Session #

Invalidation of STL Iterators

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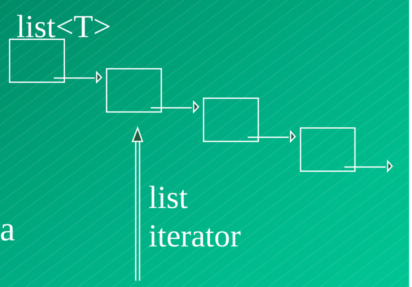
why talk about invalid iterator?

- iterators are a fundamental concept in the STL
  - play an important role as glue between containers and algorithms
- only valid iterators yield predictable results
  - invalid iterators should never be used
- in practice we make mistakes
  - invalid iterators are used inadvertently
- knowledge about invalid iterators aids:
  - identifying and avoiding invalid iterators
  - tracking down bugs caused by invalid iterators

agenda

- valid iterators and iterator ranges
- invalid iterators
  - – singular iterators
  - – past-the-end iterators
  - – out-of-range iterators
  - – dangling iterators
  - – inconsistent iterators

what is an iterator?



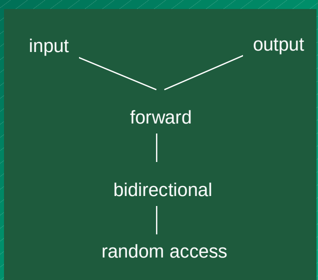
- generalized pointer:
  - – gives access to all elements in a sequence
  - – required operations:
    - dereferencing operator (`*p`)
    - incrementing operator (`p++`)
    - comparison operator (`p==q`)

iterators = generalized pointers

```
template <class Iterator, class T>
Iterator find(Iterator begin
             ,Iterator end
             ,const T& value)
{ while (begin != end && *begin != value)
    begin++;
  return begin;
}
```


combining containers and algorithms

Compare "iterators provided" to "iterators required":



- A container description includes the strongest iterator categories it provides.
- An algorithm description includes the weakest iterator categories it requires.

iterators in the STL

iterator	iterator concept
pointer to array	random access
iterator to vector / deque	random access
iterator to list	bidirectional
iterator to (multi)set / (multi)map	bidirectional
iterator to input stream	input
iterator to output stream	output
insert iterator	output

validity

valid iterators

- can be advanced, dereferenced and compared
- more precisely:
  - support all operations of their iterator category

valid iterator range

- consists of valid iterators (beginning and past-the-end)
- end iterator must be reachable

valid iterators - examples

```
istream_iterator<string> beg(cin),end;
vector<string> vec(beg,end);

list<string> lst;

copy(vec.begin(),vec.end(),
     front_inserter(lst));

copy(lst.begin(), lst.end(),
     ostream_iterator<int>(cout,"\n"));
```

input stream iterators

container iterators

insert iterator

output stream iterator

subtle bugs - invalid iterators

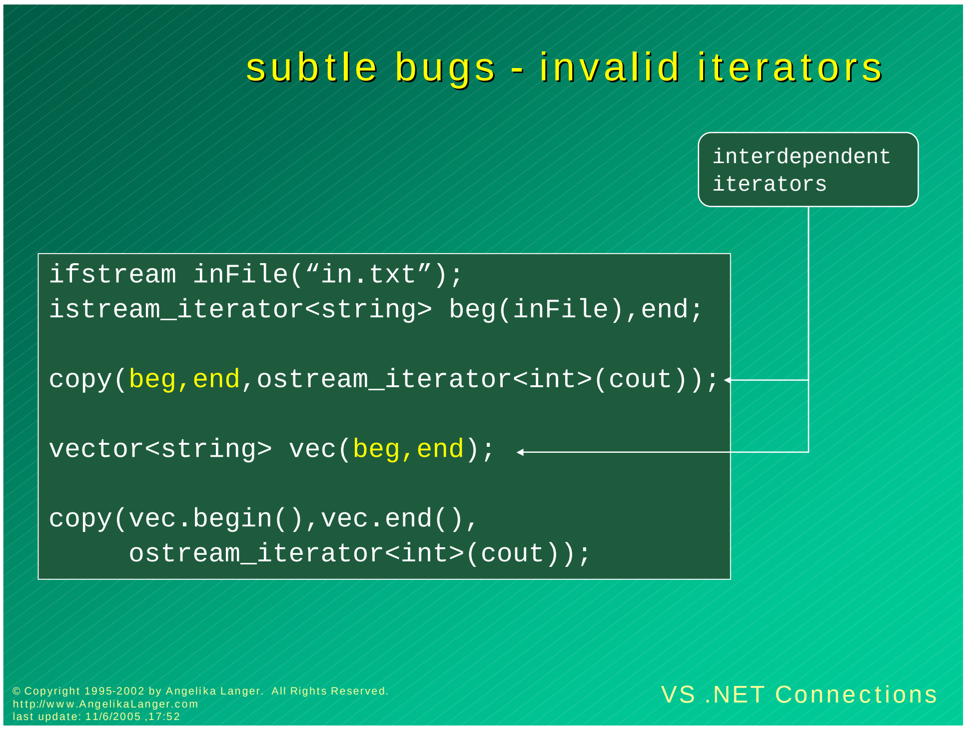
dangling iterator

```
istream_iterator<string> beg(ifstream("in.txt")),end;
copy(beg,end,ostream_iterator<int>(ofstream("out.txt")));

vector<string> vec(beg,end);
list<string> lst;
list<string> lst::iterator outIter;
copy(vec.begin(),vec.end(),outIter);
copy(vec.begin(),vec.end(),lst.begin() );
```

out-of-range iterator

singular iterator


subtle bugs - invalid iterators
interdependent iterators
ifstream inFile(“in.txt”);
istream_iterator<string> beg(inFile),end;
copy(beg,end,ostream_iterator<int>(cout));
vector<string> vec(beg,end);
copy(vec.begin(),vec.end(),
ostream_iterator<int>(cout));
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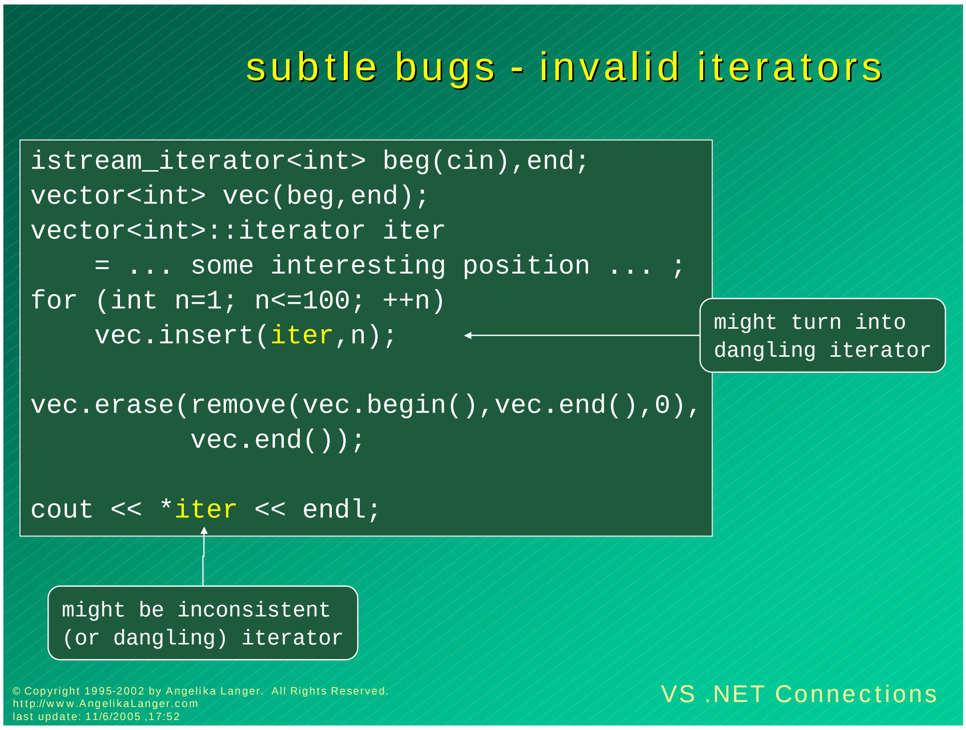
subtle bugs - invalid iterators
istream_iterator<int> beg(cin),end;
vector<int> vec(beg,end);
vector<int>::iterator iter
= ... some interesting position ... ;
for (int n=1; n<=100; ++n)
vec.insert(iter,n);
might turn into dangling iterator
vec.erase(remove(vec.begin(),vec.end(),0),
vec.end());
cout << *iter << endl;
might be inconsistent (or dangling) iterator
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invalid iterators

golden rule #1: **Never use invalid iterators.**

- result of using invalid iterators is undefined
- expressions such as `*iter`, `++iter`, etc.
  - exhibit "undefined behavior"
    - which can be anything
    - from returning a valid and useful result
    - to a program crash or reformatting of your hard-disk

agenda

- valid iterators and iterator ranges
- "invalid" iterators
  - singular iterators
  - past-the-end iterators
  - out-of-range iterators
  - dangling iterators
  - inconsistent iterators

singular iterators - definition

quote from the standard:

Iterators can have singular values that are not associated with any container.

Results of most expressions are undefined for singular values; the only exception is an assignment of a non-singular value to an iterator that holds a singular value. In this case the singular value is overwritten the same way as any other value.

singular iterators - examples

- uninitialized pointers

```
int* ptr;
```

- default-constructed container iterators

```
list<int>::iterator iter;
```

- default-constructed iterator adapters

```
reverse_iterator<int*> rIter;
```

- dereferenceable and past-the-end values are non-singular
  – example: default-constructed input stream iterators

```
istream_iterator<int> eof;
```

why do we care?

- singular iterators can be created
- can be used inadvertently as input or output iterators

example:

```
int array[100];
int* begin, end;

list<int> lst;
list<int>::iterator out;

copy(begin,end,out);
```

singular iterators

singular iterators

- are not associated with any container

- only assignment is defined
  - results of most expressions are undefined for singular iterators
  - only assignment of a non-singular iterator to a singular iterator is valid

golden rule #2:

Never perform any operation on a singular iterator except assignment of a non-singular iterator.

agenda

- valid iterators and iterator ranges
- "invalid" iterators
  - singular iterators
  - past-the-end iterators
  - out-of-range iterators
  - dangling iterators
  - inconsistent iterators

past-the-end iterators - definition

quote from the standard:

> *Just as a regular pointer to an array guarantees that there is a pointer value pointing past the last element of the array, so for any iterator type there is an iterator value that points past the last element of a corresponding container. These values are called past-the-end values.*
>
> *Values of an iterator i for which the expression *i is defined are called dereferenceable. The library never assumes that past-the-end values are dereferenceable.*

additional requirement in the standard:

Iterators that can be incremented must be dereferenceable.

past-the-end iterators - examples

- non-dereferenceable past-the-end iterators
  - end-of-container iterator `container.end()`
  - end-of-array iterator `array+size`
  - end-of-input-stream iterator `istream_iterator<T>()`
  - reverse past-the-end iterator `container.rend()`
  - reverse end-of-array iterator `reverse_iterator<elemT*>(array)`

- dereferenceable past-the-end iterator:

```
int arr[500];
...
int* where = find(arr,arr+100,5);
```


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why do we care?

- past-the-end iterators can be created
- can be used inadvertently as input or output iterators

example:

```
int array[100];
list<int> lst;

copy(array,array+100,lst.begin());
```

past-the-end iterator

- list is empty

  ⇨ begin iterator equals end iterator

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invalid operations inside algorithm

copy legal
compare legal
dereference illegal
advance illegal

```
template <class In, class Out>
Out copy ( In first, In last,
           Out result)
{
  while (first != last)
     *result++ = *first++;
  return result;
}
```


valid operations

- past-the-end iterators support all operations of their respective iterator category
  - except dereferencing and increment

`pastTheEnd--` or `pastTheEnd-N`

- valid for a bidirectional or random-access iterator
- example: `list.end()--` or `vector.end()-1`

`pastTheEnd-begin`

- distance can be calculated for a random-access iterators
- example: `vector.end()-vector.begin()`

`insert(pastTheEnd,value)`

- insertion before past-the-end iterator is allowed
- example: `container.insert(container.end(),value)`

valid operations - example

legal pointer arithmetics

```
istream_iterator<int> in(cin),eof;
vector<int> vec(in,eof);
sort(vec.begin(),vec.end());
cout << *(vec.begin()) << “\t” << *(vec.end()-1);

vector<int>::iterator pos;
pos = lower_bound(vec.begin(),vec.end(),VALUE);
vec.insert(pos,VALUE);
```

legal; even for pos == vec.end()

past-the-end iterators

- point past the last sequence element
  - used as end of an iterator range
- might be non-dereferenceable and non-incrementable
  - expressions `*iter` and `++iter` might be invalid
  - no algorithm dereferences or advances a past-the-end iterator

golden rule #3:

> Never dereference or increment the past-the-end iterator of an iterator range.

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agenda

- valid iterators and iterator ranges
- "invalid" iterators
  - – singular iterators
  - – past-the-end iterators
  - – out-of-range iterators
  - – dangling iterators
  - – inconsistent iterators
- case study

out-of-range iterators - definition

Out-of-range iterators are iterators that have been advanced beyond the range of valid elements contained in a sequence.

- – beyond the past-the-end iterator of the sequence via incrementing or pointer arithmetics
- – beyond the beginning of the sequence via decrementing or pointer arithmetics

The result of any operation on an out-of-range iterators is undefined.

why do we care?

- out-of-range iterators can inadvertently be created
  - often implicitly inside an algorithm
- all operations are invalid, yet they might work somehow
  - knowledge of their behavior aids bugs tracking

example:

```
istream_iterator<string> in(cin),eof;
vector<string> vec; vec.reserve(100);

copy(in,eof,vec.begin());
```

might be advanced beyond capacity

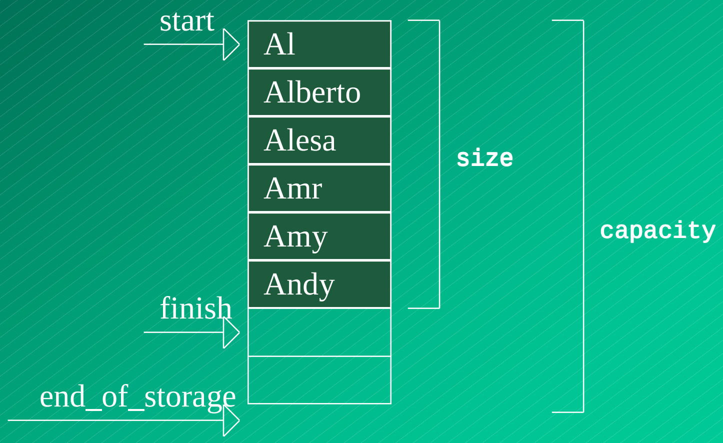
- algorithm might advance iterator beyond capacity
- unpredictable result
  ⇨ memory corruption w/o program crash

common situation in the STL

- out-of-range iterators can be created inadvertently
  - whenever size of sequence is determined by information other than the sequence itself
- examples:
  - all algorithms that take output iterator
    - size of output sequence determined by size of input sequence
    - `copy(), remove_copy_if(), transform(), merge(), ...`
  - algorithms with more than one input sequence
    - size of 2nd input sequence determined by size of 1st input sequence
    - binary `transform()`

typical implementation of vector

non-empty vector



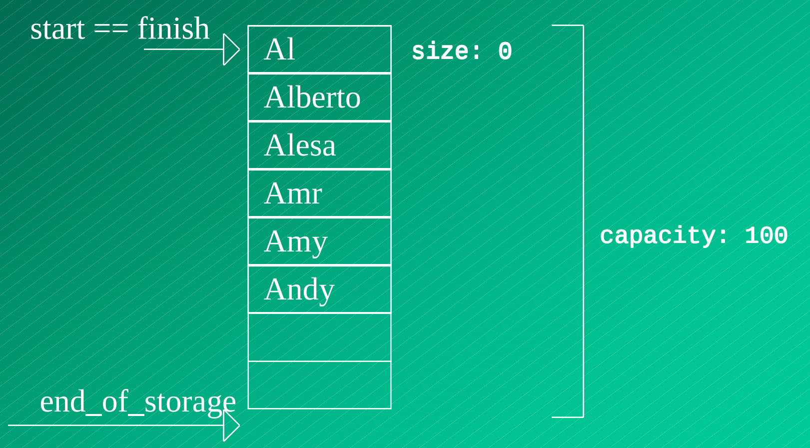
example using vector

```
istream_iterator<string> in(cin),eof;
vector<string> vec; vec.reserve(100);

copy(in,eof,vec.begin());
```

might be advanced beyond capacity

- in our example the vector is empty, but has memory reserved (`size: 0, capacity: 100, begin == end`)
- `copy()` overwrites reserved positions until capacity is exhausted and crashes then
- vector remains empty, although elements have been overwritten
  - internals such as `size`,`capacity`,`begin`,`end` are only modified via container operations, never through iterators

vector before/after copy()



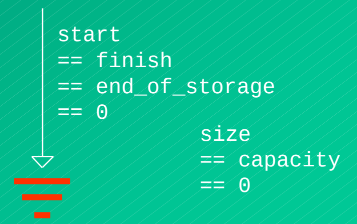
example using empty vector

```
istream_iterator<string> in(cin),eof;
vector<string> vec; // empty vector

copy(in,eof,vec.begin());
```

- if vector is empty and has no memory reserved
  (`size: 0, capacity: 0, begin == end == 0`)
  ⇨ immediate crash

empty vector

- nothing allocated
- all pointers are null pointers
- size and capacity are zero



recommendation

- avoid problem: use inserters as output destination
  - insert iterators have no valid range
  - can be incremented infinitely often

```
istream_iterator<string> in(cin),eof;
vector<string> vec;
copy(in,eof,back_inserter(vec));
```

```
cannot be advanced
beyond capacity
```

golden rule #4: Prefer inserters as output destinations over “regular” iterators.

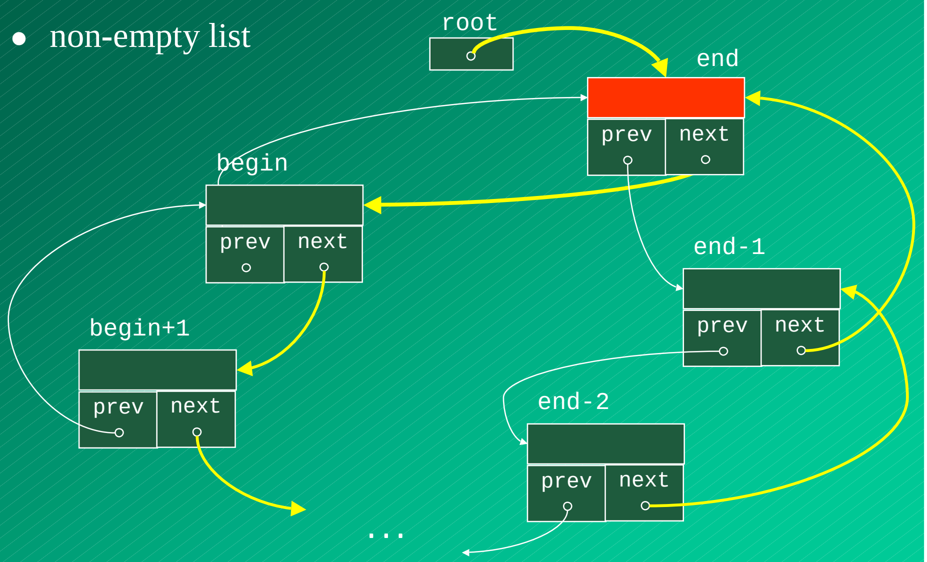
example using non-empty list

```
istream_iterator<string> in(cin),eof;
list<string> lst;
// fill and use list
// re-fill by overwriting
copy(in,eof,lst.begin());
```

- assume more input than `lst.size()`, i.e. list iterator advanced beyond end
- possible result: [GNU] / [CW] cyclic overwriting of list elements
  ⇨ no immediate crash, list corrupted
  unexpected content, crashes later
- even more confusing with read-access to out-of-range positions
  ⇨ no crash; infinite cycle over list elements

typical implementation of list

- non-empty list



example using set (after end)

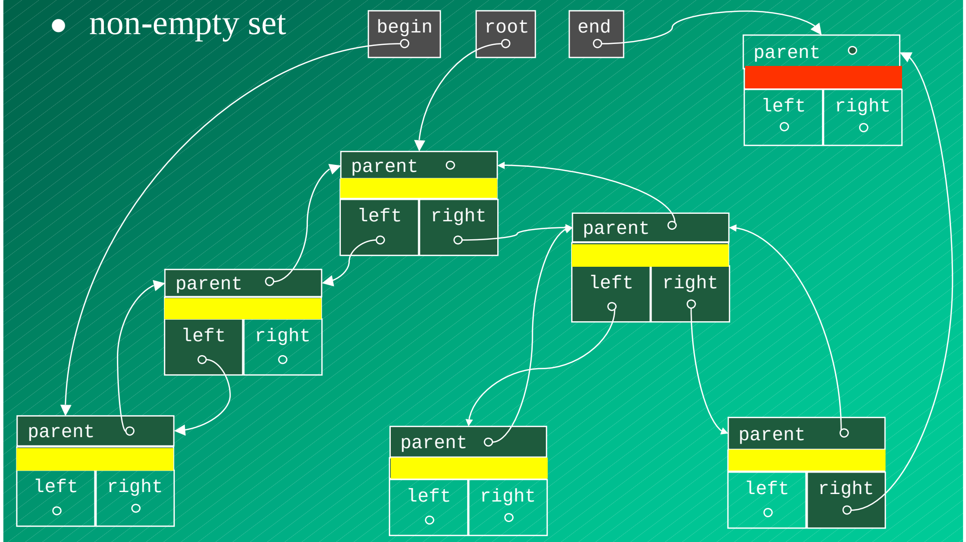
```
istream_iterator<string> in(cin),eof;
ostream_iterator<string> out(cout,"\n");
multiset<string> mset(...);  // non-empty set

transform(in,eof,mset.begin(),out,plus<string>());
```

- assume, algorithm advances set iterator beyond end
- possible result: [GNU] oscillates (`end` ↔ `end-1`) ⇨ no crash
  [CW] immediate crash ⇨ crash

- crashes if out-of-range positions are overwritten
  - modification destroys sorting order and corrupts tree structure
  - some implementations do not provide write iterators for `(multi)set`

typical implementation of set

- non-empty set



example using istream_iterator

```
istream_iterator<string> in(cin),eof;
ifstream fil("in.txt");

copy(in,eof,istream_iterator<int>(fil));
```

- assume, algorithm advances stream iterator beyond the end
- result depends on implementation of stream iterator
- possible result: [GNU] freezes at end ⇨ no crash
  [CW] crashes at end ⇨ crash

GNU implementation of istream_iterator

```
template <class elemT> class istream_iterator {
protected:
 istream* stream;     bool end_marker;   elemT value;
 void read() {
    end_marker = (*stream) ? true : false;
    if (end_marker) *stream >> value;
    end_marker = (*stream) ? true : false;
 }
public:
 istream_iterator() : end_marker(false) {}
 istream_iterator (istream& s) : stream(&s) { read(); }
 const elemT& operator*() const        {return value;}
 istream_iterator<elemT>& operator++()
 { read(); return *this; }
};
```

will freeze if out of range

Metrowerks implementation

```
template <class elemT> class istream_iterator {
private:
 istream* stream;    elemT value;
public:
 istream_iterator() : stream(0) {}
 istream_iterator (istream& s) : stream(&s)
 { if (!(*stream >> value)) stream = 0; }
 const elemT& operator*() const {return value;}
 istream_iterator<elemT>& operator++()
 { if (!(*stream >> value)) stream = 0;
   return *this;
 }
};
```

will crash if out of range

out-of-range iterators

- have been advanced beyond the range of valid elements
  – result of illegal advance operations on legal iterators
- all operations are illegal
  – need not crash, but might exhibit "interesting" behavior

golden rule #5: Never advance an iterator beyond its valid range.

- output stream iterators and inserters have no valid range
  – can be incremented infinitely often

agenda

- valid iterators and iterator ranges
- "invalid" iterators
  – singular iterators
  – past-the-end iterators
  – out-of-range iterators
  – dangling iterators
  – inconsistent iterators

dangling iterators - definition

- a dangling iterator points to a sequence element
  – that does not exists or
  – was moved to a different memory location or
  – is otherwise not accessible
- all operations on dangling iterators
  – exhibit undefined behavior
- dangling iterators can inadvertently be created
  – due to lifetime dependencies
  – due to operations that invalidate iterators

why do we care?

- lifetime dependencies are frequently overlooked
- invalidation through operations is even less obvious

example: stream iterators depend on the stream

```
istream_iterator<string> in(ifstream(”in.txt")),eof;
copy(in,eof,ostream_iterator<string>(cout,”\n”));
```

dangling iterator

problem:

– lifetime of temporary stream object ceases at end of statement ⇨ file closed ⇨ dangling iterator
– possible results: program crash

recommendation

golden rule #6:

Never use temporary stream objects in conjunction with stream iterators.

- a stream iterator is like a pointer to a stream
- don't point to anything ephemeral

lifetime of stream long enough

```
ifstream inFil(”in.txt");
istream_iterator<string> in(inFil),eof;
copy(in,eof,ostream_iterator<string>(cout,”\n”));
```


lifetime dependencies

- iterators need a sequence over which they iterate
- the sequence must life longer than the iterator

- examples:
  - container iterator (or pointer to array) needs container (or array)
    - ⇨ container (or array) must live longer
  - stream iterator need stream
    - ⇨ stream must live longer
  - insert iterator needs container and position (i.e. container iterator)
    - ⇨ container must live longer
    - ⇨ container iterator must remain valid
  - iterator adapter needs adaptee (i.e. underlying adapted iterator)
    - ⇨ underlying iterator must live longer

dangling iterators

- iterators are pointer-like objects
  - introduce the same lifetime dependencies as pointers
  - sequence must live longer than iterator
- all operations on dangling iterators are illegal
  - usually (but not always) lead to a program crash

golden rule #7:

> Iterators are "pointers". Keep an eye on lifetime dependencies between iterator and container.

• stream iterators	depend on stream
• container iterators	depend on container
• iterator adapters	depend on adaptee

agenda

- valid iterators and iterator ranges
- "invalid" iterators
  - singular iterators
  - past-the-end iterators
  - out-of-range iterators
  - dangling iterators
  - inconsistent iterators

inconsistent iterators - definition

Inconsistent iterators are iterators that return unexpected values when they are dereferenced.

- can happen as a side-effect of `erase()` and `insert()` on `vector` or `deque`
- can be the result of a modifying algorithm

Dereferencing an inconsistent iterator is invalid in the sense that it yields unexpected results.

inconsistent iterators - examples

- inconsistent iterator after modifying algorithm:

```
string arr[500];
... fill with elements ...
string* where = find(arr,arr+500,"Tom");
sort(arr,arr+500);
cout << *where << endl;   <- need not print: Tom
```

- inconsistent iterator after `erase()`:

```
vector<string> vec(arr,arr+500);
vector<string>::iterator where
     = find(vec.begin(),vec.end(),"Tom");
vec.erase(vec.begin(),where);
cout << *where << endl;   <- need not print: Tom
```

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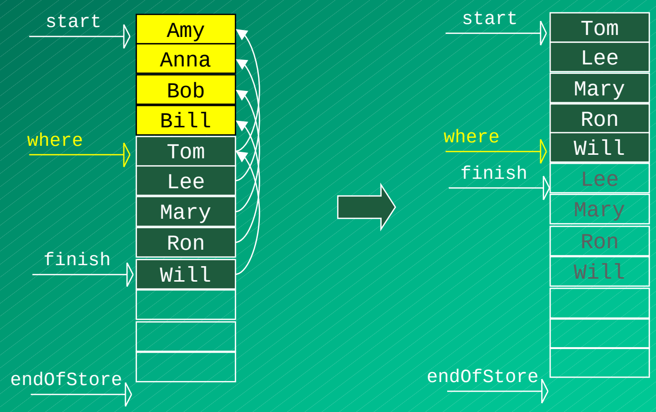
erase from vector



why do we care?

- inconsistent iterators are side effects of operations and algorithms
- occasionally programmers are not aware of the side effects

compare:

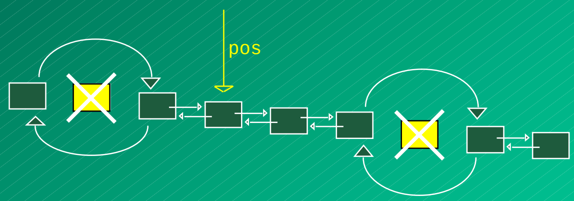
```
list<acc> clients(...);
list<acc>::iterator pos = ... position ... ;
clients.remove_if(inDebt());
cout<<*pos<<endl;
```

to:

```
vector<acc> clients(...);
vector<acc>::iterator pos = ... position ... ;
remove_if(clients.begin(),clients.end(),inDebt());
cout<<*pos<<endl;
```

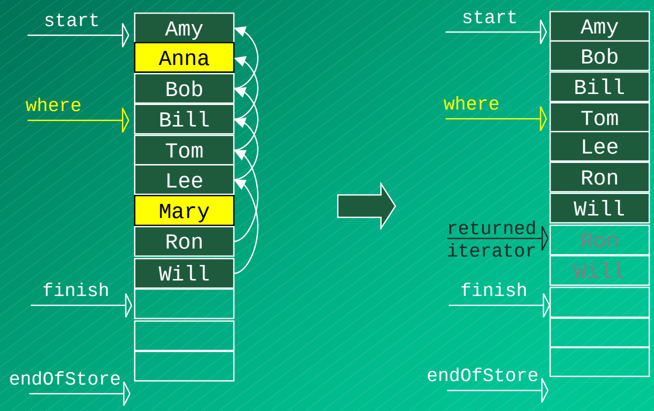
remove_if() on list

- iterator is not affected
  – unless it points to one of the removed elements



remove_if() on vector

- iterator is affected
  – if it points to a position after the first point of removal



inconsistent iterators

happen as side effect of

- container operations
  - `insert()` and `erase()` on `vector` and `deque`
- algorithms
  - "inplace" algorithms (modify input sequence)
    `remove(), sort(), partition(), replace(), ...`
  - "copy" algorithms (modify output sequence)
    `remove_copy(), transform(), merge(), ...`
- functors
  - functors supplied to algorithms or container operations might modify element content
  - is prohibited, but not enforced

modifying functor - example (prohibited)

- count frequent flyers and raise their status

```
bool freqFlyer(clientRec& client)
{ if (client.getMiles() >= 1000000)
  { client.setStatus(GOLD); return true; }
  return false;
}
```

```
list<clientRec> clients;
... populate set ...
size_t cnt =
    count_if(clients.begin(), clients.end(), freqFlyer);
```

- clearly a modification of sequence elements
  - leads to "inconsistent" iterators
  - prohibited by the standard, but cannot be prevented

inside an algorithm

```
template <class InputIterator, class Predicate>
size_t count_if (InputIterator first, InputIterator last,
                ,Predicate pred)
{
  size_t cnt=0;
  while (first != end)
    if (pred(*first++)) ++cnt;
  return cnt;
}
```

- predicate can modify sequence element through dereferenced iterator
  - if argument is passed by reference

modifying functor - example (permitted)

- modification through functor of `for_each()`

```
class raiseStatus {
 size_t _cnt;
public:
 raiseStatus() : _cnt(0) { }
 void operator()(clientRec& client)
 { if (client.getMiles() >= 1000000)
   { client.setStatus(GOLD); ++_cnt; }
 }
 size_t getCnt() { return _cnt; }
};
```

```
list<clientRec> clients;
... populate set ...
size_t cnt =
    for_each(clients.begin(), clients.end(), raiseStatus())
    .getCnt();
```

inconsistent iterators

- return surprising results on dereferencing
  - side effect of erase() and insert() on vector and deque
  - side effect of modifying algorithms
  - side effect of modifying functors
- all operations are legal
  - but element content is "interesting"

golden rule #8:

> Mind modifications of the element content through container operations, algorithms and functors.

agenda

- valid iterators and iterator ranges
- "invalid" iterators
  - singular iterators
  - past-the-end iterators
  - out-of-range iterators
  - dangling iterators
  - inconsistent iterators
- case study

insertion pitfall

```
template <class Container>
void repeatedPrepend(Container src,size_t N)
{ Container buf;
  insert_iterator<Container> insIter(buf,buf.begin());
  for (int i=0; i<N; i++)
  {  copy(src.begin(),src.end(),insIter);
  }
}
```

- results: (`src`: A B C , `N`: 3)

  vector: A B C crash
  deque: A A B C A B C B C or same as vector
  list: A B C A B C A B C
  multiset: A A A B B B C C C

insertion pitfall

- every iteration (triggered via the insert iterator) invokes the container's `insert()` operation
- insertion can invalidate iterators

- `vector`:
  – insertion invalidates all iterators after the point of insertion; in case of reallocation invalidates all iterators
- `deque`:
  – insertion invalidates all iterators before or after the point of insertion
- `list, (mulit)set, (multi)map`:
  – insertion does not invalidate any iterators

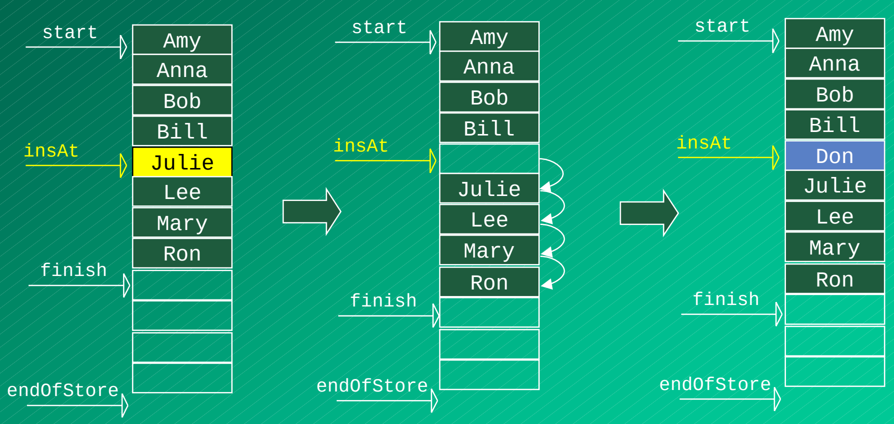
insertion into vector

```
vector<string> buf;
vector<string>::iterator insAt = ... some position ...
buf.insert(insAt,”Don”);
```

- insertion into `vector` invalidates positions *after* the point of insertion
  - – includes point of insertion

insertion into vector

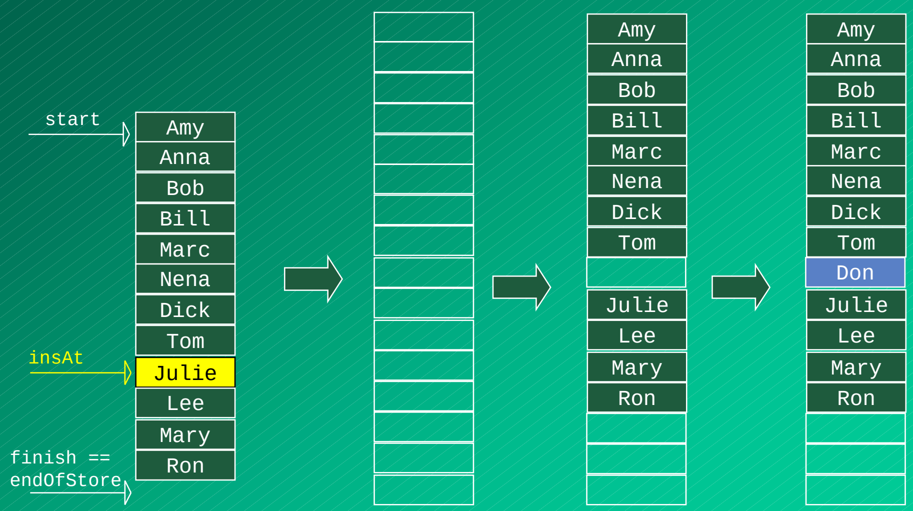
effect of `vector::insert(insAt,”Don”)`



reallocation

- if capacity is exhausted
  - new block of memory is allocated
  - all values are copied and old memory is deleted
  - ⇨ *all* iterators are invalid

insertion into vector



insertion into vector

dangling vector iterators

- reallocation of a vector's internal array invalidates all iterators pointing to the vector
- reallocation can be triggered by `insert()` and `reserve()`

golden rule #9:

> Don't re-use iterators pointing to elements in a `vector` after any calls to `insert()` or `reserve()`.

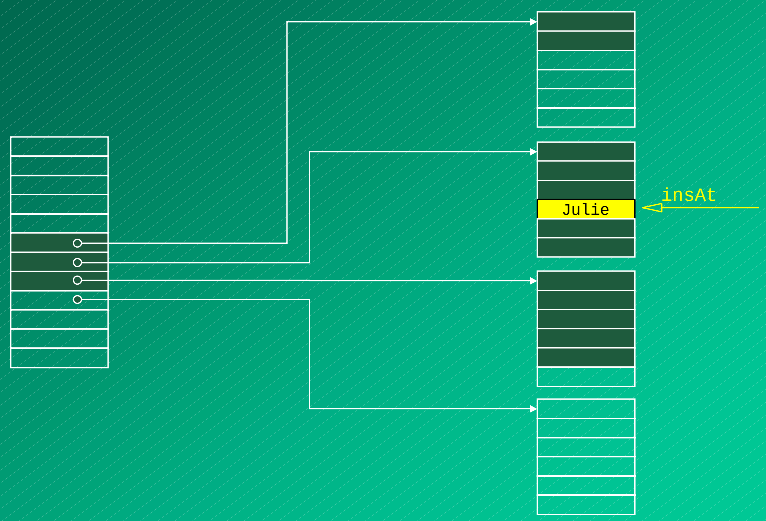
similar effects with deque

```
deque<string> buf;
deque<string>::iterator insAt = ... some position ...
buf.insert(insAt,”Don”);
```

problem:

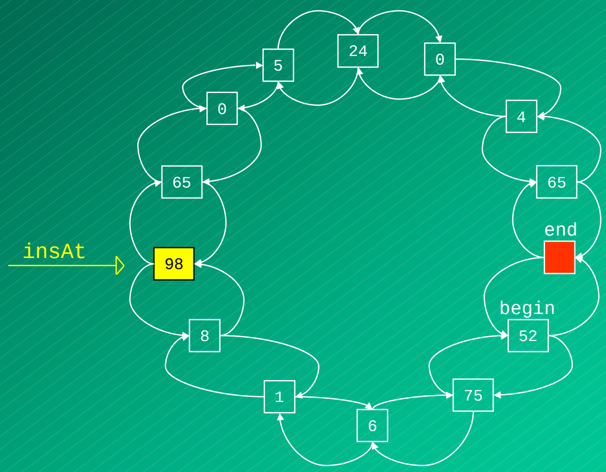
- insertion into `deque` invalidates positions *before* or *after* the point of insertion
  - may includes point of insertion

typical implementation of deque



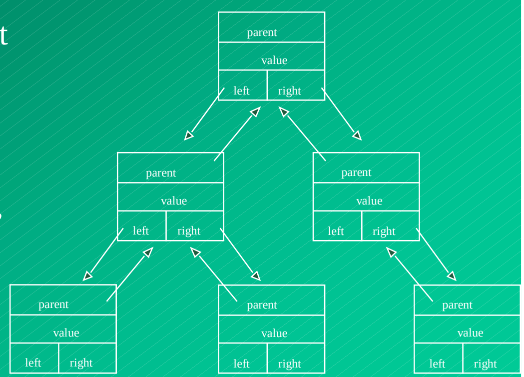
no problem with `list`

- insertion into `list` does not invalidate any iterators



not an issue with `set`

- insertion into `set` does not invalidate any iterators
  - similar to `list`
- insertion ignores position anyway
  - insertion always happens at correct position according to sorting order
  - point of insertion is just a hint
    - tree traversal starts at “hint” position
    - speeds up insertion if elements are inserted in order



insertion and dangling iterators

- insertion can invalidate point of insertion
  - details depend on (implementation of) container
  - problematic with `vector` and `deque`
  - not an issue for `list`, `(multi)set`, and `(multi)map`

golden rule #10: Don't re-use iterators used as point-of-insertion (in `insert()`) after any insertion. Use the returned iterator.

recommendation

- don't do this:

```
Container buf;
Container iterator insAt = ... some position ...
buf.insert(insAt,"Don");
```

- prefer this:

```
Container buf;
Container iterator insAt = ... some position ...
insAt = buf.insert(insAt,"Don");
```

- `insert()` returns a valid iterator pointing to the newly inserted element

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VS .NET Connections

insertion pitfall

- can we now explain the results of using an inserter ?

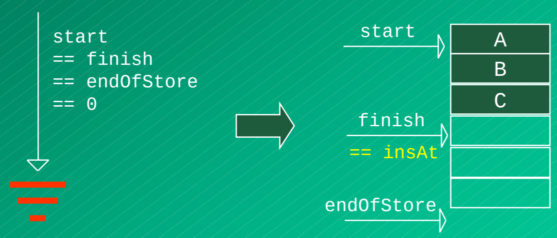
```
template <class Container>
void repeatedPrepend(Container src,size_t N)
{ Container buf;
  insert_iterator<Container> insIter(buf,buf.begin());
  for (int i=0; i<N; i++)
  {  copy(src.begin(),src.end(),insIter);
  }
}
```

- every loop step uses copy of initial inserter
  - but inserter changes as a side effect of the insertion performed in the previous step

example using vector

vector is empty

- nothing allocated; all pointers are null pointers
- 1st loop step: `insert()` called repeatedly ↓ fine
- 2nd loop step: inserter from before 1st step is used ↓ crash

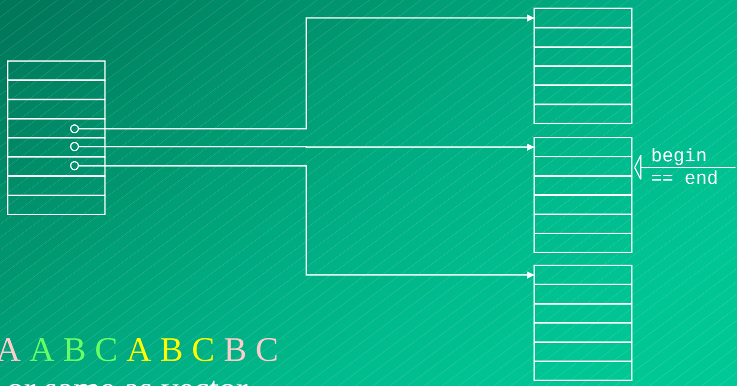


- result: A B C crash

example using deque

deque is empty

- memory is allocated, but not used

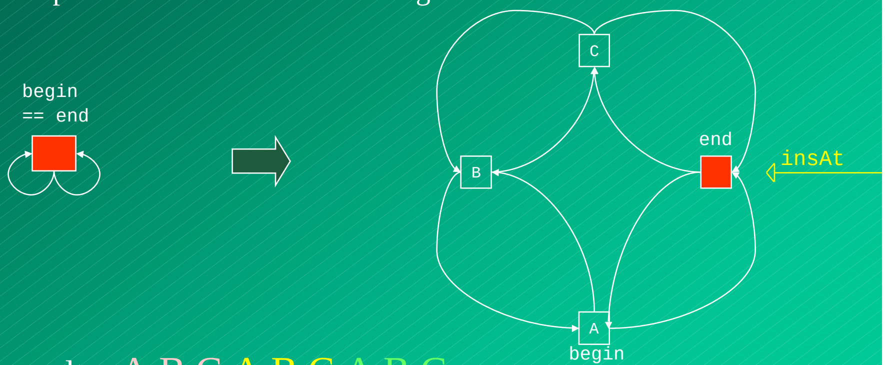


- result: A A B C A B C B C
  or same as vector

VS .NET Connections

example using list

- list is empty
  - pseudo node represents past-the-end position
  - point of insertion does no change

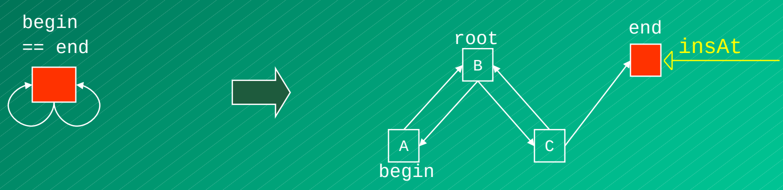


- result: A B C A B C A B C

VS .NET Connections

example using multiset

- multiset is empty
  - pseudo node represents past-the-end position
  - point of insertion is ignored anyway



- result: A A A B B B C C C

insertion pitfall - solution

- how do we avoid the problem ?
  - use iterator returned by container member function and algorithm

```
template <class Container>
void repeatedPrepend(Container src,size_t N)
{ Container buf;
  insert_iterator<Container> insIter(buf,buf.begin());
  for (int i=0; i<N; i++)
  {  insIter = copy(src.begin(),src.end(),insIter);
  }
}
```

insert iterators

- problem with the insert iterator basically was:
  - same insert iterator was re-used
  - although the underlying iterator had become invalid as a side effect of previous iterations
- "regular" use of insert iterators is safe
  - create insert iterator as temporary object
    - via creator function `inserter()`
  - pass as output iterator to an algorithm

golden rule #11: Don't re-use inserter after the underlying iterator has been invalidated. Create insert iterators as temporaries.

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Thank you!

- Please drop off your session evaluations in the basket at the back of the room!
- Your comments are greatly appreciated!