

CS32

Smallberg

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CS32

Linking C++ Files

Linking and Multiple Compilation

```
1 #include <iostream>
2 #include <stdlib>
3 #include <math>
4 using namespace std;
5
6 // Circle.h "Header File"
7
8 class Circle
9 {
10     public:
11         Circle(double x, double y, double r);
12         bool scale(double factor);
13         void draw() const;
14         double radius() const; // when you call this member function, it promises not to
                                // modify the object
15                                // when first designing functions, always consider if they
                                // should be declared const
16
17         // now let's try and make sure data can never be in a bad state
18         // always document restrictions / invariants
19
20         // Class invariant:
21         // m_r > 0 (check boundary cases)
22
23     private:
24         double m_x;
25         double m_y;
26         double m_r;
27 };
```

```
29 // double area(Circle x);    // non-member function, passing by value, x is a copy
    // of a Circle
    // double area(Circle& x);  // passing by reference, x is another name for an
    // existing Circle, cheaper
31 double area(const Circle& x); // passing by constant reference, x is another name,
    // promises not to modify x, cheaper
    // still won't compile, area() calls radius() which is
    // not a const function!
33
    // now let's implement Circle class and area()
35 // interface (what) vs. implementation (how)
37 // Circle.cpp "Implementation File"
39 #include "Circle.h"
    #include <iostream>
41 #include <cstdlib>
    #include <string>
43 #include <math>
    using namespace std;
45
    Circle::Circle(double x, double y, double r)
47 : m_x(x), m_y(y), m_r(r) // member initialization list, alternate syntax, can have
    // an empty function body following, executes before function body
    {
49     if (r <= 0) // how do we deal with this issue? constructors don't have a return
        // value
        // can't use a default value, unstated rule is for constructor not to
        // return normally if constructor doesn't create a meaningful object
51     // could use exceptions in this case, but out of the scope of this
        // class
        {
53         cerr << "Cannot create a circle with radius " << r << endl;
            exit(1);
55     }
    // m_x = x;
```

```
57 // m_y = y;
    // m_r = r;
59 }

61 bool Circle::scale(double factor)
{
63     if (factor <= 0) // how do we deal with this issue? can return a bool (not a
        constructor)
        // check boundary! we decided circle of radius 0 is invalid
65     return false;
    m_r *= factor;
67     return true;
}

69 void Circle::draw() const
71 {
    ...
73 }

75 double Circle::radius() const
{
77     return m_r;
}

79 double area(Circle x)
81 {
    const double PI = 4 * atan(1.0);
83     return PI * x.radius() * x.radius();
}

85 // let's say above code and main routine are on separate files
87 // how to get it to compile?

89 // myapp.cpp

91 #include "Circle.h" // double quotes references an actual file somewhere
```

```

#include <iostream> // angle brackets references some predefined directories,
                    compiler specific
93 using namespace std;

95 int main()
{
97     Circle c(8, -3, 3.7);
    Circle d(-2, 5, 10);
99     d.scale(2);    // some people argue to always test for valid return values
    // d.m_r = -10; // how do we prevent this? public / private distinction
101                     // now won't compile, main() isn't a member function
                    // but how can area() access the m_r member now?
103                     // use a public accessor function
                    // possible language alternative: what if private variables were
                    // accessible but not modifiable?
105                     // then it's very difficult to change implementations! principle of
                    // abstraction
    d.draw();
107     cout << area(d);
    double e;
109     cin >> e;
    if(!d.scale(e)) // now we can check if scale() was valid
111     ...
}

```

- normally, compiler takes c++ source code (.cpp), translates to an object file (.obj)
- object file is still not executable, example code only has code for the main routine
 - object file defines the main routine
 - object file needs the implementations for
 - * Circle::Circle()
 - * Circle::scale()
 - * Circle::draw()
 - * area()
 - * operator <<
 - some of these implementations are found in the library code: defines <<, other standard library functions
- object file must be linked with the library code to generate an executable (linker)

- if Circle's functions still aren't implemented, building will generate a linker error, **not** a compilation error
 - implementing functions more than once is another linker error
- preferably, split large programs across multiple files
 - compiling and linking many object files is better than compiling one large file (*separate compilation*)
 - will reuse different up-to-date object files instead of recompiling and then relink (*relinking faster than recompilation*)

Header Files

- in example code, compiling the two files creates two object files that satisfy each other
 - but we would have had to declare the entire Circle class **twice**
 - use *header files*!
 - * for every class, convention is to have a header file and implementation file
 - * `#include "Header.h"` acts as if entire header file code has been copied here, shorthand
 - * don't have to explicitly compile header files!
 - eg. command line compilation: `g32 -o myapp myapp.cpp Circle.cpp`
 - or `g32 -o myapp *.cpp`
 - using `*` as a wildcard
- **never** `#include .cpp` files!
 - can lead to multiple defined functions

Include Guards

```
// Point.h
2 // =====

4 #ifndef POINT_INCLUDED // "include guard"
   #define POINT_INCLUDED
6 class Point
   {
8   ...
   };
```

```
10 #endif // POINT_INCLUDED

12 // Circle.h
13 // =====
14
15 #ifndef CIRCLE_INCLUDED
16 #define CIRCLE_INCLUDED
17
18 #include "Point.h"
19
20 class Circle
21 {
22     ...
23     Point m_center;
24     double m_r;
25 }
26 #endif // CIRCLE_INCLUDED
27
28 // myapp.cpp
29 // =====
30
31 // #include "Point.h" // bad rule, necessitates including both header files to use
32 // Circle class, and Point.h before Circle.h
33 #include "Circle.h"
34 // #include "Point.h" // this would lead to a multiple defined linking error!
35 // declares Point class twice
36 #include "Point.h" // this is fine after adding include guards
37
38 int main()
39 {
40     Circle c(...);
41     Point p(...);
42     ...
43 }
```

- As a general rule, header files should **always** include other header files they need

to compile

- but could lead to errors when including both Circle.h and Point.h
 - can use *include guards* with #ifndef, #endif
 - include guard is not necessary when multiple .cpp files include the same file
 - every header's include guard name should have different names
 - convention of #define HEADER_INCLUDED

Circular Dependency

```
1 // Student.h
2 // =====
3
4 #ifndef STUDENT_INCLUDED
5 #define STUDENT_INCLUDED
6
7 // #include "Course.h" // needs to know what a course is, leads to circular
8 // dependency
9
10 class Course;
11
12 class Student
13 {
14     ...
15     void enroll(Course* cp);
16     ...
17     Course* m_studyList[10];
18     ...
19 };
20 #endif // STUDENT_INCLUDED
21
22 // Course.h
23 // =====
24
25 #ifndef COURSE_INCLUDED
26 #define COURSE_INCLUDED
```

```
27 // #include "Student.h" // needs to know what a student is, leads to circular
    dependency
29 class Student;
31 class Course
    {
33     ...
    Student* m_roster[1000];
35     ...
    };
37 #endif // COURSE_INCLUDED
39 // blah.cpp
    // =====
41 #include "Student.h"
43 #include "Course.h"
45 void f(Student* sp, Course* cp)
    {
47     sp->enroll(cp);
    }
49 // foo.cpp fine to have multiple includes and incomplete type declarations
51 //=====
53 #include <iostream>
54 #include <iostream>
55 #include <iostream>
56 class A;
57 class A;
58 class A // but only one actual declaration of class A
59 {
    ...
```

```
61 };
```

- *circular dependency!* will not resolve by including headers
- the compiler just needs to know how big the class declarations are
 - but all pointers to class types are the **same** size
 - thus, don't need to know all the details of a class to use a pointer to that class
 - * or to use a class as a *parameter* or a *return type*
 - so convention is to use incomplete type declarations whenever possible (**cheaper**)
 - * avoid unnecessary `#include`'s
 - as soon as details of a class are necessary, the header file **must** be included
 - * eg. using member functions, constructors, etc.

Constructing with Member Initialization Lists

```
1  class Circle
2  {
3      public:
4          Circle(double x, double y, double r);
5          ...
6      private:
7          double m_x;
8          double m_y;
9          double m_r;
10 };
11
12 Circle::Circle(double x, double y, double r);
13     : m_x(x), m_y(y)
14 {
15     m_r = r;
16 }
17
18 class StickFigure
19 {
20     public:
21     StickFigure(double bl, double headDiam, std::string nm, double hx, double hy);
```

```
private:
23     std::string m_name;
        Circle m_head;
25     double m_bodyLength;
};

27
StickFigure:: StickFigure(double bl, double headDiam, std::string nm, double hx,
        double hy)
29 : m_name(nm), m_head(hx, hy, headDiam/2), m_bodyLength(bl)
    // must initialize m_head here, m_name is optional to initialize here
31    // good practice to initialize everything here
{
33    // m_name = nm; // first empty string then assignment, slightly more expensive
    // m_x = hx;    // private members of Circle! can't use simple assignment
35    // m_y = hy;
    // m_r = headDiam / 2;
37    // m_head = ??? // already previously constructed with default constructor (won't
        compile, didn't exist)
    // m_bodyLength = bl;
39    ...
}

41
struct Employee
43 {
    string name;
45     double salary;
    int age;
47 };

49 Employee e;

51 // ===== compiler-written constructor:
    // Employee::Employee()
53 // {}

55 Circle c(-2, 5, 10);
```

```

57 // first m_x and m_y are initialized in member initialization list, then m_r is
    // updated in constructor body
59 StickFigure sf(5, 4, "Fred", -2, 7);
    // m_name first empty string, then "Fred"
    // but if assigned using member initializer list, doesn't call default constructor,
    // cheaper

```

- construction/assignment nuances
 - for built-in types, **simple**: just change the contents
 - * doesn't matter if value is assigned later in body or initialized
 - for class types, **different**:
 - * whenever object of a class type is declared/created, a constructor is **always** called
 - * when assigning to a class type, it's an *already* constructed object, assignment != construction
 - * eg. string starts out with empty string
 - * for member objects in a class, may **have** to use member initialization list to construct them with parameters
 - recall: if you declare no constructors at all, the compiler writes a zero-argument constructor (default constructor)
- steps of construction:
 1. construct the base object
 2. construct each data member, consulting the *member initialization list*
 - if not listed:
 - * built-in type: left uninitialized
 - * class type: default-constructed (having no default constructor is an **error**)
 3. execute *body of constructor*

Pointers, Dynamic Arrays, & Resource Management

Writing a String type a la Smallberg

```

2 class String
  {

```

```
public:
4 // String(); // should empty string have a nullptr or a pointer
  to a zero byte?
  // nullptr is cheaper/faster (more users benefit),
  pointer to zero byte acts like any other String (programmer benefits)
6
  String(const char* text = ""); // can use a default parameter instead of a
  default constructor
8 // acts as a constructor that can be called
  without arguments, default constructor!
  // default constructor means a constructor that
  CAN be called with zero arguments
10
  // String(String other); // WRONG syntax for copy constructor, won't
  compile! cyclical, needs to call itself as a copy constructor
12 String(const String& other); // correct copy constructor syntax using a const
  reference
14 ~String();

16 // void assign(const String& rhs); // right hand side
  // void operator=(const String& rhs); // we want to chain operator
18 // String operator=(const String& rhs); // creates an extra copy, wasteful
  String& operator=(const String& rhs);
20
22 void swap(String& other); // for copy and swap idiom

private:
24 // Class invariant: // always make sure to document all cases
  // m_text points to a dynamically allocated array of m_len+1 chars
26 // m_len >= 0
  // m_len == strlen(m_text)
28 // char m_text[???]; // should there be a limit on the number of characters?
  char* m_text; // now has a dynamic size
30 int m_len; // how to find end of the String? store size? append zero
  byte? why not both?
```

```
};
32
String::String(const char* text) // text is a pointer to constant chars!
34 {
    if (text == nullptr)          // let's produce empty string if nullptr was passed
36     text = "";                 // text can point to different places, but can't modify
                                // those chars
    m_len = strlen(text);
38    // m_text = text;           // WRONG! can't just copy the pointer, m_text then
                                // could have its string value changed elsewhere
                                // instead, m_text should hold its own char array
40    m_text = new char[m_len+1]; // can use a non constant array size when using new
                                // operator!
                                // char built-in-type, so uninitialized
42    // Blah* bp = new Blah[n]; // on the other hand, default-constructors called n-
                                // times for the blah objects!
    strcpy(m_text, text);
44 }

46 // String::String()           // let's make this as similar to the other constructor
                                // as possible
    // {
48    //     m_len = 0;
    //     m_len = strlen("");
50    //     m_text = new char[1];
    //     m_text = new char[m_len+1];
52    //     m_text[0] = '\0';
    //     strcpy(m_text, "");
54    //     // now we can actually combine the constructors into one!
    // }

56
String::String(const String& other)
58 {
    m_len = other.m_len;        // yes, this member function can access the private data
                                // members of any String
```

```

60 // m_text = other.m_text; // no, this leads to the same issue as the compiler
    generated copy constructor, memory leaks
    m_text = new char[m_len+1];
62 strcpy(m_text, other.m_text);

64 // m_len = other.size(); // could alternatively copy using only member functions,
    but could be much less efficient!
    // m_text = new char[m_len+1];
66 // for (int k = 0; k < m_len; k++)
    // m_text[k] = other.charAt(k);
68 // m_text[m_len] = '\0';
}

70 String::~~String()
72 {
    // delete m_text; // BUT different forms of delete!
    // for single dynamic objects, use delete p;
    // for array of dynamic objects, use delete [] p;
76 delete [] m_text;
}

78 // void String::assign(const String& rhs) // we want to allow chaining operator
80 String& String::operator=(const String& rhs) // operator notation, overloaded
    assignment operator
    // can only overload existing operators
    // eg. s.operator[](k); equivalent to s[
    k];
{
84 if (this != &rhs)
    {
86 // delete [] m_text; // no more memory leak
    // m_len = rhs.m_len;
88 // m_text = new char[m_len+1];
    // strcpy(m_text, rhs.m_text);
90

```



```
String temp(rhs);           // "copy-and-swap" approach for
assignment operators
92 swap(temp);               // works better with assignment, checks
for self assignment, elegant!

                               // swap swaps the pointers
94                               // temp is destructed at the end
}

96 return *this;             // allows for chaining assignment
operator
}

98
void swap(String& other)
100 {
    char* temp = m_text;
102 m_text = other.m_text;
    other.m_text = temp;
104
    int temp2 = m_len;
106 m_len = other.m_len;
    other.m_len = temp2;
108 }

110 char* f(...); // returns a c-string

112 void h()
{
114 String s("Hello"); // passing an array of characters to constructor
                        // double-quoted string literals already have a zero byte
                        appended
116 String s2;          // acts same as if String s2("");
String s3(f(...)); // what if null pointer? (can test) or no zero byte? (can't
really deal with this problem)
118 ...
char line[1000];
120 cin.getline(line, 1000);
String t(line);
```

```
122  cin.getline(line, 1000); // will overwrite line! since t simply holds a pointer,
                               // t would now hold a different String if m_text was
                               initialized by pointer assignment
124  }

126  void g()
    {
128      for (...)
          h();
130  } // memory leak! dynamically allocated memory isn't released! memory is a finite
      resource
      // "garbage" memory fills up over time unless there is a destructor
```

Default Parameter Values

- void f(int i, double d)
- void f(int i)
- if these functions act the same as if f(int i, 3.7), can combine into the **same** function using default values:
 - void f(int i, double d = 3.7)
 - * this acts as both a one **and** two argument function
 - * defaults to value of 3.7 for d if called with only one argument
 - eg. void g(int i, Point p = Point(), double d = 3.7)
 - * acts as a one, two, and three argument function
 - * can call:
 - g(10, p, 4.8);
 - g(10, p); acts as g(10, p, 3.7)
 - g(10); acts as g(10, Point(), 3.7)
 - * **cannot** call:
 - g(10, , 4.8);
 - once you have provide a default value for an argument, **all** the other following arguments must also contain default values
 - default values can be **any** expression (even dynamically allocated objects), not necessarily constant
 - only **cannot** depend on the other parameters
- default values only go in the prototype (header), **NOT** the implementation
- can lead to ambiguities/compile issues
 - eg. function with two parameters (one default), and same name function

with only one parameter

* **cannot** call that function with one argument

Copy Constructors & Assignment Operator Overloading

```
1 // continued from String class above
3 void f(String t) // default copy constructor copies the length and pointer to
  dynamic array from s to t
{
5   // eg. t.set(0, 'J'); // here, value of s has changed out from under it! (because s
  and t both point to the same array)
  String u("WOW");
7   ...
  // u = t;      // compiler generates an assignment operator that simply copies each
  data member from t into u
9   // in this case, leads to a memory leak: replaces and loses pointer
  to dynamic array ("WOW")
  // u.assign(t); // let's try writing a member function for assignment
11  u = t;        // means u.operator=(t);
  ...
13 }             // t goes away at the end of a function, t's destructor is called,
  deletes dynamic array

15 void g()
{
17   String s("Hello");
  f(s);
19   ...
}             // tries to delete the same dynamic array, undefined behavior
21             // as it is, can't pass our String class by value (copy)
             // solution: we have to write our own copy constructor that creates
  a new dynamic array
23
// all the following examples involve copies and have the same issues
25 // tries to delete the same dynamic arrays twice
```

```
String s("Hello");
27 String t(s);

29 String h()
{
31     String x;
    ...
33     return x;
}

35 // Ex. Overloading copy constructor from String class
37
String::String(const String& other)
39 {
    m_len = other.m_len;    // yes, this member function can access the private data
                           // members of any String
41    // m_text = other.m_text; // no, this leads to the same issue as the compiler
                           // generated copy constructor
    m_text = new char[m_len+1];
43    strcpy(m_text, other.m_text);

45    // m_len = other.size(); // could alternatively copy using only member functions,
                           // but could be much less efficient!
    // m_text = new char[m_len+1];
47    // for (int k = 0; k < m_len; k++)
    //     m_text[k] = other.charAt(k);
49    // m_text[m_len] = '\0';
}

51 // Ex. Overloading assignment operator from String class
53
// void String::assign(const String& rhs)    // we want to allow chaining operator
55 String& String::operator=(const String& rhs) // operator notation, overloaded
    assignment operator

                                         // can only overload existing operators
```

```

57                                     // eg. s.operator[](k); equivalent to s[
    k];
{
59  if (this != &rhs)
    {
61      // delete [] m_text;                // no more memory leak
        // m_len = rhs.m_len;
63      // m_text = new char[m_len+1];
        // strcpy(m_text, rhs.m_text);

65      String temp(rhs);                // "copy-and-swap" approach for
assignment operators
67      swap(temp);                    // works better with assignment, checks
for self assignment, elegant

                                     // swap swaps the pointers
69                                     // temp is destructed at the end
    }
71  return *this;                    // allows for chaining assignment
    operator
}

```

Copy Construction

- passing by value passes a **COPY**... how do copies work? copying is done by a *copy constructor*!
 - copy constructor creates an object based on another object
 - there are certain language constructs where copy constructor is called automatically (like default constructor)
 - * eg. passing by value, returning an object, copy constructing (String t(s);)
 - alternate syntax for copy construction String s3 = s1;
 - * initializing a brand new object
 - compiler writes its own **default** copy constructor, simply copies each member into copy (*shallow copy*)
 - using compiler generated copy constructor with **dynamically** allocated objects can lead to issues
 - * error trying to delete dynamic objects **multiple** times

- using copy constructor on classes composed of other classes with their own copy constructor
 - * **automatically** calls those specific classes' copy constructors

Assignment Operator

- copying is **NOT** the same as assignment!
 - assignment operator does **NOT** call copy constructor
 - * can only construct once
 - * copy constructor theoretically wouldn't work in this case either, doesn't delete old dynamic memory
 - constructor: **nothing** in this to begin with (initialization)
 - assignment: there **is** stuff in this to begin with
 - compiler generated assignment operator copies each member (*shallow copy*)
 - make sure to check for errors from aliasing (don't sink your own ships)
- you can overload **operators** in c++
 - example syntax in prototype: void String::operator=(...)
 - * eg. s.operator
 - can only overload **existing** operators
 - for assignment operator, convention is to return (*this) as a String reference in order to allow for **chain** assignment
 - * assignment associates from right to left
 - * eg. i = j = k = 0;
 - have to ensure assigning an object to itself still works
 - * eg. i = i;
 - * otherwise, we may delete dynamic memory and then try to access there **again**

Inline Methods

- inline function code is **embedded** directly into the calling function by the compiler (for speed)
 - all functions with their body defined in their class are automatically inline
 - speed up program, but may make the .exe file larger

```
2 inline int bar(int a) // in function prototype
  inline int foo::bar(int a)
  inline ItemType foo<ItemType>::bar(ItemType a)
```

Data Structures and Algorithms

Linked Lists

- types of arrays so far:
 - *fixed size* array
 - * number of elements **has** to be known at compile time
 - * keep track of size
 - *dynamically allocated* array
 - * now number of elements **doesn't** have to be known at compile time
 - * but, now have to keep track of current size *as well as* max capacity
 - could be done with numbers or pointers
 - *resizeable* array (vector)
 - * when going over capacity, dynamically allocate a **larger** array
 - how much to extend capacity by?
 - general rule of thumb, 1.5 * current capacity
 - * copy all items into new array
 - * delete old array, reassign to new array and increase capacity
- Pros and Cons of Arrays
 - **Pros**
 - * same time to access each element
 - compiler knows where elements are stored contiguously
 - * easy to add to the end of the array
 - **Cons**
 - * hard to *maintain the order*, such as inserting in the **middle** or **beginning**
 - weigh pros and cons when considering data structures!
 - difficult to insert in the middle because memory for an array is contiguous
- how to make a data structure where the memory is *incontiguous*?
 - each value could hold a pointer to the next!
 - 65 -> 35 -> 69 -> 420 -> 666
 - how to signify end of the sequence? use nullptr
 - have a variable hold the first element of the list

Possible Approaches

- this is a **linked list**!
 - **first** element: **head** / **front**
 - each element is a **node**

- **last element: tail / back**
- to insert in the middle, instead of having to shift elements:
 - * allocate a **new node**
 - * put data of interest in **new node**
 - * **new node** points to previous node's next node
 - * previous node points to **new node**
- only way to traverse right now is **forward** through the pointers, one step at a time
- can't jump into the **middle** of the list
- other considerations:
 - * save pointer to the last node if doing operations often around the tail
 - but in a one item list, head = tail
 - * have each node also point to the previous node (*doubly-linked list*)
 - much easier to insert and delete
 - don't have to go through the loop again to find the previous node
 - can also travel **backwards**
 - * make a *circular list*
 - last node points back to the head
 - *no more nullptr's*, fewer special considerations (but head, tail, empty **still** special cases)
 - * add a *dummy node*
 - even though it doesn't hold a value, now there is **always** at least one node present
 - *no more special cases!*
 - acts as a placeholder
 - no longer needs a tail pointer

General Tips

- **Tips:**
 - general rule: any time you write p->something, *make sure to check*
 - * p has previously been **given** a value
 - * p is **not** the nullptr
 - **draw diagrams!**
 - * check *typical situation* (activity in the middle), at the head, at the tail
 - * empty list, one-element list
 - don't do things in the *wrong order*
 - * general rule: set values in the new node **first**

Implementation


```
1 struct Node
2 {
3     int data;
4     Node* next; // this is fine to the compiler, but can't have a node within a node
5 };
6
7 struct Node // doubly-linked list
8 {
9     int data;
10    Node* next; // successor
11    Node* prev; // predecessor
12 }
13
14 Node* head; // head points to the first element
15 // if head == nullptr, list is empty
16
17 // Print out all values of the list
18
19 // while (head != nullptr)
20 // {
21 //     cout << head->data << endl;
22 //     head = head->next;
23 // } // but now we can't go backwards, we lost head pointer!
24
25 for (Node* p = head; p != nullptr; p = p->next)
26     cout << p->data << endl;
27
28 // Find an element of the list
29
30 Node* p;
31 for (p = head; p != nullptr && p->data != 42; p = p->next)
32     ;
33 if (p == nullptr)
34     cout << "Target value is not in the list" << endl;
35 else
```

```
    cout << "p->data is " << p->data << endl;
37 // check for nullptr everywhere! can't cout a nullptr
    // what if the element isn't in the list?
39 // would this work with an empty list?
    // short-circuit with p != nullptr!
41
    // Insert element after another
43
    Node* p;
45 for (p = head; p != nullptr && p->data != 42; p = p->next)
        ;
47 if (p != nullptr)
    {
49     Node* newGuy = new Node;
        newGuy->data = 32;
51     newGuy->next = p->next;
        p->next = newGuy;
53 }
```

Stacks and Queues

- collection of data, but with a **limited** possibility of actions
- if so, implementing the data structure could be **simpler**

Stacks

- eg. the data structure runtime has to maintain:
 - calling a function suspends the current function
 - opens a new environment for the new function
 - falls back to the previous environment
 - all additions and removals happen at the **end** of the structure!
- new items **always** inserted at the end, only **last** item can be removed
- **LIFO** - *last in, first out*
- this is a **stack**!
- **Stack**:
 - create an empty stack
 - push an item onto a stack
 - pop an item from the stack (only when not empty)

- look at the top item on the stack (only when not empty)
 - is the stack empty?
- more possible stack functionalities
 - how many items are in the stack?
 - look at any item in the stack

Queues

- what about similar, but with waiting in line? (first in line is served first)
- new items **always** inserted at the end, but only **first** item can be removed
- **FIFO** - *first in, first out*
- this is a **queue**!
- **Queue**:
 - create an empty queue
 - enqueue an item (at the tail / back)
 - dequeue an item (from the head / front) (only when not empty)
 - look at front item in the queue (no need to look at back of the queue) (only when not empty)
 - is the queue empty?
- more possible queue functionalities
 - how many items are in the queue?
 - look at the back item in the queue
 - look at any item in the queue
- these aren't low level data structures, both can be **implemented** with arrays or linked lists
- these have limitations, rather than *general purpose* arrays / linked lists

Priority Queues

- *priority queue* - extension of queue, every item has a *priority value*
 - items of same priority ordered by **FIFO** (so a queue)
- eg. printer printing pages: 1000, 1, 1
 - if treated as a normal queue, average wait time would be ~1000 for each print job
 - if instead we **prioritize** shorter print jobs, average wait time would be ~350 for each print job
 - * should also include an “aging scheme” so that items in the queue for a long time eventually get processed
- unsorted sequence:
 - *insertion*: $O(1)$ (just push end)
 - *remove*: $O(N)$ (find highest priority item)

- sorted sequence:
 - *insertion*: $O(N)$ (insert in order)
 - *remove*: $O(1)$ (just pop end)
- BST:
 - *insertion*: $O(\log N)$
 - *remove*: $O(\log N)$
 - but if we're always approaching from the top side of the BST, high time complexity to rebalance the tree...
 - * use a **heap**!

Syntax

```
1 #include <stack>
   using namespace std;
3
   int main()
5 {
   stack<int> s;
7   s.push(10);
   s.push(20);
9   int n = s.top(); // n == 20
   s.pop();          // void! (varies with different libraries / languages)
11  if (!s.empty())
       cout << s.size();
13 }

15 #include <queue>
   using namespace std;
17
   int main()
19 {
   queue<int> q;
21   q.push(10);      // not enqueue / dequeue
   q.push(20);
23   int n = q.front(); // n == 10
   q.pop();
```

```
25  if (!q.empty())
    {
27      cout << q.size() << endl;
      cout << q.back() << endl; // c++ allows this
29  }
}
```

Stack Implementations

- with an array:
 - have to maintain capacity and current size
 - to push, assign value and increment size
 - to pop, simply **decrement** the counter
 - thus top is the “end” of array
- with a **linked list**:
 - maintain just head pointer
 - to push, add node to the head, not the tail
 - thus treat the head as the top, **easiest** to get to
 - to pop, remove node from head

Queue Implementations

- with an array:
 - have to maintain capacity, head, and tail
 - head at position 0, tail at position one beyond last item in queue
 - * number of items in queue then just tail - head
 - * to enqueue, assign value and increment tail
 - * if tail moved up to capacity
 - should we shift head and tail back to the beginning of the array?
 - could be array space usable before the head
 - eg. size of 2, but 98 spaces earlier in array with values that have been dequeued
 - instead, treat the array **circularly** and wrap back around!
 - called “*circular array*” or “*ring buffer*”
 - if head == tail, queue is either empty or full, how to distinguish?
 - instead maintain another variable for the current size
 - when dequeuing, would have to shift all values backwards
 - * instead, simply *shift the head forward!*
 - * head is position of the first item in queue

- with a **linked list**:
 - maintain head and tail pointers
 - to enqueue, add node to tail
 - to dequeue, remove node from head
 - unique case when empty or one element (*boundary case*)
 - usually no dummy node, singly linked (but tail still points to the end)

Evaluating Expressions with Algorithms

- eg. sample custom expression for a database could be:
 - dept = 'IT' and salary >= 70000 and name != 'SMITH'
- *Prefix Notation*:
 - does **not** need to consider precedence:
 - * every operator takes a certain number of operands
 - f(x,y,z)
 - add(sub(8, div(6, 2)), 1)
 - + - 8 / 6 2 1
- *Infix Notation*:
 - **issues** with precedence and associativity
 - 8 - 6 / 2 + 1
- *Postfix Notation*:
 - does **not** need to consider precedence
 - 8 6 2 / - 1 +

Evaluating Postfix Expression

- How do we parse through an infix expression *in one go* to solve these expressions?
 - **translate** into postfix and do it!
 - eg. 8 6 2 / - 1 +
 - * can use an *algorithm with a stack* to solve
 - * ever operator should match with two operands immediately before it
 - * going from left to right:
 - if at an operand, **push** it onto stack
 - if at an operator, **pop** its operands, and **push** the result of the expression
 - should end with a *single result* in stack
 - * ~~8 6 2 /~~
 - * ~~8 3 -~~
 - * ~~5 1 +~~

* 6

Translating Infix to Postfix

- How do we **translate** an infix expression into postfix?
 - also use an *algorithm with a stack*
 - going from left to right:
 - * if at an operand, put it in new postfix expression
 - * if at an operator and stack is empty, **push** it onto the stack
 - * otherwise if precedence is **strictly** higher than top of stack **push** it onto the stack
 - if top of stack is open parenthesis, always **push**
 - * otherwise if precedence is not **strictly** higher than top of stack, **pop** it from the stack, check again
 - * if come to open parenthesis, **push** it onto stack
 - * if come to close parenthesis, **pop** until we come to an open parenthesis
 - * at end, **pop** everything off the stack
 - eg. $8 - ((2 + 1) * 2 - 3) + 4$
 - **Expression:** $8\ 2\ 1\ +\ 2\ *\ 3\ -\ -\ 4\ +$
 - **Operator Stack:** $-\ ((\ +) \ *\ -) +$

Trees

- tree has a distinguished node (*root*), and one **unique** path from the root to **any** node
 - *parent / child* node relationships
 - *leaf* node has no children vs. *interior* node
 - *depth* of a node
 - *height* of the tree (max node *depth*)
- alternatively, every node *really only needs* two pointers / children (left and right)
 - called a **binary tree**
- every node has **data** and **pointers** to indicate structure of a tree
- operations with trees can be done more easily with *recursion*
 - *base cases* for trees:
 - * empty tree, sometimes leaf nodes
 - *recursive cases* must solve smaller problem:
 - * fewer nodes / breaking down into sub-trees
 - * shorter height
- information can be passed up or down the tree recursively
- **processing patterns:**

- *pre-order traversal*:
 - * process node => process children of that node
- *in-order traversal*:
 - * for binary trees: process left subtree => process the node => process right subtree
- *post-order traversal*:
 - * process children of a node => process that node (passing info up)
- *level-order traversal*:
 - * process each level's nodes from left to right => process next level
- all $O(N)$
- draw counter-clockwise loop around tree to visualize:
 - * pre-order: dot on left
 - * in-order: dot under
 - * post-order: dot on right

Example

```

1 struct Node
2 {
3     string data;
4     // Node* children[5]; // instead, variable number of children
5     vector<Node*> children; // "singly-linked"
6     Node* parent;          // "doubly-linked", optional
7 };
8
9 Node* root = nullptr;      // empty tree
10
11 // approach with a stack, or with recursion ...
12 int countNodes(const Node* t)
13 {
14     if (t == nullptr)      // only base case is empty tree, leaf node handled
15         generally
16         return 0;
17     int total = 1;
18     for (int k = 0; k < t->children.size(); k++)
19         total += countNodes(t->children[k]);
20     return total;

```



```

20 }

22 // print indented list
void printTree(const Node* t, int depth = 0); // default parameter for depth in
    prototype

24 // void printTree(const Node* t) // have to keep track of depth for indents
26 void printTree(const Node* t, int depth)
{
28     if (t != nullptr)
    {
30         cout << string(2*depth, ' ') << t->data << endl; // temporary string with space
            chars
            for (int k = 0; k < t->children.size(); k++)
32         {
            // cout << " "; // won't work, subtrees don't know how
            deep they are
34             // printTree(t->children[k], ++depth); // reassigning depth!
            printTree(t->children[k], depth+1);
36         }
    }
38 }

40 // could overload printTree() with helper function
void printTree(const Node* t) { printTree(t, 0); }

42
44 int main()
{
    Node* windsor;
46     ...
    printTree(windsor); // could overload printTree() or just use default parameter
48 }

```

Binary Trees

- any valid tree can be represented as a binary tree

- either empty, or a node with a left binary subtree and a right binary subtree
- how to *convert* a tree with arbitrary number of children to a binary tree?
 - left points to one of the children, right points to “siblings”

```
1 struct Node
2 {
3     string data;
4     Node* left;
5     Node* right;
6 }
7
8 // eg. for a family tree
9 struct Node
10 {
11     string data;
12     Node* oldestChild;
13     Node* nextYoungerSibling;
14 }
```

- *complete binary tree* is a binary tree that is filled at every level
 - except possibly the bottom, which is filled left to right
 - only one configuration for every number of filled nodes

Binary Search Tree

- special application of a binary tree
- either empty, or a node with a left BST and a right BST such that:
 - the value at every node in the left BST is \leq the value at this node and
 - the value at every node in the right BST is \geq the value at this node
- *traversals* always $O(N)$, visit every item
- *search*: $O(\log N)$, similar to binary search on a sorted array
 - worst case $O(N)$
- example *insert* algorithm: ($O(\log N)$, search and then insert)
 - if empty, add as first node
 - otherwise, if less than current item, follow nodes to the left
 - otherwise, if greater than current item, follow nodes to the right
 - loop recursively
 - but this could lead to **unbalanced** sort trees with $O(N)$ searching!

- example *removal* algorithm: ($O(\log N)$, search and then insert)
 - must keep track of parent
 - if target is a leaf node:
 - * *unlink* from its parent (set parent to point to nullptr) and *delete* it
 - if has one child:
 - * *relink* its parent to target's only child and *delete* it
 - if has two children:
 - * **replace** its values with: (don't actually *delete* the node itself)
 - the largest value in its left subtree and *then delete* that node
 - ie. one step to the left and all the way to the right
 - the smallest value in its right subtree and *then delete* that node
 - ie. one step to the right and all the way to the left
 - thus, this utilizes a simpler deletion algorithm for the replacement
 - how do we choose which value to promote when deleting a node?
 - * alternate left and right, or just randomly choose
- **balanced BST's**:
 - **AVL tree** - height of left subtree and right subtree differ by no more than one
 - * *search*: always $O(\log N)$, always balanced
 - * *insertion*: first insert using “dumb” algorithm and then rebalance the tree ($O(\log N)$, worse constant than “dumb” approach)
 - * *deletion*: $O(\log N)$, worse constant than “dumb” approach
 - **2-3 Tree** - every node has two children (holds 1 value) or three children (holds 2 values)
 - * all leaf nodes are at the same depth
 - * *search*: don't have to go as deep
 - * *insertion*: combination of splitting and promoting nodes
 - **Red-Black Tree** 2-3-4 trees - can represent structure using regular BST's
 - * each node has extra boolean value defining its type / rules
 - * no adjacent red nodes, every path from root to descendant has same number of black nodes
 - * left and right subtrees differ up to a factor of 2
 - * *less work* for balancing, but good enough
 - * *all operations*: $O(\log N)$, better constant for insert / deletion than AVL tree
 - * used with STL containers, eg. set

```
struct Node
```

```
{
```

```
4  string data;
   Node* left;
   Node* right;
6  }

8  // inorder traversal
   void printTree(const Node* t)
10 {
    if (t == nullptr)
12     return;
    printTree(t->left); // print left subtree
14     cout << t->data << endl;
    printTree(t->right); // print right subtree
16 }
```

Hash Table

- we want to organize items indexed by ints, eg. 40,000 9-digit student IDs with student records
- if we had an array that is subscripted by the ID
 - lookup would be **constant** $O(1)$, simply jump to the subscripted ID!
 - **BUT** wasted space in the array (1 billion slots in array, and what if the student record is large)
- now, have the array hold pointers instead of the actual student record
 - less space needed (only allocate 40,000 student records), but still empty slots in array
- now, organize the student ID's into various **buckets**
 - easy to determine what bucket student ID belongs to
 - can check even fewer elements in that bucket
 - * buckets can be *empty* or have different *number* of items
 - eg. bucket number is last 4 digits of the student ID, 10,000 buckets with 4 elements each
- general *insert* algorithm:
 - determine which bucket
 - add item into bucket
 - * order of items in a bucket doesn't matter, so few items, just use the simplest insert operation
 - * eg. front of a linked list

- this is a **hash table**!
- **collision** - two different keys map to the same bucket
- **load factor** = # of items / # of buckets
 - tradeoff between many empty buckets and a long list
 - as load factor increases, collision chance and search time increase
 - * 0.7 load factor
- hash table with **fixed** number of buckets is actually $O(N)$ but with a really low constant of proportionality
 - eg. for the student ID's, $O(\frac{1}{10000}N)$
 - slower as buckets become more full
 - for large enough N , BST still wins out!
- *compared to BST*:
 - hash table has a *start-up* time
 - * must initialize the buckets to nullptrs!
 - BST allows for easy sorted order *traversal*
 - * possible solution with hash table:
 - every item in a bucket has a pointer to the next ordered item
 - probably doubly-linked
 - so, go with hash table **unless** we want to visit items in order
 - * but if we don't have to visit sorted items often...
 - simply add all items from hash table into a vector, then sort the pointers / values
 - this is $O(N\log N)$, worse than $O(N)$ for BST traversal
 - but BST costs $O(\log N)$ for *every* insert
 - * paying $O(\log N)$ cost somewhere, hash table may be more efficient

Dynamic / Resizable Hash Table

- *fixed* limit on the load factor
- resize hash table and **reallocate** entire table with new buckets once limit is reached
 - eg. twice as many buckets
 - but now keys may be rehashed to different buckets (mod buckets gives a different value)
 - * must be re-added
 - then add the new item
 - newly reallocated table has low load factor, then starts to fill up until max load factor
- has constant time $O(1)$, but every so often has to do a rehash $O(N)$ when inserting
 - but **on average**, still $O(1)$! (*amortized*, averaged)

- however, big rehashes can cause spikes of bad time complexity
- instead, use **incremental** rehashing:
 - rehash some of the table at one time instead of entire table (eg. 5 elements)
 - when new table is partially rehashed:
 - * search, insertion, and deletion must check *both* tables (still $O(1)$)
 - every insertion / deletion will incrementally rehash more elements from the first table
 - but now, **every** insertion has a constant runtime!
 - * ie. 20% of the time, in two-table mode, have a higher constant runtime

Hash Functions

- **hash function** - key \rightarrow integer (then take integer and scale to number of buckets)
 - then, integer mod number of buckets to scale to buckets
 - eg. strings, add up the ASCII codes; /1000 or %1000 for numbers
 - * could also multiply ASCII codes
 - * selecting digits, folding (adding digits), modulo arithmetic, string to int
 - use a prime number for number of buckets
 - * eg. $h(x) = x \% \text{numBuckets}$
 - * reduces collisions
 - * deals with distributions that aren't uniform
 - want cheap, deterministic, uniformly distributed result
- collision resolution schemes
 - *linear probing* - **closed** hash - data stored in a fixed-size array
 - * “closed” number of buckets
 - * if bucket is occupied, scan down from bucket until we hit the first open bucket
 - buckets represented as arrays
 - if at end of buckets, wrap around to the front
 - when searching, now have to probe linearly until we find our value or hit empty bucket
 - * issue of primary clustering (values are as close to intended bucket as possible)
 - longer probing sequences and time to search
 - difficult to delete items, limit on # of items to hold!
 - deleting items may disrupt the linear probing
 - * less efficient, faster growth in search time
 - * more memory efficient
 - * average number of checks for insert/find: $\frac{1}{2}(1 + \frac{1}{1 - L})$

- *separate chaining* - **open** hash tables - data stored in linked-lists, **not** size-limited
 - * in case of collision, just add another value to the linked-list
 - * more efficient, slower growth in search time
 - * average number of checks for insert/find: $1 + L/2$
- sample hash function for strings:

```

// FNV-1 variation (Folwer-No-Vo) - fast while maintaining low collision with high
// dispersion
2 unsigned int h = 2166136261U; // ensure positive, U removes compiler warning for
// large integer
// "offset basis"
4 for (int k = 0; k < key.size(); k++)
{
6   h += key[k];
   h *= 16777619; // FNV_prime, eg. 2^40 + 2^8 + 0xb3
8 }

10 // STL hash function
#include <functional>
12
unsigned int hashFunc(const std::string& key)
14 {
   std::hash<std::string> str_hash; // define string hashing object
16   unsigned int hashValue = str_hash(key);
   return hashValue % NUM_BUCKETS;
18 }

```

Heap

- **(max) heap** - a complete binary tree where each node has a value \geq all the nodes in its subtrees
 - order and what's in each child isn't important...
- eg:

```

2      60      80
      40  50  70  20
4  10  30

```

- **min heap** - a complete binary tree where each node has a value less than or equal to all the nodes in its subtrees
- is a complete binary tree
- *insertion*:
 - first add the item to make a complete binary tree (only one possible location)
 - then, if the item is greater than its parent, simply swap them
 - * “bubble” up the new items to its proper position (reheapify)
 - * $O(\log N)$ to bubble up
- *removal*: (only want to remove max item)
 - remove root
 - promote bottom-most item (of complete binary tree) and **promote** it to the root
 - * ie. remake tree into a complete binary tree
 - “trickle” down the root to its proper position (reheapify)
 - * at each level, make sure parent is larger than both its children
 - $O(\log N)$ to trickle down
- **heap sort / partial heap sort**:
 - insert all items into a heap ($O(N \log N)$) and then extract however many items ($O(K \log N)$)
 - uses heaps to sort an array partially, eg. top N items
 - approximately $O(N \log N)$
- but in either case, have to calculate position of the bottom-right node / parent and children nodes in the tree
 - there is another representation that allows for this calculation to be done in constant time
 - * use arrays!
- number nodes from left to right, top to bottom from 0 to $N-1$, and use that number as the index in an array
 - given node number i , is there a formula that generates the parent and children of i ?
 - * $(i-1)/2$ gives the parent of i (using integer division)
 - * $2i+1$ and $2i+2$ gives the children of i , provided they are less than the number of nodes
 - now it is constant time to find the bottom-most item of the tree! (given at

N-1)

- can still use the same bubble up / trickle down algorithms (they still have the same complexity)
- use array *operations* but visualize with a tree!

Tables

- made up of multiple *records* (represented by a struct)
 - each record has related *fields*
- a table can be represented by a collection of structs
- how to efficiently search by different fields (eg. name, ID, phone number)?
 - retain one table, but:
 - use secondary data structures called *indexes*
 - * eg. maps mapping name to slot in vector, id to slot in vector, etc.
 - when updating and deleting records, must update across all indexes
- use BST to store data in order
- use hash table for fast searching when order isn't important (eg. phone numbers)

Graphs

- made up of **nodes** (vertices) and **edges** (arcs) connecting them
 - graphs can have *undirected* or *directed* edges
 - * *cyclic* graph where a path leads back to a node vs. *acyclic* graph
 - * directed, acyclic graphs are relatively common
- graphs can model many different types of problems
- there are many graph algorithms of different time complexities
 - “graph theory”
 - eg. *topological sort*
- *implementation*:
 - use a 2-d array if lots of edges between vertices but few vertices
 - each element indicates if there is an edge between vertex i & j
 - * called an **adjacency matrix**
 - multiplying an adjacency matrix by itself yields a matrix showing us vertices 2, 3, etc. edges apart
 - could also use an array of lists if few edges and many vertices
 - * eg. list graph[n]
- breadth-first and depth-first traversals also apply to graphs
 - forward until dead end vs. exploring graph in growing concentric circles
- can have *weighted* edges on graphs
 - use Dijkstra's Algorithm to find the shortest path between any two nodes

in a graph

- * uses settled / unsettled vertices

Standard Template Library (STL)

- we've seen stacks and queues in the STL
- using STL requires *using namespace std*

Vectors

- dynamically resizable array
- error checking **not** built into subscript operator, because it would be expensive!
 - to be safe, check if subscript is out of bounds
- at() function *does* do bounds checking
- inserting in the middle is expensive
- jumping to different elements is cheap (via brackets)

```
#include <vector>
2 using namespace std;

4 vector<int> vi;
  vi.empty(); // true
6 vi.push_back(10);
  vi.push_back(20);
8 vi.push_back(30); // no push_front()
  cout << vi.size(); // writes 3 (doesn't work for arrays!)
10 cout << vi.front(); // writes 10
   cout << vi.back(); // writes 30
12 vi[1] = 40; // gives a reference to that value, vi[3] = 50; would be
   // undefined behavior
   for (size_t k = 0; k < vi.size(); k++) // size_t, unsigned integer type
14   cout << vi[k] << endl;
   // writes 10 40 30, one per line
16 vi.pop_back(); // undefined if vector is empty, vi.empty()
   for (size_t k = 0; k < vi.size(); k++)
18   cout << vi[k] << endl;
```

```

    // writes 10 40, one per line
20 vi.at(1) = 60;
    vi.at(3) = 70;    // throws exception
22
    vector<double> vd(10);    // vd.size() is 10, each element is 0.0
24 vector<string> vs(10, "Hello"); // vs.size() is 10, each element is "Hello"
    int a[5] = { 10, 20, 30, 40, 50 };
26 vector<int> vx(a, a+5);    // passing a range of values in a container
    // vx.size() is 5, vx[0] is 10, vx[1] is 20, ..., vx[4] is 50
28
    // optionally:
30 vector<int> vx = {10,20,30,40,50}; // C++11
    vector<int> vx {10,20,30,40,50}; // C++11
32 vector<int> vx(100);    // all 100 elements are default initialized /
    constructed

34 // common mistake:
    vector<int> vi;
36 // vi[0] = 10; // undefined! vi.size() is 0, no elements!

```

Implementation

- *data members*:
 - dynamically allocated array
 - size
 - capacity
- *empty*:
 - nullptr to array
 - size, cap of 0
- *at full capacity*:
 - allocates a larger capacity, copies values, deletes old values, retargets pointer, update capacity
- this means saving a pointer can leave a dangling pointer *later on* after a push-back!
 - *anything pointing* to the vector can become **invalidated**!
 - remember the position instead of saving a pointer...

List

- linked list
 - similar functions as the vector class (push_back, pop_back, front, back, size, empty)
 - * but *also* has push_front and pop_front
- subscript and at() are **not** given with a list!
 - very expensive
- inserting / deleting in the middle is not as expensive
- jumping to elements is expensive

```
#include <list>
2 using namespace std;
  list<int> li;
4 li.push_back(20);
  li.push_back(30);
6 li.push_front(10);
  cout << li.size(); // writes 3
8 cout << li.front(); // writes 10
  cout << li.back(); // writes 30
10 li.push_front(40);
  li.pop_front(); // also pop_back()
```

Set

- *associative containers*:
 - designed so that searching for items is efficient
- eg. a set is a collection that **doesn't** allow duplicates
 - more efficient than searching in an unordered container
 - no [] operator!
 - * but *can* iterate over the container
 - guaranteed to iterate through set *in order* using < operator
 - requirement for items in set to have < operator *defined*
 - set's definition of duplicate:
 - !(a < b) and !(a < c), then a == b
 - this definition only works well with total ordering (eg. not case-sensitive strings)
 - other containers use different operators for ordering

- set and multiset use a Red-Black Tree (BST) for implementation
 - standard requires logarithmic time for all operations
 - multiset allows for duplicate values
- unordered_set / unordered_multiset use a Hash Table implementation
 - #include
 - unordered_set.find(x)

```
#include <set> // defines std::set and std::multiset
2
set<int> s;
4 s.insert(10);
s.insert(30);
6 s.insert(20);
s.insert(10);
8 cout << s.size(); // writes 3
if (s.find(20) == s.end())
10 ... not found ...
for (set<int>::iterator p = s.begin(); p != s.end(); p++)
12 cout << *p << endl;
// guaranteed to write out 10 20 30
14 s.erase(10);
```

Map

- another *associative container*
- maps one related value to another
 - eg. people to their phone number, ie. strings to ints
- maps can only associate in **one** direction!
 - to search efficiently in both directions, need *two* maps
- **doesn't** allow duplicates
- map class stores each association in a **struct** variable:
 - eg. string first, int second
- use iterators to traverse through
 - can access first and second variables similar to a struct
- maps are automatically maintained in *alphabetical* order for the key!
 - thus if associating a complex data type, operator **<** **must** be defined to order items

- * but only for the **left-hand** side of the map (key)
- map and multimap use a Red-Black Tree (BST) for implementation
 - $O(\log N)$ for all operations
- multimap allows for duplicate keys
- unordered_map / unordered_multimap use a Hash Table implementation
 - requires `<`, `==` operator
 - a hash function for the type
 - * provided for built-in type, strings, thread-ID's, etc.
 - * have to write hash function for other custom types

```

#include <map> // defines std::map and std::multimap
2  using namespace std;

4  map<string, double> ious;
   string name;
6  double amt;
   while (cin >> name >> amt)
8     ious[name] += amt; // overloaded subscript operator, can add new maps or update
                          maps in this way

10  cout << ious.size() << " people owe me money" << endl;
     for (map<string, double>::iterator p = ious.begin(); p != ious.end(); p++)
12     cout << p->first << " owes me $" << p->second << endl;

14  map<string, int> name2Phone; // string to int, but not the other way around!
     name2Phone["Carey"] = 0001112222;
16  name2Phone["Joe"] = 2223334444;
     // name2Phone[1112223333] = "Ed"; // doesn't compile

18
     map<string, int>::iterator it;
20  it = name2Phone.find("Joe"); // locate an association
     if (it == name2Phone.end())
22     cout << "not found!" << endl;
     else
24  {
       cout << it->first; // look at the pair of values pointed to by

```

```

    iterator
26     cout << it->second;
    }
28
    map<int, string> fones2Names;    // int to string
30
    // dealing with duplicate keys:
32
    // use a multimap...
34    // equal_range() returns a pair of iterators indicating the range of equal keys
    multimap<string, double> borrowings;
36    pair<multimap<string, double>::iterator, multimap<string, double>::iterator> pr =
                                   borrowings.equal_range("fred");
38    if (pr.first == pr.second)
        ...not found...
40    else
        for (multimap<string, double>::iterator p = pr.first; p != pr.second; p++)
42        cout << "fred borrowed $" << p->second << endl;

44    // alternatively, use a map with another STL container for more than one value
    map<string, list<double>> borrowings;
46
    // unordered_map as a hash table
48    #include <unordered_map>
    using namespace std;
50
    unordered_map<string, double> ious;

```

Auto Keyword

- how to *reduce* verbeage when declaring iterators?
- declaration: `sometype v = initializer;`
- **auto** keyword sets variable type to the initializer automatically in a declaration
 - type is determined at compile time (NOT a varying type)

```

1 // pair<multimap<string,double>::iterator, multimap<string,double>::iterator> pr =
  borrowings.equal_range("fred");
  auto pr = borrowings.equal_range("fred"); // returns a pair, pr will be a variable of
  type pair, less redundant
3
  // for (multimap<string,double>::iterator p = pr.first; p != pr.second; p++)
5 for (auto p = pr.first; p != pr.second; p++)

7 // map<string,int>::iterator p = ious.find("fred");
  auto p = ious.find("fred");
9
  auto* p = new Circle(...); // p is Circle*
11 auto* p = f(...);           // if f returns a Shape*, p is Shape*

```

Iterators

- nodes and pointers in the list class are hidden from the user (they are abstracted away)
- instead provide something that acts like a pointer, called an **iterator**
 - no longer have to do messy pointer work
 - abstract way of traversing through elements
 - iterator is a class type, `begin()` and `end()` return iterators
- we can follow iterators with dereference operator, and use `++` and `--`
 - but can **not** use general pointer arithmetic, eg. adding 7 to an iterator
 - * but you **can** with **VECTORS!** (cheaper!)
- using iterators, possible to:
 - *loop / traverse* through a list
 - *insert* a value (value is inserted just *before* the passed iterator)
 - * returns an iterator pointing to the inserted value
 - * passed iterator remains the same (*unless* used with a vector, then becomes **UNDEFINED** to use!)
 - when inserting a value into a vector, the vector may have been **RESIZED** and **REALLOCATED!**
 - when reallocation occurs, **all** iterators become invalidated!
 - but when `begin()` and `end()` are *recalled* they return a valid iterator
 - *erase* a value (erase value passed iterator is pointing to)
 - * returns an iterator pointing to the value after the erased value
 - * the passed iterator becomes **UNDEFINED** to use!

- iterators *can't* hold a value of nullptr!
- sometimes need to use a const iterator (when a container is passed as const reference)
- notes on lists: (doubly-linked list)
 - *cannot* use [] operator
 - *cannot* use comparison operators with iterators (>, <, <=, >=), there is no valid ordering
 - using iterator to traverse a list is always safe
- notes on vectors: (dynamic array)
 - *can* use [] to access elements in a vector
 - comparison operators are *valid*
 - but could **invalidate** iterators when using push_back()

```

1  structure<data type>::iterator it      // a pointer to an element in a container
2  structure<data type>::const_iterator it // constant iterator for constant reference
   li.begin(); // an iterator pointing to beginning of the list
4  li.end();   // an iterator pointing to just after last value of the list
           // can't follow the iterator here, must decrement first!
6  li.back();  // an iterator pointing to the last element of the list

8  // can use these iterators to initialize a vector
   list<double> ld(10);           // ld.size() is 10, each element is 0.0
10 list<string> ls(10, "Hello");   // ls.size() is 10, each element is "Hello"
   vector<string> vs(ls.begin(), ls.end()); // vs.size() is 10, vs[0] is "Hello", vs[1]
           is "Hello", ..., vs[9] is "Hello"

12 // Iterators with Lists:

14 for (list<int>::iterator p = li.begin(); p != li.end(); p++)
16     cout << *p << endl; // writes 10 20 30, one per line
   // can also use rbegin() and rend() for reverse traversal (still would increment to
   // advance the iterator)

18 // can also use constant iterators to promise not to change the list

20 list<int>::iterator p = li.end();
   p--;
22 p--; // given a list with {10, 20, 30}, p points to 20

```

```
// p -= 2 won't compile
24
list<int>::iterator q = li.insert(p, 40); // insert() inserts value just before the
    iterator
26 // list is now {10, 40, 20, 30}
    // q points to 40 (the inserted value), p still points to 20
28
list<int>::iterator q = li.erase(p);      // erase() erases value iterator points to
30 // list is now {10, 40, 30}
    // q points to 30 (value after erased value), now UNDEFINED to use p!
32
for (list<int>::iterator p = l.begin(); p != l.end();)
34     if (*p == 30)
        p = l.erase(p); // remove value pointed by p, and reassign the return value back
            to it (no need to increment)
36     else
        p++;
38
// Iterators with Vectors:
40
vector<int>::iterator p = vi.end() - 2;
42 // given a vector with {10, 20, 30}, p points to 20
44
vector<int>::iterator q = vi.insert(p, 40); // insert() inserts value just before the
    iterator
    // vector is now {10, 40, 20, 30}
46 // q points to 40 (the inserted value), now UNDEFINED to use p! (vector could have
    been RESIZED and values REALLOCATED!)
48 p = vi.erase(q);                      // erase() erases value iterator points
    to
    // vector is now {10, 20, 30}
50 // p points to 20 (value after erased value), now UNDEFINED to use q!
```

Iterators with Templates

A find function:

```
2 // b points to beginning, e points to just after the end
3 int* find(int* b, int* e, const int& target)
4 {
5     for ( ; b != e; b++)
6         if (*b == target)
7             break;
8     return b; // going to be generalized later for iterators, can't return nullptr
9 } // we return just past the end value if target not found

10 // Template Version:
11 template<typename T>
12 T* find(T* b, T* e, const T& target)
13 {
14     for ( ; b != e; b++)
15         if (*b == target) // T must have an equality comparison operator
16             break; // but this WOULDN'T work when called with "Fred" (a pointer to
17                 // a char array!)
18     return b; // we want to decouple the target type from the traversing type
19                 // (to use with pointers / iterators)
20 }
21 string* sp = find(sa, sa+4, string("Fred")); // would need a temporary string object
22                 // to use correct equality comparison

23 // Template Version w/ Iterators:
24 template<typename Iter, typename T>
25 Iter find(Iter b, Iter e, const T& target)
26 {
27     for ( ; b != e; b++)
28         if (*b == target) // CAN compare string (*b) to a char pointer!
29             break;
30     return b;
31 }
```

```

int* p = find(a, a+5, k);
32 if (p == a+5)
    ... not found ...
34
list<string>::iterator q = find(ls.begin(), ls.end(), "Fred");
36 if (q == ls.end())
    ... not found ...
38
vector<int>::iterator r = find(vi.begin(), vi.begin()+5, 42);
40 if (r == vi.begin()+5)
    ... not found ...

```

STL Algorithms

- `#include`
- `find(v.begin(), v.end(), val)`
 - also works with arrays: `find(&a[0], &a[5], 19)`
- `reverse(v.begin(), v.end())`
- `sort(v.begin(), v.end())` (uses quick sort, not supported with list, needs random access)
 - list has its *own* sort member function (special case, uses merge sort)
- `set_intersection()` - compute intersection of two sorted collections of data
- can pass a **predicate function** with many of these functions:
 - calls that predicate function on each of the elements!

```

1 template<typename Iter, typename Func>
  Iter find_if(Iter b, Iter e, Func f)
3 {
    for ( ; b != e; b++)
5         if (f(*b)) break; return b;
    }
7
bool isNegative(int k) { return k < 0; }
9 bool isEmpty(string s) { return s.empty(); }

11 int main()
    {

```

```
13  vector<int> vi;
    vector<int>::iterator p = find_if(vi.begin(), vi.end(), isNegative);
15  if (p == vi.end())
    ... not found ...
17  list<string> ls;
    list<string>::iterator q = find_if(ls.begin(), ls.end(), isEmpty);
19  }

21  bool isGreater(int i, int j) { return i > j; }
    bool makesLessThan(const Employee& e1, const Employee& e2) { return e1.salary() < e2.
        salary(); }
23  bool hasBetterRecord(const Team& t1, const Team& t2)
    {
25      if (t1.wins() > t2.wins())
        return true;
27      if (t1.wins() < t2.wins())
        return false; return
29      t1.ties() > t2.ties();
    }
31

    int main()
33  {
    vector<int> vi;
35    sort(vi.begin(), vi.end()); // uses <
    sort(vi.begin(), vi.end(), isGreater);
37    Employee ea[100];
    sort(ea, ea+100, makesLessThan);
39    vector<Team> league;
    sort(league.begin(), league.end(), hasBetterRecord);
41

    list<int> li;
43    li.sort(); // uses <
    list<Employee> le;
45    le.sort(makesLessThan);
    }
47
```

```
// pointers to functions:
49 int (*ptr) (int); // ptr points to any function that returns an int and takes a
    single int
    ptr = squared;
51 cout << ptr(5);
```

Recursion

- to solve larger problems, *break down* into smaller problems
 - but there needs to be one or more *base cases* (stopping condition)
 - * ie. situations that can be solved without a recursive call
 - proof of termination
 - *recursive cases* - must solve a smaller problem, closer to a base case (simplifying step)
 - * usually:
 1. divide input problem in **half** (merge sort)
 2. operate on input that is *one smaller*
 3. eg. back to front (last and the rest), front to back (first and the rest), divide and conquer
- eg. to **sort** an unsorted pile of N items
 - if ($N > 1$)
 - * split into two unsorted piles of $N/2$ items
 - * sort left subpiles
 - * sort right subpiles
 - * **merge** two resulting sorted subpiles into one sorted pile
 - base cases: N is 1 or 0
- some issues
 - odd N? merge algorithm still works
 - down to one item?
 - * would **continue** trying to sort/split a single item
 - * **infinite** recursion!
- some steps:
 1. write function header
 - find out what / num of arguments, return type
 2. define “**magic**” function
 - solves problem, but only with a smaller subset / n
 - **same** parameters and return type!

3. add base case code
 - deal with **simplest** possible inputs
4. solve problem w/ magic function (*recursive leap of faith*)
5. remove magic...
6. validate function
 - test with simplest possible inputs
 - test with incrementally more complex inputs
- recursion vs. iterative solutions?
 - for simple recursion (one recursive call), easily implementable with iteration
 - * iterative solution is usually *faster*
 - for more than one recursive calls, *simpler* to write and implement
 - * divide and conquer recursion
- recursion can be **expensive**! (lots of local variables)
 - **DON'T** use recursion when it isn't necessary!
 - don't let recursive calls get too deep
- can use *recursive helper functions* to simplify complex parameters
 - eg. binary search's confusing bot / top parameters

Recursion Examples

Sorting Algorithm

- **indexing**: a subarray starts at b and goes to one item before end

```
1 void sort(int a[], int b, int e)
  {
3   if (e - b > 1) // more than one element
    {
5     int mid = (b + e) / 2;
      sort(a, b, mid);
7     sort(a, mid, e);
      merge(a, b, m, e);
9   }
  }
```

Finding a Target

```
bool contains(int a[], int n, int target)
2 {
    if (n <= 0)
4         return false;
    if (a[0] == target)
6         return true;
    return contains(a+1, n-1, contains); // pointer arithmetic, start at second element
        of array
8 }
// Order matters!
10 bool contains(int a[], int n, int target)
{
12     if (n <= 0)
        return false;
14     if (contains(a+1, n-1, target)) // calls n recursive calls even if early element is
        already target
        return true;
16     return a[0] == target;
}
18 // Back to front!
bool contains(int a[], int n, int target)
20 {
    if (n <= 0)
22         return false;
    if (a[n-1] == target)
24         return true;
    return contains(a, n-1, contains);
26 }
```

- some initial issues:
 - never return false
 - have to check subscript / pointer arithmetic is valid
 - so, return false if $n \leq 0$
- optimize to reduce recursive calls
- front to back vs. back to front approach

Solving a Maze

```

1 bool solve(start, goal)
2 {
3     if (start == goal) // if we're at the goal
4         return true
5     mark this position as visited // check where we've been
6     for each direction
7         if moving one step is possible and not been visited,
8             if (solve(pos reached by that move), goal)
9                 return true
10    return false
11 }

```

- some initial issues:
 - don't check where we've been
 - starting at the goal
- is recursion solving a simpler problem?
 - distance not necessarily shorter, because of *walls*
 - mark where we have visited, reducing unvisited places

Big-O

-
- how do we categorize the speed of an algorithm?
 - can't just compare runtimes
 - * must account for hardware differences
 - count steps in the algorithm in terms of N
 - * any basic operation is a step
 - * but we don't really care for speed with a small N
 - * or about the exact details
 - so we can disregard the lower-order terms
 - * can also generalize and disregard the leading coefficient
 - finding the worst case scenario
 - a function $f(N)$ is $O(g(N))$, if there exists N_0 and k s.t. for all $N \geq N_0$, $f(N) \leq k * g(N)$
 - $f(N)$ is “order $g(N)$ ”

Operations with Arrays

- $O(1)$ - accessing elements in an array (*constant time*)
- $O(\log N)$ - binary searching elements in an array (*logarithmic time*)
 - always dividing in half, $\log_2 N$ gives number of comparisons
 - * can disregard base 2, all logarithms are proportional
 - grows very slowly over constant time
- $O(N)$ - searching elements in an array (*linear time*)
- $O(N \log N)$ - grows very slowly over linear time (*linear logarithmic time*)
- $O(2^N)$ - printing all possible subsets in a collection
 - one more item doubles the time

More Examples

Process for Evaluating Big-O

- work *inside-out*, starting from the most deeply nested statement
- have to account for *hidden* loops
 - eg. loops in embedded functions

```

1  for (int i = 0; i < N; i++)
    c[i] = a[i] + b[i];
3  // basic operations all take a constant amount of time
   // array subscript operator is simply multiplication and addition
5  // every loop takes constant time, runs N times, this algorithm is O(N)

7  for (int i = 0; i < N; i++) // entire algorithm is O(N^2)
  {                             // body of loop is O(N)
9    a[i] *= 2;                 // O(1)
    for (int j = 0; j < N; j++) // happens N times, O(N)
11     d[i][j] = a[i] * b[j];   // array subscripts are O(1)
  }

13 // work inside out, from most deeply nested statement
   // shouldn't assume every loop in a loop is O(N^2)...
15 // if inner loop only ran up to 100, algorithm would be O(N)
   // little trivial differences, eg. starting at 1 or going to N-1, aren't important
17
   for (int i = 0; i < N; i++) // entire algorithm is O(N^2)

```

```

19 {                                     // body of loop is  $O(N)$ 
    if (find(a, a+N, 10*i) != a+N) // find() is  $O(N)$ , comparison is  $O(1)$ 
21     count++;                       //  $O(1)$ 
}
23 // not just  $O(N)$  simply because there is one loop! (find() itself is  $O(N)$ !)
// have to count the hidden for loops!
25 // how do we account for if statements?
// for worst case scenario, assume body of if will always execute
27
for (int i = 0; i < N; i++) //  $O(N^2)$ 
29 {                         //  $O(i) + O(1) = O(i)$ 
    a[i] *= 2;              //  $O(1)$ 
31     for (int j = 0; j < i; j++) //  $O(i)$ 
        d[i][j] = a[i] * b[j]; //  $O(1)$ 
33 }
// sum of all numbers from 1 to  $N-1$  is  $\frac{1}{2} N^2 - \frac{1}{2} N$ 
35 // still  $O(N^2)$ ! (ignore constant proportionality, for now)

37 for (int i = 0; i < N; i++) //  $O(N^2 \log N)$ 
{                               //  $O(N \log N)$ 
39     a[i] *= 2;               //  $O(1)$ 
    for (int j = 0; j < N; j++) //  $O(N \log N)$ 
41         d[i][j] = f(a, N); //  $O(\log N)$ 
}
43 // given  $f()$  is  $O(\log N)$ 

45 // example with STL set
void addItem(set<int> &s, int q)
47 {
    for (int i = 0; i < q*q; i++) //  $O(Q^2 \log Q^2)$ 
49         s.insert(i);           //  $O(\log N)$  to insert
}
// in worse case,  $N$  will eventually become  $Q^2$ 

```

Multiple Variables

- what if the Big-O depends on multiple parameters / variables?

- have to keep track of both parameters!
 - * either variable could dominate the other

```

2 for (...R times...) //  $O(R \log C)$ 
  for (...C times...) //  $O(C \log C)$ 
    f(...c)           //  $O(\log C)$ 

```

STL Cheat Sheet

- [Big-O of STL container operations](#)

Table 1: STL

Container	Insertion	Deletion	Access	Find
list (linked list)	$O(1)^*$	$O(1)^*$	$O(1)$ - top or end, $O(N)$ - middle	$O(N)$
vector (resizeable array)	$O(N)$ - top or middle, $O(1)$ - end	same as inserting	$O(1)$	$O(N)$
set (set of unique items)	$O(\log N)$	$O(\log N)$	NA	$O(\log N)$ - tree
map (maps one item to another)	$O(\log N)$	$O(\log N)$	$O(\log N)$	$O(\log N)$ - tree
queue and stack	$O(1)$ - push	$O(1)$ - pop	$O(1)$ - top	NA

*to get to the middle, may first have to iterate through N items at $O(N)$

Sorting Algorithms

General rules:

1. don't choose a sort until you know the requirements of the problem
2. always choose the simplest sorting algorithm possible that meets your needs

stable sort:

- takes into account initial ordering when sorting
- maintains the order of similar-values items

unstable sort:

- re-orders items without taking into account their initial ordering

Selection Sort

- loop through unchecked indices, find **minimum** and swap
 - even if no swap is necessary (ie. minimum at current index)
 - * this algorithm would still check the rest of the items
- no best or worse case, *always* $O(N^2)$
- learning nothing on each pass
 - only useful when swapping/movements is really *expensive* compared to comparisons
- example sort:

```

1 | 5 3 7 6 1 8 2 4
  | 3 7 6 5 8 2 4
3 | 1 2 7 6 5 8 3 4
  | 1 2 3 6 5 8 7 4
5 | 1 2 3 4 5 8 7 6
  | 1 2 3 4 5 6 7 8
7 | 1 2 3 4 5 6 7 8
  | 1 2 3 4 5 6 7 8

```

- Implementation:

```

1 void selectionSort(int A[], int n)
2 {
3     for (int i = 0; i < n; i++)
4     {
5         int minIndex = i;
6         for (int j = i+1; j < n; j++)
7         {
8             if (A[j] < A[minIndex])

```

```

10     }
    swap(A[i], A[minIndex]);
12 }
}

```

Bubble Sort

- check **pairs** of items, put them in sorted order
- after one loop, the largest item is *guaranteed* to be shifted to the last item
- loop again, stopping right before that largest item
 - we can skip steps by setting the stopping position at the last swap
- *best case*: $O(N)$ - already sorted
- *worst case*: $O(N^2)$ - reverse order, swapping all the time
- *average case*: still $O(N^2)$ - but constant of proportionality is *half* as bad
- example sort:

```

1  5 3 7 6 1 8 2 4 |
   3 5 6 1 7 2 4 | 8 # 8 is largest item
3  3 5 1 6 2 4 | 7 8
   3 1 5 2 4 | 6 7 8
5  1 3 2 4 | 5 6 7 8
   1 2 | 3 4 5 6 7 8 # put stopping position at last swap
7  | 1 2 3 4 5 6 7 8 # if no swaps, array is sorted

```

- Implementation:

```

1  void bubbleSort(int Arr[], int n)
   {
3   bool atLeastOneSwap;
   do
5   {
       atLeastOneSwap = false;
7       for (int j = 0; j < (n-1); j++)
           {
9           if (Arr[j] > Arr[j + 1])

```

```
11     {
12         swap(Arr[j], Arr[j+1]);
13         atLeastOneSwap = true;
14     }
15 }
16 while (atLeastOneSwap == true);
17 }
```

Shell Sort

- built on underlying sort called *h-sorting*
 - pick a value for *h*
 - for every element in the array:
 - * if $a[i]$ and $a[i+h]$ are out of order, swap them
 - if any elements were swapped in the last pass, repeat again with same *h*
 - eg. when an element is 3-sorted, every element is smaller than the element 3 items later
 - 1-sorting is a bubble sort
- *shell sort* approach:
 - select a sequence of decreasing *h*-values **ending** with 1
 - * eg. 8, 4, 2, 1
 - then 8-sort, 4-sort, 2-sort, finally 1-sort the array
- $\sim O(N^{1.25})$ depending on the decrement sequence!
 - does not require much extra storage

Insertion Sort

- similar to ordering a hand of cards as they are dealt
 - insert cards picked up in order into the hand
 - * examine cards in hand one by one to figure out where to put the next card
 - hand is always **in order**
- *best case*: $O(N)$ - already sorted
- *worst case*: $O(N^2)$ - reverse order, have to compare with all previous items
- *average case*: $O(N^2)$ - but constant of proportionality is *half* as bad as previous algorithms
- *slightly* better than bubble sort

- **except** if all itmes are *no more* than some **constant** distance out of place, only shifting constant times, then insertion sort is $O(N)$!
- example sort:

```

1 5 | 3 7 6 1 8 2 4
   3 5 | 7 6 1 8 2 4
3 3 5 7 | 6 1 8 2 4 # got lucky, only one comparison
   3 5 6 7 | 1 8 2 4
5 1 3 5 6 7 | 8 2 4 # lots of comparisons and shifting
   1 2 3 5 6 7 8 | 4
7 1 2 3 4 5 6 7 8 |

```

- Implementation:

```

1 void insertionSort(int A[], int n)
  {
3   for(int s = 2; s <= n; s++)
      {
5       int sortMe = A[ s - 1 ];
          int i = s - 2;
7       while (i >= 0 && sortMe < A[i])
          {
9           A[i+1] = A[i];
              --i;
11          }
          A[i+1] = sortMe;
13      }
  }

```

Merge Sort

- **merging** two sorted piles is $O(N)$
- but what is the runtime for a recursive algorithm?
- $T(N) = 2T(N/2) + O(N)$ (*recurrence relation*) $\sim O(N \log N)$ (*all cases*)
 - much better runtime than $O(N^2)$
 - * **except** if all itmes are *no more* than some constant items out of place

- may take longer than insertion sort
- doesn't require *random access* (fine with arrays, vectors, lists)
 - list's sort member function uses merge sort
 - * lists are easy to swap / copy items, so could be *faster* than quick sort if expensive to move items
- because merge function needs secondary arrays to merge, this can slow things down compared to quicksort
- requires extra storage ($O(N)$) to have a good constant of proportionality
- Merge() Implementation:

```

void merge(int data[], int n1, int n2)
2 {
    int i=0, j=0, k=0;
    4 int* temp = new int[n1+n2]; // needs a temporary array!
    int* sechalf = data + n1;
    6
    while (i < n1 || j < n2)
    8 {
        if (i == n1)
            10 temp[k++] = sechalf[j++];
        else if (j == n2)
            12 temp[k++] = data[i++];
        else if (data[i] <= sechalf[j])
            14 temp[k++] = data[i++];
        else
            16 temp[k++] = sechalf[j++];
    }
    18 for (i=0; i<n1+n2; i++)
        data[i] = temp[i];
    20 delete [] temp;
}

```

Quick Sort

- **partition** array around a pivot/divider ($O(N)$)
 - pivot should evenly divide array, but hard to find median (merge sort would be faster at this point)

- * so choose first value or a random pivot
- * recursively sort each half
- similar relationship to merge sort: pick a pivot (constant run time), recursively sort
- other possible *improvements* (Sedgewick):
- 1. find **median** of a small sample for the pivot, eg. first 3 items
 - but this is bad if array is already sorted
 - instead, median of 3 (first, middle, last)
 - * 3 is the best compared to 5, 7, etc. values
 - * not necessarily first, middle, last (vulnerable to forcing an $O(N^2)$), can be random
- 2. have quick sort abandon sub-arrays of size 9 or fewer
 - but the various pivots are still in their right place!
 - then call **insertion sort** / **heap sort** across the entire array!
 - items are no more than constant distance (9) out of place, so $O(N)$ for insertion sort!
 - 9 is the sweet spot
- 3. STL uses a *variation* on quick sort called **introsort**:
 - deep recursion happens if there are bad pivot choices
 - when depth exceeds some limit ($2\log N$)
 - * sort stops using quick sort for this *sub-region*, instead uses **heap sort**
 - completely avoid $O(N^2)$ runtime!
 - *always* $O(N\log N)$
- *best case*: $O(N\log N)$
- *average case*: $O(N\log N)$ - depends on the split, but *better* constant of proportionality than merge sort
- *worst case*: $O(N^2)$ - every pivot is the worst possible pivot, least or biggest value (mostly sorted or reverse order)
 - $T(N) = O(N) + T(N - 1) \sim O(N^2)$
- good sort to use if occasional $O(N^2)$ is acceptable
 - but requires *random access* (so only for arrays/vectors, **not** lists)!
 - * picking pivot requires *random access*
- example sort:

```

1 [5]3 7 6 1 8 2 4 # partition array around first pivot
   4 2           6 7 # swap elements that are on wrong side from either end
3 1 3 4 2 [5]8 6 7 # put pivot in corresponding spot when the ends meet
  [1]3 4 2         # sort left half

```

```

5  1  [3] 2  4           # one item is a base case, sort right sub-half
   1  2  [3] 4
7           [8] 6  7 # sort right half
           7  6 [8]
9           6  7      # two items is another base case
   1  2  3  4  5  6  7  8

```

- Implementation:

```

void QuickSort(int Array[], int First, int Last)
2 {
   if (Last - First >= 1 )
4 {
    int PivotIndex;
    PivotIndex = Partition(Array,First,Last);
    QuickSort(Array,First,PivotIndex-1); // left
    QuickSort(Array,PivotIndex+1,Last); // right
  }
10 }

12 int Partition(int a[], int low, int high)
   {
14   int pi = low;
    int pivot = a[low];
16   do
    {
18     while ( low <= high && a[low] <= pivot )
        low++;
    while ( a[high] > pivot )
        high--;
22     if ( low < high )
        swap(a[low], a[high]);
24   }
    while ( low < high );
26   swap(a[pi], a[high]);
    pi = high;

```

```
28 return(pi);  
}
```

Heap Sort

- using **heaps**
 - approach: we can sort by inserting all the items into a **maxheap**, and then extracting them one by one
 - instead, build the maxheap *in place*...
1. **interpret** unsorted array into a complete binary tree (in array notation, not necessarily a maxheap right now)
 - starting from the bottom right item, make a heap out of the current subtree by *trickling* down
 - then work upwards through tree / *backwards* in the array
 - but bottom most leaf nodes are already heaps of their own (only one item)
 - so we can start the recursion at $N/2 - 1$ (in the array)
 - want to sort in ascending order, but we made a *maxheap*?
 2. **remove** each item:
 - swap position 0 of array with $N-1$, reduce N by 1, use same trickle down approach as extracting an item
 - just like when extracting from a maxheap, but swapping an item instead of deleting
 - when down to two items, just swap in order
- $O(N\log N)$, not as good constant of proportionality as quick sort
 - use this if we only need a certain number of items in order (can stop heap sort early)

Stability of Sorts

- a **stable** sort maintains items that have equal value in the original order they were in
 - only $O(N\log N)$ sort that guarantees this is **merge sort**

Table 2: Comparing Sorts

Sort	Stability	Big(O)	Notes
Selection Sort	Unstable	Always $O(N^2)$	Simple to implement, works with linked lists. Minimizes number of item-swaps (good if swaps are expensive)
Insertion Sort	Stable	$O(N)$ when sorted or nearly sorted, $O(N^2)$ otherwise	Simple to implement, works with linked lists.
Bubble Sort	Stable	$O(N)$ when sorted or nearly sorted, simple to implement	Works with linked lists. (slow, not recommended)
Shell Sort	Unstable	$\sim O(N^{1.25})$	OK with linked lists. Used in embedded systems due to fixed RAM usage.
Quick Sort	Unstable	$O(N \log N)$ average, $O(N^2)$ for nearly, sorted, reverse sorted or repeated values (but $O(N \log N)$ with introsort, and best constant of proportionality)	Limited pivot choice with linked lists, can be parallelized across multiple cores, can require $O(N)$ slots of RAM for recursion (worst) or $O(\log N)$ (average).

Sort	Stability	Big(O)	Notes
Merge Sort	Stable	$O(N \log N)$ always	Works with linked lists, can be parallelized across multiple cores. Used for sorting data on disk (external sorting), requires $O(N)$ slots of extra memory for merging. Requires extra storage to have a good constant of proportionality.
Heap Sort	Unstable	$O(N \log N)$ always	Used in embedded systems due to low RAM usage / performance.

Inheritance

Drawing with Shapes

```

1 class Shape // Circles and Rectangles are Shapes
  {
3   virtual void move(double xnew, double ynew);
   virtual void draw() const; // now, program will decide at runtime which appropriate
   function to call
5   double m_x;
   double m_y;
7 };

9 void Shape::move(double xnew, double ynew) // same move() function for every shape
  {

```

```
11  m_x = xnew; // compilation error if m_x and m_y aren't declared in the class Shape
    m_y = ynew;
13  }

15  class Circle : public Shape // tells compiler a Circle is a kind of Shape
    {
17      // void move(double xnew, double ynew); // inherits move() function from Shape
      virtual void draw() const;           // good practice to denote virtual here
19      // double m_x;                       // inherits data members from Shape
      // double m_y;
21      double m_r;
    };

23
    class Rectangle : public Shape
25  {
      // void move(double xnew, double ynew); // inherits move() function from Shape
27      virtual void draw() const;           // good practice to denote virtual here
      virtual double diag() const;
29      // double m_x;                       // inherits data members from Shape
      // double m_y;
31      double m_dx;
      double m_dy;
33  };

35  void Shape::draw() const // how do we call the derived class's draw()? declared
    virtual in prototype
    {
        // for now, we have to implement this generic draw()
        function
37      ... draw a cloud ... // generic draw action for any shape...
    }

39  void Circle::draw() const { draw a circle }
    void Rectangle::draw() const { draw a rectangle }

41
    // etc for other shapes...
43  // let's draw a picture...
```

```

45 // ???* pic[100]; Wouldn't work, different shape classes
   // Circle* ca[100];
47 // Rectangle* ra[100];
   Shape* pic[100];    // can hold Circles AND Rectangles
49 pic[0] = new Circle; // how do we tell compiler Circle is a type of shape? (in
   declaration)
                           // converts Circle pointer to a Shape pointer
51                           // pic really does contain pointers to shapes
   pic[1] = new Rectangle;
53 pic[2] = new Circle;

55 for (int k = 0; k < ...; k++)
   pic[k]->draw();    // assumes all shapes have a draw() function
57 // for( int k = 0; k < ...; k++)
   //   ca[k]->draw();
59 // for( int k = 0; k < ...; k++)
   //   ra[k]->draw();

61
   void f(Shape* x)    // for any shape now
63 {
   // converts Circle reference to Shape reference
   x->move(...,...); // move() works with all shapes
65 x->draw();          // but draw() is different for every type of Shape!
   }

67 // void f(Circle* x)
   // {
69 //   x->move(...,...);
   //   x->draw();
71 // }
   // void f(Rectangle* x)
73 // {
   //   x->move(...,...);
75 //   x->draw();
   // }

77
   double Rectangle::diag() const
79 {

```



```

81  }
    return sqrt(m_dx*m_dx + m_dy*m_dy);
83  double Square::diag() const // a reason to override a virtual function:
    {                               // a more efficient implementation
    return m_dx * sqrt(2);
85  }

```

- lots of **repetition**, some of these functions should work for every shape
 - our move() function will take the same parameters for *all shapes*, just absolute x and y coordinates
 - have to use multiple arrays and functions:
 - * array for **each** shape type, needs a *family of functions* for different shapes
 - error prone to add a new shape!
- how to reduce repetition and make it easier to add new objects / classes?
 - find a **generalization**!
 - circles and rectangles are all shapes
 - need approach that *works for all shapes*

Inheritance

- this is **inheritance**!
 - **goals** of inheritance:
 - * **reuse**:
 - every public function from base class is automatically reused in derived class
 - **not** private members, however!
 - * **extension**:
 - *adding new functions* or data to a derived class
 - however, unknown to the base class!
 - * **specialization**:
 - **override** existing functions from base using the virtual keyword in declaration
 - can still call base function using :: operator
 - *general steps* for inheritance:
 - * figure out what to **represent** (bunch of shapes)
 - * define base class with functions *common to all* derived classes (area(), draw())
 - * write derived classes with **specialized** versions of each common func-

tion

- * using **polymorphism**, we can access derived variables with base ptr / reference
- * remember to define virtual destructor in base class
- generalization: Circles and Rectangles are a **subclass** of Shape
 - in c++, they are both *derived classes* of Shape
- Shape is a **superclass**
 - in c++, Shape is a *base class*
- a derived class pointer is *automatically converted* to a base class pointer (*upcast* is automatic)
 - Derived* => Base* (pointer to base within the specific derived class)
 - Derived& => Base& (same for references)
 - Derived => Base (c++ allows this, ie. *slicing*)
 - * eg. Shape s(C); s = c;
 - * converts to the base object **within** the derived object
 - * **BUT** we lose the derived object
 - * preferable to use pointers or references
 - **NO** automatic conversion from Base* => Derived*
 - * *downcast*, have to use static_cast<SomeDerivedClass*>
 - * must be sure our conversion is meaningful:
 - undefined behavior if base ptr doesn't actually point to a derived object of that type
- can't have **contrary** relationship where two classes can't be derived from *each other*!

Inheritance in Memory

- how can compiler access data members in a base class then?
 - every derived object has an **embedded** base object within it
 - compiler calculates the **layout** of the derived objects in memory
 - this is how the *automatic conversion works* between base and derived classes
 - **note:** *can't access* a derived class's members given a pointer to its base class

Functions within Base and Derived Classes

- how to make sure every shape can be drawn and moved?
 - add to **declaration** of Shape
 - but the **implementation** for some functions are *different for each type* of shape...

- draw() might be different, but move() would act the same for different types
 - * don't have to repeat the implementation of move() for every type of shape!
 - just implement move() **IN** shape, and remove declaration of move() from the derived classes
 - the derived classes **inherit** the move() function from Shape!
 - * we can do the same for the data members that are the *same for all shapes*
- just have to implement what makes derived classes **different** from their base classes
 - * eliminates *duplication of code*!

Virtual Functions

- what about for draw()?
 - different implementation for every shape...
 - but *still needs to be declared within Shape*, so that f() would compile!
 - * must guarantee *all shapes have* a draw()
 - for now, we need a **generic** draw() for just a Shape
 - how do we call the derived class's specific draw() functions?
 - * tell compiler to make the decision at runtime **NOT** compile-time (would call generic draw())
 - *static binding*: compile-time binding, call **generic** function no matter what (cheaper!)
 - *dynamic binding*: runtime binding, call **appropriate** function depending on object
 - different binding options for different languages
 - **usually**: dynamic by default, have to indicate static
 - **c++**: static by default, have to indicate dynamic (keyword **virtual** in **declaration**)
 - * optional to repeat virtual in all the implementations of derived classes' functions
- *virtual functions* allow base class functionality to be redefined in derived classes
 - can still access base class functions using base:: prefix
 - * eg. Person::talks()

Overriding Functions

```
1 class WarningSymbol : public Shape
```

```

{
3  void move(double xnew, double ynew);
    ...
5  }

7  void WarningSymbol::move(double xnew, double ynew)
{
9  // move(xnew, ynew); // won't work, recursive call
   // this->Shape::move(xnew, ynew);
11 Shape::move(xnew, ynew);
    ... move like a Shape
13 ... flash 3 times
}

15
WarningSymbol ws(...);
17 ws.move(...); // warning symbol DOES flash! compiler calls the immediate move()
f(ws);          // warning symbol does NOT flash! calls Shape's move() function!
19 Shape* sp = &ws;
sp->move(...); // warning symbol does NOT flash!

21
void f(Shape& x)
23 {
    x.move(...);
25 }

```

- what if we then have a new Shape that **doesn't** move like all the other shapes?
 - eg. warning symbol that flashes 3 times
 - let's write a new move() that calls Shape's move()
- if we write a new move() function:
 - works correctly when called as a WarningSymbol object
 - but when called after being **converted** to a Shape, *will not flash!*
- **redefining** base class move as virtual **would** fix the problem
 - BUT could be expensive to redefine a large program like this
- in our example case, let's redefine move() as virtual

Virtual Functions Demystified

```

1 Shape sp;
  if (...)
3   sp = new Rectangle(...)
  else ...    // sp is some other shape
5
  sp->draw();    // how does compiler know which draw() to call?
7               // effectively: call function sp->vptr[1] points to
// sp->diag(); // remember, we can't do this, can only call Shape functions with a
                Shape ptr...

```

- **polymorphism** refers to the same function call leading to multiple actions
 - eg. when using a base pointer or a base reference to access a derived object
- compiler makes a table holding virtual functions (ie. *virtual table*, vtbl)
 - **Shape's** vtbl holds move() and draw()
 - * the position of these functions in vtbl is the **same** for all derived classes
 - **Rectangle's** vtbl holds move(), draw(), and diag()
 - * the move() *points to Shape's* move() since Rectangle doesn't override it
- but how do we know which slot in vtbl to go to?
 - the compiler adds an *extra data member* whenever classes have a virtual function
 - * *virtual pointer*, vptr, that points to vtbl!
 - * all constructors also **initialize** the vptr to point to the correct vtbl
- this implementation of virtual functions *doesn't require recompilation* when more Shape types are added

Pure Virtual Functions

```

class Shape
2 {
  virtual void move(double xnew, double ynew);
4  // virtual void draw() const; // still necessary to declare here!
  virtual void draw() const = 0; // no longer need generic draw() implementation!
6                                     // a pure virtual function (Shape now an abstract
    class)
  double m_x;

```

```

8  double m_y;
   };
10 // void Shape::draw() const
   // {                               // for now, we have to implement this generic draw()
   //     function
12 //     ... draw a cloud ...
   // }

```

- how do we *get rid* of the implementation of this generic, unnecessary draw() function?
 - ie. avoid writing “dummy” logic
- use *pure virtual* function that points to null in the vtbl
 - no longer providing an implementation that is automatically inherited
- what happens if we call draw() with a Shape that **isn't** part of a derived object?
 - now, it is a *compilation error* to create a Shape!
- if a class contains *at least one* pure virtual function:
 - this is now an *abstract class* / *abstract base class* (ABC)
 - * NOT allowed to create objects of that class type!
 - * not an issue:
 - many other abstractions eg. shape, mammal, many base classes
 - however, can still have references / pointers to a Shape!
 - * can also still *construct* abstract class within another!
- *derived classes* can also be abstract
 - eg. ClosedFigure inheriting from Shape with pure virtual function fill-Color()
 - ClosedFigure will inherit the pure virtual function draw() from Shape!
- *failing to declare* pure virtual function in a derived class means it would also be abstract
- ABC's also **force** user to implement certain functions to prevent bugs

Construction

```

1  class Shape
   {
3  public:
   Shape(double x, double y);
5  private:
   double m_x;

```

```

7   double m_y;
   };
9   Shape::Shape(double x, double y)
    : m_x(x), m_y(y)
11  {}

13  class Circle : public Shape
    {
15  public:
    Circle(double x, double y, double r);
17  private:
    double m_r;
19  };
    Circle::Circle(double x, double y, double r)
21  // : m_x(x), m_y(y), m_r(r) // wrong! trying to access private members of Shape
    : Shape(x, y), m_r(r)
23  {}

```

- steps of construction:
 1. construct the base object (no matter where its listed)
 2. construct each data member, consulting the *member initialization list*
 - if not listed:
 - * built-in type: left uninitialized
 - * class type: default-constructed (having no default constructor is an **error**)
 3. execute *body of constructor*
- steps of destruction:
 1. execute body of destructor
 2. destroy data members / objects
 3. destroy the base object

Destruction

```

1  class Shape
   {
3  public:
   ...

```

```

5  virtual void draw() = 0;
   // virtual ~Shape() = 0; // should be virtual
7  virtual ~Shape();
   }
9
   Shape::~~Shape()
11 {}

13 class Polygon : public Shape
   {
15 public:
   ...
17 virtual ~Polygon();
   private:
19 ...
   Node* head; // collection of coordinates
21 }
   ****
23 Shape *sp;
   if (...)
25     sp = new Circle(...);
   else
27     sp = new Polygon(...);
   delete sp; // calls Shape's destructor! leads to memory leak

```

- base class's destructor must be declared virtual to call the correct destructor!
- compiler error that there is *no implementation* for the base object destructor
 - can't be a pure virtual function:
 - * destructor for all derived classes **call** this destructor
 - but since we declared it, destructor is *no longer* compiler generated
- *in general*: if a class is designed as a base class, declare its destructor as virtual and implement

Function and Class Templates

Function Templates

- *multiple* functions for the *same* operations with *different* types
 - we can overload these functions
 - eg. `minimum(int a, int b)`, `minimum(double a, double b)`
 - * same algorithm for finding the minimum...
 - * but *different machine language* for comparing ints vs. doubles (different byte sizes)
 - * but source code is **identical**!
- instead, can we tell compiler the **pattern** for the algorithm?
 - pattern for manufacturing a function
 - use **template** syntax in c++
- multiple templated function calls of the same type call same function for that type
- can also have multi-type templates
- *steps for templates*:
 - match some template function (doesn't consider conversions)
 - * "*template argument deduction*"
 - have to match the type *exactly*, except for matching to `const` in template (simple conversion)
 - * at least one formal parameter must be defined by the template
 - instantiated template must compile
 - compiled code must function properly
 - * eg. comparing c-strings with `<` only compares the pointers, undesired result
 - instead would need another `minimum()` using `strcmp(a, b)`
- non-template functions *takes precedence* over a template function
 - specific case over general case
- should pass by *constant reference* instead of value to deal with expensive types!
 - because it's possible to take any type in the template
- template functions **must** be declared and implemented in header files!
 - use `#include` to use the templated functions

```
template<typename T> // typename and class are interchangeable (besides convention)
2 T minimum(const T& a, const T& b) // more efficient to pass by const reference
{
4     if (a < b)
        return a;
6     else
```

```

    return b;
8 }
template<typename T1, typename T2>
10 ?? minimum(T1 a, T2 b) // would work if called with int double, double int, int int,
    etc.
{
12     if (a < b)
        return a;
14     else
        return b;
16 }

18 int k = 3;
double x = 3.0;
20 minimum(k, 3);    // compiler manufactures code for minimum() with ints
minimum(x, 3.14); // same for doubles
22 minimum(k, x);    // no matching function template! doesn't consider conversions!
                    // now would match second template function (multi-type)
24                    // but could return an int instead of a double depending on order
                    // of parameters
                    // this is impractical...

26 Chicken c1, c2;
// minimum(c1, c2); // comparison operator not overloaded for chickens!

```

Useful Construction Syntax

```

1 template<typename T>
T sum(const T a[], int n) // could sum up ints, chars... strings(?)
3 {
    // T total = 0;          // no constructor for strings with just an int...
5    // T total;             // would work for strings now, starts as empty string
                             // but for primitives, would be uninitialized
7    T total = T();          // calls default constructor for strings, appropriate value
                             // for built-in types (0 false, nullptr)
    for (int k = 0; k < n; k++)

```

```

9     total += a[k];
    return total;

11

    string x(10, '*');
13     cout << x;           // if only using an object once, can use temporary object
    cout << string(10, 'x'); // string of 10 stars
15     double(x);           // can also use this syntax for built-in types with
                             appropriate value (0, false, nullptr)
}

```

Template Errors

- used to have vague compile error messages when using templates
 - hard to track down errors across multiple functions, eg. code example below
 - * only pointer is being passed
 - we *never* see the function compiled from template
- now compilers provide a *traceback* of function calls

```

    template<typename T>
2   void g(T x)
    {
4       T y(x);
        minimum(x, y);
6   }

    template<typename T>
8   void f(T x)
    {
10      g(x);
    }

12   int main()
    {
14      f(i); // int
        f(d); // double
16      f(c); // chicken, compiler error!
    }

```

Class Templates

- making a stack class:
 - could use a type alias for different types
 - but what about different stack types in the *same* program
 - **class templates** solve this
- write a **pattern** for manufacturing classes!
- similar syntax:
- special syntax for returning an internal struct!

```
1  template<typename T>
   class Stack
3  {
   public:
5     Stack();
   Stack(const Stack<T>& other);
7     Stack<T>& operator=(const Stack<T>& rhs);
   void push(const T& x);
9     T top() const;
   int size() const; // should stil return an int!
11    ...
   SomeStruct returnStruct();
13    SomeStruct* returnStructPtr();
   ...
15 private:
   T m_data[100];
17   int m_top;

19   struct SomeStruct
   {
21       T temp;
       int tempNum;
23       ...
   }
25 }

27 template<typename T>
```

```

29 inline T Stack<T>::someInlineFunc(T a) {}

31 template<typename T>
Stack<T>::Stack() : m_top(0) {}

33 template<typename T>
Stack<T>::Stack(const Stack<T> other) {}

35
37 template<typename T>
Stack<T>& Stack<T>::operator=(const Stack<T> rhs) {}

39 template<typename T>           // for every function, have to restate the
    template
void Stack<T>::push(const T& x) {} // works on a stack of T's

41
43 template<typename T>
T Stack<T>::top() const {}

45 template<typename T>
typename Stack<T>::SomeStruct Stack<T>::returnStruct() {}

47
49 template<typename T>
typename Stack<T>::SomeStruct* Stack<T>::returnStructPtr() {}

51 int main()
{
53     Stack<int> si;           // manufactures constructor, destructor
    si.push(3);              // known to be a stack of ints, manufactures push function
    with ints

55     Stack<Coord> sc;        // manufactures constructor, destructor
    // error if Coord has no default constructor!

57     sc.push(Coord(3,5));    // manufactures push with Coords
}

```

Template Specialization

```
1 template<> // can define specific behaviors for chars, such as uppercase / lowercase
2 class Pair<char>
3 {
4     // must redefine entire class!
5     // (also possible to only specialize certain functions)
6     ...
7 }
```

Appendix

File Input / Output

- #include
- #include
 - defines std::ofstream (output file stream)
 - defines std::ifstream (input file stream)

Output

```
1 ofstream outfile("results.txt"); // outfile is a name of our choosing. (forward
   slash for windows)
2 if ( ! outfile )                // Did the creation fail?
3 {
4     cerr << "Error: Cannot create results.txt!" << endl;
5     ... return with failure ...
6 }
7 outfile << "This will be written to the file" << endl;
  outfile << "2 + 2 = " << 2+2 << endl;
```

Input

```
ifstream infile("data.txt"); // infile is a name of our choosing
```

```
2  if ( ! infile )           // Did opening the file fail?
    {
4   cerr << "Error: Cannot open data.txt!" << endl;
    ... return with failure ...
6  }

8  // read an integer:
   int k;
10  infile >> k;
    // If you want to consume and ignore the rest of the line the
12  // number is found on, follow this with
   infile.ignore(10000, '\n');
14
   // read a std::string:
16  std::string s;
   infile >> s;           // read the next word into s
18  // or
   getline(infile, s);    // read a whole line into s
20
   // read the next character from the input, whether it's a letter, blank, newline, or
   // whatever:
22  char c;
   infile.get(c);
24
   // check for end of the input file:
26  // Example 1
   std::string s;
28  getline(infile, s);
   if ( ! infile)
30   cerr << "End of file when trying to read a string" << end;

32  // Example 2 - read and process each line of a file until end
   std::string s;
34  // getline returns infile; the while tests its success/failure state
   while (getline(infile, s))
36  {
```

```
    ... process s
38 }

// Example 3 - read and process each character of a file until end
char c;
// get returns infile; the while tests its success/failure state
42 while (infile.get(c))
44 {
    ... process c
46 }

// Example 4 - read and process each integer in a file until end
int k;
// operator>> returns infile; the while tests its success/failure state
50 while (infile >> k)
52 {
    ... process k
54 }

56 // while(!infile.eof()) // does not return true until after attempt to read past eof
    is made!
```

Stream Parameters

```
void greet(ostream& outf)    // outf is a name of our choosing
2 {                          // not ofstream, pass by reference (can reference cout
    or a ofstream attached to file)
    outf << "Hello" << endl;
4 }
int main()
6 {
    ofstream outfile("greeting.txt");
8     if ( ! outfile )
    {
10         cerr << "Error: Cannot create greeting.txt!" << endl;
```



```
    return 1;
12 }
    greet(outfile); // writes Hello to the file greetings.txt
14 greet(cout);    // writes Hello to the screen
}

16
int countLines(istream& inf) // inf is a name of our choosing
18 {
    int lineCount = 0;
20 string line;
    while (getline(inf, line))
22 lineCount++;
    return lineCount;
24 }

26 int main()
{
28 ifstream infile("data.txt");
    if ( ! infile )
30 {
        cerr << "Error: Cannot open data.txt!" << endl;
32 return 1;
    }
34 int fileLines = countLines(infile); // reads from the file data.txt
    cout << "data.txt has " << fileLines << " lines." << endl;
36 cout << "Type lines, then ctrl-Z (Windows) or ctrl-D (UNIX):" << endl;
    int keyboardLines = countLines(cin); // reads from keyboard
38 cout << "You typed " << keyboardLines << " lines." << endl;
}
```

Object Oriented Design Steps

- generally, two phases:
 - determine overall class design
 - determine class data structures / algorithms
- *class design*:

1. classes and objects necessary
 2. outward-facing functionality
 3. data each class holds
 4. how they interact
- *class design steps:*
 1. identify potential **classes**
 - *nouns* in the spec.!
 - eg. calendar, appointments, time-slot, password, start-time, end-time, participants
 - * narrow down into classes (calendar, appointment)
 2. identify **operations**
 - what actions need to be performed in spec (*verbs*!)
 - eg. add new appnt., remove existing, check other users' calendars, supply password
 - * associate actions with classes (functions)
 3. determine *relationships & data*
 - *general relationships:*
 - * Class A **uses** objects of class B, not necessarily contains
 - * Class A **has-a** (contains) objects of class B (**composition**)
 - * Class A **is-a** specialized version of class B
 - * this determines private data & inheritance
 - * eg. calendar contains appointments, has a password, uses other calendars
 4. determine **interactions**
 - determine how each class interacts with the others
 - come up with *use-cases*:
 - * eg. user wants to add (locate, update) an appointment, determine if they have an appointment
 - class design is an **iterative** process!
 - *tips:*
 - **avoid** using dynamic cast to identify common types of objects
 - * instead add functions to check for various *classes of behaviors*
 - * eg. if (p->requiresOilToOperate()) ...
 - **avoid** defining specific isClass() functions for every object
 - * instead add functions to check for various *common behaviors*
 - **avoid** duplication of member variables in related subclasses
 - * instead move to base class with accessor / mutator methods
 - **never** make data members public or protected
 - * class constants may be, however
 - **never** make a function public if only used in class that holds it

- * instead private or protected
- **never** return list / vector / iterator / pointers to private objects
 - * instead do all the processing within the class if action needs to be taken

Discussion

Administrative

- Midterms 1/30, 2/26
- Final 3/16
- Start early, develop incrementally, read what you write !!!

1.18.19

- Can use Valgrind tool to detect memory leaks
- Class Composition
 - when class contains member variables that are objects
 - Order of Construction (*inside to outside*)
 - * member variables constructed in order (in order of the *member variable listing*, member initialization list doesn't matter)
 - * then current class constructor
 - Order of Destruction (*outside to inside*)
 - * current class destructor called first
 - * member variables destructed in **reverse** order
 - class composition != class **inheritance**
- Copy Constructors
 - *shallow copy* just copies all data members
 - *deep copy* (redefine default copy constructor) is needed in the cases of pointers / when not **SHARING** the same addresses / using dynamic memory
 - similar to writing assignment operator (make sure to delete current dynamic memory and return **this* at the end)
- Data Structures
 - 3 functions
 - * how to store and organize
 - * how to add and remove data
 - * how to apply functions (eg. search data)
 - add, contain, remove...
 - Pros / cons for every structure and differing efficiency / complexity

2.1.19

- **Linked Lists:**
 - made up of Nodes with **value** and **pointer**
 - *head pointer* points to first term
 - loop-free
 - **variations:**
 - * doubly linked, sorted, circular
 - **Operations:**
 - * insertion, search, removal
 - **pros:** efficient insertion, flexible memory, simple implementation
 - **cons:** complex searching and delete