

Modern C++ Programming

10. OBJECT-ORIENTED PROGRAMMING II

POLYMORPHISM AND OPERATOR OVERLOADING

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Polymorphism

Polymorphism

Polymorphism

Polymorphism (meaning “having multiple forms”) is the capability of an entity of *mutating* its behavior in accordance with the specific usage *context*

Polymorphism dispatch can be implemented at

- **Compile-time** (static polymorphism): when the called instance is known before the program start
- **Run-time** (dynamic polymorphism): when the called instance is known only during the execution, i.e. depends on run-time values

In C++, the term **polymorphic** is strongly associated with dynamic polymorphism (*overriding*)

Function Binding

Connecting the function call to the function body is called *Binding*

- In **Early Binding** or *Static Binding* or *Compile-time Binding*, the compiler identifies the type of object at compile-time
 - the program can jump directly to the function address
- In **Late Binding** or *Dynamic Binding* or *Run-time binding*, the run-time identifies the type of object at execution-time and *then* matches the function call with the correct function definition
 - the program has to read the address held in the pointer and then jump to that address (less efficient since it involves an extra level of indirection)

C++ achieves **late binding** by declaring a **virtual** function

Polymorphism Forms

- **Ad-hoc polymorphism:** when it involves to a set of individually specified types, e.g. function overloading

```
void f(int);  
void f(double);
```

- *Parametric polymorphism:* when it involves generic types, e.g. templates

```
template<typename T>  
void f(T);
```

- *Subtyping:* when it operates on elements of subtypes, e.g. virtual functions

```
// B : A  
void f(A*); // also works for B if the called function are virtual
```

- *Preprocessing*

```
#define ADD(x, y) x + y // ADD(3, 4) or ADD(3.0, 4.0)
```

- *Function/Operator overloading*

```
void f(int);  
void f(double);
```

- *Templates*

```
template<typename T>  
void f(T); // f(3) or f(3.0)
```

- *Virtual functions* (see next slides)

Mechanism	Implementation	Form
Preprocessing	static	Parametric
Function/Operator overloading	static	Ad-hoc
Template	static	Parametric
Virtual function	dynamic	Subtyping

Dynamic Polymorphism in C++

- At run-time, objects of a *base class* behave as objects of a *derived class*
- A **Base** class may define and implement polymorphic methods, and **derived** classes can **override** them, which means they provide their own implementations, invoked at run-time depending on the context

```
struct A {  
    void f() { cout << "A"; }  
};  
struct B : A {  
    void f() { cout << "B"; }  
};  
void g(A& a) { a.f(); } // accepts A and B  
                      // note: g(B&) would only accept B  
A a; B b;  
g(a);    // print "A"  
g(b);    // print "A" not "B"!!!
```

Polymorphism - virtual method

```
struct A {  
    virtual void f() { cout << "A"; }  
}; // now "f()" is virtual, evaluated at run-time  
  
struct B : A {  
    void f() override { cout << "B"; }  
    // now B::f() overrides A::f(), run-time dispatch  
    // 'virtual void f()' is also valid  
}; // 'override' is a c++11 feature, more details in the next slides  
  
void g(A& a) { a.f(); } // accepts A and B  
  
A a;  
B b;  
g(a); // print "A"  
g(b); // NOW, print "B"!!!
```

When virtual works

```
struct A {  
    virtual void f() { cout << "A"; }  
};  
  
struct B : A {  
    void f() override { cout << "B"; }  
};  
  
void f(A& a) { a.f(); } // ok, print "B"  
void g(A* a) { a->f(); } // ok, print "B"  
void h(A a) { a.f(); } // does not work with pass-by value!! print "A"  
  
B b;  
f(b); // print "B"  
g(&b); // print "B"  
h(b); // print "A" (cast to A)
```

Polymorphism Dynamic Behavior

```
struct A {
    virtual void f() { cout << "A"; }
};

struct B : A {
    void f() override { cout << "B"; }
};

A* get_object(bool selectA) {
    return (selectA) ? new A() : new B();
}

get_object(true)->f(); // print "A"
get_object(false)->f(); // print "B"
```

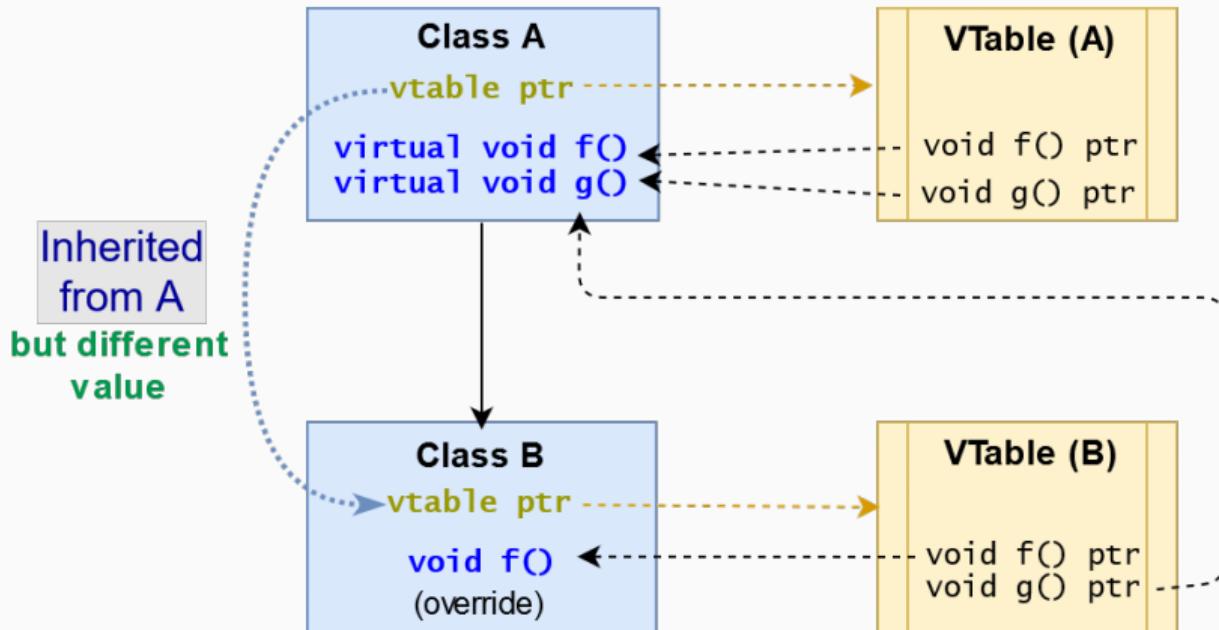
vtable

The **virtual table** (vtable) is a lookup table of functions used to resolve function calls and support *dynamic dispatch* (late binding)

A *virtual table* contains one entry for each `virtual` function that can be called by objects of the class. Each entry in this table is simply a function pointer that points to the *most-derived* function accessible by that class

The compiler adds a *hidden* pointer to the base class which points to the virtual table for that class (`sizeof` considers the vtable pointer)

```
struct A {  
    virtual void f();  
    virtual void g();  
};  
  
struct B : A {  
    void f() override;  
};
```



Does the vtable really exist? (answer: YES)

```
struct A {  
    int x = 3;  
    virtual void f() { cout << "abc"; }  
};  
  
A* a1 = new A;  
A* a2 = (A*) malloc(sizeof(A));  
  
cout << a1->x; // print "3"  
cout << a2->x; // undefined value!!  
a1->f(); // print "abc"  
a2->f(); // segmentation fault 💀
```

Lesson learned: Never use `malloc` in C++

Virtual Method Notes

`virtual` classes allocate one extra pointer (hidden)

```
struct A {  
    virtual void f1();  
    virtual void f2();  
};  
  
class B : A {};  
  
cout << sizeof(A); // 8 bytes (vtable pointer)  
cout << sizeof(B); // 8 bytes (vtable pointer)
```

override Keyword (C++11)

The `override` keyword ensures that the function is `virtual` and is overriding a `virtual` function from a base class

- It forces the compiler to check the base class to see if there is a `virtual` function with this exact signature
- `override` clearly expresses the intent of the function, making the code easier to understand

`override` implies `virtual` (`virtual` should be omitted)

```
struct A {  
    virtual void f(int a);           // a "float" value is casted to "int"  
};                                // ***  
  
struct B : A {  
    void f(int a) override;          // ok  
    void f(float a);                // (still) very dangerous!!  
};                                // ***  
  
// void f(float a) override;        // compile error not safe  
// void f(int a) const override; // compile error not safe  
};  
  
// *** f(3.3f) has a different behavior between A and B
```

final Keyword

final Keyword (C++11)

The `final` keyword prevents inheriting from classes or overriding methods in derived classes

```
struct A {  
    virtual void f(int a) final; // "final" method  
};  
  
struct B : A {  
// void f(int a); // compile error f(int) is "final"  
    void f(float a); // dangerous (still possible)  
}; // "override" prevents these errors  
  
struct C final { // cannot be extended  
};  
// struct D : C { // compile error C is "final"  
// };  
// 
```

Virtual Methods (Common Error 1)

All classes with at least one `virtual` method should declare a `virtual destructor`

```
struct A {
    ~A() { cout << "A"; }    // <-- here the problem (not virtual)
    virtual void f(int a) {}
};

struct B : A {
    int* array;
    B() { array = new int[1000000]; }
    ~B() { delete[] array; }
};

//-----
void destroy(A* a) {
    delete a;    // call ~A()
}

B* b = new B;
destroy(b); // without virtual, ~B() is not called
            // destroy() prints only "A" -> huge memory leak!!
```

Virtual Methods (Common Error 2)

Do not call virtual methods in constructor and destructor

- *Constructor:* The derived class is not ready until constructor is completed
- *Destructor:* The derived class is already destroyed

```
struct A {  
    A() { f(); } // what instance is called? "B" is not ready  
              // it calls A::f(), even though A::f() is virtual  
    virtual void f() { cout << "Explosion"; }  
};  
struct B : A {  
    B() = default; // call A(). Note: A() may be also implicit  
  
    void f() override { cout << "Safe"; }  
};  
  
B b; // call B(), print "Explosion", not "Safe"!!
```

Virtual Methods (Common Error 3)

Do not use default parameters in virtual methods

Default parameters are not inherited

```
struct A {
    virtual void f(int i = 5) { cout << "A::" << i << "\n"; }
    virtual void g(int i = 5) { cout << "A::" << i << "\n"; }
};

struct B : A {
    void f(int i = 3) override { cout << "B::" << i << "\n"; }
    void g(int i)      override { cout << "B::" << i << "\n"; }
};

A a; B b;
a.f();      // ok, print "A::5"
b.f();      // ok, print "B::3"

A& ab = b;
ab.f();    // !!! print "B::5" // the virtual table of A
           // contains f(int i = 5) and
ab.g();    // !!! print "B::5" // g(int i = 5) but it points
           // to B implementations
```

Pure Virtual Method

A **pure virtual method** is a function that must be implemented in derived classes (concrete implementation)

Pure virtual functions can have or not have a body

```
struct A {  
    virtual void f() = 0; // pure virtual without body  
    virtual void g() = 0; // pure virtual with body  
};  
void A::g() {} // pure virtual implementation (body) for g()  
  
struct B : A {  
    void f() override {} // must be implemented  
    void g() override {} // must be implemented  
};
```

A class with one *pure virtual function* cannot be instantiated

```
struct A {  
    virtual void f() = 0;  
};  
  
struct B1 : A {  
//  virtual void f() = 0; // implicitly declared  
};  
  
struct B2 : A {  
    void f() override {}  
};  
  
// A a; // "A" has a pure virtual method  
// B1 b1; // "B1" has a pure virtual method  
B2 b2; // ok
```

Abstract Class and Interface

- A class is **interface** if it has only *pure virtual* functions and optionally (*suggested*) a virtual destructor. Interfaces do not have implementation or data
- A class is **abstract** if it has at least one *pure virtual* function

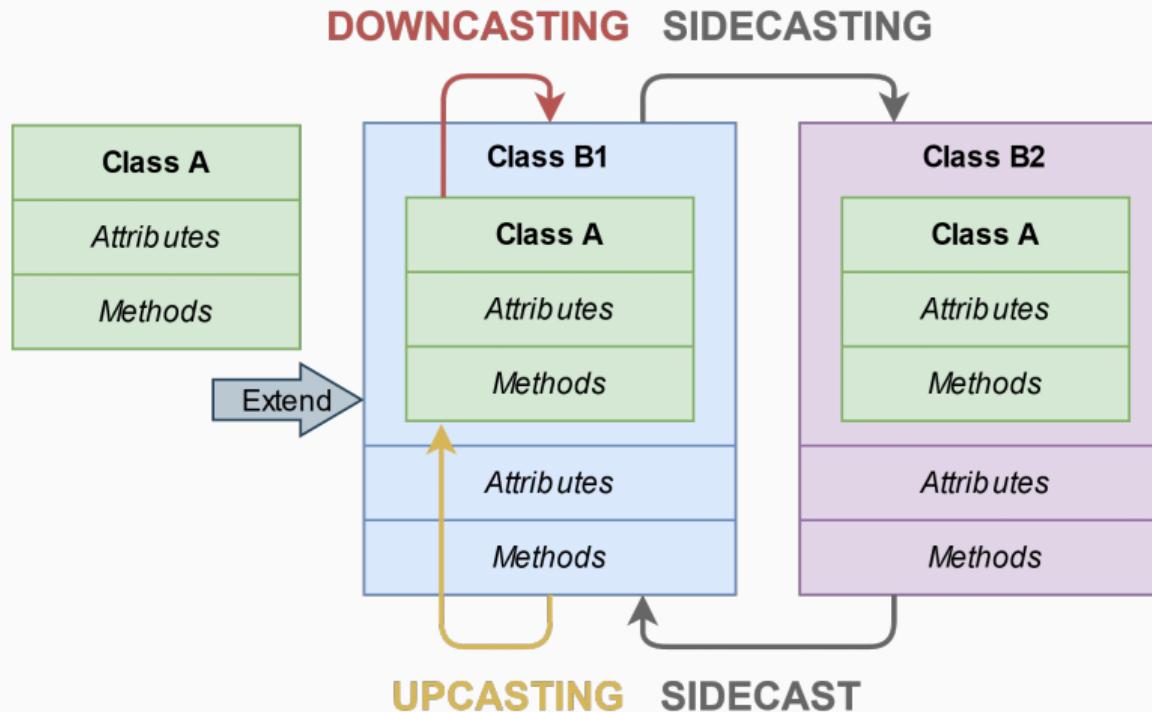
```
struct A {          // INTERFACE
    virtual ~A();  // to implement
    virtual void f() = 0;
};

struct B {          // ABSTRACT CLASS
    B() {}        // abstract classes may have a constructor
    virtual void g() = 0; // at least one pure virtual
protected:
    int x;         // additional data
};
```

Inheritance Casting and Run-time Type Identification ★

Hierarchy Casting

Class-casting allows implicit or explicit conversion of a class into another one across its hierarchy



Hierarchy Casting

Upcasting Conversion between a derived class reference or pointer to a base class

- It can be *implicit* or *explicit*
- It is safe
- `static_cast` or `dynamic_cast` // see next slides

Downcasting Conversion between a base class reference or pointer to a derived class

- It is only *explicit*
- It can be dangerous
- `static_cast` or `dynamic_cast`

Sidecasting (*Cross-cast*) Conversion between a class reference or pointer to another class of the same hierarchy level

- It is only *explicit*
- It can be dangerous
- `dynamic_cast`

Upcasting and Downcasting Example

```
struct A {  
    virtual void f() { cout << "A"; }  
};  
struct B : A {  
    int var = 3;  
    void f() override { cout << "B"; }  
};  
  
A a;  
B b;  
A& a1 = b; // implicit cast upcasting  
  
static_cast<A&>(b).f();           // print "B" upcasting  
static_cast<B&>(a).f();           // print "A" downcasting  
cout << b.var;                   // print 3 (no cast)  
cout << static_cast<B&>(a).var; // potential segfault!!! downcasting  
                                // "var" does not exist in "A"
```

Sidecasting Example

```
struct A {  
    virtual void f() { cout << "A"; }  
};  
  
struct B1 : A {  
    void f() override { cout << "B1"; }  
};  
struct B2 : A {  
    void f() override { cout << "B2"; }  
};  
  
B1 b1;  
B2 b2;  
dynamic_cast<B2&>(b1).f();      // sidecasting, throw std::bad_cast  
dynamic_cast<B1&>(b2).f();      // sidecasting, throw std::bad_cast  
// static_cast<B1&>(b2).f(); // compile error
```

Run-time Type Identification

RTTI

Run-Time Type Information (RTTI) is a mechanism that allows the type of object to be *determined at runtime*

C++ expresses RTTI through three features:

- `dynamic_cast` keyword: conversion of polymorphic types
- `typeid` keyword: identifying the exact type of object
- `type_info` class: type information returned by the `typeid` operator

RTTI is available only for classes that are *polymorphic*, which means they have *at least one virtual method*

`type_info` and `typeid`

`type_info` class has the method `name()` which returns the name of the type

```
struct A {  
    virtual void f() {}  
};  
  
struct B : A {};  
  
A a;  
B b;  
A& a1 = b; // implicit upcasting  
cout << typeid(a).name(); // print "1A"  
cout << typeid(b).name(); // print "1B"  
cout << typeid(a1).name(); // print "1B"
```

dynamic_cast

`dynamic_cast`, differently from `static_cast`, uses *RTTI* for deducing the correctness of the output type

This operation happens at run-time and it is expensive

`dynamic_cast<New>(Obj)` has the following properties:

- Convert between a derived class `Obj` to a base class `New` → *upcasting*.
`New/Obj` are both pointers or references
- Throw `std::bad_cast` if `New/Obj` are *references* and `New/Obj` cannot be converted
- Returns `NULL` if `New/Obj` are *pointers* and `New/Obj` cannot be converted

dynamic_cast Example 1

```
struct A {  
    virtual void f() { cout << "A"; }  
};  
  
struct B : A {  
    void f() override { cout << "B"; }  
};  
  
A a;  
B b;  
dynamic_cast<A&>(b).f();      // print "B" upcasting  
  
// dynamic_cast<B&>(a).f(); // throw std::bad_cast  
// wrong downcasting  
  
dynamic_cast<B*>(&a);        // returns nullptr  
// wrong downcasting
```

dynamic_cast Example 2

```
struct A {
    virtual void f() { cout << "A"; }
};

struct B : A {
    void f() override { cout << "B"; }
};

A* get_object(bool selectA) {
    return (selectA) ? new A() : new B();
}

void g(bool value) {
    A* a = get_object(value);
    B* b = dynamic_cast<B*>(a); // downcasting + check
    if (b != nullptr)
        b->f();      // executed only when it is safe
}
```

Operator Overloading

Operator Overloading

Operator Overloading

Operator overloading is a special case of polymorphism in which some *operators* are treated as polymorphic functions and have different behaviors depending on the type of its arguments

```
struct Point {  
    int x, y;  
  
    Point operator+(const Point& p) const {  
        return {x + p.x, y + p.y};  
    }  
};  
  
Point a{1, 2};  
Point b{5, 3};  
Point c = a + b; // "c" is (6, 5)
```

Operator Overloading

Category	Operators
Arithmetic	+ - * / % ++ -
Comparison	== != < <= > >= <=>
Bitwise	& ^ ~ << >>
Logical	! &&
Compound Assignment Arithmetic	+= -= *= /= %=
Compound Assignment Bitwise	>= <<= = &= ^=
Subscript	[]
Function call	()
Address-of, Reference, Dereferencing	& -> ->* *
Memory	new new[] delete delete[]
Comma	,

- Categories not in bold are rarely used in practice
- Operators that cannot be overloaded: ? . .* :: sizeof typeid

Comparison Operator operator<

Relational and comparison operators `operator<, <=, ==, >= >` are used for comparing two objects

In particular, the `operator<` is used to determine the ordering of a set of objects (e.g. sort)

```
#include <algorithm>
struct A {
    int x;

    bool operator<(A a) const {
        return x * x < a.x * a.x;
    }
};

A array[] = {5, -1, 4, -7};
std::sort(array, array + 4);
// array: {-1, 4, 5, -7}
```

C++20 allows overloading the **spaceship operator** `<=>` (also called *three-way comparison*) for replacing all comparison operators `operator<, <=, ==, >= >`

```
struct A {  
    bool operator==(const A&) const; // *** equal comparison is special,  
    bool operator!=(const A&) const; //      see next slides  
    bool operator<(const A&) const;  
    bool operator<=(const A&) const;  
    bool operator>(const A&) const;  
    bool operator>=(const A&) const;  
};  
  
// replaced by  
struct B {  
    auto operator<=>(const B&) const;  
};
```

```
struct Obj {  
    int x;  
  
    auto operator<=>(const Obj& other) const {  
        return x - other.x; // or even better "x <=> other.x"  
    }  
};  
  
Obj a{3};  
Obj b{5};  
a < b;           // true, operator< is generated  
(a <=> b) < 0; // true
```

Note: a non-defaulted `operator<=>` doesn't generate the operators `==` and `!=` (see next slide)

The compiler can also generate the code for the *spaceship operator* `= default`, even for multiple fields and arrays, by using the default comparison semantic of its members

```
struct Obj {  
    int x;  
    char y;  
    short z[2];  
  
    auto operator<=>(const Obj&) const = default;  
    // if x == other.x, then compare y  
    // if y == other.y, then compare z  
    // if z[0] == other.z[0], then compare z[1]  
};  
  
Obj a{3}, b{5};  
a == b; // false, operator== is generated (= default)  
a != b; // true, operator!= is generated (= default)
```

The *spaceship operator* returns one of following ordering (classes) `<compare>`:

std::strong_ordering

- If `a` is equivalent to `b`, `f(a)` is also equivalent to `f(b)`
- Exactly one of `<`, `==`, or `>` must be true
 - e.g., integral types (`int`, `char`)

std::weak_ordering

- If `a` is equivalent to `b`, `f(a)` may not be equivalent to `f(b)`
- Exactly one of `<`, `==`, or `>` must be true
 - e.g., rectangles `R{2, 5} == R{5, 2}`

std::partial_ordering

- If `a` is equivalent to `b`, `f(a)` may not be equivalent to `f(b)`
- `<`, `==`, or `>` may all be false
 - e.g., floating-point (`float` with `Nan`)

Subscript Operator operator[]

The **array subscript operator[]** allows accessing to an object in an array-like fashion

The operator accepts everything as parameter, not just integers

```
struct A {  
    char permutation[] {'c', 'b', 'd', 'a', 'h', 'y'};  
  
    char& operator[](char c) { // read/write  
        return permutation[c - 'a'];  
    }  
    char operator[](char c) const { // read only  
        return permutation[c - 'a'];  
    }  
};  
  
A a;  
a['d'] = 't';
```

Multidimensional Subscript Operator `operator[]`

C++23 introduces the *multidimensional subscript operator* and replaces the standard behavior of the *comma operator*

```
struct A {
    int operator[](int x) { return x; }
};

struct B {
    int operator[](int x, int y) { return x * y; } // not allowed before C++23
};

int main() {
    A a;
    cout << a[3, 4]; // return 4 (bug)
    B b;
    cout << b[3, 4]; // return 12, C++23
}
```

Function Call Operator `operator()`

The **function call operator** `operator()` is generally overloaded to create objects which behave like functions, or for classes that have a primary operation (see Basic Concepts IV lecture)

```
#include <numeric> // for std::accumulate

struct Multiply {
    int operator()(int a, int b) const {
        return a * b;
    }
};

int array[] = { 2, 3, 4 };
int factorial = std::accumulate(array, array + 3, 1, Multiply{});
cout << factorial; // 24
```

static operator() and static operator[]

C++23 introduces the `static` version of the *function call operator* `operator()` and the *subscript operator* `operator[]` to avoid passing the `this` pointer

```
#include <numeric> // for std::accumulate

struct Multiply {
    // int         operator()(int a, int b); // declaration only
    static int operator()(int a, int b); // best efficiency, no need to access
};                                         // internal data members

struct MyArray {
    // int         operator[](int x);
    static int operator[](int x);           // best efficiency
};
int array[] = { 2, 3, 4 };
int factorial = std::accumulate(array, array + 3, 1, Multiply{});
```

The **conversion operator** `operator T()` allows objects to be either implicitly or explicitly (casting) converted to another type

```
class MyBool {  
    int x;  
public:  
    MyBool(int x1) : x{x1} {}  
  
    operator bool() const { // implicit return type  
        return x == 0;  
    }  
};  
  
MyBool my_bool{3};  
bool b = my_bool; // b = false, call operator bool()
```

C++11 **Conversion operators** can be marked **explicit** to prevent implicit conversions. It is a good practice as for class constructors

```
struct A {  
    operator bool() { return true; }  
};  
  
struct B {  
    explicit operator bool() { return true; }  
};  
  
A a;  
B b;  
bool    c1 = a;  
// bool c2 = b; // compile error: explicit  
bool    c3 = static_cast<bool>(b);
```

Return Type Overloading Resolution ★

```
struct A {  
    operator float() { return 3.0f; }  
    operator int()   { return 2;     }  
};  
  
auto f() {  
    return A{};  
}  
  
float x = f();  
int   y = f();  
cout << x << " " << y; // x=3.0f, y=2
```

Increment and Decrement Operators operator++/-

The increment and decrement operators `operator++`, `operator-` are used to update the value of a variable by one unit

```
struct A {  
    int* ptr;  
    int pos;  
    A& operator++() {      // Prefix notation (++var):  
        ++ptr;             // returns the new copy of the object by-reference  
        ++pos;  
        return *this;  
    }  
    A operator++(int a) { // Postfix notation (var++):  
        A tmp = *this;     // returns the old copy of the object by-value  
        ++ptr;  
        ++pos;  
        return tmp;  
    }  
};
```

The **assignment operator** `operator=` is used to copy values from one object to another *already existing* object

```
#include <algorithm> //std::fill, std::copy
struct Array {
    char* array;
    int    size;

    Array(int size1, char value) : size{size1} {
        array = new char[size];
        std::fill(array, array + size, value);
    }
    ~Array() { delete[] array; }

    Array& operator=(const Array& x) { .... } // --> see next slide
};

Array a{5, 'o'}; // ["ooooo"]
Array b{3, 'b'}; // ["bbb"]
```

- First option:

```
Array& operator=(const Array& x) {  
    if (this == &x)           // (1) Check for self assignment  
        return *this;  
    delete[] array;          // (2) Release class resources  
    size = x.size;           // (3) Re-initialize class resources  
    array = new int[x.size];  
    std::copy(x.array, x.array + size, array); // (4) deep copy  
    return *this;  
}
```

- Second option (less intuitive):

```
Array& operator=(Array x) { // pass by-value  
    swap(*this, x);         // now we need a swap function for A  
    return *this;            // x is destroyed at the end  
}                           // --> see next slide
```

swap method:

```
friend void swap(A& x, A& y) {  
    using std::swap;  
    swap(x.size, y.size);  
    swap(x.array, y.array);  
}
```

- **why using std::swap ?** if swap(x, y) finds a better match, it will use that instead of std::swap
- **why friend ?** it allows the function to be used from outside the structure/class scope

Stream Operator operator«

The **stream operation** `operator«` can be overloaded to perform input and output for user-defined types

```
#include <iostream>

struct Point {
    int x, y;

    friend std::ostream& operator<<(std::ostream& stream,
                                         const Point& point) {
        stream << "(" << point.x << "," << point.y << ")";
        return stream;
    }
    // operator<< is a member of std::ostream -> need friend
}; // implementation and definition can be splitted (not suggested for operator<<)
Point point{1, 2};
std::cout << point; // print "(1, 2)"
```

Operators Precedence

Operators preserve precedence and **short-circuit** properties

```
struct MyInt {  
    int x;  
  
    int operator^(int exp) { // exponential  
        int ret = 1;  
        for (int i = 0; i < exp; i++)  
            ret *= x;  
        return ret;  
    }  
};  
MyInt x{3};  
int y = x^2;  
cout << y; // 9  
int z = x^2 + 2;  
cout << z; // 81 !!!
```

Binary Operators Note

Binary operators should be implemented as friend methods

```
struct A {};
struct C {};

struct B : A {
    bool operator==(const A& x) { return true; }
};

struct D : C {
    friend bool operator==(const C& x, const C& y) { return true; } // inline
};

// bool operator==(const C& x, const C& y) { return true; } // out-of-line

A a; B b; C c; D d;
b == a; // ok
// a == b; // compile error // "A" does not have == operator
c == d; // ok, use operator==(const C&, const C&)
d == c; // ok, use operator==(const C&, const C&)
```

C++ Object Layout



Overview

The term **layout** refers to how an object is arranged in memory

C++ defines four types of *layouts*:

- aggregate
- trivial copyable
- standard layout
- plain-old data (POD)

Such *layouts* are important to understand how the C++ objects interact with pure C API and for optimization purposes, e.g. pass in registers, `memcpy`, and serialization

Aggregate

An **aggregate** is an array, struct, or class which supports *aggregate initialization* (form of list-initialization) through curly braces syntax {}

- No *user-provided* constructors
- No `private / protected non-static` data members and *base class*
- No `virtual` functions
- * No base classes, until C++17
- * No *brace-or-equal-initializers* for non-static data members, until C++14
- R Apply recursively to *base classes non-static* data members

No restrictions:

- `Non-static` uninitialized (until C++14) data and function members
- `static` data and function members

```
struct Aggregate {
    int x;          // ok, public member
    int y[3];       // ok, arrays are also fine
    int z { 3 };   // only C++14

    Aggregate() = default;           // ok, defaulted constructor
    Aggregate& operator=(const& Aggregate); // ok, function
private:                           // copy-assignment
    void f() {}                  // ok, private function
};

struct NotAggregate1 {
    NotAggregate1();   // !! user-provided constructor
    virtual void f(); // !! virtual function
};

class NotAggregate2 : NotAggregate1 { // !! the base class is not an aggregate
    int         x; // !! x is private
    NotAggregate1 y; // !! y is not an aggregate (recursive property)
};
```

```
struct Aggregate1 {
    int x;
    struct Aggregate2 {
        int a;
        int b[3];
    } y;
};

int      array1[3] = {1, 2, 3};
int      array2[3] = {1, 2, 3};
Aggregate1 agg1     = {1, {2, {3, 4, 5}}};
Aggregate1 agg2     = {1, {2, {3, 4, 5}}};
Aggregate1 agg3     = {1, 2, 3, 4, 5};
```

Trivial Class

A [Trivial Class](#) is a class [trivial copyable](#) (supports `memcpy`)

Trivial copyable:

- No *user-provided* `copy/move/default` constructors, destructor, and `copy/move assignment` operators
 - No `virtual` functions
- R Apply recursively to *base classes* and `non- static` data members

No restrictions:

- *User-declared* constructors different from `copy/move/default`
- Functions or `static ,non- static` data members initialization
- `protected / private` members

```
struct NonTrivial {  
    NonTrivial();      // !! user-provided constructor  
    virtual void f(); // !! virtual function  
};  
  
struct Trivial1 {  
    Trivial1() = default; // ok, defaulted constructor  
    Trivial1(int) {}       // ok, user-default constructor  
    static int x;          // ok, static member  
    void f();              // ok, function  
  
private:  
    int z { 3 }            // ok, private and initialized  
};  
struct Trivial2 : Trivial1 { // ok, base class is trivial  
    int Trivial1[3];        // ok, array of trivials is trivial  
};
```

Standard-Layout

A [standard-layout class](#) is a class with the same memory layout of the equivalent C struct or union (useful for communicating with other languages)

- No `virtual` functions
 - Only one control access (`public` / `protected` / `private`) for all *non- static* data members
 - No base classes with *non- static* data members
 - No base classes of the same type as the first *non- static* data member
- R Apply recursively to *base* classes and *non- static* data members

```
struct StandardLayout1 {
    StandardLayout1(); // ok, user-provided constructor
    void f();         // ok, non-virtual function
};

class StandardLayout2 : StandardLayout1 {
    int x, y;        // ok, both are private
    StandardLayout1 y; // ok, 'y' is not the first data member
};

struct StandardLayout4 : StandardLayout1, StandardLayout2 {
    // ok, can use multiple inheritance as long as only
    // one class in the hierarchy has non-static data members
};
```

Plain Old Data (POD)

Plain Old Data (POD): Trivial copyable (**T**) + Standard-Layout (**S**)

- (**T**) No *user-provided* copy/move/default constructors, destructor, and copy/move assignment operators
 - (**S**) Only one control access (`public` / `protected` / `private`) for all *non- static* data members
 - (**S**) No base classes with *non- static* data members
 - (**S**) No base classes of the same type as the first *non- static* data member
 - (**T, S**) No `virtual` functions
- R Apply recursively to *base classes* and *non- static* data members

C++ std Utilities

C++11 provides three utilities to check if a type is POD, Trivial Copyable, Standard-Layout

- `std::is_pod` checks for POD, deprecated in C++20
- `std::is_trivially_copyable` checks for trivial copyable
- `std::is_standard_layout` checks for standard-layout

```
#include <type_traits>

struct A {
    int x;
private:
    int y;
};

cout << std::is_trivially_copyable_v<A>; // true
cout << std::is_standard_layout_v<A>;    // false
cout << std::is_pod_v<A>;                // false
```

Object Layout Hierarchy

