Introduction to C++

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Introduction

Bibliography and useful online resources

- *Learn C++*, `https://learncpp.com/`: online resource with tutorials, examples and exercises
- *C++ Core Guidelines*: guidelines for the correct use of C++
- B. Stroustrup, *A tour of C++*, 3rd edition, Addison-Wesley. Part of the contents from the 2nd edition is available online at `https://isocpp.org/tour`
- B. Stroustrup, *Programming: Principles and Practice Using C++*, 2nd edition, Addison-Wesley
- B. Stroustrup, *The C++ Programming Language*, 4th edition, Addison-Wesley
- Online reference: C++ reference, `https://cppreference.com/`

Course outline

- Elements of computer architecture and operating systems
- Introduction to Linux/Unix
- Why C++
- Objects, types, variables
- Expressions
- Statements and structured programming
- Functions
- User-defined types and classes
- Generic programming and templates
- The Standard Library, containers, algorithms
- Error management
- Dynamic memory allocation
- Dynamic polymorphism (aka object-oriented programming)
- Elements of software engineering and supporting tools

Elements of computer architecture

The language of a computer

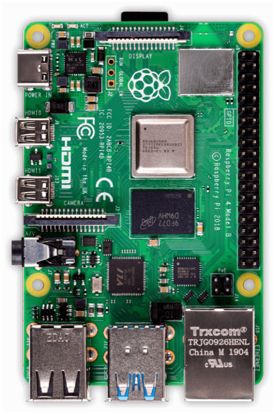
- A *computer* is a device that executes programs
- A *program* is a collection of instructions to perform a specific task
- For a computer to understand instructions, these need to be expressed in a language that the computer can understand

Many types of computers

(from https://www.samsung.com/)

(from https://www.ifixit.com/)

Many types of computers (cont.)



(from https://www.raspberrypi.org/)

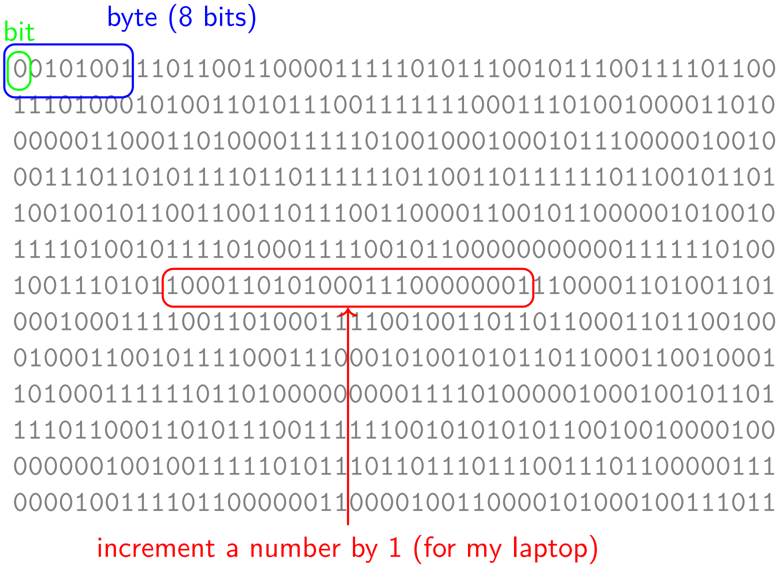
(from https://www.fairphone.com/)

Many types of computers (cont.)

Many types of computers (cont.)

(from https://wiki.u-gov.it/confluence/display/SCAIUS)

Computers understand a binary language



```
0010100111011001100001111101011100101110011110 1100
```

Programming language

- A (high-level) programming language is an artificial language to write programs that is closer to humans

```
int increment(int n)
{
  return n + 1;
}
```

- More or less equivalent to the mathematical function

$$\texttt{increment}(n) = n + 1 \quad \forall n \in \mathbb{Z}$$

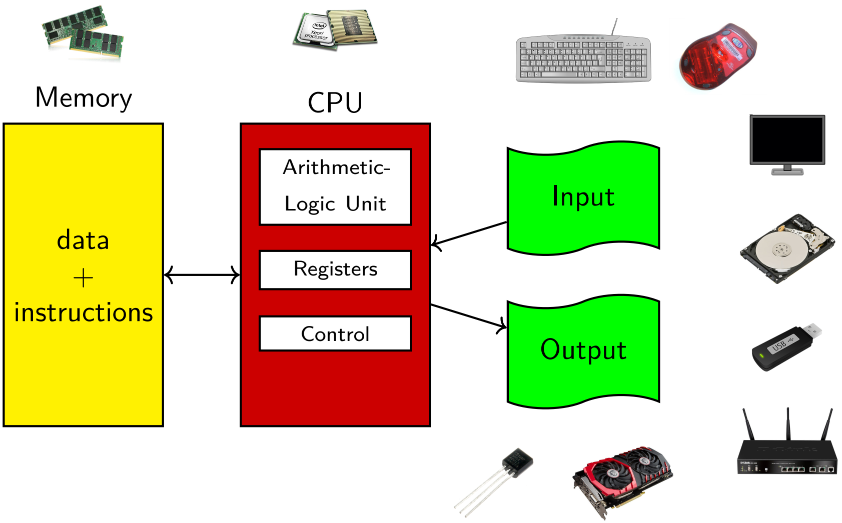
- Some form of translation needs to be applied to the program written in a high-level language to transform it into a program expressed in a binary language
    - A program expressed in a binary language is usually called *executable*

Programming language (cont.)

- To complicate things, the binary language is computer-specific (the correct term is *architecture*-specific)
  - An Instruction Set Architecture (ISA) defines, among other things, the binary instructions understood by a computer implementing that architecture
  - Many ISAs have been defined over the years, many still in use
  - i386, **x86_64**, SPARC, MIPS, **ARM**, VAX, Alpha, RiscV, PowerPC, . . .
- The translation from high-level language to binary language is done by other programs
  - compilers and interpreters

The Von Neumann architecture

Despite their differences, all architectures are inspired at the architecture first described by John Von Neumann in 1945.



The Von Neumann architecture (cont.)

- Imagine memory as a looooong tape divided into locations whose content you can read and write
  - Each location has the same size (let's assume one byte, i.e. 8 bits)
  - A piece of data can occupy multiple locations
- Each memory location is identified by an index
  - e.g. location at position 8'363'944
- During execution, executables (i.e. binary programs) and the data they manage stay both in memory, typically in different regions
- The CPU fetches binary instructions from memory into its registers and executes them
- Typical instructions:
  - read data (e.g. a number) from a memory location into a register
  - write data (e.g. a number) from a register to a memory location
  - manipulate data (e.g. increment a number or add two numbers) in registers

Also data are binary

...0100111011001100001111010111001011100111101100
11101000101001101011100111111100011101001000011010
00000110001101000011111010010001000101110000010010
00111011010111101101111110110011011111101100101101
10010010110011001101110011000011001011000001010010
1111010010111101000111100101100000000000001111110100
$100111\boxed{01100011011010010110000101101111}000000001101$
00010001111001101000111100100110110110001101100100
01000110010111100011100010100101011011000110010001
10100011111101101000000000111101000001000100101101
00001001111011000000110000100110000101000100111...

- read as integer number, the value is 1667850607
- read as floating-point number, the value is 4.30511×10^{21}
- read as character string, the value is “ciao”

Basics

C++

- There are many programming languages, with very different characteristics
- Why C++?
  - general purpose
  - support for multiple styles of programming (*paradigms*)
  - much used in scientific fields, but also in games, finance, telecommunications, embedded, . . .
  - available on most architectures and operating systems
  - efficient
  - ISO standard

A minimal C++ program

- This program does nothing, successfully (details will be explained)

```
int main() {}
```

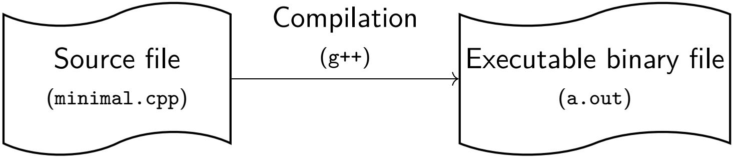
- Let's write these 13 characters (including spaces) in a **text document**, which we call `minimal.cpp`, using Visual Studio Code
  - In C++ terms, this text document is called source file
  - Also, let's start using the *shell*, writing commands in a *Terminal* instead of clicking icons with the mouse

```
$ ⟵ this is the shell prompt
$ code minimal.cpp ↵ ⟵ write this command (hit "Enter" at the end)
$ cat minimal.cpp ↵ ⟵ the cat command shows the contents of a text file
int main() {}
$
```

- Before executing the program we need to translate it into the language of the computer

A minimal C++ program (cont.)

- In C++ the translation into a binary format is the job of the compiler, which produces an executable file



```
$ g++ minimal.cpp
$ ls ←—— the ls command lists the contents of a directory
a.out  minimal.cpp
$ ./a.out ←—— this command executes the program
$ g++ minimal.cpp -o minimal
$ ls
a.out  minimal  minimal.cpp
$ ./minimal
$
```

- The −o option passed to the g++ command allows to give another name to the final executable

Spaces

- Spaces are (almost) irrelevant

```
int main(){}
```

```
int
main(   ) {
   }
```

space needed here

```
intmain(){ }
```

- Tools exist to consistently format source code to improve readability
    - They are customizable
    - You are **required** to use them

```
$ clang-format minimal.cpp
int main()
{
}
$
```

```
# .clang-format file
...
AllowShortFunctionsOnASingleLine: false
BraceWrapping:
  AfterFunction:   true
  ...
```

- NL.4

Syntax check

- The compiler can translate a program into a binary executable only if the code is syntactically correct

```
intmain() {}
```

```
$ g++ minimal.cpp
minimal.cpp:1:9: error: ISO C++ forbids declaration of 'intmain' with ...
    1 | intmain() {}
      |         ^
$
```

- Error messages are usually precise about the cause of the error, but not always
- Learn to interpret error messages

Comments

- Code can contain comments

```
int main() // comment until the end of the line
{
}
```

```
int main()
{
  /* possibly multi-line comment
     that goes until the final marker
     and cannot nest */
}
```

- Comments are ignored by the compiler and are equivalent to spaces
- Comments are for humans
  - Prefer expressive code
  - NL.1, NL.2, NL.3

Basic notions of Input and Output

- The input and output system allows a program to interact with the external world
- One mechanism offered by C++ to do input and output is the *I/O streams* interface, which allows the creation and the manipulation of *stream* entities
    - Values are extracted from an input stream
    - Values are inserted into an output stream
- Input and output streams connected to the terminal are automatically available to a program
    - `std::cin`, `std::cout` (and `std::cerr` for errors)
- To extract and insert values, use the stream *operators* >> and <<, respectively

Hello

A less minimal C++ program (details will be explained)

```
#include <iostream> // import I/O utilities
#include <string> // import string utilities

int main() // start the program from here
{
  std::cout << "What's your name? "; // print a message on the terminal
  std::string name; // some space is needed in memory for a string
  std::cin >> name; // read a string from the terminal into that space
  std::cout << "Hello, " << name << '\n'; // print a multi-part message
}
```

```
$ g++ hello.cpp -o hello ↵
$ ./hello ↵
What's your name? Francesco ↵
Hello, Francesco
$
```

Objects

- The constructs in a C++ program create, destroy, refer to, access, and manipulate objects
- An object is a region of storage (i.e. memory)
    - it has a type
    - it has a lifetime
    - it can have a name

Types

- A type gives meaning to a piece of storage
    - What's the meaning of a piece of storage that contains the sequence of bits 01100011011010010110000101101111?
    - Read as a sequence of alphabetic characters, it's the letters *c*, *i*, *a*, *o*
    - Read as an integer number, it's 1667850607
    - Read as a floating-point number, it's about 4.30511×10^{21}
- A type identifies a set of values and the operations that can be applied to those values
    - C++ is a strongly typed language (mostly)
- A type is also associated with a machine representation for the values belonging to the type

Types (cont.)

- The compiler checks that program instructions are compatible with the type system
    - C++ is a statically typed language (mostly)
- C++ defines a few fundamental types and provides mechanisms to build compound types on top of them

Fundamental types

- arithmetic types
  - integral types
    - signed integer types: `short int`, `int`, `long int`, `long long int`
    - unsigned integer types: `unsigned short int`, `unsigned int`, `unsigned long int`, `unsigned long long int`
    - character types: `char`, `signed char`, `unsigned char`, ...
    - boolean types: `bool`
  - floating-point types: `float`, `double`, `long double`
- `std::nullptr_t`
  - type of the null pointer `nullptr`
- `void`
  - denotes absence of type information

Size and representation may depend on the actual computer architecture where the program runs

int

Type representing a signed integer number

- Set of values: subset of $\mathbb{Z}$
- Operations: addition, subtraction, multiplication, division, remainder, comparisons, ...
- Representation: 2's complement
- With N bits, values are in the range $[-2^{N-1}, 2^{N-1} - 1]$
- Intended to have the natural size suggested by the architecture. Typical size is 32 bits (4 bytes)
    - $[-2\,147\,483\,648, +2\,147\,483\,647]$
- Default type you should use to count and do integer arithmetic
    - ES.102

7	0111
6	0110
5	0101
4	0100
3	0011
2	0010
1	0001
0	0000
-1	1111
-2	1110
-3	1101
-4	1100
-5	1011
-6	1010
-7	1001
-8	1000

Identifiers

- An *identifier* is a sequence of letters (including _) and digits, starting with a letter
    - Avoid _ at the beginning
- Identifiers are used to name entities in a program
    - Choose meaningful names
    - Get used to write in English
- NL.8

Keywords

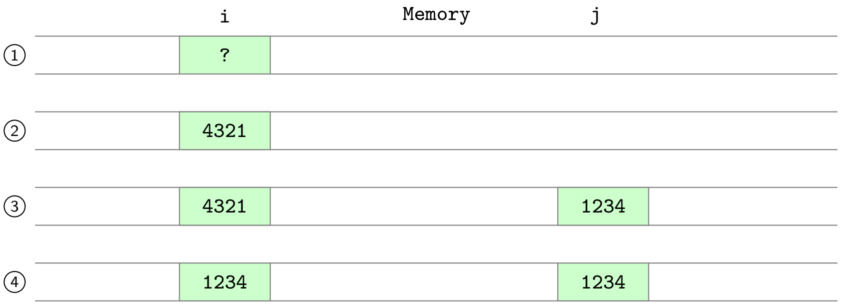
The following identifiers are reserved

alignas	consteval	final	or_eq	throw
alignof	constexpr	float	override	true
and	constinit	for	private	try
and_eq	const_cast	friend	protected	typedef
asm	continue	goto	public	typeid
auto	co_await	if	register	typename
bitand	co_return	import	reinterpret_cast	union
bitor	co_yield	inline	requires	unsigned
bool	decltype	int	return	using
break	default	long	short	virtual
case	delete	module	signed	void
catch	do	mutable	sizeof	volatile
char	double	namespace	static	wchar_t
char8_t	dynamic_cast	new	static_assert	while
char16_t	else	noexcept	static_cast	xor
char32_t	enum	not	struct	xor_eq
class	explicit	not_eq	switch	
compl	export	nullptr	template	
concept	extern	operator	this	
const	false	or	thread_local	

Variables

- A variable is an identifier that gives a name to an *object*

```
① int i;           // declaration; the value is undefined
② i = 4321;        // assignment of a constant
③ int j{1234};     // declaration and initialization in one step
④ i = j;           // assignment of j's value to i
```



NB At the end `i` and `j` have the same value but remain distinct objects

Literals

A literal is a constant **value** of a certain **type** included in the source code

- integer
- floating point
- character
- string
- boolean
- null pointer
- user-defined

Integer literals

decimal	non-0 decimal digit followed by zero or more digits • `1 -98 123456789 -1'234'567'890`
binary	`0b` or `0B` followed by binary digits • `0b110111010101101 0B111'0101'1011'1100'1101'0001'0101`
exadecimal	`0x` or `0X` followed by hexadecimal digits • `-0xdead 0xDEad123f 0XdeAD'123F`
octal	`0` followed by octal digits • `01 -077 07'654'321` • N.B. A `0` in front of a number is meaningful!

Integer literals are of type `int`

`std::string`

- A *compound* (*user-defined*) type to represent a string of characters
- Provided by the C++ Standard Library
- Many operations available
- An `std::string` can be initialized with a string literal, a sequence of escaped or non-escaped characters between double quotes
  - `"hello"` `"hello'\n'world"` `"hello \"world\""`
  - `\n` means "newline"
- The type of a string literal is **not** `std::string`

```
std::string corso{"Programmazione per la Fisica"};
corso = corso + "\nAnno Accademico 2023/2024";
```

concatenate

Expressions

- An expression is a sequence of operators and their operands that specifies a computation
- Literals and variables are typical operands, but there are others

```
1 + 2
i = 1 + 2       // assignment
i == j          // equality comparison
sqrt(x) > 1.42
std::cout << "hello, " << name << '\n'
a > 0 ? a - 1 : a + 1
```

- The evaluation of an expression typically produces a result
- Some expressions have *side-effects*
  - They modify the state of the program, i.e. the state of memory, or the external world
- Avoid complicated expressions (ES.40)

Operators

Arithmetic	Logical	Comparison	Increment	Assignments	Access	Other
`+a`	`!a`	`a == b`	`++a`	`a = b`	`a[b]`	`a(···)`
`-a`	`a && b`	`a != b`	`--a`	`a += b`	`*a`	`a, b`
`a + b`	`a || b`	`a < b`	`a++`	`a -= b`	`&a`	`? :`
`a - b`		`a > b`	`a--`	`a *= b`	`a->b`	
`a * b`		`a <= b`		`a /= b`	`a.b`	
`a / b`		`a >= b`		`a %= b`		
`a % b`				`a &= b`		
`~a`				`a |= b`		
`a & b`				`a ^= b`		
`a | b`				`a <<= b`		
`a ^ b`				`a >>= b`		
`a << b`						
`a >> b`						

Plus: casts, allocation and deallocation, static introspection, . . .

- Rules exist for associativity, commutativity and precedence
  - When in doubt use parentheses (ES.41)
- Many operators can be overloaded for user-defined types
  - e.g. + to concatenate strings

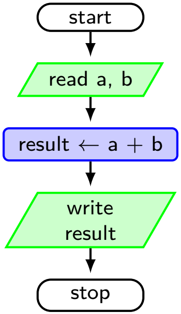
Flow control

Algorithm

A finite sequence of precisely defined steps to solve a problem

Sum of two numbers

A program that reads two numbers from input and writes their sum to output



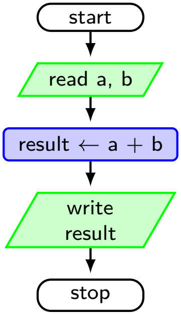
Statement

Statements are units of code that are executed in sequence

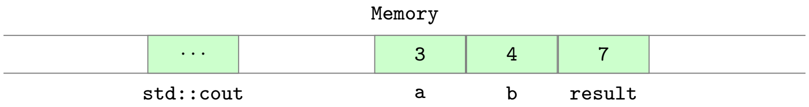
- expression statement
- compound statement or block
- declaration statement
- selection statement
- iteration statement
- jump statement
- ...

Sum of two numbers

A program that reads two numbers from input and writes their sum to output



```
#include <iostream>

int main()
{
  int a;
  int b;
  std::cin >> a >> b;
  int result{a + b};
  std::cout << result << '\n';
}
```



Expression statement

- An expression followed by a semicolon (;)
- The value of the expression (if any) is discarded
- The expression can have side effects
    - Indeed, we often write statements with the purpose to change data in memory or to do I/O (input/output)

```
b + 2;
a = b + 2;
std::cin >> a >> b;
; // empty statement
```

Compound statement (or block)

A sequence of zero or more statements enclosed between braces ({})

```
{
   found = true;
   ++i;
   int n{3};
   std::cout << n;
}
```

```
{ found = true; ++i; ··· } // all on one line
```

Declaration statement

- A declaration statement introduces one or more new identifiers into a C++ program, possibly initializing them
  - typically variables, but not only
- A declaration of a **variable** in a **block** makes the variable of automatic storage duration, unless otherwise specified
  - the corresponding object is automatically created each time the declaration is executed
  - the corresponding object is automatically destroyed each time the execution reaches the end of the block
- A declaration should introduce only one identifier (ES.10)
- A variable should be declared only in the moment it's actually needed (ES.21)
- A variable should be initialized at the point of declaration (ES.20)
  - There are very few exceptions, if any, to this recommendation

Scope

The scope of a name appearing in a program is the, possibly discontiguous, portion of source code where that name is valid

- block scope
- function scope
- class scope
- namespace scope (including the global one)
- ...

Block scope

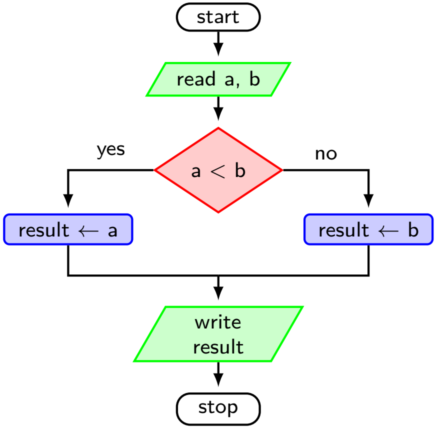
- The scope of a name declared in a block starts at the point of declaration and ends at the }

```
{
  num + 1;          // error
  int num;          // scope of num begins only here
  std::cin >> num;  // ok
}                   // scope of num ends here
std::cout << num;   // error
```

- The scope of a variable should be as small as possible (ES.5)
  - Declare a variable only when it's needed
  - If possible/meaningful, initialize it

The smallest of two numbers

A program that reads two numbers from input and writes the smallest to output



```
#include <iostream>

int main()
{
  int a;
  int b;
  std::cin >> a >> b;
  int result;
  if (a < b) {
    result = a; // (1)
  } else {
    result = b; // (2)
  }
  std::cout << result << '\n'; // (3)
}
```

`result` cannot be defined in (1) and/or (2), otherwise it would not be visible in (3)

if then else

- Selection statement to choose one of two flows of instructions depending on a boolean condition
- Two (basic) forms:
  - `if (` *condition-expr* `)` *statement* `else` *statement*
  - `if (` *condition-expr* `)` *statement*

```
if (a < b) {
  result = a;   // "true" branch
} else {
  result = b;   // "false" branch
}
```

```
int i{···};
if (i < 0) {
  i = -i;   // "true" branch
}
```

- *condition-expr* can be any expression whose result is of type (convertible to) `bool`, i.e. either true or false
- *statement* can be a block, possibly including multiple statements
  - In fact, the statement should always be a block

bool

Type representing a boolean value

- Set of values: *false*, *true*
- Operations: logical conjunction (*and*), disjunction (*or*) and negation (*not*), assignment, comparison
- Size: typically 1 byte
- Representation: like the `int`s `0` and `1`
- Literals: `false` and `true`

```
bool b{true};
b = i == j;
bool b2{i != 1234;}
bool b3{b2 && i < j};    // and
bool b4{i < j || i < k}; // or
bool b5{!(i == j)};      // not
```

- Note the use of parenthesis in `!(i == j)` to have the right precedence of application of operators

assignment equality inequality

Logical operations

and True if both operands are true

op1	op2	op1 **&&** op2
`false`	`false`	`false`
`false`	`true`	`false`
`true`	`false`	`false`
`true`	`true`	`true`

op2 is evaluated only if op1 is `true`

or True if at least one operand is true

op1	op2	op1 || op2
`false`	`false`	`false`
`false`	`true`	`true`
`true`	`false`	`true`
`true`	`true`	`true`

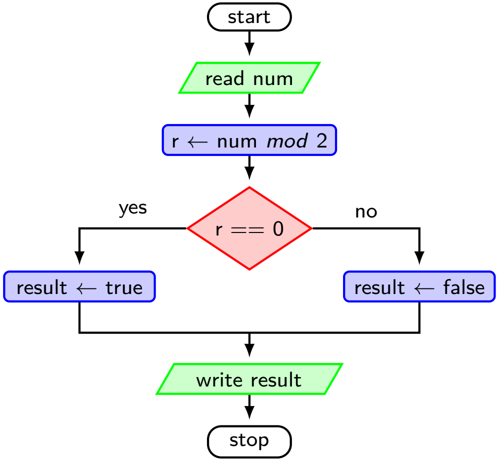
op2 is evaluated only if op1 is `false`

not Operand's negation (or logical complement)

op	!op
`false`	`true`
`true`	`false`

Example: is a number even?

A program that reads a number from input and tells if it's even



```
#include <iostream>

int main()
{
  int num;
  std::cin >> num;
  int r{num % 2};
  bool result;
  if (r == 0) {
    result = true;
  } else {
    result = false;
  }
  // print 0/1
  std::cout << result << '\n';
  // print false/true
  std::cout << std::boolalpha
        << result << '\n';
}
```

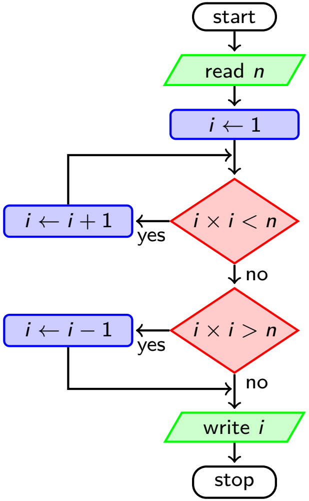
The whole `if` can be removed defining `bool result{r == 0};`

Exercise: the smallest of three numbers

Write a program that reads three numbers from standard input and writes the smallest one to standard output

Integer square root

Write a program that computes the integer square root of a non-negative integer number, i.e. the largest integer number whose square is not greater than the given number



```
#include <iostream>

int main()
{
  int n;
  std::cin >> n;
  int i{1};
  while (i * i < n) {
    ++i;   // equivalent to i = i + 1
  }
  if (i * i > n) {
    --i;   // equivalent to i = i - 1
  }
  std::cout << i << '\n';
}
```

`while` loop

`while (` *condition-expr* `)` *statement*

- Execute repeatedly *statement* until *condition-expr* becomes false
- *condition-expr* is evaluated at the beginning of each iteration
  - If *condition-expr* is already `false` at the beginning, *statement* is never executed
- *statement* can be any statement
  - It's better if the statement is always a block
- *statement* should modify something so that the evaluation of *condition-expr* may change
  - Otherwise the loop may never terminate

Sum of the first N numbers

Write a program that reads a non-negative integer number N from standard input, computes the sum of the first N numbers and writes the result to standard output

```
#include <iostream>

int main()
{
  int n;
  std::cin >> n;
  int sum{0}; // or just sum{}
  int i{1};
  while (i <= n) {
    sum += i;   // sum = sum + i
    ++i;
  }
  std::cout << sum << '\n';
}
```

```
#include <iostream>

int main()
{
  int n;
  std::cin >> n;
  int sum{0};

  for (int i{1}; i <= n; ++i) {
    sum += i;

  }
  std::cout << sum << '\n';
}
```

`for` loop

`for (` *init-statement condition-expr*$_{opt}$ `;` *expression*$_{opt}$ `)` *statement*

- Execute *init-statement*, which may be a single `;`
  - If *init-statement* contains declarations (e.g. the `i` variable in the previous example), the scope of the declared names is the loop
- Execute repeatedly *statement* until *condition-expr* becomes false
- *condition-expr* is evaluated at the beginning of each iteration
  - If *condition-expr* is already false at the beginning, *statement* is never executed
  - But *init-statement* is always executed

`for` loop (cont.)

`for (` *init-statement condition-expr*$_{opt}$ `;` *expression*$_{opt}$ `)` *statement*

- *expression* is evaluated at the end of each iteration
- *statement* and/or *expression* should modify something so that the evaluation of *condition-expr* may change
  - Otherwise the loop may never terminate
- A `for` loop can always be transformed into a `while` loop and viceversa
  - Prefer a `for` loop when there is an obvious variable that controls the loop
  - ES.72, ES.73

Integer square root with a `for` loop

Write a program that computes the integer square root of a non-negative integer number, i.e. the largest integer number whose square is not greater than the given number

```
#include <iostream>

int main()
{
  int n;
  std::cin >> n;
  int i{1};
  while (i * i < n) {
    ++i;
  }
  if (i * i > n) {
    --i;
  }
  std::cout << i << '\n';
}
```

```
#include <iostream>

int main()
{
  int n;
  std::cin >> n;
  int i{1};  // NB outside the loop
  for ( ; i * i < n; ++i) ;  // or {}


  if (i * i > n) {
    --i;
  }
  std::cout << i << '\n';
}
```

Exercise: the largest/smallest of N numbers

Write a program that reads an arbitrary sequence of numbers from standard input and writes the largest (or smallest) one to standard output
Hint 1: press Ctrl-D in the terminal to tell the program there is nothing more to read from standard input
Hint 2: the expression `std::cin.good()` tells if it's still possible to read something from `std::cin`

`double`

Type representing a floating-point number

- Set of values: subset of $\mathbb{R}$
- Operations: addition, subtraction, multiplication, division, comparisons, ...
- Representation: IEEE 754
- 64 bits, smallest values $\approx \pm 10^{-308}$, largest values $\approx \pm 10^{308}$
- Precision is about 16 decimal digits
- Literals in the form *sign*$_{opt}$ *significand* *exponent*$_{opt}$
    - `42.0 1.  -1.5 12.34e3 -.34E-3 -1234e-2`
    - $\cdots$`e`n / $\cdots$`E`n means $\times 10^n$

`float`

Type representing a floating-point number

- Set of values: subset of $\mathbb{R}$
- Operations: addition, subtraction, multiplication, division, comparisons, ...
- Representation: IEEE 754
- 32 bits, smallest values $\approx \pm 10^{-38}$, largest values $\approx \pm 10^{38}$
- Precision is about 7 decimal digits
- Literals in the form *sign*$_{opt}$ *significand* *exponent*$_{opt}$ `F`
  - `42.0f 1.F -1.5f 12.34e3F -.34E-3f -1234e-2F`
  - Same as double but with an `f` or `F` suffix

Handle floating-point numbers with care

- Floating-point numbers are **not** real numbers
  - Finite representation $\implies$ there is a previous and a next
- When managing floating-point numbers one should take into account rounding errors and inexact representations

```
float x{1'000'000'000.f};
std::cout << std::setprecision(10)
  << x - 32 << ' ' << x << ' ' << x + 32 // 1000000000 1000000000 1000000000
  << x + 32 - x << ' ' << x - x + 32;    // 0 32
```

- Floating-point math in general is not associative
- When comparing floating-point numbers avoid the use of equality
- See What Every Computer Scientist Should Know About Floating Point Arithmetic

Exercise: accumulate 0.001

Write a program that accumulates the `float` `0.001` (think a time step of one millisecond) 1'000'000 times and prints the accumulated value. Discuss the result.

Standard mathematical functions

The `cmath` header includes many ready-to-use mathematical functions

- Exponential
- Power
- Trigonometric
- Interpolation
- Hyperbolic
- Floating-point manipulation, classification and comparison
- ...

```
#include <cmath>
...
double x{···};
std::sqrt(x);
std::pow(x, .5);
std::sin(x);
std::log(x);
std::abs(x);
```

Type conversions

- A value of type T1 may be converted **implicitly** to a value of type T2 in order to match the expected type in a certain situation

```
1 + 2.3
```

  - between numbers and bool
  - between signed and unsigned numbers
  - between numbers of different size
  - between integral and floating-point numbers
  - ...
- Conversions sometimes are surprising
- Conversions can be explicit using `static_cast`

```
1 + static_cast<int>(2.3)
```

- Mechanims exist to define implicit and explicit conversions involving user-defined types

const-safety

- Data qualified as `const` is logically immutable
- Data that is meant to be immutable should be `const` (Con.4)

```
int const x{1'000'000'000}; // or const int
std::cout << x + 32;    // ok, read-only
x += 32;                // error, trying to modify
int const y;            // error, not initialized and not modifiable later
```

```
std::string const message{"Hello"};
std::cout << message + " Francesco";      // ok, read-only
message += " Francesco";                  // error, trying to modify
std::string const empty_message;          // ok! empty string
```

- Primitive types (e.g. `int`) and user-defined types such as `std::string`) behave differently with respect to *default initialization*, i.e. without an explicit initial value
    - User-defined types can define what default initialization means
    - For `std::string` it means "empty string"
    - More later

Functions

Functions

- A function abstracts a piece of code that performs a well-defined task behind a well-defined interface
- A function associates a block of statements with
  - a name
  - a list of zero or more parameters
- A function may return a result
- Let's consider the code that computes the integer square root
  - Let's give it a name $\rightarrow$ `isqrt`
  - We pass `isqrt` a number $\rightarrow$ the list of parameters has only one item of type `int`
  - `isqrt` computes a value that we want back $\rightarrow$ the function returns a value of type `int`
- F.1, F.10

The isqrt function

```
#include <iostream>

int main()
{
  int n;
  std::cin >> n;
  int i{1};
  while (i * i < n) {
    ++i;
  }
  if (i * i > n) {
    --i;
  }
  std::cout << i << '\n';
}
```

```
#include <iostream>

int isqrt(int n)  // function definition
{
  int i{1};
  while (i * i < n) {
    ++i;
  }
  if (i * i > n) {
    --i;
  }
  return i;       // return statement
}

int main()
{
  int n;
  std::cin >> n;
  int i{isqrt(n)};  // function call
  std::cout << i << '\n';
}
```

Names on the two sides of the call are independent

Function declaration

- A function declaration contains the essential information needed to invoke the function
  return-type function-name (*parameter-list*) ;
- If the declaration is followed by the actual block of statements (the *implementation* of the function), it is also a definition
  return-type function-name (*parameter-list*) { ··· }
  - Note the block scope
- Each parameter in the parameter list is of the form
  type $name_{opt}$
  - *type* is mandatory
  - *name* is optional
    - in the declaration, but useful for documentation purposes
    - in the definition if it's not used (F.9)

Function declaration (cont.)

- Parameters are separated by commas
- The parameter list can be empty, i.e. `()`
- If the function returns nothing, the return type is `void`

```
int isqrt(int);                            // declaration
int count_words(std::string s) { ··· }  // definition
double pow(double base, double exp);   // declaration
void print(std::string);                   // declaration
int generate_random_number() { ··· }    // definition
```

Returning from a function

- Within the function block, the `return` statement returns the result (and the control) to the calling function
- For a function returning a non-`void` type
  `return` *expression* `;`
  The result of *expression* must be convertible to the return type
- For a function returning `void`
  `return;`
  At the end of the function, `return;` is optional

Returning from a function (cont.)

- A function has only one entry point, but it may have multiple exit points, i.e. there can be multiple `return` statements

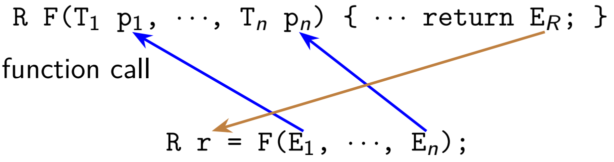
```
bool is_prime(int n) {
  // simple cases
  if (n == 2) { return true; }
  if (n == 1 || n % 2 == 0) { return false; }

  // complex cases
  ...

  return result;
}
```

Invoking a function

- Invoking/calling a function is a type of expression of the form $F(E_1, E_2, \ldots, E_N)$
  - F is an expression that identifies a function, typically its name
  - The E_i's are expressions, whose values are "passed" to the function

```
int s = isqrt(24);
std::cout << count_words("Hello, " + name);
print(std::to_string(pow(isqrt(24), 2)));
```

- Given a function



$$\texttt{R F(T}_1\ \texttt{p}_1\texttt{, }\cdots\texttt{, T}_n\ \texttt{p}_n\texttt{) \{ }\cdots\texttt{ return E}_R\texttt{; \}}$$

and a function call

$$\texttt{R r = F(E}_1\texttt{, }\cdots\texttt{, E}_n\texttt{);}$$

  - Each $\texttt{p}_i$ is initialized with the value of expression $\texttt{E}_i$
  - `r` is initialized with the value of expression $\texttt{E}_R$

Invoking a function (cont.)

- A function needs to be declared/defined before it's used

```
int main()
{
  ...
  isqrt(num); // error
  ...
}

int isqrt(int n)
{
   ...
}
```

```
int isqrt(int n)
{
  ...
}

int main()
{
  ...
  isqrt(num); // ok
  ...
}
```

```
int isqrt(int);

int main()
{
  ...
  isqrt(num); // ok
  ...
}

int isqrt(int n)
{
  ...
}
```

Function definition

- The lifetime of parameters ends at the end of the block

```
bool is_prime(int n)
{
  ... n ...
} // the lifetime of n ends here
```

- A function can call other functions

```
bool is_prime(int n)
{
  ...
  int div{2};
  int const s{isqrt(n)};
  while (div <= s) {
  ...
}
```

- A function should not be too long (F.3)
- A function should perform a single logical operation (F.2)
- Split long/complex functions into multiple parts, each implemented as a function

Recursive functions

- A function can call itself, directly or indirectly
  - This is called *recursion*
  - Often an elegant alternative to a loop
  - Not easy to master, don't abuse

```
int sum_n(int n)
{
  // assume n >= 0
  if (n == 0) {  // base case
    return 0;
  } else {      // recursive case
    return n + sum_n(n - 1);
  }
}
```

Function overloading

- Multiple functions can have the same name
  - But different lists of parameters (number and/or types)
- The compiler chooses the function that best matches the arguments in the call
  - It usually does what is expected, possibly applying appropriate implicit conversions, but not always
  - Compilation error if there is no match or no unique best match
- The return type doesn't matter

```
void foo(int);
int  foo(int, char);
bool foo(double);
int  foo(std::string s);

foo(0);              // call foo(int)
foo(0, '0');         // call foo(int, char);
foo(0.);             // call foo(double)
foo(std::string{}); // call foo(std::string)
foo(0L);             // long int, ambiguous, error
foo('a');            // call foo(int)
foo("a");            // call foo(std::string)
```

The `main` function

- The `main` (special) function is the entry point of a program
- It can have two forms
  - `int main() {···}`
  - ...(see later)
- If there is no `return` statement at the end, an implicit `return 0;` is assumed
  - 0 means success, different from 0 means failure
  - Or use `EXIT_SUCCESS` and `EXIT_FAILURE` from `<cstdlib>`
  - The returned value is available to the shell via the `$?` variable

```
#include <cstdlib>

int main() {
  int n;
  std::cin >> n;
  if (std::cin.fail() || n < 0) {
    std::cerr << "Invalid number\n";
    return EXIT_FAILURE;
  }
  ...
}
```

Exercises

- Write a function `pow` that takes two `int`s and computes and returns the value of the first (the base) raised to the power of the second (the exponent)
- Write a function `gcd` that takes two `int`s and computes the Gratest Common Denominator using the Euclid's algorithm
- Write a function `lcm` that takes two `int`s and computes the Least Common Multiple
- Write a function `is_prime` that takes an `int` and tells if it's a prime number
- More on edabit, leetcode, ...

How do we know the code we write is correct?

- Correctness is the absence of defects (also known as bugs) in a software
- Correctness is the result of the application of multiple good practices to the software developmente process
- One of the most effective techniques is **testing**
  - Execute the code with reasonable and unreasonable input and see if it behaves according to the expectations
  - The purpose of testing is to (try to) break the code

Testing can reveal the presence of bugs, not prove their absence!

- Here we focus on a form of testing called *unit testing*, where the units (of code) under test are, for example, functions
- There are many tools/frameworks to do unit testing (Google Test, Catch, Doctest, Boost.Test, . . .)
- Let's use Doctest (`https://github.com/doctest/doctest`)

How to use Doctest

- On Compiler Explorer it's available selecting it under "Libraries"
- Otherwise download locally a single *header file* into the directory containing your code, e.g. using `wget` or `curl`
- At the top of your C++ file add the lines

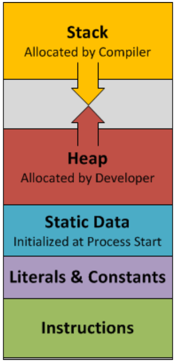
```
#define DOCTEST_CONFIG_IMPLEMENT_WITH_MAIN
#include "doctest.h"
```

- Don't add `main` into your file
- After the declarations of the function(s) you want to test, add lines like the following:

```
TEST_CASE("Testing isqrt") {
  CHECK(isqrt(0) == 0);
  CHECK(isqrt(9) == 3);
  CHECK(isqrt(10) == 3);
  CHECK(isqrt(-1) == 0);
  ...
}
```

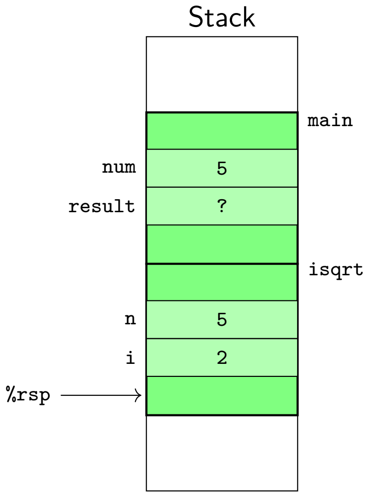
Memory layout of a process

- A process is a running program
- When a program is started the operating system brings the contents of the corresponding file into memory according to well-defined conventions
    - Stack
        - function local variables
        - function call bookkeeping
    - Heap
        - dynamic allocation
    - Global data
        - literals and variables
        - initialized and uninitialized (set to 0)
    - Program instructions



Functions and the stack

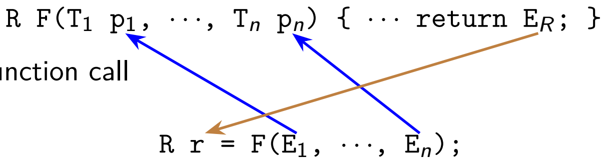
```
int isqrt(int n)
{
  int i{1};
  while (i * i < n) {
    ++i;
  }
  if (i * i > n) {
    --i;
  }
  return i;
}

int main()
{
  int num;
  std::cin >> num;
  int result{isqrt(num)};
  std::cout << result << '\n';
}
```



The state of the stack just before returning from isqrt

Pass by-value, return by-value

Given a function



$$\texttt{R F(T}_1\texttt{ p}_1\texttt{, }\cdots\texttt{, T}_n\texttt{ p}_n\texttt{) \{ }\cdots\texttt{ return E}_R\texttt{; \}}$$

and a function call

$$\texttt{R r = F(E}_1\texttt{, }\cdots\texttt{, E}_n\texttt{);}$$

- Each $\texttt{p}_i$ is initialized with the value of expression $\texttt{E}_i$
  - Every time the function is called a new $\texttt{p}_i$ is created, which gets destroyed at the end of the function
  - NB if $\texttt{E}_i$ is just a variable, $\texttt{p}_i$ is another object (a copy) and changing it inside the function doesn't change the original object corresponding to the variable
- $\texttt{r}$ is initialized with the value of expression $\texttt{E}_R$

Stack frame

- A piece of memory allocated and dedicated to the execution of a function
- It contains local variables (including function parameters), return address, saved registers, ...
- Managed in a Last-In, First-Out (LIFO) way
- The size of the stack frame is computed by the compiler
- There is a special register (the stack pointer register, `%rsp`) that indicates the frame of the currently running function
- At runtime the allocation/deallocation of a frame consists simply in subtracting/adding that frame size to the stack pointer register

Conditional/ternary operator expression

$$expression_{condition} \;\texttt{?}\; expression_{true} \;\texttt{:}\; expression_{false}$$

```
int gcd(int a, int b)
{
  return (b == 0) ? a : gcd(b, a % b);
}
```

- Evaluate $expression_{condition}$, whose value is of type (convertible to) `bool`
- If `true`, $expression_{true}$ is evaluated and the resulting value is the value of the whole expression
- If `false`, $expression_{false}$ is evaluated and the resulting value is the value of the whole expression
- Similar to an `if` statement, but usable (and useful) where only an expression is allowed
- The types of $expression_{true}$ and $expression_{false}$ are subject to some constraints, but let's assume that they have to be the same

`break` and `continue` for loops

- Within a loop block, the `break` statement allows to terminate the loop
- Within a loop block, the `continue` statement allows to jump to the end of the current iteration of the loop
- The same effect can be obtained with appropriate use of conditionals, but the resulting code may be more complicated (ES.77)

Object initialization with braces

- An object can be initialized specifying its value between {}

```
int i{123};
float f{123.F};
std::string s{"hello"};
```

- Introduced as a *universal* form of initialization that could replace all others, but there are situations where it's not usable
- Protects against *narrowing*, i.e. loss of information caused by implicit conversions

```
double d{1.};            // ok, no conversion
float f1{1.};            // ok, no information loss
float f2{d};             // error
float f3{9'999'999};     // ok, no information loss
float f3{99'999'999};    // error
int i{1.};               // error
int g{d};                // error
```

`char`

Type representing a character

- Set of values: letters in the alphabet (lower- and upper-case), digits, punctuation marks, some special characters, . . .
- Size: typically 1 byte, but not necessarily
- Representation: let's assume the ASCII encoding
- Literals: characters between single quotes
  - `'a' 'B' '7' ',' '?'  '#' '/'`
- Some character literals need to be expressed as \-escaped sequences
  - `'\'' '\\' '\n' '\t' '\0'`
- A `char` is an integral type so it supports integral operations
  - `std::cout << '9' - '0'; // 9`
  - `c < 'z';`

Exercises

- Write a function that takes a `char` and returns the corresponding lowercase character if it is a letter; the same char otherwise
    - e.g. 'A' → 'a', 'a' → 'a', ';' → ';'
- Write a function that takes two numeric operands of type `double` and one operator of type `char` and returns the result of applying that operator to the two operands. For example if the two operands have values 2.0 and 3.0 respectively and the operator has value `'+'`, then the function returns a result with value 5.0. If the operator is invalid, the function returns 0.

Pointers and references

Passing by value may be inconvenient

- Consider a function that increments an `int` object

```
void increment(??? n) {
  // ++n
}

int number{42};
increment(number);
// number == 43
```

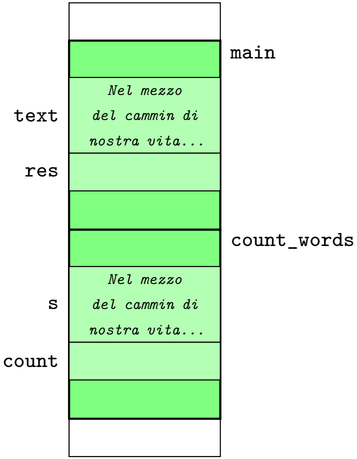
- NB The function does not **return** the new value; it modifies the passed object **in place**
- We cannot write `void increment(int n)`, because the function would modify a **copy** of the original object

Passing by value may be expensive

Let's consider a function that counts the number of words in a string

```
int count_words(std::string s)
{
  int count{0};
  ··· s ···
  return count;
}

int main()
{
  std::string text{···};
  int const res{count_words(text)};
  std::cout << res << '\n';
}
```

- s is a **copy** of text
- I'm slightly cheating: not all string memory goes on the stack


main
text
Nel mezzo del cammin di nostra vita...
res
count_words
s
Nel mezzo del cammin di nostra vita...
count

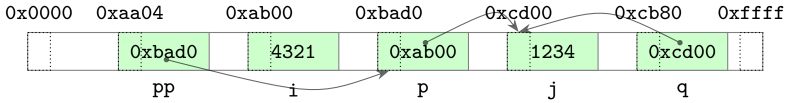
Hexadecimal notation

- Numbers in hexadecimal notation are represented in base sixteen
- Each digit has a value between zero and fifteen (included)
- Sixteen symbols are needed for the digits
  - 0 ... 9, A, B, C, D, E, F (also lowercase)
- In C++ numeric literals (i.e. constants) can be expressed in hexadecimal notation, prepending `0x` (or `0X`) to the hexadecimal representation
  - `0x9 == 9`, `0xA == 10`, `0x10 == 16`
- Easy conversion between hex and binary representation: each hex digit corresponds to four bits
- Hex literals are typically used to represent raw contents of memory or memory addresses

Hex	Dec	Bin
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111

Pointers

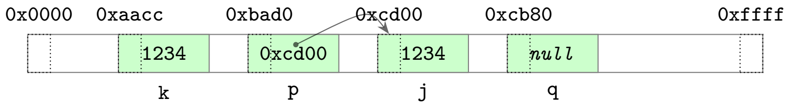
Where in memory does a given object reside?



```
int i{4321};
int j{1234};
std::cout << &i;  // 0xab00, address-of operator
std::cout << &j;  // 0xcd00
int* p{&i};       // pointer declarator
std::cout << &p;  // 0xbad0
int** pp{&p};     // &p is of type int**
p = &j;
int* q{p};        // p and q point to the same object
```

Note that `int*` is a new type and so is `int**`

Pointers (cont.)



```
int j{1234};
int* p{&j};
std::cout << *p; // 1234, dereference operator
int k{*p};       // k is a copy of j
*p = 5678;
++*p;            // or ++(*p) for more clarity
int* q{p};
q = nullptr;
*q;              // undefined behavior
```

Dereferencing a null pointer is a logical error (i.e. a bug)

Pointers (cont.)

- *address-of* operator: `&`
  - Given an object, it returns its address in memory
- *dereference* operator: `*`
  - Given a pointer to an object, it gives access to that very object

Passing a pointer

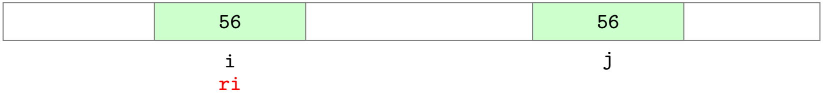
```
void increment(int* n) {
  ++(*n);
}

int number{42};
increment(&number);
// number == 43
```

```
int count_words(std::string* s)
{
  int count{0};
  ··· *s ···
  return count;
}

std::string text{···};
count_words(&text);
```

- The caller takes the address of the object and passes it to the function
- The function dereferences the pointer to get access to the object
- Be careful not to dereference a null pointer

References

- A variable declared as a reference of a type T is another name (an *alias*) for an existing object of type T



```
int i{12};
int j{56};
int& ri{i};          // reference declarator
ri == 12;            // true
ri = 34;
ri == 34 && i == 34; // true
ri = j;
ri == 56 && i == 56; // true
int& r;              // error
```

References (cont.)

- A reference must be initialized to refer to a valid object
    - A reference cannot be *null*
- A reference cannot *rebind* (be re-associated) to another object
- For a given type `T`, `T&` is a *compound* type, distinct from `T`
- Dereferencing a pointer gives back a reference to that object

```
int i{42};
int* p{&i};
int& r{*p}; // i and r are names for the same object
```

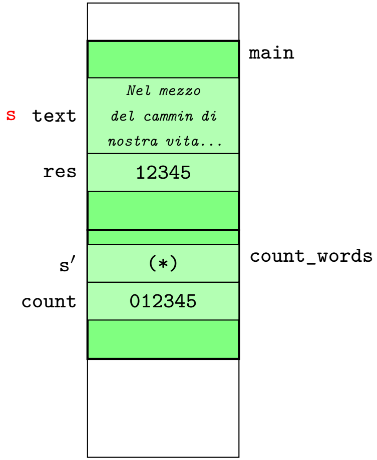
Passing by reference

```
void increment(int& n) {
  ++n;
}

int number{42};
increment(number);
// number == 43
```

- There is no difference in the caller compared to pass-by-value
- There is no difference in the body of the function compared to pass-by-value
- The only visual clue is in the parameter declaration

Passing by reference (cont.)

```
int count_words(std::string& s)
{
   int count{0};
   ··· s ··· // just use s
   return count;
}

int main()
{
   std::string text{···};
   int const res{count_words(text)};
   std::cout << res << '\n';
}
```



(*) In general it's unspecified if a reference occupies storage. Here probably it does and a pointer (called s′) is passed behind the scenes.

const and references

```
std::string text{···};
std::string& rtext{text};        // ok, can read/modify text via rtext
std::string const& crtext{text}; // ok, crtext is a read-only view of text
```

```
std::string const text{···};
std::string& rtext{text};        // error, else could modify text via rtext
std::string const& crtext{text}; // ok, can only read text via crtext
```

```
int count_words(std::string const& s)
{
  // this function can only read from s
   ...
}
```

const and pointers

```
std::string text{···};
std::string* ptext{&text};        // ok, can read/modify name via *ptext
std::string const* cptext{&text}; // ok, can only read text via *cptext
```

```
std::string const text{···};
std::string* ptext{&text};        // error, else could modify text via *ptext
std::string const* cptext{&text}; // ok, can only read text via *cptext
```

How to pass arguments to functions

- For input parameters
  - If the type is primitive, pass by value

```
int isqrt(int n);         // good
int isqrt(int const& n); // bad! pessimization
```

  - Otherwise pass by const reference

```
int count_words(std::string const&);
```

- For output parameters, prefer to return a value or pass by non-const reference

```
int read_from_cin();      // may be more difficult to overload for other types
void read_from_cin(int& n);
```

- For input-output parameters, pass by non-const reference

```
void to_lowercase(std::string& s);
```

- Parameter passing

Returning a reference

- A function can return a reference only if the referenced object survives the end of the function
  - Otherwise, in the caller, the reference would refer to an object that doesn't exist anymore
- In particular do not return a reference to a function local variable
  - F.43

```
// bad
int& add(int a, int b) {
  int result{a + b};
  return result;
}
```

```
// acceptable
int& increment(int& a) {
  ++a;
  return a;
}
```

- Useful to chain multiple function calls on the same object

```
std::string& to_lower(std::string& s) { ··· ; return s; }
std::string& trim_right(std::string& s) { ··· ; return s; }
std::string& trim_left(std::string& s) { ··· ; return s; }

std::string s{···};
trim_left(trim_right(tolower(s)));
```

range-for loop

`for` (*range-declaration* : *range-expression*) *statement*

- Simplified form of a `for` loop, to iterate on all the elements of a *range* (sequence), such as a string of characters (ES.71)
- Execute repeatedly *statement* for all the elements of the range
- *range-declaration* declares a variable of the same type of an element of the range
    - Can (and should) be a (const) reference
- *range-expression* represents the range to iterate over
- More on ranges later

```
std::string s{"Hello!"};
for (char& c : s) {
  c = std::toupper(c);
}

for (int i : {1, 2, 3, 4, 5}) {
  std::cout << i << ' ';
}
```

auto

Let the compiler deduce the type of a variable from the initializer, i.e. from the expression used to initialize the object

```
auto z;                          // error, no initializer
auto i = 0;                      // int
auto const f = 0.F;              // float const
auto r = i + f;                  // float
auto s = std::string{"hello"}; // std::string
auto& rs = s;                    // std::string&
auto const& cri = i;             // int const&
auto j = rs;                     // std::string
auto& g = f;                     // float const&
auto p = &i;                     // int*
auto q = p;                      // int*
auto* t = p;                     // int*
```

- `auto` never deduces a reference
- `auto` preserves constness of references
- Personal preference to use `=` instead of `{}` when initializing an `auto` variable
  - Both `auto i{0}` and `auto i = 0;` are fine

auto/trailing return type

- When the return type of a function is `auto` the compiler will deduce it from the return statement(s)
  - Only usable in a function definition

```
auto isqrt(int n)    // auto deduced as int
{
  int result;
  ...
  return result;
}
```

- If there are multiple return statements their expressions must have the same type
- Trailing return type

```
int foo(···);
auto foo(···) -> int; // equivalent
```

Enumerations

- An *enumeration* is a distinct type with named constants, called *enumerators* (Enum.2)

```
enum class Operator { Plus, Minus, Multiplies, Divides };
```

- When used, an enumerator is specified with the name of the enumeration followed by the scope-resolution operator (`::`)

```
auto op = Operator::Plus; // op is of type Operator
```

- By default, an enumerator has the value of the previous enumerator incremented by one and the first enumerator has value 0
- An enumerator can be given a value explicitly (Enum.8)

```
enum class Operator { Plus = -2, Minus, Multiplies = 42, Divides };
```

The values are respectively -2, -1, 42 and 43.

Enumerations (cont.)

- An enumeration has an integral *underlying type*, by default `int`
- A different underlying type can be selected (Enum.7)

```
enum class byte : unsigned char { };
```

  Note that in this case there are no enumerators → a way to define a new integral type different from the underlying type

- All values of the underlying type are valid values for the enumeration object

```
Operator op{55};  // ok
```

- Conversions to the underlying type need to be explicit

```
int i{Operator::Plus};                      // error
int i{static_cast<int>(Operator::Plus)};  // ok
```

Enumerations (cont.)

- There is also a less strict version of an enumeration: the *unscoped* enumeration (Enum.3)

```
enum Operator { Plus, Minus, Multiplies, Divides }; // NB no class
```

- The symbols of the enumerators are visible in the enclosing scope
  - i.e. the enumerators are not specified with the name of the enumeration followed by `::`

```
Operator op{Plus};  // ok, no need to use Operator::
```

- The conversion to the underlying type is implicit

```
int i{Plus};  // ok
```

- Prefer the scoped enumeration

The switch statement

The switch statement transfers control to one of multiple statements, depending on the value of a condition (ES.70)

```
double compute(char op, double left, double right)
{
  double result;

  switch (op) {
    case '+':
      result = left + right;
      break;
    ...
    case '/':
      result = (right != 0.) ? left / right : 0.;
      break;
    default:
      result = 0.;
  }

  return result;
}
```

The `switch` statement (cont.)

- The condition is an expression whose evaluation gives an integral or enumeration value
    - Cannot switch on strings, for example
- An enumeration plays well with `switch` statements

```
double compute(Operator op, double left, double right)
{
  switch (op) {
    case Operator::Plus:       return left + right;
    case Operator::Minus:      return left - right;
    case Operator::Multiplies: return left * right;
    case Operator::Divides:    return right != 0. ? left / right : 0.;
    default: return 0.;
  }
}
```

The `switch` statement (cont.)

- Each statement, possibly compound, is introduced either by a `case` label or by a `default` label
- Each `case` label specifies a unique integral constant
- Typically each statement is followed by a `break` statement, to jump after the `switch`, otherwise control *falls through* the next instruction, even if this is part of a statement introduced by another label
  - The compiler typically warns about falling through, but sometimes it's ok and the warning can be silenced with the `[[fallthrough]]` (ES.78) *attribute*
- There can be at most one `default` label, not necessarily at the end (ES.79)
- The same statement can be introduced by multiple `case` labels

Data abstraction

Data abstraction

- The C++ language has a strong focus on building lightweight data abstractions
  - The source code can use terminology and notation close to the problem domain, making it more expressive
  - There is little (if any) overhead in terms of space or time during execution
- `class` and `struct` are the primary mechanism to define new compound types on top of fundamental types C.1

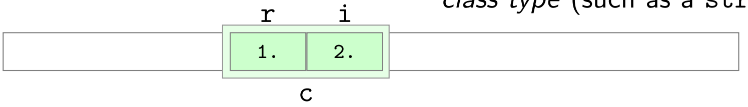
Data structure

- Let's introduce a type to represent complex numbers
- We can pass/return `Complex` objects to/from functions, take pointers and references, ...

```
struct Complex {
  double r; // data member (field)
  double i;
};

double norm2(Complex c);
Complex sqrt(Complex c);

Complex c{···};
double n{ norm2(c) };
Complex c2{ sqrt(c) };

Complex& cr{c};  // reference
Complex* cp{&c}; // pointer
```

```
double norm2(Complex c) {
  return c.r * c.r + c.i * c.i;
}

double norm2(Complex const& c) {
  return c.r * c.r + c.i * c.i;
}
```

- A `Complex` is composed of two `double`s
- The `.` (dot) operator allows to access a member of an object of *class type* (such as a `struct`)



Operations

It's possible to define operations on user-defined types

```
struct Complex {
  double r;
  double i;
};

bool operator==(Complex const& a, Complex const& b) {
  return a.r == b.r && a.i == b.i;
}

Complex operator+(Complex const& a, Complex const& b) {
  return Complex{a.r + b.r, a.i + b.i};
}

c2 = c1       // generated by the compiler, if used
c1 == c2
c1 + c2
z = z * z + c
2. * c1
...
```

Operator overloading

- C++ offers the possibility to define the meaning of most of the operators available for fundamental types when applied to user-defined types
- Syntactically this is done via the definition of appropriate functions
- Given an operator `@`, the function name is called `operator@`
- Although there are some constraints on the number and types of the parameters and on the type of the return value, the overloaded operators are just functions
- The behaviour of the overloaded operator should reproduce the behaviour of the original one
- Some behaviours cannot be changed, e.g. associativity

Exercises

- Define some other operators and functions for Complex
- Write a function to compute the solutions of an equation of the form $ax^2 + bx + c = 0$, given the three coefficients (Hint: F.21)

More data abstraction

Imagine to change the Complex type to use the polar form

```
struct Complex {
  double rho;
  double theta;
};
```

- As a consequence, all client code has to change

```
double norm2(Complex const& c) { return c.rho * c.rho; }
```

- Not all combinations of (ρ, θ) are valid
  - $\rho \geq 0, \theta \in [0, 2\pi)$

```
Complex c{-1, -1}; // valid?
c.rho = -1;        // valid?
```

- We wish we could
  - have more isolation between client code and implementation
  - enforce an internal relation (*class invariant*) between data members

Private representation, public interface

- The internal representation of a data structure should be considered an implementation detail
- The manipulation of objects should happen through a well-defined function-based interface
- Known as encapsulation C.3 C.9
- Data member variables (also known as fields) are often named in a special way
    - `_` suffix or `m_` prefix

```
class Complex {
 private: // cartesian form
  double r_;
  double i_;
 public:
  // associated functions (member functions, also known as methods)
};

Complex c{1., 2.}; // error
auto norm2(Complex const& c) {
  return c.r_ * c.r_ + c.i_ * c.i_; // error
}
```

Construction

- A class can have a special function, called constructor, which is called to initialize the storage of an object when it is created
  - It should initialize all data members, in order to establish the *class invariant* C.40 C.41
- The constructor's name is the same as the class name
- Data members are initialized in the order of declaration and should preferably be initialized in the *member initialization list* C.47 C.49

```
class Complex {
 private:
  double r_;
  double i_;
 public:
  Complex(double x, double y) // no return type
      : r_{x}, i_{y} // member initialization list
  { /* nothing else to do */ }
  ...
};

Complex c{1., 2.}; // or (1., 2.)
```

Private representation, public interface (cont.)

- The internal representation of a class should be considered an implementation detail
- The manipulation of objects should happen through a well-defined function-based interface

```
class Complex {
 private:
  double r_;
  double i_;
 public:
  Complex(double x, double y) : r_{x}, i_{y} {}
  double real() { return r_; } // member function (method)
  double imag() { return i_; }
};

double norm2(Complex c) {
  return c.real() * c.real() + c.imag() * c.imag();
}
```

- For a `class`, `private` is the default and can be omitted

Private representation, public interface (cont.)

- Member functions (methods) can of course also mutate an object

```
class Complex {
 public:
  void add(Complex const& other) {
    r_ += other.r_; // no need to use other.real() (*)
    i_ += other.i_;
  }
  ...
};

Complex c{1., 2.};
Complex d{3., 4.};
c.add(d);
c.real(); // 4.

c.add(Complex{3., 4.}); // valid
c.add({3., 4.});        // also valid
```

- (*) Control of access to the private part is per class, not per object

Private representation, public interface (cont.)

- Member functions that don't modify the object should be declared **`const`**

```
class Complex {
  double r_;
  double i_;
 public:
  Complex(double x, double y) : r_{x}, i_{y} {}
  auto real() const              // cannot modify this object
  { return r_; }
  auto add(Complex const& other) // can modify this object
  { r_ += ···; }
};

Complex c{1.,2.};
c.real();                // ok
c.add({3.,4.});          // ok
Complex const cc{1.,2.};
cc.real();               // ok
cc.add({3.,4.});         // error
```

Private representation, public interface (cont.)

- It's not rare to have functions with the same name, but in two different forms: one that reads and one that modifies the internal state
  - Example of function overloading

```
class Complex {
 public:
  double real()          const { return r_; }
  void   real(double d)        { r_ = d; }
  ...
};
```

```
Complex c{1.,2.};
c.real(0.);
c.real();             // return 0.
```

```
Complex const c{1.,2.};
c.real(0.);          // error
c.real();            // ok
```

- Alternatively, methods can be prefixed with `get_/set_`
  - e.g. `double get_real();`, `void set_real(double);`

Member vs free function

```
class Complex {
 public:
  double norm2() const { // member function
    return r_ * r_ + i_ * i_;
  }
  ...
};

double norm2(Complex const& c) { // free function
  return c.real() * c.real() + c.imag() * c.imag();
}

Complex c{···};
c.norm2(); // call the member function
norm2(c);  // call the free function
```

- The public part of a class should ideally provide a safe, efficient and complete interface, yet minimal
- Prefer a free function, if possible C.4
  - Extend the functionality of a class without modifying existing code

`std::string` (cont.)

- A user-defined type to represent a sequence of characters
- Provided by the C++ Standard Library
- Provides many member functions
    - Construction
    - Capacity (e.g. `size()`, `empty()`)
    - Assignment (e.g. `=`, `assign()`)
    - Comparison (`==`, `!=`, `<`, `>`, `<=`, `>=`)
    - Access to a character (e.g. `[]`, `back()`, `front()`)
    - Insertion/removal (e.g. `insert()`, `append()`, `erase()`)
    - Search (e.g. `find()`)
    - ...

Construction (cont.)

- A class can have multiple constructors

```
class Complex {
  double r_;
  double i_;
 public:
  Complex(double x, double y) : r_{x}, i_{y} {}
  Complex(double x) : r_{x}, i_{0.} {}
  Complex() : r_{0.}, i_{0.} {} // default constructor
  ...
};

Complex c1{1., 2.};
Complex c2{1.};        // meaning {1., 0.}
Complex c3;            // or {}, meaning {0., 0.}; () cannot be used here
Complex cf();          // this is a function declaration!
```

- The default constructor (i.e. the constructor without parameters) can be automatically generated by the compiler, but only if there are no other constructors

Construction (cont.)

- A constructor can **delegate** the construction to another, usually more generic, constructor C.51

```
class Complex {
  double r_;
  double i_;
 public:
  Complex(double x, double y) : r_{x}, i_{y} {}
  Complex(double x) : Complex{x, 0.} {}      // delegating constructor
  Complex() : Complex{0., 0.} {}             // delegating constructor
  ...
};

Complex c1{1., 2.};
Complex c2{1.};       // meaning {1., 0.}
Complex c3;           // meaning {0., 0.}
```

Construction (cont.)

- A data member can be given a **default initializer**, which is used if the member is not explicitly initialized in the called constructor

```
class Complex {
  double r_{0.};
  double i_{0.};
 public:
  Complex(double x, double y) : r_{x}, i_{y} {}
  Complex(double x) : r_{x} {} // i_ initialized with 0
  Complex() = default; // r_ and i_ initialized with 0
  ...
};

Complex c1{1., 2.};
Complex c2{1.};         // meaning {1., 0.}
Complex c3;             // meaning {0., 0.}
```

- `= default` tells the compiler to generate the default implementation for a *special member function* (such as the default constructor) C.45 C.80
  - Do not use `{}`

Construction (cont.)

- For any function, a parameter can be given a default value, in case the corresponding argument is omitted
- Arguments can be omitted starting from the right
- **Default function arguments** can be used also for a constructor

```
class Complex {
  double r_;
  double i_;
 public:
  Complex(double x = 0., double y = 0.) : r_{x}, i_{y} {}
  ...
};

Complex c1{1., 2.};
Complex c2{1.};       // meaning {1., 0.}
Complex c3;           // meaning {0., 0.}
```

explicit constructor

```
class Complex {
  ...
  Complex(double x = 0., double y = 0.) : r_{x}, i_{y} {}
};

double norm2(Complex const& c) { ··· }

norm2(1.); // callable with a double (-> Complex)
norm2(1);  // callable with an int (-> double -> Complex)
c + 3;     // call operator+ with two Complex
3 + c;     // call operator+ with two Complex, only if free function
```

- The (one-parameter) constructor is used for the conversion
- An `explicit` constructor prevents the implicit conversion

```
class Complex {
  ...
  explicit Complex(double x = 0., double y = 0.) ···
};

norm2(1.);          // error
norm2(Complex{1.}); // ok
```

explicit constructor (cont.)

- An `explicit` constructor prevents also the implicit construction of an object from a list of arguments between braces
  - e.g. in a function call or in a `return` statement

```
class Complex {
  ...
  Complex(double x, double y) ···
};

Complex operator+(···)
{
  ...
  return {r, i}; // ok
}
```

```
class Complex {
  ...
  explicit Complex(double x, double y) ···
};

Complex operator+(···)
{
  ...
  // return {r, i}; // error
  return Complex{r, i}; // ok
}
```

- Better start with explicit constructors, especially for the constructor callable with one argument, and relax the constraint later C.46

Pointers and data structures

- *address-of* operator: `&`
    - Given an object it returns its address in memory
- *dereference* operator: `*`
    - Given a pointer to an object it returns a reference to that object
- *structure dereference* operator: `->`
    - Given a pointer to an object of class/struct type, it returns a reference to a member of that object

```
struct S {
  int n;
  void f();
};

S q{···};
S* p = &q;
p->n;         // equivalent to (*p).n
p->f();       // equivalent to (*p).f()
```

The `this` pointer

Within the body of a member function of a class `T`, the keyword **`this`**

- is a pointer of type `T*` (or `T const*` if the method is `const`)
- points to the object for which the method was called

```
struct Foo {
  void bar() {
    ... this ...;
  }
};

Foo alfa;
Foo beta;
alfa.bar(); // inside bar, this is &alfa
beta.bar(); // inside bar, this is &beta
```

operator@ in terms of operator@=

- Typically, a symmetric `operator@` (e.g. `operator+`) is implemented in terms of a member `operator@=` (e.g. `operator+=`)

```
Complex operator+(Complex const& lhs, Complex const& rhs)
{
  Complex result{lhs};   // create the result as a copy of lhs
  return result += rhs;  // add rhs to the result and return it
}
```

- Typically, `operator@=` returns a reference to the object being operated on

```
class Complex {
  ...
  Complex& operator+=(Complex const& rhs) {
    r_ += rhs.r_;
    i_ += rhs.i_;
    return *this; // *this means self
  }
};
```

Example: rational numbers

- Let's implement a class to represent rational numbers
- The representation is with two integers, such that
    - The fraction is irreducible, i.e. their GCD (Greatest Common Denominator) is 1
    - If the number is negative the sign is kept in the numerator
    - The denominator is different from 0

Example: rational numbers (cont.)

```
class Rational
{
  int n_;
  int d_;
 public:
  Rational(int num = 0, int den = 1) : n_{num}, d_{den}
  {
    if (d_ == 0) {
      // construction must fail
    }
    // reduce
    auto const g{ std::gcd(n_, d_) }; // in <numeric>
    n_ /= g;
    d_ /= g;
    // fix sign
    if (d_ < 0) {
      n_ = -n_;
      d_ = -d_;
    }
  }
  ...
};
```

Class invariant

- A **class invariant** is a relation between the data members of a class that constrains the values that such members can assume
    - It defines what is a valid state for an object of that class
    - It must always hold for an object of that class
- The invariant is established by the constructor
- The invariant is preserved by **public** methods
    - The invariant holds when the function is entered $\implies$ the implementation can make assumptions
    - The invariant may be violated during the execution of the function
    - The invariant is re-established before exiting the function
- C.2

assert

Check that a certain boolean expression is satisfied at run time

- for example, a class invariant at the end of a constructor or a condition at the beginning of a function (a *pre-condition*)

```
#include <cassert>

class Rational {
  ...
  Rational(int num = 0, int den = 1) : n{num}, d{den} {
    ...
    assert(std::gcd(n, d) == 1 && d > 0);
  }
  Rational& operator/=(int n) {
    assert(n != 0);
    ...
  }
};

bool operator==(Rational const& l, Rational const& r)
{
  assert(std::gcd(l.num(), l.den()) == 1 && std::gcd(r.num(), r.den()) == 1);
  return l.num() == r.num() && l.den() == r.den();
}
```

`assert` (cont.)

- If the asserted condition is not satisfied, it means that the state of the program does not conform to the expectations of the programmer, i.e. to the design
- The state may even be corrupted → it's probably wiser to `terminate` the program as soon as possible to avoid causing damage
- Very useful to identify logical errors (i.e. bugs)
    - Be generous with the number of `assert`s in your code
- Can be disabled for performance reasons (`g++ -DNDEBUG` ···)
    - Avoid side effects in `assert`s (e.g. assignments or calls to non-const methods), because they would disappear from the executable

assert (cont.)

- assert (but also Doctest's CHECK) is a *preprocessor macro*
- Macros obey syntactic rules that are different from those of C++ proper

```
assert(Rational{1,2} == Rational{2,4});   // error (*)
assert(Rational(1,2) == Rational(2,4));   // ok
assert((Rational{1,2} == Rational{2,4})); // ok
```

  * macro "assert" passed 3 arguments, but takes just 1

- Macros *expand* to arbitrary text, which is then passed to the real C++ compiler
- A bit more about the preprocessor later in the course

Exceptions

- Exceptions provide a general mechanism to:
    - notify the occurrence of an error in the program execution, typically when a function is not able to accomplish its task, i.e. to satisfy its *post-condition*
        - using a `throw` expression
    - transfer control to a handler defined in a previous function in the call chain, where the exception can be managed
        - using a `try`/`catch` statement
- Exceptions help separate application logic from error management
- A typical use is in constructors and operators, that have a fixed function signature
- Exceptions cannot be ignored
    - If a handler is not found the program is `terminated`

Exceptions (cont.)

```
struct E {};

auto function3() {
  ··· // this part is executed
  throw E{};
  ··· // this part is not executed
}

auto function2() {
  ··· // this part is executed
  function3();
  ··· // this part is not executed
}

auto function1() {
  try {
    ··· // this part is executed
    function2();
    ··· // this part is not executed
  } catch (E const& e) {
    ··· // use e
  }
}
```

- An exception is an object
- After being raised (`thrown`), an exception is propagated up the stack of function calls until a suitable `catch` clause (handler) is found
- If no suitable handler (i.e. one compatible with the type of the exception) is found, the program is `terminated`
- Exceptions should be caught by (const) reference
- During *stack unwinding* the stack frames are properly cleaned up

Exceptions in constructors

- An exception is typically raised by a constructor to inform that it is not able to properly initialize the object C.42
  - i.e. it's not able to establish the class invariant
- Let's apply this to Rational, using the standard-provided exception `std::runtime_error`
  - it can be constructed with a string or a string literal
  - it provides a `what()` method to retrieve that string, e.g. in the handler

Exceptions in constructors (cont.)

```
class Rational {
  ...
  Rational(int num = 0, int den = 1) : n{num}, d{den} {
    if (d == 0) {
      throw std::runtime_error{"denominator is zero"}; // in <stdexcept>
    }
    ...
  }
};

auto do_computation() {
  ...
  Rational{n,m} // m here happens to be 0
  ...
}

try {
  do_computation();
  ...
} catch (std::runtime_error const& e) {
  // manage the error, e.g. log a message on stdandard error
  std::cerr << e.what() << '\n';
}
```

Nested class

- A class can be defined within the definition of another class
    - in either the public or private section

```
class Regression {
  ...
  class Result { ··· };
  Result fit() const { ··· }
};

Regression reg;
...
Regression::Result result{ reg.fit() }; // or auto result{···}
```

- The nested class can access the private members of the outer class

Type alias

- A type alias is another name for an existing type

```
using Length = double;
typedef double Length; // equivalent, old alternative

Length len{1.}; // len is of type double
```

- A type alias does **not** introduce a new type

```
void walk(double d) { ··· }
void walk(Length l) { ··· } // error, redefinition of walk
```

Type alias (cont.)

- Type aliases are often used to declare types within a class

```
class FitResult { ··· };

class Regression {
  ...
 public:
  using Result = FitResult;
  Result fit() const { ··· }
};

Regression::Result result{ reg.fit() }; // result is of type FitResult
```

Structured binding

- A *structured binding* declaration declares multiple variables and initializes them from values of struct members (and other entities, following a certain *protocol*)

```
struct Point {
  double x;
  double y;
};

Point p{1.,2.};
auto [a, b] = p;
std::cout << a << ' ' << b; // print 1 2
```

- The variables can be declared as (const) references to the struct members

```
Point p{1.,2.};
auto& [a, b] = p; // a is a ref to p.x, b is a ref to p.y
a = 3.;
b = 4.;
std::cout << p.x << ' ' << p.y; // print 3 4
```

Templates

Class template

- Let's consider again the `Complex` class
- What if we want `float` members?

```cpp
class Complex {
  double r;
  double i;
 public:
  Complex(
      double x = double{}
    , double y = double{}
  ) : r{x}, i{y} {}
  double real() const { return r; }
  double imag() const { return i; }
};
```

```cpp
class Complex {
  float r;
  float i;
 public:
  Complex(
      float x = float{}
    , float y = float{}
  ) : r{x}, i{y} {}
  float real() const { return r; }
  float imag() const { return i; }
};
```

Class template (cont.)

We can transform `Complex` into a *template*, with the floating-point type a parameter of that template

```
template<typename FP> // or, template<class FP>
class Complex {
  static_assert(std::is_floating_point_v<FP>); // (*)
  FP r;
  FP i;
 public:
  Complex(FP x = FP{}, FP y = FP{}) : r{x}, i{y} {}
  FP real() const { return r; }
  FP imag() const { return i; }
};

Complex c;                     // error
Complex<double> d;             // instantiation of a Complex<double> type
Complex<float> f;              // different type than d
Complex e{1.,1.};              // Complex<double> deduced
d + e;                         // ok
d + f;                         // possibly error
Complex<int> i;                // acceptable?
```

* compile-time check + type introspection

Class template (cont.)

- A class template can be seen as a type *generator*
- A class template is parameterized by one or more template parameters (types, but not only)
- A template *specialization* identifies a template name and a set of template arguments corresponding to the template parameters
  - Template arguments can be explictly specified (e.g. following the template name between angular brackets <>) or deduced based on constructor arguments
- When a class template specialization is used in a context where a type is needed, the compiler *instantiates* a new type
  - Identical instantiations are merged together
- Only member functions that are actually used are instantiated
- There are ways to constrain the arguments used to instantiate a template
  - Notably, C++20 has introduced *concepts*

Function template

```
double norm2(Complex const& c) { ··· } // not valid any more
norm2(f);                             // error; f is of type Complex<float>
```

```
auto norm2(Complex<float> const& c) {
  return c.real() * c.real() + c.imag() * c.imag();
}
norm2(f); // ok
norm2(d); // error; d is of type Complex<double>
```

```
auto norm2(Complex<double> const& c) {
  return c.real() * c.real() + c.imag() * c.imag();
}
norm2(d); // ok
```

```
template<typename FP> // or template<class FP>
auto norm2(Complex<FP> const& c) {
  return c.real() * c.real() + c.imag() * c.imag();
}
auto nf = norm2(f); // nf is of type float
auto nd = norm2(d); // nd is of type double
```

Function template (cont.)

```
template<typename FP>
auto norm2(Complex<FP> const& c)
{ return c.real() * c.real() + c.imag() * c.imag(); }

template<typename C>
auto norm2(C const& c)
{ return c.real() * c.real() + c.imag() * c.imag(); }

norm2(f); // ok
norm2(d); // ok
std::complex<float> g;
norm2(g); // ok!

namespace std {
  template<class T>
  class complex {
    ...
   public:
    T real() const;
    T imag() const;
  };
}
```

This shows the basic idea behind generic programming

Function template (cont.)

- A function template can be seen as a function *generator*
- A function template is parameterized by one or more template parameters (types, but not only)
- A template *specialization* identifies a template name and a set of template arguments corresponding to the template parameters
  - Template arguments can be explictly specified (e.g. following the template name between angular brackets <>) or deduced based on function arguments
- When a function template specialization is used in a context where a function is needed, the compiler *instantiates* a new function
  - Identical instantiations are merged together
- Only functions that are actually used are instantiated
- There are ways to constrain the arguments used to instantiate a template
- Usually there is no separate definition of a function template

Template argument deduction

- In order to instantiate a template every template argument has to be known
- Template arguments can be deduced from function call arguments

```
template<class F> F norm2(Complex<F> const& c) {···}

Complex<float> f;
norm2(f);          // no need to specify norm2<float>(f)
norm2<float>(f);   // ok, be explicit
norm2<double>(f);  // instantiate and call norm2<double>, probably failing
```

- Sometimes it's not possible to deduce all template arguments from function parameters

```
template<class Number>
Number lexical_cast(std::string const& s) // convert a string to a number
{···}

auto d = lexical_cast<double>("3.14"); // the destination type is needed
```

Template argument deduction (cont.)

- Constructor calls can be used to deduce *class* template arguments
  - Constructor Template Argument Deduction (CTAD)

```
template<class FP> class Complex {···};

Complex d;              // error, cannot deduce FP
Complex<double> e;      // ok
Complex f{1.};          // ok, Complex<double>
Complex<double> g{1.}; // ok
Complex<float> h{1.};  // ok, 1. -> 1.F
```

- If CTAD is not available (e.g. in older C++ versions), leverage function template argument deduction

```
template<class FP>
auto make_complex(FP r, FP i) {
  return Complex<FP>(r, i);
}

auto c = make_complex(1.,2.); // instead of Complex c{1.,2.}
```

Exercises

- Write an `operator+` that adds two complex numbers of different types
- Transform the `Rational` class into a class template, where the parameter is the type used to represent numerator and denominator. Adapt the operators.
  Write a program that instantiates the `Rational` class with integral types such as `int`, `long int`, `long long int`, `short int`. Combine objects of those types using the operators.

Non-type template parameters

- A class/function template parameter need not be a type
- A template parameter can be a value, which must be known at compile time

```
template<int I> struct C { ··· };
C<2> c2;
C<3> c3;              // different type
int n; std::cin >> n;
C<n> c4;              // error, n is not a compile-time constant
```

- The type of the value needs to satisfy certain constraints
- Integral types (e.g. `int`, `char`, `bool`) and enumeration types are allowed, other *structural* types (including floating-point types) since C++20

```
template<double D> struct F { ··· }; // ok since C++20
```

- Type and non-type template parameters can be mixed

```
template<class T, int N> struct array { ··· };
template<class T, T v> struct integral_constant { ··· };
```

The C++ Standard Library

Namespaces

- How can we guarantee that in a program composed of thousands of files, written by thousands of people, using third-party libraries, there are no conflicts between identifiers?
- Namespaces are a mechanism to partition the space of names in a program to prevent such conflicts

```
// in <vector>
namespace std {
  template<class T> vector { ··· };
}

// in <algorithm>
namespace std {
  template<class It, class T> find(It first, It last, T const& v) { ··· }
}
```

- Namespaces can be re-opened, even in other files
  - But namespace `std` cannot be re-opened by a user, unless explicitly allowed by the specification
- Namespaces can be nested

Namespaces (cont.)

- A **namespace alias** gives another name to an existing namespace

```
namespace ch = std::chrono;

auto t0 = ch::system_clock::now(); // std::chrono::system_clock::now()
```

- A **using declaration** makes a namespace symbol visible in the current scope

```
using std::string;

string s;
```

- A **using directive** makes all the namespace symbols visible in the current scope

```
using namespace std;

string s;
```

- Avoid "using directives". They are especially bad in the global scope and in header files

Namespaces (cont.)

- It's good practice to put all entities of a software component into a namespace

```
namespace stats {

struct Result { ··· };
class Regression { ··· };

Result fit(Regression const&);

}
```

- Within a namespace, when using a name declared in that namespace, there is no need to namespace-qualify it (i.e. prepending *namespace*`::`)

The C++ standard library

- The standard library contains components of general use
  - containers (data structures)
  - algorithms
  - strings
  - input/output
  - mathematical functions
  - random numbers
  - regular expressions
  - concurrency and parallelism
  - filesystem
  - ...
- The subset containing containers and algorithms is known as STL (Standard **Template** Library)
  - But templates are everywhere

Containers of objects

- A program often needs to manage collections of objects
    - e.g. a string of characters, a dictionary of words, a list of particles, a matrix, . . .
- A *container* is an object that contains other objects
- The C++ Standard Library provides a few container classes
    - implemented as class templates
    - different characteristics and operations, some common traits

`std::vector<T>`

Dynamic container of elements of type `T`

- its size can vary at runtime
- layout is contiguous in memory
- container you should use by default
- be careful with initialization: `{}` vs `()`
    - check if there is a constructor that takes an `std::initializer_list`

```
#include <vector>

std::vector<int> a;      // empty vector of ints
std::vector<int> b{2};   // one element, initialized to 2
std::vector<int> c(2);   // two elements (!), value-initialized (0 for int)
std::vector<int> d{2,1}; // two elements, initialized to 2 and 1
std::vector<int> e(2,1); // two elements, both initialized to 1


auto f = b; // make a copy, f and b are two distinct objects
f == b;     // true
```

`std::vector<T>` (cont.)

- The `size` method gives the number of elements in the vector
- The `empty` method tells if the vector is empty
- `operator[]` gives access to the i^{th} element

```
std::vector<int> vec{4,2,7};

assert(!vec.empty());
std::cout << vec.size(); // print 3
vec[1] = 5;              // vec is now {4,5,7}
std::cout << vec[1];     // print 5
```

Counting starts from 0!

```
vec[0];              // first element
vec[1];              // second element
vec[vec.size()-1]; // vec[2], third and last element
vec[vec.size()];   // vec[3], element doesn't exist, undefined behaviour!
```

std::vector<T> (cont.)

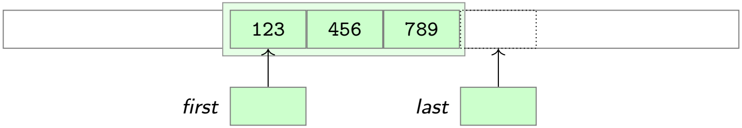
- The push_back method adds an element at the end of the vector

```
vec.push_back(-2);       // vec is now {4,5,7,-2}
vec.push_back(0);        // vec is now {4,5,7,-2,0}
std::cout << vec.size(); // print 5
```

```
// fill a vector with numbers read from standard input
std::vector<double> v;
for (double d; std::cin >> d; ) {
  v.push_back(d);
}
```

Iterators and ranges

- An iterator is an object that indicates a position within a range
  - A container, such as a vector, is a range
- In fact, a pair of iterators [*first*, *last*) represents a range
  - the range is *half-open*
    - *first* points to the first element of the range
    - *last* points to **one past** the last element of the range
  - *first* == *last* means the range is empty



- Ranges are typically obtained from containers calling methods `begin` and `end`

```
std::vector<int> v {···};
auto first = v.begin(); // std::vector<int>::iterator
auto last  = v.end();   // std::vector<int>::iterator
```

Operations on iterators

- Syntactically, operations on iterators are inspired by pointers
- There is a minimal set of operations supported by an iterator `it`
- `*it` gives access to the element pointed to by `it`

```
std::vector<int> v {1,2,3};
auto it = v.begin();
std::cout << *it; // print 1
*it = 4;          // v is now {4,2,3}
```

```
auto it = v.end();

*it; // undefined behaviour, it doesn't point inside the range
```

Operations on iterators (cont.)

- `it->`*`member`* gives access to a member (data or function) of the element pointed to by `it`
  - equivalent to `(*it).`*`member`*, note the parenthesis

```
std::vector<Point> v {Point{1,2}, Point{3,4}};
auto it = v.begin();
std::cout << (*it).x; // print 1
std::cout << it->x;   // equivalent
```

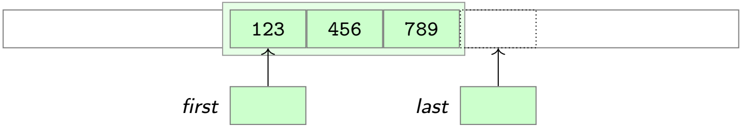
```
struct Point {
  double x;
  double y;
};
```

```
std::vector<std::string> v {"hello", "world"};
auto itv = v.begin();    // itv points to the first string in the vector
auto its = itv->begin(); // its points to the first character
                         //   of the first string ('h');
                         //   a string is a container of characters
```

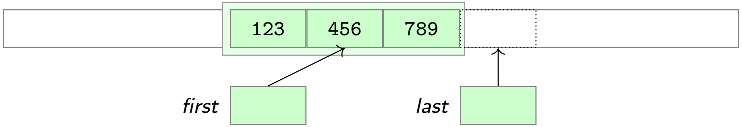
Operations on iterators (cont.)

- `++it` advances `it` so that it points to the next element in the range

```
std::vector<int> v {123, 456, 789};
auto first = v.begin();
auto last  = v.end();
std::cout << *first; // print 123
```



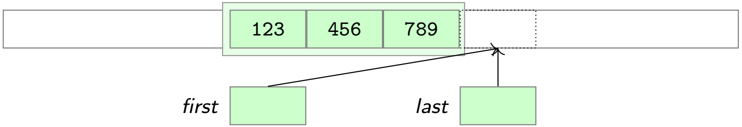
```
++first;
std::cout << *first; // print 456
```



Operations on iterators (cont.)

- `it1 == it2` (`it1 != it2`) tells if `it1` and `it2` point to the same element (different elements) of the range

```
++first; ++first;
first == last;  // true
```



- Other operations (`--it`, `it + n`, `it += n`, `it < it2`, ...) may be supported, depending on the underlying range
  - vector iterators support them all

Example: add all elements of a vector (Iteration on a container)

```
std::vector<int> c { ··· };
```

```
auto sum = 0;
for (int i {0}, n = c.size(); i != n; ++i) {
  auto const& v = c[i];
  sum += v;
}
```

```
auto sum = 0;
for (auto it = c.begin(), last = c.end(); it != last; ++it) {
  auto const& v = *it;
  sum += v;
}
```

```
auto sum = 0;
for (auto const& v : c) { // translates to the loop with iterators
  sum += v;
}
```

```
auto sum = std::accumulate(c.begin(), c.end(), 0); // algorithm
```

`std::vector<T>` (cont.)

- The erase method removes the element pointed to by the iterator passed as argument (must not be `end()`)

```
// remove the central element
auto it = v.begin() + v.size() / 2; // iterator to the middle element
v.erase(it);                         // size decreased by 1
```

- The erase method can remove a range, passing two iterators

```
// erase the 2nd half of the vector
auto it = v.begin() + v.size() / 2; // iterator to the middle element
v.erase(it, v.end());                // size ~halved here
```

- In general, iterators pointing to erased elements are not valid anymore
  - For a vector, iterators pointing to elements following the erased one are also invalidated, including the end iterator

```
v.erase(it);
*it;        // undefined behaviour (UB)
++it;       // UB, be careful in loops
it = ···;  // ok
```

`std::vector<T>` (cont.)

- The `insert` method inserts an element before the position indicated by an iterator

```
// insert the value 42 in the middle of the vector
auto it = v.begin() + v.size() / 2;
v.insert(it, 42);                  // size increased by 1
```

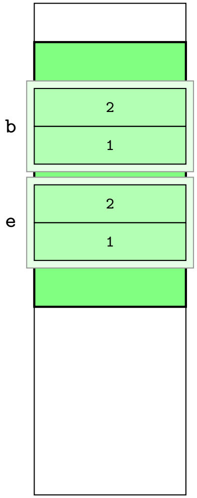
- Other overloads of `insert` are available, see reference
- Existing iterators pointing to elements after the insertion position are invalidated
    - If a memory reallocation occurs (see later), all existing iterators pointing into the vector are invalidated

std::array<T, N>

Container of N elements of type T

- N known at compile time
- layout is contiguous in memory

```
#include <array>

// 2 ints, uninitialized
std::array<int,2> a;

// 2 ints, initialized to 1 and 2
std::array<int,2> b{1,2};

// 2 ints, value-initialized (0 for int)
std::array<int,2> c{};

// 2 ints, initialized to 1 and 0
std::array<int,2> d{1};

// make a copy
auto e = b;  // std::array<int,2>
assert(e == b);
```



std::array<T, N> (cont.)

- The size method gives the number of elements in the array (which corresponds to N)
- operator[] gives access to the i^{th} element

```
int const M {4};
std::array<int, M> arr{1,2}; // {1,2,0,0}

std::cout << arr.size(); // print 4
arr[1] = 3;              // arr is now {1,3,0,0}
std::cout << arr[1];     // print 3
```

- begin, end, empty, front, back methods
- No push_back or insert, the size is fixed.

Type aliases (cont.)

- Type aliases can be templates

```
// array of 3 T's
template<class T> using Array3 = std::array<T, 3>;

Array3<double> a; // std::array<double, 3>
```

```
// array of N bytes
template<int N> using ArrayOfBytes = std::array<std::byte, N>;

ArrayOfBytes<16> b; // std::array<std::byte, 16>
```

Algorithms

- Generic functions that operate on ranges of objects
- Implemented as function templates
- Sum all the elements of a container `cont` of `int`s

```
int sum {0};
for (auto it = cont.begin(), last = cont.end(); it != last; ++it) {
  sum += *it;
}
```

```
auto sum = std::accumulate(cont.begin(), cont.end(), 0); // better
```

- Find an element equal to `val` in a container `cont`

```
auto it = cont.begin();
auto const last = cont.end();
for (; it != last; ++it) {
  if (*it == val) {
    break;
  }
}
```

```
auto it = std::find(cont.begin(), cont.end(), val); // better
```

Generic programming

- A style of programming in which algorithms are written in terms of concepts

```
template<class InputIterator, class Tp>
Tp accumulate(InputIterator first, InputIterator last, Tp init)
{
    for (; first != last; ++first)
        init = init + *first;
    return init;
}
```

```
template <class Iterator, class T>
Iterator find(Iterator first, Iterator last, const T& value)
{
  for (; first != last; ++first)
    if (*first == value) break;
  return first;
}
```

Concepts

- A *concept* is a set of requirements that a type needs to satisfy at compile time
    - e.g. supported expressions, nested typedefs, memory layout, ...
- Concepts constrain the types that can be used as template arguments
    - Implicit until C++20, based on how those types are used in a class/function template definition
    - C++20 introduces a specific syntax and a set of generally useful concepts (not further discussed)

```
template<class T>
concept Incrementable = requires(T t) { ++t; };

template<Incrementable T>
auto advance(T& t) { ++t; }

int i {42};
advance(i); // ok, int is a model of Incrementable

struct S {};
S s;
advance(s); // error, S is not a model of Incrementable
```

Hierarchy of iterators

```
// InputIterator (find)
while (first != last && !(*first == value)) ++first;
```

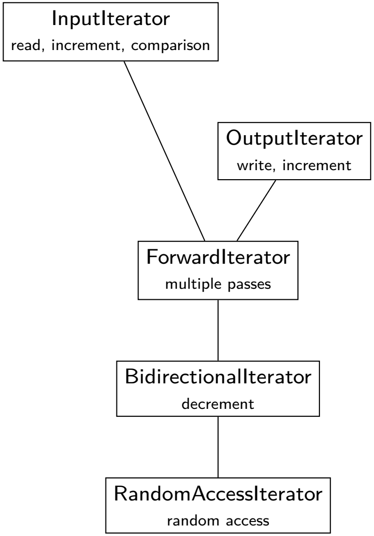
```
// OutputIterator (generate_n)
for (; n > 0; ++first, --n) *first = gen();
```

```
// ForwardIterator (generate)
for (; first != last; ++first) *first = gen();
```

```
// ForwardIterator (adjacent_find)
auto i = first;
while (++i != last) ···
```

```
// BidirectionalIterator (reverse)
if (first == --last) break;
```

```
// RandomAccessIterator (reverse)
for (; first < --last; ++first) ···
```



Examples of algorithms

Non-modifying	`all_of any_of for_each count count_if mismatch equal find find_if adjacent_find search ...`
Modifying	`copy copy_if fill generate transform remove replace swap reverse rotate shuffle sample unique ...`
Partitioning	`partition stable_partition ...`
Sorting	`sort partial_sort nth_element ...`
Set	`includes set_union set_intersection ...`
Min/Max	`min max minmax clamp ...`
Comparison	`equal lexicographical_compare ...`
Numeric	`iota accumulate inner_product partial_sum adjacent_difference reduce ...`
	...

Algorithms in action

```
std::array a {23, 54, 41, 0, 18};

// sort the array in ascending order
std::sort(std::begin(a), std::end(a));

// sum up the array elements, initializing the sum to 0
auto s = std::accumulate(std::begin(a), std::end(a), 0);

// append the partial sums of the array elements into a vector
std::vector<int> v;
std::partial_sum(std::begin(a), std::end(a), std::back_inserter(v));

auto p = std::inner_product(std::begin(a), std::end(a), std::begin(v), 0);

// find the first element with value 42, if existing
auto it = std::find(std::begin(v), std::end(v), 42);
```

Why using standard algorithms

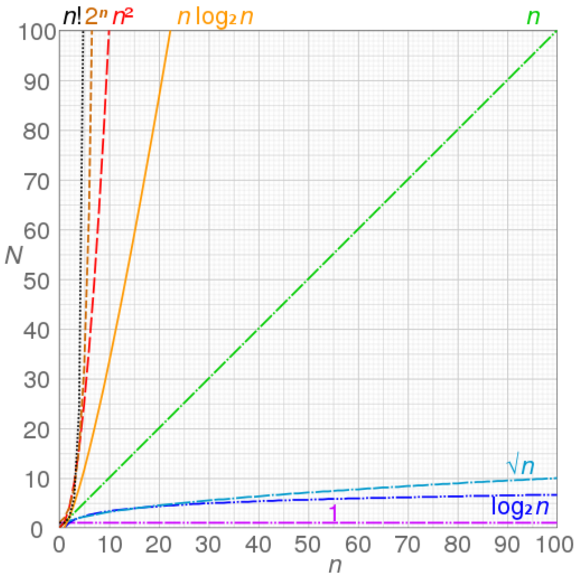
- They are correct
- They express intent more clearly than a raw `for`/`while` loop
- They are efficient
  - They give computational complexity guarantees
  - How fast do they run? how much additional memory do they need?
- They enable easy access to *parallelism*

```
#include <execution>

std::vector<int> v {···};

std::sort(std::execution::par, v.begin(), v.end());

auto it = std::find(std::execution::par, v.begin(), v.end(), 123);
```

Computational complexity

- A measure of how many resources a computation will need for a given input size
  - Typically the resource is time but can be space (memory)
  - For example: how many comparisons does the sort algorithm do for a range of one million elements?
- Of typical interest are the average case and the worst case
- The complexity is a function f of the input size n, but usually only the asymptotic behaviour is given
  - Big-O notation
  - $\mathcal{O}(g(n))$ means that, for a large n, $f(n) \leq cg(n)$, for some constant c
  - Note how constant factors don't matter in big-O notation
- For example
  - `std::vector<T>::push_back` is (amortized) $\mathcal{O}(1)$
  - `std::binary_search` is $\mathcal{O}(\log n)$
  - `std::find` is $\mathcal{O}(n)$
  - `std::sort` is $\mathcal{O}(n \log n)$

Computational complexity (cont.)



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Functions

- A function associates a sequence of statements (the function *body*) with a name and a list of zero or more parameters
- A function may return a value
- Multiple functions can have the same name → *overloading*
    - different parameter lists
- A function returning a `bool` is called a *predicate*

```
bool less(int n, int m) { return n < m; }
```

Algorithms and functions

```
template <class Iterator, class T>
Iterator find(Iterator first, Iterator last, const T& value)
{
  for (; first != last; ++first)
    if (*first == value)
      break;
  return first;
}

auto it = find(v.begin(), v.end(), 42);
```

```
template <class Iterator, class Predicate>
Iterator find_if(Iterator first, Iterator last, Predicate pred)
{
  for (; first != last; ++first)
    if (pred(*first))          // unary predicate
      break;
  return first;
}

bool lt42(int n) { return n < 42; }

auto it = find_if(v.begin(), v.end(), lt42);
auto it = find_if(v.begin(), v.end(), [](int n) { return n < 42; } );
```

Some algorithms are customizable passing a function

Function objects

A mechanism to define *something-callable-like-a-function*

- A class with an `operator()`

```cpp
auto lt42(int n)
{
  return n < 42;
}




auto b = lt42(32); // true

std::vector v {61,32,51};
auto it = std::find_if(
    v.begin(), v.end(),
    lt42
); // *it == 32
```

```cpp
struct LessThan42 {
  auto operator()(int n) const
  {
    return n < 42;
  }
};

LessThan42 lt42{};
// or: auto lt42 = LessThan42{};
auto b = lt42(32); // true

std::vector v {61,32,51};
auto it = std::find_if(
    v.begin(), v.end(),
    lt42 // or directly: LessThan42{}
); // *it == 32
```

Function objects (cont.)

A function object, being the instance of a class, can have state

```
class LessThan {
  int m_;
 public:
  explicit LessThan(int m) : m_{m} {}
  auto operator()(int n) const {
    return n < m_;
  }
};

LessThan lt42 {42};
auto b1 = lt42(32); // true
// or: auto b1 = LessThan{42}(32);
LessThan lt24 {24};
auto b2 = lt24(32); // false
// or: auto b2 = LessThan{24}(32);

std::vector v {61,32,51};
auto i1 = std::find_if(..., lt42); // *i1 == 32
// or: auto i1 = std::find_if(..., LessThan{42});
auto i2 = std::find_if(..., lt24); // i2 == v.end(), i.e. not found
// or: auto i2 = std::find_if(..., LessThan{24});
```

Function objects (cont.)

An example from the standard library

```
#include <random>

// random bit generator
std::default_random_engine eng;

// generate N 32-bit unsigned integer numbers
for (int n = 0; n != N; ++n) {
  std::cout << eng() << '\n';
}

// generate N floats distributed normally (mean: 0., stddev: 1.)
std::normal_distribution<float> dist;
for (int n = 0; n != N; ++n) {
  std::cout << dist(eng) << '\n';
}

// generate N ints distributed uniformly between 1 and 6 included
std::uniform_int_distribution<> roll_dice(1, 6);
for (int n = 0; n != N; ++n) {
  std::cout << roll_dice(eng) << '\n';
}
```

Lambda expression

- A concise way to create an unnamed function object
- Useful to pass actions/callbacks to algorithms, threads, frameworks, . . .

```
struct LessThan42 {
  auto operator()(int n)
  {
    return n < 42;
  }
};

class LessThan {
  int m_;
 public:
  explicit LessThan(int m)
    : m_{m} {}
  auto operator()(int n) const
  {
    return n < m_;
  }
};
```

```
std::find_if(..., LessThan42{});

std::find_if(..., [](int n) {
                    return n < 42;
                  }
);

std::find_if(..., LessThan{m});

auto m = ···;
std::find_if(..., [=](int n) {
                    return n < m;
                  }
);
std::find_if(..., [m = ···](int n) {
                    return n < m;
                  }
);
```

Lambda closure

The evaluation of a lambda expression produces an unnamed function object (a *closure*)

- The `operator()` corresponds to the code of the body of the lambda expression
- The data members are the captured local variables

```
auto v = 42;

auto lt = [v](int n)
          { return n < v; }

auto r = lt(5); // true
```

```
class SomeUniqueName {
  int v;
 public:
  explicit SomeUniqueName(int v)
    : v{v} {}
  auto operator()(int n) const
  { return n < v; }
};

auto v = 42;
auto lt = SomeUniqueName{v};
auto r = lt(5); // true
```

- Two lambda expressions produce objects of different types, even if they are identical

Lambda capture

- Automatic variables used in the body of the lambda need to be captured
  - `[]` capture nothing
  - `[=]` capture all (what is needed) by value
  - `[k]` capture `k` by value
  - `[&]` capture all (what is needed) by reference
  - `[&k]` capture `k` by reference
  - `[=, &k]` capture all by value but `k` by reference
  - `[&, k]` capture all by reference but `k` by value

```
auto v = 3;
auto l = [&v] {};
```

```
class SomeUniqueName {
  int& v;
 public:
  explicit SomeUniqueName(int& v)
    : v{v} {}
  ...
};

auto l = SomeUniqueName{v};
```

- Global variables are available without being captured

Lambda explicit return type

- The return type of the call operator can be explicity specified

```
[=](int n) -> bool { return n < v; }
```

becomes

```
class SomeUniqueName {
  ...
  bool operator()(int n) const
  { return n < v; }
};
```

Generic lambda

- If a parameter of the lambda expression is `auto`, the lambda expression is *generic*
- The call operator is a template

```
[](auto n) { ··· }
```

becomes

```
class SomeUniqueName {
  ...
  template<typename T>
  auto operator()(T n) const { ··· }
};
```

Lambda: const and mutable

- By default the call to a lambda is const
  - Variables captured by value are not modifiable
- A lambda can be declared mutable
  - The parameter list is mandatory
- If present, the explicit return type goes after mutable

```
[i]() mutable -> bool {··· ++i ···}
```

```
class SomeUniqueName {
  int i;
  ...
  bool operator()() {··· ++i ···}
};
```

- Variables captured by reference can be modified

```
int v = 3;
[&v] { ++v; } (); // NB the lamdba is immediately invoked
assert(v == 4);
```

- There is no immediate way to capture by const&, but one can use std::as_const

Lambda: dangling reference

- Be careful not to have dangling references in a closure
- It's similar to a function returning a reference to a local variable

```
auto make_lambda() // auto here is unavoidable
{
  int v = 3;
  return [&] { return v; }; // return a closure
}

auto l = make_lambda();
auto d = l(); // the captured variable is dangling here
```

- Capture by reference only if the lambda closure doesn't survive the current scope

Exercises

- Given a vector of `int`s, compute the product of the numbers (Hint: use `std::accumulate`)
- Generate `N` numbers, using one of the available random number distributions, and insert them in a `std::vector` (Hint: use `std::generate_n`)
- Compute the mean and the standard deviation of the generated numbers (Hint: use `std::accumulate`)

Don't forget the tests!

std::function

- *Type-erased* wrapper that can store and invoke any callable entity with a certain signature
  - function, function object, lambda, member function

```
#include <functional>

using Function = std::function<int(int,int)>; // signature

Function f1 { std::plus<int>{} };
Function f2 { [](int a, int b) { return a * b; } };
Function f3 { [](auto a, auto b) { return std::gcd(a,b); } };
```

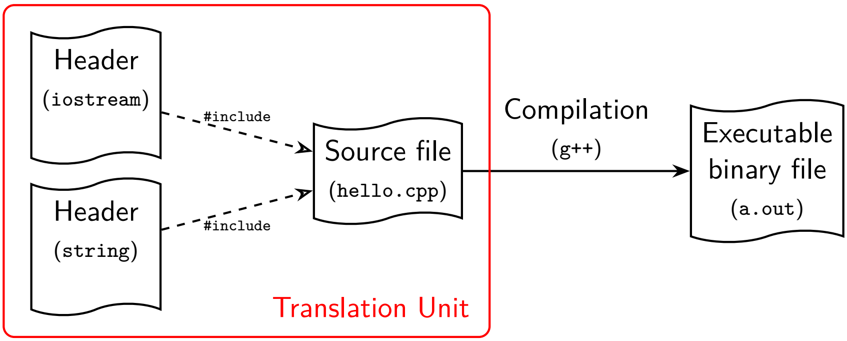
- Some space and time overhead, so use only if a template parameter is not satisfactory

```
std::vector<Function> functions { f1, f2, f3 };

for (auto& f : functions) {
  std::cout << f(121, 42) << '\n'; // 163 5082 1
}
```

Compilation model

The C++ compilation model

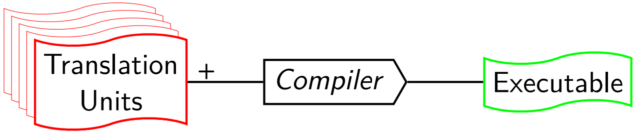
This is the **current** model; C++20 has introduced *modules* (not further discussed)



- The production of the *translation unit* is the first step of the overall *compilation* process
- It is accomplished by running the *preprocessor* on a source file
- To stop the compilation process after the preprocessing:
    - `g++ -E hello.cpp`

The C++ compilation model (cont.)

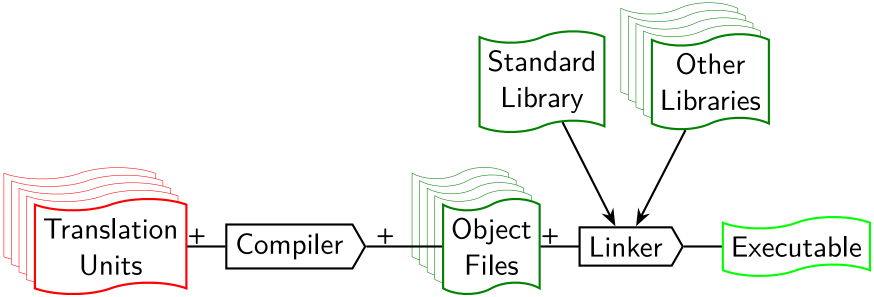
- A typical C++ program is composed of many files, i.e. there are many translation units



- How to distribute source code over multiple files?
- How to expose functionality from one translation unit so that it can be used in another?
- **Physical** design

The C++ compilation model (cont.)

- The overall process to translate C++ source code to the final binary executable consists of multiple stages



- To produce object files without linking:
  - `g++ -c hello.cpp`
- To keep all the intermediate files generated during the compilation process:
  - `g++ -save-temps hello.cpp`

Definition vs Declaration

- A definition is a declaration that fully defines an entity
- Examples:

```
bool less_than(int a, int b) { // function definition
  return a < b;
}

class Sample { // class definition
 public:
  void add(double x) // member function definition
  {
    ++N_;
    sum_x_ += x;
    ...
  }
  ...
};
```

Definition vs Declaration (cont.)

- A declaration that is **not** a definition just introduces the name (and, when applicable, the type) of the entity
- Examples:

```
bool less_than(int a, int b); // function declaration (prototype)

class Sample; // class (forward) declaration

class Sample { // class definition
 public:
  void add(double x); // member function declaration
  ...
};
```

One-Definition Rule (ODR)

- An entity can be defined only once in each translation unit
- More generally, an entity can be defined only once in the whole program, with exceptions
- Some entities can be defined in multiple translation units, provided the definitions are identical (*token-by-token* in the source code)
    - Class definitions
    - *inline* functions and variables
    - Class and function templates
    - ...
- To guarantee that definitions are identical in all translation units they typically appear in **header files**, which are then `#included` where needed
- The compiler may not be able to diagnose violations of the ODR
    - The generated executable may behave incorrectly

Definition vs Declaration during compilation and linking

- During the compilation step:
    - Calling a function requires the previous declaration of that function
    - The declaration of a function requires the previous declaration of the types involved
    - Creating and manipulating an object require the definition of the corresponding type (the type has to be *complete*)
- During the linking step:
    - Everything has to be properly defined

Header and source files

- Header files are the primary mechanism to guarantee that declarations and definitions are identical in all translation units
  - Because they are `#included` in other header and source files where those declarations and definitions are needed
- For a given software component, a typical situation foresees
  - One **header** file containing free function declarations, class definitions with member function declarations, template definitions
    - The contents of the header file represent the **interface** of the component
  - One **source** file containing definitions of free and member functions and of any other entity needed for the implementation
    - **Suggestion** the source file `#includes` the corresponding header file as the first `#include`
  - One file with the unit **tests**
  - But there is much flexibility in how to distribute definitions between header and source files, especially for functions

Header and source files (cont.)

- A function defined in a header file needs to be declared **`inline`**

```
inline double norm2(Complex const& c)
{
  return c.real() * c.real() + c.imag() * c.imag();
}
```

- `inline` informs the compiler/linker that all the definitions of the function, even if they are in multiple translation units, are equal
  - NB the `inline` keyword is not (any more) an optimization hint to the compiler
- Function templates and member functions (methods) defined inside the class are implicitly `inline`

Member functions defined outside the class

- A method must be declared inside the class, but can be **just** declared inside the class, i.e. not also defined

```
class Sample {
  ...
  void add(double);
};
```

- When defining a method outside the class, the method name must be prefixed with the class name followed by the *scope* operator `::`, i.e. *class-name*`::`*method-name*

```
void Sample::add(double x) {
  ++N_;
  sum_x_ += x;
  ...
}
```

Member functions defined outside the class (cont.)

- The method can be defined in the same file (normally a header file) or even in another file (normally the corresponding source file)
- As for free functions, if the definition is in a header file, the method should be declared `inline`

```
inline void Sample::add(double d) {
  ++N_;
  sum_x_ += x;
  ...
}
```

Include guards

- A header (file) may be included, directly or indirectly, multiple times in the **same** translation unit

```
#include "result.hpp"
#include "sample.hpp" // sample.hpp already includes result.hpp
```

- Multiple definitions of the same entity would be available in the **same** translation unit, which is illegal
- Placing an *include guard* at the beginning of each header file prevents multiple inclusions in the **same** translation unit

```
// file result.hpp
#ifndef RESULT_HPP
#define RESULT_HPP
...
// classes, functions, templates, ...
...
#endif
```

To inline or not to inline?

- Pros:
  - A compiler can optimize more because it sees more code → faster execution
    - Definitions of inline functions contained in included header files become part of the translation unit
  - Header-only libraries (i.e. everything is in one or more header files) are easier to distribute (e.g. `doctest`)
- Cons:
  - More physical coupling between software components
    - Visibility of implementation details
    - Every time a header file changes all the including files need to be recompiled → longer compilation times
  - The code of the inlined functions may be included many times in the final binary, making it larger and causing inefficient use of the memory system → slower execution

Build systems

- When a project includes more than a few files, keeping track of compilation dependencies between them becomes difficult
- A project may foresee multiple *artifacts*: executables, libraries (i.e. collection of object files), tests, ...
- A project may depend on other projects, e.g. other libraries
- Usually multiple variants of a project are needed: one for debug, one for testing with code coverage, one for release, one for measuring performance (*profiling*), ...
    - Each variant foresees different compilation flags
- ...
- In practice, all the above cannot be done manually and an automatic system is required
- Such a system is usually called **build system**
- Many build systems exist. We'll use **CMake**

CMake

- *CMake is an open-source, cross-platform family of tools designed to build, test and package software*
- Most used tool to build C++ projects
- Build targets, dependencies, options, ... are expressed declaratively in a file called `CMakeLists.txt`

```
cmake_minimum_required(VERSION 3.16)
project(mandelbrot_sfml VERSION 0.1.0)

find_package(SFML 2.5 COMPONENTS graphics REQUIRED)

string(APPEND CMAKE_CXX_FLAGS " -Wall -Wextra")

add_executable(mandelbrot_sfml main.cpp)
target_link_libraries(mandelbrot_sfml PRIVATE sfml-graphics)
```

- See code/mandelbrot_cmake for a basic example

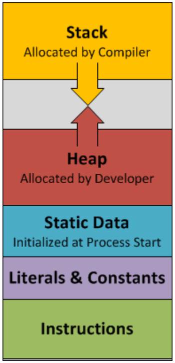
Static data and functions

Non-local objects

- Objects can be created outside a function block

```
#include <random>

std::default_random_engine eng;

auto seed_rand(int s) { eng.seed(s); }
auto get_rand()       { return eng(); }
auto print_rand()     { std::cout << get_rand(); }
```

- eng above is a *global* variable
- They have *static* storage duration, i.e. they live for the whole program duration
- They live in the **Static Data** memory segment
- They are initialized before `main` is called and destroyed after `main` has finished



Non-local objects (cont.)

- Initialization
  - Memory for non-local variables is guaranteed to be at least initialized to all zeroes
  - They may be initialized to a constant value known at compile time
  - They may be initialized dynamically at runtime, e.g. with the result of a function call
- Warning
  - Non-local variables make reasoning about the program more difficult because they encourage to work by side effects
  - The order of initialization and destruction is deterministic only in the same translation unit
  - Better avoid them, especially if mutable (i.e. non constant)

Constants

- One useful application of non-local variables is to define constants, possibly inside a namespace

```
namespace std::numbers {
  inline constexpr double e  = ··· ;
  inline constexpr double pi = ··· ;
  ...
}
```

- `inline` means that there is only one object in the whole program (like for function definitions)
    - to be used if the definitions are in a header file
- `constexpr` guarantees that the initialization can be done at compile time
    - possibly through the execution of a *constexpr* function (not further discussed)
    - it implies `const`
- Of course constants can be defined locally as well

Class `static` data members

- A class data member declared `static` is not part of any object of that class
- A static data member
    - exists even if there are no objects of that class
    - has static storage duration
    - is defined out-of-class ...
    - ...unless it's declared `inline` (C++17) or `constexpr` (which implies `inline`) or is a `const` integral type

```
struct X {
  static int n;
};
// probably in a .cpp file
int X::n = 42;
```

```
struct X {
  inline static int n = 42;
};
```

Class `static` data members (cont.)

- A static data member is usually accessed using the scope operator `::`

```
class std::chrono::system_clock {
 public:
  static constexpr bool is_steady = ··· ;
  ...
};

std::cout << std::chrono::system_clock::is_steady;
```

- But if there is an object of that type, one can use the `.` operator on that object

```
std::chrono::system_clock clock;
std::cout << clock.is_steady;
```

Class `static` member functions

- A class member function declared `static` is not associated with any object of that class
- They are similar to normal functions, but defined in the scope of a class, so that they can access the other members
- A static member function can access static data members, but cannot access non-static data members
    - It cannot be declared as `const`

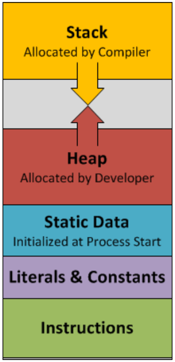
```
class std::chrono::system_clock {
 public:
  static time_point now() { ··· }
  ...
};
// system_clock::now() could also be defined out-of-class
```

```
using namespace std::chrono_literals;
std::this_thread::sleep_until(std::chrono::system_clock::now() + 15ms);
```

Explicit Memory Management (Resource Management)

Memory layout of a process

- A process is a running program
- When a program is started the operating system brings the contents of the corresponding file into memory according to well-defined conventions
  - Stack
    - function local variables
    - function call bookkeeping
  - Heap
    - dynamic allocation
  - Global data
    - literals and variables
    - initialized and uninitialized (set to 0)
  - Program instructions



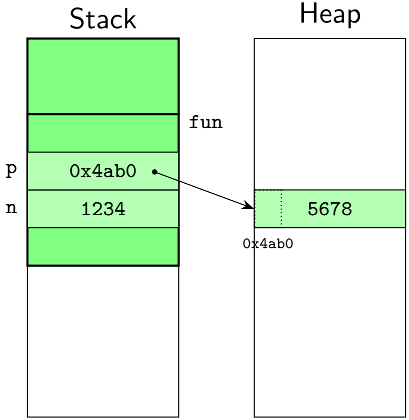
Dynamic memory allocation

- It's not always possible or convenient to construct objects on the stack, where they would be destroyed at the end of the function that created them
- An object (array of objects) can be constructed on the *free store* (*heap*)
    - `new` expression (for an array: `new []`)
        - allocate memory for the object(s)
        - run the object(s) constructor
- The lifetime of an object (array of objects) on the heap is **explictly** managed by the developer
    - explicit destruction of the object(s) when not needed any more
    - `delete` expression (for an array: `delete []`)
        - run the object(s) *destructor* (see later)
        - deallocate the memory previously allocated for the object(s)
- Contrast this to the **automatic** destruction of an object at the end of the scope when the object is created on the stack

Dynamic allocation of an object

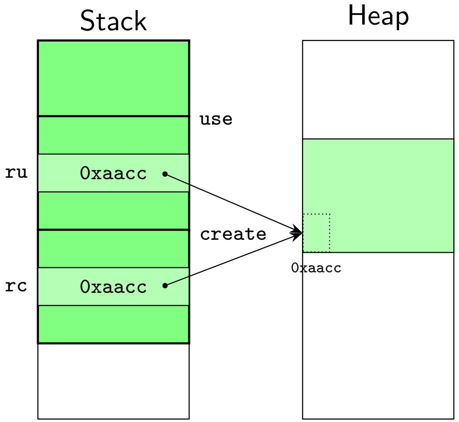
```
auto fun()
{
   int n {1234};
   int* p = new int{5678};
   ...
   delete p;
}
```

- `delete p` gives the area on the heap back to the system
- `delete p` does **not** modify `p`
- After `delete p`, the only safe operation on `p` is an assignment
  - `p = ...;`
- if `p` is `nullptr`, `delete p` is well defined and does nothing



Returning a dynamically-allocated object from a function

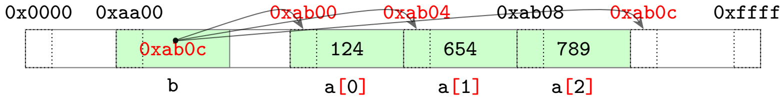
```
Sample* create()
{
   auto rc = new Sample{};
   rc->add(···);
   ...
   return rc;
}

auto use()
{
   auto ru = create();
   ru->stats();
   ...
   delete ru;
}
```



Note how the lifetime of a dynamically-allocated object is explicitly managed by the developer

(native) Array of objects

Contiguous sequence of homogeneous objects in memory

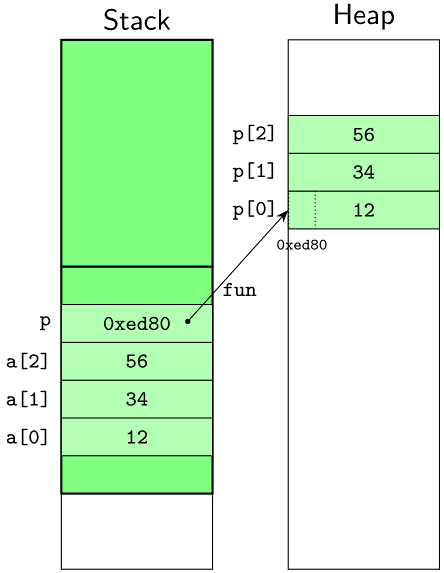


```
int a[3] = {123, 456, 789}; // int[3], the size must be a constant
                            // and can be deduced from the initializer
++a[0];
a[3];                       // undefined behavior
// "arrays decay to pointers at the slightest provocation"
auto b = a;                 // int*, size information lost
assert(b == &a[0]);
++b;                        // increase by sizeof(int)
assert(b == &a[1]);
*b = 654;
b += 2;                     // increase by 2 * sizeof(int)
*b;                         // undefined behavior
if (b == a + 3) { ... }     // ok, but not more than this
```

Dynamic allocation of an array of objects

```
auto fun()
{
  int a[3] {12, 34, 56};
  int* p = new int[3] {12, 34, 56};
  ...
  delete [] p;
}
```

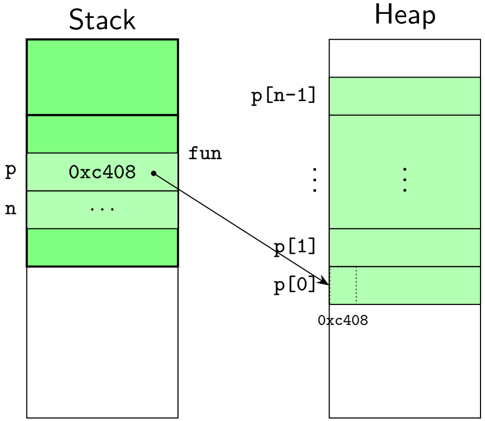
- p points to the first element of the array
- p does **not** carry “array” information



Dynamic allocation of an array of objects of dynamic size

Arrays allocated on the heap are most useful when their size is available only at runtime

```
auto fun()
{
   int n;
   std::cin >> n;
   auto p = new int[n];
   ...
   delete [] p;
}
```



Null-terminated byte strings

- A null-terminated byte string (NTBS) is an array of non-null characters followed by the null character (`char{0}` or `'\0'`)
    - `char[]` (`char*`) if characters are modifiable
    - `char const[]` (`char const*`) if characters are not modifiable
    - Also known as “C-strings”
- The `std::strlen` function returns the length of an NTBS
    - Linear complexity, scan the array until `'\0'` is found
- A string literal has type `char const[N]`, with `N` constant
    - For example, the type of `"ciao"` is `char const[5]`
- An `std::string` can be initialized with an NTBS
- To get the NTBS representation of an `std::string` use the `c_str` method
    - It returns a `char const*` to the internal array

The `main` function

- The `main` (special) function is the entry point of a program
- It can have two forms
  - `int main() {···}`
  - `int main(int argc, char* argv[]) {···}`
- If there is no `return` statement, an implicit `return 0;` is assumed
  - 0 means success, different from 0 means failure
- `argc` is the number of arguments on the command line, `argv` is an array of C-strings representing the arguments
  - `argv[0]` is (usually) the name of the program
  - `argv[argc]` is `nullptr`
- Many libraries exist to parse the command line, e.g. Lyra, cxxopts, Boost.Program_options

Managing raw arrays

- Managing raw arrays **correctly** is difficult
- Passing an array around makes it decay to a pointer to its first element, loosing important type information
- How do you pass an array to a function?
  - Need to pass pointer and size
  - C++20 introduces `std::span`
- How do you return an array from a function?
  - Left as an exercise
- Better use higher-level tools, such as `std::string`, `std::array` and `std::vector`

Weaknesses of a T*

- Critical information is not encoded in the type
  - Am I the owner of the pointee? Should I delete it?

```
Shape* s = create_shape();                    // (probably) delete

std::string str{"hello"};
char const* cs = str.c_str();                 // don't delete
char      * cd = str.data();                  // don't delete, const is irrelevant
```

  - Is the pointee an object or an array of objects? of what size?

```
Shape* s = create_shapes();                    // (probably) delete []
```

  - Was it allocated with `new`, `malloc` or even something else?
    - `malloc` is a C function that allocates raw memory, which is then de-allocated passing the pointer to the function `free`
    - e.g. the `fopen` function returns a `FILE*`, which will be released passing it to the `fclose` function

Weaknesses of a `T*` (cont.)

- Owning pointers are prone to leaks

```
{
  auto p = new Circle{···};
  ...
  // ops, forgot to delete p
}
```

- Owning pointers are prone to double `deletes`

```
{
  auto p = new Circle{···};
  ...
  delete p;
  ...
  delete p; // ops, delete again
}
```

Weaknesses of a T* (cont.)

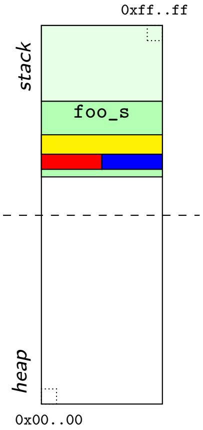
- Owning pointers are unsafe in presence of exceptions

```
{
  auto p = new Circle{···};
  ···                          // potentially throwing code
  delete p;                    // leak if exception thrown
}
```

- Runtime overhead, in space and time
  - dynamic allocation/deallocation
  - indirection

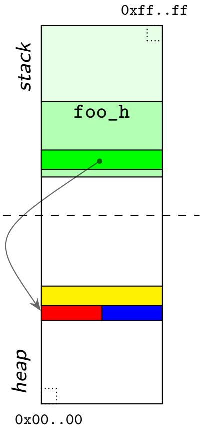
Stack vs Heap: space

```
struct S {
  int    n;
  float  f;
  double d;
};

auto foo_s() {
  S s;
  ...
}

auto foo_h() {
  S* s = new S;
  ...
}
```



Occupancy:

- `sizeof(S)`



Occupancy:

- `sizeof(S)` + `sizeof(S*)`
- plus `new` internal space overhead

Stack vs Heap: time

Stack

```
void stack()
{
  int m{123};
  ...
}
```

```
stack():
     subq %4, %rsp
     movl $123, (%rsp)
     ...
     addq $4, %rsp
     ret
```

Heap

```
void heap()
{
  int* m = new int{123};
  ...
  delete m;
}
```

```
heap():
     subq $8, %rsp
     movl $4, %edi
     call operator new(unsigned long)
     movl $123, (%rax)
     movq %rax, (%rsp)
     ...
     movl $4, %esi
     movq %rax, %rdi
     call operator delete(void*, unsigned long)
     addq $8, %rsp
     ret
```

```
$ g++ -O3 heap.cpp && ./a.out
1000000 iterations: 0.035745 s
```

i.e. ∼35 ns for each `new`/`delete` (on my laptop)

Investigating memory problems

- One of the simplest tools to use is the *Address Sanitizer* (ASan)
- The compiler instruments the executable so that at runtime ASan can catch many (but not all!) memory problems
- Some space and time overhead at runtime, but acceptable at least during testing

```
$ g++ -fsanitize=address leak.cpp
$ ./a.out

=================================================================
==18338==ERROR: LeakSanitizer: detected memory leaks
...
```

Guidelines on dynamic objects

- Do not unnecessarily allocate on the heap, i.e. use the stack when possible
- If unavoidable, think thoroughly about ownership and use a resource-managing object, e.g.
    - containers and strings
    - *smart pointers* (see later)
- Ideally the residual meaning of a raw pointer (`T*`) should be “I’m pointing to **one** element and I’m **not** its owner”

Resource management

- Dynamic memory is just one of the many types of resources manipulated by a program:
  - thread, mutex, socket, file, ...
- C++ offers powerful tools to manage resources
  - *"C++ is my favorite garbage collected language because it generates so little garbage"*

Destruction

- At the end of a block statement (i.e. when the closing brace } is encountered) all objects of automatic storage duration are automatically *destroyed*
- Destroying an object means
    - for a class type, a special member function, called *destructor*, if present, is run
    - all the sub-objects (e.g. data members) are destroyed, recursively
    - the storage is freed
- The order of destruction is the opposite of the order of construction/definition
    - a later-defined object can use a previously-defined one

```
{
  S s{···};
  ...
  T t{s};
  ...
} // t is destroyed first, then s
```

The destructor

- The *destructor* is a special class member function that is called when an object of that class goes out of scope and has to be destroyed
- The purpose of the destructor is to leave no garbage behind
- A class can have only one destructor, declared as `~classname()`

```
class DynamicArray {
  ...
  int* m_data;
 public:
  DynamicArray(int n): m_data{new int[n]} {···}
  ~DynamicArray()
  {
    delete [] m_data;
  }
  ...
};
```

RAII idiom

- Resource Acquisition Is Initialization
  - The constructor accepts/acquires a resource
  - The destructor releases it
- The object is responsible for the correct lifetime management of that resource
- Guaranteed no leak nor double release, even in presence of exceptions

Controlling copying

- The compiler automatically generates the copy operations for a class, if used
  - The copy constructor creates a new object as a copy of another object

```
DynamicArray original{···};
auto copy{original}; // auto copy = original
```

  - The copy assignment operator changes the value of an existing object as a copy of another object

```
DynamicArray v1{···};
DynamicArray v2{···};
v2 = v1;
```

- Ideally, after a copy the two objects should compare equal
- The generated operations may not be correct, especially in presence of managed resources (e.g. dynamically-allocated memory)
- The copy operations can be explicitly provided or suppressed

Controlling copying (cont.)

- The copy constructor typically takes an object of the same class by const reference

```
DynamicArray(DynamicArray const& other) : ··· {···}
```

- The copy assignment operator typically:
  - takes an object of the same class by const reference
  - returns the object itself by reference
  - checks for auto-assignment

```
DynamicArray& operator=(DynamicArray const& other)
{
  if (this != &other) {
    ...
  }
  return *this;
}
```

Controlling copying (cont.)

```
class DynamicArray
{
  int m_size = 0; int* m_data = nullptr;
 public:
  DynamicArray(int n, int v = int{}) : m_size{n}, m_data{new int[m_size]}
  { std::fill(m_data, m_data + m_size, v); }
  ~DynamicArray() { delete[] m_data; }
  DynamicArray(DynamicArray const& other)
      : m_size{other.m_size}, m_data{new int[m_size]}
  { std::copy(other.m_data, other.m_data + m_size, m_data); }
  DynamicArray& operator=(DynamicArray const& other)
  {
    if (this != &other) {
      delete[] m_data;
      m_size = other.m_size;
      m_data = new int[m_size];
      std::copy(other.m_data, other.m_data + m_size, m_data);
    }
    return *this;
  }
  ...
};
```

Smart pointers

- A *smart pointer* is an object that behaves like a pointer, but also manages the lifetime of the pointed-to object (i.e. the pointee)
- It leverages the RAII idiom
  - Resource Acquisition Is Initialization
  - Resource (e.g. memory) is acquired in the constructor
  - Resource (e.g. memory) is released in the destructor

Smart pointers (cont.)

```
template<typename Pointee>
class SmartPointer {
  Pointee* m_p;
 public:
  explicit SmartPointer(Pointee* p): m_p{p} {}
  ~SmartPointer() { delete m_p; }
  Pointee* operator->() { return m_p; }
  Pointee& operator*() { return *m_p; }
};

class Sample { ··· };

{
  SmartPointer<Sample> sp{new Sample{}};
  sp->add(···);
  (*sp).stats();
}
```

At the end of the scope (i.e. at the closing `}`) `sp` is destroyed and its destructor `deletes` the pointee

`std::unique_ptr<T>`

Standard smart pointer

- Exclusive ownership
- Minimal overhead, if any
- Non-copyable, movable

```
class Sample { ··· };

void take(std::unique_ptr<Sample> q);        // by value

std::unique_ptr<Sample> p{new Sample{}}; // explicit new
auto p = std::make_unique<Sample>();     // better (*)
auto r = p;                              // error, non-copyable
take(p);                                 // error, non-copyable
auto r = std::move(p);                   // ok, movable
take(std::move(r));                      // ok, movable
```

(*) The possible arguments passed to `make_unique` are *forwarded* to the constructor

Disabling copy operations

- If a class cannot support copy semantics, its copy operations should be suppressed
- The cleanest way to do it is to mark the copy operations as `= delete`

```
template<typename Pointee>
class UniquePtr {
  Pointee* m_p;
 public:
  explicit UniquePtr(Pointee* p): m_p{p} {}
  ~UniquePtr() { delete m_p; }
  UniquePtr(UniquePtr const&) = delete;
  UniquePtr& operator=(UniquePtr const&) = delete;
  Pointee* operator->() { return m_p; }
  Pointee& operator*() { return *m_p; }
};
```

- Note that a deleted copy ctor is still a ctor and would disable the generation of the default ctor
- `= delete` is a general mechanism that can be applied to any function

Move semantics

- It allows to properly *move* (i.e. pass) the responsibility of a resource from one managing object to another
- Mainly driven by optimization considerations but also a solution to a proper management of resources
- Introduced in the language by C++11, thanks to a new type of reference, called *rvalue reference*
- An *rvalue reference* is identified by the token `&&`, e.g. `int&&`

Controlling moving

- The compiler automatically generates the move operations for a class, if used
  - The move constructor creates a new object, re-using the resources owned by another object

```
UniquePtr<int> p{new int{42}};
auto q{std::move(p)}; // auto q = std::move(p)
```

  - The move assignment operator changes the value of an existing object, re-using the resources owned by another object

```
UniquePtr<int> p{new int{12}};
UniquePtr<int> q{new int{34}};
q = std::move(p);
```

- `std::move` enables the use of a move operation instead of the corresponding copy operation
  - In practice it's a `static_cast` of an lvalue reference to an rvalue reference

Controlling moving (cont.)

- If there are no resources involved, a move operation in fact becomes a copy operation
- Move operations typically modify the source object, to steal its internal resources
- After a move the two objects are typically different
- A move should leave the original object in a *"valid but unspecified state"*
  - i.e. **the class invariant is preserved**
  - not always easy, especially for the move constructor
- Move operations should be declared `noexcept`, which means "this function/operation doesn't fail" (more or less)
- The automatically generated operations may not be correct
- The move operations can be explicitly provided or suppressed

Controlling moving (cont.)

```
template <typename Pointee> class UniquePtr
{
  Pointee* m_p;
 public:
  explicit UniquePtr(Pointee* p = nullptr) : m_pp {}
  ~UniquePtr() { delete m_p; }
  UniquePtr(UniquePtr const&) = delete;
  UniquePtr& operator=(UniquePtr const&) = delete;
  UniquePtr(UniquePtr&& other) noexcept
      : m_p{std::exchange(other.m_p, nullptr)}
  {
  }
  UniquePtr& operator=(UniquePtr&& other) noexcept
  {
    delete m_p;
    m_p = std::exchange(other.m_p, nullptr);
    return *this;
  }
  ...
};
```

Controlling moving (cont.)

- The move constructor typically takes an object of the same class by (non-const!) rvalue reference

```
UniquePtr(UniquePtrs&& other) : ··· {···}
```

- The move assignment operator typically:
    - takes an object of the same class by (non-const) rvalue reference
    - returns the object itself by reference
    - does **not** check for auto-assignment

```
UniquePtr& operator=(UniquePtr&& other)
{
  ...
  return *this;
}
```

Special member functions

- A class has five special member functions
  - Plus the default constructor

```
class MyClass {
  MyClass(MyClass const&);             // copy constructor
  MyClass& operator=(MyClass const&); // copy assignment
  MyClass(MyClass&&);                  // move constructor
  MyClass& operator=(MyClass&&);       // move assignment
  ~MyClass();                          // destructor
};
```

- The compiler can generate them automatically according to some convoluted rules
  - The behavior depends on the behavior of data members
- General guidelines:

Rule of zero	Don't declare them and rely on the compiler
Rule of five	If you need to declare one, declare them all

  - Consider using `=default` and `=delete`

std::shared_ptr<T>

Standard smart pointer

- Shared ownership (reference counted)
- Some space and time overhead
  - for the management, not for access
- Copyable and movable

```
class Sample { ··· };

void take(std::shared_ptr<Sample> q);        // by value

std::shared_ptr<Sample> p{new Sample{}};     // explicit new
auto p = std::make_shared<Sample>();         // better (*)
auto s = p;                                 // ok, copyable
take(p);                                    // ok, copyable
auto s = std::move(p);                      // ok, movable
take(std::move(s));                         // ok, movable
```

(*) The possible arguments passed to `make_shared` are *forwarded* to the constructor

Using smart pointers

- Give an owning raw pointer (e.g. the result of a call to `new`) to a smart pointer as soon as possible
- Prefer `unique_ptr` unless you need `shared_ptr`
  - You can always move a `unique_ptr` into a `shared_ptr`
  - But not viceversa
- Access to the raw pointer is available
  - e.g. to pass to legacy APIs
  - *smart*`_ptr<T>::get()`
    - returns a **non-owning** `T*`
  - `unique_ptr<T>::release()`
    - returns an **owning** `T*`
    - must be explicitly managed
- Arrays are supported

```
std::unique_ptr<int[]> p{new int[n]}; // destructor calls 'delete []'
```

Smart pointers and functions

Pass a smart pointer to a function only if the function needs to rely on the smart pointer itself

- by value of a `unique_ptr`, to transfer ownership

```
void take(std::unique_ptr<Sample> q);
auto p = std::make_unique<Sample>();
take(p);            // error
take(std::move(p)); // ok
```

- by value of a `shared_ptr`, to keep the resource alive

```
auto s = std::make_shared<Sample>();
std::thread t{[=] { do_something_with(s); }};
```

- by reference (possibly `const`), to interact with the smart pointer itself

```
void print_count(std::shared_ptr<Sample> const& s) {
  std::cout << s.use_count() << '\n';
}
auto s = std::make_shared<Sample>();
print_count(s);
```

Smart pointers and functions (cont.)

- Otherwise pass the pointee by (const) reference/pointer

```
void stats(std::shared_ptr<Sample> s) { if (s) s->stats(); }
void stats(Sample* t)                 { if (t) t->stats(); } // better
void stats(Sample& t)                 { t.stats(); }         // better

auto s = std::make_shared<Sample>();
stats(s);
stats(s->get());
if (s) stats(*s);
```

- Return a smart pointer from a function if the function has dynamically allocated a resource that is passed to the caller

```
auto create() { return std::make_unique<Sample>(); }

auto u = create();     // std::unique_ptr<Sample>
std::shared_ptr<Sample> s = std::move(u);

std::shared_ptr<Sample> s = create();
```

Smart pointer custom deleter

- A smart pointer is a general-purpose resource handler
- The resource release is not necessarily done with `delete`
- `unique_ptr` and `shared_ptr` support a *custom deleter*

```
FILE* f = std::fopen(···);
...
std::fclose(f);
```

Usual problems:

- Who owns the resource?
- Forgetting to release
- Releasing twice
- Early return/throw

```
std::shared_ptr<FILE> file{
    std::fopen(···),                    // pointer
    [](FILE* f) { std::fclose(f); } // deleter
};
```

Taxonomy of STL Containers

Sequence The client decides where an element gets inserted

- **`array`**, `deque`, `forward_list`, `list`, **`vector`**

Associative The container decides where an element gets inserted

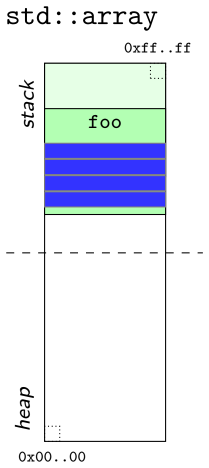
  Ordered The elements are sorted based on a key

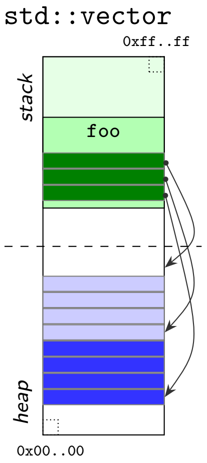
  - **`map`**, `multimap`, `set`, `multiset`

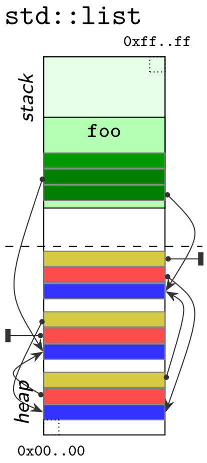
  Unordered The position of an element depends on the *hash* of its key

  - `unordered_map`, `unordered_multimap`, `unordered_set`, `unordered_multiset`

Sequence containers





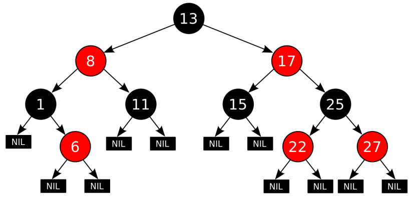


Sequence containers (cont.)

- `std::array`
  - fixed size, contiguous in memory
  - typical operations
    - `operator[]`
    - iteration with `begin`/`end`
- `std::vector`
  - dynamic size, contiguous in memory
  - typical operations
    - `push_back`
    - `operator[]`
    - iteration with `begin`/`end`
- `std::list`
  - dynamic size, non-contiguous in memory, iterator stability
  - typical operations
    - `push_back`, `push_front`, `insert`
    - iteration with `begin`/`end`

Associative ordered containers

- They contain ordered values (`set` and `multiset`) or key-value pairs (`map` and `multimap`)
- Search, removal and insertion have logarithmic complexity
- Typically implemented as balanced (red-black) trees



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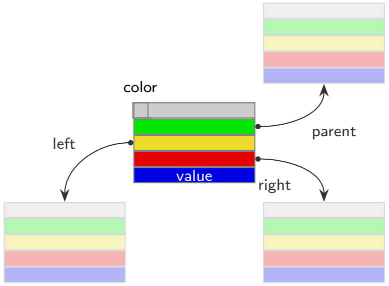


Dynamic polymorphism

Polymorphism

The provision of a single interface to entities of different types

static Based on concepts and templates

```
template<class Iterator, class T>
Iterator std::find(Iterator f, Iterator l, T const& v);

std::vector<int> v{···};
auto it = std::find(v.begin(), v.end(), 12);

std::list<Command> l{···};
auto it = std::find(l.begin(), l.end(), Command{"send"});
```

dynamic Based on inheritance and virtual functions

Inheritance

```
struct Base {
  int a;
  Base(int a) : a{a} {}
  void f();
  int operator()() const;
};

struct Derived : Base {
  double d;
  Derived(int i, double d)
    : Base{i+1}, d{d} {}
  int h() const;
};

Derived de{42, 3.14};
de.d;
de.h();
de.a;   // Base::a
de.f(); // Base::f
de();   // Base::operator()
Base* b1 = &de;
Base& b2 = de;
```

- A class may be declared as *derived* from one or more *base* classes
  - A hierarchy can be formed
- Members of the base class are also members of the derived class
  - Let's ignore access control (`private`, `public`) for the moment
- Constructing a `Derived` object constructs also the corresponding `Base` *sub-object*, either explicitly (like in this case) or implicitly
- `Derived*` can be implicitly converted to `Base*`
- A `Derived` object can bind to `Base&`

Dynamic polymorphism

Typical use case: a graphics system of shapes

```
struct Circle { // is a Shape
  Point c;
  double r;
  void move(Point p);
  Point where() const;
};

struct Rectangle { // is a Shape
  Point ul;
  Point lr;
  void move(Point p);
  Point where() const;
};

std::vector<Shape> shapes;                       // I wish I could do this
for (auto const& s : shapes) { s.where(); }     // wish
for (auto& s : shapes) { s.move(Point{1,2}); } // wish
```

Let's ignore access control (private, public) for a moment

Dynamic polymorphism (cont.)

```
struct Shape {                       // abstract base class
  virtual Point where() const = 0; // pure virtual function
  virtual ~Shape();                  // virtual dtor; no '= 0' here
};

struct Circle : Shape { // derived class
  Point c;
  int r;
  Point where() const override;
};

struct Rectangle : Shape { // derived class
  Point ul;
  Point lr;
  Point where() const override;
};

Shape* create_shape();   // return new Circle/Rectangle
auto s = create_shape();
s->where();
delete s;                // better use a smart pointer
```

Dynamic polymorphism (cont.)

- A non-static member function (i.e. a method) is a **virtual** function if it is first declared with the keyword `virtual` or if it **override**s a virtual member function declared in a base class
- A class with a virtual member function is called a **polymorphic** class.
- Virtual functions support **dynamic binding** and **object-oriented programming**
  - A call to a virtual function made through a pointer/reference to a base class is dispatched to the corresponding function of the actual derived class object behind that pointer/reference
- Overridden functions must have the same signature
  - Beware of member function hiding

Dynamic polymorphism (cont.)

- A virtual function is **pure** if its declaration ends with `= 0`
  - A pure virtual function cannot be defined (i.e. have an implementation) – with one exception (see later)
- A class is **abstract** if it has at least one pure virtual function
  - No objects of an abstract class can be created
  - An abstract class is typically used to represent an *interface*

Dynamic polymorphism (cont.)

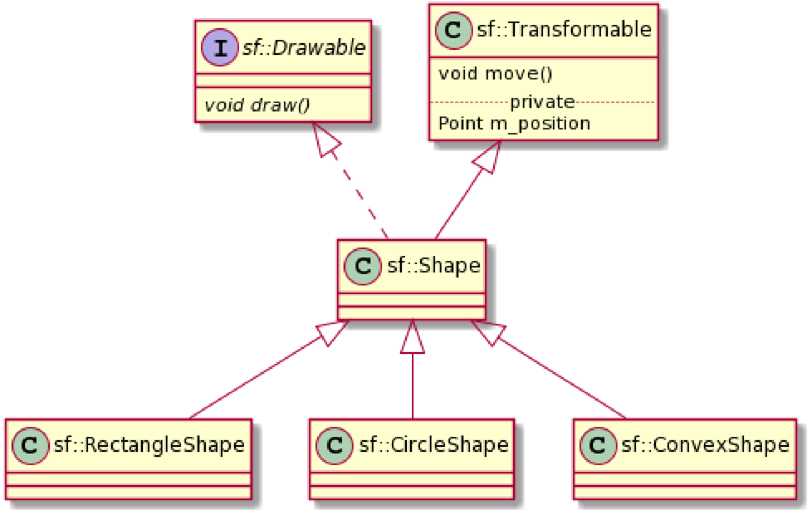
```
struct Base {
  virtual void f(int) = 0;
};

struct Derived : Base {
  void f(int) override {···}
};

Base b;                  // error
Base* b1 = new Derived; // ok, owning pointer, remember to delete
b1->f(0);                // calls Derived::f
Derived d;               // ok
Base* b2 = &d            // ok, non-owning pointer, don't delete
b2->f(0);                // calls Derived::f
Base& b3 = d;            // ok
b3.f(0);                 // calls Derived::f
```

Mixing interface and implementation

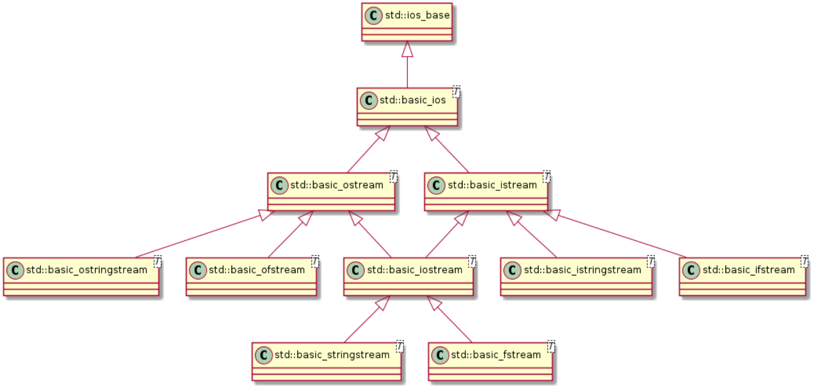
```
struct Shape {
  Point p;
  Shape(Point p) : p{p} {}
  virtual ~Shape();
  virtual Point where() const { return p; } // not pure; default implementation
};

struct Circle : Shape {
  int r;
  Circle(Point p, double d) : Shape{p}, r{d} {}
  // where() implementation is inherited from Shape
};

struct Rectangle : Shape {
  Point lr;
  Rectangle(Point p1, Point p2) : Shape{p1}, lr{p2} {}
  Point where() const override { return (p + lr) / 2; } // p is inherited
};
```

Not recommended, especially for data members

Example: SFML



An example from the Standard Libary: I/O streams



```
namespace std {
  using istream = basic_istream<char>;
  using ostream = basic_ostream<char>;
  using istringstream = basic_istringstream<char>;
  using ostringstream = basic_ostringstream<char>;
  using ifstream = basic_ifstream<char>;
  using ofstream = basic_ofstream<char>;
  ...
  istream cin;
  ostream cout;
}
```

I/O Streams

- C++ provides an Input/Output library based on the concept of *streams*, which abstract input/ouput devices
- `std::cin` and `std::cout` are streams attached to the standard input and output of the program (typically attached to the terminal)
- Other stream classes allow I/O from/to files and strings
- Since they are part of a polymorphic hierarchy these objects can be passed to functions implemented in terms of the base class
  - For example the *streaming* operators << and >>

File I/O

```
std::ifstream is{"/tmp/in"};  // open /tmp/in for reading
std::ofstream os{"/tmp/out"}; // open /tmp/out for writing
if (!is || !os) {
  // manage error
}
double d;
while (is >> d) {
  os << std::setw(12) << d * 2 << '\n';
}
```

- `fstream` constructor opens the file, destructor closes it
- There are explicit `open` and `close` methods
- Many other operations/options (mostly inherited)

String I/O

```
std::istringstream is{"12. 14. -42."};
std::ostringstream os;

double d;
while (is >> d) {
  os << std::setw(12) << d * 2 << '\n';
}

std::cout << os.str();
// "          24\n          28\n         -84\n"
```

- `stringstream` constructor possibly allocates memory, destructor deallocates
- The `str` method can be used to get/set the contents of the `stringstream`
- Many other operations/options (mostly inherited)

operator<<

- `operator<<` is usually implemented as a free function
  - Note that the object we want to stream is the second parameter

```
class Complex {
  double r;
  double i;
 public:
  double real() const;
  double imag() const;
  ...
};

inline std::ostream& operator<<(std::ostream& os, Complex const& c)
{
  os << '(' << c.real() << ',' << c.imag() << ')';
  return os;
}
```

- To be more general, it should actually be a function template and accept/return `std::basic_ostream<···>`

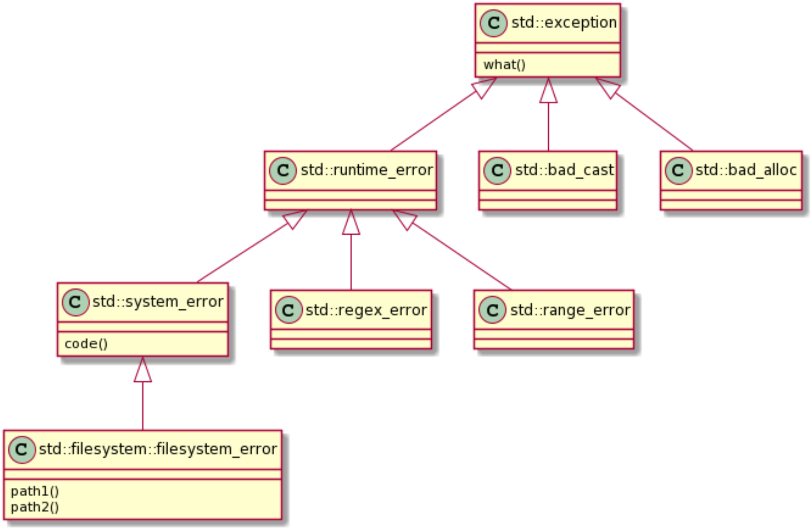
friend functions

- Sometimes a free function (e.g. `operator<<` needs private data that are not exposed (or not exposed efficiently) via the public interface
- In that case it can be implemented as a `friend` free function

```
class Complex {
  double r; double i;
 public:
  friend std::ostream& operator<<(std::ostream& os, Complex const& c) {
    os << '(' << c.r << ',' << c.i << ')';
    return os;
  }
  ...
};
```

- Note how the function, being defined inside the class definition, is automatically `inline`
- It can be just declared inside the class definition and be defined outside, even in another file
- *friendship* has a much broader usage than shown here
  - E.g. a whole class can be `friend` of another

Another example from the Standard Library: Exceptions



Note: the hierarchy is incomplete

Multiple exception-catch clauses

- A `try`-block can have multiple catch clauses
- The first that matches the type of the exception is chosen
- The order is important: put the more specific ones first

```
auto read_from(std::filesystem::path const& p) {
  std::ifstream is(p);
  if (!is) {
    throw std::filesystem::filesystem_error{
      "read_from", p, std::make_error_code(std::errc::invalid_argument)
    };
  }
  ...
}

int main() {
  try {
    read_from("/tmp/data");
    ...
  } catch (std::filesystem::filesystem_error const& e) {
    std::cerr << e.path1(); return EXIT_FAILURE;
  } catch (std::exception const& e) {
    std::cerr << e.what(); return EXIT_FAILURE;
  } catch (...) { // it's really three dots!
    std::cerr << "unknown exception"; return EXIT_FAILURE;
  }
}
```

Overriding vs hiding

```
struct Base {
  virtual void f(int);
};

struct Derived : Base {
  void f(int); // overriding, virtuality is "inherited"
};

Derived d;
Base& b = d;
b.f(1);          // call Derived::f(int)
```

- A virtual function should specify exactly one of `virtual`, `override`, or `final`
- A `final` virtual function cannot be overridden in a derived class
- A class can be declared `final` and cannot be derived from

```
struct Derived final { ··· };
```

Overriding vs hiding (cont.)

```
struct Base
{
  virtual void f(int);
};

struct Derived : Base
{
  virtual void f(unsigned); // this is another function, hiding Base::f
};

Derived d;
Base& b = d;
b.f(1);          // call Base::f(int)
b.f(1U);         // call Base::f(int)
d.f(1);          // call Derived::f(unsigned)
d.f(1U);         // call Derived::f(unsigned)
```

- Virtual functions should specify exactly one of `virtual`, `override`, or `final`
- Specifying `override` (or `final`) would have caused a compilation error

Overriding vs hiding (cont.)

```
struct Base
{
    virtual void f(int) const;
};

struct Derived : Base
{
  virtual void f(int); // this is another function, hiding Base::f
};

Derived d;
Base& b = d;
b.f(1);          // call Base::f(int) const
```

- Virtual functions should specify exactly one of `virtual`, `override`, or `final`
- Specifying `override` (or `final`) would have caused a compilation error

Slicing

A base class without pure virtual functions is not abstract any more

- It can be instantiated
- It can be copied
    - unless precautions are taken, e.g. copy/move operations are `deleted`

```
struct Shape
{
  Point p;
  Shape(Point p): p{p} {}
  virtual ~Shape() = default;
  virtual Point where() const { return p; }
};

struct Rectangle : Shape {···};

Shape s; // desirable?
Shape s2 = s1; // desirable?
Rectangle rect{···};
Shape s = rect; // desirable??
```

Slicing (cont.)

```
void process1(Shape& shape) // by reference
{
  ··· shape.where() ··· // Point{2., 4.}
}

void process2(Shape shape) // by value
{
  ··· shape.where() ··· // Point{1., 7.}
}

auto rect = Rectangle{Point{1., 7.}, Point{3., 1.}};
process1(rect);
process2(rect);
```

- When an object `obj` of a derived class is passed to a function that takes a parameter of a base class **by value**, only the base class sub-object of `obj` is passed to the function

Keeping the base class abstract

- It's good practice to keep base classes abstract
- A base class without pure virtual functions is not abstract any more
- To prevent this, declare the destructor as pure virtual
- Yet the destructor needs to be defined
  - So that derived classes are properly destroyed

```
struct Shape {
  Point ul;
  Shape(Point p): p{p} {}
  virtual ~Shape() = 0;
  virtual Point where() const; // non-pure virtual function
};
inline Shape::~Shape() = default; // or any other implementation

Shape s; // not really desirable
```

Access control

A member of a class can be

`public`	Its name can be used **anywhere** without access restriction
`private`	Its name can be used **only by members** and friends of the class in which it is declared
`protected`	Its name can be used only **by members** and friends of the class in which it is declared, **by classes derived** from that class, and by their friends

Accessibility through derivation

```
class Base {
 private:
  ...
 protected:
  ...
 public:
  ...
};

class Derived : public|private|protected Base {};
```

Derivation itself can be

`public`	public in B → public in D protected in B → protected in D • Sub-typing (*is-a* relationship) • This is the one you should use
`private`	public or protected in B → private in D • Implementation inheritance
`protected`	public or protected in B → protected in D • Rarely, if ever, used

protected access

```
class Shape {
 protected:
  Point p;
 public:
  Shape(Point p) : p{p} {}
  virtual ~Shape() = default;
  virtual Point where() const { return p; }
  virtual double area() const = 0;
};

class Rectangle : public Shape { // is-a
 private:
  Point lr;
 public:
  Rectangle(Point p1, Point p2) : Shape{p1}, lr{r} {}
  double area() const override { ··· std::abs(p.x - lr.x) ··· }
};
```

- protected and public members represent an interface
- Data members are a poor interface, keep them private

Structural inheritance

- Inheritance is applicable also in non-polymorphic situations
- To reuse and possibly extend the implementation and the interface of a class
- A way to create a distinct type with the same implementation and interface of another
- Consider composition, i.e. a member, or private inheritance

```
class Vector : public std::vector<int> {
  using std::vector<int>::vector; // inherit constructors
};

void process(std::vector<int>&); // #1
void process(Vector&);           // #2
void signal(std::vector<int>&);  // #3

std::vector<int> v1{···};
Vector v2{···};             // all std::vector ctors are available
process(v1);                // call #1
process(v2);                // call #2
signal(v2);                 // call #3
```

Destruction and inheritance

- In case of polymorphic inheritance, the destructor of a base class should be
    - `public` and `virtual`, or
    - `protected` and non-`virtual`
- In case of structural inheritance, don't delete through a pointer to the base class

```
class Vector : public std::vector<int> {};

Vector v;                             // ok

Vector* pv = new Vector;
delete pv;                            // ok

std::vector<int>* ps = new Vector;
delete ps;                            // undefined behavior
```

Copying/moving and inheritance

- Dynamic polymorphism and value semantics don't play well together
  - See slicing
- The copy/move operations of a base class shouldn't be publicly accessible, but they need to be accessible to a derived class
  - Declare them `protected`

```
class Base
{
  ...
 protected:
  Base(Base const&);
  Base& operator=(Base const&);
  Base(Base&&);
  Base& operator=(Base&&);
 public:
  ...
};
```

Copying/moving and inheritance (cont.)

- If you need some form of *deep* copy, consider providing a virtual *clone* operation

```
class Base
{
 public:
  virtual Base* clone() const = 0;
};

class Derived: public Base
{
 public:
  Derived* clone() const override
  {
    return new Derived{*this}; // call the copy ctor of Derived
  }
};
```

- Note the return type: an overridden function can return a derived class
    - *co-variant* return type

Epilog

What we have learnt in this course

- Introduction to Linux
- Elements of computer architecture and operating systems
- Why C++
- Objects, types, variables
- Expressions
- Statements and structured programming
- Functions and function objects
- User-defined types and classes and operator overloading
- Generic programming and templates
- The Standard Library, containers and algorithms
- Dynamic memory allocation and resource management
- Dynamic polymorphism (aka object-oriented programming)
- Error management
- Elements of software engineering and supporting tools

Where to go from here

- C++ is a large and complex language and has a large and complex standard library
  - Many more libraries are available from third parties
  - See, for example, vcpkg or conan
- We have just scratched the surface of what the language and the libraries provide
- There are many high-quality resources to go deeper
  - Learn C++
  - News, Status & Discussion about Standard C++
  - C++ reference
  - C++ Core Guidelines
  - C++ Conference (presentations, videos)
  - C++ Now Conference (presentations, videos)
  - Meeting C++ Conference (presentations, videos)
  - Italian C++ Community
  - C++ Weekly
  - Existing source code (e.g. boost libraries or SFML)