CSCI-1200 Data Structures — Fall 2022
Lecture 6 — Templated Classes & Vector Implementation

Announcements: Test 1 Information

- Test 1 will be held **Thursday, Sept 22nd, 2022 from 6:00-7:50pm**.
  - Students will be randomly assigned to a test room, section, row, and seat. This is not necessarily the room listed on your SIS class schedule. Test 1 seat assignments will be posted late evening Tuesday Sept 20th on Submitty and by email.
  - All students should indicate their right- or left-handedness through the Submitty gradeable "Left-/Right- Handed Exam Seating" ASAP so they get an appropriate seat assignment.
  - No make-ups will be given except for pre-approved absence or emergency or illness, and a written excuse from the Dean of Students or the Student Experience office or the RPI Health Center will be required.
  - If you have a letter from Disability Services for Students and you have not already emailed it to `ds_instructors@cs.rpi.edu`, please do so IMMEDIATELY. Shianne Hulbert will be in contact to make arrangements for your test accommodations.
- Coverage: Lectures 1-6, Labs 1-4, and Homeworks 1-2.
  - Practice problems from previous tests are available on the course website.
  - Sample solutions to the practice problems will be posted on Wednesday morning.
  - The best way to prepare is to completely work through and write out your solution to each problem, *before* looking at the answers.
  - You should practice timing yourself as well. The test will be 110 minutes and there will be 100 points. If a problem is worth 25 points, budgeting 25 minutes for yourself to solve the problem is a good time management technique.
  - Most code boxes will include the # of lines in the instructor's solution. Use this as a guide or hint. You will not be graded on matching this number exactly, but if your solution is much longer or much shorter you may have misread or misunderstood the problem instructions.
  - Since we're out of practice taking exams on paper, you're also encouraged to practice *legibly* handwriting your answers to the practice problems on paper.
- OPTIONAL: Prepare a 2 page, black & white, 8.5x11", portrait orientation .pdf of notes you would like to have during the test. This may be digitally prepared or handwritten and scanned or photographed. The file may be no bigger than 2MB. You will upload this file to Submitty gradeable "Test 1 Notes Page (Optional)" before Wednesday Sept 21st @11:59pm. We will print this and attach it to your test. No other notes may be used during the test.
- Bring to the test room:
- Additional Notes:
  - Please use the restroom before entering the exam room. Except for emergencies, students must remain in their seats until they are ready to turn in their exam.
  - Bring your Rensselaer photo ID card. We will be checking IDs when you turn in your exam.
  - Bring your own pencil(s) & eraser (pens are ok, but not recommended). The test *will* involve handwriting code on paper (and other short answer problem solving). Neat legible handwriting is appreciated. We will be somewhat forgiving to minor syntax errors – it will be graded by humans not computers :)
  - Do not bring your own scratch paper. The exam packet will include sufficient scratch paper.
  - Computers, cell-phones, smart watches, calculators, music players, etc. are not permitted. Please do not bring your laptop, books, backpack, etc. to the test room – leave everything in your dorm room. *Unless you are coming directly from another class or sports/club meeting.*

Review from Lectures 4 & 5

- Arrays and pointers; Pointer arithmetic and dereferencing; Types of memory ("automatic", static, dynamic)
- Dynamic allocation of arrays; Drawing pictures to explain stack vs. heap memory allocation; Memory debugging

Today's Lecture

- Designing our own container classes:
  - Mimic the interface of standard library (STL) containers
  - Study the design of memory management.
  - Move toward eventually designing our own, more sophisticated classes.
- Vector implementation
- Templated classes (*including* compilation and instantiation of templated classes)
- Copy constructors, assignment operators, and destructors

6.1 Templated Class Declarations and Member Function Definitions

- In terms of the layout of the code in `vec.h` (pages 4 & 5 of the 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:

```
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(...
```

6.2 Typedef

- The keyword `typedef` can be used to create an *alias* / alternate name / shortcut for an existing type. Once created the names are used as ordinary type names.
- For example `Vec<int>::size_type` is the return type of the size() function, defined here as an `unsigned int`. We define the `Vec<T>::size_type` type in the `public` area of `Vec`.

6.3 Vector Public Interface

- In creating our own version of the STL vector class, we focus on the familiar functions in 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 resize(size_type n, const T& fill_in_value = T());
  void clear();
  bool empty() const;
  size_type size() const;
```

- To implement our own generic (a.k.a. templated) vector class, we will implement all of these operations, manipulate the underlying representation, and discuss memory management.

6.4 Member Variables

Now, looking inside the `Vec<T>` class at the private 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 pictures, which we will do in class, will help clarify this, especially the distinction between `m_size` and `m_alloc`.

6.5 operator[]

- Access to the individual locations of a `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 Vec` objects. This also returns `m_data[i]`, but as a const reference, so it can not be modified.

6.6 Increasing the Size of the Vec – `push_back`

- `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.

6.7 Exercises

- Finish the definition of `Vec::push_back`.
- Write the `Vec::resize` function.

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

- What would happen if we don't implement our own versions of the copy constructor and the assignment operator?
- C++ compilers provide default versions of these if they are used but not explicitly implemented. These defaults just copy the values of the member variables, one-by-one. For example, the default copy constructor would look like this:

```
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 is dangerous and incorrect behavior for the `Vec` class. We don't want to just copy the `m_data` pointer. We really want to create a copy of the entire array! Let's look at this more closely...

6.9 Exercise: Compiler-Written Default Copy Constructor

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<double>`.

```
Vec<double> v(4, 0.0);
v[0] = 13.1;  v[2] = 3.14;
Vec<double> 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 what happens by drawing a picture of the memory of both `u` and `v`.

6.10 Implementation Requirements for Classes With Dynamically Allocated Memory

- For `Vec` (and other classes with dynamically-allocated memory) to work correctly, each object must do its own dynamic memory allocation and deallocation. We must be careful to keep the memory of each object instance separate from all others.
- All dynamically-allocated memory for an object should be released when the object is finished with it or when the object itself goes out of scope (through what's called a *destructor*).
- To prevent the creation and use of default versions of these operations, we must write our own:
  - *Copy constructor*
  - *Assignment operator*
  - *Destructor*

6.11 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.
- **Exercise:** In our `Vec` class, the actual copying is done in a private member function called `copy`. Write the private member function `copy`.

6.12 Destructor (the "constructor with a tilde/twiddle")

- The destructor is called implicitly when an automatically-allocated object goes *out of scope* or a dynamically-allocated object is *deleted*. It can never be called explicitly!
- The destructor is responsible for deleting 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.

6.13 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.

6.14 Assignment Operator

- 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.
- 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. In fact, it often makes sense to write a private helper function used by both the copy constructor and the assignment operator.
  - Return a reference to the (copied) current object, using the `this` pointer.

6.15 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 that are 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 for templated classes 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. (Normally we don't `#include .cpp` files!) See also diagram on page 7 of this handout.

  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.

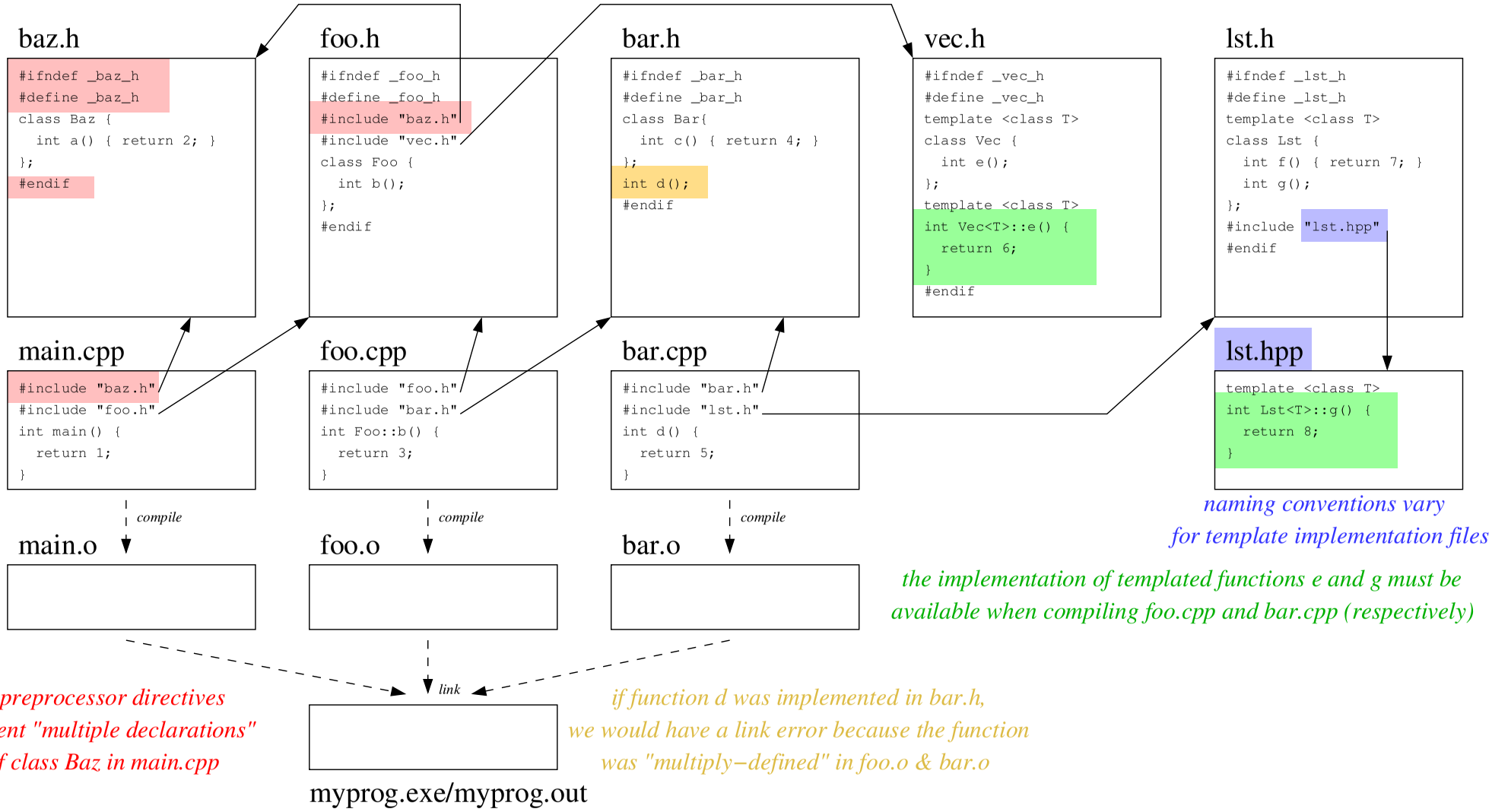
6.16 Vec Declaration & Implementation (`vec.h`)

```
#ifndef Vec_h_
#define Vec_h_

// 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.

template <class T> class Vec {
public:
  // TYPEDEFS
  typedef unsigned int size_type;

  // CONSTRUCTORS, ASSIGNMNENT OPERATOR, & DESTRUCTOR
  Vec() { create(); }
  Vec(size_type n, const T& t = T()) { create(n, t); }
  Vec(const Vec& v) { copy(v); }
  Vec& operator=(const Vec& v);
  ~Vec() { destroy(); }

  // MEMBER FUNCTIONS AND OTHER OPERATORS
  T& operator[] (size_type i) { return m_data[i]; }
  const T& operator[] (size_type i) const { return m_data[i]; }
  void push_back(const T& t);
  void resize(size_type n, const T& fill_in_value = T());
  void clear() { destroy();  create(); }
  bool empty() const { return m_size == 0; }
  size_type size() const { return m_size; }

private:
  // PRIVATE MEMBER FUNCTIONS
  void create();
  void create(size_type n, const T& val);
  void copy(const Vec<T>& v);
  void destroy() { delete [] m_data; }

  // 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 = NULL;
  m_size = m_alloc = 0;  // No memory allocated yet
}

// 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 (size_type i = 0; i < m_size; i++) {
    m_data[i] = val;
  }
}

// Assign one vector to another, avoiding duplicate copying.
template <class T> Vec<T>& Vec<T>::operator=(const Vec<T>& v) {
  if (this != &v) {
    destroy();
    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) {
  // EXERCISE: COMPLETE THIS FUNCTION



}

// Add an element to the end, resize if necesssary.
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
    // EXERCISE: COMPLETE THIS FUNCTION



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

// 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) {
  // EXERCISE: COMPLETE THIS FUNCTION



}
#endif
```

6.17 File Organization & Compilation of Templated Classes

The diagram on the next page shows the typical and suggested file organization for non-templated vs. templated classes. Common mistakes and the resulting compilation errors are noted.



naming conventions vary for template implementation files

the implementation of templated functions e and g must be available when compiling foo.cpp and bar.cpp (respectively)

the preprocessor directives prevent "multiple declarations" of class Baz in main.cpp

if function d was implemented in bar.h, we would have a link error because the function was "multiply–defined" in foo.o & bar.o