

Topic 6

Dynamic array vs. linked list

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

10/30/2019

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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

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Pablo Picasso, "Accordianist"

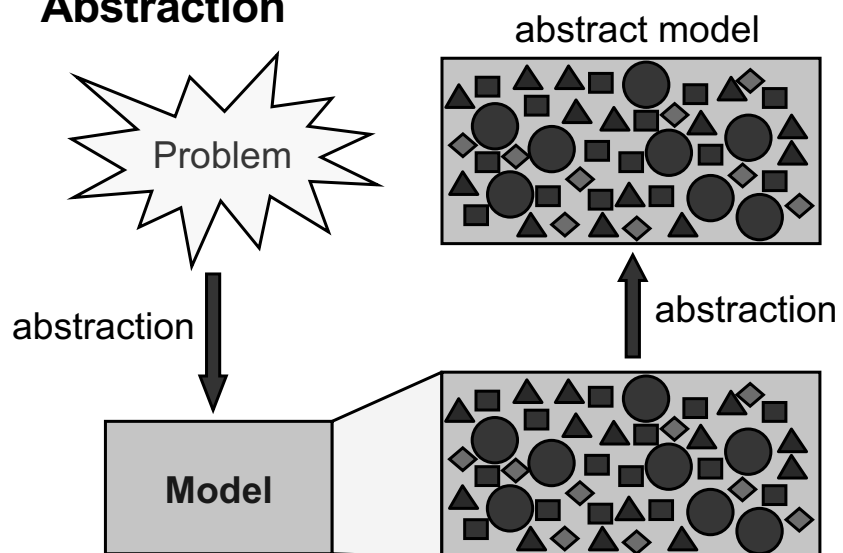


Saver Containers

Abstract ?? Containers??

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Abstraction



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Data Types

- ◆ “A data type, as defined in many object-oriented languages, is a class”
 1. Data member
 - Define data
 2. Member functions
 - Define operations

So, what does the “Abstract” in
“Abstract Data Type” mean?

Some Quotes about ADT...

- ◆ “...precisely specified independent of any particular implementation”
- ◆ “You don't know how the ADT computes, but you know **what** it computes”
- ◆ “The implementer of the class can change the implementation for maintenance, bug fixes or optimization reasons, without disturbing the client code”

ADT in Programming

- ◆ Obviously, these kinds of classes are not specific to any type of algorithms
 - In other words, they can be implemented independently of the algorithms that use them
- ◆ 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?

ADT in Programming

- ◆ That's why they are called "Abstract Data Types", or "Container Classes", and 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.
- ◆ The more and cleverer you use them, the better your program will be
 - That's the main purpose of learning this course

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

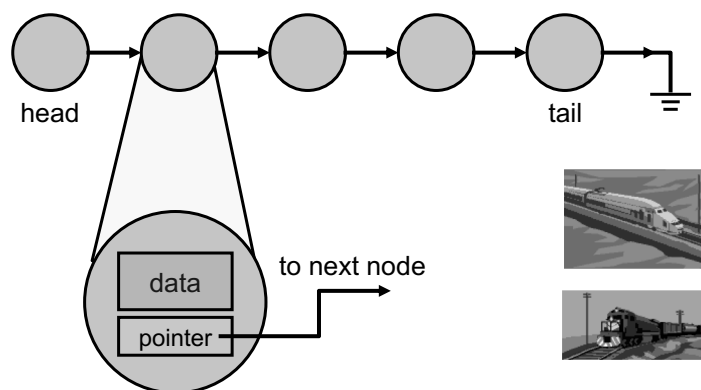
4. Miscellaneous Types

- 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;
};

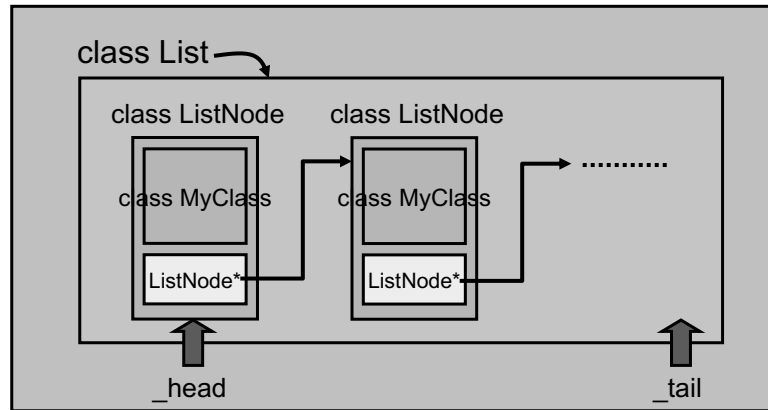
class List
{
    ListNode* _head;
    ListNode* _tail;
};

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

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

In other words...

class MyTop



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More memory usage with data encapsulation??

◆ Simple C-style implementation

```
struct MyStruct
{
    int      _id;
    string   _name;

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

◆ C++ implementation with data encapsulation

```
class MyClass
{
    int      _id;
    string   _name;
};
class ListNode
{
    MyClass  _data;
    ListNode* _next;
};
class List
{
    ListNode* _head;
};
```

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

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Linked List Implementation (III)

◆ Template implementation

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

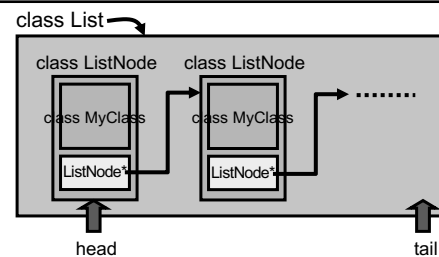
One implementation
multiple instantiations

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

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

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Complexity Analysis (Singly Linked List)

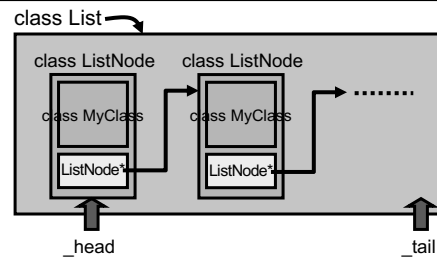


```
push_front(d) {
    ListNode* liNode
    = new ListNode(d);
    liNode->_next
    = _head;
    _head = liNode;
}
```

```
push_back(d) {
    ListNode* liNode
    = new ListNode(d);
    _tail->_next
    = liNode;
    _tail = liNode;
}
// Any corner case?
// What if "_tail"
// is NOT known?
```

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Complexity Analysis (Singly Linked List)



```
pop_front() {
    ListNode* liNode
    = _head;
    _head
    = _head->_next;
    delete liNode;
}
// What if "_head ==
NULL"?
```

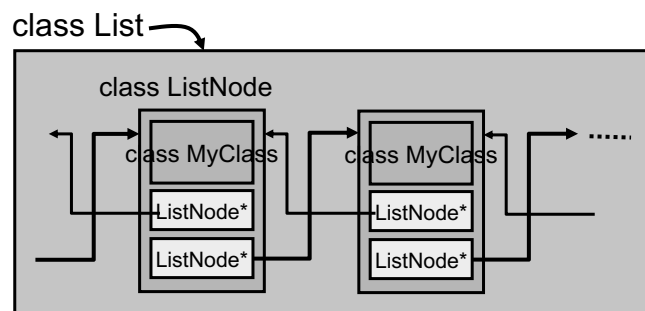
```
pop_back() {
    .....
    delete _tail;
    .....
}
// How to find the
one in front of
_tail?
```

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() $O(n)$ // even if tail is known
- size() $O(n)$ or $O(1)$
- empty() $O(1)$ // complexity 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



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Memory Overhead

- ◆ Assume (64-bit machine)
 - Pointer: 8 Bytes
 - Data: d Bytes
 - Total: n data
 - ◆ Overhead = total memory – data memory
 - Data memory = d * n
1. Singly Linked List: $(d + 8) * n + 8 * 2$
 - Overhead = $8 * n + 16$ (~ 8Bytes/data)
 2. Doubly Linked List: $(d + 16) * n + 8 * 2$
 - Overhead = $16 * n + 16$ (~ 16Bytes/data)

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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” using Linked List?

Why not?

Linear access

VS.

Random access

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;
};
```

Does user need to know how List is implemented?

```
→ for (ListNode<T>* node = myList.getHead();
      node != 0; node = node->getNext()) {
    ... } why not "node != myList.getTail()?"
```

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 != myList.end(); 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?"
(iterators for Linked List, Array,... etc)

➔ 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; } Why return '0'?
    iterator end() { return 0; } ← Is this a good
    };                                implementation?
```

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A List::iterator 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;
    }
}
```

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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?

Object or pointer data in a List

- ◆ When the destructor of ListNode<T> is called, will the destructor of _data be called?

- Yes, if _data is an object type
- No, if _data is a pointer type

- ◆ Uh? Memory leak?

- NO!! If _data is an object type, then it is a COPY of the data outside the List.
- If it is a pointer, then it shares the same data storage. You can't delete it by List.

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


List<T>::pop_front()

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

[Question] How about "_tail"?
When should we care?

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

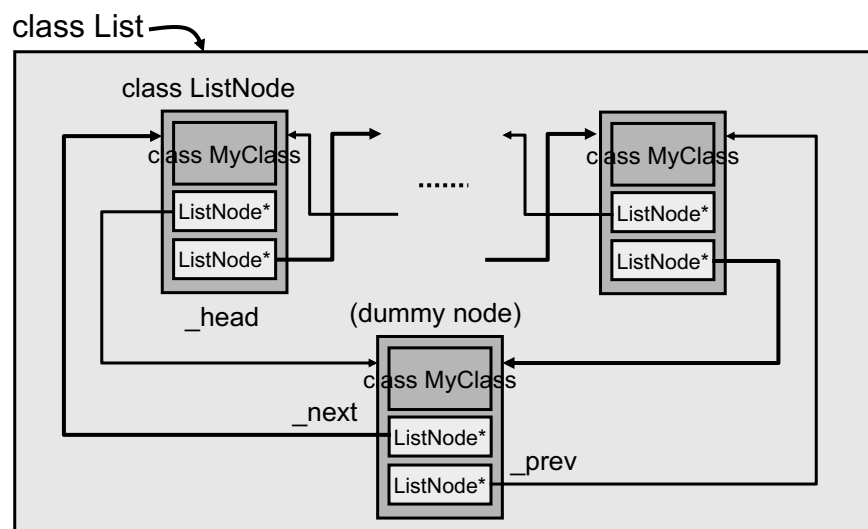
Destructors of List and ListNode

```
ListNode<T>::~~ListNode() {  
    // Do nothing.  
    // But Will call the destructor of "T _data"  
    // But if "T" is a pointer type,  
    // ➔ will not free the memory it points to.  
}  
  
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()
→ what happen if it has just one element or is empty?
5. Do we need “_tail”?

Sorting in Linked List

- ◆ As we say, since the iterators in linked list are not randomly accessible, it's not possible to implement binary search on it.
- ◆ Sorting on Linked List: $O(n^2)$
 - Bubble sort, selection sort, etc.

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"

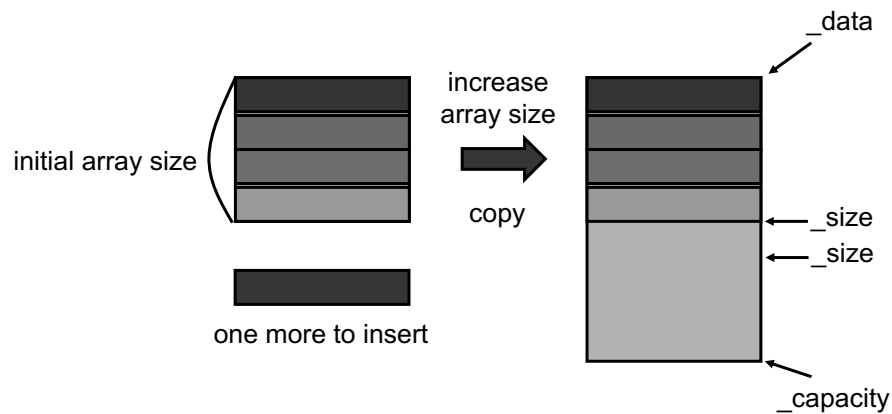
Static Array

- ◆ 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 or anywhere
 - $O(n)$ 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
- ◆ Dynamic array removes the array size limitation, and when compared to linked list, its performance (runtime and memory) is actually 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 $O(\log n)$ // why?

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

Memory Overhead of Dynamic Array

- ◆ Assume (64-bit machine)
 - Pointer: 8 Bytes
 - Data: d Bytes
 - Total: n data
- ◆ Overhead = total memory – data memory
 - Data memory = $d * n$
- ◆ Dynamic Array Overhead = 24 Bytes only (why??)
 - (cf) Singly Linked List = $8 * n + 16$
 - (cf) Doubly Linked List = $16 * n + 16$

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 runtime and memory overhead than BST!!

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

- ◆ Don't worry about sorting for Array<T>, we call STL:
 - void sort(RandomAccessIterator first, RandomAccessIterator last, StrictWeakOrdering comp);
→ as long as operator < is overloaded, you can use sort()
- ◆ No need to implement class ArrayNode<T>. Why??
- ◆ The capacity always grows from: $0 \rightarrow 1 \rightarrow 2 \rightarrow 4 \rightarrow 8 \rightarrow \dots \rightarrow 2^n$

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  
};
```