C++ Containers
(Standard Template Library)

Why Container Classes?

- Many programs use arrays, vectors, lists, queues, stacks, sets to store information.
- Both C++ and Java provide container classes that automatically manage memory, i.e. they allocate additional memory when more elements are added.
- The supported container classes greatly reduce the amount of code and programming needed and improve productivity.
- Container classes and OOP are closely related:
  - Containers hold objects of different derived classes
  - Polymorphism properly invokes the correct methods

Container Class (For Code Reuse)

- A container needs to be able to hold items of different types (i.e. classes). Examples
  - list of strings, integers, floating points, student objects
  - queues of undergraduates, graduate students, staff and faculty
  - maps: name → address, student ID → name, course title → classroom
- C++ *standard template library* (STL) and Java container classes provide such functionality.
- A question that will need to be answered: How do we write containers that work for a variety of class types and primitive types?

Selecting a container class

- random or sequential accesses?
- allow unique or duplicate items?
- O(1) or O(N) for array-like access (using [index])
- efficient insert / delete?
  - front
  - end
  - middle
- Java containers ***cannot*** store primitive types (int, char, float ...), they can store objects only. Primitive types, however, have corresponding object types (e.g. Integer, Boolean) that can be held in containers.
- C++ containers can store primitives.

Efficiency

operation	vector	deque	list
array-like access	O(1)	O(1)	O(N)
insert/delete at front	O(N)	O(1)+	O(1)
insert/delete at end	O(1)+	O(1)+	O(1)
insert/delete in middle	O(N)	O(N)	O(1)

N: current number of items

Two suggestions when using containers

- If code you are writing can ever exist in a multithreaded environment
  - Make sure the container is thread safe or add your own synchronization
  - Make sure actions on objects stored in the container are thread safe
- If you have the choice of using a Java or C++ container or writing your own, use the supplied one
  - Even if yours and their's are both O(N), their constant will almost certainly be smaller than yours
  - If thread safe, smart people will have spent lots of time tuning this to avoid unnecessary synchronization

C++ Vector

```
// VectorBasic.cc From Prof Kak

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

void print( vector<int> );

int main() {
    vector<int> vec;

    vec.push_back( 34 );
    vec.push_back( 23 );     // size is now 2
    print( vec );            // 34 23

    vector<int>::iterator p;
    p = vec.begin();
    *p = 68;
    *(p + 1) = 69;
    //  *(p + 2) = 70;       // WRONG
    print( vec );            // 68 69
    vec.pop_back();          // size is now 1
    print( vec );            // 68

    vec.push_back(101);
    vec.push_back(103);      // size is now 3
    int i = 0;
    while ( i < vec.size() )
        cout << vec[i++] << "  ";
    cout << endl;            // 68 101 103

    vec[0] = 1000;
    vec[1] = 1001;
    vec[2] = 1002;

    print( vec );            // 1000 1001 1002


    return 0;
}

void print( vector<int> v ) {
    cout << "\nvector size is: ";
    cout << v.size() << endl;
    vector<int>::iterator p = v.begin();
    while ( p != v.end() )
        cout << *p++ << "  ";

    cout << endl << endl;
}
```

```
// VectorBasic.cc From Prof Kak

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

void print( vector<int> );

int main()
{
   vector<int> vec;

   vec.push_back( 34 );
   vec.push_back( 23 );      // size is now 2
   print( vec );             // 34 23
```

Function prototype for a print function that takes a *vector* of *ints* as an argument.

Declare a *vector* of *ints* called *vec.*

Add to the back of the vector *34* and *23.*

Iterators

- Iterators are easy ways to traverse a collection of objects
- To be safe, unless allowed or specified by the documentation:
  - Don’t assume an order for how objects are visited
  - Don't change what is being iterated on - be especially careful of adds and deletes
  - Don't assume iterators are thread safe
    - *CopyOnWriteArrayList* is
    - *Vector* iterator is not

Note the pointer based notation. p really an iterator

```
vector<int>::iterator p;
p = vec.begin();
*p = 68;
*(p + 1) = 69;
//   *(p + 2) = 70;          // WRONG
print( vec );                // 68 69
vec.pop_back();              // size is now 1
print( vec );                // 68
```

Attempted access of an undefined element.

```
vec.push_back(101);
vec.push_back(103);        // size is now 3

int i = 0;
while ( i < vec.size())
   cout << vec[i++] << "<< endl;// 68 101 103
```

```
vec[0] = 1000;
vec[1] = 1001;
vec[2] = 1002;
print( vec );        // 1000 1001 1002
```

```
void print( vector<int> v ) {
    cout << "\nvector size is: ";
    cout << v.size() << endl;
    vector<int>::iterator p = v.begin();
    while ( p != v.end() )
        cout << *p++ << "  ";
    cout << endl << endl;
}
```

Iterators *necessary* in an OO language for encapsulation

- If an iterators were not provided, you would have to know how elements are physically stored or linked to access them
- With iterators, you only need an interface to access them
- It will give you elements, but you don't need to know the details of how the elements are stored
- Same is true with vector through pointer -- allowing you to say (as was done erroneously in an earlier slide) that (p+2) = ... would imply something *more than you can know from what your program has already done* about the storage allocated.

C++ Vector

- contiguous memory
- efficient access (**array-like** [index])
- efficient insert / delete at the end (allocate more memory occasionally)
- **inefficient** insert / delete at the front (will move all elements down to do the insertion)
- automatic expand / shrink allocated memory (allocate more than necessary to reduce allocation / release / copy overhead)
- occasional copying of the whole vector

C++ Iterator

pointer notation (really an iterator) to traverse a vector or other STL (standard template library) container

```
vector<int> v;
cout << "\nvector size is: " << v.size() << endl;
vector<int>::iterator p = v.begin();
while ( p != v.end() ) {
     cout << *p << "  ";
        p++;
}
```

Reallocating storage can cause iterators to be invalid.

C++ List

```cpp
#include <iostream>        // for cout, endl
#include <string>
#include <list>
using namespace std;

void print(list<string>&);

int main() {
        list<string> animals; //(A)

        animals.push_back("cheetah"); //(B)
        animals.push_back("lion"); //(C)
        animals.push_back("cat"); //(D)
        animals.push_back("fox"); //(E)
        animals.push_back("elephant"); //(F)
        animals.push_back("cat"); // duplicate cat           //(G)

        print(animals); // cheetah lion cat fox
        // elephant cat

        animals.pop_back(); //(H)
        print(animals); // cheetah lion cat fox
        // elephant

        animals.remove("lion"); // first occurrence of lion   //(I)
        print(animals); // cheetah cat fox elephant

        animals.push_front("lion"); //(J)
        print(animals); // lion cheetah cat fox elephant
        animals.pop_front(); //(K)
        print(animals); // cheetah cat fox elephant

        animals.insert(animals.end(), "cat"); //(L)
        print(animals); // cheetah cat fox elephant cat

        animals.sort(); //(M)
        print(animals); // cat cat cheetah elephant fox

        animals.unique(); //(N)
        print(animals); // cat cheetah elephant fox

        //another list needed for demonstrating splicing and merging:
        list<string> pets; //(O)
        pets.push_back("cat");
        pets.push_back("dog");
        pets.push_back("turtle");
        pets.push_back("bird");

        animals.splice(animals.begin(), pets, pets.begin() ); //(P)
        print(animals); // cat cat cheetah elephant fox
        print(pets); // dog turtle bird

        pets.sort(); // bird dog turtle          //(Q)

        animals.merge(pets); //(R)

        cout << pets.empty() << endl; // true        //(S)

        print(animals); // bird cat cat cheetah       //(T)
        // dog elephant fox
        // turtle
        return 0;
}

void print(list<string>& li) { //(U)
        typedef list<string>::const_iterator CI;
        cout << "The number of items in the list: " << li.size() << endl;;
        for (CI iter = li.begin(); iter != li.end(); iter++) {
                cout << *iter << " ";
        }
        cout << endl << endl;
}
```

```cpp
#include <iostream>
#include <string>
#include <list>
using namespace std;

void print(list<string>&);
```

```
int main() {
    list<string> animals; //(A)

    animals.push_back("cheetah"); //(B)
    animals.push_back("lion"); //(C)
    animals.push_back("cat"); //(D)
    animals.push_back("fox"); //(E)
    animals.push_back("elephant"); //(F)
    animals.push_back("cat"); // duplicate cat

    print(animals); // cheetah lion cat fox
                    // elephant cat

    animals.pop_back(); //(H)
    print(animals); // cheetah lion cat fox elephant

    animals.remove("lion"); // first occurrence of lion
    print(animals); // cheetah cat fox elephant
```

```
animals.push_front("lion");
print(animals); // lion cheetah cat fox elephant
animals.pop_front();
print(animals); // cheetah cat fox elephant

animals.insert(animals.end(), "cat");
print(animals); // cheetah cat fox elephant cat

animals.sort();
print(animals); // cat cat cheetah elephant fox

animals.unique();
print(animals); // cat cheetah elephant fox
```

Only examines adjacent elements so most useful on sorted lists

```
//another list needed for demonstrating
//splicing and merging:
list<string> pets; //(O)
pets.push_back("cat");
pets.push_back("dog");
pets.push_back("turtle");
pets.push_back("bird");
animals.splice(animals.begin(), pets, pets.begin() );
print(animals); // cat cat cheetah elephant fox
print(pets); // dog turtle bird

pets.sort(); // bird dog turtle

animals.merge(pets);

cout << pets.empty() << endl; // true

print(animals); // bird cat cat cheetah
                // dog elephant fox
                // turtle
```

typedef creates a type CI used to declare variables (e.g., *iter* below)

With a const_iterator, iterator can be changed, but not what it points to

```
void print(list<string>& li) { //(U)
    typedef list<string>::const_iterator CI;
    cout << "The number of items in the list: ";
  cout << li.size() << endl;;
    for (CI iter = li.begin(); iter != li.end(); iter++) {
        cout << *iter << " ";
    }
    cout << endl << endl;
}
```

C++ Vector of objects

```cpp
#include <iostream>
#include <vector>
#include <algorithm> // for sort( )  Algorithm is a collection of templates
using namespace std;

class X {
  int p;
public:
  X( ) {
    p = 42;
  }
  X(int q) {
    p = q;
  }
  int getp( ) const {
    return p;
  }
  void changeState(int pp) {
    p = pp;
  }
};
```

Zero arg constructor

getters and setters for *p*

Overloaded comparison operators

```
// Chapter 12 explains the syntax shown for the two
// operator overloading for class X;
bool operator<(const X& x1, const X& x2) {
   return x1.getp( ) < x2.getp( );
}

bool operator==(const X& x1, const X& x2) {
   return x1.getp( ) == x2.getp( );
}
```

which “==” is used?

- Could be member functions
- Need to declare as

```
bool operator==(const X& x2) const;
```

later called by sort which passes a *const* *this* pointer

```
void print(vector<X>);

int main( ) {
  vector<X> vec;

  X x1(2);
  X x2(3);
  X x3(5);

  vec.push_back(x1);
  vec.push_back(x3);
  vec.push_back(x2);

  print(vec); // 2 5 3
  x2.changeState(1000);

  // change made to x2 above does not affect copy
  // of x2 in vec;
  print(vec); // 2 5 3
```

forward declaration of print. Why can't it be declared as a member function?

```
// vector elements initialized by X's no-arg
// constructor:
vector<X> vec_2(5);
print(vec_2); // 42 42 42 42 42
vec_2.resize(7);
print(vec_2); // 42 42 42 42 42 42 42

// uninitialized increase in the vector capacity
vec_2.reserve(10);
cout << vec_2.capacity( ) << endl; // 10
print(vec_2); // 42 42 42 42 42 42 42
// size still returns 7;
cout << vec_2[8].getp( ) << endl;  // undefined
```

- *reserve(n)* gives the vector a *capacity* of at least *n*, it may be more
- If capacity is already *n*, essentially a no-op

```
    // set up vector for sorting
    vec_2[0] = X(12);
    vec_2[1] = X(36);
    vec_2[2] = X(3);
    vec_2[3] = X(56);
    vec_2[4] = X(2);

    sort(vec_2.begin( ), vec_2.end( ));
    print(vec_2); // 2 3 12 26 42 42 56
    vec_2.clear( );
    print(vec_2); // nothing printed, empty
    cout << vec_2.capacity( ) << endl; // 10
    return 0;
}
```

- *sort* is a member of the *algorithms* Standard Template Library
- *sort(vec_2.begin( ), vec_2.end( ));* causes a *template* to be expanded (if not done already) that creates a sort that operates on the range given.
- *sort* operates on the elements of the vector via an

```
void print(vector<X> v) {
   cout << "\nvector size is: ";
   cout << v.size( ) << endl;
   vector<X>:: iterator p = v.begin( );
   while (p != v.end( )) {
     cout << (*p++).getp( ) << " ";
   }
   cout << endl << endl;
}
```

Note that *p* is an iterator, not a pointer.

"*" and "++" are over-loaded operators that get the element currently indicated by the iterator or move to the next element, respectively

More natural in a C/C++ context than *.get( )* and *.next( )*

Why Create New Containers?

- need efficient ways to store and access objects
- reuse the same implementation for different classes

Creating New C++ Containers

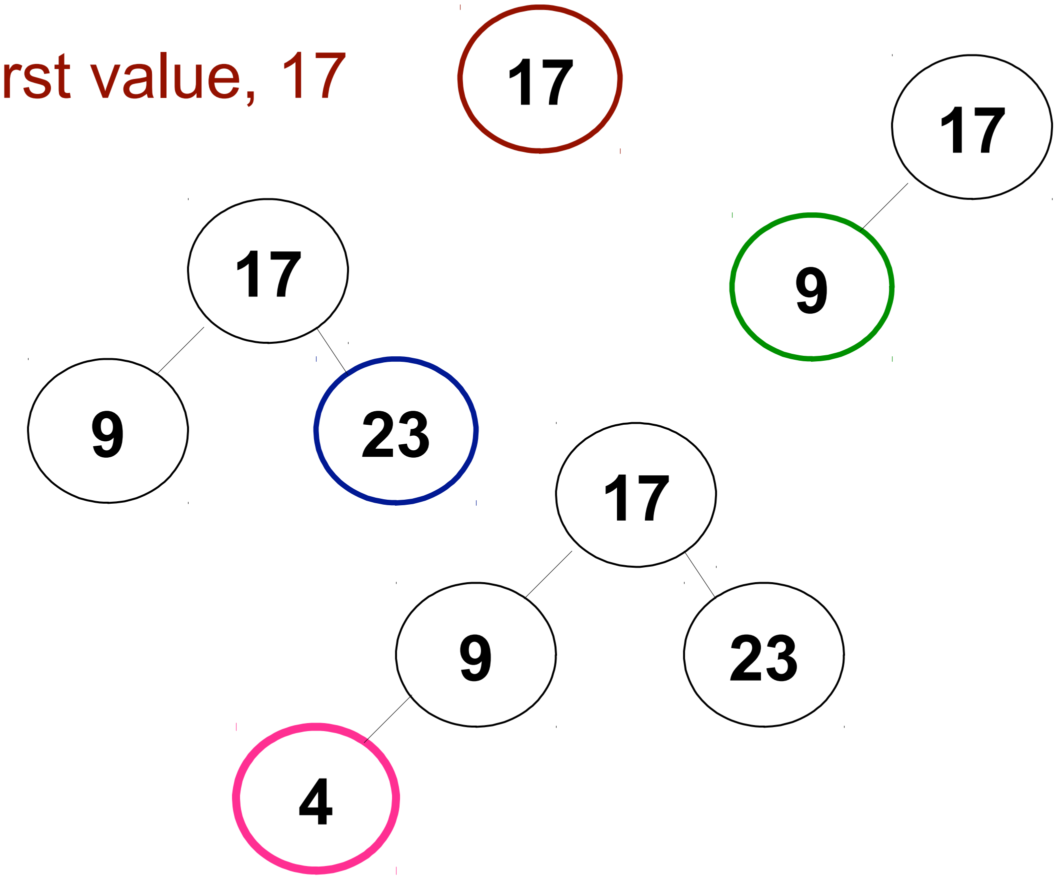
C++ Binary Search Tree

Binary Search Tree

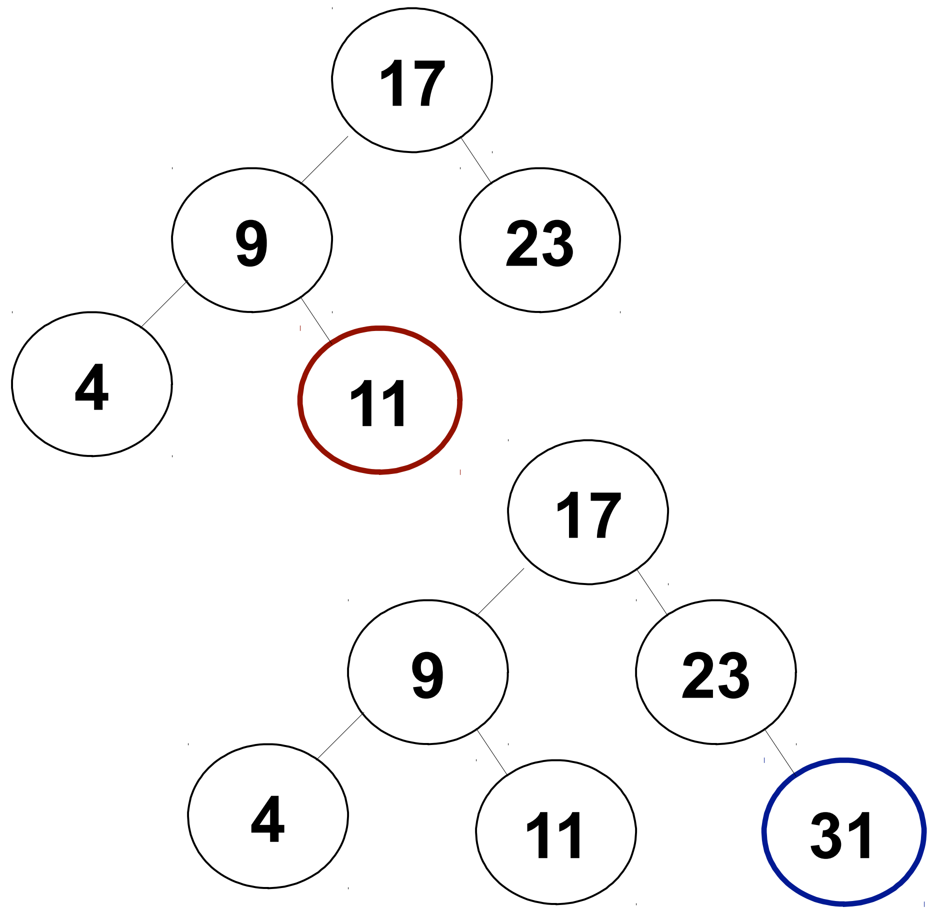
- A tree contains a group of nodes.
- A node can have a left child and a right child.
- If a node has no child, the node is a called a leaf node.
- Each node has a unique value.
- When a new value is inserted to the tree, if the value already appears, the insertion has no effect.
- If the value is smaller than a node, the value is inserted as the left child of the node. If the node already has a left child, the value is inserted as a child of the child (recursively).

- insert the first value, 17
- insert 9
- insert 23

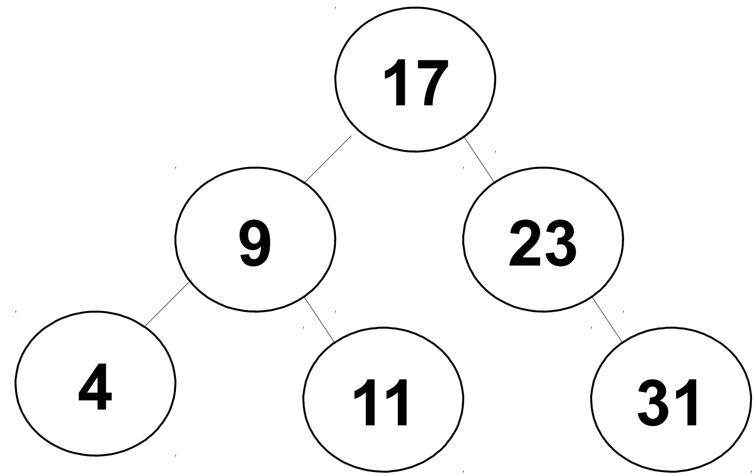
- insert 4



- insert 11
- insert 31



Traverse Tree (In-Order)



if (left child is not empty)
{ visit left child; }
print value;
if (right child is not empty)
{ visit right child; }

⇒ The output values are sorted.
4, 9, 11, 17, 23, 31

```
#include <iostream>
#include <string>
using namespace std;
template <class TPL> class BinaryNode {
   BinaryNode * bn_left;
   BinaryNode * bn_right;
   TPL bn_content;
public:
   BinaryNode(TPL content);
   virtual ~BinaryNode( );
   void insertContent(TPL content);
   bool searchContent(TPL content) const;
   void print(int depth) const;
};
```

View this as a declaration of a symbol that has type *class*, just as *int i* is a variable of type int.

This is the .h stuff for the template

```
#include <iostream>
#include <string>
using namespace std;
template <class TPL> class BinaryNode {
   BinaryNode * bn_left;
   BinaryNode * bn_right;
   TPL bn_content;
public:
   BinaryNode(TPL content);
   virtual ~BinaryNode( );
   void insertContent(TPL content);
   bool searchContent(TPL content) co
   void print(int depth) const;
};
```

Two ways to declare this:

class TPL or *typename TPL*

Some say use *class* if expecting a class name, *typename* if expecting class or primitive, i.e., is a usage hint.

```
#include <iostream>
#include <string>
using namespace std;
template <class TPL> class BinaryNode {
   BinaryNode * bn_left;
   BinaryNode * bn_right;
   TPL bn_content;
public:
   BinaryNode(TPL content);
   virtual ~BinaryNode( );
   void insertContent(TPL content);
   bool searchContent(TPL content) const;
   void print(int depth) const;
};
```

Some people prefer *typename* to avoid overloading of *class.*

If you have template parameters to a template, ***must*** use typename.

Some history about *class, typname*

This will never appear on a 30862 test that I give

For details see

http://stackoverflow.com/questions/213121/use-class-or-typename-for-template-parameters

and

http://blogs.msdn.com/b/slippman/archive/2004/08/11/212768.aspx

From Lippman: When C++ designed, the decision was made to not make an additional keyword to declare types that are parameters to templates. Why add another keyword to the language? Now, consider the following:

```
template <class T> class Demonstration {
public:
   void method( ) {
      T::A *aObj; // expression or declaration?
   }
};
```

Consider this code snippet

```
template <class T> class Demonstration {
public:
   void method( ) {
      T::A *aObj; // expression or declaration?
   }
};
```

Programmer clearly wants to declare a pointer to *aObj* that is of type *A* that is defined within template parameter type *T*.

C++ compilers will interpret this as a static (class) variable from the class *T (T::A)* multiplied times a local variable *aObj*, with the result discarded.

How to fix this?

```
template <typename T> class Demonstration {
public:
   void method( ) {
      typename T::A *aObj; // expression or declaration?
   }
};
```

Create a new keyword *typename* and change the code to the above. Instructs the compiler to treat what follows a a declaration.

Once the keyword was introduced the ISO standards committee decided to revisit the use of *class* and allow typename to be used there, as well.

```
template <class TPL>
BinaryNode<TPL>::BinaryNode(TPL
content) {
   bn_content = content;
   bn_left = NULL;
   bn_right = NULL;
}
```

This is the .cpp stuff for the template.

In particular, this declares a constructor for the *BinaryNode<TPL>* class

```
template <class TPL> void BinaryNode<TPL>::insertContent(TPL
                                               content){
  if (content == bn_content) {return;} // no duplicates
  if (content < bn_content) {
    if (bn_left == NULL) {
      BinaryNode<TPL> *newnode = new BinaryNode<TPL>(content);
      bn_left = newnode;
    } else {
      bn_left->insertContent(content);
    }
  } else {
    if (bn_right == NULL) {
      BinaryNode<TPL> * newnode = new BinaryNode<TPL>(content);
      bn_right = newnode;
    } else {
      bn_right->insertContent(content);
    }
  }
}
```

More of the .cpp file

```
template <class TPL> bool BinaryNode<TPL>::searchContent(
                                        TPL content) const {
   if (content == bn_content) {return true;}
   if (content < bn_content) {
      if (bn_left == NULL) {return false;}
      return bn_left->searchContent(content);
   } else {
      if (bn_right == NULL) {return false;}
      return bn_right->searchContent(content);
   }
}
```

More of the .cpp file

```cpp
template <class TPL> void BinaryNode<TPL>::print(
                          int depth) const {
  if (bn_left != NULL) {bn_left->print(depth+1);}
  for (int identcnt = 0; identcnt < depth; identcnt++)
  {
    cout << "\t";
  }
  cout << bn_content << endl;
  if (bn_right != NULL) {bn_right->print(depth+1);}
}

template <class TPL> BinaryNode<TPL>::~BinaryNode( ) {
  if (bn_left != NULL) {delete bn_left;}
  if (bn_right != NULL) {delete bn_right;}
}
```

More of the .cpp file

The student class

```
class Student {
   string s_name;
public:
   Student(string name): s_name(name) { }
   Student(const Student& orig): s_name(orig.s_name){ }
   Student( ) {s_name = "";}
   bool operator< (const Student& arg2) {
      return (s_name < arg2.s_name);
   }
   bool operator==(const Student& arg2) {
      if (s_name == arg2.s_name) {return true;}
      else {return false;}
   }
   friend ostream& operator<< (
               ostream& os, const Student& stu);
};

ostream& operator<< (ostream& os, const Student& stu) {
   os << stu.s_name << endl;
   return os;
}
```

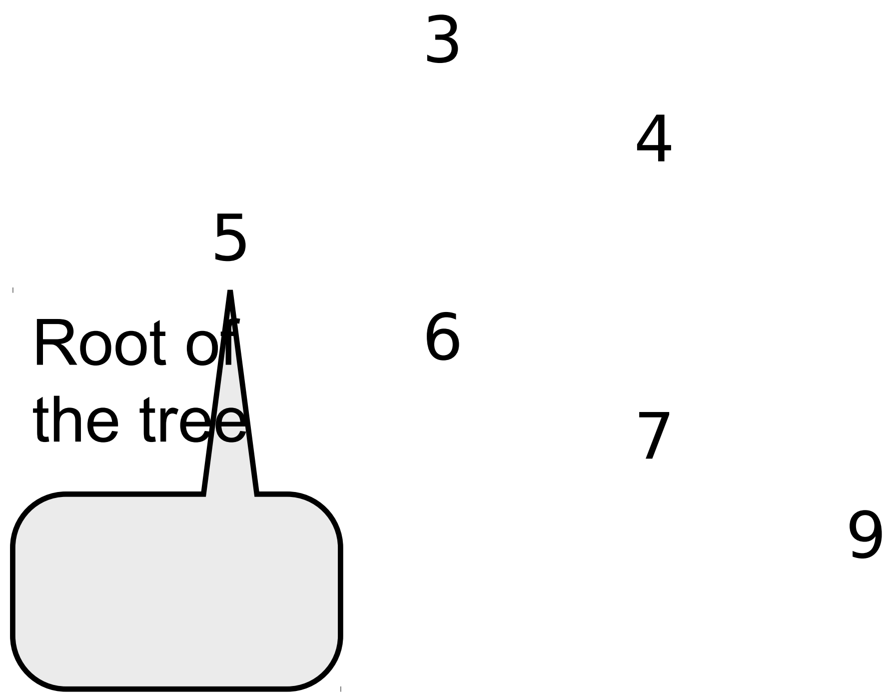
The **user** class

```
class User {
   int u_age;
public:
   User(int age): u_age(age) { };
   User( ): u_age(0) { }
   bool operator< (const User& arg2) {
      return (u_age < arg2.u_age);
   }
   bool operator== (const User& arg2) {
      return (u_age == arg2.u_age);
   }
   friend ostream& operator<< (ostream& os,
                              const User& user);
};

ostream& operator<< (ostream& os, const User& usr) {
   os << usr.u_age << endl;
   return os;
}
```

The main fct.

```
int main(void) {
   BinaryNode<int> bnint(5);
   bnint.insertContent(3);
   bnint.insertContent(6);
   bnint.insertContent(4);
   bnint.insertContent(7);
   bnint.insertContent(6);
   bnint.insertContent(9);
   bnint.print(0);
   cout << ______" << endl;
```



The main fct.

```
Student stu1("John");
Student stu2("Mary");
Student stu3("Tom");
Student stu4("Amy");
Student stu5("Ted");
BinaryNode<Student> bnstu(stu1);
bnstu.insertContent(stu2);
bnstu.insertContent(stu3);
bnstu.insertContent(stu4);
bnstu.insertContent(stu5);
bnstu.print(0);
cout << "__________" << endl;
```

Amy

John

Mary

Ted

Tom

The main fct.

```
User usr1(21);
User usr2(28);
User usr3(19);
User usr4(17);
User usr5(22);
User usr6(20);
User usr7(18);
BinaryNode<User> bnusr(usr1);
bnusr.insertContent((User)3);
bnusr.insertContent(usr2);
bnusr.insertContent(usr3);
bnusr.insertContent(usr4);
bnusr.insertContent(usr5);
bnusr.insertContent(usr6);
bnusr.insertContent(usr7);
bnusr.print(0);
cout << "___________" << endl;
```

3
17
18
19
20
21
22
28

```
User usr1(21);
User usr2(28);
User usr3(19);
User usr4(17);
User usr5(22);
User usr6(20);
User usr7(18);
BinaryNode<User> bnusr(usr1);
bnusr.insertContent((User)3);
bnusr.insertContent(usr2);
bnusr.insertContent(usr3);
bnusr.insertContent(usr4);
bnusr.insertContent(usr5);
bnusr.insertContent(usr6);
bnusr.insertContent(usr7);
bnusr.print(0);
cout << "__________" << endl;
```

from stackoverflow: “This is legal because C++ interprets any constructor that can be called with a single argument of type `T` as a means of implicitly converting from `T`s to the custom object “type.

3

17

18

19

20

21

22

28

The main fct.

```
cout << bnint.searchContent(11) << " "
     << bnint.searchContent(10) << endl;
Student stu6("Ted");
cout << bnstu.searchContent(stu6)<< " "
     << bnstu.searchContent(stu2)<< endl;
cout << bnusr.searchContent(usr2)<< " "
     << bnusr.searchContent(usr4)<< endl;
```

```
0  0
1  1
1  1
```

The template language is Turing complete

- Any computable problem can be solved by C++'s Template language
- I don't suggest you exploit this, in general

Template solution to factorials

```
#include <iostream>
template <int N> struct Factorial {
    enum { val = Factorial<N-1>::val * N };
};

template<>
struct Factorial<0> {
    enum { val = 1 };
};

int main() {
    // Value generated at compile time.
    // Most compilers limit recursion depth
    std::cout << Factorial<4>::val << "\n";
}
```

http://stackoverflow.com/questions/189172/c-templates-turing-complete

Instantiating templates

- Declare and define the template in the same file, as we did here
- This will ensure that the template is *instantiated.*
- If the template is not clearly defined to the C++ compiler, it will not be instantiated
  – classes intended to be created by the template will not exist
- Template instantiation is difficult for the C++ system
  – A template for a type can only be instantiated once, otherwise multiple copies of static variables will exist or there will be linker errors
  – Every template must be instantiated once for each use with a type

Two common models

- The *Borland* model
  - each compilation unit (file) that uses a template instantiation creates an instantiation.
  - The equivalent of a *common* block is created for class statics
  - The linker collapses these into a single version
- The AT&T C++ *Cfront* model
  - Create a repository where template instantiations live
  - Only allow one/per template<type>
  - Problems when multiple programs live in the same directory or one program spans multiple directories

Array initialization in C++

Java - DefaultInitCpp/DefaultInitClassArray2.cpp - Eclipse SDK

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DefaultInitClassArray2.cpp

```cpp
using namespace std;
class Date {
public:
    int d, m, y;
    Date() { d = 1; m = 1; y = 1970; }
};
class User {
public:
    string name;
    int age;
    Date dateOfBirth;
    User() { name = "Zaphod"; age = 10; }
};
User uGlobal[10];               // global array
int main()
{
    User uLocal[10];            // local array
    cout << uLocal[1].name << endl;                   // Zaphod
    cout << uLocal[1].age << endl;                    // 10
    cout << uLocal[1].dateOfBirth.y << endl;          // 1970
    cout << uLocal[1].dateOfBirth.m << endl;          // 1

    cout << uGlobal[1].name << endl;                  // Zaphod
    cout << uGlobal[1].age << endl;                   // 10
    cout << uGlobal[1].dateOfBirth.y << endl;         // 1970
    cout << uGlobal[1].dateOfBirth.m << endl;         // 1
    return 0;
}
```

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