HEP C^{++}course

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CERN

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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
  - 248 slides, 342 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 `https://github.com/hsf-training/cpluspluscourse`
- latest pdf under raw/download/talk/C++Course_full.pdf

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

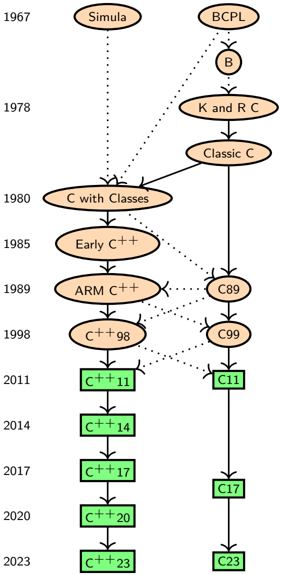
Detailed outline

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...

status

- A new C++specification every 3 years
  - C++20 is ready, officially published by ISO in December 2020
  - C++23 is feature complete since 25th of July 2022
- Bringing each time a lot of goodies

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How to use C++XX features

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

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

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

Why we use it?

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

Why is C++ our language of choice?

Adapted to large projects

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

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Fast

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

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Adapted to large projects

- statically and strongly typed
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Fast

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

What we get

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

Language basics

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)

$C^{++}98$

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

Portable numeric types

C++98

Requires inclusion of a specific header

```
#include <cstdint>

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

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

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

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

Integer literals

$C^{++}98$

```
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 = 0x4d2.1E6p3; // hexfloat, 0x4d2.1E6 * 2^3
                        // = 1234.12 * 2^3 = 9872.95

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

Useful aliases

C++98

Requires inclusion of headers

```
#include <cstddef> // and many other headers

size_t s = sizeof(int); // unsigned integer
                        // can hold any variable's size

#include <cstdint>

ptrdiff_t c = &s - &s;  // signed integer, can hold any
                        // diff between two pointers

// int, which can hold any pointer value:
intptr_t i = reinterpret_cast<intptr_t>(&s);   // signed
uintptr_t i = reinterpret_cast<uintptr_t>(&s); // unsigned
```

Arrays and Pointers

Static arrays

C++98

```
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;
```

Pointers

C++98

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int i = 4;
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Memory layout

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

Pointers

C++98

```
int i = 4;
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pi = 0x3000	0x3004
i = 4	0x3000

Pointers

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Memory layout

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j = 5	0x3008
pi = 0x3000	0x3004
i = 4	0x3000

Pointers

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

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Memory layout

	0x3028
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ai[2] = 3	0x3014
ai[1] = 2	0x3010
ai[0] = 1	0x300C
j = 5	0x3008
pi = 0x3000	0x3004
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Pointers

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

int ai[] = {1,2,3};
int *pai = ai; // decay to ptr
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Memory layout

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pai = 0x300C	0x3018
ai[2] = 3	0x3014
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pi = 0x3000	0x3004
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int i = 4;
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Memory layout

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	0x3024
k = 3	0x3020
paj = 0x3010	0x301C
pai = 0x300C	0x3018
ai[2] = 3	0x3014
ai[1] = 2	0x3010
ai[0] = 1	0x300C
j = 5	0x3008
pi = 0x3000	0x3004
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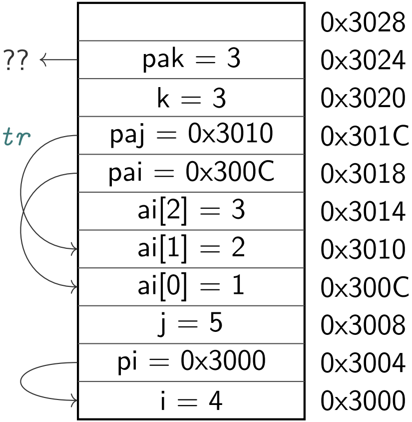
Memory layout



nullptr

C++11

A pointer to nothing

- if a pointer doesn't point to anything, set it to `nullptr`
- same as setting it to 0 or `NULL` (before C++11)
- triggers compilation error when assigned to integer

nullptr

C^{++}11

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- same as setting it to 0 or `NULL` (before C^{++}11)
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Example code

```
void* vp = nullptr;
int* ip = nullptr;
int i = NULL;      // OK -> 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, can be tested

// 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

Scopes / namespaces

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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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 '::')

```
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

$C^{++}17$

Easier way to declare nested namespaces

$C^{++}98$

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

$C^{++}17$

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

Class and enum types

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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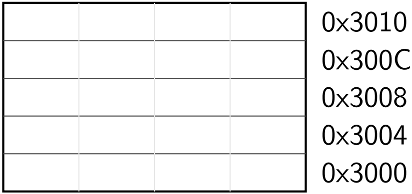

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Memory layout

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←	78.5		→	0x3004
25	?	?	?	0x3000

student

struct $C^{++}98$

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Memory layout

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

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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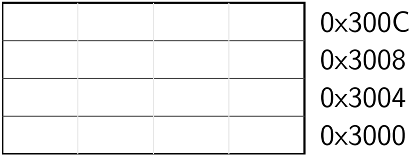

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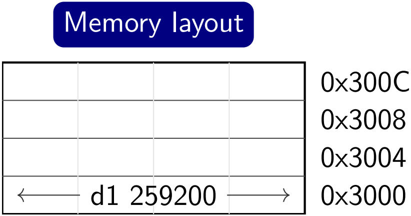

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Memory layout

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

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Memory layout

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

union

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  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
d1 3	?	?	?	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
d1 3	?	?	?	0x3000

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

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

Scoped enumeration, aka enum class C++11

Same syntax as enum, with scope

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

Only advantages

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

```
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++98

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

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

More sensible example

C++98

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

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

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

More sensible example

C++98

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

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

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

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

```

```
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 uint64_t myint;
myint toto = 17;
typedef int pos[3];
```

$C^{++}11$

```cpp
using myint = uint64_t;
myint toto = 17;
using pos = int[3];

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

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
- They can be used as function arguments

Example:

```
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
```

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

Advantages of pointers

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

Good practice: References

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

Functions

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";
}
```

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
```

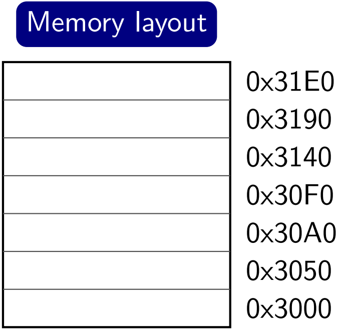
Functions: parameters are passed by value

C++98

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

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

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



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C++98

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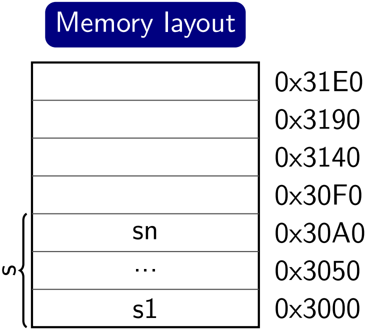
  ...
}
printBSp(s); // no copy
```



Functions: parameters are passed by value

C++98

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

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

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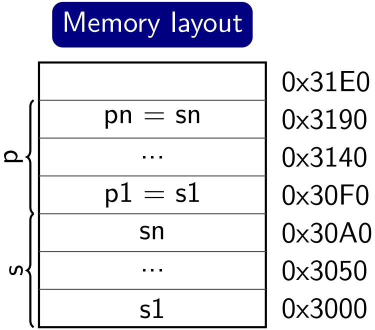
```



Functions: parameters are passed by value $C^{++}98$

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BigStruct s;

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

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void printBSp(BigStruct &q) {
  ...
}
printBSp(s); // no copy
```
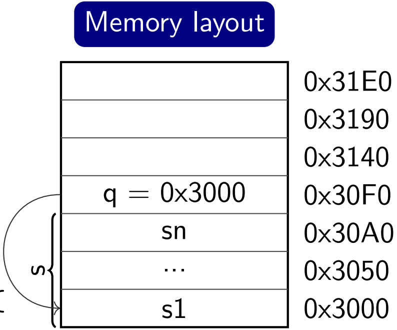
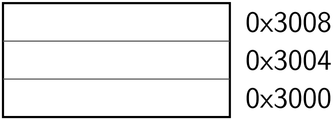



Functions: pass by value or reference?

C++98

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

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

void changeSS2(SmallStruct &q) {
  q.a = 2;
}
changeSS2(s);
// s.a == 2
```

Memory layout



Functions: pass by value or reference? C++98

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

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

void changeSS2(SmallStruct &q) {
  q.a = 2;
}
changeSS2(s);
// s.a == 2
```

Memory layout

	0x3008
	0x3004
s.a = 1	0x3000

Functions: pass by value or reference? C++98

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

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

void changeSS2(SmallStruct &q) {
  q.a = 2;
}
changeSS2(s);
// s.a == 2
```

Memory layout

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

Functions: pass by value or reference? C++98

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

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

void changeSS2(SmallStruct &q) {
  q.a = 2;
}
changeSS2(s);
// s.a == 2
```

Memory layout

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

Functions: pass by value or reference? $C^{++}98$

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

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

void changeSS2(SmallStruct &q) {
  q.a = 2;
}
changeSS2(s);
// s.a == 2
```

Memory layout

	0x3008
	0x3004
s.a = 1	0x3000

Functions: pass by value or reference? C++98

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  p.a = 2;
}
changeSS(s);
// s.a == 1

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  q.a = 2;
}
changeSS2(s);
// s.a == 2
```

Memory layout

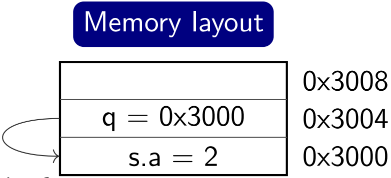
	0x3008
q = 0x3000	0x3004
s.a = 1	0x3000

Functions: pass by value or reference? C++98

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

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

void changeSS2(SmallStruct &q) {
  q.a = 2;
}
changeSS2(s);
// s.a == 2
```



Functions: pass by value or reference?

C++98

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

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

void changeSS2(SmallStruct &q) {
  q.a = 2;
}
changeSS2(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
- Prefer references for mandatory parameters to avoid copies
- Use pointers for optional parameters to allow `nullptr`
- 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
- Prefer references for mandatory parameters to avoid copies
- Use pointers for optional parameters to allow `nullptr`
- Use `const` for safety and readability whenever possible

Syntax

```
struct T {...}; T a;
void f(T value);             f(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
```

Functions

C++98

Exercise: Functions

Familiarise yourself with pass by value / pass by reference.

- Go to `code/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

C++98

Example: don't! Everything in one long function

```
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
- Arrays and Pointers
- Scopes / namespaces
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- References
- Functions
- Operators
- Control structures
- Headers and interfaces
- Auto keyword

Operators(1)

$C^{++}98$

Binary & Assignment Operators

```
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 & 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
```

Increment / Decrement

```cpp
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 & 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

Use wisely

```
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(2)

C++98

Bitwise and Assignment Operators

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

Operators(2)

C++98

Bitwise and Assignment Operators

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

Boolean Operators

```
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

```
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
```

Operators(3)

C++98

Comparison Operators

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

Precedences

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

Details can be found on cppreference

Operators(3)

C++98

Comparison Operators

```cpp
bool a = (3 == 3);  // true
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bool c = (4 <  4);  // false
bool d = (4 <= 4);  // true
bool e = (4 >  4);  // false
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```

Precedences

Don't use

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

Details can be found on cppreference

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
```

Precedences

Don't use - use parentheses

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

Details can be found on cppreference

Control structures

Control structures: if

C++98

if syntax

```
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

```
int collatz(int a) {
  if (a <= 0) {
    std::cout << "not supported";
    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

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

Control structures: conditional operator

$C^{++}98$

Syntax

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

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

Practical example

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

Do not abuse it

- 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 : instructiond; 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 : instructiond; 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 };
...
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 emitted
  case 'c':
    g();
    [[fallthrough]]; // Warning suppressed
  case 'd':
    h();
}
```

Init-statements for if and switch

$C^{++}17$

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

$C^{++}17$

```
if (Value val = GetValue(); condition(val)) {
  f(val);
} else {
  g(val);
}
h(val); // compile error
```

Init-statements for if and switch $C^{++}17$

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

$C^{++}17$

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

$C^{++}98$

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;
}
```

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

Control structures: for loop $C^{++}98$

for loop syntax

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

- Initializations and 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;
}
```

- Initializations and 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

Syntax

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

Example code

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

Init-statements for range-based loops C++20

Allows to limit variable scope in range-based loops

C++17

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

C++20

```cpp
std::array data = {"hello", ",", "world"};
for (std::size_t i = 0; auto& 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

C++98

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

Bad example

```
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 `code/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

```
// file inclusion
#include "hello.hpp"
// macro constants and function-style macros
#define MY_GOLDEN_NUMBER 1746
#define CHECK_ERROR(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 = uint64_t;
#elif
  using myint = uint32_t;
#endif
```

Preprocessor

C++98

```cpp
// file inclusion
#include "hello.hpp"
// macro constants and function-style macros
#define MY_GOLDEN_NUMBER 1746
#define CHECK_ERROR(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 = uint64_t;
#elif
  using myint = uint32_t;
#endif
```

Use 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
... // content
#endif
```

Pragma once (non-standard)

```
#pragma once
... // content
```

Auto keyword

2 Language basics

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

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

```
std::vector<int> v;
int a = v[3];
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

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

Practical usage

```
std::vector<int> v;
auto a = v[3];
const auto b = v.size();
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 `code/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)

Objects and Classes

3. Object orientation (OO)
   - Objects and Classes
   - Inheritance
   - Constructors/destructors
   - Static members
   - Allocating objects
   - Advanced OO
   - Operators
   - Functors

What are classes and objects

C++98

Classes (or "user-defined types")

C structs on steroids

- with inheritance
- with access control
- including methods

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 : MyFirstClass.hpp

```cpp
#pragma once
struct MyFirstClass {
  int a;
  void squareA();
  int sum(int b);
};
```

Implementation : MyFirstClass.cpp

```cpp
#include "MyFirstClass.hpp"
void MyFirstClass::squareA() {
  a *= a;
}
void MyFirstClass::sum(int b) {
  return a + b;
}
```

Implementing methods

C++98

Standard practice

- usually in .cpp, outside of class declaration
- using the class name as namespace
- when reference/pointer to the object is needed, use **this** keyword

```
void MyFirstClass::squareA() {
  a *= a;
}

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

this keyword

C++98

How to know an object's address?

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

```cpp
void externalFunc(MyStruct & s);

struct MyStruct {
  void invokeExternalFunc() {
    externalFunc(*this); // Pass a reference to ourself
  }
};
```

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

```
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;
}
```

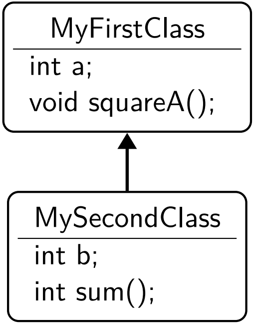
Inheritance

First inheritance

$C^{++}98$

```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
```

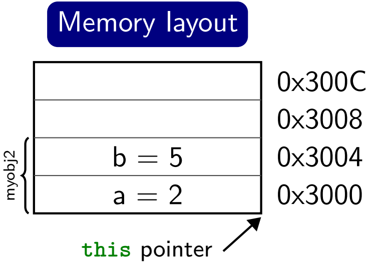


First inheritance

C++98

```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
```



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*
- A `struct` is just a `class` that defaults to *public* access

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*
- A `struct` is just a `class` that defaults to *public* access

```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

$C^{++}98$

public / *private* keywords

private allows access only within the class

public allows access from anywhere

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

```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) C++98

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 `class` 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 `class` if nothing is specified

Net result for external code

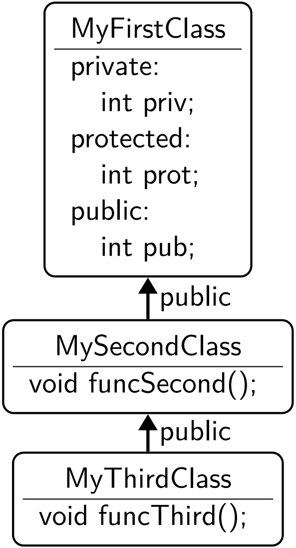
- only public members of public inheritance are accessible

Net result for grand child code

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

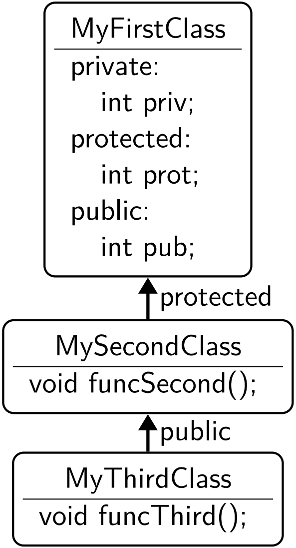
Managing inheritance privacy - public

$C^{++}98$




```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
}
```

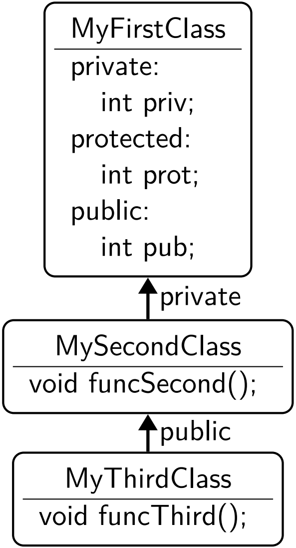
Managing inheritance privacy - protected $C^{++}98$




```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

C++98




```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)

- Objects and Classes
- Inheritance
- Constructors/destructors
- Static members
- Allocating objects
- Advanced OO
- Operators
- Functors

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 MyFirstClass {
public:
  MyFirstClass();
  MyFirstClass(int a);
  ~MyFirstClass();
  ...
protected:
  int a;
};
```

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

MyFirstClass(int a_):a(a_) {}

~MyFirstClass() {}
```

Class Constructors and Destructors

C++98

```
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 MyFirstClass {
  int a;
  MyFirstClass();
  MyFirstClass(int a);
};
struct MySecondClass : MyFirstClass {
  int b;
  MySecondClass();
  MySecondClass(int b);
  MySecondClass(int a, int b);
};
MySecondClass::MySecondClass() : MyFirstClass(), b(0) {}
MySecondClass::MySecondClass(int b_)
  : MyFirstClass(), b(b_) {}
MySecondClass::MySecondClass(int a_, int b_)
  : MyFirstClass(a_), b(b_) {}
```

Copy constructor

$C^{++}98$

Concept

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

Copy constructor

C++98

Concept

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

```cpp
struct MySecondClass : MyFirstClass {
  MySecondClass();
  MySecondClass(const MySecondClass &other);
};
```

Copy constructor

C++98

Concept

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

```cpp
struct MySecondClass : MyFirstClass {
  MySecondClass();
  MySecondClass(const MySecondClass &other);
};
```

The rule of 3/5/0 (C++98/C++11 and newer) - cppreference

- if a class has a destructor, a copy/move constructor or a copy/move assignment operator, it should have all three/five. strive for having none.

Class Constructors and Destructors

C++98

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

C++98

Concept

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

```
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.

```cpp
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

- when no user defined constructor, a default is provided
- any user-defined constructor disables the default one
- but they can be enforced
- rule can be more subtle depending on members

Practically

```
ClassName() = default; // provide default if possible
ClassName() = delete;  // disable default constructor
```

Delegating constructor

C++11

Idea

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

Practically

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

Constructor inheritance

C++11

Idea

- avoid having to re-declare parent's constructors
- by stating that we inherit all parent constructors

Practically

```
struct BaseClass {
  BaseClass(int value);
};
struct DerivedClass : BaseClass {
  using BaseClass::BaseClass;
};
DerivedClass a{5};
```

Member initialization

C++11

Idea

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

Practically

```cpp
struct BaseClass {
  int a{5}; // also possible: int a = 5;
  BaseClass() = default;
  BaseClass(int _a) : a(_a) {}
};
struct DerivedClass : BaseClass {
  int b{6};
  using BaseClass::BaseClass;
};
DerivedClass d{7}; // a = 7, b = 6
```

Calling constructors

C++11

After object declaration, arguments within {}

```cpp
struct A {
  int a;
  float b;
  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 a;
  float b;
  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
```

Calling constructors for arrays and vectors

C++11

list of items given within {}

```
int ip[3]{1,2,3};
int* ip = new int[3]{1,2,3};
std::vector<int> v{1,2,3};
```

Calling constructors for arrays and vectors

C++11

list of items given within {}

```cpp
int ip[3]{1,2,3};
int* ip = new int[3]{1,2,3};
std::vector<int> v{1,2,3};
```

C++98 nightmare

```cpp
int ip[3]{1,2,3};             // OK
int* ip = new int[3]{1,2,3};  // not allowed
std::vector<int> v{1,2,3};    // not allowed
```

Static members

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

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

```cpp
class Text {
public:
  static std::string upper(std::string) {...}
private:
  static int callsToUpper; // add `inline` in C++17
};
int Text::callsToUpper = 0; // required before C++17
std::string uppers = Text::upper("my text");
// now Text::callsToUpper is 1
```

Allocating objects

3. Object orientation (OO)
   - Objects and Classes
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   - Operators
   - Functors

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

C++98

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

C++98

On the stack

- objects are created when declared (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

C++98

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

C++98

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

Polymorphism

C++98

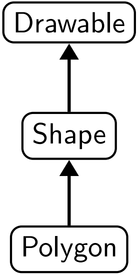
the concept

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

```
Polygon p;

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

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



Polymorphism

C++98

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
}
```

Memory layout

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

Polymorphism

C++98

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
}
```

Memory layout

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

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C++98

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Memory layout

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...	0x3008
Drawable.b	0x3004
Drawable.a	0x3000

Shape

Inheritance privacy and polymorphism

C++98

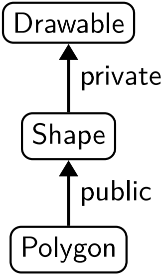
Only public inheritance is visible to code outside the class

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

```
Polygon p;

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

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



Method overriding

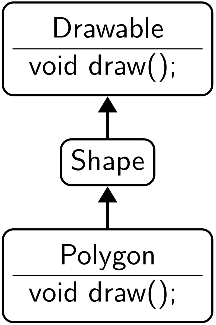
C++98

the idea

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

```
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

C++98

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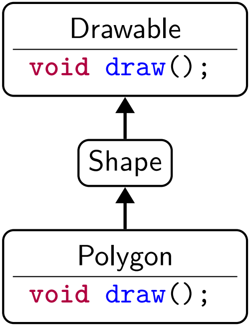
```cpp
Polygon p;
p.draw(); // Polygon.draw

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



Virtual methods

C++98

the concept

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- for these, the most derived object's implementation is used (i.e. the dynamic type behind a pointer/reference)
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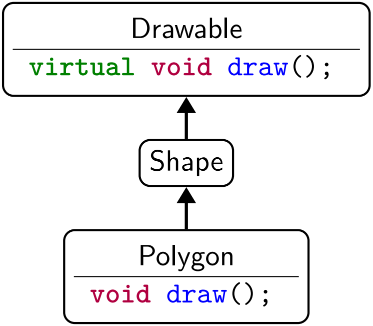
```cpp
Polygon p;
p.draw(); // Polygon.draw

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

Practically

```cpp
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)

```cpp
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 get a compiler warning

Pure Virtual methods

C++98

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

C++98

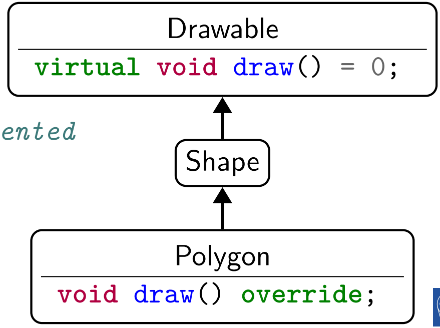
Concept

- 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

C++98

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:

```cpp
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++98

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++98

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

Drawable
virtual void draw() = 0;

Overriding overloaded methods

C++98

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

C++98

Exercise: Polymorphism

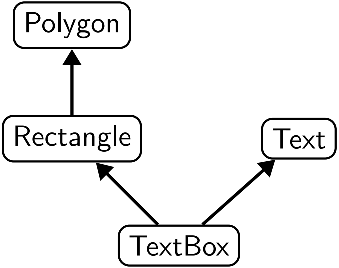
- go to code/polymorphism
- look at the code
- open trypoly.cpp
- create a Pentagon, call its perimeter method
- create a Hexagon, call its perimeter method
- create a Hexagon, call its parent's perimeter method
- retry with virtual methods

Multiple Inheritance

C++98

Concept

- one class can inherit from multiple parents




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

The diamond shape

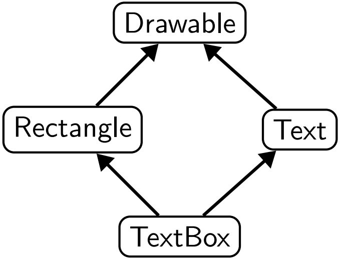
C++98

Definition

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

Problem

- are the members of the grand parent replicated?



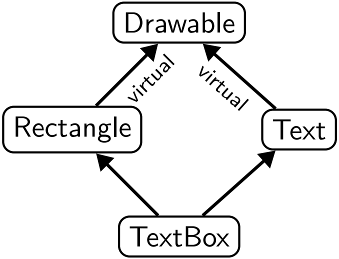
Virtual inheritance

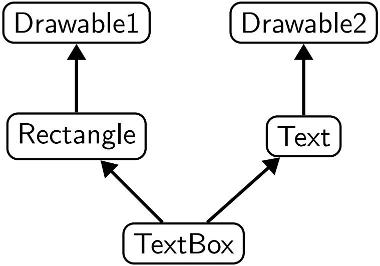
C++98

Solution

- inheritance can be *virtual* or not
- *virtual* inheritance will "share" parents
- standard inheritance will replicate them

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





Multiple inheritance advice

C++98

Do not use multiple inheritance

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

Multiple inheritance advice

C++98

Do not use multiple inheritance

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

Do not use diamond shapes

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

Virtual inheritance

C++98

Exercise: Virtual inheritance

- go to code/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

Virtual inheritance

C++98

Warning

in case of virtual inheritance it is the most derived class that calls the virtual base class's constructor

Operators

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

Operators' example

C++98

```cpp
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)
```

Operators

C++98

Defining operators of a class

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

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

Why to have non-member operators? C++98

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 to 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)'
```

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 `code/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

Functors

3 Object orientation (OO)

- Objects and Classes
- Inheritance
- Constructors/destructors
- Static members
- Allocating objects
- Advanced OO
- Operators
- Functors

Functors

C++98

Concept

- a class that implements `operator()`
- allows to use objects in place of functions
- and as objects have constructors, allow to construct functions

```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
```

Functors

C++98

Typical usage

- pass a function to another one
- or to an STL algorithm

```
struct BinaryFunction {
  virtual double operator() (double a, double b) = 0;
};
double binary_op(double a, double b, BinaryFunction &func) {
  return func(a, b);
}
struct Add : BinaryFunction {
  double operator() (double a, double b) override
  { return a+b; }
};
Add addfunc;
double c = binary_op(a, b, addfunc);
```

Core modern C++

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

Constness

Constness

C++98

The const keyword

- indicate that the element to the left is constant
- this element won't be modifiable in the future
- this is all checked at compile time

```
// standard syntax
int const i = 6;

// error : i is constant
i = 5;

// also ok, when nothing on the left,
// const applies to the element on the right
const int j = 6;
```

Constness and pointers

C++98

```
// pointer to a constant integer
int a = 1, b = 2;
int const *i = &a;
*i = 5; // error, int is const
i = &b; // ok, pointer is not const

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

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

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

int const & const l = a; // compile error
```

Member function constness

C++98

The const keyword for member functions

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

```
struct Example {
  void foo() const {
    // type of 'this' is 'Example const*'
    m_member = 0; // Error: member function is const
  }
  int m_member;
};
```

Method constness

C++98

Constness is part of the type

- T const and T are different types
- however, T is automatically cast to T const when needed

```cpp
void func(int & a);
void funcConst(int const & a);

int a = 0;
int const b = 0;

func(a);       // ok
func(b);       // error
funcConst(a); // ok
funcConst(b); // ok
```

constness

C++98

Exercise: Constness

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

Exceptions

4 Core modern C++

- Constness
- Exceptions
- Templates
- Lambdas
- The STL
- Pointers and RAII

Exceptions

C++98

The concept

- 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

C++98

Throwing exceptions

- objects of any type can be thrown (even e.g. `int`)
  - prefer standard exception classes
- throw objects by value

```cpp
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

Catching exceptions

- a catch clause catches an exception 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

```
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();
}
```

Exceptions

C++98

Rethrowing exceptions

- a caught exception can be rethrown
- 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

C++98

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 c5;
    g();
    cout << "done"; // not run
  } catch(const exception&) {
    // c1, c3 and c5 have been
    // destructed
  }
}
```

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++17

Good practice: Exceptions

- throw exceptions by value, catch them by (const) reference
- 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
  - consider `assert` and tests
- *don't* use exceptions to provide alternative/skip return values
  - you can use `std::optional` or `std::variant`
  - avoid using the global C-style `errno`
- never throw in destructors
- see also the C++ core guidelines and the ISO C++ FAQ

Exceptions

C++98

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

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

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

  - either no exceptions is thrown or they are handled internally
  - checked at compile time
  - so allows the compiler to optimise 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);
```

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

Templates

4 Core modern C^{++}

- Constness
- Exceptions
- Templates
- Lambdas
- The STL
- Pointers and RAII

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

Warning

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

```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>
```

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 required 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

```cpp
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 {
  Polygon(float radius);
  float perimeter() {return 2*N*sin(PI/N)*m_radius;}
  float m_radius;
};

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

Template specialization

C++98

Specialization

Templates can be specialized for given values of their parameter

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

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

The full power of templates

C++98

Exercise: Templates

- go to code/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
- Pointers and RAII

Trailing function return type $C^{++}11$

An alternate way to specify a function's return type

```
ReturnType func(Arg1 a, Arg2 b);  // classic
auto func(Arg1 a, Arg2 b) -> ReturnType;
```

Trailing function return type

C++11

An alternate way to specify a function's return type

```
ReturnType func(Arg1 a, Arg2 b);  // classic
auto func(Arg1 a, Arg2 b) -> ReturnType;
```

Advantages

- Allows to simplify inner type definition

```
class Class {
  using ReturnType = int;
  ReturnType func();
}
Class::ReturnType Class::func() {...}
auto Class::func() -> ReturnType {...}
```

- C++14: `ReturnType` not required, compiler can deduce it
- used by lambda expressions

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

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

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

Usage example

```cpp
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);
```

Capturing variables

C++11

Python code

```python
increment = 3
data = [1,9,3,8,3,7,4,6,5]
map(lambda x : x + increment, data)
```

Capturing variables

C++11

Python code

```python
increment = 3
data = [1,9,3,8,3,7,4,6,5]
map(lambda x : x + increment, data)
```

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);
```

Capturing variables

C++11

Python code

```python
increment = 3
data = [1,9,3,8,3,7,4,6,5]
map(lambda x : x + increment, data)
```

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
- captured variables are listed within initial []

Capturing variables

C++11

The capture list

- local variables outside the lambda must be explicitly captured
- captured variables are listed within initial []

Example

```
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

```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);
```

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, and the lambda's `operator()` is `const`.

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

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

Capture list - this

C++11

Inside a (non-static) member function, we can capture this.

```
[    this](...) { use(*this); };
[       &](...) { use(*this); };
[&, this](...) { use(*this); };
[       =](...) { use(*this); }; // deprecated in C++20
[=, this](...) { use(*this); }; // allowed in C++20
```

Since the captured this is a pointer, *this refers to the object by reference.

Capture list - this

C++11

Inside a (non-static) member function, we can capture `this`.

```
[   this](...) { use(*this); };
[      &](...) { use(*this); };
[&, this](...) { use(*this); };
[      =](...) { use(*this); }; // deprecated in C++20
[=, this](...) { use(*this); }; // allowed in C++20
```

Since the captured `this` is a pointer, `*this` refers to the object by reference.

```
[   *this](...) { use(*this); }; // C++17
[&, *this](...) { use(*this); }; // C++17
[=, *this](...) { use(*this); }; // C++17
```

The object at `*this` is captured by value (the lambda gets a copy).

Details in this blog post.

Generic lambdas

C++14

Generic lambdas (aka. polymorphic lambdas)

- The type of lambda parameters may be `auto`.

```cpp
auto add = [](auto a, auto b) { return a + b; };
```

- The generated `operator()` becomes a template function:

```cpp
template <typename T, typename U>
auto operator()(T a, U b) const { return a + b; }
```

- The types of `a` and `b` may be different.

Explicit template parameters (C++20)

```cpp
auto add = []<typename T>(T a, T b)
  { return a + b; };
```

- The types of `a` and `b` must be the same.

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 consequence

- lambda expressions create ordinary objects
- they can in particular be inherited from!

Higher-order lambdas

C++11

Example - godbolt

```cpp
auto build_incrementer = [](int inc) {
  return [inc](int value) { return value + inc; };
};
auto inc1 = build_incrementer(1);
auto inc10 = build_incrementer(10);
int i = 0;
i = inc1(i);   // i = 1
i = inc10(i);  // i = 11
```

How it works

- `build_incrementer` returns a function object
- this function's behavior depends on a parameter
- note how `auto` is useful here!

Lambda improvements $C^{++}20$

Lambda improvements in $C^{++}20$

- Allowed in unevaluated contexts,
  e.g. within **decltype**, **sizeof**, **typeid**, etc.
- Without captures, are default-constructible and assignable

Examples

```cpp
struct S {
  decltype([](int i) { std::cout << i; }) f;
} s;
s.f(42); // prints "42"

template <typename T>
using CudaPtr = std::unique_ptr<T,
                    decltype([](T* p){ cudaFree(p); })>;

std::set<T, decltype([](T a, T b) { ... })> s2;
```

The STL

4 Core modern C++
- Constness
- Exceptions
- Templates
- Lambdas
- The STL
- Pointers and RAII

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

```
#include <vector>
#include <algorithm>

std::vector<int> vi{5, 3, 4}; // initializer list
std::vector<int> vr(3); // constructor taking int

std::transform(vi.begin(), vi.end(),       // range1
               vi.begin(),                 // start range2
               vr.begin(),                 // start result
               std::multiplies{}); // function objects

for(auto n : vr) {
  std::cout << n << ' ';
}
```

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
- examples
  - string, string_view (C++17)
  - list, forward_list (C++11), vector, deque, array (C++11)
  - map, set, multimap, multiset
  - unordered_map (C++11), unordered_set (C++11)
  - stack, queue, priority_queue
  - span (C++20)
- non-containers: pair, tuple (C++11), optional (C++17), variant (C++17), any (C++17)
- see also the string and container library on cppreference

Containers: std::vector

C++11

```
#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

```cpp
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
```

STL's concepts

C++98

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
  - iterator
  - reverse_iterator
  - const_iterator

STL's concepts

C++98

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

C++98

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)

```cpp
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)

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

STL way (since C++98)

```cpp
std::vector<int> v = ...;
int sum = std::accumulate(v.begin(), v.end(), 0);
// std::reduce(v.begin(), v.end(), 0); // 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 sin(x)/(x + DBL_MIN); });

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

More examples

C++11

```
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!

C++98

Using the STL

C++98

Exercise: STL

- go to code/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!

Pointers and RAII

4 Core modern C++

- Constness
- Exceptions
- Templates
- Lambdas
- The STL
- Pointers and RAII

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

They need initialization

```cpp
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;
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

```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

```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

```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);
```

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 object semantic to acquire/release resources

- wrap the resource inside an object
- acquire resource in constructor
- release resource in destructor
- create this object on the stack so that it is automatically destructed when leaving the scope, including in case of exception
- use move semantics to pass the resource around

RAII in practice

C++98

File class

```cpp
class File {
public:
  File(const char* filename) :
    m_handle(std::fopen(filename, "w+")) {
    if (m_handle == nullptr) { throw ... }
  }
  ~File() { std::fclose(m_handle); }
  void write (const char* str) {
    if (std::fputs(str, m_handle) == EOF) {
      throw ...
    }
  }
private:
  std::FILE* m_handle;
};
```

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!") ;

  // 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

an RAII pointer

- wraps a regular pointer
- has move only semantic
  - the pointer has unique ownership
  - copying will result in a compile error
- in `<memory>` header

std::unique_ptr

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Usage

```cpp
std::unique_ptr<Foo> p{ new Foo{} }; // allocation
std::cout << p.get() << " points to "
          << p->someMember << '\n';
void f(std::unique_ptr<Foo> ptr);
f(std::move(p)); // transfer ownership
// deallocation when exiting f
assert(p.get() == nullptr);
```

Quiz

C++11

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

What do you expect ?

Quiz

C++11

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

What do you expect ?

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

- directly allocates a unique_ptr
- no `new` or `delete` calls anymore!

std::make_unique

C++14

- directly allocates a unique_ptr
- no **new** or **delete** calls anymore!

make_unique usage

```
// allocation of one Foo object,
// calls new Foo(arg1, arg2) internally
auto a = std::make_unique<Foo>(arg1, arg2);
std::cout << a.get() << " points to "
          << a->someMember << '\n';
// allocation of an array of Foos
// calls default constructor
auto b = std::make_unique<Foo[]>(10);
// deallocations 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 `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 `unique_ptr` is move only

A question of ownership

```
unique_ptr<T> producer();
void observer(const T&);
void modifier(T&);
void consumer(unique_ptr<T>);
unique_ptr<T> pt{producer()}; // Receive ownership
observer(*pt);                // Keep ownership
modifier(*pt);                // Keep ownership
consumer(std::move(pt));      // Transfer ownership
```

unique_ptr usage summary

C++11

It's about lifetime management

- Use `unique_ptr` in functions taking part in lifetime management
- Otherwise use raw pointers or references

shared_ptr, make_shared

C++11

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

make_shared : creates a shared_ptr

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

smart pointers

C++98

Exercise: Smart pointers

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

```
$ valgrind --leak-check=full --track-origins=yes ./smartPointers
```

- Go through `problem1()` to `problem3()` and fix the leaks using smart pointers.
- `problem4()` is the most difficult. Skip if not enough time.

Useful tools

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

C++ editor

5 Useful tools

- C++ editor
- Code management
- 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

Code management

5 Useful tools

- C^{++}editor
- Code management
- Code formatting
- The Compiling Chain
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Code management tool

Please use one!

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

It will soon save your day

A few tools

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

Git crash course

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

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

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

$ git diff f24a6ce bb54d15
```

Code formatting

5 Useful tools

- C^{++}editor
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- Debugging

clang-format

.clang-format

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

Run clang-format

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

clang-format

Exercise: clang-format

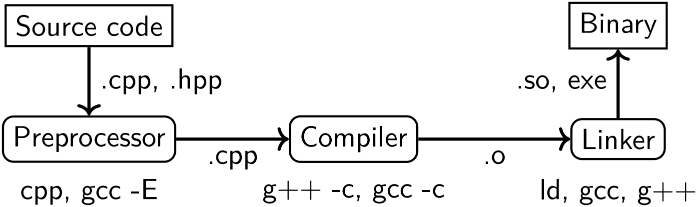
- Go to any example
- Format code with:
  `clang-format --style=GNU -i <file.cpp>`
- Inspect changes, try `git diff .`
- Revert changes using `git checkout -- <file.cpp>` or `git checkout .`
- Go to code directory and create a .clang-format file
  `clang-format -style=LLVM -dump-config > .clang-format`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

The Compiling Chain

5 Useful tools
- C^{++}editor
- Code management
- Code formatting
- The Compiling Chain
- 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
  slightly better error reporting
  free and open source, based on LLVM
- icc icx: Intel's compilers, proprietary but now free
  optimized for Intel hardware
  icc being replaced by icx, based on LLVM
- Visual C++ / MSVC: Microsoft's C++ compiler on Windows

My preferred choice today

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

Useful compiler options (gcc/clang)

Get more warnings

-Wall -Wextra	get all warnings
-Werror	force yourself to look at warnings

Optimization

-g	add debug symbols
-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

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
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)
target_compile_features(hello PUBLIC cxx_std_17)
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 code/functions
- preprocess functions.cpp (cpp or gcc -E -o output)
- compile functions.o and Structs.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 functions target
    - run make clean; make
    - look at the collect 2 line, from the end up to "-o functions"
- see library dependencies with 'ldd functions'

Web tools

5 Useful tools

- C++editor
- Code management
- Code formatting
- The Compiling Chain
- Web tools
- Debugging

Godbolt / Compiler Explorer

Concept

An online generic compiler with immediate feedback. Allows:

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

Typical usage

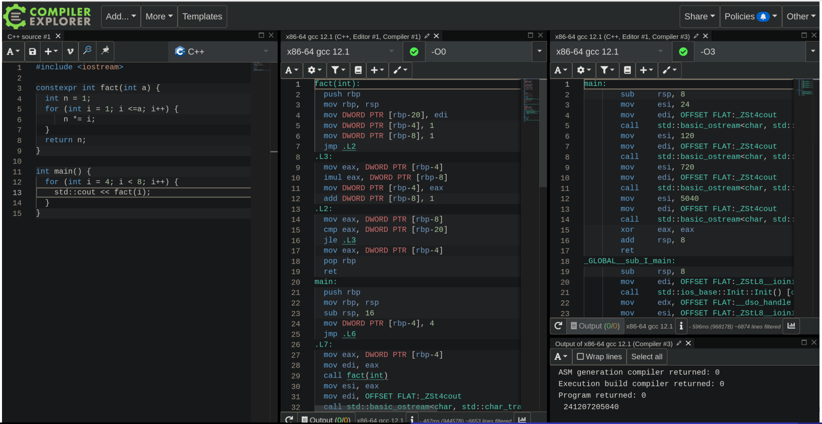
- check small pieces of code on different compilers
- check some new C++ functionality and its support
- optimize small pieces of code
- NOT relevant for large codes

Godbolt by example

Check effect of optimization flags

https://godbolt.org/z/Pb8WsWjEx

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



cppinsights

Concept

Reveals the actual code behind C++ syntactic sugar

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

Typical usage

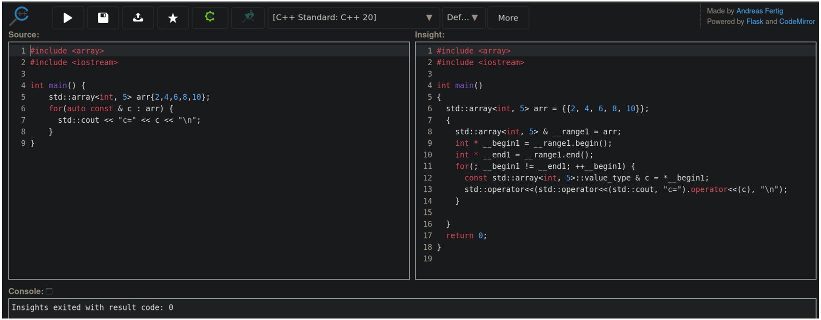
- understand how things work behind the C++ syntax
- debug some non working pieces of code

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

- C++ editor
- Code management
- Code formatting
- The Compiling Chain
- Web tools
- **Debugging**

Debugging

The problem

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

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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
- no error message, no clue

The solution : debuggers

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

Existing tools

- gdb THE main player
- lldb the debugger coming with clang/LLVM
- gdb-oneapi the Intel OneAPI debugger

They usually can be integrated into your IDE

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 code/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
- use -Wall -Wextra and see warning

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`