Classes
In C++ classes are the main kind of user-defined type. Informal specification of a class definition:

```cpp
class-keyword name {
    member-specification
};
```

- `class-keyword` is either `struct` or `class`
- `name` can be any valid identifier (like for variables, functions, etc.)
- `member-specification` is a list of declarations, mainly variables (“data members”), functions (“member functions”), and types (“nested types”)
- The trailing semicolon is mandatory!
Data Members

- Declarations of data members are variable declarations
- `extern` is not allowed
- Declarations without `static` are called *non-static* data members, otherwise they are *static* data members
- `thread_local` is only allowed for static data members
- Declaration must have a *complete type* (see later slide)
- Name of the declaration must differ from the class name and must be unique within the class
- Non-static data members can have a *default value*

```cpp
struct Foo {
    // non-static data members:
    int a = 123;
    float& b;
    const char c;
    // static data members:
    static int s;
    thread_local static int t;
};
```
Memory Layout of Data Members

- Every type has a size and an alignment requirement (see last lecture)
- To be compatible between different compilers and programming languages (mainly C), the memory layout of objects of class type is fixed
- Non-static data members appear in memory by the order of their declarations
- Size and alignment of each data-member is accounted for → leads to “gaps” in the object, called *padding bytes*
- Alignment of a class type is equal to the largest alignment of all non-static data members
- Size of a class type is at least the sum of all sizes of all non-static data members and at least 1
- static data members are stored separately
Size, Alignment and Padding

struct C {
    int i;
    int* p;
    char b;
    short s;
};

sizeof(i) == 4
alignof(i) == 4
sizeof(p) == 8
alignof(p) == 8
sizeof(b) == 1
alignof(b) == 1
sizeof(s) == 2
alignof(s) == 2
sizeof(C) == 24
alignof(C) == 8

Reordering the member variables in the order p, i, s, b would lead to
sizeof(C) == 16!

In general: Order member variables by decreasing alignment to get the fewest padding bytes.
Member Functions

- Declarations of member functions are like regular function declarations
- Just like for data members, there are non-static and static (with the `static` specifier) member functions
- Non-static member functions can be `const-qualified` (with `const`) or `ref-qualified` (with `const&`, `&`, or `&&`)
- Non-static member functions can be `virtual` (see next lecture)
- There are some member functions with special functions:
  - Constructor and destructor
  - Overloaded operators

```cpp
struct Foo {
    void foo(); // non-static member function
    void cfoo() const; // const-qualified non-static member function
    void rfoo() &; // ref-qualified non-static member function
    static void bar(); // static member function
    Foo(); // Constructor
    ~Foo(); // Destructor
    bool operator==(const Foo& f); // Overloaded operator ==
};
```
Classes

Members

Accessing Members

Given the following code:

```c
struct C {
    int i;
    static int si;
};
C o; // o is variable of type C
C* p = &o; // p is pointer to o
```

the members of the object can be accessed as follows:

- non-static and static member variables and functions can be accessed with the `member-of` operator: `o.i`, `o.si`
- As a shorthand, instead of writing `(*p).i`, it is possible to write `p->i`
- Static member variables and functions can also be accessed with the `scope resolution` operator: `C::si`
Writing Member Functions

- In a non-static member function members can be accessed implicitly without using the member-of operator (preferred)
- Every non-static member function has the implicit parameter `this`
- In member functions without qualifiers and ref-qualified ones `this` has the type `C*`
- In const-qualified or const-ref-qualified member functions `this` has the type `const C*`

```cpp
struct C {
    int i;
    int foo() {
        this->i; // Explicit member access, this has type C*
        return i; // Implicit member access
    }

    int foo() const { return this->i; /* this has type const C* */ }
    int bar() & { return i; /* this (implicit) has type C* */ }
    int bar() const& { return this->i; /* this has type const C* */ }
};
```
Out-of-line Definitions

• Just like regular functions, member functions can have separate declarations and definitions.
• A member function that is defined in the class body is said to have an *inline definition*.
• A member function that is defined outside of the class body is said to have an *out-of-line definition*.
• Member functions with inline definitions implicitly have the `inline` specifier.
• Out-of-line definitions must have the same qualifiers as their declaration.

```cpp
struct Foo {
    void foo1() { /* ... */ } // Inline definition
    void foo2();
    void foo_const() const;
    static void foo_static();
};
// Out-of-line definitions
void Foo::foo2() { /* ... */ }
void Foo::foo_const() const { /* ... */ }
void Foo::foo_static() { /* ... */ }
```
Forward Declarations (1)

Classes can be *forward-declared*

- **Syntax:** `class-keyword name ;`
- Declares a class type which will be defined later in the scope
- The class name has *incomplete type* until it is defined
- The forward-declared class name may still be used in some situations (more details next)

**Use Cases**

- Allows classes to refer to each other
- Can reduce compilation time (significantly) by avoiding transitive includes of an expensive-to-compile header
- Commonly used in header files
Forward Declarations (2)

Example

```cpp
#include "expensive_header.hpp"

/* implementation */

class A;
class ClassFromExpensiveHeader;

class B {
    ClassFromExpensiveHeader* member;

    void foo(A& a);
};
class A {
    void foo(B& b);
};
```
A forward-declared class type is *incomplete* until it is defined

- In general, no operations that require the size and layout of a type to be known can be performed on an incomplete type
  - E.g. pointer arithmetics on a pointer to an incomplete type
  - E.g. Definition or call (but not declaration) of a function with incomplete return or argument type

- However, some declarations can involve incomplete types
  - E.g. pointer declarations to incomplete types
  - E.g. member function declarations with incomplete parameter types

- For details: See the reference documentation
 Constructors

- Constructors are special functions that are called when an object is *initialized*
- Constructors have no return type, no const- or ref-qualifiers, and their name is equal to the class name
- The definition of a constructor can have an *initializer list*
- Constructors can have arguments, a constructor without arguments is called *default constructor*
- Constructors are sometimes implicitly defined by the compiler

```cpp
struct Foo {
    Foo() {
        std::cout << "Hello\n";
    }
};
```

```cpp
struct Foo {
    int a;
    Bar b;
    // Default constructor is implicitly defined, does nothing with a, calls default constructor of b
};
```
Initializer List

- The initializer list specifies how member variables are initialized before the body of the constructor is executed.
- Other constructors can be called in the initializer list.
- Members should be initialized in the order of their definition.
- Members are initialized to their default value if not specified in the list.
- `const` member variables can only be initialized in the initializer list.

```cpp
struct Foo {
    int a = 123; float b; const char c;
    // default constructor initializes a (to 123), b, and c
    Foo() : b(2.5), c(7) {} // initializes a and b to the given values
    Foo(int a, float b, char c) : a(a), b(b), c(c) {}  
    Foo(float f) : Foo() {
        // First the default constructor is called, then the body
        // of this constructor is executed
        b *= f;
    }
};
```
Initializing Objects

• When an object of class type is initialized, an appropriate constructor is executed
• Arguments given in the initialization are passed to the constructor
• C++ has several types of initialization that are very similar but unfortunately have subtle differences:
  • default initialization (Foo f;)
  • value initialization (Foo f{}; and Foo())
  • direct initialization (Foo f(1, 2, 3);)
  • list initialization (Foo f{1, 2, 3};)
  • copy initialization (Foo f = g;)
• Simplified syntax: class-type identifier(arguments); or class-type identifier{arguments};
Converting and Explicit Constructors

- Constructors with exactly one argument are treated specially: They are used for *explicit* and *implicit conversions*.
- If implicit conversion with such constructors is not desired, the keyword `explicit` can be used to disallow it.
- Generally, you should use `explicit` unless you have a good reason not to.

```cpp
struct Foo {
    Foo(int i);
};
void print_foo(Foo f);
// Implicit conversion, // calls Foo::Foo(int)
print_foo(123);
// Explicit conversion, // calls Foo::Foo(int)
static_cast<Foo>(123);

struct Bar {
    explicit Bar(int i);
};
void print_bar(Bar f);
// Implicit conversion, // compiler error!
print_bar(123);
// Explicit conversion, // calls Bar::Bar(int)
static_cast<Bar>(123);
```
Copy Constructors

- Constructors of a class C that have a single argument of type C& or const C& (preferred) are called *copy constructors*
- They are often called implicitly by the compiler whenever it is necessary to copy an object
- The copy constructor is often implicitly defined by the compiler
- See more details in lecture about ownership

```cpp
struct Foo {
    Foo(const Foo& other) { /* ... */ }
};

void doFoo(Foo f);
Foo f;
Foo g(f); // Call copy constructor explicitly
doFoo(g); // Copy constructor is called implicitly
```
Destructors

• The destructor is a special function that is called when the lifetime of an object ends
• The destructor has no return type, no arguments, no const- or ref-qualifiers, and its name is \texttt{~class-name}
• For objects with automatic storage duration (e.g. local variables) the destructor is called implicitly at the end of the scope in reverse order of their definition
• Calling the destructor twice on the same object is undefined behavior

```cpp
Foo a;
Bar b;
{
    Baz c;
    // c.\texttt{~Baz() is called};
}
// b.\texttt{~Bar() is called}
// a.\texttt{~Foo() is called}
```
Writing Destructors

• The destructor is a regular function that can contain any code
• Most of the time the destructor is used to explicitly free resources
• Destructors of member variables are called automatically at the end in reverse order

```cpp
struct Foo {
    Bar a;
    Bar b;
    ~Foo() {
        std::cout << "Bye\n";
        // b.~Bar() is called
        // a.~Bar() is called
    }
};
```
Member Access Control

- Every member of a class has **public**, **protected**, or **private** access
- When the class is defined with `class`, the default access is **private**
- When the class is defined with `struct`, the default access is **public**
- **public** members can be accessed by everyone, **protected** members only by the class itself and its subclasses, **private** members only by the class itself

```cpp
class Foo {
    int a; // a is private
    public:
    // All following declarations are public
    int b;
    int getA() const { return a; }
    protected:
    // All following declarations are protected
    int c;
    public:
    // All following declarations are public
    static int getX() { return 123; }
};
```
A class body can contain *friend declarations*

- A friend declaration grants a function or another class access to the private and protected members of the class which contains the declaration
- **Syntax:** `friend function-declaration ;`
  - Declares a function as a friend of the class
- **Syntax:** `friend function-definition ;`
  - Defines a non-member function and declares it as a friend of the class
- **Syntax:** `friend class-specifier ;`
  - Declares another class as a friend of this class

Notes

- Friendship is non-transitive and cannot be inherited
- Access specifiers have no influence on friend declarations (i.e. they can appear in `private:` or `public:` sections)
Example

class A {
    int a;
    friend class B;
    friend void foo(A&);
};
class B {
    friend class C;
    void foo(A& a) {
        a.a = 42;  // OK
    }
};
class C {
    void foo(A& a) {
        a.a = 42;  // ERROR
    }
};
void foo(A& a) {
    a.a = 42;  // OK
}
Nested Types

- For nested types classes behave just like a namespace
- Nested types are accessed with the scope resolution operator ::
- Nested types are friends of their parent

```cpp
struct A {
    struct B {
        int getI(const A& a) {
            return a.i; // OK, B is friend of A
        }
    };
    private:
    int i;
};
Foo::Bar b; // reference nested type Bar of class Foo
```
Constness of Member Variables

- Accessing a member variable through a *non-const lvalue* yields a *non-const lvalue* if the member is non-const and a *const lvalue* otherwise.
- Accessing a member variable through a *const lvalue* yields a *const lvalue*.
- Exception: Member variables declared with `mutable` yield a *non-const lvalue* even when accessed through a *const lvalue*.

```cpp
struct Foo {
    int i;
    const int c;
    mutable int m;
};
Foo& foo = /* ... */;
const Foo& cfoo = /* ... */;
```

<table>
<thead>
<tr>
<th>Expression</th>
<th>Value Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>foo.i</td>
<td>non-const lvalue</td>
</tr>
<tr>
<td>foo.c</td>
<td>const lvalue</td>
</tr>
<tr>
<td>foo.m</td>
<td>non-const lvalue</td>
</tr>
<tr>
<td>cfoo.i</td>
<td>const lvalue</td>
</tr>
<tr>
<td>cfoo.c</td>
<td>const lvalue</td>
</tr>
<tr>
<td>cfoo.m</td>
<td>non-const lvalue</td>
</tr>
</tbody>
</table>
Constness and Member Functions

- The value category through which a non-static member function is accessed is taken into account for overload resolution
- For \textit{non-const lvalues} non-const overloads are preferred over const ones
- For \textit{const lvalues} only const-(ref-)qualified functions are selected

```
struct Foo {
    int getA() { return 1; }
    int getA() const { return 2; }
    int getB() & { getA(); }
    int getB() const& { getA(); }
    int getC() const { getA(); }
    int getD() { return 3; }
};

Foo& foo = /* ... */;
const Foo& cfoo = /* ... */;
```

<table>
<thead>
<tr>
<th>Expression</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>foo.getA()</td>
<td>1</td>
</tr>
<tr>
<td>foo.getB()</td>
<td>1</td>
</tr>
<tr>
<td>foo.getC()</td>
<td>2</td>
</tr>
<tr>
<td>foo.getD()</td>
<td>3</td>
</tr>
<tr>
<td>cfoo.getA()</td>
<td>2</td>
</tr>
<tr>
<td>cfoo.getB()</td>
<td>2</td>
</tr>
<tr>
<td>cfoo.getC()</td>
<td>2</td>
</tr>
<tr>
<td>cfoo.getD()</td>
<td>error</td>
</tr>
</tbody>
</table>


Casting and CV-qualifiers

• When using `static_cast`, `reinterpret_cast`, or `dynamic_cast` (see next lecture), cv-qualifiers cannot be “casted away”
• `const_cast` must be used instead
• Syntax: `const_cast < new_type > ( expression )`
• `new_type` may be a pointer or reference to a class type
• `expression` and `new_type` must have same type ignoring their cv-qualifiers
• The result of `const_cast` is a value of type `new_type`
• Modifying a const object through a non-const access path is undefined behavior!

```cpp
struct Foo {
  int a;
};
const Foo f{123};
Foo& fref = const_cast<Foo&>(f); // OK, cast is allowed
int b = fref.a; // OK, accessing value is allowed
fref.a = 42; // undefined behavior
```
Use Cases for `const_cast`

Most common use case of `const_cast`: Avoid code duplication in member function overloads.

- A class may contain a const and non-const overload of the same function with identical code
- Should only be used when absolutely necessary (i.e. not for simple overloads)

```cpp
class A {
    int* numbers;
    int& foo() {
        int i = /* ... */;
        // do some incredibly complicated computation to
        // get a value for i
        return numbers[i]
    }
    const int& foo() const {
        // OK as long as foo() does not modify the object
        return const_cast<A*>(this)->foo();
    }
};
```
Operator Overloading

- Classes can have special member functions to overload built-in operators like +, ==, etc.
- Many overloaded operators can also be written as non-member functions
- Syntax: `return-type operator op (arguments)`
- Overloaded operator functions are selected with the regular overload resolution
- Overloaded operators are not required to have meaningful semantics
- Almost all operators can be overloaded, exceptions are: :: (scope resolution), . (member access), .* (member pointer access), ?: (ternary operator)
- This includes “unusual” operators like: = (assignment), () (call), * (dereference), & (address-of), , (comma)
Binary Arithmetic and Relational Operators

The expression $lhs \ op \ rs$ is mostly equivalent to

\[ lhs.\text{operator} \ op(\text{\emph{rhs}}) \] or

\[ \text{operator} \ op(lhs, \ rhs) \] for binary operators.

- As calls to overloaded operators are treated like regular function calls, the
  overloaded versions of || and && lose their special behaviors
- Relational operators usually take their arguments by const reference

```cpp
struct Int {
    int i;
    Int operator+(const Int& other) const { return Int{i + other.i}; }
};
bool operator==(const Int& a, const Int& b) const { return a.i == b.i; }

Int a{123}; Int b{456};
a + b; /* is equivalent to */ a.operator+(b);
a == b; /* is equivalent to */ operator==(a, b);
```
C++ also has the unary `+` and `−` operators which can also be overloaded with member functions.

```cpp
struct Int {
    int i;
    Int operator+() const { return *this; }
    Int operator-() const { return Int{-i}; }
};

Int a{123};
+a; /* is equivalent to */ a.operator+();
-a; /* is equivalent to */ a.operator-();
```
Increment and Decrement Operators

Overloaded pre- and post-increment and -decrement operators are distinguished by an (unused) `int` argument.

- `C& operator++(); C& operator--();` overloads the pre-increment or -decrement operator, usually modifies the object and then returns `*this`
- `C operator++(int); C operator--(int);` overloads the post-increment or -decrement operator, usually copies the object before modifying it and then returns the unmodified copy

```cpp
struct Int {
    int i;
    Int& operator++() { ++i; return *this; }
    Int operator--(int) { Int copy{*this}; --i; return copy; }
};
Int a{123};
++a; // a.i is now 124
a++; // ERROR: post-increment is not overloaded
Int b = a--; // b.i is 124, a.i is 123
--b; // ERROR: pre-decrement is not overloaded
```
Subscript Operator

Classes that behave like containers or pointers usually override the \textit{subscript operator} \texttt{[]}.

- \texttt{a[b]} is equivalent to \texttt{a.operator[]}(b)
- Type of \texttt{b} can be anything, for array-like containers it is usually \texttt{size_t}

```cpp
struct Foo { /* ... */ };  
struct FooContainer {
    Foo* fooArray;
    Foo& operator[](size_t n) { return fooArray[n]; } 
    const Foo& operator[](size_t n) const { return fooArray[n]; } 
};
```
### Dereference Operators

Classes that behave like pointers usually override the operators `*` (dereference) and `->` (member of pointer).

- **operator** `*()` usually returns a reference
- **operator** `->()` should return a pointer or an object that itself has an overloaded `->` operator

```cpp
struct Foo { /* ... */ };
struct FooPtr {
    Foo* ptr;
    Foo& operator*() { return *ptr; }
    const Foo& operator*() const { return *ptr; }
    Foo* operator->() { return ptr; }
    const Foo* operator->() const { return ptr; }
};
```
Assignment Operators

- The simple assignment operator is often used together with the copy constructor and should have the same semantics (see also: future lecture about copy and move semantics)
- All assignment operators usually return `*this`

```cpp
struct Int {
    int i;
    Foo& operator=(const Foo& other) { i = other.i; return *this; }
    Foo& operator+=(const Foo& other) { i += other.i; return *this; }
};

Foo a{123};
a = Foo{456}; // a.i is now 456
a += Foo{1}; // a.i is now 457
```
Conversion Operators

A class C can use converting constructors to convert values of other types to type C. Similarly, conversion operators can be used to convert objects of type C to other types.

Syntax: operator type ()
- Conversion operators have the implicit return type type
- They are usually declared as const
- The explicit keyword can be used to prevent implicit conversions
- Explicit conversions are done with static_cast
- operator bool() is usually overloaded to be able to use objects in an if statement

```cpp
struct Int {
    int i;
    operator int() const {
        return i;
    }
};
Int a{123};
int x = a; // OK, x is 123

struct Float {
    float f;
    explicit operator float() const {
        return f;
    }
};
Float b{1.0};
float y = b; // ERROR, implicit conversion
float y = static_cast<float>(b); // OK
```
Argument-Dependent Lookup

- Overloaded operators are usually defined in the same namespace as the type of one of their arguments
- Regular unqualified lookup would not allow the following example to compile
- To fix this, unqualified names of functions are also looked up in the namespaces of all arguments
- This is called Argument Dependent Lookup (ADL)

```cpp
namespace A { class X {}; X operator+(const X&, const X&); } 
int main() {
    A::X x, y;
    operator+(x, y); // Need operator+ from namespace A
    A::operator+(x, y); // OK
    x + y; // How to specify namespace here?
    // -> ADL finds A::operator+()
}
```
Defaulted Member Functions

- Most of the time the implementation of default constructors, copy constructors, copy assignment operators, and destructors is trivial
- To let the compiler generate the trivial implementation automatically, `= default;` can be used instead of a function body

```cpp
struct Foo {
    Bar b;
    Foo() = default; /* equivalent to: */ Foo() {}
    ~Foo() = default; /* equivalent to: */ ~Foo() {}

    Foo(const Foo& f) = default;
    /* equivalent to: */
    Foo(const Foo& f) : b(f.b) {}

    Foo& operator=(const Foo& f) = default;
    /* equivalent to: */
    Foo& operator=(const Foo& f) {
        b = f.b; return *this;
    }
};
```
Deleted Member Functions

- Sometimes, implicitly generated constructors or assignment operators are not wanted
- Writing `= delete;` instead of a function body explicitly forbids implicit definitions
- In other cases the compiler implicitly deletes a constructor in which case writing `= default;` enables it again

```cpp
struct Foo {
    Foo(const Foo&) = delete;
};
Foo f; // Default constructor is defined implicitly
Foo g(f); // ERROR: copy constructor is deleted
```
Other User-Defined Types
Other User-Defined Types

Unions

- In addition to regular classes declared with `class` or `struct`, there is another special class type declared with `union`
- In a union only one member may be “active”, all members use the same storage
- Size of the union is equal to size of largest member
- Alignment of the union is equal to largest alignment among members
- Strict aliasing rule still applies with unions!
- Most of the time there are better alternatives to unions, e.g. `std::array<char, N>` or `std::variant`

```cpp
union Foo {
    int a;
    double b;
};
sizeof(Foo) == 8;
alignof(Foo) == 8;
```

```cpp
Foo f; // No member is active
f.a = 1; // a is active
std::cout << f.b; // Undefined behavior!
f.b = 12.34; // Now, b is active
std::cout << f.b; // OK
```
Enums

- C++ also has user-defined enumeration types
- Typically used like integral types with a restricted range of values
- Also used to be able to use descriptive names instead of “magic” integer values
- Syntax: `enum-key name { enum-list };`
- `enum-key` can be `enum, enum class,` or `enum struct`
- `enum-list` consists of comma-separated entries with the following syntax: 
  `name [ = value ]`
- When `value` is not specified, it is automatically chosen starting from 0

```cpp
enum Color {
    Red, // Red == 0
    Blue, // Blue == 1
    Green, // Green == 2
    White = 10,
    Black, // Black == 11
    Transparent = White // Transparent == 10
};
```
Using Enum Values

- Names from the enum list can be accessed with the scope resolution operator
- When `enum` is used as keyword, names are also introduced in the enclosing namespace
- Enums declared with `enum` can be converted implicitly to `int`
- Enums can be converted to integers and vice versa with `static_cast`
- `enum class` and `enum struct` are equivalent
- Guideline: Use `enum class` unless you have a good reason not to

```
Color::Red; // Access with scope resolution operator
Blue; // Access from enclosing namespace
int i = Color::Green; // i == 2, implicit conversion
int j = static_cast<int>(Color::White); // j == 10
Color c = static_cast<Color>(11); // c == Color::Black
```
Type Aliases

- Names of types that are nested deeply in multiple namespaces or classes can become very long
- Sometimes it is useful to declare a nested type that refers to another, existing type
- For this type aliases can be used
- Syntax: `using name = type;`
- `name` is the name of the alias, `type` must be an existing type
- For compatibility with C type aliases can also be defined with `typedef` with a different syntax but this should never be used in modern C++ code

```cpp
namespace A::B::C { struct D { struct E {}; }; }
using E = A::B::C::D::E;
E e; // e has type A::B::C::D::E
struct MyContainer {
    using value_type = int;
};
MyContainer::value_type i = 123; // i is an int
```
Common Type Aliases

In C++ the following aliases are defined in the std namespace and are commonly used:

- **intN_t**: Integer types with exactly N bits, usually defined for 8, 16, 32, and 64 bits
- **uintN_t**: Similar to intN_t but unsigned
- **size_t**: Used by the standard library containers everywhere a size or index is needed, also result type of sizeof and alignof
- **uintptr_t**: An integer type that is guaranteed to be able to hold all possible values that result from a reinterpret_cast from any pointer
- **intptr_t**: Similar to uintptr_t but signed
- **ptrdiff_t**: Result type of expressions that subtract two pointers
- **max_align_t**: Type which has alignment as least as large as all other scalar types