Topic 8

Dynamic array vs. linked list: Which one is better?

資料結構與程式設計
Data Structure and Programming

Sep, 2011

In the following topics,

we will introduce several **special** types of

Data Structures,

for example, list, array, set, map, hash, graph, etc.

Some people call them

Abstract Data Types (ADT)

or **(an easier-to-understand name)**

Container Classes

Abstract Data Types (ADTs)

- Or called "container classes". Usually treated as special "utilities" for a programmer
  - Examples are:
    - List, array, queue, stack, set, map, heap, hash, string, bit vector, matrix, tree, graph, etc.
- What they provide ---
  - Interface functions to operate on the data stored in the class
  - The implied complexity of these functions
- What they don't show (Abstracted away...) ---
  - What are the data members inside?
  - How the functions are implemented?

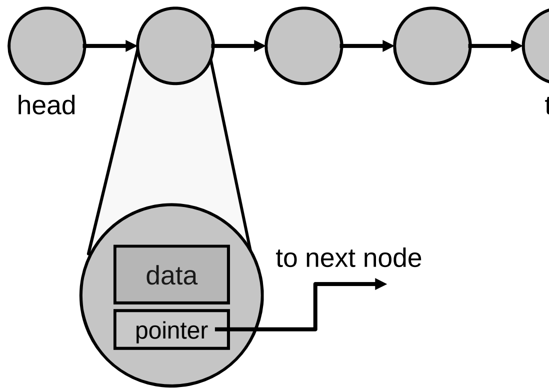
Classification of ADTs

1. Linear (Sequence) Data Types
   - List, array, queue, stack
2. Associative Data Types
   - Set, map, hash, heap
3. Topological Data Types
   - Tree, graph
4. Miscellaneous Types
   - String, bit vector, matrix

- Usually OOP programmer will implement these classes just once *(or adopt the existing ones)*, and later utilize them in various programs

Basic Concepts of Linked List

◆ An abstract data type in which the data are linked as a list



Linked List Implementation (I)

◆ Simple C-style implementation

```
struct MyStruct
{
   // define data here...
   int        _id;
   string     _name;

   // define the pointer here...
   MyStruct*  _next;
};

struct MyTop
{
   MyStruct*  _dataList;
   MyStruct*  _dataPointer;
};
```

data and pointer mixed together

list and pointer not distinguished

Linked List Implementation (II)

•Data encapsulation → Abstract Data Type
→ Like a container

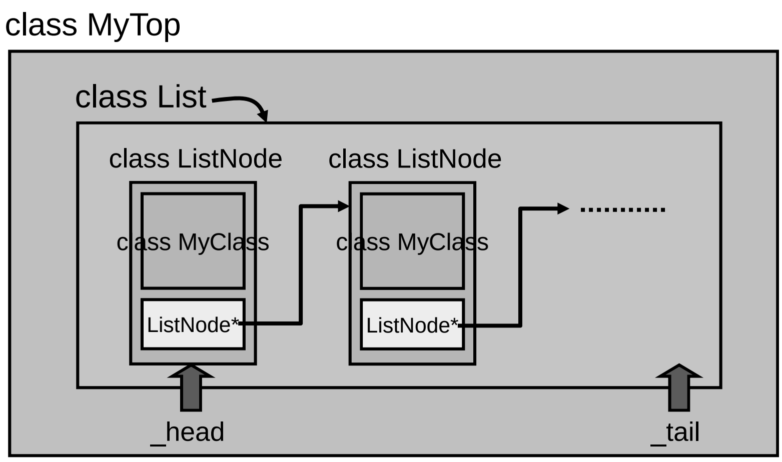
```
class MyClass
{
   // define data here..
   int        _id;
   string     _name;
};

class ListNode
{
   MyClass    _data;
   ListNode*  _next;
};
```

```
class List
{
   ListNode*  _head;
   ListNode*  _tail;
};

class MyTop
{
   List     _dataList;
   MyClass* _dataPtr;
};
```


In other words...



- However, whenever we need a list with different data type, we still need to define a new List class

Linked List Implementation (III)

◆ Template implementation

```
template <class T>
class ListNode
{
   T              _data;
   ListNode<T>*   _next;
};

template <class T>
class List
{
   ListNode<T>*   _head;
   ListNode<T>*   _tail;
};
```

One implementation
multiple instantiations

```
List<int>     intList;
List<char>    charList;
List<MyClass> myList;
...
```


Remember: Standard Template Library (STL)

- First drafted by Alexander Stepanov and Meng Lee of HP in 1992
  - Became IEEE standard in 1994
- A C++ library of container classes, algorithms, and iterators
  - Provides many of the basic algorithms and data structures of computer science
- The STL is a *generic* library
  - Platform independent
  - Its components are heavily parameterized
  - Almost every component in the STL is a template.
- An useful reference: http://www.sgi.com/tech/stl/

Standard Template Library

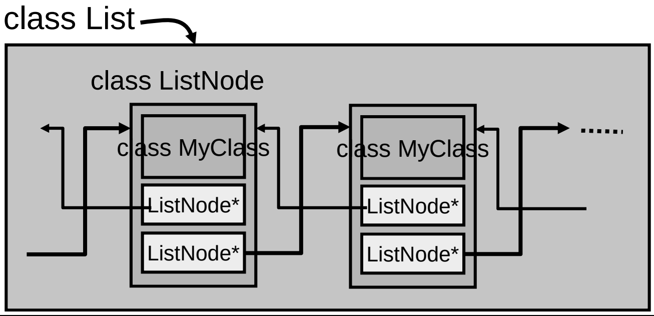
1. Container classes
   - list, slist, vector, deque, map, set, multimap, multiset, etc
   - Adaptors: stack, queue, etc
   - Non-template: string, bit_vector, etc
2. Iterators
   - Trivial iterator, input iterator, output iterator, forward iterator, bidirectional iterator, random access iterator, etc
3. Algorithms
   - for_each, sort, partial_sum, sort, find, copy, swap, etc.
4. Functional object
   - plus, minus, less, greater, logical_and, etc
5. Utility
   - Rational operators, pair, etc
6. Memory allocation
   - alloc, pthread_alloc, construct, uninialized_copy, etc

Complexity Analysis (Singly Linked List)

- push_front() O(1)
  push_back() O(1) // if tail is known, else O(n)
  pop_front() O(1)
  pop_back() O(n)
  size() O(n) or O(1)
  empty() O(1) // not equal to (size() == 0)
  insert(pos, data) O(n) (before pos) or O(1) (after pos)
  erase(pos) O(n)
  find(data) O(n)

Singly vs. Doubly Linked List

- Some operations, like "erase(node)" have linear complexity for singly linked list (Why?)
  - Don't know the previous nodes
- Doubly Linked List



Memory Overhead

- Assume (32-bit machine)
  - Pointer: 4 Bytes
  - Data: d Bytes
  - Total: n data
- Overhead = total memory – data memory
  - Data memory = d * n

1. Singly Linked List: (d + 4) * n + 8
   - Overhead = 4 * n + 8 (~ 4Bytes/data)
2. Doubly Linked List: (d + 8) * n + 8
   - Overhead = 8 * n + 8 (~ 8Bytes/data)

Complexity Analysis (Doubly Linked List)

- push_front() O(1)
  push_back() O(1)
  pop_front() O(1)
  pop_back() O(1)
  size() O(n) or O(1)
  empty() O(1) // != (size() == 0)
  insert(pos, data) O(1)
  erase(pos) O(1)
  find(data) O(n) ⟸

"Find" Operation

- One common way to speed up "find" operation is to keep the data always sorted
  - [Note] Binary Search: O($\log_2$ n)

	10	100	1000	10K	100K
O(1)	1	1	1	1	1
O($\log_2$ n)	4	7	10	14	17
O(n)	10	100	1000	10K	100K

- But, can we implement "binary search" by using Linked List?

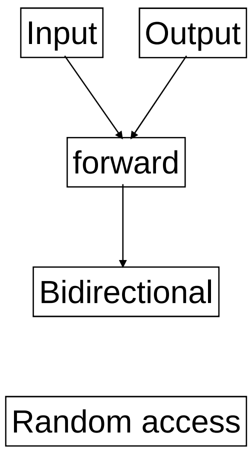
Why not?

Linear access

vs.

Random access

Remember: Hierarchy of Iterators



Container	Iterator type	Operators
list	bidirectional	*, ++, --
slist	forward	*, ++
vector	random access	*, ++, --, +/-
deque	random access	*, ++, --, +/-
map	bidirectional	*, ++, --
multimap	bidirectional	*, ++, --
set	bidirectional	*, ++, --
multiset	bidirectional	*, ++, --
Adaptors	none	N/A

Access a ListNode & Traverse a List

```
template <class T>
class ListNode
{
   T             _data;
   ListNode<T>*  _next;
};
template <class T>
class List
{
   ListNode<T>*  _head;
   ListNode<T>*  _tail;
};
```

➔
```
for (ListNode<T>* node = myList.getHead();
       node != 0; node = node->getNext()) {
     ... }
```


List Iterator

- In many standard List implementations, “class ListNode” is actually ***hidden*** from the user ---
  - Why should user know about the class “ListNode”?
    - User only interfaces with “class List”
    - The internal data field “ListNode*” is just one way of implementing “List”
- Use a generic interface class “List Iterator” to traverse a List

The Goal...

```
iterator li;
for (li = myList.begin();
     li != 0; li++) ...
--------- (compared to) ---------
ListNode<T> *n;
for (n = myList.head();
     n != 0; n = n->getNext();
```

➔ Overload “=“, “!=“, “++”
for class iterator

List Iterator Implementation

- ```
  class iterator {
  // Conventionally, use lower case “i” for “iter...”
     ListNode<T>*   _node;

  public:
     iterator(const ListNode<T>* const n = 0):
                          _node(n) {}

     const T& operator *() const;
     iterator& operator ++ ();
     iterator operator ++ (int);
     iterator& operator = (const iterator& i);
     bool operator != (const iterator& i) const;
  };
  ```

➔ Act as a “wrapper class” for ListNode<T>*
  ```

But the question is:

"How to distinguish this generic iterator class from others?"

➔ One possible way is to declare it inside the "List" class

List Iterator Implementation (cont'd)

```
template <class T>
class List {
   ListNode<T>*    _head;
   ListNode<T>*    _tail;

   // Conventionally, use lowercase "i"
   class iterator {
      ListNode<T>*   _node;
   public:
      iterator(const ListNode<T>* const n = 0):
               _node(n) {}
   ...
   }

   // implicitly calling the iterator(_head) constructor
   iterator begin() { return _head; }
   iterator end() { return 0; }
};
```

Why return '0'? Is this a good implementation?

A List Example

```
int main() {
   List<int> intList;
   for (int i = 0; i < 10; ++i)
      intList.push_back(i * 2);

   List<int>::iterator li;
   for (li = intList.begin();
        li != intList.end(); li++) {
      cout << *li << endl;
   }
}
```


List<T>::push_back(const T& d)

```
void push_back(const T& d) {
   ListNode<T>* t
   = new ListNode<T>(d, 0);
   if (_tail != 0)
      _tail->setNext(t);
   else // _head = _tail = 0
      _head = t;
   _tail = t;
}
```

```
template <class T>
class ListNode {
  T        _data;
  ListNode<T>* _next;
};
```

[Question] Who frees the ListNode* memory?

List<T>::pop_front()

```
void pop_front() {
   if (empty()) return;
   ListNode<T>* t = _head->getNext();
   delete _head;
   _head = t;
}
```

[Question] How about “_tail”?

[Question] How about “_data” inside “_head”? Will it be destructed or “deleted”?

Destructors of List and ListNode

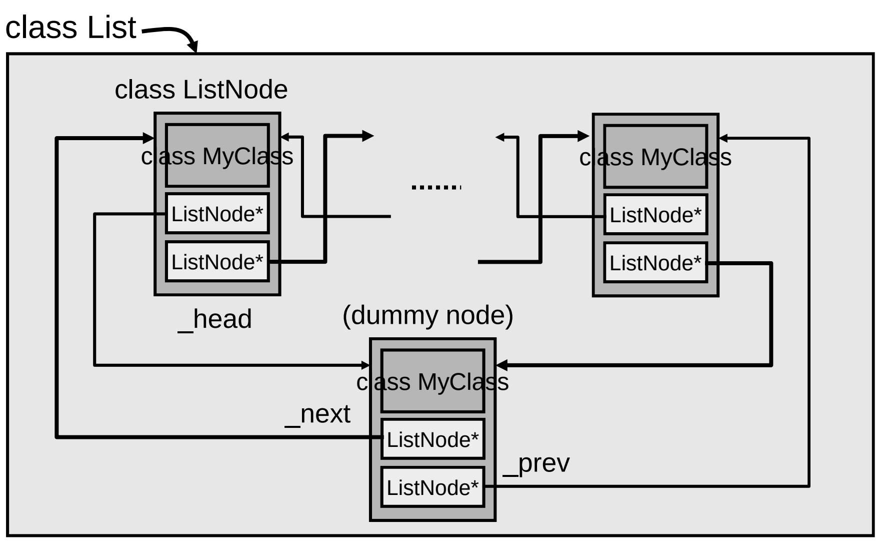
```
ListNode<T>::~ListNode() {
   // Do nothing.
   // But Will call the destructor of “T  _data”
   // But if “T” is a pointer type,
   // ➔ will not free its memory (why??)
}

List<T>::~List() {
   ListNode<T>* thisNode = _head;
   while (thisNode != 0) {
      ListNode<T>* nextNode = thisNode->getNext();
      delete thisNode;
      thisNode = nextNode;
   }
}
```

Note about the “end()”

- Remember, in STL, “end()” actually points to the next to the last node.
- In the previous example, we return ‘0’ for “end()”
  - ➔ Any problem?
    - Potential misjudgment on “n == end()”
    - How to do backward traversal?
- The solution in HW#5 (also in STL’s list<T>)
  - Create a dummy ListNode<T>* as the end

Dummy ListNode<T>* as the end()



Dummy ListNode<T>* as the end()

◆ Things to consider...

1. What happens when the List<T> is just constructed?
2. size(), empty()?
3. push_back(), push_front()

   ➔ need to properly update _head, _tail
4. pop_back(), pop_front()

   ➔ when happen if it has just one element or is empty?

Sorted list

◆ In homework #5, we require the elements in List<T> be always sorted

- No "push_back()", "push_front()"

  ➔ "insert(const T&)" instead
- Also implement "erase(const T&)" and "erase(iterator)"
- What's the complexity for "find(const T&)"?
- Can binary search work here?

Classification of ADTs

1. Linear (Sequence) Data Types
   - List, array, queue, stack
2. Associative Data Types
   - Set, map, hash, heap
3. Topological Data Types
   - Tree, graph
4. Miscellaneous Types
   - String, bit vector, matrix

◆ Usually OOP programmer will implement these classes just once *(or adopt the existing ones)*, and later utilize them in various programs

Array vs. List

◆ In many programmers' view, "array" is less favorable than "list" because they think the array class is ---

1. Limited in size (i.e. array bound)
2. Expensive in "erase" operation
3. No clear advantage other than "random access by index"

➔ That's because they don't know enough about "Dynamic Array"

Static Array

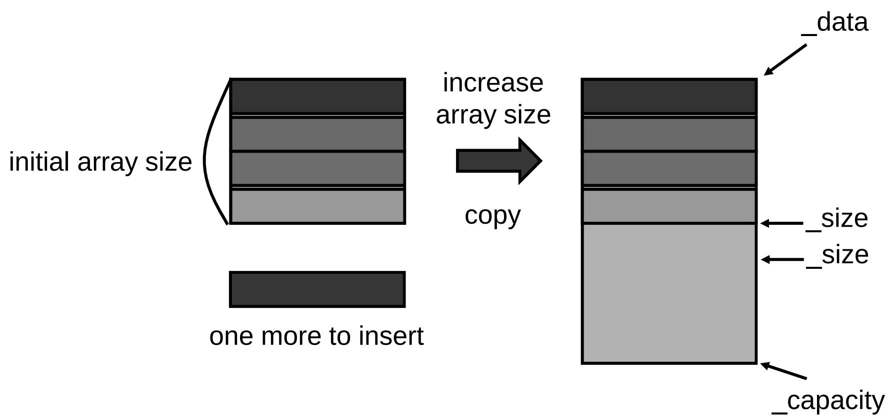
- Array with fixed size   // e.g.   int arr[100];
- "Insert/erase()" operation
  - O(1) if inserted at the end
  - If the element order is not important
    - O(1) insert anywhere (how?)
    - O(1) erase
  - If the element order does matter
    - O(n) insert at the beginning
    - O(n) erase
    - ➔ Is this common? (comparing to list...)
- "Find()" operation
  - Can have O($\log_2$ n) complexity (how?)

Static vs. Dynamic Array

- Static array is indeed limited in usage, and may create memory problems
  - Not recommended in general

- However, dynamic array removes the array size limitation, and when compared with linked list, its performance (runtime and memory) is much better
  - Highly recommended

Basic Concept of Dynamic Array



Dynamic Array Implementation

```
template <class T>
class Array
{
   T*        _data;
   size_t    _size;
   size_t    _capacity

public:
   Array(size_t t = 0)
   : _size(t), _capacity(t) {
      _data = initCapacity(t);
   }
};
```

“Size” in Dynamic Array

- **`[Note] In previous example, _size = t, not 0`**
  - ➔ **`follow the semantics of STL`**
  - **`We can access array[0 ~ (t-1)] after construction`**
- [compare]
  - Array<int> arr1; // size = 0
    arr1[0] = i; // Error!!
    arr1.push_back(i); // OK; size becomes 1
  - Array<int> arr2(10); // size = 10
    arr2[0] = i; // OK
    arr2.push_back(j); // What’s the size now?

“Capacity” in Dynamic Array

- Initialized in array constructor
- When _size == _capacity, how to grow?
  - ➔ Doubled (e.g. 2→4, 3→6, 5→10, etc)
  - Issue: How to do memory management?
    - Remember: difficult to recycle if different in size

  [Sol#1] Powered of 2 in memory allocation
  - Issue: waste memory
    - Many arrays may have size < 10, but only have capacity choices as {2, 4, 8, 16 }

  [Sol#2] Hybrid (1, 2, 3, ...7, 8, 16, ..., 2^n, ...)

Important Member Functions for Array

```
1. T& operator [] (size_type i);
2. const T&
   operator [] (size_type i) const;
3. void push_back(const T& d) {
      if (_size == _capacity)
         expand();
      data[_size++] = d;
   }
4. void resize(size_type s);
```

// s can be smaller or larger than _size

Complexity Analysis (Dynamic Array)

◆ push_front()	O(n) or O(1) // if order not matters
push_back()	O(1)
pop_front()	O(n) or O(1) // if order not matters
pop_back()	O(1)
size()	O(1) // not O(n), why?
empty()	O(1)
insert(pos, data)	O(n) or O(1) // if order not matters
erase(pos)	O(n) or O(1) // if order not matters
find(data)	O(n) or O(log n)

If order does not matter, almost all operations are O(1)!!

Memory Overhead of Dynamic Array

- Assume (32-bit machine)
  - Pointer: 4 Bytes
  - Data: d Bytes
  - Total: n data
- Overhead = total memory – data memory
  - Data memory = d * n + 4
- Dynamic Array Overhead = 8 Bytes only (why??)
  - (cf) Singly Linked List = 4 * n + 8
  - (cf) Doubly Linked List = 8 * n + 8

The Data in the Array Can be Sorted

- Option #1 (dynamic)
  - Whenever a data is inserted, update the array so that the elements are in right order
  - O(log n) in finding the place to insert; O(n) in updating the array
    - ➔ Inserting n elements ➔ $O(n^2)$ // NOT O(n log n)
    - ➔ Array may not be the best ADT
    - ➔ In such case, "balanced binary search tree (BST)" (e.g. STL Set/Map) should be better
- Option #2 (static)
  - If we care about the order only after all the elements are inserted
    - ➔ Sorted only once
    - ➔ Inserting n elements ➔ O(n log n)
  - Has the same "find()" complexity as "set" or "map", but much less memory overhead than BST!!

Some notes about the Array<T> in HW#5

- Similar to the class List<T>, the elements in Array<T> should always be sorted
- No need to implement class ArrayNode<T>. Why??
- The capacity should grow: 1 → 2 → 4 → 8 → ... → 2^n

Performance Comparison: Dynamic Array vs. Linked List

- Task 1
  1. Insert n data (1 by 1)
- Task 2
  1. Insert n data (1 by 1)
  2. Destroy the ADT (remove all)
- Task 3
  1. Alternatively insertions and deletions
- Task 4
  1. Sort the data

(Try different scenarios and report in HW #5)

"vector" and "list" in STL

- In fact, many wrapper classes around the real data members
- In essence…
  - class vector {
    T* _M_start;
    T* _M_finish;
    T* _M_end_of_storage;
    };
  - class list {
    std::_List_node_base *_M_node;
    };
    class _List_node_base {
    std::_List_node_base *_M_next;
    std::_List_node_base *_M_prev;
    };

Other Linear ADT

1. Queue (also known as FIFO)
2. Stack (also known as FILO)

- Use "adaptor class" to implement on top of other linear ADT
  - For example,

```
template <class T, class C = Array<T> >
class Stack {
   C    _elements;
public:
   // only define operations
   // that make sense to "stack"
   // e.g. push(), pop(), top(), etc
};
```