C++: An Overview

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C++ Overview

- What is C++?
- Origination and Evolution of C++
- Why Use C++?
- How Does C++ Differ from Java?
- C++ and Java Minimal Examples
- Compiling C++

What is C++?

C++ is a general purpose programming language designed to make programming more enjoyable for the serious programmer.

–Bjarne Stroustrup, *The C++ Programming Language, First Edition*

What is C++ (cont'd)?

- Based on C
  - Supports procedural programming paradigm
  - Can link with compiled C code (and libraries)
  - Portable (using preprocessor)
- Adds polymorphism
  - Run-time (dynamic) binding of function calls
- Adds inheritance
  - Reuse interfaces
  - Reuse implementations

What is C++ (cont'd)?

- Adds generic code (template class) support
- Adds exception handling
- Supports large-scale programming
  - Separate compilation
  - Namespaces
  - Libraries (archives)

Origination of C++

- Designed in early 1980's by Bjarne Stroustrup of Bell Labs
- Backward compatible with C, as much as possible
  - First "compiler", *cfront*, actually translated C++ to C
- Improvements over C
  - Stronger typechecking
  - Supports data abstraction
  - Supports object-oriented programming
  - Supports generic programming

Evolution of C++

- Added namespaces, exception handling, run-time type identification (RTTI), improved templates, *etc.*
- Improved compilers
- Added Standard Template Library (STL) containers and algorithms
- Standardized by ANSI, DIN, BSI, ISO (ISO/IEC 14882)

Why Use C++?

- To maximize execution speed
- To support reuse, with separation of interface and implementation
- To support data abstraction and dynamic binding
- For portability
- For backward source compatibility with C
- For link compatibility with C, Basic, Fortran, Ada, *etc.*
- To maximize execution speed

How Does C++ Differ from Java?

- C++ programs run standalone; the Java interpreter loads and runs any class with a **main ()** method
- Can separate C++ class interface (header) from implementation (definitions)
- C++ allows multiple inheritance of implementations
- C++ supports generic programming with template classes
- C+ memory must be managed by programmer; it does not provide built-in garbage collection like Java
  – C++ pointer variables access memory
- C++ passes arguments by value, by default

How Does C++ Differ from Java? (cont'd)

- C++ arrays are not first class citizens
- C++ allows operator overloading
- C++ allows global variables, but they should be avoided
- C++ has a preprocessor; Java relies on the constrained language definition for portability
- Built-in C++ types are implementation dependent

A Stack Example

```
// File Stack.h
typedef int T;
class Stack {
public:
  Stack (size_t size);
  Stack (const Stack &s);
  void operator= (const Stack &s);
  ~Stack (void);
  void push (const T &item);
  void pop (T &item);
  int is_empty (void) const;
  int is_full (void) const;
  // ...
private:
  size_t top_;
  size_t size_;
  T *stack_;
};
```


A Stack Example (cont'd)

- Manager operations

```
Stack::Stack (size_t size)
  : top_ (0), size_ (size),
    stack_ (new T[size]) {}

Stack::Stack (const Stack &s)
  : top_ (s.top_), size_ (s.size_),
    stack_ (new T[s.size_]) {
  for (size_t i = 0; i < s.size_; i++)
    this->stack_[i] = s.stack_[i];
}

void Stack::operator= (const Stack &s) {
  if (this == &s) return;
  delete [] this->stack_;
  this->stack_ = new T[s.size_];
  this->top_ = s.top_;
  this->size_ = s.size_;
  for (size_t i = 0; i < s.size_; i++)
    this->stack_[i] = s.stack_[i];
}

Stack::~Stack (void) {
  delete [] this->stack_;
}
```

Benefits

1. Data hiding and data abstraction, *e.g.*,

```
Stack s1 (200);
s1.top_ = 10 // Error flagged by compiler!
```

2. The ability to declare multiple stack objects

```
Stack s1 (10), s2 (20), s3 (30);
```

3. Automatic initialization and termination

```
{
  // Constructor automatically called.
  Stack s1 (1000);
  // ...
  // Destructor automatically called
}
```


A Stack Example (cont'd)

- Accessor and worker operations

```
int Stack::is_empty (void) const {
  return this->top_ == 0;
}

int Stack::is_full (void) const {
  return this->top_ == this->size_;
}

void Stack::push (const T &item) {
  this->stack_[this->top_++] = item;
}

void Stack::pop (T &item) {
  item = this->stack_[--this->top_];
}
```


Drawbacks

1. Error handling is obtrusive
   - Use exception handling to solve this
2. The example is limited to a single type of stack element (**int** in this case)
   - We can use C++ templates to remove this limitation
3. Function call overhead
   - We can use C++ inline functions to remove this overhead

A Stack Example (cont'd)

- Use case

```
#include "Stack.h"
void foo (void) {
  Stack s1 (1), s2 (100);
  T item;

  if (!s1.is_full ())
    s1.push (473);
  if (!s2.is_full ())
    s2.push (2112);
  if (!s2.is_empty ())
    s2.pop (item);
  // Access violation caught
  // at compile-time!
  s2.top_ = 10;

  // Termination handled automatically
  // via destructor.
}
```

Template Implementation in C++ (cont'd)

- Note the minor changes to the code to accommodate parameterized types

```
#include "Stack.h"
void foo (void)
{
  Stack<int> s1(1000);
  Stack<float> s2(100);
  s1.push(-291);
  s2.push(3.1416);
}
```


Template Implementation in C++

- A parameterized type Stack class interface using C++

```
// typedef int T;
template <class T>
class Stack {
public:
  Stack (size_t size);
  ~Stack (void)
  void push (const T &item);
  void pop (T &item);
  int is_empty (void);
  int is_full (void);
  // ...
private:
  size_t top_;
  size_t size_;
  T *stack_;
};
```


Template Implementation in C++ (cont'd)

- Another parameterized type Stack class

```
template <class T, size_t SIZE>
class Stack {
public:
  Stack (void);
  ~Stack (void)
  void push (const T &item);
  void pop (T &item);
  // ...
private:
  size_t top_;
  size_t size_;
  T stack_[SIZE];
};
```

- To use:

```
Stack<int, 200> s1;
```


Template Implementation in C++ (cont'd)

- A parameterized type Stack class implementation using C++

```
template <class T> inline
Stack<T>::Stack (size_t size)
  : top_ (0), size_ (size),
  stack_ (new T[size]) { }

template <class T> inline
Stack<T>::~Stack (void) {
  delete [] this->stack_;
}

template <class T> inline void
Stack<T>::push (const T &item) {
  this->stack_[this->top_++] = item;
}

template <class T> inline void
Stack<T>::pop (T &item) {
  item = this->stack_[--this->top_];
}
```

C++ Object-Oriented Features

- C++ provides three characteristics generally associated with object-oriented programming:
  - *Data Abstraction*
    - Package a class abstraction so that only the *public interface* is visible and the *implementation details* are hidden from clients
    - Allow parameterization based on *type*
  - *Single and Multiple Inheritance*
    - A derived class inherits operations and attributes from one or more base classes, possibly providing additional operations and/or attributes

C++ Object-Oriented Features (cont'd)

- *Dynamic Binding*
  - The actual type of an object (and thereby its associated operations) need not be fully known until run-time
  - Compare with C++ **`template`** feature, which is handled at compile-time
- C++'s object-oriented features encourage designs that
  1. Explicitly distinguish *general properties* of related concepts from
  2. *Specific details* of particular instantiations of these concepts
- *e.g.*, an object-oriented graphical shapes library design using inheritance and dynamic binding
- This approach facilitates extensibility and reusability

Inheritance Preview

- A type can *inherit* or *derive* the characteristics of another *base* type. These derived types act just like the base type, except for an explicit list of:
  1. Operations that are implemented differently, *i.e.*, overridden
  2. Additional operations and extra data members
  3. Modified method access privileges
- C++ supports both single and multiple inheritance, *e.g.*,

```
class X { /* . . . */ };
class Y : public X { /* . . . */ };
class Z : public X { /* . . . */ };
class YZ : public Y, public Z { /* . . . */ };
```


Dynamic Binding Preview

- Dynamic binding is a mechanism used along with inheritance to support a form of *polymorphism*
- C++ uses **`virtual`** functions to implement dynamic binding:
  - The actual method called at run-time depends on the class of the object used when invoking the virtual method
- C++ allows the class definer the choice of whether to make a method virtual or not
  - This leads to time/space performance vs. flexibility tradeoffs
    - Depending on the compiler, virtual methods may introduce a small amount of overhead for each virtual function call

Object-Oriented Implementation in C++ (cont'd)

- Use interface inheritance to create a specialized (i.e., bounded) version of a stack:

```
#include "Stack.h"
#include "Array.h"

template <class T>
class B_Stack : public Stack<T>
{
public:
  B_Stack (size_t size = 100);
  virtual void push (const T &item);
  virtual void pop (T &item);
  virtual int is_empty (void) const;
  virtual int is_full (void) const;
  // ...
private:
  Array<T> stack_; // user-defined
  size_t top_; // built-in
};
```


Dynamic Binding Preview (cont'd)

```
class X { // Base class
public:
  // Non-virtual
  int m (void) {cout << "X::m";}
  // Virtual
  virtual int vm (void) {cout << "X::vm";}
};
class Y : public X { // Derived class
public:
  // Non-virtual
  int m (void) {cout << "Y::m";}
  // Virtual
  virtual int vm (void) {cout << "Y::vm";}
};

void foo (X *x) {
  x->m (); %// direct call: _m_1X (x);
  x->vm (); %// indirect call: (*x->vptr[1])
}

int main (int, char *[]) {
  X x; Y y;
  foo (&x); // X::m, X::vm
  foo (&y); // X::m, Y::vm
}
```


Object-Oriented Implementation in C++ (cont'd)

- class **B_Stack** implementation

```
template <class T>
B_Stack<T>::B_Stack (size_t size)
  : top_ (0), stack_ (size) {
}

template <class T> void
B_Stack<T>::push (const T &item) {
  this->stack_.set (this->top_++, item);
}

template <class T> void
B_Stack<T>::pop (T &item) {
  this->stack_.get (--this->top_, item);
}

template <class T> int
B_Stack<T>::is_full (void) const {
  return this->top_ >= this->stack_.size ();
}
```


Object-Oriented Implementation in C++

- Defining an abstract base class in C++

```
template <class T>
class Stack
{
public:
  virtual void push (const T &item) = 0;
  virtual void pop (T &item) = 0;
  virtual int is_empty (void) const = 0;
  virtual int is_full (void) const = 0;
  // Template method
  void top (T &item) {
    this->pop (item);
    this->push (item);
  }
};
```

- By using "pure virtual methods," we can guarantee that the compiler won't allow instantiation!

Object-Oriented Implementation in C++ (cont'd)

- Likewise, interface inheritance can create a totally different "unbounded" implementation:

```
// Forward declaration.
template <class T> class Node;
template <class T>
class UB_Stack : public Stack<T>
{
public:
  UB_Stack (size_t hint = 100);
  ˜UB_Stack (void);
  virtual void push (const T &new_item);
  virtual void pop (T &top_item);
  virtual int is_empty (void) const {
    return this->head_ == 0;
  }
  virtual int is_full (void) const { return 0; }
  // ...
private:
  // Head of linked list of Node<T>'s.
  Node<T> *head_;
};
```


Object-Oriented Implementation in C++ (cont'd)

- class **Node** implementation

```
template <class T>
class Node {
friend template <class T> class UB_Stack;
public:
  Node (T i, Node<T> *n = 0)
    : item_ (i), next_ (n) {}
private:
  T item_;
  Node<T> *next_;
};
```


Object-Oriented Implementation in C++ (cont'd)

- Class **UB_Stack** implementation:

```
template <class T>
UB_Stack<T>::UB_Stack (size_t hint): head_ (0) {}

template <class T> void
UB_Stack<T>::push (const T &item) {
  Node<T> *t = new Node<T> (item, this->head_);
  assert (t != 0);
  this->head_ = t;
}

template <class T> void
UB_Stack<T>::pop (T &top_item) {
  top_item = this->head_->item_;
  Node<T> *t = this->head_;
  this->head_ = this->head_->next_;
  delete t;
}

template <class T>
UB_Stack<T>::˜UB_Stack (void) {
  // delete all Nodes...
  for (T t; this->head_ != 0; this->pop (t))
    continue;
}
```


Function and Operator Overloading

Two or more functions or operators may be given the same name provided the *type signatures* are unique.

```
double square (double);
Complex square (const Complex &);
void move (int);
void move (int, int);
```

A function's return type is not considered when distinguishing between overloaded instances

- *e.g.*, the following declarations are ambiguous:

```
double operator/ (const Complex &, const Complex &);
complex operator/ (const Complex &, const Complex &);
```

C++ Classes

- The class is the basic data abstraction unit in C++
- The class mechanism facilitates the creation of user-defined Abstract Data Types (ADTs)
  - A class declarator defines a type comprised of data members, *as well as* method operators
    - Data members may be either *built-in* or *user-defined*
  - Classes are "cookie cutters" used to define objects
    - a.k.a. *instances*

C++ Classes (cont'd)

- For efficiency and C compatibility reasons, C++ has two *type systems*
  1. One for built-in types, *e.g.*, **`int`**, **`float`**, **`char`**, **`double`**, *etc.*
  2. One for user-defined types, *e.g.*, **`class`**es, **`struct`**s, **`union`**s, **`enum`**s, *etc.*
- Note that constructors, overloading, inheritance, and dynamic binding only apply to user-defined types
  - This minimizes surprises, but is rather cumbersome to document and explain . . .

C++ Classes (cont'd)

- General characteristics of C++ classes:
  - Any number of class objects may be defined
    - *i.e.*, objects, which have *identity*, *state*, and *behavior*
  - Class objects may be dynamically allocated and deallocated
  - Passing class objects, pointers to class objects, and references to class objects as parameters to functions are legal
  - Vectors of class objects may be defined
- A **`class`** serves the same purpose as a Java **`class`**, and a similar purpose to a C **`struct`**

Class Vector Example

- There are several significant limitations with built-in C and C++ arrays, *e.g.*,
  - The size must be a compile-time constant, *e.g.*,

```
void foo (int i) {
  int a[100], b[100]; // OK
  int c[i]; // Error!
}
```

  - Array size cannot vary at run-time
  - Legal array bounds run from 0 to *size* - 1
  - No range checking performed at run-time, *e.g.*,

```
int a[10], i;
for (i = 0; i <= 10; i++)
  a[i] = 0;
```

  - Cannot perform full array assignments, *e.g.*,

```
a = b; // Error!
```

Class Vector (Attempted) Usage

```
// File test.cpp
#include ''Vector.h''
void foo (size_t size) {
  // Call constructor
  Vector user_vec (size);
  // Error, no dynamic range
  int c_vec[size];

  c_vec[0] = 0;
  user_vec.set (0, 0);

  for (size_t i = 1;
       i < user_vec.size ();
       i++) {
    int t;
    user_vec.get (i - 1, t);
    user_vec.set (i, t + 1);
    c_vec[i] = c_vec[i - 1] + 1;
  }
```


Class Vector (Attempted) Usage (cont'd)

```
  // Error, private and protected data inaccessible
  size = user_vec.size_ - 1;
  user_vec.buf_[size] = 100;

  // Run-time error, index out of range
  if (user_vec.set (user_vec.size (), 1000) == false)
    cout << ''range error'' << endl;

  // Index out of range not detected at runtime!
  c_vec[size] = 1000;

  // Destructor called when user_vec leaves scope
}
```


Class Vector Interface

```
// File Vector.h
#ifndef VECTOR_H
#define VECTOR_H

typedef int T;
class Vector {
public:
  Vector (size_t len = 100);
  ~Vector (void);
  size_t size (void) const;

  bool set (size_t i, const T &item);
  bool get (size_t i, T &item) const;

private:
  size_t size_;
  T *buf_;
  bool in_range (size_t i) const;
};
#endif /* VECTOR_H */
```


Class Vector Implementation

```
// File Vector.cpp.
#include ''Vector.h''

bool Vector::in_range (size_t i) const
{
  return i < this->size ();
}

bool Vector::set (size_t i, const T &item) {
  if (this->in_range (i)) {
    this->buf_[i] = item;
    return true;
  }
  else return false;
}

bool Vector::get (size_t i, T &item) const {
  if (this->in_range (i)) {
    item = this->buf_[i];
    return true;
  }
  else return false;
}
```

C++ Objects

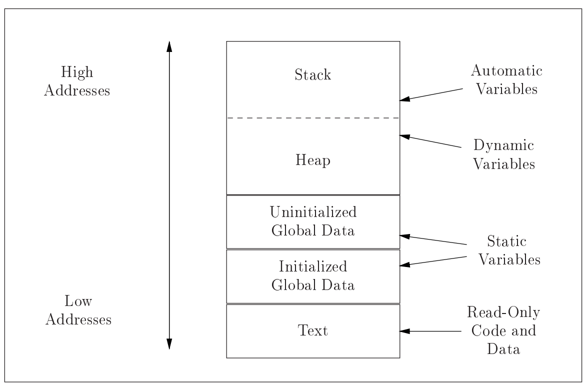
- A C++ object is an instance of a **`class`** (or any other C++ type for that matter . . .)
- An object can be instantiated or disposed either implicitly or explicitly, depending on its *life-time*
- The life-time of a C++ object is either *static*, *automatic*, or *dynamic*
  - C++ refers to this as the *storage class* of an object

C++ Objects (cont'd)

- Life-time or *storage class*:

1. *Static*
   - *i.e.*, it lives throughout life-time of process
   - *static* can be used for local, global, or class-specific objects (note, their *scope* is different)
2. *Automatic*
   - *i.e.*, it lives only during function invocation, on the *run-time stack*
3. *Dynamic*
   - *i.e.*, it lives between corresponding calls to operators **`new`** and **`delete`**
   - Dynamic objects often have life-times that extend beyond the existence of the functions that create them

C++ Objects (cont'd)



- Typical layout of memory objects in the process address space

C++ Objects (cont'd)

- Most C++ implementations do *not* support automatic garbage collection of dynamically allocated objects
  - In garbage collection schemes, the *run-time system* is responsible for detecting and deallocating unused dynamic memory
  - Note, it is very difficult to implement garbage collection correctly in C++ due to pointers and unions
- Therefore, programmers *must* explicitly deallocate objects when they want them to go away
  - C++ constructors and destructors are useful for automating certain types of memory management . . .

C++ Comments

- C++ allows two commenting styles:
  1. The traditional C bracketed comments, which may extend over any number of lines, *e.g.*, /* This is a multi-line C++ comment */
  2. The "continue until end-of-line" comment style, *e.g.*, // This is a single-line C++ or Java comment
- C-style comments do not nest. However, C++ and C styles nest, so it is possible to comment out code containing other comments, *e.g.*,

```
/* assert (i < size) // check index range */
// if (i != 0 /* check for zero divide */ && 10 / i)
```


Const Type Qualifier

- C++ data objects and methods are qualifiable with the keyword **`const`**, making them act as *read-only* objects
  - *e.g.*, placing them in the *text segment*
  - **`const`** only applies to objects, *not* to types
- Examples
  - `const int max_age = 100;`
  - `const char question = 'y';`

Const Type Qualifier (cont'd)

- User-defined **`const`** data objects:
  - A **`const`** qualifier can also be applied to an object of a user-defined type, *e.g.*,

```
const String string_constant (''Hi, I'm read-only!'');
const Complex complex_zero (0.0, 0.0);
string_constant = "This will not work!"; // ERROR
complex_zero += Complex (1.0); // ERROR
%complex_zero == Complex (0.0); // OK
```

- Ensuring *const correctness* is an important aspect of designing C++ interfaces, *e.g.*,
  1. It ensures that **`const`** objects may be passed as parameters
  2. It ensures that data members are not accidentally corrupted

Const Type Qualifier (cont'd)

- **`const`** methods of a user-defined object are read-only, *e.g.*,

```
class String {
public:
  size_t size (void) const { return this->len_; }
  void set (size_t index, char new_char);
private:
  char *array_;
  size_t len_;
};

const String string_constant (''Read-only'');
cout << string_constant.size (); // Fine
```

- Can't call a non-**`const`** function with a **`const`** object

```
string_constant.set (1, 'c'); // Error
```

Stream I/O

- C++ extends standard C library I/O with *stream* and *iostream* classes
- Several goals
  1. *Type-Security*
     - Reduce type errors for I/O on built-in and user-defined types
  2. *Extensibility* (both above and below)
     - Allow user-defined types to interoperate syntactically with existing printing facilities
     - Contrast with **printf/scanf**-family
     - Transparently add new underlying I/O devices to the iostream model
     - *i.e.*, share higher-level formatting operations

Boolean Type

- C++ has a **bool** built-in type
  - The **bool** values are called **true** and **false**
  - Converting numeric or pointer type to **bool** takes 0 to **false** and anything else to **true**
  - **bool** promotes to **int**, taking **false** to 0 and **true** to 1
  - All operators that conceptually return truth values return **bool**
    - *e.g.*, the operands of
      && || !

Type Cast Syntax

- C++ introduces a new type cast syntax in addition to Classic C style casts. This function-call syntax resembles the type conversion syntax in Ada and Java, *e.g.*,

```
// function prototype from math.h library
double log10 (double param);

/* C style type cast notation */
if ((int) log10 ((double) 7734) != 0);

// C++ function-style cast notation
if (int (log10 (double (7734))) != 7734);
```

- This "function call" is performed at compile time

Default Parameters

- C++ allows default argument values in function definitions
  - If trailing arguments are omitted in the actual function call these values are used by default, *e.g.*,

```
void assign_grade (const char *name,
                   const char *grade = ''A'');

assign_grade (''Bjarne Stroustrup'', ''C++'');
// Bjarne needs to work harder on his tasks

assign_grade (''Jean Ichbiah'');
// Jean gets an A for Ada!
```

- Default arguments are useful in situations when one must change a class without affecting existing source code
  - *e.g.*, add new params at *end* of argument list (with default values)

Default Parameters (cont'd)

- Default parameter passing semantics are similar to those in languages like Java:
  - *e.g.*, only trailing arguments may have defaults
    ```
    // Incorrect
    int x (int a = 10, char b, double c = 10.1);
    ```
  - Note, there is no support for *named parameter passing*
- However, it is not possible to omit arguments in the middle of a call, *e.g.*,
  ```
  int foo (int = 10, double = 2.03, char = 'c');

  foo (100, , 'd'); /* ERROR!!! */
  foo (1000); /* OK, calls foo (1000, 2.03, 'c');
  ```
- There are several arcane rules that permit successive redeclarations of a function, each time adding new default arguments

Declaration Statements

- C++ allows variable declarations to occur anywhere statements occur within a block
  - The motivations for this feature are:
    1. To localize temporary and index variables
    2. Ensure proper initialization
  - This feature helps prevent problems like:
    ```
    int i, j;
    /* many lines of code . . . */
    // Oops, forgot to initialize!
    while (i < j) /* . . . */;
    ```
  - Instead, you can use the following
    ```
    for (int i = x, j = y; i < j; )
      /* . . . */;
    ```