COMP6771
Advanced C++ Programming

Week 7.2
Custom Iterators

In this lecture

Why?

- When we define our own types, if we want them to be iterable we need to define that functionality ourselves.

What?

- Custom Iterators
- Iterator Invalidation
- Iterator Types

Iterator revision

- Iterator is an abstract notion of a **pointer**
- Iterators are types that abstract container data as a sequence of objects
  - The glue between containers and algorithms
    - Designers of algorithms don't care about details about data structures
    - Designers of data structures don't have to provide extensive access operations

```
1 std::vector v{1, 2, 3, 4, 5};
2 ++(*v.begin()); // vector<int>'s non-const iterator
3 *v.begin(); // vector<int>'s const iterator
4 v.cbegin(); // vector<int>'s const iterator
```

Iterator invalidation

- Iterator is an abstract notion of a **pointer**
- What happens when we modify the container?
  - What happens to iterators?
  - What happens to references to elements?
- Using an invalid iterator is undefined behaviour

```
1  std::vector v{1, 2, 3, 4, 5};
2  // Copy all 2s
3  for (auto it = v.begin(); it != v.end(); ++it) {
4    if (*it == 2) {
5      v.push_back(2);
6    }
7  }
8  // Erase all 2s
9  for (auto it = v.begin(); it != v.end(); ++it) {
10   if (*it == 2) {
11     v.erase(it);
12   }
13 }
```

Iterator invalidation - push_back

- Think about the way a vector is stored
- "If the new size() is greater than capacity() then all iterators and references (including the past-the-end iterator) are invalidated. Otherwise only the past-the-end iterator is invalidated."

```
1 std::vector v{1, 2, 3, 4, 5};
2 // Copy all 2s
3 for (auto it = v.begin(); it != v.end(); ++it) {
4   if (*it == 2) {
5     v.push_back(2);
6   }
7 }
```

https://en.cppreference.com/w/cpp/container/vector/push_back

Iterator invalidation - erase

- "Invalidates iterators and references at or after the point of the erase, including the end() iterator."
- For this reason, erase returns a new iterator

```cpp
std::vector v{1, 2, 3, 4, 5};
// Erase all even numbers (C++11 and later)
for (auto it = v.begin(); it != v.end(); ) {
  if (*it % 2 == 0) {
    it = v.erase(it);
  } else {
    ++it;
  }
}
```

https://en.cppreference.com/w/cpp/container/vector/erase

Iterator invalidation - general

- Containers generally don't invalidate when you modify values
- But they may invalidate when removing or adding elements
- std::vector invalidates everything when adding elements
- std::unordered_(map/set) invalidates everything when adding elements

Iterator traits

- Each iterator has certain properties
  - Category (input, output, forward, bidirectional, random-access)
  - Value type (T)
  - Reference Type (T& or const T&)
  - Pointer Type (T* or T* const)
    - Not strictly required
  - Difference Type (type used to count how far it is between iterators)
- When writing your own iterator, you need to tell the compiler what each of these are

Iterator requirements

A custom iterator class should look, at minimum, like this

```
class Iterator {
 public:
  using iterator_category = std::forward_iterator_tag;
  using value_type = T;
  using reference = T&;
  using pointer = T*; // Not strictly required, but nice to have.
  using difference_type = int;

  reference operator*() const;
  Iterator& operator++();
  Iterator operator++(int) {
    auto copy{*this};
    ++(*this);
    return copy;
  }
  // This one isn't strictly required, but it's nice to have.
  pointer operator->() const { return &(operator*()); }

  friend bool operator==(const Iterator& lhs, const Iterator& rhs) { ... };
  friend bool operator!=(const Iterator& lhs, const Iterator& rhs) { return !(lhs == rhs); }
};
```

Container requirements

- All a container needs to do is to allow std::[cr]begin / std::[cr]end
  - This allows use in range-for loops, and std algorithms
- Easiest way is to define begin/end/cbegin/cend methods
- By convention, we also define a type Container::[const_]iterator

```
class Container {
  // Make the iterator using one of these by convention.
  class iterator {...};
  using iterator = ...;

  // Need to define these.
  iterator begin();
  iterator end();

  // If you want const iterators (hint: you do), define these.
  const_iterator begin() const { return cbegin(); }
  const_iterator cbegin() const;
  const_iterator end() const { return cend(); }
  const_iterator cend() const;
};
```

Dissecting IntStack

- The iterator traits
- The overloaded operators (*, ->)
- The equality operators
- The constructor (default to nullptr)
- The private data
  - The iterator is defined inside the class, so gets access to private data
  - Iterator defines the container as a friend class for the constructors
- Key points in the List Class:
  - begin() – returns an Iterator object
  - end() – returns an Iterator object (with nullptr as private data)
- Note: The Iterator Class does not modify the List/Node data except through returning references.

Custom bidirectional iterators

- Need to define operator--() on your iterator
  - Need to move from c.end() to the last element
    - c.end() can't just be nullptr
- Need to define the following on your container:

```
class Container {
  // Make the iterator
  class reverse_iterator {...};
  // or
  using reverse_iterator = ...;

  // Need to define these.
  reverse_iterator rbegin();
  reverse_iterator rend();

  // If you want const reverse iterators (hint: you do), define these.
  const_reverse_iterator rbegin() const { return crbegin(); }
  const_reverse_iterator crbegin();
  const_reverse_iterator rend() const { return crend(); }
  const_reverse_iterator crend() const;
};
```

Automatic reverse iterators

- Reverse iterators can be created by std::reverse_iterator
  - Requires a **bidirectional iterator**
- You should be able to just copy-and-paste the following code

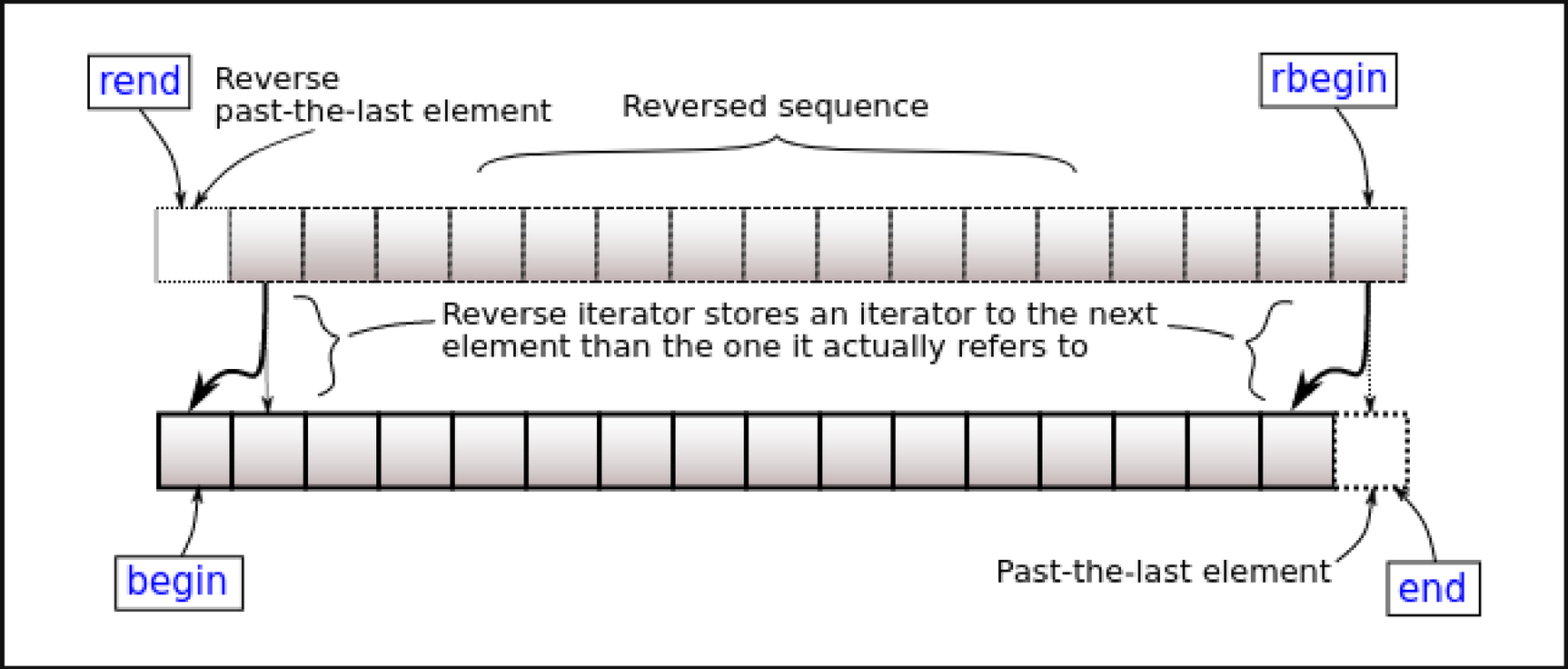
```
class Container {
  // Make the iterator using these.
  using reverse_iterator = std::reverse_iterator<iterator>;
  using const_reverse_iterator = std::reverse_iterator<const_iterator>;

  // Need to define these.
  reverse_iterator rbegin() { return reverse_iterator{end()}; }
  reverse_iterator rend() { return reverse_iterator{begin()}; }

  // If you want const reverse iterators (hint: you do), define these.
  const_reverse_iterator rbegin() const { return crbegin(); }
  const_reverse_iterator rend() const { return crend(); }
  const_reverse_iterator crbegin() const { return const_reverse_iterator{cend()}; }
  const_reverse_iterator crend() const { return const_reverse_iterator{cbegin()}; }
};
```

Automatic reverse iterators

- Reverse iterators can be created by std::reverse_iterator
  - rbegin() stores end(), so *rbegin is actually *(--end())



Random access iterators

```
class Iterator {
  ...
  using reference = T&;
  using difference_type = int;

  Iterator& operator+=(difference_type rhs) { ... }
  Iterator& operator-=(difference_type rhs) { return *this += (-rhs); }
  reference operator[](difference_type index) { return *(*this + index); }

  friend Iterator operator+(const Iterator& lhs, difference_type rhs) {
    Iterator copy{*this};
    return copy += rhs;
  }
  friend Iterator operator+(difference_type lhs, const Iterator& rhs) { return rhs + lhs; }
  friend Iterator operator-(const Iterator& lhs, difference_type rhs) { return lhs + (-rhs); }
  friend difference_type operator-(const Iterator& lhs, const Iterator& rhs) { ... }

  friend bool operator<(Iterator lhs, Iterator rhs) { return rhs - lhs > 0; }
  friend bool operator>(Iterator lhs, Iterator rhs) { return rhs - lhs < 0; }
  friend bool operator<=(Iterator lhs, Iterator rhs) { !(lhs > rhs); }
  friend bool operator>=(Iterator lhs, Iterator rhs) { !(lhs < rhs); }
}
```

See legacy requirements for random access iterators

Feedback