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# C++ Primer

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# What is C++?

C++ is a general-purpose programming language with a bias towards systems programming that:

- Is a better C
- Supports data abstraction (e.g., classes)
- Supports object-oriented programming (e.g., inheritance)
- Supports generic programming (e.g., reusable generic containers and algorithms)
- Supports functional programming (e.g., template metaprogramming, lambda functions)

(see the C++ Super-FAQ at https://isocpp.org/faq)

# History of C++

- Extension of C
- Early 1980s: Bjarne Stroustrup
- Supports OOP (Object Oriented Programming)
  - Objects are reusable software components (attempt to model items in the real world)
  - Object-oriented programs are easier to understand, correct, and modify
- C++ is a hybrid language
  - C-style programming
  - OOP-style
- Standardized
  ISO *International Standard ISO/IEC 14882:2014(E) – Programming Language C++*
  - Current standard: C++14
  - Working draft: C++17

# Object-oriented programming (OOP)

- OOP is a methodology for organizing data and functions
- In OOP, functions (called methods) are attached/associated with the data (objects) (whereas in procedural-based programming, functions act on data)
- In OOP, functions can only be invoked through an object
- Note: C++ allows both object-oriented and procedural programming

- OOP provides a clean interface between programmer and user
- OOP facilitates code reuse through composition/aggregation, inheritance, and polymorphism
  - Aggregation: a whole is made out of parts (but does not own the parts)
  - Composition: a whole is made out of parts (and owns the parts)
  - Inheritance: new classes inherit some of the properties and behavior of existing classes
  - Polymorphism: code/operation behaves differently in different contexts

# Roles in OOP

- Design (architect)
  Think how to solve a problem using objects (language agnostic)
- Implement
  Code C++ classes, functions, etc. (requires detailed understanding of design)
- Use
  Make use of C++ classes in user code (requires high-level understanding of design)

# C and C++ concepts

And no, I'm not a walking C++ dictionary. I do not keep every technical detail in my head at all times. If I did that, I would be a much poorer programmer. I do keep the main points straight in my head most of the time, and I do know where to find the details when I need them.

Bjarne Stroustrup

# Scope

- A scope is a region of program text
  - Global scope (outside any language construct)
  - Class scope (within a class)
  - Local scope (between { … } braces)
  - Statement scope (e.g. in a for-statement)
- A name in a scope can be seen from within its scope and within scopes nested within that scope
  - Only after the declaration of the name (“can’t look ahead” rule)
  - Class members can be used within the class before they are declared
- A scope keeps “things” local
  - Prevents my variables, functions, etc., from interfering with yours
  - Remember: real programs have **many** thousands of entities
  - Locality is good!
    - Keep names as local as possible

# Scope

```
// no r, i, or v here
class My_vector {
    vector<int> v; // v is in class scope

  public:
    int largest() // largest is in class scope
    {
        int r = 0;    // r is local
        for (int i = 0; i < v.size(); ++i) // i is in statement scope
            r = max(r, abs(v[i]));
        // no i here
        return r;
    }
    // no r here
};
// no v here
```

# Namespaces

- Address the problem of naming conflicts between different parts of the code.
- Namespaces define the context (scope) in which names (types, functions, variables) are defined:

```
// namespace.h


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

```
// namespace.cpp
#include <iostream>

namespace myscope {
  void foo() {
        std::cout << “calling my foo()” << std::endl;
  }
}
```

C++ “standard” namespace

- Calling foo() from the mycode namespace:

```
myscope::foo();
```

- Multiple namespace blocks with the same name are allowed.
- Nested namespaces are allowed (e.g., `chrono::vehicle::ChVehicle`)

# Namespaces

- using-directive: avoid explicitly prepending the namespace for all declared names:

```
#include <iostream>
using namespace std;
int main(int argc, char* argv[]) {
    foo();  // equivalent to calling myscope::foo()
}
```

- using-declaration: avoid explicitly prepending the namespace for a single name:

```
#include <iostream>
using std::cout;
using std::endl;
int main(int argc, char* argv[]) {
    cout << “Hello World!” << endl;
}
```

- Do not put ‘using namespace’ directives in header files!
  - It forces all includes of that header to use that namespace, potentially resulting in ambiguities.

# Constants

- C-style constants (using macros)

```
#define PI 3.1415926
```

- C++ style constants (using `const`)

```
const double PI = 3.1415926;
```

- New style: provides **type** and **scope**

# Pointers

- A pointer is an object whose value is the address in memory where another object is stored
- A pointer to an object of type T is denoted by T*
- A null pointer does not refer to a valid address location; null pointer value provided by the keyword `nullptr`
- Accessing the object to which a pointer refers is called dereferencing
  - Dereferencing a pointer is done with the indirection operator *
  - If p is a pointer, then *p is the object to which the pointer refers
- If x is an object of type T, then &x is the address of x (a pointer of type T*)

```
int a;
int* p = nullptr; // p is a pointer to an int
int* p1 = &a;     // p1 is a pointer to an int (and points to the address of a)
```

# References

- References are aliases (for an **already existing** object):

```
int var;
int& ref = var;
```

- From here on, `ref` is an alias for `var`. You cannot make `ref` an alias for another variable.
- References are **not** pointers.

- Note:
  - Above are so-called lvalue references
  - There is also the concept of rvalue references (used in the context of move constructors and move assignment operators)

# Parameter passing by reference

- Avoids (potentially expensive) copying

```
void swap(int& x, int& y) {
    int tmp;
    tmp = x;
    x = y;
    y = tmp;
}
```

```
// call swap() function

int a = 2;
int b = 3;

swap(a,b);
```

- Const reference parameters

```
int compare(const MyType& x, const MyType& y);
```

  - Guarantee that a function does not modify parameters passed as const references
  - Compiler-time check

# Pointers vs. references

- Both can be used to refer to some other entity (e.g., an object or a function)
- Two key differences:
  - References must refer to something; pointers can have null value (`nullptr`)
  - References cannot be rebound; pointers can be modified to point to some other entity
- References have cleaner syntax; to be used, pointers must be dereferenced
- Pointers typically require memory management (`new`/`delete`)
- Prefer using references instead of pointers, unless:
  - You need to refer to "nothing" (`nullptr`)
  - You need to change what you refer to

# Classes and objects

# Classes

- A class is a **user-defined type**
- A class specifies:
    - How objects of that type are represented (through its member variables)
    - What operations can be performed on such objects (through its member functions)
- A class can have zero or more **members**:
    - **Data** members (define the representation of objects of the class)
    - **Function** members (define operations on objects of the class)
    - **Type** members (define types associated with the class)
- The interface is the part of a class accessible to users
- The implementation of a class is the internal part of a class (accessible to users only indirectly, through the class interface)

# Class access specifiers

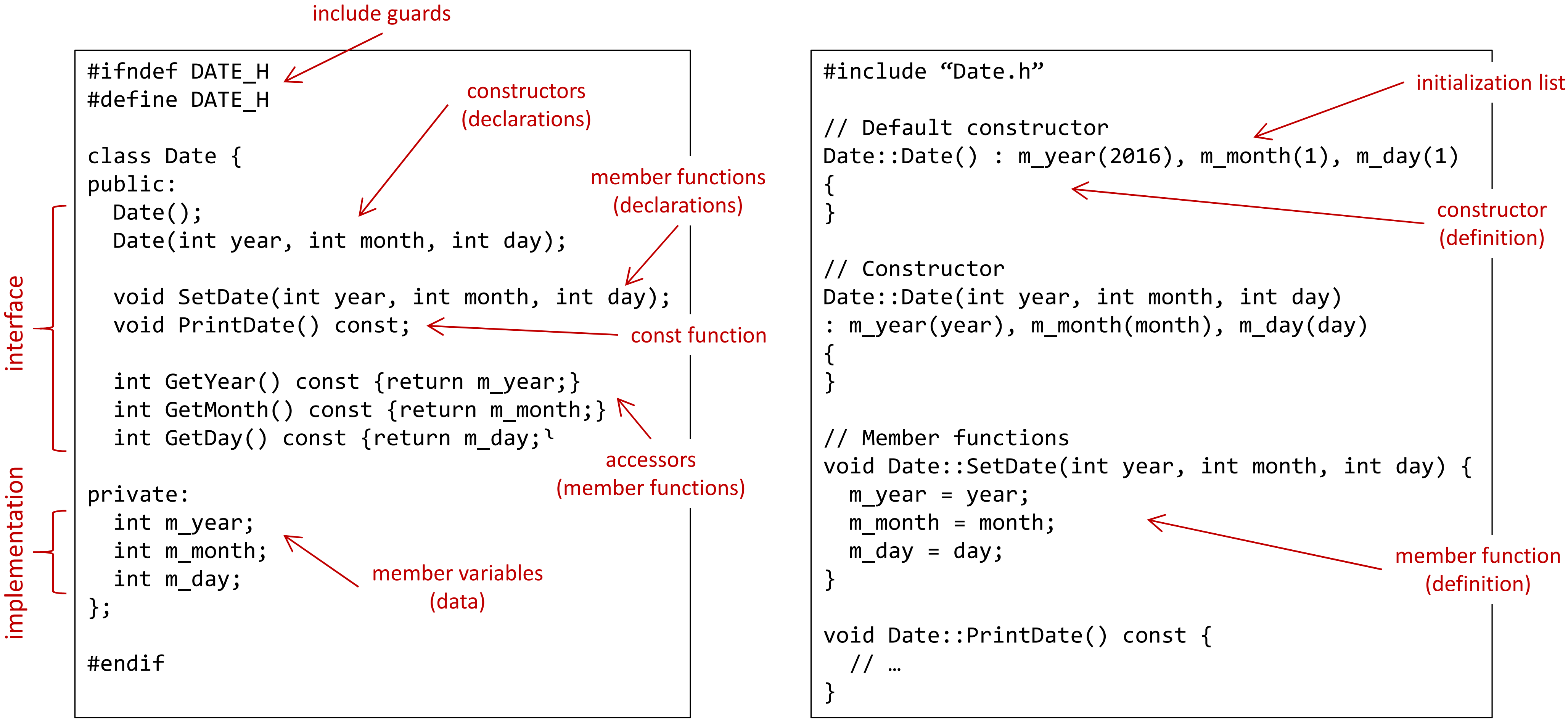
- Control the access level that users have to the class members
- There are three levels of access:
  - **public**: these members can be accessed by any code
  - **protected**: these members can be accessed by derived classes (related to inheritance)
  - **private**: these members can only be accessed by other members of the class (also by friends of the class)

- The public members constitute the class interface
- The private and protected members constitute the class implementation

# Objects

- Classes are “first-class citizens”! They have the **same standing** as all built-in types
- Objects are variables of a certain class type (instances of that class)
- Objects can be passed to functions
- The return value of a function can be an object
- You can implement type-conversion operations to automatically convert objects from one class to another
- All rules for resolving overloaded functions also apply to functions with object arguments

# Example of a class



interface

implementation

include guards

constructors (declarations)

member functions (declarations)

const function

accessors (member functions)

member variables (data)

```
#ifndef DATE_H
#define DATE_H

class Date {
public:
  Date();
  Date(int year, int month, int day);

  void SetDate(int year, int month, int day);
  void PrintDate() const;

  int GetYear() const {return m_year;}
  int GetMonth() const {return m_month;}
  int GetDay() const {return m_day;}

private:
  int m_year;
  int m_month;
  int m_day;
};

#endif
```

Date.h (header file)

initialization list

constructor (definition)

member function (definition)

```
#include “Date.h”

// Default constructor
Date::Date() : m_year(2016), m_month(1), m_day(1)
{
}

// Constructor
Date::Date(int year, int month, int day)
: m_year(year), m_month(month), m_day(day)
{
}

// Member functions
void Date::SetDate(int year, int month, int day) {
  m_year = year;
  m_month = month;
  m_day = day;
}

void Date::PrintDate() const {
  // …
}
```

Date.cpp (implementation file)

# The Date class

- `Date` is a class. It is a new **data type**
- Entities such as `today` or `election_day` are **instances** of the `Date` class and each one represents an **object** of type `Date`
- Note: class ≠ object
- `m_year, m_month, m_day` are member variables (data members)
- `SetDate()` is a member function (method)

```
#include “Date.h”

int main(int argc, char* argv[]) {
   Date today(2016, 11, 14);
   today.Print();
}
```

# Constructors and destructors

- A constructor is a member function which initializes the class.
- A constructor has
  - the same name as the class itself
  - no return type
- A class can have more than one constructor, as long as the argument lists differ.
- A constructor is called automatically whenever a new instance of a class is created.
- You must supply the arguments to the constructor when a new instance is created.
- If no constructor is specified, the compiler generates a default constructor for you.
  - may not be what you want!

# Constructors and destructors

- A destructor is a member function which deletes an object.
- A destructor function is called automatically when the object goes out of scope:
  1. the function ends
  2. the program ends
  3. a block containing temporary variables ends
  4. a *delete* operator is called
- A destructor has:
  - the same name as the class but is preceded by a tilde (~)
  - no arguments and no return value

# Constructors and destructors

```
/// Geometric object representing a piecewise cubic
/// Bezier curve in 3D.
class ChApi ChLineBezier : public ChLine {

  public:
    ChLineBezier() : m_own_data(false), m_path(NULL) {}
    ChLineBezier(ChBezierCurve* path);
    ChLineBezier(const std::string& filename);
    ChLineBezier(const ChLineBezier& source);
    ChLineBezier(const ChLineBezier* source);
    ~ChLineBezier();

    // ...
    // ...

 private:
    bool m_own_data;       ///< owns the data?
    ChBezierCurve* m_path; ///< pointer to Bezier curve
};
```

```
ChLineBezier::ChLineBezier(ChBezierCurve* path)
: m_own_data(false), m_path(path) {
    complexityU = static_cast<int>(m_path->getNumPoints());
}

ChLineBezier::ChLineBezier(const std::string& filename) {
    m_path = ChBezierCurve::read(filename);
    m_own_data = true;
    complexityU = static_cast<int>(m_path->getNumPoints());
}

ChLineBezier::ChLineBezier(const ChLineBezier& source) : ChLine(source) {
    m_path = source.m_path;
    m_own_data = false;
    complexityU = source.complexityU;
}

ChLineBezier::ChLineBezier(const ChLineBezier* source) : ChLine(*source) {
    m_path = source->m_path;
    m_own_data = false;
    complexityU = source->complexityU;
}

ChLineBezier::~ChLineBezier() {
    if (m_own_data)
        delete m_path;
}
```

# Smart pointers

C makes it easy to shoot yourself in the foot. C++ makes it harder, but when you do, you blow away your whole leg!

Bjarne Stroustrup

# Dynamic memory in C++

- Dynamic memory allocated using operator `new`
  - new is followed by a data type specifier and, if needed, the number of elements (within `[]`)
  - new returns a pointer to the beginning of the new block of memory allocated
  - new can use any variable value for size (since memory is assigned at run time)

- Dynamic memory no longer needed can be freed with the operator `delete`
  - The value passed to `delete` must be a pointer previously allocated with new or `nullptr`
  - `delete` releases memory of a single element allocated using new
  - `delete[]` releases memory allocated for arrays of elements using new and size in brackets

```
ChBody* body = new ChBody(ChMaterialSurfaceBase::DVI);
ChBody* body_array = new ChBody[5];
// ...
delete body;
delete[] body_array;
```

can only use the default constructor

# Smart pointers

- In C/C++ programming, pointers are the main source of errors and bugs
  - Memory leaks, due to how pointers interact with memory (allocation/deallocation)
  - Dangling pointer (result of failing to delete a pointer to dynamically allocated memory)
  - Corrupted free store (result of “deleting” the same memory location twice)

- Solution: use smart pointers

- RAII – Resource Acquisition Is Initialization
  - Holding a resource is tied to the object lifetime
  - Resource allocation (acquisition) is done during object creation (initialization), by the constructor
  - Resource deallocation (release) is done during object destruction, by the destructor
  - If objects are destructed properly, no resource leaks occur

# Shared pointers

- Smart pointers are essential to the RAII programming idiom
- Smart pointers are class objects that behave like built-in pointers
- Smart pointers support pointer operations:
  - dereferencing (operator *)
  - member operator (operator ->)

- Smart pointers do additional things that regular pointers do not: automatic memory management

- C++11 introduced comprehensive implementation of smart pointers
  - std::auto_ptr
  - std::shared_ptr
  - std::unique_ptr
  - std::weak_ptr

# Common construct

```
void foo() {
    myClass* p(new myClass);
    p->DoSomething();

    // ...

    delete p;
}
```

- This code will work fine (most of the time). What if somewhere in the function DoSomething() an exception gets thrown?
  - delete never gets called → memory leak

- Use of a smart pointer solves this issue because the smart pointer will be cleaned up whenever it gets out of scope (whether through normal execution or during an exception)

# std::auto_ptr

- auto_ptr is a class template (available through the C++ Standard Library header <memory>) that provides basic RAII features for C++ raw pointers

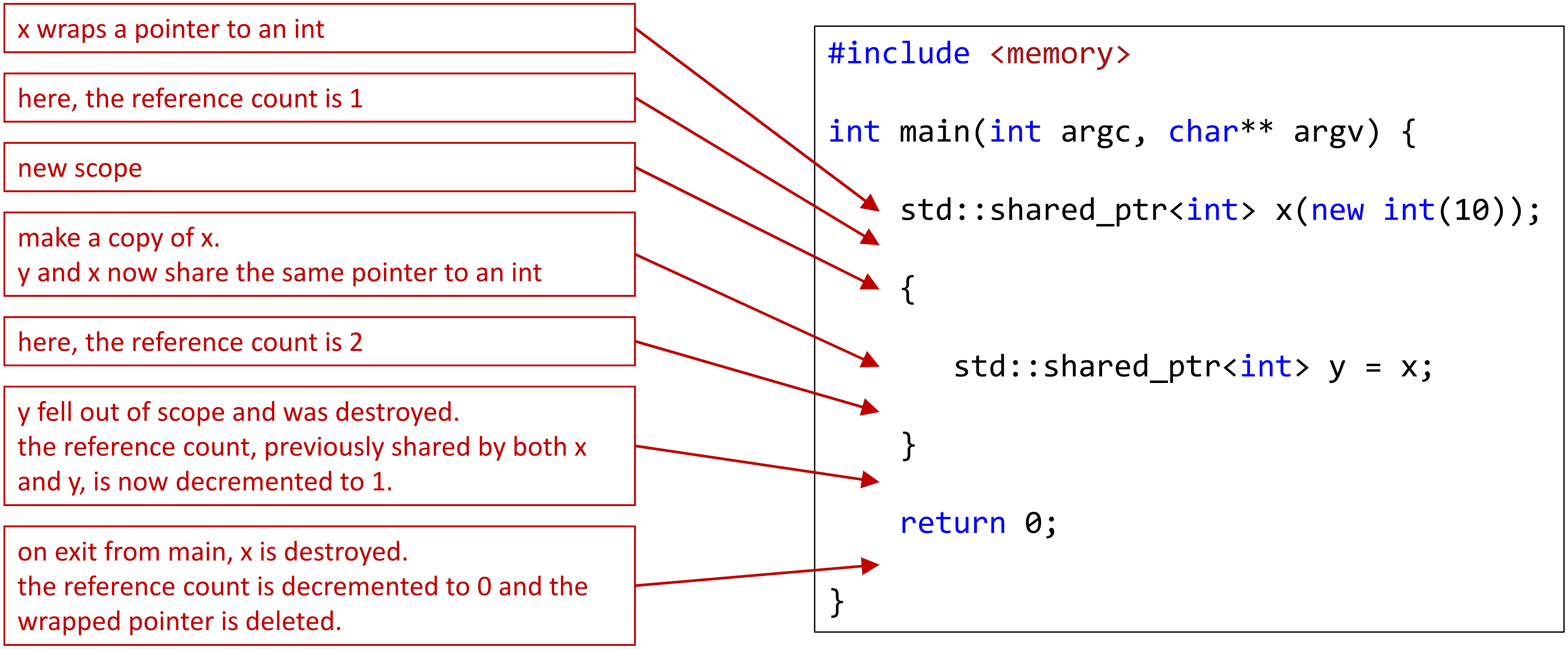
- The auto_ptr<T> template class describes an object that stores (wraps) a pointer to a single allocated object of type T* and ensures that the object to which it points is destroyed automatically when control leaves a scope

```
void foo() {
    std::auto_ptr<myClass> p(new myClass);
    p->DoSomething();

    // ...

    // ~~delete p;~~
    // p’s destructor called automatically as it goes out of scope
}
```

# std::shared_ptr

- Introduced in C++11 (together with std::unique_ptr and std::weak_ptr)
- std::shared_ptr is a smart pointer; i.e., a C++ object with overloaded dereference and indirection operators
- std::shared_ptr is a reference-counted object; i.e., it holds (wraps) a pointer to an object and a pointer to a shared reference counter
- Every time a copy of the smart pointer is made, the reference counter is incremented
- When a shared pointer is destroyed, the reference counter is decremented
- When the counter reaches zero, the managed object (the wrapped raw pointer) is deleted (its destructor is called)

# std::shared_ptr



x wraps a pointer to an int

here, the reference count is 1

new scope

make a copy of x.
y and x now share the same pointer to an int

here, the reference count is 2

y fell out of scope and was destroyed.
the reference count, previously shared by both x and y, is now decremented to 1.

on exit from main, x is destroyed.
the reference count is decremented to 0 and the wrapped pointer is deleted.

```
#include <memory>

int main(int argc, char** argv) {

    std::shared_ptr<int> x(new int(10));

    {

       std::shared_ptr<int> y = x;

    }

    return 0;

}
```

# Prefer using std::make_shared

- When creating `std::shared_ptr` objects, prefer to use **`std::make_shared`** over explicitly using **`new`** with `shared_ptr`

```
auto ball = std::make_shared<ChBody>(ChMaterialSurfaceBase::DEM);             ✓

auto ball = std::shared_ptr<ChBody>(new ChBody(ChMaterialSurfaceBase::DEM));  ✗
```

- More efficient
- Control block (reference count) and owned block (wrapped pointer) can be allocated together
- One memory allocation instead of two (better cache efficiency)
- Better exception safety (avoids resource leaks)

# std::weak_ptr & std::unique_ptr

- There are some situations where std::shared_ptr has problems (if the sharing graph has cycles, the reference counter cannot reach zero)
- std::weak_ptr can be used to break such a cycle

- std::unique_ptr is a smart pointer that models unique ownership, meaning that at any time in your program there shall be only one (owning) pointer to the pointed object
- std::unique_ptr is non-copyable

- std::weak_ptr and std::unique_ptr introduced in C++11

# Inheritance and polymorphism

# Inheritance

- Inheritance implements the “is a” relationship
- Example: Circle – Shape relationship
  - Circle is “a kind of a” Shape
  - Circle is “derived from” Shape
  - Circle is “a specialized” Shape
  - Circle is a “subclass” of Shape
  - Circle is a “derived class” of Shape
  - Shape is the “base class” of Circle
- Circle inherits properties and methods of Shape and adds its own behavior
- In C++, expressed through public inheritance:

```
class Circle : public Shape {
  public:
  // ...
};
```

# Polymorphism

- Polymorphism: a call to a member function will cause a different function to be executed depending on the object type
- Inheritance polymorphism
  - Public inheritance creates sub-types
  - Hinges crucially on the fact that a pointer to a derived class is type-compatible with a pointer to its base class
  - Typically refers to using virtual methods
- Interface polymorphism
  - Template parameters also induce a subtype relation

# Virtual functions

- Inheritance polymorphism depends on public virtual member functions
  - Base class declares a member function virtual
  - Derived classes override the base class definition of that function

- Overriding happens only if the function signatures are the same
  - Otherwise, it just overloads the function or operator name

- Without virtual: you get "early binding"
  - which method gets called is decided at compile time, based on type of pointer you call through
- With virtual: you get "late binding"
  - which method gets called is decided at run time, based on type of pointed-to object

- Use `final` (C++11) to prevent (further) overriding of a virtual method
- Use `override` (C++11) in the derived class to ensure that the signatures match
  - compiler error otherwise

# Virtual functions example

```cpp
class Animal {
public:
    void eat() { std::cout << "I'm eating generic food."; }
}

class Cat : public Animal {
public:
    void eat() { std::cout << "I'm eating a rat."; }
}
```

```cpp
Animal* animal = new Animal;
Cat* cat = new Cat;

animal->eat(); // outputs: "I'm eating generic food."
cat->eat();    // outputs: "I'm eating a rat."
```

```cpp
void func(Animal* xyz) {
    xyz->eat();
}
```

```cpp
Animal *animal = new Animal;
Cat* cat = new Cat;

func(animal); // outputs: "I'm eating generic food."
func(cat);    // outputs: "I'm eating generic food."
```

✗

```cpp
class Animal {
public:
    virtual void eat() { std::cout << "I'm eating generic food."; }
}

class Cat : public Animal {
public:
    virtual void eat() override { std::cout << "I'm eating a rat."; }
}
```

```cpp
Animal* animal = new Animal;
Cat* cat = new Cat;

animal->eat(); // outputs: "I'm eating generic food."
cat->eat();    // outputs: "I'm eating a rat."
```

```cpp
void func(Animal* xyz) {
    xyz->eat();
}
```

```cpp
Animal *animal = new Animal;
Cat* cat = new Cat;

func(animal); // outputs: "I'm eating generic food."
func(cat);    // outputs: "I'm eating a rat."
```

✓

http://stackoverflow.com/questions/2391679/why-do-we-need-virtual-functions-in-c

# Abstract Base Classes (ABCs)

- Used to implement interfaces (and cleanly separate interface from implementation)
  - At design level, an ABC corresponds to an abstract concept
  - At programming level, an ABC is a base class that contains one or more pure virtual member functions

- An ABC cannot be instantiated
  - Cannot instantiate a class that declares pure virtual functions
  - Cannot instantiate a class that inherits pure virtual functions that are not overridden

- A pure virtual function is declared with =0

```
class A {
public:
    virtual void foo() = 0;
};
```

# The C++ Standard Template Library

- The C++ STL (Standard Template Library) is a powerful set of C++ template classes to provides general-purpose templatized classes and functions that implement many popular and commonly used algorithms and data structures like vectors, lists, queues, and stacks.

- Components

| | |
|---|---|
| Containers | Containers are used to manage collections of objects of a certain kind. There are several different types of containers like deque, list, vector, map etc. |
| Algorithms | Algorithms act on containers. They provide the means by which you will perform initialization, sorting, searching, and transforming of the contents of containers. |
| Iterators | Iterators are used to step through the elements of collections of objects. These collections may be containers or subsets of containers. |

http://www.tutorialspoint.com/cplusplus/cpp_stl_tutorial.htm

```cpp
#include <iostream>
#include <vector>
using namespace std;

int main() {
    // create a vector to store int
    vector<int> vec;
    int i;

    // display the original size of vec
    cout << "vector size = " << vec.size() << endl;

    // push 5 values into the vector
    for (i = 0; i < 5; i++){
        vec.push_back(i);
    }

    // display extended size of vec
    cout << "extended vector size = " << vec.size() << endl;

    // access 5 values from the vector
    for (i = 0; i < 5; i++){
        cout << "value of vec [" << i << "] = " << vec[i] << endl;
    }

    // use iterator to access the values
    vector<int>::iterator v = vec.begin();
    while (v != vec.end()) {
        cout << "value of v = " << *v << endl;
        v++;
    }

    return 0;
}
```

push_back() – inserts value at the end of the vector, expanding its size as needed

size() – returns the size of the vector

begin() – returns an iterator to the start of the vector

end() – returns an iterator at the end of the vector

[http://www.tutorialspoint.com/cplusplus/cpp_stl_tutorial.htm](http://www.tutorialspoint.com/cplusplus/cpp_stl_tutorial.htm)

# References and Resources

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- Andrei Alexandrescu, *Modern C++ Design: Generic Programming and Design Patterns Applied*
- Andrei Alexandrescu & Herb Sutter, *C++ Coding Standards: 101 Rules, Guidelines, and Best Practices*
- Scott Meyer, *Overview of the New C++ (C++11/14)*

- The C++ super-FAQ – https://isocpp.org/faq
- C++ reference wiki – http://en.cppreference.com