Compilers

```
module = Module(
    code="ELEE1147",
    name="Programming for Engineers",
    credits=15,
    module_leader="Seb Blair BEng(H) PGCAP MIET MIHEEM FHEA"
)
```

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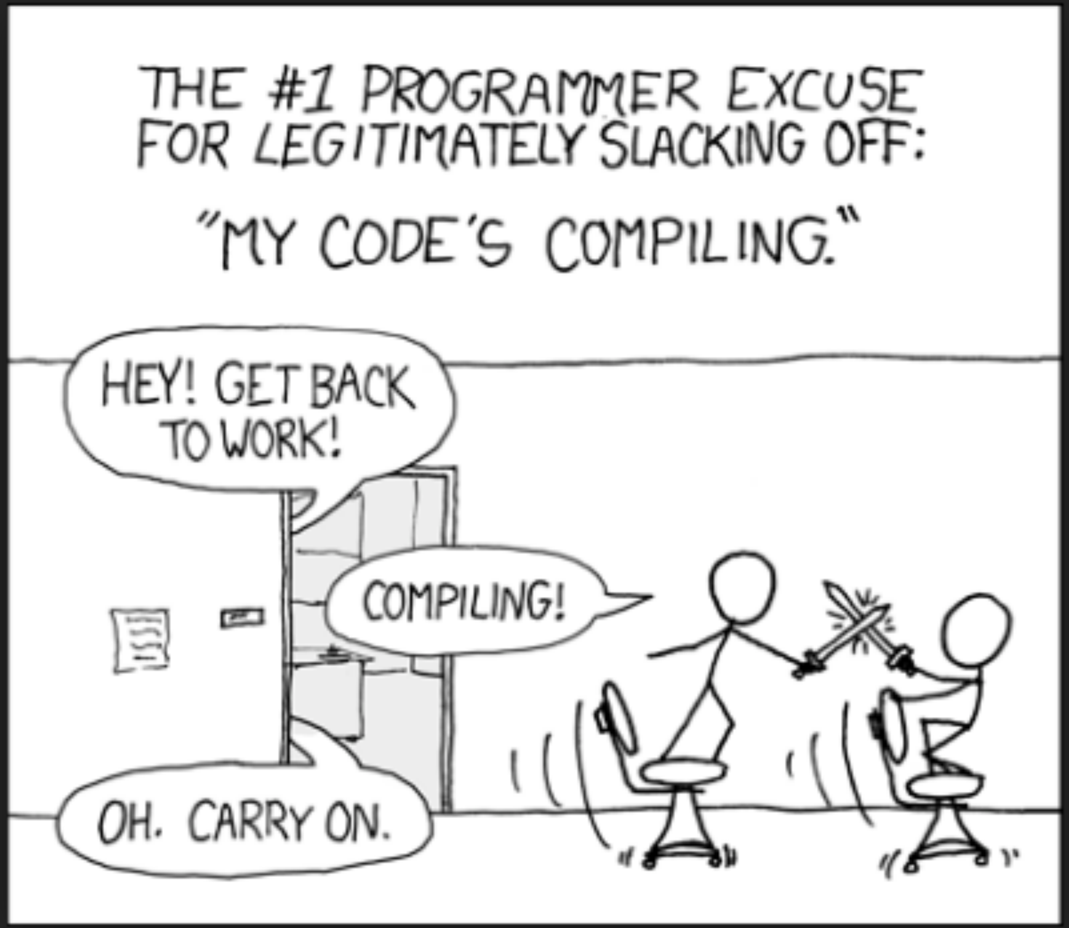
What we will cover

1. We will understand how ‘high’ and ‘low’ level programming languages are compiled to machine code so that it controls the hardware.
2. We will compare a number of programming languages and how they compile to machine code.

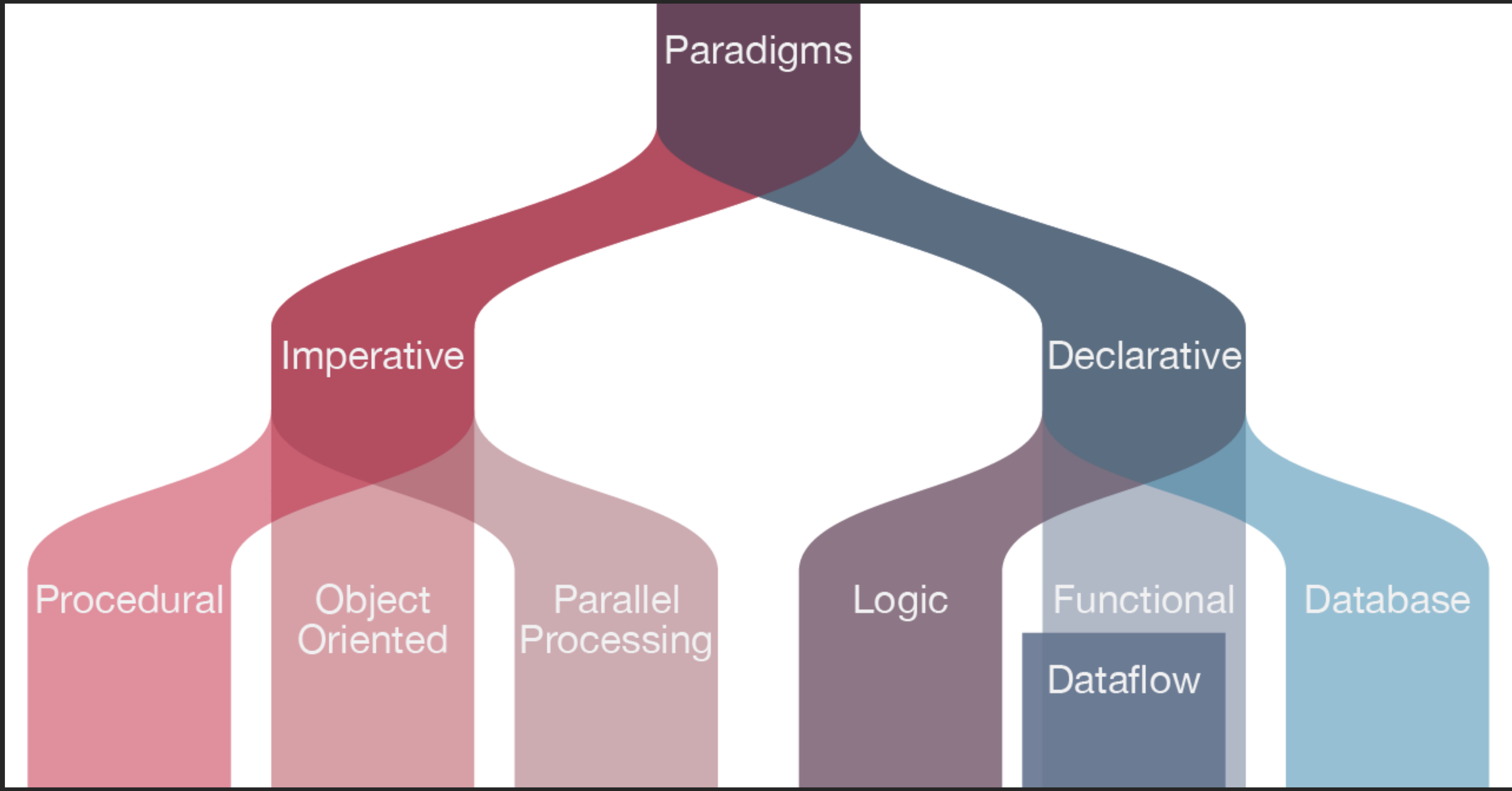


What is programming?

- A programming language is a computer language programmers use to develop software programs, scripts, or other sets of instructions for computers to execute...
- Automate process, Create digital records, Communication ,Simulation/emulation, …
- But ultimately programming provides instructions on how hardware is controlled, remember at the end of the day it is all zeroes and ones that represent electrical signals.

Programming Paradigms

- ~1605 programming lanaguages
- 94 Types
- 65 Paradigms



Human Language and Programming Languages

Are they all in English?

Linotte

It has been a developer for using French keywords:

```
BonjourLeMonde:
  début
    affiche "Bonjour le monde!"

------------------------

HelloWorld:
  beginning
    poster "Hello world!
```

Has a web engine for HTML and PHP and JSP.

SAKO

System Automatycznego Kodowania Operacji (Automatic Operation Encoding System) programming language, which uses polish as for its keywords:

```
LINIA
  TEKST:
  HELLO WORLD
KONIEC

---------------------------------

LINE
  TEXT:
  HELLO WORLD
END
```

Really only used in the late 1950s and early 1960s for the XYZ computers.

Rapira

Rapira is another awesome example of non-english programming languages. It uses Russian keywords:

```
ПРОЦ СТАРТ()

    ВЫВОД: 'Привет, мир!'

КОН ПРОЦ

-------------------

proc start()
     output: 'Hello, world!!!';
end proc
```

EPL

易语言 (Easy Programming Language, as known as EPL):

```
公开 类 启动类
{
  公开 静态 启动()
  {
    控制台.输出("你好，世界！");
  }
}

-------------------

public class startup class
{
  public static start()
  {
    console.output("Hello, World!");
  }
}
```

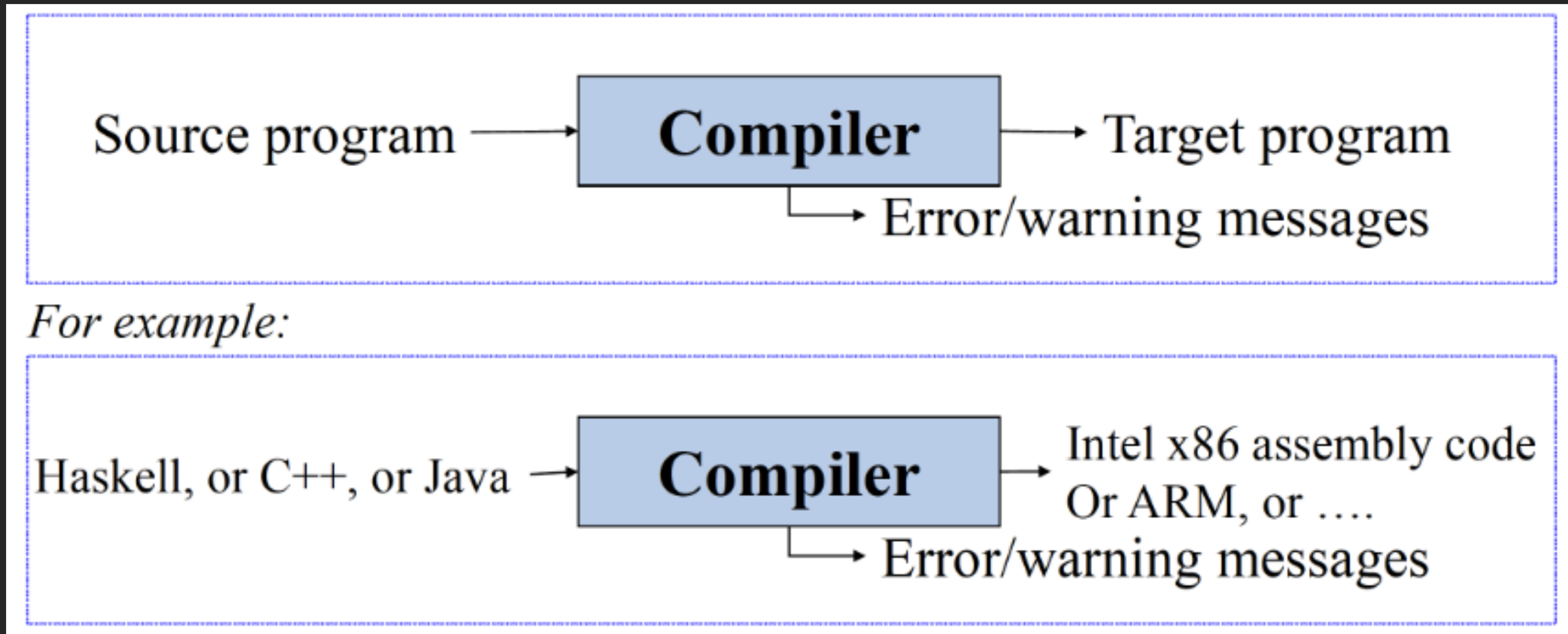
Compiler

A compiler is a program that `processes` source code written in a programming language.

- **Program Processing:** A compiler serves as a crucial tool in handling programs written in various programming languages.
- **Program Generation:** It functions as a program generator, capable of producing executable programs in a specified language.
- **Language Translation:** The compiler translates programs written in one language into equivalent programs in another language.

- **Increased Productivity:** Allows for faster and more efficient development by focusing on the logic and design rather than intricate details.
- **Enhanced Readability:** Code becomes more readable and understandable, facilitating collaboration and maintenance.
- **Code Portability:** Encourages code portability by minimizing dependencies on specific hardware or architecture

- Translates from one language into another
- Output a low level program which behaves as specified by
  the input, higher level program.
- Mediate between higher level human concepts, and the
  word by word data manipulation which the machine performs.



GCC

GCC compiler example

```
$ gcc -S -O test.c
```

Input file `test.c`

```c
int A;
int B;
test_fun()
{
  A = b + 123;
}
```

Output file `test.out`

```
.comm _A,4
.comm _B,4
_test_fun:
pushl %ebp
movl %esp,%ebp
movl _B,%eax
addl $123,%_A
movl %ebp,%esp
popl %ebp
ret
```

The flag `S` tells the compiler to produce assembly code, `O` turns optimisation on

Assembly code

- **Assembly code** is a `low-level` programming language that serves as an `interface` between `high-level` programming languages and the computer's `hardware`.
- **Human-Readable Machine Code:** Assembly code is a human-readable representation of machine code, making it more understandable than binary machine code.
- **Close to Hardware:** Unlike high-level languages, assembly code provides a direct correspondence to the architecture and operations of the underlying hardware.

Symbolic Representation

- Uses mnemonics and symbols to represent machine instructions, making it more comprehensible than raw machine code.

Binary	Opcode	Mnemonic	Description
1000 0111	87	`ADD A`	Add the contents of the register A to that of the accumulator
0011 1010	3A	`LDA`	Load data stored in the given memory address
0111 1001	79	`MOV A C`	Move data from register A to C
1100 0011	C3	`JMP`	Jump to instruction in specified memory address
1100 0001	C1	`POP` B	Pop from stack and copy to memory register B + C

Example

- The .data section declares a null-terminated string "Hello, Assembly!".
- `msg` - name of the varibable
- `db` - Define Byte
  - `msg db 'Hello', 0xA ; stores 6 bytes: H, e, l, l, o, newline`
    - `010001000`, `01100101`, `01101100`, `01101100`, `01101111`,
- `0xA` means new line
  - `00001010`

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

int main(){

  //Declare and initialise the string
  char msg [] = "Hello, Assembly!";

  // Write the message to stdout
  write(1, msg, strlen(msg));

  // Exit the program with a return code of 0
  exit(0);
}
```

```
section .data
  msg db 'Hello, Assembly!', 0xA  ; Message with newline (0xA = '\n')

section .text
  global _start

_start:
  ; Write the message to stdout
  mov eax, 4          ; syscall: write
  mov ebx, 1          ; file descriptor: stdout
  mov ecx, msg        ; pointer to the message
  mov edx, 17           ; length of message (16 chars + newline)
  int 0x80            ; invoke the kernel

; Exit the program
  mov eax, 1          ; syscall: exit
  xor ebx, ebx        ; exit code 0
  int 0x80            ; invoke the kernel
```

Example:

- The .text section contains the program logic.

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

int main(){

  //Declare and initialise the string
  char msg [] = "Hello, Assembly!";

  // Write the message to stdout
  write(1, msg, strlen(msg));

  // Exit the program with a return code of 0
  exit(0);
}
```

```
section .data
  msg db 'Hello, Assembly!', 0xA  ; Message with newline (0xA = '\n')

section .text
  global _start

_start:
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  int 0x80          ; invoke the kernel

; Exit the program
  mov eax, 1        ; syscall: exit
  xor ebx, ebx      ; exit code 0
  int 0x80          ; invoke the kernel
```

Example:

- The _start label marks the entry point of the program.

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

int main(){

  //Declare and initialise the string
  char msg [] = "Hello, Assembly!";

  // Write the message to stdout
  write(1, msg, strlen(msg));

  // Exit the program with a return code of 0
  exit(0);
}
```

```asm
section .data
  msg db 'Hello, Assembly!', 0xA  ; Message with newline (0xA = '\n')

section .text
  global _start

_start:
  ; Write the message to stdout
  mov eax, 4          ; syscall: write
  mov ebx, 1          ; file descriptor: stdout
  mov ecx, msg        ; pointer to the message
  mov edx, 17           ; length of message (16 chars + newline)
  int 0x80            ; invoke the kernel

; Exit the program
  mov eax, 1          ; syscall: exit
  xor ebx, ebx        ; exit code 0
  int 0x80            ; invoke the kernel
```

Example:

Register	Meaning	Value
`eax`	syscall number	4 = write
`ebx`	file descriptor	1 = stdout
`ecx`	pointer to buffer	address of msg
`edx`	number of bytes to write	17
`mov`	Copy data from one place to another	-
`int`	Software interrupt (calls the kernel) Control/Interrupt	-

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

int main(){

  //Declare and initialise the string
  char msg [] = "Hello, Assembly!";

  // Write the message to stdout
  write(1, msg, strlen(msg));

  // Exit the program with a return code of 0
  exit(0);
}
```

```
section .data
  msg db 'Hello, Assembly!', 0xA  ; Message with newline (0xA = '\n')

section .text
  global _start

_start:
  ; Write the message to stdout
  mov eax, 4        ; syscall: write
  mov ebx, 1        ; file descriptor: stdout
  mov ecx, msg      ; pointer to the message
  mov edx, 17         ; length of message (16 chars + newline)
  int 0x80          ; invoke the kernel

; Exit the program
  mov eax, 1        ; syscall: exit
  xor ebx, ebx      ; exit code 0
  int 0x80          ; invoke the kernel
```

Example:

Register	Role	Value
eax	syscall number	1 = exit
ebx	exit code	0 = success
int	0x80 syscall trigger	invokes the kernel
xor	Bitwise XOR (commonly used to zero a register) Logical/ bitwise	-

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

int main(){

  //Declare and initialise the string
  char msg [] = "Hello, Assembly!";

  // Write the message to stdout
  write(1, msg, strlen(msg));

  // Exit the program with a return code of 0
  exit(0);
}
```

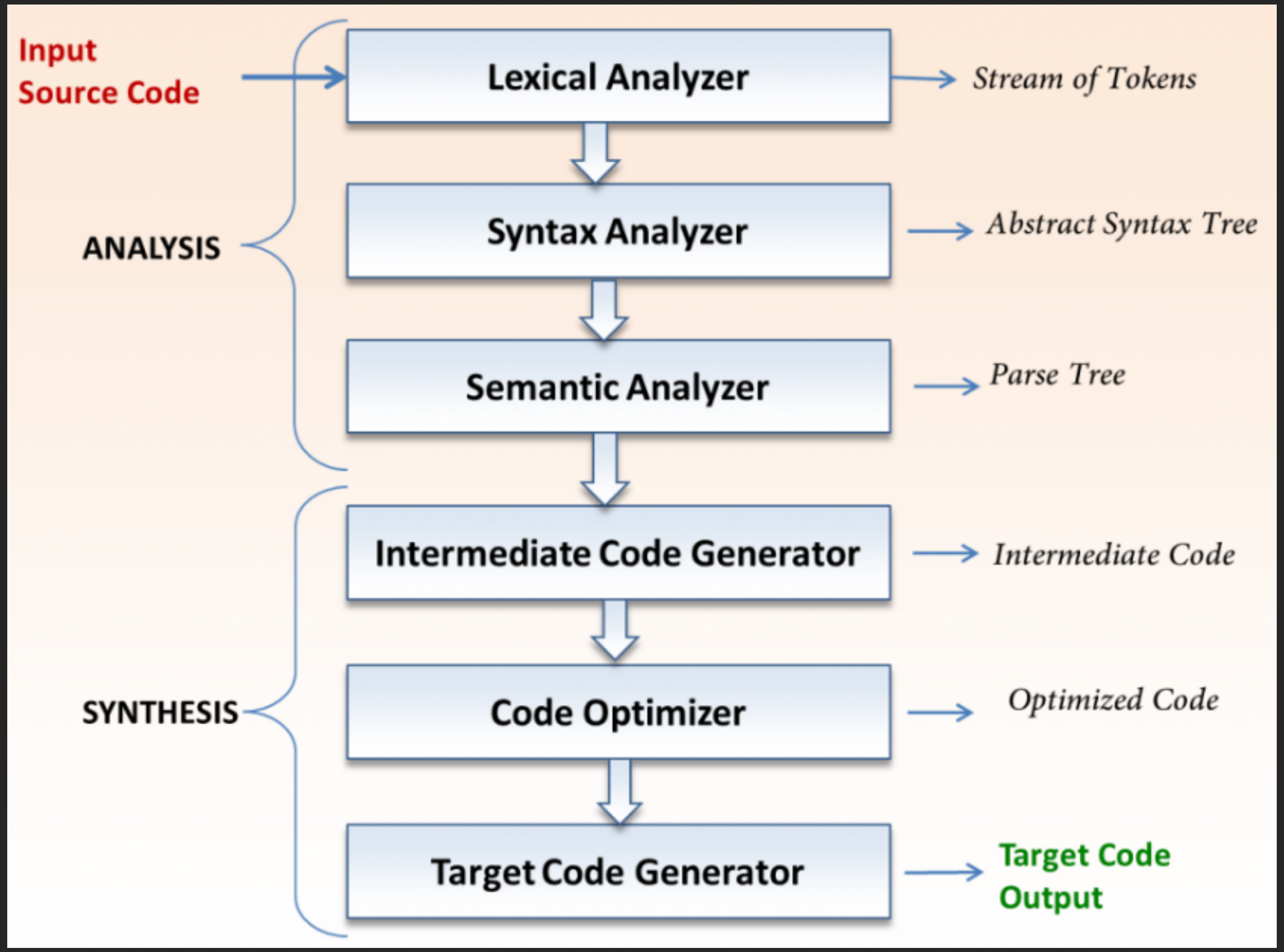
```asm
section .data
  msg db 'Hello, Assembly!', 0xA  ; Message with newline (0xA = '\n')

section .text
  global _start

_start:
  ; Write the message to stdout
  mov eax, 4          ; syscall: write
  mov ebx, 1          ; file descriptor: stdout
  mov ecx, msg        ; pointer to the message
  mov edx, 17           ; length of message (16 chars + newline)
  int 0x80            ; invoke the kernel

; Exit the program
  mov eax, 1          ; syscall: exit
  xor ebx, ebx        ; exit code 0
  int 0x80            ; invoke the kernel
```

Compiling Stages



Lexical Analysis

The compiler begins converting the series of characters into tokens

Token name	Example token values
identifier	`n`, `q`
keyword	`int`, `float`, `if`, `else`, `return`, `while`
separator	`{ }`, `( )`, `[ ]`, `;`
operator	`+`, `-`, `*`, `/`, `=`, `<`, `>`, `:`, `?`
literal	`True`, `false`, `6.02e23`, `"string"`
comment	`// this is a comment`

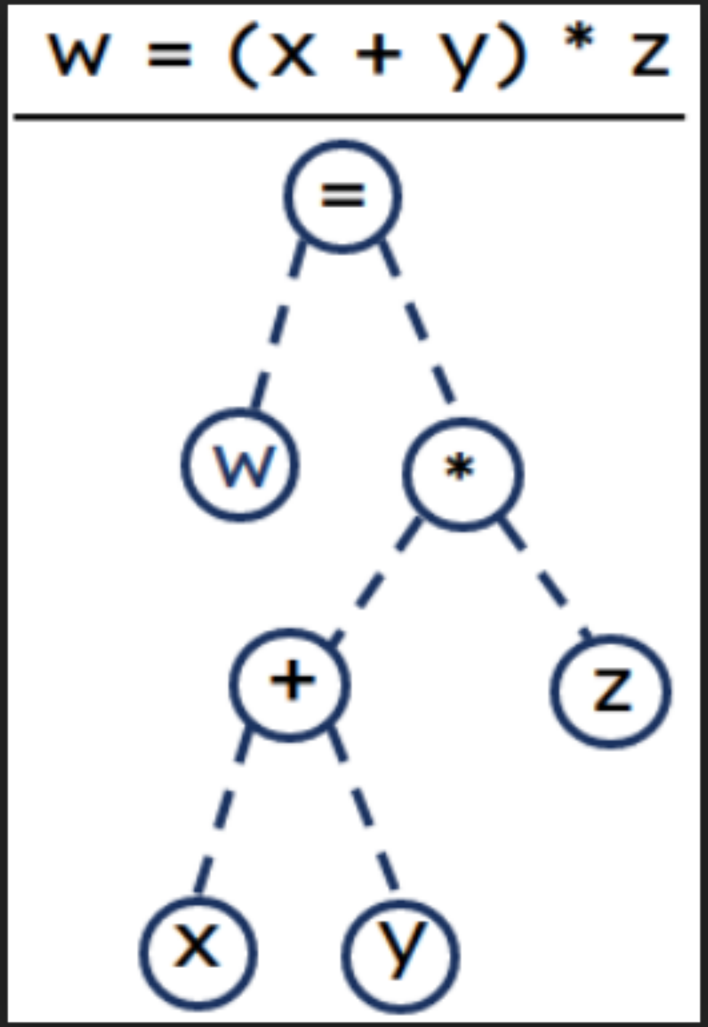
High Level Code

```
int n = 11;
float q = 1.618f;
if (n < 12)
{
  return q;
}
else
{
  return n;
}
```

Syntax Analysis

Syntax analysis is based on the rules based on the specific programming language by constructing the parse tree with the help of tokens.

- Interior node: record with an operator filed and two files for children
- Leaf: records with 2/more fields; one for token and other information about the token
- Ensure that the components of the program fit together meaningfully
- Gathers type information and checks for type compatibility
- Checks operands are permitted by the source language



Semantic Analyser

The Semantic Analyser checks for type mismatches, incompatible operands, improper function calls, undeclared variables, and more — including **implicit type conversions**.

```c
int n = 11;
float q = 1.618 * n;
```

- Type Promotion: `int → float`
- Operation: `float * float = float`
- Safe, no data loss

```c
float f = 3.9;
int x = f * 2;
```

- Promotes `2` to `2.0f`
- Computes `3.9 * 2.0 = 7.8`
- Then **casts** **`7.8 → 7`** **(truncation)**
- Type Conversion: `float → int`
- Potential data loss

Intermediate Code Generation

Removes unnecessary code lines.

Arranges the sequence of statements to speed up the execution of the program without wasting resources.

Original

```
a = int_to_float(10)
b = c * a
d = e + b
f = d
```

Stage	IR Code

Intermediate Representation	t1 = 10
	t2 = int_to_float t1
	t3 = c * t2
	t4 = e + t3
	f = t4

Optimised IR	t2 = 10.0f
	t3 = c * t2
	f = e + t3

Fully Optimised	f = e + (c * 10.0f)

Code Generation

Now we are going to see how we go from C to Assembly to machine code…

```c
int square(int num) {
    return num * num;
}
```

```
square:
  pushq   %rbp
  movq    %rsp, %rbp
  movl    %edi, -4(%rbp)
  movl    -4(%rbp), %eax
  imull   %eax, %eax
  popq    %rbp
  ret
```

	Memory Addresses
	0x0007556ff0e0
	0x0007556ff0df
	0x0007556ff0de
saved %rbp	**0x0007556ff0dd**
	...
	0x0007556ff0da
↑ %rbp	**0x0007556ff0d9**

Code Generation

Instruction sets up the stack frame, and how it maps to our memory layout.

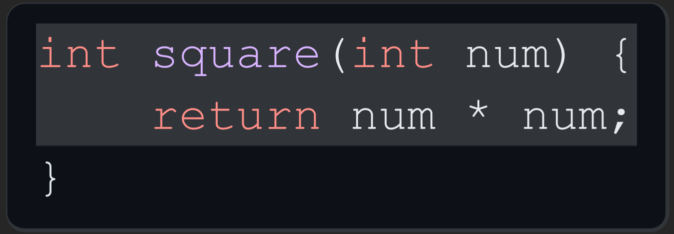
```c
int square(int num) {
    return num * num;
}
```

```
square:
  pushq   %rbp
  movq    %rsp, %rbp
  movl    %edi, -4(%rbp)
  movl    -4(%rbp), %eax
  imull   %eax, %eax
  popq    %rbp
  ret
```

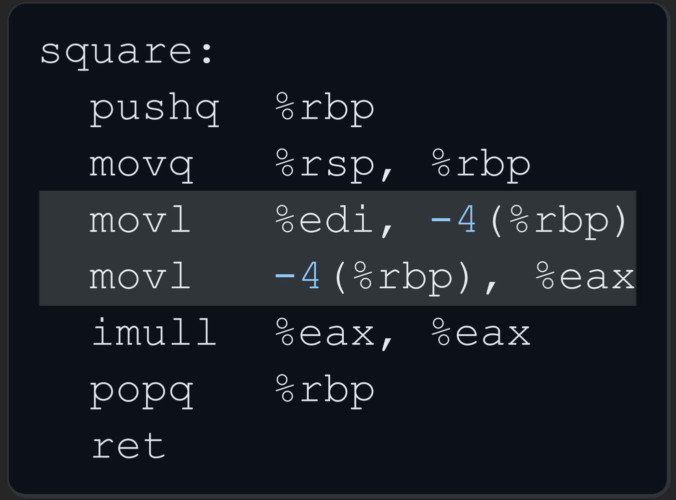
	Memory Addresses
	0x0007556ff0e0
	0x0007556ff0df
	0x0007556ff0de
saved %rbp	**0x0007556ff0dd**
	...
	0x0007556ff0da
↑ **new %rbp**	**0x0007556ff0d9**

Code Generation

Now we are going to see how we go from C to Assembly to machine code…



```c
int square(int num) {
    return num * num;
}
```



```
square:
  pushq   %rbp
  movq    %rsp, %rbp
  movl    %edi, -4(%rbp)
  movl    -4(%rbp), %eax
  imull   %eax, %eax
  popq    %rbp
  ret
```

	Memory Addresses
	0x0007556ff0e0
	0x0007556ff0df
	0x0007556ff0de
saved %rbp	**0x0007556ff0dd**
	...
	0x0007556ff0da
↓ **num**	**0x0007556ff0d5**

Code Generation

Now we look at the final operation: `imull %eax, %eax`, which computes `num * num`. This instruction directly maps to the C expression and uses the loaded value from the stack.

```c
int square(int num) {
    return num * num;
}
```

```
square:
  pushq   %rbp
  movq    %rsp, %rbp
  movl    %edi, -4(%rbp)
  movl    -4(%rbp), %eax
  imull   %eax, %eax
  popq    %rbp
  ret
```

	Memory Addresses
	0x0007556ff0e0
	0x0007556ff0df
	0x0007556ff0de
saved %rbp	**0x0007556ff0dd**
	...
	0x0007556ff0da
num	**0x0007556ff0d5**
eax = num*num	**(register)**

Code Generation

Finally, we examine the `popq %rbp` instruction — the function epilogue that restores the previous stack frame, preparing for return to the caller.

```c
int square(int num) {
    return num * num;
}
```

```
square:
  pushq   %rbp
  movq    %rsp, %rbp
  movl    %edi, -4(%rbp)
  movl    -4(%rbp), %eax
  imull   %eax, %eax
  popq    %rbp
  ret
```

	Memory Addresses
↑ **restored %rbp**	**0x0007556ff0dd**
	0x0007556ff0dc
	0x0007556ff0db
	0x0007556ff0da
num	0x0007556ff0d5

Code Generation: Assembly and Hex Representation

```c
int square(int num) {
    return num * num;
}
```

∴

```
square:
  pushq  %rbp
  movq   %rsp, %rbp
  movl   %edi, -4(%rbp)
  movl   -4(%rbp), %eax
  imull  %eax, %eax
  popq   %rbp
  ret
```

```
HEX
55
48 89 e5
89 7d fc
8b 45 fc
0f af c0
5d
c3
```

Symbol Management Table

A symbol table contains a record for each identifier with fields for the attributes of the identifier.

Operation	Function
`allocate`	to allocate a new empty symbol table
`free`	to remove all entries and free storage of symbol table
`lookup`	to search for a name and return a pointer to its entry
`insert`	to insert a name in a symbol table and return a pointer to its entry
`set_attribute`	to associate an atrribute to a given entry
`get_attribute`	to get an attribute associated with a given entry

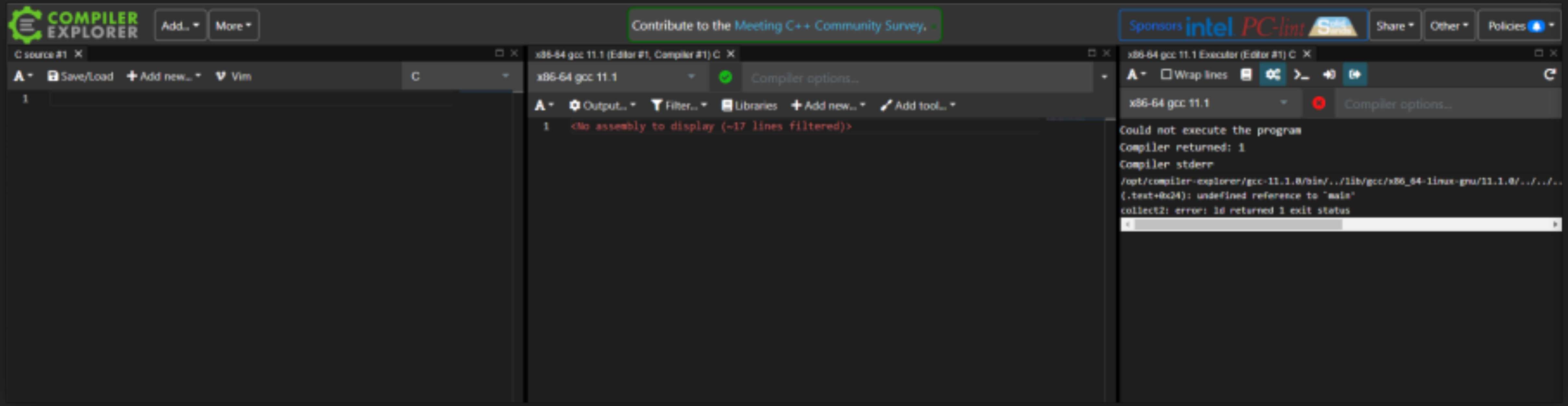
Error Handling Routine

During compilation process error(s) may occur in all the below-given phases:

- Lexical analyser: Wrongly spelled tokens
- Syntax analyser: Missing parenthesis
- Semantic analyser: Mismatched data types, missing arguments
- Intermediate code generator: Mismatched operands for an operator
- Code Optimizer: When the statement is not reachable
- Code Generator: Unreachable statements
- Symbol tables: Error of multiple declared identifiers

Labs

You are going experience programming in several languages <C , Python and Ada> to do similar operations, and see how the code compiles and the subsequent outputs!



```
<No assembly to display (~17 lines filtered)>
```

```
Could not execute the program
Compiler returned: 1
Compiler stderr
/opt/compiler-explorer/gcc-11.1.0/bin/../lib/gcc/x86_64-linux-gnu/11.1.0/../../..
(.text+0x24): undefined reference to `main'
collect2: error: ld returned 1 exit status
```

https://uniofgreenwich.github.io/ELEE1147_Exercises/Compilers/compilers.html