The C++ Standard Template Library (containers, iterators, and algorithms)

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Overview

- Common tasks and ideals
- Generic programming
- Containers, algorithms, and iterators
- The simplest algorithm: find()
- Parameterization of algorithms
  - find_if() and function objects
- Sequence containers
  - vector and list
- Associative containers
  - map, set
- Standard algorithms
  - copy, sort, …
  - Input iterators and output iterators
- List of useful facilities
  - Headers, algorithms, containers, function objects

Common tasks

- Collect data into containers
- Organize data
  - For printing
  - For fast access
- Retrieve data items
  - By index (e.g., get the **N**th element)
  - By value (e.g., get the first element with the value **"Chocolate"**)
  - By properties (e.g., get the first elements where “**age<64**”)
- Add data
- Remove data
- Sorting and searching
- Simple numeric operations

Observation

We can (already) write programs that are very similar independent of the data type used

- Using an **int** isn’t that different from using a **double**
- Using a **vector<int>** isn’t that different from using a **vector<string>**

Ideals

We'd like to write common programming tasks so that we don't have to re-do the work each time we find a new way of storing the data or a slightly different way of interpreting the data

- Finding a value in a **vector** isn't all that different from finding a value in a **list** or an array
- Looking for a **string** ignoring case isn't all that different from looking at a **string** not ignoring case
- Graphing experimental data with exact values isn't all that different from graphing data with rounded values
- Copying a file isn't all that different from copying a vector

Ideals (continued)

- Code that's
  - Easy to read
  - Easy to modify
  - Regular
  - Short
  - Fast
- Uniform access to data
  - Independently of how it is stored
  - Independently of its type
- …

Ideals (continued)

- …
- Type-safe access to data
- Easy traversal of data
- Compact storage of data
- Fast
  - Retrieval of data
  - Addition of data
  - Deletion of data
- Standard versions of the most common algorithms
  - Copy, find, search, sort, sum, …

Examples

- Sort a vector of strings
- Find an number in a phone book, given a name
- Find the highest temperature
- Find all values larger than 800
- Find the first occurrence of the value 17
- Sort the telemetry records by unit number
- Sort the telemetry records by time stamp
- Find the first value larger than “Petersen”?
- What is the largest amount seen?
- Find the first difference between two sequences
- Compute the pairwise product of the elements of two sequences
- What are the highest temperatures for each day in a month?
- What are the top 10 best-sellers?
- What’s the entry for “C++” (say, in Google)?
- What’s the sum of the elements?

Generic programming

- Generalize algorithms
  - Sometimes called “lifting an algorithm”
- The aim (for the end user) is
  - Increased correctness
    - Through better specification
  - Greater range of uses
    - Possibilities for re-use
  - Better performance
    - Through wider use of tuned libraries
    - Unnecessarily slow code will eventually be thrown away
- Go from the concrete to the more abstract
  - The other way most often leads to bloat

Lifting example (concrete algorithms)

```
double sum(double array[], int n)       // one concrete algorithm (doubles in array)
{
    double s = 0;
    for (int i = 0; i < n; ++i ) s = s + array[i];
    return s;
}

struct Node { Node* next; int data; };

int sum(Node* first)                    // another concrete algorithm (ints in list)
{
    int s = 0;
    while (first) {                     // terminates when expression is false or zero
        s += first->data;
        first = first->next;
    }
    return s;
}
```

Lifting example (abstract the data structure)

// pseudo-code for a more general version of both algorithms

```
int sum(data)            // somehow parameterize with the data structure
{
    int s = 0;                      // initialize
    while (not at end) {            // loop through all elements
        s = s + get value;          // compute sum
        get next data element;
    }
    return s;                       // return result
}
```

- We need three operations (on the data structure):
  - not at end
  - get value
  - get next data element

Lifting example (STL version)

// Concrete STL-style code for a more general version of both algorithms

```
template<class Iter, class T>        // Iter should be an Input_iterator
                                     // T should be something we can + and =
T sum(Iter first, Iter last, T s)    // T is the "accumulator type"
{
    while (first!=last) {
        s = s + *first;
        ++first;
    }
    return s;
}
```

- Let the user initialize the accumulator

```
float a[] = { 1,2,3,4,5,6,7,8 };
double d = 0;
d = sum(a,a+sizeof(a)/sizeof(*a),d);
```

Lifting example

- Almost the standard library accumulate
  - A bit for terseness is simplified
- Works for
  - arrays
  - **vector**s
  - **list**s
  - **istream**s
  - …
- Runs as fast as "hand-crafted" code
  - Given decent inlining
- The code's requirements on its data has become explicit
  - We understand the code better

The STL

- Part of the ISO C++ Standard Library
- Mostly non-numerical
  - Only 4 standard algorithms specifically do computation
    - Accumulate, inner_product, partial_sum, adjacent_difference
  - Handles textual data as well as numeric data
    - E.g. string
  - Deals with organization of code and data
    - Built-in types, user-defined types, and data structures
- Optimizing disk access was among its original uses
  - Performance was always a key concern

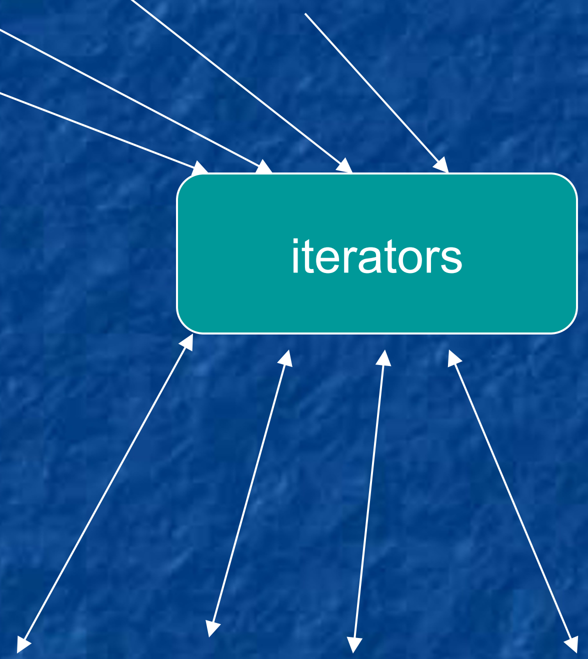
The STL

- Designed by Alex Stepanov
- General aim: The most general, most efficient, most flexible representation of concepts (ideas, algorithms)
  - Represent separate concepts separately in code
  - Combine concepts freely wherever meaningful
- General aim to make programming “like math”
  - or even “Good programming *is* math”
  - works for integers, for floating-point numbers, for polynomials, for …

Basic model

- Algorithms

  sort, find, search, copy, …



- Containers

  vector, list, map, unordered_map, …

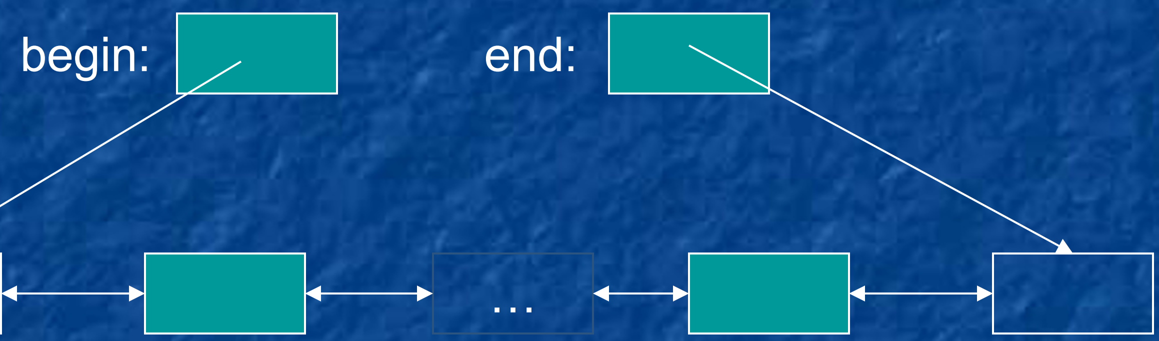
- Separation of concerns
  - Algorithms manipulate data, but don't know about containers
  - Containers store data, but don't know about algorithms
  - Algorithms and containers interact through iterators
    - Each container has its own iterator types

The STL

- An ISO C++ standard framework of about 10 containers and about 60 algorithms connected by iterators
  - Other organizations provide more containers and algorithms in the style of the STL
    - Boost.org, Microsoft, SGI, …
- The best known and most widely used example of generic programming

Basic model

- A pair of iterators defines a sequence
  - The beginning (points to the first element – if any)
  - The end (points to the one-beyond-the-last element)



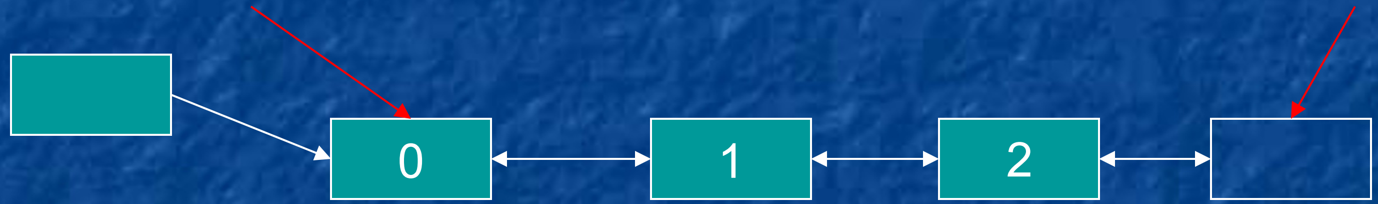
- An iterator is a type that supports the "iterator operations"
  - ++ Go to next element
  - * Get value
  - == Does this iterator point to the same element as that iterator?
- Some iterators support more operations (e.g. --, +, and [ ])

Containers

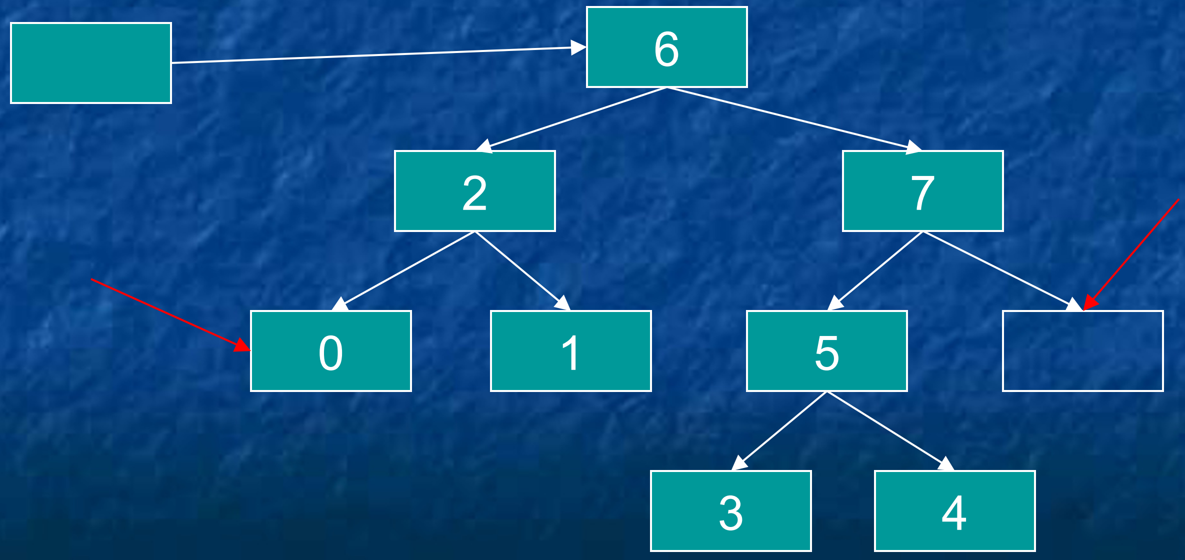
(hold sequences in difference ways)

- **vector**

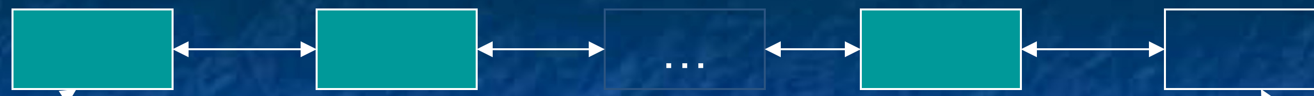
- **list**
(doubly linked)



- **set**
(a kind of tree)



The simplest algorithm: **find()**




```
// Find the first element that equals a value
template<class In, class T>
In find(In first, In last, const T& val)
{
    while (first!=last && *first != val) ++first;
    return first;
}

void f(vector<int>& v, int x)        // find an int in a vector
{
    vector<int>::iterator p = find(v.begin(),v.end(),x);
    if (p!=v.end()) { /* we found  x */ }
    // …
}
```

We can ignore (“abstract away”) the differences between containers

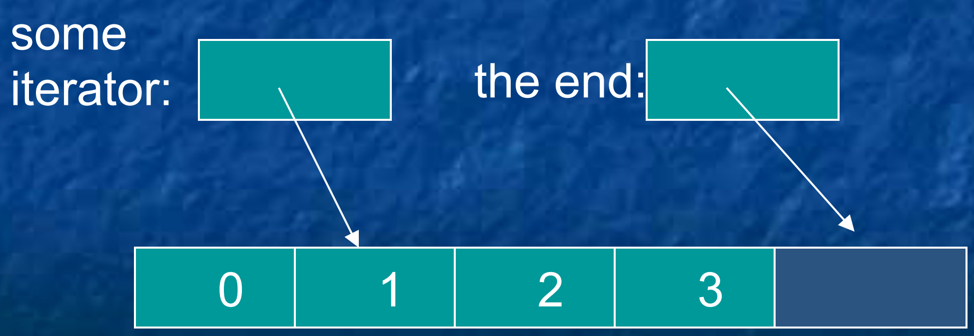
find()

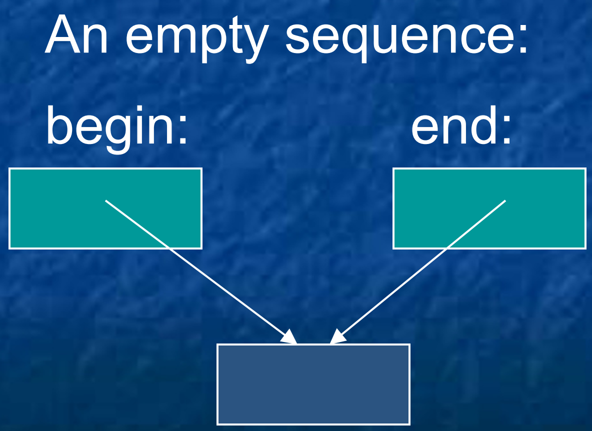
generic for both element type and container type

```
void f(vector<int>& v, int x)                    // works for vector of ints
{
    vector<int>::iterator p = find(v.begin(),v.end(),x);
    if (p!=v.end()) { /* we found  x */ }
    // …
}

void f(list<string>& v, string x)                // works for list of strings
{
    list<string>::iterator p = find(v.begin(),v.end(),x);
    if (p!=v.end()) { /* we found  x */ }
    // …
}

void f(set<double>& v, double x)                 // works for set of doubles
{
    set<double>::iterator p = find(v.begin(),v.end(),x);
    if (p!=v.end()) { /* we found  x */ }
    // …
}
```

Algorithms and iterators

- An iterator points to (refers to, denotes) an element of a sequence
- The end of the sequence is "one past the last element"
  - *not* "the last element"
  - That's necessary to elegantly represent an empty sequence
  - One-past-the-last-element isn't an element
    - You can compare an iterator pointing to it
    - You can't dereference it (read its value)
- Returning the end of the sequence is the standard idiom for "not found" or "unsuccessful"





Simple algorithm: **find_if()**

- Find the first element that matches a criterion (predicate)
  - Here, a predicate takes one argument and returns a **bool**

```
template<class In, class Pred>
In find_if(In first, In last, Pred pred)
{
    while (first!=last && !pred(*first)) ++first;
    return first;
}

void f(vector<int>& v)
{
    vector<int>::iterator p = find_if(v.begin(),v.end,Odd());
    if (p!=v.end()) { /* we found an odd number */ }
    // …
}
```

A predicate

Predicates

- A predicate (of one argument) is a function or a function object that takes an argument and returns a **bool**
- For example
  - A function

    ```
    bool odd(int i) { return i%2; } // % is the remainder (modulo) operator
    odd(7);                         // call odd: is 7 odd?
    ```

  - A function object

    ```
    struct Odd {
            bool operator()(int i) const { return i%2; }
    };
    Odd odd;        // make an object odd of type Odd
    odd(7);         // call odd: is 7 odd?
    ```

Function objects

- A concrete example using state

```
template<class T> struct Less_than {
    T val;      // value to compare with
    Less_than(T& x) :val(x) { }
    bool operator()(const T& x) const { return x < val; }
};

// find x<43 in vector<int> :
p=find_if(v.begin(), v.end(), Less_than(43));

// find x<"perfection" in list<string>:
q=find_if(ls.begin(), ls.end(), Less_than("perfection"));
```

Function objects

- A very efficient technique
  - inlining very easy
    - and effective with current compilers
  - Faster than equivalent function
    - And sometimes you can’t write an equivalent function
- The main method of policy parameterization in the STL
- Key to emulating functional programming techniques in C++

Policy parameterization

- Whenever you have a useful algorithm, you eventually want to parameterize it by a "policy".
  - For example, we need to parameterize sort by the comparison criteria

```
struct Record {
    string name;          // standard string for ease of use
    char addr[24];        // old C-style string to match database layout
    // …
};

vector<Record> vr;
// …
sort(vr.begin(), vr.end(), Cmp_by_name());     // sort by name
sort(vr.begin(), vr.end(), Cmp_by_addr());     // sort by addr
```

Comparisons

```
// Different comparisons for Rec objects:

struct  Cmp_by_name {
    bool operator()(const Rec& a, const Rec& b) const
        { return a.name < b.name; }         // look at the name field of Rec
};

struct  Cmp_by_addr {
    bool operator()(const Rec& a, const Rec& b) const
        { return 0 < strncmp(a.addr, b.addr, 24); }         // correct?
};

// note how the comparison function objects are used to hide ugly
// and error-prone code
```

Policy parameterization

- Whenever you have a useful algorithm, you eventually want to parameterize it by a “policy”.
  - For example, we need to parameterize sort by the comparison criteria

```
vector<Record> vr;
// …
sort(vr.begin(), vr.end(),
        [] (const Rec& a, const Rec& b)
                { return a.name < b.name; }        // sort by name
   );

sort(vr.begin(), vr.end(),
        [] (const Rec& a, const Rec& b)
                { return 0 < strncmp(a.addr, b.addr, 24); }  // sort by addr
   );
```

Policy parameterization

- Use a named object as argument
  - If you want to do something complicated
  - If you feel the need for a comment
  - If you want to do the same in several places
- Use a lambda expression as argument
  - If what you want is short and obvious
- Choose based on clarity of code
  - There are no performance differences between function objects and lambdas
  - Function objects (and lambdas) tend to be faster than function arguments

vector

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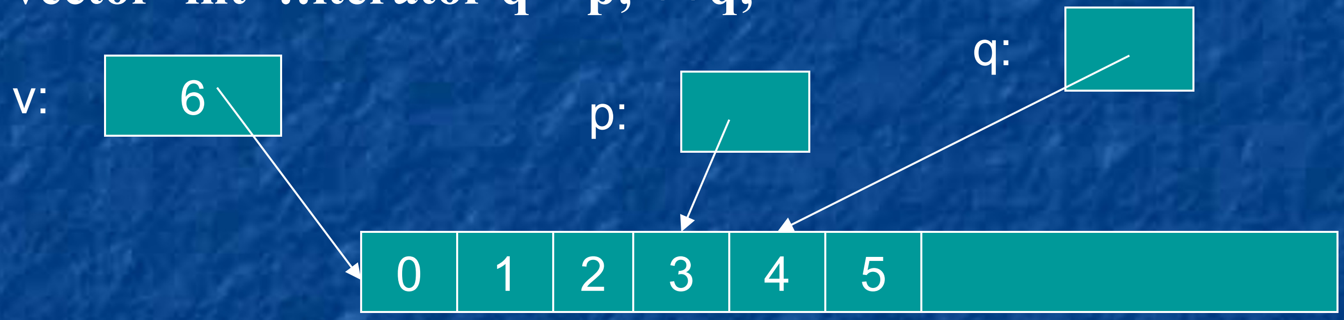
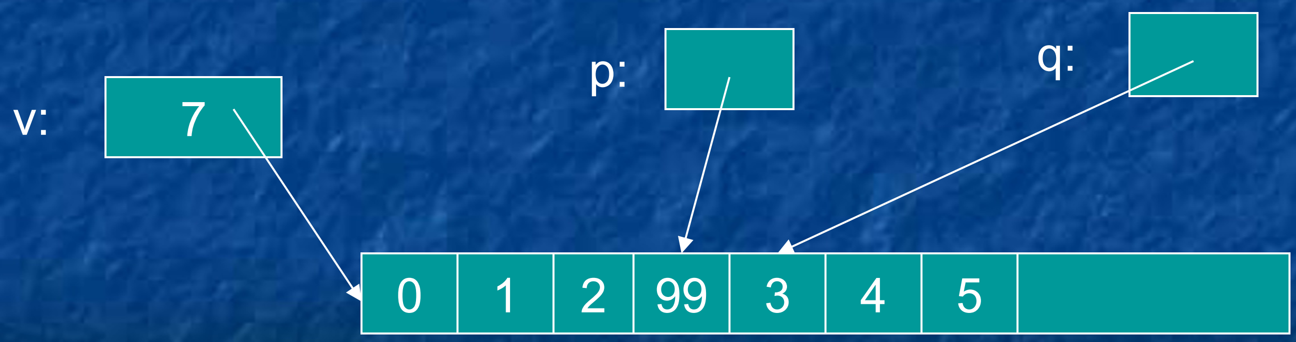
```
template<class T> class vector {
    T* elements;
    // …
    using value_type = T;
    using iterator = ???;   // the type of an iterator is implementation defined
                            // and it (usefully) varies (e.g. range checked iterators)
                            // a vector iterator could be a pointer to an element
    using const_iterator = ???;

    iterator begin();                   // points to first element
    const_iterator begin() const;
    iterator end();                     // points to one beyond the last element
    const_iterator end() const;

    iterator erase(iterator p);                 // remove element pointed to by p
    iterator insert(iterator p, const T& v);    // insert a new element v before p
};
```

insert() into vector

vector<int>::iterator p = v.begin(); ++p; ++p; ++p;
vector<int>::iterator q = p; ++q;

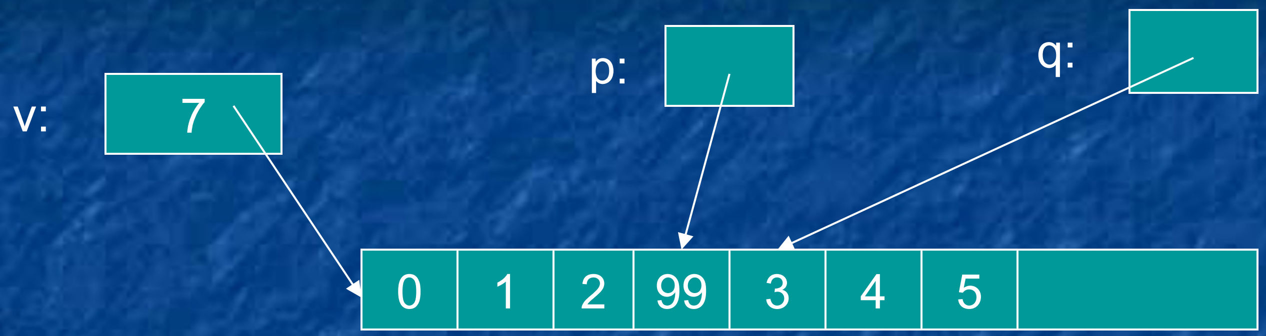


p=v.insert(p,99); *// leaves **p** pointing at the inserted element*

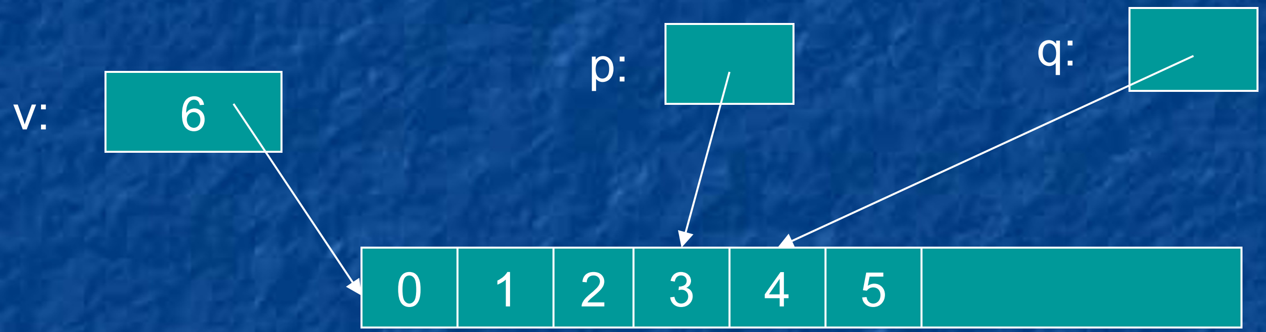


- Note: q is invalid after the **insert()**
- Note: Some elements moved; all elements could have moved

erase() from vector



p = v.erase(p); *// leaves **p** pointing at the element after the erased one*



- vector elements move when you insert() or erase()
- Iterators into a vector are invalidated by insert() and erase()

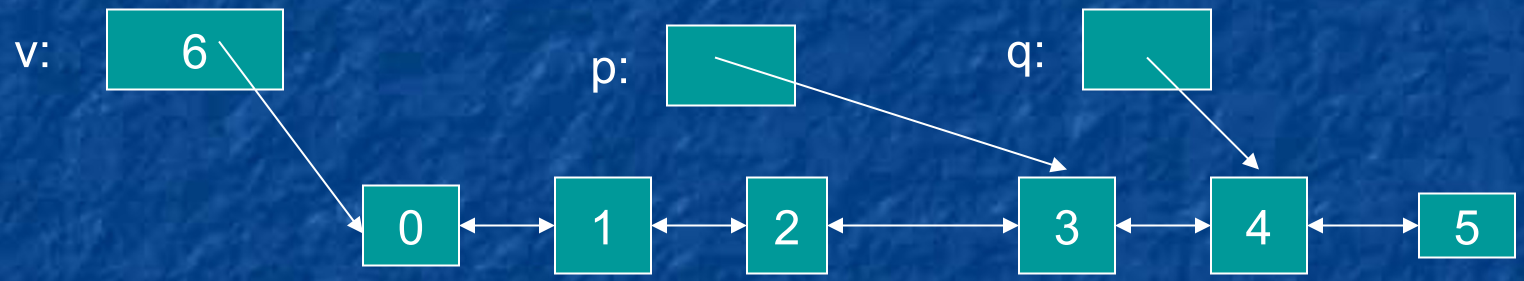
list

Link: T value | Link* pre | Link* post

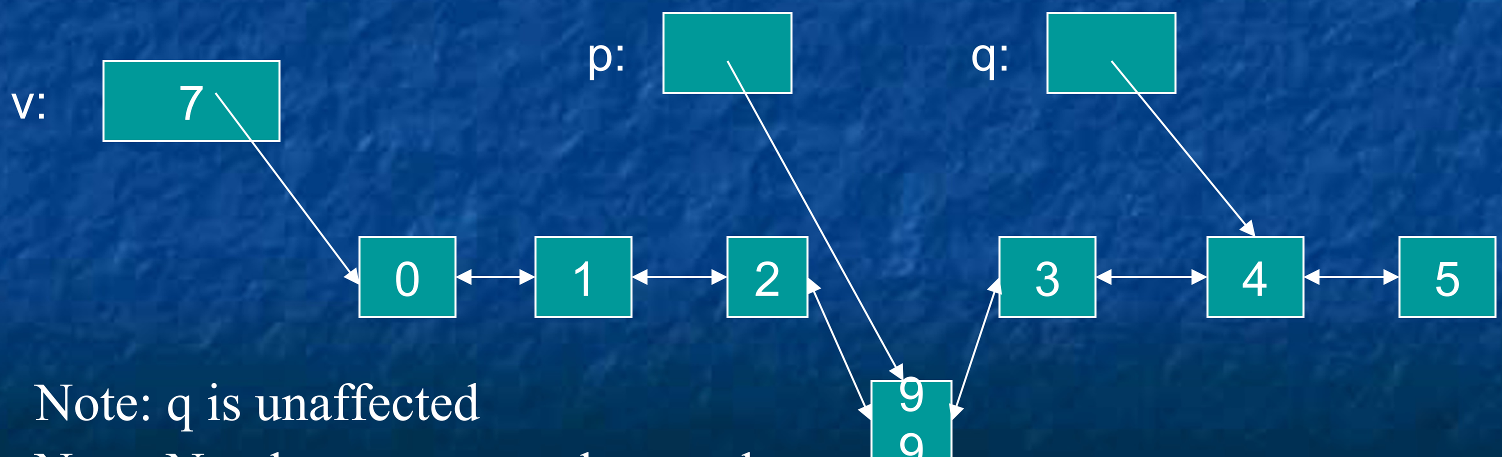
```
template<class T> class list {
    Link* elements;
    // …
    using value_type = T;
    using iterator = ???;   // the type of an iterator is implementation defined
                            // and it (usefully) varies (e.g. range checked iterators)
                            // a list iterator could be a pointer to a link node
    using const_iterator = ???;

    iterator begin();                     // points to first element
    const_iterator begin() const;
    iterator end();                       // points one beyond the last element
    const_iterator end() const;

    iterator erase(iterator p);                 // remove element pointed to by p
    iterator insert(iterator p, const T& v);  // insert a new element v before p
};
```

insert() into list

```
list<int>::iterator p = v.begin(); ++p; ++p; ++p;
list<int>::iterator q = p; ++q;
```



v = v.insert(p,99); // leaves **p** pointing at the inserted element



- Note: q is unaffected
- Note: No elements moved around

erase() from list

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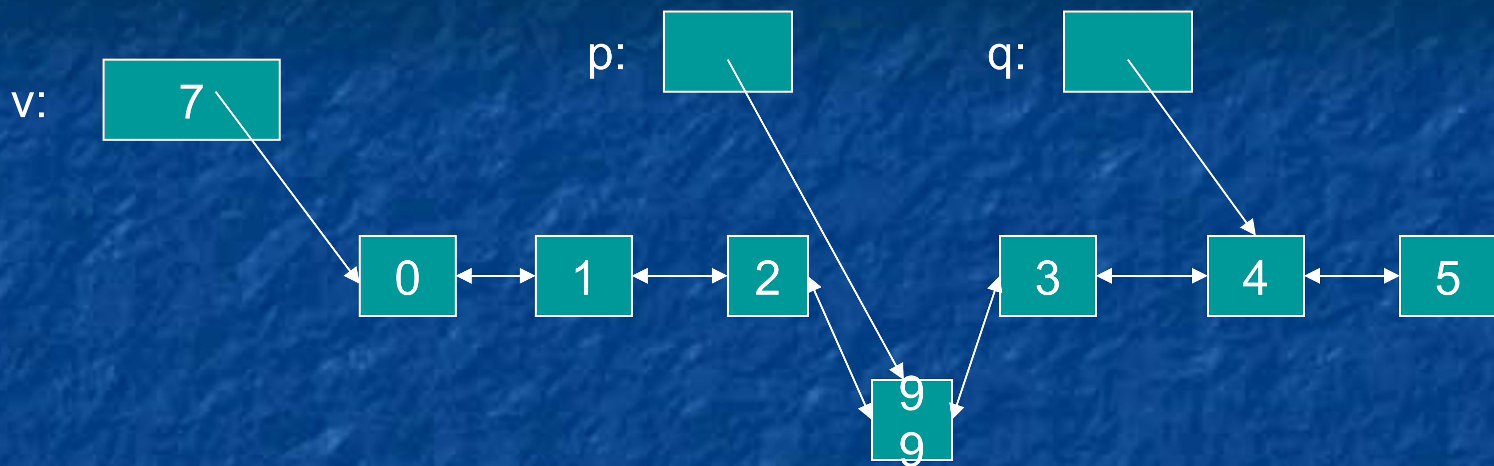
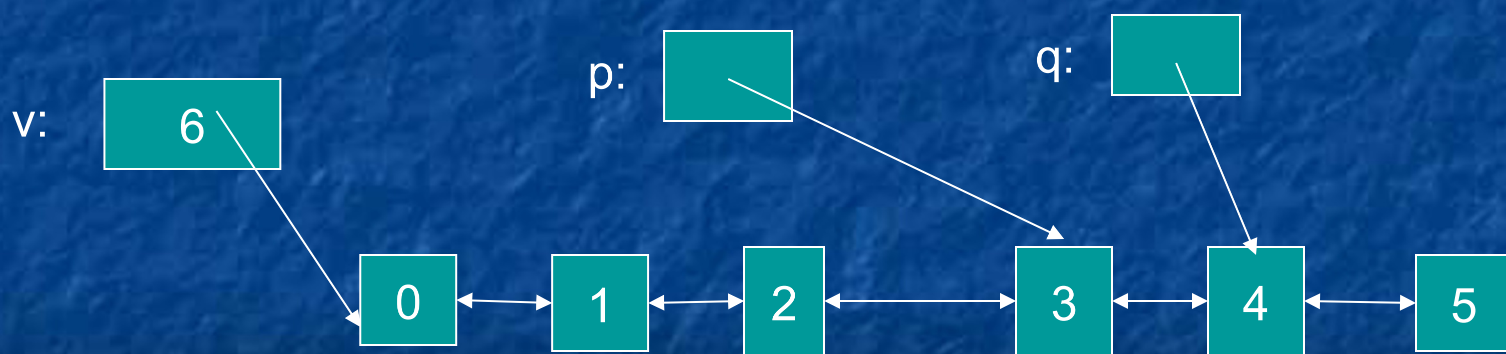


p = v.erase(p); *// leaves p pointing at the element after the erased one*



- Note: list elements do not move when you insert() or erase()

Ways of traversing a vector

```
for(int i = 0; i<v.size(); ++i)                              // why int?
    …   // do something with v[i]

for(vector<T>::size_type i = 0; i<v.size(); ++i)     // longer but always correct
    …   // do something with v[i]

for(vector<T>::iterator p = v.begin(); p!=v.end(); ++p)
    …   // do something with *p
```

- Know both ways (iterator and subscript)
  - The subscript style is used in essentially every language
  - The iterator style is used in C (pointers only) and C++
  - The iterator style is used for standard library algorithms
  - The subscript style doesn’t work for lists (in C++ and in most languages)
- Use either way for vectors
  - There are no fundamental advantages of one style over the other
  - But the iterator style works for all sequences
  - Prefer **size_type** over plain **int**
    - pedantic, but quiets compiler and prevents rare errors

Ways of traversing a vector

```
for(vector<T>::iterator p = v.begin(); p!=v.end(); ++p)
    …     // do something with *p

for(vector<T>::value_type x : v)
    …     // do something with x

for(auto& x : v)
    …     // do something with x
```

- "Range **for**"
  - Use for the simplest loops
    - Every element from **begin()** to **end()**
  - Over one sequence
  - When you don't need to look at more than one element at a time
  - When you don't need to know the position of an element

Vector vs. List

- By default, use a **vector**
  - You need a reason not to
  - You can “grow” a vector (e.g., using **push_back()**)
  - You can **insert()** and **erase()** in a vector
  - Vector elements are compactly stored and contiguous
  - For small vectors of small elements all operations are fast
    - compared to lists
- If you don’t want elements to move, use a **list**
  - You can “grow” a list (e.g., using **push_back()** and **push_front()**)
  - You can **insert()** and **erase()** in a list
  - List elements are separately allocated
- Note that there are more containers, e.g.,
  - map
  - unordered_map

Some useful standard headers

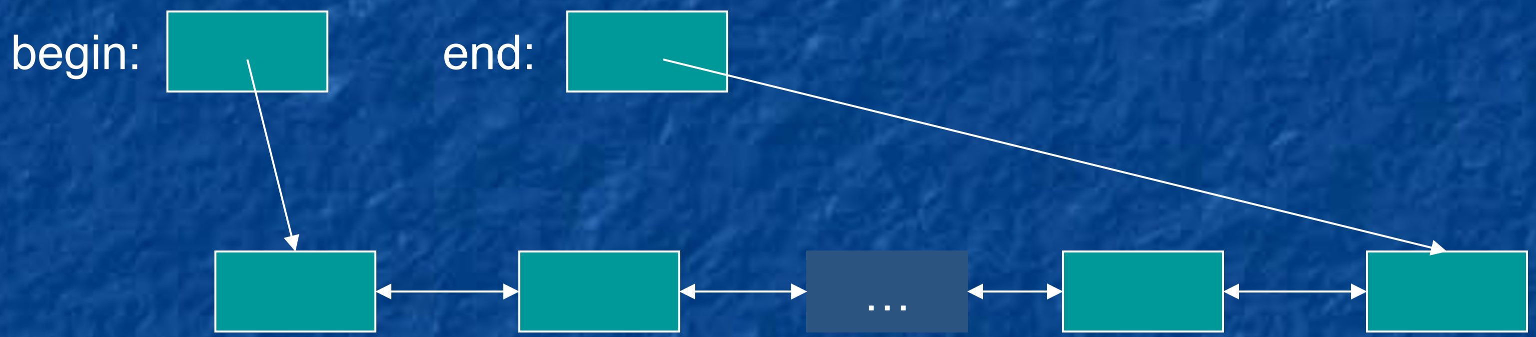
- **<iostream>** I/O streams, cout, cin, …
- **<fstream>** file streams
- **<algorithm>** sort, copy, …
- **<numeric>** accumulate, inner_product, …
- **<functional>** function objects
- **<string>**
- **<vector>**
- **<map>**
- **<unordered_map>** hash table
- **<list>**
- **<set>**

Overview

- Common tasks and ideals
- Containers, algorithms, and iterators
- The simplest algorithm: find()
- Parameterization of algorithms
  - find_if() and function objects
- Sequence containers
  - vector and list
- Algorithms and parameterization revisited
- Associative containers
  - map, set
- Standard algorithms
  - copy, sort, …
  - Input iterators and output iterators
- List of useful facilities
  - Headers, algorithms, containers, function objects

Basic model

- A pair of iterators defines a sequence
  - The beginning (points to the first element – if any)
  - The end (points to the one-beyond-the-last element)



- An iterator is a type that supports the "iterator operations" of
  - ++ Point to the next element
  - * Get the element value
  - == Does this iterator point to the same element as that iterator?
- Some iterators support more operations (*e.g.*, --, +, and [ ])

Accumulate (sum the elements of a sequence)

```
template<class In, class T>
T accumulate(In first, In last, T init)
{
    while (first!=last) {
        init = init + *first;
        ++first;
    }
    return init;
}
```

v:				
	1	2	3	4

```
int sum = accumulate(v.begin(), v.end(), 0);    // sum becomes 10
```

Accumulate (sum the elements of a sequence)

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```
void f(vector<double>& vd, int* p, int n)
{
    double sum = accumulate(vd.begin(), vd.end(), 0.0); // add the elements of vd
    // note: the type of the 3rd argument, the initializer, determines the precision used

    int si = accumulate(p, p+n, 0);  // sum the ints in an int (danger of overflow)
                                     // p+n means (roughly) &p[n]

    long sl = accumulate(p, p+n, long(0));   // sum the ints in a long
    double s2 = accumulate(p, p+n, 0.0);     // sum the ints in a double

    // popular idiom, use the variable you want the result in as the initializer:
    double ss = 0;
    ss = accumulate(vd.begin(), vd.end(), ss);  // do remember the assignment
}
```

Accumulate

(generalize: process the elements of a sequence)

*// we don't need to use only +, we can use any binary operation (e.g., *)*
*// any function that "updates the **init** value" can be used:*

```
template<class In, class T, class BinOp>
T accumulate(In first, In last, T init, BinOp op)
{
    while (first!=last) {
        init = op(init, *first);            // means "init op *first"
        ++first;
    }
    return init;
}
```

Accumulate

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// often, we need multiplication rather than addition:

```
#include <numeric>
#include <functional>
void f(list<double>& ld)
{
    double product = accumulate(ld.begin(), ld.end(), 1.0, multiplies<double>());
    // …
}
```

Note: multiplies for *

Note: initializer 1.0

*// **multiplies** is a standard library function object for multiplying*

Accumulate (what if the data is part of a record?)

```
struct Record {
    int units;              // number of units sold
    double unit_price;
    // …
};

// let the "update the init value" function extract data from a Record element:
double price(double v, const Record& r)
{
    return v + r.unit_price * r.units;
}

void f(const vector<Record>& vr) {
    double total = accumulate(vr.begin(), vr.end(), 0.0, price);
    // …
}
```

Accumulate (what if the data is part of a record?)

```
struct Record {
    int units;              // number of units sold
    double unit_price;
    // …
};

void f(const vector<Record>& vr) {
    double total = accumulate(vr.begin(), vr.end(), 0.0,   // use a lambda
                              [](double v, const Record& r)
                                   {  return v + r.unit_price * r.units; }
    );
    // …
}
```

// Is this clearer or less clear than the price() function?

Inner product

```
template<class In, class In2, class T>
T inner_product(In first, In last, In2 first2, T init)
    // This is the way we multiply two vectors (yielding a scalar)
{
    while(first!=last) {
            init  = init + (*first) * (*first2);   // multiply pairs of elements and sum
             ++first;
             ++first2;
    }
    return init;
}
```

number of units	1	2	3	4	…
*	*	*	*	*	
unit price	4	3	2	1	…

Inner product example

```
// calculate the Dow-Jones industrial index:
vector<double> dow_price;        // share price for each company
dow_price.push_back(81.86);
dow_price.push_back(34.69);
dow_price.push_back(54.45);
// …
vector<double> dow_weight;       // weight in index for each company
dow_weight.push_back(5.8549);
dow_weight.push_back(2.4808);
dow_weight.push_back(3.8940);
// …
double dj_index = inner_product(   // multiply (price,weight) pairs and add
        dow_price.begin(), dow_price.end(),
        dow_weight.begin(),
        0.0);
```

Inner product example

```
// calculate the Dow-Jones industrial index:
vector<double> dow_price = {      // share price for each company
    81.86, 34.69, 54.45,
    // …
};
vector<double> dow_weight = {    // weight in index for each company
    5.8549, 2.4808, 3.8940,
    // …
};

double dj_index = inner_product(    // multiply (price,weight) pairs and add
        dow_price.begin(), dow_price.end(),
        dow_weight.begin(),
        0.0);
```

Inner product (generalize!)

```
// we can supply our own operations for combining element values with "init":
template<class In, class In2, class T, class BinOp, class BinOp2 >
T inner_product(In first, In last, In2 first2, T init, BinOp op, BinOp2 op2)
{
    while(first!=last) {
        init  = op(init, op2(*first, *first2));
        ++first;
        ++first2;
    }
    return init;
}
```

Map (an associative array)

- For a **vector**, you subscript using an integer
- For a **map**, you can define the subscript to be (just about) any type

Key type

Value type

```
int main()
{
    map<string,int> words;          // keep (word,frequency) pairs
    for (string s; cin>>s; )
      ++words[s];                   // note: words is subscripted by a string
                                    // words[s] returns an int&
                                    // the int values are initialized to 0
    for (const auto&  p : words)
            cout << p.first << ": " << p.second << "\n";
}
```

An input for the words program (the abstract)

This lecture and the next presents the STL (the containers and algorithms part of the C++ standard library). It is an extensible framework dealing with data in a C++ program. First, I present the general ideal, then the fundamental concepts, and finally examples of containers and algorithms. The key notions of sequence and iterator used to tie containers (data) together with algorithms (processing) are presented. Function objects are used to parameterize algorithms with “policies”.

Output (word frequencies)

(data): 1
(processing): 1
(the: 1
C++: 2
First,: 1
Function: 1
I: 1
It: 1
STL: 1
The: 1
This: 1
a: 1
algorithms: 3
algorithms.: 1
an: 1
and: 5
are: 2
concepts,: 1
containers: 3
data: 1
dealing: 1
examples: 1
extensible: 1
finally: 1
framework: 1
fundamental: 1
general: 1
ideal,: 1
in: 1
is: 1
iterator: 1
key: 1
lecture: 1
library).: 1
next: 1
notions: 1
objects: 1
of: 3
parameterize: 1
part: 1
present: 1
presented.: 1
presents: 1
program.: 1
sequence: 1
standard: 1
the: 5
then: 1
tie: 1
to: 2
together: 1
used: 2
with: 3
“policies”.: 1

Map (an associative array)

- For a **vector**, you subscript using an integer
- For a **map**, you can define the subscript to be (just about) any type

Key type

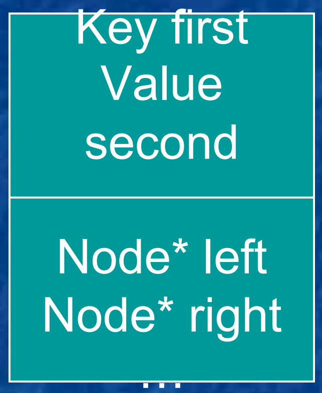
Value type

```
int main()
{
    map<string,int> words;                  // keep (word,frequency) pairs
    for (string s; cin>>s; )
            ++words[s];                     // note: words is subscripted by a string
                                            // words[s] returns an int&
                                            // the int values are initialized to 0
    for (const auto&  p : words)
            cout << p.first << ": " << p.second << "\n";
}
```

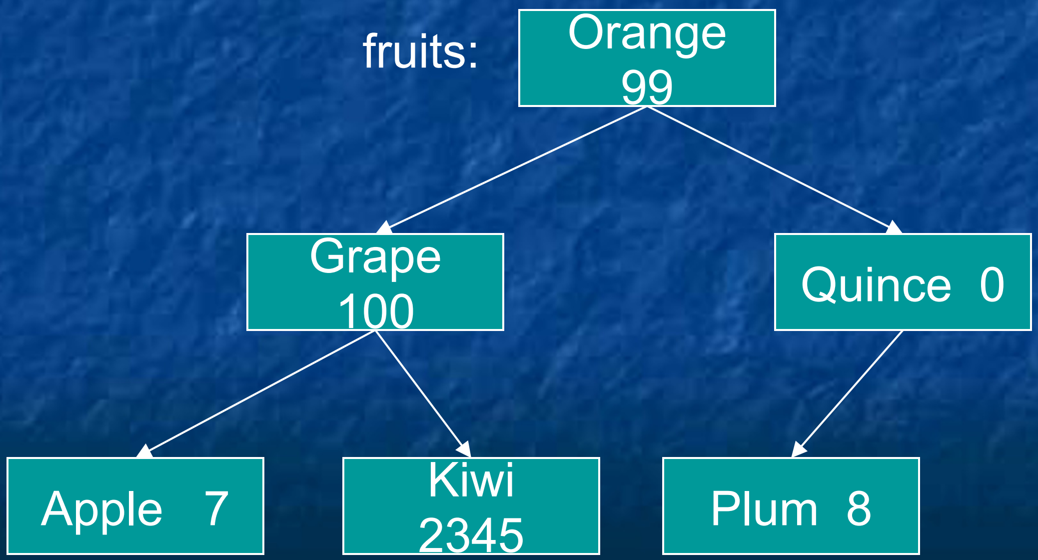
Map

- After **vector**, **map** is the most useful standard library container
  - Maps (and/or hash tables) are the backbone of scripting languages
- A **map** is really an ordered balanced binary tree
  - By default ordered by < (less than)
  - For example, **map<string,int> fruits**;

Map node:



fruits:



Some implementation defined type

Map

```
// note the similarity to vector and  list

template<class Key, class Value> class map {
    // …
    using value_type = pair<Key,Value>;          // a map deals in (Key,Value) pairs

    using iterator = ???;                // probably a pointer to a tree node
    using const_iterator = ???;

    iterator begin();              // points to first element
    iterator end();                // points to one beyond the last element

    Value& operator[ ](const Key&); // get Value for Key; creates pair if
                                    // necessary, using Value( )
    iterator find(const Key& k);        // is there an entry for k?

    void erase(iterator p);                  // remove element pointed to by p
    pair<iterator, bool> insert(const value_type&);      // insert new (Key,Value) pair
    // …                                                 // the bool is false if insert failed
};
```

Map example (build some maps)

```
map<string,double> dow;     // Dow-Jones industrial index (symbol,price) , 03/31/2004
            // http://www.djindexes.com/jsp/industrialAverages.jsp?sideMenu=true.html
dow["MMM"] = 81.86;
dow["AA"] = 34.69;
dow["MO"] = 54.45;
// …
map<string,double> dow_weight;                          // dow (symbol,weight)
dow_weight.insert(make_pair("MMM", 5.8549));            // just to show that a Map
                                                        // really does hold pairs
dow_weight.insert(make_pair("AA",2.4808));
dow_weight.insert(make_pair("MO",3.8940));     // and to show that notation matters
// …
map<string,string> dow_name;        // dow (symbol,name)
dow_name["MMM"] = "3M Co.";
dow_name["AA"] = "Alcoa Inc.";
dow_name["MO"] = "Altria Group Inc.";
// …
```

Map example (some uses)

```
double alcoa_price = dow["AA"];            // read values from a map
double boeing_price = dow["BO"];

if (dow.find("INTC") != dow.end())         // look in a map for an entry
    cout << "Intel is in the Dow\n";

// iterate through a map:

for (const auto& p : dow) {
    const string& symbol = p.first;        // the "ticker" symbol
    cout << symbol  << '\t' << p.second << '\t' << dow_name[symbol] << '\n';
}
```

Map example (calculate the DJ index)

```
double value_product(
    const pair<string,double>& a,
    const pair<string,double>& b)          // extract values and multiply
{
    return a.second * b.second;
}

double dj_index =
    inner_product(dow.begin(), dow.end(),       // all companies in index
                  dow_weight.begin(),           // their weights
                  0.0,                          // initial value
                  plus<double>(),               // add (as usual)
                  value_product                 // extract values and weights
             );                                 // and multiply; then sum
```

Containers and “almost containers”

- Sequence containers
  - **vector, list, deque**
- Associative containers
  - **map, set, multimap, multiset**
- “almost containers”
  - array, **string, stack, queue, priority_queue, bitset**
- New C++11 standard containers
  - **unordered_map** (a hash table), **unordered_set,** …
- For anything non-trivial, consult documentation
  - Online
    - SGI, RogueWave, Dinkumware
  - Other books
    - Stroustrup: The C++ Programming language 4^{th} ed. (Chapters 30-33, 40.6)
    - Austern: Generic Programming and the STL
    - Josuttis: The C++ Standard Library

Algorithms

- An STL-style algorithm
  - Takes one or more sequences
    - Usually as pairs of iterators
  - Takes one or more operations
    - Usually as function objects
    - Ordinary functions also work
  - Usually reports “failure” by returning the end of a sequence

Some useful standard algorithms

r=find(b,e,v)	r points to the first occurrence of v in [b,e)
r=find_if(b,e,p)	r points to the first element x in [b,e) for which p(x)
x=count(b,e,v)	x is the number of occurrences of v in [b,e)
x=count_if(b,e,p)	x is the number of elements in [b,e) for which p(x)
sort(b,e)	sort [b,e) using <
sort(b,e,p)	sort [b,e) using p
copy(b,e,b2)	copy [b,e) to [b2,b2+(e-b)) there had better be enough space after b2
unique_copy(b,e,b2)	copy [b,e) to [b2,b2+(e-b)) but don't copy adjacent duplicates
merge(b,e,b2,e2,r)	merge two sorted sequence [b2,e2) and [b,e) into [r,r+(e-b)+(e2-b2))
r=equal_range(b,e,v)	r is the subsequence of [b,e) with the value v (basically a binary search for v)
equal(b,e,b2)	do all elements of [b,e) and [b2,b2+(e-b)) compare equal?

Copy example

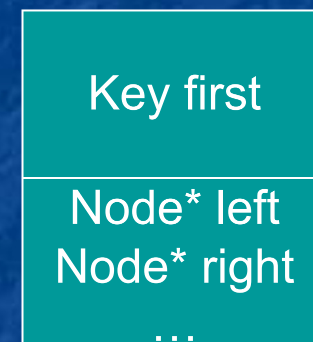
```
template<class In, class Out> Out copy(In first, In last, Out res)
{
    while (first!=last) *res++ = *first++;
                        // conventional shorthand  for:
                        //  *res = *first; ++res; ++first
    return res;
}

void f(vector<double>& vd, list<int>& li)
{
    if (vd.size() < li.size()) error("target container too small");
    copy(li.begin(), li.end(), vd.begin());    // note: different container types
                                               // and different element types
                                               // (vd better have enough elements
                                               // to hold copies of li's elements)
    sort(vd.begin(), vd.end());
    // …
}
```

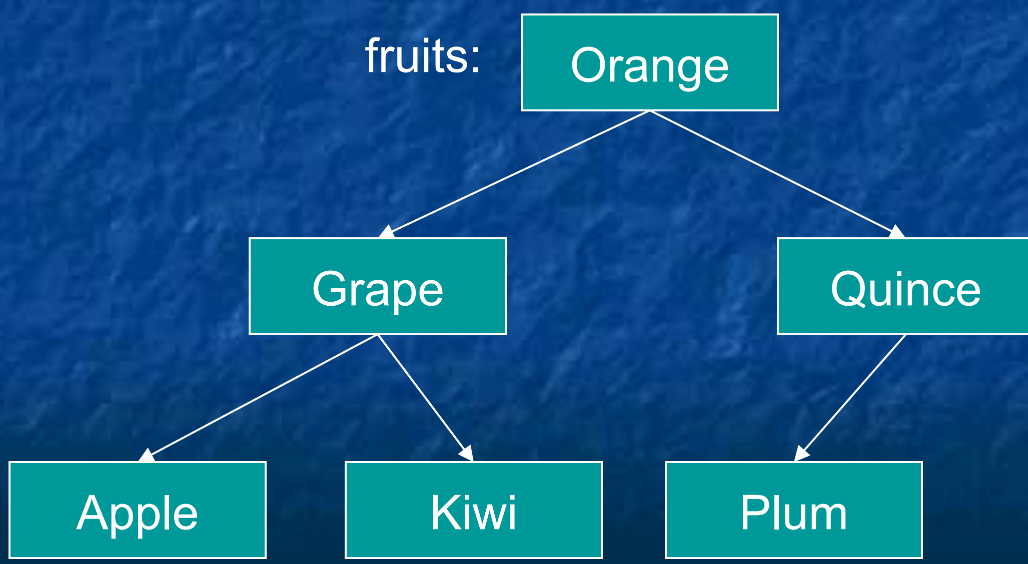
Set

- A **set** is really an ordered balanced binary tree
  - By default ordered by <
  - For example, **set<string> fruits**;

set node:



fruits:



copy_if()

```
// a very useful algorithm (missing from the standard library):

template<class In, class Out, class Pred>
Out copy_if(In first, In last, Out res, Pred p)
    // copy elements that fulfill the predicate
{
    while (first!=last) {
        if (p(*first)) *res++ = *first;
        ++first;
    }
    return res;
}
```

copy_if()

```
void f(const vector<int>& v)        // "typical use" of predicate with data
                                     // copy all elements with a value less than 6
{
    vector<int> v2(v.size());
    copy_if(v.begin(), v.end(), v2.begin(),
                    [](int x) { return x<6; } );
    // …
}
```

Some standard function objects

- From <functional>
  - Binary
    - plus, minus, multiplies, divides, modulus
    - equal_to, not_equal_to, greater, less, greater_equal, less_equal, logical_and, logical_or
  - Unary
    - negate
    - logical_not
  - Unary (missing, write them yourself)
    - less_than, greater_than, less_than_or_equal, greater_than_or_equal