50.051 Programming Language Concepts

W11-S2 Semantic Analysis and Intermediate Representations (Part 1)

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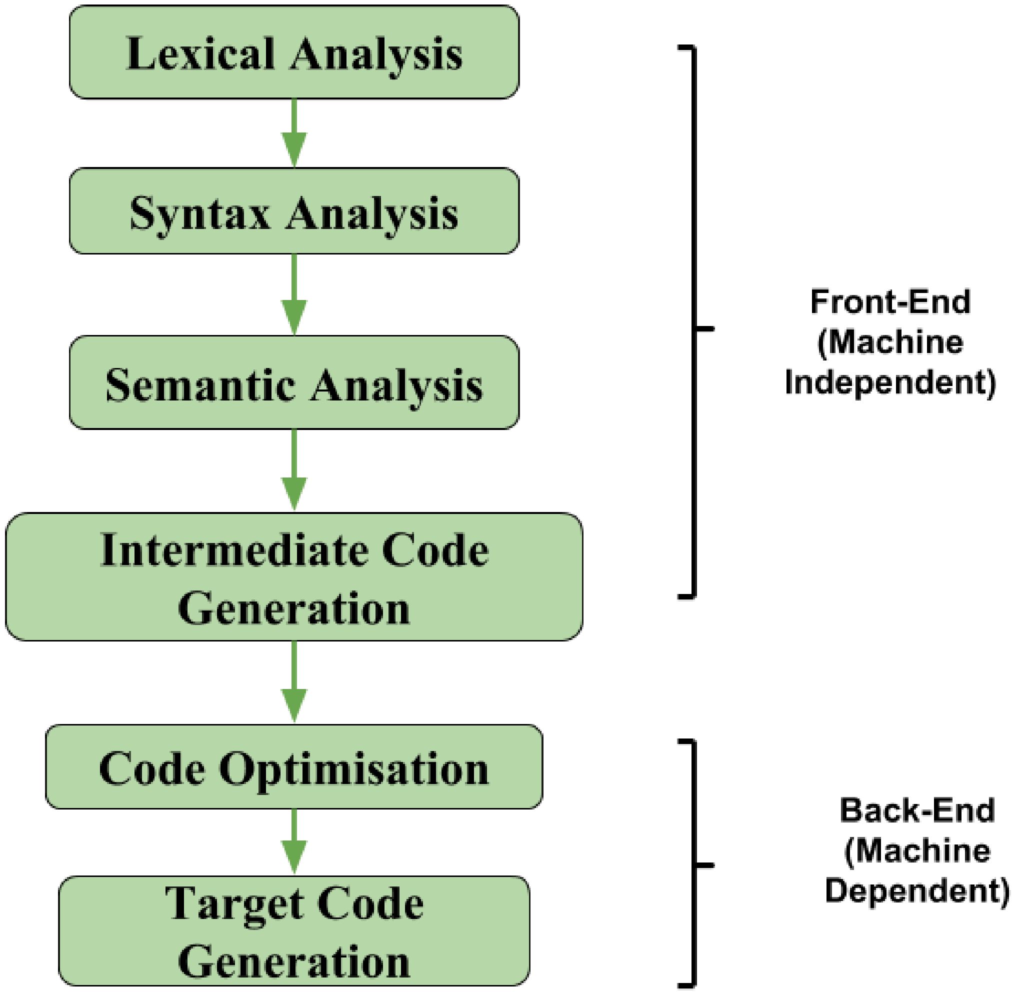
The front-end of a compiler

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.**



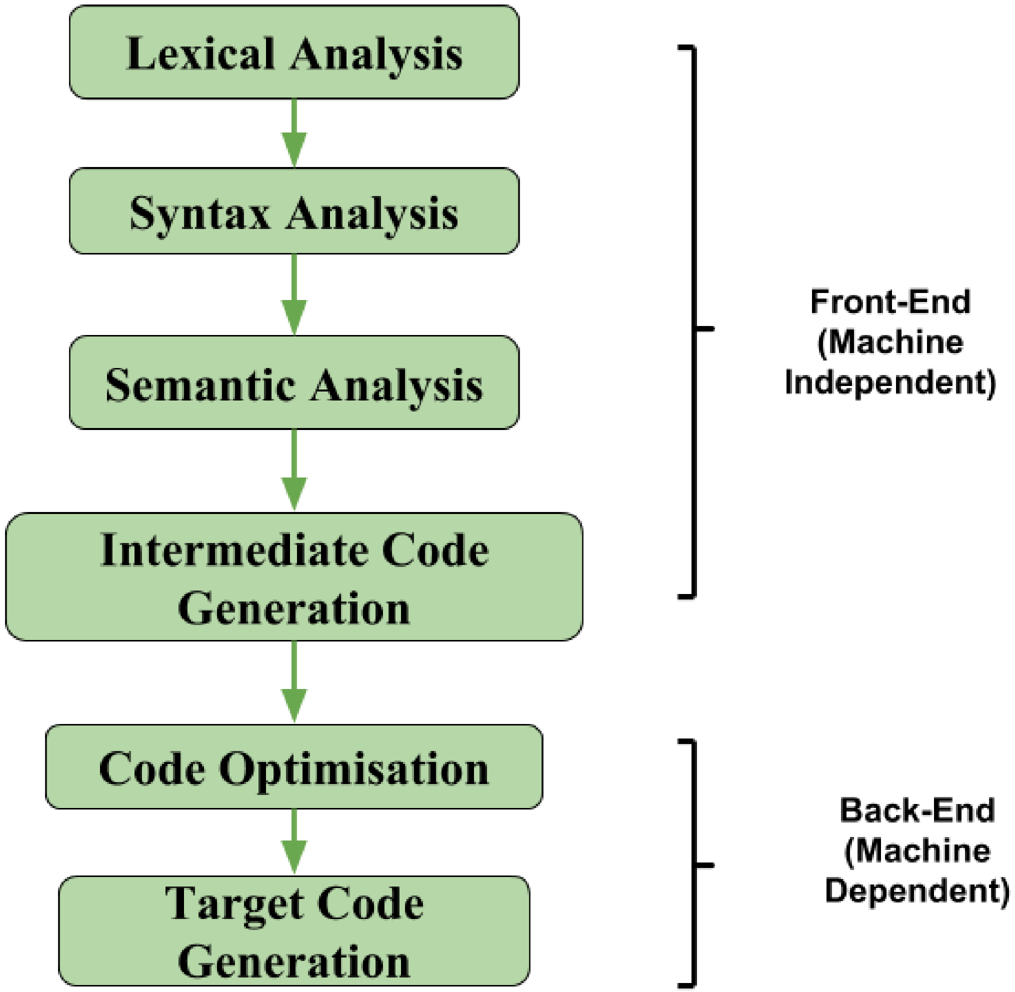
The front-end of a compiler

Lexical Analysis

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

Syntax Analysis

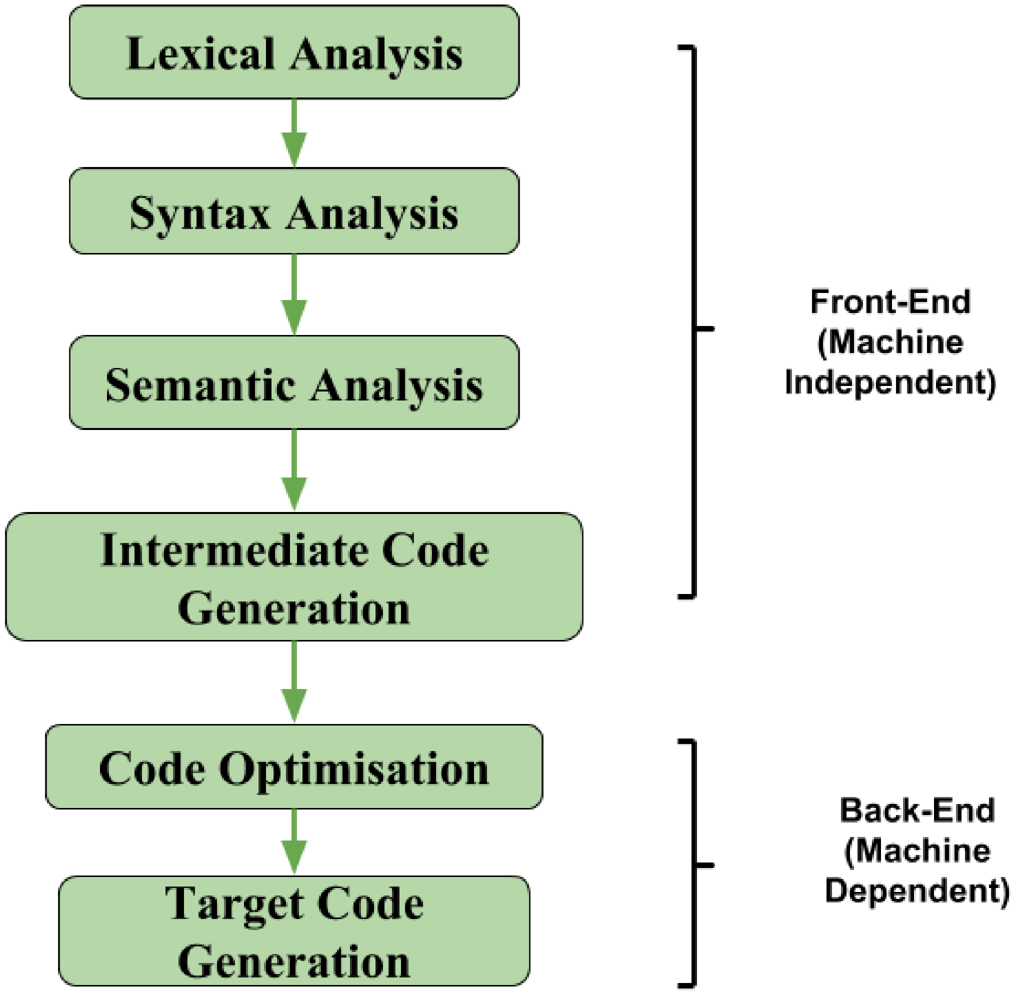
- Detects inputs that violate the syntax rules of the language
- Will typically result in impossible-to-form or ill-formed parsing trees.



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.



Restricted

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.**

(Out-of-scope, but proof is 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
#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

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>

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

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 (duh!) 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 can often be implemented as “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.

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

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

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

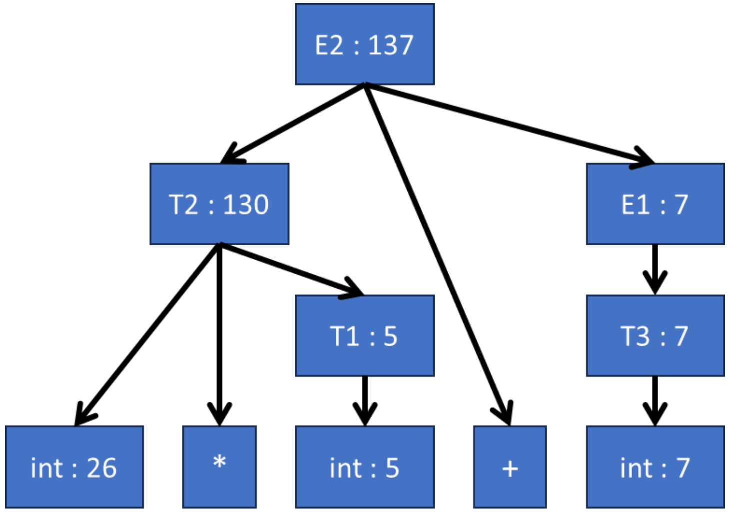
$T \rightarrow F \; \{T.val = F.val\}$

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

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

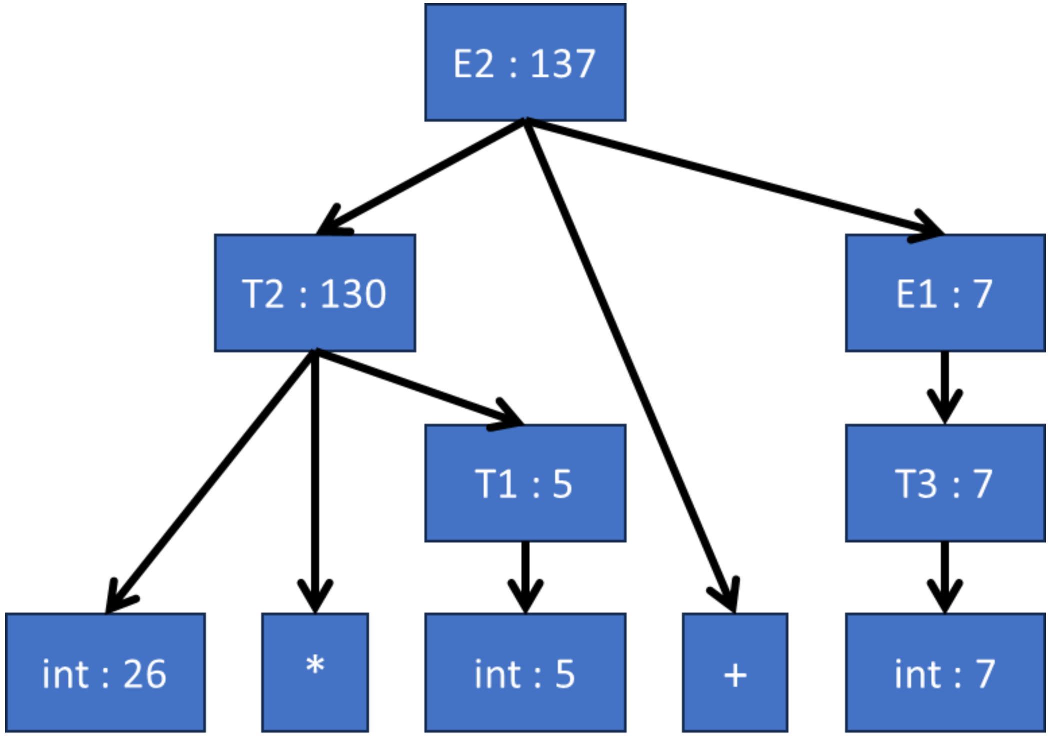
Using this CFG/SDT on 26*5 + 7 gives the following derivation and parse tree.

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

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.

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#include <stdio.h>

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

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// 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;
}
```

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

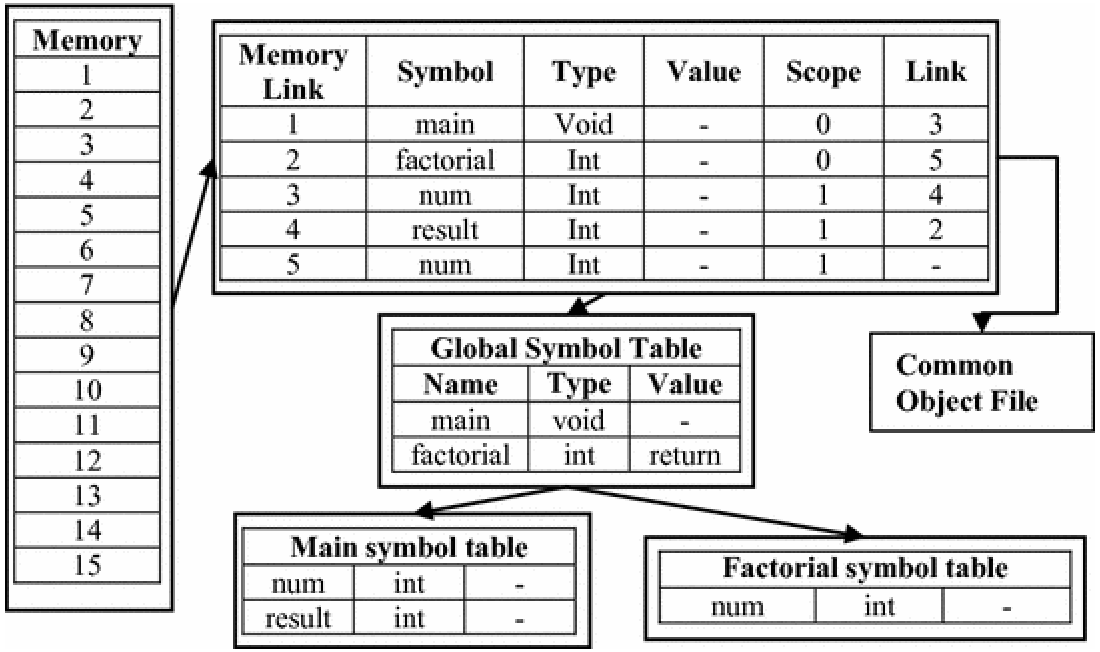
- Textual name,
- Data type,
- Declaration procedure,
- If array, number and size of dimensions,
- If procedure, number and type of parameters, location for function definition and procedure to be run by function when called,
- Etc.

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 → E + T {E.val = E1.val + T.val}

E → T {E.val = T.val}

*T → T * F {T.val = T1.val * F.val}*

T → F {T.val = F.val}

F → (E) {F.val = E.val}

F → 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 (or more) 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

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

```
#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.

Global scope

├ multiply_and_add (function)

└ main (func. scope)

Skipped for now

```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;
}
```

Open new scope with name main()

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 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.

```
#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.

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int multiply_and_add(int x, int y) {
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}

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

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    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, 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;
}
```

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)

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#include <stdio.h>

int multiply_and_add(int x, int y) {
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int main() {
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    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

```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;
}
```

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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```
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

Restricted

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

Representing the symbol table as a stack

Technically, two ways to represent the symbol table below.

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

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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.

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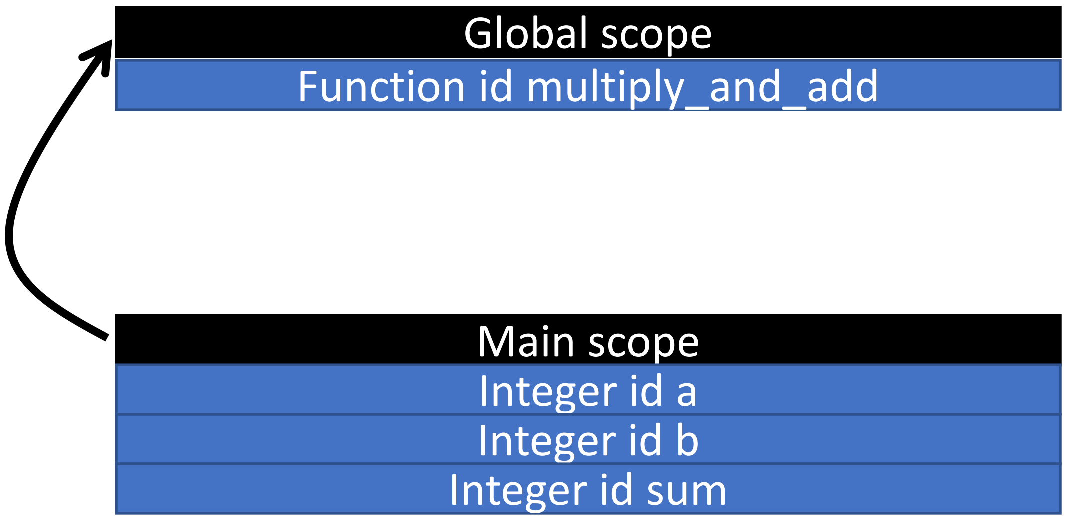

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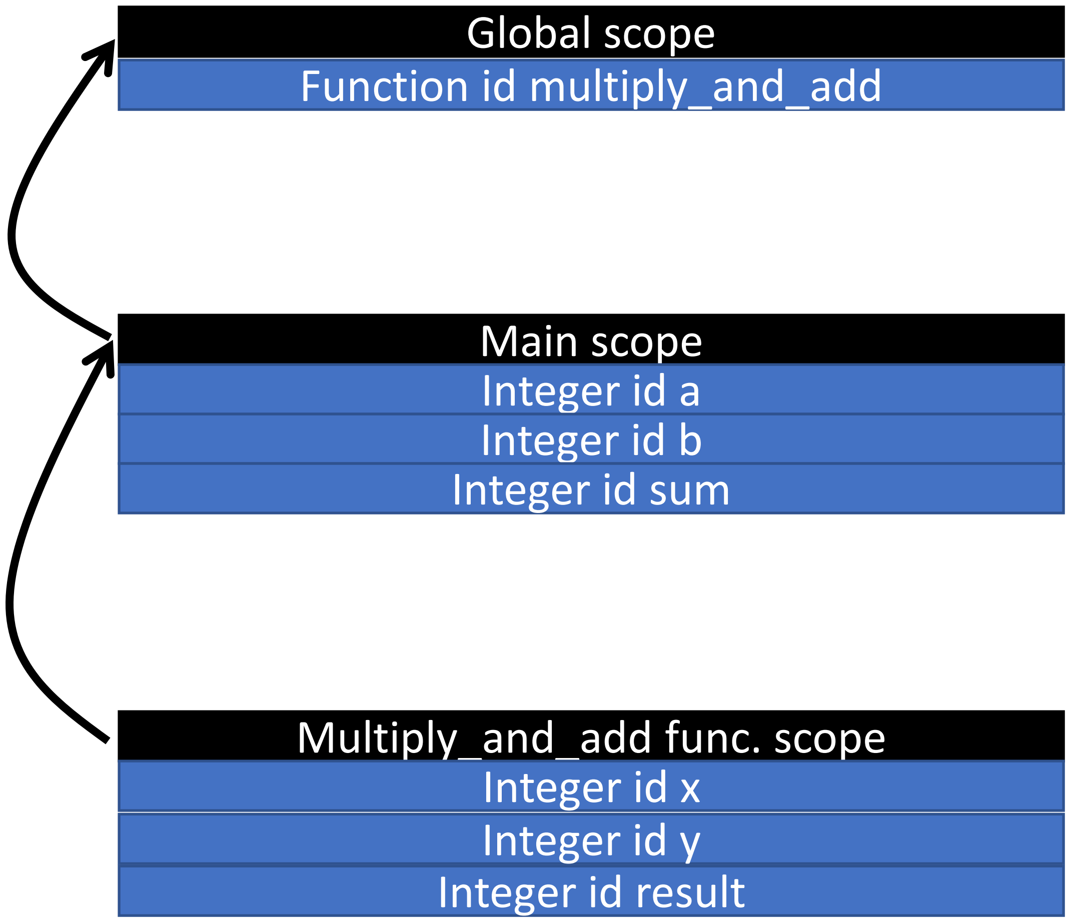

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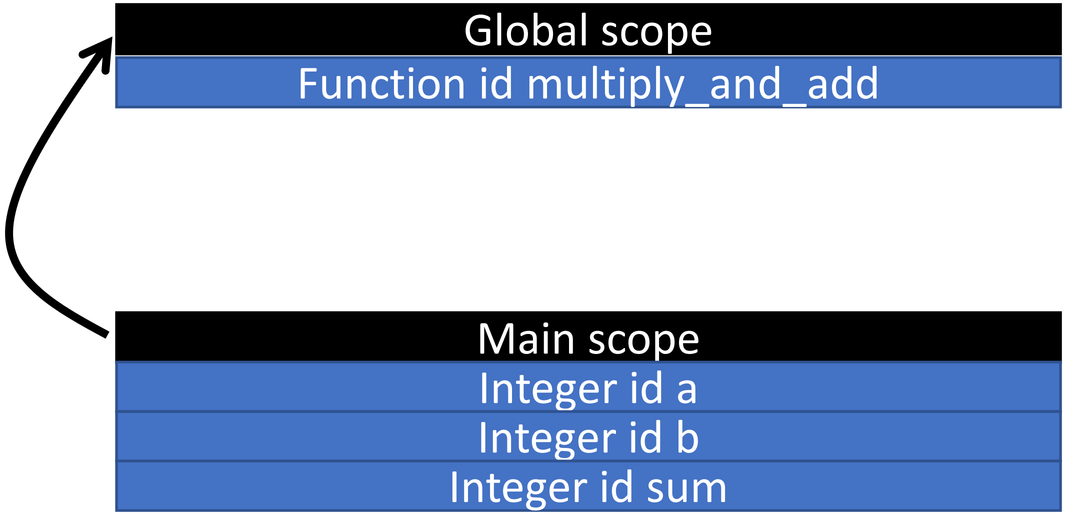

Restricted

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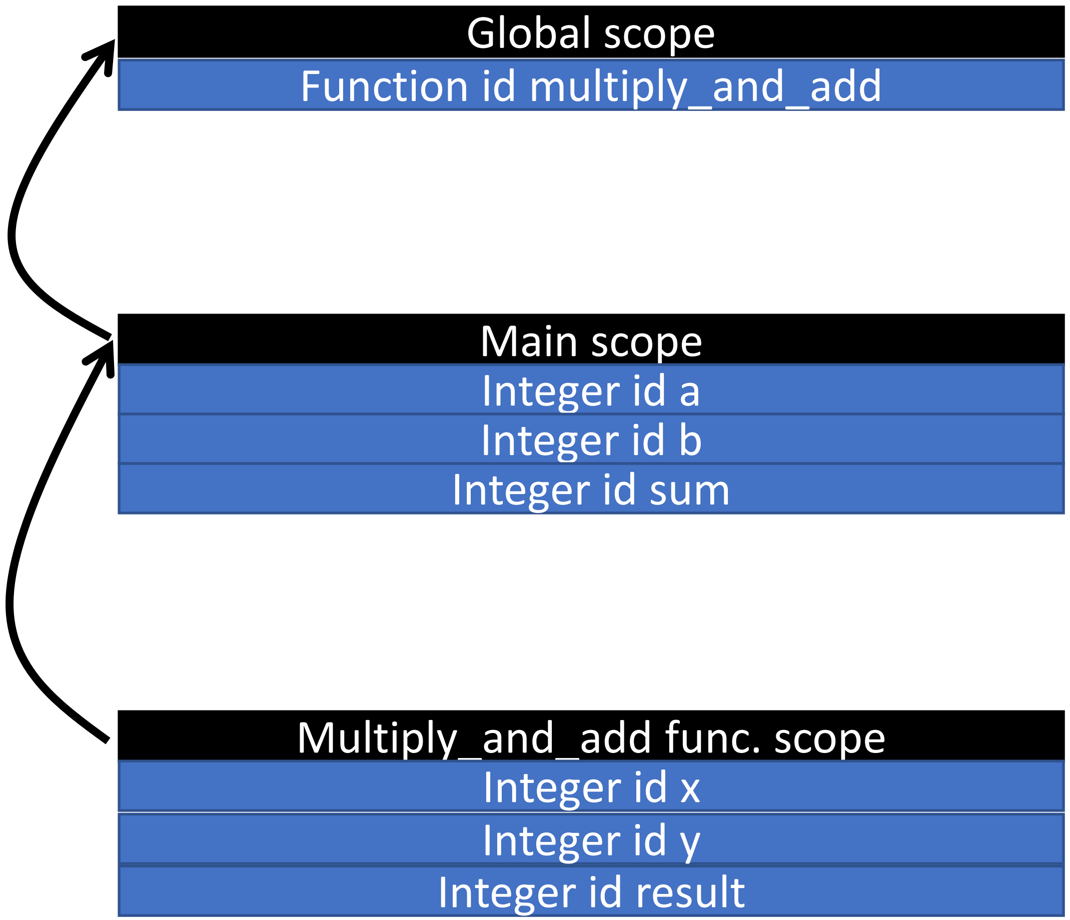
Representing the symbol table as a stack

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 this scope, and this 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, for instance, 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 the variable t is not in the scope of the function, it is in the global scope instead.
- And yet, it executes normally.
- **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
```

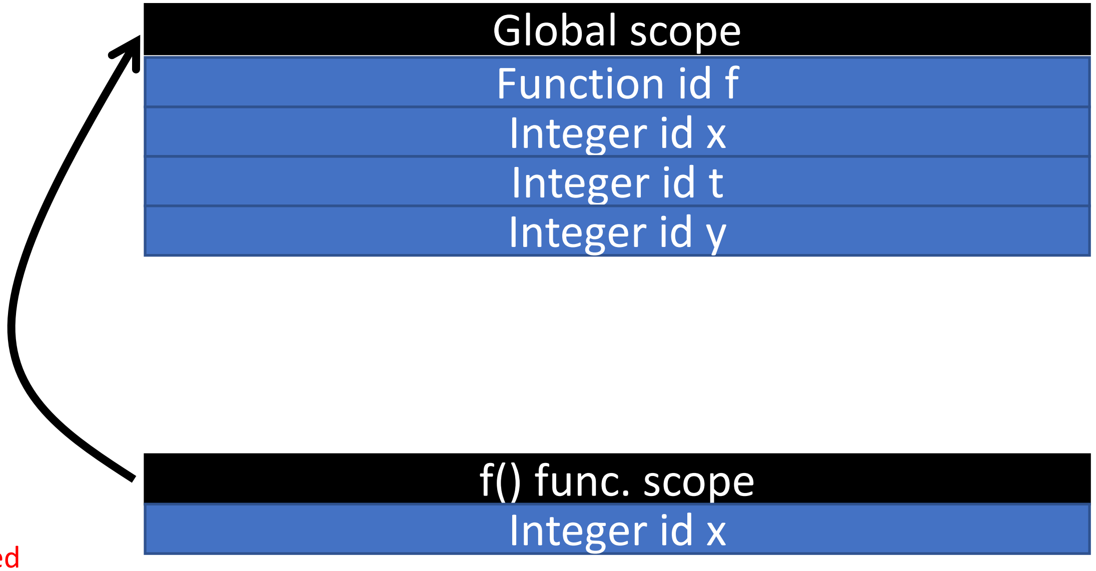
Saving the day?

- **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.

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

```python
t = 4
x = 3
y = f(x)
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 the variable 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 encode in a compiler than “LEGB”, very stable/strict and less friendly on scope “mistakes”.

Not an easy question…

```c
#include <stdio.h>

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

int main() {
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    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]
```

Advantages:

- Provides more flexibility in accessing … copes, which can make code shorter and mo…
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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) and updates this information in your compiler.
- Walk the AST gathering information about functions definitions (third pass) and update this information in your compiler.
- 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 their coding is more complex, allows for less flexibility, and the logic complexity they can check is usually 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?

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B. To store information about variables, functions, and other identifiers
C. To store the parse tree of the input code
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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

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Conclusion

- **Semantic analysis** verifies that a syntactically valid program is correctly-formed in terms of the **meaning of the program**.
- **Scope checking** is one of the semantics analysis operations and determines how variables, functions or classes are referred to.
- Scope checking is usually done with a **symbol table** implemented either as a **stack** or **spaghetti stack**.
    - Both in a static or dynamic way.
    - Both in a strict/local or LEGB way.
- 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.