1 Skip List Erase [ / 23]

In this problem you will complete the implementation of a recursive function to erase a specific value from a skip list. Remember that a skip list stores data in sorted order. Each level of a skip list chains together approximately half as many nodes as the previous level (skipping approximately every other node). We will assume our skip list stores positive integers, which allows us to use '0' as a special dummy head node.

class Node {
public:
    Node(int v, int h);
    ~Node() { delete [] ptrs; }
    int value;
    int height;
    Node** ptrs;
};

Node::Node(int v, int h) {
    value = v;
    height = h;
    ptrs = new Node*[height];
    for (int i = 0; i < height; i++) {
        ptrs[i] = NULL;
    }
}

1.1 Diagram [ / 3]

First, edit the diagram below to erase the value '6' from this skip list.

1.2 Algorithm Analysis [ / 7]

Assuming there are $n$ elements in the skip list and the maximum height of any node is $k$, what is the order notation for the running time of the erase algorithm? In the average (well-balanced) case? In the worst case? What is the relationship between $n$ and $k$ in the average (well-balanced) case? Write 4-5 concise and well-written sentences. You may want to first complete your implementation on the next page.
Now complete the implementation of the recursive `erase` function. The function should return `true` if the element was successfully removed and `false` otherwise. Make sure to handle the general case, not just the example you diagrammed on the previous page.

```cpp
bool erase(Node* before, int value, int level) {
    // sample solution: 13 line(s) of code
}

bool erase(Node* head, int value) {
    return erase(head, value, head->height-1);
}
```
Write a recursive function named `copy_except` that takes in a pointer to the root of a binary search tree and a value and returns a pointer to a full copy of the data, except the indicated value has been removed from the tree.

```cpp
template <class T> class Node {
    public:
        Node(const T& v) :
            value(v), left(NULL), right(NULL) {}  
        T value;
        Node* left;
        Node* right;
};
```

*sample solution: 25 line(s) of code*
3 Censoring Science

Alyssa P. Hacker works in the technology department at the Center for Disease Control (CDC). But she is disgusted by the most recent programming assignment she’s been asked to do. Below is a sample CDC document she needs to process. She’s been asked to make a “helpful” index of all the words in the document sorted in reverse character order (starting with the last letter in each word). Each word is accompanied by the position(s) of the occurrences of each word in the file. The corresponding output is show on the right.

the center for disease control employs evidence-based approaches to reduce disease in vulnerable populations

the diversity of experience at the center for disease control supports innovations in public health

3.1 Forbidden Words (Not a Joke)

You will notice that some words are missing from the index. Yes, indeed, these words are now forbidden from appearing in CDC budget documents. Which words are missing? Hint: there are 3 in this sample.

3.2 Reverse String Helper Function

Write a recursive helper function named reverse that returns the flipped version of its single argument.

3.3 Runtime Analysis Order Notation

Finish the implementation (next page), then analyze each step. Assume \( n \) total words and \( u \) unique words in the document, a max of \( k \) occurrences of any word, \( f \) forbidden words, and \( s \) letters in the longest word.
3.4 Implementation

Now complete the implementation below to produce this not-so-helpful index.

```cpp
std::map< > index;

// STEP 1: READ DOCUMENT
std::ifstream istr("cdc_doc.txt");
std::string s;
int i = 1;
while (istr >> s) {
    // sample solution: 1-3 line(s) of code
}

// STEP 2: PROCESS LIST OF FORBIDDEN WORDS
std::ifstream istr2("cdc_forbidden.txt");
while (istr2 >> s) {
    // sample solution: 1-3 line(s) of code
}

// STEP 3: OUTPUT THE INDEX
for (auto it = index.begin(); it != index.end(); ) {
    std::cout << std::setw(12) << it->first << " " << std::endl;
    for (auto &j : it->second) {
        std::cout << std::setw(2) << j << " ";
    }
    it = index.erase(it);
}
```

std::cout << std::endl;

```
4 Challenge Accepted! [ / 6]

Ben Bitdiddle claims that it’s impossible to write a recursive program without writing any helper functions – he means a program with no functions except main! Can you do it?

Write a complete C++ program (specify all of the #include, etc.) to compute integer powers. After compiling it (e.g., g++ -std=c++11 integer_power.cpp -o int_pow.out), executing the program with 2 arguments on the command line (e.g., ./int_pow.out 3 4) should print the answer to stdout (e.g., 81 in this example because $3^4 = 81$).

integer_power.cpp

sample solution: 24 line(s) of code

Analyze the running time of your program using order notation. Assume $b$ is the base and $p$ is the power.
Write a function named `claim_bag` that takes in 2 arguments. The first argument is of type `UnclaimedBags` and contains the records of all unclaimed luggage at the airport. The second argument is of type `BagDescription` and contains a passenger’s description of their missing bag. The function should search through the bag records and have one of three behaviors: 1) Locate the unique bag matching that description and remove it from the data structure, 2) Determine that no bag matching that description exists in the collection, or 3) Find multiple bags matching the description and request additional information. Here are the relevant `typedefs`:

```plaintext
typedef std::vector<std::pair<std::string, std::string>> BagDescription;
typedef std::list<BagDescription> UnclaimedBags;
```

Note that the description of each bag prepared by the airport’s unclaimed luggage office may be different from the description provided by the passenger. Some details may be omitted, and some details may be extra. For example, if the unclaimed bag office contains these 4 records:

- color:black  zipper:gold  size:small  wheels:wheels
- color:green  size:medium  wheels:no_wheels
- color:tan    zipper:gold  size:small  wheels:no_wheels
- color:brown  zipper:silver size:large

And a passenger comes to the office looking for a bag with features:
- `size=small`, `designer=gucci`, and `zipper=gold`
they will be told:

ERROR! 2 possible matching bags found, provide additional details

If instead they describe their bag as being:
- `size=small`, `designer=gucci`, `color=brown`, and `wheels=no_wheels`
they will be told:

ERROR! bag not found

Finally, if they revise their description to be:
- `zipper=gold`, `size=small`, `designer=gucci`, and `wheels=no_wheels`
this message will be output:

bag returned! 3 unclaimed bags remain

### 5.1 Order Notation

Assuming the airport has `n` bags, and each bag is described by a maximum or average of `a` descriptive features by the airport office and `p` descriptive features by the passenger, what is the order notation of the `claim_bag` function? Write 2-3 concise and well written sentences justifying your answer. (Note: You may want to answer this after completing the implementation on the next page.)
5.2 claim_bag Implementation

Now implement the claim_bag function. You will be graded on code organization and clarity. Do not make your code more complex to achieve a faster running time. You may write and use a helper function.

sample solution: 30 line(s) of code
6 Friends of Friends with Maps & Sets

For this problem you will write a function named `suggest_friends` that takes 2 arguments, the name of a person (as an STL `string`) and an STL `map` storing all current friendships defined with this typedef:

```cpp
typedef std::map<std::string, std::set<std::string>> friend_map;
```

The function should return an STL `set` of STL `string`s containing the names of all possible new friends for the specified person. Each possible new friend should be the friend of an existing friend.

As an example, let’s study the variable of type `friend_map` named `all_friends` to the left. Note that friendships are one way and not necessarily mutual (`alice` lists `chris` as a friend but `chris` does not list `alice` as a friend). Let’s find all possible new friends for `alice`.

We start by looking through all friends of `alice`’s current friends (just one step away). In this example, we have just one new friend suggestion for `alice`: `erin`. We make this suggestion because `alice` lists `chris` as a friend and `chris` lists `erin` as a friend. However, even though `alice` lists `bob` and `bob` lists `chris`, we do not suggest `chris` as a new friend, because `alice` has already listed him as a friend.

We do not suggest `alice` because a person does not list him/herself as a friend. And finally, we do not suggest `fred` because that potential friendship relationship is more than one step away (`alice` lists `chris`, `chris` lists `erin`, and `erin` lists `fred`). If we ask for friend suggestions for a person who does not have any friendships recorded in the map (e.g., `dave` in this example), then we will print a message to `std::cerr`.

### 6.1 Expected Output

First, complete the expected return data for the example above. Hint: In the 4 boxes below you will list 8 total names.

```cpp
suggest_friends("alice", all_friends);   { erin }
suggest_friends("bob", all_friends);     |
suggest_friends("chris", all_friends);   |
suggest_friends("dave", all_friends);    ERROR: could not find dave in the friend_map
suggest_friends("erin", all_friends);    |
suggest_friends("fred", all_friends);    |
```

### 6.2 Order Notation

Assuming the map holds friendship information for `n` people and each person lists an average or maximum of `k` other people as friends, what is the running time for the `suggest_friends` function? (Note: You may want to answer this after completing the implementation on the next page.)
6.3 Implement `suggest_friends`

Now, write the function `suggest_friends`. Be careful with syntax and make sure your function is efficient.

```cpp
std::set<std::string> suggest_friends (person, all) {
    std::set<std::string> answer;
    if (p == all.end()) {
        std::cerr << "ERROR: could not find " << person << " in the friend map" << std::endl;
    } else {
        // sample solution: 13 line(s) of code
        return answer;
    }
}
```
7 Potpourri [ / 31]

7.1 Hash Tables / Hash Functions [ / 3]
Which of the following statements are true about hash tables / hash functions?
A) A good hash function should run in \( O(1) \) time (expected).
B) A good hash function should use randomness to uniformly distribute the keys.
C) A linked list is commonly used to implement the separate chaining method of collision resolution.
D) When the amount of data stored in a hash table greatly exceeds the initial estimates, the table is resized and all data must be rehashed.
E) According to Google, the hash table is the “single most important data structure known to mankind”.
F) First available in C++11, STL’s `unordered_set` provides a hash table container class.
G) Any program using STL `map` can be improved by replacing the `map` with a hash table.

*write the letters of ALL statements above that are true*

7.2 Writing Simple String Hash Functions [ / 5]
Study the distribution of keys in this hash table of size \( n = 7 \). First, add two new words to this table, following the established pattern:

<table>
<thead>
<tr>
<th></th>
<th>bulb</th>
<th>logic</th>
<th>fold</th>
<th>cake</th>
<th>chef</th>
<th>dog</th>
</tr>
</thead>
<tbody>
<tr>
<td>idea</td>
<td>i</td>
<td>folk</td>
<td>pie</td>
<td>self</td>
<td>fern</td>
<td></td>
</tr>
<tr>
<td>sea</td>
<td>lab</td>
<td>sky</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

Now, write a simple hash function for STL strings that implements this pattern.

*sample solution: 4 line(s) of code*
A ternary heap is the same as a balanced binary heap except each node has up to 3 children instead of 2. Given the values: 13 20 6 9 7 12 15 11 24, draw both a binary heap and a ternary heap containing these values. (Smaller values have higher priority and should be removed first.)

Draw a binary heap containing the values:  

Draw a ternary heap containing the values: 

Draw the vector representation for the ternary heap structure you drew above.

Now complete the implementation of the helper functions below that will be used by percolate_up and percolate_down to access the parent and child elements within a ternary heap represented as a vector. Each function takes in the integer index of an element in the heap and returns the index of the requested parent or child element. You may assume that the caller of these functions will correctly handle the corner cases in which the parent or child does not exist.

```c
int parentOf(int index) {
}

int leftChildOf(int index) {
}

int centerChildOf(int index) {
}

int rightChildOf(int index) {
}
```
If your code is said to have a “memory leak”, which of the following statements are true?

A) Neither Valgrind nor Dr. Memory will identify the problem because these tools only detect memory corruption.
B) The problem can be corrected by adding delete statements at the end of the main function.
C) The program will crash with a segmentation fault.
D) Running this program will cause permanent damage to the RAM on your computer.
E) The program may appear to run bug-free for small test cases.
F) The program will produce different output on different hardware or different operating systems.
G) Rewriting the code to use the auto_ptr or unique_ptr will fix all memory leaks.

write the letters of ALL statements above that are true

Following the conventions from lecture, draw a diagram of the stack & heap at the end of these commands:

```
int a = 2;
int* b = new int;
int** c[2];
int* d;
c[1] = new int*;
c[0] = &b;
d = new int[a];
%c[1] = &d[0];
d[1] = a;
%c[1] = 0;
%c[0] = a*3;
(*c[1])++;
a--;```

Using all 4 variables, print the current year to std::cout.

sample solution: 1 line(s) of code

Now, write code to clean up all dynamically allocated memory (so we don’t have any memory leaks).

sample solution: ≤ 4 line(s) of code
Count Odd Find BST

Write a recursive function that takes in a pointer to the root node in a binary search tree, and a value to search for in the tree. The function should return -1 if the value is not present in the tree. If the value is found, it should return a count of the odd numbers on the path from root to value.

```cpp
class Node {
public:
    int value;
    Node *left;
    Node *right;
};
```

What is the order notation for the running time of this function given a tree with $n$ elements? Consider the best case, worst case, and average case. Write a concise and well-written 3-4 sentences explanation.
class Node {
public:
    Node(const std::string &v) : value(v) {}
    std::string value;
    std::vector<Node*> children;
};

What is the post-order traversal of the sample tree?

Now write a non-recursive function that takes in a pointer to the tree root and prints the contents in post-order. Your answer should work for any tree using this Node class (not just the sample).
In this problem, we will work with people who are either players or coaches. Some of the players are goalies. When a group of people get together, we say they form a team if they have at least one coach. If a team has at least one player who is a goalie, then we say it is a hockey team.

Here's some starter code:

```cpp
std::vector<Person*> people_a;
    people_a.push_back(new Player("goalie"));
    people_a.push_back(new Coach());
    people_a.push_back(new Player("center"));
    people_a.push_back(new Player("defense"));
std::vector<Person*> people_b;
    people_b.push_back(new Coach());
    people_b.push_back(new Coach());
    people_b.push_back(new Player("center"));
    people_b.push_back(new Player("defense"));
std::vector<Person*> people_c;
    people_c.push_back(new Player("goalie"));
    people_c.push_back(new Player("center"));
    people_c.push_back(new Player("forward"));
Team *team_a = CreateTeam(people_a);
PrintTeam("team_a",team_a);
Team *team_b = CreateTeam(people_b);
PrintTeam("team_b",team_b);
Team *team_c = CreateTeam(people_c);
PrintTeam("team_c",team_c);
```

Which produces this output:

```
team_a is a hockey team
WARNING! This group of people does not have a goalie!
team_b is a team
WARNING! This group of people does not have a coach!
WARNING! This group of people does not have a coach!
team_c is just a group of people
```

Here are few helper functions used by the code above:

```cpp
Team* CreateTeam(const std::vector<Person*>& people) {
    Team* answer = NULL;
    try {
        answer = new Hockey(people);
    } catch (const std::string& warning) {
std::cerr << "WARNING! " << warning << std::endl;
        try {
            answer = new Team(people);
        } catch (const std::string& warning) {
std::cerr << "WARNING! " << warning << std::endl;
        }
    }
    return answer;
}

void PrintTeam(const std::string &name, Team* team) {
    if (dynamic_cast<Hockey*>(team) != NULL) {
        std::cout << name << " is a hockey team" << std::endl;
    } else if (team != NULL) {
        std::cout << name << " is a team" << std::endl;
    } else {
        std::cout << name << " is just a group of people" << std::endl;
    }
}
```
10.1 Class Inheritance Diagram

First, draw the class inheritance hierarchy for the 5 classes used in this problem.

10.2 Implementation

Now, let’s complete the implementation of the 5 classes used in the code above.

class Person {
    public:
        virtual ~Person() {}
    }

class Coach {
    sample solution: 1 line(s) of code
}

class Player {
    public:
        sample solution: 1 line(s) of code
    private:
        sample solution: 2 line(s) of code
    }

    sample solution: 1 line(s) of code
}

int numCoaches(const std::vector<Person*>& members) {
    int answer = 0;
    for (int i = 0; i < members.size(); i++)
        if (dynamic_cast<Coach*>(members[i]) != NULL) answer++;
    return answer;
}
int numGoalies(const std::vector<Person*>& members) {
    return 0; // sample solution: 6 line(s) of code
}

class Team {
public:
    virtual ~Team() {} // sample solution: 1 line(s) of code
};

class Hockey {
public:
    // sample solution: 4 line(s) of code
};
# Lightning Round Terminology

Place the letter for each of the following terms next to the correct definition below. Each letter should be used exactly once. Please write your answers clearly and neatly.

| A) object-oriented programming | G) red-black trees | M) functor |
| B) operator overloading | H) inheritance | N) goto |
| C) dynamic memory allocation | I) templated class | O) breakpoint |
| D) throw exception | J) recursion | P) mutex |
| E) iterator | K) polymorphism | Q) virtual |
| F) open addressing | L) smart pointers | R) friend |

- **A**: should be used when classes have common member data and member functions
- **B**: use of classes to store data and define associated functions
- **C**: can cause deadlock
- **D**: a class with an overloaded function call operator
- **E**: an alternative to subscripting for vectors
- **F**: hash table collision resolution method
- **G**: should only be used when the meaning is intuitively clear
- **H**: something we haven’t taught, and you weren’t allowed to use
- **I**: guarantees \( O(\log n) \) performance of the STL `map` operations
- **J**: this keyword facilitates multiple inheritance involving the diamond property
- **K**: the only way a constructor can fail (other than crash)
- **L**: useful for creating custom containers that can hold a type specified at compile time
- **M**: allows access to private and protected information
- **N**: instead of placing data on the stack, it is stored on the heap
- **O**: allows us to store pointers to different types in the same vector
- **P**: can be used to solve Paint-by-Pairs puzzles
- **Q**: when you’re debugging, you might add one of these
- **R**: uses reference counting to automate object deletion
12 Short Answer [ 17]

12.1 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.

<table>
<thead>
<tr>
<th>Statement</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knows how many elements it contains.</td>
<td>BOTH</td>
</tr>
<tr>
<td>Can be used to store elements of any type.</td>
<td>BOTH</td>
</tr>
<tr>
<td>Prevents access of memory beyond its bounds.</td>
<td>ARRAY</td>
</tr>
<tr>
<td>Is dynamically re-sizable.</td>
<td>NEITHER</td>
</tr>
<tr>
<td>Can be passed by reference.</td>
<td>NEITHER</td>
</tr>
</tbody>
</table>

12.2 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.

<table>
<thead>
<tr>
<th>Statement</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

13 Concurrency and Asynchronous Computing [ 3]

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.

<table>
<thead>
<tr>
<th>Statement</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
```
14.1 Implementation Choices

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?

14.2 /= operator implementation

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:

```
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).
15.1 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.

15.2 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.
15.3 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.

15.4 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.

```c
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.
16. **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

16.1 **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.

16.2 **Playing Chess** [ ] [3]

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

16.3 **Webserver** [ ] [3]

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

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

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

17.1 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>

17.2 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.
17.3 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.

17.4 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.
**18 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:**
19  Order Notation [ /16]

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

<table>
<thead>
<tr>
<th>A) O(n)</th>
<th>B) O(1)</th>
<th>C) O(n^n)</th>
<th>D) O(n^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E) O(2^n)</td>
<td>F) O(log n)</td>
<td>G) O(n log n)</td>
<td>H) O(√n)</td>
</tr>
</tbody>
</table>

```cpp
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());
}
```

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

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

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

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

```cpp
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);
    friend ostream& operator<<(ostream &ostr, const Office &office);
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] = "";
        }
    }
}
```

20.1 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.
20.2 Declaring a Destructor

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?

20.3 Implementing a Destructor

Implement the destructor, as it would appear in the office.cpp file.
20.4 Operator Overloading

Here is the implementation of the \texttt{\textless\textgreater} stream operator as it appears within the \texttt{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 \texttt{Office} object \texttt{\textless\textgreater} 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.
21 Dynamically-Allocated Arrays

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:

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;
};
23.1 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.

23.2 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: