Lists

History of List Processing in CS

- List languages first developed for AI
- LISP: List Processing Language
  - Developed in 50-60's by John McCarthy et al.
- LL: List Language
  - Developed in 50's by Allen Newell and Herb Simon
- Lists and list processing fundamental part of language
  - lists are primitive data type
  - functions operate directly on lists
  - program itself expressed as list of lists
- "car": contents address register (getDatum())
- "cdr": contents decrement register (getNext())
- "caddr" = (car (cdr (cdr list))) = object in 3rd element

Overview

- Arrays
  - Random access: :)
  - Fixed size: cannot grow on demand after creation: : >((
- Characteristics of some applications:
  - do not need random access
  - require a data structure that can grow and shrink dynamically to accommodate different amounts of data

  □ Lists satisfy this requirement.
- Let us study
  - list creation
  - accessing elements in a list
  - inserting elements into a list
  - deleting elements from a list

List Operations

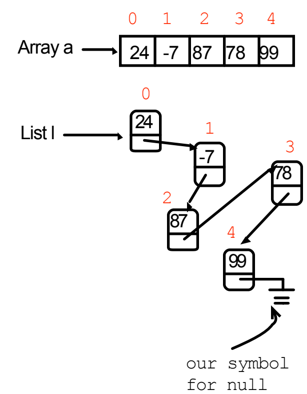
- ADT (Abstract Data Type):
  - Specify public functionality
  - Hide implementation detail from users
  - Allows us to improve/replace implementation
  - Forces us to think about fundamental operations Interface) separately from the implementation
- List Operations:
  - Create
  - Insert object
  - Delete object
  - Find object
  - Get Length, Full?, Empty?, Replace Object, …
  - Usually sequential access (not random access)

List Data Structures

- Implemented using arrays
  - Size of array
  - Number of elements in list
  - Inserts & Deletes require moving elements
  - Must copy array when it gets full
- Implemented using Java Vectors
  - import java.util.Vector (or java.util.*)
  - Size automatically expands as necessary
  - Automatically maintains number of elements
  - Inserts & Deletes still require moving elements
- Implemented as sequence of linked cells
  - We'll focus on this kind of implementation

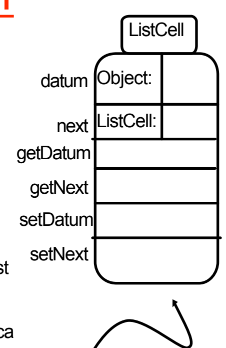
Lists

- List is a sequence of cells in which each cell contains
  - a data item of type Object
  - a reference to the next cell in the sequence
    - null if this is the last cell in the sequence
  - empty list: null
- List is a sequential-access data structure
  - to access data in position *n* of sequence, we must access cells *0..n-1*
- We will define a class called ListCell from which we will build lists.



Class ListCell

```
class ListCell {
   protected Object datum;
   protected ListCell next;

   public ListCell(Object o, ListCell n){
      datum = o;
      next = n;
   }
   public Object getDatum() {//sometimes called car
      return datum;
   }
   public ListCell getNext() {//sometimes called cdr, tail, rest
      return next;
   }
   public void setDatum(Object o) {//sometimes called rplaca
      datum = o;
   }
   public void setNext(ListCell l) {//sometimes called rplacd
      next = l;
   }
}
```



By convention, we will not show the instance methods when drawing cells.

Building a list

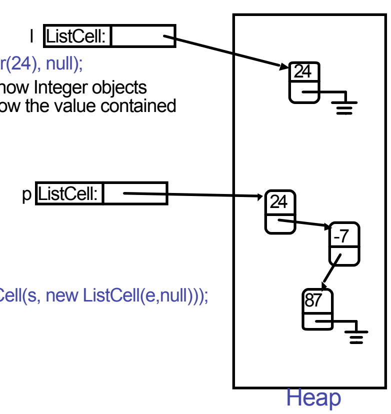
ListCell l = new ListCell(new Integer(24), null);

To keep things simple, we will not show Integer objects explicitly in our pictures, but only show the value contained in them.

Integer t = new Integer(24);
Integer s = new Integer(-7);
Integer e = new Integer(87);

One way:

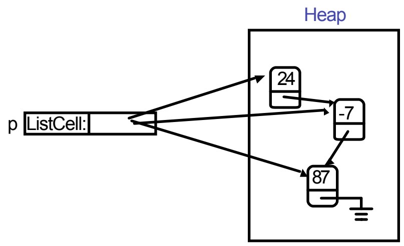
ListCell p = new ListCell(t, new ListCell(s, new ListCell(e,null)));



Building a list (contd.)

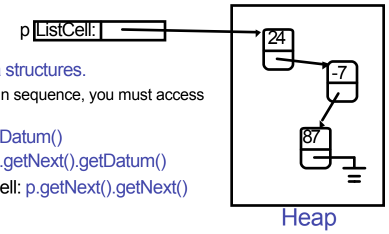
Another way:

```
Integer t = new Integer(24);
Integer s = new Integer(-7);
Integer e = new Integer(87);

ListCell p = new ListCell(e,null);
p = new ListCell(s,p);
p = new ListCell(t,p);
```



Note: assignment of form p = new ListCell(s,p); does not create a circular list.

Accessing list elements



- Lists are sequential-access data structures.
  - to access the contents of cell *n* in sequence, you must access cells *0..n-1*
- Accessing data in first cell: p.getDatum()
- Accessing data in second cell: p.getNext().getDatum()
- Accessing next field in second cell: p.getNext().getNext()

- Writing to fields in cells can be done the same way
  - p.setDatum(new Integer(53));//update data field of first cell
  - p.getNext().setDatum(new Integer(53));//update field of second cell
  - p.getNext().setNext(null);//chop off third cell

Access example: linear search

```
//scan list looking for object o and return true if found
public static boolean search(Object o, ListCell l) {
    for (ListCell current = l; current != null; current = current.getNext())
        if (current.getDatum().equals(o)) return true;
    //drop out of loop if object not found
    return false;
}
…..
ListCell p = new ListCell("hello", new ListCell("dolly", new ListCell("polly", null)));
search(" dolly", p); //returns true
search(" molly", p); //returns false
search(" dolly", null); //returns false
….
//here is another version. Why does this work? Draw stack picture to understand.
public static boolean search(Object o, ListCell l) {
    for (; l != null; l =l.getNext())
        if (l.getDatum().equals(o)) return true;
    //drop out of loop if object not found
    return false;
}
```

Recursion on lists

- Recursion can be done on lists
  - similar to recursion on integers
- Almost always
  - base case: empty list
  - recursive case: assuming you can solve problem on (smaller) list obtained by eliminating first cell, write down solution for list
- Many list problems can be solved very simply by using this idea.
  - Some problems though are easier to solve iteratively.

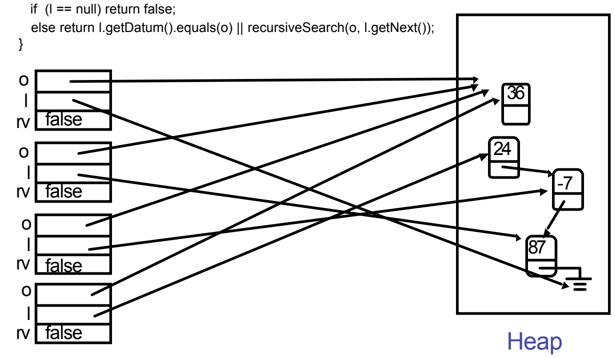
Recursion example: linear search

- Base case: empty list
  - return false
- Recursive case: non-empty list
  - if data in first cell equals object o, return true
  - else return result of doing linear search on rest of list

```
public static boolean recursiveSearch(Object o, ListCell l) {
   if  (l == null) return false;
   else return l.getDatum().equals(o) || recursiveSearch(o, l.getNext());
}
```

Execution of recursive program

```
public static boolean recursiveSearch(Object o, ListCell l) {
   if  (l == null) return false;
   else return l.getDatum().equals(o) || recursiveSearch(o, l.getNext());
}
```



Iteration is sometimes better

- Given a list, create a new list with elements in reverse order from input list.

```
//intuition: think of reversing a pile of coins
public static ListCell reverse(ListCell l) {
   ListCell rev = null ;
   for (  ; l != null; l = l.getNext())
      rev = new ListCell(l.getDatum(), rev);
   return rev;
}
```

- It is not obvious how to write this simply in a recursive divide-and-conquer style.

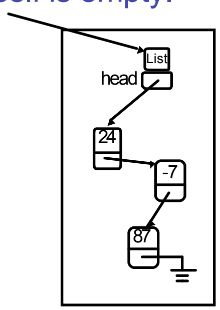
Special Cases to Worry About

- Empty list
  - add
  - find
  - delete?(!)
- Front of list
  - insert
- End of list
  - find
  - delete
- Lists with just one element

List with header

- Some authors prefer to have a List class that is distinct from ListCell class.
- List object is like a head element that always exists even if list itself is empty.

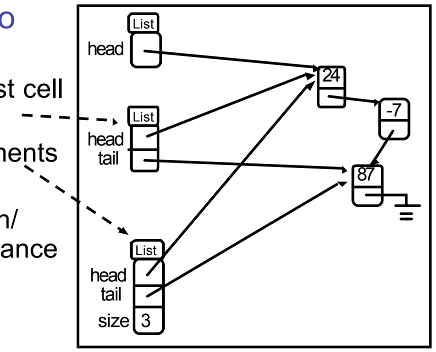
```
class List {
  protected ListCell head;
  public List (ListCell l) {
    head = l;
  }
  public ListCell getHead()
  ……….

   public void setHead(ListCell l)
 ……….
}
```



Heap

Variations of list with header

- Header can also keep other info
  - reference to last cell of list
  - number of elements in list
  - search/insertion/ deletion as instance methods
  - …..



Heap

Example of use of List class

- Let us write code to
  - insert object into unsorted list
  - delete the first occurrence of an object in an unsorted list.
- We will use the List class to show how to use this class.
  - It is just as easy to write code without the header element.
- Methods for insertion/deletion will be instance methods in the List class.
- signatures:

  public void insert(Object o);

  public void delete(Object o);
- invocation:

  p.insert(o);   p.delete(o);

Insertion into list

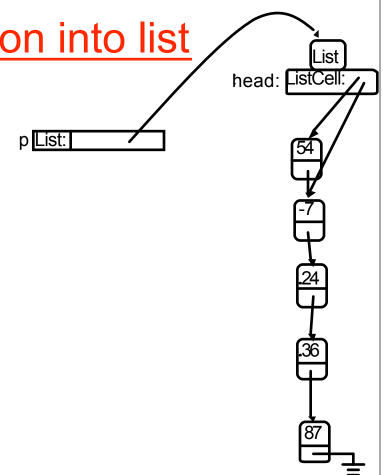
- Let us write two insert methods
  - insert at head of list

```
class List{
  protected ListCell head;
  ……..
  public void insertHead(Object o) {
    head = new ListCell(o,head);
  }
}
```

  - insert at tail of list

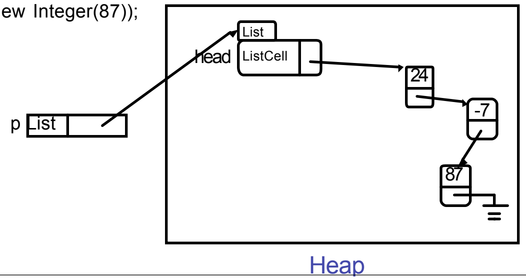
```
……..
public void insertTail(Object o) {
    if (head == null)
        head = new ListCell(o,null);
    else {// find end of list
          ListCell current = head;//cursor into list
          while(current.getNext() != null)
                current = current.getNext();
          current.setNext(new ListCell(o,null));
       }
}
```

- Invocation
  - p.insertHead(new Integer(54));
  - p.insertTail(new Integer(54));



Example of use of insert methods

```
.....
List p = new List(null); //create List object with empty list
p.insertHead(new Integer(-7)); //list now contains -7
p.insertHead(new Integer(24));//list contains 24 and -7
p.insertTail(new Integer(87));
......
```

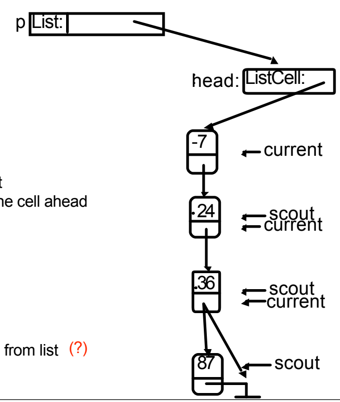


Remove first item from list

```
//extract first element of list
public Object deleteFirst(){
        //if list is not empty
        if (head != null) {
           Object t = head.getDatum();
           head = head.getNext();
           return t;
           }
        //otherwise, attempt to get from empty list
        else return "error";
}
```

Remove last item on list

```
//extract last element of list
public Object deleteLast(){
        if (head == null) return "error";
        //only one element in list?
        if (head.getNext() == null) {
                Object t = head.getDatum();
                head = null;
                return t;
        }
        //at least two elements in list
        //current and scout are cursors into list
        //both advance in lock step, scout is one cell ahead
        //stop if scout points to last cell
        ListCell current = head;
        ListCell scout = head.getNext();
        while (scout.getNext() != null){
                current = scout;
                scout = scout.getNext();
        }
        current.setNext(null);//remove last cell from list  (?)
        return scout.getDatum();
}
```



Delete object from list

- Delete first occurrence of object o from list l
- Recursive delete
- Iterative delete

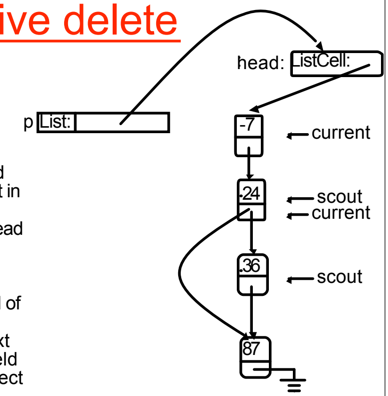
- Intuitive idea of recursive code:
  – If list l is empty, return null.
  – If first element of l is o, return rest of list l.
  – Otherwise, return list consisting of first element of l, and list that results from deleting o from rest of list l.

Recursive code for delete

```
class List{
   protected ListCell head;
   .......
  public void delete(Object o) {
     head = deleteRecursive(o, head);
  }
  public static ListCell deleteRecursive(Object o, ListCell l) {
    //if list is empty, nothing to do
    if (l == null) return null;
    //otherwise check first element of list
     else if (l.getDatum().equals(o))
           return l.getNext();
    //otherwise delete o from rest of list and update next field of l
     else  {l.setNext(deleteRecursive(o, l.getNext()));
              return l;
           }
  }
}
```

Iterative delete

- Two steps:
  - locate cell that is the predecessor of cell to be deleted
    - keep two cursors, scout and current, that traverse the list in lock step
    - scout is always one cell ahead of current
    - current starts at head of list
    - stop when scout finds cell containing o, or falls off end of list
  - if scout finds cell, update next field of current cell to next field of scout cell to splice out object o from list



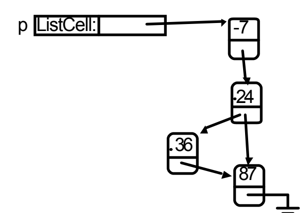
delete 36 from list

Iterative code for delete

```
public void delete(Object o) {
  //empty list?
  if (head == null) return;
  //is first element equal to o; if so splice first cell out
  if (head.getDatum().equals(o)) {
    head = head.getNext();
    return;
    }
  //walk down list; at end of loop,
  //scout will be point to first cell containing o, if any
  ListCell current = head;
  ListCell scout = head.getNext();
  while ((scout != null) && ! scout.getDatum().equals(o)) {
      current = scout;
      scout = scout.getNext();
  }
  if (scout != null) //found occurrence of o
     current.setNext(scout.getNext()); //splice out cell containing o
}
```

Insertion and deletion into sorted lists

- Assume that we have a list of Comparables sorted in increasing order.
- We want to splice a new Comparable into this list, keeping new list in sorted order as shown in figure.
- Code shows recursive code for insertion and deletion.
- We will show code that uses ListCell class directly.



Recursive insertion

Let us use notation [f,n] to denote ListCell whose
- datum is f
- next is n

Pseudo-code:

```
insert (Comparable c, ListCell l):
    if l is null return new ListCell(c,null);
    else
      suppose l is [f,n]
      if (c < f) return new ListCell(c,l);
      else return new ListCell(f, insert(c,n));
```

Compactly:

```
insert(c,null) = [c,null]
insert(c,[f,n]) = [c,[f,n]]          if c < f
                  [f, insert(c,n)]   if c >= f
```

```
//recursive insert and delete into a list sorted in increasing order

public static ListCell insertRecursive(Comparable c, ListCell l) {
      if ((l == null) || (c.compareTo(l.getDatum()) < 0))
          return new ListCell(c, l);
      else {l.setNext(insertRecursive(c,l.getNext()));
           return l;
          }
}

public static ListCell deleteRecursive(Comparable c, ListCell l) {
    if ((l == null) || (c.compareTo(l.getDatum()) < 0))
       return l;
    if  (c.compareTo(l.getDatum()) == 0)
        return l.getNext();//assume no duplicates
    else {l.setNext(deleteRecursive(c,l.getNext()));
          return l;
         }
}
```

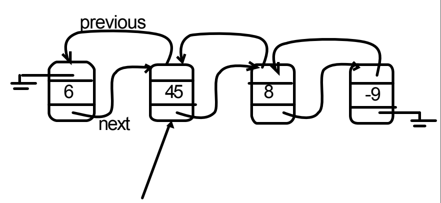
- Will insertRecursive allow us to insert duplicates?
- Suppose we want to delete duplicates as well?

```
//iterative insert, delete is similar
public static ListCell insertIter(Comparable c, ListCell l) {
   //locate cell that must point to new cell containing c
   //after insertion is done
   ListCell before = scan(c,l);
   if (before == null) return new ListCell(c,l);
   before.setNext(new ListCell(c,before.getNext()));
   return l;
}
protected static ListCell scan(Comparable c, ListCell l){
   ListCell before = null; //Cursor “before” is one cell behind cursor “l”
   for (; l != null; l = l.getNext()) {
       if (c.compareTo(l.getDatum()) < 0)  return before;
       else before = l;
   }
   //if we reach here, o is not in list
   return null;
}
```

Doubly-linked lists

- In some applications, it is convenient to have a ListCell that has references to both its predecessor and its successor in the list.

```
class DLLCell {
   protected Object datum;
   protected DLLCell next;
   protected DLLCell previous;
   …..
}
```



- In general, it is easier to work with doubly-linked lists than with lists.
- For example, reversing a DLL can be done simply by swapping the previous and next fields of each cell.
- Trade-off: DLLs require more heap space than singly-linked lists.

Fancy Lists

- 2-D lists:
  - references to cells left, right, up, down
- 3-D lists, …
- Rings, pipes, torus lists
- Lists of Lists (Nested lists)
  - ((This is a sentence.)
(This is a sentence, too.)
(This is another sentence.)
…)

Summary

- Lists are sequences of ListCell elements
  - recursive data structure
  - grow and shrink on demand
  - not random-access but sequential access data structures
- List operations:
  - create a list
  - access a list and update data
  - change structure of list by inserting/deleting cells
    - cursors
- Recursion makes perfect sense on lists. Usually
  - base case: empty list
  - recursive case: non-empty list
- Sub-species of lists
  - list with header
  - doubly-linked lists