EDAF50 – C++ Programming

3. Modularity

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Outline

Program organization

- A program consists of many separately developed parts
  - user-defined types
  - functions
  - templates
- managed by clearly defined interactions.
- Separate
  - interfaces
  - implementations

Program organization
Free functions vs. member functions

- Operations on a class can be expressed as
  - member functions
    - use for operations that need access to the representation
  - free functions
    - can be added without affecting other users of the class

- Handle declarations and definitions
  - The declaration is needed in all places it is used
  - An entity must be defined at most once
  - **`#include`**

The One Definition Rule

- For a *translation unit*, there must be no more than one definition for
  - a template
  - a type
  - a function, or
  - an object
- In the entire *program*, an object or *non-inline* function cannot have more than one definition.
- If an object or function is used, it must have a definition.
- Types and templates can be defined in multiple translation units, but must be the same.

General program structure
Example: Header file

Minimal example:

mean – a mean value library

- mean.h
- mean.cc

Use:

- main.cc

mean.h: declarations

```
double mean(double x1, double x2);
double mean(int x1, int x2);
```

General program structure
Example: Source code file

mean.cc: definitions

```
#include "mean.h"    // make declarations visible so that the
                     // compiler can check that they agree
double mean(double x1, double x2)
{
   return (x1+x2)/2;
}

double mean(int x1, int x2)
{
   return static_cast<double>(x1 + x2) / 2;
}
```

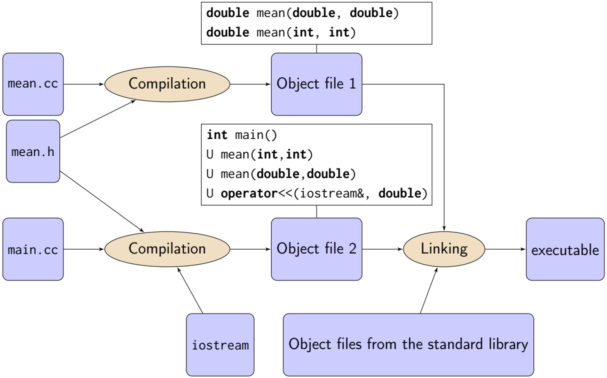
General program structure
Example: main program

main.cc: use

```
#include <iostream>
using std::cout;
using std::endl;

#include "mean.h"      // make declarations visible
                       // to be able to use them
int main()
{
   double a=2.3;
   double b=3.9;
   int m=3;
   int n=4;
   cout << mean(a, b) << endl;
   cout << mean(m, n) << endl;
}
```

- Function declarations are placed in *header files* (.h)
- The implementation is split into multiple source files (.cc)
- Separate compilation of each source file(.cc)
- Linking the program



File structure for classes
include guards

Class definitions are placed in header files (.h or .hpp)

- All users of a type need the definition
- A header file can be included more than once (e.g., via other header files)
- To avoid defining a type multiple times use *include guards*:

```
#ifndef FOO_H
#define FOO_H
//...
class Foo {
//...
};
#endif
```

Member functions are placed in a source file (.cc or .cpp)

File structure

- Java: one class per source file
- C++: A header file declares a set of classes and functions that belong together

  `<algorithm>` All standard library algorithms

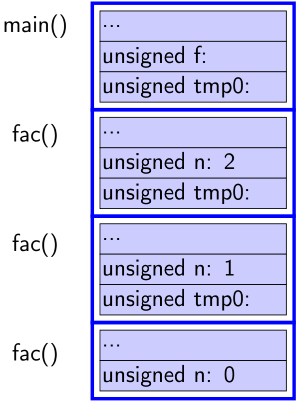
  `a header "graph.h"` may contain classes `graph`, `node`, `edge`, and functions on the graph

  - Easier to use (fewer files to include)
  - Easier to get e.g. forward declarations correct, less circular dependencies

Memory allocation
stack allocation

```
unsigned fac(unsigned n)
{
  if(n == 0)
    return 1;
  else return n * fac(n-1);
}

int main()
{
  unsigned f = fac(2);
  cout << f;
  return 0;
}
```



1. Direcly handle the error locally and continue execution
2. Categorize and pass error to another module that is expected to handle it
3. Identify the error, give an error message, and crash the program *("fail-fast", e.g.,* `assert`*)*

Level 2: exceptions (or return values)

Throwing exceptions

Example: checking arguments in the `Vector` class

```
Vector::Vector(int size) {
  if(size < 0) throw length_error("negative size");
  elem = new double[size];
  sz = size;
}

int& Vector::operator[] (int i) {
  if (i<0 || i>=sz) throw out_of_range("Vector::operator[]");
  return elem[i];
}
```

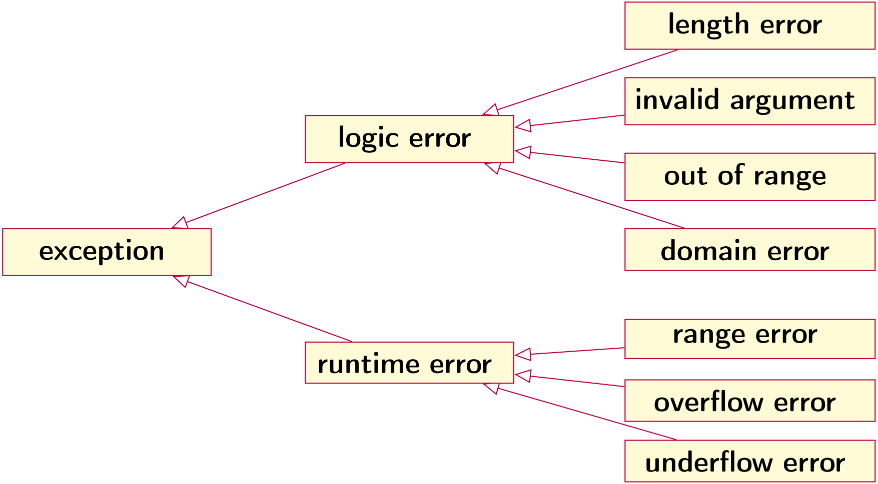
- *NB: to allow checking arguments, we use a* **`signed`** *integer type for values that should always be positive*
- `Vector` cannot reasonably handle the error locally, only the caller can know why it passed a certain argument
- `std::vector::`**`operator`**`[]` does no checks (`at()` does)

Exceptions

- Error handling is done with **`throw`** and **`catch`**. Like Java.
- *"stack unwinding"* until a matching **`catch`** is found.
- When an excepion is thrown, activation records are popped off the stack until a function containing a matching **`catch`** is found. (*"stack unwinding"*)
- If an exception is not caught, the program crashes. (by calling `std::terminate()`.)
- Standard classes for exceptions: `#include <stdexcept>`

The exception classes of the standard library

Class hierarchy for classes in `<stdexcept>`



Error handling
Catching exceptions

```
try {
        // Code that may throw
}
catch (some_exception&) {
        // Code handling some_exception
}
catch (another_exception&) {
        // Code handling another_exception
}
catch (...) {
        // default/generic exception handling
}
```

The first **catch** clause with a matching type is selected.
⇒ Catch derived classes before the base class.

... is valid C++, matches anything

Catching exceptions

Example:

```
try {
        cout << "Enter a number: ";
        int i;
        if (cin >> i) {
            int r = f(i);
            cout << "Result: " << r << endl;
        }
}
catch(std::overflow_error&) {
        cout << "Overflow error\n");
}
catch(std::exception& e) {
        cout << typeid(e).name() << ": " << e.what() << endl;
}
```

Catching exceptions

Example:

```
try {
        cout << "Enter a number: ";
        int i;
        if (cin >> i) {
            int r = f(i);
            cout << "Result: " << r << endl;
        }
}
catch(std::overflow_error&) {
        cout << "Overflow error\n");
}
catch(std::exception& e) {
        cout << typeid(e).name() << ": " << e.what() << endl;
}
```

predefined function in the class exception

Catching exceptions
... and rethrowing

```
try{
  do_something();
}
catch {std::ength_error& le) {
  // handle length error
}
catch {std::out_of_range&) {
  // handle out_of_range
}
catch (...) {
  // generic handler (just log?)
  throw;   // defult: pass on
}
```

Throwing exceptions

Creating own exceptions as subclasses

```
#include<stdexcept>

class communication_error : public runtime_error {
public:
        communication_error(const string& mess = "")
                : runtime_error(mess) {}
};
```

Throwing

```
throw communication_error("Checksum error");
```

Throwing exceptions

Creating custom exceptions

```
struct MyOwnException{
  MyOwnException(const std::string& msg, int val)
            : m{msg},v{val} {}
    std::string m;
    int v;
};
```

Using custom exceptions

```
void f() {
    throw MyOwnException("An error occurred", 17);
}

void test1() {
    try{
        f();
    } catch(MyOwnException &e) {
        cout << "Exception: " << e.m << " - " << e.v << endl;
    }
}
```

Catching exceptions

Resource mangement: destructors and "*stack unwinding*"

```
struct Foo {
  int x;
  Foo(int ix) :x{ix} {
    cout << "Foo("<<x<<")\n";}
  ~Foo() {
    cout << "~Foo("<<x<<")\n";}
};

void test(int i)
{
  Foo f(i);
  if(i == 0) {
    throw std::out_of_range("noll?");
  } else {
    Foo g(100+i);
    test(i-1);
    cout << "after call to test("
         << i-1 << ")\n";
  }
}
```

```
int main() {
 Foo f(42);
 try{
   Foo g(17);
   test(2);
 } catch(std::exception& e) {
    cout<<e.what()<< endl; }
}
```

```
Foo(42)
Foo(17)
Foo(2)
Foo(102)
Foo(1)
Foo(101)
Foo(0)
~Foo(0)
~Foo(101)
~Foo(1)
~Foo(102)
~Foo(2)
~Foo(17)
noll?
~Foo(42)
```

Catching exceptions
Resource mangement: destructors and "*stack unwinding*"

```
struct Foo {
  int x;
  Foo(int ix) :x{ix} {
    cout << "Foo("<<x<<")\n";}
  ~Foo() {
    cout << "~Foo("<<x<<")\n";}
};

void test(int i)
{
  Foo f(i);
  if(i == 0) {
    throw std::out_of_range("noll?");
  } else {
    Foo g(100+i);
    test(i-1);
    cout << "after call to test("
         << i-1 << ")\n";
  }
}
```

```
int main() {
 Foo f(42);
 try{
   Foo g(17);
   test(2);
 } catch(std::exception& e) {
    cout<<e.what()<< endl; }
}
```

```
Foo(42)
Foo(17)
Foo(2)
Foo(102)
Foo(1)
Foo(101)
Foo(0)
~Foo(0)
~Foo(101)
~Foo(1)
~Foo(102)
~Foo(2)
~Foo(17)
noll?
~Foo(42)
```

Catching exceptions

Resource mangement: destructors and "*stack unwinding*"

```
struct Foo {
  int x;
  Foo(int ix) :x{ix} {
    cout << "Foo("<<x<<")\n";}
  ~Foo() {
    cout << "~Foo("<<x<<")\n";}
};

void test(int i)
{
  Foo f(i);
  if(i == 0) {
    throw std::out_of_range("noll?");
  } else {
    Foo g(100+i);
    test(i-1);
    cout << "after call to test("
         << i-1 << ")\n";
  }
}
```

```
int main() {
 Foo f(42);
 try{
   Foo g(17);
   test(2);
 } catch(std::exception& e) {
    cout<<e.what()<< endl; }
}
```

```
Foo(42)
Foo(17)
Foo(2)
Foo(102)
Foo(1)
Foo(101)
Foo(0)
~Foo(0)
~Foo(101)
~Foo(1)
~Foo(102)
~Foo(2)
~Foo(17)
noll?
~Foo(42)
```

Catching exceptions
Resource mangement: destructors and "*stack unwinding*"

```
struct Foo {
  int x;
  Foo(int ix) :x{ix} {
    cout << "Foo("<<x<<")\n";}
  ~Foo() {
    cout << "~Foo("<<x<<")\n";}
};

void test(int i)
{
  Foo f(i);
  if(i == 0) {
    throw std::out_of_range("noll?");
  } else {
    Foo g(100+i);
    test(i-1);
    cout << "after call to test("
         << i-1 << ")\n";
  }
}
```

```
int main() {
 Foo f(42);
 try{
   Foo g(17);
   test(2);
 } catch(std::exception& e) {
    cout<<e.what()<< endl; }
}
```

```
Foo(42)
Foo(17)
Foo(2)
Foo(102)
Foo(1)
Foo(101)
Foo(0)
~Foo(0)
~Foo(101)
~Foo(1)
~Foo(102)
~Foo(2)
~Foo(17)
noll?
~Foo(42)
```

Catching exceptions
Resource mangement: destructors and "*stack unwinding*"

```
struct Foo {
  int x;
  Foo(int ix) :x{ix} {
    cout << "Foo("<<x<<")\n";}
  ~Foo() {
    cout << "~Foo("<<x<<")\n";}
};

void test(int i)
{
  Foo f(i);
  if(i == 0) {
    throw std::out_of_range("noll?");
  } else {
    Foo g(100+i);
    test(i-1);
    cout << "after call to test("
         << i-1 << ")\n";
  }
}
```

```
int main() {
 Foo f(42);
 try{
   Foo g(17);
   test(2);
 } catch(std::exception& e) {
    cout<<e.what()<< endl; }
}
```

```
Foo(42)
Foo(17)
Foo(2)
Foo(102)
Foo(1)
Foo(101)
Foo(0)
~Foo(0)
~Foo(101)
~Foo(1)
~Foo(102)
~Foo(2)
~Foo(17)
noll?
~Foo(42)
```

Catching exceptions

Resource mangement: destructors and "*stack unwinding*"

```
struct Foo {
  int x;
  Foo(int ix) :x{ix} {
    cout << "Foo("<<x<<")\n";}
  ~Foo() {
    cout << "~Foo("<<x<<")\n";}
};

void test(int i)
{
  Foo f(i);
  if(i == 0) {
    throw std::out_of_range("noll?");
  } else {
    Foo g(100+i);
    test(i-1);
    cout << "after call to test("
         << i-1 << ")\n";
  }
}
```

```
int main() {
 Foo f(42);
 try{
   Foo g(17);
   test(2);
 } catch(std::exception& e) {
    cout<<e.what()<< endl; }
}
```

```
Foo(42)
Foo(17)
Foo(2)
Foo(102)
Foo(1)
Foo(101)
Foo(0)
~Foo(0)
~Foo(101)
~Foo(1)
~Foo(102)
~Foo(2)
~Foo(17)
noll?
~Foo(42)
```

Catching exceptions

Resource mangement: destructors and "*stack unwinding*"

```
struct Foo {
  int x;
  Foo(int ix) :x{ix} {
    cout << "Foo("<<x<<")\n";}
  ~Foo() {
    cout << "~Foo("<<x<<")\n";}
};

void test(int i)
{
  Foo f(i);
  if(i == 0) {
    throw std::out_of_range("noll?");
  } else {
    Foo g(100+i);
    test(i-1);
    cout << "after call to test("
         << i-1 << ")\n";
  }
}
```

```
int main() {
 Foo f(42);
 try{
   Foo g(17);
   test(2);
 } catch(std::exception& e) {
    cout<<e.what()<< endl; }
}
```

```
Foo(42)
Foo(17)
Foo(2)
Foo(102)
Foo(1)
Foo(101)
Foo(0)
~Foo(0)
~Foo(101)
~Foo(1)
~Foo(102)
~Foo(2)
~Foo(17)
noll?
~Foo(42)
```

Specifying exceptions in C++11

The keyword **noexcept** specifies if a function may throw or not.
No specification is equal to **noexcept**(**false**).

In the function declaration

```
struct Foo {
    void f();
    void g() noexcept;
};
```

and in the function definition

```
#include<stdexcept>
void Foo::f() {
    throw std::runtime_error("f failed");
}
void Foo::g() noexcept{
    throw std::runtime_error("g lied and failed");
}
```

Exception specification
Example usage

```
#include<typeinfo> // for typeid

void test_noexcept()
{
    Foo f;

    try {
        f.f();
    }catch(std::exception &e) {
        cout << typeid(e).name() << ": " << e.what() << endl;
    }
    try {
        f.g();
    }catch(std::exception &e) {
        cout << typeid(e).name() << ": " << e.what() << endl;
    }
    cout << "done\n";
}
```

```
St13runtime_error: f failed
```

```
terminate called after throwing an instance of 'std::runtime_error'
  what():  g lied and  failed
```

Exception specification
older C++, do not use

Older C++ had "exception lists" for a function: the types of exceptions that may be generated by the function are specified with the keyword **throw**.

Example of exception list:

```
int f(int) throw(typ1, typ2, typ3) {
        //...
        throw typ1("Error of type 1 occurred");
        //...
        throw typ2("Error of type 2 occurred");
        //...
        throw typ3("Error of type 3 occurred");
}
```

No list	⇒	Any type of exception may be thrown
Empty list (**throw()**)	⇒	No exceptions may be thrown

Rules of thumb for exceptions

- Consider error handling early in the design process
- Use specific exception types, not built-in types.
  (do not `throw 17;`, `throw false;` , etc.)
- "Throw by value, catch by reference"
- If a function should not throw, declare `noexcept`.
- Specify *invariants* for your types
  - The constructor establishes the invariant, or throws.
  - Member functions can rely on the invariant.
  - Member functions must not break the invariant.
  - Example: `Vector`
    - the size `sz` is a positive number
    - the array `elem` points to has size `sz`
    - if the allocation of the array fails `std::bad_alloc` is thrown

If something can be checked at compile-time, use `static_assert`.

Static assert

If something can be checked at compile-time, use static_assert.

```
static_assert ( bool_constexpr , message )      (since C++11)
    message can be omitted.                     (since C++17)

constexpr int some_param = 10;

int foo(int x)
{
    static_assert(some_param > 100, "");
    return 2*x;
}

int main()
{
    int x = foo(5);

    std::cout << "x is " << x << std::endl;
    return 0;
}
```

```
  error: static assertion failed:
      static_assert(some_param > 100, "");
```

Static assert

<type_traits>

The standard library provides (meta)functions to query properties of types.

```
template <typename T, typename U>
void assign(T& a, const U& b)
{
    static_assert(std::is_assignable<T&,U>::value, "");
    a = b;
}
int main()
{
    int x;
    assign(x, "Foo");
    cout << "x = " << x << "\n";
}
```

gives the error

```
In instantiation of 'void assign(T&, const U&) [with T=int; U=char [4]
error: static assertion failed
   10 |     static_assert(std::is_assignable<T&,U>::value, "");
      |                                                ^~~~~
```

Stream I/O

- The C++ standard library contains facilities for
  - Structured I/O ("formatted I/O")
    - reading values of a certain type, T
    - overload `operator>>(istream&, T&)` and
    - `operator<<(ostream&, const T&)`
  - Character I/O ("raw I/O")
    - `istream& getline(istream&, string&)`
    - `istream& istream::getline(char*, streamsize)`
    - `int istream::get()`
    - `istream& istream::ignore()`
    - ...
- NB! `getline()` as free function and member of `istream`.
- `std::getline()` has an overload for using another delimiter than newline.
- Choose raw or formatted I/O based on your application

namespace

- Limit visibility of names
  - expressing which functions/classes/objects belong together
  - reduce risk of name clashes
  - cf. package in Java
- Accessing names in namespaces:
  - qualified name (with scope operator): `std::cout`
  - **using** declaration: `using std::cout;`
    - brings in a single name into the current scope
  - **using** directive: `using namespace std;`
    - brings in all names in namespace `std` into the current scope
    - avoid in general, or use in limited scope
  - never write **using**-directives in header files
    - introduces names in user code
- Namespaces *can be extended*
  - Except (with some exceptions) `std` ($\Rightarrow$ undefined behaviour)

Example

declarations (.h)

```
namespace foo {
  void test();
}

namespace bar {
  void test();
}
```

definitions (.cc)

```
using std::cout;
using std::endl;

namespace foo {
  void test()
  {
    cout << "foo::test()\n";
  }
}

void bar::test()
{
  cout << "bar::test()\n";
}
```

```
int main()
{
    foo::test();
    bar::test();
    using namespace foo;
    test();
}
```

```
foo::test()
bar::test()
foo::test()
```

namespace

- Unnamed namespaces
  - local to a particular file (also if **#include**d)
  - is used to hide names (cf. **static** in C)
  - names clash with global names

```
namespace foo {
  void test()
  {
    cout << "foo::test()\n";
  }
}
namespace {
  void test()
  {
    cout << "::test()\n";
  }
}
```

```
int main()
{
  test();
  foo::test();
  ::test();
}
```

```
::test()
foo::test()
::test()
```

- Alternative names for namespaces (*namespace aliases*):

```
namespace my_name=a_really_long_and_weird_namespace_name;
```

Argument Dependent Lookup (ADL)

Name lookup is done in *enclosing scopes*, but...

```
namespace test{
    struct Foo{
        Foo(int v) :x{v} {}
        int x;
    };
    std::ostream& operator<<(std::ostream& o, const Foo& f) {
        return o << "Foo(" << f.x << ")";
    }
} // namespace test

int main()
{
    test::Foo f(17);
    std::cout << f << '\n';
}
```

- The function **operator**<<(ostream&, **const** Foo&) is not visible in main().
- Through ADL it is found in the namespace of its argument (test).

Argument Dependent Lookup (ADL)

```
namespace test{
    struct Foo;
    std::ostream& operator<<(std::ostream& o, const Foo& f);
    using std::cout;
    void print(const Foo& f)
    {
        cout << f << '\n';
    }
    void print(int i)
    {
        cout << i << '\n';
    }
} // namespace test

int main()
{
    test::Foo f(17);

    print(f);
    print(17);
    test::print(17);
}
```

- The functions `test::operator<<()` and `test::print(const Foo&)` are found through ADL.
- The function `test::print(int)` is not found.
- unless `using test::print`.

Function calls and results
Returning objects by value

- A function cannot return references to local variables
  - the object is destroyed at **`return`** – *dangling reference*
- How (in)efficient is it to return objects by value (a copy)?

return value optimization (RVO)

The compiler may optimize away copies of objects on `return` from functions

- *return by value* often efficient, also for larger objects
- RVO allowed *even if the copy-constructor or destructor has side effects*
- avoid such side effects to make code portable

Rules of thumb for function parameters

- Return by value more often
- Do not over-use call-by-value

"reasonable defaults"

	cheap to copy	moderately cheap to copy	expensive to copy
In	`f(X)`	`f(const X&)`	
In/Out	`f(X&)`		
Out	`X f()`		`f(X&)`

For results, if the cost of copying is

- small, or moderate ($< 1k$, contiguous): return by value (modern copilers do RVO: return value optimization)
- large : call by reference as *out parameter*
  - or maybe allocate with **new** and return pointer

Call by reference or by value?
Rules of thumb

For passing an object to a function when

- you may want *to change the value* of the object
  - reference: `void f(T&);` or
  - pointer: `void f(T*);`
- you *will not* change it, it is *large* (or impossible to copy)
  - constant reference: `void f(const T&);`
- otherwise, *call by value*
  - `void f(T);`

reference or pointer?

- required parameter: pass reference
- optional parameter: pass pointer (can be `nullptr`)

```
void f(widget& w)
{
    use(w); //required parameter
}

void g(widget* w)
{
    if(w) use(w); //optional parameter
}
```

Call by reference or by value?

- How big is "large"?
  - more than a few *words*
- When to use out parameters?
  - prefer code that is obvious

    Example: two functions:

    ```
    void incr1(int& x)
    {
        ++x;
    }

    int incr2(int x)
    {
      return x + 1;
    }
    ```

    Use:

    ```
    int v = 0;
    ...

    incr1(v);

    ...

    v = incr2(v);
    ```

    Here it is much clearer that v = incr2(v) changes v

  - For multiple output values, consider returning a **struct**, a std::pair or a std::tuple

Rules of thumb for function parameters

- Return by value more often
- Do not over-use call-by-value

"reasonable defaults"

	cheap to copy	moderately cheap to copy	expensive to copy
In	`f(X)`	`f(const X&)`	
In/Out	`f(X&)`		
Out	`X f()`		`f(X&)`

Suggested reading

References to sections in Lippman

Exceptions	5.6, 18.1.1
Namespaces	18.2
I/O	1.2, 8.1–8.2, 17.5.2

Next lecture

References to sections in Lippman

Classes	2.6, 7.1.4, 7.1.5
Constructors	7.5–7.5.4
(Aggregate classes)	("C structs" without constructors) 7.5.5
Destructors	13.1.3
this and const	p 257–258
inline	6.5.2, p 273
friend	7.2.1
static members	7.6
Copying	13.1.1
Assignment	13.1.2
Operator overloading	14.1 – 14.3