Summary: C++

AgC86

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Learncpp

Author Note

All of the work done is made possible thanks to the creators of the Learncpp website.

Contents

1 Keywords

Computer program, application

Hardware, physical computer parts

Bit, binary digit

Assembler, a program that translates assembly language into machine language

Compiler, a program (or collection of programs) that reads source code (typically written in a high-level language) and translates it into some other language (typically a low-level language, such as assembly or machine language, etc.).

Interpreter, a program that directly executes the instructions in the source code without requiring them to be compiled into an executable first.

ANSI, the American National Standards Institute

ISO, the International Organization for Standardization

Language standard or **language specification**, each new formal release of the language.

Linker, the linker's job is to combine all of the object files and produce the desired output file (typically an executable file). This process is called **linking**.

Building, the full process of converting source code files into an output file.

Build configurations or **build target,** a collection of project settings that determines how your IDE will build your project.

Compiler extensions, many compilers implement their own changes to the language, often to enhance compatibility with other versions of the language, or for historical reasons.

Diagnostics, if you have done something that definitively violates the rules of the language, the compiler is required to emit a diagnostic message.

Statement, a type of instruction that causes the program to perform some action.

Identifier, the name of a function (or object, type, template, etc.).

Random Access Memory (RAM), the main memory in a computer

Object, a region of storage (usually memory) that can store a value, and has other associated properties. Typically refers to an unnamed object in memory, a variable, or a function.

Variable, an object that has been named (**identifier**).

Definition, a special kind of declaration statement for creating variables.

Instantiation, the object gets created and assigned a memory address.

Instance, instantiated object

Data type (Type), determines what kind of value (e.g. a number, a letter, text, etc.) the object will store.

Assignment, the process of giving a value to a variable **after** it has been defined.

Initialization, giving an initial value to an object at the point of definition.

Uniform or brace initialization, list initialization

Zero initialization, default initialization

Buffer, a region of memory set aside to store a collection of requested data.

Flushing, transferring collected data from the buffer to its destination.

Uninitialized, an object that hasn't been given a known value.

Undefined behavior (UB), the result of executing code whose behavior is not well-defined by the C++ language.

Implementation-defined behavior, the result of executing code whose behavior is defined by the compiler.

Unspecified behavior, this is almost identical to implementation-defined behavior. The only difference here is that the implementation (**compiler**) doesn't have to document why it behaves a certain way.

Reserved words, words reserved to the C++ language such as keywords.

Operator Arity, the number of operands that an operator takes as input.

PEMDAS, Parenthesis → Exponents → Multiplication & Division → Addition & Subtraction.

Side effects, an operator (or function) that has some observable effect beyond producing a return value.

Metasyntactic variable or **placeholder names**, a placeholder name for a function or variable when the name is unimportant to the demonstration of some concept.

Status codes or **exit codes**, the return value of a function is passed back to the caller of the function, the status code is passed back to the caller. This return value has a defined meaning (e.g. **EXIT_SUCCES)**.

DRY, don't repeat yourself

WET, write everything twice

Modular programming, the ability to write a function, test it, ensure that it works, and then know that we can reuse it as many times as we want and it will continue to work (so long as we don't modify the function -- at which point we'll have to retest it).

Unreferenced parameters, functions that have parameters that are not used in the body of the function.

Lifetime, an object's lifetime is defined to be the time between its creation and destruction. (**runtime** property)

Scope, an identifier's scope determines where the identifier can be seen and used within the source code. (**compile-time** property)

Out of scope, an identifier is out of scope anywhere it cannot be accessed within the code.

Going out of scope, we say an object goes out of scope at the end of the scope (the end curly brace) in which the object was instantiated.

Temporary object or **anonymous object**, an unnamed object that is created by the compiler to store a value temporarily.

One task rule or **separation of concerns (SoC)**, a design principle to separate an application into units, with minimal overlapping between the functions of the individual units.

Function declaration statement or **function prototype**, the function declaration consists of the function's return type, name, and parameter types, terminated with a semicolon. The names of the parameters can be optionally included. The function body is not included in the declaration.

Pure declaration, In C++, all definitions are declarations. Conversely, not all declarations are definitions. Declarations that aren't definitions are called pure declarations.

One definition rule (ODR), Only one definition of any variable, function, class type, enumeration type, concept(since C++20) or template is allowed in any one translation unit (some of these may have multiple declarations, but only one definition is allowed).

Qualified name, an identifier that includes a namespace prefix.

Using-directive statement, allows us to access the names in a namespace without using a namespace prefix.

Preprocessor directive or **directives**, instructions that start with a # symbol and end with a newline (NOT a semicolon).

Translation unit, when the preprocessor has finished processing a code file, the result is called a translation unit.

Translation, the entire process of **preprocessing**, **compiling**, and **linking**.

Transitive includes, when your code file #includes the first header file, you'll also get any other header files that the first header file includes (and any header files those include, and so on). These additional header files are sometimes called transitive includes, as they're included implicitly rather than explicitly.

Header guard or include guard, conditional compilation directives that ensure proper transitive includes, avoiding **ODR** violations.

Call stack, a list of all the active functions that have been called to get to the current point of execution. The call stack includes an entry for each function called, as well as which line of code will be returned to when the function returns. Whenever a new function is called, that function is added to the top of the call stack. When the current function returns to the caller, it is removed from the top of the call stack, and control returns to the function just below it.

Fundamental data types or **primitive types**, data types that are built into and supported by C++.

IEEE, Institute of Electrical and Electronics Engineers

Sign, the attribute of being positive, negative, or zero is called the number's sign.

Sign bit, a single bit used to store the sign of the number.

Magnitude bits, the non-sign bits that determine the magnitude of the number.

Shorthand types, types that do not use a (int) suffix or signed prefix.

C++

2 Introduction / Getting started

2.1 Introduction to programming languages

A **computer program** (also commonly called an **application**) is a **set of instructions** that the computer can perform in order to perform some task(s). The process of creating a program is called programming. Programmers typically create programs by producing source code (commonly shortened to code), which is a list of commands typed into one or more text files.

The collection of **physical** computer **parts** that make up a computer and execute programs is called the **hardware**. When a computer program is loaded into memory and the hardware sequentially executes each instruction, this is called **running** or **executing** the program.

2.1.1 Machine language

The collection of physical computer parts that make up a computer and execute programs is called the **hardware**. When a computer program is loaded into memory and the hardware sequentially executes each instruction, this is called **running** or **executing** the program.

Example: **1011000 0110001**

Each instruction is composed of a sequence of 1s and 0s. Each individual 0 or 1 is called a **binary digit** or **bit** for short. The number of bits that make up a single command varies.

Example:

- Some CPUs process instructions are always 32 bits long
- Other CPUs from the x86/x64 family have instructions that can be variable in length

Each set of binary digits is interpreted by the CPU into a command to do a very specific job, such as **compare these two numbers**, or **put this number in that memory location**.

However, because different **CPUs have different instruction sets**, instructions that were written for one CPU type could not be used on a CPU that didn’t share the same instruction set. Back in the day this meant that programs generally weren’t **portable**.

2.1.2 Assembly language

Because machine language is so hard for humans to read and understand, assembly language was invented. In an assembly language, each instruction is identified by a short abbreviation (**rather than a set of bits**), and names and other numbers can be used.

Here is the same instruction as above in assembly language: **mov al, 061h**

This makes assembly much easier to read and write than machine language. However, the **CPU cannot understand assembly language directly**. Instead, the assembly **program must be translated** into machine language before it can be executed by the computer. This is done by using a program called an **assembler**.

Assembly languages still require a lot of instructions to do even simple tasks. While the individual instructions themselves are somewhat human readable, understanding what an entire program is doing can be challenging. Assembly isn’t portable, a program written in assembly for one CPU will likely not work on hardware that uses a different instruction set, and would have to be rewritten or extensively modified.

2.1.3 High-level languages

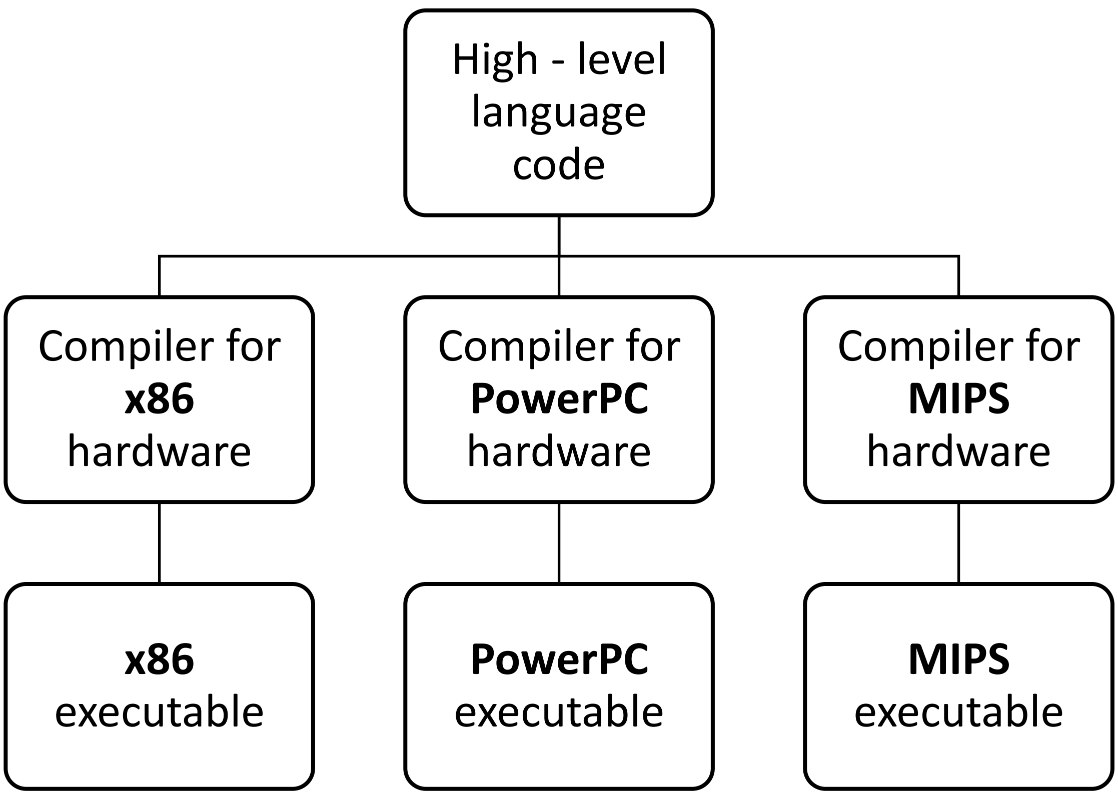
Now that we know some of the downsides:

- Hard to read
- Not portable
- A lot of work for simple instructions

This is where higher-level languages come into play. To address the readability and portability concerns, new programming languages such as C, C++, Pascal (and later, languages such as Java, Javascript, and Perl) were developed. These languages are called **high level languages**, as they are designed to allow the programmer to write programs without having to be as concerned about what kind of computer the program will be run on.

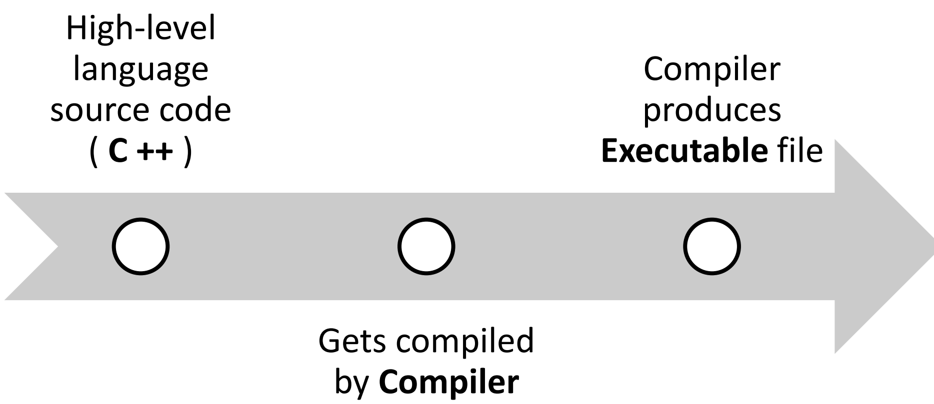
Here is the same instruction as above in C/C++: **a = 97;**

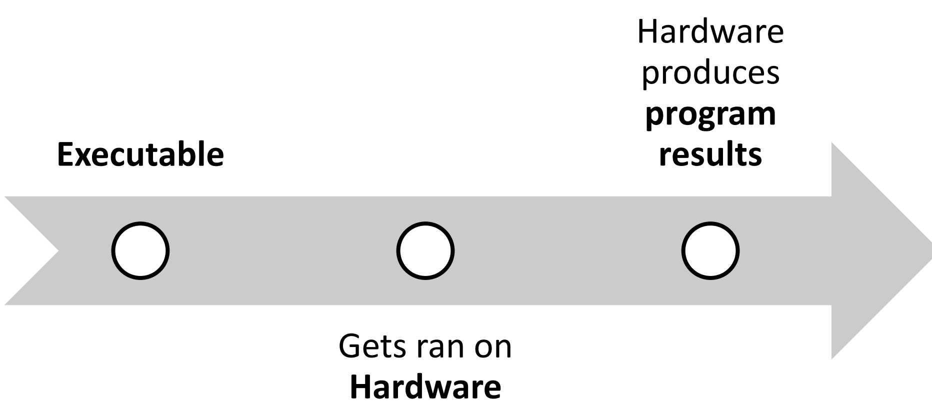
Much like assembly programs, programs written in high level languages must be translated into a format the computer can understand before they can be run. There are two primary ways this is done: compiling and interpreting. Most languages can be compiled or interpreted. Traditionally languages like **C, C++, and Pascal** are compiled, whereas “**scripting**” languages like **Perl** and **Javascript** tend to be interpreted. **Some languages, like Java, use a mix of the two**. Programs can be compiled (or interpreted) for many different systems, **and you don’t have to change the program to run on different CPUs** (you **just recompile** for that CPU).


High - level language code
Compiler for **x86** hardware
Compiler for **PowerPC** hardware
Compiler for **MIPS** hardware
x86 executable
PowerPC executable
MIPS executable

2.1.3.1 Compiling

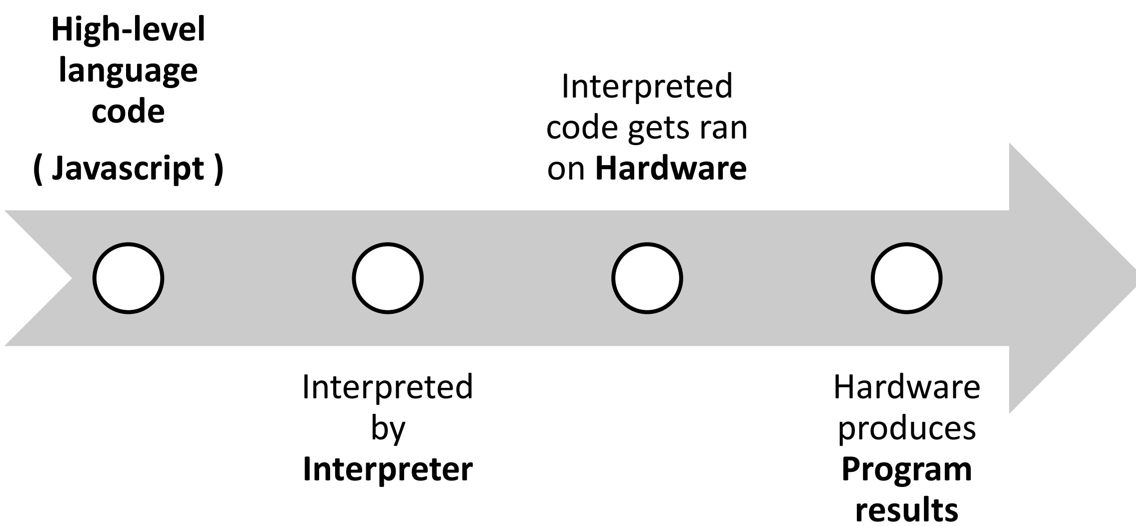
A **compiler** is a program (or collection of programs) that reads source code (typically written in a high-level language) and **translates** it **into** some other language (typically a **low-level language**, such as assembly or machine language, etc.). Most often, these low-level language files are then combined into an executable file (containing machine language instructions) that can be run or distributed to others. Notably, **running** the executable file **does not require** the **compiler** to be installed (because the **code has already been compiled and put into the executable file**).





2.1.3.2 Interpreter

An **interpreter** is a program that **directly executes** the **instructions** in the source code without requiring them to be compiled into an executable first. Interpreters tend to be **more flexible than compilers**, but are **less efficient** when running programs because the interpreting process needs to be done every time the program is run. **This also means the interpreter must be installed on every machine where an interpreted program will be run.**



2.2 Introduction to C / C++

2.2.1 Before C++, there was C

C was created by **Dennis Ritchie** in 1972, primarily to **serve as a systems programming language** (To write Operating Systems with).

Goals for C:

- Minimalistic
- Easy to compile
- Efficient access to memory
- Efficient code
- Self-contained (Not reliant on other languages)

2.2.1.1 Brief history: C

Essentially, it was designed to give the programmer a lot of control, while still encouraging hardware and operating systems independence.

2.2.1.1.1 1973: Unix

It was so flexible that in 1973 the **Unix** operating system was written in C and Assembly.

2.2.1.1.2 1978: "The C Programming Language"

In 1978, Brian **Kernighan** and Dennis **Ritchie** published a book called "**The C Programming Language**". This book, which was commonly known as **K&R**, provided an informal specification for the language and **became a de facto standard**.

2.2.1.1.3 1983: Forming of ANSI committee

In 1983, the American National Standards Institute (ANSI) formed a committee to establish a formal standard for C.

2.2.1.1.4 1989: Release: C89 standard / ANSI C

In 1989 (committees take forever to do anything), they finished, and released the C89 standard, more commonly known as ANSI C.

2.2.1.1.5 1990: Release: C90 standard: An adoption of ANSI C by the ISO

In 1990 the International Organization for Standardization (ISO) adopted ANSI C (with a few minor modifications). This version of C became known as C90. Compilers eventually became ANSI C/C90 compliant, and programs desiring maximum portability were coded to this standard.

2.2.1.1.6 1999: Release: C99 standard: An extended version of C90

In 1999, the ISO committee released a new version of C called C99. C99 adopted many features which had already made their way into compilers as extensions, or had been implemented in C++.

2.2.1.1.7 Later releases

- 2011: **C11**
- 2017: **C17**
- 2023: **C23**

2.2.1.2 Brief history: C++

C++ was created by **Bjarne Stroustrup** in 1979, primarily to **serve as an extension to C.** It is best thought of as a "superset" of C. Though new releases of C like the **C99 standard** introduced new features that weren't in C++.

Goals for C:

- More features
- Object-oriented

2.2.1.2.1 1998: C++ standardized by the ISO Committee

C++ was standardized in 1998 by the ISO committee (this means the ISO standards committee approved a document describing the C++ language, to help ensure all compilers adhere to the same set of standards)

2.2.1.2.2 2003: Release: C++03 standard

A minor update to the language was released in 2003 (called C++03).

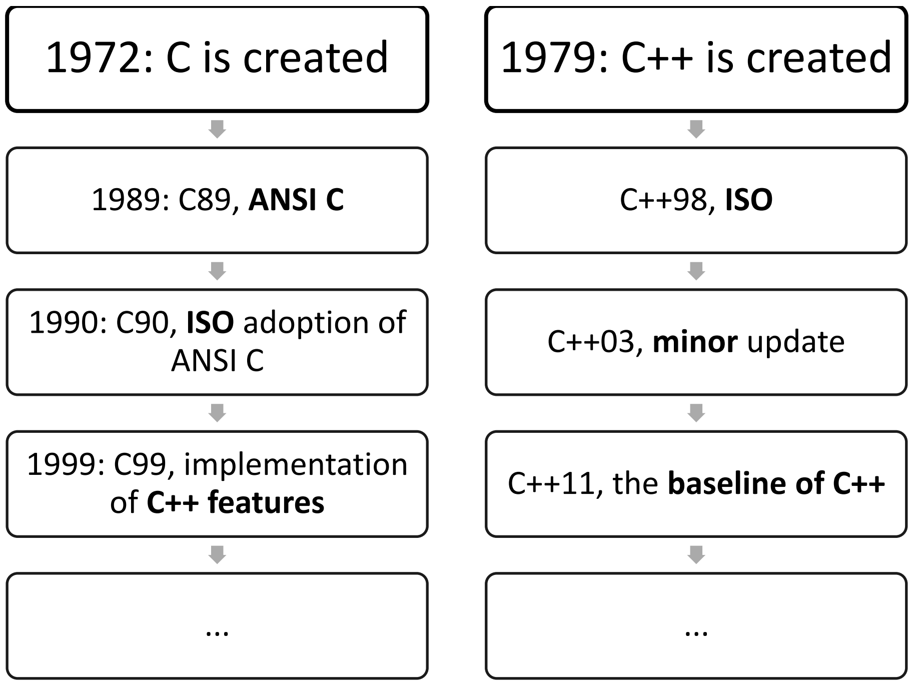
2.2.1.2.3 Later releases

Five major updates to the C++ language (**C++11, C++14, C++17, C++20, and C++23**) have been made since then, each adding additional functionality. **C++11 in particular added a huge number of new capabilities, and is widely considered to be the new baseline version of the language.** Future upgrades to the language are expected every three or so years.

Each new formal release of the language is called a **language standard** (or **language specification**).

Standards are named after the year they are released in. For example, there is no C++15, because there was no new standard in 2015.

2.2.1.3 Summary of language standards

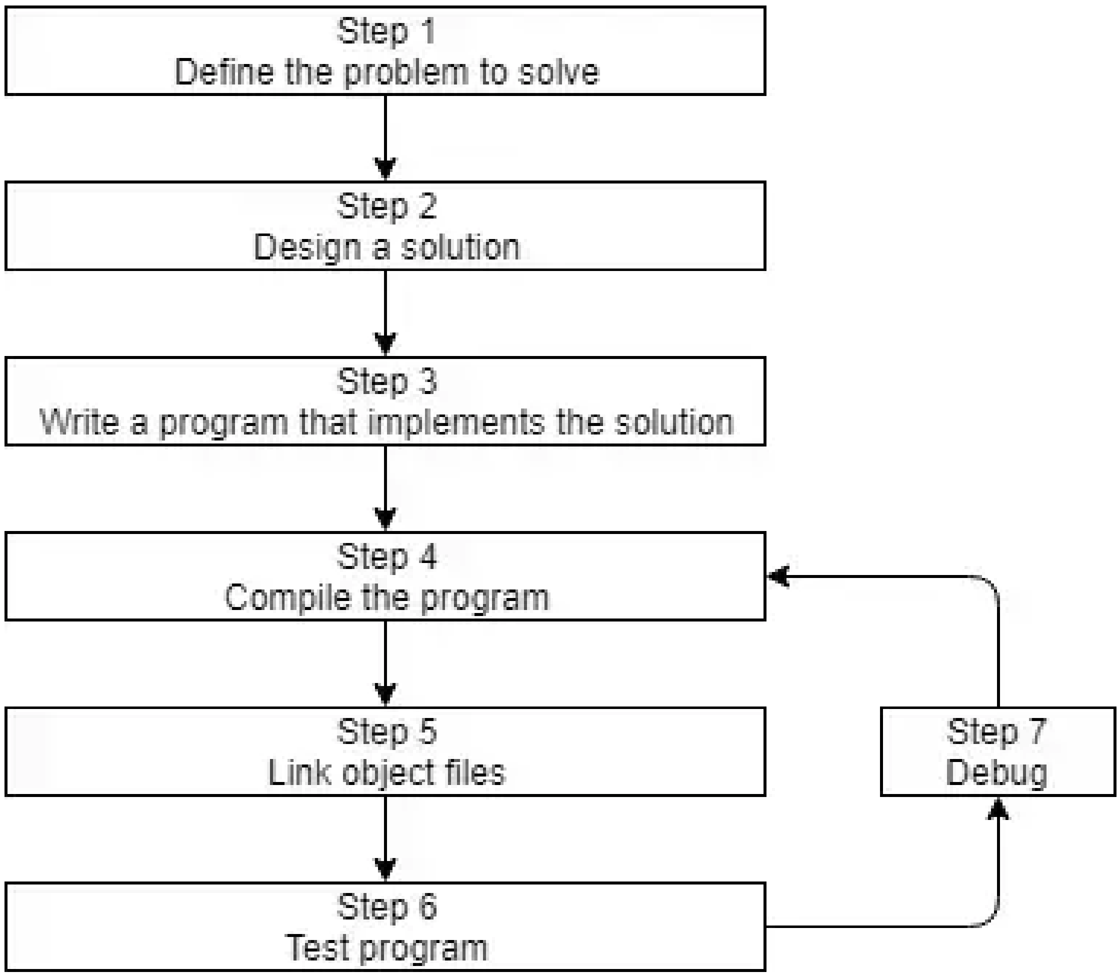


2.2.2 C / C++ philosophy

The underlying design philosophy of C and C++ can be summed up as “**trust the programmer**” -- which is **both wonderful and dangerous**. C++ is designed to allow the programmer a **high degree of freedom** to do what they want. However, **this also means the language often won’t stop you from doing things that don’t make sense**, because it will assume you’re doing so for some reason it doesn’t understand. There are quite a few pitfalls that new programmers are likely to fall into if caught unaware. **This is one of the primary reasons why knowing what you shouldn’t do in C/C++ is almost as important as knowing what you should do.**

2.3 Introduction to C++ development

2.3.1 C++ development flow



2.4 Introduction to the compiler, linker and libraries

2.4.1 Compiling your source code

In order to compile C++ source code files, we **use a C++ compiler**. The C++ compiler **sequentially goes through each** source code (.cpp) **file** in your program. The compiler does two important tasks:

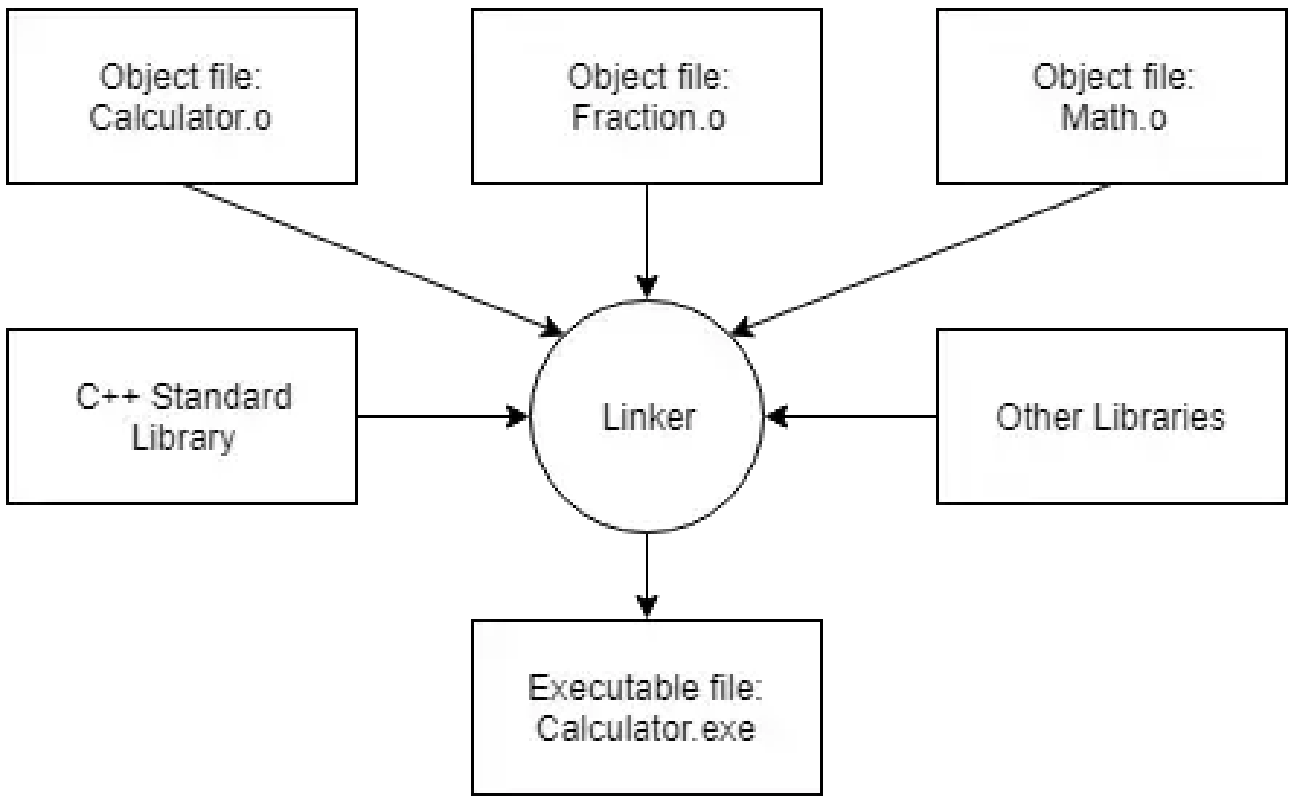
- **Checks** your C++ **code** to make sure it follows the rules of the C++ language.
    - **If it does not, the compiler will give you an error** (and the corresponding line number) to help pinpoint what needs fixing. **The compilation process will also be aborted until the error is fixed.**
- **Translates** your C++ **code** into machine language instructions.
    - These instructions are **stored in an intermediate** file called an **object file**. The **object file also contains metadata that is required or useful in subsequent steps**. These files carry the .**o / .obj extension** and will have the **same name as** your **.cpp Files**.

2.4.2 Linking object files and libraries

After the compiler has successfully finished, another program called the **linker** kicks in. The **linker's job is to combine all of the object files and produce the desired output file** (typically an executable file). This process is called **linking**.

The linker's flow:

- Read each object file to make sure they are valid
- Resolve cross-file dependencies
    - These are things you use something from one file to the other
    - **If** the linker is **unable to connect a reference** to something with its definition, you'll get a **linker error**, and **the linking process will abort**.
- Linking library files
    - A **library file** is a collection **of precompiled code** that has been "packaged up" for reuse in other programs.
    - C++ comes with an extensive library called the **C++ Standard Library** (usually shortened to *standard library*) that provides a set of useful capabilities for use in your programs.
    - You can also optionally **link other libraries**.
        - Example: C++ doesn't let you play sounds by standard. And figuring out how to code sound is a lot of work. Instead, you'd probably download a library that already knew how to do those things, and use that.


Object file:
Calculator.o
Object file:
Fraction.o
Object file:
Math.o
C++ Standard
Library
Linker
Other Libraries
Executable file:
Calculator.exe

2.4.3 Building

Because there are multiple steps involved, the term **building** is often **used to refer to the full process** of converting source code files into an executable that can be run. A specific executable produced as the result of building is sometimes called a **build**.

2.4.3.1 Build types

- **Build**
  - **compiles** all ***modified*** **code files** in the project or workspace/solution, and **then links the object files into an executable.**
  - If no code files have been modified since the last build, this option does nothing.
- **Clean**
  - **removes all cached objects and executables** so the next time the project is built, all files will be recompiled and a new executable produced.
- **Rebuild**
  - does a "**clean**", **followed by** a "**build**".
- **Compile**
  - recompiles a **single code file** (regardless of whether it has been cached previously).
  - This option **does not invoke the linker** or produce an executable.
- **Run/start**
  - **executes the executable from a prior build.**
  - Some IDEs (e.g. Visual Studio) will **invoke a "build" before doing a "run"** to ensure you are running the latest version of your code.

For this summary I'm not going to go into IDE's to use or how to build your first program or what IDE's look like.

2.5 Configuring your compiler

2.5.1 Build configurations

A **build configuration** (also called a **build target**) is a collection of project settings that determines how your IDE will build your project. The build configuration typically includes things like what the executable will be named, what directories the IDE will look in for other code and library files, whether to keep or strip out debugging information, how much to have the compiler optimize your program, etc. Generally, you will want to leave these settings at their default values unless you have a specific reason to change something.

When you create a new project in your IDE, most IDEs will set up two different build configurations for you: a release configuration, and a debug configuration.

2.5.1.1 Debug configuration

The **debug configuration** is designed to help you debug your program, and is generally the one you will use when writing your programs. This configuration turns off all optimizations, and includes debugging information, which makes your programs larger and slower, but much easier to debug. The debug configuration is usually selected as the active configuration by default. We'll talk more about debugging techniques in a later lesson.

2.5.1.2 Release configuration

The **release configuration** is designed to be used when releasing your program to the public. This version is typically optimized for size and performance, and doesn't contain the extra debugging information. Because the release configuration includes all optimizations, this mode is also useful for testing the performance of your code (which we'll show you how to do later in the tutorial series).

2.5.2 Compiler extensions

The C++ standard defines rules about how programs should behave in specific circumstances. And in most cases, compilers will follow these rules. However, many compilers implement their own changes to the language, often to enhance compatibility with other versions of the language (e.g. C99), or for historical reasons. These compiler-specific behaviors are called **compiler extensions**.

Writing a program that makes use of a compiler extension **allows you to write programs that are incompatible with the C++ standard**. Programs using non-standard extensions **generally will not compile on other compilers** (that don't support those same extensions), or if they do, they may not run correctly.

Frustratingly, compiler extensions are **often enabled by default**. This is particularly damaging for new learners, who may think some behavior that works is part of official C++ standard, when in fact **their compiler is simply over-permissive**.

Because compiler extensions are never necessary, and cause your programs to be non-compliant with C++ standards, **we recommend turning compiler extensions off**.

In visual studio this setting is called the **Conformance mode** and **belongs to the C/C++ language settings.** It should be set to Yes or Permissive- (non-permissive).

2.5.3 Warnings and error levels

When you write your programs, the compiler will check to ensure you've followed the rules of the C++ language (assuming you've turned off compiler extensions).

2.5.3.1 Diagnostics

If you have done something that definitively violates the rules of the language, the compiler is required to emit a **diagnostic message** (often called a **diagnostic** for short). The C++ standard does not define how diagnostic messages should be categorized or worded. However, there are some common conventions that compilers have adopted.

2.5.3.2 Errors

If compilation cannot continue due to the violation, then the compiler will emit an **error**, providing both line number containing the error, and some text about what was expected vs what was found. Errors stop the compilation from proceeding. **The actual error may be on that line, or on a preceding line.** Once you've identified and fixed the erroneous line(s) of code, you can try compiling again.

2.5.3.3 Warnings

If compilation can continue despite the violation, the compiler may decide to emit either an error or a **warning**. Warnings are similar to errors, but they do not halt compilation.

In some cases, the compiler may identify code that does not violate the rules of the language, but that it believes could be incorrect. In such cases, the compiler may decide to emit a warning as a notice to the programmer that something seems amiss.

Best practice: Don't let warnings pile up, resolve them immediately (as if they were errors).

By default, most compilers will only generate warnings about the most obvious issues. However, **you can request your compiler be more assertive** about providing warnings for things it finds strange.

Best practice: Turn your warning levels up to the maximum, especially when learning.

2.5.3.4 Treating warnings as errors

It is also possible to tell your compiler to treat all warnings **as if they were errors** (in which case, the compiler will halt compilation if it finds any warnings). **This is a good way to enforce the recommendation that you should fix all warnings (if you lack self-discipline, which most of us do)**.

Best practice: Enable "Treat warnings as errors". This will force you to resolve all issues causing warnings.

2.5.4 Choosing a language standard

With many different versions of C++ available (C++98, C++03, C++11, C++14, C++17, C++20, C++23, etc.) how does your compiler know which one to use? **Generally, a compiler will pick a standard to default to. Typically**, the default is ***not* the most recent** language standard -- many default to C++14, which is missing many of the latest and greatest features.

2.5.4.1 Code names for in-progress language standards

Finalized language standards are named after the years in which they are finalized (e.g. C++17 was finalized in 2017).

However, **when a new language standard is being worked on**, it's not clear in what year the finalization will take place. **Consequently, upcoming language standards are given code names**, which are then replaced by the actual names upon finalization of the standard. You may still see the code names used in places (particularly for the latest in-progress language standard that doesn't have a finalized name yet).

2.5.4.2 Which language standard should you use?

In professional environments, it's common to choose a language standard that is one or two versions back from the latest standard (e.g. if C++20 were the latest version, that means C++14 or C++17). This is typically done to ensure the compiler makers have had a chance to resolve defects, and so that best practices for new features are well understood. Where relevant, this also helps ensure better cross-platform compatibility, as compilers on some platforms may not provide full support for newer language standards immediately.

For personal projects and while learning, we recommend choosing the latest finalized standard, as there is little downside to doing so.

All the information regarding the C++ standard can be found on: https://isocpp.org/.

Even after a language standard is finalized, compilers supporting that language standard often still have missing, partial, or buggy support for certain features.

3 Basics

3.1 Statements and the structure of a program

3.1.1 Statements

A computer program is a **sequence** of instructions that tell the computer what to do.
A **statement** is a type of instruction that causes the program to *perform some action*.

Statements are by far the most common type of instruction in a C++ program. This is because they are the **smallest independent unit of computation** in the C++ language. In that regard, they act much like sentences do in natural language. When we want to convey an idea to another person, we typically write or speak in sentences (not in random words or syllables). In C++, when we want to have our program do something, we typically write statements.

Most (but not all) statements in C++ end in a semicolon. If you see a line that ends in a semicolon, it's probably a statement.

In a high-level language such as C++, a single statement may compile into many machine language instructions.

3.1.1.1 Different kinds of statements

- Declaration
- Jump
- Expression
- Compound
- Selection (Conditionals)
- Iteration (Loops)
- Try blocks

3.1.2 *Functions and the main function*

In C++, **statements are typically grouped into units called functions**. A function is a collection of statements that get executed sequentially (in order, from top to bottom). As you learn to write your own programs, you'll be able to create your own functions and mix and match statements in any way you please (we'll show how in a future lesson).

Important rule:

Every C++ program must have a **special function named main (all lower-case letters).** When the program is run, the statements inside of main are **executed in sequential order.** Programs typically terminate (finish running) after the last statement inside function main has been executed (though programs may abort early in some circumstances, or do some cleanup afterwards).

3.1.3 *Identifiers*

In programming, the name of a **function (or object, type, template, etc.)** is called its **identifier**.

3.1.4 *Syntax and syntax errors*

In English, sentences are constructed according to specific grammatical rules that you probably learned in English class in school. For example, normal sentences end in a period. **The rules that govern how sentences are constructed in a language is called syntax.** If you forget the period and run two sentences together, this is a violation of the English language syntax.

C++ has a syntax too: rules about how your programs must be constructed in order to be considered valid. When you compile your program, the compiler is responsible for making sure your program follows the basic syntax of the C++ language. If you violate a rule, the compiler will complain when you try to compile your program, and issue you a syntax error.

3.2 Comments

A comment is like leaving a note in your source code. It is ignored by the compiler and is mostly to help programmers document the code in some way.

3.2.1 Single-line comments

We start by writing the // symbol. Everything before that gets compiled but everything after the symbol up until the new line is a comment.

3.2.2 Multi-line comments

We start by writing the /* symbol and end with the */ symbol. Everything in between the first and the last symbol gets ignored by the compiler. The use here is to have a ‘’section” where you can write comments.

3.2.3 Best practice

Comment your code liberally, and write your comments as if speaking to someone who has no idea what the code does. Don’t assume you’ll remember why you made specific choices.

3.3 Introduction to objects and variables

You learned that the **majority of instructions in a program are statements**, and that **functions are groups of statements** that execute sequentially.

3.3.1 Key Insight

Programs are **collections of instructions that manipulate data** to produce a desired result.

3.3.2 Random Access Memory (RAM)

The main memory in a computer is called **Random Access Memory** (often called **RAM** for short). When we run a program, the operating system loads the program into RAM. Any **data that is hardcoded** into the program itself (e.g. text such as "Hello, world!") is **loaded at this point**.

The operating system **also reserves some additional RAM for the program to use** while it is running. Common uses for this memory are to store values entered by the user, to store data read in from a file or network, or to store values calculated while the program is running (e.g. the sum of two values) so they can be used again later.

You can think of RAM as a series of numbered boxes that can be used to store data while the program is running.

In some older programming languages (like Applesoft BASIC), you could directly access these boxes (e.g. you could write a statement to "go get the value stored in mailbox number 7532").

3.3.2.1 Quick summary

- Executable get ran
    - OS directly loads hardcoded values into memory
    - OS reserves additional space for data to be manipulated while the program is running

3.3.3 Objects & Variables

In C++, **direct memory access is discouraged**. Instead, we **access memory indirectly through an object**. An object is a **region of storage** (usually memory) that can store a value, and has other associated properties (that we'll cover in future lessons). How the compiler and operating system work to assign memory to objects is beyond the scope of this lesson. But the key point here is that rather than say "go get the value stored in mailbox number 7532", we can say, "go get the value stored by this object". **This means we can focus on using objects to store and retrieve values, and not have to worry about where in memory those objects are actually being placed.**

3.3.3.1 Key insight

An **object** is used **to store a value in memory**. A **variable is an object** that has been named (identifier). Naming our objects let us refer to them again later in the program.

3.3.3.2 Nomenclature

In general programming, the term *object* typically refers to an unnamed object in memory, a variable, or a function. **In C++, the term *object* has a narrower definition that excludes functions.**

3.3.3.3 Instantiation & Instances, a runtime occurrence

In order to create a variable, we use a special kind of declaration statement called a **definition.**

At compile time, when the compiler sees this statement, **it makes a note to itself** that we are defining a variable, giving it the name x, and that it is of type int (more on types in a moment). **From that point forward** (with some limitations that we'll talk about in a future lesson), **whenever the compiler sees the identifier x, it will know that we're referencing this variable.**

When the program is run (called **runtime**), the variable will be instantiated. **Instantiation** is a fancy word that **means the object will be created and assigned a memory address**. Variables must be instantiated before they can be used to store values. For the sake of example, **let's say that variable *x* is instantiated at memory location 140. Whenever the program uses variable x, it will access the value in memory location 140**. An instantiated object is sometimes called an **instance**.

3.3.4 Data types

A **data type** (more commonly just called a **type**) determines what kind of value (e.g. a number, a letter, text, etc.) the object will store. In C++, the type of a variable must be known at **compile-time** (when the program is compiled), and that type cannot be changed without recompiling the program. This means an integer variable can only hold integer values. If you want to store some other kind of value, you'll need to use a different type. Or do type conversion, which is something we'll get into more depth in, later on.

3.3.4.1 Defining a variable of a certain type

Int a;	← This is a **definition**
Int a, b;	← This defines two variables
Int a, int b;	← Wrong, compiler error
Int a, double b;	← Wrong, compiler error

In both cases these variables are of the integer type which allows them to store a numeric value into memory (not floating-point numeric values). There is **no need to specify the type twice** when defining variables, since it's in the same statement the compiler will know what type, it is.

Best practice: Although the language allows you to do so, **avoid defining multiple variables of the same type in a single statement**. Instead, define each variable in a separate statement on its own line (and then **use a single-line comment to document what it is used for**).

3.4 Variable assignment

3.4.1 Quick recap

In previous lessons we covered:

- **Instantiation** (the process of an object getting created and assigned to its memory address by the runtime system).
- **Definition** (Defining a variable by assigning it a type and identifier).

3.4.2 Variable assignment

After a variable has been defined, you can give it a value (in a separate statement) using the *= operator*. This process is called **assignment**, and the *= operator* is called the **assignment operator**.

```
Float pi;        ← Definition
pi = 3.14f;      ← Assignment
```

By default, assignment copies the value on the right-hand side of the *= operator* to the variable on the left-hand side of the operator. This is called **copy assignment**. This can be used to manipulate our variable.

Example: Since the type is already defined and the compiler knows about it we can access the variable by its **identifier (name)** and copy a different value into it.

```
pi = 3.141592f; ← Not definition but assigned a different value
```

3.5 Variable initialization

One downside of **assignment** is that it **requires at least two statements**: one to define the variable, and another to assign the value. **These two steps can be combined**. When an object is defined, you can optionally give it an initial value. **The process of specifying an initial value for an object is called initialization**, and the syntax used to initialize an object is called an **initializer**.

```
Float pi;          ← Definition
pi = 3.14f;        ← Assignment

Float pi = 3.14f;  ← Defined & Assigned → Initialized
```

3.5.1 Forms of initialization

```
int a;        // no initializer, just a definition (default initialization by compiler)

int b = 5;    // initial value after equals sign (copy initialization)

int c ( 6 );  // initial value in parenthesis (direct initialization)


// List initialization methods (C++11) (preferred)

int d { 7 };  // initial value in braces (direct list initialization)

int e = { 8 }; // initial value in braces after equals sign (copy list initialization)

int f {};     // initializer is empty braces (value initialization)
```

3.5.1.1 Default initialization

When no initializer is provided (such as for variable a above), this is called **default initialization**. In most cases, default initialization performs no initialization, and **leaves a variable with an indeterminate value.**

3.5.1.2 Copy initialization

When an initial value is provided after an equals sign, this is called **copy initialization**. This form of initialization was inherited from C. Much like copy assignment, this copies the value on the right-hand side of the equals into the variable being created on the left-hand side.

Copy initialization had fallen out of favor in modern C++ due to being less efficient than other forms of initialization for some complex types. However, C++17 remedied the bulk of these issues, and copy initialization is now finding new advocates. **You will also find it used in older code (especially code ported from C), or by developers who simply think it looks more natural and is easier to read.**

3.5.1.3 Direct initialization

When an initial value is provided inside parenthesis, this is called **direct initialization**.

Direct initialization was initially introduced to allow for more efficient initialization of complex objects (those with class types, which we'll cover in a future chapter). **Just like copy initialization, direct initialization had fallen out of favor in modern C++**, largely due to being superseded by list initialization. However, we now know that list initialization has a few quirks of its own, and so direct initialization is once again finding use in certain cases.

3.5.1.4 List initialization

The modern way to initialize objects in C++ is to use a form of initialization that makes use of curly braces. This is called **list initialization** (or **uniform initialization** or **brace initialization**). List initialization has an added benefit: “narrowing conversions” in list initialization are ill-formed. **This means that if you try to brace initialize a variable using a value that the variable cannot safely hold, the compiler is required to produce a diagnostic (usually an error).** When a variable is initialized using empty braces, value initialization takes place. **In most cases, value initialization will initialize the variable to zero (or empty, if that’s more appropriate for a given type).** In such cases where zeroing occurs, this is called **zero initialization**.

Essentially writing:

Int a {};	**is the same as writing**	**int a = 0;**

3.5.1.5 Best practice

Prefer direct list initialization (or value initialization) for initializing your variables.

- **Compiler errors** (a good way to identify if the type is compatible with the value you are trying to assign to it)
- **Zero initialization > Default initialization**

Prepend the **[[maybe_unused]]** attribute if you initialize a variable but **don’t want the compiler warning you that it’s not being used.**

3.6 Introduction to iostream

3.6.1 The input/output library

The input/output library (io library) is **part of the C++ standard library** that deals with basic input and output. We'll use the functionality in this library to get input from the keyboard and output data to the console. **The io part of iostream stands for input/output**.

To use the functionality defined within the iostream library, we need to include the iostream header at the top of any code file that uses the content defined in iostream.

```
#include <iostream>

// rest of code that uses iostream functionality here
```

3.6.2 *Cout: Character output*

The *iostream* library contains a few predefined variables for us to use. One of the most useful Is **std::cout**, which allows us to send data to the console to be printed as text. *cout* stands for "**character output**".

```
#include <iostream> // for std::cout

int main()

{

   std::cout << "Hello world!"; // print Hello world! to console

   return 0;

}
```

In this program, we have included *iostream* so that we have access to *std::cout*. Inside our *main* function, we use *std::cout*, along with the **insertion operator (<<)**, to send the text *Hello world!* to the console to be printed. To print more than one thing on the same line, the insertion operator (<<) can be used multiple times in a single statement to concatenate (link together) multiple pieces of output.

```
Int X {};

std::cout << "The variable named X is equal to: " << X;
```

3.6.2.1 Cout Buffer

Consider a rollercoaster ride at your favorite amusement park. Passengers show up (at some variable rate) and get in line. Periodically, a train arrives and boards passengers (up to the maximum capacity of the train). When the train is full, or when enough time has passed, the train departs with a batch of passengers, and the ride commences. Any passengers unable to board the current train wait for the next one.

This analogy is similar to how output sent to std::cout is typically processed in C++. Statements in our program request that output be sent to the console. However, that output is typically not sent to the console immediately. Instead, the requested output "gets in line", and is stored in a region of memory set aside to collect such requests (called a **buffer**). Periodically, the buffer is **flushed**, meaning all of the data collected in the buffer is transferred to its destination (in this case, the console).

3.6.3 Endl: End line

So, what happens when we write the following?

```
std::cout << "Hi!";

std::cout << "My name is Alex.";
```

Result: Hi!My name is Alex. ← Notice there is **no space between sentence 1 and 2**, there is **also no newline**. It all gets written on the same line.

If we want to print separate lines of output to the console, we need to tell the console to move the cursor to the next line. We can do that by outputting a newline. A **newline** is an **OS-specific** character or sequence of characters that moves the cursor to the start of the next line.

```
std::cout << "Hi!" << std::endl;  // std::endl will cause the cursor to move to the next line

std::cout << "My name is Alex." << std::endl;
```

Hi!

My name is Alex.

3.6.3.1 Endl vs. \n

Using **std::endl** is often inefficient, as it actually does **two jobs**: it outputs a **newline** (moving the cursor to the next line of the console), **and** it **flushes the buffer** (which is slow). If we output multiple lines of text ending with **std::endl**, we will get multiple flushes, which is slow and probably unnecessary.

When outputting text to the console, we typically don't need to explicitly flush the buffer ourselves. **C++'s output system is designed to self-flush periodically**, and it's both simpler and more efficient to let it flush itself.

To output a newline without flushing the output buffer, we use \n (inside either single or double quotes), which is a special symbol that the compiler interprets as a newline character. \n moves the cursor to the next line of the console without causing a flush, so it will typically perform better. \n is also more concise to type and can be embedded into existing double-quoted text.

3.6.3.2 Best practice

- Output a newline **whenever a line** of output **is complete**.
- Prefer **\n over std::endl**

3.6.4 Cin: Character input

std::cin is another predefined variable that is defined in the iostream library.
Whereas std::cout prints data to the console using the insertion operator (<<), std::cin (which stands for "character input") reads input from keyboard using the **extraction operator (>>)**. The input must be stored in a variable to be used.

```
int x{};          // define variable x to hold user input (and value-initialize it)

std::cin >> x;    // get number from keyboard and store it in variable x

std::cout << "You entered " << x << '\n';
```

3.6.4.1 Best practice

There’s some debate over whether it’s necessary to initialize a variable immediately before you give it a user provided value via another source (e.g. std::cin), since the user-provided value will just overwrite the initialization value. In line with our previous recommendation that variables should always be initialized, **best practice is to initialize the variable first.**

3.7 Uninitialized variables and undefined behavior

Unlike some programming languages, C/C++ does not automatically initialize most variables to a given value (such as zero). When a variable that is not initialized is given a memory address to use to store data, **the default value of that variable is whatever (garbage) value happens to already be in that memory address!** A variable that has not been given a known value (through initialization or assignment) is called an **uninitialized variable**.

3.7.1 Nomenclature

Many readers expect the terms “initialized” and “uninitialized” to be strict opposites, but they really aren’t! In common language, “initialized” means the object was provided with an initial value at the point of definition. “Uninitialized” means the object has not been given a known value yet (through any means, including assignment). Therefore, an object that is not initialized but is then assigned a value is no longer uninitialized (because it has been given a known value).

To recap:

- **Initialized = The object is given a known value at the point of definition.**
- **Assignment = The object is given a known value beyond the point of definition.**
- **Uninitialized = The object has not been given a known value yet.**

3.7.2 As an aside

This lack of initialization is a performance optimization inherited from C, back when computers were slow. Imagine a case where you were going to read in 100,000 values from a file. **In such case, you might create 100,000 variables, then fill them with data from the file.**

If C++ initialized all of those variables with default values upon creation, this would result in 100,000 initializations (which would be slow), and for little benefit (since you’re overwriting those values anyway). For now**, you should always initialize your variables because the cost of doing so is minuscule compared to the benefit**. Once you are more comfortable with the language, there may be certain cases where you omit the initialization for optimization purposes. But this should always be done selectively and intentionally.

3.7.3 *WARNING: Debug mode initializes with preset values*

Some compilers, such as Visual Studio, *will* initialize the contents of memory to some preset value when you're using a debug build configuration. This will not happen when using a release build configuration.

3.7.4 *Undefined behavior*

Using the value from an uninitialized variable is our first example of undefined behavior. **Undefined behavior** (often abbreviated **UB**) is the result of executing code whose behavior is not well-defined by the C++ language. In this case, the C++ language doesn't have any rules determining what happens if you use the value of a variable that has not been given a known value. Consequently, if you actually do this, undefined behavior will result.

3.7.5 *Implementation-defined behavior*

Implementation-defined behavior means the behavior of some syntax is **left up to the implementation (the compiler) to define**. Such behaviors must be consistent and documented, but different compilers may produce different results.
Example:

```
sizeof(int) // the number of bytes assigned to an integer type depends on the compiler
```

3.7.6 *Unspecified behavior*

This is almost identical to implementation-defined behavior. The only difference here is that the **implementation (compiler) doesn't have to document why it behaves a certain way.**

3.7.7 *Best practice*

Avoid implementation-defined and unspecified behavior whenever possible, as they may cause your program to malfunction on other implementations.

3.8 Keywords and naming identifiers

3.8.1 Keywords

A - C	D - P	R - Z
alignas (C++11)	decltype (C++11)	reflexpr (reflection TS)
alignof (C++11)	default (1)	register (2)
and	delete (1)	reinterpret_cast
and_eq	do	requires (C++20)
asm	double	return
atomic_cancel (TM TS)	dynamic_cast	short
atomic_commit (TM TS)	else	signed
atomic_noexcept (TM TS)	enum (1)	sizeof (1)
auto (1) (2) (3) (4)	explicit	static
bitand	export (1) (3)	static_assert (C++11)
bitor	extern (1)	static_cast
bool	false	struct (1)
break	float	switch
case	for (1)	synchronized (TM TS)
catch	friend	template
char	goto	this (4)
char8_t (C++20)	if (2) (4)	thread_local (C++11)
char16_t (C++11)	inline (1)	throw
char32_t (C++11)	int	true
class (1)	long	try
compl	mutable (1)	typedef
concept (C++20)	namespace	typeid
const	new	typename
consteval (C++20)	noexcept (C++11)	union
constexpr (C++11)	not	unsigned
constinit (C++20)	not_eq	using (1)
const_cast	nullptr (C++11)	virtual
continue	operator (4)	void
co_await (C++20)	or	volatile
co_return (C++20)	or_eq	wchar_t
co_yield (C++20)	private (3)	while
	protected	xor
	public	xor_eq

- (1) — meaning changed or new meaning added in C++11.
- (2) — meaning changed or new meaning added in C++17.
- (3) — meaning changed or new meaning added in C++20.
- (4) — new meaning added in C++23.

3.8.2 Identifiers

3.8.2.1 Naming rules

Now that you know how you can name a variable, let's talk about how you should name a variable (or function). First, it is a convention in C++ that **variable names should begin with a lowercase letter.** If the variable name is a **single word or acronym, the whole thing should be written in lowercase letters.**

- Names **must begin with a letter or an underscore**
- Names **cannot contain whitespaces or special characters** like !, #, %, etc.
- **Reserved words** (like C++ keywords, such as int) **cannot be used** as names
- Note: names are case-sensitive

3.8.2.2 Beste practice:

When working in an existing program, use the conventions of that program (even if they don't conform to modern best practices). Use modern best practices when you're writing new programs. In any case, **avoid abbreviations** (**unless** they are **common/unambiguous**). Although they reduce the time you need to write your code, they make your code harder to read.

3.9 Whitespace and basic formatting

Whitespace is a term that refers to characters that are used for formatting purposes. In C++, this refers primarily to **spaces, tabs, and newlines**.

Whitespace in C++ is generally **used for 3 things**:

- Separating certain language elements
- Inside text
- Formatting code

3.9.1.1 Whitespace rules

- **Separate language elements** such as keywords and identifiers
- **Comments** on a newline have to be re-assigned to be comments again: **//**
- **Preprocessor** using directives must be **on separate lines**
- Quoted text
  - **Spaces** in between tags **are taken literally** by the compiler
  - **Newlines** within text is only allowed in a certain format, just pressing enter in text such as a string is **not allowed**.

```
int x; // int and x must be whitespace separated

int

x; // this is also valid
```

The whitespace between the **keyword** int and the **identifier** x makes it so that the compiler doesn't see **intx**, it would see **intx** as an identifier. It doesn't matter how much whitespace there is between them as the compiler will strip this out

```cpp
int main()
{
    std::cout << "Hello
        World!\n";

    return 0;
}
```

← **Incorrect newline implementation**

Error List

Entire Solution | 13 Errors | 0 Warnings | 0

Code	Description
C2065	'n': undeclared identifier
C2065	'World': undeclared identifier
E0065	expected a ';'
C2017	illegal escape sequence
E0008	missing closing quote
E0008	missing closing quote
C2001	newline in constant
C2001	newline in constant
C2143	syntax error: missing ';' before '!'
C2143	syntax error: missing ';' before 'return'
C2143	syntax error: missing ';' before 'string'
C2146	syntax error: missing ';' before identifier 'World'
E0007	unrecognized token

← **Error output**

```cpp
int main()
{
    std::cout << "Hello"
        "World!\n";

    return 0;
}
```

← **Correct newline implementation**

3.9.1.2 Using whitespace to format code

Whitespace is otherwise generally ignored. This means we can use whitespace wherever we like to format our code in order to make it easier to read.
Examples: less readable → more readable

```cpp
#include <iostream>
int main(){std::cout<<"Hello world";return 0;}
```

```cpp
#include <iostream>
int main() {
std::cout << "Hello world";
return 0;
}
```

```cpp
#include <iostream>

int main()
{
    std::cout << "Hello world";

    return 0;
}
```

3.9.1.3 Basic formatting

Unlike some other languages, **C++ does not enforce any kind of formatting restrictions** on the programmer. For this reason, we say that **C++ is a whitespace-independent language**.

This is a mixed blessing. On one hand, it's nice to have the freedom to do whatever you like. On the other hand, many different methods of formatting C++ programs have been developed throughout the years, and you will find (sometimes significant and distracting) disagreement on which ones are best. **Our basic rule of thumb is that the best styles are the ones that produce the most readable code, and provide the most consistency.**

3.9.1.4 Recommendations

1. It's fine to use **either tabs or spaces** for indentation (most IDEs have a setting where you can convert a tab press into the appropriate number of spaces).

   Developers who prefer spaces tend to do so because it ensures that code is precisely aligned as intended regardless of which editor or settings are used.

   Proponents of using tabs wonder why you wouldn't use the character designed to do indentation for indentation, especially as you can set the width to whatever your personal preference is.

2. There are **two conventional styles** for function braces each with their own variations

   K & R or **C-style**, puts the opening bracket on the same line as the statement

   Reduces the amount of vertical whitespace (as you aren't devoting an entire line to an opening curly brace), so you can fit more code on a screen. This enhances code comprehension, as you don't need to scroll as much to understand what the code is doing.

```
int main(){
    std::cout << "Hello World!\n";

    return 0;
}
```

Allman, put the opening bracket on a separate line right under the statement

This **enhances readability**, and is **less error prone** since your brace pairs should always be indented at the same level. If you get a compiler error due to a brace mismatch, it's very easy to see where the issue came from.

```cpp
int main()
{
    std::cout << "Hello World!\n";

    return 0;
}
```

3. Each statement within curly braces should start one tab in from the opening brace of the function it belongs to

4. **Lines should not be too long. Typically, 80 characters** has been the de facto standard for the maximum length a line should be. If a line is going to be longer, it should be split (**at a reasonable spot**) into multiple lines.

5. If a long line is **split** with an operator (e.g. << or +), **the operator should be placed at the beginning of the next line**, not the end of the current line.

```cpp
int main()
{
    std::cout << "Hello"
              << "World!\n";

    return 0;
}
```

6. Use whitespace to make your code easier to read by aligning values or comments or adding spacing between blocks of code.

Harder to read:

```
cost = 57;
pricePerItem = 24;
value = 5;
numberOfItems = 17;
```

Easier to read:

```
cost          = 57;
pricePerItem  = 24;
value         = 5;
numberOfItems = 17;
```

7. Use the built-in automatic formatting feature for consistency, if available.

3.9.1.5 Style guides

A **style guide** is a concise, opinionated document containing (sometimes arbitrary) programming conventions, formatting guidelines, and best practices. The goal of a style guide is to ensure that all developers on a project are programming in a consistent manner.

- C++ Core Guidelines by Bjarne Stroustrup and Herb Sutter
- Google
- LLVM
- GCC / GNU

We generally **favor the C++ Core Guidelines**, as they are up to date and widely applicable.

3.10 Introduction to literals

Consider the following two statements:

```cpp
int main()
{
    std::cout << "Hello world!";
    int x{ 5 };

    return 0;
}
```

“”Hello world!”‘ and **‘5’** are **literal constants.** They are fixed values inserted directly into the source code. Literals and variables both have a value (and a type). Unlike a variable (whose value can be set and changed through initialization and assignment respectively), **the value of a literal is fixed (5 is always 5).** This is why literals are called constants.

3.10.1 Compiler-related

```cpp
3  int main()
4  {
5      std::cout << 5 << '\n'; // print the value of a literal
6
7      int x{ 5 };
8      std::cout << x << '\n'; // print the value of a variable
9      return 0;
10 }
```

On line 7, we’re creating a variable named x, and initializing it with value 5. **The compiler will generate code that copies the literal value 5 into whatever memory location is given to x.**

On line 8, **when we print x, the compiler will generate code that causes std::cout to print the value at the memory location of x** (which has value 5).

Thus, both output statements do the same thing (print the value 5). But **in the case of the literal, the value 5 can be printed directly**. In the case of the variable, the value 5 must be fetched from the memory the variable represents. This also explains why a literal is constant while a variable can be changed. A literal’s value is placed directly in the executable, and the executable itself can’t be changed after it is created. A variable’s value is placed in memory, and the value of memory can be changed while the executable is running.

3.11 Introduction to Operators

In mathematics, an **operation** is a process involving zero or more input values (called **operands**) that produces a new value (called an *output value*). The specific operation to be performed is denoted by a symbol called an **operator**.

You are likely already quite familiar with standard arithmetic operators from common usage in mathematics, including addition (**+**), subtraction (**-**), multiplication (*****), and division (**/**). In C++, assignment (**=**) is an operator as well, as are insertion (**<<**), extraction (**>>**), and equality (**==**). While most operators have symbols for names (e.g. +, or ==), there are **also a number of operators** that **are keywords** (e.g. **new, delete,** and **throw**).

The number of operands that an operator takes as input is called the operator's **arity**. Few people know what this word means, so don't drop it in a conversation and expect anybody to have any idea what you're talking about. **Operators in C++ come in four different arities:**

- **Unary**, acts on **one** operand
  An example of a unary operator is the - operator. For example, given -5, operator- takes literal operand 5 and flips its sign to produce new output value -5.

- **Binary**, acts on **two** operands (often named the left and right operand)
  An example of a binary operator is the + operator. For example, given 3 +
  4, operator+ takes the left operand 3 and the right operand 4 and applies mathematical addition to produce new output value 7. The insertion (<<) and extraction (>>) operators are binary operators, taking std::cout or std::cin on the left side, and the value to output or variable to input to on the right side.

- **Ternary**, acts on **three** operands
  There is only one of these in C++ (the conditional operator), which we'll cover later.

- **Nullary**, acts on **zero** operands
  There is also only one of these in C++ (the throw operator), which we'll also cover later.

Note that some operators have more than one meaning depending on how they are used. For example, operator- has two contexts. It can be used in unary form to invert a number's sign (e.g. to convert 5 to -5, or vice versa), or it can be used in binary form to do subtraction (e.g. 4 - 3).

3.11.1 Chaining operators

Operators can be **chained together such that the output of one operator can be used as the input for another operator**. For example, given the following: **2 * 3 + 4**, the multiplication operator goes first, and converts left operand 2 and right operand 3 into return value 6 (which becomes the left operand for the plus operator). Next, the plus operator executes, and converts left operand 6 and right operand 4 into new value 10.

We'll talk more about the order in which operators execute when we do a deep dive into the topic of operators. For now, it's enough to know that the arithmetic operators execute in the same order as they do in standard mathematics: **Parenthesis first, then Exponents, then Multiplication & Division, then Addition & Subtraction**. This ordering is sometimes abbreviated ***PEMDAS***, or expanded to the mnemonic "Please Excuse My Dear Aunt Sally".

3.11.2 Return values and side effects

Most operators in C++ just use their operands to calculate a return value. There are a few operators that do not produce return values (such as delete and throw). We'll cover what these do later. Some operators have additional behaviors. An operator (or function) that has some observable effect beyond producing a return value is said to have a **side effect**.

For example, when x = 5 is evaluated, **the assignment operator has the side effect of assigning the value 5 to variable x.** The changed value of x is observable (e.g. by printing the value of x) even after the operator has finished executing. **std::cout << 5 has the side effect of printing 5 to the console.** We can observe the fact that 5 has been printed to the console even after std::cout << 5 has finished executing.

Operators with side effects are usually **called for** the behavior of **the side effect rather than for the return value** (if any) those operators produce.

3.11.3 Nomenclature

In common language, the term “side effect” is typically used to mean a secondary (often negative or unexpected) result of some other thing happening (such as taking medicine). For example, a common side effect of taking oral antibiotics is diarrhea. As such, we often think of side effects as things we want to avoid, or things that are incidental to the primary goal.

In C++, **the term “side effect” has a different meaning: it is an observable effect of an operator or function beyond producing a return value.**

Since assignment has the observable effect of changing the value of an object, this is considered a side effect. We use certain operators (e.g. the assignment operator) primarily for their side effects. In such cases, the side effect is both beneficial and predictable (and it is the return value that is often incidental).

3.12 Introduction to expressions

An **expression** is a non-empty **sequence of literals, variables, operators, and function calls** that calculates a single value. The process of executing an expression is called **evaluation**, and the single value produced is called the **result** of the expression. When an expression is evaluated, **each of the terms inside the expression are evaluated**, until a single value remains.

While most expressions are used to calculate a value, **expressions can also identify an object** (which can be evaluated to get the value held by the object) or a function.

Example:

```
2               // 2 is a literal that evaluates to value 2
"Hello world!"  // "Hello world!" is a literal that evaluates to text "Hello world!"
x               // x is a variable that evaluates to the value of x
2 + 3           // operator+ uses operands 2 and 3 to evaluate to value 5
five()          // evaluates to the return value of function five()
```

As you can see, literals evaluate to their own values. Variables evaluate to the value of the variable. Operators (such as **operator+**) use their operands to evaluate to some other value. We haven't covered function calls yet, but in the context of an expression, function calls evaluate to whatever value the function returns. **Expressions involving operators with side effects are a little trickier:**

```
x = 5           // x = 5 has side effect of assigning 5 to x, evaluates to x
x = 2 + 3       // has side effect of assigning 5 to x, evaluates to x
std::cout << x  // has side effect of printing value of x to console, evaluates to std::cout
```

Note that **expressions do not end in a semicolon**, and **cannot be compiled by themselves**. For example, if you were to try compiling the expression x = 5, your compiler would complain (probably about a missing semicolon). Rather, expressions are always evaluated as part of statements.

If you were to break **int x {2+3};** down into syntax, it would look like this:

```
type identifier {expression};
```

Type could be any valid type (we chose **int**). **identifier** could be any valid name (we chose **x**). And **expression** could be any valid expression (we chose **2 + 3**, which uses two literals and an operator).

Key insight: Wherever you can use a single value in C++, you can use a value-producing expression instead, and the expression will be evaluated to produce a single value.

3.12.1 *Useless expression statements*

We can also make expression statements that compile but have no effect. For example, the expression statement (**2 * 3**;) is an expression statement whose **expression evaluates to the result value of 6, which is then discarded**. While **syntactically valid**, such expression statements are useless. **Some compilers (such as gcc and Clang) will produce warnings** if they can detect that an expression statement is useless.

3.12.2 *Subexpressions, full expressions and compound expressions*

Simplifying a bit, a **subexpression** is an expression used as an operand. For example, the **subexpressions of x = 4 + 5** are **x** and **4 + 5.** The **subexpressions of 4 + 5** are **4** and **5**.

A **full expression** is an expression that is not a subexpression. **x = 4 + 5** Is the full expression.

In casual language, a **compound expression** is an expression that contains two or more uses of operators. **x = 4 + 5** is a **compound expression because it contains two uses of operators** (**operator=** and **operator+**)

3.12.3 *Recap*

What is the difference between a statement and an expression?

Statements are used when we want the program to **perform an action**.

Expressions are used when we want the program to **calculate a value**.

3.13 Chapter summary

A **statement** is a type of instruction that causes the program to perform some action. Statements are often terminated by a semicolon.

A **function** is a collection of statements that execute sequentially. Every C++ program must include a special function named main. When you run your program, execution starts at the top of the main function.

In programming, the name of a function (or object, type, template, etc.) is called its **identifier**.

An **object** is a **region of storage** (usually memory) that can store a value, and has other associated properties. In C++, **direct memory access is discouraged**. Instead, **we access memory indirectly through an object**.

A **variable is an object** that has been named (identifier). Naming our objects let us refer to them again later in the program.

To create a variable, we use a **definition statement**. Later we can **assign** it a value. When the program is run, each defined variable is **instantiated**, which means it is assigned a memory address. The process of **specifying an initial value** for an object is called **initialization**, and the syntax used to initialize an object is called an **initializer**.

The rules that govern how elements of the C++ language are constructed is called **syntax**. A **syntax error** occurs when you violate the grammatical rules of the language.

Every C++ program must have a special function named **main**(all lower - case letters) which is of the int type. (because the number being returned is the exit status code of main)

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

Comments allow the programmer to leave notes in the code. C++ supports two types of comments. Line comments start with a **//** and run to the end of the line. Block comments start with a **/*** and go to the paired ***/** symbol. Don't nest block comments.

Data is any information that can be moved, processed, or stored by a computer. A single piece of data is called a **value**.

A **data type** tells the compiler how to interpret a piece of data into a meaningful value. An **integer** is a number that can be written without a fractional component.

Initialization Type	Example	Note
Default initialization	int x;	In most cases, leaves variable with indeterminate value
Copy initialization	int x = 5;	
Direct initialization	int x (5);	
Direct list initialization	int x { 5 };	Narrowing conversions disallowed
Copy list initialization	int x = { 5 };	Narrowing conversions disallowed
Value initialization	int x {};	Usually performs zero initialization

Direct initialization is sometimes called **parenthesis initialization**.

List initialization (**including value initialization**) **is** sometimes called **uniform initialization or brace initialization**. You should prefer brace initialization over the other initialization forms, and prefer initialization over assignment.

A **literal constant** is a fixed value inserted directly into the source code. Examples are 5 and "Hello world!".

An **operation** is a process involving zero or more input values, called **operands**. The specific operation to be performed is denoted by the provided **operator**. The result of an operation produces an output value.

Unary operators take one operand. **Binary** operators take two operands, often called left and right. **Ternary** operators take three operands. **Nullary** operators take zero operands.

An **expression** is a sequence of literals, variables, operators, and function calls that are evaluated to produce a single output value. The calculation of this output value is called **evaluation**. The value produced is the **result** of the expression.

An **expression statement** is an expression that has been turned into a statement by placing a semicolon at the end of the expression.

When writing programs, add a few lines or a function, compile, resolve any errors, and make sure it works. Don't wait until you've written an entire program before compiling it for the first time!

First-draft programs are often messy and imperfect. Most code requires cleanup and refinement to get great!

4 Functions and files

4.1 Introduction to functions

In the last chapter, we defined a function as a **collection of statements** that execute sequentially. While that is certainly true, that definition doesn't provide much insight into why functions are useful. Let's update our definition: A function is a **reusable sequence of statements** designed to do a particular job.

You already know that every executable program must have a function named main (which is where the program starts execution when it is run). However, **as programs start to get longer and longer, putting all the code inside the main function becomes increasingly hard to manage**. Functions provide a way for us to **split our programs into small, modular chunks that are easier to organize, test, and use**. Most programs use many functions. The C++ standard library comes with plenty of already-written functions for you to use -- however, it's just as common to write your own. Functions that you write yourself are called **user-defined functions**.

A program will be executing statements sequentially inside one function when it encounters a **function call**. A function call is an expression that tells the CPU to **interrupt the current function and execute the called function**. The CPU "**puts a bookmark**" at the current point of execution, and then **calls** (executes) the function named in the function call. When the called function ends, **the CPU returns back to the point it bookmarked**, and resumes execution.

The function initiating the function call is the **caller**, and the function being called is the **callee** or **called** function.

4.1.1 User-defined functions

Functions that you write yourself are called **user-defined functions**.

The start of a user-defined function is informally called the **function header**, and it tells the compiler about the existence of a function, the function's name (**identifier**), and some other information that we'll cover in future lessons (like the return type and parameter types).

The **parentheses** after the identifier tell the compiler that we're **defining a function**.

The curly braces and statements in-between are called the **function body**. This is where the statements that determine what your function does will go.

```cpp
void PrintTheSumOf(int a, int b)
{
    //  Great, we just landed here from main()
    //  Now let's execute this sequentially

    std::cout << "Inside of PrintTheSumOf()" << "\n";
    //  Ok here we print some text to show we are inside of this function


    int sum{ a + b };
    //  Here we initialize a variable (named object) with the integer type
    //  It's a good thing that we assign it a value as to avoid undefined behaviour
    //  In this case the name is sum and it holds the expression a operator+ b (our initializer)
    //  Now or compiler will instantiate it!

    std::cout << sum << "\n";
    //  This statement is little more complicated
    //  We use cout and operator<< to display the sum and then add a new line

    std::cout << "Ending of PrintTheSumOf()" << std::endl;
}


int main()
{
    // Because this is main, this is the actual start of the program

    PrintTheSumOf(3 ,7);
    //  We encounter a fuction, we know this because of the parenthesis
    //  It seems to be doing something with two literal numbers
    //  Good thing it has a name (identifier), let's jump there
    //  But first we take note of this location so it's easy to jump back when we're done
    //  READ PrintTheSumOf()

    std::cout << "back inside of main()" << std::endl;

    return 0;
    //  This is the absolute end of our program
    //  Because main is a special function there is a lot going on
    //  The literal 0 here mean the program can exit with succes
    //  The literal 1 would mean the program exits with failure
}
```

4.1.1.1 Functions can call functions that call other functions

You've already seen that function **main can call another function**. **Any function can call any other function.** In the following program, function main calls function doA, which calls function doB:

```
#include <iostream> // for std::cout

void doB()
{
    std::cout << "In doB()\n";
}


void doA()
{
    std::cout << "Starting doA()\n";

    doB();

    std::cout << "Ending doA()\n";
}

// Definition of function main()
int main()
{
    std::cout << "Starting main()\n";

    doA();

    std::cout << "Ending main()\n";

    return 0;
}
```

4.1.1.2 Nested functions are not supported

Unlike some other programming languages, in C++, functions cannot be defined inside other functions. The following program is not legal:

```
#include <iostream>

int main()
{
    void foo() // Illegal: this function is nested inside function main()
    {
        std::cout << "foo!\n";
    }

    foo(); // function call to foo()
    return 0;
}
```

The proper way to write the above program is:

```
#include <iostream>

void foo() // no longer inside of main()
{
    std::cout << "foo!\n";
}

int main()
{
    foo();
    return 0;
}
```

4.1.1.3 As an aside…

"**foo**" is a meaningless word that is often used as a **placeholder name for a function or variable** when the name is unimportant to the **demonstration of some concept**. Such words are called **metasyntactic variables** (though in common language they're often called "**placeholder names**" since nobody can remember the term "metasyntactic variable"). Others include: bar, baz and 3-letter words that end in "oo", such as goo, moo and boo.

For those interested in etymology (how words evolve), RFC 3092 is an interesting read.

4.2 Function return values (value-returning functions)

When you write a user-defined function, you get to determine whether your function will return a value back to the caller or not. To return a value back to the caller, two things are needed.

First, your function has to indicate **what type of value will be returned**. This is done by **setting the** function's return **type**, which is the type that is defined before the function's name. Note that this doesn't determine what specific value is returned -- it only determines what type of value will be returned. Void is a special case that doesn't have to return anything. We explore functions that return void further in the next lesson.

Second, inside the function that will return a value, we use a **return statement** to indicate the specific value being returned to the caller. The specific value returned from a function is called the **return value**. When the return statement is executed, the function exits immediately, and the return value is **copied** from the function back to the caller. **This process is called return by value.**

When a called function returns a value, **the caller may decide to use that value in an expression or statement** (e.g. by using it to initialize a variable, or sending it to std::cout) or ignore it (by doing nothing else). If the caller ignores the return value, it is discarded (nothing is done with it).

```
#include <iostream>

int getValueFromUser() // this function now returns an integer value
{
    std::cout << "Enter an integer: ";
    int input{};
    std::cin >> input;

    return input; // return the value the user entered back to the caller
}

int main()
{
    int num { getValueFromUser() }; // initialize num with the return value of getValueFromUser()

    std::cout << num << " doubled is: " << num * 2 << '\n';

    return 0;
}
```

When this program executes, the first statement in main will create an int variable named num. When the program goes to initialize num, it will see that there is a function call to getValueFromUser(), so it will go execute that function. Function getValueFromUser, asks the user to enter a value, and then it returns that value back to the caller (main). This return value is used as the initialization value for variable num.

4.2.1 Revisiting main()

You now have the conceptual tools to understand how the main() function actually works. When the program is executed, the operating system makes a function call to main(). Execution then jumps to the top of main(). The statements in main() are executed sequentially. **Finally, main() returns an integer value (usually 0), and your program terminates.**

C++ disallows calling the main() function explicitly. **C** does allow main() to be called explicitly, so some C++ compilers will allow this for compatibility reasons. For now, you should also **define your main() function at the bottom of your code file**, below other functions, and avoid calling it explicitly.

4.2.1.1 Status codes

The **return value** from main() is sometimes called a **status code** (also sometimes called an **exit code**, or rarely a return code). Just like the return value of a function is passed back to the caller of the function, the status code is passed back to the caller of the program. The caller of the program can then use this status code to determine whether your program ran successfully or not.

0: Indicates that the program ran successfully without any errors. This is the standard value for a successful program termination. Alternatively, we can write **EXIT_SUCCESS** (defined in the standard library).

1: Indicate that the program encountered some form of error or abnormal termination. Alternatively, we can write **EXIT_FAILURE** (defined in the standard library).

```
#include <stdlib.h>


int main()
{
    return EXIT_FAILURE;
}
```

4.2.2 A value-returning function that does not return a value will produce undefined behavior

A function that returns a value is called a **value-returning function**. A function is value-returning if the return type is anything other than void. **A value-returning function must return a value** of that type (**using a return statement**), otherwise undefined behavior will result.

In most cases, compilers will detect if you've forgotten to return a value. However, in some complicated cases, the compiler may not be able to properly determine whether your function returns a value or not in all cases, so you should not rely on this.

The only exception to the rule that a value-returning function must return a value via a return statement is for function **main()**. The function **main()** will **implicitly return the value 0 if no return statement is provided**. That said, it is best practice to explicitly return a value from **main**, both to show your intent, and for consistency with other functions (which will exhibit undefined behavior if a return value is not specified).

4.2.3 Functions can only return a single value

A value-returning function can only return a single value back to the caller each time it is called. Note that the value provided in a return statement doesn't need to be literal -- it can be the result of any valid expression, including a variable or even a call to another function that returns a value. There are various ways to work around the limitation of functions only being able to return a single value, which we'll cover in future lessons.

4.2.4 The function author can decide what the return value means

The meaning of the value returned by a function is determined by the function's author. Some functions use return values as status codes, to indicate whether they succeeded or failed. Other functions return a calculated or selected value. Other functions return nothing.

Because of the wide variety of possibilities here, it's a good idea to document your function with a comment indicating what the return values mean.

4.2.5 *Reusing functions*

While this program works, it's a little redundant. In fact, this program violates one of the central tenets of good programming: **Don't Repeat Yourself** (often abbreviated **DRY**).

Why is repeated code bad? If we wanted to change the text "Enter an integer:" to something else, we'd have to update it in two locations. And what if we wanted to initialize 10 variables instead of 2? That would be a lot of **redundant code** (making our programs longer and harder to understand), and a lot of **room for typos to creep in**.

```cpp
#include <iostream>

int getValueFromUser()
{
    std::cout << "Enter an integer: ";
    int input{};
    std::cin >> input;

    return input;
}

int main()
{
    int x{ getValueFromUser() }; // first call to getValueFromUser
    int y{ getValueFromUser() }; // second call to getValueFromUser

    std::cout << x << " + " << y << " = " << x + y << '\n';

    return 0;
}
```

In this program, we call **getValueFromUser** twice, once to initialize variable **x**, and once to initialize variable **y**. That saves us from duplicating the code to get user input, and reduces the odds of making a mistake. Once we know **getValueFromUser** works, we can call it as many times as we desire.

This is the **essence of modular programming**: the ability to write a function, test it, ensure that it works, and then know that we can reuse it as many times as we want and it will continue to work (so long as we don't modify the function -- at which point we'll have to retest it).

4.2.6 Best practice

Follow **DRY**: "**don't repeat yourself**". If you need to do something more than once, consider how to modify your code to **remove as much redundancy as possible**. Variables can be used to store the results of calculations that need to be used more than once (so we don't have to repeat the calculation). Functions can be used to define a sequence of statements we want to execute more than once. And loops (which we'll cover in a later chapter) can be used to execute a statement more than once.

Like all best practices, **DRY is meant to be a guideline, not an absolute**. Reader Yariv has noted that DRY can harm overall comprehension when code is broken into pieces that are too small.

The opposite of DRY is WET ("Write everything twice").

4.3 Void functions (non-value returning functions)

Functions are **not required to return a value** back to the caller. To tell the compiler that a function does not return a value, a return type of void is used. A function that does not return a value is called a **non-value returning function** (or a **void function**). Trying to return a value from a non-value returning function will result in a **compilation error**.

```
void printHi()
{
    std::cout << "Hi" << '\n';

    // This function does not return a value so no return statement is needed
}

int main()
{
    printHi(); // okay: function printHi() is called, no value is returned

    return 0;
}
```

4.3.1 Void return statement

A void function will automatically return to the caller at the end of the function. No return statement is required.

A return statement (with no return value) **can be used** in a void function -- such a statement will cause the function to return to the caller at the point where the return statement is executed. This is the same thing that happens at the end of the function anyway. Consequently, putting an empty return statement at the end of a void function is **redundant**.

Best practice:

Do **not** put a return statement at the end of a non-value returning function.

4.4 Introduction to function parameters and arguments

In the previous lesson, we learned that we could have a function return a value back to the function's caller. Now we need a way to **pass values of objects in order to manipulate them in our functions**, this is where parameters and arguments come in.

In many cases, it is useful to be able to pass information to a function being called, so that the function has data to work with. For example, if we wanted to write a function to add two numbers, we need some way to tell the function which two numbers to add when we call it. Otherwise, how would the function know what to add? We do that via function **parameters and arguments**.

A function **parameter** is a variable **used in the header** of a function. Function parameters work almost identically to variables defined inside the function, but with **one difference: they are initialized** with a **value** provided **by the caller of the function**.

Function parameters are defined in the function header by placing them in between the parenthesis after the function name, with multiple parameters being separated by commas.

An **argument** is a value that is passed from the caller to the function when a function call is made.

```
#include <iostream>
#include <string>

void foo(std::string sentence)
{
    std::cout << sentence << '\n';
}

int main()
{
    foo("Hello World!");

    return 0;
}
```

In the example above we ask for a sentence to be passed of the type std::string, the variable **sentence is the parameter**. The **literal "Hello World!" is the argument** we pass.

4.4.1 *How parameters and arguments work together*

When a function is called, all of the **parameters of the function are created as variables**, and the **value of each of the arguments is copied into the matching parameter** (using **copy initialization**).

This process is called **pass by value**. Function parameters that utilize pass by value are called **value parameters**.

Note that the **number of arguments must generally match the number of function parameters**, or the compiler will throw an error. The argument passed to a function can be any valid expression (as the argument is essentially just an initializer for the parameter, and initializers can be any valid expression).

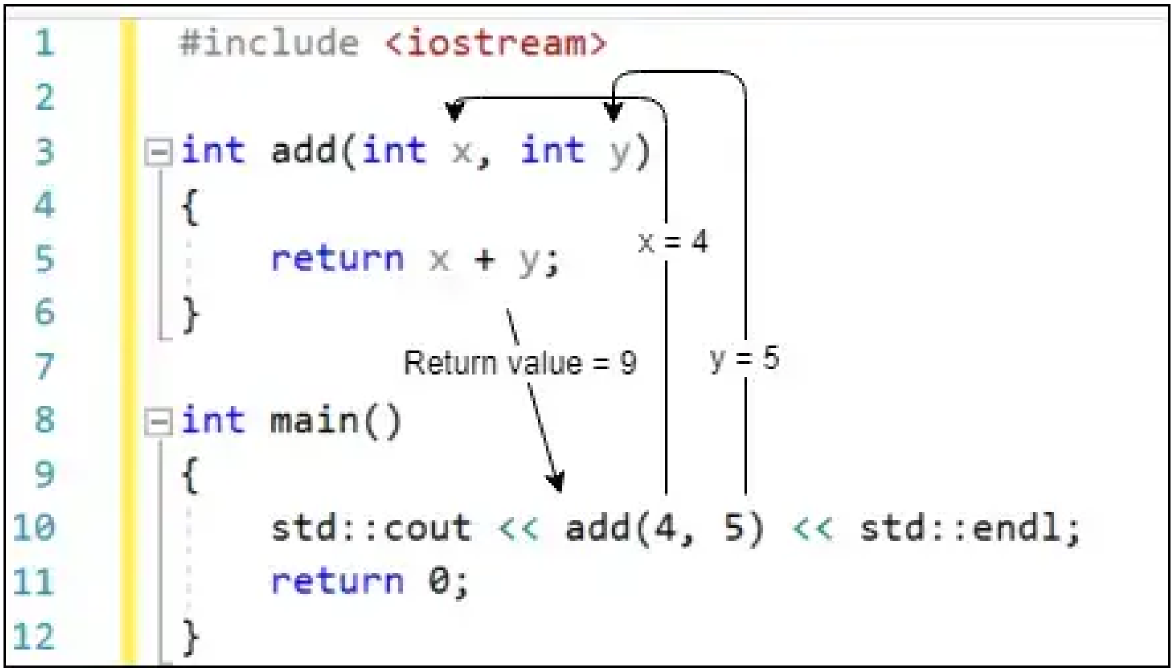
4.4.2 *Using return values as arguments*

Now we step it up a bit, in previous lesson we discussed return values. We could also use these by passing them to another function.

```cpp
#include <iostream>

int getValueFromUser()
{
    std::cout << "Enter an integer: ";
    int input{};
    std::cin >> input;

    return input;
}

void printDouble(int value)
{
    std::cout << value << " doubled is: " << value * 2 << '\n';
}

int main()
{
    printDouble(getValueFromUser());

    return 0;
}
```

4.4.3 How parameters and return values work together

By using both parameters and a return value, we can create functions that take data as input, do some calculation with it, and return the value to the caller.



4.4.4 *Unreferenced parameters*

In certain cases, you will encounter functions that have parameters that are not used in the body of the function. These are called unreferenced parameters.

This can happen when a function parameter was once used, but is not used any longer. Just like with unused local variables, your compiler will probably warn you.

If the unused function parameter were simply removed, then any existing call to the function would break (because the function call would be supplying more arguments than the function could accept).

```
void doSomething(int count) // warning: unreferenced parameter count
{
    // This function used to do something with count but it is not used any longer
}

int main()
{
    doSomething(4);

    return 0;
}
```

In a function definition, the **name of a function parameter is optional**. Therefore, in cases where a function parameter needs to exist but is not used in the body of the function, you can simply omit the name. A parameter without a name is called an **unnamed parameter**.

```
void doSomething(int) // ok: unnamed parameter will not generate warning
{
}
```

Best practice:

When a function parameter **exists but is not used in the body of the function, do not give it a name**. You can optionally put a name inside a comment.

4.5 Introduction to local scope

Variables defined inside the body of a function are called **local variables** (as opposed to global variables, which we'll discuss in the future).

4.5.1 Lifetime

In Introduction to objects and variables, we discussed how a variable definition such as int x; causes the variable to be instantiated (created) when this statement is executed. **Function parameters are created and initialized when the function is entered, and variables within the function body are created and initialized at the point of definition.**

```
int add(int x, int y) // x and y created and initialized here
{
    int z{ x + y };   // z created and initialized here

    return z;
}  // z, y, and x destroyed here
```

The natural follow-up question is, "**so when is an instantiated variable destroyed?**". **Local** variables are destroyed in the **opposite order of creation at the end of the set of curly braces** in which it is defined (or for a function parameter, at the end of the function).

Much like a person's lifetime is defined to be the time between their birth and death, an object's **lifetime** is defined to be the time between its creation and destruction. Note that **variable creation and destruction happen when the program is running** (called **runtime**), not at compile time. Therefore, **lifetime is a runtime property**.

4.5.1.1 What happens when an object is destroyed?

In most cases, **nothing**. The **destroyed object becomes invalid**, and any **further use of the object will result in undefined behavior**. At some point after destruction, the memory used by the object will be freed up for reuse.

Advanced:

If the object is a **class type object**, prior to destruction, a special function called a **destructor** is **invoked**. In many cases, the destructor does nothing, in which case no cost is incurred.

4.5.2 Local scope

An identifier's **scope** determines where the identifier can be seen and used within the source code. When an identifier **can be seen and used**, we say **it is in scope**. When an identifier **cannot be seen**, we cannot use it, and we say **it is out of scope**.

Scope is a compile-time property, and trying to use an identifier when it is not in scope will result in a compile error.

A local variable's scope begins at the point of variable definition, and stops at the end of the set of curly braces in which it is defined (or for function parameters, at the end of the function). **This ensures variables cannot be used before the point of definition** (even if the compiler opts to create them before then). Local variables defined in one function are also not in scope in other functions that are called.

4.5.2.1 "Out of scope" vs "going out of scope"

The terms "out of scope" and "going out of scope" can be confusing to new programmers.

An identifier is **out of scope anywhere it cannot be accessed** within the code.

The term "going out of scope" is **typically applied to objects** rather than identifiers. We say an object **goes out of scope at the end of the scope** (the end curly brace) in which the object was instantiated. A local variable's **lifetime ends at the point where it goes out of scope**, so local variables are destroyed at this point. Note that **not all types of variables are destroyed** when they go out of scope.

```cpp
#include <iostream>

int add(int x, int y) // x and y are created and enter scope here
{
    // x and y are usable only within add()
    return x + y;
} // y and x go out of scope and are destroyed here

int main()
{
    int a{ 5 }; // a is created, initialized, and enters scope here
    int b{ 6 }; // b is created, initialized, and enters scope here

    // a and b are usable only within main()

    std::cout << add(a, b) << '\n'; // calls add(5, 6), where x=5 and y=6

    return 0;
} // b and a go out of scope and are destroyed here
```

4.5.2.2 Functional separation

Names used for function parameters or variables declared in a function body are only visible within the function that declares them. This means **local variables within a function can be named without regard for the names of variables in other functions**. This helps keep functions independent.

We could have variable x in function add() and variable x in main() and they wouldn't interfere because of functional separation.

4.5.2.3 Where to define local variables

In modern C++, the best practice is that local variables inside the function body should be defined as close to their first use as reasonable.

4.5.2.4 As an aside

Due to the limitations of older, more primitive compilers, the C language used to require all local variables be defined at the top of the function. The equivalent C++ program using that style would look like this:

```
#include <iostream>

int main()
{
    int x{}, y{}, sum{}; // how are these used?

    std::cout << "Enter an integer: ";
    std::cin >> x;

    std::cout << "Enter another integer: ";
    std::cin >> y;

    sum = x + y;
    std::cout << "The sum is: " << sum << '\n';

    return 0;
}
```

This style is suboptimal for several reasons:

- The intended use of these variables isn't apparent at the point of definition. You have to scan through the entire function to determine where and how each variable is used.

- The intended initialization value may not be available at the top of the function (e.g. we can't initialize sum to its intended value because we don't know the value of x and y yet).

- There may be many lines between a variable's initializer and its first use. If we don't remember what value it was initialized with, we will have to scroll back to the top of the function, which is distracting.

This restriction was lifted in the C99 language standard.

4.5.3 Introduction to temporary objects

A **temporary object** (also sometimes called an **anonymous object**) is an unnamed object that is created by the compiler to store a value temporarily.

Temporary objects have no scope at all (this makes sense, since scope is a property of an identifier, and temporary objects have no identifier).

Temporary objects are **destroyed at the end of the full expression** in which they are created. In the case where a temporary object is used to initialize a variable, the **initialization happens before the destruction of the temporary**.

Example:

The **caller** receives a **copy of the value** so that it has a value it can use even after input is destroyed.

But where is the value that is copied back to the caller stored? We haven't defined any variables in main(). The answer is that the **return value is stored in a temporary object**. This temporary object is then passed to the next function that needs it.

4.6 Why functions are useful, and how to use them effectively

This chapter I'm not going into detail as it's been hinted at before why functions are useful. However here is a quick summary:

- Organization
- Reusability
- Testing
- Extensibility
- Abstraction

New programmers often combine calculating a value and printing the calculated value into a single function. However, **this violates the "one task" rule of thumb for functions**

A function that calculates a value should return the value to the caller and let the caller decide what to do with the calculated value (such as call another function to print the value).

Some others might name this as **separation of concerns**.

4.7 Forward declarations and definitions

Take a look at this seemingly innocent sample program:

```
1  #include <iostream>
2
3  int main()
4  {
5      std::cout << "The sum of 3 and 4 is: " << add(3, 4) << '\n';
6      return 0;
7  }
8
9  int add(int x, int y)
10 {
11     return x + y;
12 }
```

Output: add.cpp(5) : error C3861: 'add': identifier not found

The reason this program doesn't compile is because the **compiler compiles** the contents of code files **sequentially**. This mean **top to bottom**.

When the compiler reaches the function call to add on line 5 of main, it doesn't know what add is, because we haven't defined add until line 9! That produces the error, identifier not found.

This is somewhat misleading, given that add wasn't ever defined in the first place. Despite this, it's useful to generally note that it is fairly common for a single error to produce many redundant or related errors or warnings. It can sometimes be hard to tell whether any error or warning beyond the first is a consequence of the first issue, or whether it is an independent issue that needs to be resolved separately.

Best practice: When addressing compilation errors or warnings in your programs, **resolve the first issue** listed and then compile again.

To fix this problem, we need to address the fact that the compiler doesn't know what add is. **There are two common ways to address the issue**.

- Reorder the function definitions
- **Use a forward declaration**

We might not always have the option available to reorder in a sequential manner.

4.7.1 *Forward declaration*

A **forward declaration** allows us to tell the compiler about the existence of an identifier before actually defining the identifier.

In the case of functions, this allows us to tell the compiler about the existence of a function before we define the function's body. This way, when the compiler encounters a call to the function, it'll understand that we're making a function call, and can check to ensure we're calling the function correctly, even if it doesn't yet know how or where the function is defined.

To write a forward declaration for a function, we use a **function declaration statement** (also called a **function prototype**). The function declaration consists of the **function's return type, name, and parameter types, terminated with a semicolon**. The names of the parameters can be optionally included. The function body is not included in the declaration.

```
#include <iostream>

int add(int x, int y); // forward declaration of add() (using a function declaration)

int main()
{
    std::cout << "The sum of 3 and 4 is: " << add(3, 4) << '\n'; // this works because we forward declared add() above
    return 0;
}

int add(int x, int y) // even though the body of add() isn't defined until here
{
    return x + y;
}
```

It is worth noting that function declarations **do not need to specify the names of the parameters** (as they are not considered to be part of the function declaration).

Beste practice: Keep the parameter names in your function declarations.

4.7.2 Why forward declarations?

You may be wondering why we would use a forward declaration if we could just reorder the functions to make our programs work.

Most often, forward declarations are used to tell the compiler about the existence of some **function** that has been **defined in a different code file**. Reordering isn't possible in this scenario because the caller and the callee are in completely different files!

Forward declarations can also be used to define our functions in an **order-agnostic manner**. This allows us to define functions in whatever order **maximizes organization** (e.g. by clustering related functions together) or reader understanding.

Less often, there are times when we have **two functions that call each other**. Reordering isn't possible in this case either, as there is no way to reorder the functions such that each is before the other. Forward declarations give us a way to resolve such circular dependencies.

4.7.3 Forgetting the function body

New programmers often wonder **what happens if they forward declare a function but do not define it**.

The answer is: it **depends**. If a forward declaration is made, but the **function is never called, the program will compile and run fine**. However, if a forward declaration is made and **the function is called**, but the program never defines the function, the **program will compile okay**, but the **linker will complain that it can't resolve the function call**.

4.7.4 *Identifier declaration*

Forward declarations are most often used with functions. However**, forward declarations can also be used with other identifiers** in C++, **such as variables and types**. Variables and types have a different syntax for forward declaration, so we'll cover these in future lessons.

4.7.5 *Declarations vs. definitions*

In C++, you'll frequently hear the words "**declaration**" and "**definition**" used, and often interchangeably. What do they mean? You now have enough fundamental knowledge to understand the difference between the two.

A **declaration** tells the compiler about the existence of an identifier and its associated type information.

A **definition** is a declaration that actually implements (for functions and types) or instantiates (for variables) the identifier.

In C++, **all definitions are declarations**. Conversely, **not all declarations are definitions**. Declarations that aren't definitions are called **pure declarations**. Types of pure declarations include forward declarations for function, variables, and types.

Term	Technical Meaning	Examples

Declaration	Tells compiler about an identifier and its associated type information.	void foo(); // function forward declaration (no body)
		void goo() {}; // function definition (has body)
		int x; // variable definition

Definition	Implements a function or instantiates a variable. Definitions are also declarations.	void foo() { } // function definition (has body) int x; // variable definition
Pure declaration	A declaration that isn't a definition.	void foo(); // function forward declaration (no body)
Initialization	Provides an initial value for a defined object.	int x { 2 }; // 2 is the initializer

4.7.6 The one definition rule (ODR)

The one definition rule (or **ODR** for short) is a well-known rule in C++. The ODR has three parts:

- Within a **file**, each function, variable, type, or template **in a given scope** can only have **one definition**. Definitions occurring in different scopes (e.g. local variables defined inside different functions, or functions defined inside different namespaces) do not violate this rule.

- Within a **program**, each function or variable in a given scope can only have one definition. This rule exists because programs can have more than one file (we'll cover this in the next lesson). **Functions and variables not visible to the linker are excluded from this rule** (discussed further in lesson: Internal linkage).

- **Types, templates, inline functions, and inline variables are allowed to have duplicate definitions** in different files, so long as each definition is identical. We haven't covered what most of these things are yet, so don't worry about this for now -- we'll bring it back up when it's relevant.

```
int add(int x, int y)
{
     return x + y;
}

int add(int x, int y) // violation of ODR, we've already defined function add(int, int)
{
     return x + y;
}

int main()
{
    int x{};
    int x{ 5 }; // violation of ODR, we've already defined x
}
```

4.8 Programs with multiple code files

As programs get larger, it is common to split them into multiple files for organizational or reusability purposes. One advantage of working with an IDE is that they make working with multiple files much easier. You already know how to create and compile single-file projects. Adding new files to existing projects is very easy.

Let's say we **define** the function **add(int x, int y)** in a **separate file** named **add.cpp**. For context we'll use this in the **main function inside of our main.cpp file**.

Your compiler **may compile either** add.cpp or main.cpp **first**. Either way, main.cpp will **fail to compile**. The reason is **it doesn't know what identifier add is**.

Remember, the compiler **compiles each file individually**. It does not know about the contents of other code files, or remember anything it has seen from previously compiled code files. So even though the compiler may have seen the definition of function add previously (if it compiled add.cpp first), **it doesn't remember**.

This **limited visibility and short memory is intentional**, for a few reasons:

- It allows the source files of a project to be **compiled in any order**.
- When we change a source file, **only that source file needs to be recompiled**.
- It **reduces** the **possibility of naming conflicts** between identifiers in different files.

```cpp
#include <iostream>

int add(int x, int y); // needed so main.cpp knows that add() is a function defined elsewhere

int main()
{
    std::cout << "Sum of 5 + 2 = " << add(5,2) << '\n';

    return 0;
}
```

```cpp
#include <iostream>

int add(int x, int y)
{
    return x + y;
}
```

Now, when the compiler is compiling main.cpp**, it will know what identifier add is** and be satisfied. **The linker will connect** the **function call to** add in main.cpp to the **definition of function** add in add.cpp.

Using this method, we can give files access to functions that live in another file.

4.9 Naming collisions and an introduction to namespaces

Let’s say you are driving to a friend’s house for the first time, and the address given to you is 245 Front Street in Mill City. Upon reaching Mill City, you take out your map, only to discover that **Mill City actually has two different Front Streets across town from each other**! Which one would you go to? Unless there were some additional clues to help you decide (e.g. you remember your friend’s house is near the river) you’d have to call your friend and ask for more information. Because this would be **confusing and inefficient** (particularly for your mail carrier), in most countries, all street names and house addresses within a city are **required to be unique**.

Similarly, **C++ requires that all identifiers be non-ambiguous**. If two identical identifiers are introduced into the same program in a way that the compiler or linker can’t tell them apart, the compiler or linker will produce an error. This error is generally referred to as a **naming collision** (or **naming conflict**).

If the colliding identifiers are introduced into the **same file**, the **result will be a compiler error**. If the colliding identifiers are introduced into **separate files** belonging to the same program, the **result will be a linker error**.

Most naming collisions occur in two cases:

- Two (or more) identically named functions (or global variables) are introduced into **separate files** belonging to the same program. This will result in a **linker error**, as shown above.

- Two (or more) identically named functions (or global variables) are introduced into the **same file**. This will result in a **compiler error**.

As programs get larger and use more identifiers, the odds of a naming collision being introduced increases significantly. The good news is that **C++ provides plenty of mechanisms for avoiding naming collisions**. **Local scope**, which keeps local variables defined inside functions from conflicting with each other, is one such mechanism. **But local scope doesn’t work for function names. So how do we keep function names from conflicting with each other?**

4.9.1 Scope regions

Back to our address analogy for a moment, having two Front Streets was only problematic because those streets existed within the same city. On the other hand, if you had to deliver mail to two addresses, one at 245 Front Street in Mill City, and another address at 245 Front Street in Jonesville, there would be no confusion about where to go. Put another way, cities **provide groupings that allow us to disambiguate** addresses that might otherwise conflict with each other.

A **scope region** is an **area of source code** where **all declared identifiers are considered distinct from names declared in other scopes** (much like the cities in our analogy). Two identifiers with the same name can be declared in separate scope regions without causing a naming conflict. However, within a given scope region, all identifiers must be unique, otherwise a naming collision will result.

4.9.1.1 Function body

The **body of a function is one example of a scope region**. Two identically-named identifiers can be defined in separate functions without issue -- because each function provides a separate scope region, there is no collision. However, if you try to define two identically-named identifiers within the same function, a naming collision will result, and the compiler will complain.

4.9.1.2 Namespaces

A **namespace** provides **another type of scope region** (called **namespace scope**) that allows you to declare names inside of it for the purpose of disambiguation. Any names declared inside the namespace won’t be mistaken for identical names in other scopes.

A name declared in a scope region (such as a namespace) won’t be mistaken for an identical name declared in another scope.

Unlike functions (which are designed to contain **executable statements**), **only declarations and definitions** can **appear in** the scope of a **namespace**. For example, two identically named functions can be defined inside separate namespaces, and no naming collision will occur.

Key insight: Only declarations and definitions can appear in the scope of a namespace (not executable statements). However, a function can be defined inside a namespace, and that function can contain executable statements.

4.9.1.3 The global namespace

In C++, **any name** that is **not defined inside a class, function, or a namespace** is considered to be part of an implicitly-defined namespace called the **global namespace** (sometimes also called the **global scope**).

We discuss the global namespace in more detail later on.

For now, there are **two things** you should know:

- Identifiers declared inside the global scope are **in scope from the point of declaration to the end of the file.**

- Although variables **can be defined in the global namespace**, **this should generally be avoided**.

4.9.1.4 The std namespace

When C++ was originally designed, all of the identifiers in the C++ standard library (including std::cin and std::cout) were available to be used without the std:: prefix (they were part of the global namespace).

However, this meant that any identifier in the standard library could potentially conflict with any name you picked for your own identifiers (also defined in the global namespace). Code that was working might suddenly have a naming conflict when you #included a new file from the standard library. Or worse, programs that would compile under one version of C++ might not compile under a future version of C++, as new identifiers introduced into the standard library could have a naming conflict with already written code.

So, **C++ moved all of the functionality in the standard library** into a namespace **named std** (short for “**standard**”).

It turns out that **std::cout‘s** name isn’t really **std::cout**. It’s actually just **cout**, and **std** is the **name of the namespace that identifier cout is part of**. Because cout is defined in the std namespace, the name cout won’t conflict with any objects or functions named cout that we create outside of the std namespace (such as in the global namespace).

When accessing an identifier that is defined in a namespace (e.g. **std::cout**), you need to tell the compiler that we’re looking for an identifier defined inside the namespace (**std**).

4.9.1.4.1 *Explicit namespace qualifier std::*

The most straightforward way to tell the compiler that we want to use cout from the std namespace is by explicitly using the **std:: prefix**.

The **::** symbol is an operator called the **scope resolution operator**. The identifier to the **left** of the :: symbol **identifies the namespace** that the name to the right of the :: symbol is contained within. If no identifier to the left of the :: symbol is provided, the global namespace is assumed.

When an identifier includes a namespace prefix, the identifier is called a **qualified name**.

Best practice: Do this. Explicitly use the scope resolution operator to tell the compiler where the identifier is and avoid naming collisions.

4.9.1.4.2 *Using namespace std*

Another way to access identifiers inside a namespace is to use a **using-directive statement**.

A **using directive** allows us to **access the names in a namespace without using a namespace prefix**.

Many texts, tutorials, and even some IDEs recommend or use a using-directive at the top of the program. However, used in this way, **this is a bad practice, and highly discouraged**.

When using a using-directive in this manner, any identifier we define may conflict with any identically named identifier in the std namespace. Even worse, while an identifier name may not conflict today, it may conflict with new identifiers added to the std namespace in future language revisions. **This was the whole point of moving all of the identifiers in the standard library into the std namespace in the first place!**

4.9.2 Curly braces and indented code

In C++, curly braces are **often used to delineate a scope region** that is nested within another scope region (braces are also used for some non-scope-related purposes, such as list initialization).

For example, a function defined inside the global scope region uses curly braces to separate the scope region of the function from the global scope.

In certain cases, identifiers defined outside the curly braces may still be part of the scope defined by the curly braces rather than the surrounding scope -- **function parameters** are a good example of this.

4.10 Introduction to the preprocessor

When you compile your project, you might expect that the compiler compiles each code file exactly as you've written it. **This actually isn't the case**.

Instead, prior to compilation, each code (.cpp) file goes through a **preprocessing** phase. In this phase, a program called the **preprocessor** makes various changes to the text of the code file. The preprocessor does not actually modify the original code files in any way -- rather, all changes made by the preprocessor happen either temporarily in-memory or using temporary files.

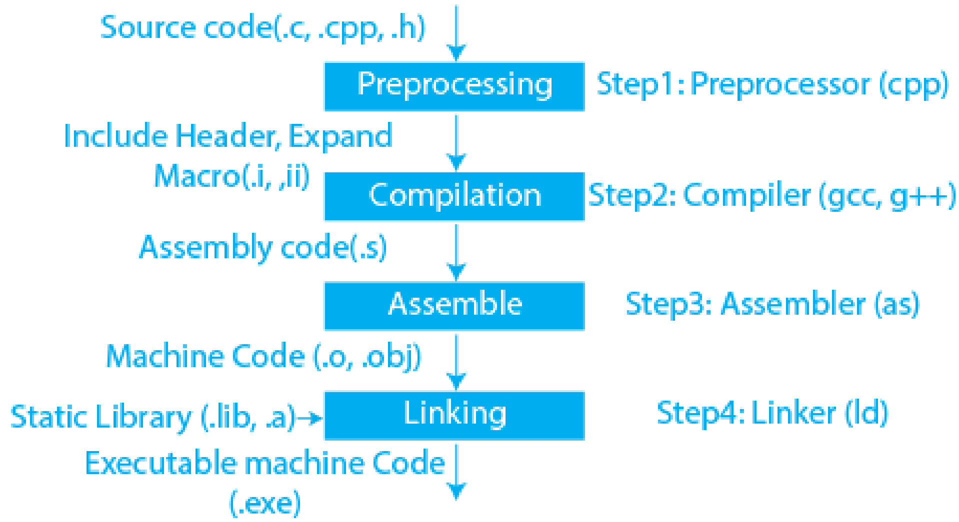
Historically, the preprocessor was a separate program from the compiler, **but in modern compilers, the preprocessor may be built right into the compiler itself.**

Most of what the preprocessor does is fairly uninteresting. For example, it strips out comments, and ensures each code file ends in a newline. However, the preprocessor does have one very important role: it is what processes #**include** directives.

When the preprocessor has finished processing a code file, the result is called a translation unit. This **translation unit** is what is then compiled by the compiler.

The entire process of preprocessing, compiling, and linking is called translation.

4.10.1 Translation process



4.10.2 Preprocessor directives

When the preprocessor runs, it scans through the code file (from top to bottom), looking for preprocessor directives. **Preprocessor directives** (often just called **directives**) are **instructions that start with a #** symbol and **end with a newline (NOT a semicolon)**. These directives tell the preprocessor to perform certain text manipulation tasks. Note that the preprocessor does not understand C++ syntax -- instead, the directives have their own syntax (which in some cases resembles C++ syntax, and in other cases, not so much).

4.10.2.1 Include

You've already seen the **#include** directive in action (generally to #include <iostream>). When you **#include a file**, **the preprocessor replaces the #include directive with the contents of the included file**. The included contents are then preprocessed (**which may result in additional #includes being preprocessed recursively**), then the rest of the file is preprocessed.

Once the preprocessor has finished processing the code file plus all of the #included content, the result is called a **translation unit**. The translation unit is what is sent to the compiler to be compiled.

4.10.2.2 Macro defines

The **#define directive** can be used to create a **macro**. In C++, **a macro is a rule that defines how input text is converted into replacement output text**.

There are **two** basic **types** of macros: **object-like macros, and function-like macros**.

Function-like macros act like functions, and serve a similar purpose. Their use is generally **considered unsafe**, and almost anything they can do can be done by a normal function.

Object-like macros can be defined in one of two ways:

- #define IDENTIFIER
    - Used for **conditional compilation**
    - **#If**
    - **#Ifdef**
    - **#Ifndef**
    - **#endif**

- #define IDENTIFIER substitution_text

The top definition has no substitution text, whereas the bottom one does. Because **these are** preprocessor **directives** (**not statements**), note that **neither form ends with a semicolon**.

The identifier for a macro uses the same naming rules as normal identifiers: they can use letters, numbers, and underscores, cannot start with a number, and should not start with an underscore. By convention, macro names are typically all upper-case, separated by underscores.

4.11 Header files

As programs grow larger (and make use of more files), it becomes increasingly tedious to have to forward declare every function you want to use that is defined in a different file. Wouldn't it be nice if you could **put all your forward declarations in one place and then import them when you need them**?

C++ code files (with a .cpp extension) are not the only files commonly seen in C++ programs. The other type of file is called a **header file**. Header files **usually have a .h** extension, but you will **occasionally see them with a .hpp extension** or no extension at all. The primary purpose of a header file is to propagate declarations to code (.cpp) files.

When you **#include** a file, the **content** of the included file **is inserted at the point of inclusion**. This provides a useful way to pull in declarations from another file.

Note: **including definitions in a header file results in a violation of the one-definition rule.**

Best practice:

- Always include header guards (we'll cover these next lesson).
- Do not define variables and functions in header files (for now).
- Give a header file the same name as the source file it's associated with (e.g. grades.h is paired with grades.cpp).
- Each header file should have a specific job
- Be mindful of which headers you need to explicitly include for the functionality that you are using in your code files, to avoid inadvertent transitive includes.
- A header file should #include any other headers containing functionality it needs. Such a header should compile successfully when #included into a .cpp file by itself.
- Only #include what you need (don't include everything just because you can).
- Do not #include .cpp files.
- Prefer putting documentation on what something does or how to use it in the header. It's more likely to be seen there. Documentation describing how something works should remain in the source files.

4.11.1 Standard library header files

Consider the following program:

```
#include <iostream>

int main()
{
    std::cout << "Hello, world!";
    return 0;
}
```

This program prints “Hello, world!” to the console using std::cout. However, **this program never provided a definition or declaration for std::cout**, so how does the compiler know what std::cout is?

The answer is that **std::cout has been forward declared in the “iostream” header file**. When we #include <iostream>, **we’re requesting that the preprocessor copy all of the content (including forward declarations for std::cout) from the file named “iostream**” into the file doing the #include.

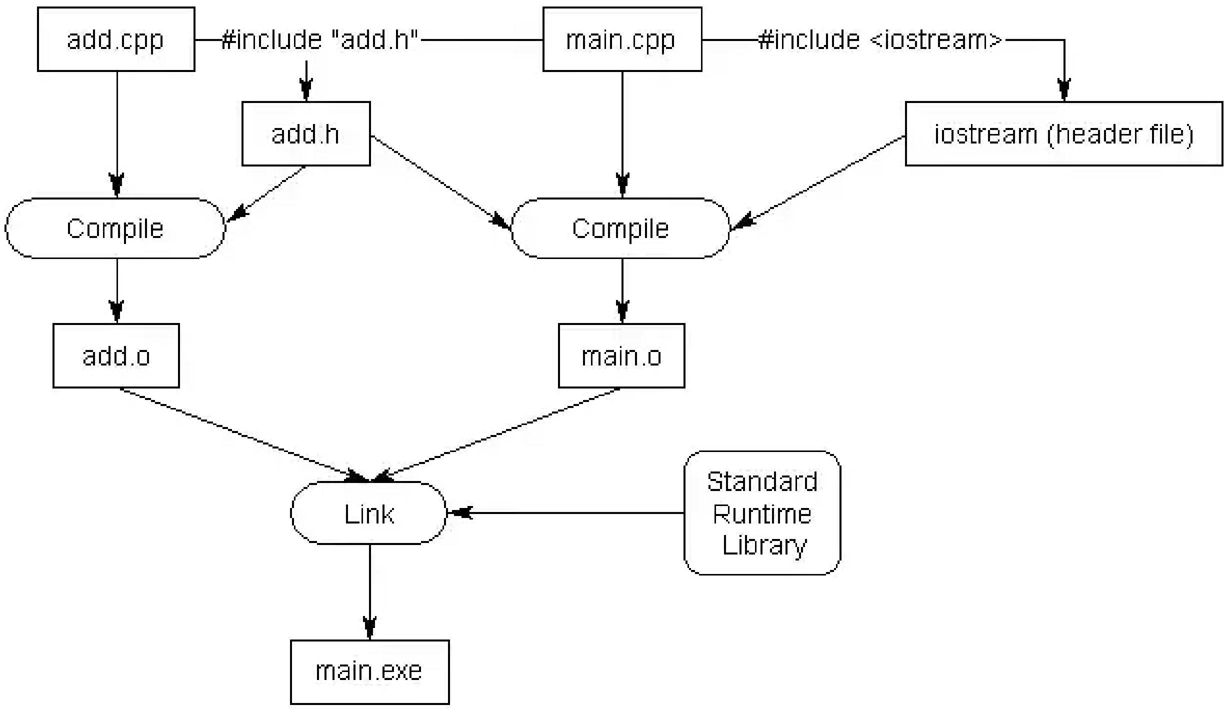
We use angled brackets here to help the preprocessor. This way we tell it that we didn’t write it ourselves and it will start looking in the **include directories**. These are configured according to the **IDE**, they can also be modified / configured according to the needs of a project.

4.11.2 Why doesn’t iostream have a .h extension?

Iostream.h is a different header file than iostream! **When C++ was first created, all of the headers in the standard library ended in a .h suffix**.

When the language was standardized by the ANSI committee, they decided to move all of the names used in the standard library into the **std namespace to help avoid naming conflicts** with user-declared identifiers. However, this presented a problem: if they moved all the names into the std namespace, none of the old programs (that included iostream.h) would work anymore!

To work around this issue, C++ introduced new header files that lack the .h extension. These new header files declare all names inside the std namespace. This way, older programs that include #include <iostream.h> do not need to be rewritten, and newer programs can #include <iostream>.



4.11.3 #include order

To maximize the chance that missing includes will be flagged by compiler, order your #includes as follows:

1. The paired header file
2. Other headers from your project
3. 3rd party library headers
4. Standard library headers

The headers for each grouping should be sorted alphabetically (unless the documentation for a 3rd party library instructs you to do otherwise).

4.11.4 Including header files from other directories

Another common question involves how to include header files from other directories.

One (**bad**) way to do this is to include a **relative path** to the header file you want to include as part of the #include line.
For example:

- #include "headers/myHeader.h"
- #include "../moreHeaders/myOtherHeader.h"

While this will compile (assuming the files exist in those relative directories), the downside of this approach is that **it requires you to reflect your directory structure in your code**. If you ever update your directory structure, your code won't work anymore.

A better method is to tell your compiler or IDE that you have a bunch of header files in some other location, so that it will look there when it can't find them in the current directory. This can generally be done by setting an include path or search directory in your IDE project settings.

The nice thing about this approach is that if you ever change your directory structure, you only have to change a single compiler or IDE setting instead of every code file.

4.11.5 Headers may include other headers

It's common that a header file will need a declaration or definition that lives in a different header file. Because of this, **header files will often #include other header files**.

When your code file #includes the first header file, **you'll also get any other header files that the first header file includes** (and any header files those include, and so on). These additional header files are sometimes **called transitive includes**, as they're **included implicitly** rather than explicitly.

The content of these transitive includes are available for use in your code file. However, **you generally should not rely on the content of headers that are included transitively** (unless reference documentation indicates that those **transitive includes** are required). The implementation of header files may change over time, or be different across different systems. If that happens, your code may only compile on certain systems, or may compile now but not in the future. This is easily avoided by explicitly including all of the header files the content of your code file requires.

4.12 Header guards

4.12.1 The duplicate definition problem

In Forward declarations and definitions, we noted that a variable or function identifier can only have one definition (the one definition rule).

Thus, a program that defines a variable identifier more than once will cause a compile error. Similarly, programs that define a function more than once will also cause a compile error.

While these programs are easy to fix (remove the duplicate definition), with header files, it's quite easy to end up in a situation where a definition in a header file gets included more than once. This can happen when a header file #includes another header file (which is common).

square.h:

```
int getSquareSides()
{
    return 4;
}
```

wave.h:

```
#include "square.h"
```

main.cpp:

```
#include "square.h"
#include "wave.h"

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

This seemingly innocent looking program won't compile! Here's what's happening. First, main.cpp #includes square.h, which copies the definition for function getSquareSides into main.cpp. Then main.cpp #includes wave.h, which #includes square.h itself. This copies contents of square.h (including the definition for function getSquareSides) into wave.h, which then gets copied into main.cpp.

The good news is that we can avoid the above problem via a mechanism called a **header guard** (also called an **include guard**). Header guards are conditional compilation directives that take the following form:

```
#ifndef SOME_UNIQUE_NAME_HERE
#define SOME_UNIQUE_NAME_HERE

// your declarations (and certain types of definitions) here

#endif
```

When this header is #included, the preprocessor will check whether SOME_UNIQUE_NAME_HERE has been previously defined in this translation unit. **If this is the first time we're including the header, SOME_UNIQUE_NAME_HERE will not have been defined**. **Consequently, it #defines SOME_UNIQUE_NAME_HERE** and includes the contents of the file. If the header is included again into the same file, SOME_UNIQUE_NAME_HERE will already have been defined from the first time the contents of the header were included, and the contents of the header will be ignored (thanks to the #ifndef).

All of your header files should have header guards on them. SOME_UNIQUE_NAME_HERE can be any name you want, but **by convention is set to the full filename** of the header file, typed in all caps, using underscores for spaces or punctuation. For example, square.h would have the header guard:

```
#ifndef SQUARE_H
#define SQUARE_H

int getSquareSides()
{
    return 4;
}

#endif
```

Even the standard library headers use header guards.

SUMMARY:

- Header guards **prevent a header file from being included multiple times within the same translation unit** (a single .cpp file and all the headers it includes).

- They **do not prevent the same header file from being included once in multiple translation units** (different .cpp files).

- **Duplicate declarations are** fine -- but even if your header file is composed of all declarations (no definitions) it's still a best practice to include header guards.

BEST PRACTICE:

This is the reason why we **shouldn't put functions in a header** file.

4.12.2 Can't we just avoid definitions in header files?

We've generally told you not to include function definitions in your headers. So, you may be wondering why you should include header guards if they protect you from something you shouldn't do.

There are quite a few cases we'll show you in the future where it's necessary to put non-function definitions in a header file. For example, C++ will let you create your own types. These **custom types are typically defined in header files**, so the type definitions can be propagated out to the code files that need to use them. Without a header guard, a code file could end up with multiple (identical) copies of a given type definition, which the compiler will flag as an error.

So even though it's not strictly necessary to have header guards at this point in the tutorial series, **we're establishing good habits now, so you don't have to unlearn bad habits** later.

4.12.3 #pragma once

Modern compilers support a simpler, alternate form of header guards using the #pragma preprocessor directive.

#pragma once serves the same purpose as header guards: to avoid a header file from being included multiple times. With traditional header guards, the developer is responsible for guarding the header (by using preprocessor directives #ifndef, #define, and #endif). **With #pragma once, we're requesting that the compiler guard the header**. How exactly it does this is an implementation-specific detail.

For most projects, #pragma once works fine, and many developers now prefer it because it is easier and less error-prone. Many IDEs will also auto-include #pragma once at the top of a new header file generated through the IDE.

Because #pragma once is not defined by the C++ standard, it is possible that some compilers may not implement it. For this reason, **some development houses (such as Google) recommend using traditional header guards**. In this tutorial series, **we will favor header guards**, as **they are the most conventional way to guard headers**. However, support for #pragma once is fairly ubiquitous at this point, and **if you wish to use #pragma once instead, that is generally accepted in modern C++.**

4.13 How to design your first programs

4.13.1 Steps

1. Define your goal
   - In order to write a successful program, you first need to define what your goal is. Ideally, you should be able to state this in a sentence or two. It is often useful to express this as a user-facing outcome.

2. Define the requirements
   - While defining your problem helps you determine what outcome you want, it's still vague. The next step is to think about requirements.

   - Requirements is a fancy word for both the constraints that your solution needs to abide by (e.g. budget, timeline, space, memory, etc.…), as well as the capabilities that the program must exhibit in order to meet the users' needs. Note that your requirements should similarly be focused on the "what", not the "how".

3. Define your tools, targets and backup plan
   - System architecture
   - Backup plans for your project
   - What parts of the standard library
   - Solo or co-op coding?
   - Define a testing / feedback / release strategy

4. Break hard problems down into easy problems

5. Figure out the sequence of events

4.13.2 Advice

- Keep your programs **simple to start**.
- **Add** features **over time**.
- **Focus on one area** at a time.
- **Test each piece of code** as you go.
- **Don't** invest in **perfect**ing **early code**.
- **Optimize for maintainability**, not performance.

4.14 Chapter 2 summary

A **function** is a reusable sequence of statements designed to do a particular job. Functions you write yourself are called **user-defined** functions.

A **function call** is an expression that tells the CPU to execute a function. The function initiating the function call is the **caller**, and the function being called is the **callee** or **called** function. Do not forget to include parenthesis when making a function call.

The curly braces and statements in a function definition are called the **function body**.

A function that returns a value is called a **value-returning function**. The **return type** of a function indicates the type of value that the function will return. The **return statement** determines the specific **return value** that is returned to the caller. A return value is copied from the function back to the caller -- this process is called **return by value**. Failure to return a value from a non-void function will result in undefined behavior.

The return value from function main is called a **status code**, and it tells the operating system (and any other programs that called yours) whether your program executed successfully or not. By consensus a return value of 0 means success, and a non-zero return value means failure.

Practice **DRY** programming -- "don't repeat yourself". Make use of variables and functions to remove redundant code.

Functions with a return type of **void** do not return a value to the caller. A function that does not return a value is called a void function or non-value returning function. Void functions can't be called where a value is required.

A return statement that is not the last statement in a function is called an **early return**. Such a statement causes the function to return to the caller immediately.

A **function parameter** is a variable used in a function where the value is provided by the caller of the function. An **argument** is the specific value passed from the caller to the function. When an argument is copied into the parameter, this is called **pass by value**.

Function parameters and variables defined inside the function body are called **local variables**. The time in which a variable exists is called its **lifetime**. Variables are created and destroyed at **runtime**, which is when the program is running. A variable's **scope** determines where it can be seen and used. When a variable can be seen and used, we say it is **in scope**. When it cannot be seen, it cannot be used, and we say it is **out of scope**. **Scope is a compile-time property**, meaning it is enforced at compile time.

Whitespace refers to characters used for formatting purposes. In C++, this includes spaces, tabs, and newlines.

A **forward declaration** allows us to tell the compiler about the existence of an identifier before actually defining the identifier. To write a forward declaration for a function, we use a **function prototype**, which includes the function's return type, name, and parameters, but no function body, followed by a semicolon.

A **definition** actually implements (for functions and types) or instantiates (for variables) an identifier. A **declaration** is a statement that tells the compiler about the existence of the identifier. In C++, all definitions serve as declarations. **Pure declarations** are declarations that are not also definitions (such as function prototypes).

Most non-trivial programs contain multiple files.

When two identifiers are introduced into the same program in a way that the compiler or linker can't tell them apart, the compiler or linker will error due to a **naming collision**. A **namespace** guarantees that all identifiers within the namespace are unique. The std namespace is one such namespace.

The **preprocessor** is a process that runs on the code before it is compiled. **Directives** are special instructions to the preprocessor. Directives start with a # symbol and end with a newline. A **macro** is a rule that defines how input text is converted to a replacement output text.

Header files are files designed to propagate declarations to code files. When using the #include directive, the #include directive is replaced by the contents of the included file. When including headers, use angled brackets when including system headers (e.g. those in the C++ standard library), and use double quotes when including user-defined headers (the ones you write). When including system headers, include the versions with no .h extension if they exist.

Header guards prevent the contents of a header from being included more than once into a given code file. They do not prevent the contents of a header from being included into multiple different code files.

5 Debugging

5.1 Syntax and semantic errors

A **syntax error** occurs when you write a statement that is **not valid according to the grammar** of the C++ language.

A **semantic error** occurs when a statement is **syntactically valid**, but d**oes not do what the programmer intended**.

5.2 Process

- Find the root cause of the problem
  - Find the line of code that's not working correctly
- Understand the problem
  - Why does it occur?
  - Should it even be fixed or is the behavior correct?
- Determine a fix
- Write the fix.
- Retest to ensure the problem has been fixed.
- Retest to ensure no new problems have emerged.

5.3 Strategy

1. Figure out how to reproduce the problem
2. Run the program and gather information to narrow down where the problem is
3. Repeat the prior step until you find the problem

5.3.1 Tactics

1. Commenting out the code
2. Validate the code flow
3. Print out values
4. Use integrated debug mode
   a. Breakpoints
   b. Stepping
   c. Watching variables
   d. Watch the call stack

6 Fundamental data types

6.1 Introduction to fundamental data types

6.1.1 Bits, bytes, and memory addressing

Computers have random access memory (RAM) that is available for programs to use. When a variable is defined, **a piece of that memory is set aside** for that variable.

The smallest unit of memory is a **binary digit** (also called a **bit**), which can hold a value of 0 or 1. You can think of a bit as being like a traditional light switch -- either the light is off (0), or it is on (1). There is no in-between. If you were to look at a random segment of memory, all you would see is …011010100101010… or some combination thereof.

Memory is organized into sequential units called **memory addresses** (or **addresses** for short). Similar to how a street address can be used to find a given house on a street, the memory address allows us to find and access the contents of memory at a particular location.

Perhaps surprisingly, in modern computer architectures, each bit does not get its own unique memory address. This is because the number of memory addresses is limited, and the need to access data bit-by-bit is rare. Instead, each memory address holds 1 byte of data. A byte is a group of bits that are operated on as a unit. The modern standard is that a **byte** is comprised of **8 sequential bits**.

6.1.2 Data types

Because all data on a computer is just a sequence of bits, we use a **data type** (often called a "**type**" for short) to tell the compiler how to interpret the contents of memory in some meaningful way. You have already seen one example of a data type: the integer. When we declare a variable as an integer, we are telling the compiler "The piece of memory that this variable uses is going to be interpreted as an integer value".

When you give an object a value, **the compiler and CPU** take care of **encoding** your value **into** the appropriate **sequence of bits** for that data type, **which are then stored in memory** (remember: memory can only store bits). For example, if you assign an integer object the value 65, that value is converted to the sequence of bits 0100 0001 and stored in the memory assigned to the object.

Conversely, when the object is evaluated to produce a value, that sequence of bits is reconstituted back into the original value. Meaning that 0100 0001 is converted back into the value 65.

Fortunately, the compiler and CPU do all the hard work here, so **you generally don't need to worry about how values get converted into bit sequences and back.**

6.1.3 *Fundamental data types*

C++ comes with built-in support for many different data types. These are called **fundamental data types**, but are often informally called **basic types, primitive types, or built-in types**.

Types	Category	Meaning	Example
float double long double	Floating Point	a number with a fractional part	3.14159
bool	Integral (Boolean)	true or false	true
char wchar_t char8_t (C++20) char16_t (C++11) char32_t (C++11)	Integral (Character)	a single character of text	'c'
short int int long int long long int (C++11)	Integral (Integer)	positive and negative whole numbers, including 0	64
std::nullptr_t (C++11)	Null Pointer	a null pointer	nullptr
void	Void	no type	n/a

6.1.4 *The _t suffix*

Many of the types defined in newer versions of C++ (e.g. std::nullptr_t) use a _t suffix. **This suffix means "type"**, and **it's a common nomenclature applied to modern types**.

If you see something with a _t suffix, it's probably a type. But many types don't have a _t suffix, so this isn't consistently applied.

6.2 Void

Void is the easiest of the data types to explain. Basically, void means “**no type**”!

Void is our first example of an **incomplete type**.

An incomplete type is a type that has been declared but not yet defined. The compiler knows about the existence of such types, but does not have enough information to determine how much memory to allocate for objects of that type. void is intentionally incomplete since it represents the lack of a type, and thus cannot be defined.

Void is a bit of a special type and it’s only used in certain contexts.

For example: a void type variable doesn’t work. This is because it is an incomplete type and they **cannot be instantiated**.

6.2.1 Void contexts

- Most commonly, void is used to indicate that a **function does not return a value**.
    - Note: a **value-returning return statement will cause a compiler error**.

- Deprecated functions that don’t take parameters (**C-specific**)
    - We put **void as a parameter** without an identifier.
    - Note: Although this will compile in C++ (for backwards compatibility reasons), **this use of keyword void is considered deprecated in C++.**
    - **Best practice:** Empty parameter list instead of void. (**implies** an **implicit void**)

- Void pointers
    - Will be discussed later on since it’s an advanced use of the keyword.

6.3 Object sizes and the sizeof operator

6.3.1 Object sizes

To recap, memory on modern machines is typically organized into **byte-sized units**, with **each byte** of memory having a **unique address**.

Up to this point, it has been useful to think of memory as a bunch of cubbyholes or mailboxes where we can put and retrieve information, and variables as names for accessing those cubbyholes or mailboxes. However, **this analogy is not quite correct in one regard**.

Most objects actually take up more than 1 byte of memory. A single object may use 1, 2, 4, 8, or even more consecutive memory addresses. The amount of memory that an object uses is based on its data type.

Because we typically access memory through variable names (and not directly via memory addresses), the compiler is able to hide the details of how many bytes a given object uses from us. When we access some variable x, the compiler knows how many bytes of data to retrieve (based on the type of variable x), and can handle that task for us. **Even so, there are several reasons it is useful to know how much memory an object uses.**

First, **the more memory an object uses, the more information it can hold**.

A single bit can hold **2 possible values**, a 0, or a 1

2 bits can hold **4 possible values**

3 bits can hold **8 possible values**

To generalize, an object with n bits (where **n is an amount**) can hold 2n (2 to the power of n, also commonly written **2^n**) unique values.

Example 1:

2-byte object (2 bytes **= 8 bits**)

Formula: 2^n = **2^8** = **256 possible values, range 0 - 255**

Example 2:

4-byte integer (4 bytes **= 32 bits**)

Formula: 2^n = 2^32 = **4294967296 possible values, range 0 - 4294967295**

Thus, the size of the object puts a limit on the amount of unique values it can store.

Second, **computers have a finite amount of free memory**. Every time we define an object, a small portion of that free memory is used for as long as the object is in existence. Because modern computers have a lot of memory, this impact is usually negligible. **However, for programs that need a large amount of objects or data (e.g. a game that is rendering millions of polygons), the difference between using 1-byte and 8-byte objects can be significant**.

6.3.2 Fundamental data type sizes

The obvious next question is "how much memory do variables of different data types take?".

Surprisingly the **C++ standard does not define the exact size in bits**. However, it **does define a minimum size** (in bits).

In this tutorial series, we will take a simplified view, by making some reasonable assumptions that are generally true for modern architectures:

- **A byte is 8 bits**.
- Memory is byte addressable, so the **smallest object is 1 byte**
- Floating point support is IEEE-754 compliant.
- We are on a **32-bit or 64-bit architecture**.

Category	Type	Minimum Size	Typical Size	Note
Boolean	bool	1 byte	1 byte	
character	char	1 byte	1 byte	always exactly 1 byte
	wchar_t	1 byte	2 or 4 bytes	
	char8_t	1 byte	1 byte	
	char16_t	2 bytes	2 bytes	
	char32_t	4 bytes	4 bytes	
integer	short	2 bytes	2 bytes	
	int	2 bytes	4 bytes	
	long	4 bytes	4 or 8 bytes	
	long long	8 bytes	8 bytes	
floating point	float	4 bytes	4 bytes	
	double	8 bytes	8 bytes	
	long double	8 bytes	8, 12, or 16 bytes	
pointer	std::nullptr_t	4 bytes	4 or 8 bytes	

Tip:

For maximum portability, you shouldn't assume that variables are larger than the specified minimum size.

Alternatively, if you want to assume that a type has a certain size (e.g. that an int is at least 4 bytes), you can use static_assert to have the compiler fail a build if it is compiled on an architecture where this assumption is not true. We cover how to do this in the Assert and static_assert lesson.

6.3.3 The sizeof operator

In order to determine the size of data types on a particular machine, C++ provides an operator named sizeof. The **sizeof** operator is a unary operator that takes either a type or a variable, and returns its size in bytes.

You can also use the sizeof operator on a **variable name**.

sizeof **does not include dynamically allocated memory** used by an object. We discuss dynamic memory allocation in a future lesson.

6.4 Signed integers

An integer is an integral type that can represent positive and negative whole numbers, including 0. C++ has **4 primary fundamental integer types** available for use:

- **Short int** **16 bits**
- **Int** **16 – 32 bits** (Typically, 32 bits on modern architectures)
- **Long int** **32 bits**
- **Long long int** **64 bits**

The key difference between the various integer types is that **they have varying sizes**.

Technically, the **bool** and **char** types **are considered to be integral types** (because **these types store their values as integer values**). For the purpose of the next few lessons, we'll exclude these types from our discussion.

When writing negative numbers in everyday life, we use a negative sign. For example, -3 means "negative 3". We'd also typically recognize +3 as "positive 3" (though common convention dictates that we typically omit plus prefixes).

This attribute of being positive, negative, or zero is called the number's sign.

By default, integers in C++ are **signed**, which means the number's **sign is stored as part of the number**. Therefore, a signed integer can hold both positive and negative numbers (and 0).

In binary representation, a single bit (called the **sign bit**) is used to store the sign of the number. The non-sign bits (called the **magnitude bits**) determine the magnitude of the number.

Best practice for defining:

Prefer the **shorthand types** that do not use the int suffix or signed prefix.

6.4.1 Signed integer ranges

As you learned in the last section, a variable with n bits can hold 2n possible values. But which specific values? We call the set of specific values that a data type can hold its **range**. The range of an integer variable is determined by **two factors**: its size (in bits), and whether it is signed or not.

By definition, an 8-bit signed integer has a range of -128 to 127. This means a signed integer can store any integer value between -128 and 127 **(inclusive) safely**.

Here's a table containing the range of signed integers of different sizes:

Size/Type	Range
8 bit signed	-128 to 127
16 bit signed	-32,768 to 32,767
32 bit signed	-2,147,483,648 to 2,147,483,647
64 bit signed	-9,223,372,036,854,775,808 to 9,223,372,036,854,775,807

For the math inclined, an n-bit signed variable has a range of $\mathbf{-(2^{n-1})}$ to $\mathbf{2^{n-1}}$.

6.4.2 Overflow

What happens if we try to assign a value that is higher than the range of the fundamental data type?

The C++20 standard makes this blanket statement: "If during the evaluation of an expression, the result is not mathematically defined or not in the range of representable values for its type, the **behavior is undefined**". Colloquially, this is called **overflow**.

If an arithmetic operation (such as addition or multiplication) attempts to create a value outside the range that can be represented, this is called **integer overflow** (or **arithmetic overflow**). For signed integers, integer overflow will result in undefined behavior.

In general, **overflow results in information being lost**, which is almost never desirable. If there is any suspicion that an object might need to store a value that falls outside its range, use a type with a bigger range!

6.4.3 Integer division

When doing division with two integers (called **integer division**), C++ always produces an integer result. Since integers can't hold fractional values, any fractional portion is simply dropped (not rounded!).

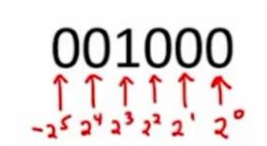
Warning: Be careful when using integer division, as **you will lose any fractional parts of the quotient**. However, if it's what you want, integer division is safe to use, as the results are predictable.

6.4.4 Two's compliment

Two's compliment representation is a way of representing positive and negative numbers in binary.

Let's take 001000 for example: first we calculate the indexes separately because they make part of the whole number. In binary if any number at a certain position is set to 1 then we add them to know what the whole byte evaluates to.

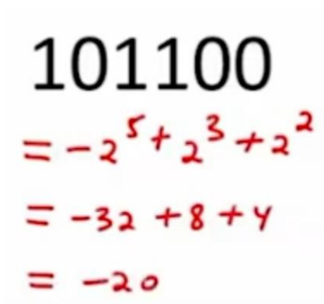
6.4.4.1 Positive two's compliment



In this case 2^3 is 8. Also note that the 0 with the most value is signed (negative)

6.4.5 Negative two's compliment

The same rules as before apply except this time the signed bit is set to 1 and for this value it counts -2^5 (-32). This is important because when we add all of the positive magnitude bits we then also subtract the signed bit.



6.5 Unsigned integers, and why to avoid them

We covered signed integers, which are a set of types that can hold positive and negative whole numbers, including 0.

C++ also supports unsigned integers. Unsigned integers are integers that can only hold non-negative whole numbers.

To define an unsigned integer, we **use the unsigned keyword**. By convention, this is placed before the type.

A 1-byte unsigned integer has a range of 0 to 255. Compare this to the 1-byte signed integer range of -128 to 127. **Both can store 256 different values, but signed integers use half of their range for negative numbers, whereas unsigned integers can store positive numbers that are twice as large.**

When no negative numbers are required, unsigned integers are well-suited for networking and systems with little memory, because unsigned integers can store more positive numbers without taking up extra memory.

6.5.1 Overflow

Important note: Oddly, the **C++ standard explicitly says "a computation involving unsigned operands can never overflow"**. This is contrary to general programming consensus that integer overflow encompasses both signed and unsigned use cases. **Given that most programmers would consider this overflow, we'll call this overflow despite the C++ standard's statements to the contrary.**

If an unsigned value is out of range, it is divided by one greater than the largest number of the type, and only the **remainder kept**.

6.5.2 Controversy over unsigned numbers

Many developers (and some large development houses, such as Google) believe that developers should generally avoid unsigned integers. This is largely **because of two behaviors** that can cause problems.

First, with signed values, it takes a little work to accidentally overflow the top or bottom of the range because those values are far from 0. **With unsigned numbers, it is much easier to overflow the bottom of the range, because the bottom of the range is 0, which is close to where the majority of our values are.** Another common **unwanted wrap-around happens when an unsigned integer is repeatedly decremented by 1**, until it tries to decrement to a negative number. You'll see an example of this when loops are introduced.

Second, and more insidiously, **unexpected behavior can result when you mix signed and unsigned integers**. In C++, if a mathematical operation (e.g. arithmetic or comparison) has one signed integer and one unsigned integer, the **signed integer will usually be converted to an unsigned integer. And the result will thus be unsigned.**

Best practice: Favor signed numbers over unsigned numbers for holding quantities (even quantities that should be non-negative) and mathematical operations. Avoid mixing signed and unsigned numbers.

6.5.3 So, when should you use unsigned numbers?

There are still a few cases in C++ where it's okay / necessary to use unsigned numbers.

First, unsigned numbers are preferred when dealing with **bit manipulation** (covered in chapter O -- that's a capital 'o', not a '0'). They are also useful when well-defined wrap-around behavior is required (**useful in some algorithms like encryption and random number generation**).

Second, use of unsigned numbers is still unavoidable in some cases, mainly those having to do with **array indexing**. We'll talk more about this in the lessons on arrays and array indexing.

Also note that if you're developing for an embedded system (e.g. an Arduino) or some other **processor/memory limited context**, use of unsigned numbers is more common and accepted (and in some cases, unavoidable) for performance reasons.

6.6 Fixed-width integers and size_t

we covered that C++ only guarantees that integer variables will have a minimum size -- but they could be larger, depending on the target system.

6.6.1 Why isn't the size of the integer variables fixed?

The short answer is that this goes back to the early days of C, when computers were slow and performance was of the utmost concern. C opted to intentionally leave the size of an integer open so that the compiler implementers could pick a size for int that performs best on the target computer architecture.

6.7 Introduction to scientific notation

6.8 Floating point numbers

6.9 Boolean values

6.10 Introduction to if statements

6.11 Chars

6.12 Introduction to type conversion and static_cast