50.051 Programming Language Concepts

W12-S1 Semantic Analysis and Intermediate Representations

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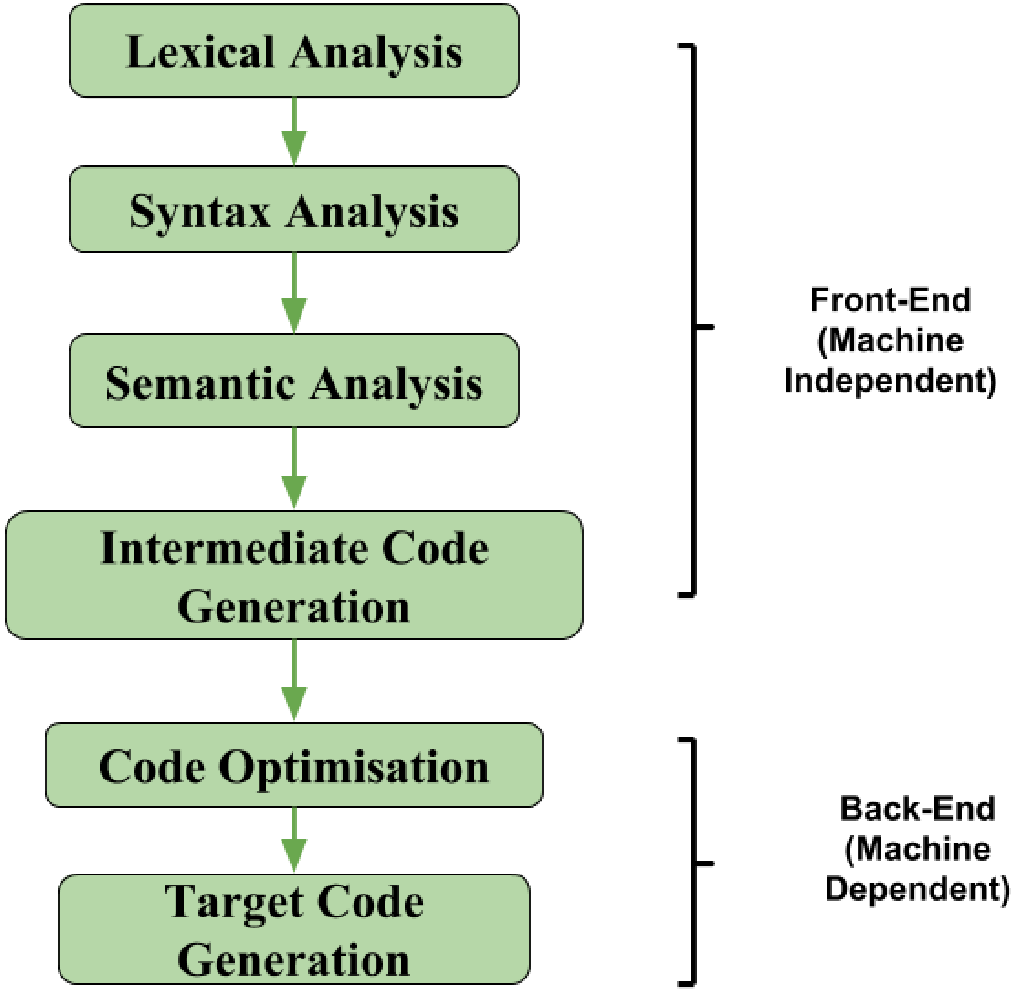
The front-end of a compiler

Definition (The front-end part of a compiler):

The **front-end of a compiler** is responsible for analysing the source code, and converting it into a form that can be used by the rest of the compiler.

It involves tasks, such as:

- **Lexical analysis,**
- **Syntax analysis,**
- and **Semantic analysis.**



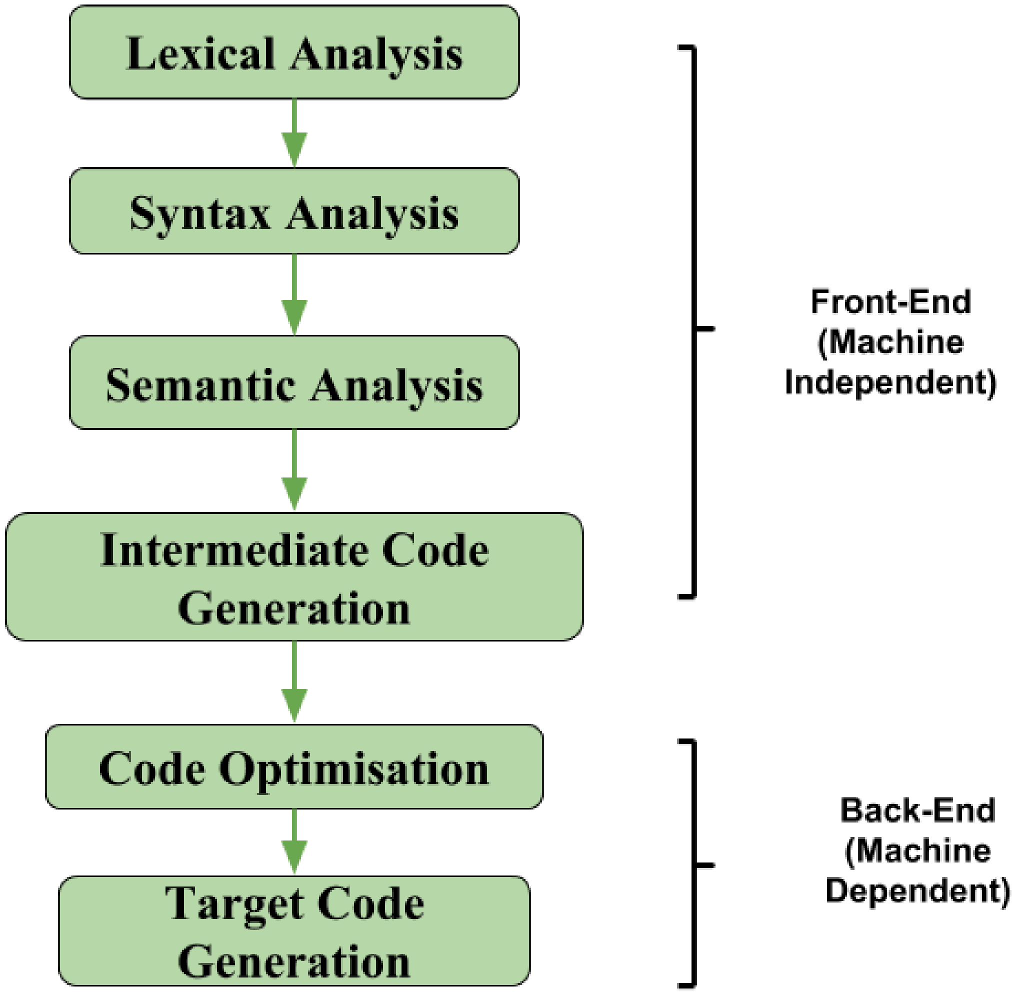
The front-end of a compiler

Lexical Analysis

- Detects illegal tokens in source code (e.g. incorrect use of identifiers, literals, etc.)

Syntax Analysis

- Detects inputs that violate the syntax rules of the language
- Will typically result in impossible-to-form or ill-formed parsing trees.

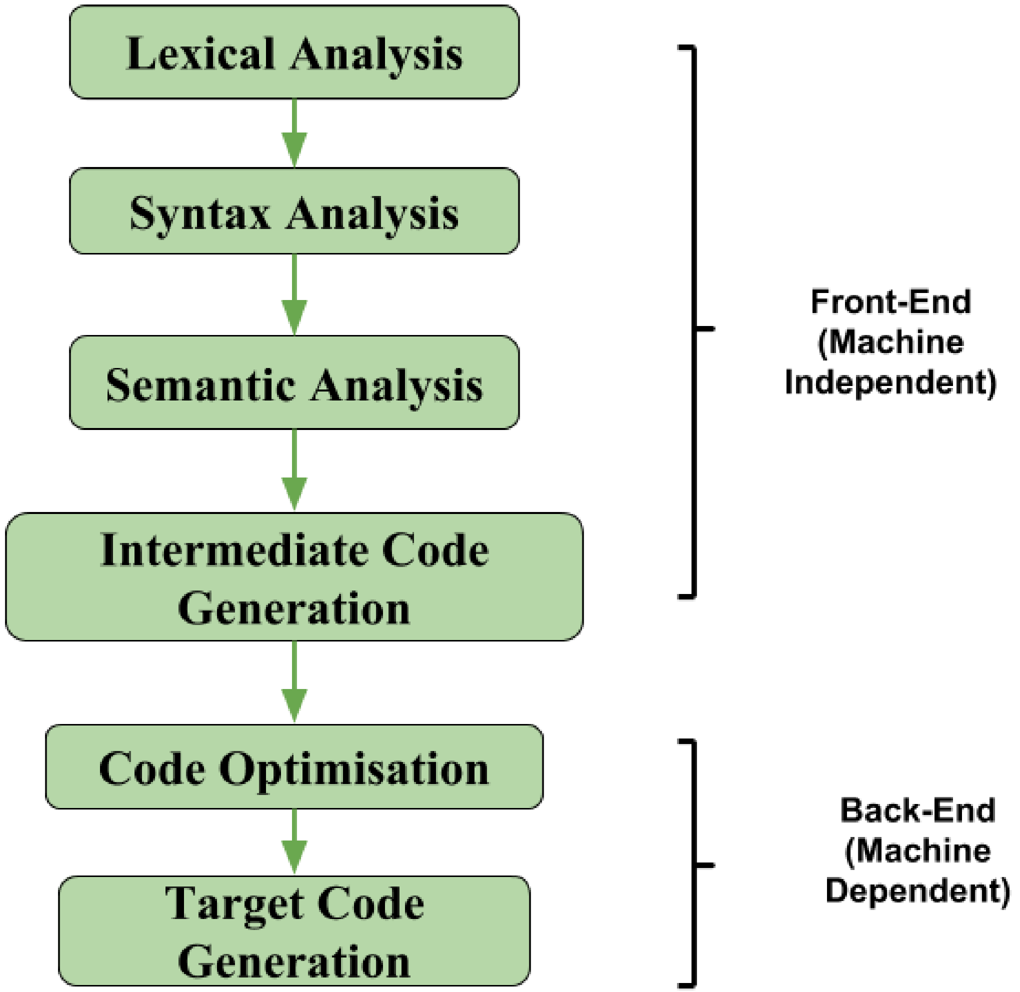


Restricted

The front-end of a compiler

Semantic Analysis

- Final step in the “front-end” phase, whose job is to check that the **source code is legal**.
- Ensures that the program has a **well-defined meaning**.
- Should catch **all remaining errors** that lexical analysis and syntax analysis could not catch.
- Errors that require **contextual information** about the code.



Examples of remaining errors

Scope problems

- A variable is defined after it is called for the first time.
- A function is defined after it is called for the first time and no function prototypes were mentioned.
- A variable defined in a function is called outside of the function.
- A variable name is defined twice.
- Etc.

```c
#include <stdio.h>

int main() {
    int y;
    y = x + 7;
    int x = 3;
    return 0;
}
```

```c
#include <stdio.h>

int main() {
    int x = 3;
    int x = 7;
    return 0;
}
```

```c
#include <stdio.h>

// Subfunction2 is defined first, but it calls subfunction1
int subfunction2(int x) {
    return subfunction1(x) + 2;
}

// Subfunction1 is defined later, but it is called by subfunction2
int subfunction1(int x) {
    return x * 3;
}

int main() {
    int x = 5;
    printf("Result from subfunction1: %d\n", subfunction1(x));
    return 0;
}
```

Examples of remaining errors

Why cannot we just catch these errors during parsing?

- Try writing a CFG that will be able to prevent duplicate variable definitions?
- For most programming languages, using a CFG to do that is **provably impossible.**
- Proof using the pumping lemma for context-free languages, or Ogden's lemma.

```c
#include <stdio.h>

int main() {
    int y;
    y = x + 7;
    int x = 3;
    return 0;
}
```

```c
#include <stdio.h>

int main() {
    int x = 3;
    int x = 7;
    return 0;
}
```

```c
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// Subfunction2 is defined first, but it calls subfunction1
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int subfunction1(int x) {
    return x * 3;
}

int main() {
    int x = 5;
    printf("Result from subfunction1: %d\n", subfunction1(x));
    return 0;
}
```

Examples of remaining errors

```c
#include <stdio.h>

int main() {
    char* x = "hello";
    float y = x + 7.5;
    printf("%f", y);
    return 0;
}
```

Type problems

- An operation attempts to combine two invalid types together (e.g. summing a string and a float together).
- An operation attempts to convert a variable of a certain type in another type that is not feasible.
- Etc.

```c
#include <stdio.h>

struct Point {
    int x;
    int y;
};

int main() {
    struct Point p = {3, 4};
    int z;

    // The following line tries to convert a struct
    // (Point) to an int, which is not feasible.
    z = (int)p;

    printf("Point: (%d, %d)\n", p.x, p.y);
    printf("Converted to int: %d\n", z);

    return 0;
}
```

Examples of remaining errors

And more problems that have to do with classes!

- A class inherits from another class that is not defined yet.
- A child class attempts to use a method that was neither defined in the child class itself, nor the parent class it inherited from.
- Operators on custom classes being used incorrectly.
- Etc.

```c
#include <stdio.h>

int main() {
    char* x = "hello";
    float y = x + 7.5;
    printf("%f", y);
    return 0;
}
```

```c
#include <stdio.h>

struct Point {
    int x;
    int y;
};

int main() {
    struct Point p = {3, 4};
    int z;

    // The following line tries to convert a struct
    // (Point) to an int, which is not feasible.
    z = (int)p;

    printf("Point: (%d, %d)\n", p.x, p.y);
    printf("Converted to int: %d\n", z);

    return 0;
}
```

Examples of remaining errors

Important fact: These errors cannot be checked during the lexical analysis or the syntax analysis, as they require some context.

- Cannot be checked by a context-free grammar.
- Often depends on values and context, not syntax.
- May sometimes require and involve computation.

What to do then?

- Instead, will need to **define a set of semantic rules for scoping and types** explicitly.
- And then, **perform additional checks after parsing**.
- These checks will be implemented in the form of “if-else” checks.

Where are we at now?

At the end of the lexical analysis and parsing phase.

- We have successfully **tokenized our source code and produced a stream of Tokens objects** (containing information about token type, lexeme, value, line number/position, etc.).
- We have established **a derivation for the language CFG and the given stream of tokens**.
- We have produced a **parse tree** following from that derivation.
- Using **Syntax Directed Translation**, we could define a **list of elementary operations** to be executed, matching each production rule we used and eventually obtain an **Abstract Syntax Tree**.

Implementing an SDT for Arithmetic CFG

Consider the CFG below, modified with the following SDT rules.

$E \rightarrow E + T \ \{E.val = E1.val + T.val\}$

$E \rightarrow T \ \{E.val = T.val\}$

$T \rightarrow T * F \ \{T.val = T1.val * F.val\}$

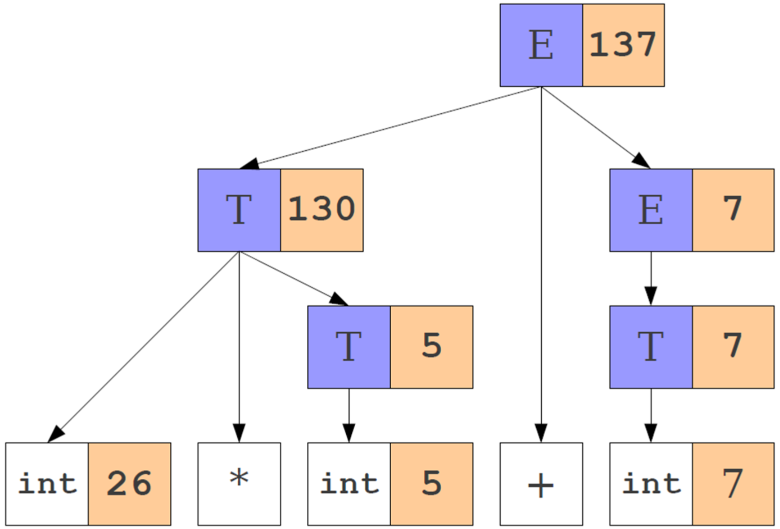
$T \rightarrow F \ \{T.val = F.val\}$

$F \rightarrow (E) \ \{F.val = E.val\}$

$F \rightarrow num \ \{F.val = num.val\}$

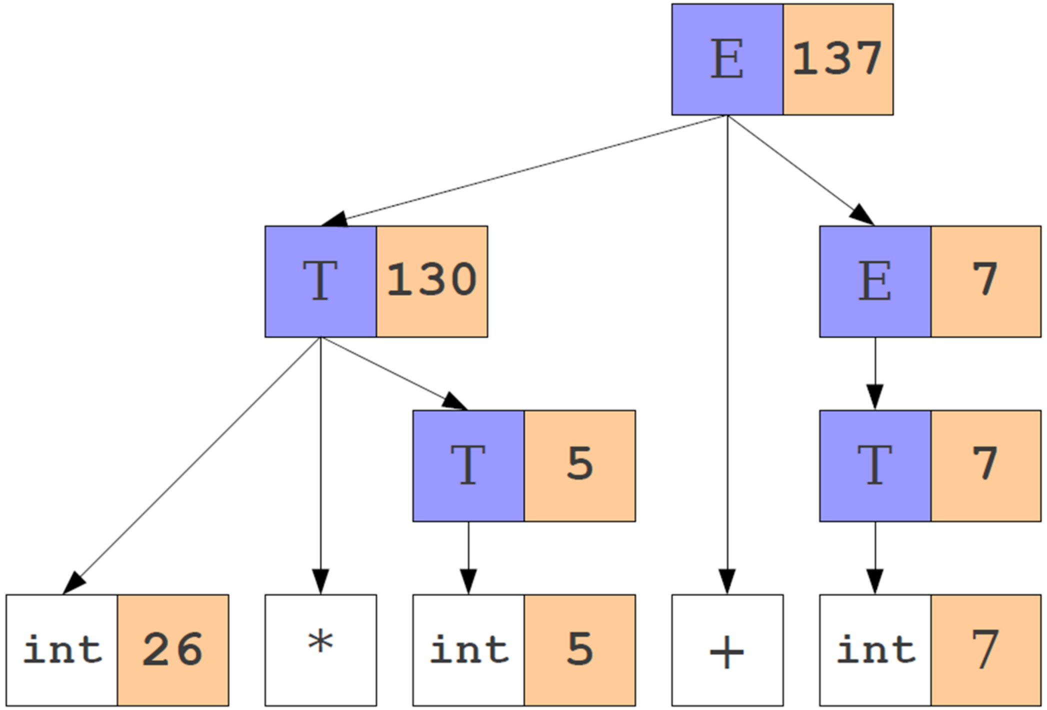
Using this CFG/SDT on 26*5 + 7 gives the following derivation and parse tree.

Sequence of operations in parse tree = bottom-up reading = DFS!



Implementing an SDT for Arithmetic CFG

Using these steps, on the string "26*5 + 7", then gives the following Abstract Syntax Tree and list of SDT rules…



And the list of operations below:

I1.val = 26

I2.val = 5

T1.val = i2.val

*T2.val = T1.val*i1.val*

I3.val = 7

T3.val = i3.val

E1.val = T3.val

E.val = T2.val + E1.val

Restricted

Semantic analysis and ASTs

Objective: The answer to the semantic problems

- Scope problems,
- Type problems,
- And more,…

And the checks to be conducted, both rely on the **Abstract Syntax Tree** produced by the syntax analysis step.

Problem #1: Scope

Scope problems

- A variable is defined after it is called for the first time.
- A function is defined after it is called for the first time and no function prototypes were mentioned.
- A variable defined in a function is called outside of the function.
- A variable name is defined twice.
- Etc.

```c
#include <stdio.h>

int main() {
    int y;
    y = x + 7;
    int x = 3;
    return 0;
}
```

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int main() {
    int x = 3;
    int x = 7;
    return 0;
}
```

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int subfunction1(int x) {
    return x * 3;
}

int main() {
    int x = 5;
    printf("Result from subfunction1: %d\n", subfunction1(x));
    return 0;
}
```

First things first

Definition (Scope):

The **scope** of an identifier (variable/function name, etc.) is the **portion of the program in which this identifier is accessible**.

- Decides if a variable can be called outside of a function,
- Resolves ambiguity about identifiers with similar names used in different functions,
- Etc.

```c
#include <stdio.h>

void function1() {
    int x = 10;
}

int main() {
    function1();
    printf("The value of x is %d\n", x);
    return 0;
}
```

```c
#include <stdio.h>

void function1() {
    int x = 10;
    printf("The value of x in function1 is %d\n", x);
}

void function2() {
    int x = 20;
    printf("The value of x in function2 is %d\n", x);
}

int main() {
    function1();
    function2();
    return 0;
}
```

First things first

Definition (Static and Dynamic Scope):

Most languages have a **static scope**.

- A **static scope depends only on the program code, not its runtime behaviour**.
- Typically C and Java.

Some languages are **dynamically scoped**.

- A **dynamic scope may depend on the execution of the program and is decided during runtime**.
- For instance, JavaScript (?) and LaTeX.

Is static better than dynamic? Not a kind of debate I want to participate in!

Static scoping

Let us start with **static scoping**.

Some questions that need to be answered for static scoping are:

- How can we tell what object a particular identifier refers to?
- How do we store this information?

Need a **symbol table** to keep track of symbols/identifiers!

*(**Note:** Dynamic scoping follows roughly the same ideas, just not happening during compile time, but during runtime instead!)*

Symbol table

Definition (symbol table in a compiler):

A **symbol table** contains information about identifiers, that might prove useful to the compiler. It simply represents a mapping from a name to the thing that name refers to. This information typically consists of

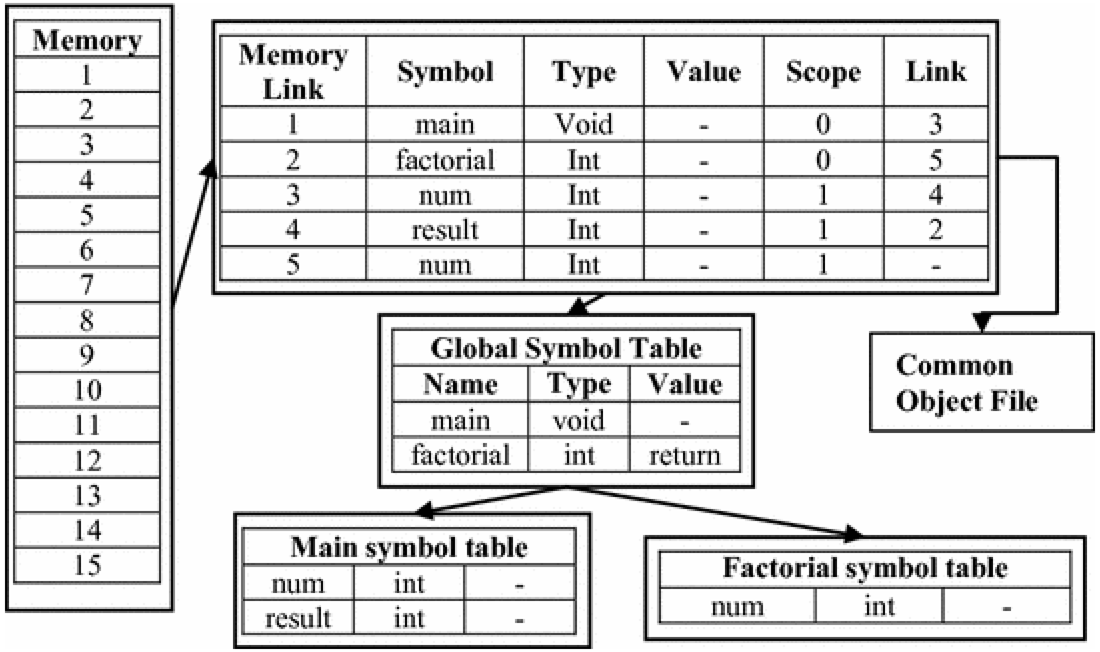
- Textual name,
- Data type,
- Declaration procedure,
- If array, number and size of dimensions,
- If procedure, number and type of parameters, location for function definition and procedure to be run by function when called,
- Etc.

Implementing a symbol table

Simple solution: Define our symbol table as a **hash table** of some sort.

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

- What does this look like in practice?
- What operations need to be defined on it?
- How do we implement it?



Forgot about hash tables?

Time to go back to the contents of [50.004 Algorithms]!

Implementing a symbol table

For simplicity: can be 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 an identifier name corresponds to.
- **Remove symbol:** Remove entry from the current scope.

Implementing an SDT for Arithmetic CFG

Consider the CFG below, modified with the following SDT rules.

$$E \rightarrow E + T \; \{E.val = E1.val + T.val\}$$

$$E \rightarrow T \; \{E.val = T.val\}$$

$$T \rightarrow T * F \; \{T.val = T1.val * F.val\}$$

$$T \rightarrow F \; \{T.val = F.val\}$$

$$F \rightarrow (E) \; \{F.val = E.val\}$$

$$F \rightarrow num \; \{F.val = num.val\}$$

In practice, the symbol table actions could be added to our Syntax-Driven Translation rules!

We would then have **two SDT instructions per CFG rule**:

- One that defines the elementary operation to be used (in a language close to the 3-address format),
- And one describing the symbol table updates.

Implementing a symbol table

Before demo: the idea is to process each portion of the program that creates a scope independently (e.g. block statements, function calls, classes, etc.):

- **Start by entering a new scope**.
- **Add all variable declarations to the symbol table**.
- **Process the body of the block/function/class**.
- **Exit the scope**.

Most of the semantic analysis is defined in terms of recursive AST traversals like this.

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

Global scope

```c
#include <stdio.h>

int multiply_and_add(int x, int y) {
    int result = x * y + x;
    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

```
#include <stdio.h>

int multiply_and_add(int x, int y) {
    int result = x * y + x;
    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

Add identifier for function to scope

Global scope

├ multiply_and_add (function)

(could also add information about parameters types and return types)

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

Skipped for now

```
#include <stdio.h>

int multiply_and_add(int x, int y) {
    int result = x * y + x;
    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

Open new scope with name main()

Global scope
├ multiply_and_add (function)
└ main (func. scope)

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

```c
#include <stdio.h>

int multiply_and_add(int x, int y) {
    int result = x * y + x;
    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

Add identifier for variable to scope

```
Global scope
 ├ multiply_and_add (function)
 └ main (func. scope)
    ├ a (int, 3)
```

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

```c
#include <stdio.h>

int multiply_and_add(int x, int y) {
    int result = x * y + x;
    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

Add identifier for variable to scope

```
Global scope
  ├ multiply_and_add (function)
  └ main (func. scope)
      ├ a (int, 3)
      ├ b (int, 4)
```

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

```c
#include <stdio.h>

int multiply_and_add(int x, int y) {
    int result = x * y + x;
    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

Add identifier for variable to scope

Also, open a new scope for function call

```
Global scope
  ├ multiply_and_add (function)
  └ main (func. scope)
      ├ a (int, 3)
      ├ b (int, 4)
      └ sum (int, ?)
          ├ multiply_and_add (func. scope)
```

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

```c
#include <stdio.h>

int multiply_and_add(int x, int y) {
    int result = x * y + x;
    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

Add identifiers for variable to scope

```
Global scope
  ├ multiply_and_add (function)
  └ main (func. scope)
      ├ a (int, 3)
      ├ b (int, 4)
      └ sum (int, ?)
            ├ multiply_and_add (func. scope)
                  ├ x (int, parameter, 3)
                  ├ y (int, parameter, 4)
```

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

```c
#include <stdio.h>

int multiply_and_add(int x, int y) {
    int result = x * y + x;
    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

Add identifier for variable to scope

```
Global scope
 ├ multiply_and_add (function)
 └ main (func. scope)
    ├ a (int, 3)
    ├ b (int, 4)
    └ sum (int, ?)
        ├ multiply_and_add (func. scope)
            ├ x (int, parameter, 3)
            ├ y (int, parameter, 4)
            └ result (int, 15)
```

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

```c
#include <stdio.h>

int multiply_and_add(int x, int y) {
    int result = x * y + x;
    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

Return = transfer value of identifier result to identifier sum and close function scope

```
Global scope
 ├ multiply_and_add (function)
 └ main (func. scope)
    ├ a (int, 3)
    ├ b (int, 4)
    └ sum (int, 15)
       ├ multiply_and_add (func. scope)
          ├ x (int, parameter, 3)
          ├ y (int, parameter, 4)
          └ result (int, 15)
```

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

```c
#include <stdio.h>

int multiply_and_add(int x, int y) {
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    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

Return = transfer value of identifier result to identifier sum and close function scope

Global scope
├ multiply_and_add (function)
└ main (func. scope)
  ├ a (int, 3)
  ├ b (int, 4)
  └ sum (int, 15)

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

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int multiply_and_add(int x, int y) {
    int result = x * y + x;
    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

Print fetches identifier sum from symbol table

```
Global scope
 ├ multiply_and_add (function)
 └ main (func. scope)
    ├ a (int)
    ├ b (int)
    └ sum (int)
```

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

```
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int multiply_and_add(int x, int y) {
    int result = x * y + x;
    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

Return 0 and close function scope main()

Global scope
- ├ multiply_and_add (function)
- └ main (func. scope)
  - ├ a (int, 3)
  - ├ b (int, 4)
  - └ sum (int, 15)

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

Global scope

├ multiply_and_add (function)

```
#include <stdio.h>

int multiply_and_add(int x, int y) {
    int result = x * y + x;
    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

Return 0 and close function scope main()

Implementing a symbol table

Consider the code below.

During execution, the symbol table will be created as follows.

Global scope

```
#include <stdio.h>

int multiply_and_add(int x, int y) {
    int result = x * y + x;
    return result;
}

int main() {
    int a = 3;
    int b = 4;
    int sum = multiply_and_add(a, b);
    printf("Result: %d\n", sum);
    return 0;
}
```

In fact, close global scope and end

Representing the symbol table as a stack

Technically, two ways to represent the symbol table below.

- **Simple stack**
- **Spaghetti stack**

```
Global scope
 ├ multiply_and_add (function)
 └ main (func. scope)
    ├ a (int)
    ├ b (int)
    └ sum (int)
       ├ multiply_and_add (func. scope)
          ├ x (int, parameter)
          ├ y (int, parameter)
          └ result (int)
```

Representing the symbol table as a stack

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- **Simple stack**
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```
Global scope
 ├ multiply_and_add (function)
 └ main (func. scope)
    ├ a (int)
    ├ b (int)
    └ sum (int)
       ├ multiply_and_add (func. scope)
          ├ x (int, parameter)
          ├ y (int, parameter)
          └ result (int)
```

Simple stack

- Opening a new scope simply adds on top of the existing stack.

Global scope

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Global scope
 ├ multiply_and_add (function)
 └ main (func. scope)
    ├ a (int)
    ├ b (int)
    └ sum (int)
       ├ multiply_and_add (func. scope)
          ├ x (int, parameter)
          ├ y (int, parameter)
          └ result (int)
```

Simple stack

- Opening a new scope simply adds on top of the existing stack.

Global scope

Function id multiply_and_add

Representing the symbol table as a stack

Technically, two ways to represent the symbol table below.

- **Simple stack**
- **Spaghetti stack**

```
Global scope
 ├ multiply_and_add (function)
 └ main (func. scope)
    ├ a (int)
    ├ b (int)
    └ sum (int)
        ├ multiply_and_add (func. scope)
            ├ x (int, parameter)
            ├ y (int, parameter)
            └ result (int)
```

Simple stack

- Opening a new scope simply adds on top of the existing stack.

Global scope
Function id multiply_and_add
Main scope
Integer id a
Integer id b
Integer id sum

Representing the symbol table as a stack

Technically, two ways to represent the symbol table below.

- **Simple stack**
- **Spaghetti stack**

```
Global scope
 ├ multiply_and_add (function)
 └ main (func. scope)
    ├ a (int)
    ├ b (int)
    └ sum (int)
       ├ multiply_and_add (func. scope)
          ├ x (int, parameter)
          ├ y (int, parameter)
          └ result (int)
```

Simple stack

- Opening a new scope simply adds on top of the existing stack.

Global scope
Function id multiply_and_add
Main scope
Integer id a
Integer id b
Integer id sum
Multiply_and_add func. scope
Integer id x
Integer id y
Integer id result

Representing the symbol table as a stack

Technically, two ways to represent the symbol table below.

- **Simple stack**
- **Spaghetti stack**

```
Global scope
 ├ multiply_and_add (function)
 └ main (func. scope)
    ├ a (int)
    ├ b (int)
    └ sum (int)
       ├ multiply_and_add (func. scope)
          ├ x (int, parameter)
          ├ y (int, parameter)
          └ result (int)
```

Simple stack

- Opening a new scope simply adds on top of the existing stack.

Global scope
Function id multiply_and_add
Main scope
Integer id a
Integer id b
Integer id sum

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Spaghetti stack

- Treat the symbol table as a linked structure of scopes.
- Each scope stores a pointer to its parents, but not vice-versa.

Global scope

Restricted

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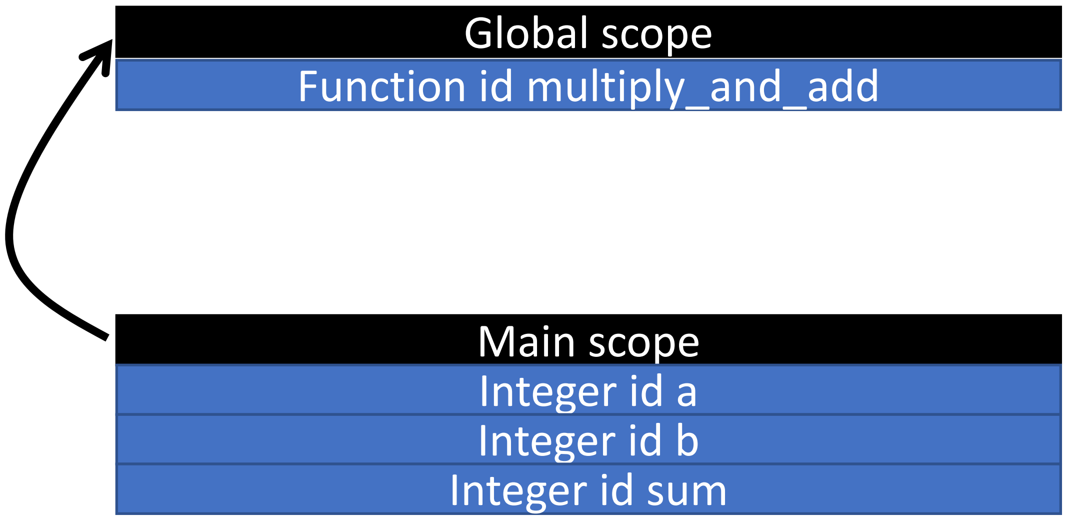

Restricted

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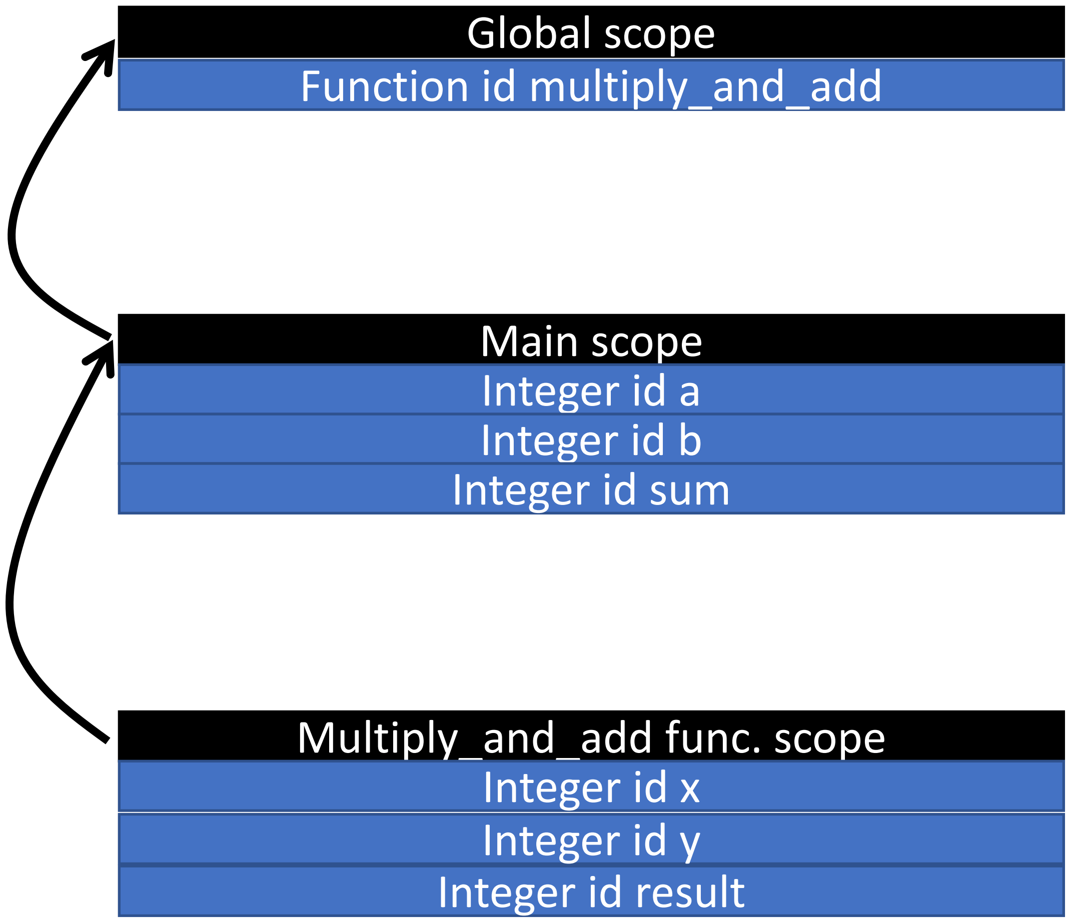

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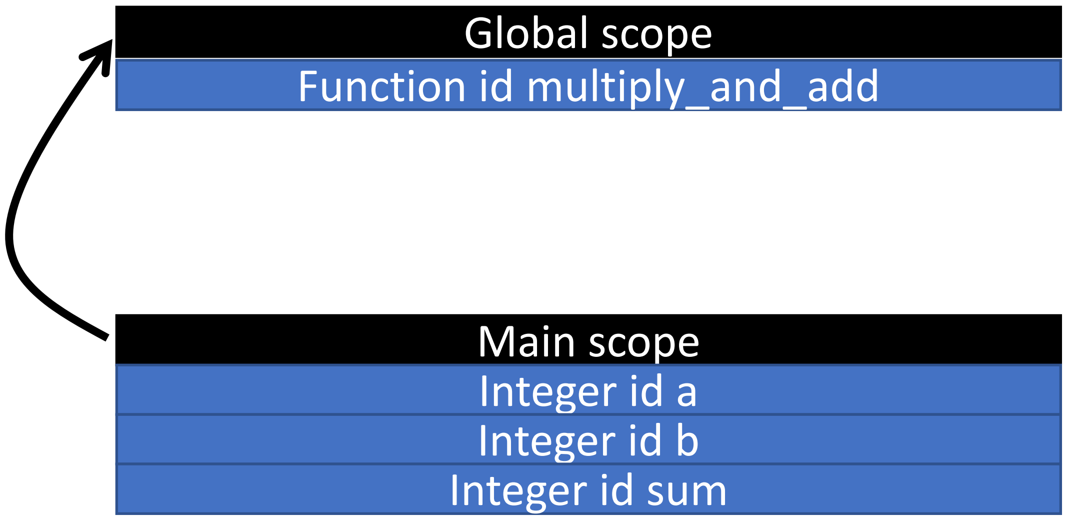

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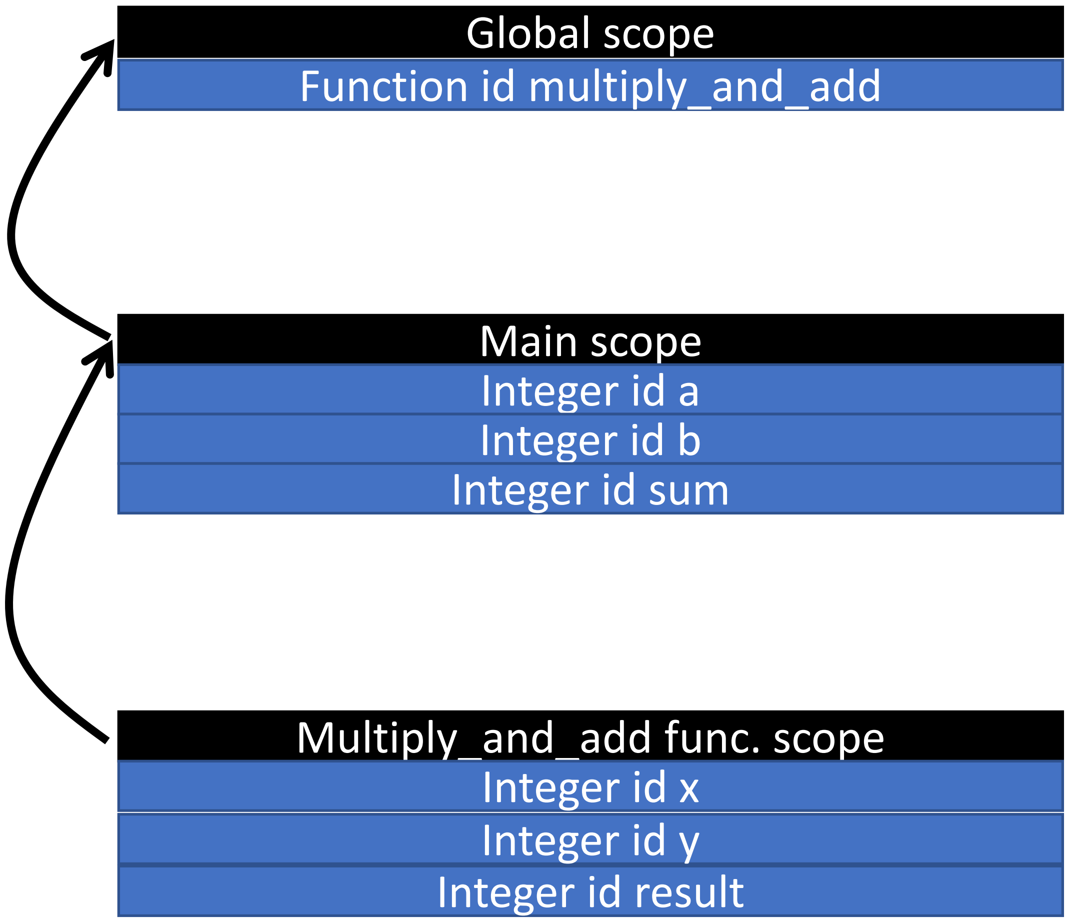
Representing the symbol table as a stack

Spaghetti stack

- Treat the symbol table as a linked structure of scopes.
- Each scope stores a pointer to its parents, but not vice-versa.
- **Observation:** From any point in the program, symbol table appears to be a simple stack containing elements of the scope and the scope only.
- **Better?**



Catching scope errors

Scope problems

- A variable is defined after it is called for the first time.
- A function is defined after it is called for the first time and no function prototypes were mentioned.
- A variable defined in a function is called outside of the function.
- A variable name is defined twice.
- Etc.

Most scope problems will be caught when

- An operation retrieving something from the symbol table fails (variable/function undefined in scope, etc.).
- An operation tries adding a variable/function with an identifier name that already exists in table (identifier defined twice in same scope).

Saving the day?

Consider the example on the right.

- Function f() requires two parameters x and t to compute the returned value.
- But t is not in the scope of the function, it is in the global scope instead.
- **Question:** How does Python save the day, in your opinion?

```python
def f(x):
    return x + t + 2
```

```python
t = 4
x = 3
y = f(x)
print(y)
```

```
9
```

Saving the day?

- **Reason:** In Python, when you reference a variable inside a function, it first looks for that variable within the local scope of the function.
- If it does not find it there, it tries searching for it in the next enclosing scope, which in this case is the global scope.

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def f(x):
    return x + t + 2
```

```python
t = 4
x = 3
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print(y)
```
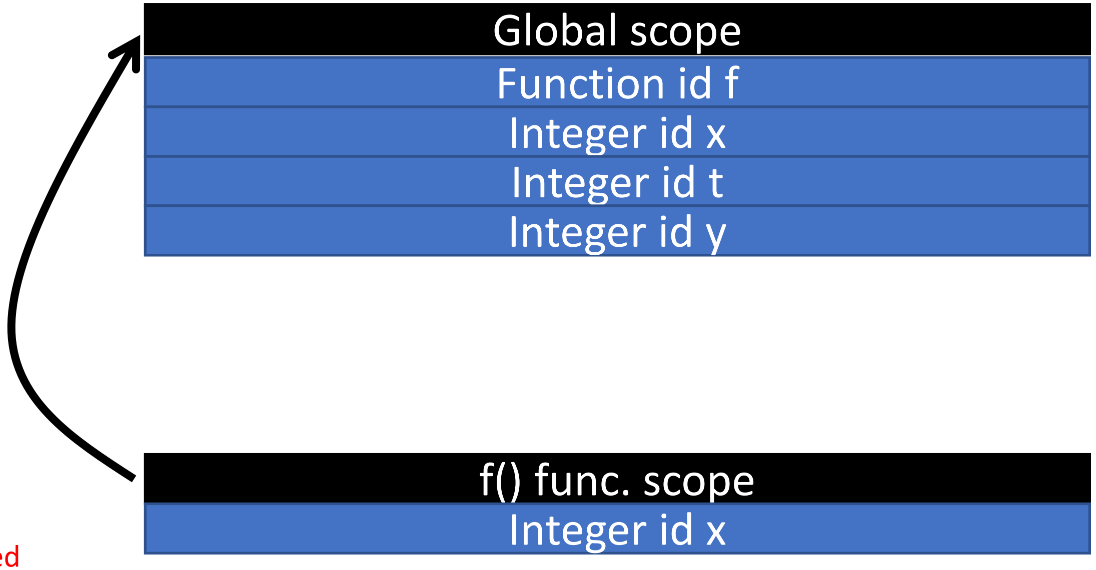

```
9
```



The LEGB rule

In fact: The scoping rule used in Python is called the "LEGB" rule, which stands for Local, Enclosing, Global, and Built-in.

It is a spaghetti stack with different levels of scope.

When a variable is referenced, Python searches in the following order.

- **Local scope:** variables defined within the function.
- **Enclosing scope:** variables defined in any enclosing functions, from innermost to outermost.
- **Global scope:** variables defined at the top level.
- **Built-in scope:** predefined built-in names in Python, like print(), sum(), etc.

How about C then?

Consider the example on the right.

- Function f() requires two parameters x and t to compute the returned value.
- But t is not in the scope of the function, it is in the global scope instead.
- **Question #2:** Also works in the equivalent implementation in C?

```c
#include <stdio.h>

int f(int x) {
	return x + t + 2;
}

int main() {
	int x = 4;
	int t = 3;
	int y = f(x);
	printf("%d", y);
	return 0;
}
```

Restricted

How about C then?

Answer: In C, variables have a **block scope**, which means that a variable is only accessible within the block of code it is defined in.

Better or worse than LEGB?

Usually more stable and simpler to encoder in a compiler than “LEGB”, very stable/strict and less friendly on “mistakes”.

Not an easy question…

```c
#include <stdio.h>

int f(int x) {
    return x + t + 2;
}

int main() {
    int x = 4;
    int t = 3;
    int y = f(x);
    printf("%d", y);
    return 0;
}
```

In short, the block scope (C)

Advantages:

- Encourages local reasoning: You can understand the behavior of a variable just by looking at the block of code it is defined in.
- Reduces the chance of accidentally using the wrong variable, as variables with the same name in different scopes do not conflict.

Disadvantages:

- Requires the use of global variables or explicit parameter passing to share data between functions, which can make the code more complex and error-prone.

In short, the LEGB scope (Python)

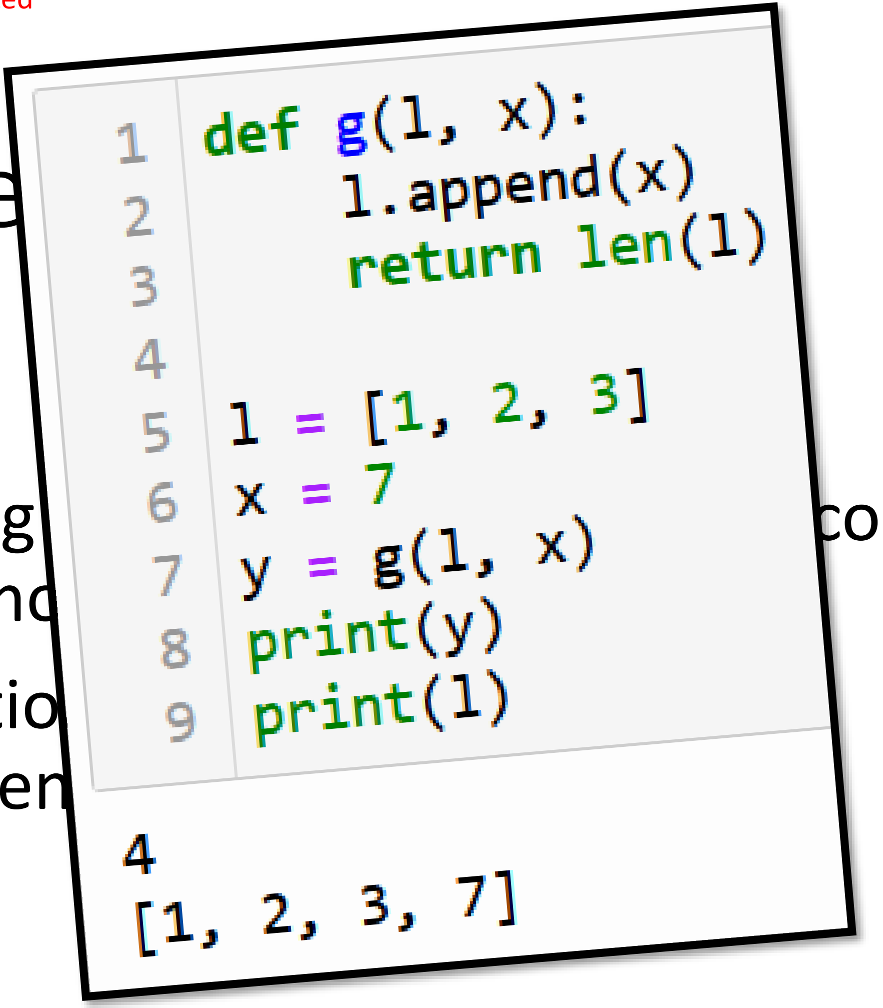
Advantages:

- Provides more flexibility in accessing variables from different scopes, which can make code shorter and more convenient to write.
- Allows for closures, which are functions that remember the environment they were created in, enabling more functional programming techniques.

Disadvantages:

- Can lead to unintended side effects if a variable from an outer scope is accidentally used or modified.
- Can make it harder to reason about the code since a variable might be accessed or modified in multiple scopes.

In short, the LEGB scope



```python
def g(l, x):
    l.append(x)
    return len(l)

l = [1, 2, 3]
x = 7
y = g(l, x)
print(y)
print(l)
```

```
4
[1, 2, 3, 7]
```

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Single-pass vs. multi-pass compilers

Definition (single-pass vs. multi-pass compilers):

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**.

What happens in multi-pass compilers

For instance, on each pass, the compiler could check one specific aspect of the source code. For instance,

- Do lexical analysis, produce tokens stream and completely parse the input file into an abstract syntax tree (first pass).
- Walk the AST, gathering information about classes definitions (second pass).
- Walk the AST gathering information about functions definitions (third pass).
- Etc.

Could combine some of these, though they are logically distinct.

Single-pass vs. multi-pass compilers

Which is better: single-pass or multi-pass compilers?

In general, **single-pass compilers** are usually faster than **multi-pass compilers**, but the logic complexity they can check is reduced.

Another debate I do not want to be part of!

Quiz time!

What is the primary purpose of semantic analysis in a compiler?

A. To generate intermediate code

B. To check the syntax of the input code

C. To optimize the generated code

D. To ensure the input code is semantically correct and meaningful

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What is a symbol table used for in a compiler?

A. To store the intermediate code representation
B. To store information about variables, functions, and other identifiers
C. To store the parse tree of the input code
D. To store the machine code generated by the compiler

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Which of the following best describes a static scoping rule?

A. The visibility of a variable only depends on its position in the source code

B. The visibility of a variable depends on the call history of functions

C. The visibility of a variable depends on the order of function calls at runtime

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In a compiler that uses syntax-directed translation, what is the purpose of the SDT instructions?

A. To perform lexical analysis
B. To create a parse tree
C. To replace each production rule used in a derivation with intermediate code instructions
D. To let us know how to update the symbol table
E. To convert intermediate code to machine code

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In a compiler, what is the purpose of a "spaghetti stack"?

A. To optimize memory usage during parsing
B. To store the parse tree during syntax analysis
C. To maintain the symbol table as a linked structure of scopes
D. To generate machine code for the target architecture

Quiz time!

In a compiler, what is the purpose of a "spaghetti stack"?

A. To optimize memory usage during parsing

B. To store the parse tree during syntax analysis

C. **To maintain the symbol table as a linked structure of scopes**

D. To generate machine code for the target architecture

Conclusion

- **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 variables, functions 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**.
- Simple semantic analysers will operate in a **single pass**, while some semantic analysers operate in **multiple passes** in order to gain more information about the program.