Object Oriented Programming in C++

Acknowledgements

- Lecture notes are based on material created by Andrew Ryan and Geoff Leech with minor edits by John Thangarajah, Xiangmin (Emily) Zhou and Paul Miller.

Course Details

- Instructor: *Paul Miller*
  - Email: paul.miller@rmit.edu.au
  - Please contact me either via the blackboard discussion forums or via email. Please reserve use of email to personal issues or getting help with significant amounts of code is involved.

Course Details

- All course material is offered via google drive
  - This includes:
    - Lecture Notes and lecture recordings
    - Tutorials and Laboratory Exercises - the chats will focus on the tutorial exercises whereas the labs help you get the assessed work done.
    - Assignments (also for submission!)
    - Sample Source Code
  - On blackboard you will find:
    - Discussion forum: send your questions/comments/concerns about the course there!
    - Announcements and assignment results.

Prerequisites

- This course requires you to have completed, and have an understanding of
  - Programming 1 (Java)
  - Programming in C
- A lot of knowledge is assumed, so be sure you know this.

You will also be required to pick up a fair amount of knowledge about data structures fairly early in the course. In this course we expect you to develop your own datastructures to solve a problem and for that reason, material around this is covered early.

Prerequisites

- STOP!
- It is expected that you will know
  - Basic object oriented concepts
  - Fundamentals of the C language
  - Fundamentals of the Java language
- If you are unsure of these, perhaps reconsider doing this course in another semester.
- Feel free to e-mail me to discuss your options.

Objectives of this course

- Develop object-oriented applications using the full C++ language, with
  - *Efficiency*
  - *Reliability* and *Maintainability*
- Apply the fundamental principles of object-oriented programming
  - *Encapsulation* for reliability and maintainability
  - *Inheritance* for extensibility and eliminating code duplication
  - *Polymorphism* for adaptability
- Learn how, when, and why to choose among different C++ constructs and coding techniques

Objectives of this course

- Understand the C++ runtime environment
  - And C++'s relation to other programming languages
- Use the C++ Standard Library components
  - Template containers and exceptions
  - Strings and utility classes
  - Standard IO

Assessment

- Assessment for this course is by assignments and by an examination
  - Assignment 1 (W6) is worth 20 marks
  - Assignment 2 (W12) is worth 30 marks
  - Examination is worth 50 marks

Plagiarism

- Submitting an assignment containing other people's work.
- Helping other students to plagiarise.

All submitted work must be your own.

The only exception is: other people's work can be included if the assignment has explicit instructions to do so. All copied work (from the internet, other students, or staff) must be fully referenced.

A student submitting copied work will receive **no marks** for that assignment. Partial marks will **not** be given, **even if only part** of the assignment was copied. If this means that a hurdle is not reached, then the student fails the subject.

A student who plagiarises a second time will be sent to the disciplinary committee. Penalties include failure, fines and expulsion from the university.

For more information, see "Plagiarism" on http://www.rmit.edu.au/browse;ID=p1l82w9nky8a

Guide to lecture series

- Lecture 1
  - Administration, basics of the language, input and output to screen, data types, declarations and definitions, arrays, pointers and references, flow of control.
  - C++ compilation and program structure.
- Lecture 2
  - Functions, call-by value, address and reference, Classes and objects, Object oriented concepts, visibility, Member functions, constructors, destructors
- Lecture 3
  - Standard Template Library, datastructures and algorithms

Guide to lecture series

- Lecture 4
  - Introduction to C++14

- Lecture 5

  Strings and streams, file I/O, I/O manipulators, string streams

- Lecture 6
  - Inheritance, polymorphism, is-a versus has-a, object hierarchies, abstract base classes, virtual functions and pure virtual functions

Guide to lecture series

- Lecture 7
  - Multiple inheritance, virtual base classes, protocol classes
  - Operator overloading, uses, abuses, canonical forms of operators, declaring as member functions vs declaring as free functions. Friend functions.
- Lecture 8
  - Exceptions, exception safety, exception handling, try/catch blocks, throw lists, implications of thrown exceptions.

Guide to lecture series

- Lecture 9
  - Template classes, template functions, generic programming principles, member template functions.
- Lecture 10
  - More on C++14 and Good Software Design / software development practices.

Guide to lecture series

- Lecture 11
  - Optimisation, profiling, efficiency, in-lining, memory pools
- Lecture 12
  - Where to from here? Future directions, what more can you learn?

Any questions?

- Feel free to ask questions during lectures, during breaks, on Blackboard.
- Post your questions on blackboard rather than emailing, so that all of you can share your QAs.

Bit of history - C, C++, and Other OOPLs

- C was designed in the early 1970s
  - To implement the UNIX operating system
- The design goals of C included
  - Efficiency - easy to compile to efficient machine code
  - Hardware access and flexibility - vital for implementing operating systems
  - Portability - of the language
  - Conciseness
- The design goals of C++ <u>*did not*</u> include
  - Reliability - compile and run time checks

C, C++, and Other OOPLs (cont.)

- Object Oriented Programming (OOP) predates C - Simula 67
  - But was a boutique academic area
  - Focus in the 70's was on "structured programming"
- In the 70's object-oriented and object-based languages gradually became more mainstream
  - Smalltalk and Ada
- Classes were added to a C dialect in the early 80's
  - By Bjarne Stoustrup, of Bell Laboratories
- By the early 90's, C++ was the emerging leading language for OOP
- C++'s goals included
  - Downward compatibility with C - reuse/mixing of C/C++
  - Efficiency - no loss of performance over C
  - Flexibility - to meet different programming styles

C, C++, and Other OOPLs (cont.)

- Java was a new OOP, in the mid 90’s, addressing C++’s drawbacks
  - Focus was on reliability and simplicity
  - Portability
    - Below the source level through an intermediate language - Java Byte codes and standard-sized data types
  - Complexity and additional functionality moved into libraries
    - For graphics, tasking, memory management, as appeared later with Java/J2EE
- Java’s main drawback over C/C++ was performance
  - But the J2EE library was a major productivity gain

C, C++, and Other OOPLs (cont.)

- Java had its limitations
  - Performance - x5 times slower than C/C++ even with Just In Time (JIT) compilers
  - Portability an issue
    - Assumes a Java Virtual Machine (JVM) for runtime support
    - JVMs are subtly different for each computer platform
  - No standardization
    - C++ is an international (ISO) standard
    - SUN still holds the Java standard/certification

C, C++, and Other OOPLs (cont.)

- Early in 2000 Microsoft released .NET
- .NET solved many of the problems associated with Windows software development
  - Many incompatible libraries (e.g., SDK, MFC, ATL, COM, DCOM, ActiveX) and languages (C/C++, Visual Basic)
    - Solution: a portable intermediate language - MSIL standardized through ECMA
    - All .NET languages compile into MSIL and can be mixed and matched - a Visual Basic class can inherit from a C# class
  - “DLL hell” - dynamic linking is unreliable and insecure
    - Solution: assemblies in MSIL, with builtin meta data, versioning, and security
- .NET uses a “Just In Time” (JIT) compilers
  - To overcome performance problems of intermediate languages

C, C++, and Other OOPLs (cont.)

- There is no one best OOPL, each has their strengths and application areas
  - C++ - efficient, but few standard libraries
  - .NET - limited, at present, to Windows
  - Java - portable, but performance limited

Modern software development focuses on libraries and assembling programs from reusable components rather than "coding from scratch"

Let’s start!

- Time for some C++
- We’ll start with the original “Hello, World!” example made famous by Kernighan and Ritchie.

Hello World

```
// hello world program

#include <iostream>
#include <cstdlib>

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

   std::cout << "Hello, World!" << endl;

   return EXIT_SUCCESS;

}
```

- Let’s take a look at each section in turn.

Hello World

```
// hello world program
#include <iostream>
#include <cstdlib>
```

- The first part is a comment. In C++, we can use `/*...*/` and `//` comments in the same way as we would from Java.
- `//` means anything that follows on the same line is a comment.

Hello World

- You can use `/*...*/` comments to make a comment span multiple lines, e.g.

```
/*
 * Hello world program
 */
```

Hello World

- The second part of the code example is a `#include` directive. These take the contents of another file, and automatically include them at this point.
- These files are usually called *header files*.

Hello World

- The `iostream` header file is provided with the Standard C++ Library, and gives us declarations that we can use to output data to screen, and get data from the user.
- Other header files are available for your use.
- Let’s now skip ahead a line to look at the next segment of code

Hello World

```
int main(int argc, char* argv[])
```

- This is the main function. All code begins executing in the main function.
  - Note that, unlike Java, the main function returns an `int`.
  - Moreover, the main() method is NOT inside the class; rather, it is a *global function*.
  - It also has different arguments (Java has a `String[]` as its argument list). In this code example, we don't use the arguments, although they function exactly like they would in C.

Hello World

- The actual body of code is:

```
{
    std::cout << "Hello, World!" << endl;
    return EXIT_SUCCESS;
}
```

- `std::cout` (see-out) is our console-output – the console is the screen as we see it. We use `cout` to display messages to the user. `cout` exists in the Standard C++ Library (`std`).

Hello World

- The '<<' is called the stream insertion operator.
- This operator takes the `"Hello, World!"` string that we provided, and inserts it into the `cout` stream. This is then displayed on the screen.
  - Operators can be *overloaded* (to be described in the future…!)
- The final part of the line, `endl`, is a directive to `cout` to end the line, and start a new line.
- `endl` also exists in the Standard C++ Library.

Hello World

- All objects in the Standard C++ Library exist in namespace `std`,
- We need to either provide a global using directive, or individually specify each object we intend to use, like `using std::cout;`
- If we don't specify a using directive, we can manually specify the namespace whenever we use an object.

```
std::cout << "Hello, World!" << std::endl;
```

Hello World

- The final part of the program is the return code:

```
    return EXIT_SUCCESS;
}
```

- You need to send a message to the operating system that the program succeeded or failed. This value can then be processed by scripts, etc.

Compiling our program

- To compile our programs, we use g++.

```
g++ -o helloworld hello.cpp -Wall \
     -pedantic -std=c++14
```

- Assumes file containing our program is hello.cpp.
- Note that `g++` syntax is the same as `gcc` syntax.
- `g++` is installed on most Unix/Linux systems.

Running the program

- To run the program, type the following:

```
./helloworld
```

- We can change the executable name by altering the value after the `-o` option.
- If we compile with `-g`, we can also use `gdb` to run:

```
gdb ./helloworld
```

It is expected in this course that you already know how to use gdb and valgrind.

Data types

- Now we’ll look at other data types that C++ provides.
- C++ provides the same data types as C, plus a few more.
- The following table summarises these…

Basic data types

`char`	Character
`Short`	Short integer
`int`	integer
`long`	long integer
`float`	Single-precision floating point
`double`	Double-precision floating point
`bool`	Boolean (true/false)
`#include <string>` `std::string`	String class.

Data type uses

- `char`s, `int`s, `long`s, `float`s, `double`s function the same way as they do in Java, except:
  - `char`s are only 1 byte long.
  - There are no standard sizes of most data types (other than `char`). The C rules apply here:
    - `short <= int <= long`
- The string class is part of the Standard C++ library, and isn't a POD-type (plain ol' data-type).

Example 2: Adding two `int`s

```
#include <iostream>

int main() {
  std::cout << "Enter two numbers: ";
  int i, j;
  std::cin >> i >> j;
  std::cout << "\nThe sum is: " << i+j << "\n”;
  return 0;
}
```

- Note how operators are different between `cout` and `cin`.

Declaration or definition?

```
int a;
```

- This is a declaration. “I **declare** that `a` is an `int`”. We do not provide `a` with a value.

```
a = 2;
```

- This is a definition. “I **define** `a` to be 2”.

```
int a = 2;
```

- We can combine the two. This is both a declaration and a definition.

Arrays and pointers

- C++ supports C operations with pointers, e.g.

```
int a;

int* pA = &a;
```

- Likewise, we can declare and define arrays of data types:

```
int array[100];
```

Const datatypes

- C++ has eliminated `#define`'s from C, using `const` instead:

```
const int MAX_SIZE=100;

int array[MAX_SIZE];
```

- Const data is exactly like `final` data types in Java.

```
final int MAX_SIZE=100;  // same as C++ const
```

Example 3: What's the meaning of life?

```
#include <iostream>

using namespace std;

int main() {
   const int answer = 42;
   cout << answer << " is the answer" << endl;
}
```

- `const` is used as Java `final`.
- You can associate "left-to-right" using `<<`.

Example 3 (cont): Namespaces

- The next part of the first example we'll look at is:

```
using namespace std;
```

- Namespaces are similar in idea to Java's packages. In fact, saying `using namespace std` is the same as saying `import java.lang.*` in Java.
- These are called **using directives**.

Namespaces (cont.)

```
#include <iostream>

int main() {
  using std::cin;
  std::cout << "Enter two numbers: ";
  int i, j;
  cin >> i >> j;
  using namespace std;
  cout << "\nTheir sum is: " << i+j << "\n";
  return 0;
}
```

- Note that `using` makes `cin` visible in this scope.
- Same for `using namespace`, makes `cout` visible in this scope.

Flow control

- C++ has the same flow control structures as C and Java:
  - `if` statements,
  - `do..while` loops,
  - `while` loops,
  - `for` loops, and
  - the conditional operator.

If statements

```
if (a < b) {
   //
}
else if (a < c) {
 //
}
else {
 //
}
```

..should be a familiar flow control structure!

While loop

```
while (a < b) {
 //

}
```

- Continue looping while condition is true.
- No guarantee the `while` loop will be executed. (The condition is tested **before** the loop executes).

Do…while loop

```
do {
    //
} while (a < b);
```

- Same as a `while` loop, but the condition is tested **after** the loop is executed.
- Guaranteed to execute at least once.

For loop

- The workhorse loop!

```
for (int i=0;i<MAX_SIZE;++i) {
    //
}
```

- Initialise counter to some value (`int i=0`), test a condition **before** the loop, and perform an action (`++i`) after the loop.

Conditional operator

- Great for short (and probably unreadable) code.

```
(a < b) ? 1 : 0;
```

- Is the same as:

```
if (a < b) {
    return 1;
}
else {
    return 0;
}
```

References

- References in C++ are different to references in Java.
- In C++ a reference is an alias for another object.

```
int a = 4;

int& refA = a; // refA is a ref to a

cout << refA; // outputs “4”

refA = 5; // refA is alias for a, so a is changed

cout << a; // outputs “5”
```

The C/C++ Preprocessor

- C and C++ use the same preprocessor
  - A preprocessor is run before compilation takes place
- Common preprocessor directives are: `#include`, `#define`, and `#ifdef`

```
#ifndef H_UTILITIES
#define H_UTILITIES
// A file of useful macros
#define PI 3.14159265
#define MAX(X, Y) (X > Y ? X : Y)

...

#endif
```

This idiom prevents this header file (in `utilities.h`) being included twice

An "inline function"

```
#include <iostream>
#include "utilities.h"

int main() {
  std::cout << "Enter two numbers: ";
  int i, j;
  std::cin >> i >> j;
  std::cout << "\nTheir max is: " << MAX(i, j);
  return 0;
}
```

Read in the contents of this local file

The C/C++ Preprocessor (cont.)

- `#include <xxx>` indicates a library header file
  - The `.h` file name extension is not used now in standard C++
- `#include "yyy.h"` indicates a local (project specific) header file
- `#ifdef` is used for “conditional compilation”
  - Compile flags can control what is compiled into an application
  - However, complex conditional compilation can be very hard to maintain
- `#define` is now largely obsolete as inline functions can be nightmares to maintain (consider `MAX(++i, j)`)
  - For simple constants, such as `PI` above, use a C++ const definition
  - For inline functions, such as `MAX` above, use the `inline` function modifier

Storage Allocation

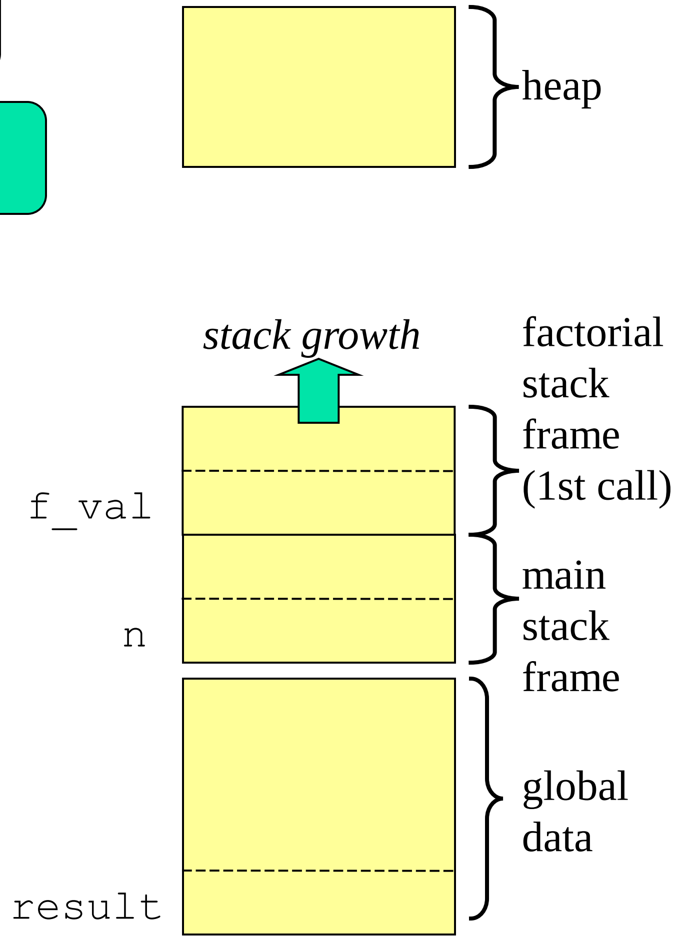
- For efficiency, C/C++ were designed around the memory model and instruction sets of computers
  - *Memory* is sequentially addressed
  - Machine instructions reference memory addresses either with
    - A *fixed* (constant) memory address
    - An *offset* address - the sum of a constant and the contents of a register
- C/C++ allocates storage in 3 areas:
  - *Global* - fixed addresses
  - *Stack* - simple offset addresses from a stack pointer register
  - *Heap* - complex offset addresses

Storage Allocation (cont.)

```
#include <iostream>

int result;
int factorial(int n) {
  int f_val = n;
  if (f_val == 1) return f_val;
  else return f_val*factorial(n-1);
}

int main() {
   std::cout << "Enter a number: ";
   int n;
   std::cin >> n;
   std::cout << "\nThe factorial is: "
          << factorial(n);
   return 0;
}
```

global data

local data



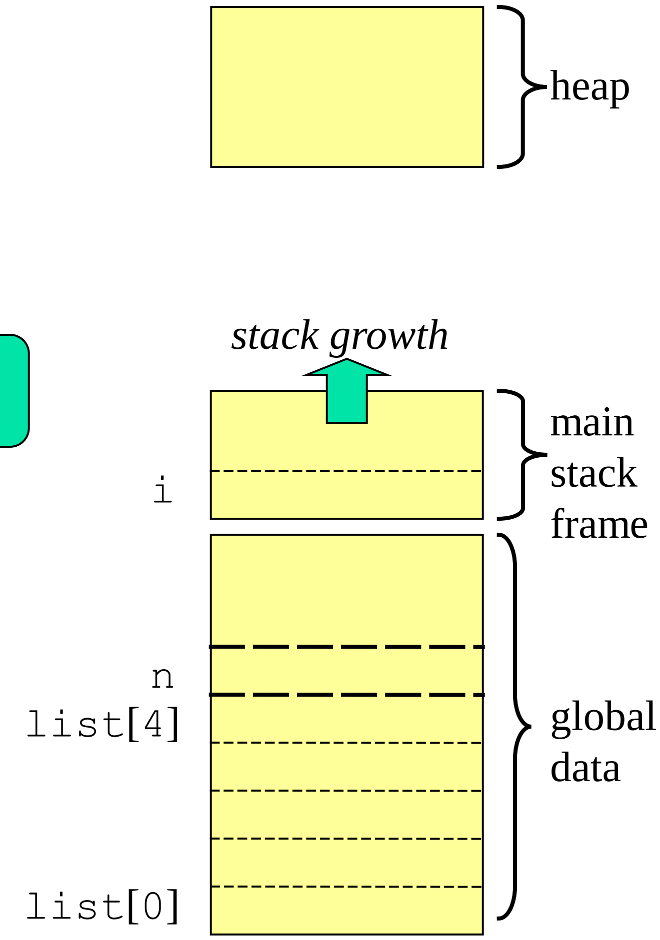
- What happens on input 3?
- What happens on input -3?

Arrays

```
#include <iostream>

const int MAX = 5;
int list[MAX];
int sum = 0;

int main() {
  std::cout << "Enter " << MAX
  <<
    " numbers: ";
  for (int i=0; i<MAX; ++i) {
    std::cin >> list[i];
    sum += list[i];
  }
  std::cout << "\nTheir sum is:
  " << sum;
  return 0;
}
```

array of 5 ints

i local to for loop



- C/C++ arrays have a fixed size
  - Declared as type `var_name[const_size]`
  - Indexed from `0` through `const_size-1`

Arrays (cont.)

- `list` points to the first element of the array
  - `list` is a **`const`** pointer to an **`int`**
  - C/C++ define array accessing as pointer arithmetic
  - `list[i]` means the same as `*(list + i)` -
    "add `i` to the address `list`, then dereference it (get the contents)"
- Because array indexing is just a shorthand for pointer arithmetic, C/C++ programs often use pointers instead of array indexing
  - The two loops below generate the same machine instructions!

```
...
for (int i=0; i<MAX; ++i) {
  std::cin >> list[i];
  sum += list[i];
}
...
```

`ip` is an int pointer: ++ increments `ip`

`*ip` gets the contents of what `ip` points to

```
...
for (int* ip=list; ip<list+MAX; ++ip) {
  std::cin >> *ip;
  sum += *ip;
}
...
```

`list+MAX == &list[MAX]`

Arrays (cont.)

- C/C++ allow a program to take the address of, or dereference, any object.
  - `&name` means "get the address of `name`"
  - `*ptr` means "get the contents of what `ptr` points to (dereference `ptr`)"

```
...
int i;
int main() {
  int* ip=&i;
  *ip = 42;
  std::cout << i;
  ...;
}
```

global variables are initialized to zero by default; local variables are initially undefined

`ip` now points to `i`

or `std::cout << *ip`

Arrays (cont.)

- There is no bounds checking on C/C++ arrays!
  - Accessing `list[-1]` or `list[MAX]` leads to "undefined" run time behaviour
  - Since storage is generally allocated sequentially, what might assigning to `list[MAX]` do?
- C/C++ arrays are unsafe and should generally be avoided. Use standard library containers instead
- C++ provides standard library containers that
  - Grow automatically as elements are added
  - Throw exceptions on access outside the container bounds
  - Check at compile time that the elements are the right type
    - Unlike Java, C++ does not provide "heterogeneous object containers"

Containers

```
#include <iostream>
#include <vector>
std::vector<int> int_input;

int main() {
  std::cout << "Enter numbers, terminate with a non-number\n";
  int num;
  int sum = 0;
  while (std::cin >> num) {
    int_input.push_back(num)
  }
  for (int i=0; i<int_input.size(); ++i) {
    sum += int_input[i];
  }
  std::cout << "\nTheir sum is: " << sum;
  return 0;
}
```

`int_input` is a *specialization* of the generic library **`template`** class `list`

`>>` is false on invalid input

`push_back` and `size` are standard container methods

Containers (cont.)

- The standard template class containers include:
- Sequences: `list`, `vector`, `deque`
  - Access to the `front` (except `vector`) and `back` via `push` and `pop`
  - Random access array indexing: **`operator`**[ ] (except for `list`)
- Associative containers: `map`, `multimap`, `set`, `multiset`
- The preferred way to traverse a container in C++ is using an *iterator*
- Similar to Java's iterator and enumeration interfaces

Containers (cont.)

`typedef` in C/C++ creates an alias for a type name

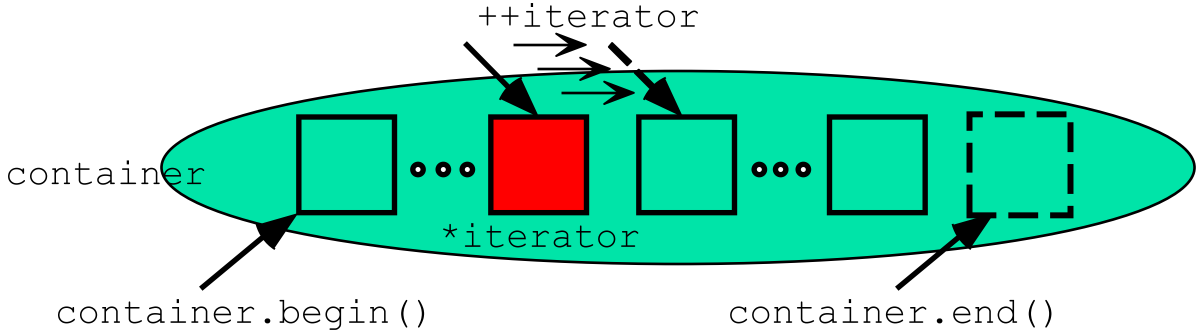
```
...
typedef std::vector<int> int_container;
int_container int_input;

int main() {
  ... // as above
  for (int_container::iterator it=int_input.begin();
       it!=int_input.end(); ++it) {
    sum += *it;
  }
  std::cout << "\nTheir sum is: " << sum;
  return 0;
}
```

Containers (cont.)

- Traversing, or *iterating*, over a container is common
  - For `vector`s, we can do this using subscripting, `[]`
  - Most containers, such as `set`, and `map`, do not support this
- An *iterator* is an object that encapsulates the state and behavior necessary to iterate over a container
- An *iterator* requires just three simple operations
  - *increment* (`operator++`) Move the iterator forward to the next object
  - *dereference* (`operator*`) Fetch the current object the iterator points to
  - *comparison* (`operator== !=`) Compare iterators

Containers (cont.)

- Container have `begin()` and `end()` functions that return iterators for use in comparisons.



Strings

- C strings are just (fixed size) arrays of `char`acters
  - Pointer arithmetic can be used with C strings as with any other array
  - C provides a very unsafe library for C string manipulation
  - However, C strings should <u>not</u> be used in C++ applications, except for literal constants

Strings (cont.)

```
#include <string.h>

int main() {
  const char* name1 = "bat";
  char name2[9] = "fruit";
  strcat(name2, name1);
  char* name3;
  strcpy(name3, name2);
  ...
}
```

"`bat`" is a *string literal* with a terminating `'\0'` thus it occupies 4 bytes of storage, not 3

concatenate "`bat`" onto "`fruit`", requires 10 bytes, so overwrite other stack storage

`name3` is unititialized, could point anywhere thus `strcpy` copies into a random location

Strings (cont.)

- C++ provides `std::string`
  - Dynamically sized strings, with a wide range of functions and operators
  - Similar to Java's `StringBuffer`

```
#include <string>
#include <iostream>
int main() {
  std::string name1 = "bat";
  std::string name2 = "fruit";
  name2 += name1; // or name2.append(name1)
  std::string name3;
  name3 = name1;
  std::cout << name3;
  ...
}
```

`std::string`'s can be constructed from `char*`'s and converted to `char*`'s

`name3` is a copy of `name1`, C++ assignment defaults to copying values <u>not</u> references

output operator overloaded for `std::string` as well as **`char*`**

  - More to be discussed later…