Systems Architecture

1. Introduction to C

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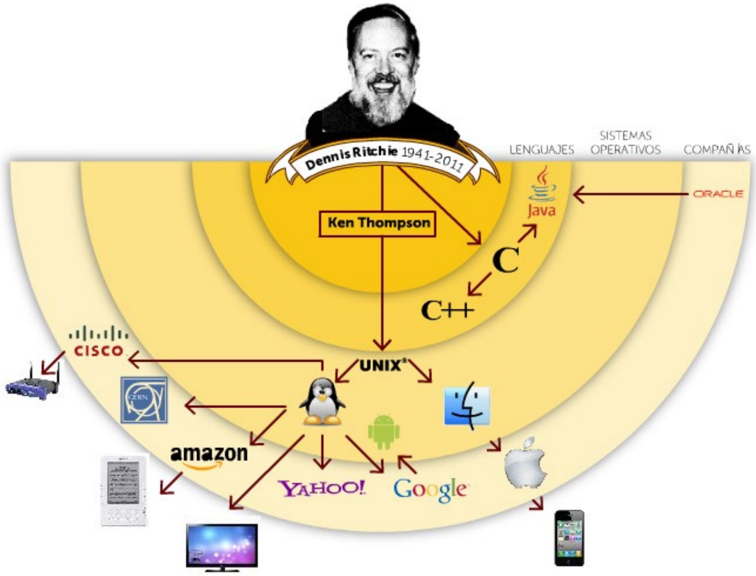
1. Introduction

- C is a general purpose programming language developed by **Dennis Ritchie** between 1969 and 1972 at Bell Laboratories
  - Originally C was oriented to the implementation of operating systems, specifically **Unix** (with Ken Thompson)
  - It was first standardized by the ANSI (American National Standards Institute) in 1989
  - It was ratified as an ISO (International Organization for Standardization) standard in 1990

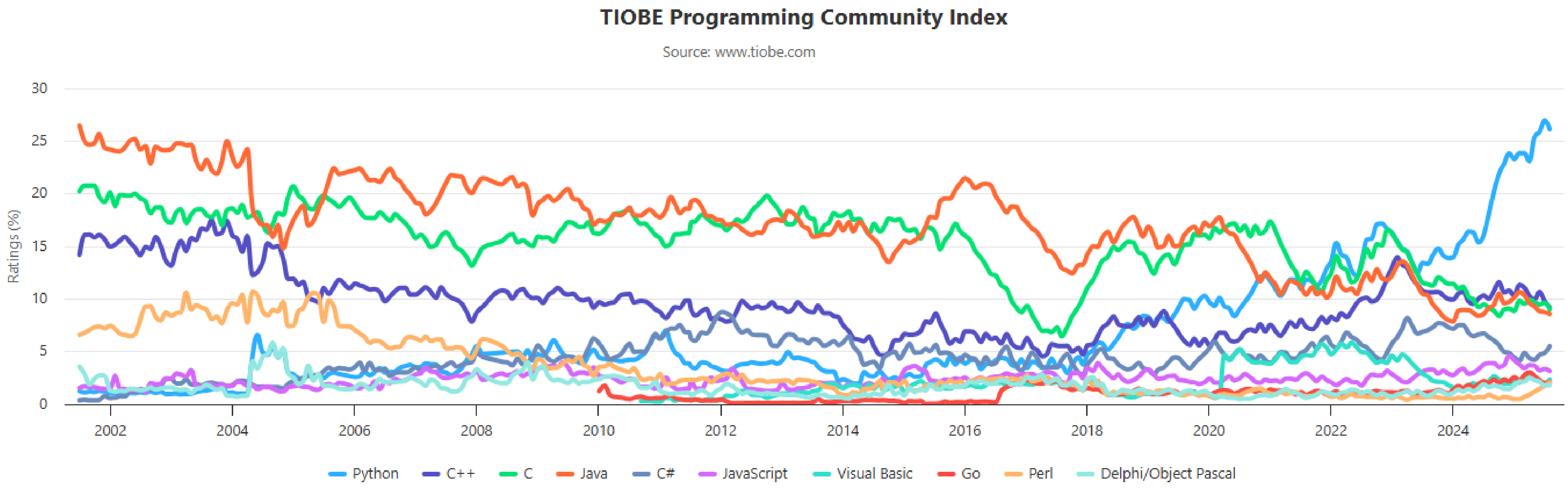


Source: Dennis Ritchie biography by Moisés Cuevas

Source: Wikipedia
https://en.wikipedia.org/wiki/Dennis_Ritchie

1. Introduction

- Today C is still one of the most widely used languages



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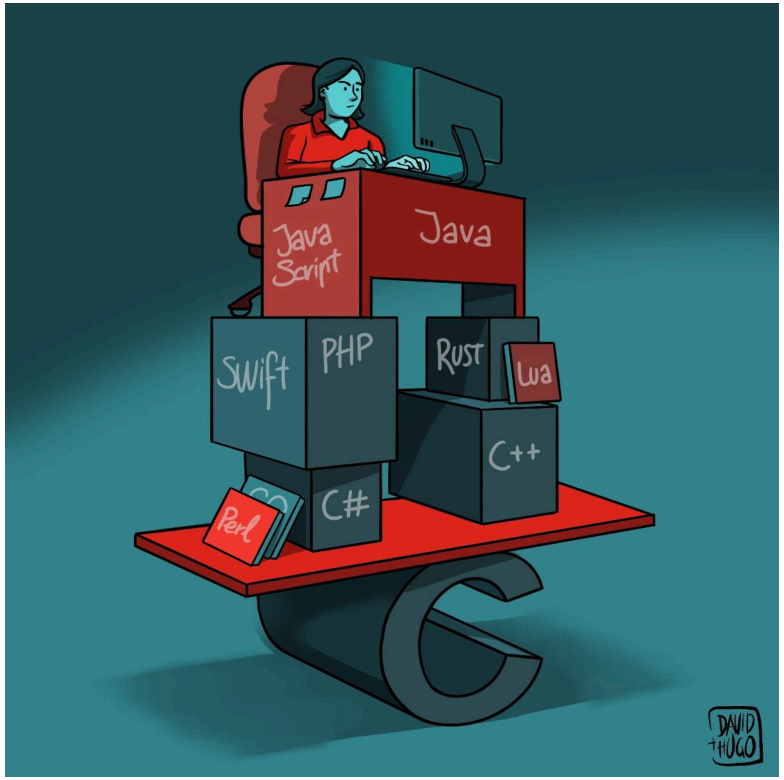
1. Introduction

- C is considered the foundation of modern programming languages



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Source: Bonilista nº 647, 3 September 2023, La Historia del lenguaje C

1. Introduction - Main features of C

- The C programming language can be classified in several ways:
  - C is a **general-purpose** programming language
    - C can be used both **application programming** and **system programming**
  - C is a **high-level** programming language
    - Although it allows certain low level handling (direct memory access)
    - For that reason, it is sometimes classified as a *medium-level* language
  - C is a **compiled** language (the C source code must be converted into machine code to be executed)
  - C is **imperative** (based on statements that are executed sequentially) and **procedural** (it relies on subroutines called *functions* to perform computations)
  - C is **statically-typed** (the type of a variable is known at compile-time) and **weakly-typed** (it allows variables of one type to be used as if they were of another)

1. Introduction - General-purpose vs domain-specific

- A **general-purpose language** (GPL) is a programming language that can create all types of programs
  - For instance: C, Java, Python, among others
  - GPLs are *Turing complete*, which means that they can theoretically solve any computational problem
- A **domain-specific language** (DSL) is a computer language specialized to a particular application domain
  - For instance: MATLAB (intended primarily for numeric computing), SQL (for relational database queries), VHDL (for hardware description)
  - DSLs can be (or not) *Turing complete*

1. Introduction - Application and system programming

- An **applications programming language** is used for implementing user applications, like desktop applications, command-line interface tools, or mobile apps
  - For instance: C, Java, Python, JavaScript, and others
  - Application software generally don't directly access hardware or low-level resources. Instead these languages use *system calls*
- A **system programming language** is used for implementing system software, i.e., software designed to provide a platform for other software, such as operating systems, devices drivers, or server-side components
  - For instance: C, C++, Go, Rust, and others
  - Unlike application software, most system software are not directly used by end users

1. Introduction - Programming language levels

High level program

```java
public class HelloWorld {

    public static void main(String[] args) {
        System.out.println("Hello World");
    }

}
```

Java

```c
#include <stdio.h>

int main() {
    printf("Hello world\n");
    return 0;
}
```

It provides abstractions (close to the natural language) independent of a particular type of computer. Programmer friendly, portable, easier to create, debug, and maintain

Low-level program (assembly)

```asm
org 0x100     ; .com files always start 256 bytes into the segment

mov dx, msg   ; the address of or message in dx
mov ah, 9     ; ah=9 - "print string" sub-function
int 0x21      ; call dos services

mov ah, 0x4c  ; "terminate program" sub-function
int 0x21      ; call dos services

msg db 'Hello, World!', 0x0d, 0x0a, '$'  ; $-terminated message
```

x86

Mnemonics that represent basic instructions that can be directly translated to machine code. Highly memory efficient but non-portable and much more difficult to create, debug, and maintain

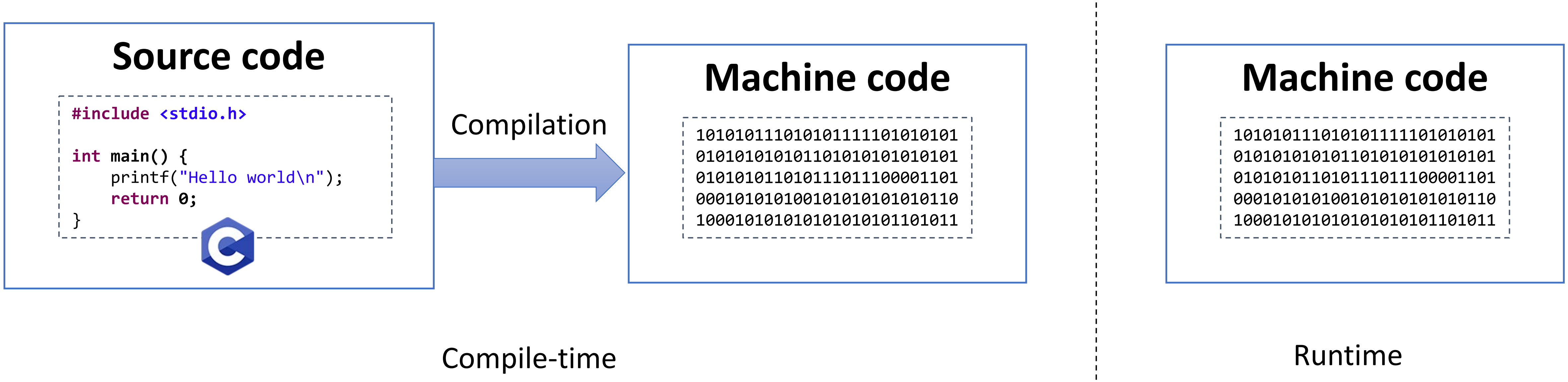
Machine code

```
1010101110101011111010101010101010101011010101010101010101010110101
1101110000110100010101010010101010101011010001010101010101010110101
```

Executable code (1's and 0's). Each instruction causes the CPU to perform a specific task (e.g. load value, arithmetic operation, etc.)

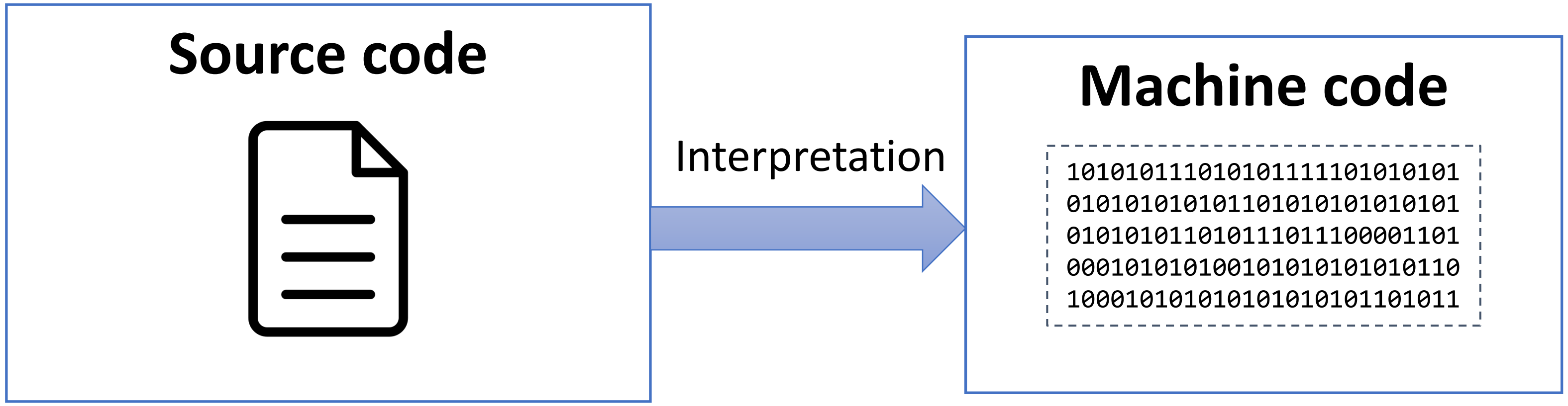
1. Introduction - Compiled vs. interpreted

- **Compiled** languages need a *build* step, i.e., they need to be manually compiled to be executed on a computer
  - This process is sometimes called *ahead-of-time* (AOT) compilation
  - Examples of pure compiled languages are C, C++, Erlang, Haskell, Rust, and Go



1. Introduction - Compiled vs. interpreted

- **Interpreted** languages are executed directly into machine-language instructions without a previous compilation

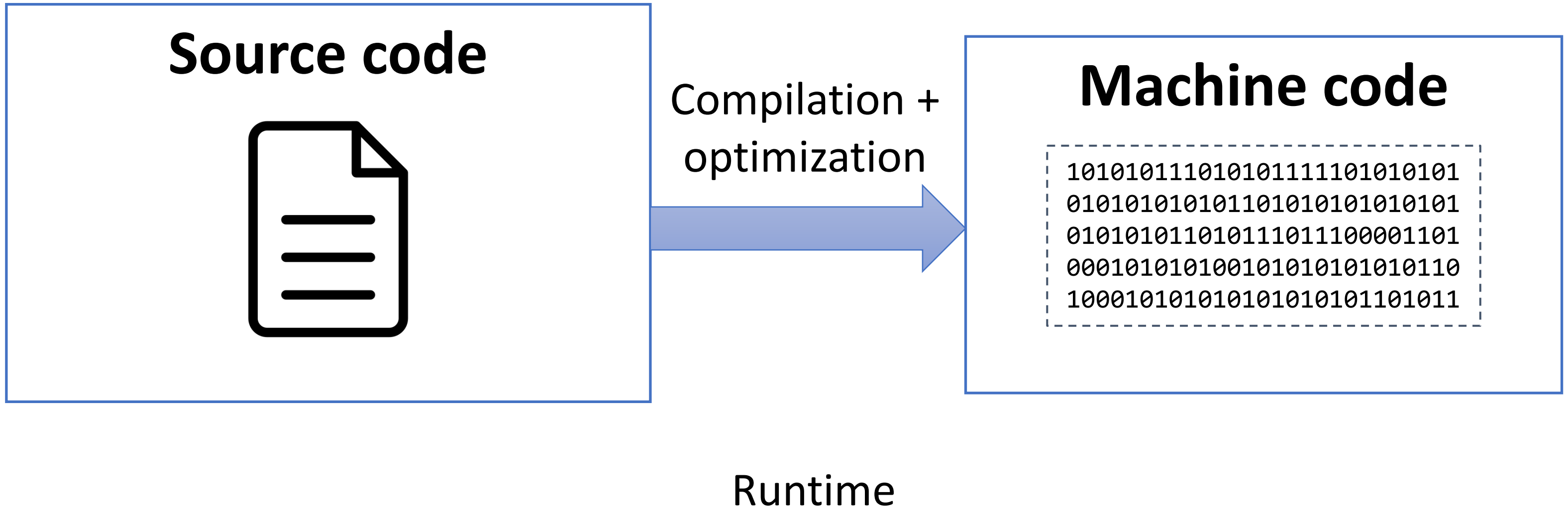


Runtime

  – Nevertheless, there are few implementations of pure interpreted languages nowadays, because interpreting source code directly would be quite slow

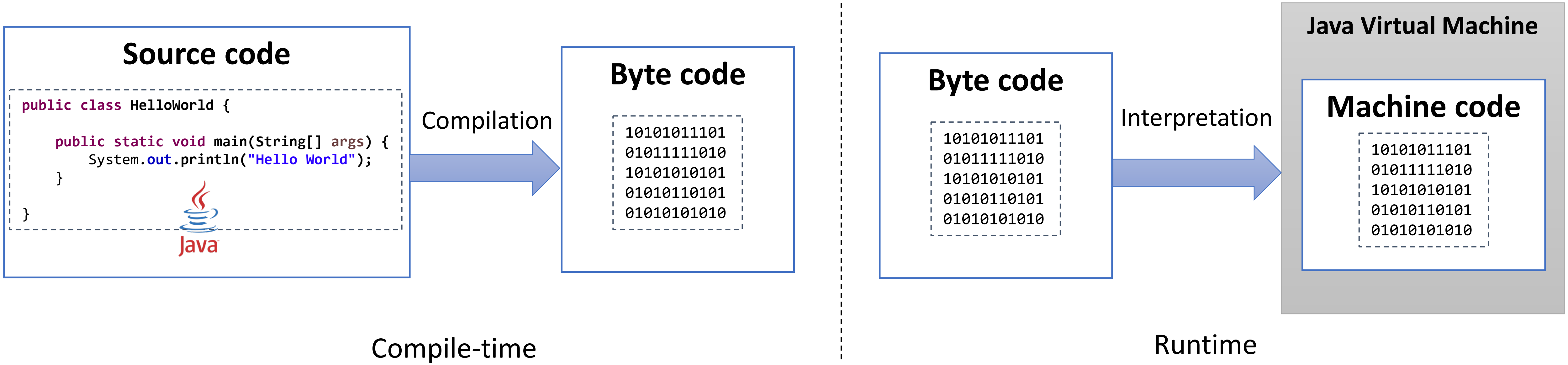
1. Introduction - Compiled vs. interpreted

- Instead, modern interpreted languages use an alternative approach called *just-in-time* (JIT)
  - JIT involves the compilation during execution of a program (at *runtime*) rather than before execution
  - Different optimizations are done in runtime to provide a better performance
  - Examples of interpreted languages using JIT are Python, JavaScript, or Ruby



1. Introduction - Compiled vs. interpreted

- Other languages, like Java, use a mixed strategy:
    1. Compile-time: Compilation of the source code into some intermediate format called *bytecode*
    2. Runtime: bytecodes are interpreted (also using JIT) in the Java Virtual Machine (JVM)



1. Introduction - Programming paradigms

- Programming paradigms are a way to classify programming languages based on their features
- The two major programming paradigms nowadays are:

Imperative
Programs are based on statements (or commands) that are executed sequentially

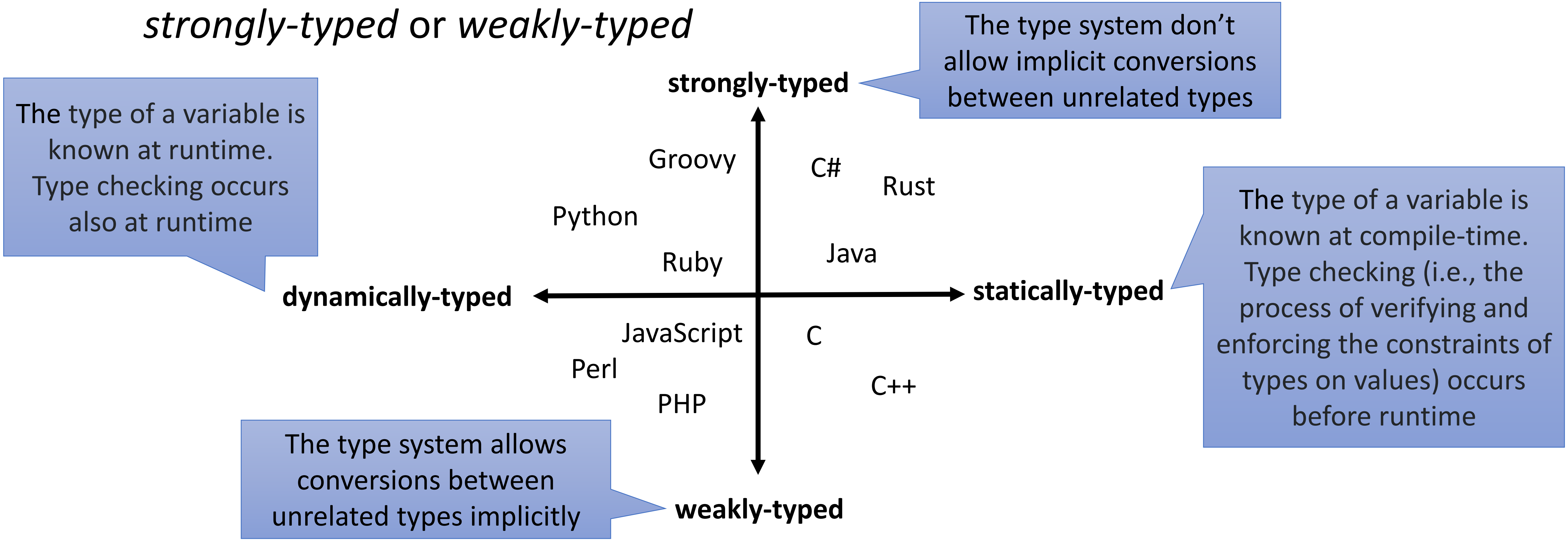
- **Procedural**
  It relies on procedures (or subroutines) to perform computations
- **Object-oriented**
  It relies on objects (entities with an state and behavior) to implement programs

Declarative
Programs describe their desired results without explicitly listing the commands or steps that must be performed

- **Functional**
  Programs are constructed by applying and composing functions
- **Logic**
  Programs are based on formal logic rules and facts

1. Introduction - Type system

- In programming, a **type** is a set of value (e.g. integers, characters, etc.)
- The rules that applies for types in a given programming languages is called *type system*, and it is usually classified as *static* or *dynamic*, and as *strongly-typed* or *weakly-typed*



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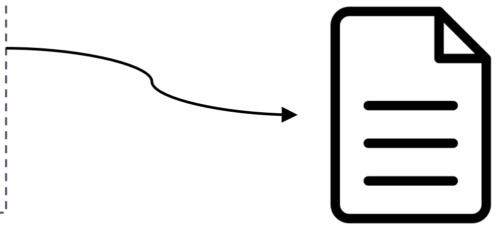
2. "Hello world" in C

```c
#include <stdio.h>

int main() {
    printf("Hello world\n");
    return 0;
}
```

hello_world.c



- The **`main()`** function is used by convention as the entry point of the program

https://github.com/bonigarcia/c-programming

Repository with code examples

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2. "Hello world" in C

```c
#include <stdio.h>

int main() {
    printf("Hello world\n");
    return 0;
}
```

- Statements end with semicolons `;`
- We define blocks of statements in curly brackets (braces) `{ }`
- The `printf()` function displays a text string in the standard output (`stdout`)
- To use that function, we need to include its code from the standard library **`stdio.h`** using the directive **`#include`**
- With **`return`** we terminate the function, returning a value to the calling process
  - The exit code is a numerical value returned by a program to the operating system upon its completion
  - The exit code **`0`** means *success*. Different than **`0`** means some error (e.g., **`1`** means *general error*)

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2. “Hello world” in C

```c
#include <stdio.h>

int main() {
    printf("Hello world\n");
    return 0;
}
```

First, we use the compiler gcc (GNU Compiler Collection) from the shell to compile a c program (.c file)

Then, we invoke the binary name from the shell to execute it

By convention, the generated executable is called a.out by default. We can explicitly set a different binary name using the flag -o <name>

Compile-time	Runtime
gcc hello.c	./a.out
gcc hello.c -o hello	./hello

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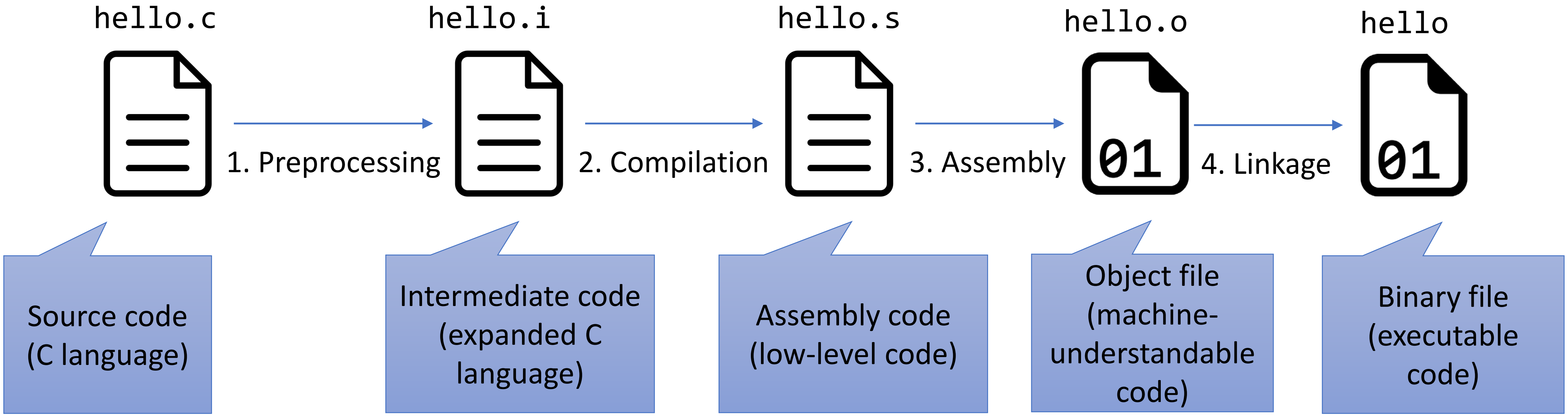
3. The build process

- The build process in C has actually 4 stages:



3. The build process

1. Preprocessing: The preprocessor converts the source code (.c) into some intermediate file (.i) doing the following:
   - Removing comments
   - Expanding **macros** (expressions defined using the `#define` directive)
   - Expanding included files (include content of files defined using the `#include` directive)
2. Compilation: The compiler converts the intermediate file into an assembly file (.s) which has low-level instructions
3. Assembly: The assembler will convert the assembly code into object code (.o)
   - Object code holds the translated machine code from the original source code. Object code is not yet executable because:
     - It may contain references to functions or variables that are defined in other object files
     - It does not have an entry point required by the operating system to start the program execution
4. Linkage: The linker merges all the object(s) code into a single one (executable)

3. The build process

- Others GCC commands:

```
gcc hello.c -o hello -save-temps
```

Generates binary file but does not delete temporal files (.i, .s, and .o)

```
gcc hello.c -E -o hello.i
```

Only generates intermediate code (.i)

```
gcc hello.c -S -o hello.s
```

Only generates assembly code (.s)

```
gcc hello.c -c -o hello.o
```

Only generates object file (.o)

```
gcc hello.c -o hello -Wall
```

Generates binary file and check all warnings

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4. Data types

- A data **type** defines the set of values for a variable
- There are four groups of data types in C:

Basic Primary data types (integers, characters, etc.)	**Enumerated** Integer values associated to labels
Void No value (for functions without return or generic pointers)	**Derived** Arrays, unions, structures, and pointers

4. Data types - Basic types

- The basic types in C are the following:

Data type	Description	Typical memory size (in bytes)	Range	Format specifier
`char`	Characters with sign	1	-128 to 127	`%c`
`unsigned char`	Characters without sign	1	0 to 255	`%c`
`short`	Short integers with sign	2	−32,768 to 32,767	`%hi` or `%hd`
`unsigned short`	Short integers without sign	2	0 to 65,535	`%hu`
`int`	Integers with sign	4	-2,147,483,648 to 2,147,483,647	`%i` or `%d`
`unsigned int`	Integers without sign	4	0 to 4,294,967,295	`%u`
`long`	Long integer with sign	8	-9.2e18 to 9.2e18	`%li` or `%ld`
`unsigned long`	Long integer	8	0 to 1.8E19	`%lu`
`float`	Decimal	4	1.1e-38 to 3.4e38	`%f`
`double`	Decimal with double precision	8	2.2e-308 0 to 1.7e308	`%lf`

4. Data types - Basic types

- A character variable holds **ASCII** value, i.e., an integer number between 0 and 127

ASCII TABLE

Decimal	Hexadecimal	Binary	Octal	Char
0	0	0	0	[NULL]
1	1	1	1	[START OF HEADING]
2	2	10	2	[START OF TEXT]
3	3	11	3	[END OF TEXT]
4	4	100	4	[END OF TRANSMISSION]
5	5	101	5	[ENQUIRY]
6	6	110	6	[ACKNOWLEDGE]
7	7	111	7	[BELL]
8	8	1000	10	[BACKSPACE]
9	9	1001	11	[HORIZONTAL TAB]
10	A	1010	12	[LINE FEED]
11	B	1011	13	[VERTICAL TAB]
12	C	1100	14	[FORM FEED]
13	D	1101	15	[CARRIAGE RETURN]
14	E	1110	16	[SHIFT OUT]
15	F	1111	17	[SHIFT IN]
16	10	10000	20	[DATA LINK ESCAPE]
17	11	10001	21	[DEVICE CONTROL 1]
18	12	10010	22	[DEVICE CONTROL 2]
19	13	10011	23	[DEVICE CONTROL 3]
20	14	10100	24	[DEVICE CONTROL 4]
21	15	10101	25	[NEGATIVE ACKNOWLEDGE]
22	16	10110	26	[SYNCHRONOUS IDLE]
23	17	10111	27	[ENG OF TRANS. BLOCK]
24	18	11000	30	[CANCEL]
25	19	11001	31	[END OF MEDIUM]
26	1A	11010	32	[SUBSTITUTE]
27	1B	11011	33	[ESCAPE]
28	1C	11100	34	[FILE SEPARATOR]
29	1D	11101	35	[GROUP SEPARATOR]
30	1E	11110	36	[RECORD SEPARATOR]
31	1F	11111	37	[UNIT SEPARATOR]
32	20	100000	40	[SPACE]
33	21	100001	41	!
34	22	100010	42	"
35	23	100011	43	#
36	24	100100	44	$
37	25	100101	45	%
38	26	100110	46	&
39	27	100111	47	'
40	28	101000	50	(
41	29	101001	51	)
42	2A	101010	52	*
43	2B	101011	53	+
44	2C	101100	54	,
45	2D	101101	55	-
46	2E	101110	56	.
47	2F	101111	57	/
48	30	110000	60	0
49	31	110001	61	1
50	32	110010	62	2
51	33	110011	63	3
52	34	110100	64	4
53	35	110101	65	5
54	36	110110	66	6
55	37	110111	67	7
56	38	111000	70	8
57	39	111001	71	9
58	3A	111010	72	:
59	3B	111011	73	;
60	3C	111100	74	<
61	3D	111101	75	=
62	3E	111110	76	>
63	3F	111111	77	?
64	40	1000000	100	@
65	41	1000001	101	A
66	42	1000010	102	B
67	43	1000011	103	C
68	44	1000100	104	D
69	45	1000101	105	E
70	46	1000110	106	F
71	47	1000111	107	G
72	48	1001000	110	H
73	49	1001001	111	I
74	4A	1001010	112	J
75	4B	1001011	113	K
76	4C	1001100	114	L
77	4D	1001101	115	M
78	4E	1001110	116	N
79	4F	1001111	117	O
80	50	1010000	120	P
81	51	1010001	121	Q
82	52	1010010	122	R
83	53	1010011	123	S
84	54	1010100	124	T
85	55	1010101	125	U
86	56	1010110	126	V
87	57	1010111	127	W
88	58	1011000	130	X
89	59	1011001	131	Y
90	5A	1011010	132	Z
91	5B	1011011	133	[
92	5C	1011100	134	\
93	5D	1011101	135	]
94	5E	1011110	136	^
95	5F	1011111	137	_
96	60	1100000	140	`
97	61	1100001	141	a
98	62	1100010	142	b
99	63	1100011	143	c
100	64	1100100	144	d
101	65	1100101	145	e
102	66	1100110	146	f
103	67	1100111	147	g
104	68	1101000	150	h
105	69	1101001	151	i
106	6A	1101010	152	j
107	6B	1101011	153	k
108	6C	1101100	154	l
109	6D	1101101	155	m
110	6E	1101110	156	n
111	6F	1101111	157	o
112	70	1110000	160	p
113	71	1110001	161	q
114	72	1110010	162	r
115	73	1110011	163	s
116	74	1110100	164	t
117	75	1110101	165	u
118	76	1110110	166	v
119	77	1110111	167	w
120	78	1111000	170	x
121	79	1111001	171	y
122	7A	1111010	172	z
123	7B	1111011	173	{
124	7C	1111100	174	|
125	7D	1111101	175	}
126	7E	1111110	176	~
127	7F	1111111	177	[DEL]

Source: Wikipedia
https://en.wikipedia.org/wiki/ASCII

4. Data types - Basic types

- The first argument in function `printf` (i.e., a string) can include *format specifiers* (i.e., subsequences beginning with %)
  - In this case, the additional arguments are formatted and inserted in the resulting string replacing their respective specifiers

```c
#include <stdio.h>

int main() {
    char character = 'c';
    int integer = 255;
    float float_num = 1.2;
    double double_num = 3.1e33;

    printf("This is a character: %c\n", character);
    printf("This is an integer: %d\n", integer);
    printf("This is a float: %f\n", float_num);
    printf("This is a double: %g\n", double_num);
    printf("This is an integer in hexadecimal: %X\n", integer);

    return 0;
}
```

```
This is a character: c
This is an integer: 255
This is a float: 1.200000
This is a double: 3.1e+33
This is an integer in hexadecimal: FF
```

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4. Data types - Basic types

- The operator **sizeof** generates the storage size (in bytes) of an expression or a data type

```c
#include <stdio.h>

int main() {
    printf("The size of a CHAR is %ld bytes\n", sizeof(char));
    printf("The size of a SHORT is %ld bytes\n", sizeof(short));
    printf("The size of a INT is %ld bytes\n", sizeof(int));
    printf("The size of a LONG is %ld bytes\n", sizeof(long));
    printf("The size of a FLOAT is %ld bytes\n", sizeof(float));
    printf("The size of a DOUBLE is %ld bytes\n", sizeof(double));

    return 0;
}
```

```
The size of a CHAR is 1 bytes
The size of a SHORT is 2 bytes
The size of a INT is 4 bytes
The size of a LONG is 4 bytes
The size of a FLOAT is 4 bytes
The size of a DOUBLE is 8 bytes
```

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4. Data types - Enumerated types

- Enumeration are a user defined data types used to assign names to integer constants
  - These names make a program easy to read and maintain
  - The keyword **enum** is used to declare new enumeration types in C

```c
#include <stdio.h>

int main() {
    enum days {
        MONDAY, TUESDAY, WEDNESDAY, THURSDAY, FRIDAY, SATURDAY, SUNDAY
    };

    enum days today = SATURDAY;
    enum days tomorrow = SUNDAY;

    printf("Today is %d\n", today);
    printf("Tomorrow is %d\n", tomorrow);

    if (today == SATURDAY || today == SUNDAY) {
        printf("It's the weekend!\n");
    }

    return 0;
}
```

```
Today is 5
Tomorrow is 6
It's the weekend!
```

4. Data types - Type definitions

- The keyword **typedef** in C allows to create an additional name (alias) for another data type

```c
#include <stdio.h>

int main() {
    typedef unsigned char byte;
    byte character = 'd';
    printf("My character is: %c\n", character);

    return 0;
}
```

```
My character is: d
```

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4. Data types - Type conversions

- Converting one type explicitly into another is known as **type casting** (or type-conversion)
- We convert the values from one type to another explicitly using the cast operator as follows:

```
(type) expression
```

```
#include <stdio.h>

int main() {
    int sum = 17, count = 5;
    double mean;

    mean = (double) sum / count;
    printf("Mean: %f\n", mean);

    return 0;
}
```

```
Mean: 3.400000
```

4. Data types - Type conversions

- Implicit type conversion is known as **type promotion** (or coercion)

```c
#include <stdio.h>

int main() {
    int i = 1;
    char c = 'A'; // The ASCII value of 'A' is 65
    int sum;

    sum = i + c;
    printf("Sum: %d\n", sum);

    return 0;
}
```

```
Sum: 66
```

4. Data types - Type conversions

- Implicit type conversion is known as **type promotion** (or coercion)

```c
#include <stdio.h>

int main() {
    int i = 65;
    char c = i; // 65 is the ASCII value of 'A'

    printf("%d as a character is %c\n", i, c);

    return 0;
}
```

```
65 as a character is A
```

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5. Variables

- **Variables** are containers for storing data values
- We distinguish three ways of handling variables:
  1. **Declaration**: statement to specify the variable name and its data type
  2. **Assignment**: set a value to the variable using the operator =
  3. **Initialization**: initial assignment during declaration

```c
#include <stdio.h>

int main() {
    int a; // declaration
    a = 10; // assignment

    int b = 10; // initialization

    return 0;
}
```

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5. Variables - Scope

- The **scope** is the range within a program for which an item (e.g., a variable) is valid (beyond that, it cannot be accessed)
- There are two types of variables depending on its scope:
  - Global variables: defined outside a function, usually on top of the program
  - Local variables: defined inside a function or block. They can be used only by statements that are inside that function or block of code

```c
#include <stdio.h>

/*
 These are global variables
 (multi-line comment)
 */
int a = 1;
int b;

int main() {
    int c, d = 2; // local variables
    char e;

    e = 'z'; // assignments
    b = 7;
    c = 5;

    printf("a=%d b=%d c=%d d=%d e=%c\n", a, b, c, d, e);

    return 0;
}
```

```
a=1 b=7 c=5 d=2 e=z
```

5. Variables - Scope

- We need to be careful with the variable scope. For example:

```
#include <stdio.h>

int main() {
    int a = 1;

    if (a > 0) {
        int b = 2;

        printf("a=%d and b=%d\n", a, b);
    }

    printf("a=%d and b=%d\n", a, b);

    return 0;
}
```

What happens here?

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5. Variables - Shadowing

- *Shadowing* appears when a variable is defined in a scope with the same name of another one valid in a higher level scope

```
#include <stdio.h>

int b = 0;

int main() {
    int a = 1;

    if (a > 0) {
        int b = 2;

        printf("a=%d and b=%d\n", a, b);
    }

    printf("a=%d and b=%d\n", a, b);

    return 0;
}
```

What happens here?

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6. Constants

- Constants refer to fixed values that the program may not alter during its execution. There are different ways to define constants in C:
  - Using a macro defined with the preprocessor directive **#define**
  - Using the keyword **const**
  - Using the enumerated types

```c
#include <stdio.h>

#define MAX 64

int main() {
    const int num = 15;
    enum parity {
        ODD = 1, EVEN = 2
    };

    printf("MAX=%d\n", MAX);
    printf("num=%d\n", num);
    printf("EVEN=%d ODD=%d\n", EVEN, ODD);

    return 0;
}
```

```
MAX=64
num=15
EVEN=2 ODD=1
```

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7. Code style

- Some usual guidelines in C:
  - Use meaningful names for variables, constants and functions
  - Use *snake-case* (underscores for multi-word names, e.g. `file_name`) and not *camel-case* (use of capital letter except the initial word, e.g. `fileName`)
  - Use the same indentation level (3 or 4 spaces, or 1 tab)
  - Use the same style for opening braces (in the same line or just above)
  - Define constants macros in uppercase
- Best practices:
  - Avoid code duplication (DRY - Don’t Repeat Yourself)
  - Group related functions in a separate module
  - Use an automated code formatter, for example:

Windows and Linux: *Ctrl + Shift + F*
macOS: *Command + Shift + F*

Windows: *Shift + Alt + F*
Linux: *Ctrl + Shift + I*
macOS: *Shift + Option + F*

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8. Takeaways

- C is a programming language: general-purpose, high-level, compiled, imperative and procedural, statically and weakly-typed
- C programs are organized using procedures called **functions**. At least, the function **`main()`** should be defined (i.e., the program entry point)
- The build process in C is done with GCC and has 4 steps: preprocessing, compilation, assembly, and linkage
- There are four groups of data types in C: basic (**`int`**, **`char`**, etc.), enumerated (**`enum`**), void (**`void`**), and derived (arrays, unions, structures, and pointers)
- Depending its scope, there are two types of variable in C: global (defined outside a function) and local (defined inside a function or block)