x = 137;
int y = 42;
void Function1() {
    Print(x + y);
}
void Function2() {
    int x = 0;
    Function1();
}
void Function3() {
    int y = 0;
    Function2();
}
Function1();
Function2();
Function3();
```




```
> 179
>
```

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();
```




```
> 179
>
```

Dynamic Scoping

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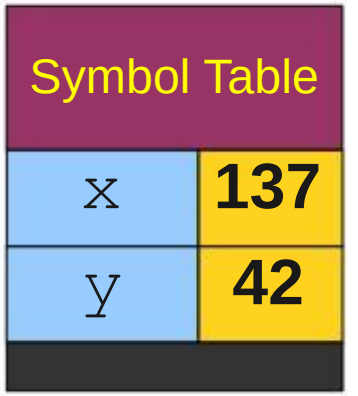
    int x = 0;
    Function1();
}
void Function3() {
    int y = 0;
    Function2();
}
Function1();
Function2();
Function3();
```




```
> 179
>
```

Dynamic Scoping

```
int x = 137;
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void Function1() {
    Print(x + y);
}
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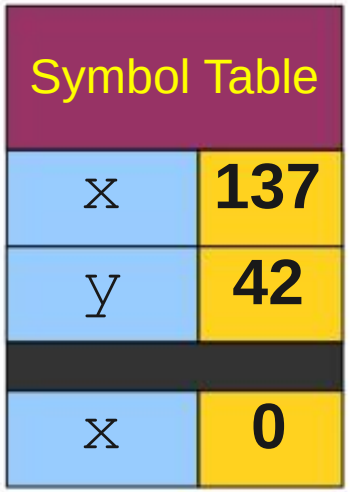
    int x = 0;
    Function1();
}
void Function3() {
    int y = 0;
    Function2();
}
Function1();
Function2();
Function3();
```




```
> 179
>
```

Dynamic Scoping

```
int x = 137;
int y = 42;
void Function1() {
    Print(x + y);
}
void Function2() {
    int x = 0;
    Function1();
}
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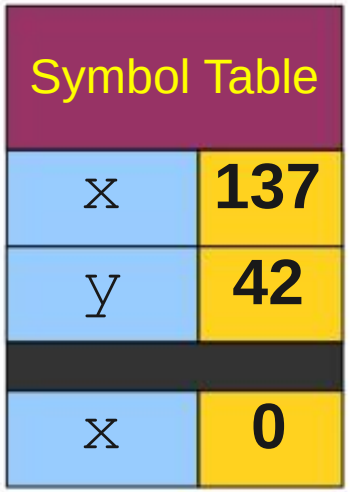
    int y = 0;
    Function2();
}
Function1();
Function2();
Function3();
```




```
> 179
>
```

Dynamic Scoping

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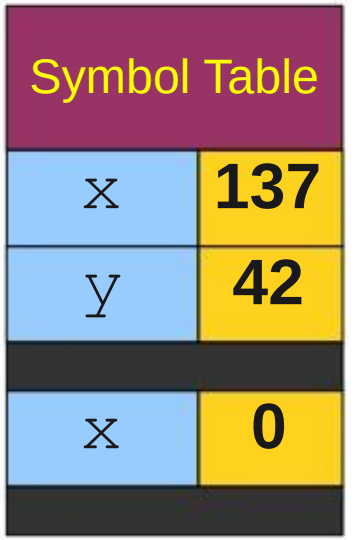
```




```
> 179
>
```

Dynamic Scoping

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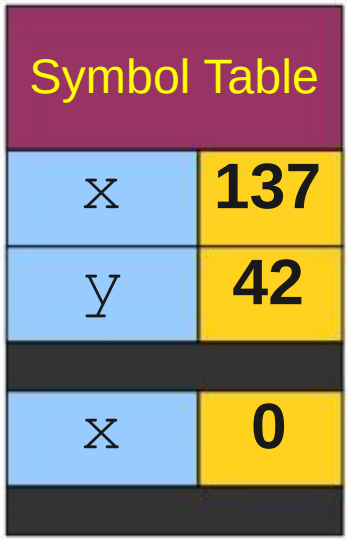
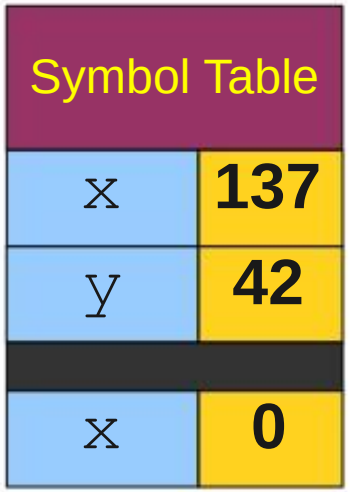
    Function2();
}
Function1();
Function2();
Function3();
```




```
> 179
> 42
>
```

Dynamic Scoping

```
int x = 137;
int y = 42;
void Function1() {
    Print(x + y);
}
void Function2() {
    int x = 0;
    Function1();
}
void Function3() {
    int y = 0;
    Function2();
}
Function1();
Function2();
Function3();
```




```
> 179
> 42
>
```

Dynamic Scoping

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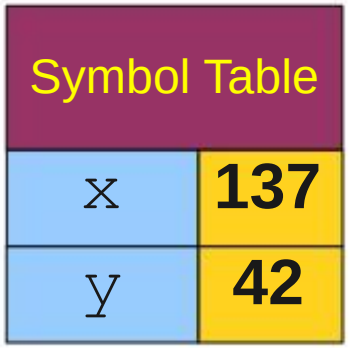
Function2();
Function3();
```




```
> 179
> 42
>
```

Dynamic Scoping

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

Symbol Table	
x	137
y	42

```
> 179
> 42
>
```

Dynamic Scoping

```
int x = 137;
int y = 42;
void Function1() {
    Print(x + y);
}
void Function2() {
    int x = 0;
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Function1();
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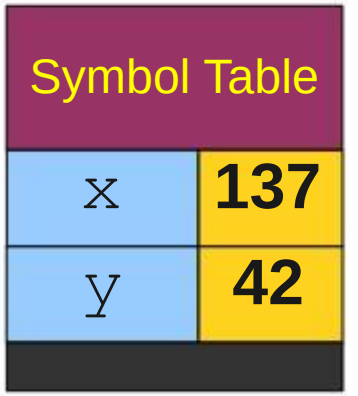
Function3();
```




```
> 179
> 42
>
```

Dynamic Scoping

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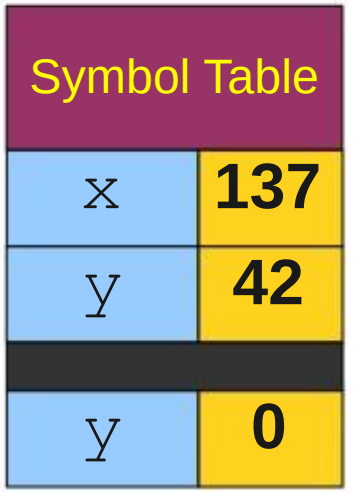
```




```
> 179
> 42
>
```

Dynamic Scoping

```
int x = 137;
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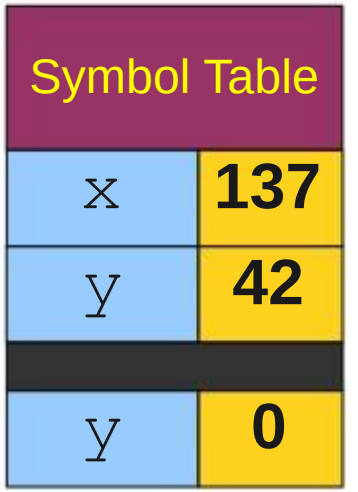


```
> 179
> 42
>
```

Dynamic Scoping

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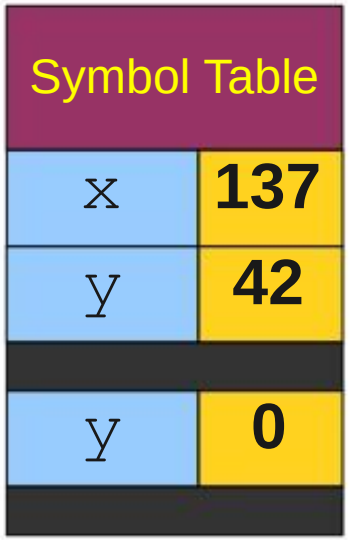


```
> 179
> 42
>
```

Dynamic Scoping

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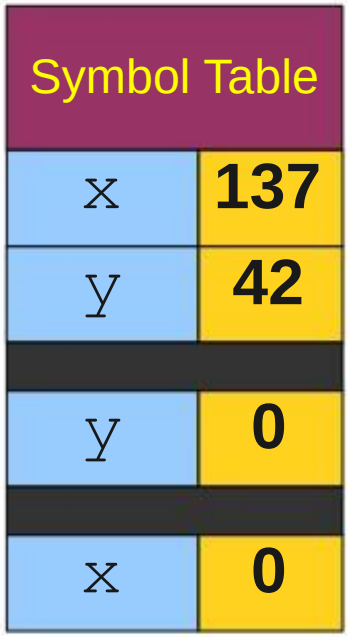


```
> 179
> 42
>
```

Dynamic Scoping

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Function3();
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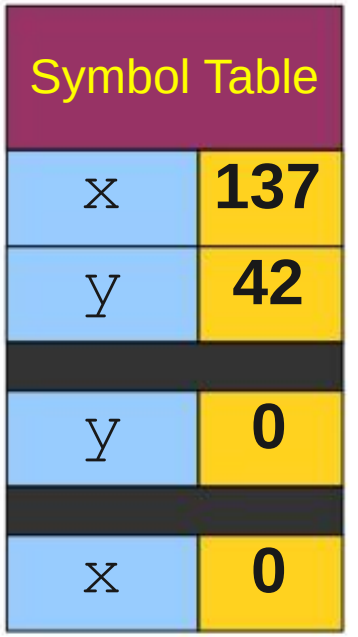


```
> 179
> 42
>
```

Dynamic Scoping

```
int x = 137;
int y = 42;
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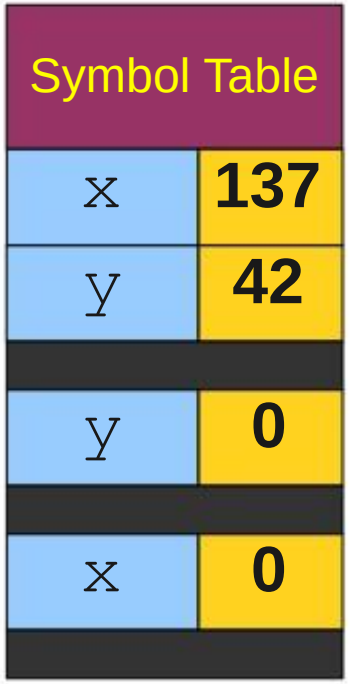
Function3();
```




```
> 179
> 42
>
```

Dynamic Scoping

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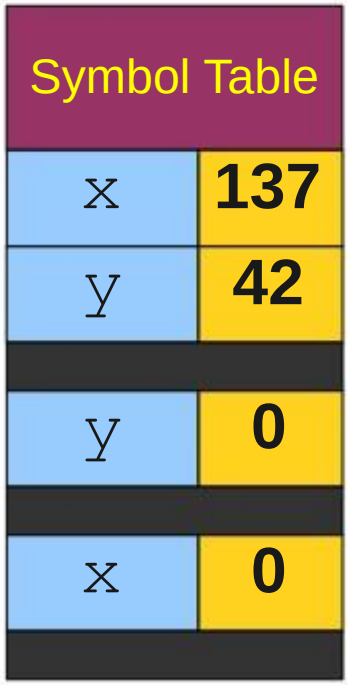
Function2();
Function3();
```




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

Dynamic Scoping in Practice

- Examples: Perl, Common LISP.

- 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;
};
```

C++

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

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

Java

Scoping in C++ and Java

```
class A {
public:
    /* … */

private:
    B  myB
};

class B {
public:
    /* … */

private:
    A  myA;
};
```

Error: B not declared

C++

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

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

Perfectly fine!

Java

Single- and Multi-Pass Compilers

- Some compilers can combine scanning, parsing, semantic analysis, and code generation into the same pass.
  - These are called **single-pass compilers**.
  - One-pass compilers are smaller and faster than multi-pass compilers
  - E.g. C, C++, Pascal

- Other compilers rescan the input multiple times.
  - These are called **multi-pass compilers**.
  - Multi-pass compilers generate more flexible programs
  - E.g. Java, C#

Scoping in Multi-Pass Compilers

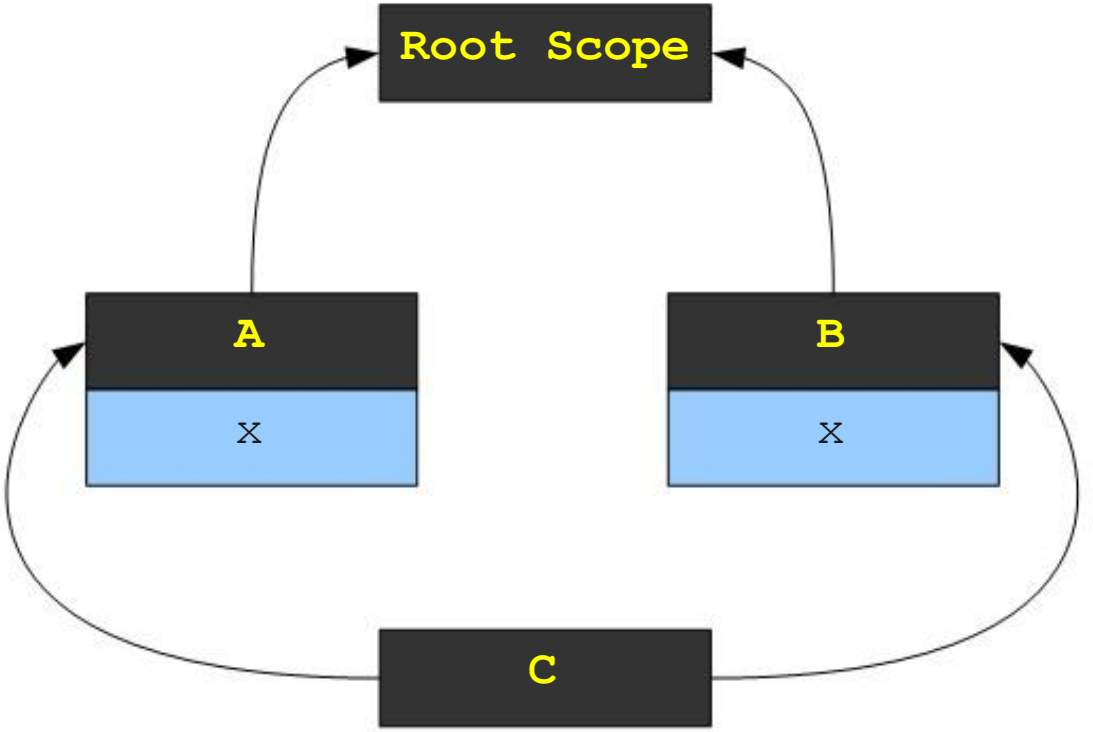
- Completely parse the input file into an abstract syntax tree (AST): first pass.
- Walk the AST, gathering information about classes: second pass.
- Walk the AST checking other properties (if needed) : third pass.

Scoping with Multiple Inheritance

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

class B {
public:
    int x;
};

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



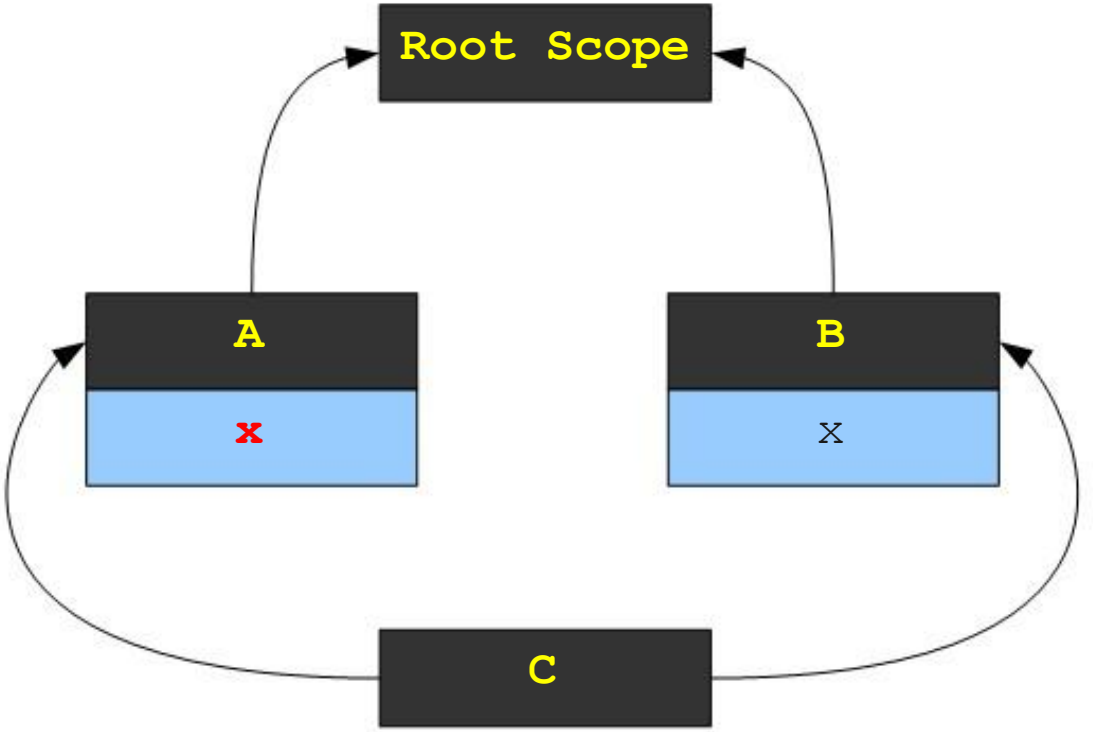
Ambiguous - which x?

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;
    }
}
```



Next Time

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