

CSCI-1200 Computer Science II — Spring 2006

Lecture 18 — Templated Classes and Vectors

Test 3 — General Information

- Test 3 will be held **Tuesday, April 11th, 2006 10-11:50am, West Hall Auditorium**. No make-ups will be given except for emergency situations, and even then a written excuse from the Dean of Students office will be required.
- Coverage: Lectures 1-19, Labs 1-10, HW 1-7.
- Closed-book and closed-notes *except for 1 sheet of 8.5x11 inch paper (front & back) that may be handwritten or printed*. Computers, cell-phones, palm pilots, calculators, PDAs, etc. are not permitted and must be turned off.
- All students must bring their Rensselaer photo ID card.
- Practice problems are available on the course website. An optional review session will be held on **Sunday April 9th, from 7-9pm in DCC 324**. Bring your questions!

Review from Lecture 17

- Arrays and pointers
- Different types of memory (“automatic”, static, dynamic)
- Dynamic allocation of arrays

18.1 Today’s Lecture

- Designing our own container classes:
 - Mimic the interface of standard library containers
 - Study the design of memory management code and iterators.
 - Move toward eventually designing our own, more sophisticated classes.
- Vector implementation
- Templated classes
- Copy constructors, assignment operators and destructors

18.2 Vector Public Interface

- In creating our own version of the vector class, we will start by considering the public interface:

```
public:
    // Member functions and other operators
    T& operator[] (size_type i);
    const T& operator[] (size_type i) const;
    void push_back(const T& t);
    void clear();
    bool empty() const;
    iterator erase(iterator p);
    size_type size() const;
    void resize(size_type n);
```

```
public:
    // Iterator operations
    iterator begin();
    const_iterator begin() const;
    iterator end();
    const_iterator end();
```

- This appears to be quite simple and in fact it is. We will focus on each piece, but especially on the use of templates, on the underlying representation, and on memory management.

18.3 Templated Class Declarations and Member Function Definitions

- In terms of just the layout of the code in `vec.h` (last page of handout), the biggest difference is that this is a *templated class*. The keyword `template` and the template type name must appear before the class declaration, e.g., `template <class T> class Vec`
- Within the class declaration, `T` is used as a type and all member functions are said to be “templated over type `T`”. In the actual text of the code files, templated member functions are often defined (written) *inside the class declaration*.
- The templated functions defined outside the template class declaration must be preceded by the phrase: `template <class T>` and then when `Vec` is referred to it must be as `Vec<T>`. For example, for member function `create` (two versions), we write:

```
template <class T> void Vec<T>::create
```

18.4 Syntax and Compilation

- Templated classes and templated member functions are not created/compiled/instantiated until they are needed. Compilation of the class declaration is triggered by a line of the form: `Vec<int> v1;` with `int` replacing `T`. This also compiles the default constructor for `Vec<int>` because it is used here. Other member functions are not compiled unless they are used.
- When a different type is used with `Vec`, for example in the declaration: `Vec<double> z;` the template class declaration is compiled again, this time with `double` replacing `T` instead of `int`. Again, however, only the member functions used are compiled.
- This is very different from ordinary classes, which are usually compiled separately and all functions are compiled regardless of whether or not they are needed.
- The templated class declaration and the code for all used member functions must be provided where they are used. As a result, member functions definitions are often included within the class declaration or defined outside of the class declaration but still in the `.h` file. If member function definitions are placed in a separate `.cpp` file, this file must be `#include-d`, just like the `.h` file, because the compiler needs to see it in order to generate code.

Note: Including function definitions in the `.h` for ordinary non-templated classes may lead to compilation errors about functions being “multiply defined”. Some of you have already seen these errors.

18.5 Member Variables

Now, looking inside the `Vec<T>` class at the member variables:

- `m_data` is a pointer to the start of the array (after it has been allocated). Recall the close relationship between pointers and arrays.
- `m_size` indicates the number of locations currently in use in the vector. This is exactly what the `size()` member function should return,
- `m_alloc` is the total number of slots in the dynamically allocated block of memory.

Drawing a picture, which we will do in class, will help clarify this, especially the distinction between `m_size` and `m_alloc`.

18.6 Typedefs, Iterators and Pointers

- Several types are created through `typedef` statements in the first `public` area of `Vec`. Once created the names are used as ordinary class type names. For example `Vec<int>::iterator` is an iterator type defined by the `Vec<int>` class. It is just a `T *`.

Also, `Vec<int>::size_type` is the size type, defined here as an `unsigned int`.

- Thus, internal to the declarations and member functions, `T*` and `iterator` **may be used interchangeably**.
- Also, the `++` and `--` operators on pointers automatically apply to iterators.

18.7 operator[]

- Access to the individual locations of the Vec is provided through `operator[]`. Syntactically, use of this operator is translated by the compiler into a call to a function called `operator[]`. For example, if `v` is a `Vec<int>`, then:

```
v[i] = 5;
```

translates into:

```
v.operator[](i) = 5;
```

- In most classes there are two versions of `operator[]`:
 - A non-const version returns a reference to `m_data[i]`. This is applied to non-const Vec objects.
 - A const version is the one called for `const str` objects. This also returns `m_data[i]`, but as a const reference, so it can not be modified. This version is the one used for const Vec objects.

18.8 Default Versions of Assignment Operator and Copy Constructor Are Dangerous!

- Before we write the copy constructor and the assignment operator, we consider what would happen if we didn't write them.
- C++ compilers provide default versions of these if they are not provided. These defaults just copy the values of the member variables, one-by-one. For example, the default copy constructor just like the following:

```
template <class T>
Vec<T> :: Vec(const Vec<T>& v)
: m_data(v.m_data), m_size(v.m_size), m_alloc(v.m_alloc)
{}
```

In other words, it would construct each member variable from the corresponding member variable of `v`. This can be dangerous, as the following exercise illustrates.

18.9 Exercise

Suppose we used the default version of the assignment operator and copy constructor in our `Vec<T>` class. What would be the output of the following program? Assume all of the operations **except** the copy constructor behave as they would with a `std::vector<int>`.

```
Vec<int> v(4, 0.0);
v[0] = 13.1; v[2] = 3.14;
Vec<int> u(v);
u[2] = 6.5;
u[3] = -4.8;
for (unsigned int i=0; i<4; ++i)
    cout << u[i] << " " << v[i] << endl;
```

Explain why this happens by drawing a picture of the memory of both `u` and `v`.

18.10 Classes With Dynamically Allocated Memory

- Each object must do its own dynamic memory allocation. We must be careful to keep the memory of each object instance separate from all others. This requires that we write (very carefully) our own:
 - *Copy constructor*
 - *Assignment operator*
- Dynamic memory should be released when an object is finished with it. This is done through what's called a *destructor*.

18.11 Copy Constructor

- This constructor must dynamically allocate any memory needed for the object being constructed, copy the contents of the memory of the passed object to this new memory, and set the values of the various member variables appropriately.
- In our `Vec` class, the actual copying is done in a private member function called `copy`.

18.12 Exercise: Write the private member function `copy`

```
// Create the vector as a copy of the given vector.  
template <class T>  
void Vec<T>::copy(const Vec<T>& v) {
```

```
}
```

18.13 Aside (1): the “`this`” pointer

- All class objects have a special pointer defined called `this` which simply points to the current class object, and it may not be changed.
- The expression `*this` is a reference to the class object.
- The `this` pointer is used in several ways:
 - Make it clear when member variables of the current object are being used.
 - Check to see when an assignment is self-referencing.
 - Return a reference to the current object.

18.14 Aside (2): Assignment operators, generally speaking

- Assignment operators of the form: `v1 = v2;`
are translated by the compiler as: `v1.operator=(v2);`
- Cascaded assignment operators of the form: `v1 = v2 = v3;`
are translated by the compiler as: `v1.operator=(v2.operator=(v3));`
- Therefore, the value of the assignment operator (`v2 = v3`) must be suitable for input to a second assignment operator. This in turn means the result of an assignment operator ought to be a reference to an object.

18.15 Assignment operator for `Vec`

- The implementation of an assignment operator usually takes on the same form for every class:
 - Do no real work if there is a self-assignment.
 - Otherwise, destroy the contents of the current object then copy the passed object, just as done by the copy constructor.
 - Return a reference to the (copied) current object, using the `this` pointer.

18.16 Destructor

- Called implicitly when an automatic object goes out of scope or a dynamic object is deleted. It can never be called explicitly!
- Must delete the dynamic memory “owned” by the class.
- The syntax of the function definition is a bit weird. The `~` has been used as a logic negation in other contexts.

18.17 Increasing the Size of the Vec

- `push_back(T const& x)` adds to the end of the array, increasing `m_size` by one `T` location. But what if the allocated array is full (`m_size == m_alloc`)?
 1. Allocate a new, larger array. The best strategy is generally to double the size of the current array. Why?
 2. If the array size was originally 0, doubling does nothing. We must be sure that the resulting size is at least 1.
 3. Then we need to copy the contents of the current array.
 4. Finally, we must delete current array, make the `m_data` pointer point to the start of the new array, and adjust the `m_size` and `m_alloc` variables appropriately.
- Only when we are sure there is enough room in the array should we actually add the new object to the back of the array.
- Finish the definition of `Vec::push_back`:

```
// Add an element to the end, resize if necessary.
template <class T> void Vec<T>::push_back(const T& val) {
    if (m_size == m_alloc) {
        // Allocate a larger array, and copy the old values

    }
    // Add the value at the last location and increment the bound
    m_data[m_size] = val;
    ++ m_size;
}
```

18.18 Exercise: Write the `Vec::erase` and `Vec::resize` functions

```
// Shift each entry of the array after the iterator. Return the iterator,
// which will have the same value, but point to a different location.
template <class T> typename Vec<T>::iterator Vec<T>::erase(iterator p) {

}

// If n is less than or equal to the current size, just change the size. If n is
// greater than the current size, the new slots must be filled in with the given value.
// Re-allocation should occur only if necessary. push_back should not be used.
template <class T> void Vec<T>::resize(size_type n, const T& fill_in_value) {

}

}
```

vec.h

```

// Assign one vector to another, avoiding duplicate copying.
template <class T>
Vec<T>& Vec<T>::operator=(const Vec<T>& v) {
    if (this != &v) {
        delete [] m_data;
        this -> copy(v);
    }
    return *this;
}

// Create the vector as a copy of the given vector.
template <class T>
void Vec<T>::copy(const Vec<T>& v) {
}

// Add an element to the end, resize if necessary.
template <class T>
void Vec<T>::push_back(const T& val) {
    if (m_size == m_alloc) {
        // Allocate a larger array, and copy the old values
        ++ m_size;
    }
    // Add the value at the last location and increment the bound
    m_data[m_size] = val;
}

// Shift each entry of the array after the iterator. Return the iterator,
// which will have the same value, but point to a different location.
template <class T>
typename Vec<T>::iterator Vec<T>::erase(iterator p) {
}

// If n is less than or equal to the current size, just change the size. If n is
// greater than the current size, the new slots must be filled in with the given value.
// Re-allocation should occur only if necessary. push_back should not be used.
template <class T>
void Vec<T>::resize(size_type n, const T& fill_in_value) {
}

//endif
}

#ifdef Vec_h_
// Simple implementation of the vector class, revised from Koenig and Moo.
// The class is templated, just like the vector class is in the standard library.
// Unlike non-templated classes, there is no separate .cpp file and no separate
// compilation. This header file must be #included where needed.
// This class is implemented using a dynamically allocated array (of T's) as its
// We ensure that that m_size is always <= m_alloc and when a push_back or resize
// call would violate this condition, the data is copied to a larger array.
// The code here, uses new and delete for its dynamic memory allocation instead of
// the more sophisticated allocators discussed in Section 11.5 of the text.

template <class T> class Vec {
public:
    // TYPEDEFS
    typedef T* iterator;
    typedef const T* const_iterator;
    typedef unsigned int size_type;
    // CONSTRUCTORS, ASSIGNMENT OPERATOR, & DESTRUCTOR
    Vec() { this->create(); }
    Vec(size_type n, const T& t = T()) { this->create(n, t); }
    Vec(const Vec& v) { copy(v); }
    Vec& operator=(const Vec& v);
    ~Vec() { delete [] m_data; }
    // MEMBER FUNCTIONS AND OTHER OPERATORS
    const T& operator[] (size_type i) { return m_data[i]; }
    void push_back(const T& t);
    iterator erase(iterator p);
    void resize(size_type n, const T& fill_in_value = T());
    void clear() { delete [] m_data; create(); }
    bool empty() const { return m_size == 0; }
    size_type size() const { return m_size; }
    // ITERATOR OPERATIONS
    iterator begin() { return m_data; }
    const_iterator begin() const { return m_data; }
    iterator end() { return m_data + m_size; }
    const_iterator end() const { return m_data + m_size; }
private:
    // PRIVATE MEMBER FUNCTIONS
    void create();
    void create(size_type n, const T& val);
    void copy(const Vec<T>& v);
    // REPRESENTATION
    T* m_data; // Pointer to first location in the allocated array
    size_type m_size; // Number of elements stored in the vector
    size_type m_alloc; // Number of array locations allocated, m_size <= m_alloc
};

// Create an empty vector (null pointers everywhere).
template <class T>
void Vec<T>::create() {
    m_data = 0; // Null pointer
    m_size = m_alloc = 0; // No memory locations
}

// Create a vector with size n, each location having the given value
template <class T>
void Vec<T>::create(size_type n, const T& val) {
    m_data = new T[n];
    m_size = m_alloc = n;
    for (T* p = m_data; p != m_data + m_size; ++p)
        *p = val;
}
#endif

```