

Algorithms and Analysis

Lesson 7: *Iterate*



Array iteration, iterators

Outline

1. **Iterators**
2. The C++ Iterator Pattern
3. Linked-List Iterators
4. Generic Programming



Iterators

- One common task you want to do on a collection of objects is to iterate through each component
- If we have a standardised method for all collections then it is much easier to remember what to do
- But we can also write code that works for any collection that follows this pattern
- This pattern is known as the **iterator pattern**
- The pattern was first developed in C++, but is commonly used in many other languages

Iterators

- One common task you want to do on a collection of objects is to iterate through each component
- If we have a standardised method for all collections then it is much easier to remember what to do
- But we can also write code that works for any collection that follows this pattern
- This pattern is known as the **iterator pattern**
- The pattern was first developed in C++, but is commonly used in many other languages

Iterators

- One common task you want to do on a collection of objects is to iterate through each component
- If we have a standardised method for all collections then it is much easier to remember what to do
- But we can also write code that works for any collection that follows this pattern
- This pattern is known as the **iterator pattern**
- The pattern was first developed in C++, but is commonly used in many other languages

Iterators

- One common task you want to do on a collection of objects is to iterate through each component
- If we have a standardised method for all collections then it is much easier to remember what to do
- But we can also write code that works for any collection that follows this pattern
- This pattern is known as the **iterator pattern**
- The pattern was first developed in C++, but is commonly used in many other languages

Iterators

- One common task you want to do on a collection of objects is to iterate through each component
- If we have a standardised method for all collections then it is much easier to remember what to do
- But we can also write code that works for any collection that follows this pattern
- This pattern is known as the **iterator pattern**
- The pattern was first developed in C++, but is commonly used in many other languages

Iterating Over C Arrays

- In C we would typically use a for-loop to iterate over an array

```
int n = 10; // size of array
int* begin = malloc(n*sizeof(10)); // malloc returns beginning
of array
int* end = begin + n; // address past end of array

int sum = 0;
for(int* pt = begin; pt != end; pt++) {
    sum += *pt; // need to dereference pointer
}
```


Iterating Over C Arrays

- In C we would typically use a for-loop to iterate over an array

```
int n = 10; // size of array
int* begin = malloc(n*sizeof(10)); // malloc returns beginning
of array
int* end = begin + n; // address past end of array

int sum = 0;
for(int* pt = begin; pt != end; pt++) {
    sum += *pt; // need to dereference pointer
}
```

Iterating Over C Arrays

- In C we would typically use a for-loop to iterate over an array

```
int n = 10; // size of array
int* begin = malloc(n*sizeof(10)); // malloc returns beginning
of array
int* end = begin + n; // address past end of array

int sum = 0;
for(int* pt = begin; pt != end; pt++) {
    sum += *pt; // need to dereference pointer
}
```

Iterating Over C Arrays

- In C we would typically use a for-loop to iterate over an array

```
int n = 10; // size of array
int* begin = malloc(n*sizeof(10)); // malloc returns beginning
of array
int* end = begin + n; // address past end of array

int sum = 0;
for(int* pt = begin; pt != end; pt++) {
    sum += *pt; // need to dereference pointer
}
```

- Ugly

Iterating Over C Arrays

- In C we would typically use a for-loop to iterate over an array

```
int n = 10; // size of array
int* begin = malloc(n*sizeof(10)); // malloc returns beginning
of array
int* end = begin + n; // address past end of array

int sum = 0;
for(int* pt = begin; pt != end; pt++) {
    sum += *pt; // need to dereference pointer
}
```

- Ugly, but efficient

Iterating Over C Arrays

- In C we would typically use a for-loop to iterate over an array

```
int n = 10;                                // size of array
int* begin = malloc(n*sizeof(10));          // malloc returns beginning
of array
int* end = begin + n;                       // address past end of array

int sum = 0;
for(int* pt = begin; pt != end; pt++) {
    sum += *pt;                             // need to dereference pointer
}
```

- Ugly, but efficient
- Acts as a prototype for C++ iterators

Outline

1. Iterators
2. **The C++ Iterator Pattern**
3. Linked-List Iterators
4. Generic Programming



C++ Iterator Pattern

- The C++ iterator pattern says for every `container<T>` we create a nested class called

`container::iterator`

which acts as a pointer (for arrays this could just be a pointer to the array)

- The class should implement

- ★ a dereferencing operator `T operator* ()`

- ★ an increment operator `operator++ ()`

- ★ a not equal function

`bool operator!=(const ITER&, const ITER&)`

where `ITER` is `container::iterator`

C++ Iterator Pattern

- The C++ iterator pattern says for every `container<T>` we create a nested class called

`container::iterator`

which acts as a pointer (for arrays this could just be a pointer to the array)

- The class should implement

- ★ a dereferencing operator `T operator* ()`

- ★ an increment operator `operator++ ()`

- ★ a not equal function

`bool operator!=(const ITER&, const ITER&)`

where `ITER` is `container::iterator`

C++ Iterator Pattern

- The C++ iterator pattern says for every `container<T>` we create a nested class called

`container::iterator`

which acts as a pointer (for arrays this could just be a pointer to the array)

- The class should implement

- ★ a dereferencing operator `T operator* ()`

- ★ an increment operator `operator++ ()`

- ★ a not equal function

`bool operator!=(const ITER&, const ITER&)`

where `ITER` is `container::iterator`

C++ Iterator Pattern

- The C++ iterator pattern says for every `container<T>` we create a nested class called

`container::iterator`

which acts as a pointer (for arrays this could just be a pointer to the array)

- The class should implement

- ★ a dereferencing operator `T operator* ()`

- ★ an increment operator `operator++ ()`

- ★ a not equal function

`bool operator!=(const ITER&, const ITER&)`

where `ITER` is `container::iterator`

A Beginning and an Ending

- In addition the iterator class we should have two methods

- ★ `begin()`

- ★ `end()`

that return iterators representing the first element and an iterator representing one position past the last element

A Beginning and an Ending

- In addition the iterator class we should have two methods

- ★ `begin()`

- ★ `end()`

that return iterators representing the first element and an iterator representing one position past the last element

- Wow! That seems awfully complicated

A Beginning and an Ending

- In addition the iterator class we should have two methods

- ★ `begin()`

- ★ `end()`

that return iterators representing the first element and an iterator representing one position past the last element

- Wow! That seems awfully complicated
- Don't panic!

A Beginning and an Ending

- In addition the iterator class we should have two methods

- ★ `begin()`

- ★ `end()`

that return iterators representing the first element and an iterator representing one position past the last element

- Wow! That seems awfully complicated
- Don't panic! **We can hack this**

Minimal Iterator

```
template <typename>
class Container<T> {
private:

    class iterator {    // this is a nested class
    public:
        iterator() {...}           // constructor
        iterator operator++() {...} // increment
        T& operator*() {...}       // dereference
        bool operator!=(const iterator& rhs){
            // code to determine inequality
        }
    }

public:

    iterator begin() {...}          // return begin iter
    iterator end() {...}            // return end iter

}
```

Minimal Iterator

```
template <typename>
class Container<T> {
private:

    class iterator {    // this is a nested class
public:
    iterator() {...}    // constructor
    iterator operator++() {...} // increment
    T& operator*() {...} // dereference
    bool operator!=(const iterator& rhs){
        // code to determine inequality
    }
}

public:

    iterator begin() {...} // return begin iter
    iterator end() {...}   // return end iter

}
```


Minimal Iterator

```
template <typename>
class Container<T> {
private:

    class iterator {    // this is a nested class
public:
    iterator() {...}    // constructor
    iterator operator++() {...} // increment
    T& operator*() {...} // dereference
    bool operator!=(const iterator& rhs){
        // code to determine inequality
    }
}

public:

    iterator begin() {...}    // return begin iter
    iterator end() {...}    // return end iter

}
```

Minimal Iterator

```
template <typename>
class Container<T> {
private:

    class iterator {    // this is a nested class
public:
    iterator() {...}    // constructor
    iterator operator++() {...} // increment
    T& operator*() {...} // dereference
    bool operator!=(const iterator& rhs){
        // code to determine inequality
    }
}

public:

    iterator begin() {...}    // return begin iter
    iterator end() {...}    // return end iter

}
```

Minimal Iterator

```
template <typename>
class Container<T> {
private:

    class iterator {    // this is a nested class
public:
    iterator() {...}    // constructor
    iterator operator++() {...} // increment
    T& operator*() {...} // dereference
    bool operator!=(const iterator& rhs){
        // code to determine inequality
    }
}

public:

    iterator begin() {...}    // return begin iter
    iterator end() {...}    // return end iter

}
```

Minimal Iterator

```
template <typename>
class Container<T> {
private:

    class iterator {    // this is a nested class
public:
    iterator() {...}    // constructor
    iterator operator++() {...} // increment
    T& operator*() {...} // dereference
    bool operator!=(const iterator& rhs){
        // code to determine inequality
    }
}

public:

    iterator begin() {...}    // return begin iter
    iterator end() {...}    // return end iter

}
```

Array-based iterators

- For array based containers such as vector we don't actually need to create an iterator class as we can just use the normal pointer

```
template <typename T>
class Array {
private:
    T *data;
    unsigned length;
    unsigned capacity;

public:
    ...
    typedef T* iterator;           // iterator is pseudonym for T*
    iterator begin() {return data;}
    iterator end() {return data+length;}
};
```

Array-based iterators

- For array based containers such as vector we don't actually need to create an iterator class as we can just use the normal pointer

```
template <typename T>
class Array {
private:
    T *data;
    unsigned length;
    unsigned capacity;

public:
    ...
    typedef T* iterator;           // iterator is pseudonym for T*
    iterator begin() {return data;}
    iterator end() {return data+length;}
};
```

Array-based iterators

- For array based containers such as vector we don't actually need to create an iterator class as we can just use the normal pointer

```
template <typename T>
class Array {
private:
    T *data;
    unsigned length;
    unsigned capacity;

public:
    ...
    typedef T* iterator;           // iterator is pseudonym for T*
    iterator begin() {return data;}
    iterator end() {return data+length;}
};
```

- That's all we need

Using Array Iterators

```
main() {  
  
    Array<string> elements(4): {"earth", "water", "wind", "fire"};  
  
    for(Array::iterator it=elements.begin(); it!=elements.end(); ++it) {  
        cout << *it << endl;  
    }  
  
    for(auto it=elements.begin(); it!=elements.end(); ++it) {  
        cout << *it << endl;  
    }  
  
    for(string& element: elements) { // range-based loop  
        cout << element << endl;  
    }  
}
```


Using Array Iterators

```
main() {  
  
    Array<string> elements(4): {"earth", "water", "wind", "fire"};  
  
    for(Array::iterator it=elements.begin(); it!=elements.end(); ++it) {  
        cout << *it << endl;  
    }  
  
    for(auto it=elements.begin(); it!=elements.end(); ++it) {  
        cout << *it << endl;  
    }  
  
    for(string& element: elements) { // range-based loop  
        cout << element << endl;  
    }  
}
```

Using Array Iterators

```
main() {  
  
    Array<string> elements(4): {"earth", "water", "wind", "fire"};  
  
    for(Array::iterator it=elements.begin(); it!=elements.end(); ++it) {  
        cout << *it << endl;  
    }  
  
    for(auto it=elements.begin(); it!=elements.end(); ++it) {  
        cout << *it << endl;  
    }  
  
    for(string& element: elements) { // range-based loop  
        cout << element << endl;  
    }  
}
```

Using Array Iterators

```
main() {  
  
    Array<string> elements(4): {"earth", "water", "wind", "fire"};  
  
    for(Array::iterator it=elements.begin(); it!=elements.end(); ++it) {  
        cout << *it << endl;  
    }  
  
    for(auto it=elements.begin(); it!=elements.end(); ++it) {  
        cout << *it << endl;  
    }  
  
    for(string& element: elements) { // range-based loop  
        cout << element << endl;  
    }  
}
```

Outline

1. Iterators
2. The C++ Iterator Pattern
3. **Linked-List Iterators**
4. Generic Programming



Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list

Linked-List Iterators

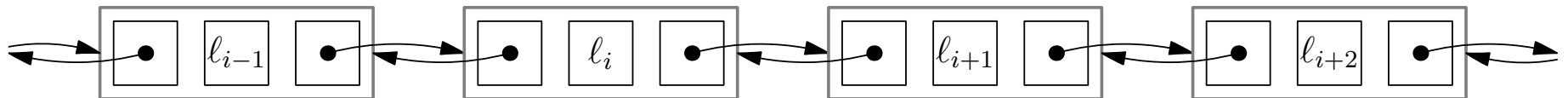
- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list

Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list

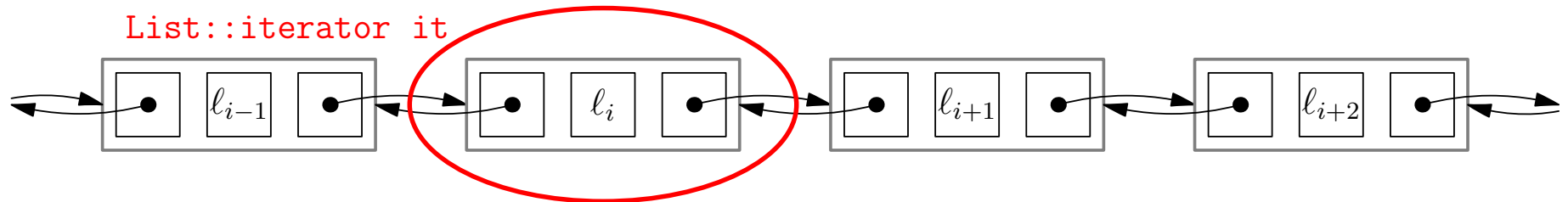
Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list



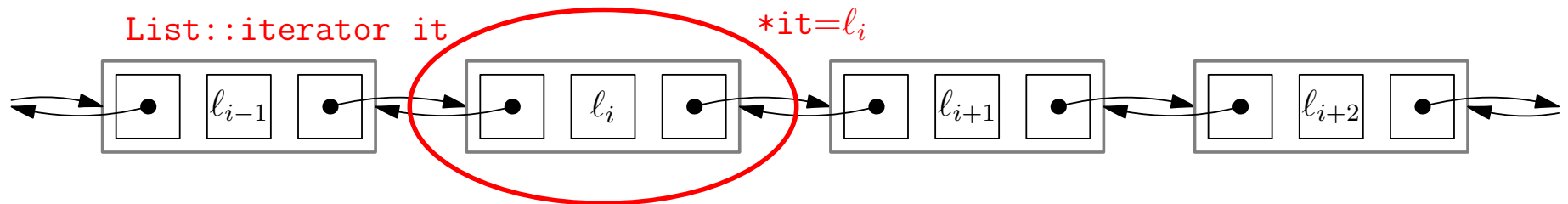
Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list



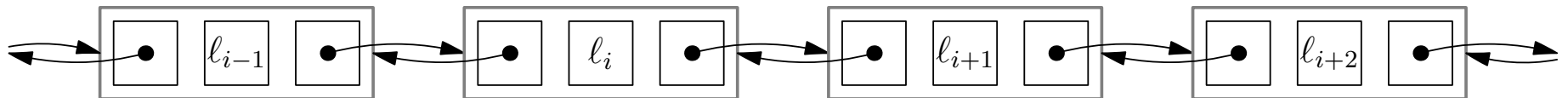
Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list



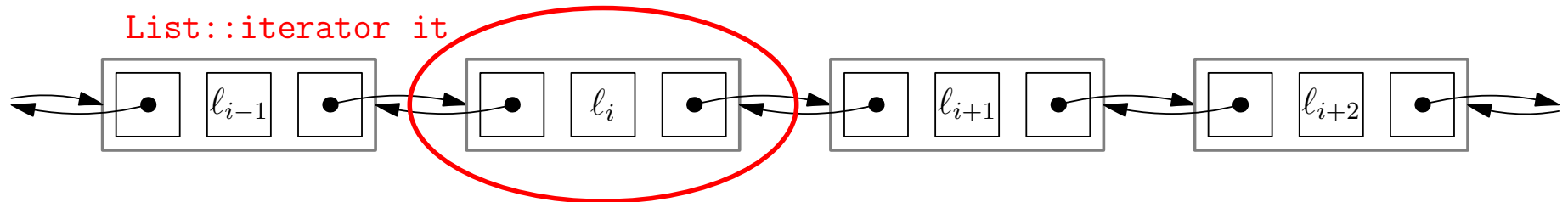
Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list



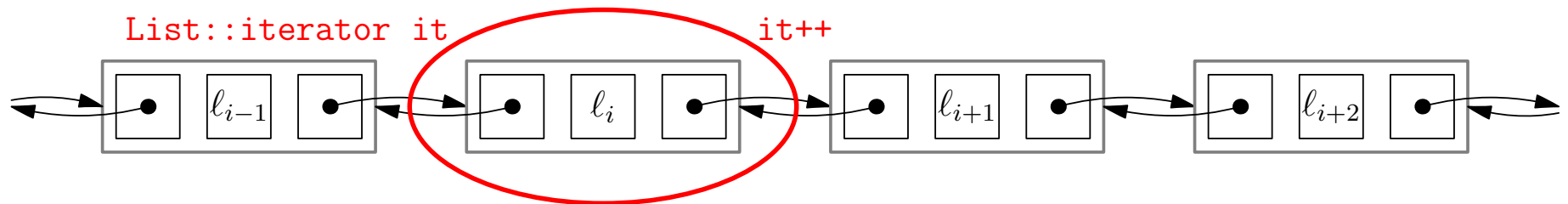
Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list



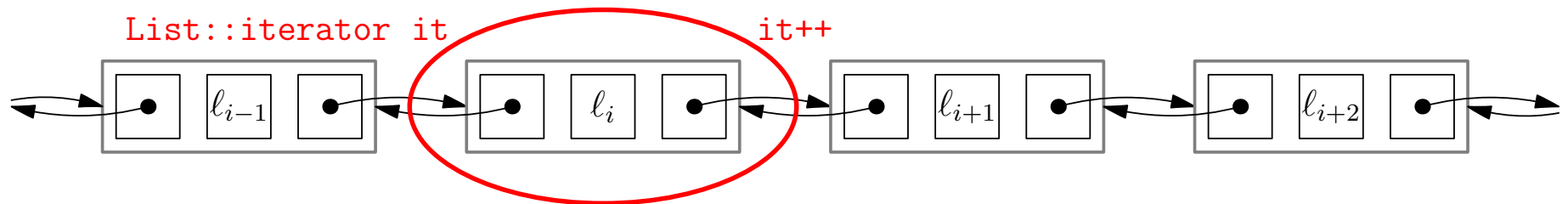
Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list



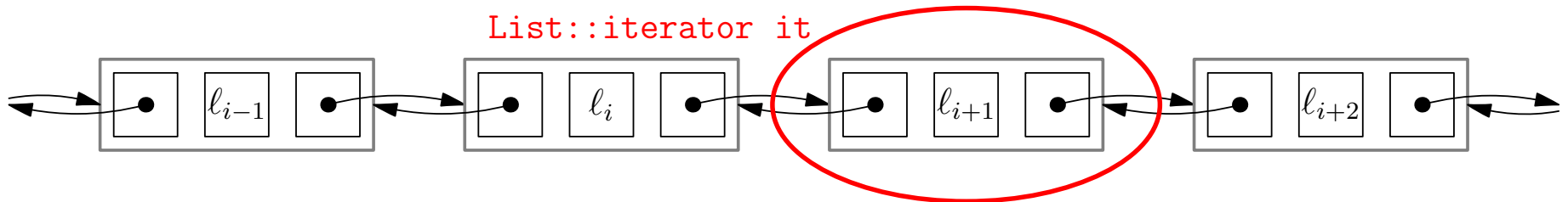
Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list



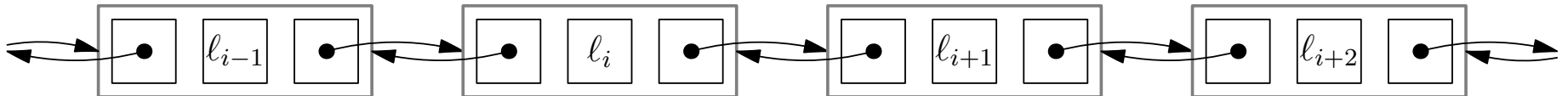
Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list



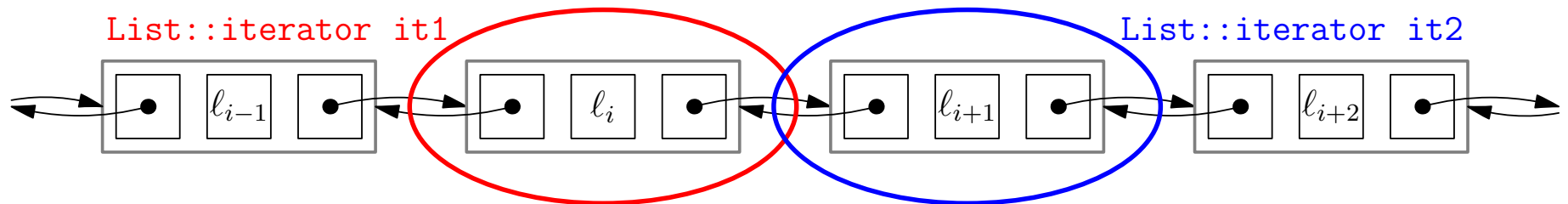
Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list



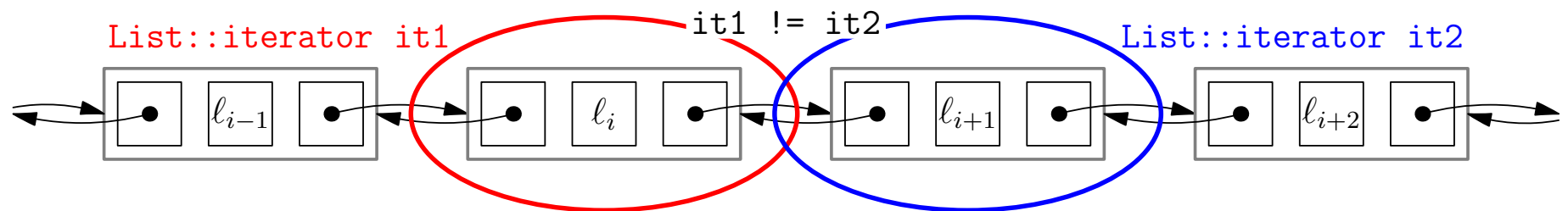
Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list



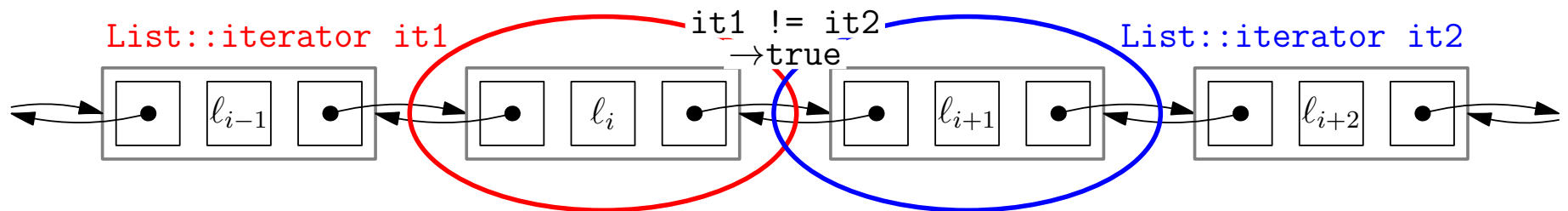
Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list



Linked-List Iterators

- Linked-lists are not array based
- To use the iterator we need to implement the iterator class
- The object instantiated from the class should represent the position we are in the linked list



Linked-List

```
template <typename T>  
class MyList {    // My linked list class
```

Linked-List

```
template <typename T>
class MyList {    // My linked list class
private:
    struct Node{    // A simple node nested class
        Node(T value, Node *node): value(value), next(node) {}
        T value;
        Node *next;
    };
};
```

Linked-List

```
template <typename T>
class MyList {    // My linked list class
private:
    struct Node{    // A simple node nested class
        Node(T value, Node *node): value(value), next(node) {}
        T value;
        Node *next;
    };

    struct iterator {    // An iterator class
```

Linked-List

```
template <typename T>
class MyList {    // My linked list class
private:
    struct Node{    // A simple node nested class
        Node(T value, Node *node): value(value), next(node) {}
        T value;
        Node *next;
    };

    struct iterator {    // An iterator class
        Node* entry;    // Holds node pointer
```

Linked-List

```
template <typename T>
class MyList {    // My linked list class
private:
    struct Node{    // A simple node nested class
        Node(T value, Node *node): value(value), next(node) {}
        T value;
        Node *next;
    };

    struct iterator {    // An iterator class
        Node* entry;    // Holds node pointer
        iterator(Node* pt): entry(pt) {}    // constructor
    };
};
```


Linked-List

```
template <typename T>
class MyList {    // My linked list class
private:
    struct Node{    // A simple node nested class
        Node(T value, Node *node): value(value), next(node) {}
        T value;
        Node *next;
    };

    struct iterator {    // An iterator class
        Node* entry;    // Holds node pointer
        iterator(Node* pt): entry(pt) {}    // constructor
        T& operator*() {return entry->value;}    // dereferencing
    };
};
```

Linked-List

```
template <typename T>
class MyList {    // My linked list class
private:
    struct Node{    // A simple node nested class
        Node(T value, Node *node): value(value), next(node) {}
        T value;
        Node *next;
    };

    struct iterator {    // An iterator class
        Node* entry;    // Holds node pointer
        iterator(Node* pt): entry(pt) {}    // constructor
        T& operator*() {return entry->value;}    // dereferencing
        iterator& operator++() {    // next entry ++it
            entry = entry->next;
            return iterator(entry);
        }
    };
};
```

Linked-List

```
template <typename T>
class MyList {    // My linked list class
private:
    struct Node{    // A simple node nested class
        Node(T value, Node *node): value(value), next(node) {}
        T value;
        Node *next;
    };

    struct iterator {    // An iterator class
        Node* entry;    // Holds node pointer
        iterator(Node* pt): entry(pt) {}    // constructor
        T& operator*() {return entry->value;}    // dereferencing
        iterator& operator++() {    // next entry ++it
            entry = entry->next;
            return iterator(entry);
        }
        bool operator!=(const iterator& other) const {
            return entry != other.entry;
        }
    };
};
```

Linked-List

```
template <typename T>
class MyList {
private:
    struct Node{...}

    struct iterator {...}
```

Linked-List

```
template <typename T>
class MyList {
private:
    struct Node{...}

    struct iterator {...}

    Node* head;           // head of linked list
```

Linked-List

```
template <typename T>
class MyList {
private:
    struct Node{...}

    struct iterator {...}

    Node* head;           // head of linked list
    unsigned no_elements;
```

Linked-List

```
template <typename T>
class MyList {
private:
    struct Node{...}

    struct iterator {...}

    Node* head;           // head of linked list
    unsigned no_elements;

public:
    MyList(): head(nullptr), no_elements(0) {}
    void add(T value) {...}
```

Linked-List

```
template <typename T>
class MyList {
private:
    struct Node{...}

    struct iterator {...}

    Node* head;           // head of linked list
    unsigned no_elements;

public:
    MyList(): head(nullptr), no_elements(0) {}
    void add(T value) {...}

    iterator begin() {return iterator(head);}
    iterator end() {return iterator(nullptr);}
}
```


Increment Operators

- C++ has a pre-increment operator `++a` and a post-increment operator `a++`

- The pre-increment operator increments `it` and returns the incremented version, e.g.

```
iterator& operator++() {++it; return it;} // defines ++it
```

- The post-increment operator copies `it` increments it and returns the copy, e.g.

```
T& operator++(int) {T v = it->value; ++it; return v;} // defines it++
```

- The `int` argument is not used, but tells the compiler which increment is which
- We might want to implement `it++`

Increment Operators

- C++ has a pre-increment operator `++a` and a post-increment operator `a++`

- The pre-increment operator increments `it` and returns the incremented version, e.g.

```
iterator& operator++() {++it; return it;} // defines ++it
```

- The post-increment operator copies `it` increments it and returns the copy, e.g.

```
T& operator++(int) {T v = it->value; ++it; return v;} // defines it++
```

- The `int` argument is not used, but tells the compiler which increment is which
- We might want to implement `it++`

Increment Operators

- C++ has a pre-increment operator `++a` and a post-increment operator `a++`

- The pre-increment operator increments `it` and returns the incremented version, e.g.

```
iterator& operator++() {++it; return it;} // defines ++it
```

- The post-increment operator copies `it` increments it and returns the copy, e.g.

```
T& operator++(int) {T v = it->value; ++it; return v;} // defines it++
```

- The `int` argument is not used, but tells the compiler which increment is which
- We might want to implement `it++`

Increment Operators

- C++ has a pre-increment operator `++a` and a post-increment operator `a++`

- The pre-increment operator increments `it` and returns the incremented version, e.g.

```
iterator& operator++() {++it; return it;} // defines ++it
```

- The post-increment operator copies `it` increments it and returns the copy, e.g.

```
T& operator++(int) {T v = it->value; ++it; return v;} // defines it++
```

- The `int` argument is not used, but tells the compiler which increment is which
- We might want to implement `it++`

Increment Operators

- C++ has a pre-increment operator `++a` and a post-increment operator `a++`

- The pre-increment operator increments `it` and returns the incremented version, e.g.

```
iterator& operator++() {++it; return it;} // defines ++it
```

- The post-increment operator copies `it` increments it and returns the copy, e.g.

```
T& operator++(int) {T v = it->value; ++it; return v;} // defines it++
```

- The `int` argument is not used, but tells the compiler which increment is which

- We might want to implement `it++`

Const Iterators

- C++ uses the compiler to test whether functions change their argument or not

```
func1(Class obj)    // obj is copied so will only modify copy  
func2(Class& obj)   // passed by reference, might change obj  
func3(const Class& Obj) // will not change obj
```

- func3 will only call methods of Obj that are const

```
class Class {  
    void method() const;    // won't change the object  
    void change();         // might change the object  
}
```

- We want to declare a `const_iterator` with

```
const T& operator*() const // const dereferencing operator
```

Const Iterators

- C++ uses the compiler to test whether functions change their argument or not

```
func1(Class obj)    // obj is copied so will only modify copy  
func2(Class& obj)   // passed by reference, might change obj  
func3(const Class& Obj) // will not change obj
```

- func3 will only call methods of Obj that are const

```
class Class {  
    void method() const; // won't change the object  
    void change();       // might change the object  
}
```

- We want to declare a `const_iterator` with

```
const T& operator*() const // const dereferencing operator
```

Const Iterators

- C++ uses the compiler to test whether functions change their argument or not

```
func1(Class obj)    // obj is copied so will only modify copy
func2(Class& obj)   // passed by reference, might change obj
func3(const Class& Obj) // will not change obj
```

- func3 will only call methods of Obj that are const

```
class Class {
    void method() const; // won't change the object
    void change();       // might change the object
}
```

- We want to declare a `const_iterator` with

```
const T& operator*() const // const dereferencing operator
```


Const Iterators

- C++ uses the compiler to test whether functions change their argument or not

```
func1(Class obj)    // obj is copied so will only modify copy
func2(Class& obj)   // passed by reference, might change obj
func3(const Class& Obj) // will not change obj
```

- func3 will only call methods of Obj that are const

```
class Class {
    void method() const;    // won't change the object
    void change();         // might change the object
}
```

- We want to declare a `const_iterator` with

```
const T& operator*() const // const dereferencing operator
```

Const Iterators

- C++ uses the compiler to test whether functions change their argument or not

```
func1(Class obj)    // obj is copied so will only modify copy
func2(Class& obj)   // passed by reference, might change obj
func3(const Class& Obj) // will not change obj
```

- func3 will only call methods of Obj that are const

```
class Class {
    void method() const; // won't change the object
    void change();       // might change the object
}
```

- We want to declare a `const_iterator` with

```
const T& operator*() const // const dereferencing operator
```

Const Iterators

- C++ uses the compiler to test whether functions change their argument or not

```
func1(Class obj)    // obj is copied so will only modify copy
func2(Class& obj)   // passed by reference, might change obj
func3(const Class& Obj) // will not change obj
```

- func3 will only call methods of Obj that are const

```
class Class {
    void method() const; // won't change the object
    void change();       // might change the object
}
```

- We want to declare a const_iterator with

```
const T& operator*() const // const dereferencing operator
```

Bidirectional Iterators

- For the linked list we have implemented a **forward iterator**
- This is the only iterator possible for a singly linked list
- For a doubly linked list we can implement a **bidirectional iterator**
- This requires us to implement the decrement operators

```
iterator& operator--();      // implements --obj  
T operator--(int);          // implements obj--
```

- There also exist **random-access iterators** that implements methods including

```
T& operator[int i]          // returns i'th element  
operator+=[int i]           // move forward i places
```

Bidirectional Iterators

- For the linked list we have implemented a **forward iterator**
- This is the only iterator possible for a singly linked list
- For a doubly linked list we can implement a **bidirectional iterator**
- This requires us to implement the decrement operators

```
iterator& operator--();      // implements --obj  
T operator--(int);          // implements obj--
```

- There also exist **random-access iterators** that implements methods including

```
T& operator[int i]          // returns i'th element  
operator+=[int i]           // move forward i places
```

Bidirectional Iterators

- For the linked list we have implemented a **forward iterator**
- This is the only iterator possible for a singly linked list
- For a doubly linked list we can implement a **bidirectional iterator**
- This requires us to implement the decrement operators

```
iterator& operator--();      // implements --obj  
T operator--(int);          // implements obj--
```

- There also exist **random-access iterators** that implements methods including

```
T& operator[int i]          // returns i'th element  
operator+=[int i]           // move forward i places
```

Bidirectional Iterators

- For the linked list we have implemented a **forward iterator**
- This is the only iterator possible for a singly linked list
- For a doubly linked list we can implement a **bidirectional iterator**
- This requires us to implement the decrement operators

```
iterator& operator--();      // implements --obj  
T operator--(int);          // implements obj--
```

- There also exist **random-access iterators** that implements methods including

```
T& operator[int i]          // returns i'th element  
operator+=[int i]           // move forward i places
```

Bidirectional Iterators

- For the linked list we have implemented a **forward iterator**
- This is the only iterator possible for a singly linked list
- For a doubly linked list we can implement a **bidirectional iterator**
- This requires us to implement the decrement operators

```
iterator& operator--();           // implements --obj  
T operator--(int);               // implements obj--
```

- There also exist **random-access iterators** that implements methods including

```
T& operator[](int i)             // returns i'th element  
operator+=(int i)                // move forward i places
```


Outline

1. Iterators
2. The C++ Iterator Pattern
3. Linked-List Iterators
4. **Generic Programming**



Range-Based For Loop

- C++ allows you to iterate over collections elegantly

```
Collection<string> collection;
```

```
for (string& element: collection) {  
    print(element); // or whatever function you want  
}
```

- This is syntactic sugar! The compiler just replaces this with

```
for(auto& it=collection.begin(); it!=collection.end(); ++it) {  
    print(*it);  
}
```

- This works for any class that has an iterator
- **auto** just works out the correct type

Range-Based For Loop

- C++ allows you to iterate over collections elegantly

```
Collection<string> collection;
```

```
for (string& element: collection) {  
    print(element); // or whatever function you want  
}
```

- This is syntactic sugar! The compiler just replaces this with

```
for(auto& it=collection.begin(); it!=collection.end(); ++it) {  
    print(*it);  
}
```

- This works for any class that has an iterator
- **auto** just works out the correct type

Range-Based For Loop

- C++ allows you to iterate over collections elegantly

```
Collection<string> collection;
```

```
for (string& element: collection) {  
    print(element); // or whatever function you want  
}
```

- This is syntactic sugar! The compiler just replaces this with

```
for(auto& it=collection.begin(); it!=collection.end(); ++it) {  
    print(*it);  
}
```

- This works for any class that has an iterator
- **auto** just works out the correct type

Range-Based For Loop

- C++ allows you to iterate over collections elegantly

```
Collection<string> collection;
```

```
for (string& element: collection) {  
    print(element); // or whatever function you want  
}
```

- This is syntactic sugar! The compiler just replaces this with

```
for(auto& it=collection.begin(); it!=collection.end(); ++it) {  
    print(*it);  
}
```

- This works for any class that has an iterator
- **auto** just works out the correct type

Range-Based For Loop

- C++ allows you to iterate over collections elegantly

```
Collection<string> collection;
```

```
for (string& element: collection) {  
    print(element); // or whatever function you want  
}
```

- This is syntactic sugar! The compiler just replaces this with

```
for(auto& it=collection.begin(); it!=collection.end(); ++it) {  
    print(*it);  
}
```

- This works for any class that has an iterator
- **auto** just works out the correct type
- By being pretty ranged-based for loops reduce bugs in code

Generic Algorithms

- Iterators allow us to write generic functions

- E.g. summing elements

```
template <typename Iter, typename T>
T accum(It it, It end, T init) {
    for(; it != end; ++it)
        init += *it;
    return init;
}
```

- This will sum many collections

```
int array[20];
vector<double> v[5];
set<int> s;
```

```
cout << " array sum = " << accum(&array[0], &array[20], 0) << endl;
cout << "vector sum = " << accum(v.begin(), v.end(), 0.0) << endl;
cout << " set sum = " << accum(s.begin(), s.end(), 0) << endl;
```

Generic Algorithms

- Iterators allow us to write generic functions

- E.g. summing elements

```
template <typename Iter, typename T>
T accum(Iter it, Iter end, T init) {
    for(; it != end; ++it)
        init += *it;
    return init;
}
```

- This will sum many collections

```
int array[20];
vector<double> v[5];
set<int> s;
```

```
cout << " array sum = " << accum(&array[0], &array[20], 0) << endl;
cout << "vector sum = " << accum(v.begin(), v.end(), 0.0) << endl;
cout << " set sum = " << accum(s.begin(), s.end(), 0) << endl;
```


Generic Algorithms

- Iterators allow us to write generic functions

- E.g. summing elements

```
template <typename Iter, typename T>
T accum(Iter it, Iter end, T init) {
    for(; it != end; ++it)
        init += *it;
    return init;
}
```

- This will sum many collections

```
int array[20];
vector<double> v[5];
set<int> s;
```

```
cout << " array sum = " << accum(&array[0], &array[20], 0) << endl;
cout << "vector sum = " << accum(v.begin(), v.end(), 0.0) << endl;
cout << " set sum = " << accum(s.begin(), s.end(), 0) << endl;
```

Generic Algorithms

- Iterators allow us to write generic functions

- E.g. summing elements

```
template <typename Iter, typename T>
T accum(It it, It end, T init) {
    for(; it != end; ++it)
        init += *it;
    return init;
}
```

- This will sum many collections

```
int array[20];
vector<double> v[5];
set<int> s;
```

```
cout << " array sum = " << accum(&array[0], &array[20], 0) << endl;
cout << "vector sum = " << accum(v.begin(), v.end(), 0.0) << endl;
cout << " set sum = " << accum(s.begin(), s.end(), 0) << endl;
```

std::algorithm

- The standard template library includes a library `<algorithm>` that uses iterators to offer generic algorithms
- There are a lot of algorithms available, e.g.
 - ★ `count_if()`: counts elements that satisfies condition
 - ★ `max_element()`: returns maximum element
 - ★ `find()`: find an element
 - ★ `find_if()`: find first element that satisfies condition
 - ★ `all_of()`: true if all elements satisfy condition
 - ★ `any_of()`: true if any element satisfies condition

std::algorithm

- The standard template library includes a library `<algorithm>` that uses iterators to offer generic algorithms
- There are a lot of algorithms available, e.g.
 - ★ `count_if()`: counts elements that satisfies condition
 - ★ `max_element()`: returns maximum element
 - ★ `find()`: find an element
 - ★ `find_if()`: find first element that satisfies condition
 - ★ `all_of()`: true if all elements satisfy condition
 - ★ `any_of()`: true if any element satisfies condition

std::algorithm

- The standard template library includes a library `<algorithm>` that uses iterators to offer generic algorithms
- There are a lot of algorithms available, e.g.
 - ★ `count_if()`: counts elements that satisfies condition
 - ★ `max_element()`: returns maximum element
 - ★ `find()`: find an element
 - ★ `find_if()`: find first element that satisfies condition
 - ★ `all_of()`: true if all elements satisfy condition
 - ★ `any_of()`: true if any element satisfies condition

std::algorithm

- The standard template library includes a library `<algorithm>` that uses iterators to offer generic algorithms
- There are a lot of algorithms available, e.g.
 - ★ `count_if()`: counts elements that satisfies condition
 - ★ `max_element()`: returns maximum element
 - ★ `find()`: **find an element**
 - ★ `find_if()`: find first element that satisfies condition
 - ★ `all_of()`: true if all elements satisfy condition
 - ★ `any_of()`: true if any element satisfies condition

std::algorithm

- The standard template library includes a library `<algorithm>` that uses iterators to offer generic algorithms
- There are a lot of algorithms available, e.g.
 - ★ `count_if()`: counts elements that satisfies condition
 - ★ `max_element()`: returns maximum element
 - ★ `find()`: find an element
 - ★ `find_if()`: find first element that satisfies condition
 - ★ `all_of()`: true if all elements satisfy condition
 - ★ `any_of()`: true if any element satisfies condition

std::algorithm

- The standard template library includes a library `<algorithm>` that uses iterators to offer generic algorithms
- There are a lot of algorithms available, e.g.
 - ★ `count_if()`: counts elements that satisfies condition
 - ★ `max_element()`: returns maximum element
 - ★ `find()`: find an element
 - ★ `find_if()`: find first element that satisfies condition
 - ★ `all_of()`: true if all elements satisfy condition
 - ★ `any_of()`: true if any element satisfies condition

std::algorithm

- The standard template library includes a library `<algorithm>` that uses iterators to offer generic algorithms
- There are a lot of algorithms available, e.g.
 - ★ `count_if()`: counts elements that satisfies condition
 - ★ `max_element()`: returns maximum element
 - ★ `find()`: find an element
 - ★ `find_if()`: find first element that satisfies condition
 - ★ `all_of()`: true if all elements satisfy condition
 - ★ `any_of()`: true if any element satisfies condition

Modifying Algorithms

- `for_each()`: perform operation of each element
- `move()`: move elements in a range
- `copy()`: copy range of elements
- `copy_if()`: copy range if condition is true
- `merge()`: merge two ranges
- `replace_if()`: replace element if ...

Modifying Algorithms

- `for_each()`: perform operation of each element
- `move()`: move elements in a range
- `copy()`: copy range of elements
- `copy_if()`: copy range if condition is true
- `merge()`: merge two ranges
- `replace_if()`: replace element if ...

Modifying Algorithms

- `for_each()`: perform operation of each element
- `move()`: move elements in a range
- `copy()`: copy range of elements
- `copy_if()`: copy range if condition is true
- `merge()`: merge two ranges
- `replace_if()`: replace element if ...

Modifying Algorithms

- `for_each()`: perform operation of each element
- `move()`: move elements in a range
- `copy()`: copy range of elements
- `copy_if()`: copy range if condition is true
- `merge()`: merge two ranges
- `replace_if()`: replace element if ...

Modifying Algorithms

- `for_each()`: perform operation of each element
- `move()`: move elements in a range
- `copy()`: copy range of elements
- `copy_if()`: copy range if condition is true
- `merge()`: merge two ranges
- `replace_if()`: replace element if ...

Modifying Algorithms

- `for_each()`: perform operation of each element
- `move()`: move elements in a range
- `copy()`: copy range of elements
- `copy_if()`: copy range if condition is true
- `merge()`: merge two ranges
- `replace_if()`: **replace element if ...**

Sorting and Searching

- `reverse()`: reverse range
- `rotate()`: cyclically rotate range
- `shuffle()`: random shuffle
- `sort()`: sort collection
- `stable_sort()`: use a stable sort
- `make_heap()`: make a heap
- `binary_search()`: use binary search

Sorting and Searching

- `reverse()`: reverse range
- `rotate()`: cyclically rotate range
- `shuffle()`: random shuffle
- `sort()`: sort collection
- `stable_sort()`: use a stable sort
- `make_heap()`: make a heap
- `binary_search()`: use binary search

Sorting and Searching

- `reverse()`: reverse range
- `rotate()`: cyclically rotate range
- `shuffle()`: random shuffle
- `sort()`: sort collection
- `stable_sort()`: use a stable sort
- `make_heap()`: make a heap
- `binary_search()`: use binary search

Sorting and Searching

- `reverse()`: reverse range
- `rotate()`: cyclically rotate range
- `shuffle()`: random shuffle
- `sort()`: sort collection
- `stable_sort()`: use a stable sort
- `make_heap()`: make a heap
- `binary_search()`: use binary search

Sorting and Searching

- `reverse()`: reverse range
- `rotate()`: cyclically rotate range
- `shuffle()`: random shuffle
- `sort()`: sort collection
- `stable_sort()`: use a stable sort
- `make_heap()`: make a heap
- `binary_search()`: use binary search

Sorting and Searching

- `reverse()`: reverse range
- `rotate()`: cyclically rotate range
- `shuffle()`: random shuffle
- `sort()`: sort collection
- `stable_sort()`: use a stable sort
- `make_heap()`: make a heap
- `binary_search()`: use binary search

Sorting and Searching

- `reverse()`: reverse range
- `rotate()`: cyclically rotate range
- `shuffle()`: random shuffle
- `sort()`: sort collection
- `stable_sort()`: use a stable sort
- `make_heap()`: make a heap
- `binary_search()`: use binary search

Why Use Algorithms

- This is just a selection of some algorithms available
- Using these algorithms you will get a correct and efficient implementation
- You could write them yourself, but by when you use standard algorithms it makes your code very readable
- It is slightly disappointing you don't get to write your own algorithms as they are cool

Why Use Algorithms

- This is just a selection of some algorithms available
- Using these algorithms you will get a correct and efficient implementation
- You could write them yourself, but by when you use standard algorithms it makes your code very readable
- It is slightly disappointing you don't get to write your own algorithms as they are cool

Why Use Algorithms

- This is just a selection of some algorithms available
- Using these algorithms you will get a correct and efficient implementation
- You could write them yourself, but by when you use standard algorithms it makes your code very readable
- It is slightly disappointing you don't get to write your own algorithms as they are cool

Why Use Algorithms

- This is just a selection of some algorithms available
- Using these algorithms you will get a correct and efficient implementation
- You could write them yourself, but by when you use standard algorithms it makes your code very readable **and maintainable**
- It is slightly disappointing you don't get to write your own algorithms as they are cool

Why Use Algorithms

- This is just a selection of some algorithms available
- Using these algorithms you will get a correct and efficient implementation
- You could write them yourself, but by when you use standard algorithms it makes your code very readable and maintainable
- It is slightly disappointing you don't get to write your own algorithms as they are cool

Why Use Algorithms

- This is just a selection of some algorithms available
- Using these algorithms you will get a correct and efficient implementation
- You could write them yourself, but by when you use standard algorithms it makes your code very readable and maintainable
- It is slightly disappointing you don't get to write your own algorithms as they are cool, but you will end up with much more solid code

Lessons

- C++ iterators are not the easiest thing to get your head around
- They are the major tool for writing generic algorithms
- Once you get used to them, they are not that difficult to code
- They also provide a classic example of how to build generic systems
- Learning to use the `<algorithm>` will take you to yet another level

Lessons

- C++ iterators are not the easiest thing to get your head around
- They are the major tool for writing generic algorithms
- Once you get used to them, they are not that difficult to code
- They also provide a classic example of how to build generic systems
- Learning to use the `<algorithm>` will take you to yet another level

Lessons

- C++ iterators are not the easiest thing to get your head around
- They are the major tool for writing generic algorithms
- Once you get used to them, they are not that difficult to code
- They also provide a classic example of how to build generic systems
- Learning to use the `<algorithm>` will take you to yet another level

Lessons

- C++ iterators are not the easiest thing to get your head around
- They are the major tool for writing generic algorithms
- Once you get used to them, they are not that difficult to code
- They also provide a classic example of how to build generic systems
- Learning to use the `<algorithm>` will take you to yet another level

Lessons

- C++ iterators are not the easiest thing to get your head around
- They are the major tool for writing generic algorithms
- Once you get used to them, they are not that difficult to code
- They also provide a classic example of how to build generic systems
- Learning to use the `<algorithm>` will take you to yet another level