Program a Game Engine from Scratch

Mark Claypool

Development Checkpoint #3

Vector & Object

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4.5 The Game World

The game world itself is full of objects: bad guys running around; walls that enclose buildings and spaces; trees, rocks and other obstacles; and the hero, rushing to save the day. The exact types of objects depend upon the genre of game, of course, but in nearly all games, the game engine has many objects to manage (game objects are introduced in Section 4.5.1 on page 73).

The game world needs to store and access groups of objects. In addition, the game programmer needs to access game objects in order to make them react to input or perform game-specific functions. So, the game world needs to manage them efficiently and present them in a convenient fashion. The game programmer might want a list of all the solid game objects, a list of all the game objects within the radius of an explosion, or a list of all the Saucer objects. It is the job of the world manager to store the game objects and provide these lists in response to game programmer queries. Section 4.5.2 on page 77 introduces lists of game objects.

The game world not only stores and provides access to the game objects, it also needs to update them, move them around, see if they collide, and more. Section 4.5.4 (page 87) introduces methods to update game objects, with Section 4.5.5 (page 88) providing details on events, of vital importance for understanding how a game engine connects to game programmer code.

4.5.1 Game Objects

Game objects are a fundamental game programmer abstraction for items in the game. For example, consider Saucer Shoot from Section 3.3. As in many games, there are opponents to defeat (i.e., Saucers), the player character (i.e., the Hero), projectiles that can be launched (i.e., Bullets), and other game objects (e.g., Explosions, Points, etc.). Other games may have obstacles or boundaries to bypass (e.g., walls, doors), items that can be picked up (e.g., gold coins, health packs), and even other characters to interact with (e.g., non-player characters). The game engine needs to access all these game objects, for example, to get an object’s position. The game engine also needs to update these objects, for example, to change the location as the game object moves. Thus, a core attribute for a game object, and the first one used in Dragonfly, is the object’s position, stored as a 2d vector.

4.5.1.1 The Vector Class

The Vector class represents a 2d vector. When used for a position, the Vector is sufficient to hold a 2d location in the game world. Some future version of Dragonfly could provide a third dimension, z, and/or provide coordinates as floating point numbers. The header file for the Vector class is described in Listing 4.26. Vector mostly holds the attributes \( x \) and \( y \), with methods to get and set them. In addition to the default constructor (which set \( x \) and \( y \) to 0), on line 9, Vector has a constructor that sets \( x \) and \( y \) to initial values.

```cpp
class Vector {

Listing 4.26: Vector.h
```
private:
  float m_x; // Horizontal component.
  float m_y; // Vertical component.

public:

  // Create Vector with (x,y).
  Vector(float init_x, float init_y);

  // Default 2d (x,y) is (0,0).
  Vector();

  // Get/set horizontal component.
  void setX(float new_x);
  float getX() const;

  // Get/set vertical component.
  void setY(float new_y);
  float getY() const;

  // Set horizontal & vertical components.
  void setXY(float new_x, float new_y);

  // Return magnitude of vector.
  float getMagnitude() const;

  // Normalize vector.
  void normalize();

  // Scale vector.
  void scale(float s);

  // Add two Vectors, return new Vector.
  Vector operator+(const Vector &other) const;
};

To make a Vector more generally useful, methods and operators on lines 26 to 35 are provided.

Vector getMagnitude(), shown in Listing 4.27, returns the magnitude (size) of the vector.

Listing 4.27: Vector getMagnitude()

```cpp
float Vector::getMagnitude() {
  float mag = sqrt(x*x + y*y)
  return mag
}
```

Vector scale(), shown in Listing 4.27, resizes (changes the magnitude) of the vector by the scale factor, leaving the direction for the vector unchanged.

Listing 4.28: Vector scale()

```cpp
void Vector::scale(float s) {
  x = x * s
}
```
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Vector normalize(), shown in Listing 4.29, takes a vector of any length and, keeping it pointing in the same direction, changes its length to 1 (also called a unit vector). The if check is to avoid a possible division by zero.

Listing 4.29: Vector normalize()

```
void Vector::normalize()
{
    length = getMagnitude();
    if (length > 0)
    {
        x = x / length;
        y = y / length;
    }
}
```

Overloading the addition operator (+ in v1 + v2) for a Vector is shown in Listing 4.30. The method is called on the first vector (the Vector on the left-hand side of the ‘+’) with the second vector provided as an argument (the Vector on the right-hand side of the ‘+’). The variable v holds the new Vector, with x and y values added from the components of the other two vectors and then returned.

Listing 4.30: Vector operator+

```
Vector Vector::operator+(const Vector & other) const {
    Vector v; // Create new vector.
    v.x = x + other.x; // Add x components.
    v.y = y + other.y; // Add y components.
    return v; // Return new vector.
}
```

Other Vector operators (optional) The addition operator (+) is core since adding two vectors is used for many operations. However, there are other operators that may useful for a general Vector class, including: subtraction (-), multiplication (*), division (/), comparison (== and !=) and not (!). The aspiring programmer may want to implement them, using Listing 4.30 as a reference.

4.5.1.2 The Object Class

With the Vector class in place, the Object class can now be specified. The Object class definition is provided in Listing 4.31.

Listing 4.31: Object.h

```
#include <string>
#include "Vector.h"

class Object {
private:
```
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```cpp
int m_id;    // Unique game engine defined identifier.
std::string m_type; // Game programmer defined type.
Vector m_position; // Position in game world.

public:
  // Construct Object. Set default parameters and
  // add to game world (WorldManager).
  Object();

  // Destroy Object.
  // Remove from game world (WorldManager).
  virtual ~Object();

  // Set Object id.
  void setId(int new_id);

  // Get Object id.
  int getId() const;

  // Set type identifier of Object.
  void setType(std::string new_type);

  // Get type identifier of Object.
  std::string getType() const;

  // Set position of Object.
  void setPosition(Vector new_pos);

  // Get position of Object.
  Vector getPosition() const;
};
```

Each Object has a unique id, initialized in the constructor (Object()), that may be of use in some games to uniquely identify an game object. The id is obtained from a static integer declared in the Object constructor that starts at 0 and is incremented each time Object() is called. The method getId() can be used to obtain an Object’s id. The method setId() can be used to set an id manually, but in many games this is never used.7

The type is a string primarily used to identify the Object type in game code. For example, a Bullet object can invoke setType("Bullet"), allowing a Saucer object to query a collision event to see whether or not the type was a “bullet”, destroying oneself as an action. For the base Object constructor, the type can just be set to "Object".

The Object setPosition() and getPosition() methods allow changing the attribute position (via set) and retrieving it (via get).

Objects will have many attributes eventually (such as altitude, solidness, bounding boxes for collisions, animations for rendering sprite images, ...) but for now merely storing the position of the game world is sufficient.

Note that the destructor for Object is virtual on line 20. This is necessary since...

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6In most cases, the game programmer can uniquely identify an object by its memory address, but an integer may be more convenient. Moreover, a network game cannot count on a game object that is replicated on another computer to have the same memory address.

7A common exception is for synchronizing game worlds in a networked computer game.
Objects are deleted by the engine, not the game programmer, and the virtual keyword makes sure the right destructor is called for derived game objects. If the destructor was not virtual, when an Object was deleted by the engine, only ~Object() would be invoked and not the destructor for a game programmer object that inherited from it.

### 4.5.2 Lists of Objects

In order to handle the management and presentation of game objects to the game programmer, the world manager needs a data structure that supports lists of game objects, lists that can be created and passed around (inside the engine and to the game programmer) in a convenient to use and efficient to handle manner. In passing the lists to the game programmer, if the Objects themselves are changed (e.g., say, by decreasing the hit points of Objects damaged in an explosion), updates need to happen to the “real” objects as seen by the world manager. While there are numerous libraries that could be used for building efficient lists (e.g., the Standard Template Library or the Boost C++ Library), list performance is fundamental to game engine performance, both for Dragonfly as well as for other game engines, so implementing game object lists provides an in-depth understanding that may impact game engine performance. Plus, there are additional programming skills to be gained by implementing lists from scratch.

There are different implementation choices possible for lists of game objects, including linked lists, arrays, hash tables, trees and more. For ease of implementation and performance efficiency, an array is used for lists of game objects in Dragonfly. In addition, the iterator design pattern is used to provide a way to access the list without exposing the underlying data representation. In general, separating iteration from the container class keeps the functionality for the collection separate from the functionality for iteration. This simplifies the collection (not having it cluttered with iteration methods), allows several iterations to be active at the same time, and decouples collection algorithms from collection data structures, while still leaving the details of the container implementation encapsulated. This last point means the internals of the list data structure can be changed (e.g., replace the array with a linked list) without changing the rest of the game engine or any dependent game programmer code.

For reference, consider a basic list of integers (ints), shown in Listing 4.32.

#### Listing 4.32: List of integers implemented as an array

```cpp
const int MAX = 100;

class IntList {

private:
    int list[MAX];
    int count;

public:
    IntList() {
        count = 0;
    }

    // Clear list.
```

// Clear list.
void clear() {
    count = 0;
}

// Add item to list.
bool insert(int x) {
    if (count == MAX) // Check if room.
        return false;
    list[count] = x;
    count++;
    return true;
}

// Remove item from list.
bool remove(int x) {
    for (int i=0; i<count; i++) {
        if (list[i] == x) { // Found...
            for (int j=i; j<count-1; j++) // ...so scoot over
                list[j] = list[j+1];
            count--;
            return true; // Found.
        }
    }
    return false; // Not found.
}

The list starts out empty, by setting the count of items to 0 in the constructor. Basic operations allow the programmer to insert() items, remove() items, and clear() the entire list. Clearing the list and adding items to the list are quite efficient. Removing items from the list is rather inefficient, requiring the entire list to be traversed each time. The list is searched from the beginning to find the item to remove and then the rest of the list is traversed to “scoot” the items over one spot. Rather than scoot the items over, a “pop and swap” operation could be used:

This has the advantage of not iterating through the remainder of the list, but the disadvantage of changing the list order after the remove() operation. Plus, given the search required to find the item to delete, the remove() operation is still $O(n)$, where $n$ is the number of list items. However, perhaps most importantly, copying the list, which in a game engine happens often as many lists are created and destroyed by both the engine and the game programmer, is efficient as compilers (and programmers) handle fixed sized chunks of memory efficiently.

While arrays are efficient, it is still not a good design for the game engine to have entire objects inside the list. In other words, the int in Listing 4.32 should not be replaced by an

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8Tests with the Dragonfly Bounce benchmark modified to delete 50% of items added each time showed negligible performance differences between “pop-and-swap” and “scoot.”
Object representing a game object. Instead, lists of game objects are handled by having pointers to the game objects. So, int is replaced with Object *. Using pointers allows the game engine to reference the game object’s attributes and methods and still remain efficient for creating the many needed lists of objects needed. Basically, copying a list of pointers is much faster (and uses less memory) than copying a list of game objects. In addition, lists passed from the engine to, say, the game code refer to the original Objects (via the pointers) and not copies. Last but not least, having Object pointers allows for polymorphism, as in Listing 1.1 on page 7, when Object methods are resolved.

Listing 4.33: ObjectList.h

```cpp
const int MAX_OBJECTS = 5000;
#include "Object.h"
#include "ObjectListIterator.h"
class ObjectListIterator;

class ObjectList {
private:
    int m_count;        // Count of objects in list.
    Object *m_p_obj[MAX_OBJECTS]; // Array of pointers to objects.

public:
    friend class ObjectListIterator;

    // Default constructor.
    ObjectList();

    // Insert object pointer in list.
    // Return 0 if ok, else -1.
    int insert(Object *p_o);

    // Remove object pointer from list.
    // Return 0 if found, else -1.
    int remove(Object *p_o);

    // Clear list (setting count to 0).
    void clear();

    // Return count of number of objects in list.
    int getCount() const;

    // Return true if list is empty, else false.
    bool isEmpty() const;

    // Return true if list is full, else false.
    bool isFull() const;
};
```

Notice that line 14 of Listing 4.33 refers to an “ObjectListIterator” class that has not been defined. This class is defined in Section 4.5.2.1 and is used for efficient traversal of the list without exposing the attributes and internal structure of the list publicly. Line 5
is needed to act as a forward reference for the compiler, allowing compilation to proceed, as long as the ObjectListIterator class is defined before linking. Make sure this is also put inside the df:: namespace (see page 53).

### 4.5.2.1 ObjectList Iterators

The ObjectList class, as described in Section 4.5.2, is a fine container class, but does not allow traversal of the items (Objects) in the list. Fortunately, this can be rectified by defining an iterator for the ObjectList class. In general, iterators “know” how to traverse through a container class without exposing the internal data methods and structure publicly. Iterators do this by being a friend of the container class, giving them access to the private and protected attributes of the class. Defining an iterator decouples traversing the container from the container iteration. This allows, for instance, the structure of the container to be changed (e.g., from a static array to a linked list) without redefining all the code that uses the container.

There can be more than one iterator for a given list instance, each keeping its own position. Note, however, that adding or deleting items to a list during iteration may cause the iterator to skip or repeat iteration of an item (not necessarily the one added) – the program should not crash, but the iteration may not touch each item once and only once.

There are 3 primary steps in coding an iterator for a container:

1. Understand container class (e.g., List)
2. Design iterator class for container class
3. Add iterator materials:
   - Add iterator as friend class of container class

To illustrate these steps, consider creating a IntListIterator for the List defined in Listing 4.32 on page 77. Step 1 is to understand the implementation of List, in terms of the attributes p_obj[] array and the count used to store and keep track of list members. Step 2 is to define an iterator for IntList, provided by IntListIterator in Listing 4.34. The constructor for IntListIterator (line 7) needs a pointer to the IntList object it will iterate over, which it stores in attribute p_list. Since the iterator does not change the contents of the list, this pointer is declared as const. The index attribute is used to keep track of where the iterator resides in the list during iteration. The first() method resets the iterator to the beginning of the list. Subsequently, next() and isDone() allow iteration until the end of the list. The method currentItem() returns the current item that the iterator is on. Note, although not shown for brevity, index should be error checked for bounds in currentItem() and next().

Listing 4.34: Iterator for IntList class

```cpp
class IntListIterator {

private:
    const IntList *p_list; // Pointer to IntList iterating over.
    int index;            // Index of current item.
```
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```cpp
public:
    IntListIterator(const IntList *p_l) {
        p_list = p_l;
        first();
    }

    // Set iterator to first item.
    void first() {
        index = 0;
    }

    // Iterate to next item.
    void next() {
        if (index < p_list -> count)
            index++;
    }

    // Return true if done iterating, else false.
    bool isDone() {
        return (index == p_list -> count);
    }

    // Return current item.
    int currentItem() {
        return p_list -> item[index];
    }
};
```

For step 3, in order for the IntListIterator to access the private member of the IntList class, namely the `item[]` array and the list `count`, IntListIterator must be declared as a `friend` class inside `IntList.h`.

```cpp
friend class IntListIterator;
...
```

Both `IntList.h` and `IntListIterator.h` need forward references to class IntListIterator and class IntList, respectively, for compilation.

Once the IntListIterator is defined, a programmer that wants to iterate over an instance of List, say `my_list`, first creates an iterator:

```cpp
IntListIterator li(&my_list);
```

Then, the programmer calls `first()`, `currentItem()`, and `next()` until `isDone()` returns true.

Listing 4.35: Iterator with while() loop

```cpp
li.first();
while (!li.isDone()) {
    int item = li.currentItem();
    li.next();
}
```

A `for` loop has a bit shorter syntax:
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Listing 4.36: Iterator with for() loop

```cpp
for (li.first(); !li.isDone(); li.next())
    int item = li.currentItem();
```

For Dragonfly, the complete header file for an ObjectListIterator is defined in Listing 4.37. Having the default constructor `private` on line 8 makes it explicit that a List must be provided to the iterator when created.

Listing 4.37: ObjectListIterator.h

```cpp
#include "Object.h"
#include "ObjectList.h"

class ObjectList;

class ObjectListIterator {

private:
    ObjectListIterator();  // Must be given list when created.
    int m_index;           // Index into list.
    const ObjectList *m_p_list;  // List iterating over.

public:
    // Create iterator, over indicated list.
    ObjectListIterator(const ObjectList *p_l);

    void first();  // Set iterator to first item in list.
    void next();   // Set iterator to next item in list.
    bool isDone() const;  // Return true if at end of list.

    // Return pointer to current Object, NULL if done/empty.
    Object *currentObject() const;
};
```

4.5.2.2 Overloading + for ObjectList (optional)

A useful abstraction for game programmers is to combine two ObjectLists, the result being a third, combined list holding all the elements of the first list and all the elements of the second list. A method named `add()` could combine two lists, written as part of the ObjectList class (e.g., `ObjectList::add()`) or as a stand alone function. However, a natural abstraction is to use the addition (`+`) operator, overloading it to combine ObjectLists in the expected way.

In C++, operators are just functions, albeit special functions that perform operations on objects without directly calling the objects’ methods each time. Unary operators act on a single piece of data (e.g., `my_int++`), while binary operators operate on two pieces of data (e.g., `new_int = my_int1 + my_int2`). For ObjectLists, overloading the binary addition (`+`) operator is helpful. The syntax for overloading an operator is the same as for declaring a method, except the keyword `operator` is used before the operator itself.

Overloading the addition operator for an ObjectList is shown in Listing 4.38. The method is called on the first list (the ObjectList on the left-hand side of the `+`), with the second list provided as an argument (the ObjectList on the right-hand side of the `+`).
The variable `big_list` holds the combined list, starting out by copying the contents of the first list (`*this` on line 4). The method then proceeds to iterate through the second list, inserting each element from the second list into the first list on line 10. Once finished iterating over all elements in the second list, the method returns the combined list `big_list` on line 14.

Listing 4.38: ObjectList operator+

```cpp
// Add two lists, second appended to first.
ObjectList ObjectList::operator+(ObjectList list)
{
    // Start with first list.
    ObjectList big_list = *this

    // Iterate through second list, adding each element.
    ObjectListIterator li(&list)
    for (li.first(); not li.isDone(); li.next())
        Object *p_o = li.currentObject()
        big_list.insert(p_o) // Add element from second, to first list.
    end for

    // Return combined list.
    return big_list
}
```

Since ObjectLists are implemented as arrays, a more efficient `+` operation could allocate one array of memory large enough for both lists, then, using `memcpy()` or something similar, copy the first list then the second list into the allocated memory. Care must be taken to get the pointers and memory block length correct. That is left as option for the reader to explore outside this text.

However, as an advantage, the implementation in Listing 4.38 is agnostic of the actual implementation of ObjectList. The lists could be implemented as either arrays or linked lists with pointers or some other internal structure and the code would still work.

Once defined, the ObjectList `+` operator can be called explicitly, such as:

```cpp
ObjectList list_1, list_2;
ObjectList list_both = ObjectList+(list_1, list_2);
```

but a more natural representation is to call it as intended:

```cpp
ObjectList list_1, list_2;
ObjectList list_both = list_1 + list_2;
```

### 4.5.2.3 Dynamically-sized Lists of Objects (optional)

A significant potential downside of the code shown in Listing 4.32 and Listing 4.33 is that the maximum size of the list needs to be specified at compile time. If the list grows larger than this maximum, items cannot be added to the list – the container class data structure cannot do anything besides return an error code. This is true even when there is memory available on the computer to store more list items. A full list is potentially problematic – for example, the world manager can no longer manage any more Ogres or the player cannot
put more Oranges into a backpack. Specifying a larger maximum size and then recompiling
the game engine and the game is hardly an option for most players!

What can be done instead is to make arrays that dynamically resize themselves to
be larger as more items are required to be stored in the list. This has two tremendous
advantages: 1) the maximum size of the list does not need to be known by the engine ahead
of time, and 2) game object lists do not have to all be as large as the potential maximum
size, but can instead be small when a small list is required and only become large when a
large list is required, thus saving runtime memory and runtime processing time when lists
are copied and returned. The downside of this approach is that more runtime overhead is
incurred when a list grows. If done right, however, this runtime overhead can be infrequent
and fairly small.

The basic idea of dynamically sized lists is to allocate a relatively small array to start.
Then, if the array gets full (via insert()), the memory is re-allocated to make the array
larger. In order to avoid having the re-allocation happen every time a new item is inserted,
the re-allocation is for a large chunk of memory. A good guideline for the size of the larger
chunk is twice the size of the list that is currently allocated.

In order to make this change, first, the ObjectList attribute for the list needs to be
changed from an array to a list of pointers, such as Object **p_list.\(^9\)

Next, the ObjectList constructor needs to allocate memory for the list dynamically. This
can certainly be done via new, but memory can be efficiently resized using C’s realloc().\(^10\)
The initial allocation uses malloc() to create a list of size MAX_COUNT_INIT. MAX_COUNT_INIT
is defined to be 1, but other sizes can certainly be chosen. The ObjectList destructor
should free() up memory, if it is allocated.

Listing 4.39: Re-declaring list to be dynamic array array

```c
max_count = MAX_COUNT_INIT; // Initial list size (e.g., 1).
p_item = (Object **) malloc(sizeof(Object *));
```

In the insert() method, if the list is full (isFull() returns true) then the item array
is re-allocated to be twice as large, shown in Listing 4.40.

Listing 4.40: Re-allocating list size to twice as large

```c
Object **p_temp_item;
p_temp_item = (Object **)
    realloc(p_item, 2*sizeof(Object *) * max_count);
p_item = p_temp_item;
max_count *= 2;
```

The default copy constructor and assignment operator provided by C++ only do “shallow” copies, meaning any dynamically allocated data items are not copied. Since the revised
List class has dynamically allocated memory for the items, a new copy constructor and as-
ignment operator need to be created, each doing a “deep” copy. The copy constructor and
assignment operator prototypes look like:

\(^9\)The variable name is changed from list to explicitly depict that this is a pointer with dynamically
allocated memory.

\(^10\)Preliminary investigation running the Bounce benchmark and Saucer Shoot on both Linux Mint and
Windows 7 suggests about 20% of the time when a list needs to expand, the memory block can be extended
via realloc(), while 80% of the time the new block must be allocated elsewhere.
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Listing 4.41: Copy and assignment operator prototypes

```cpp
ObjectList::ObjectList(const ObjectList &other);
ObjectList &operator=(const ObjectList &rhs);
```

In the assignment operator, memory for the copy needs to be dynamically allocated and copied over, along with the static attributes:

Listing 4.42: Deep copy of list memory

```cpp
p_item = (Object **) malloc(sizeof(Object *) * other.max_count);
memcpy(p_item, other.p_item, sizeof(Object *) * other.max_count);
max_count = other.max_count;
count = other.count;
```

The assignment operator is similar, but with two additions before doing the deep copy: 1) the item being copied, \(\textit{rhs}\), must be checked to see if it is the same object (\(*\textit{this}\)) to avoid copying the list over itself. Doing this check makes sense for efficiency and can also prevent some crashes in copying the memory over itself; 2) if the current object (\(*\textit{this}\)) has memory allocated (\(p_{\text{item}}\) is not \texttt{NULL}), then that memory should be \texttt{free()}’d. Not doing this results in a memory leak.

Note, the above code needs additional error checking (not shown) since calls to \texttt{malloc()} and \texttt{realloc()} can fail (returning \texttt{NULL}).

Lastly, the ObjectList destructor is not shown, but needs to check if (\(p_{\text{item}}\) is not \texttt{NULL}), and, if so, then that memory needs to be \texttt{free()}’d.

4.5.3 Development Checkpoint #3!

If you have not continued to do so, resume development now.

1. Create the Vector and Object classes, using the headers from Listing 4.26 and Listing 4.31, respectively. Add \texttt{Vector.cpp} and \texttt{Object.cpp} to the project and stub out each method so it compiles.

2. Implement both Vector and Object. Then, test even though the logic is fairly simple in both of these classes since they are primarily holders of attributes.

3. Create the ObjectList class, using the header from Listing 4.33. Refer to Listing 4.32 for method implementation details, remembering that ObjectList uses a static array of Object pointers. Add \texttt{.cpp} code to the project and stub out each method so it compiles.

4. Implement ObjectList and test. At this point, write a test program that inserts and removes elements from an ObjectList. Be sure to test boundary conditions – check if the \texttt{isFull()} method works, too, when the list reaches maximum size.

5. Create the ObjectListIterator class, using the header from Listing 4.37. Refer to Listing 4.34 for method implementation details. Add \texttt{.cpp} code to the project and stub out each method so it compiles.
6. Compile the iterator and write test code, referencing Listing 4.35 or Listing 4.36 for example code that uses the iterator. While iterating, adjust Object positions during run-time and print out values to verify code is working. Test cases where the list is empty, too.

Make sure to test all the above code thoroughly to be sure it is trustworthy (robust). Make sure the code is easy to read and commented sufficiently so it can be re-factored later as needed – the Object class is definitely re-visited as game objects grow in attributes and functionality.