CSCI 104
C++ STL; Iterators, Maps, Sets

Mark Redekopp
David Kempe

Revised: 05/2022

Container Classes

- C++ Standard Template Library provides one or more implementations of the various ADTs
  - DynamicArrayList => C++: std::vector<T>
  - LinkedList => C++: std::list<T>
  - Deques => C++: std::deque<T>
  - Sets => C++: std::set<T>
  - Maps => C++: std::map<K,V>
- Question:
  - Consider the get(i) method. What is its time complexity for…
  - ArrayList => O(____)
  - LinkedList => O(____)

Container Classes

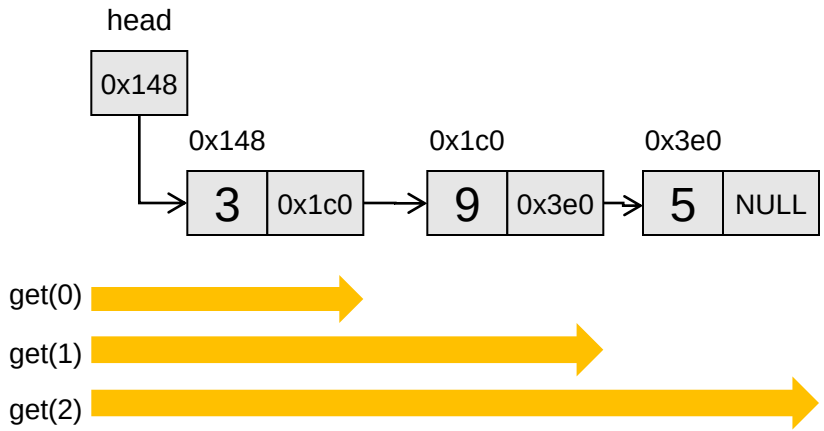
- ArrayLists, LinkedList, Deques, etc. are classes used simply for storing (or contain) other items
- C++ Standard Template Library provides implementations of all of these containers
  - DynamicArrayList => C++: std::vector<T>
  - LinkedList => C++: std::list<T>
  - Deques => C++: std::deque<T>
  - Sets => C++: std::set<T>
  - Maps => C++: std::map<K,V>
- Question:
  - Consider the get(i) method. What is its time complexity for…
  - ArrayList => O(1) // contiguous memory, so just go to location
  - LinkedList => O(i) or O(n) // must traverse the list to location i

Iteration

- Consider how you iterate over all the elements in a list
  - Use a for loop and get() or operator[]
- For an array list this is fine since each call to at() is O(1)
- For a linked list, calling get(i) requires taking i steps through the linked list
  - 0^{th} call = 1 step
  - 1^{st} call = 2 steps
  - 2^{nd} call = 3 steps
  - $1+2+\ldots+n-2+n-1+n = O(n^2)$
- You are re-walking over the linked list a lot of the time

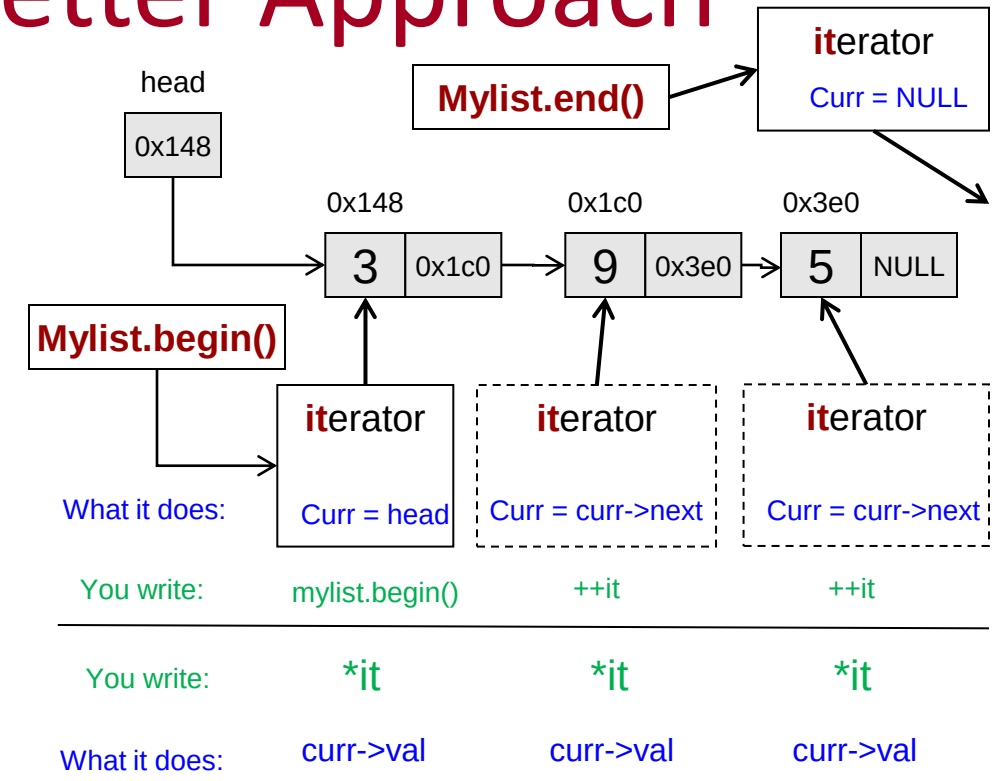
```
ArrayList<int> mylist;
...
for(int i=0; i < mylist.size(); ++i)
{
  cout << mylist.get(i) << endl;
}
```

```
LinkedList<int> mylist;
...
for(int i=0; i < mylist.size(); ++i)
{
  cout << mylist.get(i) << endl;
}
```



Iteration: A Better Approach

- Solution: Don't use get()
- Use an **iterator**
  - An object containing an internal state variable (i.e. a pointer or index) that moves one step in the list at a time as you iterate, saving your position
- Iterator tracks the internal location of each successive item
- Iterators provide the semantics of a **pointer** to the values in the list
- Assume
  - `mylist.begin()` returns an iterator to the beginning item
  - `mylist.end()` returns an iterator "one-beyond" the last item
  - ++it (preferred) or it++ moves iterator on to the next value




```
// new iterator approach
LinkedList<int> mylist;
...
iterator it;
for(it = mylist.begin();
    it !=  mylist.end();
    ++it)
{ cout << *it << endl; }
```

```
// old index approach
int size =
   mylist.size();
int i;
for(i = 0;
    i < size;
    i++)
{ cout << mylist[i]; }
```

Iterators

- List implementations may allow us to use array-like indexing (e.g. `myvec[i], myvec.at(i), myvec.get(i)`) that finds the correct data "behind-the-scenes" (giving the illusion that data is contiguous in memory though it may not be)
- To iterate over the whole set of items we could use a counter variable and the array indexing ('myvec[i]'), but it can be more efficient (based on how the data structure is actually implemented) to keep an internal pointer to the next item and update it appropriately
- C++ STL containers define 'helper' classes called **iterators** that store these internal pointers and help iterate over each item or find an item in the container

Iterators

- Iterators are a new class type defined **in the scope of each container**
  - Type is ***container*::iterator** (vector<int>::iterator is a type)
- Initialize them with *objname*.begin(), check whether they are finished by comparing with *objname.end()*, and move to the next item with ++ operator

```
#include <iostream>
#include <vector>
using namespace std;
int main()
{
  vector<int> my_vec(5); // 5 = init. size
  for(int i=0; i < 5; i++){
    my_vec.push_back(i+50);
  }
  vector<int>::iterator it;
  for(it = my_vec.begin() ; it != my_vec.end(); ++it){
     cout << *it << endl;
  }
}
```

```
// vector.h
template<class T>
class vector
{
  class iterator {

  };
};
```

Iterators

- Iterator variable has same semantics as a **pointer** to an item in the container
  - Use * to 'dereference' and get the actual item
  - Since you're storing integers in the vector below, the iterator acts and looks like an **int***

```
#include <iostream>
#include <vector>
using namespace std;
int main()
{
  vector<int> my_vec(5); // 5 = init. size
  for(int i=0; i < 5; i++){
    my_vec.push_back(i+50);
  }
  for(vector<int>::iterator it = my_vec.begin() ; it != my_vec.end(); ++it){
     cout << *it << endl;
  }
  return 0;
}
```

Iterator Tips

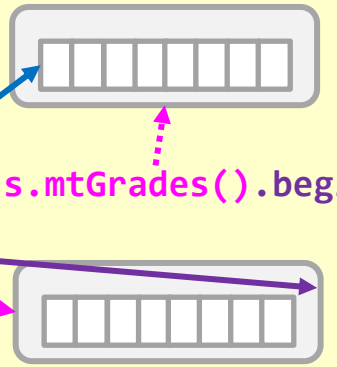
- Think of an iterator variable **as a pointer**…when you declare it, it points at nothing
- Think of **begin()** as returning the **address of the first item** but really returns an iterator to the first item.
- Think of **end()** as returning the **address AFTER the last item** (i.e. off the end of the collection or maybe NULL) but really returns an iterator to the one-off-the-end)
  - So as long as your iterator is less than or not equal to the end() iterator, you are safe

Iterator Pro Tip 1

- NEVER (accidentally) compare iterators from different containers (i.e. always compare iterators obtained from the same instance of the data structure)
  - May allow iterator to go off the end of a container

```
#include <iostream>
#include <vector>
#include <cstdlib>
using namespace std;

int main()
{
  Scores s;
  ...
  for(vector<int>::iterator it = s.mtGrades().begin() ;
      it != s.mtGrades().end();
      ++it)
  {
     cout << *it << endl;
  }
  return 0;
}
```

```
class Scores {
 public:
   vector<int> mtGrades()
      { return mt; }
 private:
  vector<int> mt;
};
```



WRONG!

```
vector<int> g = s.mtGrades();
for(vector<int>::iterator it = g.begin();
     it != g.end();  ++it)
{ ... }
```

RIGHT!

C++ STL Algorithms

- Many useful functions defined in <algorithm> library
  - http://www.cplusplus.com/reference/algorithm/sort/
  - http://www.cplusplus.com/reference/algorithm/count/
- All of these functions usually accept iterator(s) to elements in a container

```
#include <iostream>
#include <vector>
#include <cstdlib>
using namespace std;

int main()
{
  vector<int> my_vec(5); // 5 = init. size
  for(int i=0; i < 5; i++){
    my_vec.push_back(rand());
  }
  sort(my_vec.begin(), my_vec.end());
  for(vector<int>::iterator it = my_vec.begin() ; it != my_vec.end(); ++it){
     cout << *it << endl;
  }
  return 0;
}
```

Maps (a.k.a. Dictionaries or Ordered Hashes)

ASSOCIATIVE CONTAINERS

Student Class

```
class Student {
 public:
  Student();
  Student(string myname, int myid);
  ~Student();
  string get_name() { return name; } // get their name
  void add_grade(int score);  // add a grade to their grade list
  int get_grade(int index);   // get their i-th grade
 private:
  string name;
  int id;
  vector<int> grades;
};
```

Note: This class is just a sample to hold some data and will be used as the 'value' in a map shortly.

Creating a List of Students

- How should I store multiple students?
  - Array, Vector, LinkedList?
- It depends on what we want to do with the student objects and ***HOW we want to access them***
  - If we only iterating over all elements a list performs fine
  - If we want to access random (individual) elements where we have to search for them, lists give poor performance.
  - **O(n) [linear search] or O(log n) [binary search] to find student or test membership**

```
#include <vector>
#include "student.h"
using namespace std;

int main()
{
  vector<Student> studs;
  ...

  unsigned int i;
  // compute average of 0-th score
  double avg = 0;
  for(i=0; I < studs.size(); i++){
    avg += studs[i].get_grade(0);
  }
  avg = avg / studs.size();

  // check "Tommy"'s score
  int tommy_score= -1;
  for(i=0; i < studs.size(); i++){
    if(studs[i].get_name() == "Tommy"){
       tommy_score = studs[i].get_grade (2);
       break;
    }
  }
  cout<< "Tommy's score is: " <<
          tommy_score << endl;
}
```

ITERATE OVER ALL ELEMENTS (LIST GIVES FINE PERFORMANCE)

FIND A SINGLE ELEMENT (LIST GIVES BAD PERFORMANCE)

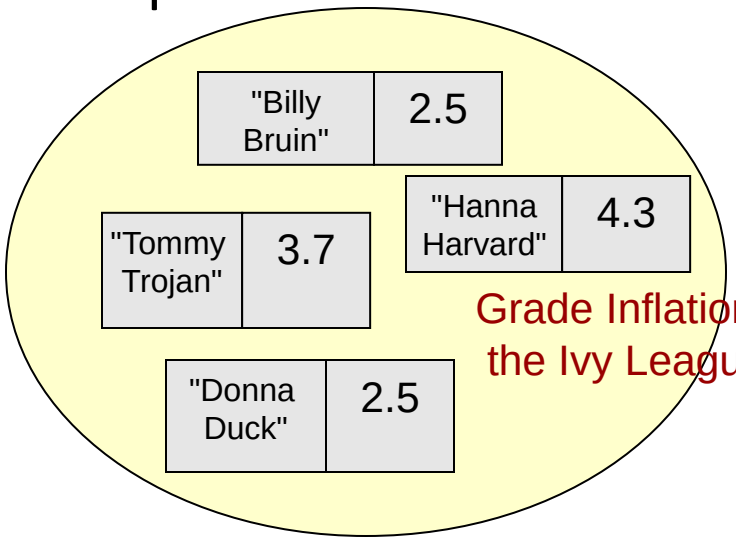
Index and Data Relationships

- Arrays and vectors are indexed with integers 0…N-1 and have no relation to the data
- Could we some how index our data with a meaningful "keys"
  - `studs["Tommy"].get_score(2)`
- YES!!! Associative Containers

```
#include <vector>
#include "student.h"
using namespace std;

int main()
{
  vector<student> studs;
  ...

  unsigned int i;

  // compute average of 0-th score
  double avg = 0;
  for(i=0; I < studs.size(); i++){
    avg += studs[i].get_grade(0);
  }
  avg = avg / slize1.size();

  // check "Tommy"'s score
  int tommy_score= -1;
  for(i=0; i < studs.size(); i++){
    if(studs[i].get_name() == "Tommy"){
       tommy_score = studs[i].get_grade(2);
       break;
    }
  }
  cout<< “Tommy’s score is: “ <<
           tommy_score << endl;
}
```

Maps / Dictionaries

- Stores key,value pairs
  - Example: Map student names to their GPA
- Keys must be unique (can only occur once in the structure)
- No constraints on the values
- No inherent ordering between key,value pairs
  - Can't ask for the 0^{th} item…
- Operations:
  - Insert
  - Remove
  - Find/Lookup



C++ Pair Struct/Class

- C++ library defines a struct 'pair' that is templatized to hold two values (first and second) of different types
  - Templates (more in a few weeks) allow types to be specified differently for each map that is created
- C++ map class internally stores its key/values in these ***pair*** objects
- Defined in 'utility' header but if you #include <map> you don't have to include utility
- Can declare a pair as seen in option 1 or call library function `make_pair()` to do it

```
template <class T1, class T2>
struct pair {
  T1 first;
  T2 second;
}
```

```
#include <iostream>
#include <utility>
#include <string>
using namespace std;

void func_with_pair_arg(pair<char,double> p)
{   cout << p.first << " " << p.second <<endl;  }

int main()
{
  string mystr = "Bill";
  pair<string, int> p1(mystr, 1);
  cout << p1.first << " " << p1.second <<endl;

  // Option 1: Anonymous pair constructed and passed
  func_with_pair_arg( pair<char,double>('c', 2.3) );

  // Option 2: Same thing as above but w/ less typing
  func_with_pair_arg( make_pair('c', 2.3) );
}
```

Bill 1
c 2.3
c 2.3

Associative Containers

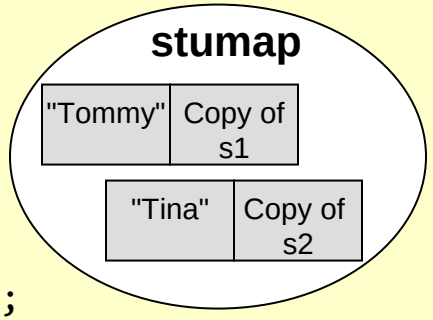
- C++ STL 'map' class can be used for this purpose
- Maps store (key,value) pairs where:
  - key = index/label to access the associated value
  - Stored value is a copy of actual data
- Other languages refer to these as 'hashes' or 'dictionaries'
- Keys must be unique
  - Just as indexes were unique in an array or list
- Value type should have a default constructor [i.e. Student()]
- Key type must have less-than (<) operator defined for it
  - Use C++ string rather than char array
- **Efficient at finding specified key/value and testing membership (O(log_2n))**

NEVER use a 'for' loop to iterate through a map to FIND a key,value pair. Just use find()...it's O(log n)

```
#include <map>
#include "student.h"
using namespace std;

int main()
{
  map<string,Student> stumap;
  Student s1("Tommy",86328);
  Student s2("Tina",54982);
  ...
  // Option 1:  this will insert the pair:
  //   {Tommy,Copy of s1}
  stumap[ "Tommy" ] = s1;
  // Option 2:  using insert()
  stumap.insert( pair<string,Student>("Tina", s2));
  // or stumap.insert( make_pair("Tina", s2));
  ...
  int tommy_score= stumap["Tina"].get_grade(1);
```

Returns 'Copy of s2' and then you can call Student member functions

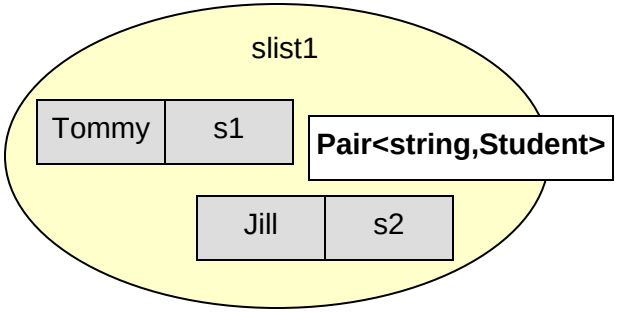
```
  stumap.erase( "Tommy" );
  cout << "Tommy dropped the course..Erased!";
  cout << endl;
}
```



stumap is a map that associates C++ strings (keys) with Student objects (values)

Maps & Iterators

- If you still want to process each element in a map you can still iterate over all elements in the map using an iterator object for that map type
- Recall: Iterator is a "pointer'/iterator to a pair struct
  - it->first is the key
  - it->second is the value




```
#include <map>
#include "student.h"
using namespace std;

int main()
{
  map<string,student> stumap;
  Student s1("Tommy",86328);
  Student s2("Jill",54982);
  ...
  stumap["Tommy"] = s1;
  stumap[s1.get_name()].add_grade(85);

  stumap["Jill"] = s2
  stumap["Jill"].add_grade(93);
  ...

  map<string,student>::iterator it;
  for(it = stumap.begin(); it != stumap.end(); ++it){
    cout << "Name/key is " << it->first;
    cout << " and their 0th score is ";
    cout << it->second.get_grade(0);
  }
}
```

Name/key is Tommy and their 0th score is 85
Name/key is Jill and their 0th score is 93

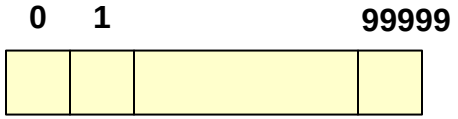
Map Membership [Find()]

- Check/search whether key is in the map object using *find()* function
- Pass a key as an argument
- Find returns an iterator
- If key is IN the map
  - Returns an iterator/pointer to that (key,value) pair
- If key is NOT IN the map
  - Returns an iterator equal to *end()'s* return value
- **Runs in log(n) time**
  - **Do not loop/iterate to find something in a map (or set)**

```
#include <map>
#include "student.h"
using namespace std;

int main()
{
  map<string,student> stumap;
  Student s1("Tommy",86328), s2("Jill",14259);
  string name;

  stumap["Tommy"] = s1;    // Insert an item
  stumap["Tommy"].add_grade(85);  // Access it


  if(stumap.find("Jill") != stumap.end() ){
    cout << "Jill exists!" << endl;
  }
  else {
    cout << "Jill does not exist" << endl;
    stumap["Jill"] = s2;  // So now add him
  }
  cin >> name;
  map<string,student>::iterator it = stumap.find(name);
  if( it != stumap.end() ){
    cout << it->first << " got score=" <<
            it->second.get_grade(0) << endl;
  }
}
```

Another User of Maps: Sparse Arrays

- Sparse Array: One where there is a large range of possible indices but only small fraction will be used (e.g. are non-zero, etc.)
- Example 1: Using student ID's to represent students in a course (large 10-digit range, but only 30-40 used)
- Example 2: Count occurrences of zip codes in a user database
  - Option 1: Declare an array of 100,000 elements (00000-99999)
    - Wasteful!!
  - Option 2: Use a map
    - Key = zipcode, Value = occurrences



Set Class

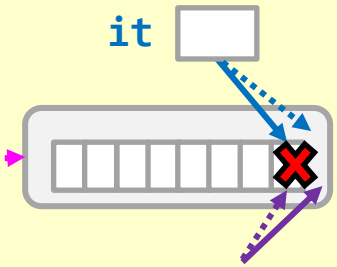
- C++ STL "set" class is like a list but each value **can appear just once**
- Think of it as a map that stores just keys (no associated value)
- **Keys are unique**
- **insert()** to add a key to the set
- **erase()** to remove a key from the set
- Very efficient at testing membership (**$O(\log_2 n)$**)
  - Is a specific key in the set or not!
- Key type must have a less-than (<) operator defined for it
  - Use C++ string rather than char array
- Iterators to iterate over all elements in the set
- **find()** to test membership

```
#include <set>
#include <string>
using namespace std;

int main()
{
  set<string> people;

  people.insert("Tommy");
  people.insert("Johnny");
  string myname = "Jill";
  people.insert(myname);

  for(set<string>::iterator it=people.begin();
      it != people.end();
      ++it){
    cout << "Person: " << *it << endl;
  }
  myname = "Tommy";
  if(people.find(myname) != people.end()){
    cout<< "Tommy is a CS-related major!" << endl;
  }
  else {
    cout<< "Tommy wants to change his major!" << endl;
  }
  people.erase("Johnny"); // erase Johnny
  // more code
  return 0;
}
```

Iterator Pro Tip 2a

- You should **NOT MODIFY** a container (vector, map, set) as you iterate through it
  - May allow iterator to go off the end of a container

```
#include <iostream>
#include <vector>
#include <cstdlib>
using namespace std;

int main()
{
  vector<int> s;
  ...
  for(vector<int>::iterator it = s.begin(); it != s.end(); ++it)
  {
     if(*it == 0) s.erase(it);
  }
  return 0;
}
```



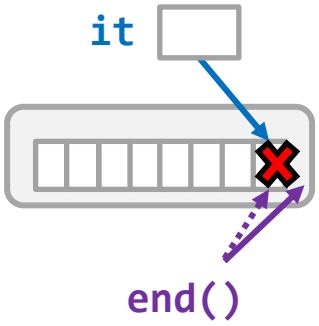
WRONG! Do NOT modify the container as you iterate throughit

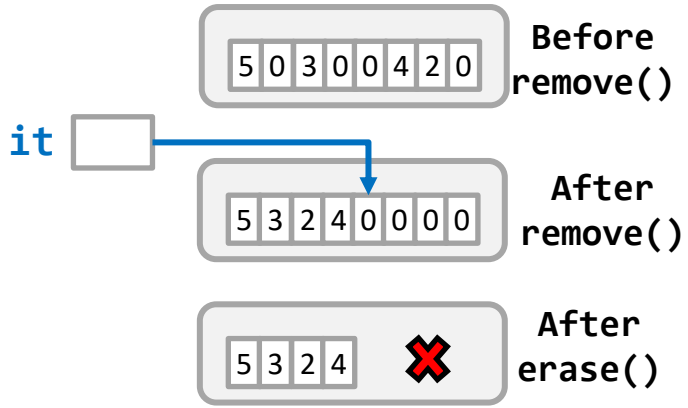
Iterator Pro Tip 2b

- If you must modify the container as you iterate through take time to understand how the iterator works and research correct methods
  - For vectors, use the std::remove and std::erase idiom (Wikipedia link)
  - Though not efficient, one could iterate through a copy while erasing from the original

```
vector<int>::iterator it = s.begin();
while(it != s.end()){
   if(*it == 0) s.erase(it);
   else         ++it;
}
```

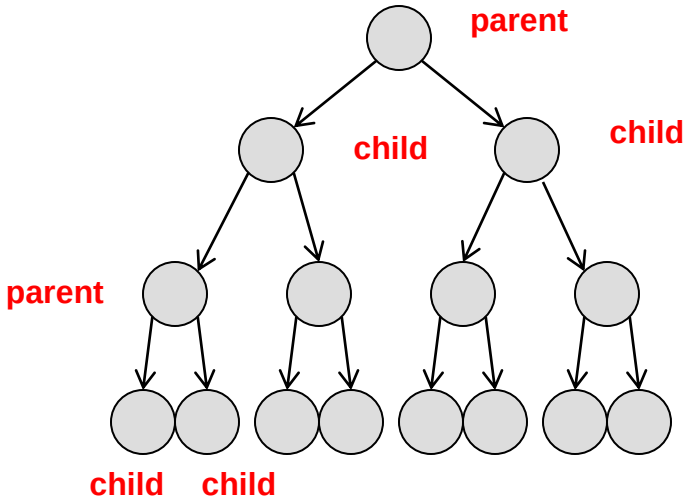
```
vector<int>::iterator it;
it = std::remove(s.begin(), s.end(), 0);
s.erase(it, s.end());
```





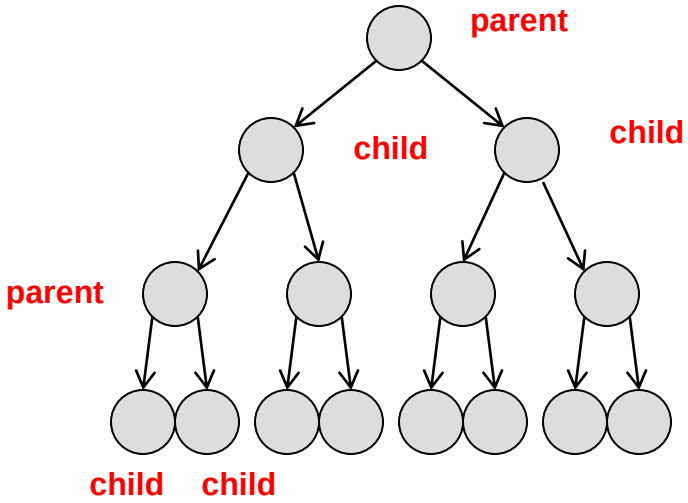
A Deeper Look: Binary Tree

- Data structure where each node has at most 2 children (no loops/cycles in the graph) and at most one parent
- Tree nodes w/o children are called "leaf" nodes
- Depth of binary tree storing N elements? _____



A Deeper Look: Binary Tree

- Data structure where each node has at most 2 children (no loops/cycles in the graph) and at most one parent
- Tree nodes w/o children are called "leaf" nodes
- Depth of binary tree storing N elements? $\log_2 n$



Binary Search Tree

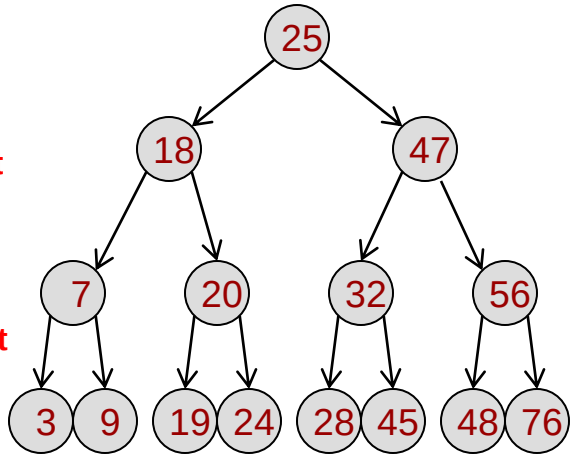
- Tree where all nodes meet the property that:
  - All descendants on the left are less than the parent's value
  - All descendants on the right are greater than the parent's value
- Can find value (or determine it doesn't exit) in log2n time by doing binary search

Q: is 19 in the tree?

19 < 25..left

19 > 18..right

19 < 20..left



Q: is 34 in the tree?

34 > 25..right

34<47..left

34>32..right

34 != 45 and we're at a leaf node...34 does not exist

Trees & Maps/Sets

- Maps and sets use binary trees internally to store the keys
- This allows logarithmic find/membership test time
- This is why the less-than (<) operator needs to be defined for the data type of the key