CSCI 104
Iterators
Mark Redekopp
David Kempe
ITERATORS
**Iteration**

- Consider how you iterate over all the elements in a list
  - Use a for loop and get() or operator[
- For an array list this is fine since each call to get() is O(1)
- For a linked list, calling get(i) requires taking i steps through the linked list
  - 0th call = 0 steps
  - 1st call = 1 step
  - 2nd call = 2 steps
  - 0+1+2+...+n-2+n-1 = O(n^2)
- You are repeating the work of walking the list...

```cpp
ArrayList<int> mylist;
... for(int i=0; i < mylist.size(); ++i)
{    cout << mylist.get(i) << endl;
}

LinkedList<int> mylist;
... for(int i=0; i < mylist.size(); ++i)
{    cout << mylist.get(i) << endl;
}
```

![Linked List Diagram](image-url)
Iteration: A Better Approach

- Solution: Don't use get(i)
- Use an iterator
  - Stores internal state variable (i.e. another pointer) that remembers where you are and allows taking steps efficiently
- Iterator tracks the internal location of each successive item
- Iterators provide the semantics of a pointer (they look, smell, and act like a pointer to the values in the list
- Assume
  - Mylist.begin() returns an "iterator" to the beginning item
  - Mylist.end() returns an iterator "one-beyond" the last item
  - ++it (preferrer) or it++ moves iterator on to the next value

```c++
LinkedList<int> mylist;
...
iterator it = mylist.begin();
for(it = mylist.begin();
    it != mylist.end();
    ++it)
{
    cout << *it << endl;
}
```
Why Iterators

• Can be more efficient
  – Keep internal state variable for where you are in your iteration process so you do NOT have to traverse (re-walk) the whole list every time you want the next value

• Hides the underlying implementation details from the user
  – User doesn't have to know whether it's an array or linked list behind the scene to know how to move to the next value
    • To take a step with a pointer in array: ++ptr
    • To take a step with a pointer in a linked list: ptr = ptr->next
  – For some of the data structures like a BST the underlying structure is more complex and to go to the next node in a BST is not a trivial task
REVIEW OF OPERATOR
OVERLOADING
A "Dumb" Pointer Class

• Challenge: Use operator overloading to make a "Dumb" pointer class (i.e. show how an object can do what a pointer can already do)

• Operator*
  – Should return reference (T& to item pointed at

• Operator->
  – Per C++ standard (just do it)…should return a pointer (T*) to item be referenced

• Operator++() - Preincrement
  – Should return reference to itself iterator& (i.e. return *this)

• Operator++(int) - Postincrement
  – Should return another iterator pointing to current item will updating itself to point at the next

• Operator== & !=

```cpp
template <typename T>
class DumbPtr
{
private:
  T* p_;  
public:
  DumbPtr(T* p) : p_(p) { }
  T& operator*() { return *p_; }
  T* operator->() { return p_; }
  DumbPtr& operator++() // pre-inc
  { ++p_; return *this; }
  DumbPtr operator++(int) // post-inc
  { DumbPtr x; x.p_ = p_; ++p_; return x; }
  bool operator==(const DumbPtr& rhs);
  { return p_ == rhs.p_; }
  bool operator!=(const DumbPtr& rhs);
  { return p_ != rhs.p_; }
};

int main()
{
  int data[10];
  DumbPtr<int> ptr(data);
  for(int i=0; i < 10; i++){
    cout << *ptr;  ++ptr;
  }
  string s;  DumbPtr<string> sptr(&s);
  cout << sptr->size() << endl;
}
```
Pre- vs. Post-Increment

• Recall what makes a function signature unique is combination of name AND number/type of parameters
  – int f1() and void f1() are the same
  – int f1(int) and void f1() are unique

• When you write: obj++ or ++obj the name of the function will be the same: operator++

• To differentiate the designers of C++ arbitrarily said, we'll pass a dummy int to the operator++() for POST-increment

• So the prototypes look like this...
  – Preincrement: iterator& operator++();
  – Postincrement: iterator operator++(int);
    • Prototype the 'int' argument, but ignore it...never use it...
    • It's just to differentiate pre- from post-increment
**Pre- vs. Post-Increment**

- Consider an expression like the following (a=1, b=5):
  - \((a++ \times b) + (a \times ++b)\)
  - \(1 \times 5 + 2 \times 6\)
  - Operator++ has higher precedence than multiply (*), so we do it first but the post increment means it should appear as if the old value of a is used
  - To achieve this, we could have the following kind of code:
    - \(a++ \Rightarrow \{\text{int } x = a; a = a+1; \text{ return } x; \}\)
      - Make a copy of a (which we will use to evaluate the current expr.
      - Increment a so its ready to be used the next time
      - Return the copy of a that we made
  - Preincrement is much easier because we can update the value and then just use it
    - \(++b \Rightarrow \{ b = b+1; \text{ return } b; \}\)

- Takeaway: Post-increment is "less efficient" because it causes a copy to be made
More operator overloading...

DEFINING ITERATORS
Building Our First Iterator

• Let's add an iterator to our Linked List class
  – Will be an object/class that holds some data that allows us to get an item in our list and move to the next item
  – How do you iterate over a linked list normally:
    • Item<T>* temp = head;
    • While(temp) temp = temp->next;
  – So my iterator object really just needs to model (contain) that 'temp' pointer

• Iterator needs following operators:
  – *
  – ->
  – ++
  – == / !=
  – < > <= >= + - (maybe)

```cpp
template <typename T>
struct Item {
    T val;
    Item<T>* next;
};

template <typename T>
class LList {
public:
    LList();  // Constructor
    ~LList();  // Destructor

private:
    Item<T>* head_;
};
```
Implementing Our First Iterator

- We store the Item<T> pointer to our current item/node during iteration
- We return the value in the Item when we dereference the iterator
- We update the pointer when we increment the iterator

```cpp
template<typename T>
class LList {
  public:
    LList() { head_ = NULL; }
    class iterator {
      private:
        Item<T>* curr_;  // This is private to iterator and cannot be accessed by LList<T>
      public:
        iterator& operator++();
        iterator operator++(int);
        T& operator*();
        T* operator->();
        bool operator!=(const iterator & other);
        bool operator==(const iterator & other);
    }
  private:
    Item<T>* head_;  // This is private to LList<T>
    int size_;  // This is private to LList<T>
};
```

Note: Though class iterator is defined inside LList<T>, it is completely separate and what's private to iterator can't be accessed by LList<T> and vice versa.
Outfitting LList to Support Iterators

- begin() and end() should return a new iterator that points to the head or end of the list.
- But how should begin() and end() seed the iterator with the correct pointer?

```cpp
template<typename T>
class LList
{
public:
    LList() { head_ = NULL; }

class iterator {
    private:
        Item<T>* curr_;
    public:
        iterator& operator++();
        iterator operator++(int);
        T& operator*();
        T* operator->();
        bool operator!=(const iterator & other);
        bool operator==(const iterator & other);
    };

    iterator begin() { ??? }
    iterator end() { ??? }

    private:
        Item<T>* head_;
        int size_;
};
```
Outfitting LList to Support Iterators

• We could add a public constructor...
• But that's bad form, because then anybody outside the LList could create their own iterator pointing to what they want it to point to...
  – Only LList<T> should create iterators
  – So what to do??

```cpp
template<typename T>
class LList
{
public:
    LList() { head_ = NULL; }

    class iterator {
        private:
            Item<T>* curr_;
        public:
            iterator(Item<T>* init) : curr_(init) {}
            iterator& operator++() ;
            iterator operator++(int);
            T& operator*();
            T* operator->();
            bool operator!=(const iterator & other);
            bool operator==(const iterator & other);
        };

    iterator begin()  { ???  }
    iterator end() { ???  }

private:
    Item<T>* head_;
    int size_;   
};
```
Friends and Private Constructors

• Let's only have the iterator class grant access to its "trusted" friend: Llist

• Now LList<T> can access iterators private data and member functions

• And we can add a private constructor that only 'iterator' and 'LList<T>' can use
  – This prevents outsiders from creating iterators that point to what they choose

• Now begin() and end can create iterators via the private constructor & return them

```cpp
template<typename T>
class LList
{
    public:
        LList() { head_ = NULL; }

    class iterator {
        private:
            Item<T>* curr_;
        iterator(Item<T>* init) : curr_(init) {}

        public:
            friend class LList<T>;
            iterator(Item<T>* init);
            iterator& operator++();
            iterator operator++(int);
            T& operator*();
            T* operator->();
            bool operator!=(const iterator & other);
            bool operator==(const iterator & other);
    };

    iterator begin() { iterator it(head_);
        return it;     }
    iterator end()    { iterator it(NULL);
        return it;    }

    private:
        Item<T>* head_;
        int size_;}
```

© 2022 by Mark Redekopp. This content is protected and may not be shared, uploaded, or distributed.
Expanding to ArrayLists

• What internal state would an ArrayList iterator store?
• What would begin() stuff the iterator with?
• What would end() stuff the iterator with that would mean "1 beyond the end"?
Const Iterators

- If a LList<T> is passed in as a const argument, then begin() and end() will violate the const'ness because they aren't declared as const member functions
  - iterator begin() const;
  - iterator end() const;
- While we could change them, it would violate the idea that the List will stay const, because once someone has an iterator they really CAN change the List's contents
- Solution: Add a second iterator type: const_iterator

```
template<typename T>
class LList
{
  public:
    LList() { head_ = NULL; }

    class iterator {
    }
    // non-const member functions
    iterator begin() { iterator it(head_); return it; }
    iterator end() { iterator it(NULL); return it; }
  private:
    Item<T>* head_; int size_; }

void printMyList(const LList<int>& mylist)
{
  LList<int>::iterator it;
  for(it = mylist.begin(); // compile error
    it != mylist.end();
    ++it)
  {
    cout << *it << endl; }
```
Const Iterators

- The const_iterator type should return references and pointers to const T's
- We should add an overloaded begin() and end() that are const member functions and return const_iterators

```cpp
template<typename T>
class LList
{
public:
    LList() { head_ = NULL; }

    class iterator {
        ...
    };
    iterator begin();
    iterator end();

    class const_iterator {
        private:
            Item<T>* curr_;
        const_iterator(Item<T>* init);

        public:
            friend class LList<T>;
            iterator& operator++();
            iterator operator++(int);
            T const & operator*();
            T const * operator->();
            bool operator!=(const iterator & other);
            bool operator==(const iterator & other);
    };
    const_iterator begin() const;
    const_iterator end() const;
};
```
Const Iterators

• An updated example

```cpp
void printMyList(const LList<int>& mylist) {
    LList<int>::const_iterator it;
    for(it = mylist.begin(); // no more error
        it != mylist.end();
        ++it) {
        cout << *it << endl; }
}
```
!= vs <

• It's common idiom to have the loop condition use != over <

• Some iterators don't support '<' comparison
  – Why? Think about what we're comparing with our LList<T>::iterator
  – We are comparing the pointer...Is the address of Item at location 1 guaranteed to be less-than the address of Item at location 2?

```cpp
void printMyList(const LList<int>& mylist) {
    LList<int>::const_iterator it;

    for(it = mylist.begin(); it != mylist.end(); ++it)
    {   cout << *it << endl; }

    for(it = mylist.begin(); it < mylist.end(); ++it)
    {   cout << *it << endl; }
}
```
Kinds of Iterators

• This leads us to categorize iterators based on their capabilities (of the underlying data organization)

• Access type
  – Input iterators: Can only READ the value be pointed to
  – Output iterators: Can only WRITE the value be pointed to

• Movement/direction capabilities
  – Forward Iterator: Can only increment (go forward)
    • ++it
  – Bidirectional Iterators: Can go in either direction
    • ++it or --it
  – Random Access Iterators: Can jump beyond just next or previous
    • it + 4 or it - 2

• Which movement/direction capabilities can our LList<T>::iterator naturally support
Recall: Implicit Type Conversion

- Would the following if condition make sense?
  - No! If statements want Boolean variables

- But you've done things like this before
  - Operator>> returns an ifstream

- So how does ifstream do it?
  - With an "implicit type conversion operator overload"
  - Student::operator bool()
    - Code to specify how to convert a Student to a bool
  - Student::operator int()
    - Code to specify how to convert a Student to an int

```cpp
class Student {
    private: int id; double gpa;
};
int main()
{
    Student s1;
    if(s1){ cout << "Hi" << endl; }
    return 0;
}

ifstream ifile(filename);
...
while( ifile >> x )
{
    ...  }
```

```cpp
class Student {
    private:
        int id; double gpa;
    public:
        operator bool() { return gpa>= 2.0; }
        operator int() { return id; }
};

Student s1;
if(s1) // calls operator bool() and
    int x = s1; // calls operator int()
Iterators With Implicit Conversions

- Can use operator bool() for iterator

```cpp
template<typename T>
class LList
{
    public:
        LList() { head_ = NULL; }

    class iterator {
        private:
            Item<T>* curr_;
        public:
            operator bool()
            {
                return curr_ != NULL;
            }
    };

    void printMyList(LList<int>& mylist)
    {
        LList<int>::iterator it = mylist.begin();
        while(it){
            cout << *it++ << endl;
        }
    }
};
```
Finishing Up

• Iterators provide a nice abstraction between user and underlying data organization
  – Wait until we use trees and other data organizations
• Due to their saved internal state they can be more efficient than simpler approaches [ like get(i) ]
Plugging the leaks

SMART POINTERS
C++11, 14, 17

• Most of what we have taught you in this class are language features that were part of C++ since the C++98 standard

• New, helpful features have been added in C++11, 14, and now 17 standards
  – Beware: compilers are often a bit slow to implement the standards so check the documentation and compiler version
  – You often must turn on special compile flags to tell the compiler to look for C++11 features, etc.
    • For g++ you would need to add: `-std=c++11` or `-std=c++0x`

• Many of the features in these revisions to C++ are originally part of 3rd party libraries such as the Boost library
Pointers or Objects? Both!

- In C++, the dereference operator (*) should appear before...
  - A pointer to an object
  - An actual object
- "Good" answer is
  - A Pointer to an object
- "Technically correct" answer...
  - EITHER!!!!
- Due to operator overloading we can make an object behave as a pointer
  - Overload operator *, &,->, ++, etc.

```cpp
class Thing
{
};

int main()
{
    Thing t1;
    Thing *ptr = &t1

    // Which is legal?
    *t1;
    *ptr;
}
```
A "Dumb" Pointer Class

- We can make a class operate like a pointer
- Use template parameter as the type of data the pointer will point to
- Keep an actual pointer as private data
- Overload operators
- This particular class doesn't really do anything useful
  - It just does what a normal pointer would do

```cpp
template <typename T>
class dumb_ptr
{
private:
  T* p_;  
public:
  dumb_ptr(T* p) : p_(p) {}  
  T& operator*() { return *p_; }  
  T* operator->() { return p_; }  
  dumb_ptr& operator++()  // pre-inc  
  { ++p_; return *this; }
};

int main()
{
  int data[10];
  dumb_ptr<int> ptr(data);

  for(int i=0; i < 10; i++){
    cout << *ptr;  ++ptr;
  }
}
```
A "Useful" Pointer Class

- I can add automatic memory deallocation so that when my local "unique_ptr" goes out of scope, it will automatically delete what it is pointing at.

```cpp
template <typename T>
class unique_ptr
{
private:
    T* p_;    
public:
    unique_ptr(T* p) : p_(p) { }
    ~unique_ptr() { delete p_; }    
    T& operator*() { return *p_; }
    T* operator->() { return p_; }
    unique_ptr& operator++() // pre-inc
    { ++p_; return *this; }
};

int main()
{
    unique_ptr<Obj> ptr(new Obj);
    // ...
    ptr->all_words()
    // Do I need to delete Obj?
}
```
A "Useful" Pointer Class

• What happens when I make a copy?
• Can we make it impossible for anyone to make a copy of an object?

– Remember C++ provides a default "shallow" copy constructor and assignment operator

```cpp
template <typename T>
class unique_ptr
{
private:
    T* p_;
public:
    unique_ptr(T* p) : p_(p) {} 
~unique_ptr() { delete p_; }
    T& operator*() { return *p_; }
    T* operator->() { return p_; }
    unique_ptr& operator++() // pre-inc
    { ++p_; return *this; }
};

int main()
{
    unique_ptr<Obj> ptr(new Obj);
    unique_ptr<Obj> ptr2 = ptr;
    // ...
    ptr2->all_words();
    // Does anything bad happen here?
}
```
Hiding Functions

• Can we make it impossible for anyone to make a copy of an object?
  – Remember C++ provides a default "shallow" copy constructor and assignment operator

• Yes!!
  – Put the copy constructor and operator= declaration in the private section...now the implementations that the compiler provides will be private (not accessible)

• You can use this technique to hide "default constructors" or other functions

```cpp
template <typename T>
class unique_ptr
{
  private:
    T* p_;  
  public:
    unique_ptr(T* p) : p_(p) {}  
    ~unique_ptr() { delete p_; }
    T& operator*() { return *p_; }
    T* operator->() { return p_; }
    unique_ptr& operator++() // pre-inc
    { ++p_; return *this; }
  private:
    unique_ptr(const UsefulPtr& n);  
    unique_ptr& operator=(const UsefulPtr& n);
};

int main()
{
  unique_ptr<Obj> ptr(new Obj);  
  unique_ptr<Obj> ptr2 = ptr;
  // Try to compile this?
}
```
A "shared" Pointer Class

• Could we write a pointer class where we can make copies that somehow "know" to only delete the underlying object when the last copy of the smart pointer dies?

• Basic idea
  – shared_ptr class will keep a count of how many copies are alive
  – shared_ptr destructor simply decrements this count
    • If count is 0, delete the object

```cpp
template<typename T>
class shared_ptr
{
public:
    shared_ptr(T* p);
    ~shared_ptr();
    T& operator*();
    shared_ptr& operator++();
};

shared_ptr<Obj> f1()
{
    shared_ptr<Obj> ptr(new Obj);
    cout << "In F1\n" << *ptr << endl;
    return ptr;
}

int main()
{
    shared_ptr<Obj> p2 = f1();
    cout << "Back in main\n" << *p2;
    cout << endl;
    return 0;
}
```
A "shared" Pointer Class

• Basic idea
  – shared_ptr class will keep a count of how many copies are alive
  – Constructors/copies increment this count
  – shared_ptr destructor simply decrements this count
    • If count is 0, delete the object

```cpp
int main()
{
    shared_ptr<Obj> p1(new Obj);
    doit(p1);
    return 0;
}

void doit(shared_ptr<Obj> p2)
{
    if(...){
        shared_ptr<Obj> p3 = p2;
    }
}
```
A "shared" Pointer Class

• Basic idea
  – shared_ptr class will keep a count of how many copies are alive
  – shared_ptr destructor simply decrements this count
    • If count is 0, delete the object

```cpp
int main()
{
    shared_ptr<Obj> p1(new Obj);
    doit(p1);
    return 0;
}

void doit(shared_ptr<Obj> p2)
{
    if(...){
        shared_ptr<Obj> p3 = p2;
    }
}
```
A "shared" Pointer Class

• Basic idea
  – shared_ptr class will keep a count of how many copies are alive
  – shared_ptr destructor simply decrements this count
    • If count is 0, delete the object

```cpp
int main()
{
    shared_ptr<Obj> p1(new Obj);
    doit(p1);
    return 0;
}

void doit(shared_ptr<Obj> p2)
{
    if(...){
        shared_ptr<Obj> p3 = p2;
    }
}
```
A "shared" Pointer Class

• Basic idea
  – `shared_ptr` class will keep a count of how many copies are alive
  – `shared_ptr` destructor simply decrements this count
    • If count is 0, delete the object

```cpp
int main()
{
    shared_ptr<Obj> p1(new Obj);
    doit(p1);
    return 0;
}

void doit(shared_ptr<Obj> p2)
{
    if(...){
        shared_ptr<Obj> p3 = p2;
    }
    // p3 dies
}
```
A "shared" Pointer Class

• Basic idea
  – shared_ptr class will keep a count of how many copies are alive
  – shared_ptr destructor simply decrements this count
    • If count is 0, delete the object

```cpp
int main()
{
    shared_ptr<Obj> p1(new Obj);
    doit(p1);
    return 0;
}

void doit(shared_ptr<Obj> p2)
{
    if(...){
        shared_ptr<Obj> p3 = p2;
    } // p3 dies
    } // p2 dies
```
A "shared" Pointer Class

• Basic idea
  – shared_ptr class will keep a count of how many copies are alive
  – shared_ptr destructor simply decrements this count
    • If count is 0, delete the object

```cpp
int main()
{
    shared_ptr<Obj> p1(new Obj);
    doit(p1);
    return 0;
} // p1 dies

void doit(shared_ptr<Obj> p2)
{
    if(...){
        shared_ptr<Obj> p3 = p2;
    } // p3 dies
} // p2 dies
```
C++ shared_ptr

- C++ std::shared_ptr / boost::shared_ptr
  - Boost is a best-in-class C++ library of code you can download and use with all kinds of useful classes
- Can only be used to point at dynamically allocated data (since it is going to call delete on the pointer when the reference count reaches 0)
- Compile in g++ using '-std=c++11' since this class is part of the new standard library version

```cpp
#include <memory>
#include "obj.h"
using namespace std;

shared_ptr<Obj> f1()
{
    shared_ptr<Obj> ptr(new Obj);
    // ...
    cout << "In F1\n" << *ptr << endl;
    return ptr;
}

int main()
{
    shared_ptr<Obj> p2 = f1();
    cout << "Back in main\n" << *p2;
    cout << endl;
    return 0;
}
```

$ g++ -std=c++11 shared_ptr1.cpp obj.cpp
C++ shared_ptr

• Using shared_ptr's you can put pointers into container objects (vectors, maps, etc) and not have to worry about iterating through and deleting them

• When myvec goes out of scope, it deallocates what it is storing (shared_ptr's), but that causes the shared_ptr destructor to automatically delete the Objs

• Think about your project homeworks...this might be (have been) nice

```cpp
#include <memory>
#include <vector>
#include "obj.h"
using namespace std;

int main()
{
    vector<shared_ptr<Obj> > myvec;

    shared_ptr<Obj> p1(new Obj);
    myvec.push_back( p1 );

    shared_ptr<Obj> p2(new Obj);
    myvec.push_back( p2 );

    return 0;
    // myvec goes out of scope...
}
```

$ g++ -std=c++11 shared_ptr1.cpp obj.cpp
shared_ptr vs. unique_ptr

• Both will perform automatic deallocation
• Unique_ptr only allows one pointer to the object at a time
  – Copy constructor and assignment operator are hidden as private functions
  – Object is deleted when pointer goes out of scope
  – Does allow "move" operation
    • If interested read more about this on your own
    • C++11 defines "move" constructors (not just copy constructors) and "rvalue references" etc.
• Shared_ptr allow any number of copies of the pointer
  – Object is deleted when last pointer copy goes out of scope
• Note: Many languages like python, Java, C#, etc. all use this idea of reference counting and automatic deallocation (aka garbage collection) to remove the burden of memory management from the programmer
References

- http://stackoverflow.com/questions/3476938/example-to-use-shared-ptr