1 Overview and Hello World

1.1 Organization

[Slide 2] Module "Concepts of C++ Programming" (CIT323000)

Goals

- Write good and modern C++ code
- Apply widely relevant C++ constructs
- Understand some advanced language concepts

Non-Goals

- Become experts in C++
- Fancy language features
- Apply involved optimizations

Prerequisites

- Fundamentals of object-oriented programming — EIDI, PGdP
- Fundamentals of data structures and algorithms — GAD
- Beneficial: operating systems, computer architecture — GBS, ERA

> This lecture assumes knowledge of imperative and object-oriented programming languages like Java (e.g., `for` loops, classes, visibility, inheritance, polymorphism).

[Slide 3] Lecture Organization

- Lecture: Mon 14:30 – 17:00, MW 0001
  - Lecturer: Dr. Alexis Engelke `engelke@in.tum.de`
  - Live stream and recording via RBG: `https://live.rbg.tum.de/`
  - Tweedback for questions during lecture
- Exercises: Tue 14:15 – 15:45, Interims II HS 3
  - Florian Drescher, Mateusz Gienieczko
- Material: `https://db.in.tum.de/teaching/ws2425/cpp/`
- Zulip-Streams: #CPP, #CPP Homeworks, #CPP Random/Memes
- Exam: written exam *on your laptop*, on-site, 90 minutes
  - Open book, but no communication/AI tools allowed
  - Same submission system as for homework

[Slide 4] Homework

- 1–2 programming tasks as homework every week

  - Released on Monday, deadline next Sunday 11:59 PM
- Automatic tests and grading, points only for completely solved tasks
  - Typically all[1] tests provided with the assignment
- Container environment provided, no support for other setups
- Submission via git+ssh only
- Grade bonus: 0.3 for 75% of exercise points
  - Applies **only** for the main exam, not for the retake
- Cheating in homework ⇝ 5.0U in final grade

[Slide 5] Literature

Primary

- **C++ Reference Documentation.** (`https://en.cppreference.com/`)
- Lippman, 2013. *C++ Primer (5th edition).* Only covers C++11.
- Stroustrup, 2013. *The C++ Programming Language (4th edition).* Only covers C++11.
- Meyers, 2015. *Effective Modern C++. 42 specific ways to improve your use of C++11 and C++14..*

Supplementary

- Aho, Lam, Sethi & Ullman, 2007. *Compilers. Principles, Techniques & Tools (2nd edition).*
- Tanenbaum, 2006. *Structured Computer Organization (5th edition).*

1.2 Introduction

[Slide 6] What is C++?

- Multi-paradigm general-purpose programming language
  - Imperative programming
  - Object-oriented programming
  - Generic programming
  - Functional programming
- Key characteristics
  - Compiled
  - Statically typed
  - Facilities for low-level programming

[Slide 7] Some C++ History

Initial development

- Bjarne Stroustrup at Bell Labs (since 1979)

[1] We may add extra cases to prevent hard-coding of test cases.

  - Originally "C with classes", renamed in 1983 to C++
- In large parts based on C
- Inspirations from Simula67 (classes) and Algol68 (operator overloading)
- Initially developed as a C++-to-C converter (Cfront)

First ISO standardization in 1998 (C++98)

- Further amendments in following years (C++03/11/14/17/20)
- Current standard: C++23

[Slide 8] C++ Standard vs. Implementations

- C++ *standard* specifies requirements for C++ *implementations* about language features and standard library
- "Implementation" consists of: compiler, standard library impl, OS, ...
- Some things are specified rigidly in the standard
- Some things are *implementation-defined*
  - Standard specifies options, implementation chooses one and documents that
  - Example: size of an `int`
- Implementations can offer extensions[2]

> Typically, implementations of the C++ compiler, the C++ standard library, the underlying C standard library, and the operating system are separated. Obviously, only few combinations are supported, but some compilers like Clang support using different standard library implementations (e.g. with `-stdlib=libc++`).
>
> - Popular C++ compilers: Clang, GCC, MSVC, EDG eccp (used as foundation for some other commercial compilers)
> - Popular C++ standard library implementations: libstdc++ (GNU), libc++ (Clang/LLVM project), MSVC STL (Microsoft)
> - Popular C standard library implementations: glibc (GNU), Microsoft CRT, (musl, does not support C++)

[Slide 9] Why Study C++?

- Performance
  - Very flexible level of abstraction
  - Direct mapping to hardware capabilities easily possible
  - Zero-overhead rule: "What you don't use, you don't pay for."
- Scales to large systems (with some discipline)
- Interoperability with other languages, esp. C
- *Huge* amount of legacy code needs developers/maintainers
  - compilers, databases, simulations, ...

[2] `https://clang.llvm.org/docs/LanguageExtensions.html`

> Studying C++ does not preclude studying other languages. C++ is not the best or right tool for every job, so you probably want to learn at least half a dozen programming languages. (My personal picks in 2024 are: C, C++, Python, Rust, Go, JavaScript.)
>
> Note that there's no such thing as a "zero-cost abstraction". They do have cost, typically during compilation. Some of these "zero-cost" abstractions *also* have some run-time cost. For example, the mere possibility of C++ exceptions can prevent optimizations.

[Slide 10] This Lecture

- Go bottom-up through important language constructs
  - Some things (e.g. standard library) appear rather late
  - Cyclic dependencies are unavoidable
- Focus: widely used constructs and important cases
  - Topic selection based on relevance real-world projects
  - Many special cases not discussed, lecture will be inaccurate at times
  - Use the C++ reference!

1.3 Hello World!

[Slide 11] Hello World!

```
#include <print>
int main() {
  std::println("Hello␣World!");
  return 0;
}
```

On the command line:

```
$ clang++ -std=c++23 -o hello hello.cpp
$ ./hello
Hello World!
```

[Slide 12] Hello World, explained[3]

```
// Make print and println available
#include <print>

// Definition of function main().
// Program execution starts at main.
int main() {
  // std:: is a namespace prefix. std is for the C++ standard library
  std::println("Hello␣World!");

  // End program with exit code 0. (zero = everything ok, non-zero = error)
  return 0;
}
```

[3] A bit hand-wavy, but we have to start somewhere.

[Slide 13] Program Arguments

- `main` can take two paramters to hold command-line arguments
  - `int argc`: number of arguments
  - `char** argv`: the actual arguments, ∼array of strings
  - First argument is the program invocation itself (e.g., `./hello2`)

```
#include <print>
int main(int argc, char** argv) {
  std::println("Hello␣{}!", argv[1]); // DON'T DO THIS
  return 0;
}
$ clang++ -std=c++23 -o hello2 hello2.cpp
$ ./hello2 World
Hello World!
$ ./hello2
Segmentation fault
```

> The program crashed! A "segmentation fault" is an access to an invalid memory address that was caught by the operating system. In this case, we accessed the second element of an array of size 1 (argc is 1). We were **lucky**[a] and got a crash! Since there are no bounds checks, something completely different could have happened.
>
> In this example, this might be easy to see, but we will very briefly look at two important debugging strategies.
>
> [a] Ok, this example will always crash. But regardless, never rely on getting crashes on mistakes.

[Slide 14] Debugging 101

- Pass `-g` to Clang to enable debug info generation
- Run `gdb ./hello2`

```
$ clang++ -g -std=c++23 -o hello2 hello2.cpp
$ gdb ./hello2
(gdb) run
Program received signal SIGSEGV, Segmentation fault.
(gdb) backtrace
// ...
#16 in main (argc=0x1, argv=0x7fffffffe868) at hello2.cpp:3
(gdb) up 16
(gdb) print argc
1
(gdb) quit
```

> To start debugging run the command `gdb myprogram`. This starts a command-line interface. Here are some useful commands:

`help`	Show general help or help about a command.
`run`	Start the debugged program.
`break`	Set a breakpoint. When the breakpoint is reached, the debugger stops the program and accepts new commands.
`delete`	Remove a breakpoint.
`continue`	Continue running the program after it stopped at a breakpoint or by pressing Ctrl+C.
`next`	Continue running the program until the next source line of the current function.
`step`	Continue running the program until the source line changes.
`nexti`	Continue running the program until the next instruction of the current function.
`stepi`	Execute the next instrution.
`print`	Print the value of a variable, expression or CPU register.
`frame`	Show the currently selected *stack frame*, i.e. the current stack with its local variables. Usually includes the function name and the current source line. Can also be used to switch to another frame.
`backtrace`	Show all stack frames.
`up`	Select the frame from the next higher function.
`down`	Select the frame from the next lower function.
`watch`	Set a watchpoint. When the memory address that is watched is read or written, the debugger stops.
`thread`	Show the currently selected thread in a multi-threaded program. Can also be used to switch to another thread.

Most commands also have a short version, e.g., `r` for `run`, `c` for `continue`, `bt` for backtrace, etc.

The documentation for `gdb` can be found here: `https://sourceware.org/gdb/current/onlinedocs/gdb/`

[Slide 15] Debugging 102

- Print debugging.

```
#include <print>
int main(int argc, char** argv) {
  std::println("argc={}", argc);
  std::println("Hello␣{}!", argv[1]);
  return 0;
}
$ clang++ -std=c++23 -o hello2 hello2.cpp
$ ./hello2 World
Hello World!
$ ./hello2
Segmentation fault
```

> Print debugging is an extremely simple, but also an extremely powerful technique. I personally use print debugging most of the time and only resort to debuggers like GDB in complex situations.

[Slide 16] Program Arguments, attempt 2

```
#include <print>
int main(int argc, char** argv) {
  if (argc >= 2)
    std::println("Hello␣{}!", argv[1]);
  else
    std::println("Hi␣there!");
  return 0;
}
$ clang++ -std=c++23 -o hello2 hello2.cpp
$ ./hello2 World
Hello World!
$ ./hello2
Hi there!
```

[Slide 17] Compiler Flags

Compiler invocation: `clang++ [flags] -o output inputs...`

- `-std=c++23` — set standard to C++23
  - Always specify the version of the C++ standard!
- `-g` — enable debugging information
- `-Wall` — enable many warnings
- `-Wextra` — enable some more warnings
  - Always compile with `-Wall -Wextra`! Warnings often hint at bugs.
- `-O0` — no optimization, typically good for debugging
- `-O1`/`-O2`/`-O3` — enable optimizations at specified level

1.4 CMake

[Slide 18] Build Systems: CMake

- Frequent use of long compiler commands is tedious and error-prone
- Manual work doesn't scale to larger projects
- Different systems may require different flags
- CMake: build system specialized for C/C++
  - Widely used by large projects and supported by many IDEs
- `CMakeLists.txt` specifies project, files, etc.
- Reference: `https://cmake.org/cmake/help/latest/`

[Slide 19] CMake Example

CMakeLists.txt:

```
# Require a specific CMake version, here 3.20 for C++23 support
cmake_minimum_required(VERSION 3.20)
# Set project name, required for every project
project(hello2)
# We use C++23, basically adds -std=c++23 to compiler flags
set(CMAKE_CXX_STANDARD 23)
set(CMAKE_CXX_STANDARD_REQUIRED ON)
# Compile executable hello2 from hello2.cpp
add_executable(hello2 hello2.cpp)
```

On the command line:

```
$ mkdir build; cd build # create separate build directory
$ cmake ..
$ cmake --build .
$ ./hello2
```

[Slide 20] Further CMake Commands and Variables

- `add_executable(myprogram a.cpp b.cpp)`
  Define an executable to be built from the source files `a.cpp` and `b.cpp`
- `add_compile_options(-Wall -Wextra)`
  Add `-Wall -Wextra` to compiler flags
- `set(CMAKE_CXX_COMPILER clang++)`
  Set C++ compiler to `clang++`
- `set(CMAKE_BUILD_TYPE Debug)`
  Set "build type" `Debug` (other values: `Release`, `RelWithDebInfo`); affects optimization and debug info

Variables can be set on the command line invocation of CMake:

```
cmake .. -DCMAKE_BUILD_TYPE=RelWithDebInfo
```

[Slide 21] Overview and Hello World – Summary

- C++ is a compiled, widely-used, multi-paradigm language
- Program execution typically starts at `int main()`
- Command line arguments accessible via `argc`/`argv`
- Basic debugging techniques: GDB and print debugging
- Important compiler options for warnings and optimizations
- Basic usage of CMake for building C++ projects

[Slide 22] Overview and Hello World – Questions

- What are key characteristics of the C++ language?
- Why is C++ one of the most important languages today?
- How to access program arguments?
- What are important flags for compiling C++ code with Clang?
- How to debug a compiled C++ program with GDB?
- What is a segmentation fault?
- What are advantages of using a build system like CMake?

2 Basic Syntax and Object Model

[Slide 24] Reminder: C++ Reference

These slides will necessarily be inaccurate or incomplete at times. Use the reference! `https://en.cppreference.com/w/cpp`

[Slide 25] Comments[1]

- "C-style" or "multi-line" comments: `/*comment */`
- "C++-style" or "single-line" comments: `//comment`

Example:

```
/* This comment is unnecessarily
   split over two lines */
int a = 42;

// This comment is also split
// over two lines
int b = 123;
```

2.1 Types

[Slide 26] Fundamental Types[2]

- `void` – empty type, has no values
  - E.g., used to indicate functions that return no value
- Integer types
  - Boolean type: `bool` (1-bit integer, `true`/`false`)
  - Integer types: `int`, `long`, `unsigned long`, ...
  - Character types: `char`, `char16_t`, ...
- Floating-point types
  - `float`, `double`, `long double`

[Slide 27] Integer Types

- Sign modifiers: `signed` (default), `unsigned`
- Size modifiers: `short`, `long` (≥32 bit), `long long` (≥64 bit)

[1] `https://en.cppreference.com/w/cpp/comment`
[2] `https://en.cppreference.com/w/cpp/language/types`

- Keyword: `int` (optional if modifiers are present)
- Order of keywords is arbitrary
  - `unsigned long long` = `long unsigned int long`
- Signed integers use two's complement (since C++20)

> By convention, sign modifiers come first, `signed` is omitted, and `int` comes last, but is omitted if a size modifier is present.

[Slide 28] Integer Types: Minimum Width

Canonical Type Specifier	Minimum Width	Minimum Range
`short`	16 bit	-2^{15} to $2^{15}-1$
`unsigned short`		0 to $2^{16}-1$
`int`	16 bit	-2^{15} to $2^{15}-1$
`unsigned`		0 to $2^{16}-1$
`long`	32 bit	-2^{31} to $2^{31}-1$
`unsigned long`		0 to $2^{32}-1$
`long long`	64 bit	-2^{63} to $2^{63}-1$
`unsigned long long`		0 to $2^{64}-1$

- Exact width of integer types is **not** specified by the standard!

[Slide 29] Fixed-Width Integer Types[3]

- Use fixed-width types from when... a fixed width is required
- `#include <cstdint>`
- `int8_t`, `int16_t`, `int32_t`, `int64_t`, `uint8_t`, `uint16_t`, `uint32_t`, `uint64_t`
- But: optional, only available if supported by implementation

- Guideline: use fixed-width types only when really required
  - E.g., data structures where size is important, bitwise operations
  - Otherwise, prefer regular integers

> Don't prematurely "optimize" by using small data types, e.g. in data structures. Modern CPUs are optimized for 32/64-bit arithmetic, and some operations on smaller data types can even be *less* efficient.
>
> There are also `size_t` and `ptrdiff_t`, which are described in when introducing pointers later.

[3] `https://en.cppreference.com/w/cpp/types/integer`

[Slide 30] Integer Literals[4]

- Decimal (`42`), octal (`052`), hexadecimal (`0x2a`), binary (`0b101010`)

- `unsigned` suffix: `42u` or `42U`
- `long` suffix: `42l` or `42L`; `long long` suffix: `42ll` or `42LL`
- Both suffixes can be combined, e.g. `42ul`, `42ull`

- Separable by single quotes, e.g. `1'000'000'000ull`, `0b0010'1010`

Quiz: What is the type of the integer literal `0xdeadcabel`?
(Assume 32-bit `int`, 32-bit `long`, as on, e.g., Windows)

A. `int` B. `long` C. `unsigned long` D. `long long`

> Fun fact: `0` is technically an octal number.

[Slide 31] Character Types

- Represent character codes and integers
- `signed char`, `unsigned char`
- `char` — implementation-defined whether signed/unsigned!
  - Use `char` only for actual characters, not for arithmetic
- Size: defined as 1 byte
- Size of byte: **at least** 8 bit[5]
- For UTF characters: `char8_t` (C++20), `char16_t`, `char32_t`

> The signedness of `char` is platform-dependent. On x86, which always had an instruction for sign extension (`movsx`), `char` tends to be signed. Early ARM processors, in contrast, did not have an instruction for sign extension, so loading a `signed char` from memory required three instructions (load, shift left, arithmetic shift right). To improve efficiency, it was decided to make `char` an unsigned data type. When porting software from x86 to ARM, this occasionally causes problems in practice.
>
> Note that on modern CPUs, the performance difference is very low. Unsigned data types tend to be slightly more efficient in some cases, but this difference is often negligible.
>
> Although a `char` is one byte large, the size of one byte is not specified by the C++ standard and only required to be at least 8 bits. Platforms that use non-8-bit bytes have become increasingly rare over the past decades, but still exist, e.g. some digital signal processors (DSPs). (Note that these tend to have no compilers for modern C++ versions. In practice, programs are almost never tested on platforms where `char` is not 8 bits.)

[4] `https://en.cppreference.com/w/cpp/language/integer_literal`
[5] Might change for C++26 to exactly 8 bits; proposal: `https://wg21.link/p3477r0`

[Slide 32] Character Literals[6]

- E.g. `'a'`, `'b'`, `'€'`
  - Any character from the source character set except: `'`, \, newline
- Escape sequences, e.g. `'\''`, `'\\'`, `'\n'`, `'\u1234'`

- UTF-8 prefix: `u8'a'`, `u8'b'`
- UTF-16 prefix: `u'a'`, `u'b'`
- UTF-32 prefix: `U'a'`, `U'b'`

[Slide 33] Floating-Point Types

- `float` – usually IEEE-754 32-bit binary format
- `double` – usually IEEE-754 64-bit binary format
- `long double` – extended precision, format varies strongly
  - Some platforms use 64-bit (like `double`), e.g. MSVC on x86
  - Some platforms use 128-bit, e.g. usually AArch64 (this is typically a softfloat implementation $\rightsquigarrow$ slow)
  - On x86, typically 80-bit x87 binary floating-point
- Usual caveats of FP arithmetic apply: infinity, signed zero, NaN

> Due to the often lower performance and strongly varying accuracy, `long double` is typically only used when the target platform is known and the extra accuracy is needed.

[Slide 34] Floating-Point Literals[7]

- Without exponent: `3.1415926`, `.5`
- With exponent: `1e9`, `3.2e20`, `.5e-6`

- `float` suffix: `1.0f` or `1.0F`
- `long double` suffix: `42.0l` or `42.0L`

- Separable by single quotes, e.g. `1'000.000'001`, `.141'592e12`

[6] `https://en.cppreference.com/w/cpp/language/character_literal`
[7] `https://en.cppreference.com/w/cpp/language/floating_literal`

2.2 Operators

[Slide 35] Operator Precedence Table (1)[8]

Prec.	Operator	Description	Associativity
1	`::`	Scope resolution	left-to-right

2	`a++ a--`
	`<type>() <type>{}`
	`a() a[]`
	`. ->`
		Postfix increment/decrement
		Functional Cast
		Function Call/Subscript
		Member Access
			left-to-right

3	`++a --a`
	`+a -a !a ~a`
	`(<type>)`
	`*a &a`
	`sizeof`
	`new new[]`
	`delete delete[]`
		Prefix increment/decrement
		plus/minus/logical not/bitwise not
		C-style cast
		Dereference/Address-of
		Size-of
		Dynamic memory allocation
		Dynamic memory deallocation
			right-to-left

[Slide 36] Operator Precedence Table (2)

Prec.	Operator	Description	Associativity
4	`.* ->*`	Pointer-to-member	left-to-right
5	`a*b a/b a%b`	Multiplication/Division/Remainder	left-to-right
6	`a+b a-b`	Addition/Subtraction	left-to-right
7	`<< >>`	Bitwise shift	left-to-right
8	`<=>`	Three-way comparison	left-to-right
9	`< <=` `> >=`	Relational $<$ and $\leq$ Relational $>$ and $\geq$	left-to-right
10	`== !=`	Relational $=$ and $\neq$	left-to-right

[8] `https://en.cppreference.com/w/cpp/language/operator_precedence`

[Slide 37] Operator Precedence Table (3)

Prec.	Operator	Description	Associativity
11	`&`	Bitwise AND	left-to-right
12	`^`	Bitwise XOR	left-to-right
13	`|`	Bitwise OR	left-to-right
14	`&&`	Logical AND	left-to-right
15	`||`	Logical OR	left-to-right

16	`a?b:c`
	`throw`
	`=`
	`+= -= *= /= %=`
	`<<= >>= &= ^= |=`
		Ternary conditional
		throw operator
		Direct assignment
		Compound assignment
		Compound assignment
			right-to-left

17	`,`	Comma	left-to-right

C++ has a wide range of operators with "typical" semantics and mostly typical precedence and associativity. Some operators like the comma operator are rarely used. The left-hand side of an assignment can not only be a variable, but everything that refers to the identity of an object. This will be covered in more detail when discussing value types and references.

Note that even if parenthesis can be omitted, it is sometimes useful to use them anyway for clarity:

```
// real-world examples from libdcraw
diff = ((getbits(len-shl) << 1) + 1) << shl >> 1; // ???
yuv[c] = (bitbuf >> c * 12 & 0xfff) - (c >> 1 << 11); // ???
```

2.3 Observable Behavior

[Slide 38] Observable Behavior

Observable behavior of C++ programs precisely defined, unless:

- *implementation-defined behavior* – documented by C++ implementation
- *unspecified behavior* – one of multiple options can happen
  - E.g., evaluation order of function arguments: one permutation must happen
- program *ill-formed* – syntax/semantic error, compiler must diagnose
- program *ill-formed, no diagnostic required* – semantically invalid, hard to diagnose
  - Typically not detectable during compilation, not too many cases
- *undefined behavior* – the standard imposes no requirements

[Slide 39] Undefined Behavior[9] (UB)

- Some violations of language rules are undefined behavior: standard enforces no restrictions ⇝ **anything** can happen
  - Typically cases, where checks would be costly or impossible

⇒ A C++ program **must never** contain undefined behavior!

- Examples: out-of-bounds array access, signed integer overflow, shift by negative index, shift larger than value size, ...
  - Signed integers: UB on overflow; unsigned integers: well-defined wrap
- Compiler can assume that program contains no undefined behavior[10]
  - Allows for more optimizations, e.g. eliminate some checks

[Slide 40] Undefined Behavior – Example

Quiz: Which answer is correct?

```
bool f1(int x) { return x + 1 > x; }
bool f2(unsigned x) { return x + 1 > x; }
```

A. The return value of `f1` is always `false`.
B. The return value of `f2` is always `true`.
C. The return value of `f1` depends on the parameter.
D. The return value of `f2` depends on the parameter.
E. `f2` might invoke undefined behavior.

> Compilers regularly make use of the assumption that undefined behavior doesn't occur. Compile these functions with optimizations and look at the generated assembly code.

2.4 Basic Syntax

[Slide 41] Variables[11]

- Declaration: type specifier followed by declarators (variable names)
- Declarator can optionally be followed by an initializer
- No initializer: *default-initialized*
  - Non-local variables: zero-initialized
  - Local variables: **not initialized**
- Access of uninitialized variable is **undefined behavior**

```
void foo() {
  unsigned i = 0, j;
  unsigned meaningOfLife = 42;
}
```

[9] https://en.cppreference.com/w/cpp/language/ub
[10] https://blog.llvm.org/2011/05/what-every-c-programmer-should-know.html
[11] https://en.cppreference.com/w/cpp/language/declarations

> As the type partly written in the type specifier and partly in the declarator (e.g., pointers, references), declaring multiple variables in a single statement is typically considered as error-prone and therefore avoided.

[Slide 42] Variable Initializers[12]

- `variableName(<expression>)`
- `variableName = <expression>`
- `variableName{<expression>}` (error on possible information loss)

```
double a = 3.1415926;
double b(42);
unsigned c = a; // OK: c == 3
unsigned d(b); // OK: d == 42
unsigned e{a}; // ERROR: potential information loss
unsigned f{b}; // ERROR: potential information loss
```

[Slide 43] Simple Statements[13]

Declaration statement: Declaration followed by a semicolon

```
int i = 0;
```

Expression statement: Any expression followed by a semicolon

```
i + 5; // valid, but useless
foo(); // valid and possibly useful
```

Compound statement (blocks): Brace-enclosed sequence of statements

```
{ // start of block
    int i = 0; // declaration statement
} // end of block, i goes out of scope
int i = 1; // declaration statement
```

[Slide 44] Scope[14]

Names in a C++ program are valid only within their *scope*

- The scope of a name begins at its point of declaration
- The scope of a name ends at the end of the relevant block
- Scopes may be shadowed resulting in discontiguous scopes (bad practice)

```
int a = 21;
int b = 0;
{
  int a = 1; // scope of the first a is interrupted
  int c = 2;
  b = a + c + 39; // a refers to the second a, b == 42
} // scope of the second a and c ends
b = a; // a refers to the first a, b == 21
b += c; // ERROR: c is not in scope
```

[12] https://en.cppreference.com/w/cpp/language/initialization
[13] https://en.cppreference.com/w/cpp/language/statements
[14] https://en.cppreference.com/w/cpp/language/scope

[Slide 45] If Statement[15]

- Conditionally execute another statement
- Condition converted to `bool` decides which branch is taken
- Optional initialization statement
- Optional `else` branch

```
if (value < 42)
  valueLessThan42();
else
  valueTooLarge();


if (unsigned n = compute(); n > 4) {
  // do something
}
// The latter is equivalent to:
{
  unsigned n = compute();
  if (n > 4) {
    // do something
  }
}
```

> The condition can *also* be a simple declaration, in which case the condition is whether the assigned variable converted to `bool` is true. Examples:
>
> ```
> if (unsigned n = compute()) {
>   // do something if n != 0
> }
> if (unsigned a = compute(0); unsigned b = compute(a)) {
>   // do something if b != 0
> } else {
>   // can also use a and b here
> }
> ```

[Slide 46] If Statement Nesting

- `else` is associated with the closest `if` that has no `else`

```
// INTENTIONALLY BUGGY!
if (condition0)
  if (condition1)
    // do something if (condition0 && condition1) == true
else
  // do something if condition0 == false
```

- When in doubt, use curly braces to make scopes explicit

```
// Working as intended
if (condition0) {
  if (condition1)
    // do something if (condition0 && condition1) == true
} else {
```

[15] https://en.cppreference.com/w/cpp/language/if

```
  // do something if condition0 == false
}
```

[Slide 47] Switch Statements[16]

- Conditional control flow transfer based on integral type
- Constant values for `case`, must be unique
- `break` exits `switch`
- Implicit fallthrough!
  - Use `[[fallthrough]];` when intended
- Condition can have declaration

```
switch (compute()) {
case 42:
  // do something for 42
  break;
case 20:
  // do something for 20
  [[fallthrough]];
case 21:
case 22:
  // do something for 20/21/22
  break;
default:
  break;
}
```

[Slide 48] While and Do-While Loops

- `while`:[17] repeatedly execute statement while condition is true
  ```
  unsigned i = 42;
  while (i < 42) {
    // never executed
  }
  ```
- `do`–`while`:[18] like `while`, but execute body at least once
  ```
  unsigned i = 42;
  do {
    // executed once
  } while (i < 42);
  ```
- `break`/`continue` to exit loop/skip remainder of body

[Slide 49] For Loops[19]

```
for (unsigned i = 0; i < 10; ++i) {
  // iterate 0, 1, 2, ..., 9
}
for (unsigned i = 0, len = getLength(); i != len; ++i) {
```

[16] https://en.cppreference.com/w/cpp/language/switch
[17] https://en.cppreference.com/w/cpp/language/while
[18] https://en.cppreference.com/w/cpp/language/do
[19] https://en.cppreference.com/w/cpp/language/for

```
  // do something; doesn't call getLength() every iteration
}
for (unsigned i = 42; i-- > 0; ) {
  // iterate 41, 40, ..., 0
}
uint8_t i = 0;
for (; i < 256; ++i)
  std::println("{}", i); // hmmm....
```

Quiz: What could be a problem of the last loop?

A. No Problem B. Syntax Error C. Endless Loop D. Undefined Behavior

> Beware of integer overflows. Reminder: signed integer overflow is undefined behavior.

[Slide 50] Basic Functions[20]

- Associate a sequence of statements (body) with a name
- Function can have parameters and a return type (can be `void`)
- Non-`void` functions must execute `return` statement
- Arguments are passed **by value** (unlike Java for classes)
  - Pass-by-reference requires explicit annotation, see later

```
void procedure(unsigned parameter0, double parameter1) {
  // do something with parameter0 and parameter1
}
unsigned meaningOfLife() {
  // complex computation, takes 7.5 million years
  return 42;
}
```

[Slide 51] Basic Function Arguments

- Parameters can be unnamed ⇝ unusable, but still required on call
- Function can specify default arguments[21] in parameter list
  - After first param with default value, all must have a default value

```
unsigned meaningOfLife(unsigned /*unused*/) {
  return 42;
}
unsigned addNumbers(int a, int b = 2, int c = 3) {
  unsigned v = meaningOfLife(); // ERROR: expected argument
  unsigned w = meaningOfLife(123); // OK
  return a + b + c;
}
int main() {
  int x = addNumbers(1); // x == 6
  int y = addNumbers(1, 1); // y == 5
  int z = addNumbers(1, 1, 1); // z == 3
}
```

[20] https://en.cppreference.com/w/cpp/language/function
[21] https://en.cppreference.com/w/cpp/language/default_arguments

2.5 Namespaces

[Slide 52] Namespaces[22]

- Large projects contain many names ⇝ organize in logical units
- *namespaces* allow preventing name conflicts

```
namespace A {
void foo() { /* do something */ }
void bar() { foo(); /* refers to A::foo */ }
} // end namespace A
namespace B {
void foo() { /* do something */ }
} // end namespace B
int main() {
  A::foo(); // qualified name lookup
  B::foo(); // qualified name lookup
  foo(); // ERROR: foo was not declared in this scope
}
```

> Typically, the outermost namespace is used for the project name (e.g., `llvm`, `clang`, `umbra`). The namespace `std` is reserved for the C++ standard library. This prevents name collisions when using libraries.
>
> This has a big advantage over the C convention of using prefixes in names (e.g., `LLVM<name>` or `stdc_<name>`): inside namespaces, typing the redundant prefix can be avoided and namespaces can be imported with a `using namespace` directive (see below).

[Slide 53] Namespace Nesting

- Namespaces can be nested

```
namespace A {
namespace B {
void foo() { /* do something */ }
} // end namespace B
} // end namespace A

// equivalent definition
namespace A::B {
void bar() { foo(); /* refers to A::B::foo */ }
} // end namespace A::B

int main() {
  A::B::bar();
}
```

[Slide 54] Namespaces: `using` and Conventions

- Typically: add comments to closing namespace brace
- Always using fully qualified names makes code easier to read

[22] https://en.cppreference.com/w/cpp/language/namespace

- But: sometimes, source is obvious and typing cumbersome...
  - `using namespace X;` imports *everything* from `X`
  - `using X::a;` imports only *a* from `X`

```
namespace A { int x; }
namespace B { int y; int z; }
using namespace A;
using B::y;
int main() {
  x = 1; // Refers to A::x
  y = 2; // Refers to B::y
  z = 3; // ERROR: z was not declared in this scope
  B::z = 3; // OK
}
```

> Be careful about `using namespace`, this might pollute your namespace and result in unwanted naming collisions. You can also use `using` declarations inside a scope like this:
>
> ```
> namespace A { int x; }
> namespace B { int y; int z; }
> int main() {
>   using namespace A;
>   using B::y;
>
>   x = 1; // Refers to A::x
>   y = 2; // Refers to B::y
>   z = 3; // ERROR: z was not declared in this scope
>   B::z = 3; // OK
> }
> ```

2.6 Memory & Object Model

[Slide 55] Memory Model

- Fundamental storage unit: *byte*
  - There can (theoretically) be more than 8 bits in a byte
- Memory consists of one or more contiguous sequences of bytes
  - Memory can have holes, e.g. due to virtual memory
- Every byte has a unique address

[Slide 56] Objects[23]

- Object: region of storage; properties:
  - Size (see next slides)
  - Alignment (see next slides)
  - Storage duration (see next slides)
  - Lifetime (see next slides)

[23] `https://en.cppreference.com/w/cpp/language/object`

  - Type
  - Value
  - Optionally: name
- C++ programs create, destroy, refer to, access, and manipulate objects
- Examples for objects: local/global variables, parameters
  - Not objects: functions, references, values

[Slide 57] Object Size and Alignment

- Size and alignment requirements are defined by the type
- `sizeof` operator[24]: query size in bytes of object/type
  - `sizeof(char)` = `sizeof(std::byte)` = 1
  - All other sizes implementation-defined
- `alignof` operator[25]: query minimum alignment in bytes of type
  - Depending on implementation, some values must be aligned in memory
  - Alignment is always a power of 2
  - Address must be a multiple of the alignment

> Bytes that are larger than the industry standard of 8 bits are very rare, but do exist. Some embedded platforms, where the smallest possible memory access granularity is 32 bits, use 32-bit bytes. On such platforms, `sizeof(int)` can be 1.
>
> An alignment of x means that the address of the object is a multiple of x. The size is always a multiple of the alignment.

[Slide 58] Storage Duration[26]

- Every object has a storage duration

Storage Duration	Begin	End	Note/Example
automatic	Scope begin	Scope end	Local variables
static	Program begin	Program end	Global variables
thread	Thread start	Thread end	`thread_local` vars
dynamic	`new`	`delete`	

- Static: allocated/initialized before `main` in non-guaranteed order[27]
- Thread: one copy of the object per thread
- Dynamic: allocation/deallocation must be done manually

[24] `https://en.cppreference.com/w/cpp/language/sizeof`
[25] `https://en.cppreference.com/w/cpp/language/alignof`
[26] `https://en.cppreference.com/w/cpp/language/storage_duration`
[27] `https://en.cppreference.com/w/cpp/language/siof`

[Slide 59] Lifetime[28]

Lifetime of an object...

- starts when it is fully *initialized*
- ends when destructor called (classes) or storage is deallocated/reused (others)
- never exceeds the lifetime of the storage (see storage duration)

- Using an object outside its lifetime is **undefined behavior**
- This is a main source of memory bugs
- Compilers can only warn about very basic errors

⇒ If compiler warns, always **fix your program**

> When the compiler warns about a possible lifetime bug, this is most likely a problem in your code. Again: fix it. There can be very rare occasions where the warning is a false positive, but in these cases, you should adjust your code nonetheless so that the warning disappears.
>
> The lifetime of a reference (see later) ends as if it were a scalar object (e.g., `int`).

[Slide 60] Lifetime: Example

Quiz: When does the lifetime of `p` end?

```
int g;
void matterOfLifeOrDeath(unsigned a) {
  thread_local int t = 1;
  unsigned c = a;
  {
    unsigned p = a + 1;
  }
  unsigned m = t - 1;
}
```

A. At the end of the function.
B. At the end of the innermost block.
C. At the end of the program.
D. When the underlying stack space is reuseed (e.g., for `m`).

[Slide 61] Lifetime: Example

Quiz: What is problematic about this function?

```
int fancyZero() { // fancy way to return zero
  int x = x ^ x;
  return x;
}
```

A. Ill-formed/compile error: `x` used before its declaration.
B. Undefined behavior: signed integer overflow.
C. Undefined behavior: `x` used outside its lifetime.

[28] `https://en.cppreference.com/w/cpp/language/lifetime`

D. Undefined behavior: `x` used outside its storage duration.

[Slide 62] Basic Syntax and Object Model – Summary

- Fundamental types: void, integral, floating-point
- Exact width, representation, etc. not specified by standard
- Undefined behavior means anything can happen
- Undefined behavior must therefore never happen
- Basic syntax similar to other C-like languages, with additions
- Use namespaces to avoid naming collisions
- C++ programs resolve around working with objects
- Objects' lifetime is often implicit, leading to subtle bugs

[Slide 63] Basic Syntax and Object Model – Questions

- What is the required minimum size of an `unsigned int`?
- Why is arithmetic on `char` problematic?
- Why is `long double` rarely used?
- What can happen when undefined behavior is encountered?
- How can compilers use undefined behavior for optimizations?
- Which variable initializer prevents loss of accuracy?
- What is the storage duration of an object?
- What is the relation between storage duration and lifetime?

3 Declarations/Definitions, Preprocessor, Linker

[Slide 65] On "Internet"

Search engines/AI are **not** your friend when it comes to C++!
Use high-quality sources. Use the C++ reference. Read the script of this lecture.

3.1 Preprocessor

[Slide 66] Compiler: Overview (1)


```
clang++ -E -o hello.ii hello.cpp
clang++ -o hello hello.ii
```

- Preprocessor transforms source code before actual compilation
- `clang++ -E` – stop after preprocessing

[Slide 67] Preprocessor[1]

- Applies textual transformation before compilation
  - E.g., to conditionally exclude certain code paths from compilation
  - Preprocessor has no knowledge about "real" C++ language semantics
- Handles preprocessor directives: lines that begin with `#`
- Outputs program without directives

Use **carefully**, avoid if possible!

[Slide 68] Preprocessor: `#include`[2]

- `#include "path/to/file"` – copy content from file at current position
- Literal textual inclusion ("copy-paste")

[1] `https://en.cppreference.com/w/cpp/preprocessor`
[2] `https://en.cppreference.com/w/cpp/preprocessor/include`

```
//--- magicNumber.inc
42

//--- magicNumber.cpp
int magic =
#include "magicNumber.inc"
  ;
```

- After preprocessing

```
// clang++ -E magicNumber.cpp
int magic =
42
  ;
```

[Slide 69] Preprocessor: Include Path

- `#include "file"`
  - Search order: current directory, include path, system path
  - Convention: use for files in current project
- `#include <file>` – search include path, then system path
  - Search order: include path, system path
  - Convention: use for libraries and system includes
- Compiler flag: `-I<directory>` – add directory to include path
- CMake: `target_include_directories(target PUBLIC src/)`
- Typical: add root of project source to include path

  ⇒ All files can be included by "absolute path"

[Slide 70] Preprocessor: `#define`[3]

- `#define SOMENAME` – define a macro with the given name
- Can have an optional textual replacement
- `#undef` – undefined previously defined macro

```
#define EMPTY
#define return never
#define ANSWER 42
#define FUNC_DECL int getAnswer()
#undef return
FUNC_DECL { EMPTY return ANSWER; EMPTY }
// Preprocessed to:
// int getAnswer() { return 42; }
```

Don't use the preprocessor like this, this is primarily for illustration.[4]

[Slide 71] Preprocessor: `#define` – Example

Quiz: What does the function `f` return?

[3] `https://en.cppreference.com/w/cpp/preprocessor/replace`
[4] NB: Re-defining keywords is undefined behavior if the standard library is included.

```
#define ONE 1
#define TWO (ONE + ONE)
#define FOUR TWO+TWO
#define SIXTEEN FOUR*FOUR
int f() { return (SIXTEEN + FOUR) * TWO + TWO; }
```

A. (compile error) B. 2 C. 26 D. 42

Don't use the preprocessor like this, this is primarily for illustration.

> When placing expressions of any kind in a macro, it is highly recommendable to wrap them with parenthesis.

[Slide 72] Preprocessor: Pre-defined Macros

- Some macros are pre-defined by the compiler
- Few are standardized, others vary between compilers
- Typically begin with double-underscore

Examples:

- `__cplusplus` – used C++ standard, e.g. `202302L`
- `__FILE__` – name of the current file
- `__x86_64__` – defined if compiling for x86-64
- Compiler flag `-D<macroname>=<expansion>` – define a macro with the (optional) expansion

> Typically, many macros are pre-defined to describe the environment. You can use `clang++ -dM -E -x c++ - </dev/null` to list all pre-defined macros and their expansions. (You can use `clang++ -- help` to understand the supplied command line flags.)

[Slide 73] Preprocessor: Conditions[5] (1)

- `#if <expr>`/`#elif <expr>`/`#ifdef <macro>`/`#ifndef <macro>`/`#else`/`#endif` – conditionally compile part of code
  - Use cases: architecture-dependent code, code only for debug builds
- Expressions can use `defined(MACRO)` to test whether a macro is defined
- Preprocessor expressions *only* operate on macros!

```
#if defined(__x86_64__)
// x86-64-specific code goes here
#elif defined(__aarch64__)
// aarch64-specific code goes here
#else
// architecture-independent code goes here
#endif
```

[5] https://en.cppreference.com/w/cpp/preprocessor/conditional

[Slide 74] Preprocessor: Conditions (2)

- `#error` – cause compilation to fail with given message

```
#if defined(__x86_64__) || defined(__aarch64__)
// x86-64 and aarch64 code goes here
#else
#error Unsupported architecture!
#endif

#if 0 // #if 0 can be used for comments, can be nested (unlike /* */)
void commentedOut() {}
#if 0
void moreCommentedCode() {}
#endif
#endif
```

[Slide 75] Preprocessor: Conditions (3)

Quiz: What does the function `f` return?

```
int j = 5;
#if j * j == 25
int f() { return j * j; }
#else
int f() { return 20; }
#endif
```

A. (compile error) B. depends on `j` C. 20 D. 25

Don't use the preprocessor like this, this is primarily for illustration.

[Slide 76] Preprocessor: Function-Like Macros

- Macros can have arguments, so they look like functions
- Again, purely textual replacement, no semantics
  - Wrap all parameters in parentheses to avoid precedence issues

```
#define MIN(a,b) ((a)<(b)?(a):(b))

int min3(int a, int b, int c) {
// Preprocessed to:
// return ((((a)<(b)?(a):(b)))<(c)?(((a)<(b)?(a):(b))):(c));
  return MIN(MIN(a, b), c);
}
```

Don't use the preprocessor like this, this is primarily for illustration.

[Slide 77] Preprocessor: Function-Like Macros (Quiz)

Quiz: Why is this macro problematic?

```
#define MIN(a,b) ((a) < (b) ? (a) : (b))
```

A. One parameter is evaluated multiple times.
B. The unnecessary parenthesis make the code difficult to read.
C. The macro doesn't compute the minimum on unsigned integers.

- Don't do this — we'll cover modern replacements later

[Slide 78] Preprocessor: Recommendations

Avoid if possible!

- Many pitfalls, code harder to read/analyze/debug
- Many use-cases have modern, safer C++ replacements (see later)

- No rule without exceptions...
- Some older code bases use preprocessor heavily
  - Primary reason we cover it so extensively here

> - Use `constexpr` global variables instead of `#define BAR 1`
> - Use type-generic functions for function-like macros
> - Use `if constexpr ()` instead of `#if`/`#endif`
>
> There are, of course, exceptions to these guidelines. But generally, avoid the use of the preprocessor and only use it for header guards and header includes.

3.2 Assertions

[Slide 79] Runtime Checks for Debugging: `assert`

- `assert(expr)` – abort program if assertion is false
- Use to check invariants
- When `NDEBUG` is defined, assert generates no code
- CMake automatically defines `NDEBUG` in release builds

```
#include <cassert>
double div(double a, int b) {
  assert(b != 0 && "divisor␣must␣be␣non-zero");
  return a / b;
}
```

> The idiom `assert(condition && "explanation")` is widely used to add a more helpful message or reasoning to the assertion. This works, because `"strings"` always get converted to a non-zero value (simplified, will be explained later together with pointers).

[Slide 80] `assert` – Implementation

- `assert(expr)` is a preprocessor macro

⇒ Expression gets *removed from source code* when `NDEBUG` is defined!

```
//--- /usr/include/assert.h (glibc) (excerpt) (code simplified for slide)

/* void assert (int expression);

   If NDEBUG is defined, do nothing.
```

```
   If not, and EXPRESSION is zero, print an error message and abort. */
#ifdef NDEBUG
# define assert(expr) ((void)(0))
#else
# define assert(expr) ((expr) ? (void)(0) : __assert_fail(#expr, /*...*/))
#endif
```

> `#expr` is stringifies the parameter `expr`, which is the string printed to the console when the assertion fails.

3.3 Declaration & Definitions

[Slide 81] Multiple Source Files

- C++ source files know nothing about each other
  - Other than `#include`, which is just copy-paste

How do they know what functions other files define?

⇝ Explicit declarations

[Slide 82] Declarations[6]

- Declarations introduce names
- Names must be declared before they can be referenced
- Variables: `int x;`
- Functions: `void fn();`
- Namespace: `namespace A { }`
- Using: `using A::x;`
- Class: `class C;`
- ...

[Slide 83] Definition[7]

- A declared name can be used, but: most uses require[8] a *definition*
  - Reading/writing value or taking address of an object
  - Calling or taking address of function
- Most declarations are also definitions, with some exceptions
  - Function declaration without body
  - Variable declarations with `extern` and no initializer

[6] `https://en.cppreference.com/w/cpp/language/declarations`
[7] `https://en.cppreference.com/w/cpp/language/definition`
[8] Formally called *odr-use*

[Slide 84] Function Declarations: Example

- Forward declaration necessary for cyclic dependencies

```
void bar(int n); // declaration, no definition

void foo(int n) { // declare + define foo
  std::println("foo");
  if (n > 0)
    bar(n - 1); // OK, bar declared above
}

void bar(int n) { // re-declare + define bar
  std::println("bar");
  if (n > 0)
    foo(n - 1); // OK, foo declared above
}
```

> Without the forward declaration of `bar`, compilation will fail, because `bar` is not declared at the function call inside `foo`.
>
> It is generally advisable to avoid cyclic dependencies.

[Slide 85] Variable Declarations: Example

```
extern int global; // declaration
int otherGlobal; // declarartion + definition, zero-initialized

int readGlobal() {
  return global;
}

int global = 5; // re-declaration + definition
```

- The first declaration is rather useless, could move definition there

[Slide 86] cv-Qualifier: `const` and `volatile`[9]

- Part of the type, can appear in variable declarations
- `const` – object cannot be modified
- `volatile` – object access has a side-effect
  - E.g., direct hardware access, communication with signal handlers

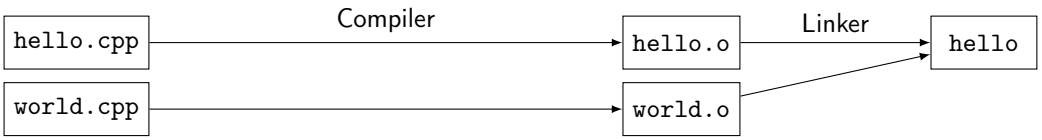
```
void function() {
  int a = 4;
  const int b = a;
  a = 0; // OK
  b = 10; // ERROR: assignment of read-only variable
  volatile int v = 5; // will not be optimized out
}
```

[9] https://en.cppreference.com/w/cpp/language/cv

> Do not use `volatile` unless you know that it is strictly require. *Do not use* volatile for synchronization across multiple threads!

3.4 Linker

[Slide 87] Compiler: Overview (2) – Multiple Files




```
clang++ -c -o hello.o hello.cpp
clang++ -c -o world.o world.cpp
clang++ -o hello hello.o world.o
```

- Compiler generates object file with machine code
  - One compile invocation compiles one *translation unit*
  - May contain references to not-yet-defined functions/globals
- Linker combines object files into executable
  - Resolve all undefined references

> The compiler invocation `clang++ -o hello hello.cpp world.cpp` internally runs all steps, but discards the intermediate results. This is impractical, because if `hello.cpp` changes but `world.cpp` did not, both need be recompiled.
>
> Separating the compiler invocations (`clang++ -c -o hello.o hello.cpp`; `clang++ -c -o world.o world.cpp`; `clang++ -o hello hello.o world.o`) allows selectively rebuilding the parts of the program that changed, significantly reducing the times of incremental builds. The compiler option `-c` instructs the compiler to stop after the compilation and emit an object file (instead of linking an executable).

[Slide 88] Multiple Files

```cpp
//--- foo.cpp
int globalVar = 7;
int foo() { return 6; }

//--- main.cpp
#include <print>
extern int globalVar;
int foo();
int main() {
  std::println("{}", globalVar * foo());
  return 0;
}
```

```
$ clang++ -std=c++23 -c -o foo.o foo.cpp
$ clang++ -std=c++23 -c -o main.o main.cpp
$ clang++ -o main main.o foo.o
$ ./main
42
```

> Declaration and definitions can be in different files. The compiler needs a declaration to know that a function/variable will exist, but does not require a definition. The definition must be supplied at link time.

[Slide 89] Multiple Files: Undefined References

```
//--- foo.cpp
int bar();
int foo() { return 2 * bar(); }

//--- main.cpp
extern int undefinedGlobal;
int main() {
  return undefinedGlobal;
}
$ clang++ -std=c++23 -c -o foo.o foo.cpp
$ clang++ -std=c++23 -c -o main.o main.cpp
$ clang++ -o main main.o foo.o
/usr/bin/ld: main.o: in function ‘main’:
main.cpp:(.text+0x8): undefined reference to ‘undefinedGlobal’
/usr/bin/ld: foo.o: in function ‘foo()’:
foo.cpp:(.text+0x8): undefined reference to ‘bar()’
clang++: error: linker command failed with exit code 1 (use -v to see invocation)
```

> If a global variable or function is referenced, but not defined in any of the object files (or libraries, including the standard library), the linker will detect this and fail. The compiler cannot detect this, as it has no knowledge about other object files or used libraries.

3.5 One Definition Rule

[Slide 90] One Definition Rule (ODR)[10]

- At most one definition of a name allowed *within one translation unit*
- Exactly one definition of every used function or variable must appear *within the entire program*
- (for more cases, exceptions, subtleties: see reference documentation)

NB: Some ODR violations make programs “ill-formed, no diagnostic required” — only the linker can diagnose such violations

[10] https://en.cppreference.com/w/cpp/language/definition#One_Definition_Rule

[Slide 91] One Definition Rule: Examples (Multiple Definitions)

```
int i = 0; // OK: declaration + definition
int i = 1; // ERROR: redefinition
```

```
//--- a.cpp
int foo() { return 1; }

//--- b.cpp
int foo() { return 2; }
clang++ -std=c++23 -c -o a.o a.cpp
clang++ -std=c++23 -c -o b.o b.cpp
clang++ a.o b.o
/usr/bin/ld: foo.o: in function `foo()':
b.cpp:(.text+0x0): multiple definition of `foo()'; a.o:a.cpp:(.text+0x0): first defined
    here
```

3.6 Header and Implementation Files

[Slide 92] Header and Implementation Files

- Duplicating declarations into every file technically possible
- But: not maintainable, error-prone

Idea: split into *implementation* (`.cpp`) and *header* (`.h`) file:

- Header file: just declarations that should be usable in other files
  - Conceptually: "API" of logical unit
  - Also should include documentation
- Implementation file: definitions for names declared in header
  - Conceptually: "implementation" of the API

Use *preprocessor* to copy-paste declaration

[Slide 93] Header and Implementation Files: Example

```
//--- sayhello.h
#include <cstdint>
/// Print "Hello!" to standard output.
void sayHello(std::uint64_t number);

//--- sayhello.cpp
#include "sayhello.h"
#include <cstdint>
#include <print>
void sayHello(std::uint64_t number) { std::println("Hello␣{}!", number); }

//--- main.cpp
#include "sayhello.h"
int main() { sayHello(1); return 0; }
```

[Slide 94] Header Guards

- Header files include other headers they require

  - E.g., for defined data types (see later)
- Transitive includes: same header might be included multiple times!
- But: can cause problems due to redefinitions

⇝ Wrap entire header with `#ifdef` and unique identifier

```
//--- sayhello.h
#ifndef CPPLECTURE_HELLO_H
#define CPPLECTURE_HELLO_H

/// Print "Hello!" to standard output.
void sayHello();

#endif // CPPLECTURE_HELLO_H
```

- Non-standard alternative

```
//--- sayhello.h
#pragma once

/// Print "Hello!" to standard output.
void sayHello();
```

> The first time `sayhello.h` is included, the macro `CPPLECTURE_HELLO_H` is not defined and therefore the remainder of the file will be considered. In particular, the macro will be defined. In a possible later second inclusion, the macro will be defined and the content of the file will be ignored.
>
> It is crucial that every header has a unique name for the header guard macro. By convention, the name of the path and file is used. This is particularly important when copying files.
>
> `#pragma once` is an alternative for the same goal. However, as there is no portable way to actually determine whether two files are the same (consider symbolic links, hard links, etc.), it is not standardized and therefore avoided by many projects.

[Slide 95] Header Files and `#include`

- Include (exactly) used header files at the beginning
  - In both, header and implementation file
  - Be careful about transitive includes
- Typically grouped by: (Example)
  1. Accompanying header file
  2. Project includes
  3. Library includes
  4. System includes
- Only include header files
- **Never** include implementation files!

[Slide 96] Typical Project Layout

```
+-- CMakeLists.txt
+-- src/
    +-- Module.cpp
    +-- Module.hpp
    +-- Printer.cpp
    +-- Printer.hpp
    +-- log/
        +-- Log.cpp
        +-- Log.hpp
        +-- LogEntry.cpp
        +-- LogEntry.hpp
    +-- main.cpp
```

- Source files and header files next to each other
- Entry points (`main()`) often separate
  - Typically small files ⇝ easier testing
- CMakeLists defines
  - `add_executable` with all sources (`*.cpp`)
  - `target_include_directories(... src)`
- Alternative layouts exist

> Some typical variants from this layout:
>
> - Headers are stored in a separate `include` directory next to `src`.
>   This is typically seen with libraries, where the public headers, which get installed and exposed to library users, are in `include` while private headers are in `src`.
> - Programs with `main` reside in a separate directory (e.g., `tools`). The main source files are compiled as a static library and executables link against the static library.
>   This is typically used when multiple programs get compiled. This way, the main source files get compiled only once and are testable, because they don't provide a program entry point.
> - One `CMakeLists.txt` per directory, which adds the source files of the directory to some variable instead of having a single top-level file that lists all files.
>   This is typically used by large projects where a single file list might not be maintainable.

[Slide 97] Tracking Changes in Source Code

```cpp
//--- a.hpp
extern int globalA;
//--- a.cpp
#include "a.hpp"
int globalA = 10;
//--- square.hpp
#include "a.hpp"
int square(int n = globalA);
```

```cpp
//--- square.cpp
#include "square.hpp"
void square(int n) {
  return n * n;
}
//--- main.cpp
#include "square.hpp"
// ...
```

Quiz: `a.hpp` changed. Which files to re-compile?

A. `a.hpp`
B. `a.cpp`
C. `a.cpp`, `square.cpp`
D. `a.cpp`, `square.cpp`, `main.cpp`
E. `a.hpp`, `a.cpp`, `square.cpp`, `main.cpp`

[Slide 98] Tracking Changes in Source Code

- Incremental compilation: only recompile files that actually changed
  - Substantially reduces build time during development
- Detecting files that need recompilation is non-trivial
  - Transitive dependencies of header files
- Build systems like CMake use compiler to output list of used includes
  - If any of the files changed, the source file needs recompilation

> It is also possible to achieve accurate tracking of updated header files with plain `Makefile`s, but it is non-trivial (it involved instructing the compiler to write dependencies to separate files and including these files in the `Makefile`). Thus, it is strongly recommendable to use a proper build system for C++ projects, which track dependencies. Examples are CMake, Meson, scons, and waf, and several others exist as well.

3.7 Linkage

[Slide 99] Linkage

- Linkage of declaration: visibility across different translation units
- No linkage: name only usable in their scope
  - E.g., local variables
- Internal linkage: can only be referenced from same translation unit
  - Global functions/variables with `static`
  - const-qualified global variables without `extern`
  - Declarations in namespace without name (“anonymous namespace”)
- External linkage: can be referenced from other translation units
  - Global functions/variables (unless `static`)

[Slide 100] Declaration Specifiers

- Variable/function declarations allow for additional specifier
- Controls storage duration *and* linkage

Specifier	Global Func/Variable	Local Variable
none	static + external	automatic + none
`static`	static + internal	static + none
`extern`	static + external	static + external
`thread_local`	thread + ext/int	thread + none

- And there's `inline` (it deserves it's own slide)

[Slide 101] Declaration Specifiers – Example

```
//--- a.cpp
static int foo = 1;
int bar = 2;
static int add(int x, int y) { return x + y; }
int countMe() {
  static int counter = 0; // static storage duration, no linkage
  return counter++
}

//--- b.cpp
static int foo = 1; // OK
int bar; // ERROR: ODR violation

// OK: a.cpp's and b.cpp's add have internal linkage
static int add(int x, int y) { return x + y; }
```

> You can use `static` on local variables. This can be useful for constant data that should only be visible inside the current function. Mutable variables with static storage duration are problematic in practice when multiple threads call the function in parallel.
>
> As a general advice, avoid mutable global variables (or local `static` variables) for this reason.

[Slide 102] Internal Linkage: Anonymous Namespaces

- Option A: Use `static` (only works for variables and functions)
  ```
  static int foo = 1; // internal linkage
  static int bar() { // internal linkage
      return foo;
  }
  ```
- Option B: Use *anonymous namespaces* (preferred)
  ```
  namespace {
  int foo = 1; // internal linkage
  int bar() { // internal linkage
  ```

```
    return foo;
}
} // end anonymous namespace
```

> In C++, prefer anonymous namespaces over `static` to change the linkage of global declarations.

[Slide 103] `inline` Specifier[11]

- `inline` – permit multiple definitions in different translation units
  - No direct relation to the inlining optimization!

```
//--- sum.h
#ifndef SUM_H
#define SUM_H

inline int sum(int a, int b) {
  return a + b;
}

#endif // SUM_H
//--- a.cpp
#include "sum.h"
// Now has definition of sum
// ...

//--- b.cpp
#include "sum.h"
// Now has definition of sum
// ...
```

- Linker keeps only one definition

> Inline definitions are useful when the presence of the definition can improve optimization, e.g. give the compiler the *opportunity* to do inlining, which would be impossible if the definition was in a different translation unit.
>
> As a downside, the function gets compiled in every translation unit that includes the definition, increasing compilation times and the size of the intermediate object files.
>
> Especially for inline definitions it is important to use header guards to prevent multiple definitions in the *same* translation unit.

[Slide 104] Declarations/Definitions, Preprocessor, Linker – Summary

- Preprocessor transforms source code before actual compilation
  - Use (almost) exclusively for header guards and header includes
- Use `assert()` for invariants, but be aware that it is a macro

[11] `https://en.cppreference.com/w/cpp/language/inline`

- Declarations introduce names, but not necessarily define them
- Exactly one definition of used func/var required in program
- For multiple files, separate header and implementation files
- There must be exactly one definition of every used name
- Exceptions: internal linkage and inline functions

[Slide 105] Declarations/Definitions, Preprocessor, Linker – Questions

- Why is the use of function-like macros problematic?
- What are state modifications inside `assert()` problematic?
- What is the difference between a declaration and a definition?
- How to declare functions and global variables?
- Why is the header guard important?
- Why is including C++ implementation files (`.cpp`) a bad idea?
- What does the `static` specifier do on local variables?
- What is the effect of an unnamed namespace?