Advanced Programming in C++

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```
#include <iostream>
#include <vector>

int main() {
  vector<string> msg {"Welcome", "to", "advanced", "C++"};
  for (const std::string & word : msg) {  // C++11 standard
    std::cout << word << ' ';
  }
  std::cout << '\n';
}
```

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This course in a nutshell

In this course, you learn advanced themes in C++ programming

The course consists of:

- Lecture: 2h per week, basic concepts
- Lab: 2h per week, getting / correcting programming tasks
- Homework: ± 2h per week, solving assignments

This course in a nutshell

Links to lecture slides and assignments are available on moodle:

- https://moodle.uni-siegen.de/course/view.php?id=34345
- updates to the slides will be made available during the term

We learn C++ by doing, hence: *follow lectures and exercises*

Disclaimer:
This course's material was inspired by similar courses from colleagues Roland Wismueller (Uni Siegen), Hannah Bast (Uni Freiburg), Federico Busato (NVIDIA, Modern C++ Programming)

Examination and grading

See the description of this course here

Enroll for both lecture *and* exercises, as well as the course work (4INFMA307-S):

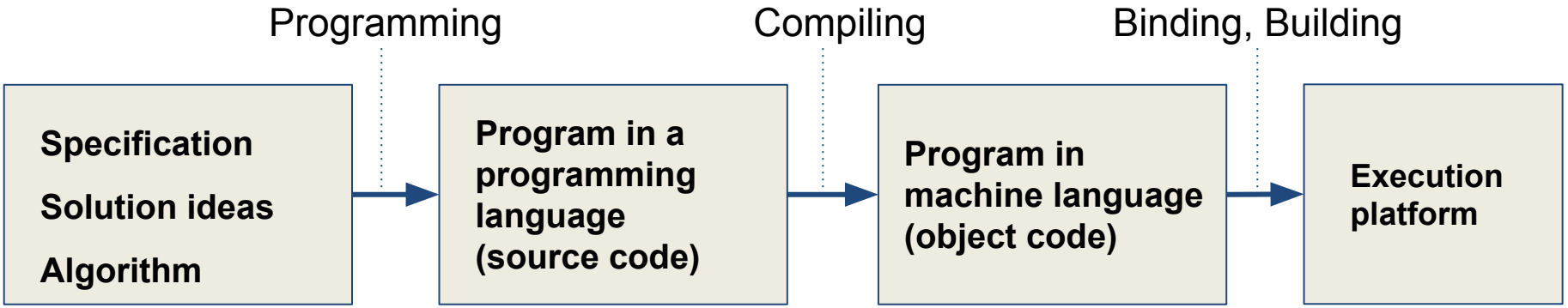
- Set of programming assignments during term: programming on paper
- These need to be delivered in-class => your presence required
- You need to pass this course work to be able to enroll for the exam

A 1-hour written exam (enroll more than 2 weeks before: 4INFMA307-P):

- 1 handwritten A4 (double-sided) page is allowed
- Bring a photo ID and a pen (blue/black ink only)
- Structure: Programming tasks *very similar* to the exercises

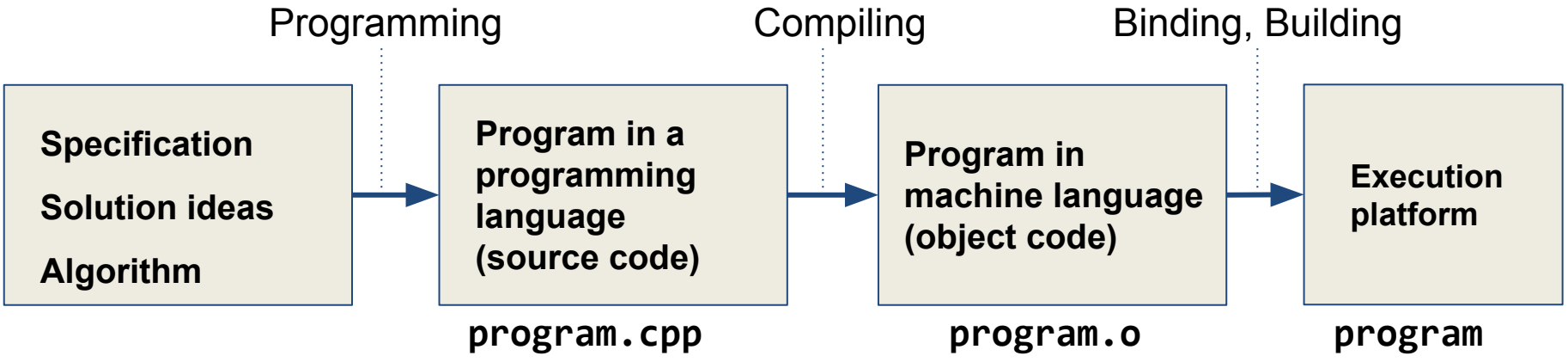
1. Designing programs

Steps in creating a program:



1. Designing programs

Steps in creating a program:



Editor:
`nano program.cpp`

GCC compiler:
`g++ program.cpp`

`./program`

1. Designing programs

1.1. Program structure:

- A program is essentially a series of *machine instructions* that tell the system what to do, step by step, similar to a recipe
- Source code allows humans to formulate instructions in an understandable fashion, which then can be translated to machine instructions → In this course, we use C++ to create source code
  - C++ source code files are text files that end with **.cpp** or **.h**
  - A *compiler* then translates these to a program that consists out of machine instructions
- Creating source code needs a file system and operating system

1. Designing programs

1.2. Using GitHub Repository, g++, editors

We will use a github repository: https://github.com/kristofvl/AdvancedCPP as a code base for the slides, all exercises, and home works from the lecture

- You will need a github account
- It allows keep track of changes, and distributing larger projects

We'll use GNU g++. For Linux or macOS, you can directly use g++
In Windows, you can install Windows Subsystem for Linux (WSL), to have a Linux environment to use g++ inside it

1. Designing programs

1.2. Using GitHub Repository, g++, editors

You are free in the use of editor. Here are a few options:

Microsoft Visual Studio Code (VSCode) , Sublime , Lapce, Zed

Text-based coding editors: Vim, Emacs, NeoVim, Helix

Not suggested: Notepad, Gedit, and other similar editors

1. Designing programs

BDay.cpp

```
/* The Birthday Paradox -- an illustration
   Author: kvl,   Date: first week     */



int main() {



  return 0;
}
```

1. Every program should mention who programmed it

2. Every program needs a function "main" that contains all code to be executed

3. The function "main" will exit and send a number (usually zero, for "no error") to the operating system

1. Designing programs

BDay.cpp

```
/* The Birthday Paradox -- an illustration
   Author: kvl,   Date: first week     */
#include <iostream>
class BDay {
 /* p(x) --> probability of x happening,  p(x) = 1 - p(not x)
    p(2 persons have same birthday) =  1 - (365-1)/365 * (365-2)/365 * ... * (365 - (n-1))/365 */
 public:
  double prob(int n);
};
double BDay::prob(int n) {
  double p = 1.0;   // probability that out of n people, 2 have the same birthday
  for (int i = 0; i < n; i++) {  // i = 1, 2, ..., n-1
     p = p * (365-i)/365;
  }
  return 1 - p;
}
int main() {
  int n = 23;
  BDayP b;  // create an object to access the prob() method:
  std::cout << "The chance that 2 of " << n << " people have a same birthday is " << b.prob(n);
  return 0;
}
```

1. Designing programs

1.3. Compiling and building a program:

- Type `g++` to launch the GCC c++ compiler: `g++ BDay.cpp`
  - `g++` creates the program, a file with the default name `a.out` in the current directory, which can be executed in the terminal: `./a.out`
- Add `-o` to specify another name: `g++ BDay.cpp -o BDay`
  - `g++` creates the file `BDay` , which can be executed: `./BDay`
- The compiler tries to compile all other needed source files and needs a `main` function in the files that specifies what your program does
  - `g++` can compile multiple files, e.g.: `g++ ex1.cpp ex2.cpp`
  - `g++` can compile code for later use in a program with `-c` :
    `g++ -c BDay.cpp`, which creates `BDay.o`
    `g++ BDayx.o` then creates the program `a.out`

1. Designing programs

1.3. Compiling and building a program:

- Add `--std` to specify which C++ standard your code is for. If for instance you use features for C++11 you need to add `--std=c++11`:

```
g++ BDay.cpp -o BDay --std=c++11
```

  Features you use may be in different standards, and you can specify them by the option `--std` to let the compiler compile the source code in different standards

1.4. Including libraries:

- The compiler can include others' code as a library that is mentioned in the source code (for example `#include <iostream>`)
  - In this course, we will see mostly such *standard* libraries, `g++` knows where to search for their files and links these:
    `g++ BDaySimple.cpp`

BDaySimple.cpp

```
/* The Birthday Paradox -- a simplification */
#include <iostream>
int main() {
  std::cout << "The chance that 2 out of 23 people have";
  std::cout << " a same birthday is about 0.5 \n";
  return 0;
}
```

1. Designing programs

1.4. Including libraries:

- The compiler can include others' code as a library that is mentioned in the source code (for example ncurses: `#include <ncurses.h>`)
  - Other non-standard libraries need to be linked explicitly with `-l`:

```
g++ BDayCentre.cpp -l ncurses
```

BDayCentre.cpp

```
/* The Birthday Paradox -- in the *middle*  */
#include <ncurses.h>  // draw text in terminal screen
int main() {
  initscr();    // initialize ncurses window
  mvaddstr(LINES/2,   COLS/3, "The chance that 2 out of 23 have");
  mvaddstr(LINES/2+1, COLS/3, "the same birthday is about 0.5. wow.");
  getch();      // capture the user's pressed key
  endwin();     // close the ncurses window
  return 0;
}
```

1. Designing programs

1.5. Indenting your code:

- To make everyone's code look the same, we recommend using **cpplint**
- We *also* recommend **2-space indentation** (see *all* examples in slideset):

```
void myFunction(bool exec, bool size) {  // indent after each {
◇◇int ret = 0;
◇◇if (exec) {  // indent after each {
◇◇◇◇for (int i = 0; i < size; i++) {  // indent after each {
◇◇◇◇◇◇ret += i;
◇◇◇◇}  // de-indent before each }
◇◇} else {  // indent after each {
◇◇◇◇ret = 12;
◇◇}  // de-indent before each }
}  // de-indent before each }
```

2.1. The basic components of a program:

- Reserved keywords
- Preprocessor directives
- Names
- Constants
- Operators
- Braces
- Separators
- Comments

```
/* The Birthday Paradox -- in short */
#include <iostream>
int main() {
  std::cout << "The chance that 2 out of";
  std::cout << " 23 people have a same";
  std::cout << " birthday is about ";
  std::cout << 0.5 << '\n';
  return 0;  // 0 back to operating system
}
```

2.1.1. Reserved C++ keywords

Reserved keywords are words that are reserved for special meaning by the language standard and cannot be used as identifiers (names for variables, functions, classes, etc.). E.g.:

`bool`	`do`	`namespace`	`switch`
`break`	`double`	`new`	`this`
`case`	`else`	`private`	`true`
`catch`	`false`	`protected`	`using`
`char`	`float`	`public`	`virtual`
`class`	`for`	`return`	`void`
`const`	`if`	`short`	`while`
`delete`	`int`	`sizeof`	

2.1.2. Preprocessor directives

Source code can also contain so-called *preprocessor directives* that start with a `#` : We will use solely:

- `#include`, followed by a source file either:
  - surrounded by `<` and `>` , for example: `#include <ncurses.h>` for source code from standard libraries
  - surrounded by `"` and `"` , for example: `#include "myCode"` for source code in the current directory
- **header guards** to ensure that code is included only once:

```
#ifndef HEADERFILE
#define HEADERFILE

#endif
```

2.1.3. Names:

You can define names to variables, parameters, functions, etc.

- these names need to be unique (so no keywords)
- they can contain only letters, digits and underscores (_)
- they need to start with letters or an underscore
- their length is nearly unlimited
- examples:

correct	wrong	reason
`Sum`	`get Name`	no empty spaces
`getName`	`Ver2-1`	minus '-' not allowed
`_all4you`	`2exp4`	starts with a digit
`__1_2`	`while`	C++ keyword

2. Data: Variables, Types, Constants

2.1.4. Constants:

`15` (integer) `3.14159f` (float) `3.14159` (double)
`'p'` (character) `"brb"` (string) `true` (boolean)

2.1.5. Operators:

`+ - * / && || = == >= <= << >> < > ...`

2.1.6. Braces:

`( ) [ ] { }`

2.1.7. Separators:

`, ; .` (space) as well as tabs or new lines

2.1.8. Comments:

- `// comment till the end of the line`
- `/* comment that spans across multiple lines */`
- note that a multi-line comment cannot contain */:
  `/* this example comment */ would cause an error */`

```
// probability that out of n people, 2

/* p(x) --> probability of x happening
   p(x) = 1 - p(not x)
   p(2 persons have same birthday) =
...*/

/** The Birthday Paradox -- illustration
*   Author:  kvl
*   Date:    last week
*/
```

IMPORTANT: Comments should explain your code but never be trivial

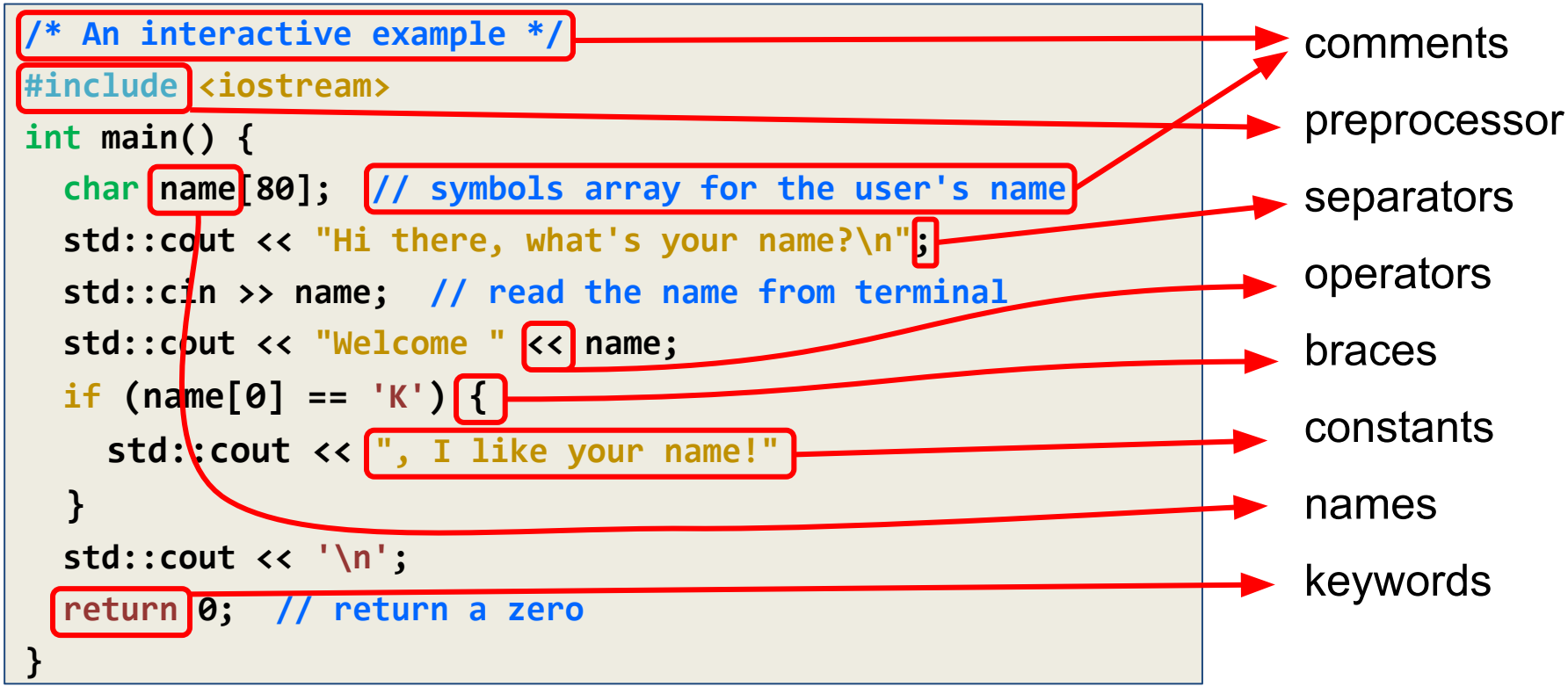
good: `int scrMaxWidth; // maximum screen width`

bad: `float aspectRatio; // this variable holds the aspect ratio`

2. Data: Variables, Types, Constants

2.1. Example:

```
/* An interactive example */
#include <iostream>
int main() {
  char name[80];  // symbols array for the user's name
  std::cout << "Hi there, what's your name?\n";
  std::cin >> name;  // read the name from terminal
  std::cout << "Welcome " << name;
  if (name[0] == 'K') {
    std::cout << ", I like your name!"
  }
  std::cout << '\n';
  return 0;  // return a zero
}
```



2.2. Variables:

- represent *memory space*, where data of a certain type can be stored
- need to be declared and ideally initialized before use:
```
int keyPressCounter = 0;  // how often did user press a key?
```
- have values that after declaration can be 'read out' and changed:
```
if (keyPressCounter > 27)  // after 27 key presses,
  keyPressCounter = 0;     // we set it back to zero
```
- can't be changed afterwards, when declared (and initialized) as **constants**: `const int answer = 42; // after this, answer stays 42`
- live in a certain *scope*, typically the function in which it was declared. After this function ends, the variable is deleted from memory.

2.3. Data types: Integral

Native type	Bytes	Range	Fixed width types <cstdint>
bool	1	true, false	
char	1	see **ASCII** table	
signed char	1	-128 -- 127	`int8_t`
unsigned char	1	0 -- 255	`uint8_t`
short	2	-2^{15} -- $2^{15}-1$	`int16_6`
unsigned short	2	0 -- $2^{16}-1$	`uint16_t`
int	4	-2^{31} -- $2^{31}-1$	`int32_t`
unsigned int	4	0 -- $2^{32}-1$	`uint32_t`
long int	4/8		`int32_t / int64_t`
long unsigned int	4/8		`uint32_t / uint64_t`
long long int	8	-2^{63} -- $2^{63}-1$	`int64_t`
long long unsigned int	8	0 -- $2^{64}-1$	`uint_64_t`

2.3. Data types: Floating-Point

Native type	Bytes	Range	Fixed width types C++23 <stdfloat>
(bfloat16)	2	$\pm 1.18 \times 10^{-38}$ -- $\pm 3.4 \times 10^{38}$	`std::bfloat16_t`
(float16)	2	0.00006 -- 65536	`std::float16_t`
float	4	$\pm 1.18 \times 10^{-38}$ -- $\pm 3.4 \times 10^{38}$	`std::float32_t`
double	8	$\pm 2.23 \times 10^{-308}$ -- $\pm 1.8 \times 10^{308}$	`std::float64_t`

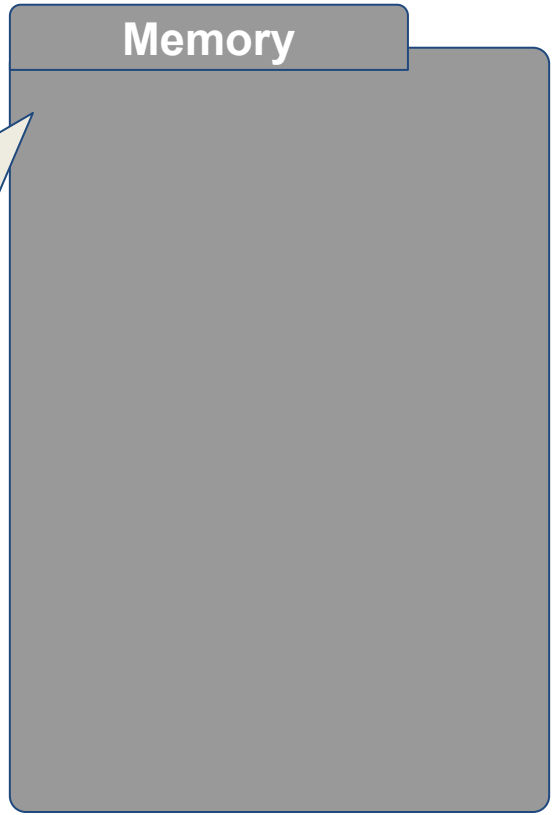
- See also `IEEE754` for more information

2.3. Data types

- A type defines: what *values* the variable can have,
  how much memory is allocated for it, and
  which *operations* are possible
- All variables and constants have a type in C++
  - for constants, you can tell the type by their form
  - for variables, this is explicit in the declaration

2.3. Data types: A (simplified) Memory View

```
/* reserving variables */
int main() {
  char mySymbol;   // store one character
  int myInteger;   // store an integer
  bool myBoolean;  // store a boolean
  float myFloat;    // store a floating point
  myInteger = 12;  // 12 = constant integer
  myFloat = 12.0f; // 12.0f= constant floating point
  mySymbol = '@';  // '@' = constant character
  myBoolean = true;  // true = constant boolean
  return 0;
}
```



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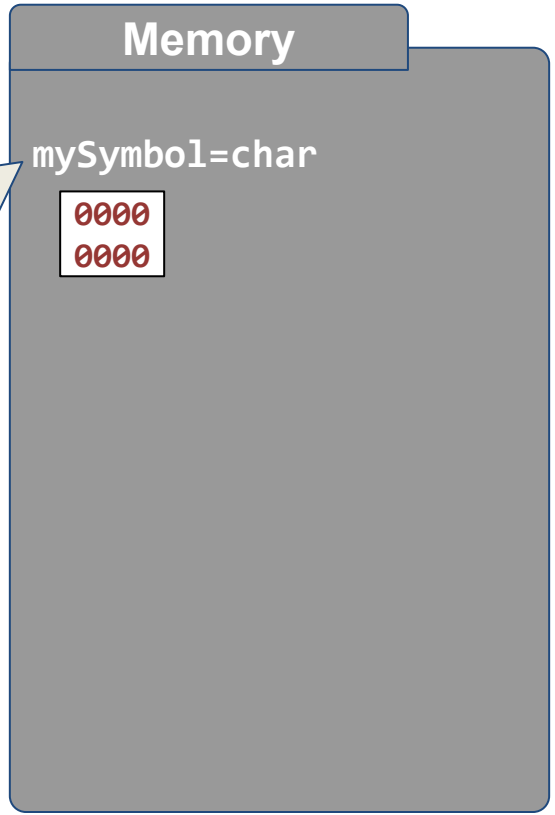

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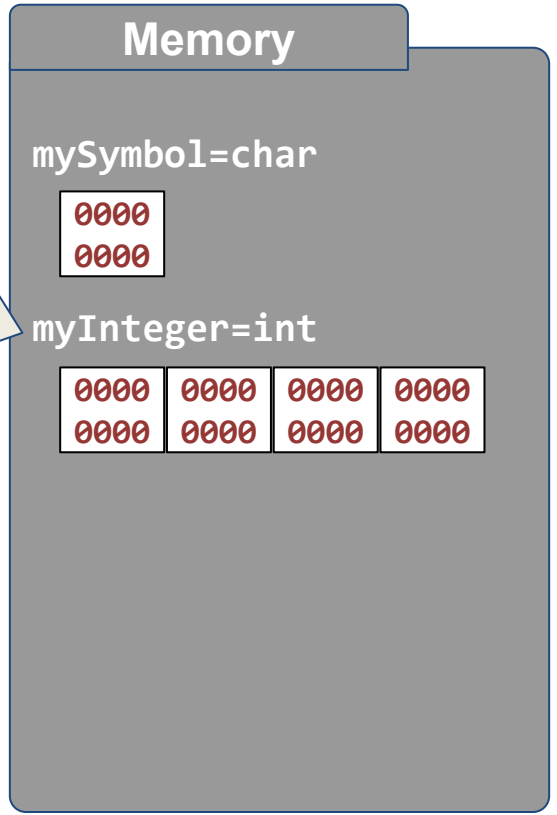

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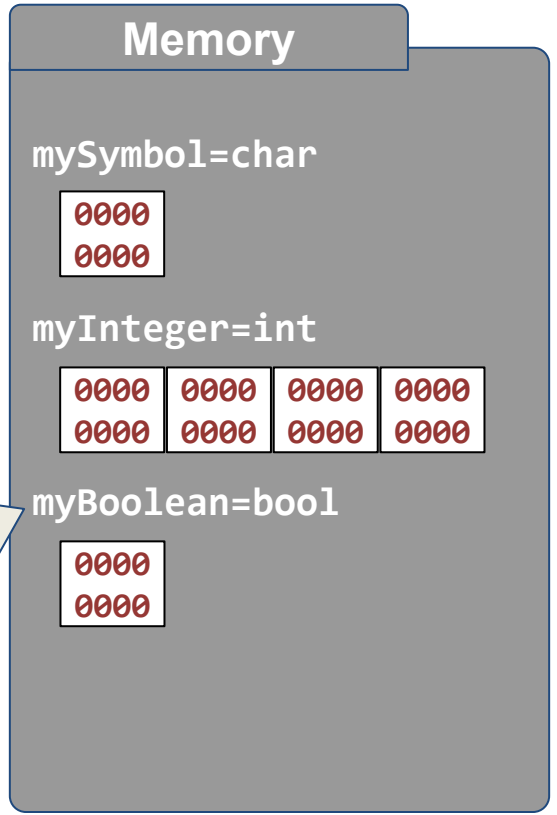

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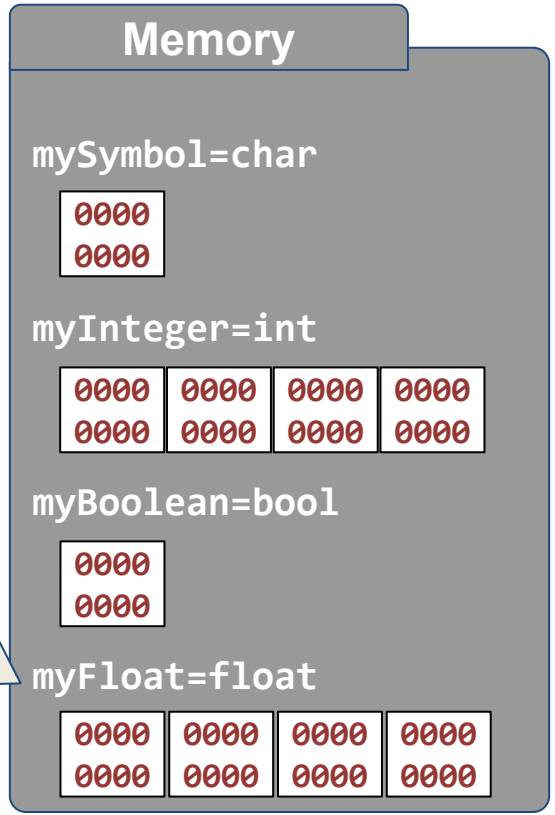

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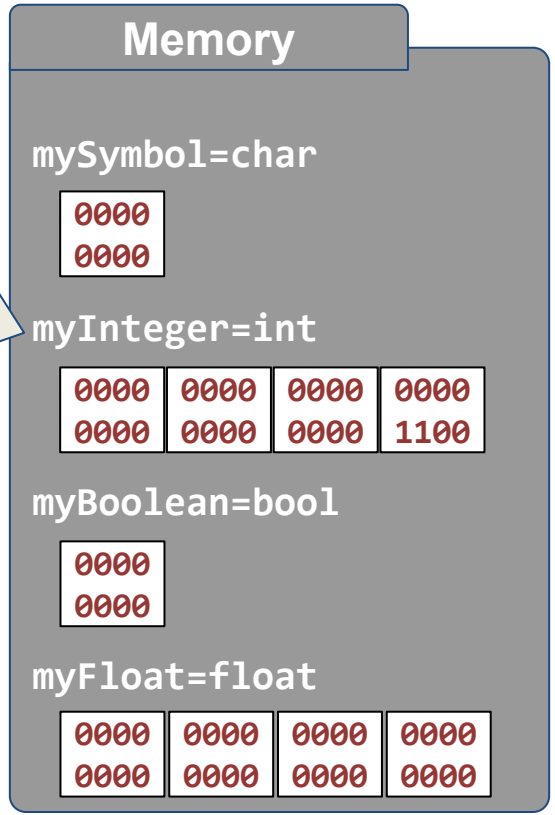

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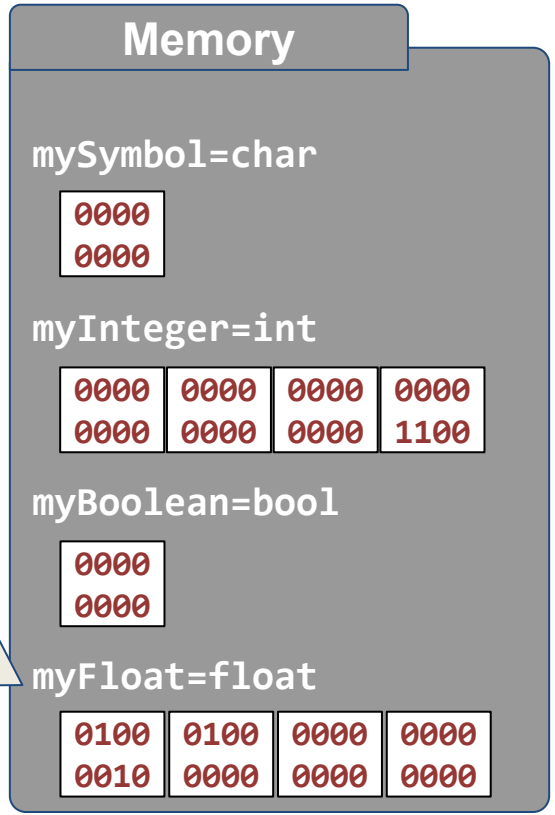

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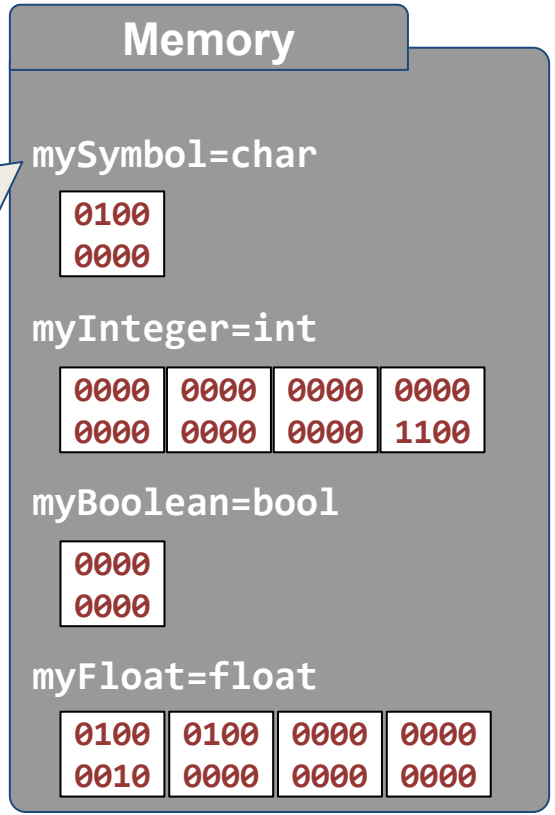

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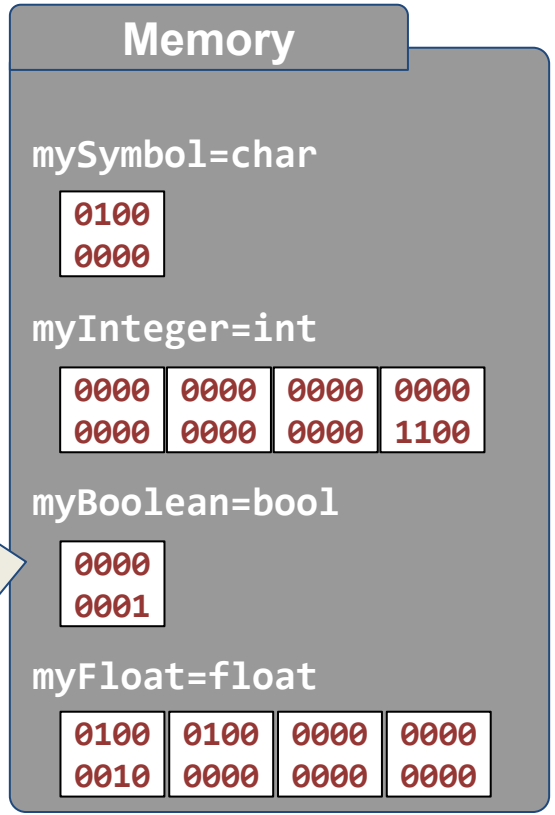


2.3. Data types: Constants

Constants for these type are visible from how they are written, mostly using a type-dependant ***suffix***:

- `int` whole numbers without suffix, e.g.: `729`, `-3628`, `0`, `-12632832`
- `unsigned int` `u` or `U`, e.g.: `56u`, `7126u`, `0U`
- `long int` `l` or `L`, e.g.: `523374631`, `-363433428L`
- `long unsigned` `ul` or `UL`, e.g.: `39ul`, `3637428UL`
- `long long int` `ll` or `LL`, e.g.: `52ll`, `1634428LL`
- `long long unsigned` `ull` or `ULL`, e.g.: `7ull`, `8428ULL`
- `float` numbers with decimal range and `f`, e.g.: `3.612f`, `5.2f`, `0.001f`
- `double` numbers with decimal range, e.g.: `3.612`, `5.2`, `0.001`
- `char` a character between single quotes, e.g.: `'?'`
- `bool` either `true` or `false`

2.3. Data types: Constants

Constants for C++23 float types use a type-dependant ***suffix***:

- `std::bfloat16_t` `bf16` or `BF16`, `3.21bf16`, `-12.345BF16`
- `std::float16_t` `f16` or `F16`, `3.21f16`, `-12.345F16`
- `std::float32_t` `f32` or `F32`, `3.21f32`, `-12.345F32`
- `std::float64_t` `f64` or `F64`, `3.21f64`, `-12.345F64`
- `std::float128_t` `f128` or `F128`, `3.21f128`, `-12.345F128`

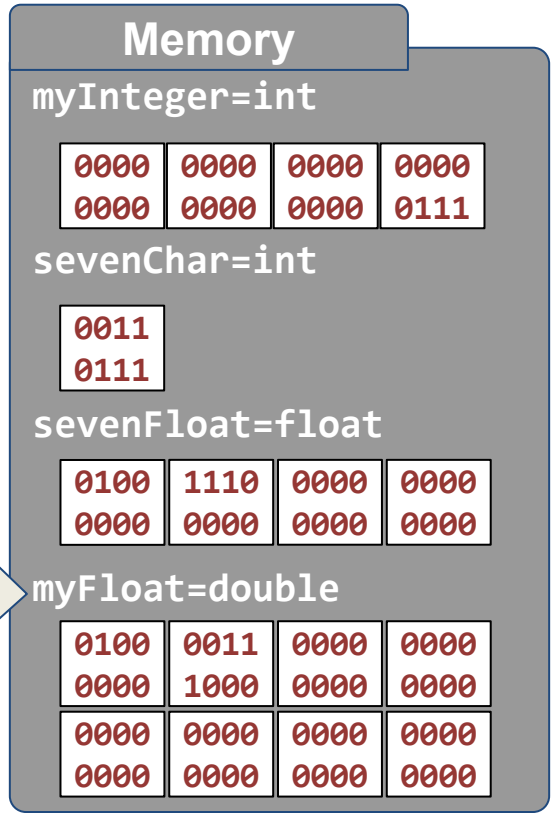
Constants for number types can use a ***prefix*** for different representations:

- Binary (since C++14): `0b`, `0b10101010`
- Octal: `0`, `0308`
- Hexadecimal: `0x` or `0X`, `0xFA77DD`, `0X1A7F`

Since C++14, digit separators `'` can be used: `80'000'000` (=80000000)

2.3. Data types: Impact in memory

```
/* reserving variables */
int main() {
  int sevenInteger = 7;      // seven as integer
  char sevenChar = '7';      // seven as character
  float sevenFloat = 7.0f;   // seven as float
  double sevenDouble = 7.0; // seven as double
  return 0;
}
```



2.3. Data types and variables

When you need a variable, you need to **declare** it first (and you can give them a value straight away, this is called **initialization**):

```
char mySymbol = '&';     // store one character and set it to '&'
int myNumber;            // store an integer, no initial value
bool areWeDone = false; // stores a boolean, set to false
float heightInMeters = 1.85f; // stores 1.85 as a float
double highPrecision;    // stores a double floating point number
```

Later, you can give variables **new values**:

```
areWeDone = true;   // we have now set this variable to true
highPrecision = 0.0;  // we have now set this variable to 0.0
```

Multiple variables can be declared at once: `int myNum = 3, yourNum = 8;`

2.3. Data types and variables

A first console output example: Initialize a variable to the symbol `a`, print its value in the console, then change its value to a `q` , then print it again.

```
#include <iostream>  // to allow use of std::cout
int main() {
  char mySymbol;   // variable to hold a character
  mySymbol = 'a';
  std::cout << mySymbol << '\n';  // prints out "a" and endline
  mySymbol = 'q';
  std::cout << mySymbol << '\n';  // prints out "q" and endline
  return 0;
}
```

2.3. Data types and variables: **auto**

Since C++11, the **auto** keyword can be used to let the compiler *deduce* the type from its initialization:

```
auto mySymbol = '&';          // a char
auto myNumber = 2 + 2;        // sum of two ints -> int
auto areWeDone = 7 < 3;       // false -> bool
auto heightInMeters = 1.85f;  // float
auto highPrecision = 1.2345;  // double
```

The auto keyword can make code more maintainable and hide complexity:

```
for ( auto i = start; i < end; i++ ) ...   // i has type of start
```

⚠ Excessive use of type hiding typically makes code less readable.

2.3. Data types and variables: **decltype**

From C++11 onwards, the **decltype** keyword can be used to inspect the declared type of an entity or expression:

```
auto myNumber = 2 + 2;          // sum of two ints -> int
decltype(myNumber) otherNumber = myNumber + 3;  // -> int
decltype('?') mySymbol = '?';
```

STL-based (see later) ways to query type:

- The **typeid** operator can be used to identify the type:

```
typeid(myNumber).name() == 'i';  // returns true
```

- **std::is_same** can be used to check whether two type are the same:

```
std::is_same<int, std::int32_t>::value;  // returns mostly true
```

2.4. Variables and scope

- A variable only exists within a **scope** (block of code, usually between curly braces `{` and `}`) and is deleted after the scope ends (after a `}`)
- Variable names cannot use names that are already taken

```
{  // from here starts one scope:
    int a = 3, b = 1;
    {          // from here starts another scope:
        c = a + b;     // error: c doesn't exist here yet
        int c = 0;
        c += a;        // this works, c is defined here
    }
    b = c;           // error: c doesn't exist here
    double a = 2.1; // error: a already taken
}
```

2.5. Type conversions

- Variables can sometimes take values from other variables and constants that do not have the same type, **implicitly** converting them
- Sticking to **explicit conversion**, using the type in braces, is clearer:

```
double myDouble = 1.1;
int aNumber = 5;
char c = 'a';
bool b = true;
myDouble = (double)aNumber;  // this works: myDouble == 5.0
myDouble = (double)c;        // this works: myDouble == 97.0
aNumber = (int)myDouble;     // works:      aNumber == 97
c = (char)98.0f;             // works too:  c == 'b'
```

2.5. Type conversions

Example: Find out what the ASCII-codes are for the symbols '?', '&', and '#'

```
#include <iostream>  // to allow use of std::cout
int main() {
  char question = '?';   // three variables to hold characters
  char ampersand = '&';   // variable to hold a character
  char hash = '#';   // variable to hold a character
  std::cout << (int)question << '\n';   // print ASCII code for '?'
  std::cout << (int)ampersand << '\n';  // print ASCII code for '&'
  std::cout << (int)hash << '\n';       // print ASCII code for '#'
  return 0;
}
```

3. Basic statements: if, switch, loops

3.1. Statements and assignments:

- Variables are the program's data, statements specify what to do with the data
- Statements *always* end with `;` and are executed sequentially
- Assignments *always* calculate the value of what is right of `=` and return this:

```
int x, y, mult;
bool b;
x = 2;                  // assignment returns 2
mult = 1;               // assignment returns 1
y = x * 7 / 2;              // y = ?     (try these out yourself
b = ( (x + y) >= 13 );      // b = ?      after learning about
x += -5;                    // x = ?      operators and
mult *= x - y;              // mult = ?   priority in the next
b = mult != 1337;           // b = ?      slides)
```

3. Basic statements: if, switch, loops

3.1. Statements and assignments:

Operators that we will use in this course:

Arithmetic operators:	+	-	*	/	%	++	--
Relational operators:	>	>=	==	!=	<=	<	? :
Logical operators:	&&	||	!				
Assignment operators:	=	+=	-=	*=	/=	%=	
	<<=	>>=					
Three-way comparison operator:	<=>						

unary operators — unary and binary operators

binary operators — ternary operator

3.1. Statements and assignments:

Arithmetic operators (try out yourself):

```
int x=5, y=9, width, length, multiply, division, remainder;

width     = x + y;                  // addition:       14
length    = width - 1;              // subtraction:    13
multiply  = x * y;                  // multiplication: 45
division  = x / y;                  // division:       0  (why?)
remainder = x % y;                  // modulo (remainder after division): 5
x++;                                // increment: x = x + 1:  6
y--;                                // decrement: x = x - 1:  8
length = width = y;                 // an assignment returns a value: 8
multiply = (x = 2) * (y = 5);       // (bad style) : 10
```

3.1. Statements and assignments:

Important to note:

- (Arithmetic) Operators do not exist for each type

  for example, `%` (modulo) does not exist for **`float`** or **`double`**

- Operators might have different behavior between types

```
int x = 7, y = 3, z;
z = x / y;       // note: z will get the value 2, since the
                 // operator '/' operates on two integers !
```

3.1. Statements and assignments:

Relational and logical operators (try out yourself):

```
double f1 = 15.2, f2 = 31.6;
bool b1 = true, b2 = false;
std::cout << (f1 == f1);                    // true  -> 1
std::cout << (b1 != b1);                    // false -> 0
std::cout << (b1 == true);                  // true  -> 1
std::cout << (f1 < f2);                     // true  -> 1
std::cout << (f1 <= f1);                    // true  -> 1
std::cout << ((f1 > f1) && (!b1));          // false -> 0
std::cout << ((b1 != b2) || (f2 >= f1) );   // true  -> 1
std::cout << (b1 || b2);                    // true  -> 1
std::cout << ( (f1 > 10.0) ? 'y' : 'n' );   // y
```

3.1. Statements and assignments:

Assignment operators (try out yourself):

```
float x = 5.1f, y = 9.2f;
int z = 7;

x = y + 1.0f;                    // results in x having the value 10.2f
y -= x;                          // y = y - x
x += 1.0f;                       // x = x + 1.0
y /= 2.0f;                       // y = y / 2.0
z %= 3;                          // z = z % 3 (note z is integer)
```

3.1. Statements and assignments:

Three-way comparison operator or spaceship operator <=> (C++20)

returns an *object* that can be directly compared with
a positive, a 0, or negative integer:

```
(3 <=> 5) == 0;       // false
('a' <=> 'a') == 0;   // true
(3 <=> 7) < 0;        // true
(7 <=> 5) < 0;        // false
```

3. Basic statements: if, switch, loops

3.1. Statements and assignments:

example 00 (difficulty level: 🌶️🌶️):

```
/**
 Try to figure out what is happening in the code below. Then try to compile the
 code, and then change the commented part so that the code's output becomes 1:
*/
#include <iostream>  // to allow use of std::cout and std::endl
int main() {
  auto i = 7;    // what type is variable i?
  auto j = 9.0;  // what type is variable j?

  bool ret = ( ( i <=> j) == 0 );  // change the '== 0' part so that the output is 1

  std::cout << ret << '\n';
  return 0;
}
```

3.2. Priority

- Operators are not always executed from left to right, as statements
- **Use braces** to avoid having to learn the table below by heart:

Prio.	Operators	Associativity
11	`,`	left to right
10	`=`, `+=`, `-=`, `*=`, `/=`, `%=`, `? :`	right to left
9	`||`	left to right
8	`&&`	left to right
7	`<`, `>`, `<=`, `>=`	left to right
6	`<<`, `>>`	left to right
5	`+`, `-`	left to right
4	`*`, `/`, `%`	left to right
3	prefix `++`, prefix `--`, unary `-`, unary +, `!`, `(`type`)`, `new`, `delete`	right to left
2	suffix `++`, suffix `--`, `.`, ->,	left to right
1	`::`	left to right

3.2. Priority

- Examples:

```
int a = 2, b = 3, c = 4;
a = b * c + d;      // a = ((b * c) + d)
a /= b * c % d;     // a = a / ((b * c) % d)
a += b = c + d;     // a = a + (b = (c + d))
```

Beware of prefix and postfix increment / decrement operators:

```
a = 10;
b = ++a;
// a = 11, b = 11
```

```
a = 10;
b = a++;
// a = 11, b = 10
```

3.3. Blocks

- Statement sequences are executed one by one, from left to right:
  `length = 10; width = 15; surface = length * width;`
- A block of statements thus implements a function (e.g., between the curly braces `{` and `}` for main) and can be used anywhere where a statement can appear. But beware that variables defined there only 'live' in the block:

```
int main() {
  int length, width, surface;
  {
    length = 10; width = 15;
    surface = length * width;
  }
  return 0;
}
```

```
int main() {
  int length = 10, width = 15;
  {
    int surf = length * width;
  }
  return surf; // error: surf unknown
}
```

3.4. Selection statements: `if` and `switch`

- Depending on a condition, selection statements can either execute the next statement, or not
- Simply for one case:

```
if ( number < 0 )   // if number is negative
  sign = '-';       // then the sign is '-'
```

- For both cases:

```
if ( number < 0 )   // if number is negative
  sign = '-';       //  then the sign is '-'
else                // otherwise:
  sign = '+';       //  the sign is '+'
```

3.4. Selection statements: `if` and `switch`

Conditions often use relational operators:

```
int x, y, sum, counter, minimum;

if (x > y) ...                  // is x bigger than y?
if (x >= y) ...                 // is x bigger or equal than y?
if (sum == x + y) ...           // is sum equal to (x+y) ?
if (x != y) ...                 // is x different from y?
if (counter < 100) ...          // is counter smaller than 100?
if (x + 1 <= 1 - y) ...         // is (x+1) smaller or equal to (1-y)?

minimum = (x < y)? x : y;  // minimum gets a new value of ...
                           // if ( x < y ), then x, else y
```

3.4. Selection statements: `if` and `switch`

Conditions also often use logical operators:

```
int x, y, counter;
bool readFlag, writeFlag;

if (readFlag || writeFlag) ...    // logical OR: readFlag or
                                  // writeFlag need to be true,
                                  // will be skipped if both are false

if ((x != 0) && (y / x < 5)) ...  // logical AND: both y/x needs to be
                                  // smaller than 5 and x shouldn't be 0

if (!(x < 0)) ...   // NOT: the same as: if (x >= 0)
```

3.4. Selection statements: `if` and `switch`

Nesting `if` statements:

```
if (number == 0)
  sign = 0;
else
  if (number > 0)
     sign = +1;
  else
     sign = -1;
```

Alternatively, using a nested `( ? : )` operator:

```
sign =  (number == 0) ? 0 : ( (number > 0) ? +1 : -1 );
```

3.4. Selection statements: `if` and `switch`

Nesting `if` statements can be tricky, **use curly braces**

```
if ( x == y )
  if ( y == z )
     allEqual = true;
else
     allEqual = false;
```

≠

```
if ( x == y ) {
  if ( y == z )
     allEqual = true;
}
else
     allEqual = false;
```

=

```
if ( x == y )
  if ( y == z )
     allEqual = true;
  else
     allEqual = false;
```

=

```
if ( x == y ) {
  if ( y == z )
     allEqual = true;
  else
     allEqual = false;
}
```

3.4. Selection statements: `if` and `switch`

Nesting many **`if`** statements:

```
if (menuItem == 1) {
          ...
} else if (menuItem == 2) {
          ...
} else if ((menuItem == 3) ||
           (menuItem == 4)) {
          ...
} else if (menuItem == 5) {
          ...
} else {
          ...
}
```

Using one **`switch`** statement:

```
switch (menuItem) {
  case 1:  ...
           break;
  case 2:  ...
           break;
  case 3:
  case 4:  ...
           break;
  case 5:  ...
           break;
  default: ...
           break;
}
```

3.5. Loops

3.5.1. The `while` loop:

```
int i, sum;
sum = 0;
i = 1;
while ( i < 7 ) {  // this block
  sum += i;        // is executed
  i++;             // repeatedly
}
```

result:

sum: `0, 1, 3, 5, 9, 14, 20`

3.5.2. The `do while` loop:

```
int i, sum;
sum = 0;
i = 1;
do {                // this block
  sum += i;         // is executed
  i++;              // repeatedly

} while ( i < 7 );
```

result:

sum: `0, 1, 3, 5, 9, 14, 20`

3.5. Loops

3.5.3. The `for` loop:

```
int i, sum = 0;
for ( i = 0; i <= 10; i++ ) {  // this block
  sum += i;                    // is executed repeatedly
}
```

Template:

initialization of loop variable

do we loop again?

in- or decrease the loop variable

```
for ( statement ; condition ; statement )
    <statement> ;
```

statement, or block of statements to repeat

3.5. Loops: **break** and **continue**

- **break** terminates the loop, the rest of the loop body will not be executed:

```
int num = 10;
while (num > 0) {
    if (num == 5) break;  // stop after num has reached 5
    num--;
}
```

- **continue** does not terminate the loop, but just skip the rest of the loop body:

```
int num = 10;
while (num > 0) {
    if (num == 5) continue;  // when num == 5, don't decrement
    num--;
}
```

3.5. Loops: When do we use which loop type?

- **`for`** loop:
  - for a given range (e.g. ” for all i = 1 … N “)
  - when you automatically need a loop variable
- **`while`** loop:
  - when the (maximal) number of repetitions is not known beforehand
  - when the repetition conditions are more complex
- **`do while`** loop:
  - when a block needs to be repeated at least once

3.5. Loops: example 02 (difficulty level: 🌶️)

```
/**
  Write a program that prints out a series of numbers, starting at 120.0 and where
  each next number is seven less than the previous one. Stop once the number is
  smaller than 43.7
  */
#include <iostream>  // to allow use of std::cout and std::endl
int main( ) {




  return 0;
}
```

3.5. Loops: example 03 (difficulty level: 🌶️🌶️)

```
/**
  Write a program that asks the user for a number, and then prints out this number
  in the terminal, followed by the half of the previous number until
  the result is smaller than ten. So for 100 it would give out: 100, 50, 25.5, 12.25
  */
#include <iostream>  // to allow use of std::cout and std::endl
int main( ) {




  return 0;
}
```

3.5. Loops: example 04 (difficulty level: 🌶️🌶️)

```
/**
  Write a program that counts from 131 down till 23, one number per line in the
  the terminal, and prints out "hop", if the number is a multiple of 7.
  */
#include <iostream>  // to allow use of std::cout and std::endl
int main( ) {




  return 0;
}
```

3.5. Loops: example 05 (difficulty level: 🌶🌶🌶)

```
/**
 Write a program that prints in the terminal all prime numbers from 3 till 99.
 Remember: A number is a prime when any division by a smaller number results in
 a remainder that is never zero.
*/
#include <iostream>  // to allow use of std::cout and std::endl
int main( ) {




  return 0;
}
```

3. Basic statements: if, switch, loops

3.5. Loops: example 06 (difficulty level: 🌶🌶🌶)

```
/**
 Write a program that draws in the terminal a big X out of the character 'X',
 depending on the variable int size (with size = 3, 4, ..., 20):
 size = 3:     size = 4:      size = 5:      etc.
   X X          X  X           X   X
    X            XX             X X
   X X           XX              X
                X  X            X X
                                X   X      */
#include <iostream>  // to allow use of std::cout and std::endl
int main( ) {



  return 0;
}
```

3.5. Loops: example 07 (difficulty level: 🌶🌶🌶🌶)

```
/**
 Write a program that draws in the terminal a bigger X out of the character 'X',
 depending on the variable int size (with size = 3, 4, ..., 20):
 size = 3:     size = 4:      size = 5:      etc.
   XX X         XX  X          XX   X
    XX           XXX            XX X
   X XX          XXX             XX
                X  XX           X XX
                               X   XX      */
#include <iostream>  // to allow use of std::cout and std::endl
int main( ) {



  return 0;
}
```

4. Functions, Recursion, Call by Value

4.1. Functions and their parameters
4.2. Recursive Functions
4.3. Call by Value
4.4. `inline` Functions, Overloading, `=delete`
4.5. Default Parameters and Function Attributes
4.6. Header files and Modules
4.7. Miscellaneous: Variadic arguments and Coroutines

4.1. Functions and their parameters

- Blocks of code can sometimes re-use the same variables and need to be used throughout a program
- For example calculating the maximum of two integers:

```
int maximum = 0, a = 12, b = 10;
{
  if (a > b) {
    maximum = a;
  } else {
    maximum = b;
  }
}
// maximum now holds the value of a or b, whichever is largest
```

4.1. Functions and their parameters: Declaring Functions

- Before you can use (call) a function, you have to declare it (similar to how we have to declare variables before use).
- A function declaration contains a return type, function name, and parameters, example:

```
int maximum( int a, int b );
```

- You typically declare *and* implement the function before **`main()`**, example:

```
int maximum( int a, int b ) {
  if (a > b) {
    return a;
  } else {
    return b;
  }
}
```

4.1. Functions and their parameters: Declaring Functions

- With each function call, formal parameters need actual parameters, *unless* the function prototype has default values:

```
#include <iostream>  // output to the console
#include <cstdint>  // we're using the uint16_t type
void drawLine(char symbol = '-', uint16_t len = 25) {
  for (auto line = 0; line < len; line++) std::cout << symbol;
  std::cout << std::endl;
}
int main() {
  drawLine();  // writes 25 times the '-' symbol to console
  drawLine(50);  // writes 50 times the '-' symbol to console
  drawLine('=', 9);  // writes 9 times the '=' symbol to console
  return 0;
}
```

4.1. Functions and their parameters: Declaring Functions

- Functions can call other functions, allowing cycles:
  function **`a()`** calls **`b()`**, **`b()`** calls **`a()`**
  → In this case, declarations need to come first, example:

```
int a();  // declaration of function a()
int b();  // declaration of function b()
int a() {  // implementation of function a():
  std::cout << "Yes" << std::endl;
  return b();
}
int b() {  // implementation of function b():
  std::cout << "No"<< std::endl;
  return a();
}
```

4.1. Functions and their parameters: Declaring Functions

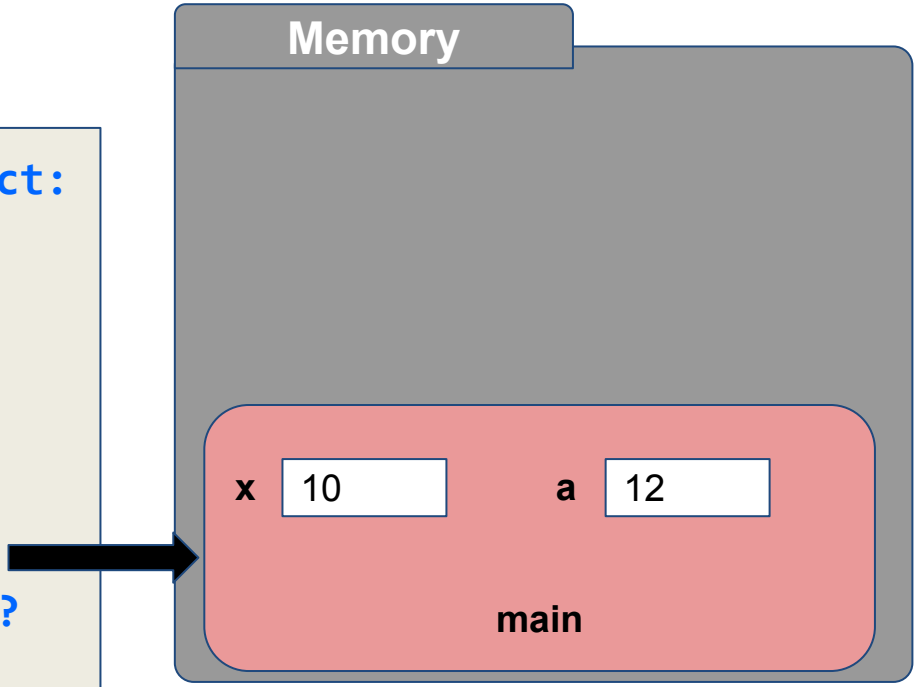
- A function declaration can have *parameters*: variables that obtain a value when the function is called and that are treated as local variables in the implementation of the function
- A function can have a return type. If not, we use `void` → Is this a type?

```
void printMaximum( int a, int b ) {  // a and b are parameters
  if (a > b) {                       // a and b can be used as variables of
    std::cout << a;                  // type integer in the implementation of
  } else {                           // the function
    std::cout << b;
  }
  std::cout << std::endl;   // note that we don't return anything
}
```

4.1. Functions and their parameters: Using Functions

- A function is *called*:

```
// declare & implement myFunct:
int myFunct(int b, int a) {
  a = 2 * b + a * a;
  return a + 1;
}
// now we can call myFunct:
int main() {
  int x = 10; int a = 12;
  a = myFunct(a, x+1);  // a?
  return 0;
}
```

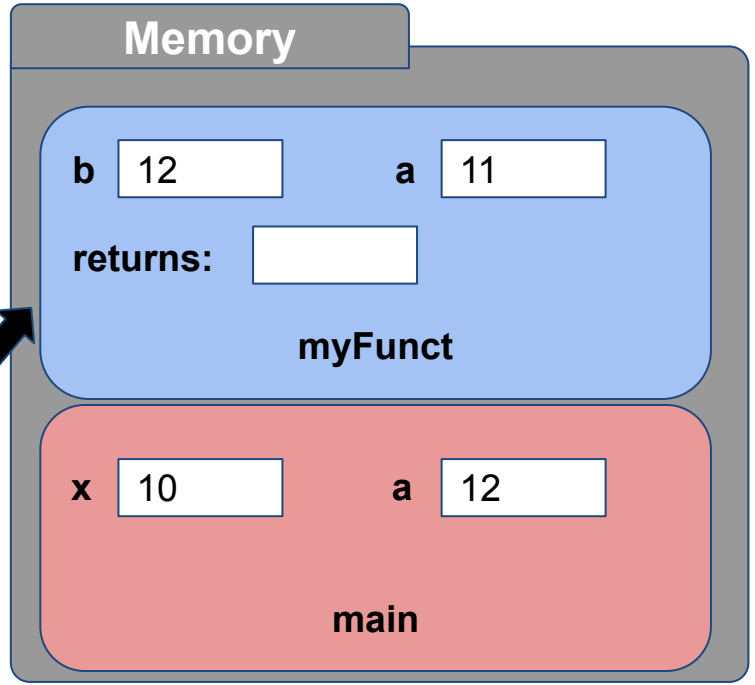


A stack is created in memory, in which the function's local variables are stored

4.1. Functions and their parameters: Using Functions

- A function is *called*:

```
// declare & implement myFunct:
int myFunct(int b, int a) {
  a = 2 * b + a * a;
  return a + 1;
}
// now we can call myFunct:
int main() {
  int x = 10; int a = 12;
  a = myFunct(a, x+1);  // a?
  return 0;
}
```

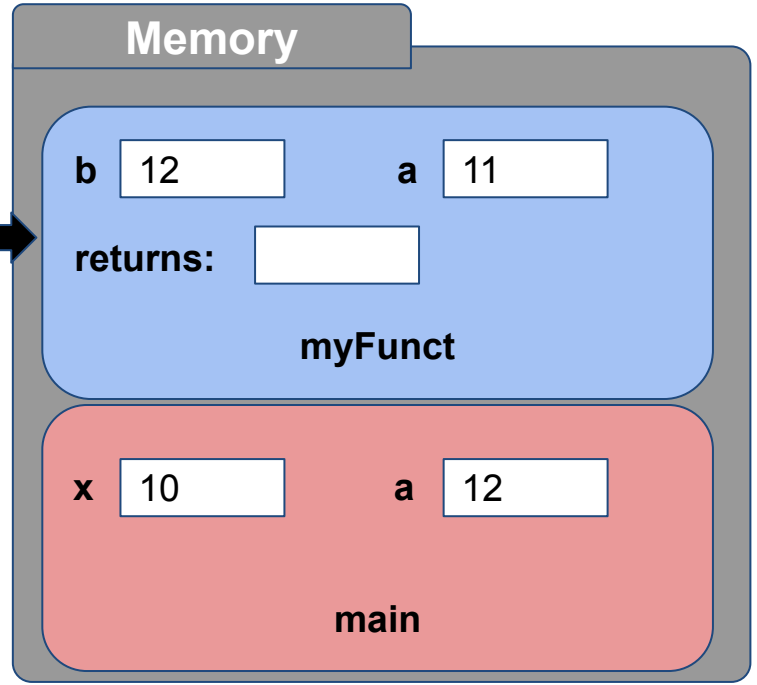


A stack is created in memory, in which the function's local variables are stored

4.1. Functions and their parameters: Using Functions

- A function is *called*:

```
// declare & implement myFunct:
int myFunct(int b, int a) {
  a = 2 * b + a * a;
  return a + 1;
}
// now we can call myFunct:
int main() {
  int x = 10; int a = 12;
  a = myFunct(a, x+1);  // a?
  return 0;
}
```

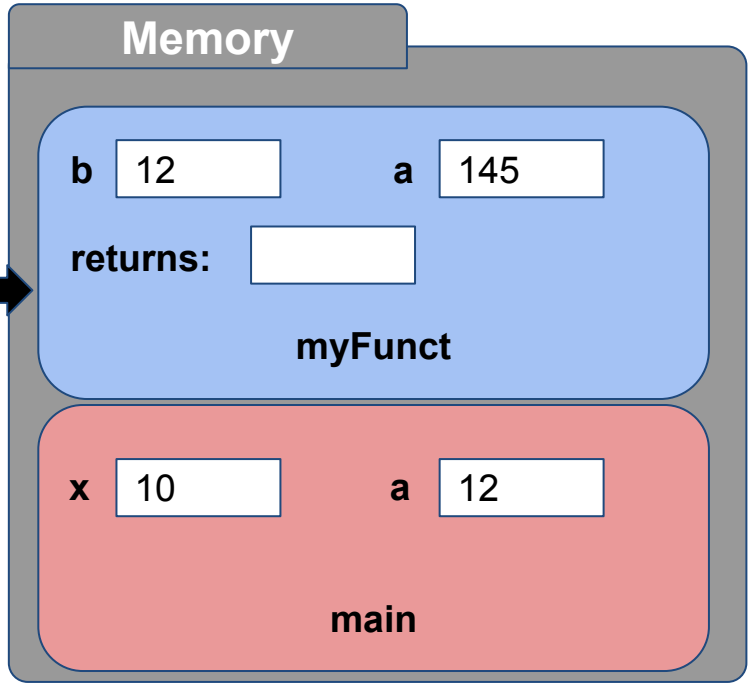


A stack is created in memory, in which the function's local variables are stored

4.1. Functions and their parameters: Using Functions

- A function is *called*:

```
// declare & implement myFunct:
int myFunct(int b, int a) {
  a = 2 * b + a * a;
  return a + 1;
}
// now we can call myFunct:
int main() {
  int x = 10; int a = 12;
  a = myFunct(a, x+1);  // a?
  return 0;
}
```



A stack is created in memory, in which the function's local variables are stored

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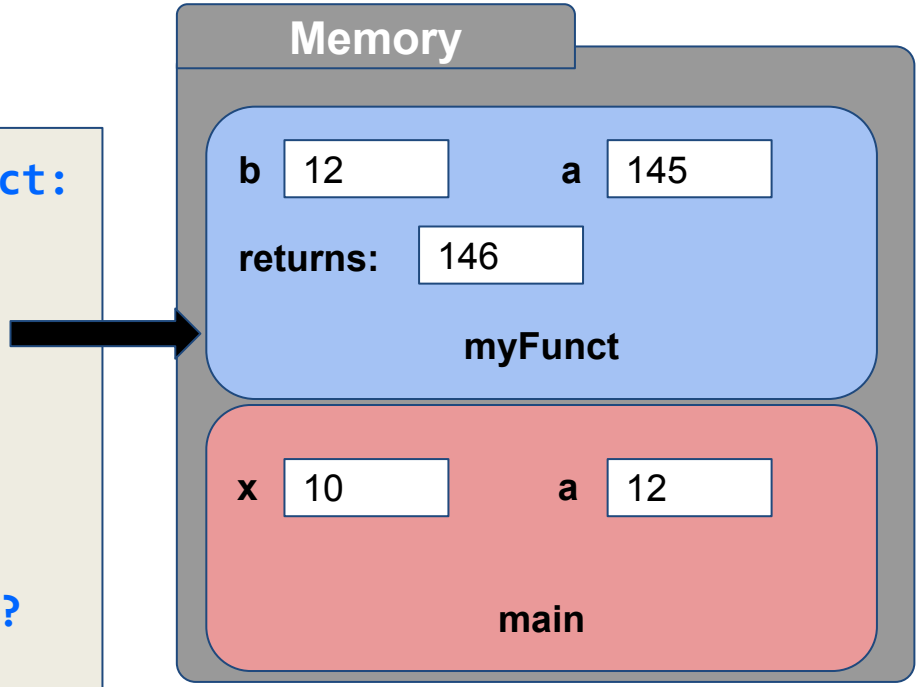
  return 0;
}
```



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int main() {
  int x = 10; int a = 12;
  a = myFunct(a, x+1);  // a?
  return 0;
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```
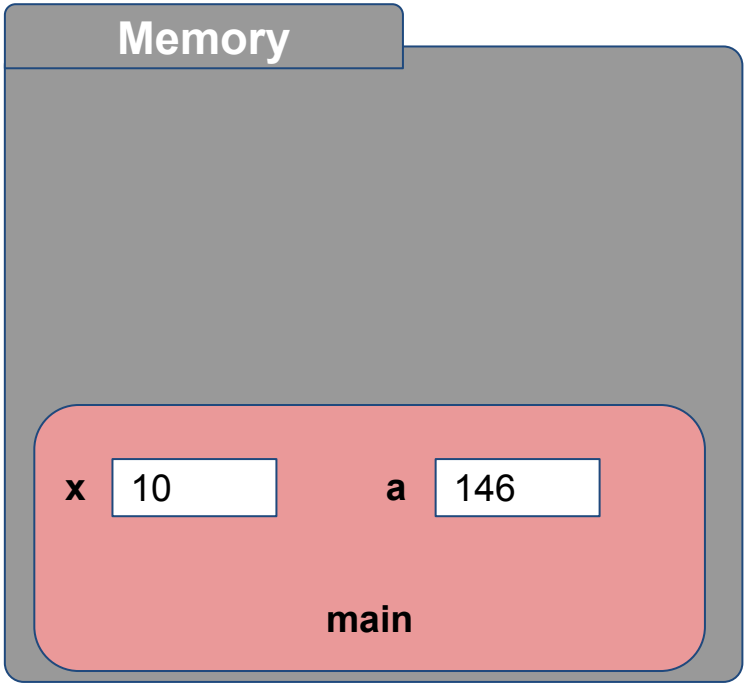



A stack is created in memory, in which the function's local variables are stored

4.1. Functions and their parameters: Using Functions

- Maze Game v.1.0: expand this code to move the player and add color

```
/* First draft of Maze Game: draw the player, respond to key presses */
#include <ncurses.h>  // functions to draw colored text in terminal
int main() {
  char c = ' ';          // used for user key input
  auto x = 10, y = 5;    // (x,y) position of player: start at (10,10)
  initscr(); curs_set(0);  // ncurses: initialize window, then hide cursor
  while ( c != 'q' ) {   // as long as the user doesn't press q ..
    mvaddch(y, x, '@');  // ncurses function: draw a @ at position (x,y)
    c = getch();         // capture the user's pressed key
    // handle here the moving
  }
  endwin();            // ncurses function: close the ncurses window
  return 0;
}
```

4.1. Functions and their parameters: Using Functions

```
/* First draft of Maze Game: draw the player, respond to key presses
   Result of the in-class programming code (see YouTube video of the lecture)
*/

#include <ncurses.h>  // functions to draw colored text in terminal

// initialize all the functions to start drawing in ncurses
void initNCurses() {
  initscr(); curs_set(0);  // ncurses: initialize window, then hide cursor
  noecho();  // don't show keys pressed in terminal
  start_color();  // use color
  init_pair(1, COLOR_BLUE, COLOR_GREEN);
  init_pair(2, COLOR_RED, COLOR_YELLOW);
}
```

4.1. Functions and their parameters: Using Functions

```
void clearScreen() {
  attron(COLOR_PAIR(1));  // set color pair to 1
  for ( auto line = 0; line < LINES; line++) {
    for ( auto col = 0; col < COLS; col++) {
      mvaddch(line, col, '.');  // ncurses function: draw '.' at (x,y)
    }
  }
  attroff(COLOR_PAIR(1));
}

// draw a symbol at (x,y) with color colorpair
void draw(int x, int y, char symbol, int colorpair) {
  attron(COLOR_PAIR(colorpair));  // set color pair to 1
  mvaddch(y, x, symbol);  // ncurses function: draw '.' at (x,y)
  attroff(COLOR_PAIR(colorpair));
}
```

4.1. Functions and their parameters: Using Functions

```
int main() {
  auto c = ' ';          // used for user key input
  auto x = 10, y = 10;   // (x,y) position of player: start at (10,10)
  initNCurses();         // initialize ncurses functionality
  while ( c != 'q' ) {    // as long as the user doesn't press q ..
    clearScreen();
    draw(x, y, '@', 2);  // draw our player
    c = getch();          // capture the user's pressed key
    switch (c) {
      case 'w': y--; break;  // go up
      case 's': y++; break;  // go down
      case 'a': x--; break;  // go left
      case 'd': x++; break;  // go right
    }
  }
  endwin();           // ncurses function: close the ncurses window
  return 0;
}
```

4.2. Recursive Functions

- A function can call itself. For example in a function to calculate the factorial of a number (notation: n!)

```
// factorial of n (n!):
double factr(double n) {
  if (n == 0.0)
    return 1.0;
  else if (n > 0.0)
    return n * factr(n-1);
}
```

```
double f = factr(3.0);
```

Mathematical definition:

$$n! = \begin{cases} 1 & \text{for } n = 0 \\ n \cdot (n-1)! & \text{for } n > 0 \end{cases}$$

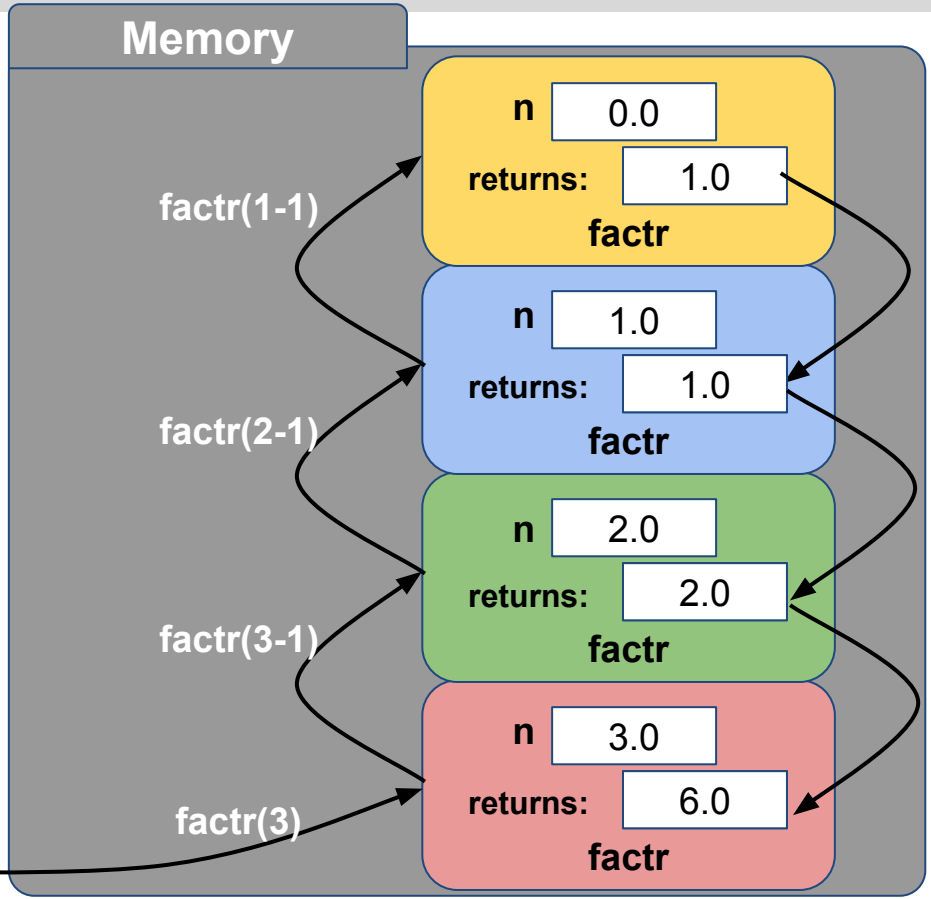
so:
2! = 2 . 1 = 2
3! = 3 . 2 . 1 = 6
4! = 4 . 3 . 2 . 1 = 24
5! = 5 . 4 . 3 . 2 . 1 = 120
and so on …

4.2. Recursive Functions

- Whenever a function is called, a new space is reserved in memory for parameters and local variables. Example:

```
double factr(double n) {
  if (n == 0.0)
    return 1.0;
  else if (n > 0.0)
    return n * factr(n-1);
}
```

```
double f = factr(3.0);
```



4.3. Call by Value

In C++, most parameters are passed **by value**

- This means, a function always receives **copies** of the actual parameters
- When the function is called, the values of the actual parameters are assigned to the formal parameters in the function declaration:

```
double factr(double n);  // n is a formal parameter of factrr
```

```
double y = factr(6.0);   // 6.0 is the actual parameter of factr
```

- With call-by-value, variables given as actual parameters are never changed
- The same variable can be simultaneously passed to multiple parameters:

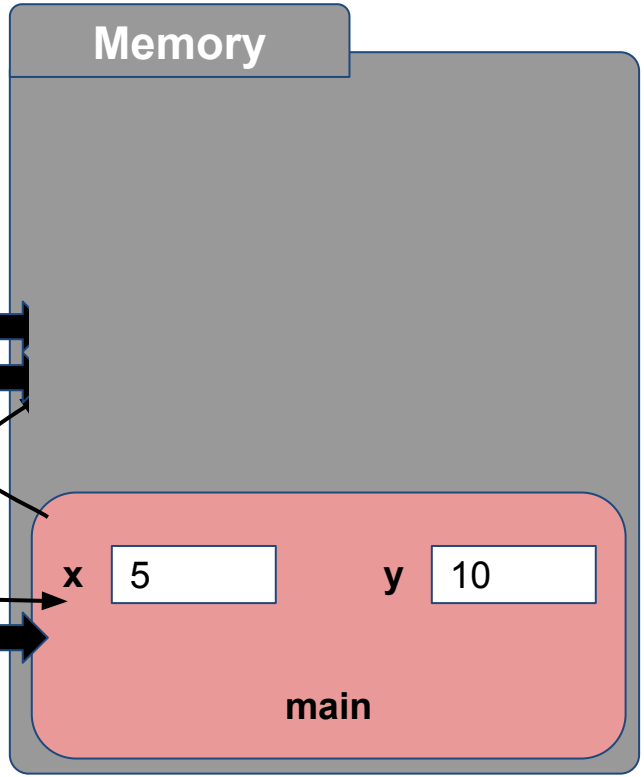
```
int a = 10;
y = maximum(a, a);    // the value 10 is copied to both parameters
```

4.3. Call by Value

In C++, parameters are passed **by value**

So the variable does not get passed, *just its value*

```
#include <iostream>  // output to terminal
void swap(int x, int y){
  int temp = 0;
  temp = x; x = y; y = temp;
}
int main()  {
  int x = 5, y = 10;
  swap(x, y);
  std::cout << x << ", " << y << std::endl;
  return 0;
}
```

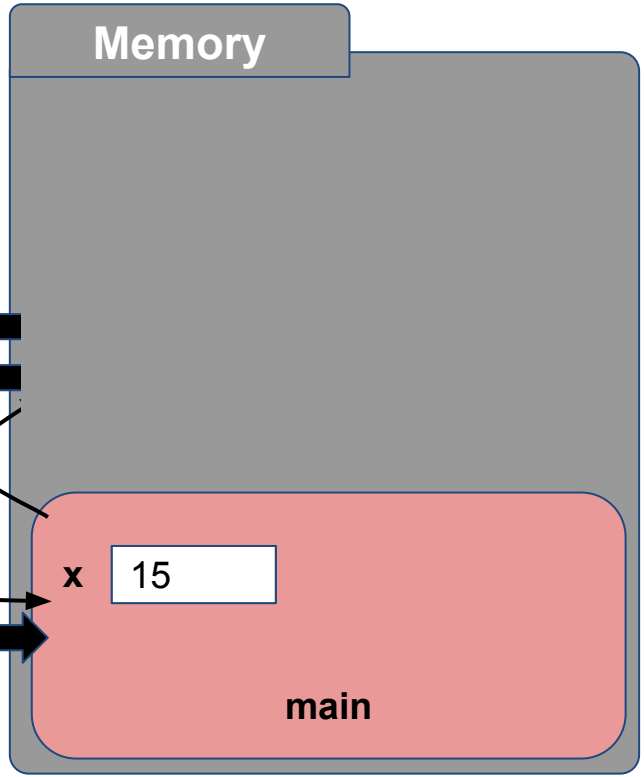


4.3. Call by Value

In C++, parameters are passed **by value**

You can use the function's return value:

```
#include <iostream>  // output to terminal
int addFive(int x) {
  x += 5;
  return x;
}
int main()  {
  int x = 10;
  x = addFive(x);
  std::cout << x << std::endl;
  return 0;
}
```



4.4. `inline` Functions, Overloading, `=delete`

- **`inline`** tells the compiler that inline substitution of a function is preferred over function call: instead of calling the function and transferring control to the function body, a copy of the function body is executed
- This avoids overhead from the function call (passing the arguments and retrieving the result)
- This may result in a larger executable (due to repeating multiple times)

```
inline int maximum( int a, int b ) {
  return (a > b)? a : b;
}
```

4.4. `inline` Functions, Overloading, `=delete`

- Sometimes, the same functionality is needed on different types:

```
auto maximum( int a, int b );
auto maximum( double a, double b );
auto maximum( char a, char b );
```

(note that `auto` is not allowed for the function's parameters, deduced return types are a C++14 extension)

- Multiple functions with the same name are allowed, if
  - the number of parameters are different, or
  - at least one parameter has a different type
- This is ***overloading*** the function name, and should be used for multiple functions of the same functionality. Note that with subtle differences, like signed/unsigned, float/double, it is hard to predict what will be called

4.4. `inline` Functions, Overloading, `=delete`

- There are four Overloading Resolution Rules
  - An exact match between parameter types
  - A promotion (e.g., char to int)
  - A standard type conversion (e.g. float and int)
  - A constructor or user-defined type conversion (see later)

- `= delete` can be used to prevent calling the wrong overload:

```
void myFunction(int) { ; }
void myFunction(double) = delete;
int main() {
  myFunction(7);    // this is fine
  myFunction(7.0);  // this results in a compilation error
  return 0;
}
```

4.5. Default Parameters and Function Attributes

- Parameters can be given a default value (If the call does not supply a value for this parameter, this default value will be used):
  - All default parameters must be the *rightmost* parameters
  - Default parameters must be declared only once
  - Default parameters can improve compile time and avoid redundant code because they avoid defining other overloaded functions

```
void myFunction(int a, int b = 7);   // declaration of myFunction

void myFunction(int a, int b) { ; }  // definition of myFunction
int main() {
  myFunction(8);    // this is fine, a = 8, b = 7
  return 0;
}
```

4.5. Default Parameters and Function Attributes

- Functions can be marked with standard properties, to express their intent:
  - `[[noreturn]]` indicates that a function does not return, for optimization purposes or compiler warnings (from C++11)
  - `[[deprecated]]` , `[[deprecated("reason")]]` indicates that the use of a function is discouraged through a compiler warning (from C++14)
  - `[[nodiscard]]` , `[[nodiscard("reason")]]` (C++17, resp. C++20) throws a warning if the function's return value is not handled

```
[[noreturn]] void myFunction() { std::exit(0); }

[[deprecated("old function, use newFunction instead")]]
void oldFunction(int p) { … }

[[nodiscard("please handle return value")]] int getMaximum() { … }
```

4.6. Header files and Modules

- It is likely that any code you will write will have to be split into several functions that call each other, instead of implementing everything in the `main()` function
- We define and implement these functions in separate files, if they form a collection that belong to each other (see for example the functions we used from ncurses)
- This is a **module**: a part of a program that can be compiled separately
- In C++, a module always should consist of two files:
  - a **header** file (`*.h`), which contains the function declarations
  - an **implementation** file (`*.cpp`), in which the functions are implemented

4.6. Header files and Modules

Maze.cpp

```
/* Second draft of Maze Game: drawing functions are our module "drawMaze" */
#include "drawMaze.h"  // functions related to drawing
int main() {
  auto c = ' ';          // used for user key input
  auto x = 10, y = 10;   // (x,y) position of player: start at (10,10)
  initNCurses();         // initialize ncurses functionality
  while ( c != 'q' ) {   // as long as the user doesn't press q ..
    clearScreen();
    draw(x, y, '@', 2);   // draw our player
    c = getch();          // capture the user's pressed key
    switch (c) {
      case 'w': y--; break;  // go up
      case 's': y++; break;  // go down
      case 'a': x--; break;  // go left
      case 'd': x++; break;  // go right
    }
  }
  endwin();           // ncurses function: close the ncurses window
  return 0;
}
```

4.6. Header files and Modules

drawMaze.h

```
/* Drawing functions declared */
#include <ncurses.h>  // functions to draw colored text in terminal

// initialize all the functions to start drawing in ncurses and use color
void initNCurses();

// clear the screen
void clearScreen();

// draw a symbol at (x,y) with color colorpair
void draw(int x, int y, char symbol, int colorpair);
```

4.6. Header files and Modules

drawMaze.cpp

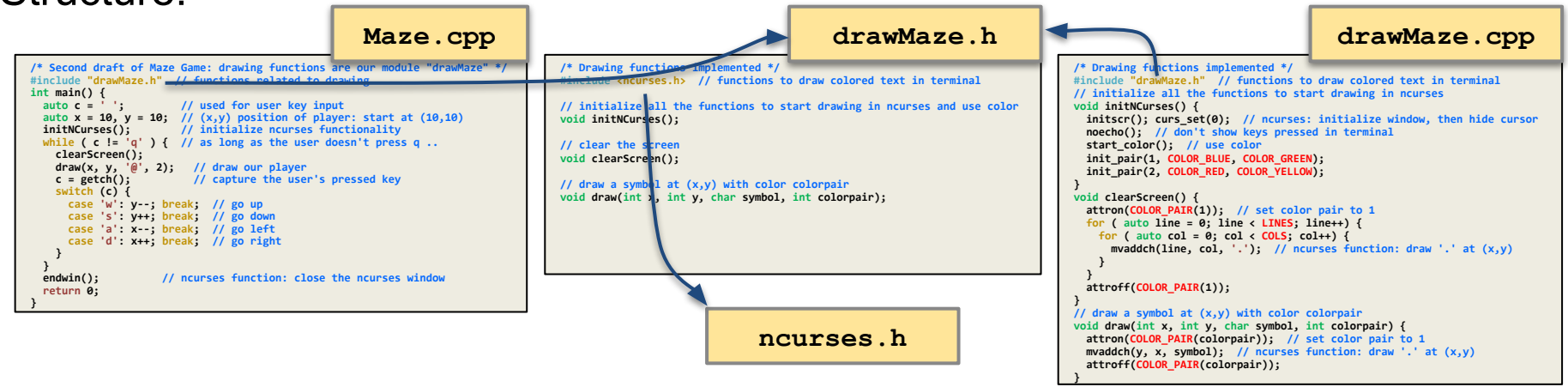
```
/* Drawing functions implemented */
#include "drawMaze.h"  // functions to draw colored text in terminal

// initialize all the functions to start drawing in ncurses
void initNCurses() {
  initscr(); curs_set(0);  // ncurses: initialize window, then hide cursor
  noecho();  // don't show keys pressed in terminal
  start_color();  // use color
  init_pair(1, COLOR_BLUE, COLOR_GREEN);
  init_pair(2, COLOR_RED, COLOR_YELLOW);
}
void clearScreen() {
  attron(COLOR_PAIR(1));  // set color pair to 1
  for ( auto line = 0; line < LINES; line++) {
    for ( auto col = 0; col < COLS; col++) {
      mvaddch(line, col, '.');  // ncurses function: draw '.' at (x,y)
    }
  }
  attroff(COLOR_PAIR(1));
}
```

4.6. Header files and Modules

drawMaze.cpp

```
// draw a symbol at (x,y) with color colorpair
void draw(int x, int y, char symbol, int colorpair) {
  attron(COLOR_PAIR(colorpair));  // set color pair to 1
  mvaddch(y, x, symbol);  // ncurses function: draw '.' at (x,y)
  attroff(COLOR_PAIR(colorpair));
}
```

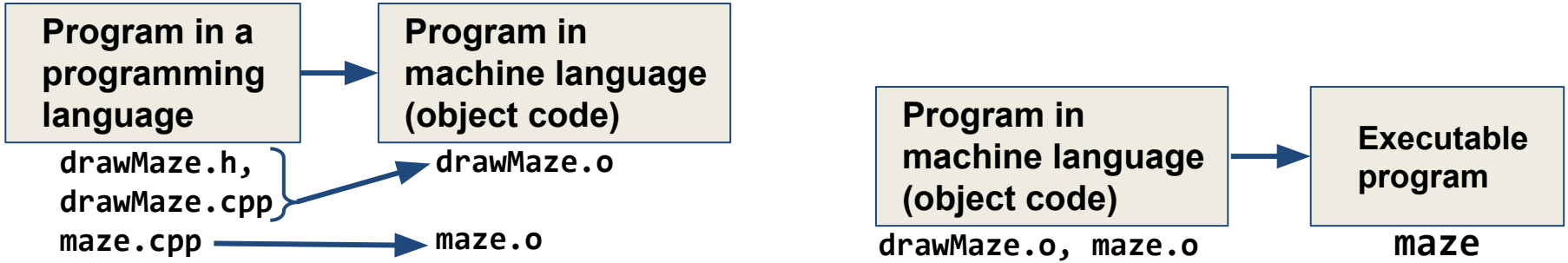
Structure:



4.6. Header files and Modules

Maze Game v.2.0: How to compile the program?

- First compile the module and the program into object files:
  `g++ -c drawMaze.cpp -std=c++11` → object file `drawMaze.o`
  `g++ -c maze.cpp -std=c++11` → object file `maze.o` is created
- Then link the object files:
  `g++ maze.o drawMaze.o -o maze -l ncurses`

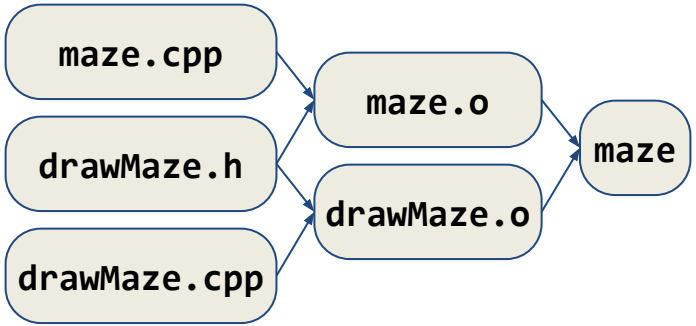


4.6. Header files and Modules

- Why use modules?
  - To **better structure** the program code: Separate modules make it easier to divide your code and find where you need to change or continue your source code
  - Make modules **re-usable** by others: Anyone can read the header (`*.h`) file and will know what functions they can use if the module is included, reading the implementation (`*.cpp`) is not needed
  - **Save compilation time**: Object files are already compiled, they just need to be linked to other modules and the program code

4.6. Header files and Modules: The **make** utility

- Revisiting the Maze Game v.2.0, we have these *dependencies*:



compile **drawMaze.cpp:**

```
g++ -c drawMaze.cpp -std=c++11
```

compile **maze.cpp:**

```
g++ -c maze.cpp -std=c++11
```

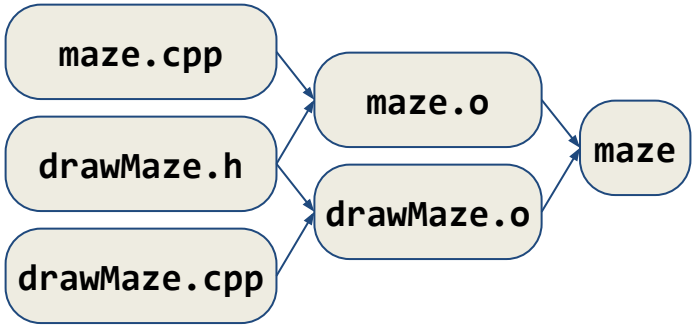
link the objects files into the executable program **maze:**

```
g++ maze.o drawMaze.o -o maze -l ncurses
```

- After a change, we want to recompile only the affected files
- The **make** program automates this process for us:
  just type **make** in the terminal, in the code's directory

4.6. Header files and Modules: The **make** utility

- We need to tell **make** about these dependencies in a specific file that we need to create in the code's directory: **Makefile**



- After each rule, we need to type a **tab** before each g++ command in **Makefile**

Makefile

```
# Rule to make our program when
# 'drawMaze.o' and 'maze.o' are compiled:
maze: drawMaze.o maze.o
  g++ drawMaze.o maze.o -o maze -l ncurses
# Rule for dependency 'maze.o':
maze.o: maze.cpp drawMaze.h
  g++ -c maze.cpp -std=c++11
# Rule for dependency 'drawMaze.o':
drawMaze.o: drawMaze.cpp drawMaze.h
  g++ -c drawMaze.cpp -std=c++11
```

Summary

```
int maximum( int a, int b );
```

- A function returns at most one value and thus must have a return type (either `int`, `float`, `double`, `bool`, `char`, etc., or `void`: no return value)
- A function has a name and a list of parameters between braces
- The parameters are variables of the types `int`, `float`, `double`, `bool`, `char`
- The function is implemented as a block following the function definition, between curly braces:
- Each time this function is called, these statements are executed with any parameters as local variables

```
int maximum( int a, int b ) {
  if (a > b) {
    return a;
  } else {
    return b;
  }
}
```

5. Arrays, Multidimensional Arrays

5.1. Arrays: Reminders

Types (`int`, `float`, `double`, `bool`, `char`, etc.) tell the compiler:

- the size of the variables (e.g., 4, 8, 1 bytes) in memory
- how these bits in memory should be interpreted
- and know the possible operations on them

For example:

if **`height`** and **`width`** are variables of type `int`, then the compiler knows

- that 4 bytes need to be reserved for each of them,
- which are organized so they span the whole numbers from -2147483648 to 2147483647
- and that **`height`** * **`width`** is a legal operation

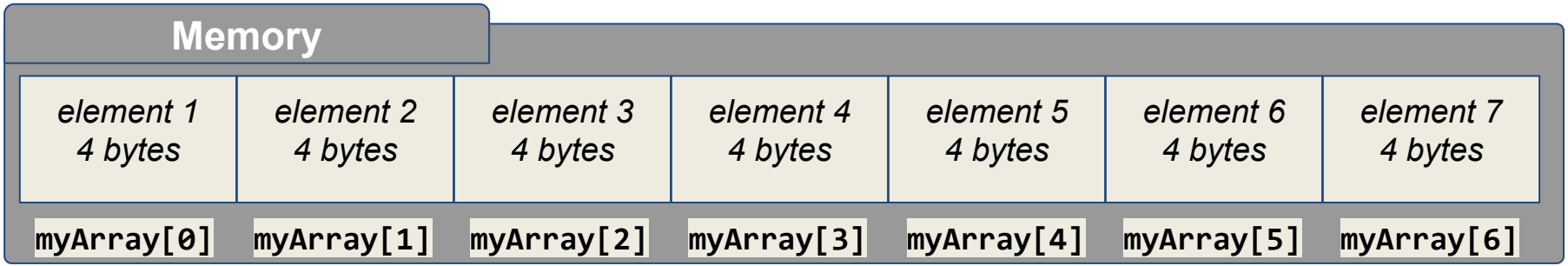
5. Arrays, Multidimensional Arrays

5.1. Arrays

- An array is a serially numbered collection of variables that are all of the same *type*
- The number of elements is the *size* of the array
- Array elements are accessible via their *index*, from 0 to size-1

For example:

`float myArray[7];` is an array of 7 `float` variables, indexed from 0 to 6:



5.1. Arrays: Initialization, sizeof

- An array can be initialized by listing the elements between curly braces, **{** and **}**, and separated by commas:

```
double myArray[] = {1.09, 2.18, 4.36, 8.72};
```

  In this case, the array will automatically get the size 4

- `sizeof` is built-in operator that returns the number of *bytes* for the given variable or type:

```
int myArraySize = sizeof(myArray) / sizeof(myArray[0]);  // 16/4
```

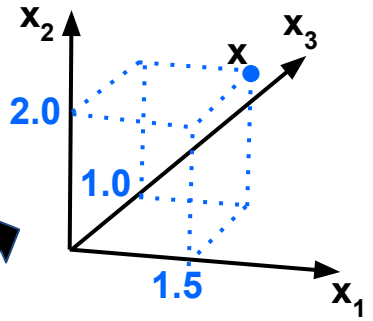
- Loops are typically used for larger arrays:

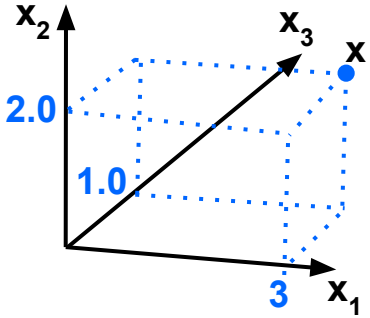
```
bool myArray[400];
for (int i = 0; i < 400; i++) myArray[i] = false;
```

5.1. Arrays

- Example: a three-dimensional vector

```
double y[3]; // y is a 3d vector
y[0] = 1.5;
y[1] = 2.0;
y[2] = 1.0;
// or shorter:
double x[] = { 1.5, 2.0, 1.0 };

x[0] = 3.0;
```





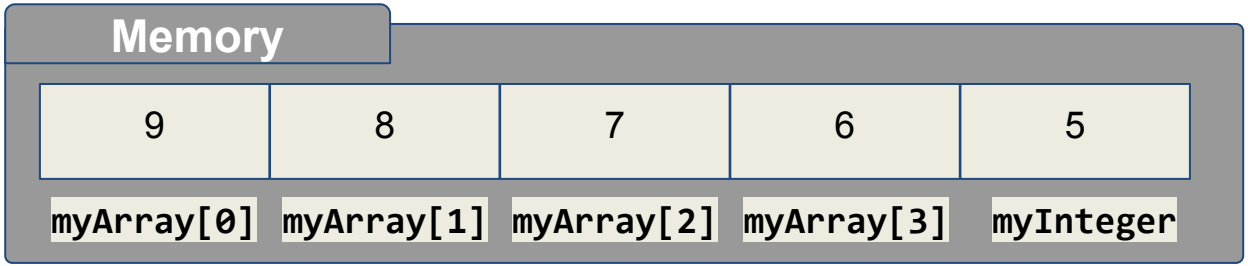
5. Arrays, Multidimensional Arrays

5.1. Arrays: Writing beyond the array boundary

- Most C++ compilers allow using *any* array indices to access array elements, even incorrect ones
- Non-existing array elements are usually other parts of memory, such as other variables or program code:

```
int myArray[4] = {9, 8, 7, 6};
int myInteger = 5;
std::cout << myArray[4] << std::endl;  // returns only a warning
```

- What could happen: `myArray[4]` returns the value of myInteger:



5.1. Arrays

Example 01 (difficulty level: 🌶️)

```
/**
  Write a program that initializes an array of 50 booleans, repeatedly having two
  elements with a true value, followed by one element with false.
  So the array starts with: true, true, false, true, true, false, true, true, …
  Do not use any variables other than myArray and a loop iteration variable.
*/

int main() {
  bool myArray[50];



  return 0;
}
```

5.1. Arrays

Example 02 (difficulty level: 🌶️🌶️)

```
/**
  Write a program that lets a user fill an array of 10 integers, using a loop,
  and then calculate and output the average of all given numbers to the terminal.
  Assume that the user enters a valid number each time.
  */
#include <iostream>  // to allow use of std::cout, std::cin, and std::endl
int main() {
  int myArray[10];




  return 0;
}
```

5.1. Arrays

Example 03 (difficulty level: 🌶🌶🌶)

```
/**
  Write a program that draws a histogram or bar chart through
  an array of 17 integers. To 'draw' the bars, use the string
  "\u2589" or an empty space.
  */
#include <iostream>  // std::cout, std::cin, and std::endl
#include <random>    // rand(), returns a pseudo-random int
int main() {
  int myArray[17];
  for (int i = 0; i < 17; i++) {  // fill array with random
    myArray[i] = ( rand() % 25 ); // numbers between 0 and 24
    // draw here with std::cout and std::endl
    std::cout << myArray[i] << std::endl;
  }
  return 0;
}
```

example output:

```
7 ▉▉▉▉▉▉▉
24▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉
23▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉
8 ▉▉▉▉▉▉▉▉
5 ▉▉▉▉▉
22▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉
19▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉
3 ▉▉▉
23▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉
9 ▉▉▉▉▉▉▉▉▉
15▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉
15▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉
17▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉
17▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉▉
12▉▉▉▉▉▉▉▉▉▉▉▉
3 ▉▉▉
2 ▉▉
```

5.2. Multidimensional Arrays

- An array can be multidimensional, for example 2-dimensional:
  ```
  int myTable[2][4] = { {1, 2, 3, 4}, {5, 6, 7, 8} };
  ```
- This array is essentially an array of 2 arrays: `myTable[0]`, `myTable[1]`
- Initialization of larger arrays typically needs nested loops:
  ```
  double map[100][20];
  for (int x = 0; x < 100; x++) {
    for (int y = 0; y < 20; y++) {
      map[x][y] = 0.0;
    }
  }
  ```
- `sizeof(myTable)` will return the total size, so 2x4x4=32 bytes
- `sizeof(myTable[0])` will return 4x4 = 16 bytes

5.2. Multidimensional Arrays: Maze Game v.3.00

- Expand on version 2.00 by drawing an actual maze in the screen background, in a tiled way (since the screen can be any size)
- Add this as a two-dimensional array that you initialize yourself in the **`clearScreen`** function to build up a maze, for example:

```
int maze[][15] = { {1, 0, 1, 1, 1, 0, 1, 1, 1, 0, 0, 0, 0, 0, 1},
                   {0, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0},
                   {1, 1, 1, 0, 1, 1, 1, 0, 0, 1, 0, 1, 1, 1, 0},
                   {1, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0},
                   {1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 1, 1, 0, 1},
                   {1, 0, 1, 0, 0, 0, 1, 0, 1, 0, 0, 1, 0, 0, 1},
                   {0, 0, 1, 0, 1, 0, 0, 0, 0, 0, 1, 1, 1, 1, 1},
                   {1, 0, 1, 0, 1, 0, 1, 1, 1, 0, 0, 0, 0, 1, 0},
                   {1, 0, 1, 0, 1, 0, 1, 0, 0, 0, 1, 1, 0, 1, 0},
                   {1, 1, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 0, 1, 0}
                 };  // array for drawing a maze as a background
```

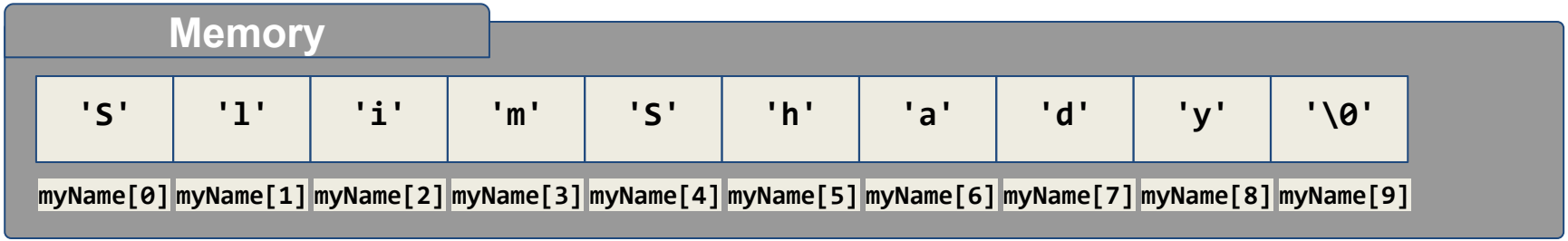
5.2. Multidimensional Arrays: Maze Game v.3.00

```
/* Third draft of Maze Game: We add an actual maze to our module "drawMaze" */
#include "drawMaze.h"  // functions related to drawing the maze and player
int main() {
  auto c = ' ';          // used for user key input
  auto x = 10, y = 10;   // (x,y) position of player: start at (10,10)
  initNCurses();         // initialize ncurses window and draw the maze
  while ( c != 'q' ) {   // as long as the user doesn't press q ..
    clearScreen();
    draw(x, y, '@', 2);   // draw our player and maze, check for collisions
    c = getch();          // capture the user's pressed key
    switch (c) {
      case 'w': y--; break;  // go up
      case 's': y++; break;  // go down
      case 'a': x--; break;  // go left
      case 'd': x++; break;  // go right
    }
  }
  endwin();           // ncurses function: close the ncurses window
  return 0;
}
```

5.3. Arrays: Strings (Arrays of char)

- Strings are sequences of symbols, for example to store textual data
- In C++, there is no built-in (primitive) string type. Sequences of characters can easily be implemented as an **array** of **`char`** variables, which *always* end with a zero (a character that has the value **`0`**, or also: **`'\0'`**, but NOT **`'0'`**):

```
char myName[10] = {'S', 'l', 'i', 'm', 'S', 'h', 'a', 'd', 'y', 0};
std::cout << yourName << std::endl;  // returns contents of yourName
```



5.3. Arrays: Strings (Arrays of char)

- Later, we will see that :

```
char yourName[] = "Marshall Bruce Mathers III";  // works, too, and
                                                 //   ends with a 0
```

- We have already used constant strings when writing output for the terminal:

```
#include <iostream>
std::cout << "This is a string!" << std::endl;
```

- The ending zero (which also is present in the constant strings such as these two above) makes sure that we never go beyond the end of the string
- As such, the empty string `""` contains still one character (with value `0`, or also: `'\0'`, but NOT `'0'`)

5.3. Arrays: Strings (Arrays of char)

- With arrays of characters, you can manage any string already, but you will see that strings are not as easy to deal with as the basic types (`int`, `float`, `double`, `bool`, `char`). For example concatenating two strings is lots of work:

```
/** Write a program that concatenates two strings, s1 and s2, no matter
    what size they have */
#include <iostream>  // use std::cout, std::cin, and std::endl
int main() {
  char s1[] = "Apples and ", s2[] = "oranges";
  // create a new string s, which contains s1 and s2 below:

  std::cout << "Concatenated string: " << s << std::endl;
  return 0;
}
```

5.4. Arrays as function parameters

- In C++, array parameters are passed ***by reference***

```
void swap( int a[10], int i, int j) {  // this swap function works!
  int temp = a[i];  // after this function ends, the original array a
  a[i] = a[j];      // will have swapped the values in its elements i
  a[j] = temp;      // and j. Variables i, j, and temp were created
}                   // at function start and are removed from memory
```

- The function above thus uses the actual array parameter, not a copy
- With ***call-by-reference***, variables given as actual parameters may be changed by the function
- In a function declaration, arrays can be of unspecified length:

```
void swap( int a[], int i, int j);  // Note we'll have to check for a's size
```

5.5. Reading char arrays from the terminal

- When trying our this approach:

```
char buffer[80];
std::cin >> buffer;
```

  you will see this has a few flaws: **`cin`** stops reading beyond the first whitespace character (so we cannot input sentences), and we might have a buffer overrun when we enter more than 80 characters

- The correct approach is to use:

```
char buffer[80];
std::cin.get( buffer, 80 );  // Reads at most 79 characters, 0 is last element
```

- In the above, **`get()`** seems to be a function, but: What exactly is **`cin`**?

5.6. Lambda Expressions and Range-based Loops (since C++11)

- Lambda expressions construct a **closure**: an unnamed function object that is capable of capturing variables in scope
- These are typically used for short code snippets that are not reused and therefore do not specifically require a name:

```
auto x = [](char symbol) { std::cout << symbol << ' '; };
```

```
auto x = [](double d, int t) -> double { return (d<t)?0:d; };
```

capture clause (see later) | parameters | return type | function body

5.6. Lambda Expressions and Range-based Loops (since C++11)

- Lambdas are the simplest way of passing functions as arguments, two other methods are (1) passing functions as pointers and (2) using the std::function<> template class → see [more in-depth information] or later in this course

5.6. Lambda Expressions and Range-based Loops (since C++11)

- The foreach loop or range-based for loop eases iterating over data
- It leaves out the iterator, initialization and stopping conditions:

```
#include <iostream>  // output to the console
int main() {
  int array[]= { 8, 2, 7, 2, 8, 7, 9, 1};
  for( auto value : array ) {  // foreach loop over array
    std::cout << value << ' ';
  }
  std::cout << std::endl;
  return 0;
}
```

5.6. Lambda Expressions and Range-based Loops (since C++11)

- **`std::for_each`** loops are similar to range-based for loops, and provided in **`<iostream>`**
- They apply a *function* to each of the elements in the range [first,last):

```
#include <iostream>  // output to the console, for_each
int main() {
  char array[] = {'H', 'e', 'l', 'l', 'o', '?'};
  std::for_each(std::begin(array), std::end(array),
                [](char sym) { std::cout << sym << ' '; });
  std::cout << std::endl;
  return 0;
}
```

6. Objects and Classes

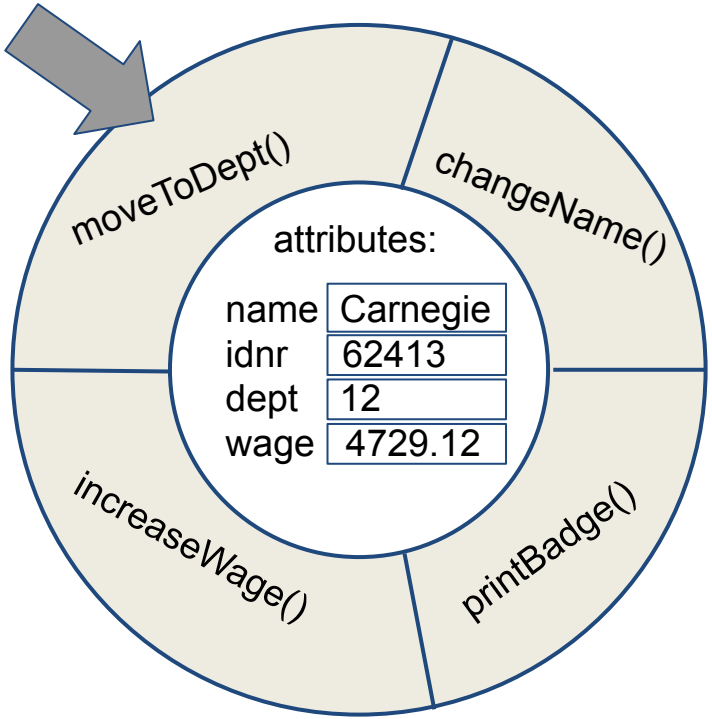
6.1. Classes and Objects

- A **class** essentially defines a new type, containing:
  - a collection of variables (data members, attributes)
  - a set of related operations (member functions, methods)
- An **object** is an instance (an entity) of a class
  - it is called object, since it usually models a real-world object
  - a class then can be viewed as a model or a blueprint for a certain class of objects

6.1. Classes and Objects

Encapsulation: The bundling together of all information, capabilities, and responsibilities (data and functions) into one single object:

```
// create a new employee:
Employee user("Carnegie", 62413,
              12, 4729.12);

// move the user to department 17:
user.movetoDept(17);
// change the user's name:
user.changeName("Carnegie-Mellon");
```

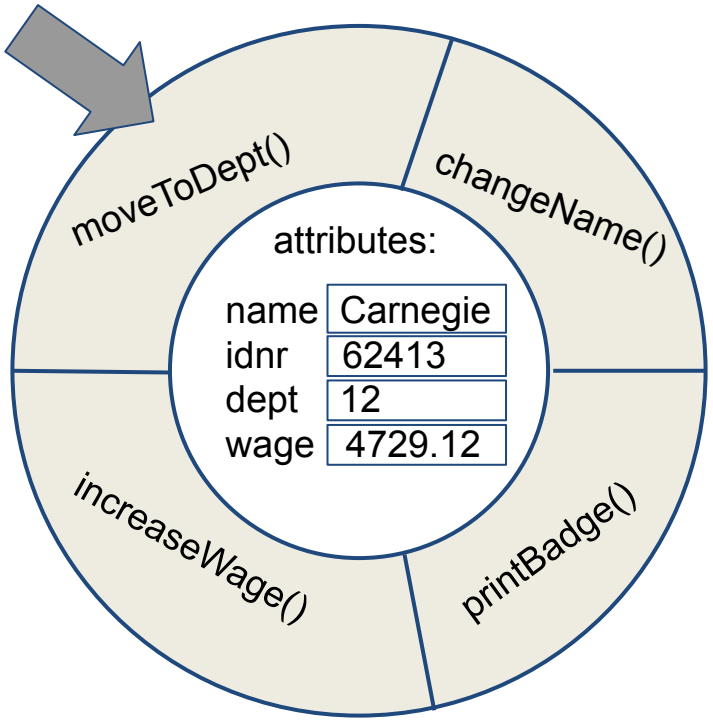


6.1. Classes and Objects

Encapsulation has two properties:

1) Data protection: Attributes are **private**, access to attributes goes through the available methods

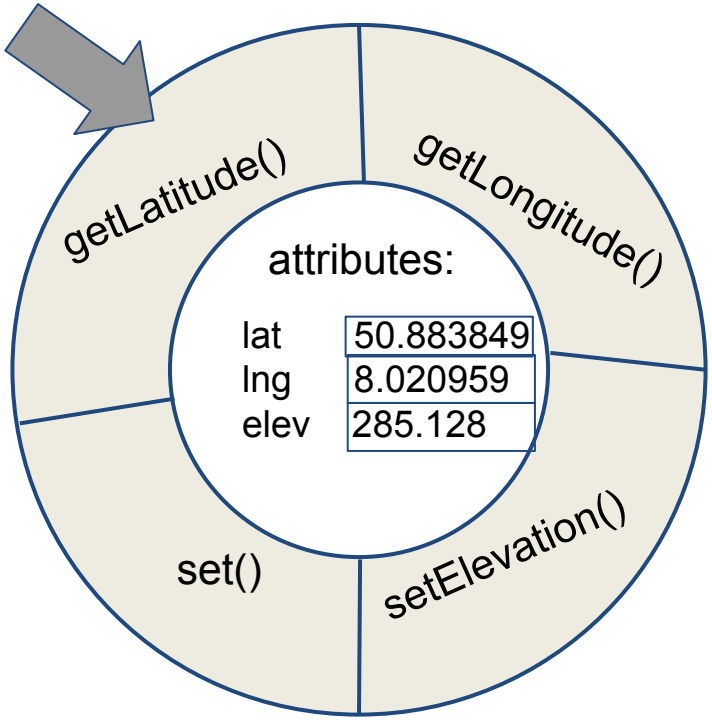
2) Information hiding: Internal implementation is hidden from external code, only the **public** interface of the class is accessible



6.1. Classes and Objects

Access to object's attributes goes through the available methods. Example:

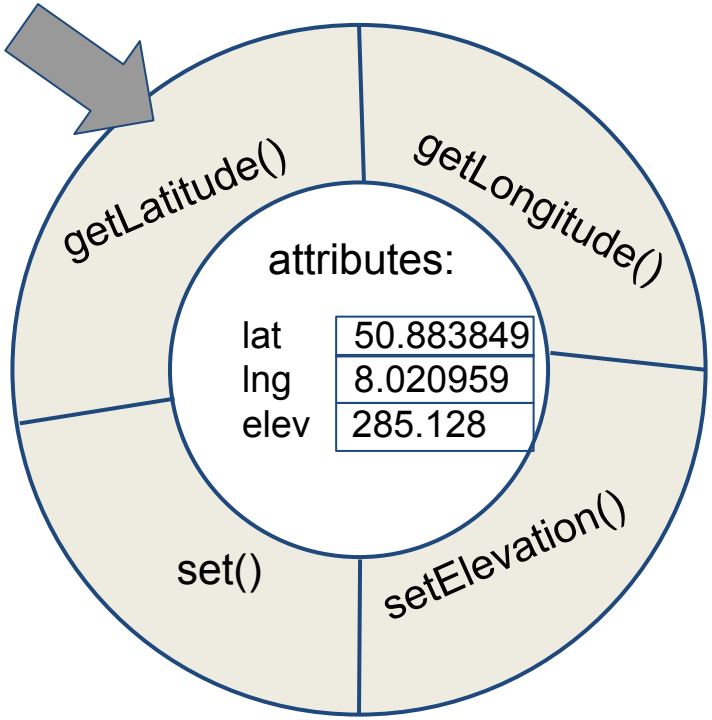
```
GPSCoord here; // GPS coordinate object

// we can modify latitude and
// longitude only together:
here.set(50.883849, 8.020959);

// we can modify the elevation:
here.setElevation(285.128);
// we can retrieve these attributes:
double lat = here.getLatitude();
double lng = here.getLongitude();
// .. but not elevation
```



6.1. Classes and Objects

Declaring a class GPSCoord:

```
// GPS coordinate class:
class GPSCoord {
 private:
  // latitude, longitude, elevation:
  double lat, lng, elev;
 public:
  // set latitude and longitude:
  void   set(double la, double lo);
  void   setElevation(double val);
  double getLatitude();
  double getLongitude();
};
```



6.1. Classes and Objects

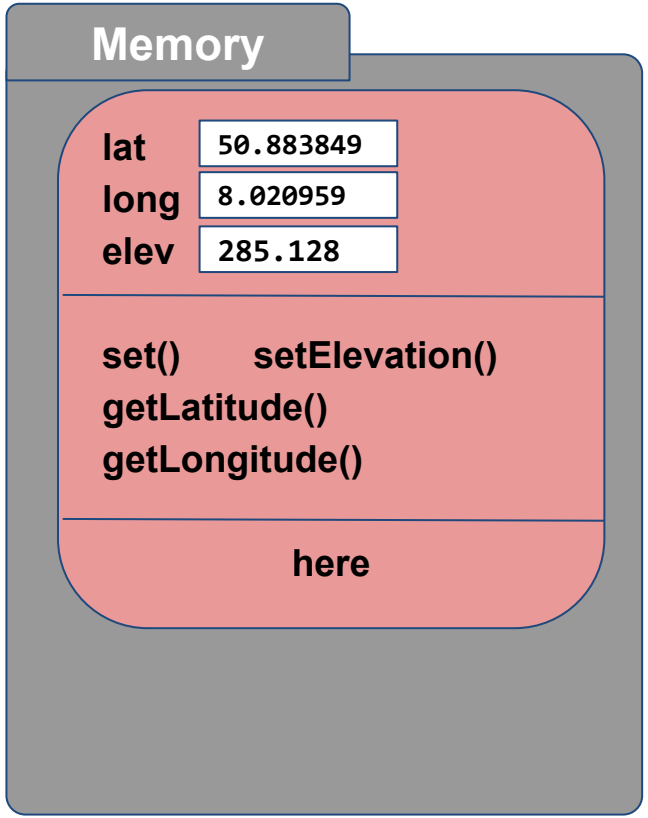
Implementing the methods for the class GPSCoord:

```
void GPSCoord::set(double la, double lo){
  lat = la; lng = lo;
}
void GPSCoord::setElevation(double val){
  elev = val;
}
double GPSCoord::getLatitude(){
  return lat;
}
double GPSCoord::getLongitude(){
  return lng;
}
```

6.1. Classes and Objects

Creating an object of the class GPSCoord:

```
GPSCoord here; // GPS coordinate object

// we can modify latitude and
// longitude only together:
here.set(50.883849, 8.020959);

// we can modify the elevation:
here.setElevation(285.128);
// we can retrieve these attributes:
double lat = here.getLatitude();
double lng = here.getLongitude();
// .. but not elevation
```

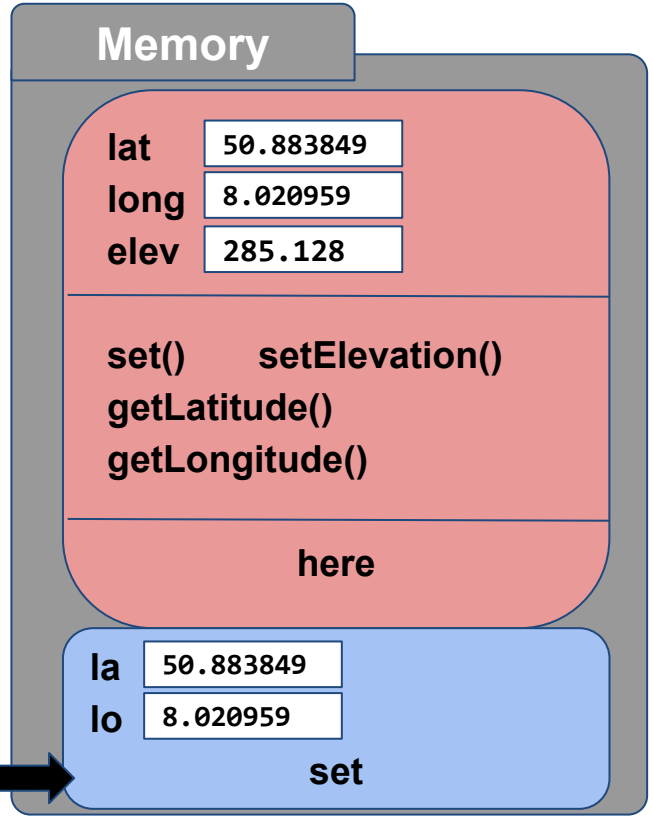


6.1. Classes and Objects

An object's method (member function) has access to *all* its attributes (variables) and methods

```
void GPSCoord::set(double la, double lo){
  lat = la; long = lo;  // defaults
  // call GPSCoord methods to update:
  lat = getLatitude();
  lng = getLongitude();
  setElevation(285.128);
}
```

```
GPSCoord here; // GPS coordinate object
// set latitude and longitude:
here.set(50.883849, 8.020959);
```



6.1. Classes and Objects

❗ Note new suggested indentation & syntax for classes. One space should come before private or public, and a colon (':') after these keywords. Example:

```
// GPS coordinate class:
class GPSCoord {
◇private:
◇◇// latitude, longitude, elevation:
◇◇double lat, lng, elev;
◇public:
◇◇// set latitude and longitude:
◇◇void set(double la, double lo);
◇◇void etElevation(double val);
◇◇double getLatitude();
◇◇double getLongitude();
};  // mind the semicolon after the declaration
```

6.1. Classes and Objects: Minor notes

Attributes could also be public (but usually aren't)
Methods can also be implemented in the class declaration

```
class Test {
 private:
  int attribute1;  // a private attribute
 public:
  bool attribute2;  // a public attribute
  void method1(int parameter) { attribute1 = parameter; };   // methods implemented
  void method2() { std::cout << attribute1 << std::endl; };  // in class declaration
};
int main(){
  Test myTest;  // create an object of class Test
  myTest.attribute2 = false;  // we can access public attributes
  myTest.method1(21); // we can call public methods
  return 0;
}
```

6.1. Classes and Objects: Minor notes

The class declaration is usually in the file **`className.h`**, the class' method implementations in the file **`className.cpp`**

Test.h

```
class Test {
 private:
  int attribute1;
 public:
  bool attribute2;
  void method1(int parameter);
  void method2();
};
```

Test.cpp

```
#include "Test.h"
void Test::method1(int parameter) {
  attribute1 = parameter;
};
void Test::method2() {
  std::cout << attribute1 << std::endl;
};
```

mainTest.cpp

```
#include "Test.h"
int main(){
  Test myTest;
  myTest.attribute2 = false;
  myTest.method1(21);
  return 0;
}
```

6.2. Constructors and Destructors

Reminder: Variables can be declared and later initialized, or they can be immediately initialized within the declaration:

```
char mySymbol = '?';
```

This declaration and initialization can be done for classes' objects as well:

```
GPSCoord myLocation(50.88385, 8.02096, 285.128);  // coordinates of Siegen
Employee user("Carnegie", 62413, 12, 4729.12);  // employee Carnegie
SizedSymbol bigQuestion('?', 14);  // a SizedSymbol '?' with size 14
```

This requires a special method with the class' name: The constructor

6.2. Constructors and Destructors

A constructor has no return value (not even void) and is automatically called

```
class Test {
 private:
  int attribute1;
 public:
  Test(int parameter) {  // this is a constructor for class Test
    attribute1 = parameter;
  };
  void method2() {
    std::cout << attribute1 << std::endl;
  };
};

int main(){
  Test myTest(21);   // object's constructor initializes is automatically called
  myTest.method2();  // this will print out '21' to the terminal
  return 0;
}
```

6.2. Constructors and Destructors

Constructors can be overloaded (distinguished by their parameters):

```
class Test {
 private:
  int attribute1, attribute2;
 public:
  // multiple constructors for class Test:
  Test() { attribute1 = 0; }; // this is a default constructor
  Test(int parameter) { attribute1 = parameter; };
  Test(int parameter1, int parameter2) { attribute1 = parameter2; };
  void method2() { std::cout << attribute1 << std::endl; };
};

int main(){
  Test myTest(4, 12);  // object of class Test has attribute1 initialized to 12
  myTest.method2();  // this will print out '12' to the terminal
  return 0;
}
```

6.2. Constructors and Destructors

- A class' default constructor is a constructor without parameters
- A class without declared constructors results in the compiler automatically generating a default constructor
- A default constructor is invoked when an object is created, but not initialized

```
class Test {
 private:
  int attribute1;
 public:
  // Test() {}  --> an automatically generated constructor would look like this
  void method2() { std::cout << attribute1 << std::endl; };
};
int main(){
  Test myTest;  // this object is initialized with empty default constructor
  return 0;
}
```

6.2. Constructors and Destructors

A destructor is automatically called whenever an object is destroyed:

```
bool myFunction(){
  Test myTest(17);  // this object is created and initialized here
  return false;     // myTest's destructor is called when function returns
}
```

This destructor is another special method with the same name as the class, starting with a ~:

```
Test::~Test() {  // this is the destructor for class Test
  // here come statements for application-specific clean up
}
```

6.2. Constructors and Destructors

Example 00 (difficulty level: 🌶️)

```
/**
  Write a program that declares, implements, and uses a class with no attributes.
  The class should print 'hello' to the terminal when its object is created and
  'bye' when its object is removed from memory.
*/
#include <iostream>     // terminal input and output classes and objects

// write the class here

int main() {
  // create a class object here

  return 0;
}
```

6.2. Constructors and Destructors

Example 01 (difficulty level: 🌶️🌶️)

```
/**
  Write a program that declares, implements, and uses a class with two attributes,
  a boolean called 'flag' and an integer called 'number', which can only be changed
  or read through a constructor. The class should also have a method 'get' with no
  parameters, which returns the integer 'number' only if 'flag' is true, and
  otherwise 0.
*/
// write the class here
int main() {
  int returnValue;
  // create a class object here
  // and use its get method
  return returnValue;
}
```

6.2. Constructors and Destructors: Maze Game v.4.00

Change the module into a class Maze, with **`mazeGame.cpp`** looking this way:

`mazeGame.cpp`

```
/* Fourth draft of Maze Game: drawing is in class "Maze" */
#include "Maze.h"  // everything related to the maze
int main() {
  auto c = ' ';        // used for user key input
  Maze maze(10, 5);    // initialize the maze and put player at (10, 5)
  while ( c != 'q' ) {  // as long as the user doesn't press q ..
    maze.draw('@', 3);    // draw player as a '@' with color pair 3
    c = getch();          // capture the user's pressed key
    switch (c) {
      case 'w': maze.up(); break;  // go up
      case 's': maze.down(); break;  // go down
      case 'a': maze.left(); break;  // go left
      case 'd': maze.right(); break;  // go right
    }
  }
  return 0;
}
```

6.3. `this` and initializing `const` attributes

Class methods often reuse attribute names, leading to a problem:

```
class Maze {
 public:
  Maze(int16_t x, int16_t y);
  …
 private:
  int16_t x, y;
  …
};
```

```
Maze::Maze(int16_t x, int16_t y) {
 // how to assign the values of
 // constructor parameters x and y
 // to class attributes x and y?
  …
}
Maze::Maze() {
 int16_t x, int16_t y;
 // how to assign the values of
 // constructor parameters x and y
 // to local variables x and y?
  …
}
```

6.3. `this` and initializing `const` attributes

One solution that works in all the class' methods is to use `this`

```
Maze::Maze(int16_t x, int16_t y) {
  this->x = x;  // attribute x = value of constructor parameter x
  this->y = y;  // attribute y = value of constructor parameter y
  ...
}
```

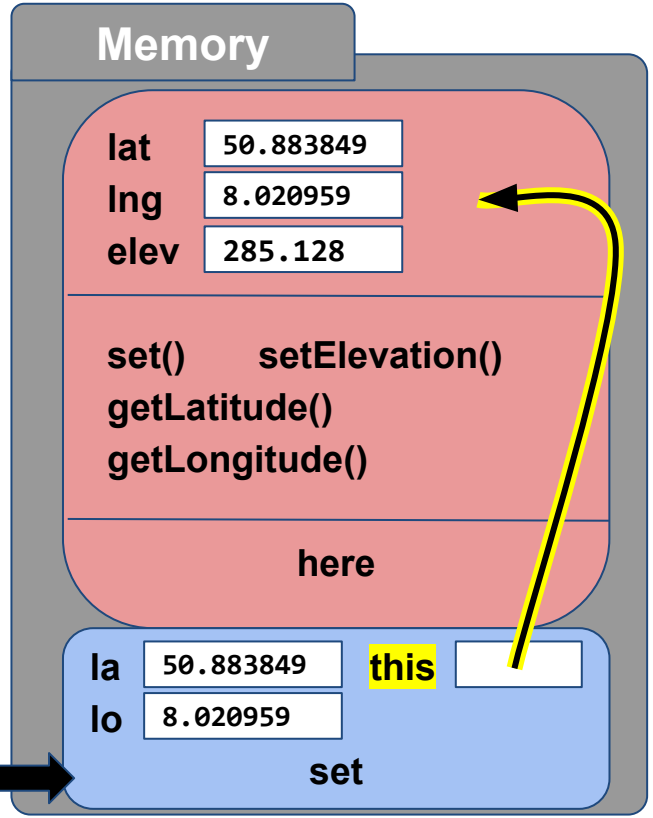
- Note: Each object gets its own copy of data members, all objects share a single copy of the class' methods
- `this` is an implicit pointer (see later) that is passed as a hidden parameter for all the class' methods, and is there available as another local variable

6.3. `this` and initializing `const` attributes

`this` is passed as a hidden parameter for all the class' methods, as an extra (pointer) variable

```
void GPSCoord::set(double lat, double lng){
  this->lat = lat;
  this->lng = lng;
  this->lat = getLatitude();
  this->lng = getLongitude();
  setElevation(285.128);
}
```

```
GPSCoord here; // GPS coordinate object
// set latitude and longitude:
here.set(50.883849, 8.020959);
```



6.3. `this` and initializing `const` attributes

Another (shorter) solution for constructors is to use this initialization syntax:

```
Maze::Maze(int16_t x, int16_t y) : x(x), y(y) {
 // attributes x and y have now the same value as constructor
 // parameters x and y
}
```

This *member initializer list* syntax in constructors is not an assignment but a real initialization of the attribute. Curly braces can also be used:

```
Maze::Maze(int16_t x, int16_t y) : x{x}, y{y} {
 // attributes x and y have now the same value as constructor
 // parameters x and y
}
```

6.3. `this` and initializing `const` attributes

This syntax addresses the problem of initializing a class' `const` attribute:

```
class Maze {
  ...
 private:
  const int16_t mazeXlen;
  const int16_t mazeYlen;
  ...
};
```

```
Maze::Maze(int16_t x, int16_t y) {
  // we cannot assign to const:
  mazeXlen = 15; // compiler error
  mazeYlen = 10; // compiler error
  ...
}
```

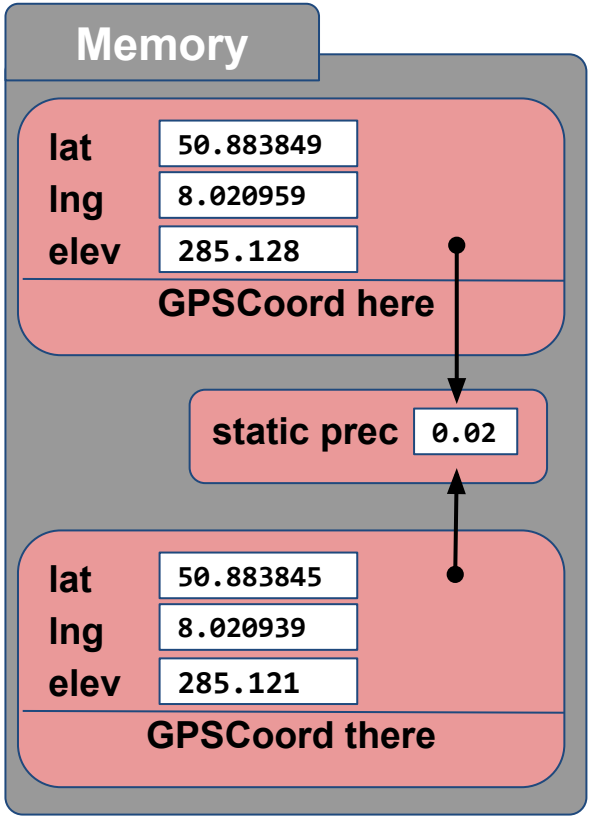
This syntax is not an assignment but an initialization, and thus works:

```
Maze::Maze(int16_t x, int16_t y) : mazeXlen(15), mazeYlen(10) {
  // mazeXlen is now 15, mazeYlen 10
  ...
}
```

6.4. `static` members

- Each object has its own class attributes
- All objects share one copy of the class' methods
- `static` attributes, or static members, are stored once across all objects. *Changing it through one object will change it for all objects.*

```
GPSCoord here;
GPSCoord there;

there.prec = 0.02;
// the following will print out 0.02:
std::cout << here.prec;
```



6.4. `static` members

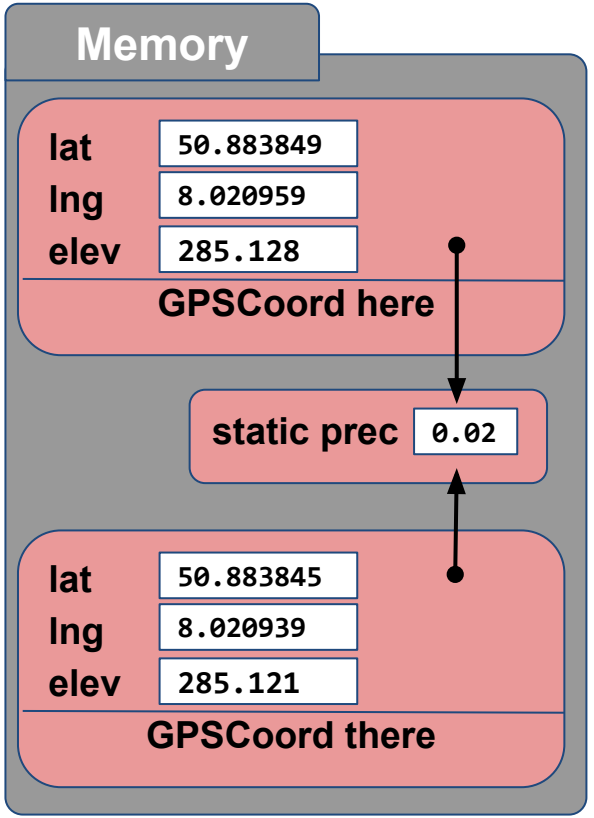
- They exist even if no objects of the class have been defined
- Static class members are declared in the class declaration, and are defined in the implementation / source file:

GPSCoord.h

```
class GPSCoord {
 public:
  // declaring a precision
  // attribute for all
  // GPSCoord objects:
  static double prec;
 ...
};
```

GPSCoord.cpp

```
// precision definition:
double GPSCoord::prec;

 ...
```

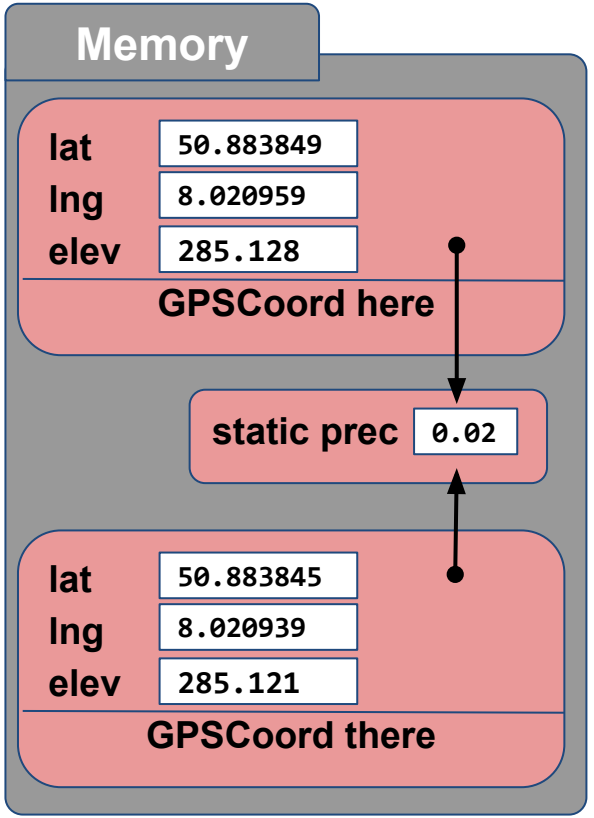


6.4. `static` members

These are not the same as **`static`** variables:

- Local variables that are declared as **`static`** are stored as global variables in the static data segment in memory
- Their size has to be known at compile time (e.g., for arrays)

```
void GPSCoord::set(){
  // this variable will stay in memory and keep
  // and keep its value after the method finishes:
  static double prec = 0.01;
  setElevation(285.128, prec);
}
```



6.4. `static` members

Example 02 (difficulty level: 🌶️)

```
/**
  Create a class with just a static member, and illustrate that it exists, even
  without any objects.
*/
#include <iostream>     // terminal output
// write the class here
// class …

int main() {
  // do not create an object here, but assign a value to static member here
  std::cout << " The value of the static member is ";
  // print its value here
  std::cout << std::endl;
  return 0;
}
```

6.5. The `string` Class

`iostream` has a class called **`std::string`**, helping in dealing with strings:

```
#include <iostream>     // terminal input and output classes and objects
int main() {
  std::string myFirstName("John");  // initialize with constructor
  std::string myLastName = "Doe";  // initialize with assignment
  std::string myString = myFirstName + myLastName;  // concatenation

  std::cout << myString << ", length = " ;
  std::cout << myString.length() << std::endl;  // returns myString length

  std::cout << " Do found at = ";
  std::cout << myString.find("Do") << std::endl;  // return position of "Do"

  std::cout << myString.compare(4, 3, "Do");  // is substring at position 4
  std::cout << std::endl;                     // and length 3 the same as "Do"?
  return 0;
}
```

6.5. The `string` Class

`iostream` has a class called **`std::string`**, helping in dealing with strings.
Several **`std::string`** alternatives use instead of **`char`**:

`std::wstring`	uses **`wchar_t`** for wide strings
`std::u8string` (since C++20)	uses **`char8_t`**
`std::u16string` (since C++11)	uses **`char16_t`**
`std::u32string` (since C++11)	uses **`char32_t`**

```
#include <iostream>     // terminal input and output classes and objects
int main() {
  std::wcout.imbue(std::locale("en_US.UTF-8"));
  std::string  myString  = "¡Hola! 日本 שלום 你好 مرحبا";  // UTF-8
  std::wstring mywString = L"¡Hola! 日本 שלום 你好 مرحبا";  // wide chars
  std::cout  << myString << sizeof(myString[0]) << std::endl;
  std::wcout << mywString << sizeof(mywString[0]) << std::endl; // ! note wcout
  return 0;
}
```

6.6. The `ifstream` and `ofstream` Classes

The module **`fstream`** contains a class **`std::ifstream`** for reading from a file:

`fileTest.cpp`

```
#include <iostream>    // terminal input/output classes & objects
#include <fstream>     // input file stream class std::ifstream

int main() {
  std::ifstream myFile("fileTest.cpp");  // initialize with constructor

  char c;
  while (myFile.get(c)) {   // get a character from the file, move to next
    std::cout << c;         // and output it to the terminal
  }

  return 0;
}
```

6.6. The `ifstream` and `ofstream` Classes

The module **`fstream`** also contains a class **`std::ofstream`** for writing to a file:

copyTest.cpp

```
#include <fstream> // in/output file stream classes

int main() {
  std::ifstream myFile("copyTest.cpp");    // initialize input and output file
  std::ofstream myFileCopy("copyTest_copy.cpp");  // streams with constructors

  char c;
  while (myFile.get(c)) {   // get a character from the input file stream
    myFileCopy << c;        // and output it to the output file stream
  }

  return 0;
}
```

6.7. The `tuple` Class

A **`std::tuple`** is a fixed-sized collection values of various data types (preview of what is still to come, as it uses templates under the hood):

```
#include <iostream> // std::cout, std::endl, and tuples functionality
int main() {
  auto myUser = std::make_tuple("James", "Smith", 187.2);  // auto = std::tuple
  // get with index-based access:
  std::cout << std::get<0>(myUser) << " " << std::get<1>(myUser);
  // get with type-based access:
  std::cout << ":" << std::get<double>(myUser) << std::endl;
  return 0;
}
```

- `get<0>(myUser)` accesses first element (hence index-based access, since C++11)
- `get<double>(myUser)` accesses the double (hence type-based access, since C++14) (works only if 1 tuple element has this type, otherwise the compiler reports an error)

6.7. The `tuple` Class

With decomposition declarations or structured bindings (since C++17), you can unpack the contents of the tuple into individual variables:

```
#include <iostream> // std::cout, std::endl, and tuples functionality
int main() {
  auto myUser = std::make_tuple("James", "Smith", 187.2);  // auto = std::tuple
  auto [fname, lname, height] = myUser;  // decomposition declaration, C++17
  std::cout << fname << " " << lname << ":" << height << std::endl;
  return 0;
}
```

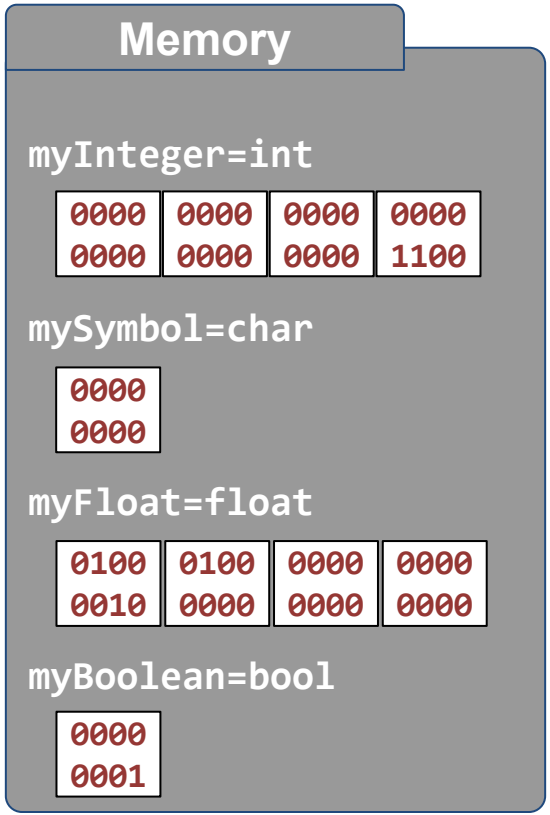
note that the first `auto` above can deduce myUser as an **std::tuple** object

7. Pointers and Memory Allocation

7.1. Pointers

Reminder: Variables and objects reside in memory. Through the variable name, you can read and change the variable's value. Its type tells the compiler how.

```
/* reserving variables */
int main() {
  int myInteger = 12;   // store an integer
  char mySymbol;   // store one character
  float myFloat = 12.0f;  // store floating point
  bool myBoolean = true;  // store a boolean
  return 0;
}
```

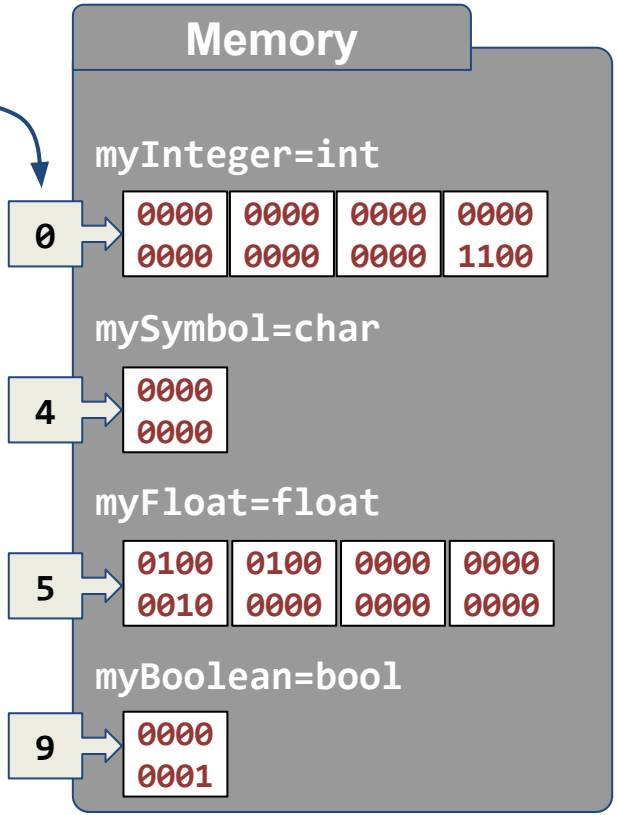


7.1. Pointers

Each memory location has a **memory address**

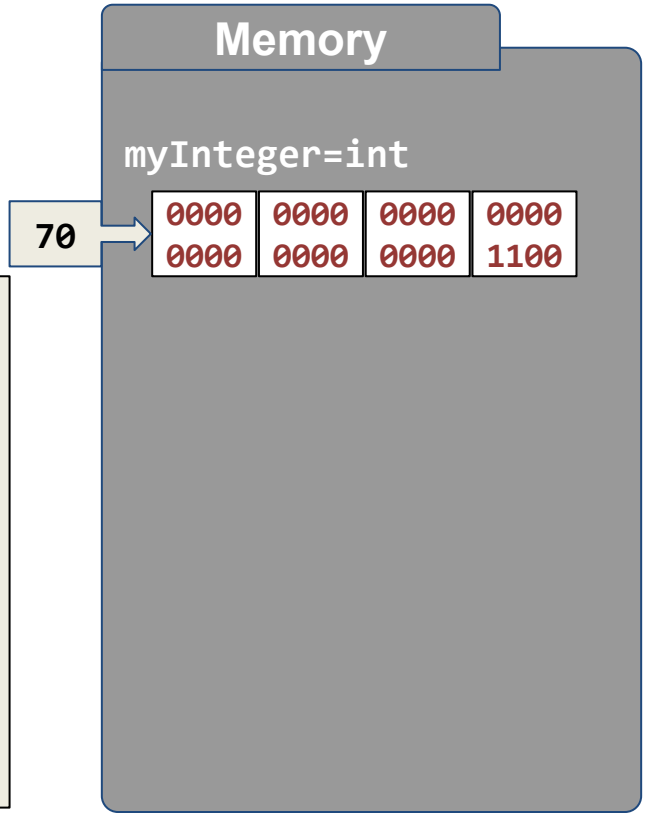
We assume here that one memory block occupies one byte.

```
/* reserving variables */
int main() {
  int myInteger = 12;    // store an integer
  char mySymbol;    // store one character
  float myFloat = 12.0f;  // store floating point
  bool myBoolean = true;  // store a boolean
  return 0;
}
```



7.1. Pointers

A pointer stores a **memory address and its associated type**

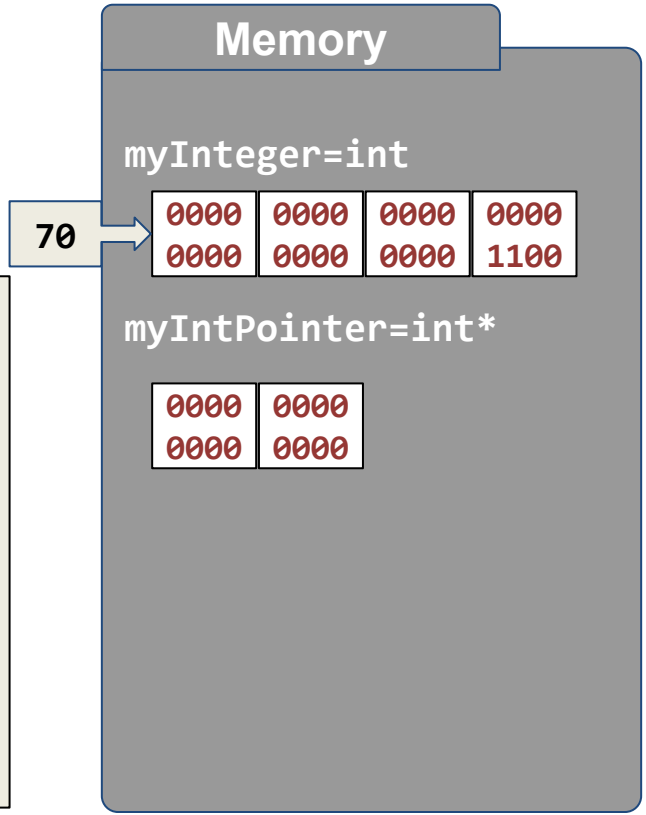



```c
/* reserving variables */
int main() {
  int myInteger = 12;    // store an integer
  int * myIntPointer;    // store a pointer to int
  myIntPointer = &myInteger;  // store floating
  *myIntPointer = 17; // myInteger is now also 17
  return 0;
}
```

7.1. Pointers

A pointer stores a **memory address and its associated type.** Pointer variables are declared by using the * operator.

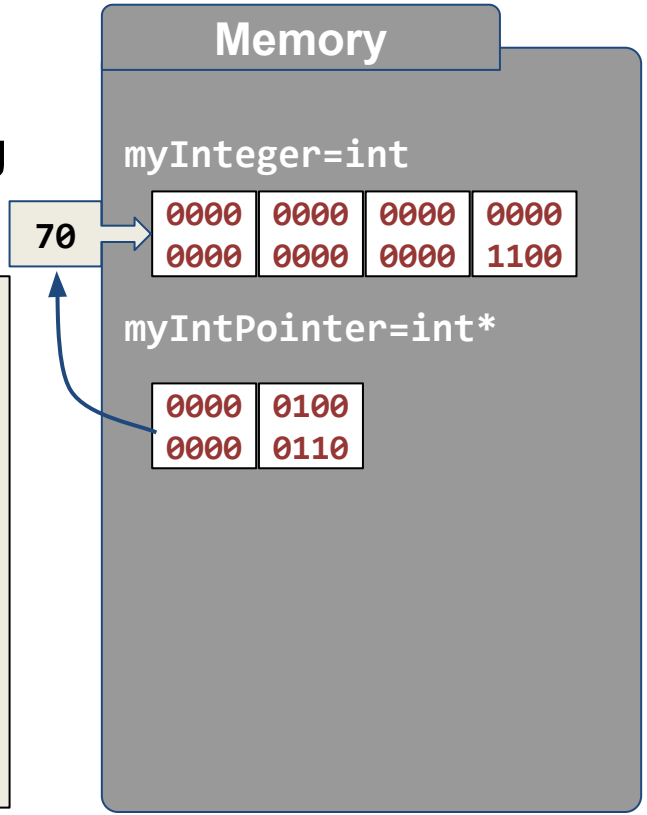
```
/* reserving variables */
int main() {
  int myInteger = 12;    // store an integer
  int * myIntPointer;    // store a pointer to int
  myIntPointer = &myInteger;  // store floating
  *myIntPointer = 17; // myInteger is now also 17
  return 0;
}
```



7.1. Pointers

Pointer variables can obtain the address of existing variables of that type using the **&** operator (returning the address of a variable)

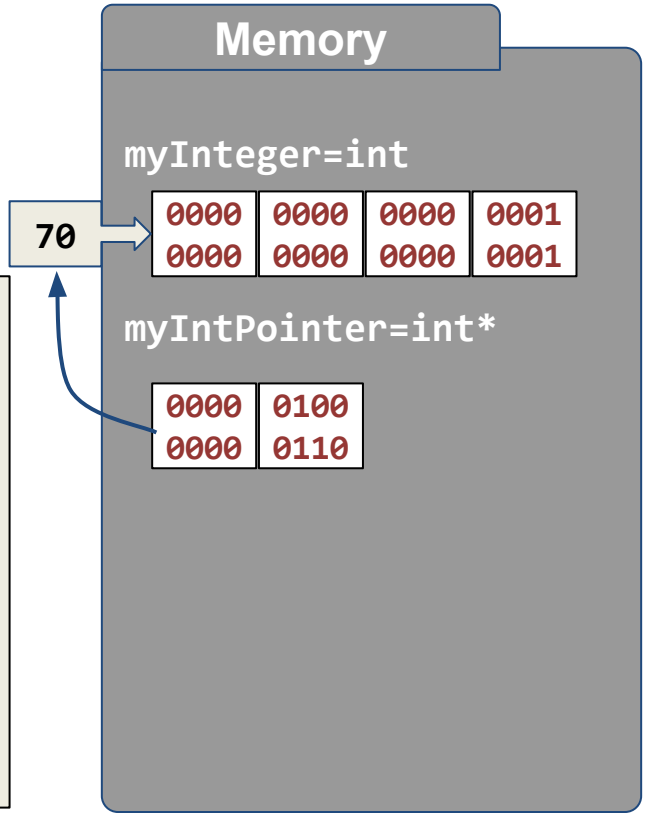
```
/* reserving variables */
int main() {
  int myInteger = 12;    // store an integer
  int * myIntPointer;    // store a pointer to int
  myIntPointer = &myInteger;  // store floating
  *myIntPointer = 17; // myInteger is now also 17
  return 0;
}
```



7.1. Pointers

Dereferencing a pointer means following the pointer's content (memory address) and accessing the variable of that type

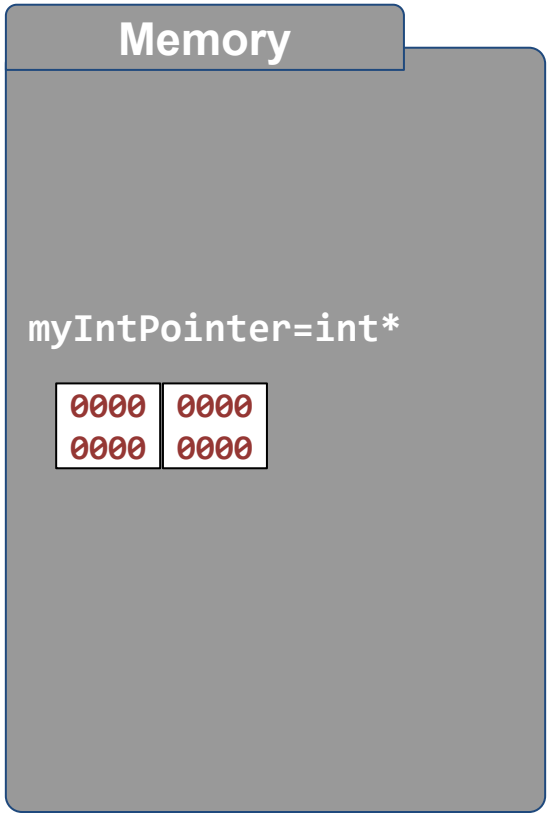
```
/* reserving variables */
int main() {
  int myInteger = 12;    // store an integer
  int * myIntPointer;    // store a pointer to int
  myIntPointer = &myInteger;  // store floating
  *myIntPointer = 17; // myInteger is now also 17
  return 0;
}
```



7.2. `new` and `delete`

A pointer assumes a memory address is reserved for a variable. Indicate that the pointer isn't pointing to a valid variable with `NULL` (or [`nullptr`] since C++11):

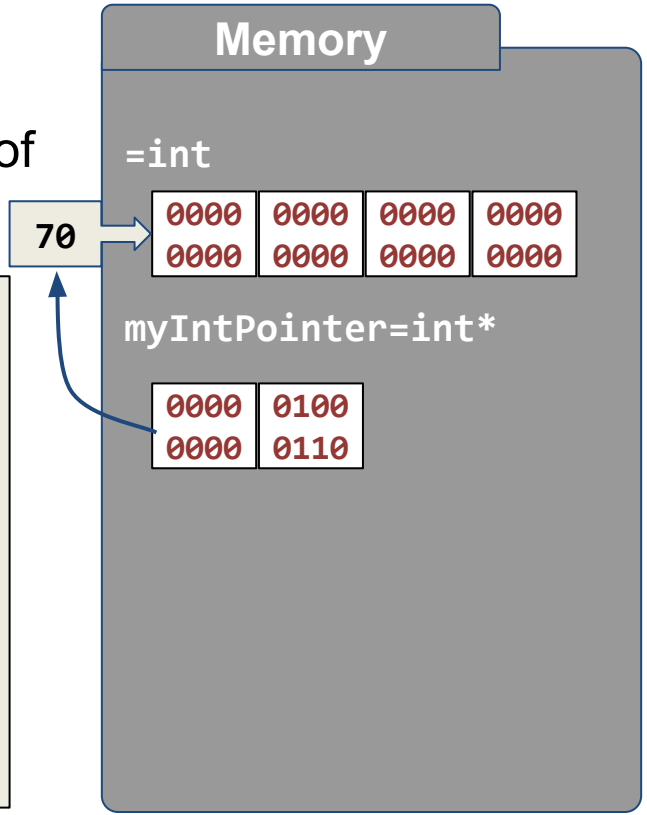
```
/* reserving variables through a pointer */
int main() {
  int * myIntPointer = NULL;  // pointer to int
  myIntPointer = new int;  // create the int
  *myIntPointer = 17;  // the int now holds 17
  delete myIntPointer;  // remove the pointer
  return 0;
}
```



7.2. `new` and `delete`

A pointer assumes a memory address is already reserved for a variable. We can create the variable of the correct type through the `new` keyword:

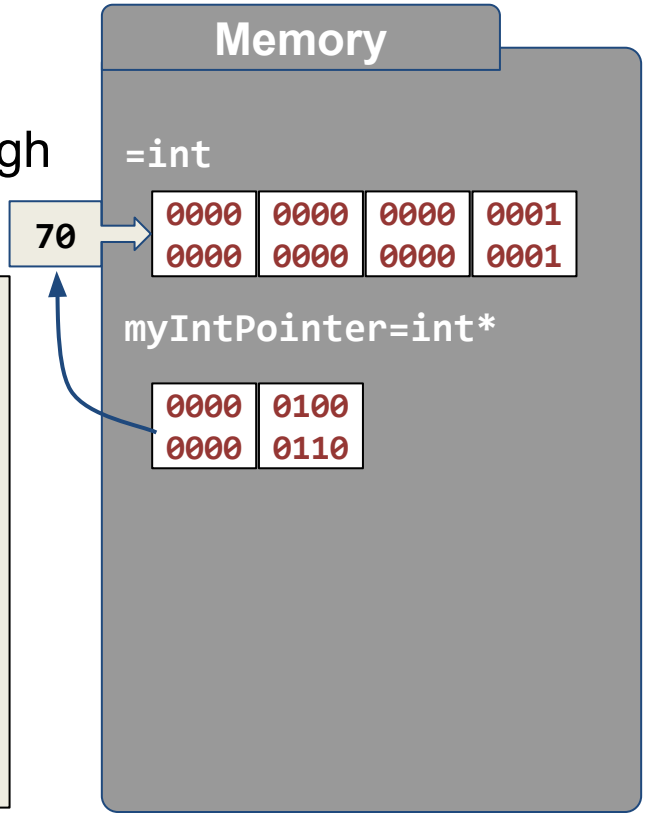
```
/* reserving variables through a pointer */
int main() {
  int * myIntPointer = NULL;  // pointer to int
  myIntPointer = new int;  // create the int
  *myIntPointer = 17;  // the int now holds 17
  delete myIntPointer;  // remove the pointer
  return 0;
}
```



7.2. `new` and `delete`

A pointer assumes a memory address is already reserved for a variable. This variable can only through the pointer be read and changed:

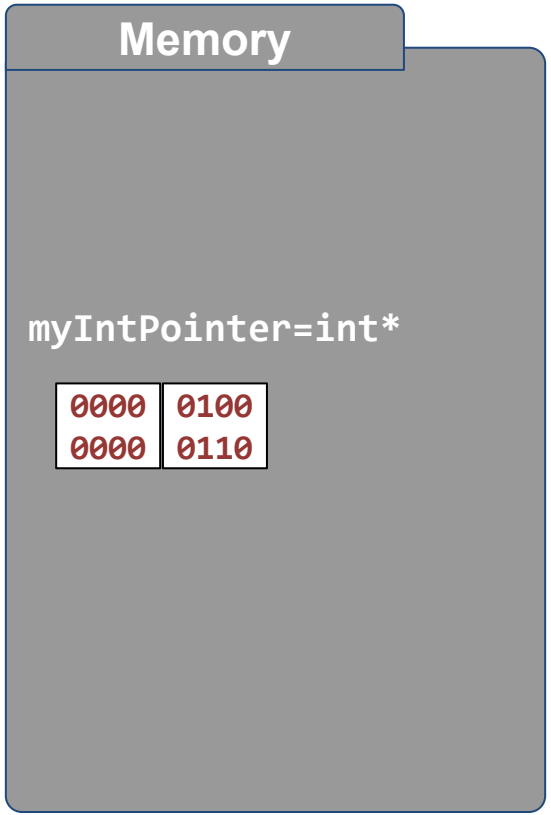
```
/* reserving variables through a pointer */
int main() {
  int * myIntPointer = NULL;  // pointer to int
  myIntPointer = new int;  // create the int
  *myIntPointer = 17;  // the int now holds 17
  delete myIntPointer;  // remove the pointer
  return 0;
}
```



7.2. `new` and `delete`

A pointer assumes a memory address is already reserved for a variable. This variable can only through the pointer be read and changed:

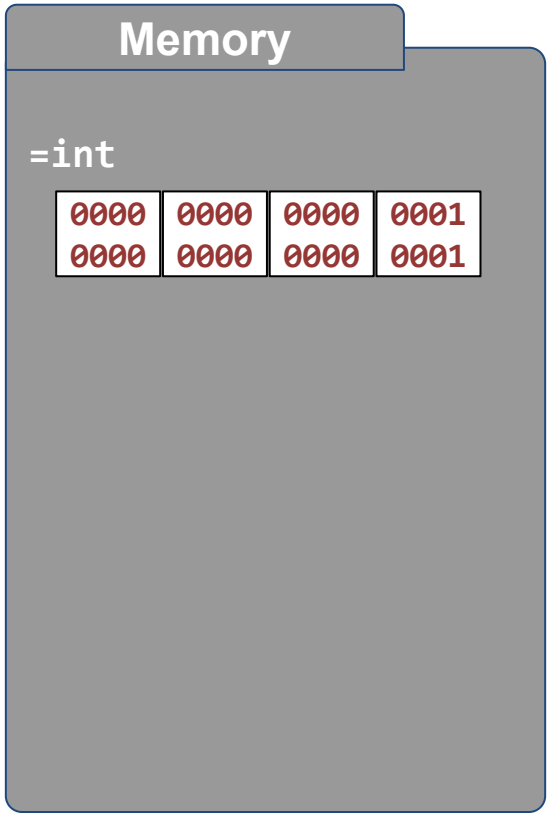
```
/* reserving variables through a pointer */
int main() {
  int * myIntPointer = NULL;  // pointer to int
  myIntPointer = new int;  // create the int
  *myIntPointer = 17;  // the int now holds 17
  delete myIntPointer;  // remove pointer's int
  return 0;
}
```



7.2. `new` and `delete`

Forgetting to `delete` a reserved variable causes a memory leak, since the pointer is removed and the variable cannot be reached anymore (but is reserved).

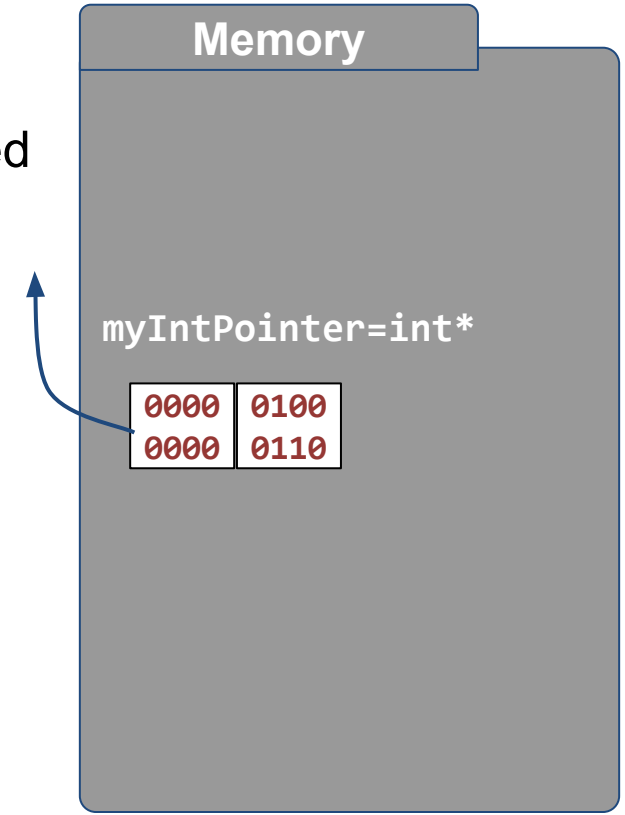
```
void myFunction() {
  int * myIntPointer = new int; // create int
  *myIntPointer = 17;
}
int main() {
  myFunction();
  // after the above function ends, myIntPointer
  // is removed, but not the int variable
  return 0;
}
```



7.2. `new` and `delete`

It is good practice to assign the pointer to `NULL` after `delete` (since the pointer still points to a non-reserved memory location, this is called a *dangling pointer*).

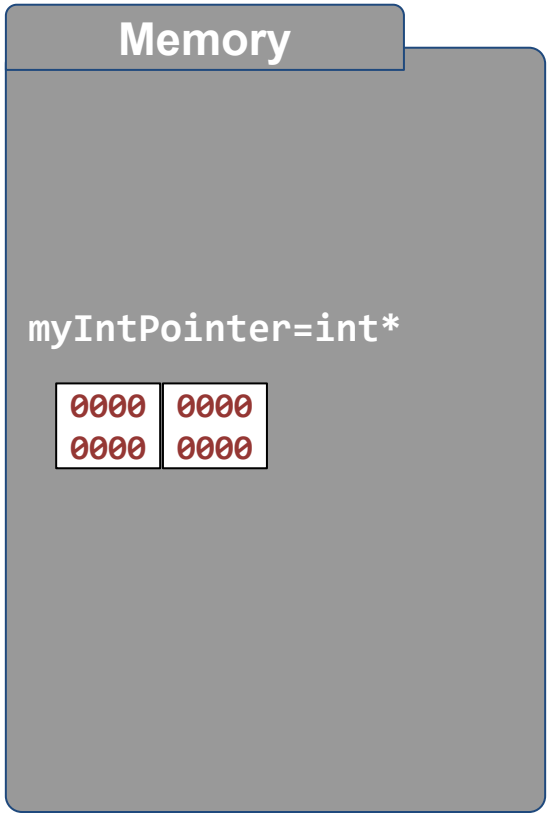
```
void myFunction() {
  int * myIntPointer = new int; // create int
  *myIntPointer = 17;
  delete myIntPointer;  // remove pointer's int
  myIntPointer = NULL;  // point to NULL
}
int main() {
  myFunction();
  return 0;
}
```



7.2. `new` and `delete`

It is good practice to assign the pointer to `NULL` after `delete` (since the pointer still points to a non-reserved memory location, this is called a *dangling pointer*).

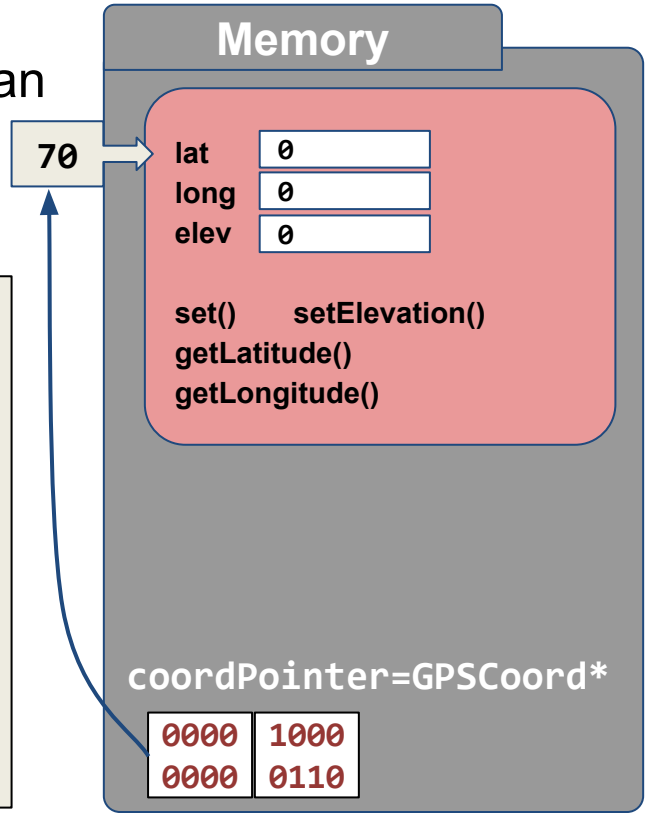
```
void myFunction() {
  int * myIntPointer = new int; // create int
  *myIntPointer = 17;
  delete myIntPointer;  // remove pointer's int
  myIntPointer = NULL;  // point to NULL
}
int main() {
  myFunction();
  return 0;
}
```



7.3. Creating and deleting objects

Pointers can also point to classes' objects. These can similarly be created and deleted in memory, too.

```
void myFunction() {
  GPSCoord * coordPointer = new GPSCoord();
  coordPointer->set(0, 0);  // access method
  delete coordPointer;  // remove object
  coordPointer = NULL; // avoid dangling pointer
}
int main() {
  myFunction();
  return 0;
}
```

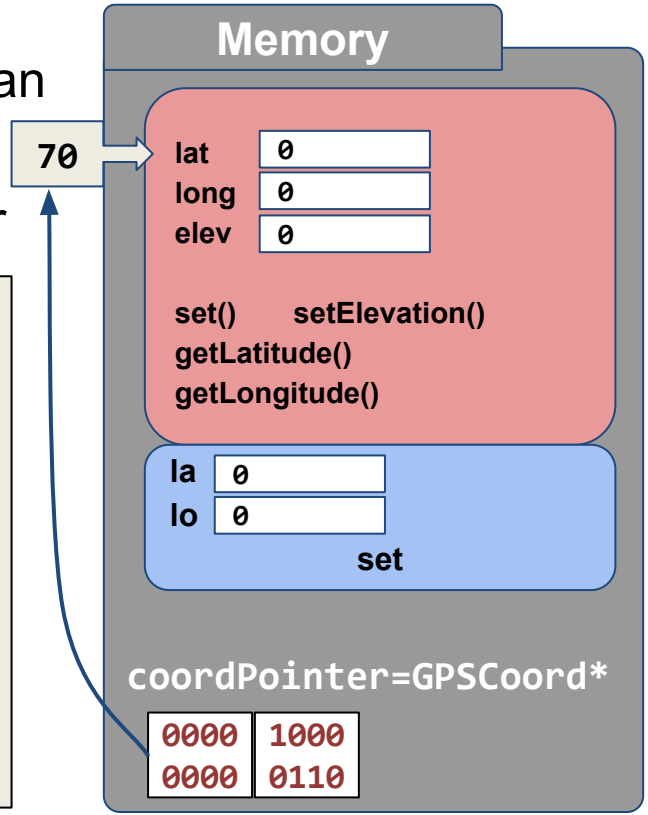


7.3. Creating and deleting objects

Pointers can also point to classes' objects. These can similarly be created and deleted in memory, too.

Attributes & methods are accessed with `->` operator

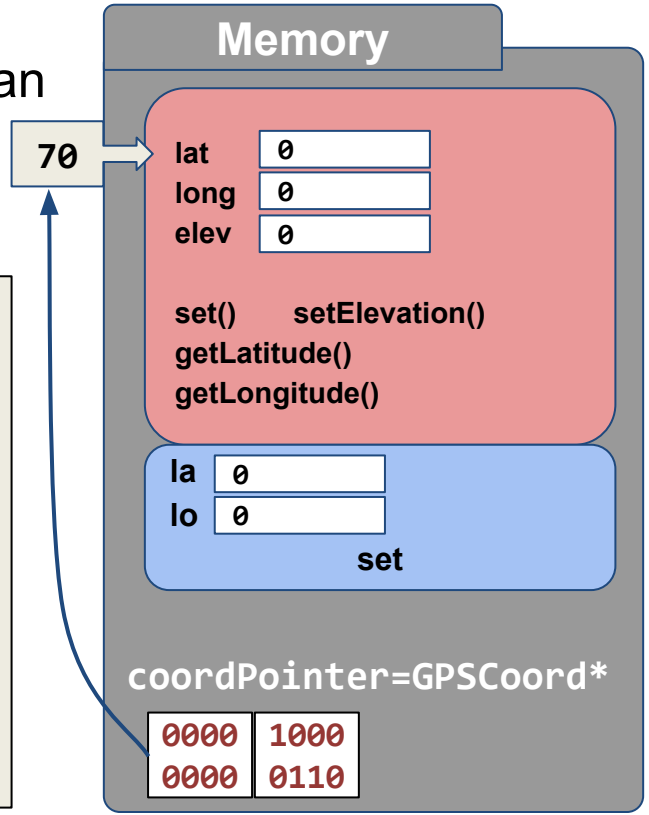
```
void myFunction() {
  GPSCoord * coordPointer = new GPSCoord();
  coordPointer->set(0, 0);  // access method
  delete coordPointer;  // remove object
  coordPointer = NULL; // avoid dangling pointer
}
int main() {
  myFunction();
  return 0;
}
```



7.3. Creating and deleting objects

Pointers can also point to classes' objects. These can similarly be created and deleted in memory, too.

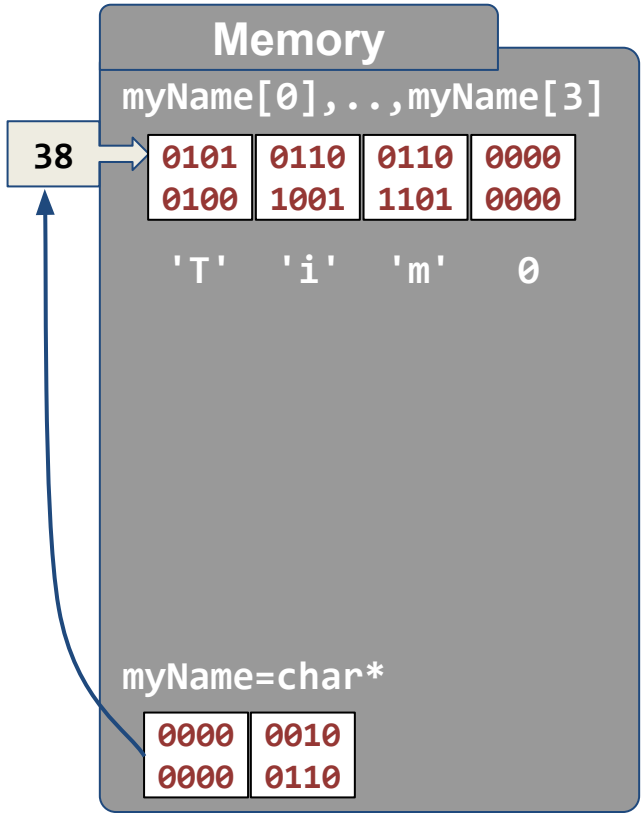
```
void myFunction() {
  GPSCoord * coordPointer = new GPSCoord();
  coordPointer->set(0, 0);  // access method
  delete coordPointer;  // remove object
  coordPointer = NULL; // avoid dangling pointer
}
int main() {
  myFunction();
  return 0;
}
```



7.4. Pointers and arrays

In C++, an array name is analogue to a pointer to the first element of the array:

```
char myName[4] = "Tim";
char * charPtr = NULL;
charPtr = myName;  // myName == &myName[0]
// note that this is invalid: myName = charPtr;

std::cout << "1st: " << *(charPtr) << std::endl;
// → gives out 'T'
std::cout << "2nd: " << myName[1] << std::endl;
// → gives out 'i'
std::cout << "3rd: " << *(charPtr+2) << std::endl;
// → gives out 'm'
```



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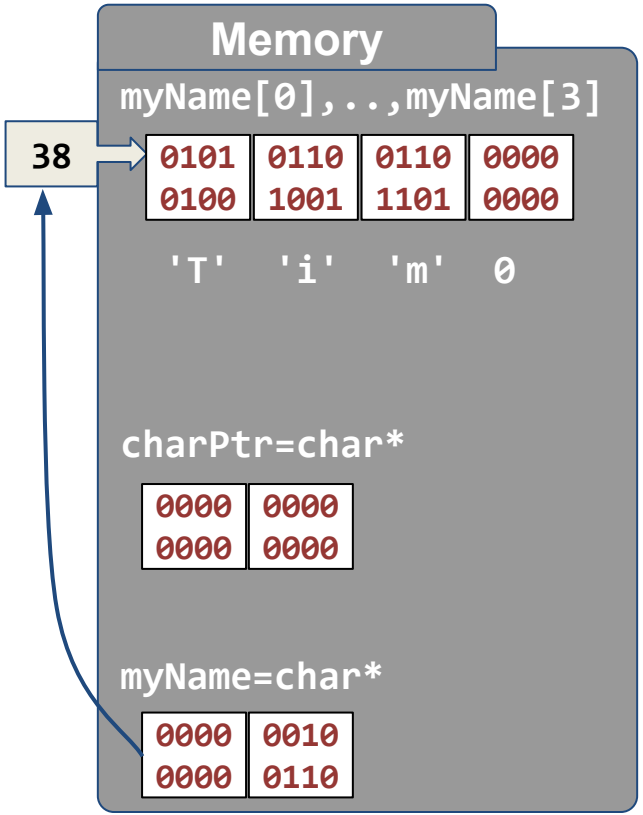
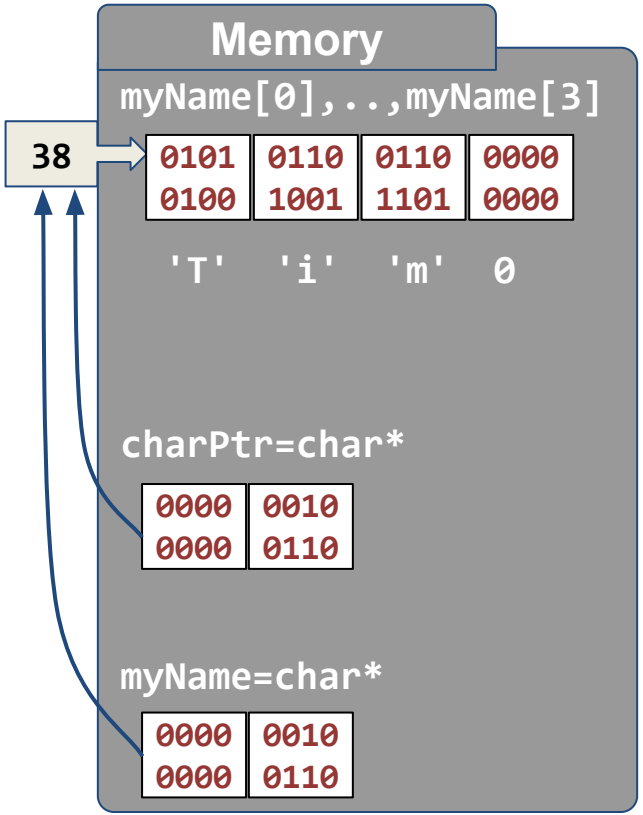
```
char myName[4] = "Tim";
char * charPtr = NULL;
charPtr = myName;  // myName == &myName[0]
// note that this is invalid: myName = charPtr;

std::cout << "1st: " << *(charPtr) << std::endl;
// → gives out 'T'
std::cout << "2nd: " << myName[1] << std::endl;
// → gives out 'i'
std::cout << "3rd: " << *(charPtr+2) << std::endl;
// → gives out 'm'
```



7.4. Pointers and arrays

In C++, an array name is analogue to a pointer to the first element of the array:

```
char myName[4] = "Tim";
char * charPtr = NULL;
charPtr = myName;  // myName == &myName[0]
// note that this is invalid: myName = charPtr;

std::cout << "1st: " << *(charPtr) << std::endl;
// → gives out 'T'
std::cout << "2nd: " << myName[1] << std::endl;
// → gives out 'i'
std::cout << "3rd: " << *(charPtr+2) << std::endl;
// → gives out 'm'
```



7.4. Pointers and arrays

Arrays can be dynamically allocated at run time with pointers:

```
// we receive a size variable here that we need an array around,
// but do not know how large it is at design time:
int size = fileData.getSize();

// We CAN create an array of the required size:
GPSCoord * myRoute = new GPSCoord[size];  // a route is created as points
for (int i = 0; i < size; i++) {
  fileData.readNext();  // read data from file, set these as route points:
  myRoute[i].set( fileData[0], fileData[1] );
  myRoute[i].setElevation( fileData[2] );
}

delete[] myRoute;  // for dynamically created arrays, delete needs []
myRoute = NULL;
```

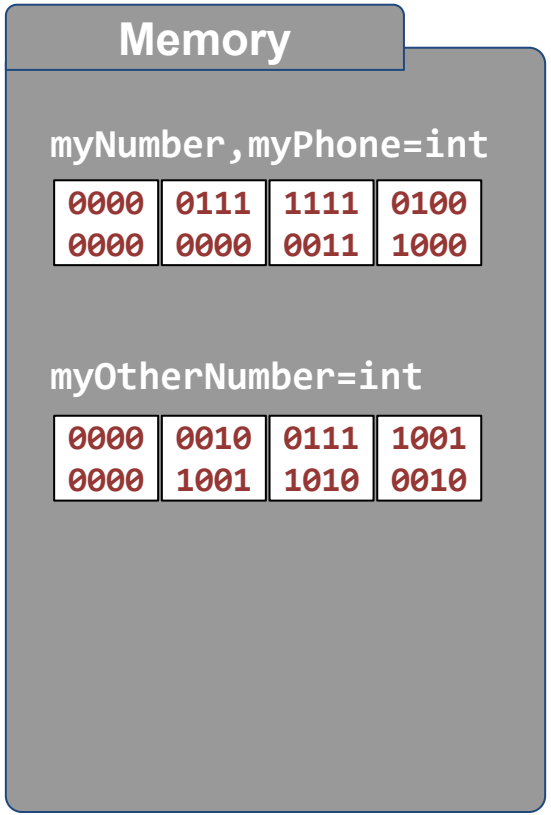
7.4. Pointers and arrays: Example 00 (difficulty level: 🌶️)

```
/* Create an array for which the length is given at runtime through an argument
   of the executable. The main function in C++ can also have two parameters:
   argc: integer containing the count of arguments in argv
   argv: array of strings holding command-line arguments.
   argv[0] is the command itself, argv[1] is first argument */
#include <iostream>

int main(int argc, char * argv[]) { // executable's arguments are passed
  // if an argument given, assume it is a number and convert from string:
  if (argc > 1) {
    int size = std::stoi(argv[1]);

    // add code to create an array of length size, and fill it with increasing
    // numbers from 1 till size, display these, and then delete the array

  }
  return 0;
}
```

7.5. References

In C++, a reference is like an alias, or second name, for a variable. A reference can only be initialized, but never reassigned to another variable.

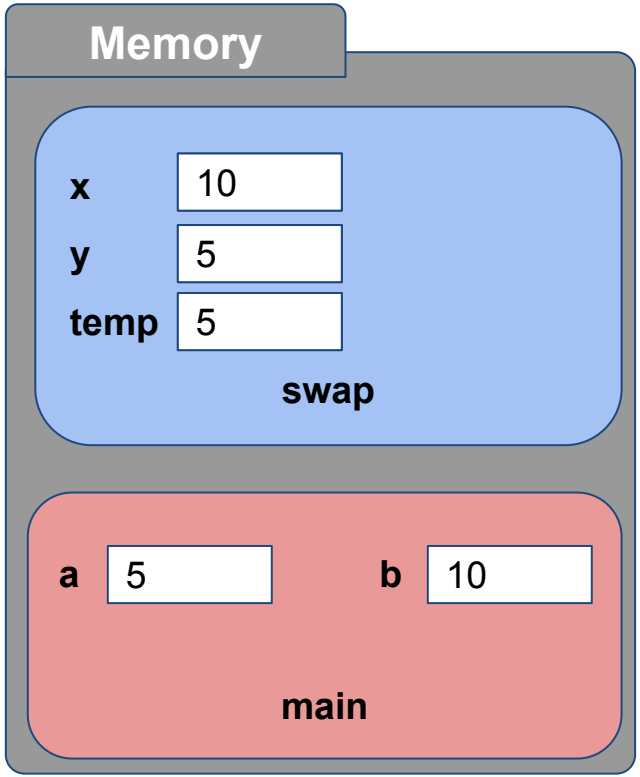
```
int myNumber = 7402312;
int & myPhone = myNumber;  // & in this declaration
// shows that this is a reference. From here on,
// myNumber and myPhone name the same variable.
int myOtherNumber = 2718354;
myPhone = myOtherNumber;
// → Now all three variable names myNumber, myPhone,
// and myOthernumber, have the same value: 2718354
// &myPhone = myOtherNumber; is invalid
```



7.6. Call-by-Reference

Reminder: the swap function below is not going to work, because variables are **passed-by-value**

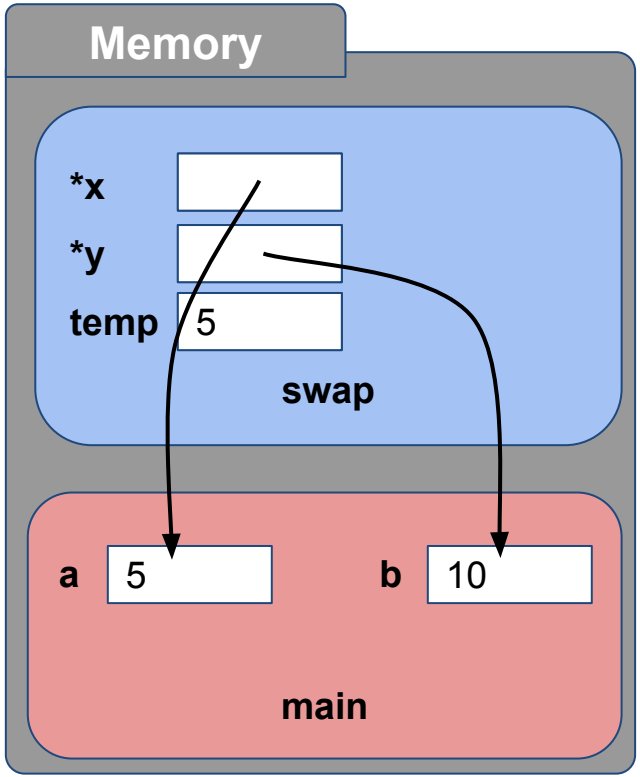
```
#include <iostream>  // output to terminal
void swap(int x, int y){
  int temp = 0;
  temp = x; x = y; y = temp;
}
int main()  {
  int a = 5, b = 10;
  swap(a, b);
  std::cout << a << ", " << b << std::endl;
  return 0;
}
```



7.6. Call-by-Reference

In C++, parameters can also be pointers. These are passed *by reference*, allowing swap to work:

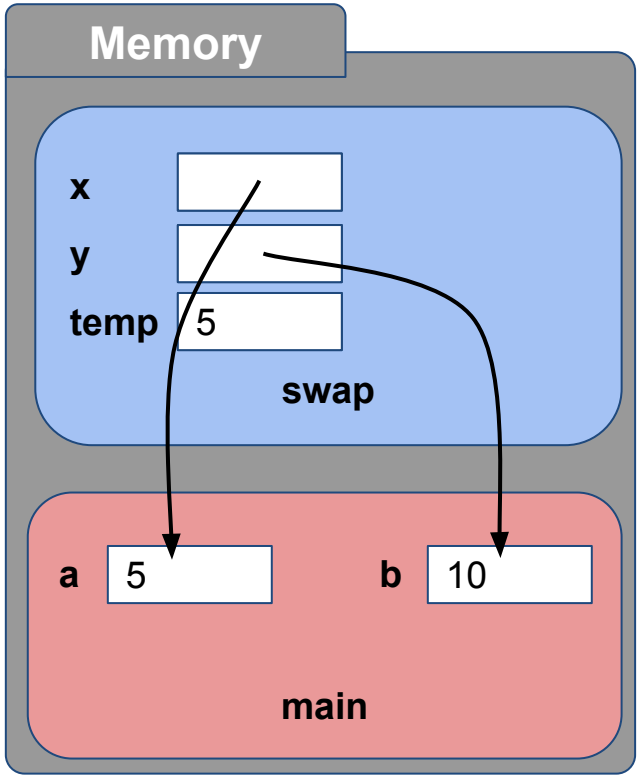
```
#include <iostream>  // output to terminal
void swap(int * x, int * y)    {
  int temp = 0;
  temp = *x; *x = *y; *y = temp;
}
int main()  {
  int a = 5, b = 10;
  swap(&a, &b);
  std::cout << a << ", " << b << std::endl;
  return 0;
}
```



7.6. Call-by-Reference

References have the same effect: These allow swap to work, too, and are safer and elegant:

```
#include <iostream>  // output to terminal
void swap(int & x, int & y)    {
  int temp = 0;
  temp = x; x = y; y = temp;
}
int main()  {
  int a = 5, b = 10;
  swap(a, b);
  std::cout << a << ", " << b << std::endl;
  return 0;
}
```



7.6. Call-by-Reference

When variables do not change, they can be passed as **`const`** references.

This is generally a clearer signature for developers calling our function/method:

```
#include <iostream>  // output to terminal
[[nodiscard("Please handle this function's return value.")]]
int sum3(const uint16_t & x, const uint16_t & y, const uint16_t & z) {
  return x + y + z;
}

int main() {
  auto a = 5, b = 10, c = 15;
  std::cout << sum3(a, b, c) << std::endl;
  return 0;
}
```

7.6. Call-by-Reference

Example 01 (difficulty level: 🌶️)

```
/* Write a class, called Check, below to illustrate in the main function that
   the pointer to an object of class Check b is indeed pointing to the object of
   class Check a. */
#include <iostream>

// write the class Check here

int main() {
  Check a;  // a is an object of class Check
  Check * b = &a;  // assign address of a to pointer b to object of class Check
  if ( b->isThisMe( &a ) ) {
    std::cout << "&a is b \n";
  }
  return 0;
}
```

7.7. Copy Constructors

We know that functions and methods create a copy of actual parameters (*pass by value*), so how are objects dealt with? How do we copy objects?

```
void UTMCoord::from(GPSCoord coord) {
  // transforms from latitude-longitude to UTM coordinates
}

int main()  {
  GPSCoord place(50.88385, 8.02096);
  UTMCoord place2;
  place2.from( place );  // place's values are copied and passed
  return 0;
}
```

7.7. Copy Constructors

How do we copy objects? ⇒ With **copy constructors**

GPSCoord.h

```
class GPSCoord {  // GPS coordinate class
 public:
  GPSCoord() {}  // default constructor
  GPSCoord(GPSCoord const & source);  // copy constructor
  void set(double lat, double lng);  // set latitude, longitude
  void setElevation(double elv);     // set elevation
  void print();  // output coordinates to console
 private:
  double lat, lng, elv;  // latitude, longitude, elevation
};
```

in GPSCoord.cpp

```
GPSCoord::GPSCoord(GPSCoord const & source) {
  lat = source.lat; lng = source.lng; elv = source.elv;
}
```

7.7. Copy Constructors

A copy constructor makes an object from another object of the same class, so in our example, we "clone" our GPSCoord object.

The copy constructor is implicitly called:

- when an object is **passed** to a function or method by value, or
- when a function or method **returns** an object

If a class does not implement a copy constructor, the C++ compiler will provide a default copy constructor, performing a ***member-wise copy*** (also known as ***shallow copy***)

So why do we ever have to implement a copy constructor ourselves?

7.7. Copy Constructors

An example of deep versus shallow copy:

```
class GPSTrace {  // class for a GPS trace

 public:
  GPSTrace(uint16_t numPoints);
  ~GPSTrace();
  // add a new point to trace at position pos:
  void setPoint(GPSCoord newPoint, uint16_t pos);
  [[nodiscard]] int print();  // print trace, forces return handling

 private:
  GPSCoord *points;  // pointer to GPS coordinates
  uint16_t numPoints;
};
```

7.7. Copy Constructors

An example of deep versus shallow copy:

```
GPSTrace::GPSTrace(uint16_t numpoints): numPoints(numpoints) {
  points = new GPSCoord[numPoints];
}

GPSTrace::~GPSTrace() {
  delete[] points; points = NULL; numPoints = 0;
}

void GPSTrace::setPoint(GPSCoord newPoint, uint16_t pos) {
  if (pos < numPoints) points[pos] = newPoint;
}
int GPSTrace::print() {  // output trace to console
  for (auto i = 0; i < numPoints; i++) points[i].print();
  return 0;
}
```

7.7. Copy Constructors

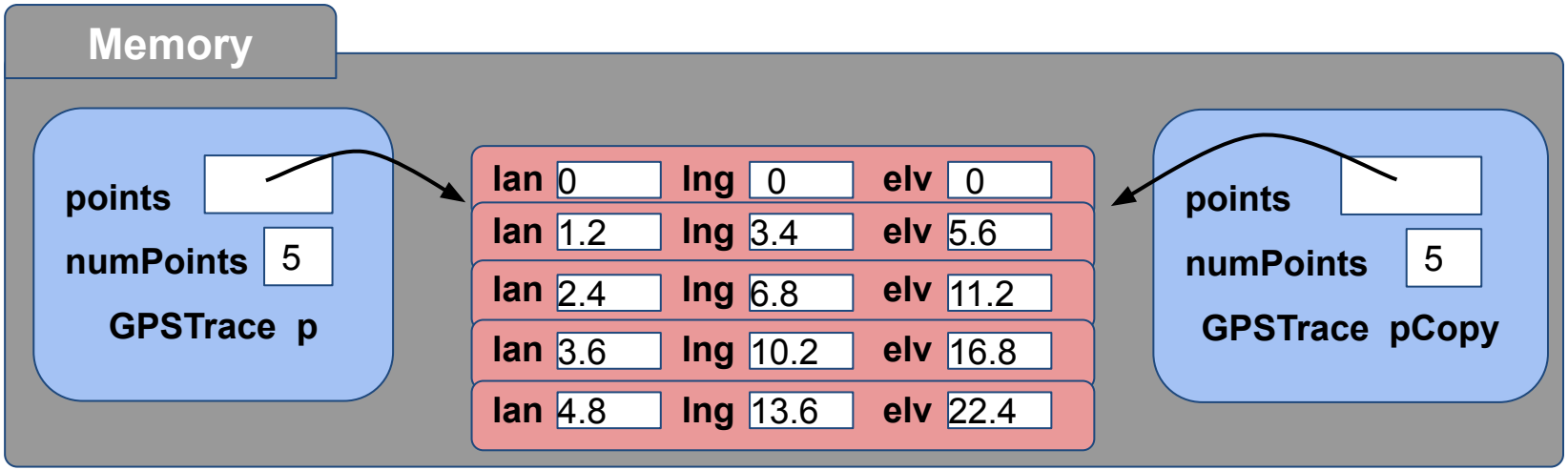
Example 02 (difficulty level: 🌶🌶)

```
/** An exercise illustrating shallow and deep copy: Add to the code of GPSTrace
    the necessary functionality that allows copying a GPSTrace and illustrate this
    in the main function below. */
#include <iostream>     // terminal output

// Classes GPSCoord and GPSTrace come here

int main() {
  GPSTrace t(5);
  for (auto i = 0; i < 5; i++ ) {  // fill in the GPS points
    GPSCoord point;
    point.set( i*1.2, i*3.4 ); point.setElevation( i*5.6 );
    t.setPoint( point, i );
  }
  return t.print();
}
```

7.7. Copy Constructors

Example 02 (difficulty level: 🌶🌶)

The standard (shallow) copy of **`p`** (e.g., **`pCopy`**) will result in this:



So the (deep) copy needs to be implemented in the copy constructor

7.8. `const` and `const` Pointers

Reminder: constants are defined with the **`const`** keyword, e.g.:

```
const int gpsTraceLength = 150;  // an integer constant
```

A constant can only be initialized, and a new value can not be assigned to a constant once it is defined. Usually this is done to protect the constant from being changed later on when this isn't planned.

7.8. `const` and `const` Pointers

`const` pointers can come in various forms, what matters is that everything on the left of the **`const`** keyword is constant. If **`const`** is on the full left, what is on its right is constant. **`const`** pointers need to be directly initialized:

```
int myInteger = 71;
const int constInt = 17;
int const *pointToConstInt = &constInt;   // pointer to const int
int * const constPointToInt = &myInteger;  // const pointer to int
int const * const cPointToCInt = &constInt;  // const pointer to const int
const int * pointToConstInt2 = &constInt;  // pointer to const int
```

7.8. `const` and `const` Pointers

`const` pointers protect pointers from being changed later in the code.

This means that changes such as: `*pointToConstInt = myInteger;`, `constPointToInt = &myInteger;`, `*cPointToCInt = myInteger;`, and `cPointToCInt = &myInteger;` will all result in an error.

For example: The **`this`** pointer in a class' methods is a **`const`** pointer to an object of the class, so cannot be changed to point to anywhere else but the current object.

7.8. `const` and `const` Pointers

`const` member functions or methods (aka *const qualified*):

```
int GPSTrace::print() const;  // output trace to console
```

`const` in them method's declaration *and* definition tells the compiler that the method should not modify the object (i.e., change the attributes)

- The compiler enforces this, and reports an error once the method's code tries to change its attributes
- Using const methods whenever possible will add guarantee that it will be used properly in the future

7.8. `const` and `const` Pointers

Example 03 (difficulty level: 🌶🌶🌶):

```
/** Print a mouse in the console, using a const pointer to avoid changes */
#include <iostream>     // terminal output
[[nodiscard]] auto * getBitmapAddress() {
    static char bitmap[] = "(^._.^)~";  // "bitmap" created in static memory
    return bitmap;  // return pointer to first element
}
int main() {
  // using a pointer to bitmap, and incrementing it, is possible:
  auto * mousePointer = getBitmapAddress();
  while ( *mousePointer != 0 )  std::cout << *(mousePointer++);
  std::cout << "\n";
  // Here mousePointer has changed, it's hard to get the original pointer.
  // Modify the above by protecting the pointer with const and redo the loop.
  return 0;
}
```

7.9. Passing functions to functions: Passing pointer to function

In C, functions can be passed as a parameter, which will be as a pointer to the function and is just the function's name:

```
#include <iostream>     // terminal output

int addTwo(int x) { return x + 2; }     // functions we can pass in callFunct
int timesFour(int x) { return x * 4; }  // since they match the signature

// callFunction takes a pointer to a function:
int callFunct(int x, int (*funct)(int) ) { return funct(x); /* = (*funct)(x) */ }

int main() {
  std::cout << "addTwo(149) = " << callFunct(149, addTwo) << "\n";
  std::cout << "timesFour(4) = " << callFunct(4, timesFour) << "\n";
  return 0;
}
```

7.9. Passing functions to functions: The `std::function`

In C++ 11 and onward, **`std::function`** can be used from **`<functional>`** (using templates, see later):

```
#include <iostream>     // terminal output
#include <functional>     // use std::function to pass functions as parameter

int addTwo(int x) { return x + 2; }     // functions we can pass in callFunct
int timesFour(int x) { return x * 4; }  // since they match the signature

// callFunction takes a pointer to a function:
int callFunct(int x, std::function<int(int)> func ) { return funct(x); }

int main() {
  std::cout << "addTwo(149) = " << callFunct(149, addTwo) << "\n";
  std::cout << "timesFour(4) = " << callFunct(4, timesFour) << "\n";
  return 0;
}
```

7.9. Passing functions to functions: Passing pointer to function

Example04 (difficulty level: 🌶🌶🌶):

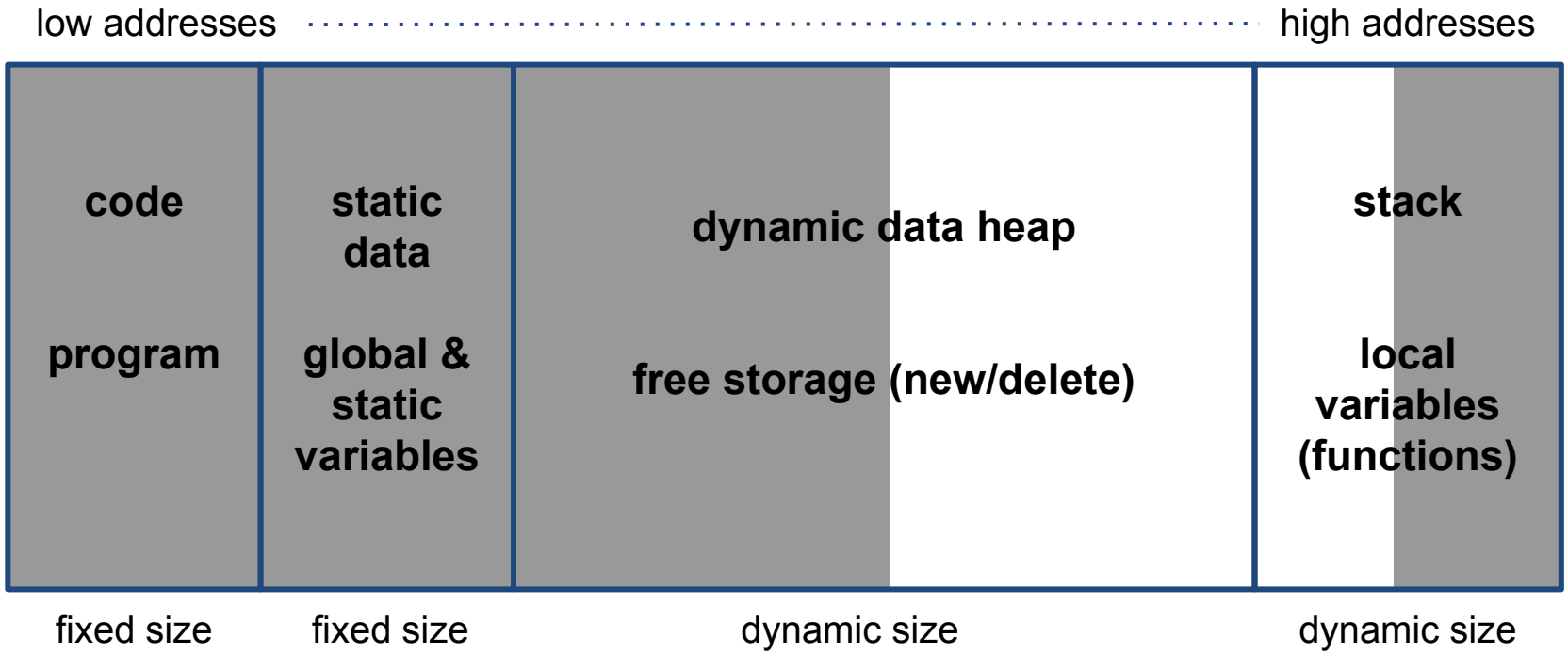
```
/** Define the class' methods below so that the main function makes sense */
#include <iostream>     // terminal output
#include <functional>     // use std::function to pass functions as parameter
class NumberSequence {  // class for sequence of whole, positive numbers

 public:
  NumberSequence(uint16_t length = 10);
  // apply the function func() to all numbers:
  void forEach(std::function<uint16_t(uint16_t)> func);
  void print() const;  // print all numbers to console

 private:
  const uint16_t length;  // length of number sequence
  uint16_t *seq;  // the numbers are stored as a dynamic array
};
```

7.9. Passing functions to functions: Passing pointer to function

Example04 (difficulty level: 🌶🌶🌶):

```
// define all NumberSequence methods here
//

uint16_t times2(uint16_t n) { return n*2; }

int main() {
    NumberSequence s;
    s.print();
    s.forEach( &times2 ); // apply the function times2 to all numbers
    s.print();
    return 0;
}
```

7.10. Overview of Memory Segments



8. Inheritance and Polymorphism

8.1. Inheritance

8.2. The **`protected`** keyword

8.3. (Delegate) constructors and destructors

8.4. **`mutable`**, **`using`**, **`friend`**, and **`delete`**

8.5. Polymorphism

8.1. Inheritance https://isocpp.org/wiki/faq/basics-of-inheritance

- Generalization: Relationship between a more general class (base class, or superclass) and a more specialized class (subclass)
  - the specialized class is consistent with the base class, but contains additional attributes, operations and/or associations
  - an object of the subclass can be used wherever an object of the super class is permitted
- Generalization is not about just summarizing common properties and behaviors, but about generalizing in the literal sense:
  Every object of the subclass is an object of the superclass

8.1. Inheritance

```
class Person {
 private:
  std::string name;
  std::string address;
  int birthYear;
 public:
  void printBadge();  // prints name
  int getAge();  // returns age in years
};
```

```
int main() {
  Staff newStaff;
  Trainee newTrainee;
  // newStaff and newTrainee objects
  // can access Person public method
  newStaff.printBadge();
  newTrainee.getAge();
  return 0;
}
```

```
class Staff: public Person {
 private:
  double salary;
 public:
  void setSalary(double s);
};
```

```
class Trainee: public Person {
 private:
  int startDay;
 public:
  int daysInTraining();
};
```

8.2. The `protected` keyword

- Private members (attributes or methods) are only accessible within the class that has defined them
- Public members are accessible from anywhere
- Protected members are accessible in the class that defines them,
  and in classes that inherit from that class

8.2. The `protected` keyword: Inaccessible from outside the class..

```
class Person {
 private:
  std::string address;
  int birthYear;
 protected:
  std::string name;
 public:
  void printBadge();  // prints name
  int getAge();  // returns age in years
};
```

```
int main() {
  Staff newStaff;
  // newStaff object cannot access
  // Person protected attributes
  // or methods from outside class:
  // std::cout << newStaff.name;
  //  -> ERROR
  return 0;
}
```

```
class Staff: public Person {
 private:
  double salary;
 public:
  void setSalary(double s);
};
```

```
class Trainee: public Person {
 private:
  int startDay;
 public:
  int daysInTraining();
};
```

8.2. The `protected` keyword: .. but accessible from child classes

```
class Person {
 private:
  std::string address;
  int birthYear;
 protected:
  std::string name;
 public:
  void printBadge();  // prints name
  int getAge();  // returns age in years
};
```

```
int Trainee::daysInTraining() {
  int returnVal;
  // Trainee cannot access Person's
  // private attributes:
  // returnVal = birthYear -> ERROR
  // but Trainee can access Person's
  // protected attributes in class:
  std::cout << name << std::endl;
  return (today()-startDay);
}
```

```
class Staff: public Person {
 private:
  double salary;
 public:
  void setSalary(double s);
};
```

```
class Trainee: public Person {
 private:
  int startDay;
 public:
  int daysInTraining();
};
```

8.3. (Delegate) constructors and destructors

Remember the special syntax in constructors, to initialize attributes:

```
class Example {
 public:
  Example(int & aVar);
 private:
  const int aConst;  // a constant
  int & aRef;        // a reference
};
// This would lead to errors:
// Example::Example(int &aVar) {
//   aConst = 47; aRef = aVar;
// }
// But this works:
Example::Example(int & aVar)
  : aConst(47), aRef(aVar) {
  // here can follow more code
}
```

Passing arguments to the base class constructor is possible with:

```
class BaseClass {
 public:
  BaseClass(int var) : var(var) {}
 private:
  int var;
};

class SubClass : public BaseClass {
 public:
  SubClass(bool myBool)
    : BaseClass(7), myBool(myBool) {}
 private:
  bool myBool;
};
```

8.3. (Delegate) constructors and destructors

Passing arguments to a base class constructor is possible with:

```
class BaseClass {
 public:
  BaseClass(int var) : var(var) {}
 private:
  int var;
};

class SubClass : public BaseClass {
 public:
  SubClass(bool myBool)
   : BaseClass(7), myBool(myBool) {}
 private:
  bool myBool;
};
```

Similarly, ***delegate constructors*** call others from the same class to reduce repetitive code (from C++11):

```
class MyClass {

 public:
  MyClass(int a1, bool b1) : a(a1), b(b1) {
    // lots of initialization work
  }
  MyClass(int a1) : MyClass(a1, true) {}
  MyClass(bool b1) : MyClass(10, b1) {}

 private:
  int  a;
  bool b;
  // ...
};
```

8.3. (Delegate) constructors and destructors

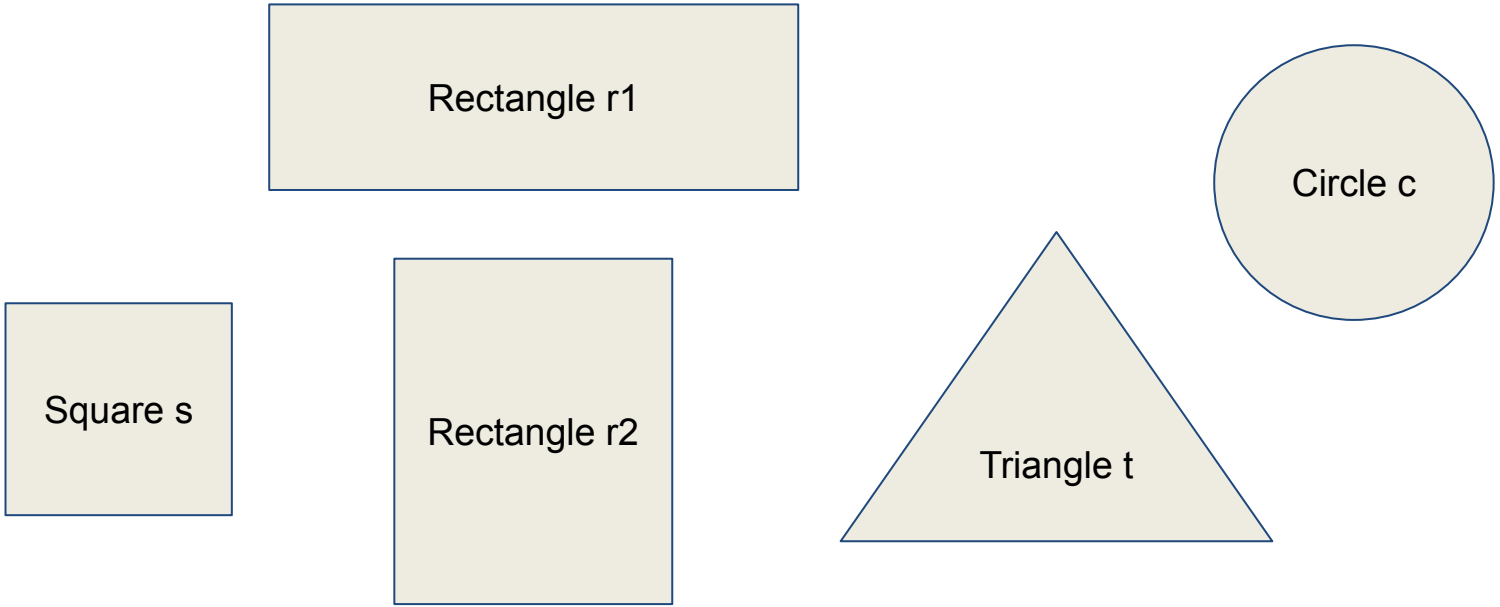
Example 00 (difficulty level: 🌶️)

```
#include <iostream>
class Book {  // a Book object always has a title and a price.
 // change this class so that the title cannot be changed, and the price can be changed by Magazine:
  Book(std::string name, double val) : title(name), price(val) {}
  void show() { std::cout << title << " - " << price << "\n"; }
  std::string title;
  double price;
};

class Magazine : public Book {  // a Magazine object uses the Book's constructor, and can apply a discount
  // change this class so that an object is created solely through Book's constructor
  void discount(double percent);
};
// implement Magazine's discount method here

int main() {
  Magazine mag(std::string("C++ Monthly"), 10.0);
  mag.show(); mag.discount(25.0);  // this should show 10 in the console, then we apply a 25 % discount
  mag.show();  // this should now show 7.5
  return 0;
}
```

8.3. (Delegate) constructors and destructors

Example 01 (difficulty level: 🌶️)

Creating 2D graphics elements such as the ones below as classes' objects



8.3. (Delegate) constructors and destructors Example 01

```
class Element {  // class representing graphic element
 public:
  Element(double x, double y) : x(x), y(y) {}
 private:
  double x, y;  // position of graphic element
};

class Rectangle : public Element {  // class representing a rectangle
 public:
  Rectangle(double x, double y, double a, double b) : Element(x, y), a(a), b(b) {}
 private:
  double a, b;  // width and height of rectangle
};

class Square : public Rectangle {  // class representing a square
 public:
  Square(double x, double y, double a) : Rectangle(x, y, a, a) {}
};
```


Assignment: Add a method to Square that prints out its location: What needs changing?

8.4. `mutable`, `using`, `friend`, and `delete`

Any **`mutable`** data members of **`const`** class instances can be modified. This is useful if most of the class' members should be constant, but a few need to be modified.

```
#include <iostream>

class A {  // class A
 public:
  int x = 4;   // public attributes, default initialized (since C++11)
  mutable int y = 3;
};

int main() {
  const A a;  // constant object of class A
  a.y = 7;    // this works, a.x would result in compile error
  std::cout << a.y << "\n";
  return 0;
}
```

8.4. `mutable`, `using`, `friend`, and `delete`

The `using` keyword can be used to change the inheritance properties of class attributes or methods:

```
class A {  // class A
 protected:
  int x = 4;   // protected attribute
};

class B : public A {  // class A
 public:
  using A::x;   // inherits x and exposes it as a public attribute
};

int main() {
  B b;
  b.x = 7;    // this works, b.x is public (even though A.x is protected)
  return 0;
}
```

8.4. `mutable`, `using`, `friend`, and `delete`

The **`friend`** keyword allows a class to access the private and protected attributes and methods of the class that is declared as a friend.

⚠️ A **`friend`** relation is **not**:

symmetric: Class A as a friend of B does not imply class B being a friend of A

transitive: A is a friend of B and B is a friend of C does not imply A is a friend of C

inherited: Class Base as a friend of class X does not imply subclass Derived is a friend of class X; Class X as a friend of class Base does not imply class X is a friend of subclass Derived

8.4. `mutable`, `using`, `friend`, and `delete`

```
#include <iostream>

class A {  // class A declares that B is a friend
 private:
  friend class B;
  int x = 4;  // private attribute
};

class B {  // class B is a friend of A
 public:
  B() { A a; y = a.x;}        // and thus can access
  int f(A a) { return a.x; }  // A's private attribute x
 private:
  int y;
};

int main() {
  A a; B b;
  std::cout << b.f(a) << "\n";
  return 0;
}
```

8.4. `mutable`, `using`, `friend`, and `delete`

A **`friend`** ***method*** can access the private and protected members of a class if it is declared a friend of that class.

```
#include <iostream>

class A {  // class A declares funct as a friend method
 private:
  int x = 4;  // private attribute
  friend int funct(A a);
};

int funct(A a) { return a.x; }  // funct is not a class method

int main() {
  A a;
  std::cout << funct(a) << "\n";
  return 0;
}
```

8.4. **mutable**, **using**, **friend**, and **delete**

Example 02 (difficulty level: 🌶️)

```
#include <iostream>

class Rectangle {  // class Rectangle has width and height as attributes and area() as a method
 public:
  Rectangle() {}  // default constructor, allows to define width and height later
  Rectangle(int x, int y): width(x), height(y) {}  // constructor that sets attributes
  int area() { return width*height; };
  // declare the friend method "enlarge()" here, with a rectangle as parameter, returning a rectangle
 private:
  int width, height;  // width and height are private, so not accessible from outside the class
};

/* define the friend method here, so that it creates and returns a copy of the rectangle that
   has twice the width and height. The friend method has access to the private attributes. */

int main() {
  Rectangle rectangle1, rectange2(3,4);  // rectangle1 will obtain twice the width and height
  rectangle1 = enlarge(rectange2);       // of rectangle2 through the enlarge method
  std::cout << rectangle1.area() << "\n";  // this should return "48" (6 times 8)
  return 0;
}
```

8.4. `mutable`, `using`, `friend`, and `delete`

The **`delete`** keyword marks a class method as deleted. Calling that method (explicitly or implicitly) will result in a compiler error. The **`delete`** keyword prevents implicitly generating default copy constructors or assignments.

```
class Element {  // class representing graphic element
 public:
  Element(double x, double y) : x(x), y(y) {}  // default constructor is deleted
  Element(Element const & e) = delete;  // copying an object gives a compiler error
  void setX(double x) { this->x = x;}
  void setX(float x) = delete;  // calling with a float results in a compiler error
 private:
  double x, y;  // position of graphic element
};

int main() {
  Element e(2.0, 3.0);
  e.setX(5.0);  // works, but: e.setX(5.0f) would fail (due to delete above)
}
```

8.4. `mutable`, `using`, `friend`, and `delete`: Maze Game v.5.00

Class Player and Maze were changed, so we can load a map and add player 2:

mazeGame.cpp

```
/* Fifth draft of Maze Game: we now use class "Player" and use a file */
#include "Maze.h"  // class that holds everything related to the maze
#include "Player.h"  // class that holds everything related to the player
int main() {
  auto c = ' ';        // used for user key input
  std::string mapFile("maze.csv");
  Maze maze(mapFile);   // initialize a maze object from this file
  Player player1(10, 5);
  Player player2(20, 7);
  while ( c != 'q' ) {  // as long as the user doesn't press q ..
    maze.draw();    // draw maze
    player1.draw('@', 3);  // draw player 1 as a '@' with color pair 3
    player2.draw('X', 3);  // draw player 2 as a 'X' with color pair 3
    c = getch();           // capture the user's pressed key
    switch (c) {
      // ...
    }
```

8.4. `mutable`, `using`, `friend`, and `delete`: Maze Game v.5.00

Modify the class Player and add a child class Enemy, so that moving the players is now part of the draw class, and the enemy can move toward the player:

`mazeGame.cpp`

```
/* Fifth draft of Maze Game: we now use class "Player" and use a file */
#include "Maze.h"  // class that holds everything related to the maze
#include "Player.h"  // class that holds everything related to the player
int main() {
  auto c = ' ';        // used for user key input
  std::string mapFile("maze.csv");
  Maze maze(mapFile);   // initialize a maze object from this file
  Player player(10, 5, 'w','s','a','d');  // player at (10,5) and moves with wasd
  EnemyPlayer enemy(20, 7);  // enemy player starts at (20,7)
  while ( c != 'q' ) {  // as long as the user doesn't press q ..
    maze.draw();    // draw maze
    player.draw('@', 3, c);     // draw player 1 as a '@' with color pair 3
    enemy.draw('X', 3, player); // draw enemy player as a 'X' with color pair 3
    c = getch();              // capture the user's pressed key
  }
```

8.5. Polymorphism

C++ provides a way to create a base object with methods that through overriding change their behavior. At run-time, objects of the base class behave as objects of a derived class

If **Sub** is a subclass of **Super**, then the following assignments are allowed:

```
Sub sub;
Super * superPtr = &sub;
Super & superRef = sub;
```

A base class pointer or reference can also point or refer to a subclass' object.

The other way round is not allowed.

8.5. Polymorphism

For example: **`Dog`** and **`Fish`** are classes that inherit from **`Animal`**. We want any objects from these classes to have a **`print()`** method, which displays the values of the classes' attributes. Then an **`Animal`** object pointer could be used to flexibly point to a **`Dog`** or **`Fish`** object and access the right **`print()`** method:

```
Animal * animal;
animal = new Dog("Scooby");
animal->print();  // prints out: I am Scooby. Bark!
animal = new Fish("Salmon");
animal->print();  // prints out: I'm Salmon (fish)
```

For polymorphism to work in C++, the base class must declare the methods in question as being **`virtual`**

8.5. Polymorphism: Example (1/2)

polyDemo.cpp

```
#include <iostream>
#include <cstdlib>

class Animal {  // Animal class stores the species and prints this in print()
 protected:
  std::string _species;
 public:
  Animal(std::string species) { _species = species; }
  virtual void print() { std::cout << "I'm " +  _species << std::endl; }
};

class Dog : public Animal {  // Dogs inherit species from Animal and have a name
 protected:
  std::string _name;
 public:
  Dog(std::string name) : Animal("dog"), _name(name) {}
  void print() { std::cout << "I am " << _name << ". Bark!" << std::endl; }
};
```

8.5. Polymorphism: Example (2/2)

polyDemo.cpp

```
class Fish : public Animal {  // Fishes have species and subspecies
 protected:
  std::string _subspecies;
 public:
  Fish(std::string subspecies) : Animal("fish"), _subspecies(subspecies) {}
  void print() { std::cout << "I'm " << _subspecies << " (fish)" << std::endl; }
};

int main() {
  Animal * animals[4];
  animals[0] = new Dog("Snowy");       // animals[] has pointers
  animals[1] = new Fish("Salmon");     // to objects of different
  animals[2] = new Dog("Scooby");      // subclasses (Dog, Fish, etc.)
  animals[3] = new Animal("some animal");  // or the animal base class
  for (int i=0; i<15; i++) {
   Animal * a = animals[rand() % 4];  // a is a polymorph variable: its
   a->print();                        // print's behavior depends on the
  }                                   // object that a points to
  return 0;
}
```

8.5. Polymorphism: Example

- Note that animals is an array of pointers to the base class (Animal)
- Yet, we can let the pointers point to a subclass of Animal (Dog, Fish, …)
- And when we call print() from Animal pointer a, the right method executes

```
Animal * animals[4];
animals[0] = new Dog("Snowy");
animals[1] = new Fish("Salmon");
…
  Animal * a = animals[rand()%4];
  a->print();
```

```
~\> g++ polyDemo.cpp -o polymorph_demo
~\> ./polymorph_demo
I'm Salmon (fish)
I am Scooby. Bark!
I'm Salmon (fish)
I am Scooby. Bark!
I am Snowy. Bark!
I'm some animal
I am Scooby. Bark!
I'm Salmon (fish)
I am Snowy. Bark!
I am Scooby. Bark!
I am Snowy. Bark!
I am Scooby. Bark!
I'm some animal
I am Scooby. Bark!
I'm Salmon (fish)
~\>
```

8.5. Polymorphism: `virtual` and late binding

Connecting the function call to the function body is called ***Binding***

Early / static / compile-time binding is done by the compiler through object type, letting the program jump to the function's address

Late / dynamic / run-time binding uses the object type while the executable is running and then matches the function call with the correct function definition: The program has to read the address held in the pointer and then jump to that address. This extra jump makes it less efficient.

C++ achieves late binding by declaring a virtual function

8.5. Polymorphism: `virtual` and late binding

C++ achieves late binding by declaring a virtual function in the base class:

```
#include <iostream>
class A {  // class A has a virtual function funct:
 public:
  virtual void funct() { std::cout << "A \n"; };
};
class B : public A {  // class B inherits from A and overrides funct:
 public:
  virtual void funct() { std::cout << "B \n"; };  // virtual here is optional
};

void g( A & a ) { a.funct(); }  // g accepts A and B as parameter

int main() {
  A a; B b;
  g(a); g(b);  // outputs first "A", and then "B"
  return 0;
}
```

8.5. Polymorphism: `virtual` and `override`

The **`override`** keyword (from C++11) ensures that the method is virtual and is overriding a virtual function from a base class:

```
#include <iostream>
class A {  // class A has a virtual function funct:
 public:
  virtual void funct() { std::cout << "A \n"; };
};
class B : public A {  // class B inherits from A and overrides funct:
 public:
  void funct() override { std::cout << "B \n"; };
};

void g( A & a ) { a.funct(); }  // g accepts A and B as parameter

int main() {
  B b; g(b);  // outputs "B"
  return 0;
}
```

8.5. Polymorphism: `final`

The **`final`** keyword (from C++11) prevents inheriting from classes or overriding methods in derived classes

```
class A final {  // class A cannot be extended
  // ...
};
class B : public A {  // leads to compile error: A is "final"
  // ...
};

class C {  // class C contains a virtual final method:
 public:
  virtual void funct() final;
};
class D : public C {
 public:
  void funct();  // leads to compile error: method funct is "final"
};
```

9. Handling of Exceptions

9.1. Assertions and debuggers

9.2. **`try`**, **`throw`**, **`catch`**

9.3. Function try blocks

9.4. **`noexcept`**

9.5. **`std::nested_exception`** and **`std::throw_with_nested`**

9.1. Assertions and debuggers

A way to ensure that a condition always should hold at some stage in the code:
If the expression supplied to **`assert()`** is false (0), the program *aborts* at the statement with an error.

example00.cpp

```
#include <iostream>  // use of std::cout, std::cin
#include <cstdlib>   // std::rand()
#include <ctime>     // std::time()
#include <cassert>   // assert()
int main() {
  std::srand( std::time(nullptr) );  // time seeds random generator (nullptr)
  double myValue = ( std::rand() % 4 ) - 2;  // gets a random value
  assert(myValue != 0);  // since we'll divide by myValue, it should not be zero
  myValue = 5 / myValue;
  std::cout << myValue << "\n";
  return 0;
}
```

9.1. Assertions and debuggers

Assert is a macro and depends on another macro, NDEBUG: If it is defined as a macro name at the point in the source code where <cassert> is included (i.e., `#define NDEBUG`), then assert will be disabled.

The program's state at particular points (e.g., after an assertion fails) can be checked in a ***debugger*** to allow watching the state of a running program. Examples: stop execution at a given code line (breakpoint), examine call stack, print / modify contents of variables, print type definitions, execute line-by-line

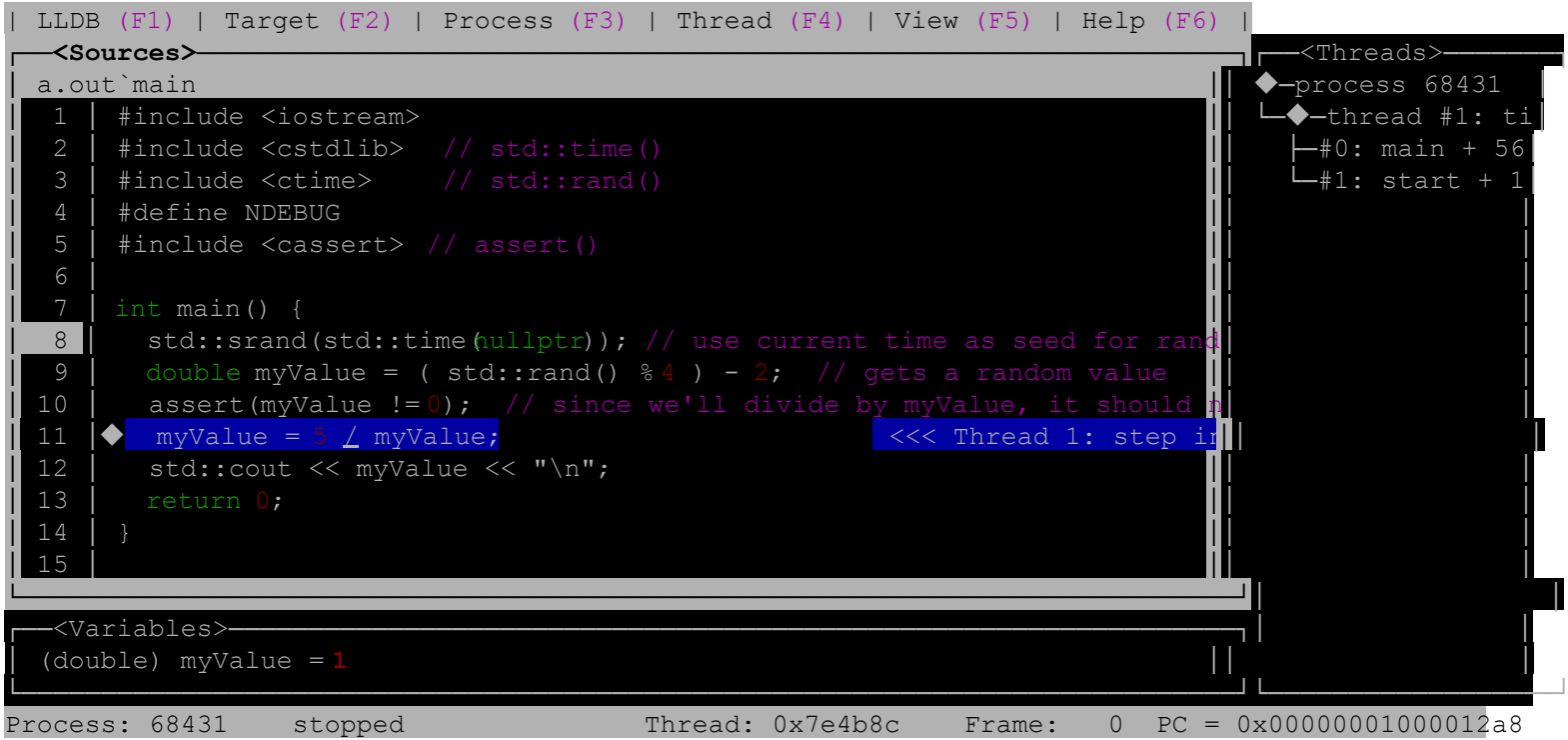
examples: ddd or gdbgui , both use gdb , or lldb → try on the previous code:

```
> g++ -g example00.cpp
> lldb a.out
```

9.1. Assertions and debuggers -- lldb example

```
> lldb a.out
bash-5.1$ lldb a.out
(lldb) target create "a.out"
Current executable set to '/Users/kvl/sciebo/UbiComp/Teaching/AdvancedCPP_43UCO1118V/a.out'
(x86_64).
(lldb) b main
Breakpoint 1: where = a.out`main + 15 at example00.cpp:8:14, address = 0x000000010000127f
(lldb) run
Process 68431 launched: '/Users/kvl/sciebo/UbiComp/Teaching/AdvancedCPP_43UCO1118V/a.out'
(x86_64)
Process 68431 stopped
* thread #1, queue = 'com.apple.main-thread', stop reason = breakpoint 1.1
    frame #0: 0x000000010000127f a.out`main at example00.cpp:8:14
   5       #include <cassert>  // assert()
   6
   7       int main() {
-> 8         std::srand(std::time(nullptr)); // use current time as seed for random generator
   9         double myValue = ( std::rand() % 4 ) - 2;  // gets a random value
   10        assert(myValue != 0);  // since we'll divide by myValue, it should not be zero
   11        myValue = 5 / myValue;
Target 0: (a.out) stopped.
(lldb) gui
```

9.1. Assertions and debuggers -- lldb example



9.1. Assertions and debuggers

Assertions versus exceptions

Both detect run-time errors in a program, *but*:

- Assert() aborts the program, for the developer to fix their code
- Exceptions allow the program to recover and continue the execution from the first matching catch
  - Examples are any areas where variables obtain values outside the developer's control (e.g., others supply your code with file names which do not exist, or array sizes that do not fit in memory)
  - When no exception matches, the program will still abort

9.2. `try`, `throw`, `catch`

When an error occurs, functions or methods may *throw* an exception, to be handled later when *catch*ing the exception. If an exception is *throw*n in the *try*-block, the *try*-block is exited and the associated *catch*-block is executed. Exceptions that go uncaught will cause the program to halt.

```
try {
  throw 0.07f;  // throw an exception of type float
}
catch (float f) {  // float is thrown
  std::cout << "Exception: " << f << "\n";
}
catch (...) { std::cout << "Exception\n"; }  // default catch
```

9.2. `try`, `throw`, `catch`

throw supplies an instance of an exception class. This can be a built-in type, but more commonly is a class derived from the **std::exception** class:

```
#include <iostream>  // std::cout, std::runtime_error, std::exception, std::cerr

int divBy(int a, int b) {
  if (b == 0) throw std::runtime_error("Divided by zero.");  // exception type runtime_error
  return a / b;
}

int main() {
  try {
    divBy(7, 0);  // this function throws an exception when b == 0
  }
  catch (const std::exception& e) {
    std::cerr << "Exception handled: " << e.what() << "\n";
  }
  return 0;
}
```

9.2. `try`, `throw`, `catch`

Throwing a *custom exception* requires a custom exception class, which inherits from **std::exception** and overrides its **what** method to return an error message:

example01.cpp

```
#include <iostream>  // std::cout, std::runtime_error, std::exception, std::ce

class MyException : public std::exception {
 public:
  MyException(const char * msg) : message(msg) {}  // Constructor sets exception message
  const char * what() { return message.c_str(); }  // Override what() to return own message
 private:
  std::string message;
};

int main() {
  try { throw MyException("Oops, my bad."); }  // create and throw object of MyException
  catch (MyException& e) { std::cerr << "Exception handled: " << e.what() << "\n"; }
  return 0;
}
```

9.2. `try`, `throw`, `catch`

The **std::exception** class has many subclasses for specific exceptions:

- logic_error
  - invalid_argument
  - domain_error
  - length_error
  - out_of_range
  - future_error (since C++11)
- bad_typeid
- bad_cast
  - bad_any_cast (since C++17)
- bad_optional_access (since C++17)
- bad_expected_access (since C++23)
- bad_weak_ptr (since C++11)
- bad_function_call (since C++11)
- bad_alloc
  - bad_array_new_length (since C++11)
- runtime_error
  - range_error
  - overflow_error
  - underflow_error
  - regex_error (since C++11)
  - system_error (since C++11)
  - ios_base::failure (since C++11)
  - filesystem::filesystem_error (since C++17)
  - tx_exception (TM TS)
  - nonexistent_local_time (since C++20)
  - ambiguous_local_time (since C++20)
  - format_error (since C++20)
- bad_exception
- ios_base::failure (until C++11)
- bad_variant_access (since C++17)

9.3. Function try blocks

Function try blocks allow to establish an exception handler around a function's body, instead of a block of code inside the function body. Function try blocks can catch both base and the current class exceptions:

```
#include <iostream>  // std::cout, std::runtime_error, std::exception, std::cerr
class Superclass {
 public:
  Superclass(int x) : x(x) { if (x < 0) throw 1; }  // an exception can be thrown here
  int x;
};
class Subclass : public Superclass {
 public:       // what if we want to catch Superclass's constructor thrown exception here? …
  Subclass(int x) : Superclass(x) {}
};
int main() {   // … instead of here?
  try { Subclass sub(-5); } catch (int) { std::cout << "Oops, my bad.\n"; }
  return 0;
}
```

9.3. Function try blocks

So instead the function try block can be wrapped around:

example02.cpp

```
#include <iostream>  // std::cout,std::runtime_error,std::exception,std::cerr
class Superclass {
 public:
  Superclass(int x) : x(x) { if (x < 0) throw 1; }  // an exception can be thrown here
  int x;
};

class Subclass : public Superclass {
 public:
  // exceptions from A's constructor are now caught here -- but note the throw --- ...
  Subclass(int x) try : Superclass(x) {}
                  catch (int) { std::cerr << "Oops, my bad."; throw; }
};

int main() {    // ... instead of here
  try { Subclass sub(-5); } catch (int) { std::cout << "Oops, my bad.\n"; }  return 0;
}
```

9.3. Function try blocks

Function try blocks for constructors are limited though: They *cannot* resolve the thrown exception:

```
class Subclass : public Superclass {
 public:
  // exceptions from A's constructor are now caught here -- but note the throw --- …
  Subclass(int x) try : Superclass(x) {}
                  catch (int) { std::cerr << "Oops, my bad."; throw; }
};
```

Once the end of the catch block is reached, exceptions will be implicitly re-thrown. Other methods and destructors, can throw, rethrow, or resolve the current exception via a return statement. Reaching the end of the catch block will implicitly resolve the exception for void-returning functions, and produces undefined behavior for value-returning functions (hence: avoid).

9.4. noexcept

Exception handling comes at a (small) cost. Since C++11, **noexcept** can be added for a class method or function declaration, to clarify that the function could throw exceptions (or not):

```
int funct() noexcept;  // funct() does not throw (same as noexcept(true))
void (*fp)() noexcept(false);  // fp points to a function that may throw
```

This allows the compiler to optimize the performance by skipping the processes associated with exception handling, resulting in faster execution of the program.

9.4. **noexcept** -- Example

example03.cpp

```
#include <iostream>  // use of std::cout, std::cerr

int divBy(int a, int b) {  // divBy could throw exceptions (noexcept omitted)
  if (b == 0)
    throw std::runtime_error("Error: Division by zero");
  return a / b;
}

int safeDivBy(int a, int b) noexcept {  // safeDivBy won't throw exceptions (noexcept)
  if (b == 0) {
    std::cerr << "Division by zero in safeDivBy\n";
    std::terminate();
  }
  return a / b;
}

int main() {
  std::cout << "divBy: " << noexcept(divBy(7, 0)) << "\n";          // → "divBy: 0"
  std::cout << "safeDivBy: " << noexcept(safeDivBy(7, 0)) << "\n";  // → "safeDivBy: 1"
  return 0;
}
```

9.5. `std::nested_exception` and `std::throw_with_nested`

In C++11 and beyond: Nesting exceptions allow to recursively stack exceptions, generated at the point of the error, without runtime overhead.

example04.cpp

```
#include <iostream>  // std::cout
#include <fstream>   // std::ifstream

void run();  // catch exception + wrap it in nested exception
void open_file(const std::string& s);  // catch exception + wrap it

// Nested exception adds 'level' spaces + prints messages via recursion & polymorphism
void print_exception(const std::exception& e, int level = 0) {
  std::cerr << std::string(level, ' ') << "exception: " << e.what() << "\n";
  try { std::rethrow_if_nested(e); }
  catch (const std::exception& nestedException) {
    print_exception(nestedException, level+1);
  }
}
```

9.5. `std::nested_exception` and `std::throw_with_nested`

```
int main() {  // runs run() and prints the caught exception
  try { run(); } catch (const std::exception& e) { print_exception(e); }
  return 0;
}

void run() {  // catch exception + wrap it in nested exception
  try { open_file("nonExistentFile.txt"); }
  catch (...) { std::throw_with_nested(std::runtime_error("run() fail")); }
}

void open_file(const std::string& s) {  // catch exception + wrap it
  try {
    std::ifstream file(s);  // open file and create an IO fail:
    file.exceptions(std::ios_base::failbit);  // raise exception
  }
  catch (...) {
    std::throw_with_nested(std::runtime_error("file error: " + s));
  }
}
```

10. Streams and Container Classes

10.1. Streams

10.2. Container Classes

10.1. Streams

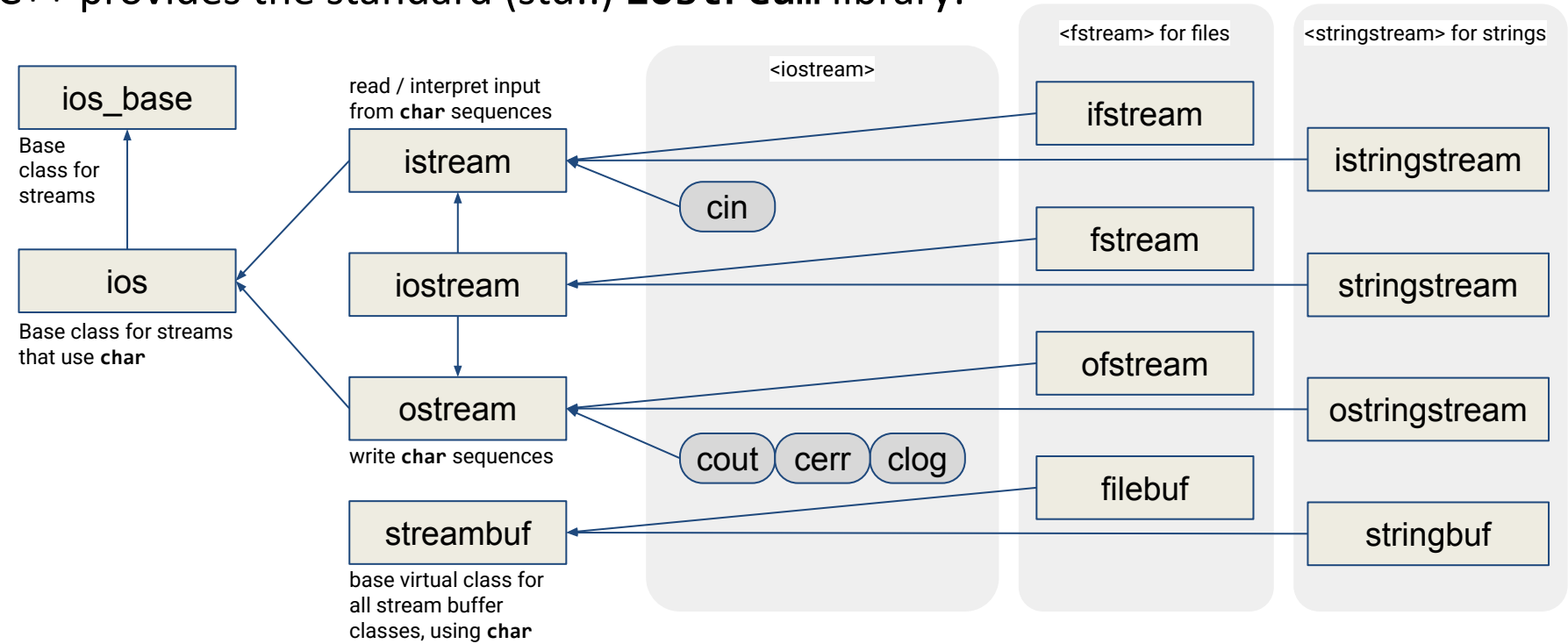
A stream class is a class which provides input and output functionality, as a standard abstraction across devices where input and output operations are performed. A stream can be represented as a source or destination, of characters of indefinite length.

For examples sending characters to and receiving characters from …

disk files, the keyboard and the console, a network connection

10.1. Streams

C++ provides the standard (std::) **`iostream`** library:



10.1. Streams

Streams have several common methods and operators, including:

- **`get`** / **`put`** a single character from/to a stream before returning
- **`read`** / **`write`** a certain amount of data from/to a stream before returning
- **`getline`** reads characters from an input stream until a delimiter character (usually **`'\n'`** is found) and places them into a string
- stream insertion operator **`<<`** for output to the stream
- stream extraction operator **`>>`** for input to the stream

10.1. Streams

Example 00 (difficulty level: 🌶🌶🌶): Install boost and compile:

```
/* change the following code to output the server reply straight to a local html file
   and add exception handling in case of file or connection problems */
#include <fstream>
#include <boost/asio.hpp>

int main() {
  const int bufferSize = 4096;
  boost::asio::ip::tcp::iostream socket("www.example.com", "http");  // socket stream
  std::ofstream outputFile("myTest.txt");  // stream to output file
  outputFile << "Reply of server:\n";
  char reply[bufferSize];
  socket << "GET / HTTP/1.1\r\nHost: www.example.com\r\nConnection: Close\r\n\r\n";
  socket << std::flush;
  socket.read(reply, bufferSize);
  outputFile << reply;  // output the reply of server to our text file
  return 0;
}
```

10.2. Container Classes

A container class is a class which implements a data structure containing objects of other classes, with well-defined access patterns (e.g., inserting, finding, removing, or sorting objects), independent of the type of objects stored inside.

Examples: Array, Stack, Queue, List, Tree

10.2. Container Classes

Illustration of a container: A queue of predefined size for integers

```
class Queue {  // Class for a queue of integers
 public:
  Queue(int size = 100) : maxSize(size), tail(0), head(0), filled(0) { items = new int[size]; }
  ~Queue() { delete[] items; items = nullptr; };
  void put(int data);
  int get();
  bool isFull() const { return filled == maxSize; }
  bool isEmpty() const { return filled == 0; }
  void clear() { filled = 0; head = 0; tail = 0; }  // clear whole queue
 private:
  int * items;   // array of integers
  int maxSize;   // size of items
  int tail;      // position in array to put
  int head;      // position in array to get from
  int filled;    // number of elements in queue
};
```

10.2. Container Classes

Illustration of a container: A queue of predefined size for integers

```
// put element at the tail of the queue, for example put(17) updates:
// items:  [  ][  ][  ][  ][  ][17][  ] … [  ][  ]
//              head              tail→
void Queue::put(int data) {   // put element at tail
  if (!isFull()) {
    items[tail] = data;
    tail = (tail+1) % maxSize;
    filled++;
  } else {
    throw std::runtime_error("queue: full on put");
  }
}
```

10.2. Container Classes

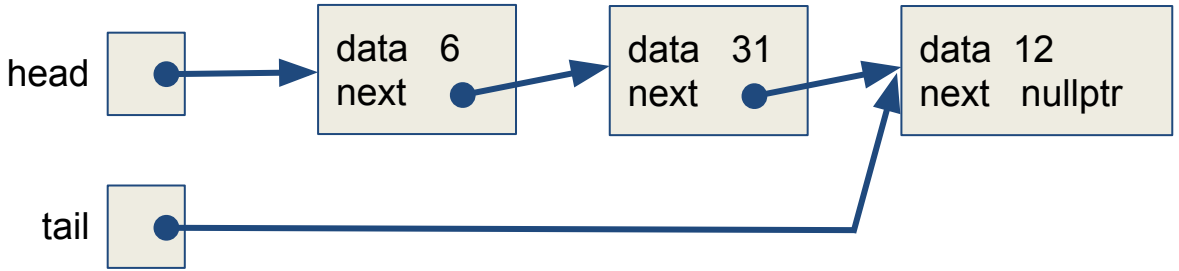
Illustration of a container: A queue of predefined size for integers

```
// gets element at the head of the queue, for example get() updates:
// items:  [  ][  ][  ][  ][  ][  ][  ] … [  ][  ]
//              head→           tail
int Queue::get() {  // get and remove element from head
  int retval;
  if (!isEmpty()) {
    retval = items[head];
    head = (head+1) % maxSize;
    filled--;
  } else {
    throw std::runtime_error("queue: empty on get");
  }
  return retval;
}
```

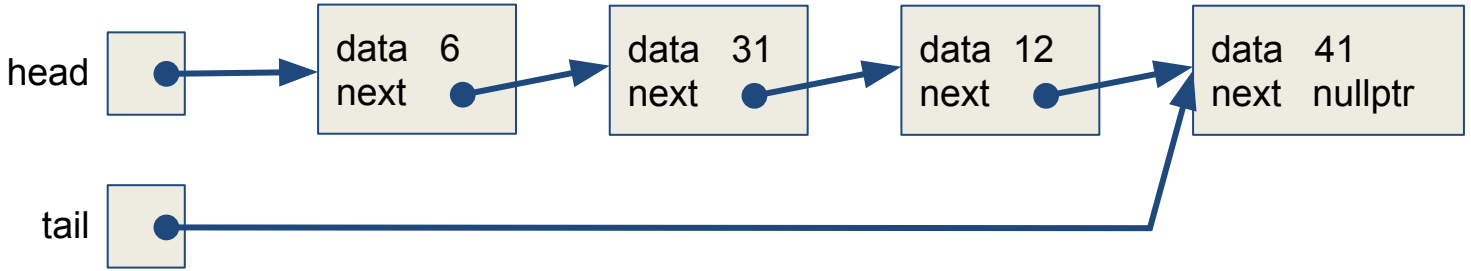
10.2. Container Classes

Illustration of a container: A queue of unlimited size for **`QueueElement`**s

```
UQueue q;
q.put(6);
q.put(31);
q.put(12);
```



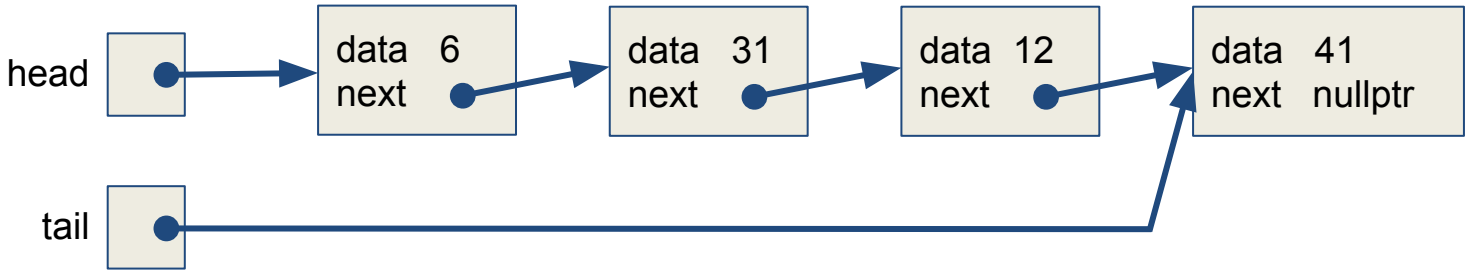

```
q.put(41);
```



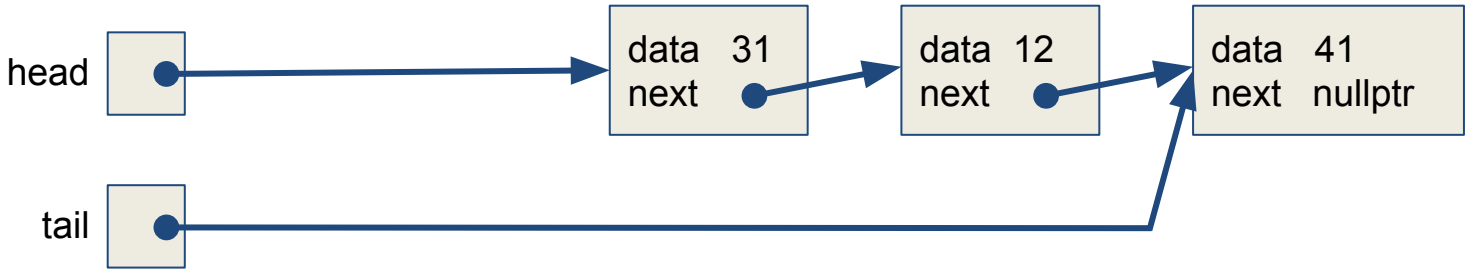
10.2. Container Classes

Illustration of a container: A queue of unlimited size for **`QueueElement`**s

```
q.put(41);
```




```
int v;
v = q.get();
```



10.2. Container Classes

Illustration of a container: A queue of unlimited size for **QueueElement**s

```
class QueueElement;  // declaration of the element class

class UQueue {  // Class for an unlimited queue of QueueElements
 public:
  UQueue() { head = tail = nullptr; }
  ~UQueue() { clear(); };
  void put(int data);
  int get();
  bool isEmpty() const;
  void clear();
 private:
  QueueElement * head;  // pointer to element to put
  QueueElement * tail;  // pointer to element to get from
};
```

10.2. Container Classes

Illustration of a container: A queue of unlimited size for **QueueElement**s

```
class QueueElement {  // element class, hidden from users
 public:
  QueueElement(int data) : data(data) , next(nullptr) {}
  int data;
  QueueElement * next;
};

void UQueue::clear() {  // iteratively clear the queue of all elements
  QueueElement * elem, * elem_next;
  for (elem = head; elem != nullptr; elem = elem_next) {
    elem_next = elem->next;
    delete elem;
  }
  head = tail = nullptr;
}
```

10.2. Container Classes

Illustration of a container: A queue of unlimited size for **QueueElement**s

```
bool UQueue::isEmpty() const {  // check whether the queue is empty
  return head == nullptr;
}

void UQueue::put(int data) {  // put in new data element at tail
  QueueElement * node = new QueueElement(data);
  if ( isEmpty() ) {
    head = tail = node;
  } else {
    tail = tail->next = node;  // tail is guaranteed to be valid
  }
}
```

10.2. Container Classes

Illustration of a container: A queue of unlimited size for **QueueElement**s

```
int UQueue::get() {  // get and remove element from head
  int retVal;
  if ( !isEmpty() ) {
    retVal = head->data;
    QueueElement * second = head->next;
    delete head;
    head = second;
  } else {
    throw std::runtime_error("uqueue: empty on get");
  }
  return retVal;
}
```

11. Templates and STL

11.1. Motivation: Revisiting the Queue class

The concept of a queue is characterized by its interface and behavior, independent of the type (or class) of elements stored inside.

But: The **`Queue`** and **`UQueue`** classes in the previous chapter can only store integers; dealing with other types or objects in the queue would require re-writing the **`QueueElement`** and **`Queue`** or **`UQueue`** classes.

Templates allow implementing a container class independent of the type of data elements.

11.1. Motivation: Revisiting the Queue class

Templates are expanded at compile-time, where the compiler does type-checking before the template expansion happens. The source code contains only the function or class, the compiled code can afterwards contain multiple copies of the same function or class. For a function for example:

```
template <class T>  T maxOf(T x, T y) {
  return (x > y)? x : y;
}

int main() {
  std::cout << maxOf<int>(12,24) << ' ';
  std::cout << maxOf<char>('d','e') << '\n';
  return 0;
}
```

```
int maxOf(int x, int y) {
  return (x > y)? x : y;
}
```

```
char maxOf(char x, char y) {
  return (x > y)? x : y;
}
```

11.1. Motivation - Template Queue Example 00

example00.cpp

```
template <class Data> class Queue {  // Template class for a queue
 public:
  Queue(int size = 100) : maxSize(size), tail(0), head(0), filled(0) {items = new Data[size];}
  ~Queue() { delete[] items; items = nullptr; };
  void put(Data data);
  Data get();
  bool isFull() const { return filled == maxSize; }
  bool isEmpty() const { return filled == 0; }
  void clear() { filled = 0; head = 0; tail = 0; }  // clear whole queue
 private:
  Data *items;    // array of Data
  int maxSize;   // size of items
  int tail;      // position in array to put
  int head;      // position in array to get from
  int filled;    // number of elements in queue
};
```

11.1. Motivation - Template Queue Example 00

example00.cpp

```
// put element at the tail of the queue, for example put(d) updates:
// items:  [  ][  ][  ][  ][  ][ d][  ] … [  ][  ]
//              head              tail→
template <class Data>
void Queue<Data>::put(Data data) {   // put element data at tail
  if (!isFull()) {
    items[tail] = data;
    tail = (tail+1) % maxSize;
    filled++;
  } else {
    throw std::runtime_error("queue: full on put");
  }
}
```

11.1. Motivation - Template Queue Example 00

example00.cpp

```
// gets element at the head of the queue, for example get() updates.
// items:  [  ][  ][  ][  ][  ][  ][  ] … [  ][  ]
//              head→              tail
template <class Data>
Data Queue<Data>::get() {  // get and remove element from head
  Data retval;
  if (!isEmpty()) {
    retval = items[head];
    head = (head+1) % maxSize;
    filled--;
  } else {
    throw std::runtime_error("queue: empty on get");
  }
  return retval;
}
```

11.1. Motivation - Template Queue Example 00

Queue are used while specifying the data type when creating the queue objects:

example00.cpp

```
int main() {
  Queue<int> intQueue(127);
  Queue<char> charQueue(21);

  // fill int and char data in both queues:
  for (auto i = 1; i <= 9; i++)  intQueue.put(i);
  for (auto i = '1'; i <= '9'; i++)  charQueue.put(i);

  // get earliest data from both queues nine times:
  for (auto i = 0; i < 9; i++) {
    std::cout << intQueue.get() << ' ' << charQueue.get() << '\n';
  }
  return 0;
}
```

11.1. Motivation - Template UQueue Example 01

example01.cpp

```
template <class Data> class QueueElement;  // element class, hidden from users

template <class Data> class UQueue {   // Template class for an unlimited queue
 public:
  UQueue() { head = tail = nullptr; }
  ~UQueue() { clear(); };
  void put(Data data);
  Data get();
  bool isEmpty() const;
  void clear();
  Data get();
 private:
  QueueElement<Data> * head;  // pointer to element to put
  QueueElement<Data> * tail;  // pointer to element to get from
};
```

11.1. Motivation - Template UQueue Example 01

example01.cpp

```
template <class Data> class QueueElement {  // element class, hidden from users
 public:
  QueueElement(Data data) : data(data) , next(nullptr) {}
  Data data;
  QueueElement<Data> * next;
};

template <class Data>
void UQueue<Data>::clear() {  // iteratively clear the queue of all elements
  QueueElement<Data> * elem, * elem_next;
  for (elem = head; elem != nullptr; elem = elem_next) {
    elem_next = elem->next;
    delete elem;
  }
  head = tail = nullptr;
}
```

11.1. Motivation - Template UQueue Example 01

example01.cpp

```
template <class Data>
bool UQueue<Data>::isEmpty() const {  // check whether the queue is empty
  return head == nullptr;
}

template <class Data>
void UQueue<Data>::put(Data data) {  // put in new data element at tail
  QueueElement<Data> * node = new QueueElement<Data>(data);
  if (isEmpty()) {
    head = tail = node;
  } else {
    tail = tail->next = node;  // tail is guaranteed to be valid
  }
}
```

11.1. Motivation - Template UQueue Example 01

example01.cpp

```
template <class Data>
Data UQueue<Data>::get() {  // get and remove element from head
  Data retVal;
  if (!isEmpty()) {
    retVal = head->data;
    QueueElement<Data> * second = head->next;
    delete head;
    head = second;
  } else {
    throw std::runtime_error("uqueue: empty on get");
  }
  return retVal;
}
```

11.1. Motivation - Template UQueue Example 01

UQueue is used while specifying the data type when creating the queue objects:

example01.cpp

```
int main() {
  Queue<int> intQueue(127);
  Queue<char> charQueue(21);

  // fill int and char data in both queues:
  for (auto i = 1; i <= 9; i++)  intQueue.put(i);
  for (auto i = '1'; i <= '9'; i++)  charQueue.put(i);

  // get earliest data from both queues nine times:
  for (auto i = 0; i < 9; i++) {
    std::cout << intQueue.get() << ' ' << charQueue.get() << '\n';
  }
  return 0;
}
```

11.2. Templates

`template <class Data>` designates Data as the parameter. This is a placeholder for a type to be specified later, when an object of the class that follows this declaration of a template. `class` is almost interchangeable with `typename` .

The later use (e.g., instantiation) of a template is often called specialization:
`UQueue<double> q;` or `Queue<Data> * n = new Queue<Data>(250);`
or `int getSize( Queue<int>& q );`

Templates tell the compiler that the class will use a type that is to be specified when the objects are created, which is why templates are *put in the header file*. The compiler will create the actual class only when it is specialized.

11.3. Using templates, inheritance, friends

Templates can have more than one parameter:

```
template <class XData, class YData>
```

Templates can have, like functions or methods, default parameters:

```
template <class XData, class YData = char>
```

Templates can have non-type parameters, too:

```
template <class XData, int max>
```

Inheritance is possible:

- Templates can inherit from other templates and from non-template classes
  ```
  template <class x> class SortableQueue<x> : public UQueue<x> {
  ```
- Non-template classes can inherit from templates:
  ```
  class IntQueue : public UQueue<int> {
  ```

11.3. Using templates, inheritance, friends

Template parameters for functions can be deduced by the compiler, i.e., without specifying the type. This is possible for template classes since C++17.

example06.cpp

```
#include <iostream>

template <class T>  T maxOf(T x, T y) {
  return (x > y)? x : y;
}

int main() {
  std::cout << maxOf<int>(12,24) << ' ';
  std::cout << maxOf<char>('d','e') << '\n';
  std::cout << maxOf(12,24) << ' ';     // these two lines have the same
  std::cout << maxOf('d','e') << '\n';  // effect as above, types are deduced
  return 0;
}
```

11.3. Using templates, inheritance, friends

Template classes can declare a non-template friend class or function, a general template friend class or function, or a type-specific template friend class or function:

```
template <class T> class A {  //
 public:
  template<class U> friend class B;
 private:
  T data;
};
template<class U> class B {
 public:
  B() { A<U> a; std::cout << "A's data: " << a.data << "\n"; };
};
int main() {
  B<int> b;
  return 0;
}
```

11.4. Templates and operator overloading

Overloading operators allows to customize the C++ operators (such as `+`, `-`, `*`, `/`, `%`, `^`, `&`, `|`, `~`, `!`, `=`, `<`, `>`, `+=`, `-=`, `*=`, `/=`, `%=`, `^=`, `&=`, `|=`, `<<`, `>>`, `>>=`, `<<=`, `==`, `!=`, `<=`, `>=`, `&&`, `||`, `++`, `--`, `,`, `->*`, `->`, `( )`, `[ ]`, `<=>`(since C++20)) for operands of user-defined types. Example:

```
#include <iostream>
class A {
 public:
  char a;
  A(char a): a(a) {}
};
std::string operator + (const A & a1, const A & a2) {
  std::string s;
  s += a1.a; s += a2.a;
  return s;
}
// A a1('a'), a2('b'); std::cout << a1+a2 << '\n';
```

11.4. Templates and operator overloading -- friend methods

example03.cpp

```
class Complex;
Complex operator + ( const Complex& obj1, const Complex& obj2);

class Complex {  // Class representing a complex number, e.g. 2.3 + 4.5 i
 public:
  Complex() : real(0), img(0) {}
  Complex(double real, double imag) : real(real), imag(imag){}
  friend Complex operator + ( Complex& obj1, const Complex& obj2);
 private:
  double real, imag;
};

Complex operator + ( const Complex& obj1, const Complex& obj2) {
  Complex temp;
  temp.real = obj1.real + obj2.real;
  temp.imag = obj1.imag + obj2.imag;
  return temp;
}
```

11.4. Templates and operator overloading -- conversions

Conversion operators can be used to convert one type to another type:

example04.cpp

```
#include <iostream>

// class representing a fraction through numerator and denominator, e.g. 7/9
class Fraction {
 public:
  Fraction(int n, int d) : n(n), d(d) {}
  // note that conversion does not have a return type:
  operator double() const { return double(n)/double(d); }
 private:
  int n, d;
};

int main() {
  Fraction frac(7, 9);
  double val = frac;  // conversion to double, double val = (double) frac;
  std::cout << val << '\n';
  return retVal;
}
```

11.4. Templates and operator overloading

With templates, now

example05.cpp

```
#include <iostream>

template <class T> class MyClass {
 public:
  MyClass(T c) : c(c) {}
  T c;
};
template <class U>
std::ostream& operator<<(std::ostream& out, const MyClass<U>& classObj) {
  out.put(classObj.c);
  return out;
}
int main() {
  MyClass<char> t('?');
  std::cout << t << '\n';
  return 0;
}
```

11.5. Standard Template Library (STL)

STL is a set of C++ template classes that:

- implement most common data structures for *containers* (queues, vectors, lists, stacks, maps, arrays, etc.), *algorithms* (sorting, search, etc.), *iterators* (to go through containers) , and *function objects or functors*
- in the form of a library of container classes, algorithms, and iterators,
- using components that are parameterized through templates.

11.5. The Standard Template Library (STL) - Vector

Dynamic array that resizes when elements are added or removed

```
std::vector<double> myVector( { 2.0, 4.0, 7.0 } );
std::vector<double> largeVector( 200, 1.0 );  // 200 elements, all ones
std::vector<double> copiedVector( myVector );  // exact copy of myVector
```

example07.cpp

```
#include <iostream>
#include <vector>
int main() {
  std::vector<std::string> name( {"John", "George", "Paul", "Smith"} );
  std::cout << "name size=" << name.size() << " of " << name.max_size();
  std::cout << " capacity=" << name.capacity() << "\n";
  for (auto i = name.begin(); i < name.end(); i++)  // use iterators
    std::cout << *i << '\n';
  name.insert(name.begin()+2, "Tom");  // insert another name at third element
  for (const std::string& i : name)  // use range based for loop
    std::cout << i << '\n';
  return 0;
}
```

11.5. The Standard Template Library (STL) - Map

Container for (key value, mapped value) pairs. Mapped values cannot have the same key values. Initialization can be done (since C++11) with initializer lists:

```
std::map<int, std::string> names = {{1,"Ann"}, {2,"Ames"}, {9,"Asa"}};

std::map<std::string, int> students;
students["Aaron"] = 173923;   // insert two new map elements
students["Zachary"] = 183211;

for (auto const& x : names)  // since C++11
  std::cout << "key:" << x.first << ",val:" << x.second << "\n";

for (auto const& [key, val] : students)  // since C++17
  std::cout << "key:" << key << ",val:" << val << "\n";
```

11.5. The Standard Template Library (STL) - Map

example08.cpp

```
#include <iostream>
#include <map>

int main() {
  std::map<std::string, int> students;
  students["Aaron"] = 173923;   // insert new map elements
  students["Zachary"] = 183211;
  students.insert( {"Patrick", 172932} );
  students.insert( std::pair<std::string,int>("Arnold", 161010) );

  for (auto const& x : names)  // since C++11
    std::cout << "key:" << x.first << ",val:" << x.second << "\n";

  for (auto const& [key, val] : students)  // since C++17
    std::cout << "key:" << key << ",val:" << val << "\n";

  return 0;
}
```

11.5. The Standard Template Library (STL) - transform

```
int increase(int x) { return (x+1); } // operation to execute

int array[] = {1, 2, 3};  // a simple container

std::transform(array, array+3, array, increase);

for ( const int & i : array )
  std::cout << i << ", ";  // output: 2, 3, 4,
```

Apart from the unary use above, transform also allows two input containers to be used (e.g., summing up elements of two containers). A functor can be passed for the given operation to be done on all elements of container, with the additional benefit of keeping its state.

11.5. The Standard Template Library (STL) - transform

Example of a functor:

```
#include <cassert>
class addX {  // this is a functor
 public:
  addX(int val) : x(val) {}  // Constructor sets how much to add
  int operator()(int y) const { return x + y; }  // ()
 private:
  int x;
};
int main() {
  addX add5(5);  // create object of functor class
  int i = add5(3);  // "call" it through the () operation
  assert(i == 8);
  return 0;
}
```

11.5. The Standard Template Library (STL) - transform

example09.cpp

```
#include <iostream>
#include <vector>
int main() {
  std::vector a( { 16.0, 17.0, 18.0 } );  // init. lists since C++17
  std::vector b( { 10.0, 30.0, 60.0 } );
  std::vector<double> c;
  double n = 2.7;
  std::transform(a.begin(), a.end(),                  // iterators to input and
                 b.begin(), std::back_inserter(c),  // output vector elements
        [=](double x, double y) {return(x - y)/n; });
       // [=] : capture all external variables (n) in lambda by value
       // [&] : capture all external variables (n) in lambda by reference

  for (const double & i : c) {
    std::cout << i << "\n";
  }
  return 0;
}
```

11.5. The Standard Template Library (STL)

More reference information about the C++ STL is given at these locations:

https://en.cppreference.com/w/cpp/standard_library
https://cplusplus.com/reference/stl/

12. Abstract Classes and `virtual`

12.1. Abstract Classes and `virtual`

Abstract classes are classes that cannot be instantiated and has one or more *pure virtual* (or abstract) methods: `virtual void print() = 0;`

A pure virtual method needs to be overridden by a concrete (i.e., non-abstract) derived class and is indicated in the declaration with the syntax `= 0` behind the method's declaration.

Abstract classes cannot be used as parameter types, as function return types, or as explicit conversion types. Pointers and references to abstract classes can be declared.

12.1. Abstract Classes and virtual

Abstract.cpp

```cpp
#include <iostream>

class AbstractClass {  // Class has pure virtual method:
 public:
  virtual void printName() const = 0;
 protected:
  std::string name = "myName";   // default initialization since C++11
};

class DerivedClass : public AbstractClass {
 public: // printName is overridden and implemented here:
  virtual void printName() const override { std::cout << name << "\n"; }
};

int main() {
  // This would fail:  AbstractClass myObject;
  DerivedClass myDerivedObject;  // The abstract class forces the
  myDerivedObject.printName();   // implementation of printName
  return 0;
}
```

12.1. Abstract Classes and **`virtual`**

`virtual` functions or method can be overridden in derived classes. The overriding is preserved, even the actual type of the class is not known at compile-time (i.e., when the derived class is handled using a pointer or reference to the base class).

`override` (since C++ 11) can be mentioned after the method declaration, to explicitly show intent to override a method. The compiler can this way stop at programmer's mistakes (for instance, when the method's name was mistyped).

`final` can be mentioned after the method declaration, to explicitly signal that no further subclasses can override this method anymore.

12.1. Abstract Classes and virtual -- override

```
#include <iostream>

class BaseClass {
 public:
  virtual void print() const {
   std::cout << "Base Class. \n";
  }
};

class DerivedClass : public BaseClass {
 public:
  virtual void print() const override {
    std::cout << "Derived Class. \n";
  }
};
```

```
int main() {

  BaseClass base; DerivedClass derived;

  BaseClass & bref = base;
  BaseClass & dref = derived;
  bref.print();  // "Base Class."
  dref.print();  // "Derived Class."

  BaseClass * bpnt = &base;
  BaseClass * dpnt = &derived;
  bpnt->print();  // "Base Class."
  dpnt->print();  // "Derived Class."

  bref.BaseClass::print(); // "Base Class."
  dref.BaseClass::print(); // "Base Class."

  return 0;
}
```

12.1. Abstract Classes and virtual -- final

Final.cpp

```
class AbstractClass {  // Class has pure virtual method:
 public:
  virtual void printName() const = 0;
};

class DerivedClass : public AbstractClass {
 public:  // printName is overridden and implemented here:
  virtual void printName() const override { std::cout << "name. \n"; }
};

class FinalClass : public DerivedClass {
 public:  // printName is final-overridden and re-implemented here:
  virtual void printName() const final { std::cout << "Name. \n"; }
};

class AnotherClass : public FinalClass {
 public:  // printName was final in FinalClass, cannot be overridden:
// virtual void printName() const { std::cout << "NAME. \n"; }
};
```

12.1. Abstract Classes and `virtual`

The following code shows that a destructor is not inherited, so objects that are freed in this way do not call the derived class' destructor:

```
#include <iostream>

class BaseClass {  // ~BaseClass illustration:
 public:
  ~BaseClass() { std::cout << " BaseClass resources freed \n"; }
};

class DerivedClass : public BaseClass {  // ~DerivedClass illustration:
 public:
  ~DerivedClass() { std::cout << "DerivedClass resources freed \n"; }
};

int main() {
  BaseClass * base = new DerivedClass;
  delete base;   // " BaseClass resources freed \n"
  return 0;
}
```

12.1. Abstract Classes and `virtual`

Yet, a *virtual* destructor from a base class is always overridden by derived destructors, allowing the following:

```
#include <iostream>

class BaseClass {  // ~BaseClass call is virtual => calls ~DerivedClass
 public:
  virtual ~BaseClass() { std::cout << " BaseClass resources freed \n"; }
};

class DerivedClass : public BaseClass {  // ~DerivedClass afterwards calls ~BaseClass,
 public:                                 // following the typical destructor order
  virtual ~DerivedClass() { std::cout << "DerivedClass resources freed \n"; }
};

int main() {
  BaseClass * base = new DerivedClass;
  delete base;   // "DerivedClass resources freed \n BaseClass resources freed \n"
  return 0;      //   ^-- note that now both are called
}
```

12.2. The Non-Virtual Interface Idiom

Remember from Chapter 8: Polymorphism in C++ relies on methods from a base class being declared as **`virtual`** .

When **`Dog`** and **`Fish`** are classes that inherit from **`Animal`**, objects from these classes have a custom **`print()`** method, overloading from Animal's **`virtual print()`** method:

```
Animal * animal;
animal = new Dog("Scooby");
animal->print();  // prints out: I am Scooby. Bark!
animal = new Fish("Salmon");
animal->print();  // prints out: I'm Salmon (fish)
```

12.2. The Non-Virtual Interface Idiom

polyDemo.cpp

```
#include <iostream>
#include <cstdlib>

class Animal {  // Animal class stores the species and prints this in print()
 protected:
  std::string _species;
 public:
  Animal(std::string species) { _species = species; }
  virtual void print() const { std::cout << "I'm " +  _species << "\n"; }
};

class Dog : public Animal {  // Dogs inherit species from Animal and have a name
 protected:
  std::string _name;
 public:
  Dog(std::string name) : Animal("dog"), _name(name) {}
  void print() const override { std::cout << "I am " << _name << ". Bark!\n"; }
};
```

12.2. The Non-Virtual Interface Idiom

polyDemo.cpp

```
class Fish : public Animal {  // Fishes have species and subspecies
 protected:
  std::string _subspecies;
 public:
  Fish(std::string subspecies) : Animal("fish"), _subspecies(subspecies) {}
  void print() const override { std::cout << "I'm " << _subspecies << " (fish)\n"; }
};

int main() {
  Animal * animals[4];
  animals[0] = new Dog("Snowy");       // animals[] has pointers
  animals[1] = new Fish("Salmon");     // to objects of different
  animals[2] = new Dog("Scooby");      // subclasses (Dog, Fish, etc.)
  animals[3] = new Animal("some animal");  // or the animal base class
  for (auto i=0; i<15; i++) {
   Animal * a = animals[rand() % 4];  // a is a polymorph variable: its
   a->print();                        // print's behavior depends on the
  }                                   // object that a points to
  return 0;
}
```

12.2. The Non-Virtual Interface Idiom

`Animal`'s **`virtual print()`** method is public. Problems that could occur here are:

- Sub classes do repeat code: The only part that changes is the string to print, but each class needs **`std::cout << ... << std::endl;`** code
- The base class **`Animal`** cannot make guarantees about what the **`print()`** does: Sub-classes may do something completely different as originally intended

This can be fixed by using a **non-virtual interface** that is supplemented by a **private virtual function** that allows polymorphic behaviour. The private virtual methods are called by public non-virtual methods: See next slide

12.2. The Non-Virtual Interface Idiom

polyNVIDemo.cpp

```
#include <iostream>
#include <cstdlib>

class Animal {  // Animal class stores the species and prints this in print()
 protected:
  std::string _species;
 public:
  Animal(std::string species) { _species = species; }
  void print() const { std::cout << getSound() << std::endl; }
 private:
  virtual std::string getSound() const { return "I'm " + _species; };
};

class Dog : public Animal {  // Dogs inherit species from Animal and have a name
 protected:
  std::string _name;
 public:
  Dog(std::string name) : Animal("dog"), _name(name) {}
 private:
  std::string getSound() const override { return "I am " + _name + ". Bark!"; }
};
```

12.2. The Non-Virtual Interface Idiom

polyNVIDemo.cpp

```
class Fish : public Animal {  // Fishes have species and subspecies
 protected:
  std::string _subspecies;
 public:
  Fish(std::string subspecies) : Animal("fish"), _subspecies(subspecies) {}
 private:
  std::string getSound() const override { return "I'm " + _subspecies + " (fish)"; }
};
int main() {
  Animal * animals[4];
  animals[0] = new Dog("Snowy");       // animals[] has pointers
  animals[1] = new Fish("Salmon");     // to objects of different
  animals[2] = new Dog("Scooby");      // subclasses (Dog, Fish, etc.)
  animals[3] = new Animal("some animal");  // or the animal base class
  for (auto i=0; i<15; i++) {
   Animal * a = animals[rand() % 4];  // a is a polymorph variable: its
   a->print();                        // print's behavior depends on the
  }                                   // object that a points to
  return 0;
}
```

12.2. The Non-Virtual Interface Idiom

Thus: Non-Virtual Interfaces decouple a class' public interface (e.g., **`Animal`**s **`print()`**) by making it non-virtual, from functions (e.g., **`getSound()`**) that are providing customization points for sub-classes (e.g., **`Dog`** or **`Fish`**).

As an idiom, Non-Virtual Interface is a programming guideline, implementing the Template Method design pattern (not to be confused with C++ templates).

A complete treatise on virtuality can be read in "Virtuality", by Herb Sutter (in C/C++ Users Journal, 19(9), September 2001).

12.3. Multiple Inheritance and the Diamond Problem

Classes can inherit in C++ from multiple base classes. Classes can thus inherit from multiple abstract classes, using multiple pure abstract classes with only pure virtual public methods and static const attributes (similar to interfaces in Java).

InterfaceExample.cpp

```
class MyInterface {
 public:
  virtual int getFormulaWithX() const = 0;
  virtual ~MyInterface() {};
 public:
  static const int X = 7;
};
```

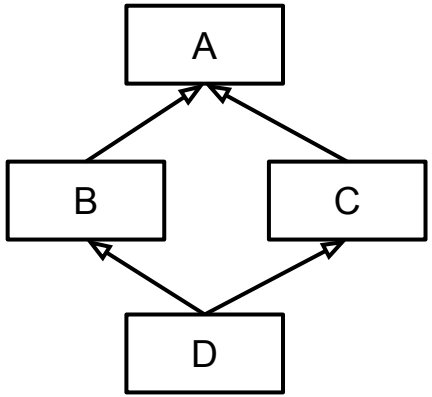
Constructors of inherited classes are called in the same order in which they are inherited. The destructors are called in reverse order of the constructors.

12.3. Multiple Inheritance and the Diamond Problem

```cpp
#include <iostream>

class ClassA {
 public:
  ClassA() { std::cout << "Class A constructed.\n"; };
};
class ClassB {
 public:
  ClassB() { std::cout << "Class B constructed.\n"; };
};
class DerivedClass : public ClassA, public ClassB {
 public:
  DerivedClass() { std::cout << "Derived Class constructed.\n"; };
};

int main() {
  DerivedClass myDerivedObject;  // note: this calls first A's, then B's constructor
  return 0;
}
```

12.3. Multiple Inheritance and the Diamond Problem

The *diamond problem* occurs when two superclasses of a class (class B and class C on the right) have a common base class (D).

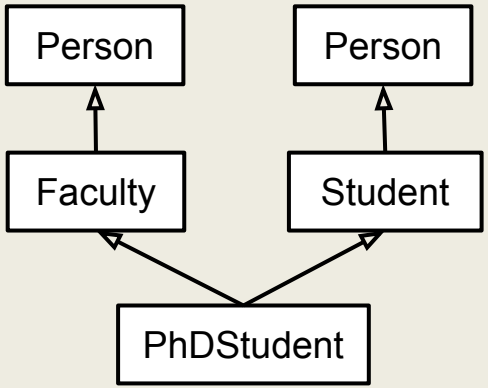


This will lead to the constructor of A being called twice (once via B and once via C). Similarly, the destructor of class A is called twice as well, and objects of class D have two copies of all of A's attributes and methods.

When B and C both inherit a method `m()` from A, which is then meant when an object `d` from Class D calls `d.m()` ?

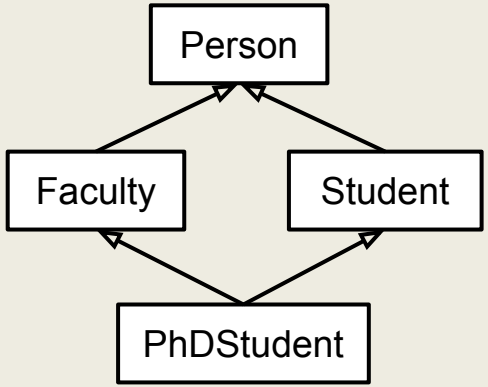
12.3. Multiple Inheritance and the Diamond Problem

```
class Person {  // Person:
public:
 Person() { std::cout << "Person constructed.\n"; };
};
class Faculty : public Person {  // Faculty is a Person
 public:
  Faculty() { std::cout << "Faculty constructed.\n"; };
};
class Student : public Person {  // Student is a Person
 public:
  Student() { std::cout << "Student constructed.\n"; };
};
class PhDStudent : public Faculty, public Student {  // PhDStudent is both
 public:
  PhDStudent() { std::cout << "PhDStudent constructed.\n"; };
};

int main() {
  PhDStudent phd;  // note: this object will contain two copies of a person
  return 0;
}
```



12.3. Multiple Inheritance and the Diamond Problem

```
class Person {  // Person:
public:
 Person() { std::cout << "Person constructed.\n"; };
};
class Faculty : virtual public Person {  // Faculty is a Person
 public:
  Faculty() { std::cout << "Faculty constructed.\n"; };
};
class Student : virtual public Person {  // Student is a Person
 public:
  Student() { std::cout << "Student constructed.\n"; };
};
class PhDStudent : public Faculty, public Student {  // PhDStudent is both
 public:
  PhDStudent() { std::cout << "PhDStudent constructed.\n"; };
};
```



Using *virtual inheritance*, C++ is told that there is one common Person subobject for both Faculty and Student and their subclasses (PhDStudent).

12.4. Templated Interfaces

```
#include <iostream>

template <class T>  // force subclasses to
class IMenuItem {   // implement printItem:
 public:
  IMenuItem(T item) : item(item) {}
  virtual void printItem() const = 0;
 protected:
  const T item;     // and hold item here, too
};

template <class T>
class Item : public IMenuItem<T>{
 public:  // implementation of printItem:
  Item(T item) : IMenuItem<T>(item) {}
  void printItem() const override {
    std::cout << "Choice: " << this->item << "\n";
  };
};
```

12.4. Templated Interfaces

```
int main() {
  // menu list where items are given an integer:
  std::array<IMenuItem<int> *, 3> menu
     = { new Item<int>(0), new Item<int>(1), new Item<int>(5)};
  for (auto i = 0; i < menu.size(); i++)
    menu[i]->printItem();
  // menu list where items are given a character:
  std::array<IMenuItem<char> *, 3> menu2
     = { new Item<char>('a'), new Item<char>('b'), new Item<char>('c')};
  for (auto i = 0; i < menu2.size(); i++)
    menu2[i]->printItem();
  // menu list where items are given a string:
  std::array<IMenuItem<std::string> *, 2> menu3
     = { new Item<std::string>(std::string("optionA")),
         new Item<std::string>(std::string("optionB"))};
  for (auto i = 0; i < menu3.size(); i++)
    menu3[i]->printItem();
  return 0;
}
```

12.4. Templated Interfaces

```
int main() {  // class template argument deduction (since C++17), range based loops
  // menu list where items are given an integer:
  std::array menu = { new Item(0), new Item(1), new Item(5)};
  for (auto i : menu) i->printItem();

  // menu list where items are given a character:
  std::array menu2 = { new Item('a'), new Item('b'), new Item('c')};
  for (auto i : menu2) i->printItem();

  // menu list where items are given a string:
  std::array menu3 = { new Item(std::string("optionA")),
                       new Item(std::string("optionB"))};
  for (auto i : menu3) i->printItem();

  return 0;
}
```

13. Enumerators, `struct` and `union`

13.1. Basics of `enum`

An enumerator (`enum`) creates a data type that can take the value in a set of named integral constants. By default, the first will be `0`, the second `1`, etc.

```
#include <iostream>
int main() {
  enum level_t { LOW, MEDIUM, HIGH };
  level_t danger = HIGH;  // note: HIGH == 2
  std::cout << danger << "\n";
  return 0;
}
```

The integer values that represent the constants can also be set and controlled explicitly. They are numbered in increasing order:

```
enum battery_t { FULL = 100, ADEQUATE = 50, EMPTY = 0 };
enum level_t { LOW = -100, MEDIUM, HIGH };  // MEDIUM == -99, HIGH == -98

enum day_t { MON = 1, TUE, WED, THU, FRI, SAT, SUN};
// MON == 1, TUE == 2, WED == 3, THU == 4, FRI == 5, SAT == 6, SUN == 7
```

13.1. Basics of **enum**

The advantage of **enum** is that the code is readable easier to maintain variables that can take any of a given set of variables :

```
#include <iostream>
int main() {
  enum level_t { LOW, MEDIUM, HIGH };
  level_t humidity = LOW;
  std::string s;
  switch (humidity) {
    case LOW: s = "low"; break;
    case MEDIUM: s = "medium"; break;
    case HIGH: s = "high"; break;
  }
  std::cout << "The humidity is " << s << "\n";
  return 0;
}
```

13.1. Basics of **enum**

Since the values are mapped to integers, this might lead to problems:

```
#include <iostream>
int main() {
  enum level_t { LOW, MEDIUM, HIGH };
  enum battery_t { FULL, ADEQUATE, EMPTY };  // LOW cannot be reused here
  level_t status1 = LOW;      // multiple types' values are basically integers,
  battery_t status2 = EMPTY;  // the following will lead to a warning only:
  std::cout << ( status1 == status2 ) << "\n";
  return 0;
}
```

Typically, **enum**s are used when values are unlikely going to change, such as week days, months, colors, card values.

13.2. Scoped enumeration `enum class`

Since C++11, a *scoped* enumeration (`enum class`) data type is a type-safe enumerator (not a class) that is not implicitly convertible to an integer.

```
enum class Level { LOW, MEDIUM, HIGH };
Level status1 = Level::LOW;  // "status1 = LOW" would lead to error

enum class Battery { FULL, ADEQUATE, EMPTY };
Battery status2 = Battery::EMPTY;  // "status2 = EMPTY" would lead to error

// the following will lead to an "invalid operands" error:
std::cout << ( status1 == status2 ) << "\n";
```

The scoped enumeration's underlying data type can be set explicitly:

```
enum class Choice : int8_t { YES, MAYBE, NO, UNKNOWN };
```

13.2. Scoped enumeration `enum class`

A scoped enumeration cannot be compared to, or use the constants as, integers.

`enum class Level { LOW, MEDIUM, HIGH };` will cause:

`Level l = Level::MEDIUM; std::cout << level;` to result in an error.

The need for scope might also make code less terse and longer:

```
enum class Level { LOW, MED, HIGH };
Level humidity = Level::LOW;
std::string s;
switch (humidity) {
  case Level::LOW: s = "low"; break;
  case Level::MEDIUM: s = "med"; break;
  case Level::HIGH: s = "high"; break;
}
```

Since C++20, `using enum` can import enumerators in the local scope:

```
enum class Level { LOW, MED, HIGH };
Level humidity = Level::LOW;
std::string s;
switch (humidity) {
  using enum Level;
  case LOW: s = "low"; break;
  case MEDIUM: s = "med"; break;
  case HIGH: s = "high"; break;
}
```

13.3. `typedef` and `struct`

Structures (preceded by `struct`) historically combine variables of different types, similar to how arrays combine variables of the same type.
Structures are semantically *very* similar to classes, but by default do not set attributes or methods to private (plus more).

```
struct anonExamEntry {
 long studentId = 0;  // initialization here
 float grade = 1.0;   // possible since C++11
};

anonExamEntry entry1;
entry1.studentId = 17017491;
entry1.grade = 2.3;
```

13.3. **typedef** and **struct**

typedef is a keyword that is used to assign a new name to any existing data-type:

```
typedef int integer; integer i = 9;
```

In C, new variables of a particular structure type would need the keyword **struct** to be added each time:

```
struct examEntry {
  long studentId;
  float grade;
};
struct examEntry entry;  // "anonExamEntry entry;" not possible in C
```

Which is why **typedef** is used to provide a new name instead:

```
typedef struct examEntry examEntry;  // "struct examentry" = "examEntry"
```

13.4. **union** and **std::variant**

A **union** is a special class type that can hold only one of its non-static attributes.
It is at least as big as needed to store the largest attribute, but is usually not larger.
Unions can have non-virtual methods, but cannot be involved in inheritance.

```cpp
#include <iostream>

union Number {   // a Number has:
  long l;        // either a long,
  unsigned u;    // or an unsigned,
  double f;      // or a double
};
```

union.cpp

```cpp
int main() {
  Number n;
  n.l = 7l;
  std::cout << n.l << '\n';
  n.f = 8.9;
  std::cout << n.f << '\n';
  std::cout << sizeof(n) << '\n';
  return 0;
}
```

13.4. **union** and **std::variant**

Since C++17, STL includes **std::variant**, which replaces many uses of unions and union-like classes:

variant.cpp

```
#include <iostream>
#include <variant>

int main() {
  std::variant<char, std::string> s;  // s stores a char or a string
  s = 'a';
  std::visit([](auto x){ std::cout << x << '\n';}, s);  // visit since C++17
  s = "string!";
  std::visit([](auto x){ std::cout << x << '\n';}, s);  // (more info here)
  return 0;
}
```

14. Performance

14.1. **`const`** correctness

14.2. **`constexpr`** – Generalized constant expressions

14.3. Move semantics

14.4. Measuring Time

14.1. `const` correctness

Using **`const`** tells the compiler that objects/variables should not change:

```
void function1(const std::string& str);   // Pass by reference-to-const

void function2(const std::string* sptr);  // Pass by pointer-to-const

void function3(std::string str);          // Pass by value
```

For the above to-const parameter functions, the C++ compiler checks whether the passed is changed, or is passed further as a const. Example:

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

void function1(const std::string& str) {
  mutate(str);           // compiler error: str is const
  std::string localCopy = str;
  mutate(localCopy);     // fine, localCopy is not const
}
```

14.1. `const` correctness

Declaring the const-ness of a parameter is just another form of type safety and should be done as soon as they are declared. A non-const variant and the const one for an object/variable can be thought of as different types.
const overloading of methods or operators allows const correctness:

```
class Item { /*...*/ };

class MyItemList {
 public:
  const Item& operator[] (int index) const;  // [] operators often have a
  Item& operator[] (int index);              // const and non-const version
  // ...
};
```

14.1. `const` correctness

`const` correctness allows:

1. Protection from accidentally changing variables / objects
2. Protection from making accidental variable assignments, e.g.:

```
void myMethod(const int x) {

  if ( x = y )   // typo: really meant if (x == y) -> error
  //  ...
}
```

3. The compiler to optimize for it

More examples can be found here.

14.1. `const` correctness

Reminder: **`const`** pointers can come in various forms, what matters is that everything on the left of the **`const`** keyword is constant. If **`const`** is on the full left, what is on its right is constant. **`const`** pointers need to be directly initialized:

```
int myInteger = 71;
const int constInt = 17;
int const * pointToConstInt = &constInt;   // pointer to const int
int * const constPointToInt = &myInteger;  // const pointer to int
int const * const cPointToCInt = &constInt;  // const pointer to const int
const int * pointToConstInt2 = &constInt;  // pointer to const int
```

14.1. `const` correctness

Reminder: Example 03 from 7. Pointers (difficulty level: 🌶🌶🌶):

```
/** Print a mouse in the console, using a const pointer to avoid changes */
#include <iostream>     // terminal output
[[nodiscard]] auto * getBitmapAddress() {
    static char bitmap[] = "(^._.^)~";  // "bitmap" created in static memory
    return bitmap;  // return pointer to first element
}
int main() {
  // using a pointer to bitmap, and incrementing it, is possible:
  auto * mousePointer = getBitmapAddress();
  while ( *mousePointer != 0 )  std::cout << *(mousePointer++);
  std::cout << "\n";
  // Here mousePointer has changed, it's hard to get the original pointer.
  // Modify the above by protecting the pointer with const and redo the loop.
  return 0;
}
```

14.2. `constexpr` – Generalized constant expressions

Since C++11, the **`constexpr`** specifier declares that the expression that follows is always evaluated at compile-time, and thus:

- can save potentially significant processing and memory usage during run-time
- but at the cost of more work to be done during compilation

When used to declare variables, these are implicitly **`const`**s. Example:

```
const int val1 = 3;          // evaluated at compile-time
const int val2 = val1 * 2;   // evaluated at compile-time
int a = 3;                   // variable a is not constant
const int val3 = a;          // evaluated at run-time
constexpr int c1 = val1;     // evaluated at compile-time
// constexpr int c2 = val3; // compile error, val3 is not constant
```

14.2. `constexpr` – Generalized constant expressions

`constexpr` can precede a function or method. In that case it will be evaluated at compile-time only when all the arguments are evaluated at compile-time:

```
constexpr int square(int value) {
  return value * value;
}
square(4);  // evaluated at compile-time
int val = 4;
square(val);  // evaluated at run-time
```

If a function has run-time features (e.g., try-catch, assertions*, virtual**, static***, non- constexpr functions, et .), it will be evaluated at run-time.
[*: allowed since C++14 (*), C++20 (**), C++23 (***)]

14.2. `constexpr` – Generalized constant expressions

`constexpr` non-static class methods of run-time objects cannot be used at compile-time if they contain data members or non-compile-time functions:

```
class A {
 public:
  int v = 3;
  constexpr int f() const { return v; }
  static constexpr int g() { return 3; }
};
```

```
A a1;
// constexpr int x = a1.f();  // compile error, f() not constexpr
constexpr int y = a1.g(); // works, same as 'A::g()' since g() is static
constexpr A a2;
constexpr int z = a2.f(); // works
```

14.2. `constexpr` – Generalized constant expressions

Since C++17, **`if constexpr`** can be used to compile code on a condition:

```
auto f() {
  if constexpr (__cplusplus == 202101L)  // __cplusplus macro holds c++ version
    return "C++23";   // const char*
  else
    return 3;  // int, returned when c++ version is not 20
}
```

Since C++20, two more keywords can be used:

- **`consteval`** guarantees compile-time evaluation and will produce an error when run-time arguments are supplied
- **`constinit`** guarantees compile-time initialization of variables and will produce an error when run-time arguments are supplied. This is weaker than **`constexpr`**, since the initialized variable *can* change its value later.

14.3. Move semantics

In C++, ***the rule of three*** is a guideline, which states that if a class defines any of the following three, then it should explicitly define all three:
(1) destructor, (2) copy constructor, and (3) copy assignment operator
to avoid their default implementation during compilation (which is usually incorrect).

Since C++11, ***the rule of five*** expands this for these two additional special *move semantics* methods:
(4) move constructor, and (5) move assignment operator
for the same reason.

More details: https://en.cppreference.com/w/cpp/language/rule_of_three

14.3. Move semantics

Example: OwnString class

OwnString_v1.cpp

```
class OwnString {
 public:
  OwnString(const char * p);                  // constructor with C string

  ~OwnString();                               // 1. Destructor
  OwnString(const OwnString & that);          // 2. Copy constructor
  OwnString & operator=(OwnString & that);// 3. Assignment operator

  // friend method that returns a reference to a concatenated string:
  friend OwnString & operator+(const OwnString & s1, const OwnString & s2);
  void show() { std::cout << data << '\n'; }

 private:
  char * data;
};
```

14.3. Move semantics

Example: OwnString class

OwnString_v1.cpp

```
OwnString::OwnString(const char * p) {
  size_t size = std::strlen(p) + 1;
  data = new char[size];
  std::memcpy(data, p, size);
}

OwnString::~OwnString() { delete[] data; }

OwnString::OwnString(const OwnString & that) {
  size_t size = std::strlen(that.data) + 1;
  data = new char[size];
  std::memcpy(data, that.data, size);  // deep copy of that.data to data
}

OwnString & OwnString::operator=(OwnString & that) {
  std::swap(data, that.data);  // see copy-swap idiom
  return *this;
}
```

14.3. Move semantics

Example: OwnString class

OwnString_v1.cpp

```
// friend operator:
OwnString & operator+(const OwnString & s1, const OwnString & s2) {
  size_t size = std::strlen(s1.data) + std::strlen(s2.data) + 1;
  char * data = new char[size];
  std::memcpy(data, s1.data, std::strlen(s1.data));
  std::memcpy(data+std::strlen(s1.data), s2.data, std::strlen(s2.data));
  OwnString * s = new OwnString(data);
  return * s;
}
```

14.3. Move semantics

Example: OwnString class

OwnString_v1.cpp

```
int main() {
  OwnString s1("ping!");  // s1 is an object from C string
  OwnString s2(s1);       // s2's copy constructor from s1: lvalue
  OwnString s3(s1+s2);    // s3's copy constructor from s1+s2: rvalue?
  s1.show(); s2.show(); s3.show();
  return 0;
}
```

In the above, **s1** as a parameter to s2's copy constructor is an **lvalue**.
(s1+s2) as a parameter for s3's copy constructor *could* be an **rvalue**, a temporary object that is removed after the statement on that line is finished.
If it were an **rvalue**, the move constructor would be called instead of the copy constructor, allowing for better performance: see next slides.

14.3. Move semantics

Example: OwnString class, *with* move constructor: Note the differences

OwnString_v2.cpp

```
class OwnString {
 public:
  OwnString(const char * p);                  // constructor with C string
  ~OwnString();                               // 1. Destructor
  OwnString(const OwnString & that);          // 2. Copy constructor
  OwnString & operator=(OwnString that);      // 3. Assignment operator (no ref)
  OwnString(OwnString&& that);                // move constructor: OwnString&&
                                              //         is an rvalue reference
  // friend method that returns an rvalue :
  friend OwnString && operator+(const OwnString & s1, const OwnString & s2);
  void show() { std::cout << data << '\n'; }
 private:
  char * data;
};
```

14.3. Move semantics

Example: OwnString class

OwnString_v2.cpp

```
// copy constructor:
OwnString::OwnString(const OwnString & that) {
  size_t size = std::strlen(that.data) + 1;
  data = new char[size];                  // deep copy of that.data to data
  std::memcpy(data, that.data, size);  // lots of work
}


// move constructor:
OwnString::OwnString(OwnString&& that) {  // OwnString&& is an rvalue
  data = that.data;                        // reference to a string
  that.data = nullptr;    // note the simplicity (versus copy constructor)
                          // setting the that.data pointer to null avoids
                          // that's destructor removing the data
}
```

14.3. Move semantics

Example: OwnString class, *with* move constructor

OwnString_v2.cpp

```
// friend operator returning an rvalue:
OwnString && operator+(const OwnString & s1, const OwnString & s2) {
  size_t size = std::strlen(s1.data) + std::strlen(s2.data) + 1;
  char * data = new char[size];
  std::memcpy(data, s1.data, std::strlen(s1.data));
  std::memcpy(data+std::strlen(s1.data), s2.data, std::strlen(s2.data));
  OwnString * s = new OwnString(data);
  return std::move(* s);  // std::move will set to rvalue
}
```

14.3. Move semantics

Example: OwnString class, *with* move constructor

OwnString_v2.cpp

```
int main() {
  OwnString s1("ping!");  // s1 is an object from C string
  OwnString s2(s1);       // s2's copy constructor from s1 (an lvalue)
  OwnString s3(s1+s2);    // s3's move constructor from s1+s2 (an rvalue)
  OwnString s4=s3+s1;     // s4's assignment operator on move constructor
                          //  of s3+s1 (an rvalue)
  s1.show(); s2.show(); s3.show(); s4.show();
  return 0;
}
```

In the above, **s1** as a parameter to s2's copy constructor is an **lvalue**, whereas **(s1+s2)** as a parameter to s3's move constructor is an **rvalue**, a temporary object that is removed after the move constructor is finished.

14.4. Measuring Time

For measuring how long a program needed to perform a task, there are three types of time measurement:

- **Wall-Clock/Real time**: Human-perceived passage of time from the start to the completion of a task (includes other processes taking resources, too)
- **User/CPU time**: The time spent by the CPU to process user code
- **System time**: The time spent by the CPU to process system calls (including I/O calls) executed into kernel code

14.4. Measuring Time - Wall-clock time

On Linux / MacOSX (resolution in microseconds):

WallClock.cpp

```
#include <time.h>       //struct timeval
#include <sys/time.h>   //gettimeofday()
#include <iostream>

int main() {
  struct timeval start, end;  // struct timeval {second, microseconds}
  ::gettimeofday(&start, NULL);
  double ret = 0;
  for (int i=0; i<0xFFFFF; i++) { ret += ret*0.3; }  // task to be measured
  ::gettimeofday(&end, NULL);
  long start_time = start.tv_sec * 1000000 + start.tv_usec;
  long end_time = end.tv_sec * 1000000 + end.tv_usec;
  std::cout << "Time: " << end_time - start_time << " microsecs.\n";
  return 0;
}
```

14.4. Measuring Time - User time

Using **`std::clock`** (resolution in nanoseconds):

UserTime.cpp

```
#include <chrono>  // clock_t, std::clock
#include <iostream>

int main() {
  clock_t start_time = std::clock();
  double ret = 0;
  for (int i=0; i<0xFFFFF; i++) { ret += ret*0.3; }  // task to be measured
  clock_t end_time = std::clock();
  float diff = static_cast<float>(end_time - start_time);  // static_cast
  diff /= CLOCKS_PER_SEC;  // POSIX-defined as 1000000
  std::cout << "Time: " << 1000*diff << " milliseconds \n";
  return 0;
}
```

14.4. Measuring Time - User & System time

Using <sys/times.h> (resolution in milliseconds):

UserSystemTime.cpp

```
#include <unistd.h>  // _SC_CLK_TCLK
#include <sys/times.h>  // struct ::tms
#include <iostream>
int main() {
  double ret = 0;
  struct ::tms start_time, end_time;
  ::times(&start_time);
  for (long i=0; i<0xFFFFFFFF; i++) { ret += ret*0.3; }  // task to measure
  ::times(&end_time);
  auto user_diff = end_time.tms_utime - start_time.tms_utime;
  auto sys_diff = end_time.tms_stime - start_time.tms_stime;
  float user = static_cast<float>(user_diff) / ::sysconf(_SC_CLK_TCK);
  float system = static_cast<float>(sys_diff) / ::sysconf(_SC_CLK_TCK);
  std::cout << "User Time:   " << user << " seconds \n";
  std::cout << "System Time: " << system << " seconds \n";
  return 0;
}
```