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
  - 256 slides, 350 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

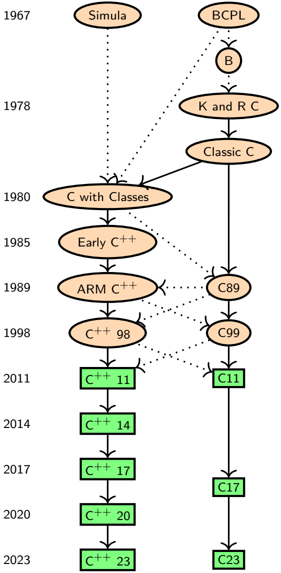
Detailed outline

History and goals

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
  - work on C++ 26 is ongoing
- 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	$\geq$4.8	$\geq$3.3
14	$\geq$4.9	$\geq$3.4
17	$\geq$7.3	$\geq$5
20	$\geq$11, 14	$\geq$19
23	>15	>20

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 to native machine code
    - unlike Java, C#, Python, ...
- allows to go close to hardware when needed

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- 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

Core syntax and types

Hello World

C++ 98

```cpp
#include <iostream>

// This is a function
void print(int i) {
  std::cout << "Hello, world " << i << std::endl;
}

int main(int argc, char** argv) {
  int n = 3;
  for (int i = 0; i < n; i++) {
    print(i);
  }
  return 0;
}
```

Comments

C^{++} 98

```cpp
// simple comment until end of line
int i;

/* multiline comment
 * in case we need to say more
 */
double /* or something in between */ d;

/**
 * Best choice : doxygen compatible comments
 * \brief checks whether i is odd
 * \param i input
 * \return true if i is odd, otherwise false
 * \see https://www.doxygen.nl/manual/docblocks.html
 */
bool isOdd(int i);
```

Basic types(1)

C++ 98

```
bool b = true;               // boolean, true or false

char c = 'a';                // min 8 bit integer
                             // may be signed or not
                             // can store an ASCII character
signed char c = 4;           // min 8 bit signed integer
unsigned char c = 4;         // min 8 bit unsigned integer

char* s = "a C string";      // array of chars ended by \0
string t = "a C++ string";// class provided by the STL

short int s = -444;          // min 16 bit signed integer
unsigned short s = 444;      // min 16 bit unsigned integer
short s = -444;              // int is optional
```

Basic types(2)

C++ 98

```cpp
int i = -123456;                 // min 16, usually 32 bit
unsigned int i = 1234567;        // min 16, usually 32 bit

long l = 0L                      // min 32 bit
unsigned long l = 0UL;           // min 32 bit

long long ll = 0LL;                // min 64 bit
unsigned long long l = 0ULL;       // min 64 bit

float f = 1.23f;                 // 32 (1+8+23) bit float
double d = 1.23E34;              // 64 (1+11+52) bit float
long double ld = 1.23E34L        // min 64 bit float
```

Portable numeric types

C++ 98

```cpp
#include <cstdint> // defines the following:

std::int8_t c = -3;      // 8 bit signed integer
std::uint8_t c = 4;      // 8 bit unsigned integer

std::int16_t s = -444;   // 16 bit signed integer
std::uint16_t s = 444;   // 16 bit unsigned integer

std::int32_t s = -674;   // 32 bit signed integer
std::uint32_t s = 674;   // 32 bit unsigned integer

std::int64_t s = -1635; // 64 bit signed integer
std::uint64_t s = 1635; // 64 bit unsigned int
```

Integer literals

C++ 98

```cpp
int i = 1234;             // decimal     (base 10)
int i = 02322;            // octal       (base  8)
int i = 0x4d2;            // hexadecimal (base 16)
int i = 0X4D2;            // hexadecimal (base 16)
int i = 0b10011010010;    // binary      (base  2) C++14

int i = 123'456'789;      // digit separators, C++14
int i = 0b100'1101'0010;  // digit separators, C++14

42          // int
42u,   42U  // unsigned int
42l,   42L  // long
42ul,  42UL // unsigned long
42ll,  42LL // long long
42ull, 42ULL // unsigned long long
```

Floating-point literals

C++ 98

```cpp
double d = 12.34;
double d = 12.;
double d = .34;
double d = 12e34;             // 12 * 10^34
double d = 12E34;             // 12 * 10^34
double d = 12e-34;            // 12 * 10^-34
double d = 12.34e34;          // 12.34 * 10^34

double d = 123'456.789'101; // digit separators, C++14

double d = 0x4d2.4p3;     // hexfloat, 0x4d2.4 * 2^3
                          // = 1234.25 * 2^3 = 9874

3.14f, 3.14F,  // float
3.14,  3.14,   // double
3.14l, 3.14L,  // long double
```

Arrays and Pointers

2 Language basics

Static arrays

C++ 98

```cpp
int ai[4] = {1,2,3,4};
int ai[] = {1,2,3,4};  // identical

char ac[3] = {'a','b','c'};    // char array
char ac[4] = "abc";            // valid C string
char ac[4] = {'a','b','c',0}; // same valid string

int i = ai[2];  // i = 3
char c = ac[8]; // at best garbage, may segfault
int i = ai[4];  // also garbage !
```

Pointers

C++ 98

```
int i = 4;
int *pi = &i;
int j = *pi + 1;

int ai[] = {1,2,3};
int *pai = ai; // decay to ptr
int *paj = pai + 1;
int k = *paj + 1;

// compile error
int *pak = k;

// seg fault !
int *pak = (int*)k;
int l = *pak;
```

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Memory layout

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

Pointers

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int i = 4;
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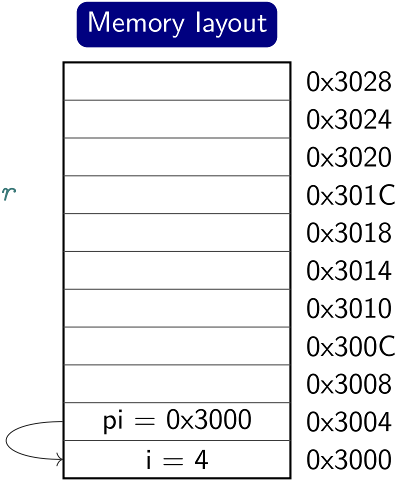

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Memory layout

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j = 5	0x3008
pi = 0x3000	0x3004
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Memory layout

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ai[1] = 2	0x3010
ai[0] = 1	0x300C
j = 5	0x3008
pi = 0x3000	0x3004
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pi = 0x3000	0x3004
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ai[2] = 3	0x3014
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??

nullptr

C++ 11

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

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

Dynamic arrays using C

C++ 98

```
#include <cstdlib>
#include <cstring>

int *bad;          // pointer to random address
int *ai = nullptr; // better, deterministic, testable

// allocate array of 10 ints (uninitialized)
ai = (int*) malloc(10*sizeof(int));
memset(ai, 0, 10*sizeof(int)); // and set them to 0

ai = (int*) calloc(10, sizeof(int)); // both in one go

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

```
#include <cstdlib>
#include <cstring>

// allocate array of 10 ints
int* ai = new int[10];   // uninitialized
int* ai = new int[10]{}; // zero-initialized

delete[] ai; // release array memory

// allocate a single int
int* pi = new int;
int* pi = new int{};
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
- Functions
- Operators
- Control structures
- Headers and interfaces
- Auto keyword

Scope

C++ 98

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

```
{ int a;
  { int b;
  } // end of b scope
} // 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

```cpp
int a = 1;
{
  int b[4];
  b[0] = a;
}
// Doesn't compile here:
// 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

b[3] = ?	0x3010
b[2] = ?	0x300C
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C++ 98

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Memory layout

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

Namespaces

C++ 98

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

```cpp
int a;
namespace n {
  int a;    // no clash
}
namespace p {
  int a;    // no clash
  namespace inner {
    int a; // no clash
  }
}
void f() {
  n::a = 3;
}
namespace p { // reopen p
  void f() {
    p::a = 6;
    a = 6;  //same as above
    ::a = 1;
    p::inner::a = 8;
    inner::a = 8;
    n::a = 3;
  }
}
using namespace p::inner;
void g() {
  a = -1; // err: ambiguous
}
```

Nested namespaces

C++ 17

C++ 98: Old way to declare nested namespaces

```
namespace A {
  namespace B {
    namespace C {
      //...
    }
  }
}
```

C++ 17: Nested declaration

```
namespace A::B::C {
  //...
}
```

C++ 17: Namespace alias

```
namespace ABC = A::B::C;
```

Class and enum types

2 Language basics
- Core syntax and types
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struct

C++ 98

"members" grouped together under one name

```
struct Individual {
  unsigned char age;
  float weight;
};

Individual student;
student.age = 25;
student.weight = 78.5f;

Individual teacher = {
  45, 67.0f
};
```

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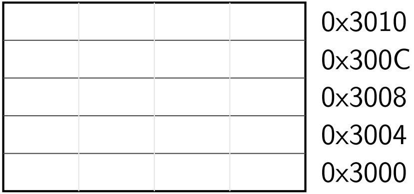

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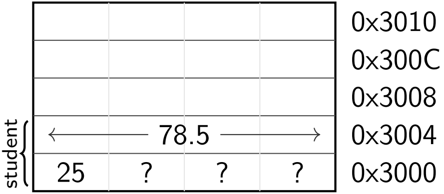

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Memory layout

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

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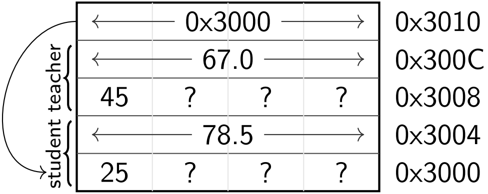

union

C++ 98

"members" packed together at same memory location

```
union Duration {
  int seconds;
  short hours;
  char days;
};
Duration d1, d2, d3;
d1.seconds = 259200;
d2.hours = 72;
d3.days = 3;
d1.days = 3; // d1.seconds overwritten
int a = d1.seconds; // d1.seconds is garbage
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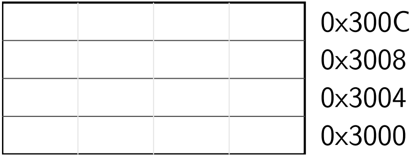

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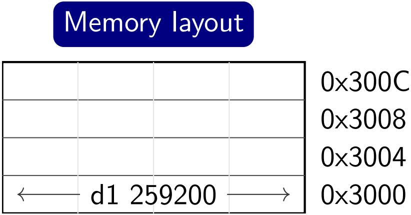

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```

Memory layout

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

union

C++ 98

"members" packed together at same memory location

```cpp
union Duration {
  int seconds;
  short hours;
  char days;
};
Duration d1, d2, d3;
d1.seconds = 259200;
d2.hours = 72;
d3.days = 3;
d1.days = 3; // d1.seconds overwritten
int a = d1.seconds; // d1.seconds is garbage
```

Memory layout

				0x300C
d3 3	?	?	?	0x3008
← d2 72 →		?	?	0x3004
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C^{++} 98

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Memory layout

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C++ 98

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```

Memory layout

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

Good practice: Avoid unions

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

Enums

C++ 98

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

```cpp
enum VehicleType {

  BIKE,  // 0
  CAR,   // 1
  BUS,   // 2
};
VehicleType t = CAR;
```

```cpp
enum VehicleType
  : int { // C++11
  BIKE = 3,
  CAR = 5,
  BUS = 7,
};
VehicleType t2 = BUS;
```

Scoped enumeration, aka enum class

C++ 11

Same syntax as enum, with scope

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

Scoped enumeration, aka enum class C^{++} 11

Same syntax as enum, with scope

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

Only advantages

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

```cpp
enum VType { Bus, Car }; enum Color { Red, Blue };
VType t = Bus;
if (t == Red) { /* We do enter */ }
int a = 5 * Car; // Ok, a = 5

enum class VT { Bus, Car }; enum class Col { Red, Blue };
VT t = VT::Bus;
if (t == Col::Red) { /* Compiler error */ }
int a = t * 5;        // Compiler error
```

More sensible example

C++ 11

```
enum class ShapeType {
  Circle,
  Rectangle
};

struct Rectangle {
  float width;
  float height;
};
```

More sensible example

C++ 11

```cpp
enum class ShapeType {
  Circle,
  Rectangle
};

struct Rectangle {
  float width;
  float height;
};
```

```cpp
struct Shape {
  ShapeType type;
  union {
    float radius;
    Rectangle rect;
  };
};
```

More sensible example

C++ 11

```cpp
enum class ShapeType {
  Circle,
  Rectangle
};

struct Rectangle {
  float width;
  float height;
};
```

```cpp
struct Shape {
  ShapeType type;
  union {
    float radius;
    Rectangle rect;
  };
};
```

```cpp
Shape s;
s.type =
  ShapeType::Circle;
s.radius = 3.4;

```

```cpp
Shape t;
t.type =
  Shapetype::Rectangle;
t.rect.width = 3;
t.rect.height = 4;
```

typedef and using

C^{++} 98 / C^{++} 11

Used to create type aliases

C^{++} 98

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

C^{++} 11

```cpp
using myint = std::uint64_t;
myint count = 17;
using position = float[3];

template <typename T> using myvec = std::vector<T>;
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

C++ 98

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:

```cpp
int i = 2;
int &iref = i; // access to i
iref = 3;      // i is now 3

// const reference to a member:
struct A { int x; int y; } a;
const int &x = a.x; // direct read access to A's x
x = 4;              // doesn't compile
a.x = 4;            // fine
```

Pointers vs References

C^{++} 98

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

Pointers vs References

C^{++} 98

Specificities of reference

- Natural syntax
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- 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

Functions

C++ 98

```cpp
// with return type
int square(int a) {
  return a * a;
}

// multiple parameters
int mult(int a,
         int b) {
  return a * b;
}
// no return
void log(char* msg) {
  std::cout << msg;
}

// no parameter
void hello() {
  std::cout << "Hello World";
}
```

Functions

C++ 98

```cpp
// with return type
int square(int a) {
  return a * a;
}

// multiple parameters
int mult(int a,
         int b) {
  return a * b;
}
```

```cpp
// no return
void log(char* msg) {
  std::cout << msg;
}

// no parameter
void hello() {
  std::cout << "Hello World";
}
```

Functions and references to returned values

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

Function default arguments C^{++} 98

```cpp
// must be the trailing
// argument
int add(int a,
        int b = 2) {
  return a + b;
}
// add(1) == 3
// add(3,4) == 7

// multiple default
// arguments are possible
int add(int a = 2,
        int b = 2) {
  return a + b;
}
// add() == 4
// add(3) == 5
```

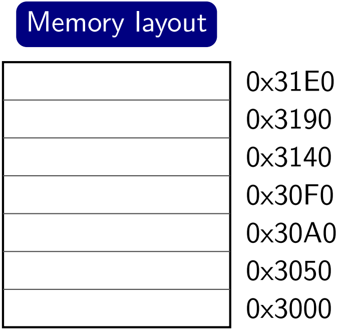
Functions: parameters are passed by value

C++ 98

```cpp
struct BigStruct {...};
BigStruct s;

// parameter by value
void printVal(BigStruct p) {
  ...
}
printVal(s); // copy

// parameter by reference
void printRef(BigStruct &q) {
  ...
}
printRef(s); // no copy
```



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C++ 98

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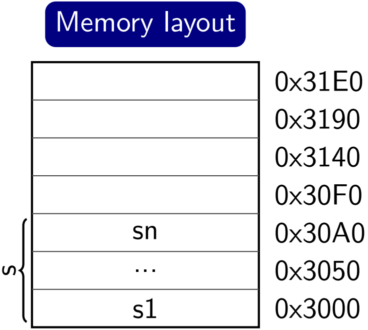

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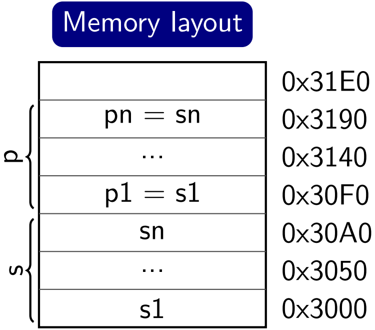

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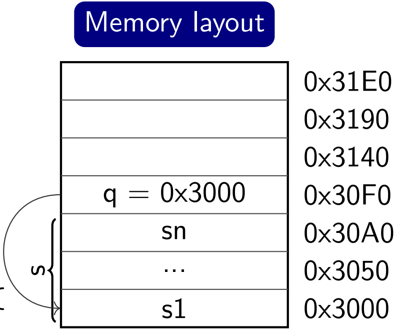
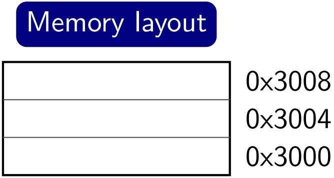


Functions: pass by value or reference?


```cpp
struct SmallStruct {int a;};
SmallStruct s = {1};

void changeVal(SmallStruct p) {
  p.a = 2;
}
changeVal(s);
// s.a == 1

void changeRef(SmallStruct &q) {
  q.a = 2;
}
changeRef(s);
// s.a == 2
```



Functions: pass by value or reference?

C^{++} 98

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void changeRef(SmallStruct &q) {
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}
changeRef(s);
// s.a == 2
```

Memory layout

	0x3008
	0x3004
s.a = 1	0x3000

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  q.a = 2;
}
changeRef(s);
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```

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	0x3008
p.a = 1	0x3004
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```

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	0x3008
p.a = 2	0x3004
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C++ 98

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  q.a = 2;
}
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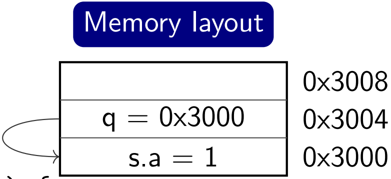
// s.a == 2
```



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  q.a = 2;
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Memory layout

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q = 0x3000	0x3004
s.a = 2	0x3000

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SmallStruct s = {1};

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}
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// s.a == 1

void changeRef(SmallStruct &q) {
  q.a = 2;
}
changeRef(s);
// 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

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

Syntax

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

Overloading

C++ 98

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

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

Functions

C^{++} 98

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`

Functions: good practices C^{++} 98

Good practice: Write readable functions

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

Example: Good

```cpp
/// Count number of dilepton events in data.
/// \param d Dataset to search.
unsigned int countDileptons(Data &d) {
  selectEventsWithMuons(d);
  selectEventsWithElectrons(d);
  return d.size();
}
```

Functions: good practices

Example: don't! Everything in one long function

```cpp
unsigned int runJob() {
  // Step 1: data
  Data data;
  data.resize(123456);
  data.fill(...);

  // Step 2: muons
  for (....) {
    if (...) {
      data.erase(...);
    }
  }
  // Step 3: electrons
  for (....) {
    if (...) {
      data.erase(...);
    }
  }

  // Step 4: dileptons
  int counter = 0;
  for (....) {
    if (...) {
      counter++;
    }
  }

  return counter;
}
```

Operators

2 Language basics

- Core syntax and types
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- Functions
- Operators
- Control structures
- Headers and interfaces
- Auto keyword

Operators(1)

C++ 98

Binary and Assignment Operators

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

Operators(1)

C++ 98

Binary and Assignment Operators

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

Increment / Decrement Operators

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

Operators(1)

C++ 98

Binary and Assignment Operators

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

Increment / Decrement Operators

Use wisely

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int k = i++;    // i = 3, k = 2
int l = --i;    // i = 2, l = 2
int m = i--;    // i = 1, m = 2
```

Operators(2)

C++ 98

Bitwise and Assignment Operators

```
unsigned i = 0xee & 0x55;   // 0x44
i |= 0xee;                  // 0xee
i ^= 0x55;                  // 0xbb
unsigned j = ~0xee;         // 0xffffff11
unsigned k = 0x1f << 3;     // 0xf8
unsigned l = 0x1f >> 2;     // 0x7
```

Operators(2)

Bitwise and Assignment Operators

```cpp
unsigned i = 0xee & 0x55;   // 0x44
i |= 0xee;                  // 0xee
i ^= 0x55;                  // 0xbb
unsigned j = ~0xee;         // 0xffffff11
unsigned k = 0x1f << 3;     // 0xf8
unsigned l = 0x1f >> 2;     // 0x7
```

Logical Operators

```cpp
bool a = true;
bool b = false;
bool c = a && b;      // false
bool d = a || b;      // true
bool e = !d;          // false
```

Operators(3)

C++ 98

Comparison Operators

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

Operators(3)

C++ 98

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auto g = (5 <=> 5); // C++20 (later)
```

Precedences

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

Details can be found on cppreference

Operators(3)

C++ 98

Comparison Operators

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bool a = (3 == 3);  // true
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Precedences — Avoid

```cpp
c &= 1+(++b)|(a--)*4%5^7; // ???
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Operators(3)

C++ 98

Comparison Operators

```
bool a = (3 == 3);  // true
bool b = (3 != 3);  // false
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bool f = (4 >= 4);  // true
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

Control structures: if

C++ 98

if syntax

```cpp
if (condition1) {
  Statement1; Statement2;
} else if (condition2)
  OnlyOneStatement;
else {
  Statement3;
  Statement4;
}
```

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

Control structures: if

C^{++} 98

Practical example

```cpp
int collatz(int a) {
  if (a <= 0) {
    std::cout << "not supported\n";
    return 0;
  } else if (a == 1) {
    return 1;
  } else if (a%2 == 0) {
    return collatz(a/2);
  } else {
    return collatz(3*a+1);
  }
}
```

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

```cpp
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

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

Do not abuse it

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

- Explicit `if`s are generally easier to read
- Use the ternary operator with short conditions and expressions
- Avoid nesting

Control structures: switch

C++ 98

Syntax

```
switch(identifier) {
  case c1 : statements1; break;
  case c2 : statements2; break;
  case c3 : statements3; break;
  ...
  default : statementsn; break;
}
```

- 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

C++ 98

Syntax

```
switch(identifier) {
  case c1 : statements1; break;
  case c2 : statements2; break;
  case c3 : statements3; break;
  ...
  default : statementsn; break;
}
```

- 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

C++ 98

Practical example

```
enum class Lang { French, German, English, Other };
Lang language = ...;
switch (language) {
  case Lang::French:
    std::cout << "Bonjour";
    break;
  case Lang::German:
    std::cout << "Guten Tag";
    break;
  case Lang::English:
    std::cout << "Good morning";
    break;
  default:
    std::cout << "I do not speak your language";
}
```

[[fallthrough]] attribute C^{++} 17

New compiler warning

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

C^{++} 17

```
switch (c) {
  case 'a':
    f();    // Warning emitted
  case 'b': // Warning probably suppressed
  case 'c':
    g();
    [[fallthrough]]; // Warning suppressed
  case 'd':
    h();
}
```

Init-statements for if and switch

C^{++} 17

Purpose

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

C^{++} 17

```cpp
if (Value val = GetValue(); condition(val)) {
  f(val); // ok
} else
  g(val); // ok
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

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

C^{++} 98

Don't confuse with a variable declaration as condition:

```cpp
if (Value* val = GetValuePtr())
  f(*val);
```

Control structures: for loop

C++ 98

for loop syntax

```
for(initializations; condition; increments) {
  statements;
}
```

- Multiple initializations / 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

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for(initializations; condition; increments) {
  statements;
}
```

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

Practical example

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

Control structures: for loop

C++ 98

for loop syntax

```
for(initializations; condition; increments) {
  statements;
}
```

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

Practical example

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

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

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

Example code

```
int v[4] = {1,2,3,4};
int sum = 0;
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

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

C++ 20

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

Control structures: while loop

C++ 98

while loop syntax

```
while(condition) {
  statements;
}

do {
  statements;
} while(condition);
```

- Braces are optional if the body is a single statement

Control structures: while loop

C^{++} 98

while loop syntax

```
while(condition) {
  statements;
}

do {
  statements;
} while(condition);
```

- Braces are optional if the body is a single statement

Bad example

```
while (n != 1)
  if (0 == n%2) n /= 2;
  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

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

```cpp
while (1) {
  if (n == 1) break;
  if (0 == n%2) {
    std::cout << n << '\n';
    n /= 2;
    continue;
  }
  n = 3 * n + 1;
}
```

Control structures

C++ 11

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

```
#include "hello.hpp"
int main() {
  printHello();
}
```

Preprocessor

C++ 98

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

Preprocessor

C++ 98

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// file inclusion
#include "hello.hpp"
// macro constants and function-style macros
#define MY_GOLDEN_NUMBER 1746
#define CHECK_GOLDEN(x) if ((x) != MY_GOLDEN_NUMBER) \
  std::cerr << #x " was not the golden number\n";
// compile time or platform specific configuration
#if defined(USE64BITS) || defined(__GNUG__)
  using myint = std::uint64_t;
#elif
  using myint = std::uint32_t;
#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

```
#ifndef MY_HEADER_INCLUDED
#define MY_HEADER_INCLUDED
... // header file content
#endif
```

Pragma once (non-standard)

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

Header / source separation

C^{++} 98

Good practice: Headers and source files

- Headers should contain declarations of functions / classes
  - Only create them if interface is used somewhere else
- Might be included/compiled many times
- Good to keep them short
- Minimise `#include` statements
- Put long code in implementation files. Exceptions:
  - Short functions
  - Templates and constexpr functions

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

Auto keyword

C++ 11

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

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

Auto keyword

C^{++} 11

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

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

Practical usage

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

Loops, references, auto

C++ 98

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

C^{++} 98

```cpp
struct MyFirstClass {
  int a;
  void squareA() {
    a *= a;
  }
  int sum(int b) {
    return a + b;
  }
};

MyFirstClass myObj;
myObj.a = 2;

// let's square a
myObj.squareA();
```

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

Separating the interface

C^{++} 98

Header: MyClass.hpp

```cpp
#pragma once
struct MyClass {
  int a;
  void squareA();
};
```

User 1: main.cpp

```cpp
#include "MyClass.hpp"
int main() {
  MyClass mc;
  ...
}
```

Implementation: MyClass.cpp

```cpp
#include "MyClass.hpp"
void MyClass::squareA() {
  a *= a;
}
```

User 2: fun.cpp

```cpp
#include "MyClass.hpp"
void f(MyClass& mc) {
  mc.squareA();
}
```

Implementing methods

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

```
#include "MyFirstClass.hpp"

void MyFirstClass::squareA() {
  a *= a;
}
int MyFirstClass::sum(int b) {
  return a + b;
}
```

Method overloading

C++ 98

The rules in C++

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

```cpp
struct MyFirstClass {
  int a;
  int sum(int b);
  int sum(int b, int c);
};

int MyFirstClass::sum(int b) { return a + b; }

int MyFirstClass::sum(int b, int c) {
  return a + b + c;
}
```

Inheritance

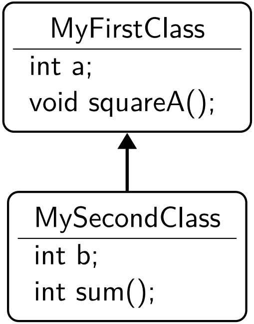
3 Object orientation (OO)
- Objects and Classes
- Inheritance
- Constructors/destructors
- Static members
- Allocating objects
- Advanced OO
- Operator overloading
- Function objects

First inheritance

C++ 98

```
struct MyFirstClass {
  int a;
  void squareA() { a *= a; }
};
struct MySecondClass :
  MyFirstClass {
  int b;
  int sum() { return a + b; }
};

MySecondClass myObj2;
myObj2.a = 2;
myObj2.b = 5;
myObj2.squareA();
int i = myObj2.sum(); // i = 9
```

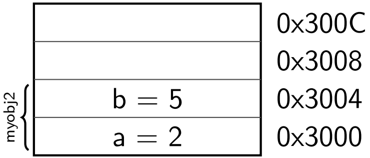


First inheritance


```cpp
struct MyFirstClass {
  int a;
  void squareA() { a *= a; }
};
struct MySecondClass :
  MyFirstClass {
  int b;
  int sum() { return a + b; }
};

MySecondClass myObj2;
myObj2.a = 2;
myObj2.b = 5;
myObj2.squareA();
int i = myObj2.sum(); // i = 9
```

Memory layout



Managing access to class members

C++ 98

public / private keywords

`private` allows access only within the class

`public` allows access from anywhere

- The default for class is `private`
- The default for struct is `public`

```cpp
class MyFirstClass {
public:
  void setA(int x);
  int getA();
  void squareA();
private:
  int a;
};
```

```cpp
MyFirstClass obj;
obj.a = 5;    // error !
obj.setA(5); // ok
obj.squareA();
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`
- The default for `struct` is `public`

```cpp
class MyFirstClass {
public:
  void setA(int x);
  int getA();
  void squareA();
private:
  int a;
};
```

```cpp
MyFirstClass obj;
obj.a = 5;   // error !
obj.setA(5); // ok
obj.squareA();
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

```cpp
class MyFirstClass {
public:
  void setA(int a);
  int getA();
  void squareA();
protected:
  int a;
};
```

```cpp
class MySecondClass :
  public MyFirstClass {
public:
  int sum() {
    return a + b;
  }
private:
  int b;
};
```

Managing inheritance privacy

C++ 98

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

C++ 98

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

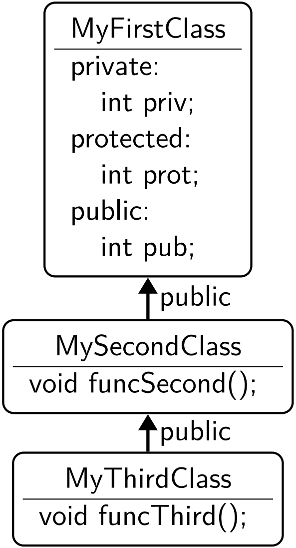
Net result for external code

- only public members of public inheritance are accessible

Net result for code in derived classes

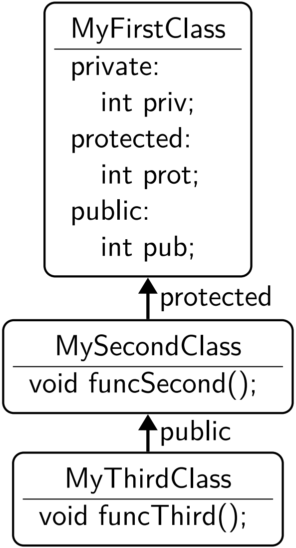
- only public and protected members of public and protected parents are accessible

Managing inheritance privacy - public



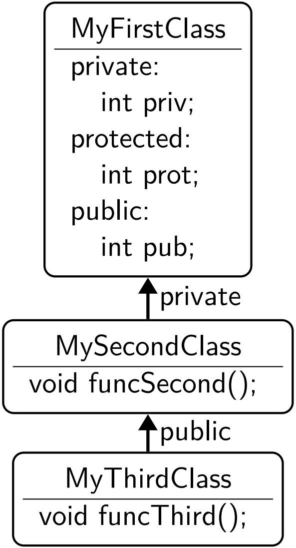

```cpp
void funcSecond() {
  int a = priv;   // Error
  int b = prot;   // OK
  int c = pub;    // OK
}
void funcThird() {
  int a = priv;   // Error
  int b = prot;   // OK
  int c = pub;    // OK
}
void extFunc(MyThirdClass t) {
  int a = t.priv; // Error
  int b = t.prot; // Error
  int c = t.pub;  // OK
}
```

Managing inheritance privacy - protected




```cpp
void funcSecond() {
  int a = priv;    // Error
  int b = prot;    // OK
  int c = pub;     // OK
}
void funcThird() {
  int a = priv;    // Error
  int b = prot;    // OK
  int c = pub;     // OK
}
void extFunc(MyThirdClass t) {
  int a = t.priv; // Error
  int b = t.prot; // Error
  int c = t.pub;  // Error
}
```

Managing inheritance privacy - private




```cpp
void funcSecond() {
  int a = priv;   // Error
  int b = prot;   // OK
  int c = pub;    // OK
}
void funcThird() {
  int a = priv;   // Error
  int b = prot;   // Error
  int c = pub;    // Error
}
void extFunc(MyThirdClass t) {
  int a = t.priv; // Error
  int b = t.prot; // Error
  int c = t.pub;  // Error
}
```

Constructors/destructors

3 Object orientation (OO)

Class constructors and destructors

C++ 98

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 ~

```cpp
class C {
public:
  C();
  C(int a);
  ~C();
  ...
protected:
  int a;
};
```

```cpp
// note: special notation for
// initialization of members
C::C() : a(0) {}

C::C(int a) : a(a) {}

C::~C() {}
```

Class constructors and destructors


```
class Vector {
public:
  Vector(int n);
  ~Vector();
  void setN(int n, int value);
  int getN(int n);
private:
  int len;
  int* data;
};
Vector::Vector(int n) : len(n) {
  data = new int[n];
}
Vector::~Vector() {
  delete[] data;
}
```

Constructors and inheritance

C++ 98

```cpp
struct First {
  int a;
  First() {} // leaves a uninitialized
  First(int a) : a(a) {}
};
struct Second : First {
  int b;
  Second();
  Second(int b);
  Second(int a, int b);
};
Second::Second() : First(), b(0) {}
Second::Second(int b) : b(b) {} // First() implicitly
Second::Second(int a, int b) : First(a), b(b) {}
```

Copy constructor

C++ 11

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

Copy constructor

C++ 11

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

```
struct C {
  C();
  C(const C &other);
};
```

Copy constructor

C^{++} 11

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

```
struct C {
  C();
  C(const C &other);
};
```

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


```
class Vector {
public:
  Vector(int n);
  Vector(const Vector &other);
  ~Vector();
private:
  int len; int* data;
};
Vector::Vector(int n) : len(n) {
  data = new int[n];
}




Vector::~Vector() { delete[] data; }
```

Class Constructors and Destructors


```cpp
class Vector {
public:
  Vector(int n);
  Vector(const Vector &other);
  ~Vector();
private:
  int len; int* data;
};
Vector::Vector(int n) : len(n) {
  data = new int[n];
}
Vector::Vector(const Vector &other) : len(other.len) {
  data = new int[len];
  std::copy(other.data, other.data + len, data);
}
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

```cpp
void print(const Vector & v) {
  std::cout << "printing v elements...\n";
}

int main {
  // calls Vector::Vector(int n) to construct a Vector
  // then calls print with that Vector
  print(3);
};
```

Explicit unary constructor

C++ 98

Concept

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

```
class Vector {
public:
  explicit Vector(int n);
  Vector(const Vector &other);
  ~Vector();
  ...
};
```

Defaulted Constructor

C++ 11

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

```
Class() = default; // provide default if possible
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

```
struct Delegate {
  int m_i;
  explicit Delegate(int i) : m_i(i) {
    ... complex initialization ...
  }
  Delegate() : Delegate(42) {}
};
```

Constructor inheritance

C++ 11

Idea

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

Practically

```
struct Base {
  explicit Base(int a);  // ctor 1
};
struct Derived : Base {
  using Base::Base;
  Derived(int a, int b); // ctor 2
};
Derived d{5};     // calls ctor 1
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

```
struct Base {
  int a{5}; // or: int a = 5;
            Base() = default;
  explicit Base(int _a) : a(_a) {}
};
struct Derived : Base {
  int b{6};
  using Base::Base;
};
Derived d1;     // a = 5, b = 6
Derived d2{7}; // a = 7, b = 6
```

Calling constructors

C++ 11

After object declaration, arguments within {}

```
struct A {
  int i;
  float f;
  A();
  A(int);
  A(int, int);
};

A a{1,2};     // A::A(int, int)
A a{1};       // A::A(int)
A a{};        // A::A()
A a;          // A::A()
A a = {1,2}; // A::A(int, int)
```

Calling constructors the old way

C++ 98

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

```
struct A {
  int i;
  float f;
  A();
  A(int);
  A(int, int);
};

A a(1,2);     // A::A(int, int)
A a(1);       // A::A(int)
A a();        // declaration of a function!
A a;          // A::A()
A a = (1,2);  // A::A(int), comma operator!
A a = {1,2};  // not allowed
```

Constructing arrays and vectors

C++ 11

List of items given within {}

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

Static members

Static members

C++ 98

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

```cpp
class Text {
public:
  static std::string upper(std::string);
private:
  static int callsToUpper; // add `inline` in C++17
};
```

Static members

C++ 98

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

```cpp
#include "Static.hpp"
int Text::callsToUpper = 0; // required before C++17

std::string Text::upper(std::string lower) {
  callsToUpper++;
  // convert lower to upper case
  // return ...;
}
std::string uppers = Text::upper("my text");
// 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

Process memory organization

C^{++} 98

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

heap
↓ … ↓
↑ … ↑
stack
data segment
code segment

The Stack

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)

```cpp
int f() {
  MyFirstClass a{3}; // constructor called
  ...
} // destructor called

int g() {
  MyFirstClass a; // default constructor called
  ...
}  // destructor called
```

The Heap

C++ 98

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

On the heap

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

```cpp
int f() {
  // default constructor called
  MyFirstClass *a = new MyFirstClass;
  delete a; // destructor is called
}
int g() {
  // constructor called
  MyFirstClass *a = new MyFirstClass{3};
} // memory leak !!!
```

Good practice: Prefer smart pointers over new/delete

Prefer smart pointers to manage objects (discussed later)

Array allocation on the heap

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

```cpp
int f() {
  // default constructor called 10 times
  MyFirstClass *a = new MyFirstClass[10];
  ...
  delete[] a; // destructor called 10 times
}
```

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

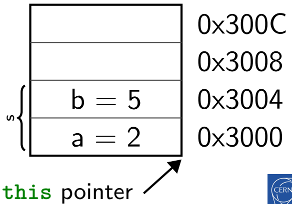
this keyword

How to know an object's address?

- Sometimes we need the address of the current object
- Or we need to pass our address / a reference 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`

```cpp
struct S {
  int a,b;
  // these two are the same:
  int getB() { return b; }       // 5
  int getB() { return this->b; } // 5
  void testAddress() {
    S* addr = this; // 0x3000
  }
} s{2,5};
```

Memory layout



Polymorphism

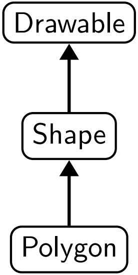
the concept

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

```cpp
Polygon p;

int f(Drawable & d) {...}
f(p);  //ok

try {
  throw p;
} catch (Shape & e) {
  // will be caught
}
```



Polymorphism

C++ 98

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```cpp
Polygon p;

int f(Drawable & d) {...}
f(p);  //ok

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} catch (Shape & e) {
  // will be caught
}
```

Memory layout

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

Polygon

Polymorphism

C^{++} 98

the concept

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

```cpp
Polygon p;

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Polymorphism

C++ 98

the concept

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- and can be used as any of them

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Polygon p;

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f(p);  //ok

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}
```

Memory layout

	0x3020
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Drawable.b	0x3004
Drawable.a	0x3000

Shape

Inheritance privacy and polymorphism

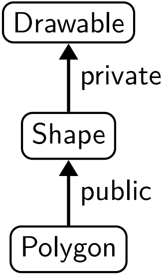
Only public base classes are visible to outside code

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

```cpp
Polygon p;

int f(Drawable & d) {...}
f(p);  // Not ok anymore

try {
  throw p;
} catch (Shape & e) {
  // ok, will be caught
}
```



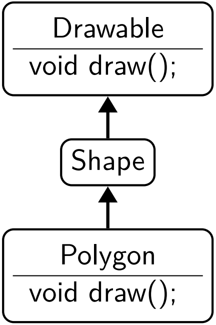
Method overriding

the idea

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

```cpp
Polygon p;
p.draw(); // ?

Shape & s = p;
s.draw(); // ?
```



Virtual methods

C++ 98

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

Virtual methods

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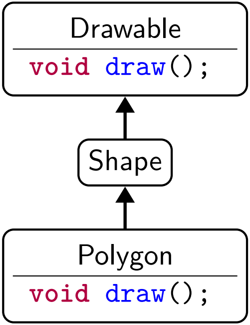
- for non-virtual methods, the static type of the variable decides

```cpp
Polygon p;
p.draw(); // Polygon.draw

Shape & s = p;
s.draw(); // Drawable.draw
```



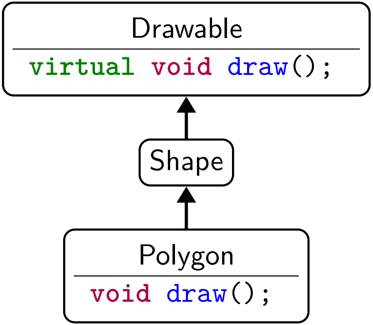
Virtual methods

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

```cpp
Polygon p;
p.draw(); // Polygon.draw

Shape & s = p;
s.draw(); // Polygon.draw
```



Virtual methods - implications

C++ 11

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

override keyword

C++ 11

Principle

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

Practically

```
struct Base {
  virtual void some_func(float);
};
struct Derived : Base {
  void some_func(float) override;
};
```

Why was override keyword introduced? C++ 11

To detect the mistake in the following code :

Without override (C++ 98)

```
struct Base {
  virtual void some_func(float);
};
struct Derived : Base {
  void some_func(double); // oops !
};
```

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

Pure Virtual methods

C++ 11

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

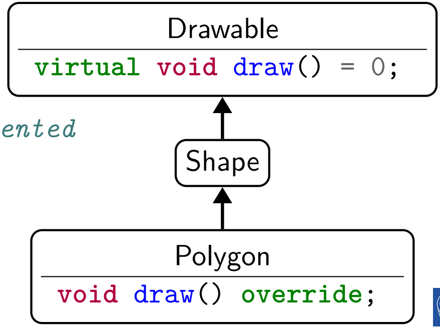
Concept

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

```cpp
// Error : abstract class
Shape s;

// ok, draw has been implemented
Polygon p;

// Shape type still usable
Shape & s = p;
s.draw();
```



Polymorphism and destruction

Owning base pointers

We sometimes need to maintain owning pointers to base classes:

```
struct Drawable {
    virtual void draw() = 0;
};
Drawable* getImpl();

Drawable* p = getImpl();
p->draw();
delete p;
```

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

Polymorphism and destruction

C++ 98

Owning base pointers

We sometimes need to maintain owning pointers to base classes:

```
struct Drawable {
    virtual void draw() = 0;
};
std::unique_ptr<Drawable> getImpl(); // better API

auto p = getImpl();
p->draw();
```

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

Polymorphism and destruction

C++ 11

Virtual destructors

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

```
struct Drawable {
    virtual ~Drawable() = default;
    virtual void draw() = 0;
};
Drawable* p = getImpl(); // returns derived obj.
p->draw();
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 C^{++} 11

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

```cpp
struct Drawable {
  virtual ~Drawable()
                   = default;
  virtual void draw() = 0;
}
```

Drawable
virtual void draw() = 0;

Overriding overloaded methods

Concept

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

```
struct BaseClass {
  virtual int foo(std::string);
  virtual int foo(int);
};
struct DerivedClass : BaseClass {
  using BaseClass::foo;
  int foo(std::string) override;
};
DerivedClass dc;
dc.foo(4);      // error if no using
```

Polymorphism

Exercise: Polymorphism

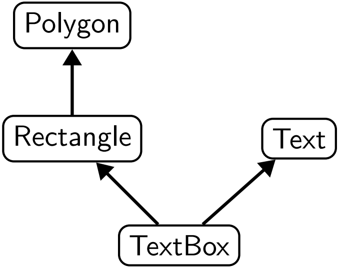
- go to `exercises/polymorphism`
- look at the code
- open trypoly.cpp
- create a Pentagon, call its perimeter method
- create a Hexagon, call its perimeter method
- create a Hexagon, call its parent's perimeter method
- retry with virtual methods

Multiple Inheritance

C++ 98

Concept

- one class can inherit from multiple parents




```cpp
class TextBox :
  public Rectangle, Text {
  // inherits from both
  // publicly from Rectangle
  // privately from Text
}
```

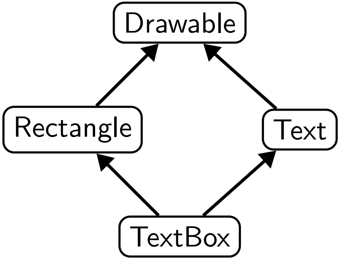
The diamond shape

Definition

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

Problem

- are the members of the grand parent replicated?



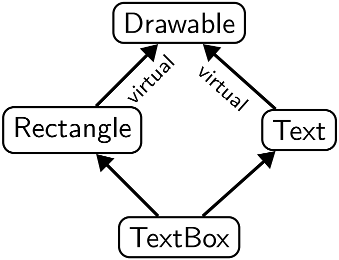
Virtual inheritance

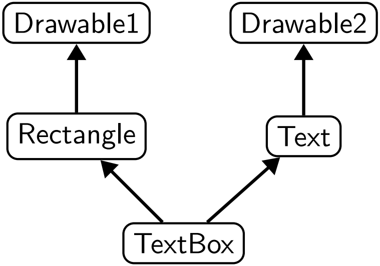
C++ 98

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

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





Multiple inheritance advice

Good practice: Avoid multiple inheritance

- Except for inheriting from interfaces (=no data members)
- And for rare special cases

Absolutely avoid diamond-shape inheritance

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

Virtual inheritance

Exercise: Virtual inheritance

- go to `exercisescode/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
- Inheritance
- Constructors/destructors
- Static members
- Allocating objects
- Advanced OO
- Operator overloading
- Function objects

Operator overloading example

C++ 98

```
struct Complex {
  float m_real, m_imaginary;
  Complex(float real, float imaginary);
  Complex operator+(const Complex& other) {
    return Complex{m_real + other.m_real,
                   m_imaginary + other.m_imaginary};
  }
};

Complex c1{2, 3}, c2{4, 5};
Complex c3 = c1 + c2; // (6, 8)
```

Operator overloading

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 operators from below)

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)

```
possible operators: + - * / % ^ & | ~ ! = < >
    += -= *= /= %= ^= &= |= << >> >>= <<=
    == != <= >= <=> && || ++ -- , ->* -> () []
```

Why have non-member operators?

Symmetry

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

Why have non-member operators?

C++ 98

Symmetry

```cpp
struct Complex {
  float m_real, m_imaginary;
  Complex operator+(float other) {
    return Complex{m_real + other, m_imaginary};
  }
};
Complex c1{2.f, 3.f};
Complex c2 = c1 + 4.f;  // ok
Complex c3 = 4.f + c1;  // not ok !!
Complex operator+(float a, const Complex& obj) {
  return Complex{a + obj.m_real, obj.m_imaginary};
}
```

Other reason to have non-member operators? C++ 98

Extending existing classes

```
struct Complex {
  float m_real, m_imaginary;
  Complex(float real, float imaginary);
};

std::ostream& operator<<(std::ostream& os,
                         const Complex& obj) {
  os << "(" << obj.m_real << ", "
            << obj.m_imaginary << ")";
  return os;
}
Complex c1{2.f, 3.f};
std::cout << c1 << std::endl; // Prints '(2, 3)'
```

Chaining operators

C++ 98

In general, return a reference to the left value

```
struct Complex {
  float m_real, m_imaginary;
  Complex& operator=( const Complex& other ) {
    m_real = other.m_real;
    m_imaginary = other.m_imaginary;
    return *this;
  }
};
Complex c1{2.f, 3.f};
Complex c2, c3;
// right to left associativity
c3 = c2 = c1;
// left to right associativity
std::cout << c1 << c2 << c3 << std::endl;
```

Friend declarations

C++ 98

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

```
class Complex {
  float m_r, m_i;
  friend Complex operator+(Complex const & a, Complex const & b);
public:
  Complex ( float r, float i ) : m_r(r), m_i(i) {}
};
Complex operator+(Complex const & a, Complex const & b) {
  return Complex{ a.m_r+b.m_r, a.m_i+b.m_i };
}
```

Operators

C++ 98

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)

Function objects

C++ 98

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

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

Function objects

C++ 20

Function objects as function arguments - godbolt

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

Core modern C^{++}

Constness

4 Core modern C^{++}

- Constness
- Exceptions
- Templates
- Lambdas
- The STL
- RAII and smart pointers

Constness

C++ 98

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

```cpp
int const i = 6;
const int i = 6; // equivalent

// error: i is constant
i = 5;

auto const j = i; // works with auto
```

Constness and pointers

C++ 98

```cpp
int a = 1, b = 2;

int const *i = &a; // pointer to const int
*i = 5; // error, int is const
i = &b; // ok, pointer is not const

int * const j = &a; // const pointer to int
*j = 5; // ok, value can be changed
j = &b; // error, pointer is const

int const * const k = &a; // const pointer to const int
*k = 5; // error, value is const
k = &b; // error, pointer is const

int const & l = a; // reference to const int
l = b; // error, reference is const

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

```cpp
struct Example {
  void foo() const {
    // type of 'this' is 'Example const*'
    data = 0; // Error: member function is const
  }
  void foo() { // ok, overload
    data = 1;  // ok, 'this' is 'Example*'
  }
  int data;
};
Example const e1; e1.foo(); // calls     const foo
Example       e2; e2.foo(); // calls non-const foo
```

Member function constness

C++ 98

Constness is part of the type

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

```cpp
void change(int & a);
void read(int const & a);

int a = 0;
int const b = 0;

change(a); // ok
change(b); // error
read(a);   // ok
read(b);   // ok
```

constness

C++ 98

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

Exceptions

C++ 98

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

```cpp
try {
  process_data(f);
} catch (const
  std::out_of_range& e) {
  std::cerr << e.what();
}
```

```cpp
void process_data(file &f) {
  ...
  if (i >= buffer.size())
    throw std::out_of_range{
      "buf overflow"};
}
```

Exceptions

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

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

Exceptions

C++ 98

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
- ...

Exceptions

C++ 98

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

```cpp
try {
  process_data(f);
} catch (const std::invalid_argument& e) {
  bad_files.push_back(f);
} catch (const std::exception& e) {
  std::cerr << "Failed to process file: " << e.what();
}
```

Good practice: Catching exceptions

- Catch exceptions by const reference

Exceptions

C++ 98

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

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

Exceptions

Catching everything

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

```cpp

try {
  callUnknownFramework();
} catch(const std::exception& e) {
  // catches std::exception and all derived types
  std::cerr << "Exception: " << e.what() << std::endl;
} catch(...) {
  // catches everything else
  std::cerr << "Unknown exception type" << std::endl;
}
```

Exceptions

C++ 98

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 RAII idiom for your own classes

```cpp
class C { ... };
void f() {
  C c1;
  throw exception{};
    // start unwinding
  C c2; // not run
}
void g() {
  C c3; f();
}
int main() {
  try {
    C c4;
    g();
    cout << "done"; // not run
  } catch(const exception&) {
    // c1, c3 and c4 have been
    // destructed
  }
}
```

Exceptions

C++ 17

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`, `std::variant` or `std::expected` (C++ 23)
  - avoid using the global C-style `errno`
- never throw in destructors
- see also the C++ core guidelines and the ISO C++ FAQ

Exceptions

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

```cpp
try {
  for (File const &f : files) {
    try {
      process_file(f);
    }
    catch (bad_file const & e) {
      ... // loop continues
    }
  }
} catch (bad_db const & e) {
  ... // loop aborted
}
```

```cpp
void process_file(File const & file) {
  ...
  if (handle = open_file(file))
    throw bad_file(file.status());
  while (!handle) {
    line = read_line(handle);
    database.insert(line); // can throw
                           // bad_db
  }
}
```

Exceptions

C++ 98

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 specifier

C++ 11

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
  - if one is thrown, ‘std::terminate‘ is called
  - 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
- RAII and smart pointers

Templates

C++ 17

Concept

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

```cpp
template<typename T>
const T & max(const T &a, const T &b) {
  return b < a ? a : b;
}
template<typename T>
struct Vector {
  int m_len;
  T* m_data;
};
template <typename T>
std::size_t size = sizeof(T);
```

Templates

C++ 98

Notes on templates

- 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

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

func(3)

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

func(5.2)

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

Templates

C++ 98

Template parameters

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

```cpp
template<typename KeyType=int, typename ValueType=KeyType>
struct Map {
  void set(const KeyType &key, ValueType value);
  ValueType get(const KeyType &key);
  ...
};

Map<std::string, int> m1;
Map<float> m2;    // Map<float, float>
Map<> m3;         // Map<int, int>
Map m4;           // Map<int, int>, C++17
```

Template parameters

C^{++} 98

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`

```
template<typename T>
T func(T a); // equivalent to:
template<class T>
T func(T a);

template<template<class> class C>
C<int> func(C<int> a); // equivalent to:
template<template<typename> class C>
C<int> func(C<int> a); // equivalent to:
template<template<typename> typename C> // C++17
C<int> func(C<int> a);
```

Template implementation

C++ 98

```
template<typename KeyType=int, typename ValueType=KeyType>
struct Map {
  // declaration and inline definition
  void set(const KeyType &key, ValueType value) {
    ...
  }
  // just declaration
  ValueType get(const KeyType &key);
};

// out-of-line definition
template<typename KeyType, typename ValueType>
ValueType Map<KeyType, ValueType>::get
   (const KeyType &key) {
  ...
}
```

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

```cpp
template<unsigned int N>
struct Polygon {
  float perimeter() {
    return 2 * N * std::sin(PI / N) * radius;
  }
  float radius;
};

Polygon<19> nonadecagon{3.3f};
```

Template specialization

C++ 98

Specialization

Templates can be specialized for given values of their parameter

```cpp
template<typename F, unsigned int N>
struct Polygon { ... }; // primary template

template<typename F> // partial specialization
struct Polygon<F, 6> {
  F perimeter() { return 6 * radius; }
  F radius;
};
template<>              // full specialization
struct Polygon<int, 6> {
  int perimeter() { return 6 * radius; }
  int radius;
};
```

The full power of templates

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++

- Constness
- Exceptions
- Templates
- Lambdas
- The STL
- RAII and smart pointers

Lambda expressions

C++ 11

Definition

A lambda expression is a function with no name

Lambda expressions

C++ 11

Definition

A lambda expression is a function with no name

Python example

```python
data = [1,9,3,8,3,7,4,6,5]

# without lambdas
def isOdd(n):
  return n%2 == 1
print(filter(isOdd, data))

# with lambdas
print(filter(lambda n:n%2==1, data))
```

C^{++} Lambdas C^{++} 11

Simplified syntax

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

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

Usage example

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

Trailing function return type

C++ 11

An alternate way to specify a function's return type

```cpp
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

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

When to use trailing return type

- Only way to specify return type for lambdas
- Allows to simplify inner type definition

```cpp
class Equation {
  using ResultType = double;
  ResultType evaluate();
}
Equation::ResultType Equation::evaluate() {...}
auto Equation::evaluate() -> ResultType {...}
```

Capturing variables

C++ 11

Adaptable lambdas

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

Capturing variables

C++ 11

Adaptable lambdas

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

First attempt in C++

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

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

Error

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

Capturing variables

C++ 11

The capture list

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

Capturing variables

C++ 11

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

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

Default capture is by value

C++ 11

Code example

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

Default capture is by value

C++ 11

Code example

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

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

Capture by reference

C++ 11

Simple example

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

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

Capture by reference

C++ 11

Simple example

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

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

Mixed case

One can of course mix values and references

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

Capture by value vs. by reference

C++ 11

See the difference between val and ref

```
int data[]{1,9,3,8,3,7,4,6,5};
int increment = 3;
auto val = [ inc](int x) { return x+inc; };
auto ref = [&inc](int x) { return x+inc; };

increment = 4;

for(int& i : data) i = val(i); // increments by 3
for(int& i : data) i = ref(i); // increments by 4
```

Init capture

C++ 14

Capture with an initializer

In C++ 14, can declare captures with initializers

```
auto f = [inc = 1+2](int x) { return x+inc; };
auto g = [inc = getInc()](int x) { return x+inc; };
for(int& i : data) i = f(i); // increments by 3
for(int& i : data) i = g(i); // unknown increment
```

Anatomy of a lambda

C++ 11

Lambdas are pure syntactic sugar - cppinsight

- They are replaced by a functor during compilation

```cpp
int sum = 0, off = 1;
auto l =
[&sum, off]



(int x) {
  sum += x + off;
};


l(42);
```

```cpp
int sum = 0, off = 1;
struct __lambda4 {
  int& sum; int off;
  __lambda4(int& s, int o)
  : sum(s), off(o) {}

  auto operator()(int x) const {
    sum += x + off;
  }
};
auto l = __lambda4{sum, off};
l(42);
```

Some nice consequences

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

Capture list

C++ 11

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
- RAII and smart pointers

The Standard Template Library

C++ 98

What it is

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

The Standard Template Library C^{++} 98

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 in practice

C++ 14

STL example - godbolt

```cpp
#include <vector>
#include <algorithm>
#include <functional>      // `import std;` in C++23
#include <iterator>
#include <iostream>

std::vector<int> in{5, 3, 4};    // initializer list
std::vector<int> out(3);  // constructor taking size
std::transform(in.begin(), in.end(),  // input range
               out.begin(),           // start result
               std::negate{});        // function obj
std::copy(out.begin(), out.end(),     // -5 -3 -4
  std::ostream_iterator<int>{std::cout, " "});
```

STL's concepts

C++ 98

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

C++ 11

```cpp
#include <vector>
std::vector<T> v{5, 3, 4}; // 3 Ts, 5, 3, 4
std::vector<T> v(100);     // 100 default constr. Ts
std::vector<T> v(100, 42); // 100 Ts with value 42
std::vector<T> v2 = v;              // copy
std::vector<T> v2 = std::move(v); // move, v is empty

std::size_t s = v.size();
bool empty = v.empty();

v[2] = 17;            // write element 2
T& t = v[1000];       // access element 1000, bug!
T& t = v.at(1000);    // throws std::out_of_range
T& f = v.front();     // access first element
v.back() = 0;         // write to last element
T* p = v.data();      // pointer to underlying storage
```

Containers: std::vector

C++ 11

```
std::vector<T> v = ...;
auto b = v.begin(); // iterator to first element
auto e = v.end();   // iterator to one past last element
// all following operations, except reserve, invalidate
// all iterators (b and e) and references to elements

v.resize(100); // size changes, grows: new T{}s appended
               //              shrinks: Ts at end destroyed
v.reserve(1000); // size remains, memory increased
for (T i = 0; i < 900; i++)
  v.push_back(i); // add to the end
v.insert(v.begin()+3, T{}); // insert after 3rd position

v.pop_back();          // removes last element
v.erase(v.end() - 3); // removes 3rd-last element
v.clear();             // removes all elements
```

Containers: std::unordered_map

C++ 11

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

```
#include <unordered_map>
std::unordered_map<std::string, int> m;
m["hello"] = 1;  // inserts new key, def. constr. value
m["hello"] = 2;  // finds existing key
auto [it, isNewKey] = m.insert({"hello", 0}); // no effect
//     ^ C++17: "Structured binding"
int val = m["world"];      // inserts new key (val == 0)
int val = m.at("monde"); // throws std::out_of_range

if (auto it = m.find("hello"); it != m.end()) // C++17
    m.erase(it);          // remove by iterator (fast)
if (m.contains("hello")) // C++20
    m.erase("hello"); // remove by key, 2. lookup, bad
for (auto const& [k, v] : m) // iterate k/v pairs (C++17)
    std::cout << k << ": " << v << '\n';
```

std::hash

C++ 11

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

```cpp
#include <functional>
std::hash<std::string> h;
std::cout << h("hello"); // 2762169579135187400
std::cout << h("world"); // 8751027807033337960

class MyClass { int a, b; ... };
template<> struct std::hash<MyClass> {
  std::size_t operator()(MyClass const& c) {
    std::hash<int> h;
    return h(c.a) ^ h(c.b); // xor to combine hashes
  }
};
```

STL's concepts

C++ 11

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

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

STL's concepts

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

STL's concepts

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

Functors / function objects

C++ 11

Example

```
struct Incrementer {
  int m_inc;
  Incrementer(int inc) : m_inc(inc) {}

  int operator()(int value) const {
    return value + m_inc;
  }
};
std::vector<int> v{1, 2, 3};
const auto inc = 42;
std::transform(v.begin(), v.end(), v.begin(),
               Incrementer{inc});
```

Prefer lambdas over functors

C++ 11

With lambdas

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

Prefer lambdas over functors

C++ 11

With lambdas

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

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

C++ 11

Iterator-based loop (since C++ 98)

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

Range-based for loops with STL containers C++ 11

Iterator-based loop (since C++ 98)

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

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

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

Range-based for loops with STL containers

C++ 11

Iterator-based loop (since C++ 98)

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

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

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

STL way (since C++ 98)

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

More examples

C++ 17

```
std::list<int> l = ...;

// Finds the first element in a list between 1 and 10.
const auto it = std::find_if(l.begin(), l.end(),
      [](int i) { return i >= 1 && i <= 10; });
if (it != l.end()) {
  int element = *it; ...
}

// Computes sin(x)/(x + DBL_MIN) for elements of a range.
std::vector<double> r(l.size());
std::transform(l.begin(), l.end(), r.begin(),
  [](auto x) { return std::sin(x)/(x + DBL_MIN); });

// reduce/fold (using addition)
const auto sum = std::reduce(v.begin(), v.end());
```

More examples

C++ 11

```cpp
std::vector<int> v = ...;

// remove duplicates
std::sort(v.begin(), v.end());
auto newEndIt = std::unique(v.begin(), v.end());
v.erase(newEndIt, v.end());

// remove by predicate
auto p = [](int i) { return i > 42; };
auto newEndIt = std::remove_if(v.begin(), v.end(), p);
v.erase(newEndIt, v.end());

// remove by predicate (C++20)
std::erase_if(v, p);
```

Welcome to lego programming!

Using the STL

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

Using the STL

C^{++} 98

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
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- Lambdas
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Pointers: why are they error prone? C++ 98

They need initialization

```
char *s;
try {
  foo(); // may throw
  s = new char[100];
  read_line(s);
} catch (...) { ... }
process_line(s);
```

Pointers: why are they error prone?

C^{++} 98

They need initialization

Seg Fault

```
char *s;
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  foo(); // may throw
  s = new char[100];
  read_line(s);
} catch (...) { ... }
process_line(s);
```

Pointers: why are they error prone? C++ 98

They need initialization — Seg Fault

```cpp
char *s;
try {
  foo(); // may throw
  s = new char[100];
```

They need to be released

```cpp
char *s = new char[100];
read_line(s);
if (s[0] == '#') return;
process_line(s);
delete[] s;
```

Pointers: why are they error prone?

C++ 98

They need initialization — Seg Fault

```cpp
char *s;
try {
  foo(); // may throw
  s = new char[100];
```

They need to be released — Memory leak

```cpp
char *s = new char[100];
read_line(s);
if (s[0] == '#') return;
process_line(s);
delete[] s;
```

Pointers: why are they error prone?

C++ 98

They need initialization — Seg Fault

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

They need to be released — Memory leak

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

They need clear ownership

```
char *s = new char[100];
read_line(s);
vec.push_back(s);
set.add(s);
std::thread t1{func1, vec};
std::thread t2{func2, set};
```

Pointers: why are they error prone?

C++ 98

They need initialization — Seg Fault

```cpp
char *s;
try {
  foo(); // may throw
  s = new char[100];
```

They need to be released — Memory leak

```cpp
char *s = new char[100];
read_line(s);
```

They need clear ownership — Who should release ?

```cpp
char *s = new char[100];
read_line(s);
vec.push_back(s);
set.add(s);
std::thread t1{func1, vec};
std::thread t2{func2, set};
```

This problem exists for any resource

C++ 11

For example with a file

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

Which problems do you spot in the above snippet?

Resource Acquisition Is Initialization (RAII) C++ 98

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

RAII in practice

C++ 98

An RAII File class

```
class File {
public:
  // constructor: acquire resource
  File(const char* filename)
    : m_handle(std::fopen(filename, "w+")) {
    // abort constructor on error
    if (m_handle == nullptr) { throw ... }
  }
  // destructor: release resource
  ~File() { std::fclose(m_handle); }
  void write (const char* str) {
    ...
  }
private:
  std::FILE* m_handle; // wrapped resource
};
```

RAII usage

C++ 98

Usage of File class

```
void log_function() {
  // file opening, aka resource acquisition
  File logfile("logfile.txt");

  // file usage
  logfile.write("hello logfile!"); // may throw

  // file is automatically closed by the call to
  // its destructor, even in case of exception!
}
```

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

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

std::unique_ptr

C++ 11

A RAII 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

std::unique_ptr

C++ 11

A RAII 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

```cpp
#include <memory>
void f(std::unique_ptr<Foo> ptr) {
  ptr->bar();
} // deallocation when f exits

std::unique_ptr<Foo> p{ new Foo{} }; // allocation
f(std::move(p)); // transfer ownership
assert(p.get() == nullptr);
```

Quiz

C++ 11

What do you expect?

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

Quiz

C++ 11

What do you expect?

```
void f(std::unique_ptr<Foo> ptr);
std::unique_ptr<Foo> uptr(new Foo{});
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

C++ 14

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

C++ 14

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

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

RAII or raw pointers

C++ 11

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

RAII or raw pointers

C++ 11

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

```
std::unique_ptr<T> produce();
void observe(const T&);
void modifyRef(T&);
void modifyPtr(T*);
void consume(std::unique_ptr<T>);
std::unique_ptr<T> pt{produce()}; // Receive ownership
observe(*pt);                     // Keep ownership
modifyRef(*pt);                   // Keep ownership
modifyPtr(pt.get());              // Keep ownership
consume(std::move(pt));           // Transfer ownership
```

std::unique_ptr usage summary

C++ 11

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

C++ 11

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

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

Quiz: std::shared_ptr in use

C++ 11

What is the output of this code? - godbolt

```cpp
auto shared = std::make_shared<int>(100);
auto print = [shared](){
  std::cout << "Use: " << shared.use_count() << " "
            << "value: " << *shared << "\n";
};
print();
{
  auto ptr{ shared };
  (*ptr)++;
  print();
}
print();
```

Quiz: std::shared_ptr in use

C++ 11

What is the output of this code? - godbolt

```cpp
auto shared = std::make_shared<int>(100);
auto print = [shared](){
  std::cout << "Use: " << shared.use_count() << " "
            << "value: " << *shared << "\n";
};
print();
{
  auto ptr{ shared };
  (*ptr)++;
  print();
}
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?

```
auto shared = std::make_shared<int>(100);
auto print = [&shared](){
  std::cout << "Use: " << shared.use_count() << " "
            << "value: " << *shared << "\n";
};
print();
{
  auto ptr{ shared };
  (*ptr)++;
  print();
}
print();
```

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

Rule of zero

C++ 11

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 RAII
  - 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 RAII class

smart pointers

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

C^{++} editor

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

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
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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
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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>)
- Most editors/IDEs can 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

5 Useful tools

- C^{++} editor
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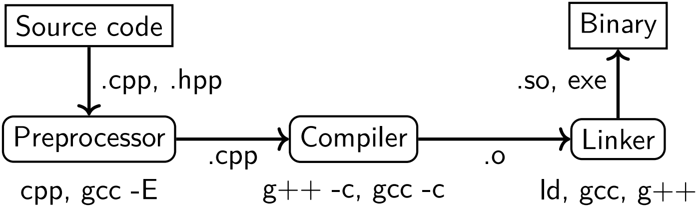
- Web tools
- Debugging

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
  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
000000000000008a T SlowToCopy::SlowToCopy(SlowToCopy const&)
0000000000000000 T SlowToCopy::SlowToCopy()
0000000000000064 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: _ZNK7Hexagon16computePerimeterEv    (./try
    undefined symbol: _ZNK7Polygon16computePerimeterEv    (./try
    undefined symbol: _ZN7HexagonC1Ef    (./trypoly.sol)
    undefined symbol: _ZN8PentagonC1Ef    (./trypoly.sol)
```

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

```
cmake_minimum_required(VERSION 3.18)
project(hello CXX)

find_package(ZLIB REQUIRED) # for external libs

add_executable(hello main.cpp util.h util.cpp)
set(CMAKE_CXX_STANDARD 20)
target_link_libraries(hello PUBLIC ZLIB::ZLIB)
```

CMake - Building

Building a CMake-based project

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

```
mkdir build # will contain all build-related files
cd build
cmake ..     # configures and generates a build system
cmake -DCMAKE_BUILD_TYPE=Release .. # pass arguments
ccmake .     # change configuration using terminal GUI
cmake-gui . # change configuration using Qt GUI
cmake --build . -j8     # build project with 8 jobs
cmake --build . --target hello  # build only hello
sudo cmake --install . # install project into system
cd ..
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‘

Web tools

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Godbolt / Compiler Explorer

Concept

An online generic compiler with immediate feedback. Allows:

- trying various compilers in the browser
- inspecting the assembly generated
- use of external libraries (over 50 available !)
- running the produced code
- sharing small pieces of code via permanent short links

Typical usage

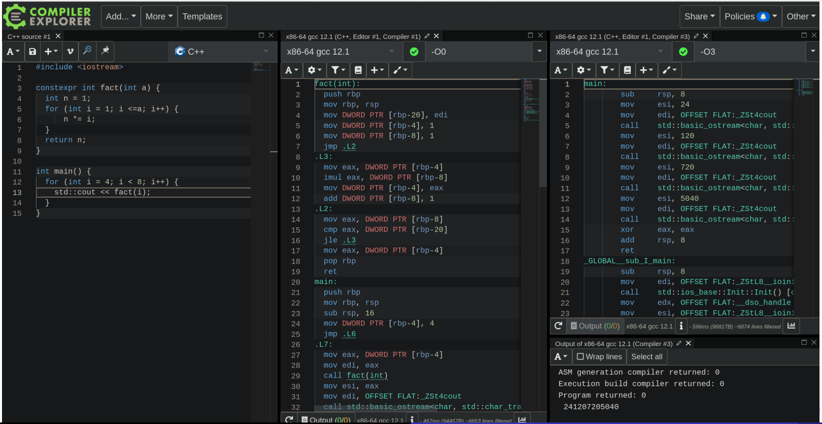
- check small pieces of code on different compilers
- check some new C^{++} functionality and its support
- optimize small pieces of code
- NOT relevant for large codes

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



cppinsights

Concept

Reveals the actual code behind C++ syntactic sugar

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

Typical usage

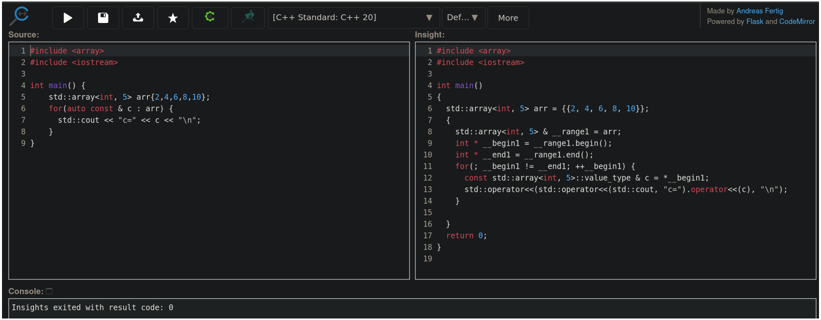
- understand how things work behind the C++ syntax
- debug some non working pieces of code

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



Debugging

5 Useful tools
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Debugging

The problem

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

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The solution: debuggers

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

Debugging

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- everything compiles fine (no warning)
- but crashes at run time
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- 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

gdb

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 ...

Native gdb	Try "tui enable" for a simple built-in UI
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

Index of Good Practices

Index of Exercises

Index of Godbolt code examples

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