CSCI-1200 Data Structures
Final Exam — Practice Problem Solutions

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.

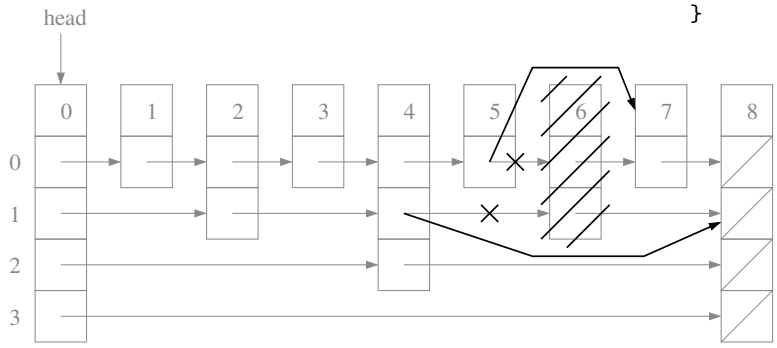
```
class Node {
public:
  Node(int v, int h);
  ~Node() { delete [] ptrs; }
  int value;
  int height;
  Node** ptrs;
};

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.

Solution:



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.*

Solution: In the average / well-balanced case, $k = \log_2 n$. We will visit each level of the structure, starting at the largest level and visit a small (constant) number of nodes to find which nodes at that level bracket the value we are searching for. Running time for erase is $O(k) = O(\log n)$ on average. In the worst case, (nearly) every node has the maximum height, and the value we are searching for is towards the end of the list. So we perform $O(n)$ to find the value in the highest level. Then edit every level in $O(k)$ running time. Overall $O(k + n)$ in the worst case.

1.3 Erase Implementation [/ 13]

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.

Solution:

```
bool erase(Node *before, int value, int level) {
  assert (before != NULL);
  assert (level >= 0 && level < before->height);
  // find closest node before this value in this level
  Node *next = before->ptrs[level];
  while (next != NULL && next->value < value) {
    before = next;
    next = before->ptrs[level];
  }
  assert (before != NULL);
  assert (before->value < value);
  // skip over the next node, if it holds what we're looking for
  if (before->ptrs[level] != NULL && before->ptrs[level]->value == value) {
    before->ptrs[level] = before->ptrs[level]->ptrs[level];
  }
  if (level == 0) {
    // once we make it to the lowest level, if we found the item, clean up memory
    if (next != NULL && next->value == value) {
      delete next;
      return true;
    }
    return false;
  } else {
    // recurse to next lowest level
    return erase(before,value,level-1);
  }
}
// "driver" helper function
bool erase(Node *head, int value) {
  return erase(head,value,head->height-1);
}
```

2 Exceptional Replication [/ 14]

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.*

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

Solution:

```
template<class T>
Node<T>* copy_except(Node<T>* root, const T& value) {
  if (root == NULL) {
    return NULL;
  }
  if (root->value == value) {
    // easy cases, no children or 1 child
    if (root->left == NULL && root->right == NULL)
      return NULL;
    if (root->left == NULL)
      return copy_except(root->right,value);
    if (root->right == NULL)
      return copy_except(root->left,value);
    // 2 children case: find substitute value
    Node<T>* tmp = root->right;
```

```
    while (tmp->left != NULL) { tmp = tmp->left; }
    Node<T>* answer = new Node<T>(tmp->value);
    answer->left = copy_except(root->left,value);
    answer->right = copy_except(root->right,tmp->value);
    return answer;
  } else {
    Node<T>* answer = new Node<T>(root->value);
    answer->left = copy_except(root->left,value);
    answer->right = copy_except(root->right,value);
    return answer;
  }
}
```

3 Censoring Science [/ 27]

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
```

```
     public 28
 experience 18
     reduce 10
        the  1 15 20
    disease  4 11 23
         of 17
     health 29
    control  5 24
         in 12 27
         to  9
     center  2 21
        for  3 22
 approaches  8
populations 14
innovations 26
   supports 25
    employs  6
         at 19
```

3.1 Forbidden Words (Not a Joke) [/ 3]

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.*

Solution: evidence-based, vulnerable, diversity (also: fetus, transgender, science-based, entitlement)

3.2 Reverse String Helper Function [/ 4]

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

Solution:

```
std::string reverse(const std::string& input) {
  if (input.size() <= 1) return input;
  return input.back() + reverse(input.substr(1,input.size()-2)) + input.front();
}
```

3.3 Runtime Analysis Order Notation [/ 8]

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.

Solution: The `reverse` function is $O(s)$,
Step 1 is $O(n * (s + log(u)))$ to read each word in the file, reverse it, and insert it into the map,
Step 2 is $O(f * (s + log(u)))$ to read each forbidden word and remove it from the map,
Step 3 is $O(u * (s + k))$ to loop over each row of the map, reverse the word, and print the positions.

3.4 Implementation [/ 12]

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

Solution:

```
  std::map<std::string,std::vector<int> > index;

  // STEP 1: READ DOCUMENT
```

```
std::ifstream istr("cdc_doc.txt");
std::string s;
int i = 1;
while (istr >> s) {
```

Solution:

```
    index[reverse(s)].push_back(i);
    i++;

  }
  // STEP 2: PROCESS LIST OF FORBIDDEN WORDS
  std::ifstream istr2("cdc_forbidden.txt");
  while (istr2 >> s) {
```

Solution:

```
    index.erase(reverse(s));

  }
  // STEP 3: OUTPUT THE INDEX
```

Solution:

```
  for (std::map<std::string,std::vector<int> >::const_iterator itr = index.begin();
       itr != index.end(); itr++) {
    std::cout << std::setw(12) << reverse(itr->first) << " ";
    for (int i = 0; i < itr->second.size(); i++) {
      std::cout << std::setw(2) << itr->second[i] << " ";

    }
    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`s, 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 $3^4 = 81$).

Solution:

```
#include <iostream>
#include <string>

int main(int argc, char* argv[]) {
  if (argc == 3) {
    // initial call, need to initialize the helper variable, product
    char* tmp[4] = { argv[0],
                     argv[1],
                     argv[2],
                     (char*) std::to_string(1).c_str() };
    main(4,tmp);
  } else if (argc == 4) {
    int base = std::stoi(argv[1]);
    int power = std::stoi(argv[2]);
    int product = std::stoi(argv[3]);
    if (power == 0) {
      // base case
      std::cout << product << std::endl;
    } else {
      // interesting recursive call.  decrement the power, update the product
      argv[2] = (char*) std::to_string(power-1).c_str();
      argv[3] = (char*) std::to_string(product*base).c_str();
      main(argc,argv);
    }
  } else {
    std::cout << "ERROR! WRONG NUMBER OF ARGUMENTS" << std::endl;
  }
}
```

Analyze the running time of your program using order notation. Assume b is the base and p is the power.

Solution: We do p recursive calls to count down from p to 1.
Each iteration is constant time. Overall = $O(p)$.

5 Claiming Lost Luggage [/ 23]

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 `typedef`s:

```
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 [/ 4]

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.)

Solution: The function must loop over all bags in the airport in a linear manner. For each bag, we must loop over all terms in both the airport database and passenger description and do an all-pairs comparison. The final answer is $O(nap)$. We cannot assume that the descriptions are sorted or otherwise organized. But if we do sort both descriptions alphabetically by category (not required for full credit), then the comparisons will be faster: $O(p \log p + n * (a \log a + p)$.

5.2 `claim_bag` Implementation [/ 19]

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.

Solution:

```
bool match(const BagDescription &bag, const std::string &feature, const std::string& value) {
  for (int i = 0; i < bag.size(); i++) {
    if (bag[i].first == feature && bag[i].second != value) {  return false;   }  }
  return true;
}

void claim_bag(UnclaimedBags &bags, const BagDescription &bag) {
  std::vector<UnclaimedBags::iterator> possible;
  for (UnclaimedBags::iterator itr = bags.begin(); itr != bags.end(); itr++) {
    bool ismatch = true;
    for (int i = 0; i < bag.size(); i++) {
      if (!match(*itr,bag[i].first,bag[i].second))
        ismatch = false;
    }
    if (ismatch == true) {  possible.push_back(itr);  }
  }
  if (possible.size() == 0) {
    std::cout << "ERROR! bag not found" << std::endl;
  } else if (possible.size() > 1) {
    std::cout << "ERROR! " << possible.size() <<
    " possible matching bags found, provide additional details" << std::endl;
  } else {
    bags.erase(possible[0]);
    std::cout << "bag returned! " << bags.size() << " unclaimed bags remain" << std::endl;
  }
}
```

6 Friends of Friends with Maps & Sets [/ 23]

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:

```
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.

alice	bob, chris, dave
bob	alice, chris
chris	dave, erin
erin	alice, fred
fred	erin

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 [/ 4]

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

`suggest_friends("alice",all_friends);` → { `erin`}

`suggest_friends("bob",all_friends);` → **Solution:** { `dave` **and** `erin` }

`suggest_friends("chris",all_friends);` → **Solution:** { `alice` **and** `fred` }

`suggest_friends("dave",all_friends);` → `ERROR: could not find dave in the friend map`

`suggest_friends("erin",all_friends);` → **Solution:** { `bob`, `chris`, **and** `dave` }

`suggest_friends("fred",all_friends);` → **Solution:** { `alice` }

6.2 Order Notation [/ 4]

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.)

Solution: $O(\log\ n)$ **to find the initial person, then we loop over** k **friends. We need to lookup each of them in the map, which is** $O(k * (\log\ n))$**. Then we will loop over their friends** $k * k$ **friends-of-friends in worst case. We will add those friends-of-friends into a set, which takes** $O(k^2\ log\ (k^2))$**. Overall:** $O(\log\ n + k * \log\ n + k^2 * \log\ k^2))$**. Since log exponents simplify, more correctly:** $O(\log\ n + k * \log\ n + k^2 * \log\ k))$**.**

6.3 Implement `suggest_friends` [/ 15]

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

```
std::set<std::string> suggest_friends(const std::string &person, const friend_map &all) {
```

```
  std::set<std::string> answer;
  friend_map::const_iterator p = all.find(person);
  if (p == all.end()) {
    std::cerr << "ERROR: could not find " << person << " in the friend map" << std::endl;
  } else {
    for (std::set<std::string>::const_iterator f = (*p).second.begin();
         f != (*p).second.end(); f++) {
      friend_map::const_iterator fs = all.find( (*f) );
      if (fs != all.end()) {
        for (std::set<std::string>::const_iterator possible = (*fs).second.begin();
             possible != (*fs).second.end(); possible++ ) {
          if (*possible != person &&
              (*p).second.find(*possible) == (*p).second.end()) {
            answer.insert(*possible);
          }
        }
      }
    }
  }
  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 re-hashed.

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.

Solution: A C D E F

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:

a idea sea	bulb i lab	logic	fold folk sky	cake pie	chef self	dog fern flag
0	1	2	3	4	5	6

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

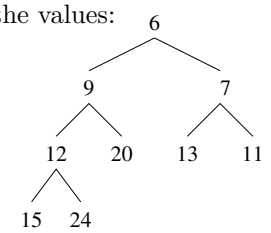
Solution:

```
int hash (const std::string& s, int n) {
  char last = s[s.size()-1];
  int val = last - 'a';
  return val % n;
}
```

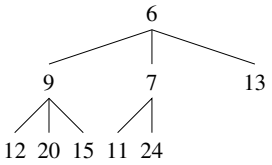
7.3 Ternary Heaps [/ 11]

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:



Solution: (one of many)

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

6	9	7	13	12	20	15	11	24
0	1	2	3	4	5	6	7	8

Solution:

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.

Solution:

```
int parentOf(int index) {
  return (index-1) / 3;
}
int leftChildOf(int index) {
  return index*3 + 1;
}
int centerChildOf(int index) {
  return index*3 + 2;
}
int rightChildOf(int index) {
  return index*3 + 3;
}
```

7.4 Memory Debugging [/ 3]

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.

Solution: E

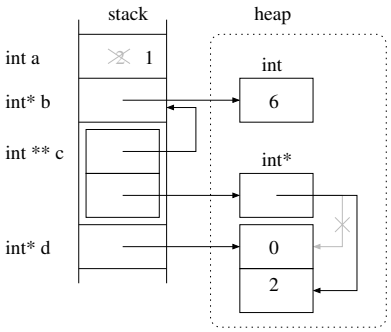
7.5 Diagramming Memory [/ 9]

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

Please be neat!

```
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--;
```

Solution:



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

Solution:

```
std::cout << **c[1] << d[0] << a << *b << std::endl;
```

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

Solution:

```
delete b;
delete [] d;
delete c[1];
```

8 Count Odd Find BST [/ 12]

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

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.

Solution:

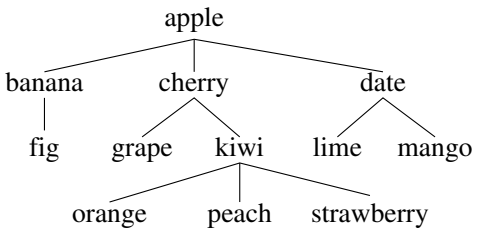
```
int count_odd_find(Node *root, int value) {
  if (root == NULL) return -1;
  if (root->value == value) return 0;
  int ret;
  if (root->value > value) {
    ret = count_odd_find(root->left,value);
  } else {
    ret = count_odd_find(root->right,value);
  }
  if (ret != -1 && root->value % 2 == 1) {
    ret += 1;
  }
  return ret;
}
```

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.

Solution: In the best case, the item we are searching for is at the root, or very close to the top and this code will stop quickly, $O(1)$, even if the tree is huge. In the worst case, the tree is unbalanced, and the item we are searching for is all the way at the lowest level of the unbalanced tree, $O(n)$. In the average case, the tree is well-balanced, with height *log* n, and we need to walk at least half the height of the tree, $O(\log\ n)$.

9 Iterative Fruit Tree Post-Order Traversal [/ 17]

```
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?

Solution:

```
fig banana grape orange peach strawberry kiwi cherry lime mango date apple
```

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).

Solution:

```
void print_iterative(Node *root) {
  // handle an empty tree
  if (root == NULL) return;
  // start with the first child of the root of tree
  std::vector<std::pair<Node*,int> > todo;
  todo.push_back(std::make_pair(root,0));
  while (todo.size() > 0) {
    std::pair<Node*,int> &current = todo.back();
    if (current.second < current.first->children.size()) {
      // before we can print this node, we must print all of its children
      todo.push_back(std::make_pair(current.first->children[current.second],0));
    } else {
      // after printing all of this node's children, we can print this node
      std::cout << " " << current.first->value;
      todo.pop_back();
      if (todo.size() > 0) {
        // increment the parent's child counter
        todo.back().second++;
      }
    }
  }
}
```

10 People and Team Inheritance [/ 18]

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:

```
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:

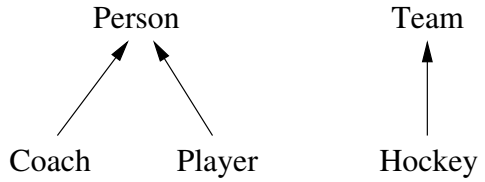
```
Team* CreateTeam(const std::vector<Person*>& people) {
  Team* answer = NULL;
  try {
    answer = new Hockey(people);
  } catch (const std::string& warning) {
    std::cerr << "WARNING!  " << warning << std::endl;
    try {
      answer = new Team(people);
    } catch (const std::string& warning) {
      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 [/ 4]

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

Solution:



10.2 Implementation [/ 14]

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

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

class Coach : public Person {
};

class Player : public Person {
public:
  Player(const std::string &t) : type(t) {}
  bool isGoalie() const { return type == "goalie"; }
private:
  std::string type;
};

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) {
  int answer = 0;
  for (int i = 0; i < members.size(); i++) {
    Player *player = dynamic_cast<Player*>(members[i]);
    if (player != NULL && player->isGoalie()) answer++;
  }
  return answer;
}

class Team {
public:
  Team(const std::vector<Person*>& members) {
    if (numCoaches(members) == 0)
      throw(std::string("This group of people does not have a coach!"));
  }
  virtual ~Team() {}
};

class Hockey : public Team {
public:
  Hockey(const std::vector<Person*>& members) : Team(members) {
    if (numGoalies(members) == 0)
      throw(std::string("This group of people does not have a goalie!"));
  }
};
```

11 Lightning Round Terminology [/ 12]

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

Soln: H should be used when classes have common member data and member functions

Soln: A use of classes to store data and define associated functions

Soln: P can cause deadlock

Soln: M a class with an overloaded function call operator

Soln: E an alternative to subscripting for vectors

Soln: F hash table collision resolution method

Soln: B should only be used when the meaning is intuitively clear

Soln: N something we haven't taught, and you weren't allowed to use

Soln: G guarantees $O(\log n)$ performance of the STL `map` operations

Soln: Q this keyword facilitates multiple inheritance involving the diamond property

Soln: D the only way a constructor can fail (other than crash)

Soln: I useful for creating custom containers that can hold a type specified at compile time

Soln: R allows access to private and protected information

Soln: C instead of placing data on the stack, it is stored on the heap

Soln: K allows us to store pointers to different types in the same vector

Soln: J can be used to solve Paint-by-Pairs puzzles

Soln: O when you're debugging, you might add one of these

Soln: L 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.

Solution: VECTOR Knows how many elements it contains.

Solution: BOTH Can be used to store elements of any type.

Solution: NEITHER Prevents access of memory beyond its bounds.

Solution: VECTOR Is dynamically re-sizable.

Solution: BOTH Can be passed by reference.

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.

Solution: False. All looping constructs are equivalent and any algorithm written using one looping construct can be re-written with the others.

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.

Solution: B

14 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:

```
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:

```
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:

```
cout << elastigirl;
```

would print this on the screen:

```
Superhero Elastigirl has power Flexible
```

But after executing the statement:

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

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

```
Elastigirl has no power
```

14.1 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?

Solution: The three methods are non-member function, member function, and friend function. It is usually preferable to consider the methods in that order. In this case we cannot implement the `/=` operator as a non-member because it requires read access to `true_identity` and write access to `power`. We can implement it as a member function of the `Superhero` class because the first argument is of type `Superhero`.

14.2 /= 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.

Solution: The following prototype for the member function should be added to the *public* portion of the `Superhero` class declaration:

```
Superhero& operator/=(const string &id);
```

And the function definition is added to the class implementation file:

```
Superhero& Superhero::operator/=(const string &id) {
  if (id == true_identity) {
    power = "";
  }
  return *this;
}
```

15 Valet Parking Maps [/38]

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:

```
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.

```
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.

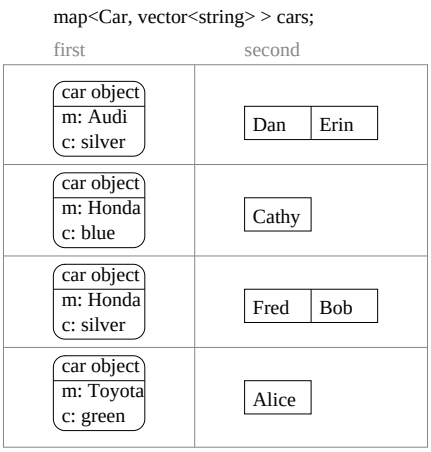
Solution: We must define `operator<` for `Car` objects so that we can sort the keys of the map.

```
bool operator<(const Car &a, const Car &b) {
  return (a.getMaker() < b.getMaker() ||
          (a.getMaker() == b.getMaker() && a.getColor() < b.getColor()));
}
```

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.*

Solution:



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.

Solution:

```
void print_cars(const map<Car,vector<string> > &cars) {
  map<Car,vector<string> >::const_iterator itr = cars.begin();
  while (itr != cars.end()) {
    Car c = itr->first;
    cout << "People who drive a " << c.getColor() << " " << c.getMaker() << ":" << endl;
    vector<string>::const_iterator itr2 = itr->second.begin();
    while (itr2 != itr->second.end()) {
      cout << "  " << *itr2 << endl;
      itr2++;
    }
    itr++;
  }
}
```

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.

```
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.

Solution:

```
bool remove_car(map<Car,vector<string> > &cars,
                const string &name, const string &color, const string &maker) {
  map<Car,vector<string> >::iterator itr = cars.find(Car(maker,color));
  if (itr == cars.end()) return false;
  if (itr->second.size() == 1 && itr->second[0] == name) {
    cars.erase(Car(maker,color));
    return true;
  }
  for (int i = 0; i < itr->second.size(); i++) {
    if (itr->second[i] == name) {
      itr->second.erase(itr->second.begin() + i);
```

```
      return true;
    }
  }
  return false;
}
```

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.

Solution: C

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.

Solution: B

16.3 Webserver [/3]

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

Solution: D

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

Performance critical application with extremely limited memory resources.

Solution: A

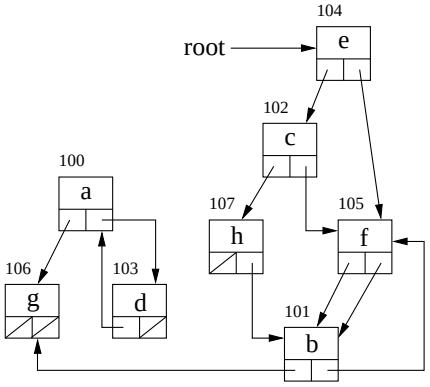
17 Short Answer [/22]

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.

address	100	101	102	103	104	105	106	107
value	a	b	c	d	e	f	g	h
left	106	106	107	100	102	101	0	0
right	103	105	105	0	105	101	0	101

Solution: The root should point to cell 104.
Cells 100 and 103 are garbage.



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.

Solution: When a non-garbage cell is copied from the old memory partition to the new memory partition, a forwarding address is left to indicate that the cell has been copied and to provide the address of the new location. All references to the old location will see the forwarding address and can then be updated as appropriate. If we don't record this forwarding address cyclical data structures will not be copied correctly: the garbage collector will repeatedly copy the same cell resulting in an infinite loop!

17.3 Concurrency and Asynchronous Computing [/4]

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.

Solution: D

17.4 Perfect Hashing for Image Compression [/7]

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.

Solution: The underlying representation is geared towards a static image because the computation of the perfect hash depends on the occupancy data. Simply changing the color of some or all of the non-white pixels is cheap. Removing non-white pixels (painting them white) or adding a non-white pixel that happens to hash to an empty spot in the hash data table is also cheap. Adding non-white pixels that collide with other pixels requires recomputation of the offset table, and possibly resizing of the hash data and/or offset tables.

18 Data Structures [/18]

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

A) vector	B) list	C) map	D) set
E) priority queue	F) hash table	G) leftist heap	

Solution:

B C D	allows efficient (sublinear) removal of the first and last elements (or the minimum and maximum elements)
A E F	uses an array or vector as the underlying representation
B C D (F) G	uses a network of nodes connected by pointers as the underlying representation
C D (E) F	the underlying data structure must be "balanced" or well-distributed to achieve the targeted performance
C D E G	requires definition of `operator<` or `operator>`
C D E F G	entries cannot be modified after they are inserted (requires re-insertion or re-processing of position)
C D (F)	duplicates are not allowed
B G	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.

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

Solution: D

```
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());
}
```

Solution: F

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

Solution: E

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

Solution: A

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

Solution: G

```
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);
```

Solution: B

20 Office Demolition [/31]

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:

```
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:

```
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:

```
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.

Solution:

default constructor	`Office();`
destructor	`~Office();`
copy constructor	`Office(const Office &office);`
assignment operator	`Office& operator=(const Office &office);`

20.2 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?

Solution: Anywhere in the `public:` interface,

```
~Office();
```

20.3 Implementing a Destructor [/12]

Implement the destructor, as it would appear in the `office.cpp` file.

Solution:

```
Office::~Office() {
  for (int i = 0; i < _num_desks; i++) {
```

```
        if (_desks[i] != "") {
          _unassigned.push(_desks[i]);
        }
      }
      delete [] _desks;
    }
```

20.4 Operator Overloading [/6]

Here is the implementation of the << stream operator as it appears within the `office.cpp` file:

```
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.

Solution: This operator has been implemented as a friend function, which is necessary to gain access to the private member variables of the `Office` object. If we had implemented it as a non-member function the function wouldn't have access to these variables and accessor functions would need to be added to the public interface, which is undesirable since that would expose the private representation unnecessarily. We cannot implement the stream operator as a member function of the `Office` class because the << syntax requires the `ostream` object to be the first argument of the operator. In order to be written as a member operator of a particular class, the first argument must be of that class type.

21 Dynamically-Allocated Arrays [/17]

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);
```

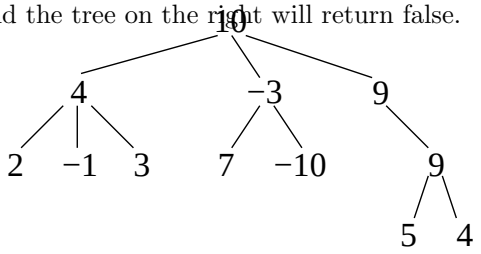
Solution:

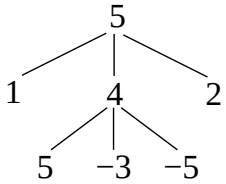
```
void even_array(const list<int>& b, int* & a, int& n) {
  n = 0;    // count
  for (list<int>::const_iterator p = b.begin(); p!=b.end(); ++p)
    if (*p % 2 == 0) ++n;
  a = new int[n];   // allocate
  int* q = a;     // store in array
  for (list<int>::const_iterator p = b.begin(); p!=b.end(); ++p)
    if (*p % 2 == 0) {
      *q = *p;
      ++q;
    }
}
```

22 Ternary Tree Recursion [/17]

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.

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





Solution:

```
bool EqualsChildrenSum(Node *node) {
  if (node == NULL) return true;
  if (node->left == NULL && node->middle == NULL && node->right == NULL)
    return true;
  int sum = 0;
  if (node->left != NULL) sum += node->left->value;
  if (node->middle != NULL) sum += node->middle->value;
  if (node->right != NULL) sum += node->right->value;
  if (sum != node->value) return false;
  return
    EqualsChildrenSum(node->left) &&
    EqualsChildrenSum(node->middle) &&
    EqualsChildrenSum(node->right);
}
```

23 Priority Queues [/16]

```
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` [/12]

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.

Solution:

```
  void pop_max() {
    assert(!m_heap.empty());
    int tmp = (size()+1)/2;
    for (int i = tmp+1; i < size(); i++) {
      if (m_heap[tmp] < m_heap[i])
        tmp = i;
    }
    m_heap[tmp] = m_heap.back();
    m_heap.pop_back();
    this->percolate_up(tmp);
  }
```

23.2 Analysis [/4]

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?

Solution: $n + \log n$ elements are visited. Running time is $O(n)$.

24 Inheritance & Polymorphism [/10]

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();
  }
}
```

Solution:

```
0
A::f
1
A::f
B::g
2
C::f
B::g
```

25 Types & Values [/15]

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
```

Solution: **Type:** `double` **Value:** `12.7`

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

Solution: **Type:** `int` **Value:** `19`

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

Solution: **Type:** `bool*` **Value:** ***memory address***

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

Solution: **Type:** `int` **Value:** ***uninitialized***

```
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
```

Solution: **Type:** `int` **Value:** `5554444`