

HEP C++ course

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Foreword

What this course is not

- It is not for absolute beginners
- It is not for experts
- It is not complete at all (would need 3 weeks...)
 - although it is already too long for the time we have
 - 252 slides, 347 pages, 13 exercises...

How I see it

Adaptative pick what you want

Interactive tell me what to skip/insist on

Practical let's spend time on real code

Where to find latest version ?

- full sources at github.com/hsf-training/cpluspluscourse
- latest pdf on [GitHub](#)



More courses

The HSF Software Training Center

A set of course modules on more software engineering aspects prepared from within the HEP community

- Unix shell
- Python
- Version control (git, gitlab, github)
- ...

<https://hepsoftwarefoundation.org/training/curriculum.html>



Outline

- 1 History and goals
- 2 Language basics
- 3 Object orientation (OO)
- 4 Core modern C++
- 5 Useful tools



Detailed outline

- 1 History and goals
 - History
 - Why we use it?
- 2 Language basics
 - Core syntax and types
 - Arrays and Pointers
 - Scopes / namespaces
 - Class and enum types
 - References
 - Functions
 - Operators
 - Control structures
- 3 Object orientation (OO)
 - Objects and Classes
 - Inheritance
 - Constructors/destructors
 - Static members
 - Allocating objects
 - Advanced OO
 - Operator overloading
 - Function objects
- 4 Core modern C++
 - Headers and interfaces
 - Auto keyword
- 5 Useful tools
 - Constness
 - Exceptions
 - Templates
 - Lambdas
 - The STL
 - RAII and smart pointers



History and goals

- 1 History and goals
 - History
 - Why we use it?
- 2 Language basics
- 3 Object orientation (OO)
- 4 Core modern C⁺⁺
- 5 Useful tools

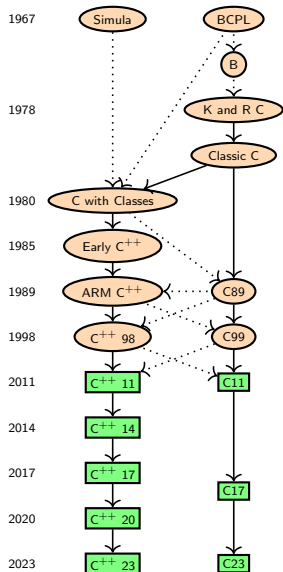


History

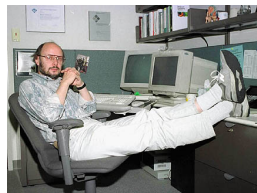
- 1 History and goals
 - History
 - Why we use it?



C/C++ origins



C inventor
Dennis M. Ritchie



C++ inventor
Bjarne Stroustrup

- Both C and C++ are born in Bell Labs
- C++ *almost* embeds C
- C and C++ are still under development
- We will discuss all C++ specs up to C++ 20 (only partially)
- Each slide will be marked with first spec introducing the feature



C++ 11, C++ 14, C++ 17, C++ 20, C++ 23, C++ 26...

Status

- A new C++ specification every 3 years
 - C++ 23 complete since 11th of Feb. 2023, awaiting ISO ballot
 - work on C++ 26 has begun
- Bringing each time a lot of goodies



C++ 11, C++ 14, C++ 17, C++ 20, C++ 23, C++ 26...

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How to use C++ XX features

- Use a compatible compiler
- add `-std=c++xx` to compilation flags
- e.g. `-std=c++17`

C++	gcc	clang
11	≥4.8	≥3.3
14	≥4.9	≥3.4
17	≥7.3	≥5
20	>11	>12

Table: Minimum versions of gcc and clang for a given C++ version



Why we use it?

- 1 History and goals
 - History
 - Why we use it?



Why is C++ our language of choice?

Adapted to large projects

- statically and strongly typed
- object oriented
- widely used (and taught)
- many available libraries



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Fast

- compiled (unlike Java, C#, Python, ...)
- allows to go close to hardware when needed



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- many available libraries

Fast

- compiled (unlike Java, C#, Python, ...)
- allows to go close to hardware when needed

What we get

- the most powerful language
- the most complicated one
- the most error prone?



Language basics

1 History and goals

2 Language basics

- Core syntax and types
- Arrays and Pointers
- Scopes / namespaces
- Class and enum types
- References
- Functions

- Operators
- Control structures
- Headers and interfaces
- Auto keyword

3 Object orientation (OO)

4 Core modern C++

5 Useful tools



Core syntax and types

- 2 Language basics
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Hello World

C++ 98

```
1  #include <iostream>
2
3  // This is a function
4  void print(int i) {
5      std::cout << "Hello, world " << i << std::endl;
6  }
7
8  int main(int argc, char** argv) {
9      int n = 3;
10     for (int i = 0; i < n; i++) {
11         print(i);
12     }
13     return 0;
14 }
```



Comments

```
1 // simple comment until end of line
2 int i;
3
4 /* multiline comment
5  * in case we need to say more
6  */
7 double /* or something in between */ d;
8
9 /**
10  * Best choice : doxygen compatible comments
11  * \brief checks whether i is odd
12  * \param i input
13  * \return true if i is odd, otherwise false
14  * \see https://www.doxygen.nl/manual/docblocks.html
15  */
16 bool isOdd(int i);
```



Basic types(1)

C++ 98

```
1  bool b = true;           // boolean, true or false
2
3  char c = 'a';           // min 8 bit integer
4                          // may be signed or not
5                          // can store an ASCII character
6  signed char c = 4;      // min 8 bit signed integer
7  unsigned char c = 4;    // min 8 bit unsigned integer
8
9  char* s = "a C string"; // array of chars ended by \0
10 string t = "a C++ string"; // class provided by the STL
11
12 short int s = -444;      // min 16 bit signed integer
13 unsigned short s = 444; // min 16 bit unsigned integer
14 short s = -444;         // int is optional
```



Basic types(2)

C++ 98

```
1  int i = -123456;           // min 16, usually 32 bit
2  unsigned int i = 1234567; // min 16, usually 32 bit
3
4  long l = 0L               // min 32 bit
5  unsigned long l = 0UL;   // min 32 bit
6
7  long long ll = 0LL;      // min 64 bit
8  unsigned long long l = 0ULL; // min 64 bit
9
10 float f = 1.23f;        // 32 (1+8+23) bit float
11 double d = 1.23E34;    // 64 (1+11+52) bit float
12 long double ld = 1.23E34L // min 64 bit float
```



Portable numeric types

C++ 98

```
1  #include <cstdint> // defines the following:
2
3  std::int8_t c = -3;    // 8 bit signed integer
4  std::uint8_t c = 4;   // 8 bit unsigned integer
5
6  std::int16_t s = -444; // 16 bit signed integer
7  std::uint16_t s = 444; // 16 bit unsigned integer
8
9  std::int32_t s = -674; // 32 bit signed integer
10 std::uint32_t s = 674; // 32 bit unsigned integer
11
12 std::int64_t s = -1635; // 64 bit signed integer
13 std::uint64_t s = 1635; // 64 bit unsigned int
```



Integer literals

```

1  int i = 1234;           // decimal      (base 10)
2  int i = 02322;         // octal      (base 8)
3  int i = 0x4d2;         // hexadecimal (base 16)
4  int i = 0X4D2;         // hexadecimal (base 16)
5  int i = 0b10011010010; // binary      (base 2) C++14
6
7  int i = 123'456'789;   // digit separators, C++14
8  int i = 0b100'1101'0010; // digit separators, C++14
9
10 42           // int
11 42u, 42U     // unsigned int
12 42l, 42L     // long
13 42ul, 42UL   // unsigned long
14 42ll, 42LL   // long long
15 42ull, 42ULL // unsigned long long

```



Floating-point literals

```

1  double d = 12.34;
2  double d = 12.;
3  double d = .34;
4  double d = 12e34;           // 12 * 10^34
5  double d = 12E34;         // 12 * 10^34
6  double d = 12e-34;        // 12 * 10^-34
7  double d = 12.34e34;      // 12.34 * 10^34
8
9  double d = 123'456.789'101; // digit separators, C++14
10
11 double d = 0x4d2.4p3;      // hexfloat, 0x4d2.4 * 2^3
12                             // = 1234.25 * 2^3 = 9874
13
14 3.14f, 3.14F, // float
15 3.14, 3.14, // double
16 3.14l, 3.14L, // long double

```



Arrays and Pointers

- 2 Language basics
 - Core syntax and types
 - Arrays and Pointers
 - Scopes / namespaces
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 - Auto keyword



Static arrays

```
1  int ai[4] = {1,2,3,4};
2  int ai[] = {1,2,3,4}; // identical
3
4  char ac[3] = {'a','b','c'}; // char array
5  char ac[4] = "abc"; // valid C string
6  char ac[4] = {'a','b','c',0}; // same valid string
7
8  int i = ai[2]; // i = 3
9  char c = ac[8]; // at best garbage, may segfault
10 int i = ai[4]; // also garbage !
```



```
1  int i = 4;
2  int *pi = &i;
3  int j = *pi + 1;
4
5  int ai[] = {1,2,3};
6  int *pai = ai; // decay to ptr
7  int *paj = pai + 1;
8  int k = *paj + 1;
9
10 // compile error
11 int *pak = k;
12
13 // seg fault !
14 int *pak = (int*)k;
15 int l = *pak;
```



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Memory layout

	0x3028
	0x3024
	0x3020
	0x301C
	0x3018
	0x3014
	0x3010
	0x300C
	0x3008
	0x3004
i = 4	0x3000

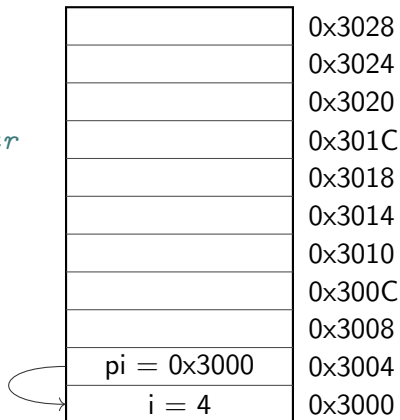


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Memory layout



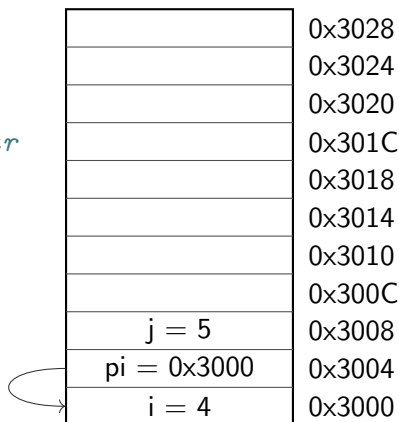
Pointers

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Memory layout



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	0x3020
	0x301C
	0x3018
ai[2] = 3	0x3014
ai[1] = 2	0x3010
ai[0] = 1	0x300C
j = 5	0x3008
pi = 0x3000	0x3004
i = 4	0x3000



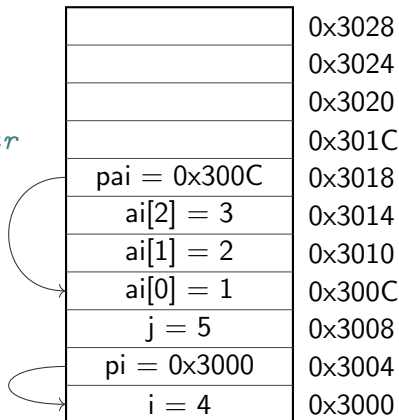
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Memory layout



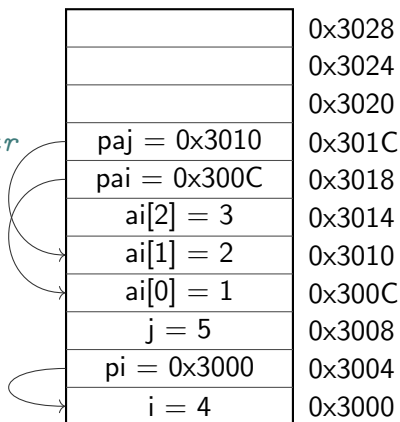
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Memory layout



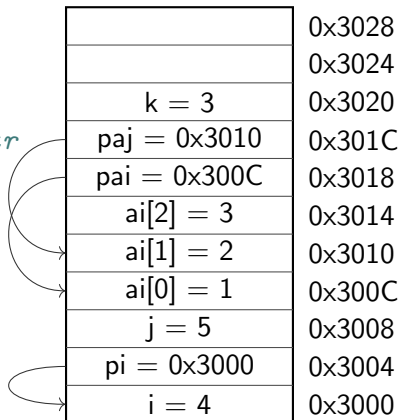
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Memory layout



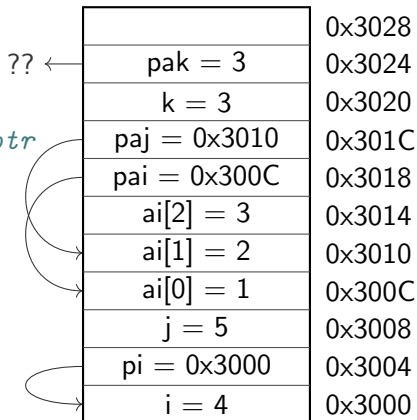
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Memory layout



A pointer to nothing

- if a pointer doesn't point to anything, set it to `nullptr`
 - useful to e.g. mark the end of a linked data structure
 - or absence of an optional function argument (pointer)
- same as setting it to 0 or `NULL` (before C++ 11)
- triggers compilation error when assigned to integer



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- triggers compilation error when assigned to integer

Example code

```
1  int* ip = nullptr;
2  int i = NULL;      // compiles, bug?
3  int i = nullptr;  // ERROR
```



Dynamic arrays using C

C++ 98

```
1  #include <cstdlib>
2  #include <cstring>
3
4  int *bad;           // pointer to random address
5  int *ai = nullptr; // better, deterministic, testable
6
7  // allocate array of 10 ints (uninitialized)
8  ai = (int*) malloc(10*sizeof(int));
9  memset(ai, 0, 10*sizeof(int)); // and set them to 0
10
11 ai = (int*) calloc(10, sizeof(int)); // both in one go
12
13 free(ai); // release memory
```

Good practice: Don't use C's memory management

Use `std::vector` and friends or smart pointers



Manual dynamic arrays using C++

C++ 98

```
1  #include <cstdlib>
2  #include <cstring>
3
4  // allocate array of 10 ints
5  int* ai = new int[10]; // uninitialized
6  int* ai = new int[10]{}; // zero-initialized
7
8  delete[] ai; // release array memory
9
10 // allocate a single int
11 int* pi = new int;
12 int* pi = new int{};
13 delete pi; // release scalar memory
```

Good practice: Don't use manual memory management

Use `std::vector` and friends or smart pointers



Scopes / namespaces

- 2 Language basics
 - Core syntax and types
 - Arrays and Pointers
 - **Scopes / namespaces**
 - Class and enum types
 - References
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Definition

Portion of the source code where a given name is valid

Typically :

- simple block of code, within {}
- function, class, namespace
- the global scope, i.e. translation unit (.cpp file + all includes)

Example

```
1 { int a;  
2   { int b;  
3     } // end of b scope  
4 } // end of a scope
```



Scope and lifetime of variables

C++ 98

Variable life time

- Variables are (statically) allocated when defined
- Variables are freed at the end of a scope

Good practice: Initialisation

- Initialise variables when allocating them!
- This prevents bugs reading uninitialised memory

```

1  int a = 1;
2  {
3      int b[4];
4      b[0] = a;
5  }
6  // Doesn't compile here:
7  // b[1] = a + 1;

```

Memory layout

	0x3010
	0x300C
	0x3008
	0x3004
a = 1	0x3000



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C++ 98

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Memory layout

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?	0x3010
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Namespaces

- Namespaces allow to segment your code to avoid name clashes
- They can be embedded to create hierarchies (separator is '::')

```

1  int a;
2  namespace n {
3      int a;    // no clash
4  }
5  namespace p {
6      int a;    // no clash
7      namespace inner {
8          int a; // no clash
9      }
10 }
11 void f() {
12     n::a = 3;
13 }
14 namespace p { // reopen p
15     void f() {
16         p::a = 6;
17         a = 6; //same as above
18         ::a = 1;
19         p::inner::a = 8;
20         inner::a = 8;
21         n::a = 3;
22     }
23 }
24 using namespace p::inner;
25 void g() {
26     a = -1; // err: ambiguous
27 }

```



Nested namespaces

C++ 17

Easier way to declare nested namespaces

C++ 98

```
1 namespace A {
2     namespace B {
3         namespace C {
4             //...
5         }
6     }
7 }
```

C++ 17

```
1 namespace A::B::C {
2     //...
3 }
```



Class and enum types

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“members” grouped together under one name

```
1  struct Individual {           14  Individual *ptr = &student;
2      unsigned char age;       15  ptr->age = 25;
3      float weight;           16  // same as: (*ptr).age = 25;
4  };
5
6  Individual student;
7  student.age = 25;
8  student.weight = 78.5f;
9
10 Individual teacher = {
11     45, 67.0f
12 };
```



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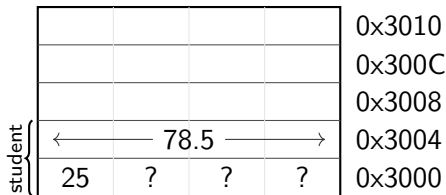
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Memory layout



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```

Memory layout

					0x3010
student teacher	←	67.0	→		0x300C
	45	?	?	?	0x3008
	←	78.5	→		0x3004
	25	?	?	?	0x3000



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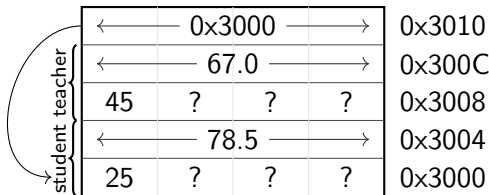
```

```

14 Individual *ptr = &student;
15 ptr->age = 25;
16 // same as: (*ptr).age = 25;

```

Memory layout



“members” packed together at same memory location

```
1 union Duration {
2     int seconds;
3     short hours;
4     char days;
5 };
6 Duration d1, d2, d3;
7 d1.seconds = 259200;
8 d2.hours = 72;
9 d3.days = 3;
10 d1.days = 3; // d1.seconds overwritten
11 int a = d1.seconds; // d1.seconds is garbage
```



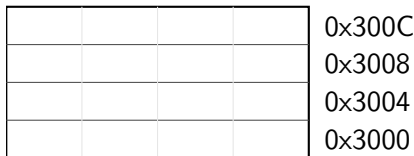
“members” packed together at same memory location

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```

Memory layout



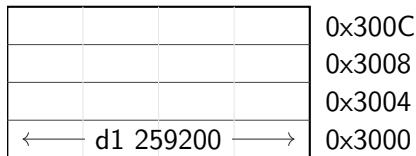
“members” packed together at same memory location

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4      char days;
5  };
6  Duration d1, d2, d3;
7  d1.seconds = 259200;
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```

Memory layout



“members” packed together at same memory location

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4     char days;
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```

Memory layout

				0x300C
				0x3008
←	d2 72	→	? ?	0x3004
←	d1 259200		→	0x3000



“members” packed together at same memory location

```

1  union Duration {
2      int seconds;
3      short hours;
4      char days;
5  };
6  Duration d1, d2, d3;
7  d1.seconds = 259200;
8  d2.hours = 72;
9  d3.days = 3;
10 d1.days = 3; // d1.seconds overwritten
11 int a = d1.seconds; // d1.seconds is garbage

```

Memory layout

				0x300C
d3 3	?	?	?	0x3008
← d2 72 →	?	?		0x3004
←———— d1 259200 —————→				0x3000



“members” packed together at same memory location

```

1  union Duration {
2      int seconds;
3      short hours;
4      char days;
5  };
6  Duration d1, d2, d3;
7  d1.seconds = 259200;
8  d2.hours = 72;
9  d3.days = 3;
10 d1.days = 3; // d1.seconds overwritten
11 int a = d1.seconds; // d1.seconds is garbage

```

Memory layout

				0x300C
d3 3	?	?	?	0x3008
← d2 72 →	?	?		0x3004
d1 3	?	?	?	0x3000



“members” packed together at same memory location

```

1  union Duration {
2      int seconds;
3      short hours;
4      char days;
5  };
6  Duration d1, d2, d3;
7  d1.seconds = 259200;
8  d2.hours = 72;
9  d3.days = 3;
10 d1.days = 3; // d1.seconds overwritten
11 int a = d1.seconds; // d1.seconds is garbage

```

Memory layout

				0x300C
d3 3	?	?	?	0x3008
← d2 72 →	?	?		0x3004
d1 3	?	?	?	0x3000

Good practice: Avoid unions

- Starting with C++ 17: prefer `std::variant`



- use to declare a list of related constants (enumerators)
- has an underlying integral type
- enumerator names leak into enclosing scope

```
1 enum VehicleType {
2
3     BIKE, // 0
4     CAR,  // 1
5     BUS,  // 2
6 };
7 VehicleType t = CAR;
```

```
8 enum VehicleType
9     : int { // C++11
10     BIKE = 3,
11     CAR = 5,
12     BUS = 7,
13 };
14 VehicleType t2 = BUS;
```



Scoped enumeration, aka enum class

C++ 11

Same syntax as enum, with scope

```
1  enum class VehicleType { Bus, Car };  
2  VehicleType t = VehicleType::Car;
```



Scoped enumeration, aka enum class

Same syntax as enum, with scope

```
1 enum class VehicleType { Bus, Car };
2 VehicleType t = VehicleType::Car;
```

Only advantages

- scopes enumerator names, avoids name clashes
- strong typing, no automatic conversion to int

```
3 enum VType { Bus, Car }; enum Color { Red, Blue };
4 VType t = Bus;
5 if (t == Red) { /* We do enter */ }
6 int a = 5 * Car; // Ok, a = 5
7
8 enum class VT { Bus, Car }; enum class Col { Red, Blue };
9 VT t = VT::Bus;
10 if (t == Col::Red) { /* Compiler error */ }
11 int a = t * 5; // Compiler error
```



More sensible example

C++ 98

```
1  enum class ShapeType {
2      Circle,
3      Rectangle
4  };
5
6  struct Rectangle {
7      float width;
8      float height;
9  };
```



More sensible example

C++ 98

```
1  enum class ShapeType {      10  struct Shape {
2      Circle,                11      ShapeType type;
3      Rectangle              12      union {
4  };                          13          float radius;
5                               14          Rectangle rect;
6  struct Rectangle {         15      };
7      float width;          16  };
8      float height;
9  };
```



More sensible example

C++ 98

```

1  enum class ShapeType {
2      Circle,
3      Rectangle
4  };
5
6  struct Rectangle {
7      float width;
8      float height;
9  };
10
17 Shape s;
18 s.type =
19     ShapeType::Circle;
20 s.radius = 3.4;
21
10 struct Shape {
11     ShapeType type;
12     union {
13         float radius;
14         Rectangle rect;
15     };
16 };
20 Shape t;
21 t.type =
22     Shapetype::Rectangle;
23 t.rect.width = 3;
24 t.rect.height = 4;

```



typedef and using

C++ 98 / C++ 11

Used to create type aliases

C++ 98

```
1 typedef std::uint64_t myint;  
2 myint count = 17;  
3 typedef float position[3];
```

C++ 11

```
4 using myint = std::uint64_t;  
5 myint count = 17;  
6 using position = float[3];  
7  
8 template <typename T> using myvec = std::vector<T>;  
9 myvec<int> myintvec;
```



References

- 2 Language basics
 - Core syntax and types
 - Arrays and Pointers
 - Scopes / namespaces
 - Class and enum types
 - **References**
 - Functions
 - Operators
 - Control structures
 - Headers and interfaces
 - Auto keyword



References

- References allow for direct access to another object
- They can be used as shortcuts / better readability
- They can be declared `const` to allow only read access

Example:

```
1 int i = 2;
2 int &ieref = i; // access to i
3 ieref = 3;     // i is now 3
4
5 // const reference to a member:
6 struct A { int x; int y; } a;
7 const int &x = a.x; // direct read access to A's x
8 x = 4;              // doesn't compile
9 a.x = 4;           // fine
```



Specificities of reference

- Natural syntax
- Cannot be `nullptr`
- Must be assigned when defined, cannot be reassigned
- References to temporary objects must be `const`

Advantages of pointers

- Can be `nullptr`
- Can be initialized after declaration, can be reassigned



Specificities of reference

- Natural syntax
- Cannot be `nullptr`
- Must be assigned when defined, cannot be reassigned
- References to temporary objects must be `const`

Advantages of pointers

- Can be `nullptr`
- Can be initialized after declaration, can be reassigned

Good practice: References

- Prefer using references instead of pointers
- Mark references `const` to prevent modification



Functions

- 2 Language basics
 - Core syntax and types
 - Arrays and Pointers
 - Scopes / namespaces
 - Class and enum types
 - References
 - **Functions**
 - Operators
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Functions

```
1 // with return type
2 int square(int a) {
3     return a * a;
4 }
5
6 // multiple parameters
7 int mult(int a,
8         int b) {
9     return a * b;
10 }
11 // no return
12 void log(char* msg) {
13     std::cout << msg;
14 }
15
16 // no parameter
17 void hello() {
18     std::cout << "Hello World";
19 }
```




```

1 // with return type          11 // no return
2 int square(int a) {         12 void log(char* msg) {
3     return a * a;          13     std::cout << msg;
4 }                            14 }
5                               15
6 // multiple parameters     16 // no parameter
7 int mult(int a,            17 void hello() {
8     int b) {               18     std::cout << "Hello World";
9     return a * b;          19 }
10 }

```

Functions and references to returned values

```

1 int result = square(2);
2 int & temp = square(2); // Not allowed
3 int const & temp2 = square(2); // OK

```



Function default arguments

```
1 // must be the trailing      11 // multiple default
2 // argument                  12 // arguments are possible
3 int add(int a,              13 int add(int a = 2,
4     int b = 2) {           14     int b = 2) {
5     return a + b;          15     return a + b;
6 }                            16 }
7 // add(1) == 3              17 // add() == 4
8 // add(3,4) == 7            18 // add(3) == 5
9
```



Functions: parameters are passed by value

```

1  struct BigStruct {...};
2  BigStruct s;
3
4  // parameter by value
5  void printVal(BigStruct p) {
6      ...
7  }
8  printVal(s); // copy
9
10 // parameter by reference
11 void printRef(BigStruct &q) {
12     ...
13 }
14 printRef(s); // no copy

```

Memory layout

	0x31E0
	0x3190
	0x3140
	0x30F0
	0x30A0
	0x3050
	0x3000



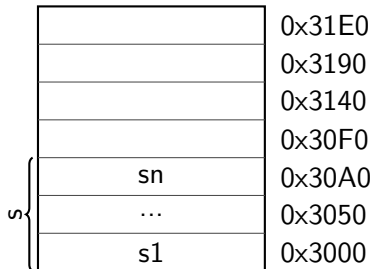
Functions: parameters are passed by value

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3
4  // parameter by value
5  void printVal(BigStruct p) {
6      ...
7  }
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9
10 // parameter by reference
11 void printRef(BigStruct &q) {
12     ...
13 }
14 printRef(s); // no copy

```

Memory layout



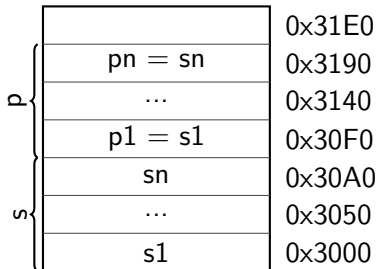
Functions: parameters are passed by value

```

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3
4  // parameter by value
5  void printVal(BigStruct p) {
6      ...
7  }
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10 // parameter by reference
11 void printRef(BigStruct &q) {
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```

Memory layout



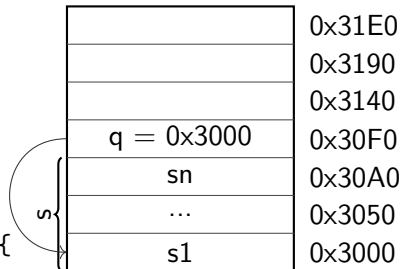
Functions: parameters are passed by value

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2  BigStruct s;
3
4  // parameter by value
5  void printVal(BigStruct p) {
6      ...
7  }
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9
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11 void printRef(BigStruct &q) {
12     ...
13 }
14 printRef(s); // no copy

```

Memory layout



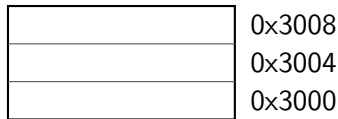
Functions: pass by value or reference?

```

1  struct SmallStruct {int a;};
2  SmallStruct s = {1};
3
4  void changeVal(SmallStruct p) {
5      p.a = 2;
6  }
7  changeVal(s);
8  // s.a == 1
9
10 void changeRef(SmallStruct &q) {
11     q.a = 2;
12 }
13 changeRef(s);
14 // s.a == 2

```

Memory layout



Functions: pass by value or reference?

```

1  struct SmallStruct {int a;};
2  SmallStruct s = {1};
3
4  void changeVal(SmallStruct p) {
5      p.a = 2;
6  }
7  changeVal(s);
8  // s.a == 1
9
10 void changeRef(SmallStruct &q) {
11     q.a = 2;
12 }
13 changeRef(s);
14 // s.a == 2

```

Memory layout

	0x3008
	0x3004
s.a = 1	0x3000



Functions: pass by value or reference?

```

1  struct SmallStruct {int a;};
2  SmallStruct s = {1};
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6  }
7  changeVal(s);
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10 void changeRef(SmallStruct &q) {
11     q.a = 2;
12 }
13 changeRef(s);
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```

Memory layout

	0x3008
p.a = 1	0x3004
s.a = 1	0x3000



Functions: pass by value or reference?

```

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5      p.a = 2;
6  }
7  changeVal(s);
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9
10 void changeRef(SmallStruct &q) {
11     q.a = 2;
12 }
13 changeRef(s);
14 // s.a == 2

```

Memory layout

	0x3008
p.a = 2	0x3004
s.a = 1	0x3000



Functions: pass by value or reference?

```

1  struct SmallStruct {int a;};
2  SmallStruct s = {1};
3
4  void changeVal(SmallStruct p) {
5      p.a = 2;
6  }
7  changeVal(s);
8  // s.a == 1
9
10 void changeRef(SmallStruct &q) {
11     q.a = 2;
12 }
13 changeRef(s);
14 // s.a == 2

```

Memory layout

	0x3008
	0x3004
s.a = 1	0x3000



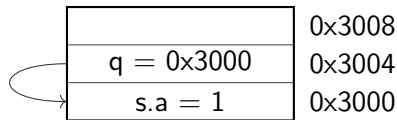
Functions: pass by value or reference?

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3
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6  }
7  changeVal(s);
8  // s.a == 1
9
10 void changeRef(SmallStruct &q) {
11     q.a = 2;
12 }
13 changeRef(s);
14 // s.a == 2

```

Memory layout



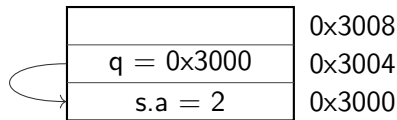
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3
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6  }
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12 }
13 changeRef(s);
14 // s.a == 2

```

Memory layout



Functions: pass by value or reference?

```

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2  SmallStruct s = {1};
3
4  void changeVal(SmallStruct p) {
5      p.a = 2;
6  }
7  changeVal(s);
8  // s.a == 1
9
10 void changeRef(SmallStruct &q) {
11     q.a = 2;
12 }
13 changeRef(s);
14 // s.a == 2

```

Memory layout

	0x3008
	0x3004
s.a = 2	0x3000



Pass by value, reference or pointer

C++ 98

Different ways to pass arguments to a function

- By default, arguments are passed by value (= copy)
good for small types, e.g. numbers
- Use references for parameters to avoid copies
good for large types, e.g. objects
- Use `const` for safety and readability whenever possible



Pass by value, reference or pointer

Different ways to pass arguments to a function

- By default, arguments are passed by value (= copy)
good for small types, e.g. numbers
- Use references for parameters to avoid copies
good for large types, e.g. objects
- Use `const` for safety and readability whenever possible

Syntax

```

1 struct T {...}; T a;
2 void fVal(T value);      fVal(a);    // by value
3 void fRef(const T &value); fRef(a);  // by reference
4 void fPtr(const T *value); fPtr(&a);  // by pointer
5 void fWrite(T &value);   fWrite(a); // non-const ref

```



Overloading

- We can have multiple functions with the same name
 - Must have different parameter lists
 - A different return type alone is not allowed
 - Form a so-called “overload set”
- Default arguments can cause ambiguities

```
1  int sum(int b);           // 1
2  int sum(int b, int c);   // 2, ok, overload
3  // float sum(int b, int c); // disallowed
4  sum(42); // calls 1
5  sum(42, 43); // calls 2
6  int sum(int b, int c, int d = 4); // 3, overload
7  sum(42, 43, 44); // calls 3
8  sum(42, 43); // error: ambiguous, 2 or 3
```



Exercise: Functions

Familiarise yourself with pass by value / pass by reference.

- Go to `exercises/functions`
- Look at `functions.cpp`
- Compile it (`make`) and run the program (`./functions`)
- Work on the tasks that you find in `functions.cpp`



Good practice: Write readable functions

- Keep functions short
- Do one logical thing (single-responsibility principle)
- Use expressive names
- Document non-trivial functions

Example: Good

```
1  /// Count number of dilepton events in data.  
2  /// \param d Dataset to search.  
3  unsigned int countDileptons(Data d) {  
4      selectEventsWithMuons(d);  
5      selectEventsWithElectrons(d);  
6      return d.size();  
7  }
```



Functions: good practices

C++ 98

Example: don't! Everything in one long function

```

1  unsigned int runJob() { 15      if (...) {
2      // Step 1: data      16          data.erase(...);
3      Data data;          17      }
4      data.resize(123456); 18  }
5      data.fill(...);     19
6                          20      // Step 4: dileptons
7      // Step 2: muons     21      int counter = 0;
8      for (...) {         22      for (...) {
9          if (...) {      23          if (...) {
10             data.erase(...); 24             counter++;
11         }                25         }
12     }                    26     }
13     // Step 3: electrons 27
14     for (...) {         28     return counter;
15     }                    29 }

```



Operators

- 2 Language basics
 - Core syntax and types
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 - **Operators**
 - Control structures
 - Headers and interfaces
 - Auto keyword



Binary and Assignment Operators

```
1  int i = 1 + 4 - 2; // 3
2  i *= 3;           // 9, short for: i = i * 3;
3  i /= 2;           // 4
4  i = 23 % i;       // modulo => 3
```



Operators(1)

Binary and Assignment Operators

```
1  int i = 1 + 4 - 2; // 3
2  i *= 3;           // 9, short for: i = i * 3;
3  i /= 2;           // 4
4  i = 23 % i;       // modulo => 3
```

Increment / Decrement Operators

```
1  int i = 0; i++; // i = 1
2  int j = ++i;   // i = 2, j = 2
3  int k = i++;   // i = 3, k = 2
4  int l = --i;   // i = 2, l = 2
5  int m = i--;   // i = 1, m = 2
```



Binary and Assignment Operators

```
1  int i = 1 + 4 - 2; // 3
2  i *= 3;           // 9, short for: i = i * 3;
3  i /= 2;           // 4
4  i = 23 % i;       // modulo => 3
```

Increment / Decrement Operators

Use wisely

```
1  int i = 0; i++; // i = 1
2  int j = ++i;   // i = 2, j = 2
3  int k = i++;   // i = 3, k = 2
4  int l = --i;   // i = 2, l = 2
5  int m = i--;   // i = 1, m = 2
```



Bitwise and Assignment Operators

```
1  unsigned i = 0xee & 0x55;    // 0x44
2  i |= 0xee;                   // 0xee
3  i ^= 0x55;                   // 0xbb
4  unsigned j = ~0xee;          // 0xffffffff11
5  unsigned k = 0x1f << 3;      // 0xf8
6  unsigned l = 0x1f >> 2;      // 0x7
```



Operators(2)

Bitwise and Assignment Operators

```
1  unsigned i = 0xee & 0x55;    // 0x44
2  i |= 0xee;                   // 0xee
3  i ^= 0x55;                   // 0xbb
4  unsigned j = ~0xee;         // 0xffffffff11
5  unsigned k = 0x1f << 3;     // 0xf8
6  unsigned l = 0x1f >> 2;     // 0x7
```

Logical Operators

```
1  bool a = true;
2  bool b = false;
3  bool c = a && b;           // false
4  bool d = a || b;          // true
5  bool e = !d;              // false
```



Comparison Operators

```
1  bool a = (3 == 3); // true
2  bool b = (3 != 3); // false
3  bool c = (4 < 4); // false
4  bool d = (4 <= 4); // true
5  bool e = (4 > 4); // false
6  bool f = (4 >= 4); // true
7  auto g = (5 <=> 5); // C++20 (later)
```



Operators(3)

C++ 98

Comparison Operators

```
1  bool a = (3 == 3); // true
2  bool b = (3 != 3); // false
3  bool c = (4 < 4); // false
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5  bool e = (4 > 4); // false
6  bool f = (4 >= 4); // true
7  auto g = (5 <=> 5); // C++20 (later)
```

Precedences

```
c &= 1+(++b) | (a--) * 4 % 5 ^ 7; // ???
```

Details can be found on [cppreference](#)



Operators(3)

Comparison Operators

```
1  bool a = (3 == 3); // true
2  bool b = (3 != 3); // false
3  bool c = (4 < 4); // false
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5  bool e = (4 > 4); // false
6  bool f = (4 >= 4); // true
7  auto g = (5 <=> 5); // C++20 (later)
```

Precedences

Avoid

```
c &= 1+(++b) | (a--) * 4 % 5 ^ 7; // ???
```

Details can be found on [cppreference](#)



Operators(3)

C++ 98

Comparison Operators

```
1  bool a = (3 == 3); // true
2  bool b = (3 != 3); // false
3  bool c = (4 < 4); // false
4  bool d = (4 <= 4); // true
5  bool e = (4 > 4); // false
6  bool f = (4 >= 4); // true
7  auto g = (5 <=> 5); // C++20 (later)
```

Precedences

Avoid - use parentheses

```
c &= 1+(++b) | (a--) * 4 % 5 ^ 7; // ???
```

Details can be found on [cppreference](#)

Control structures

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Control structures: if

if syntax

```
1  if (condition1) {  
2      Statement1; Statement2;  
3  } else if (condition2)  
4      OnlyOneStatement;  
5  else {  
6      Statement3;  
7      Statement4;  
8  }
```

- The `else` and `else if` clauses are optional
- The `else if` clause can be repeated
- Braces are optional if there is a single statement



Practical example

```
1  int collatz(int a) {
2      if (a <= 0) {
3          std::cout << "not supported\n";
4          return 0;
5      } else if (a == 1) {
6          return 1;
7      } else if (a%2 == 0) {
8          return collatz(a/2);
9      } else {
10         return collatz(3*a+1);
11     }
12 }
```



Control structures: conditional operator

C++ 98

Syntax

```
test ? expression1 : expression2;
```

- If test is **true** expression1 is returned
- Else, expression2 is returned



Control structures: conditional operator

C++ 98

Syntax

```
test ? expression1 : expression2;
```

- If test is **true** expression1 is returned
- Else, expression2 is returned

Practical example

```
1  const int charge = isLepton ? -1 : 0;
```



Control structures: conditional operator

C++ 98

Syntax

```
test ? expression1 : expression2;
```

- If test is **true** expression1 is returned
- Else, expression2 is returned

Practical example

```
1  const int charge = isLepton ? -1 : 0;
```

Do not abuse it

```
1  int collatz(int a) {  
2      return a==1 ? 1 : collatz(a%2==0 ? a/2 : 3*a+1);  
3  }
```

- Explicit **ifs** are generally easier to read
- Use the ternary operator with short conditions and expressions
- Avoid nesting



Control structures: switch

Syntax

```
1  switch(identifier) {
2      case c1 : statements1; break;
3      case c2 : statements2; break;
4      case c3 : statements3; break;
5      ...
6      default : statementsn; break;
7  }
```

- The `break` statement is not mandatory but...
- Cases are entry points, not independent pieces
- Execution “falls through” to the next case without a `break`!
- The `default` case may be omitted



Control structures: switch

Syntax

```
1  switch(identifier) {
2      case c1 : statements1; break;
3      case c2 : statements2; break;
4      case c3 : statements3; break;
5      ...
6      default : statementsn; break;
7  }
```

- The `break` statement is not mandatory but...
- Cases are entry points, not independent pieces
- Execution “falls through” to the next case without a `break`!
- The `default` case may be omitted

Use break

Avoid `switch` statements with fall-through cases



Control structures: switch

Practical example

```
1  enum class Lang { French, German, English, Other };
2  Lang language = ...;
3  switch (language) {
4      case Lang::French:
5          std::cout << "Bonjour";
6          break;
7      case Lang::German:
8          std::cout << "Guten Tag";
9          break;
10     case Lang::English:
11         std::cout << "Good morning";
12         break;
13     default:
14         std::cout << "I do not speak your language";
15 }
```



[[fallthrough]] attribute

New compiler warning

Since C++ 17, compilers are encouraged to warn on fall-through

C++ 17

```
1  switch (c) {  
2      case 'a':  
3          f();    // Warning emitted  
4      case 'b': // Warning probably suppressed  
5      case 'c':  
6          g();  
7          [[fallthrough]]; // Warning suppressed  
8      case 'd':  
9          h();  
10 }
```



Init-statements for if and switch

C++ 17

Purpose

Allows to limit variable scope in `if` and `switch` statements

C++ 17

```
1  if (Value val = GetValue(); condition(val)) {  
2    f(val); // ok  
3  } else  
4    g(val); // ok  
5  h(val); // error, no `val` in scope here
```



Init-statements for if and switch

C++ 17

Purpose

Allows to limit variable scope in `if` and `switch` statements

C++ 17

```
1  if (Value val = GetValue(); condition(val)) {  
2      f(val); // ok  
3  } else  
4      g(val); // ok  
5  h(val); // error, no `val` in scope here
```

C++ 98

Don't confuse with a variable declaration as condition:

```
7  if (Value* val = GetValuePtr())  
8      f(*val);
```



Control structures: for loop

C++ 98

for loop syntax

```
1  for(initializations; condition; increments) {  
2      statements;  
3  }
```

- Initializations and increments are comma separated
- Initializations can contain declarations
- Braces are optional if loop body is a single statement



Control structures: for loop

C++ 98

for loop syntax

```
1  for(initializations; condition; increments) {  
2      statements;  
3  }
```

- Initializations and increments are comma separated
- Initializations can contain declarations
- Braces are optional if loop body is a single statement

Practical example

```
4  for(int i = 0, j = 0 ; i < 10 ; i++, j = i*i) {  
5      std::cout << i << "^2 is " << j << '\n';  
6  }
```



Control structures: for loop

C++ 98

for loop syntax

```
1  for(initializations; condition; increments) {  
2      statements;  
3  }
```

- Initializations and increments are comma separated
- Initializations can contain declarations
- Braces are optional if loop body is a single statement

Practical example

```
4  for(int i = 0, j = 0 ; i < 10 ; i++, j = i*i) {  
5      std::cout << i << "^2 is " << j << '\n';  
6  }
```

Good practice: Don't abuse the for syntax

- The `for` loop head should fit in 1-3 lines



Range-based loops

C++ 11

Reason of being

- Simplifies loops over “ranges” tremendously
- Especially with STL containers and ranges

Syntax

```
1  for ( type iteration_variable : range ) {  
2      // body using iteration_variable  
3  }
```

Example code

```
4  int v[4] = {1,2,3,4};  
5  int sum = 0;  
6  for (int a : v) { sum += a; }
```



Init-statements for range-based loops

C++ 20

Purpose

Allows to limit variable scope in range-based loops

C++ 17

```
1  std::array data = {"hello", ",", "world"};
2  std::size_t i = 0;
3  for (auto& d : data) {
4      std::cout << i++ << ' ' << d << '\n';
5  }
```

C++ 20

```
6  for (std::size_t i = 0; auto& d : data) {
7      std::cout << i++ << ' ' << d << '\n';
8  }
```



Control structures: while loop

C++ 98

while loop syntax

```
1  while(condition) {  
2      statements;  
3  }  
4  
5  do {  
6      statements;  
7  } while(condition);
```

- Braces are optional if the body is a single statement



Control structures: while loop

while loop syntax

```
1  while(condition) {
2      statements;
3  }
4
5  do {
6      statements;
7  } while(condition);
```

- Braces are optional if the body is a single statement

Bad example

```
1  while (n != 1)
2      if (0 == n%2) n /= 2;
3      else n = 3 * n + 1;
```



Control structures: jump statements

C++ 98

- `break` Exits the loop and continues after it
- `continue` Goes immediately to next loop iteration
- `return` Exits the current function
- `goto` Can jump anywhere inside a function, avoid!



Control structures: jump statements

C++ 98

- `break` Exits the loop and continues after it
- `continue` Goes immediately to next loop iteration
- `return` Exits the current function
- `goto` Can jump anywhere inside a function, avoid!

Bad example

```
1  while (1) {  
2      if (n == 1) break;  
3      if (0 == n%2) {  
4          std::cout << n << '\n';  
5          n /= 2;  
6          continue;  
7      }  
8      n = 3 * n + 1;  
9  }
```



Exercise: Control structures

Familiarise yourself with different kinds of control structures.
Re-implement them in different ways.

- Go to `exercises/control`
- Look at `control.cpp`
- Compile it (`make`) and run the program (`./control`)
- Work on the tasks that you find in `README.md`



Headers and interfaces

- 2 Language basics
 - Core syntax and types
 - Arrays and Pointers
 - Scopes / namespaces
 - Class and enum types
 - References
 - Functions
 - Operators
 - Control structures
 - **Headers and interfaces**
 - Auto keyword



Headers and interfaces

C++ 98

Interface

Set of declarations defining some functionality

- Put in a so-called “header file”
- The implementation exists somewhere else

Header: hello.hpp

```
void printHello();
```

Usage: myfile.cpp

```
1  #include "hello.hpp"  
2  int main() {  
3      printHello();  
4  }
```



```
1 // file inclusion
2 #include "hello.hpp"
3 // macro constants and function-style macros
4 #define MY_GOLDEN_NUMBER 1746
5 #define CHECK_GOLDEN(x) if ((x) != MY_GOLDEN_NUMBER) \
6     std::cerr << #x " was not the golden number\n";
7 // compile time or platform specific configuration
8 #if defined(USE64BITS) || defined(__GNUG__)
9     using myint = std::uint64_t;
10 #elif
11     using myint = std::uint32_t;
12 #endif
```



```
1 // file inclusion
2 #include "hello.hpp"
3 // macro constants and function-style macros
4 #define MY_GOLDEN_NUMBER 1746
5 #define CHECK_GOLDEN(x) if ((x) != MY_GOLDEN_NUMBER) \
6     std::cerr << #x " was not the golden number\n";
7 // compile time or platform specific configuration
8 #if defined(USE64BITS) || defined(__GNUG__)
9     using myint = std::uint64_t;
10 #elif
11     using myint = std::uint32_t;
12 #endif
```

Good practice: Use preprocessor only in very restricted cases

- Conditional inclusion of headers
- Customization for specific compilers/platforms



Header include guards

C++ 98

Problem: redefinition by accident

- Headers may define new names (e.g. types)
- Multiple (transitive) inclusions of a header would define those names multiple times, which is a compile error
- Solution: guard the content of your headers!

Include guards

```
1  #ifndef MY_HEADER_INCLUDED  
2  #define MY_HEADER_INCLUDED  
3  ... // header file content  
4  #endif
```

Pragma once (non-standard)

```
1  #pragma once  
2  ... // header file content
```



Auto keyword

- 2 Language basics
 - Core syntax and types
 - Arrays and Pointers
 - Scopes / namespaces
 - Class and enum types
 - References
 - Functions
 - Operators
 - Control structures
 - Headers and interfaces
 - Auto keyword



Reason of being

- Many type declarations are redundant
- They are often a source for compiler warnings and errors
- Using auto prevents unwanted/unnecessary type conversions

```
1  std::vector<int> v;  
2  float a = v[3];    // conversion intended?  
3  int b = v.size(); // bug? unsigned to signed
```



Reason of being

- Many type declarations are redundant
- They are often a source for compiler warnings and errors
- Using auto prevents unwanted/unnecessary type conversions

```
1 std::vector<int> v;  
2 float a = v[3];    // conversion intended?  
3 int b = v.size(); // bug? unsigned to signed
```

Practical usage

```
1 std::vector<int> v;  
2 auto a = v[3];  
3 const auto b = v.size(); // std::size_t  
4 int sum{0};  
5 for (auto n : v) { sum += n; }
```



Exercise: Loops, references, auto

Familiarise yourself with range-based for loops and references

- Go to `exercises/loopsRefsAuto`
- Look at `loopsRefsAuto.cpp`
- Compile it (`make`) and run the program (`./loopsRefsAuto`)
- Work on the tasks that you find in `loopsRefsAuto.cpp`



Object orientation (OO)

1 History and goals

2 Language basics

3 Object orientation (OO)

- Objects and Classes
- Inheritance
- Constructors/destructors

- Static members
- Allocating objects
- Advanced OO
- Operator overloading
- Function objects

4 Core modern C++

5 Useful tools



Objects and Classes

- 3 Object orientation (OO)
 - Objects and Classes
 - Inheritance
 - Constructors/destructors
 - Static members
 - Allocating objects
 - Advanced OO
 - Operator overloading
 - Function objects



What are classes and objects

C++ 98

Classes (or “user-defined types”)

C structs on steroids

- with inheritance
- with access control
- including methods (aka. member functions)

Objects

- instances of classes

A class encapsulates state and behavior of “something”

- shows an interface
- provides its implementation
 - status, properties
 - possible interactions
 - construction and destruction



My first class

```
1  struct MyFirstClass {
2      int a;
3      void squareA() {
4          a *= a;
5      }
6      int sum(int b) {
7          return a + b;
8      }
9  };
10
11 MyFirstClass myObj;
12 myObj.a = 2;
13
14 // let's square a
15 myObj.squareA();
```

MyFirstClass
int a;
void squareA();
int sum(int b);

Separating the interface

Header: MyClass.hpp

```

1  #pragma once
2  struct MyClass {
3      int a;
4      void squareA();
5  };

```

User 1: main.cpp

```

1  #include "MyClass.hpp"
2  int main() {
3      MyClass mc;
4      ...
5  }

```

Implementation: MyClass.cpp

```

1  #include "MyClass.hpp"
2  void MyClass::squareA() {
3      a *= a;
4  }

```

User 2: fun.cpp

```

1  #include "MyClass.hpp"
2  void f(MyClass& mc) {
3      mc.squareA();
4  }

```



Good practice: Implementing methods

- usually in .cpp, outside of class declaration
- using the class name as “namespace”
- short member functions can be in the header
- some functions (templates, `constexpr`) must be in the header

```
1 void MyFirstClass::squareA() {
2     a *= a;
3 }
4
5 int MyFirstClass::sum(int b) {
6     return a + b;
7 }
```



How to know an object's address?

- Sometimes we need to pass a reference to ourself to a different entity
- For example to implement operators, see later
- All class methods can use the keyword `this`
 - It returns the address of the current object
 - Its type is `T*` in the methods of a class `T`

```
1 void freeFunc(S & s);
2 struct S {
3     void memberFunc() { // Implicit S* parameter
4         freeFunc(*this); // Pass a reference to ourself
5     }
6 };
7 S s;
8 s.memberFunc(); // Passes &s implicitly
```



Method overloading

The rules in C++

- overloading is authorized and welcome
- signature is part of the method identity
- but not the return type

```
1  struct MyFirstClass {
2      int a;
3      int sum(int b);
4      int sum(int b, int c);
5  }
6
7  int MyFirstClass::sum(int b) { return a + b; }
8
9  int MyFirstClass::sum(int b, int c) {
10     return a + b + c;
11 }
```



Inheritance

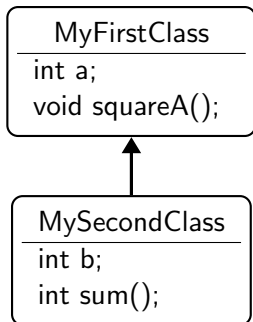
3 Object orientation (OO)

- Objects and Classes
- **Inheritance**
- Constructors/destructors
- Static members
- Allocating objects
- Advanced OO
- Operator overloading
- Function objects



First inheritance

```
1  struct MyFirstClass {
2      int a;
3      void squareA() { a *= a; }
4  };
5  struct MySecondClass :
6      MyFirstClass {
7      int b;
8      int sum() { return a + b; }
9  };
10
11  MySecondClass myObj2;
12  myObj2.a = 2;
13  myObj2.b = 5;
14  myObj2.squareA();
15  int i = myObj2.sum(); // i = 9
```



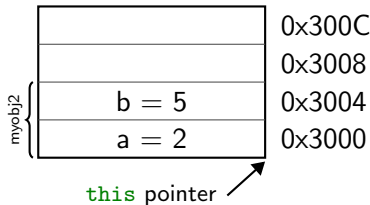
First inheritance

```

1  struct MyFirstClass {
2      int a;
3      void squareA() { a *= a; }
4  };
5  struct MySecondClass :
6      MyFirstClass {
7      int b;
8      int sum() { return a + b; }
9  };
10
11 MySecondClass myObj2;
12 myObj2.a = 2;
13 myObj2.b = 5;
14 myObj2.squareA();
15 int i = myObj2.sum(); // i = 9

```

Memory layout



Managing access to class members

public / private keywords

`private` allows access only within the class

`public` allows access from anywhere

- The default for `class` is `private`
- A `struct` is just a class that defaults to `public` access



Managing access to class members

public / private keywords

`private` allows access only within the class

`public` allows access from anywhere

- The default for class is `private`
- A `struct` is just a class that defaults to `public` access

```
1 class MyFirstClass {
2 public:
3     void setA(int x);
4     int getA();
5     void squareA();
6 private:
7     int a;
8 };
9 MyFirstClass obj;
10 obj.a = 5; // error !
11 obj.setA(5); // ok
12 obj.squareA();
13 int b = obj.getA();
```



Managing access to class members

public / private keywords

`private` allows access only within the class

`public` allows access from anywhere

- The default for class is `private`
- A `struct` is just a class that defaults to `public` access

```
1 class MyFirstClass {
2 public:
3     void setA(int x);
4     int getA();
5     void squareA();
6 private:
7     int a;
8 };
9 MyFirstClass obj;
10 obj.a = 5; // error !
11 obj.setA(5); // ok
12 obj.squareA();
13 int b = obj.getA();
```

This breaks MySecondClass !



Managing access to class members(2)

Solution is protected keyword

Gives access to classes inheriting from base class

```
1  class MyFirstClass {
2  public:
3      void setA(int a);
4      int getA();
5      void squareA();
6  protected:
7      int a;
8  };

13 class MySecondClass :
14     public MyFirstClass {
15 public:
16     int sum() {
17         return a + b;
18     }
19 private:
20     int b;
21 };
```



Inheritance can be public, protected or private

It influences the privacy of inherited members for external code.
The code of the class itself is not affected

`public` privacy of inherited members remains unchanged

`protected` inherited public members are seen as protected

`private` all inherited members are seen as private

this is the default for classes if nothing is specified



Managing inheritance privacy

Inheritance can be public, protected or private

It influences the privacy of inherited members for external code.
The code of the class itself is not affected

`public` privacy of inherited members remains unchanged

`protected` inherited public members are seen as protected

`private` all inherited members are seen as private

this is the default for classes if nothing is specified

Net result for external code

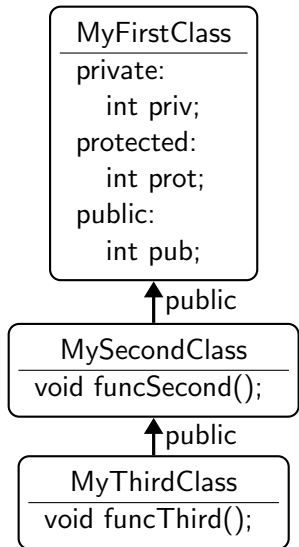
- only public members of public inheritance are accessible

Net result for code in derived classes

- only public and protected members of public and protected parents are accessible



Managing inheritance privacy - public

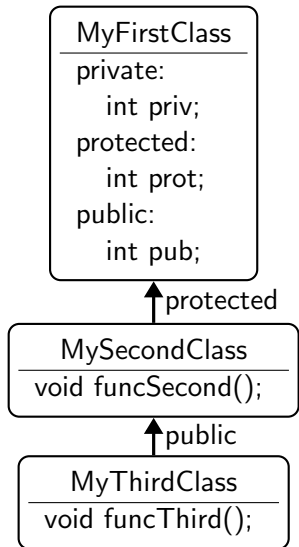


```

1 void funcSecond() {
2     int a = priv; // Error
3     int b = prot; // OK
4     int c = pub; // OK
5 }
6 void funcThird() {
7     int a = priv; // Error
8     int b = prot; // OK
9     int c = pub; // OK
10 }
11 void extFunc(MyThirdClass t) {
12     int a = t.priv; // Error
13     int b = t.prot; // Error
14     int c = t.pub; // OK
15 }
  
```



Managing inheritance privacy - protected

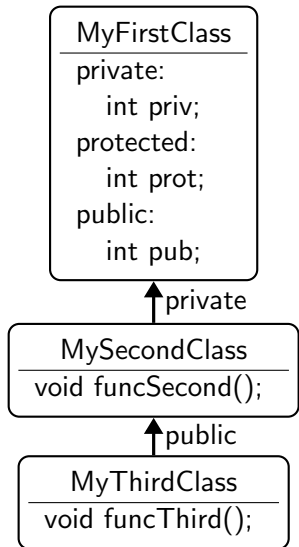


```

1 void funcSecond() {
2     int a = priv; // Error
3     int b = prot; // OK
4     int c = pub; // OK
5 }
6 void funcThird() {
7     int a = priv; // Error
8     int b = prot; // OK
9     int c = pub; // OK
10 }
11 void extFunc(MyThirdClass t) {
12     int a = t.priv; // Error
13     int b = t.prot; // Error
14     int c = t.pub; // Error
15 }
  
```



Managing inheritance privacy - private



```

1 void funcSecond() {
2     int a = priv; // Error
3     int b = prot; // OK
4     int c = pub; // OK
5 }
6 void funcThird() {
7     int a = priv; // Error
8     int b = prot; // Error
9     int c = pub; // Error
10 }
11 void extFunc(MyThirdClass t) {
12     int a = t.priv; // Error
13     int b = t.prot; // Error
14     int c = t.pub; // Error
15 }
  
```



Constructors/destructors

- 3 Object orientation (OO)
 - Objects and Classes
 - Inheritance
 - **Constructors/destructors**
 - Static members
 - Allocating objects
 - Advanced OO
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 - Function objects



Class constructors and destructors

Concept

- special functions called when building/destroying an object
- a class can have several constructors, but only one destructor
- the constructors have the same name as the class
- same for the destructor with a leading ~

```
1  class C {
2  public:
3      C();
4      C(int a);
5      ~C();
6      ...
7  protected:
8      int a;
9  };
10 // note: special notation for
11 // initialization of members
12 C::C() : a(0) {}
13
14 C::C(int a) : a(a) {}
15
16 C::~~C() {}
```



Class constructors and destructors

```
1  class Vector {
2  public:
3      Vector(int n);
4      ~Vector();
5      void setN(int n, int value);
6      int getN(int n);
7  private:
8      int len;
9      int* data;
10 };
11 Vector::Vector(int n) : len(n) {
12     data = new int[n];
13 }
14 Vector::~~Vector() {
15     delete[] data;
16 }
```



Constructors and inheritance

```
1  struct First {
2      int a;
3      First() {} // leaves a uninitialized
4      First(int a) : a(a) {}
5  };
6  struct Second : First {
7      int b;
8      Second();
9      Second(int b);
10     Second(int a, int b);
11 };
12 Second::Second() : First(), b(0) {}
13 Second::Second(int b) : b(b) {} // First() implicitly
14 Second::Second(int a, int b) : First(a), b(b) {}
```



Concept

- special constructor called for replicating an object
- takes a single parameter of type `const &` to class
- provided by the compiler if not declared by the user
- in order to forbid copy, use = `delete` (see next slides)
 - or private copy constructor with no implementation in C++ 98



Concept

- special constructor called for replicating an object
- takes a single parameter of type `const &` to class
- provided by the compiler if not declared by the user
- in order to forbid copy, use `= delete` (see next slides)
 - or private copy constructor with no implementation in C++ 98

```
1  struct C {  
2      C();  
3      C(const C &other);  
4  };
```



Concept

- special constructor called for replicating an object
- takes a single parameter of type `const &` to class
- provided by the compiler if not declared by the user
- in order to forbid copy, use `= delete` (see next slides)
 - or private copy constructor with no implementation in C++ 98

```
1 struct C {  
2     C();  
3     C(const C &other);  
4 };
```

Good practice: The rule of 3/5 (C++ 98/11) - [cppreference](#)

if a class needs a custom destructor, a copy/move constructor or a copy/move assignment operator, it should have all three/five.



Class Constructors and Destructors

```
1  class Vector {
2  public:
3      Vector(int n);
4      Vector(const Vector &other);
5      ~Vector();
6  private:
7      int len; int* data;
8  };
9  Vector::Vector(int n) : len(n) {
10     data = new int[n];
11 }
12 Vector::Vector(const Vector &other) : len(other.len) {
13     data = new int[len];
14     std::copy(other.data, other.data + len, data);
15 }
16 Vector::~~Vector() { delete[] data; }
```



Explicit unary constructor

Concept

- A constructor with a single non-default parameter can be used by the compiler for an implicit conversion.

Example - godbolt

```
1 void print(const Vector & v) {  
2     std::cout << "printing v elements...\n";  
3 }  
4  
5 int main {  
6     // calls Vector::Vector(int n) to construct a Vector  
7     // then calls print with that Vector  
8     print(3);  
9 };
```



Concept

- The keyword `explicit` forbids such implicit conversions.
- It is recommended to use it systematically, except in special cases.

```
1 class Vector {
2 public:
3     explicit Vector(int n);
4     Vector(const Vector &other);
5     ~Vector();
6     ...
7 };
```



Idea

- avoid empty default constructors like `ClassName() {}`
- declare them as `= default`

Details

- without a user-defined constructor, a default one is provided
- any user-defined constructor disables the default one
- but the default one can be requested explicitly
- rule can be more subtle depending on data members

Practically

```
1 Class() = default; // provide default if possible
2 Class() = delete; // disable default constructor
```



Delegating constructor

C++ 11

Idea

- avoid replication of code in several constructors
- by delegating to another constructor, in the initialization list

Practically

```
1  struct Delegate {
2      int m_i;
3      Delegate(int i) : m_i(i) {
4          ... complex initialization ...
5      }
6      Delegate() : Delegate(42) {}
7  };
```



Constructor inheritance

C++ 11

Idea

- avoid having to re-declare parent's constructors
- by stating that we inherit all parent constructors
- derived class can add more constructors

Practically

```
1  struct Base {
2      Base(int a);           // ctor 1
3  };
4  struct Derived : Base {
5      using Base::Base;
6      Derived(int a, int b); // ctor 2
7  };
8  Derived d{5};             // calls ctor 1
9  Derived d{5, 6};         // calls ctor 2
```



Member initialization

C++ 11

Idea

- avoid redefining same default value for members n times
- by defining it once at member declaration time

Practically

```
1  struct Base {
2      int a{5}; // also possible: int a = 5;
3      Base() = default;
4      Base(int _a) : a(_a) {}
5  };
6  struct Derived : Base {
7      int b{6};
8      using Base::Base;
9  };
10 Derived d1; // a = 5, b = 6
11 Derived d2{7}; // a = 7, b = 6
```



Calling constructors

After object declaration, arguments within {}

```
1  struct A {
2      int a;
3      float b;
4      A();
5      A(int);
6      A(int, int);
7  };
8
9  A a{1,2};    // A::A(int, int)
10 A a{1};     // A::A(int)
11 A a{};      // A::A()
12 A a;        // A::A()
13 A a = {1,2}; // A::A(int, int)
```



Calling constructors the old way

Arguments are given within (), aka C++ 98 nightmare

```
1  struct A {
2      int a;
3      float b;
4      A();
5      A(int);
6      A(int, int);
7  };
8
9  A a(1,2);    // A::A(int, int)
10 A a(1);     // A::A(int)
11 A a();      // declaration of a function!
12 A a;       // A::A()
13 A a = (1,2); // A::A(int), comma operator!
14 A a = {1,2}; // not allowed
```



Constructing arrays and vectors

List of items given within {}

```
10  int ip[3]{1,2,3};  
11  int* ip = new int[3]{1,2,3}; // not allowed in C++98  
12  std::vector<int> v{1,2,3}; // same
```



Static members

- 3 Object orientation (OO)
 - Objects and Classes
 - Inheritance
 - Constructors/destructors
 - **Static members**
 - Allocating objects
 - Advanced OO
 - Operator overloading
 - Function objects



Concept

- members attached to a class rather than to an object
- usable with or without an instance of the class
- identified by the `static` keyword

Static.hpp

```
1 class Text {
2 public:
3     static std::string upper(std::string);
4 private:
5     static int callsToUpper; // add `inline` in C++17
6 };
```



Concept

- members attached to a class rather than to an object
- usable with or without an instance of the class
- identified by the `static` keyword

Static.cpp

```
1  #include "Static.hpp"
2  int Text::callsToUpper = 0; // required before C++17
3
4  std::string Text::upper(std::string lower) {
5      callsToUpper++;
6      // convert lower to upper case
7      // return ...;
8  }
9  std::string uppers = Text::upper("my text");
10 // now Text::callsToUpper is 1
```



Allocating objects

- 3 Object orientation (OO)
 - Objects and Classes
 - Inheritance
 - Constructors/destructors
 - Static members
 - **Allocating objects**
 - Advanced OO
 - Operator overloading
 - Function objects



4 main areas

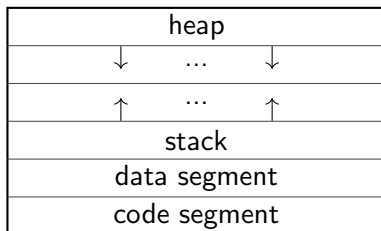
the **code segment** for the machine code of the executable

the **data segment** for global variables

the **heap** for dynamically allocated variables

the **stack** for parameters of functions and local variables

Memory layout



Main characteristics

- allocation on the stack stays valid for the duration of the current scope. It is destroyed when it is popped off the stack.
- memory allocated on the stack is known at compile time and can thus be accessed through a variable.
- the stack is relatively small, it is not a good idea to allocate large arrays, structures or classes
- each thread in a process has its own stack
 - allocations on the stack are thus “thread private”
 - and do not introduce any thread safety issues



Object allocation on the stack

On the stack

- objects are created on variable definition (constructor called)
- objects are destructed when out of scope (destructor is called)

```
1  int f() {  
2    MyFirstClass a{3}; // constructor called  
3    ...  
4  } // destructor called  
5  
6  int g() {  
7    MyFirstClass a; // default constructor called  
8    ...  
9  } // destructor called
```



Main characteristics

- Allocated memory stays allocated until it is specifically deallocated
 - beware memory leaks
- Dynamically allocated memory must be accessed through pointers
- large arrays, structures, or classes should be allocated here
- there is a single, shared heap per process
 - allows to share data between threads
 - introduces race conditions and thread safety issues!



Object allocation on the heap

C++ 98

On the heap

- objects are created by calling `new` (constructor is called)
- objects are destructed by calling `delete` (destructor is called)

```
1  int f() {
2      // default constructor called
3      MyFirstClass *a = new MyFirstClass;
4      delete a; // destructor is called
5  }
6  int g() {
7      // constructor called
8      MyFirstClass *a = new MyFirstClass{3};
9  } // memory leak !!!
```

Good practice: Prefer smart pointers over `new/delete`

Prefer smart pointers to manage objects (discussed later)



Arrays on the heap

- arrays of objects are created by calling `new[]`
default constructor is called for each object of the array
- arrays of object are destructed by calling `delete[]`
destructor is called for each object of the array

```
1 int f() {  
2     // default constructor called 10 times  
3     MyFirstClass *a = new MyFirstClass[10];  
4     ...  
5     delete[] a; // destructor called 10 times  
6 }
```

Good practice: Prefer containers over new-ed arrays

Prefer containers to manage collections of objects (discussed later)



Advanced OO

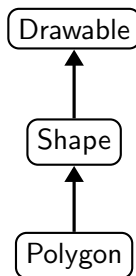
- 3 Object orientation (OO)
 - Objects and Classes
 - Inheritance
 - Constructors/destructors
 - Static members
 - Allocating objects
 - **Advanced OO**
 - Operator overloading
 - Function objects



the concept

- objects actually have multiple types simultaneously
- and can be used as any of them

```
1 Polygon p;  
2  
3 int f(Drawable & d) {...}  
4 f(p); //ok  
5  
6 try {  
7     throw p;  
8 } catch (Shape & e) {  
9     // will be caught  
10 }
```



the concept

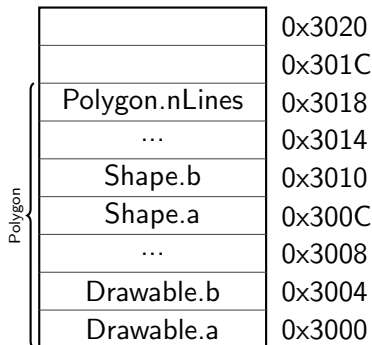
- objects actually have multiple types simultaneously
- and can be used as any of them

```

1 Polygon p;
2
3 int f(Drawable & d) {...}
4 f(p); //ok
5
6 try {
7     throw p;
8 } catch (Shape & e) {
9     // will be caught
10 }

```

Memory layout



the concept

- objects actually have multiple types simultaneously
- and can be used as any of them

```

1 Polygon p;
2
3 int f(Drawable & d) {...}
4 f(p); //ok
5
6 try {
7     throw p;
8 } catch (Shape & e) {
9     // will be caught
10 }

```

Memory layout

	0x3020
	0x301C
Polygon.nLines	0x3018
...	0x3014
Shape.b	0x3010
Shape.a	0x300C
...	0x3008
Drawable.b	0x3004
Drawable.a	0x3000

Drawable {

the concept

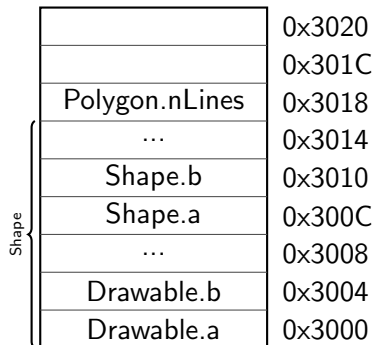
- objects actually have multiple types simultaneously
- and can be used as any of them

```

1 Polygon p;
2
3 int f(Drawable & d) {...}
4 f(p); //ok
5
6 try {
7     throw p;
8 } catch (Shape & e) {
9     // will be caught
10 }

```

Memory layout

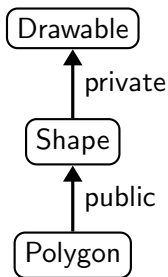


Inheritance privacy and polymorphism

Only public base classes are visible to outside code

- private and protected bases are not
- this may restrict usage of polymorphism

```
1 Polygon p;  
2  
3 int f(Drawable & d) {...}  
4 f(p); // Not ok anymore  
5  
6 try {  
7     throw p;  
8 } catch (Shape & e) {  
9     // ok, will be caught  
10 }
```

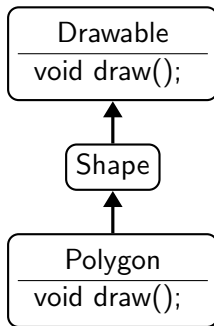


Method overriding

the idea

- a method of the parent class can be replaced in a derived class
- but which one is called?

```
1 Polygon p;  
2 p.draw(); // ?  
3  
4 Shape & s = p;  
5 s.draw(); // ?
```



the concept

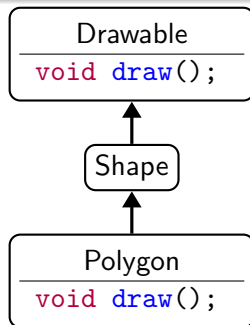
- methods can be declared `virtual`
- for these, the most derived object's implementation is used (i.e. the dynamic type behind a pointer/reference)
- for non-virtual methods, the static type of the variable decides



the concept

- methods can be declared **virtual**
- for these, the most derived object's implementation is used (i.e. the dynamic type behind a pointer/reference)
- for non-virtual methods, the static type of the variable decides

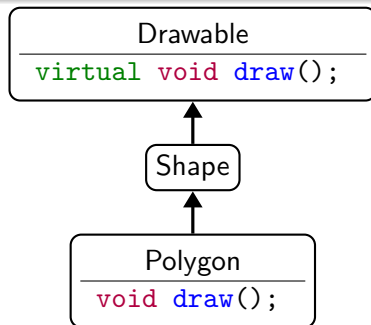
```
1 Polygon p;  
2 p.draw(); // Polygon.draw  
3  
4 Shape & s = p;  
5 s.draw(); // Drawable.draw
```



the concept

- methods can be declared **virtual**
- for these, the most derived object's implementation is used (i.e. the dynamic type behind a pointer/reference)
- for non-virtual methods, the static type of the variable decides

```
1 Polygon p;  
2 p.draw(); // Polygon.draw  
3  
4 Shape & s = p;  
5 s.draw(); // Polygon.draw
```



Mechanics

- virtual methods are dispatched at run time
 - while non-virtual methods are bound at compile time
- they also imply extra storage and an extra indirection
 - practically, the object stores a pointer to the correct method
 - in a so-called “virtual table” (“vtable”)

Consequences

- virtual methods are “slower” than standard ones
- and they can rarely be inlined
- templates are an alternative for performance-critical cases



Principle

- when overriding a virtual method
- the `override` keyword should be used
- the `virtual` keyword is then optional

Practically

```
1  struct Base {  
2      virtual void some_func(float);  
3  };  
4  struct Derived : Base {  
5      void some_func(float) override;  
6  };
```



Why was override keyword introduced?

To detect the mistake in the following code :

Without override (C++ 98)

```
1  struct Base {  
2      virtual void some_func(float);  
3  };  
4  struct Derived : Base {  
5      void some_func(double); // oops !  
6  };
```

- with `override`, you would get a compiler error
- if you forget `override` when you should have it, you get a compiler warning



Concept

- unimplemented methods that must be overridden
- marked by = 0 in the declaration
- makes their class abstract
- only non-abstract classes can be instantiated



Pure Virtual methods

Concept

- unimplemented methods that must be overridden
- marked by = 0 in the declaration
- makes their class abstract
- only non-abstract classes can be instantiated

```
1 // Error : abstract class
```

```
2 Shape s;
```

```
3
```

```
4 // ok, draw has been implemented
```

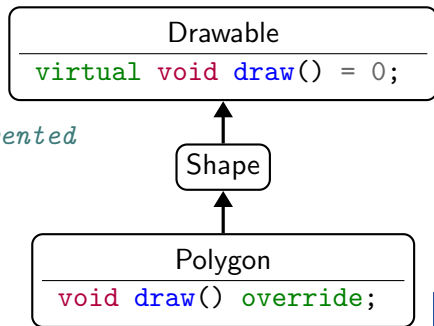
```
5 Polygon p;
```

```
6
```

```
7 // Shape type still usable
```

```
8 Shape & s = p;
```

```
9 s.draw();
```



Owning base pointers

We sometimes need to maintain owning pointers to base classes:

```
1 struct Drawable {
2     virtual void draw() = 0;
3 };
4 Drawable* getImpl();
5
6 Drawable* p = getImpl();
7 p->draw();
8 delete p;
```

- What happens when `p` is deleted?
- What if a class deriving from `Drawable` has a destructor?



Owning base pointers

We sometimes need to maintain owning pointers to base classes:

```
1 struct Drawable {
2     virtual void draw() = 0;
3 };
4 std::unique_ptr<Drawable> getImpl(); // better API
5
6 auto p = getImpl();
7 p->draw();
```

- What happens when `p` is deleted?
- What if a class deriving from `Drawable` has a destructor?



Virtual destructors

- We can mark a destructor as `virtual`
- This selects the right destructor based on the runtime type

```
1 struct Drawable {
2     virtual ~Drawable() = default;
3     virtual void draw() = 0;
4 };
5 Drawable* p = getImpl(); // returns derived obj.
6 p->draw();
7 delete p; // dynamic dispatch to right destructor
```

Good practice: Virtual destructors

If you expect users to inherit from your class and override methods (i.e. use your class polymorphically), declare its destructor `virtual`



Pure Abstract Class aka Interface

Definition of pure abstract class

- a class that has
 - no data members
 - all its methods pure virtual
 - a `virtual` destructor
- the equivalent of an Interface in Java

```
1 struct Drawable {
2     virtual ~Drawable()
3         = default;
4     virtual void draw() = 0;
5 }
```

Drawable
virtual void draw() = 0;



Overriding overloaded methods

Concept

- overriding an overloaded method will hide the others
- unless you inherit them using `using`

```
1  struct BaseClass {
2      virtual int foo(std::string);
3      virtual int foo(int);
4  };
5  struct DerivedClass : BaseClass {
6      using BaseClass::foo;
7      int foo(std::string) override;
8  };
9  DerivedClass dc;
10 dc.foo(4);      // error if no using
```



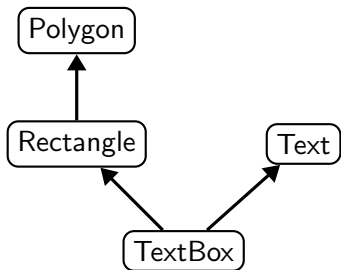
Exercise: Polymorphism

- go to `exercises/polymorphism`
- look at the code
- open `trypoly.cpp`
- create a `Pentagon`, call its `perimeter` method
- create a `Hexagon`, call its `perimeter` method
- create a `Hexagon`, call its parent's `perimeter` method
- retry with virtual methods



Concept

- one class can inherit from multiple parents



```
1 class TextBox :  
2     public Rectangle, Text {  
3     // inherits from both  
4     // publicly from Rectangle  
5     // privately from Text  
6 }
```

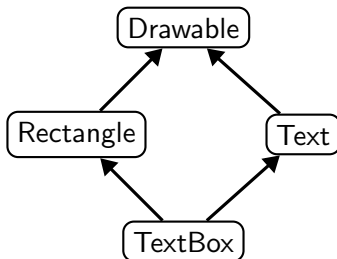


Definition

- situation when one class inherits several times from a given grand parent

Problem

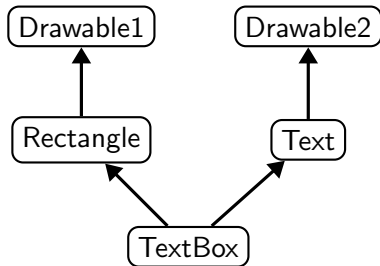
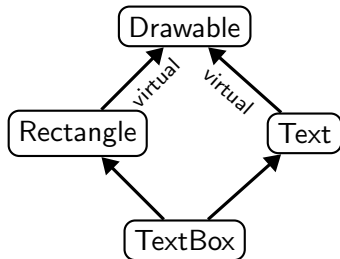
- are the members of the grand parent replicated?



Solution

- inheritance can be **virtual** or not
 - **virtual** inheritance will “share” parents
 - standard inheritance will replicate them
- most derived class will call the virtual base class's constructor

```
1 class Text : public virtual Drawable {...};  
2 class Rectangle : public virtual Drawable {...};
```



Good practice: Avoid multiple inheritance

- Except for inheriting from interfaces
- And for rare special cases



Good practice: Avoid multiple inheritance

- Except for inheriting from interfaces
- And for rare special cases

Good practice: Absolutely avoid diamond-shaped inheritance

- This is a sign that your architecture is not correct
- In case you are tempted, think twice and change your mind



Exercise: Virtual inheritance

- go to `exercisecode/virtual_inheritance`
- look at the code
- open `trymultiherit.cpp`
- create a `TextBox` and call `draw`
- Fix the code to call both draws by using types
- retry with virtual inheritance



Operator overloading

- 3 Object orientation (OO)
 - Objects and Classes
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 - Static members
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 - Advanced OO
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Operator overloading example

C++ 98

```
1  struct Complex {
2      float m_real, m_imaginary;
3      Complex(float real, float imaginary);
4      Complex operator+(const Complex& other) {
5          return Complex(m_real + other.m_real,
6                          m_imaginary + other.m_imaginary);
7      }
8  };
9
10 Complex c1{2, 3}, c2{4, 5};
11 Complex c3 = c1 + c2; // (6, 8)
```



Defining operators for a class

- implemented as a regular method
 - either inside the class, as a member function
 - or outside the class (not all)
- with a special name (replace @ by anything)

Expression	As member	As non-member
@a	(a).operator@()	operator@(a)
a@b	(a).operator@(b)	operator@(a,b)
a=b	(a).operator=(b)	cannot be non-member
a(b...)	(a).operator()(b...)	cannot be non-member
a[b]	(a).operator[](b)	cannot be non-member
a->	(a).operator->()	cannot be non-member
a@	(a).operator@(0)	operator@(a,0)



Why have non-member operators?

Symmetry

```
1  struct Complex {
2      float m_real, m_imaginary;
3      Complex operator+(float other) {
4          return Complex(m_real + other, m_imaginary);
5      }
6  };
7  Complex c1{2.f, 3.f};
8  Complex c2 = c1 + 4.f; // ok
9  Complex c3 = 4.f + c1; // not ok !!
```



Why have non-member operators?

Symmetry

```
1  struct Complex {
2      float m_real, m_imaginary;
3      Complex operator+(float other) {
4          return Complex(m_real + other, m_imaginary);
5      }
6  };
7  Complex c1{2.f, 3.f};
8  Complex c2 = c1 + 4.f; // ok
9  Complex c3 = 4.f + c1; // not ok !!
10 Complex operator+(float a, const Complex& obj) {
11     return Complex(a + obj.m_real, obj.m_imaginary);
12 }
```



Other reason to have non-member operators?

Extending existing classes

```
1  struct Complex {
2      float m_real, m_imaginary;
3      Complex(float real, float imaginary);
4  };
5
6  std::ostream& operator<<(std::ostream& os,
7                          const Complex& obj) {
8      os << "(" << obj.m_real << ", "
9          << obj.m_imaginary << ")";
10     return os;
11 }
12 Complex c1{2.f, 3.f};
13 std::cout << c1 << std::endl; // Prints '(2, 3)'
```



Concept

- Functions/classes can be declared **friend** within a class scope
- They gain access to all private/protected members
- Useful for operators such as $a + b$
- Don't abuse friends to go around a wrongly designed interface
- Avoid unexpected modifications of class state in a friend

operator+ as a friend

```
1 class Complex {
2     float m_r, m_i;
3     friend Complex operator+(Complex const & a, Complex const & b);
4 public:
5     Complex ( float r, float i ) : m_r(r), m_i(i) {}
6 };
7 Complex operator+(Complex const & a, Complex const & b) {
8     return Complex{ a.m_r+b.m_r, a.m_i+b.m_i };
9 }
```



Exercise: Operators

Write a simple class representing a fraction and pass all tests

- go to `exercises/operators`
- look at `operators.cpp`
- inspect `main` and complete the implementation of `class Fraction` step by step
- you can comment out parts of `main` to test in between



Function objects

- 3 Object orientation (OO)
 - Objects and Classes
 - Inheritance
 - Constructors/destructors
 - Static members
 - Allocating objects
 - Advanced OO
 - Operator overloading
 - Function objects



Concept

- also known as functors (no relation to functors in math)
- a class that implements `operator()`
- allows to use objects in place of functions
- with constructors and data members

```
1  struct Adder {
2      int m_increment;
3      Adder(int increment) : m_increment(increment) {}
4      int operator()(int a) { return a + m_increment; }
5  };
6  Adder inc1{1}, inc10{10};
7  int i = 3;
8  int j = inc1(i); // 4
9  int k = inc10(i); // 13
10 int l = Adder{25}(i); // 28
```



Function objects

C++ 20

Function objects as function arguments - godbolt

```
1 int count_if(const auto& range, auto predicate) {
2     int count = 0;           // ↑ template (later)
3     for (const auto& e : range)
4         if (predicate(e)) count++;
5     return count;
6 }
7 struct IsBetween {
8     int lower, upper;
9     bool operator()(int value) const {
10         return lower < value && value < upper;
11     }
12 };
13 int arr[]{1, 2, 3, 4, 5, 6, 7};
14 std::cout << count_if(arr, IsBetween{2, 6}); // 3
15 // prefer: std::ranges::count_if
```



Core modern C⁺⁺

- 1 History and goals
- 2 Language basics
- 3 Object orientation (OO)
- 4 Core modern C⁺⁺
 - Constness
 - Exceptions
 - Templates
 - Lambdas
 - The STL
 - RAI and smart pointers
- 5 Useful tools



Constness

- 4 Core modern C++
 - Constness
 - Exceptions
 - Templates
 - Lambdas
 - The STL
 - RAI and smart pointers



The `const` keyword

- indicates that the element to the left is constant
 - when nothing on the left, applies to the right
- this element won't be modifiable in the future
- this is all checked at compile time

```
1 int const i = 6;
2 const int i = 6; // equivalent
3
4 // error: i is constant
5 i = 5;
6
7 auto const j = i; // works with auto
```



Constness and pointers

```
1  int a = 1, b = 2;
2
3  int const *i = &a; // pointer to const int
4  *i = 5; // error, int is const
5  i = &b; // ok, pointer is not const
6
7  int * const j = &a; // const pointer to int
8  *j = 5; // ok, value can be changed
9  j = &b; // error, pointer is const
10
11 int const * const k = &a; // const pointer to const int
12 *k = 5; // error, value is const
13 k = &b; // error, pointer is const
14
15 int const &l = a; // reference to const int
16 l = b; // error, reference is const
17
18 int const & const l = a; // compile error
```



Member function constness

The const keyword for member functions

- indicates that the function does not modify the object
- in other words, `this` is a pointer to a constant object

```
1  struct Example {
2      void foo() const {
3          // type of 'this' is 'Example const*'
4          data = 0; // Error: member function is const
5      }
6      void foo() { // ok, overload
7          data = 1; // ok, 'this' is 'Example*'
8      }
9      int data;
10 };
11 Example const e1; e1.foo(); // calls const foo
12 Example e2; e2.foo(); // calls non-const foo
```



Member function constness

Constness is part of the type

- T `const` and T are different types
- but: T is automatically converted to T `const` when needed

```
1 void change(int & a);
2 void read(int const & a);
3
4 int a = 0;
5 int const b = 0;
6
7 change(a); // ok
8 change(b); // error
9 read(a); // ok
10 read(b); // ok
```



Exercise: Constness

- go to `exercises/constness`
- open `constplay.cpp`
- try to find out which lines won't compile
- check your guesses by compiling for real



Exceptions

- 4 Core modern C++
 - Constness
 - **Exceptions**
 - Templates
 - Lambdas
 - The STL
 - RAI and smart pointers



Purpose

- to handle *exceptional* events that happen rarely
- and cleanly jump to a place where the error can be handled

In practice

- add an exception handling block with `try ... catch`
 - when exceptions are possible *and can be handled*
- throw an exception using `throw`
 - when a function cannot proceed or recover internally

```

1  try {
2      process_data(f);
3  } catch (const
4      std::out_of_range& e) {
5      std::cerr << e.what();
6  }
7  void process_data(file &f) {
8      ...
9      if (i >= buffer.size())
10         throw std::out_of_range{
11             "buf overflow"};
12     }

```



Throwing exceptions

- objects of any type can be thrown (even e.g. `int`)

Good practice: Throwing exceptions

- prefer throwing standard exception classes
- throw objects by value

```
1  #include <stdexcept>
2  void process_data(file& f) {
3      if (!f.open())
4          throw std::invalid_argument{"stream is not open"};
5      auto header = read_line(f); // may throw an IO error
6      if (!header.starts_with("BEGIN"))
7          throw std::runtime_error{"invalid file content"};
8      std::string body(f.size()); // may throw std::bad_alloc
9      ...
10 }
```



Standard exceptions

- `std::exception`, defined in header `<exception>`
 - Base class of all standard exceptions
 - Get error message: `virtual const char* what() const;`
 - Please derive your own exception classes from this one
- From `<stdexcept>`:
 - `std::runtime_error`, `std::logic_error`,
`std::out_of_range`, `std::invalid_argument`, ...
 - Store a string: `throw std::runtime_error{"msg"}`
 - You should use these the most
- `std::bad_alloc`, defined in header `<new>`
 - Thrown by standard allocation functions (e.g. `new`)
 - Signals failure to allocate
 - Carries no message
- ...



Catching exceptions

- a catch clause catches exceptions of the same or derived type
- multiple catch clauses will be matched in order
- if no catch clause matches, the exception propagates
- if the exception is never caught, `std::terminate` is called

```
1 try {
2     process_data(f);
3 } catch (const std::invalid_argument& e) {
4     bad_files.push_back(f);
5 } catch (const std::exception& e) {
6     std::cerr << "Failed to process file: " << e.what();
7 }
```

Good practice: Catching exceptions

- Catch exceptions by const reference



Rethrowing exceptions

- a caught exception can be rethrown inside the catch handler
- useful when we want to act on an error, but cannot handle and want to propagate it

```
1 try {
2     process_data(f);
3 } catch (const std::bad_alloc& e) {
4     std::cerr << "Insufficient memory for " << f.name();
5     throw; // rethrow
6 }
```



Catching everything

- sometimes we need to catch all possible exceptions
- e.g. in main, a thread, a destructor, interfacing with C, ...

```
1
2 try {
3     callUnknownFramework();
4 } catch(const std::exception& e) {
5     // catches std::exception and all derived types
6     std::cerr << "Exception: " << e.what() << std::endl;
7 } catch(...) {
8     // catches everything else
9     std::cerr << "Unknown exception type" << std::endl;
10 }
```



Stack unwinding

- all objects on the stack between a `throw` and the matching `catch` are destructed automatically
- this should cleanly release intermediate resources
- make sure you are using the RAI1 idiom for your own classes

```
1  class C { ... };
2  void f() {
3      C c1;
4      throw exception{};
5      // start unwinding
6      C c2; // not run
7  }
8  void g() {
9      C c3; f();
10 }
11 int main() {
12     try {
13         C c4;
14         g();
15         cout << "done"; // not run
16     } catch(const exception&) {
17         // c1, c3 and c4 have been
18         // destructed
19     }
20 }
```



Good practice: Exceptions

- use exceptions for *unlikely* runtime errors outside the program's control
 - bad inputs, files unexpectedly not found, DB connection, ...
- *don't* use exceptions for logic errors in your code
 - use `assert` and tests
- *don't* use exceptions to provide alternative/skip return values
 - you can use `std::optional` or `std::variant`
 - avoid using the global C-style `errno`
- never throw in destructors
- see also the [C++ core guidelines](#) and the [ISO C++ FAQ](#)



A more illustrative example

- exceptions are very powerful when there is much code between the error and where the error is handled
- they can also rather cleanly handle different types of errors
- `try/catch` statements can also be nested

```

1  try {
2    for (File const &f : files) {
3      try {
4        process_file(f);
5      }
6      catch (bad_file const & e) {
7        ... // loop continues
8      }
9    }
10 } catch (bad_db const & e) {
11   ... // loop aborted
12 }

1  void process_file(File const & file) {
2    ...
3    if (handle = open_file(file))
4      throw bad_file(file.status());
5    while (!handle) {
6      line = read_line(handle);
7      database.insert(line); // can throw
8                               // bad_db
9    }
10 }

```



Cost

- exceptions have little cost if no exception is thrown
 - they are recommended to report *exceptional* errors
- for performance, when error raising and handling are close, or errors occur often, prefer error codes or a dedicated class
- when in doubt about which error strategy is better, profile!

Avoid

```
for (string const &num: nums) {  
    try {  
        int i = convert(num); // can  
                               // throw  
        process(i);  
    } catch (not_an_int const &e) {  
        ... // log and continue  
    }  
}
```

Prefer

```
for (string const &num: nums) {  
    optional<int> i = convert(num);  
    if (i) {  
        process(*i);  
    } else {  
        ... // log and continue  
    }  
}
```



noexcept

- a function with the `noexcept` specifier states that it guarantees to not throw an exception

```
int f() noexcept;
```

- either no exceptions is thrown or they are handled internally
- checked at compile time
- allows the compiler to optimize around that knowledge
- a function with `noexcept(expression)` is only `noexcept` when `expression` evaluates to `true` at compile-time

```
int safe_if_8B() noexcept(sizeof(long)==8);
```

Good practice: noexcept

- Use `noexcept` on leaf functions where you know the behavior
- C++11 destructors are `noexcept` - never throw from them



Templates

- 4 Core modern C++
 - Constness
 - Exceptions
 - **Templates**
 - Lambdas
 - The STL
 - RAI and smart pointers



Concept

- The C++ way to write reusable code
 - like macros, but fully integrated into the type system
- Applicable to functions, classes and variables

```
1  template<typename T>
2  const T & max(const T &a, const T &b) {
3      return b < a ? a : b;
4  }
5  template<typename T>
6  struct Vector {
7      int m_len;
8      T* m_data;
9  };
10 template <typename T>
11 std::size_t size = sizeof(T);
```



Warning

- they are compiled for each instantiation
- they need to be defined before used
 - so all template code must typically be in headers
 - or declared to be available externally (`extern template`)
- this may lead to longer compilation times and bigger binaries

1
2
3
4

```
template<typename T>  
T func(T a) {  
    return a;  
}
```

func(3)

```
int func(int a) {  
    return a;  
}
```

func(5.2)

```
double func(double a) {  
    return a;  
}
```



Template parameters

- can be types, values or other templates
- you can have several
- default values allowed starting at the last parameter

```
1  template<typename KeyType=int, typename ValueType=KeyType>
2  struct Map {
3      void set(const KeyType &key, ValueType value);
4      ValueType get(const KeyType &key);
5      ...
6  };
7
8  Map<std::string, int> m1;
9  Map<float> m2;      // Map<float, float>
10 Map<> m3;          // Map<int, int>
11 Map m4;           // Map<int, int>, C++17
```



typename vs. class keyword

- for declaring a template type parameter, the `typename` and `class` keyword are semantically equivalent
- template template parameters require C++ 17 for `typename`

```
1  template<typename T>
2  T func(T a); // equivalent to:
3  template<class T>
4  T func(T a);
5
6  template<template<class> class C>
7  C<int> func(C<int> a); // equivalent to:
8  template<template<typename> class C>
9  C<int> func(C<int> a); // equivalent to:
10 template<template<typename> typename C> // C++17
11 C<int> func(C<int> a);
```



Template implementation

```
1  template<typename KeyType=int, typename ValueType=KeyType>
2  struct Map {
3      // declaration and inline definition
4      void set(const KeyType &key, ValueType value) {
5          ...
6      }
7      // just declaration
8      ValueType get(const KeyType &key);
9  };
10
11 // out-of-line definition
12 template<typename KeyType, typename ValueType>
13 ValueType Map<KeyType, ValueType>::get
14     (const KeyType &key) {
15     ...
16 }
```



Non-type template parameter C++ 98 / C++ 17 / C++ 20

template parameters can also be values

- integral types, pointer, enums in C++ 98
- `auto` in C++ 17
- literal types (includes floating points) in C++ 20

```
1  template<unsigned int N>
2  struct Polygon {
3      float perimeter() {
4          return 2 * N * std::sin(PI / N) * radius;
5      }
6      float radius;
7  };
8
9  Polygon<19> nonadecagon{3.3f};
```



Specialization

Templates can be specialized for given values of their parameter

```
1  template<typename F, unsigned int N>
2  struct Polygon { ... }; // primary template
3
4  template<typename F> // partial specialization
5  struct Polygon<F, 6> {
6      F perimeter() { return 6 * radius; }
7      F radius;
8  };
9  template<> // full specialization
10 struct Polygon<int, 6> {
11     int perimeter() { return 6 * radius; }
12     int radius;
13 };
```



Exercise: Templates

- go to `exercises/templates`
- look at the `OrderedVector` code
- compile and run `playwithsort.cpp`. See the ordering
- modify `playwithsort.cpp` and reuse `OrderedVector` with `Complex`
- improve `OrderedVector` to template the ordering
- test reverse ordering of strings (from the last letter)
- test order based on [Manhattan distance](#) with complex type
- check the implementation of `Complex`
- try ordering complex of complex



Lambdas

- 4 Core modern C++
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 - **Lambdas**
 - The STL
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Trailing function return type

An alternate way to specify a function's return type

```
int f(float a);           // classic
auto f(float a) -> int;   // trailing
auto f(float a) { return 42; } // deduced, C++14
```



Trailing function return type

C++ 11

An alternate way to specify a function's return type

```
int f(float a);           // classic
auto f(float a) -> int;   // trailing
auto f(float a) { return 42; } // deduced, C++14
```

Advantages

- Allows to simplify inner type definition

```
1 class Equation {
2     using ResultType = double;
3     ResultType evaluate();
4 }
5 Equation::ResultType Equation::evaluate() {...}
6 auto Equation::evaluate() -> ResultType {...}
```

- Used by lambda expressions



Definition

A lambda expression is a function with no name



Definition

A lambda expression is a function with no name

Python example

```
1 data = [1,9,3,8,3,7,4,6,5]
2
3 # without lambdas
4 def isOdd(n):
5     return n%2 == 1
6 print(filter(isOdd, data))
7
8 # with lambdas
9 print(filter(lambda n:n%2==1, data))
```



Simplified syntax

```
1 auto f = [] (arguments) -> return_type {  
2     statements;  
3 };
```

- The return type specification is optional
- f is an instance of a functor type, generated by the compiler

Usage example

```
4 int data[] {1,2,3,4,5};  
5 auto f = [] (int i) {  
6     std::cout << i << " squared is " << i*i << '\n';  
7 };  
8 for (int i : data) f(i);
```



Adaptable lambdas

- Adapt lambda's behaviour by accessing variables outside of it
- This is called “capture”



Capturing variables

Adaptable lambdas

- Adapt lambda's behaviour by accessing variables outside of it
- This is called "capture"

First attempt in C++

```
1  int increment = 3;
2  int data[] {1,9,3,8,3,7,4,6,5};
3  auto f = [](int x) { return x+increment; };
4  for(int& i : data) i = f(i);
```



Capturing variables

C++ 11

Adaptable lambdas

- Adapt lambda's behaviour by accessing variables outside of it
- This is called "capture"

First attempt in C++

```
1  int increment = 3;
2  int data[] {1,9,3,8,3,7,4,6,5};
3  auto f = [](int x) { return x+increment; };
4  for(int& i : data) i = f(i);
```

Error

```
error: 'increment' is not captured
  [](int x) { return x+increment; });
                          ^
```



The capture list

- local variables outside the lambda must be explicitly captured
 - unlike in Python, Java, C#, Rust, ...
- captured variables are listed within initial `[]`



The capture list

- local variables outside the lambda must be explicitly captured
 - unlike in Python, Java, C#, Rust, ...
- captured variables are listed within initial []

Example

```
1  int increment = 3;
2  int data[] {1,9,3,8,3,7,4,6,5};
3  auto f = [increment](int x) { return x+increment; };
4  for(int& i : data) i = f(i);
```



Default capture is by value

C++ 11

Code example

```
1  int sum = 0;
2  int data[]{1,9,3,8,3,7,4,6,5};
3  auto f = [sum](int x) { sum += x; };
4  for (int i : data) f(i);
```



Default capture is by value

C++ 11

Code example

```
1  int sum = 0;
2  int data[]{1,9,3,8,3,7,4,6,5};
3  auto f = [sum](int x) { sum += x; };
4  for (int i : data) f(i);
```

Error

```
error: assignment of read-only variable 'sum'
      [sum](int x) { sum += x; });
```



Default capture is by value

C++ 11

Code example

```
1  int sum = 0;
2  int data[]{1,9,3,8,3,7,4,6,5};
3  auto f = [sum](int x) { sum += x; };
4  for (int i : data) f(i);
```

Error

```
error: assignment of read-only variable 'sum'
      [sum](int x) { sum += x; });
```

Explanation

- By default, variables are captured by value
- The lambda's `operator()` is `const`



Simple example

In order to capture by reference, add '&' before the variable

```
1  int sum = 0;
2  int data[]{1,9,3,8,3,7,4,6,5};
3  auto f = [&sum](int x) { sum += x; };
4  for (int i : data) f(i);
```



Capture by reference

C++ 11

Simple example

In order to capture by reference, add '&' before the variable

```
1  int sum = 0;
2  int data[]{1,9,3,8,3,7,4,6,5};
3  auto f = [&sum](int x) { sum += x; };
4  for (int i : data) f(i);
```

Mixed case

One can of course mix values and references

```
5  int sum = 0, off = 1;
6  int data[]{1,9,3,8,3,7,4,6,5};
7  auto f = [&sum, off](int x) { sum += x + off; };
8  for (int i : data) f(i);
```



Lambdas are pure syntactic sugar - [cppinsight](#)

- They are replaced by a functor during compilation

```

1  int sum = 0, off = 1;
2  auto l =
3  [&sum, off]
4
5
6
7  (int x) {
8      sum += x + off;
9  };
10
11
12  l(42);

13  int sum = 0, off = 1;
14  struct __lambda4 {
15      int& sum; int off;
16      __lambda4(int& s, int o)
17      : sum(s), off(o) {}
18
19      auto operator()(int x) const {
20          sum += x + off;
21      }
22  };
23  auto l = __lambda4{sum, off};
24  l(42);

```

Some nice consequence

- Lambda expressions create ordinary objects
- They can be copied, moved, or inherited from

all by value

```
[=](...) { ... };
```



Capture list

C++ 11

all by value

```
[=](...) { ... };
```

all by reference

```
[&](...) { ... };
```



Capture list

C++ 11

all by value

```
[=](...) { ... };
```

all by reference

```
[&](...) { ... };
```

mix

```
[&, b](...) { ... };
```

```
[=, &b](...) { ... };
```



The STL

- 4 Core modern C++
 - Constness
 - Exceptions
 - Templates
 - Lambdas
 - **The STL**
 - RAI and smart pointers



What it is

- A library of standard templates
- Has almost everything you need
 - strings, containers, iterators
 - algorithms, functions, sorters
 - functors, allocators
 - ...
- Portable
- Reusable
- Efficient



What it is

- A library of standard templates
- Has almost everything you need
 - strings, containers, iterators
 - algorithms, functions, sorters
 - functors, allocators
 - ...
- Portable
- Reusable
- Efficient

Use it

and adapt it to your needs, thanks to templates



STL example - godbolt

```
1  #include <vector>
2  #include <algorithm>
3  #include <functional>      // `import std;` in C++23
4  #include <iterator>
5  #include <iostream>
6
7  std::vector<int> in{5, 3, 4};    // initializer list
8  std::vector<int> out(3);      // constructor taking size
9  std::transform(in.begin(), in.end(),    // input range
10               out.begin(),             // start result
11               std::negate{});          // function obj
12  std::copy(out.begin(), out.end(),      // -5 -3 -4
13            std::ostream_iterator<int>{std::cout, " "});
```



containers

- data structures for managing a range of elements, irrespective of:
 - the data itself (templated)
 - the memory allocation of the structure (templated)
 - the algorithms that may use the structure (iterators)

Examples (→ [string](#) and [container library](#) on cppreference)

- string, string_view (C++ 17)
- list, forward_list (C++ 11), vector, deque, array (C++ 11)
- [multi]map, [multi]set (C++ 23: flat_[multi]map, flat_[multi]set)
- unordered_[multi]map (C++ 11), unordered_[multi]set (C++ 11)
- stack, queue, priority_queue
- span (C++ 20)
- non-containers: bitset, pair, tuple (C++ 11), optional (C++ 17), variant (C++ 17), any (C++ 17), expected (C++ 23)



Containers: std::vector

```
1  #include <vector>
2  std::vector<T> v{5, 3, 4}; // 3 Ts, 5, 3, 4
3  std::vector<T> v(100);    // 100 default constr. Ts
4  std::vector<T> v(100, 42); // 100 Ts with value 42
5  std::vector<T> v2 = v;    // copy
6  std::vector<T> v2 = std::move(v); // move, v is empty
7
8  std::size_t s = v.size();
9  bool empty = v.empty();
10
11 v[2] = 17; // write element 2
12 T& t = v[1000]; // access element 1000, bug!
13 T& t = v.at(1000); // throws std::out_of_range
14 T& f = v.front(); // access first element
15 v.back() = 0; // write to last element
16 T* p = v.data(); // pointer to underlying storage
```



Containers: std::vector

```
1  std::vector<T> v = ...;
2  auto b = v.begin(); // iterator to first element
3  auto e = v.end();   // iterator to one past last element
4  // all following operations, except reserve, invalidate
5  // all iterators (b and e) and references to elements
6
7  v.resize(100); // size changes, grows: new T{}s appended
8                //                shrinks: Ts at end destroyed
9  v.reserve(1000); // size remains, memory increased
10 for (T i = 0; i < 900; i++)
11     v.push_back(i); // add to the end
12 v.insert(v.begin()+3, T{}); // insert after 3rd position
13
14 v.pop_back(); // removes last element
15 v.erase(v.end() - 3); // removes 3rd-last element
16 v.clear(); // removes all elements
```



Containers: `std::unordered_map`

Conceptually a container of `std::pair<Key const, Value>`

```
1  #include <unordered_map>
2  std::unordered_map<std::string, int> m;
3  m["hello"] = 1; // inserts new key, def. constr. value
4  m["hello"] = 2; // finds existing key
5  auto [it, isNewKey] = m.insert({"hello", 0}); // no effect
6  int val = m["world"]; // inserts new key (val == 0)
7  int val = m.at("monde"); // throws std::out_of_range
8
9  if (auto it = m.find("hello"); it != m.end()) // C++17
10     m.erase(it); // remove by iterator (fast)
11  if (m.contains("hello")) // C++20
12     m.erase("hello"); // remove by key, 2. lookup, bad
13  for (auto const& [k, v] : m) // iterate k/v pairs (C++17)
14     std::cout << k << ": " << v << '\n';
```



- The standard utility to create hash codes
- Used by `std::unordered_map` and others
- Can be customized for your types via template specialization

```
1  #include <functional>
2  std::hash<std::string> h;
3  std::cout << h("hello"); // 2762169579135187400
4  std::cout << h("world"); // 8751027807033337960
5
6  class MyClass { int a, b; ... };
7  template<> struct std::hash<MyClass> {
8      std::size_t operator()(MyClass const& c) {
9          std::hash<int> h;
10         return h(c.a) ^ h(c.b); // xor to combine hashes
11     }
12 };
```



iterators

- generalization of pointers
- allow iteration over some data, irrespective of:
 - the container used (templated)
 - the data itself (container is templated)
 - the consumer of the data (templated algorithm)
- examples
 - `std::reverse_iterator`, `std::back_insert_iterator`, ...

Iterator example - godbolt

```

1  std::vector<int> const v = {1,2,3,4,5,6,7,8,9};
2  auto const end = v.rend() - 3; // arithmetic
3  for (auto it = v.rbegin();
4      it != end;           // compare positions
5      it += 2)           // jump 2 positions
6      std::cout << *it; // dereference, prints: 975

```



algorithms

- implementation of an algorithm working on data
- with a well defined behavior (defined complexity)
- irrespective of
 - the data handled
 - the container where the data live
 - the iterator used to go through data (almost)
- examples
 - for_each, find, find_if, count, count_if, search
 - copy, swap, transform, replace, fill, generate
 - remove, remove_if
 - unique, reverse, rotate, shuffle, partition
 - sort, partial_sort, merge, make_heap, min, max
 - lexicographical_compare, iota, reduce, partial_sum
- see also [105 STL Algorithms in Less Than an Hour](#) and the [algorithms library](#) on cppreference



functors / function objects

- generic utility functions
- as structs with `operator()`
- mostly useful to be passed to STL algorithms
- implemented independently of
 - the data handled (templated)
 - the context (algorithm) calling it
- examples
 - plus, minus, multiplies, divides, modulus, negate
 - equal_to, less, greater, less_equal, ...
 - logical_and, logical_or, logical_not
 - bit_and, bit_or, bit_xor, bit_not
 - identity, not_fn
 - bind, bind_front
- see also documentation on [cppreference](#)



Example

```
1  struct Incrementer {
2      int m_inc;
3      Incrementer(int inc) : m_inc(inc) {}
4
5      int operator()(int value) const {
6          return value + m_inc;
7      }
8  };
9  std::vector<int> v{1, 2, 3};
10 const auto inc = 42;
11 std::transform(v.begin(), v.end(), v.begin(),
12               Incrementer{inc});
```



Prefer lambdas over functors

With lambdas

```
1  std::vector<int> v{1, 2, 3};
2  const auto inc = 42;
3  std::transform(begin(v), end(v), begin(v),
4                [inc](int value) {
5                    return value + inc;
6                });
```



Prefer lambdas over functors

With lambdas

```
1  std::vector<int> v{1, 2, 3};
2  const auto inc = 42;
3  std::transform(begin(v), end(v), begin(v),
4                 [inc](int value) {
5                     return value + inc;
6                 });
```

Good practice: Use STL algorithms with lambdas

- Prefer lambdas over functors when using the STL
- Avoid binders like `std::bind2nd`, `std::ptr_fun`, etc.



Range-based for loops with STL containers

Iterator-based loop (since C++ 98)

```
1  std::vector<int> v = ...;
2  int sum = 0;
3  for (std::vector<int>::iterator it = v.begin();
4       it != v.end(); it++)
5     sum += *it;
```



Range-based for loops with STL containers

C++ 11

Iterator-based loop (since C++ 98)

```
1  std::vector<int> v = ...;
2  int sum = 0;
3  for (std::vector<int>::iterator it = v.begin();
4       it != v.end(); it++)
5     sum += *it;
```

Range-based for loop (since C++ 11)

```
6  std::vector<int> v = ...;
7  int sum = 0;
8  for (auto a : v) { sum += a; }
```



Range-based for loops with STL containers

C++ 11

Iterator-based loop (since C++ 98)

```
1  std::vector<int> v = ...;
2  int sum = 0;
3  for (std::vector<int>::iterator it = v.begin();
4       it != v.end(); it++)
5     sum += *it;
```

Range-based for loop (since C++ 11)

```
6  std::vector<int> v = ...;
7  int sum = 0;
8  for (auto a : v) { sum += a; }
```

STL way (since C++ 98)

```
9  std::vector<int> v = ...;
10 int sum = std::accumulate(v.begin(), v.end(), 0);
11 // std::reduce(v.begin(), v.end()); // C++17
```



More examples

```
1  std::list<int> l = ...;
2
3  // Finds the first element in a list between 1 and 10.
4  const auto it = std::find_if(l.begin(), l.end(),
5      [](int i) { return i >= 1 && i <= 10; });
6  if (it != l.end()) {
7      int element = *it; ...
8  }
9
10 // Computes sin(x)/(x + DBL_MIN) for elements of a range.
11 std::vector<double> r(l.size());
12 std::transform(l.begin(), l.end(), r.begin(),
13     [](auto x) { return std::sin(x)/(x + DBL_MIN); });
14
15 // reduce/fold (using addition)
16 const auto sum = std::reduce(v.begin(), v.end());
```



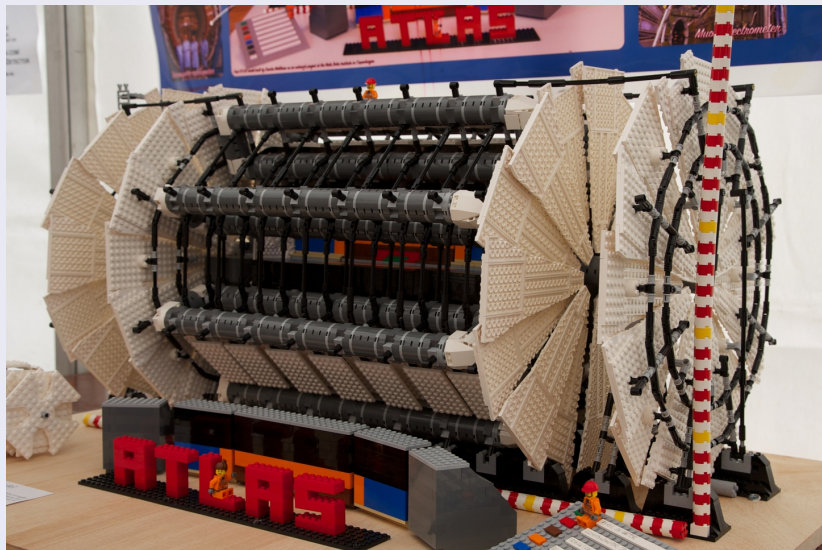
More examples

```
1  std::vector<int> v = ...;
2
3  // remove duplicates
4  std::sort(v.begin(), v.end());
5  auto newEndIt = std::unique(v.begin(), v.end());
6  v.erase(newEndIt, v.end());
7
8  // remove by predicate
9  auto p = [](int i) { return i > 42; };
10 auto newEndIt = std::remove_if(v.begin(), v.end(), p);
11 v.erase(newEndIt, v.end());
12
13 // remove by predicate (C++20)
14 std::erase_if(v, p);
```



Welcome to lego programming!

C++ 98



Exercise: STL

- go to `exercises/stl`
- look at the non STL code in `randomize.nostl.cpp`
 - it creates a vector of ints at regular intervals
 - it randomizes them
 - it computes differences between consecutive ints
 - and the mean and variance of it
- open `randomize.cpp` and complete the “translation” to STL
- see how easy it is to reuse the code with complex numbers



Be brave and persistent!

- you may find the STL quite difficult to use
- template syntax is really tough
- it is hard to get right, compilers spit out long error novels
 - but, compilers are getting better with error messages
- C++ 20 will help with concepts and ranges
- the STL is extremely powerful and flexible
- it will be worth your time!



RAII and smart pointers

- 4 Core modern C++
 - Constness
 - Exceptions
 - Templates
 - Lambdas
 - The STL
 - RAI and smart pointers



Pointers: why are they error prone?

C++ 98

They need initialization

```
1  char *s;  
2  try {  
3      foo(); // may throw  
4      s = new char[100];  
5      read_line(s);  
6  } catch (...) { ... }  
7  process_line(s);
```



Pointers: why are they error prone?

C++ 98

They need initialization

Seg Fault

```
1  char *s;
2  try {
3      foo(); // may throw
4      s = new char[100];
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6  } catch (...) { ... }
7  process_line(s);
```



Pointers: why are they error prone?

C++ 98

They need initialization

Seg Fault

```
1 char *s;  
2 try {  
3     foo(); // may throw  
4     s = new char[100];
```

They need to be released

```
1 char *s = new char[100];  
2 read_line(s);  
3 if (s[0] == '#') return;  
4 process_line(s);  
5 delete[] s;
```



Pointers: why are they error prone?

C++ 98

They need initialization

Seg Fault

```
1 char *s;  
2 try {  
3     foo(); // may throw  
4     s = new char[100];
```

They need to be released

Memory leak

```
1 char *s = new char[100];  
2 read_line(s);  
3 if (s[0] == '#') return;  
4 process_line(s);  
5 delete[] s;
```



Pointers: why are they error prone?

C++ 98

They need initialization

Seg Fault

```

1  char *s;
2  try {
3      foo(); // may throw
4      s = new char[100];

```

They need to be released

Memory leak

```

1  char *s = new char[100];
2  read_line(s);

```

They need clear ownership

```

1  char *s = new char[100];
2  read_line(s);
3  vec.push_back(s);
4  set.add(s);
5  std::thread t1{func1, vec};
6  std::thread t2{func2, set};

```

Pointers: why are they error prone?

C++ 98

They need initialization

Seg Fault

```

1  char *s;
2  try {
3      foo(); // may throw
4      s = new char[100];

```

They need to be released

Memory leak

```

1  char *s = new char[100];
2  read_line(s);

```

They need clear ownership

Who should release ?

```

1  char *s = new char[100];
2  read_line(s);
3  vec.push_back(s);
4  set.add(s);
5  std::thread t1{func1, vec};
6  std::thread t2{func2, set};

```


This problem exists for any resource

For example with a file

```
1  std::FILE *handle = std::fopen(path, "w+");
2  if (nullptr == handle) { throw ... }
3  std::vector v(100, 42);
4  write(handle, v);
5  if (std::fputs("end", handle) == EOF) {
6      return;
7  }
8  std::fclose(handle);
```

Which problems do you spot in the above snippet?



Practically

Use variable construction/destruction and scope semantics:

- wrap the resource inside a class
- acquire resource in constructor
- release resource in destructor
- create an instance on the stack
 - automatically destructed when leaving the scope
 - including in case of exception
- use move semantics to pass the resource around



An RAII File class

```
1 class File {
2 public:
3     // constructor: acquire resource
4     File(const char* filename)
5         : m_handle(std::fopen(filename, "w+")) {
6         // abort constructor on error
7         if (m_handle == nullptr) { throw ... }
8     }
9     // destructor: release resource
10    ~File() { std::fclose(m_handle); }
11    void write (const char* str) {
12        ...
13    }
14 private:
15    std::FILE* m_handle; // wrapped resource
16};
```



Usage of File class

```
1  void log_function() {  
2      // file opening, aka resource acquisition  
3      File logfile("logfile.txt");  
4  
5      // file usage  
6      logfile.write("hello logfile!"); // may throw  
7  
8      // file is automatically closed by the call to  
9      // its destructor, even in case of exception!  
10 }
```

Good practice: Use `std::fstream` for file handling

The standard library provides `std::fstream` to handle files, use it!



A RAI pointer

- wraps and behaves like a regular pointer
- get underlying pointer using `get()`
- when destroyed, deletes the object pointed to
- has move-only semantic
 - the pointer has unique ownership
 - copying will result in a compile error



A RAI pointer

- wraps and behaves like a regular pointer
- get underlying pointer using `get()`
- when destroyed, deletes the object pointed to
- has move-only semantic
 - the pointer has unique ownership
 - copying will result in a compile error

```
1  #include <memory>
2  void f(std::unique_ptr<Foo> ptr) {
3      ptr->bar();
4  } // deallocation when f exits
5
6  std::unique_ptr<Foo> p{ new Foo{} }; // allocation
7  f(std::move(p)); // transfer ownership
8  assert(p.get() == nullptr);
```



What do you expect?

```
1 void f(std::unique_ptr<Foo> ptr);  
2 std::unique_ptr<Foo> uptr(new Foo{});  
3 f(uptr); // transfer of ownership
```



What do you expect?

```

1 void f(std::unique_ptr<Foo> ptr);
2 std::unique_ptr<Foo> uptr(new Foo{});
3 f(uptr); // transfer of ownership

```

Compilation Error - `godbolt`

```

test.cpp:15:5: error: call to deleted constructor
of 'std::unique_ptr<Foo>'

```

```

    f(uptr);
    ~~~~

```

```

/usr/include/c++/4.9/bits/unique_ptr.h:356:7: note:
'unique_ptr' has been explicitly marked deleted here
unique_ptr(const unique_ptr&) = delete;
^

```



std::make_unique

- allocates and constructs an object with arguments and wraps it with `std::unique_ptr` in one step
- no `new` or `delete` calls anymore!
- no memory leaks if used consistently



std::make_unique

- allocates and constructs an object with arguments and wraps it with `std::unique_ptr` in one step
- no `new` or `delete` calls anymore!
- no memory leaks if used consistently

std::make_unique usage

```
1 {  
2     // calls new File("logfile.txt") internally  
3     auto f = std::make_unique<File>("logfile.txt");  
4     f->write("hello logfile!");  
5 } // deallocation at end of scope
```



When to use what?

- Always use RAII for resources, in particular allocations
 - You thus never have to release / deallocate yourself
- Use raw pointers as non-owning, re-bindable observers
- Remember that `std::unique_ptr` is move only



When to use what?

- Always use RAII for resources, in particular allocations
 - You thus never have to release / deallocate yourself
- Use raw pointers as non-owning, re-bindable observers
- Remember that `std::unique_ptr` is move only

A question of ownership

```
1  std::unique_ptr<T> produce();
2  void observe(const T&);
3  void modifyRef(T&);
4  void modifyPtr(T*);
5  void consume(std::unique_ptr<T>);
6  std::unique_ptr<T> pt{produce()}; // Receive ownership
7  observe(*pt); // Keep ownership
8  modifyRef(*pt); // Keep ownership
9  modifyPtr(pt.get()); // Keep ownership
10 consume(std::move(pt)); // Transfer ownership
```



Good practice: std::unique_ptr

- std::unique_ptr is about lifetime management
 - use it to tie the lifetime of an object to a unique RAII owner
 - use raw pointers/references to refer to another object without owning it or managing its lifetime
- use std::make_unique for creation
- strive for having no `new/delete` in your code
- for dynamic arrays, std::vector may be more useful



std::shared_ptr : a reference counting pointer

- wraps a regular pointer similar to `unique_ptr`
- has move and copy semantic
- uses reference counting internally
 - "Would the last person out, please turn off the lights?"
- reference counting is thread-safe, therefore a bit costly

std::make_shared : creates a `std::shared_ptr`

```
1 {  
2     auto sp = std::make_shared<Foo>(); // #ref = 1  
3     vector.push_back(sp);           // #ref = 2  
4     set.insert(sp);                 // #ref = 3  
5 } // #ref 2
```



Quiz: `std::shared_ptr` in use

What is the output of this code? - `godbolt`

```
1 auto shared = std::make_shared<int>(100);
2 auto print = [shared]() {
3     std::cout << "Use: " << shared.use_count() << " "
4         << "value: " << *shared << "\n";
5 };
6 print();
7 {
8     auto ptr{ shared };
9     (*ptr)++;
10    print();
11 }
12 print();
```



Quiz: `std::shared_ptr` in use

What is the output of this code? - `godbolt`

```
1 auto shared = std::make_shared<int>(100);
2 auto print = [shared]() {
3     std::cout << "Use: " << shared.use_count() << " "
4         << "value: " << *shared << "\n";
5 };
6 print();
7 {
8     auto ptr{ shared };
9     (*ptr)++;
10    print();
11 }
12 print();
```

```
Use: 2 value: 100
Use: 3 value: 101
Use: 2 value: 101
```



Quiz: `std::shared_ptr` in use

C++ 11

What is the output of this code?

```
1 auto shared = std::make_shared<int>(100);
2 auto print = [&shared]() {
3     std::cout << "Use: " << shared.use_count() << " "
4         << "value: " << *shared << "\n";
5 };
6 print();
7 {
8     auto ptr{ shared };
9     (*ptr)++;
10    print();
11 }
12 print();
```

```
Use: 1 value: 100
Use: 2 value: 101
Use: 1 value: 101
```



Good practice: Single responsibility principle (SRP)

Every class should have only one responsibility.

Good practice: Rule of zero

- If your class has any special member functions (except ctor.)
 - Your class probably deals with a resource, use RAI
 - Your class should only deal with this resource (SRP)
 - Apply rule of 3/5: write/default/delete all special members
- Otherwise: do not declare any special members (rule of zero)
 - A constructor is fine, if you need some setup
 - If your class holds a resource as data member:
wrap it in a smart pointer, container, or any other RAI class



Exercise: Smart pointers

- go to `exercises/smartPointers`
- compile and run the program. It doesn't generate any output.
- Run with `valgrind` if possible to check for leaks

```
$ valgrind --leak-check=full --track-origins=yes ./smartPointers
```
- In the *essentials course*, go through `problem1()` and `problem2()` and fix the leaks using smart pointers.
- In the *advanced course*, go through `problem1()` to `problem4()` and fix the leaks using smart pointers.
- `problem4()` is the most difficult. Skip if not enough time.



Useful tools

- 1 History and goals
- 2 Language basics
- 3 Object orientation (OO)
- 4 Core modern C++
- 5 Useful tools
 - C++ editor
 - Version control
 - Code formatting
 - The Compiling Chain
 - Web tools
 - Debugging



- 5 Useful tools
- C++ editor
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C++ editors and IDEs

Can dramatically improve your efficiency by

- Coloring the code for you to “see” the structure
- Helping with indenting and formatting properly
- Allowing you to easily navigate in the source tree
- Helping with compilation/debugging, profiling, static analysis
- Showing you errors and suggestions while typing

▶ Visual Studio Heavy, fully fledged IDE for Windows

▶ Visual Studio Code Editor, open source, portable, many plugins

▶ Eclipse IDE, open source, portable

▶ Emacs ▶ Vim Editors for experts, extremely powerful.

They are to IDEs what latex is to PowerPoint

CLion, Code::Blocks, Atom, NetBeans, Sublime Text, ...

Choosing one is mostly a matter of taste



Version control

- 5 Useful tools
 - C++ editor
 - **Version control**
 - Code formatting
 - The Compiling Chain
 - Web tools
 - Debugging



Version control

Please use one!

- Even locally
- Even on a single file
- Even if you are the only committer

It will soon save your day

A few tools

- ▶ **git** THE mainstream choice. Fast, light, easy to use
- ▶ **mercurial** The alternative to git
- ▶ **Bazaar** Another alternative
- ▶ **Subversion** Historical, not distributed - don't use
- ▶ **CVS** Archeological, not distributed - don't use



Git crash course

```
$ git init myProject
Initialized empty Git repository in myProject/.git/

$ vim file.cpp; vim file2.cpp
$ git add file.cpp file2.cpp
$ git commit -m "Committing first 2 files"
[master (root-commit) c481716] Committing first 2 files
...

$ git log --oneline
d725f2e Better STL test
f24a6ce Reworked examples + added stl one
bb54d15 implemented template part
...

$ git diff f24a6ce bb54d15
```



Code formatting

- 5 Useful tools
 - C++ editor
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 - Debugging



clang-format

.clang-format

- File describing your formatting preferences
- Should be checked-in at the repository root (project wide)
- `clang-format -style=LLVM -dump-config > .clang-format`
- Adapt style options with help from: <https://clang.llvm.org/docs/ClangFormatStyleOptions.html>

Run clang-format

- `clang-format --style=LLVM -i <file.cpp>`
- `clang-format -i <file.cpp>` (looks for .clang-format file)
- `git clang-format` (formats local changes)
- `git clang-format <ref>` (formats changes since git <ref>)
- Some editors/IDEs find a .clang-format file and adapt



clang-format

Exercise: clang-format

- Go to any example
- Format code with:
`clang-format --style=GNU -i <file.cpp>`
- Inspect changes, try `git diff .`
- Revert changes using `git checkout -- <file.cpp>` or `git checkout .`
- Go to exercises directory and create a `.clang-format` file
`clang-format -style=LLVM -dump-config > .clang-format`
- Run `clang-format -i <any_exercise>/*.cpp`
- Revert changes using `git checkout <any_exercise>`



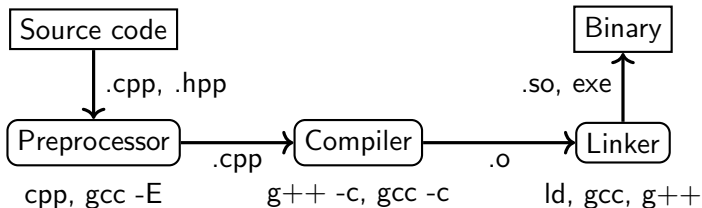
The Compiling Chain

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The compiling chain

C++ 17



The steps

`cpp` the preprocessor

handles the `#` directives (macros, includes)
creates “complete” source code (ie. translation unit)

`g++` the compiler

creates machine code from C++ code

`ld` the linker

links several binary files into libraries and executables



Compilers

Available tools

▶ **gcc** the most common and most used
free and open source

▶ **clang** drop-in replacement of gcc
slightly better error reporting
free and open source, based on LLVM

▶ **icc** ▶ **icx** Intel's compilers, proprietary but now free
optimized for Intel hardware
icc being replaced by icx, based on LLVM

▶ **Visual C++ / MSVC** Microsoft's C++ compiler on Windows

My preferred choice today

- **gcc** as the de facto standard in HEP
- **clang** in parallel to catch more bugs



Useful compiler options (gcc/clang)

Get more warnings

`-Wall -Wextra` get all warnings

`-Werror` force yourself to look at warnings

Optimization

`-g` add debug symbols (also: `-g3` or `-ggdb`)

`-Ox` 0 = no opt., 1-2 = opt., 3 = highly opt. (maybe larger binary), `g` = opt. for debugging

Compilation environment

`-I <path>` where to find header files

`-L <path>` where to find libraries

`-l <name>` link with `libname.so`

`-E / -c` stop after preprocessing / compilation



How to inspect object files?

Listing symbols : nm

- gives list of symbols in a file
 - these are functions and constants
 - with their internal (mangled/encoded) naming
- also gives type and location in the file for each symbol
 - 'U' type means undefined
 - so a function used but not defined
 - linking will be needed to resolve it
- use `-C` option to demangle on the fly

```
> nm -C Struct.o
```

```
                U strlen
                U _Unwind_Resume
0000000000000008a T SlowToCopy::SlowToCopy(SlowToCopy const&)
00000000000000000 T SlowToCopy::SlowToCopy()
00000000000000064 T SlowToCopy::SlowToCopy(std::__cxx11::basic<st
```

How to inspect libraries/executables?

Listing dependencies : ldd

- gives (recursive) list of libraries required by the given argument
 - and if/where they are found in the current context
- use `-r` to list missing symbols (mangled)

```
> ldd -r trypoly
linux-vdso.so.1 (0x00007f3938085000)
libpoly.so => not found
libstdc++.so.6 => /lib/x86_64-linux-gnu/libstdc++.so.6 (0x00
[...]
```

undefined symbol: <code>_ZNK7Hexagon16computePerimeterEv</code>	<code>(./try</code>
undefined symbol: <code>_ZNK7Polygon16computePerimeterEv</code>	<code>(./try</code>
undefined symbol: <code>_ZN7HexagonC1Ef</code>	<code>(./trypoly.sol)</code>
undefined symbol: <code>_ZN8PentagonC1Ef</code>	<code>(./trypoly.sol)</code>



Makefiles

Why to use them

- an organized way of describing building steps
- avoids a lot of typing

Several implementations

- raw Makefiles: suitable for small projects
- cmake: portable, the current best choice
- automake: GNU project solution

```
test : test.cpp libpoly.so
    $(CXX) -Wall -Wextra -o $@ $^
libpoly.so: Polygons.cpp
    $(CXX) -Wall -Wextra -shared -fPIC -o $@ $^
clean:
    rm -f *o *so *~ test test.sol
```



CMake

- a cross-platform meta build system
- generates platform-specific build systems
- see also this [basic](#) and [detailed](#) talks

Example CMakeLists.txt

```
1 cmake_minimum_required(VERSION 3.18)
2 project(hello CXX)
3
4 find_package(ZLIB REQUIRED) # for external libs
5
6 add_executable(hello main.cpp util.h util.cpp)
7 target_compile_features(hello PUBLIC cxx_std_17)
8 target_link_libraries(hello PUBLIC ZLIB::ZLIB)
```



CMake - Building

Building a CMake-based project

Start in the directory with the top-level CMakeLists.txt:

```
1 mkdir build # will contain all build-related files
2 cd build
3 cmake .. # configures and generates a build system
4 cmake -DCMAKE_BUILD_TYPE=Release .. # pass arguments
5 ccmake . # change configuration using terminal GUI
6 cmake-gui . # change configuration using Qt GUI
7 cmake --build . -j8 # build project with 8 jobs
8 cmake --build . --target hello # build only hello
9 sudo cmake --install . # install project into system
10 cd ..
11 rm -r build # clean everything
```



Compiler chain

Exercise: Compiler chain

- go to `exercises/polymorphism`
- preprocess `Polygons.cpp` (`g++ -E -o output`)
- compile `Polygons.o` and `trypoly.o` (`g++ -c -o output`)
- use `nm` to check symbols in `.o` files
- look at the Makefile
- try `make clean`; `make`
- see linking stage of the final program using `g++ -v`
 - just add a `-v` in the Makefile command for `trypoly` target
 - run `make clean`; `make`
 - look at the `collect 2` line, from the end up to `"-o trypoly"`
- see library dependencies of `'trypoly'` using `'ldd'`



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Godbolt / Compiler Explorer

Concept

An online generic compiler with immediate feedback. Allows:

- compiling online any code against any version of any compiler
- inspecting the assembly generated
- use of external libraries (over 50 available !)
- running the code produced
- using tools, e.g. ldd, include-what-you-use, ...
- sharing small pieces of code via permanent short links

Typical usage

- check small pieces of code on different compilers
- check some new C++ functionality and its support
- optimize small pieces of code
- NOT relevant for large codes



Godbolt by example

Check effect of optimization flags

<https://godbolt.org/z/Pb8WsWjEx>

- Check generated code with `-O0`, `-O1`, `-O2`, `-O3`
- See how it gets shorter and simpler

The screenshot displays the Godbolt Compiler Explorer interface with three panes. The left pane shows the C++ source code for a program that calculates the factorial of a number and prints it. The middle pane shows the assembly code generated by `gcc 12.1` with the `-O0` optimization flag. The right pane shows the assembly code generated with the `-O3` optimization flag. The `-O3` assembly is significantly shorter and simpler than the `-O0` assembly, demonstrating the effect of optimization flags.

C++ source code (left pane):

```

1 #include <iostream>
2
3 constexpr int fact(int a) {
4     int n = 1;
5     for (int i = 1; i <= a; i++) {
6         n *= i;
7     }
8     return n;
9 }
10
11 int main() {
12     for (int i = 4; i < 8; i++) {
13         std::cout << fact(i);
14     }
15 }

```

Assembly code for `-O0` (middle pane):

```

1 fact(int):
2     push rbp
3     mov rbp, rsp
4     mov DWORD PTR [rbp-20], edi
5     mov DWORD PTR [rbp-4], 1
6     mov DWORD PTR [rbp-8], 1
7     jmp .L2
8 .L2:
9     mov eax, DWORD PTR [rbp-4]
10    imul eax, DWORD PTR [rbp-8]
11    mov DWORD PTR [rbp-4], eax
12    add DWORD PTR [rbp-8], 1
13    .L2:
14    mov eax, DWORD PTR [rbp-8]
15    cmp eax, DWORD PTR [rbp-20]
16    jle .L3
17    mov eax, DWORD PTR [rbp-4]
18    pop rbp
19    ret
20 main:
21    push rbp
22    mov rbp, rsp
23    sub rsp, 16
24    mov DWORD PTR [rbp-4], 4
25    jmp .L4
26 .L4:
27    mov eax, DWORD PTR [rbp-4]
28    mov edi, eax
29    call fact(int)
30    mov esi, eax
31    mov edi, OFFSET FLAT: _ZSt4cout
32    call std::basic_ostream<char, std::char_traits<char>>::operator<<(int) const

```

Assembly code for `-O3` (right pane):

```

1 main:
2     sub     rsp, 8
3     mov     esi, 24
4     mov     edi, OFFSET FLAT: _ZSt4cout
5     call  std::basic_ostream<char, std::char_traits<char>>::operator<<(int) const
6     mov     esi, 128
7     mov     edi, OFFSET FLAT: _ZSt4cout
8     call  std::basic_ostream<char, std::char_traits<char>>::operator<<(int) const
9     mov     esi, 728
10    mov     edi, OFFSET FLAT: _ZSt4cout
11    call  std::basic_ostream<char, std::char_traits<char>>::operator<<(int) const
12    mov     esi, 5040
13    mov     edi, OFFSET FLAT: _ZSt4cout
14    call  std::basic_ostream<char, std::char_traits<char>>::operator<<(int) const
15    xor     eax, eax
16    add     rsp, 8
17    ret
18 _GLOBAL__sub_I_main:
19    sub     rsp, 8
20    mov     edi, OFFSET FLAT: _ZStL8_ioinit
21    call  std::ios_base::Init::Init() const
22    mov     edi, OFFSET FLAT: __dso_handle
23    mov     esi, OFFSET FLAT: _ZStL8_ioinit

```

Output (bottom pane):

```

Output of x86-64 gcc 12.1 (Compiler #3)
ASM generation compiler returned: 0
Execution build compiler returned: 0
Program returned: 0
24127295840

```

Concept

Reveals the actual code behind C⁺⁺ syntactic sugar

- lambdas
- range-based loops
- templates
- initializations
- auto
- ...

Typical usage

- understand how things work behind the C⁺⁺ syntax
- debug some non working pieces of code



cppinsights by example

Check how range-based loop work

<https://cppinsights.io/s/b886aa76>

- See how they map to regular iterators
- And how operators are converted to function calls

The screenshot shows the CppInsights web interface. The top bar includes navigation icons and the text "[C++ Standard: C++ 20]". The main content is split into two panels: "Source" and "Insight".

Source:

```

1 #include <array>
2 #include <iostream>
3
4 int main() {
5     std::array<int, 5> arr{2,4,6,8,10};
6     for(auto const & c : arr) {
7         std::cout << "c=" << c << "\n";
8     }
9 }

```

Insight:

```

1 #include <array>
2 #include <iostream>
3
4 int main()
5 {
6     std::array<int, 5> arr = {{2, 4, 6, 8, 10}};
7     {
8         std::array<int, 5> & __range1 = arr;
9         int * __begin1 = __range1.begin();
10        int * __end1 = __range1.end();
11        for(; __begin1 != __end1; ++ __begin1) {
12            const std::array<int, 5>::value_type & c = * __begin1;
13            std::operator<<(std::operator<<(std::cout, "c="),operator<<(c), "\n");
14        }
15    }
16    return 0;
17 }
18 }
19

```

At the bottom, the console shows "Insights exited with result code: 0".



Debugging

- 5 Useful tools
 - C++ editor
 - Version control
 - Code formatting
 - The Compiling Chain
 - Web tools
 - Debugging



Debugging

The problem

- everything compiles fine (no warning)
- but crashes at run time
- no error message, no clue



Debugging

The problem

- everything compiles fine (no warning)
- but crashes at run time
- no error message, no clue

The solution: debuggers

- dedicated program able to stop execution at any time
- and show you where you are and what you have



Debugging

The problem

- everything compiles fine (no warning)
- but crashes at run time
- no error message, no clue

The solution: debuggers

- dedicated program able to stop execution at any time
- and show you where you are and what you have

Existing tools

▶ `gdb` THE main player

▶ `lldb` the debugger coming with clang/LLVM

▶ `gdb-oneapi` the Intel OneAPI debugger



`gdb` crash course

start `gdb`

- `gdb <program>`
- `gdb <program><core file>`
- `gdb --args <program><program arguments>`

inspect state

`bt` prints a backtrace

`print <var>` prints current content of the variable

`list` show code around current point

`up/down` go up or down in call stack

breakpoints

`break <function>` puts a breakpoint on function entry

`break <file>:<line>` puts a breakpoint on that line



Exercise: gdb

- go to exercises/debug
- compile, run, see the crash
- run it in gdb (or lldb on newer MacOS)
- inspect backtrace, variables
- find problem and fix bug
- try stepping, breakpoints



Debugging UIs

User interfaces for debuggers

- offer convenience on top of command line
- windows for variables, breakpoints, call stack, active threads, watch variables in-code, disassembly, run to cursor ...

▸ **VSCode** Built-in support for gdb

▸ **CodeLLDB** VS Code plugin for LLDB

▸ **GDB dashboard** Poplar terminal UI for gdb

▸ **GEF** Modern terminal UI for gdb

- some editors and most IDEs have good debugger integration



This is the end

Questions ?

https://github.com/hsf-training/cpluspluscourse/raw/download/talk/C++Course_full.pdf
<https://github.com/hsf-training/cpluspluscourse>



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Books



A Tour of C++, Third Edition

Bjarne Stroustrup, Addison-Wesley, Sep 2022

ISBN-13: [978-0136816485](#)



Effective Modern C++

Scott Meyers, O'Reilly Media, Nov 2014

ISBN-13: [978-1-491-90399-5](#)



C++ Templates - The Complete Guide, 2nd Edition

David Vandevoorde, Nicolai M. Josuttis, and Douglas Gregor

ISBN-13: [978-0-321-71412-1](#)



C++ Best Practices, 2nd Edition

Jason Turner

<https://leanpub.com/cppbestpractices>



Clean Architecture

Robert C. Martin, Pearson, Sep 2017

ISBN-13: [978-0-13-449416-6](#)



The Art of UNIX Programming

Eric S. Raymond, Addison-Wesley, Sep 2002

ISBN-13: [978-0131429017](#)



Introduction to Algorithms, 4th Edition

T. H. Cormen, C. E. Leiserson, R. L. Rivest, C. Stein, Apr 2022

ISBN-13: [978-0262046305](#)

Conferences

- CppCon — cppcon.org —  CppCon
- C++ Now — cppnow.org —  BoostCon
- Code::Dive — codedive.pl —  codediveconference
- ACCU Conference — accu.org —  ACCUConf
- Meeting C++ — meetingcpp.com —  MeetingCPP
- See link below for more information
<https://isocpp.org/wiki/faq/conferences-worldwide>

