An introduction to C++

day 2

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slides: Hannes Hauswedell *AG Algorithmische Bioinformatik* et al.

Day	Content	State
Monday	Variables, Constness, I/O, STL (vector, string, ...)	✓
Tuesday	Control flow, functions (overloading), function templates	✓
Wednesday	Lambdas, Enums, struct/class, class template, compilation	←
Thursday	STL: tuples, more data containers, algorithms	
Friday	Holiday	
Monday	Questions, Recap, Debugging, **Test**	

Lambda functions

User-defined types

Enumerations

Class types

Separate compilation

Lambda functions

```
template <typename TElem>
void square_all_elements(std::vector<TElem> & vec)
{
    for (TElem & elem : vec)
        elem = elem * elem;
}
```

Lambda functions

```cpp
template <typename TElem>
void square_all_elements(std::vector<TElem> & vec)
{
    for (TElem & elem : vec)
        elem = elem * elem;
}
```

```cpp
template <typename TElem>
void squareroot_all_elements(std::vector<TElem> & vec)
{
    for (TElem & elem : vec)
        elem = std::sqrt(elem);
}
```

Lambda functions

```
template <typename TElem>
void square_all_elements(std::vector<TElem> & vec)
{
    for (TElem & elem : vec)
        elem = elem * elem;
}
```

```
template <typename TElem>
void squareroot_all_elements(std::vector<TElem> & vec)
{
    for (TElem & elem : vec)
        elem = std::sqrt(elem);
}
```

Seems tedious. What if we want to create function that just does "X_on_all_elements" and define X separately?

Lambda functions

```
template <typename TElem, typename TLambda>
void on_all_elements(std::vector<TElem> & vec, TLambda const & l)
{
    for (TElem & elem : vec)
        elem = l(elem);
}
```

Lambda functions

```
template <typename TElem, typename TLambda>
void on_all_elements(std::vector<TElem> & vec, TLambda const & l)
{
    for (TElem & elem : vec)
        elem = l(elem);
}
```

```
int main()
{
    auto square      = [] (auto const & elem) { return elem * elem;      };
    auto square_root = [] (auto const & elem) { return std::sqrt(elem); };

    std::vector<double> ds{0.2, 1.5, 2};

    on_all_elements(ds, square);        // ds == { 0.04, 2.25, 4 }
    on_all_elements(ds, square_root);   // ds == { 0.20, 1.50, 2 }
}
```

Lambda functions

```
auto square = [] (auto const & elem) { return elem * elem; };
```

- Lambdas are *objects* and each lambda has a distinct type – that's why we can only save them in a variable with deduced type and why functions need to take them as template parameters.

Lambda functions

```
auto square = [] (auto const & elem) { return elem * elem; };
```

- Lambdas are *objects* and each lambda has a distinct type – that's why we can only save them in a variable with deduced type and why functions need to take them as template parameters.
- A minimal Lambda that does nothing is `[](){}`.

Lambda functions

```
auto square = [] (auto const & elem) { return elem * elem; };
```

- Lambdas are *objects* and each lambda has a distinct type – that's why we can only save them in a variable with deduced type and why functions need to take them as template parameters.
- A minimal Lambda that does nothing is `[](){}`.
- `[]` introduces a Lambda definition (other things can go into the `[]` - capture group, but we won't cover that now).
- `()` contains the parameters, just like with ordinary functions except that `auto` is valid (even before C++20).
- `{}` contains the body of the lambda function.
- The return type of the Lambda is deduced by default.

Lambda functions

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User-defined types (~ "A Tour of C++")

- The arithmetic types, possibly modified by `const` and/or `&`, as well as arrays thereof are **built-in types**.
- They are *low-level*; efficiently reflect the capabilities of conventional hardware.

- C++ provides various mechanisms of abstraction for the design of higher level applications.
- You can combine these abstraction mechanisms with the built-in types to create **user-defined types**.
- User-defined types are either *enumerations* or *class types*.

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Enumerations

```
enum class Color
{
    red, blue, green, yellow
}; // ; is important!

Color invertMe(Color const c)
{
    switch (c)
    {
        case Color::red:
            return Color::green;
        case Color::green:
            return Color::red;
        case Color::blue:
            return Color::yellow;
        case Color::yellow:
            return Color::blue;
    }
}
```

- Enumerations are simple user-defined types that represent a small set of integer values by giving them names.
- Helps to make code more expressive, making it easier to read and write and prevents errors.
- Enumerations can be introduced by `enum NAME` or `enum class NAME`, the latter is a *strongly-typed* enumeration.
- Prefer strongly-typed enums!

Enumerations

Strongly-typed enums:

```
enum class Color
{
    red, blue, green, yellow
};

//    scoped ↓
Color c = Color::blue;

// not implicitly convertible:
//int i = c;

// no arithmetic operators:
//Color cc = blue + green;
```

C-style enum:

```
enum Color
{
    red, blue, green, yellow
};

// unscoped ↓
Color c = blue;

// implicitly convertible:
int i = c;                // == 1

// arithmetic operators:
Color cc = blue + green;  // == yellow
```

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Class types - struct

```cpp
struct Complex
{
    double re;
    double im;
}; // ; is important!

Complex c{1, 4};

std::cout << "real:"
          << c.re
          << " imaginary:"
          << c.im
          << '\n';

Complex c2;   // undefined
Complex c3{}; // like {0, 0}
```

- The definition on the left introduces the `Complex` class type for complex numbers.
- It consists of two *member variables*, a real part (`.re`) and an imaginary part (`.im`).
- The member variables can be accessed via the dot-operator.
- Objects of type `Complex` can be brace-initialised, both with values and default

Class types - struct

```
struct Complex
{
    double re{};
    double im{};
}; // ; is important!

Complex c{1, 4};

std::cout << "real:"
          << c.re
          << " imaginary:"
          << c.im
          << '\n';

Complex c2;   // like {0, 0}
Complex c3{}; // like {0, 0}
```

- The definition on the left introduces the `Complex` class type for complex numbers.
- It consists of two *member variables*, a real part (`.re`) and an imaginary part (`.im`).
- The member variables can be accessed via the dot-operator.
- Objects of type `Complex` can be brace-initialised, both with values and default
- Member variables of built-in type could (and should!) be *member-initialised*.

Class types - member functions

```
struct Complex
{
    double re{};
    double im{};

    void add(Complex const & c)
    {
        re += c.re;
        im += c.im;

    }
};

Complex c{1, 4};
Complex c2{2, 5};

c.add(c2);          // == {3, 9}
```

- What if we would like to be able to add two complex numbers?
- To do that, we can add a *member function*!
- Member functions are like other functions, but declared inside the body of the class.
- They can access member variables.
- They are called via `.` on an object of the type.

Class types - member functions

```cpp
struct Complex
{
    double re{};
    double im{};

    void operator+=(Complex const & c)
    {
        re += c.re;
        im += c.im;

    }
};

Complex c{1, 4};
Complex c2{2, 5};

c.operator+=(c2);    // == {3, 9}
c += c2;             // == {5, 14}
```

- But an `.add()` function is ugly...
- ... instead we can define an *operator*!
- Operators can be invoked via their name like other member functions.
- **But** they can also be invoked directly via their operator so user defined types *appear* similar to built-in types.

Class types - member functions

```
struct Complex
{
    double re{};
    double im{};

    Complex & operator+=(Complex const & c)
    {
        re += c.re;
        im += c.im;
        return *this;
    }
};

Complex c{1, 4};
Complex c2{2, 5}; Complex c3{1, 1};

c += c2 += c3;     // c == {4, 10}
                   // c2 ?
```

- Customarily those arithmetic operators that change an object, return a reference to the object itself after it was changed.
- This enables them to be "chained" and used in expressions.
- *At this point you don't need to understand what* `*this` *does except "reference to self".*

Class types - member functions

```
struct Complex
{
    double re{};
    double im{};

    Complex & operator+=(Complex const & c)
    {
        re += c.re;
        im += c.im;
        return *this;
    }
};

Complex c{1, 4};
Complex c2{2, 5}; Complex c3{1, 1};
// equivalent to without ()
c += (c2 += c3);  // c == {4, 10}
                  // c2 == {3, 6}
```

- Customarily those arithmetic operators that change an object, return a reference to the object itself after it was changed.
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Class types - member functions

```
struct Complex
{
    double re{};
    double im{};

    Complex & operator+=(Complex const & c)
    {
        re += c.re;
        im += c.im;
        return *this;
    }
};

Complex c{1, 4};
Complex c2{2, 5}; Complex c3{1, 1};
// not equivalent to without ()
(c += c2) += c3;  // c == {4, 10}
                  // c2 unchanged
```

- Customarily those arithmetic operators that change an object, return a reference to the object itself after it was changed.
- This enables them to be "chained" and used in expressions.
- *At this point you don't need to understand what* `*this` *does except "reference to self".*

Class types - member functions

```cpp
struct Complex
{
    double re{};
    double im{};

    Complex & operator+=(Complex const & c)
    {
        re += c.re;
        im += c.im;
        return *this;
    }

    Complex operator+(Complex const & c)
    {
        Complex tmp{re, im};
        tmp += c;
        return tmp;
    }
};
```

- Often some operators can be used to simplify the definition of others.
- Be aware of the different return values:
  - arithmetic+assignment: reference to self
  - regular arithmetic: new object
  - comparison: bool

Class types - member functions

```
struct Complex
{
    double re{};
    double im{};

    Complex & operator+=(Complex const & c)
    {
        re += c.re;
        im += c.im;
        return *this;
    }

    Complex operator+(Complex c) const
    {
        return (c += *this);
    }
};
int i = a + b + c; // same as (a + b) + c;
```

- Often some operators can be used to simplify the definition of others.
- Be aware of the different return values:
  - arithmetic+assignment: reference to self
  - regular arithmetic: new object
  - comparison: bool
- Member functions that don't change an object should be marked `const`; otherwise can't be called on objects of `const` type.

Class types - protection of members

```cpp
struct Complex
{
private:
    double re{};
    double im{};

public:
    Complex & operator+=(Complex const & c)
    {
        re += c.re;
        im += c.im;
        return *this;
    }
};

// private members disable easy initial.
// Complex c{1, 3.4};
// and direct access:
// std::cout << c.re; // can't do: private now
```

- Sometimes you may want to protect your member variables so that they are only accessible to member functions.
- You can use the `private` and `public` keywords to denote this difference.

Class types - protection of members

```cpp
class Complex
{
private:
    double re{};
    double im{};

public:
    Complex & operator+=(Complex const & c)
    {
        re += c.re;
        im += c.im;
        return *this;
    }
};

// private members disable easy initial.
// Complex c{1, 3.4};
// and direct access:
// std::cout << c.re; // can't do: private now
```

- Sometimes you may want to protect your member variables so that they are only accessible to member functions.
- You can use the `private` and `public` keywords to denote this difference.
- A `class` is a `struct` whose members are `private` by default.
- More on classes in the 2nd week of the course!

Class types - Quiz

```
struct Dog
{
    void bark()
    {
        std::cout << "WUFF\n";
    }
};

void ignore(Dog const & d)
{
    d.bark();
}

int main()
{
    Dog d{};
    ignore(d);
}
```

- What's going wrong here?

Class types - Quiz

```cpp
struct Dog
{
    void bark()
    {
        std::cout << "WUFF\n";
    }
};

void ignore(Dog const & d)
{
    d.bark();
}

int main()
{
    Dog d{};
    ignore(d);
}
```

- What's going wrong here?
- The member function `bark()` was not `const`-qualified so it can't be called inside of `ignore()`, because inside `ignore()` the argument is accessed via `const &`!

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Class templates

```
template <typename T>
struct Complex
{
    T re{};
    T im{};
};

Complex<double> c{3.3, 4.4};
Complex<int32_t> c2{3, 4};
```

- Similar to function templates: a class template is not a "complete type", it's a template for a type.
- By specifying all template arguments, e.g. `Complex<double>` you *instantiate* the template and declare a type.
- `Complex<double>` and `Complex<int32_t>` are different types!
- the template argument for class templates can sometimes be deduced (as for function templates), but rules are complicated

Class templates

```
template <typename T>
struct Complex
{
    T re{};
    T im{};
};

Complex<double> c{3.3, 4.4};
Complex<int32_t> c2{3, 4};
```

```
std::vector<size_t> vec;
```

- Now you know what `std::vector` is!

- Similar to function templates: a class template is not a "complete type", it's a template for a type.
- By specifying all template arguments, e.g. `Complex<double>` you *instantiate* the template and declare a type.
- `Complex<double>` and `Complex<int32_t>` are different types!
- the template argument for class templates can sometimes be deduced (as for function templates), but rules are complicated

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Separate compilation

Separate compilation

- The more code you write, the less organised your `.cpp` will get.
- To increase readability and maintainability of your code, you should split it into multiple files.
- C++ knows `.cpp` files and header files (`.hpp`, sometimes `.h`).
- Header files are like `.cpp` files, but they don't contain a `main()` function.

Separate compilation

- The more code you write, the less organised your `.cpp` will get.
- To increase readability and maintainability of your code, you should split it into multiple files.
- C++ knows `.cpp` files and header files (`.hpp`, sometimes `.h`).
- Header files are like `.cpp` files, but they don't contain a `main()` function.

- Header files are included by `#include`; headers can include other headers.
- Including a header literally results in the entire contents of the header being pasted into the current source file!
- This also means you need to avoid including a header twice (why?).
- To do that, write `#pragma once` into the header file.

Separate compilation

There are two different "styles" for organising source code:

1. A single `.cpp` file and many header files (or in the case of libraries only headers)
2. A `.cpp` file with `main()` and pairs of cpp+hpp files where declaration and definition are split:
    - declaration in the header
    - definition in the cpp

The second style is more common, but it depends also on the paradigm of programming.

Separate compilation -- header-only

`main.cpp`:

```cpp
#include "example.hpp"


int main()
{
    example_func();
}
```

`example.hpp`:

```cpp
#pragma once
#include <iostream>

void example_func()
{
    std::cout << "!!!";
}
```

- simpler build process; entire library shipped as headers
- necessary for function templates and members of class templates
- slower build-times, because all headers are parsed every time and the entire project is rebuilt on every small change

Separate compilation -- cpp+hpp

`main.cpp`:

```cpp
#include "example.hpp"


int main()
{
    example_func();
}
```

`example.hpp` (decl.):

```cpp
#pragma once

void example_func();
```

`example.cpp` (def.):

```cpp
#include <iostream>
#include "example.hpp"

void example_func()
{
    std::cout << "!!!";
}
```

- every pair of cpp+hpp is compiled separately (called *translation unit*)
- faster builds (only those parts are rebuilt that changed)
- libraries used by many programs are shared (less memory used)
- doesn't work for templates

Separate compilation -- cpp+hpp

Build-process unix

First we build an *object file* for every cpp other than main:

```
% g++ -std=c++17 -Wall -Wextra -Werror -pedantic example.cpp -c
```

(note the `-c`!) This created `example.o`.

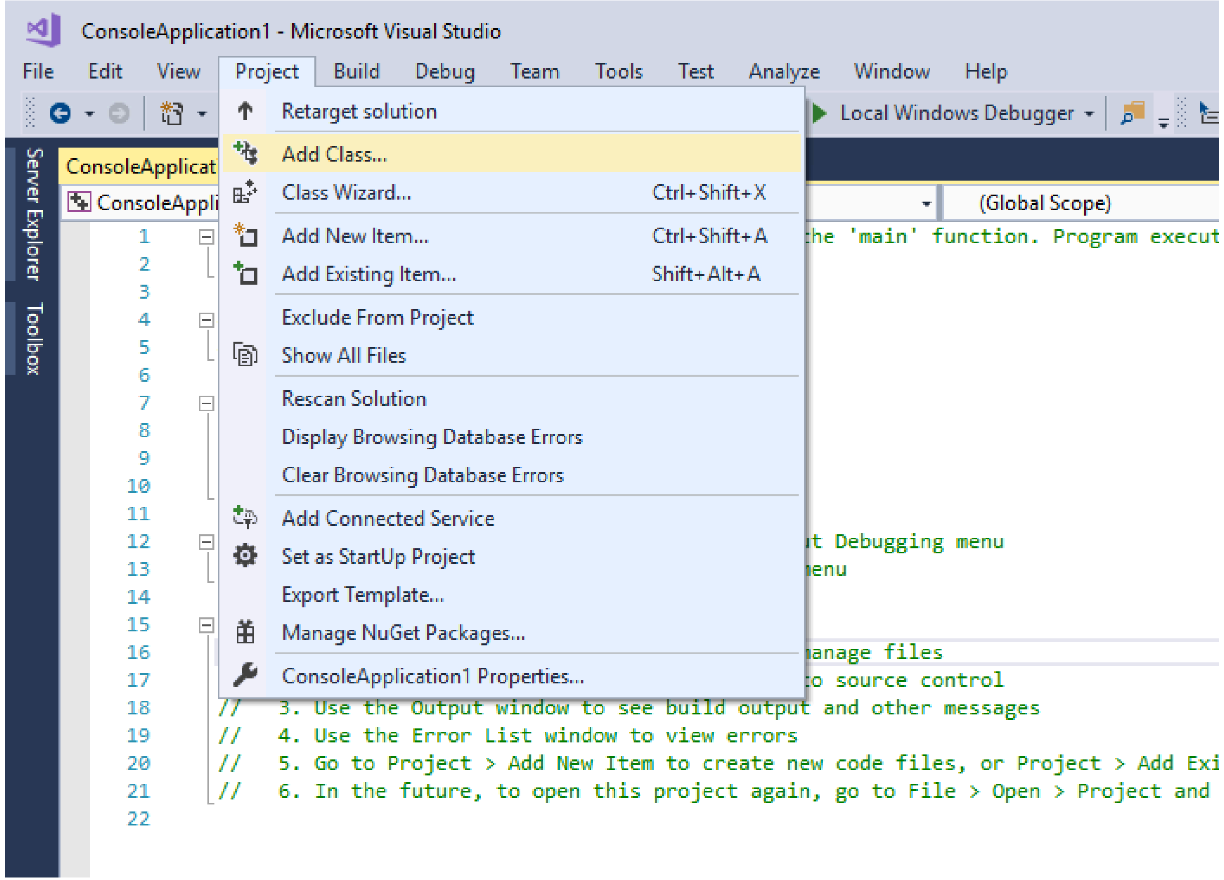
Finally we build `main.cpp` and *link* it with the existing object files:

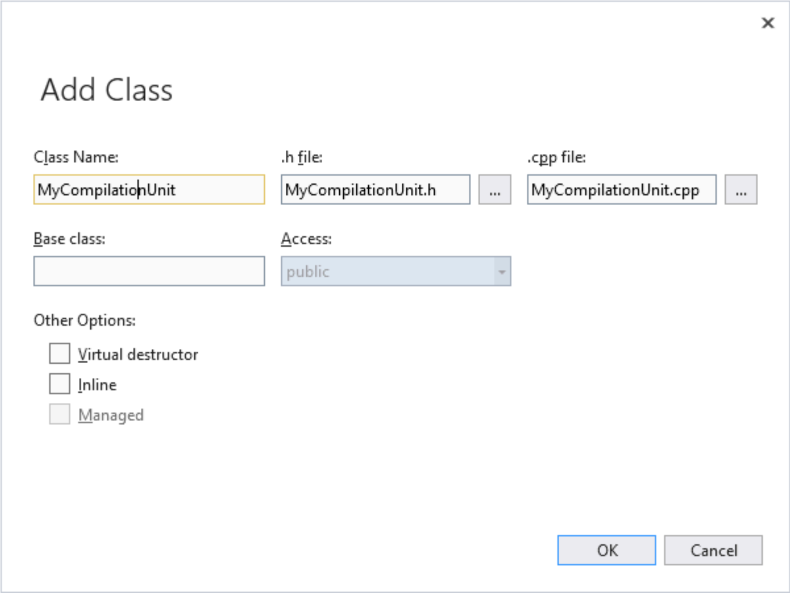
```
% g++ -std=c++17 -Wall -Wextra -Werror -pedantic main.cpp example.o
```

In larger projects *build-systems* like CMake, Meson, Gnu-Make, Ninja or a combination thereof handle this for us.

Separate compilation -- cpp+hpp

Build-process Windows





- Delete all contents from the new pair of files
- MSVC will take care of the linking

Tasks for the computer lab

Tasks for the computer lab I

- Implement a function with the following signature:

```
template <typename TLambda>
std::vector<size_t> filter(std::vector<size_t> const & input,
                           TLambda const & l)
```

- It should return a vector with those elements of the input for which the lambda function evaluates to `true`.
- Write a main()-function that tests this behaviour with three lambdas:
  1. a lambda that returns true for elements whose value is even.
  2. a lambda that returns true for elements whose value is odd.
  3. a lambda that returns true for elements that are not zero.

Tasks for the computer lab II

1. Implement a `struct Person` with the member variables `name` and `age` (what are appropriate types?).
2. Implement an `enum class` that represents gender with the three legal categories in Germany: `FEMALE`, `MALE` and `DIVERSE` (you may add more 😉).
3. Add a member variable of that type to `struct Person`.
4. Add a member function called `print()` that prints the fields in some descriptive manner.

Tasks for the computer lab III

1. Use your type from the previous task!
2. Write a main function that repeatedly asks the user to input name, age and gender and then saves those as elements of a `std::vector<Person>`. Ask the user after every input if they want to quit adding persons.
3. If they quit, sort the vector of persons by age.
    - Use `std::sort` and read up the documentation on it!
    - Implement the actual comparison as `operator<` inside `struct Person`.
    - instead implement a lambda-function that does the comparison (and is passed to `std::sort`).
4. Now sort by name (alphabetically) instead!
5. Print the first and last persons from the vector.

Tasks for the computer lab IV

1. Implement the Complex type (template)
    - with the following operators:
        - *arithmetic operators*: `+`, `-`, `*`, `/`,
        - *arithmetic assignment operators*: `+=`, `-=`, `*=`, `/=`,
        - *comparison operators*: `==`, `!=`
    - Start with a non-templated `struct`, later switch to the template version.
    - Write a main() function that properly tests the functionality!
2. Move the definition of the type into a separate header file and verify that everything works.
3. Why can templates not have their definitions in separate cpp files? Think about / find out!