Chapter 20
The STL
(containers, iterators, and algorithms)

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Abstract

- This lecture and the next present the STL – the containers and algorithms part of the C++ standard library
- The STL is an extensible framework dealing with data in a C++ program.
- First, I will 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 data together with algorithms (for general processing) are also presented.

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
  - I simplified a bit for terseness
    (see 21.5 for more generality and more details)
- 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

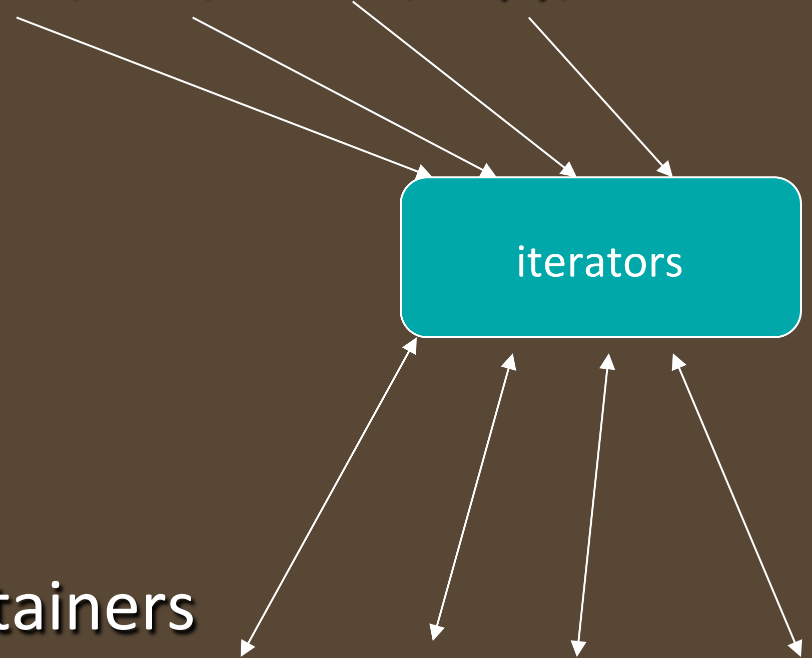
The STL

- 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

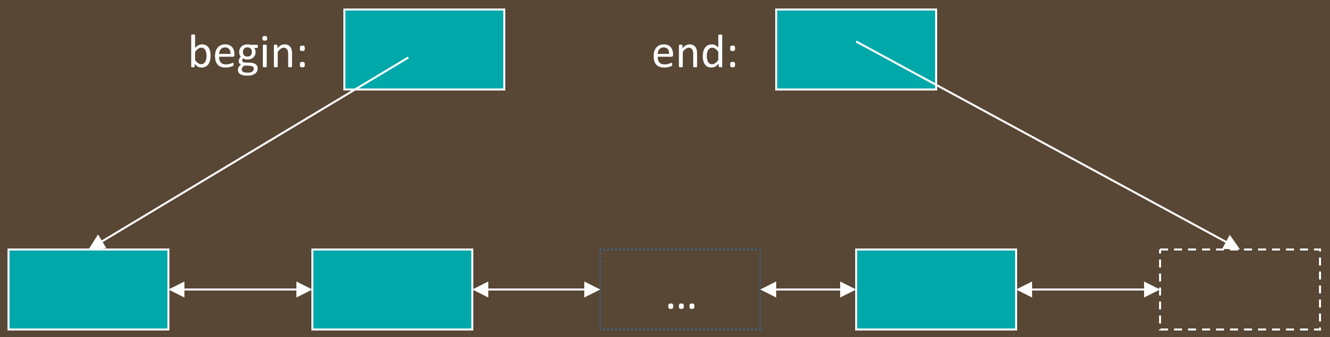
- An ISO C++ standard framework of about 10 containers and about 60 algorithms connected by iterators
  - Other organizations provide more containers and algorithms in the style of the STL
    - Boost.org, Microsoft, SGI, …
- Probably the currently best known and most widely used example of generic programming

The STL

- If you know the basic concepts and a few examples you can use the rest
- Documentation
  - SGI
    - http://www.sgi.com/tech/stl/ (recommended because of clarity)
  - Dinkumware
    - http://www.dinkumware.com/refxcpp.html (beware of several library versions)
  - Rogue Wave
    - http://www.roguewave.com/support/docs/sourcepro/stdlibug/index.html
- More accessible and less complete documentation
  - Appendix B

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)

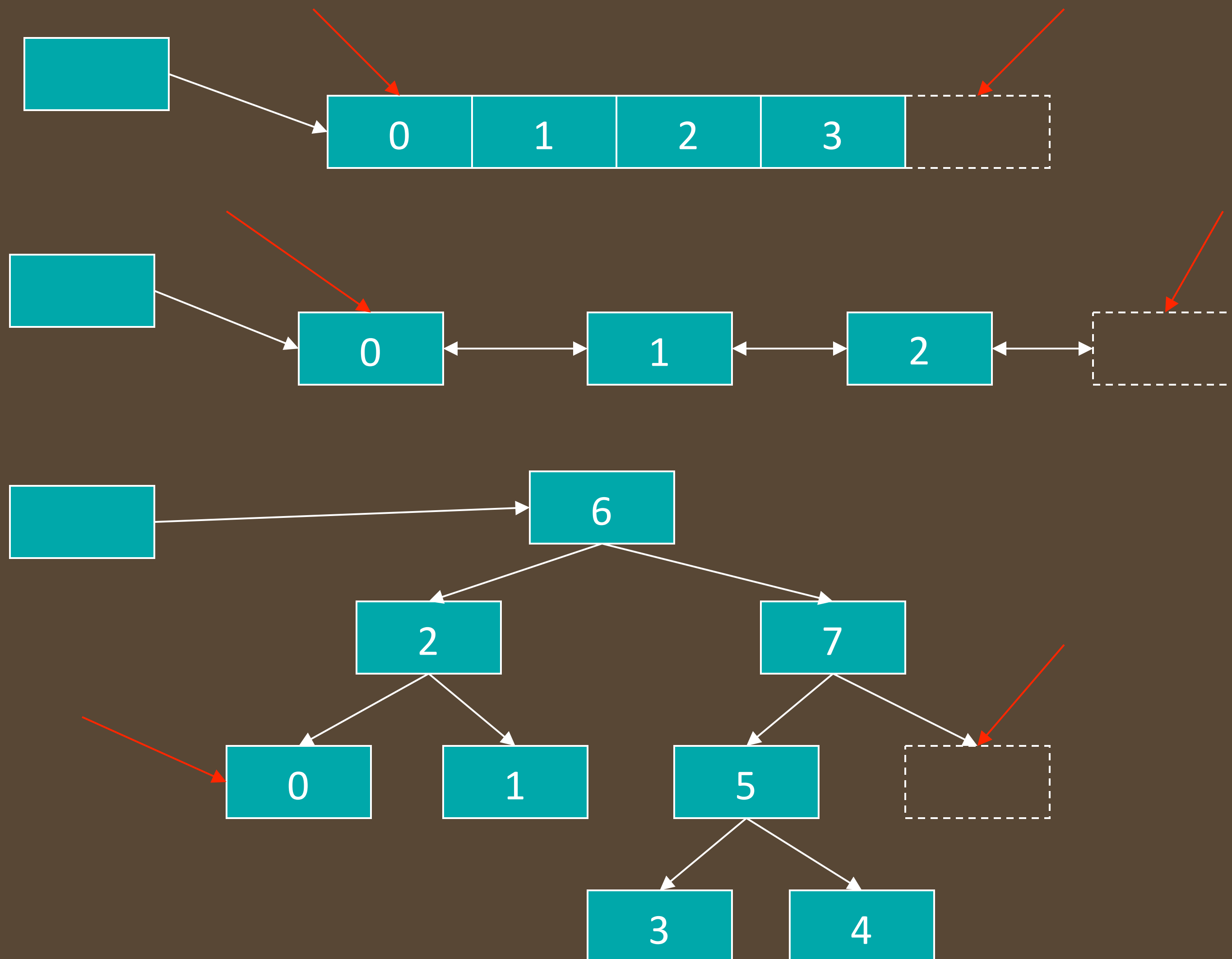


- An iterator is a type that supports the "iterator operations"
  - ++ Go to next element
  - * Get value
  - == Does this iterator point to the same element as that iterator?
- Some iterators support more operations (e.g. --, +, and [ ])

Containers

(hold sequences in difference ways)

- **vector**
- **list**
  (doubly linked)
- **set**
  (a kind of tree)



The simplest algorithm: **find()**

begin: end:

```
// 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

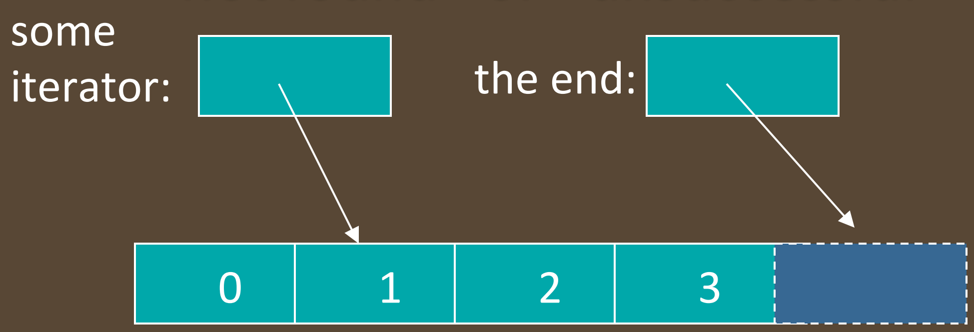
find()

generic for both element type and container type

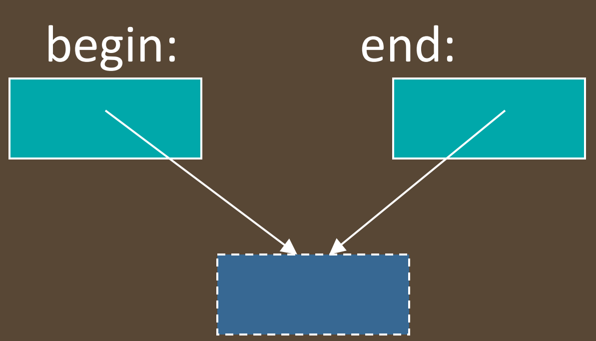
```
void f(vector<int>& v, int x)           // works for vector of ints
{
    vector<int>::iterator p = find(v.begin(),v.end(),x);
    if (p!=v.end()) { /* we found  x */ }
    // …
}

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"



An empty sequence:



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

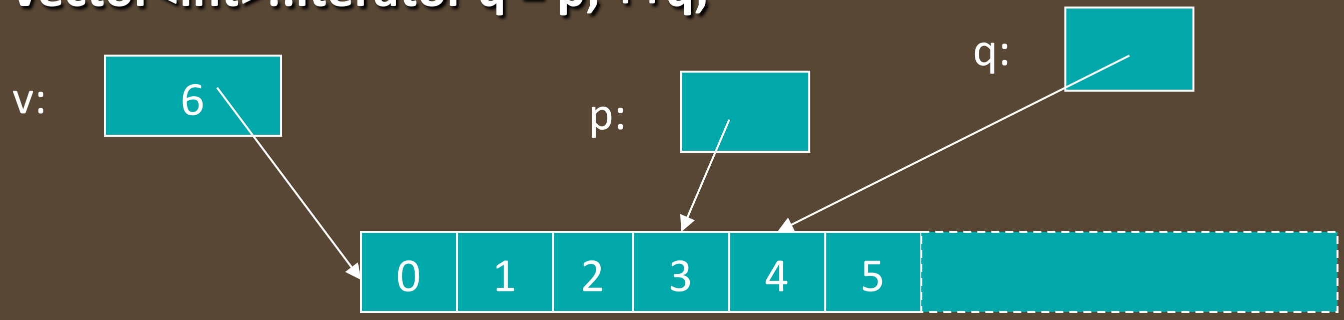
- Use a named object as argument
  - If you want to do something complicated
  - If you feel the need for a comment
  - If you want to do the same in several places
- Use a lambda expression as argument
  - If what you want is short and obvious
- Choose based on clarity of code
  - There are no performance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

vector

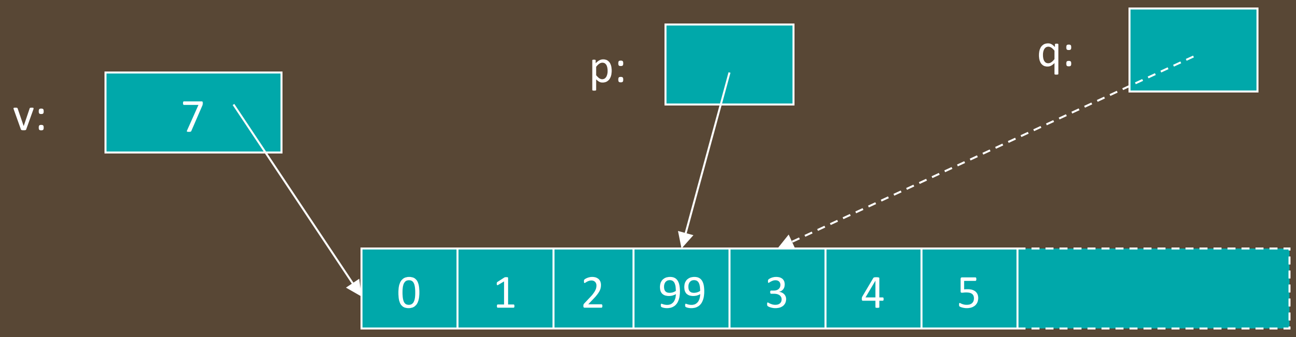
```
template<class T> class vector {
    T* elements;
    // …
    using value_type = T;
    using iterator = ???;    // the type of an iterator is implementation defined
                             // and it (usefully) varies (e.g. range checked iterators)
                             // a vector iterator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

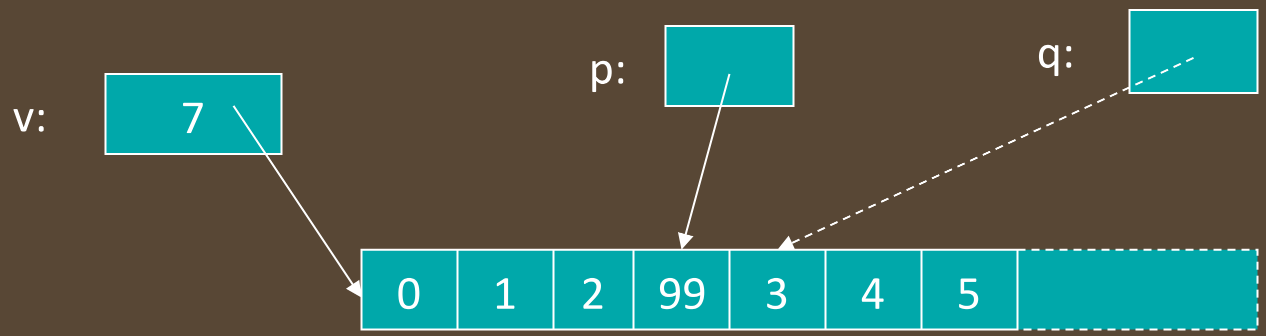


p=v.insert(p,99); *// leaves **p** pointing at the inserted element*

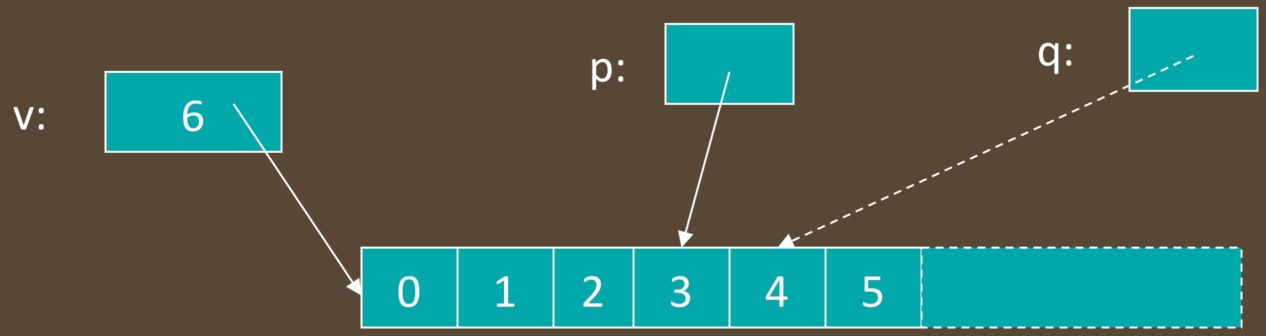


- Note: q is invalid after the **insert()**
- Note: Some elements moved; all elements could have moved

erase() from vector



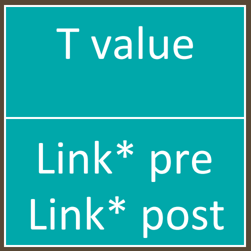
p = v.erase(p); *// leaves **p** pointing at the element after the erased one*



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

list

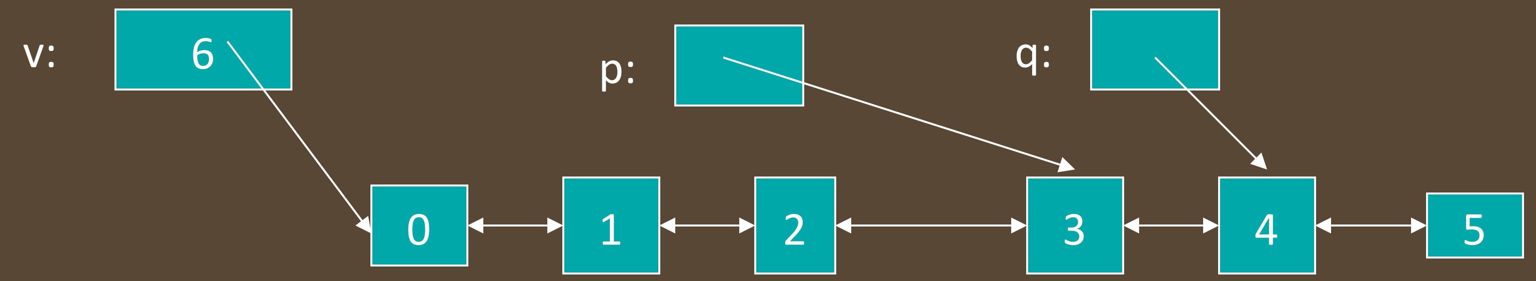
Link:



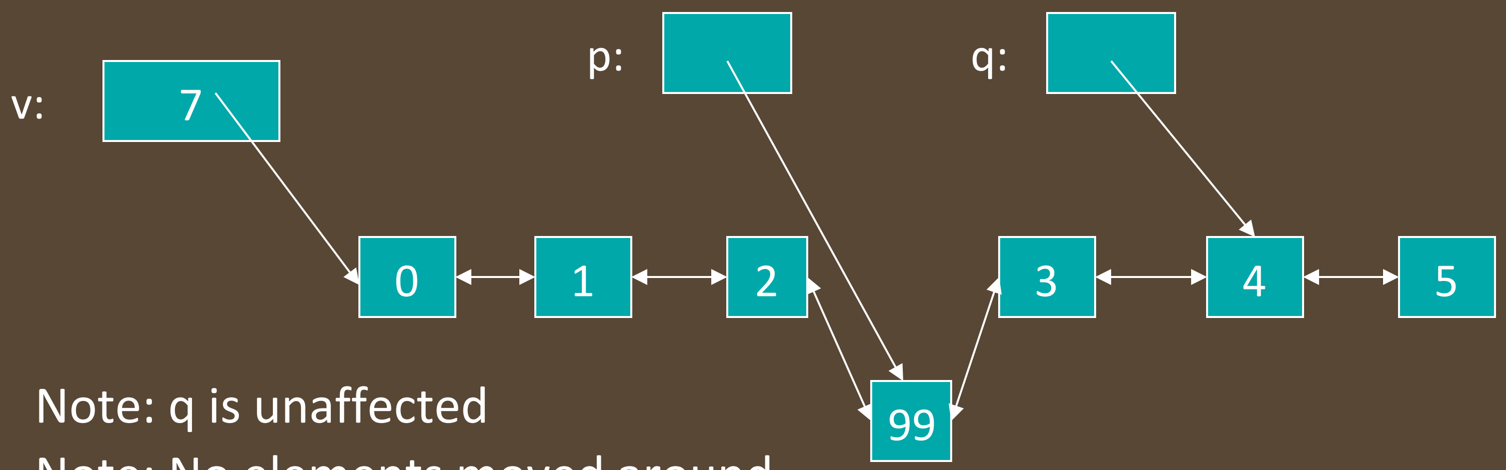

```
template<class T> class list {
    Link* elements;
    // …
    using value_type = T;
    using iterator = ???;    // the type of an iterator is implementation defined
                             // and it (usefully) varies (e.g. range checked iterators)
                             // a list iterator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

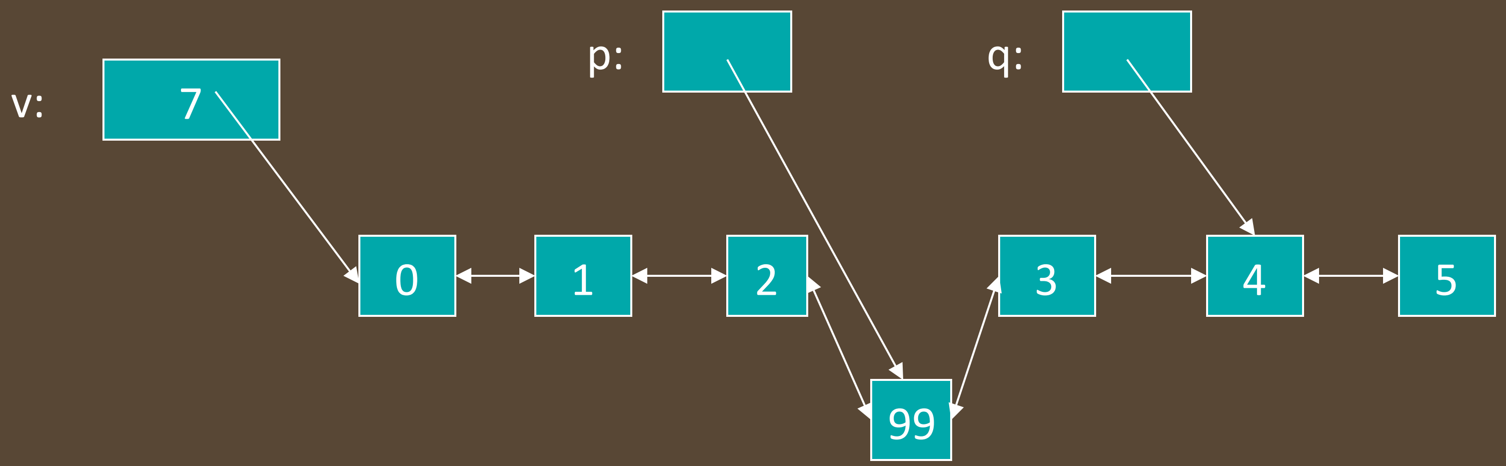


`v = v.insert(p,99);` // leaves **p** pointing at the inserted element

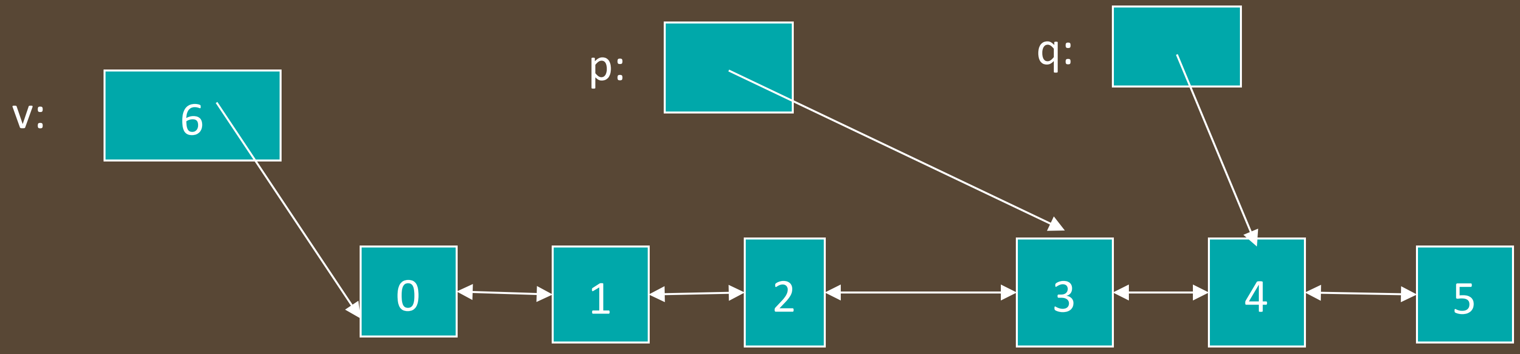


- Note: q is unaffected
- Note: No elements moved around

erase() from list



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>**

Next lecture

- Map, set, and algorithms