CSCI-1200 Data Structures
Final Exam — Practice Problems

NOTE: The final exam will be cumulative and comprehensive.
This packet contains sample questions from exams from multiple years.

1 Short Answer [ 17]

1.1 Comparing Vectors & Arrays [ 5]
The statements below can be used to compare and contrast arrays and vectors. For each statement, specify “ARRAY” if it is only true for arrays, “VECTOR” if it is only true for vectors, “BOTH” if it is true for both types, and “NEITHER” if it is true for neither type.

- Knows how many elements it contains.
- Can be used to store elements of any type.
- Prevents access of memory beyond its bounds.
- Is dynamically re-sizable.
- Can be passed by reference.

1.2 Limited Looping [ 3]
True or False There are some algorithms that must be written using a for loop and cannot be written using a while or do-while loop.

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1
2 Superhero Division [ /14]

In this problem you will add a new operator to the Superhero class from lab. Remember that a superhero has a name, a true identity, and a power, but we cannot access the true identity of a Superhero object from the public interface. Here is the basic Superhero class declaration:

```cpp
class Superhero {
public:
    // ACCESSORS
    const string& getName() const { return name; }
    const string& getPower() const { return power; }
    // INPUT STREAM OPERATOR
    friend istream& operator>>(istream &istr, Superhero &hero);
private:
    // REPRESENTATION
    string name;
    string true_identity;
    string power;
};
// OUTPUT STREAM OPERATOR
ostream& operator<<(ostream &ostr, const Superhero &hero);
```

And here is part of the Superhero class implementation:

```cpp
ostream& operator<<(ostream &ostr, const Superhero &hero) {
    if (hero.getPower() == "")
        ostr << hero.getName() << " has no power" << endl;
    else
        ostr << "Superhero " << hero.getName() << " has power " << hero.getPower() << endl;
    return ostr;
}
```

Now let’s define the /= operator on Superhero. This operator can be used to defeat a hero by dividing them from their true identity. If an attacker learns a hero’s true identity and uses it against them, the superhero loses his power. A superhero must carefully guard his true identity to prevent this attack. If the attacker does not know and just incorrectly guesses the superhero’s true identity, this /= operation does nothing. For example, suppose elastigirl is a Superhero object with name equal to “Elastigirl”, true identity equal to “Zoe”, and power equal to “Flexible”. Then the statement:

```cpp
cout << elastigirl;
```

would print this on the screen:

```
Superhero Elastigirl has power Flexible
```

But after executing the statement:

```cpp
elastigirl /= ("Zoe");
```

the output of the variable elastigirl would print on the screen as:

```
Elastigirl has no power
```
2.1 Implementation Choices [5]

Name the three different ways we can implement operator overloading. Which of these three is the most appropriate choice for the /\= operator described above? Why?

2.2 /\= operator implementation [9]

Now implement the /\= operator. Part of your job is to carefully define the prototype for this function. What should be added or changed in the superhero.h class declaration file? And what should be added or changed in the superhero.cpp class implementation file? Be specific.
You have been asked to help with a valet parking system for a big city hotel. The hotel must keep track of all of the cars currently stored in their parking garage and the names of the owners of each car. *Please read through the entire question before working on any of the subproblems.* Here is the simple `Car` class they have created to store the basic information about a car:

```cpp
class Car {
public:
    // CONSTRUCTOR
    Car(const string &m, const string &c) : maker(m), color(c) {} 
    // ACCESSORS
    const string& getMaker() const { return maker; } 
    const string& getColor() const { return color; } 
private:
    // REPRESENTATION
    string maker;
    string color;
};
```

The hotel staff have decided to build their parking valet system using a map between the cars and the owners. This map data structure will allow quick lookup of the owners for all the cars of a particular color and maker (e.g., the owners of all of the silver Hondas in the garage). For example, here is their data structure and how it is initialized to store data about the six cars currently in the garage.

```cpp
map<Car,vector<string> > cars;
cars[Car("Honda","blue")].push_back("Cathy");
cars[Car("Honda","silver")].push_back("Fred");
cars[Car("Audi","silver")].push_back("Dan");
cars[Car("Toyota","green")].push_back("Alice");
cars[Car("Audi","silver")].push_back("Erin");
cars[Car("Honda","silver")].push_back("Bob");
```

The managers also need a function to create a report listing all of the cars in the garage. The statement:

```cpp
print_cars(cars);
```

will result in this report being printed to the screen (`std::cout`):

```
People who drive a silver Audi:
  Dan
  Erin
People who drive a blue Honda:
  Cathy
People who drive a silver Honda:
  Fred
  Bob
People who drive a green Toyota:
  Alice
```

Note how the report is sorted alphabetically by maker, then by car color, and that the owners with similar cars are listed chronologically (the order in which they parked in the garage).
3.1 The Car class [6]

In order for the Car class to be used as the first part of a map data structure, what additional non-member function is necessary? Write that function. Carefully specify the function prototype (using const & reference as appropriate). Use the example above as a guide.

3.2 Data structure diagram [10]

Draw a picture of the map data structure stored by the cars variable in the example. As much as possible use the conventions from lecture for drawing these pictures. Please be neat when drawing the picture. Optional: You may also write a few concise sentences to explain your picture.
3.3 print_cars [ /9]

Write the print_cars function. Part of your job is to correctly specify the prototype for this function. Be sure to use const and pass by reference as appropriate.

3.4 remove_cars [ /13]

When guests pick up their cars from the garage, the data structure must be correctly updated to reflect this change. The remove_car function returns true if the specified car is present in the garage and false otherwise.

```cpp
bool success;
success = remove_car(cars, "Erin", "silver", "Audi");
assert (success == true);
success = remove_car(cars, "Cathy", "blue", "Honda");
assert (success == true);
success = remove_car(cars, "Sally", "green", "Toyota");
assert (success == false);
```
After executing the above statements the **cars** data structure will print out like this:

- **People who drive a silver Audi:**
  - Dan

- **People who drive a silver Honda:**
  - Fred
  - Bob

- **People who drive a green Toyota:**
  - Alice

Note that once the only blue Honda stored in the garage has been removed, this color/maker combination is completely removed from the data structure.

Specify the prototype and implement the `remove_car` function.
Suppose that a monster is holding you captive on a computational desert island, and has a large file containing double precision numbers that he needs to have sorted. If you write correct code to sort his numbers he will release you and when you return home will be allowed to move on to DSA. If you don’t write correct code, he will eventually release you, but only under the condition that you retake CS 1. The stakes indeed are high, but you are quietly confident — you know about the standard library sort function. (Remember, you are supposed to have forgotten all about bubble sort.) The monster startles you by reminding you that this is a computational desert island and because of this the only data structure you have to work with is a queue.

After panicking a bit (or a lot), you calm down and think about the problem. You realize that if you maintain the values in the queue in increasing order, and insert each value into the queue one at a time, then you can solve the rest of the problem easily. Therefore, you must write a function that takes a new double, stored in \( x \), and stores it in the queue. Before the function is called, the values in the queue are in increasing order. After the function ends, the values in the queue must also be in increasing order, but the new value must also be among them.

Here is the function prototype:

\[ \text{void insert\_in\_order(double } x, \text{ queue< } double \text{ >} \& q) \]

You may only use the public queue interface (member functions) as specified in lab. You may use a second queue as local variable scratch space or you may try to do it in a single queue (which is a bit harder). Give an “\( O \)” estimate of the number of operations required by this function.
5 Operations on Lists

5.1 Reversing a dslist

Write a \texttt{dslist<T>} member function called \texttt{reverse} that reverses the order of the nodes in the list. The head pointer should point to what was the tail node and the tail pointer should point to what was the head node. All directions of pointers should be reversed. The function prototype is:

\texttt{template \langle \text{class T} \rangle \text{void dslist<T>::reverse();}}

The function must NOT create ANY new nodes.

5.2 Sublists

Write a function to create a new singly-linked list that is a \textit{copy} of a sublist of an existing list. The prototype is:

\texttt{Node<T>\* Sublist(Node<T>\* head, \text{int low, int high})}

The \texttt{Node} class is:

\texttt{template <\text{class T}>}
\texttt{class Node {}
\texttt{public:}
\texttt{ T value;}
\texttt{ Node* next;}
\texttt{}}
The new list will contain $\text{high-low}+1$ nodes, which are copies of the values in the nodes occupying positions $\text{low}$ up through and including $\text{high}$ of the list pointed to by $\text{head}$. The function should return the pointer to the first node in the new list. For example, in the following drawing the original list is shown on top and the new list created by the function when $\text{low}=2$ and $\text{high}=4$ is shown below.

Original list

\[
\begin{array}{c}
\text{head} \quad 3.1 \quad 2.4 \quad 8.7 \quad 9.4 \quad 14.2 \quad 0.9
\end{array}
\]

New list

\[
\begin{array}{c}
\text{nhead} \quad 2.4 \quad 8.7 \quad 9.4
\end{array}
\]

A pointer to the first node of this new list should be returned. (In the drawing this would be the value of $\text{nhead}$.) You may assume the original list contains at least $\text{low}$ nodes. If it contains fewer than $\text{high}$ nodes, then stop copying at the end of the original list.
5.3 Splicing into a cs2list

Write a cs2list<T> member function called splice that takes an iterator and a second cs2list<T> object and splices the entire contents of the second list between the node pointed to by the iterator and its successor node. The second list must be completely empty afterwards. The function prototype is:

```cpp
template <class T>
void cs2list<T>::splice(iterator itr, cs2list<T>& second);
```

No new nodes should be created by this function AND it should work in $O(1)$ time (i.e. it should be independent of the size of either list).

6 Concurrency and Asynchronous Computing

Why might a group of dining philosophers starve?

A) Because it’s impossible to eat spaghetti with chopsticks.

B) Because they are all left-handed.

C) Because due to a bank error they didn’t have enough money in their joint account.

D) Because they didn’t all want to eat at the same time.
7 Garbage Collection [12]

For each of the real world systems described below, choose the *most appropriate* memory management technique. Each technique should be used exactly once.

A) Explicit Memory Management (C++)  
B) Reference Counting  
C) Stop & Copy  
D) Mark-Sweep

7.1 Student Registration System [3]

Must handle the allocation and shuffling of pointers as students register and transfer in and out of classes. Memory usage will not be a deciding factor. Fragmentation of data should be minimized.

7.2 Playing Chess [3]

Implementation of a tree-based algorithm for searching the game space. Remember that a *tree* is a *graph* with no cycles.

7.3 Webserver [3]

A collection of infrequently changing interconnected webpages. Any memory usage overhead should be low. Pauses in service are tolerable.

7.4 Hand Held Game (e.g., GameBoy or PSP, etc.) [3]

Performance critical application with extremely limited memory resources.
8  Short Answer [ /22]

8.1  Garbage Identification [ /7]

To which address in the memory below should the root variable point so that exactly 2 cells are garbage? Draw a box and pointer diagram to justify your answer and state which 2 cells are garbage.

<table>
<thead>
<tr>
<th>address</th>
<th>100</th>
<th>101</th>
<th>102</th>
<th>103</th>
<th>104</th>
<th>105</th>
<th>106</th>
<th>107</th>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
<td>e</td>
<td>f</td>
<td>g</td>
<td>h</td>
</tr>
<tr>
<td>left</td>
<td>106</td>
<td>106</td>
<td>107</td>
<td>100</td>
<td>102</td>
<td>101</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>right</td>
<td>103</td>
<td>105</td>
<td>105</td>
<td>0</td>
<td>105</td>
<td>101</td>
<td>0</td>
<td>101</td>
</tr>
</tbody>
</table>

8.2  Stop and Copy Garbage Collection [ /4]

What is the purpose of the forwarding address in Stop and Copy garbage collection? What will go wrong if you neglect to record this value? Write 2 or 3 concise and well-written sentences.
8.3 Concurrency and Asynchronous Computing

When programming with multiple threads or processes, the correct use of mutexes (locks) and condition variables will ensure that:

A) The program always returns the exact same answer.

B) The program returns an answer that was not possible if the program ran sequentially.

C) The entire program is atomic.

D) Each student in a large class will be able to successfully copy a complete set of lecture notes (with no repetitions), even if there are multiple professors.

E) Deadlock will be avoided if there are multiple mutexes, but may still happen in systems with a single lock.

8.4 Perfect Hashing for Image Compression

For the last homework, you implemented a compression scheme for 2D images. What are the drawbacks of using this format as the underlying representation for an image editing program? What types of edits to the image are simple? What types of edits will be comparatively inefficient to process? Write 3-4 concise and well-written sentences.
9 Data Structures

Indicate by letter the data structure(s) that have each characteristic listed below.

<table>
<thead>
<tr>
<th>A) vector</th>
<th>B) list</th>
<th>C) map</th>
<th>D) set</th>
</tr>
</thead>
<tbody>
<tr>
<td>E) priority queue</td>
<td>F) hash table</td>
<td>G) leftist heap</td>
<td></td>
</tr>
</tbody>
</table>

allows efficient (sublinear) removal of the first and last elements (or the minimum and maximum elements)

uses an array or vector as the underlying representation

uses a network of nodes connected by pointers as the underlying representation

the underlying data structure must be “balanced” or well-distributed to achieve the targeted performance

requires definition of `operator<` or `operator>`

entries cannot be modified after they are inserted (requires re-insertion or re-processing of position)

duplicates are not allowed

allows sublinear merging of two of instances of this data structure
10 Order Notation

Match the order notation with each fragment of code. Two of the letters will not be used.

A) O(n)  
B) O(1)  
C) O(n²)  
D) O(2ⁿ)  
E) O(n^n)  
F) O(log n)  
G) O(n \log n)  
H) O(\sqrt{n})

vector<int> my_vector;
// my_vector is initialized with \( n \) entries
// do not include initialization in performance analysis
for (int i = 0; i < n; i++) {
    my_vector.erase(my_vector.begin());
}

map<string, int> my_map;
// my_map is initialized with \( n \) entries
// do not include initialization in performance analysis
my_map.find("hello");

int foo(int n) {
    if (n == 1 || n == 0) return 1;
    return foo(n-1) + foo(n-2);
}

int k = 0;
for (int i = 0; i < \sqrt{n}; i++) {
    for (int j = 0; j < \sqrt{n}; j++) {
        k += i*j;
    }
}

set<string> my_set;
for (int i = 0; i < n; i++) {
    string s;
    cin >> s;
    my_set.insert(s);
}

float* my_array = new float[n];
// do not include memory allocation in performance analysis
my_array[n/2] = \sqrt{n};
In this problem we will explore a simple class to manage the assignment of people to offices and desks. Each Office object stores its name, the number of desks it can hold, and the names of the people assigned to those desks. An office also stores a reference to a master queue of all the people who still need to be assigned to desks. When an office is constructed, people are assigned to the office from the front of this master queue. When an office is demolished, the people who were assigned to that office should be added to the end of the queue while they wait for a new office assignment. Here is the partial declaration of the Office class:

```cpp
class Office {
public:
    Office(const string& name, int num_desks, queue<string> &unassigned);

private:
    // representation
    string _name;
    int _num_desks;
    string* _desks;
    queue<string>& _unassigned; // a reference to the master queue
};
```

In the example below we create the master queue of people who need to be assigned to desks in offices, and create and delete several Office objects:

```cpp
queue<string> unassigned;
unassigned.push("Alice");
unassigned.push("Bob");
unassigned.push("Cathy");
unassigned.push("Dan");
unassigned.push("Erin");
unassigned.push("Fred");
unassigned.push("Ginny");

Office *red = new Office("red", 4, unassigned);
Office *green = new Office("green", 2, unassigned);
cout << *red << *green;

delete red;
cout << "After deleting the red office, "
    << unassigned.size() << " people are waiting for desks." << endl;

Office *blue = new Office("blue", 3, unassigned);
cout << *blue;

cout << "Before deleting the blue & green offices, "
    << unassigned.size() << " people are waiting for desks." << endl;
delete green;
delete blue;
cout << "After deleting all of the offices, "
    << unassigned.size() << " people are waiting for desks." << endl;
```
Here is the desired output from this example:

The red office has 4 desks:
    desk[0] = Alice
    desk[1] = Bob
    desk[2] = Cathy
    desk[3] = Dan
The green office has 2 desks:
    desk[0] = Erin
    desk[1] = Fred
After deleting the red office, 5 people are waiting for desks.

The blue office has 3 desks:
    desk[0] = Ginny
    desk[1] = Alice
    desk[2] = Bob
Before deleting the blue & green offices, 2 people are waiting for desks.
After deleting all of the offices, 7 people are waiting for desks.

Here is the implementation of the constructor, as it appears in the office.cpp file:

```cpp
Office::Office(const string& name, int num_desks, queue<string> &unassigned) :
    _name(name), _num_desks(num_desks), _unassigned(unassigned) {
    _desks = new string[_num_desks]; // allocate the desk space
    for (int i = 0; i < _num_desks; i++) {
        if (_unassigned.size() > 0) { // assign from the master queue
            _desks[i] = _unassigned.front();
            _unassigned.pop();
        } else { // if there are no unassigned people, leave the desk empty
            _desks[i] = "";
        }
    }
}
```

11.1 Classes and Memory Allocation [ /10]

Anytime you write a new class, especially those with dynamically allocated memory, it is very important to consider the member functions that the compiler will automatically generate and determine if this default behavior is appropriate. List these 4 important functions by their generic names, AND write their prototypes as they would appear within the Office class declaration.
11.2 Declaring a Destructor [ /3]

The Office class is incomplete and requires implementation of a custom destructor so that people assigned to demolished offices are returned to the master queue and memory is deallocated as appropriate to avoid memory leaks. What line needs to be added to the header file to declare the destructor? Be precise with syntax. Where should this line be added: within the public, protected, or private interface?

11.3 Implementing a Destructor [ /12]

Implement the destructor, as it would appear in the office.cpp file.
Here is the implementation of the `<<` stream operator as it appears within the `office.cpp` file:

```cpp
ostream& operator<<(ostream &ostr, const Office &o) {
    ostr << "The " << o._name << " office has "
        << o._num_desks << " desks:" << endl;
    for (int i = 0; i < o._num_desks; i++) {
        ostr << " desk[" << i << "] = " << o._desks[i] << endl;
    }
    return ostr;
}
```

There are three different ways to overload an operator: as a non-member function, as a member function, and as a friend function. Which method was selected for the `Office` object `<<` stream operator? What are the reasons for this choice? Discuss why the other two methods are inappropriate or undesirable. Write 3 or 4 concise and thoughtful sentences.
Write a function that takes an STL list of integers, finds the even numbers, and places them in a dynamically-allocated array. Only the space needed for the even numbers should be allocated, and no containers other than the given list and the newly-created array may be used. As an example, given a list containing the values:

3 10 -1 5 6 9 13 14

the function should allocate an array of size 3 and store the values 10, 6 and 14 in it. It should return, via arguments, both the pointer to the start of the array and the number of values stored. No subscripting may be used — not even *(a+i) in place of a[i]. Here is the function prototype:

```c
void even_array(const list<int>& b, int* & a, int& n);
```
A ternary tree is similar to a binary tree except that each node has at most 3 children. Write a recursive function named `EqualsChildrenSum` that takes one argument, a pointer to the root of a ternary tree, and returns true if the value at each non-leaf node is the sum of the values of all of its children and false otherwise. In the examples below, the tree on the left will return true and the tree on the right will return false.

```cpp
class Node {
public:
    int value;
    Node* left;
    Node* middle;
    Node* right;
};
```
template <class T> class priority_queue {
public:
    // CONSTRUCTOR
    priority_queue() {} 
    // ACCESSORS
    int size() { return m_heap.size(); }
    bool empty() { return m_heap.empty(); }
    const T& top() const { assert(!m_heap.empty()); return m_heap[0]; }
    // MODIFIERS
    void push(const T& entry) {
        m_heap.push_back(entry);
        this->percolate_up(int(m_heap.size()-1));
    }
    void pop() { // find and remove the element with the smallest value
        assert(!m_heap.empty());
        m_heap[0] = m_heap.back();
        m_heap.pop_back();
        this->percolate_down(0);
    }
    void pop_max() { /* YOU WILL IMPLEMENT THIS FUNCTION */ }
private:
    // HELPER FUNCTIONS
    void percolate_up(int i) {
        T value = m_heap[i];
        while (i > 0) {
            int parent = (i-1)/2;
            if (value >= m_heap[parent]) break; // done
            m_heap[i] = m_heap[parent];
            i = parent;
        }
        m_heap[i] = value;
    }
    void percolate_down(int i) {
        T value = m_heap[i];
        int last_non_leaf = int(m_heap.size()-1)/2;
        while (i <= last_non_leaf) {
            int child = 2*i+1, rchild = 2*i+2;
            if (rchild < m_heap.size() && m_heap[child] > m_heap[rchild])
                child = rchild;
            if (m_heap[child] >= value) break; // found right location
            m_heap[i] = m_heap[child];
            i = child;
        }
        m_heap[i] = value;
    }
    // REPRESENTATION
    vector<T> m_heap;
};
14.1 Implementing `pop_max`

Write the new priority queue member function named `pop_max` that finds and removes from the queue the element with the largest value. Carefully think about the efficiency of your implementation. Remember that a standard priority queue stores the smallest value element at the root.

14.2 Analysis

If there are $n$ elements in the priority queue, how many elements are visited by the `pop_max` function in the worst case? What is the order notation for the running time of this function?
What is the output of the following program?

class A {
  public:
    virtual void f() { cout << "A::f\n"; }
    void g() { cout << "A::g\n"; }
  }
};

class B : public A {
  public:
    void g() { cout << "B::g\n"; }
};

class C : public B {
  public:
    void f() { cout << "C::f\n"; }
    void g() { cout << "C::g\n"; }
};

int main() {
  A* a[3];
  a[0] = new A();
  a[1] = new B();
  a[2] = new C();
  
  for (int i = 0; i < 3; i++) {
    cout << i << endl;
    a[i]->f();
    B* b = dynamic_cast<B*>(a[i]);
    if (b) b->g();
  }
}

For the last expression in each fragment of code below, give the type (int, vector<double>, Foo*, etc.) and the value. If the value is a legal address in memory, write “memory address”. If the value hasn’t been properly initialized, write “uninitialized”. If there is an error in the code, write “error”. You may want to draw a picture to help you answer each question, but credit will only be given for what you’ve written in the boxes.

double a = 5.2;
double b = 7.5;
a+b

Type: ___________________________ Value: ___________________________

int *d;
int e[7] = { 15, 6, -7, 19, -1, 3, 22 };
d = e + e[5];
*d

Type: ___________________________ Value: ___________________________

bool *f = new bool;
*f = false;
f

Type: ___________________________ Value: ___________________________

int g = 10;
int *h = new int[g];
h[0]

Type: ___________________________ Value: ___________________________

map<string, int> m;
m.insert(make_pair(string("bob"),5551111));
m.insert(make_pair(string("dave"),5552222));
m.insert(make_pair(string("alice"),5553333));
m.insert(make_pair(string("chris"),5554444));
(;++m.find("bob"))->second

Type: ___________________________ Value: ___________________________