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Linked List - Data Structures

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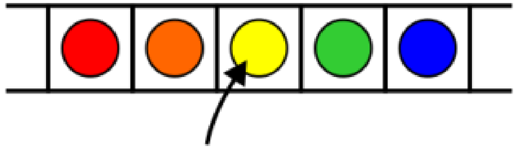
List

- Properties
  - Ordered list of items…precedes, succeeds; first, last
  - Index for each item…lookup or address item by index value
  - Finite Length for the list…can be empty, size can vary
  - Items of same type present in the list
- Operations
  - Create, destroy
  - Lookup by index, item value
  - Find size, if empty
  - Add, delete item

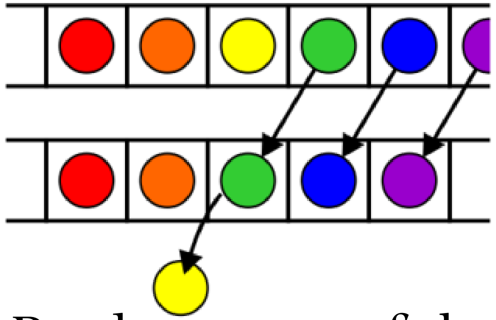
List Operations

- Operations at the kth entry of the list include:

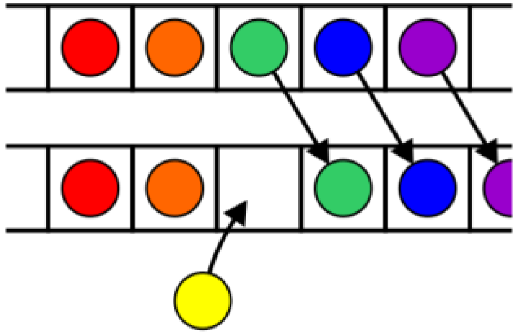
- Access to the object



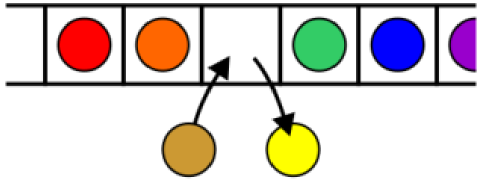
Erasing an object



- Insertion of a new object

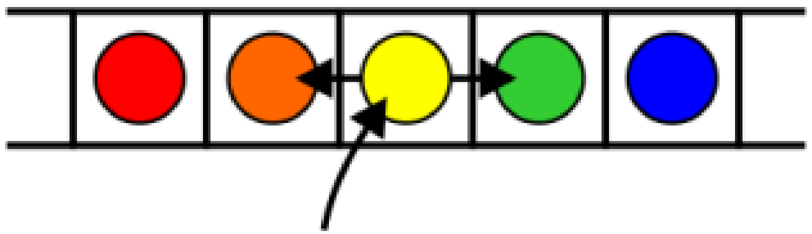


Replacement of the object



List Operations

- Given access to the kth object, gain access to either the previous or next object



- Given two abstract lists, we may want to
  - Concatenate the two lists
  - Determine if one is a sub-list of the other

Array List

Array List Operations

- List operations
  - Create/Destroy
  - Length
  - Find
  - Insert/Remove
  - Next/Previous
- List properties
  - A_i precedes A_{i+1} for $1 \leq i < n$
  - A_i succeeds A_{i-1} for $1 < i \leq n$
  - Size 0 list is defined to be the **empty list** **( )**

$$(A_1 \; A_2 \; \ldots \; A_{n-1} \; A_n)$$

`length = n`

Array List Operations

- First, create an array list.
- Then, we are able to perform: insert into, access, and erase from the values stored in the array list

Operations on an arbitrary node of the array list,

- Find the number of instances of an integer in the array list:

  int count(int) const;

- Remove all instances of an integer from the array list:

  int erase(int);

Array List Operations - Mapping Function

- Say n is the capacity of the array
- Simple mapping
  - E.g. using array for queues: add from front, remove from back.
  - get(index) = value of data at index
- Reverse mapping
  - E.g. using same array for reverse list.
  - get(index) = value of data at (n - index – 1)
- Hash-Mapping
  - get(index) = value of data at (position(0)+index) % n
  - get(0) = value of data at head

Array List Operations

- void create(initCapacity) or create(size)
  - Create array with initial capacity (optional hint)
- void set(index, item)
  - Use mapping function to set value at position
- void append(item)
  - Insert after current "last" item…use size
- void remove(index) or int erase(int)
  - Remove item at index or Erase item at index and return its data (value as integer)

Array List Operations

- item get(index)
  - Use mapping function to set value at position
  - Student is class with methods getName, get RollNumber and "student" is its object
  - e.g., student.getName(15), student.getRollNumber(15)
- int indexOf(item)
  - Get "first" index of item with given value
  - String student.getRollNumber(15)
- To analyse or check the entire list:
  - Is the linked list empty?

    boolean isEmpty() or bool empty();
  - How many objects are in the list? Counts the number of instances in the list,

    int capacity() or int size()
  - The list is empty when the list_head pointer is set to nullptr

Array List Operations

Increasing capacity

- Start with initial capacity given by user, or default
- When capacity is reached
  - Create array with more capacity, e.g. double it
  - Copy values from old to new array
  - Delete old array space
- Can also be used to shrink space
  - Example: Sparse Matrices

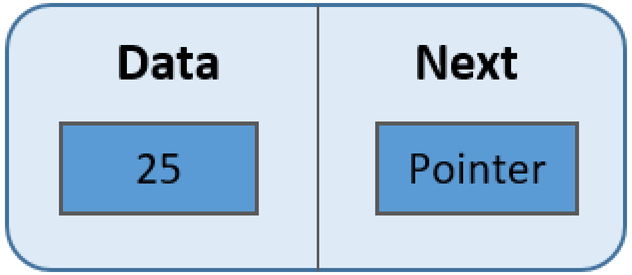
Array List Operations

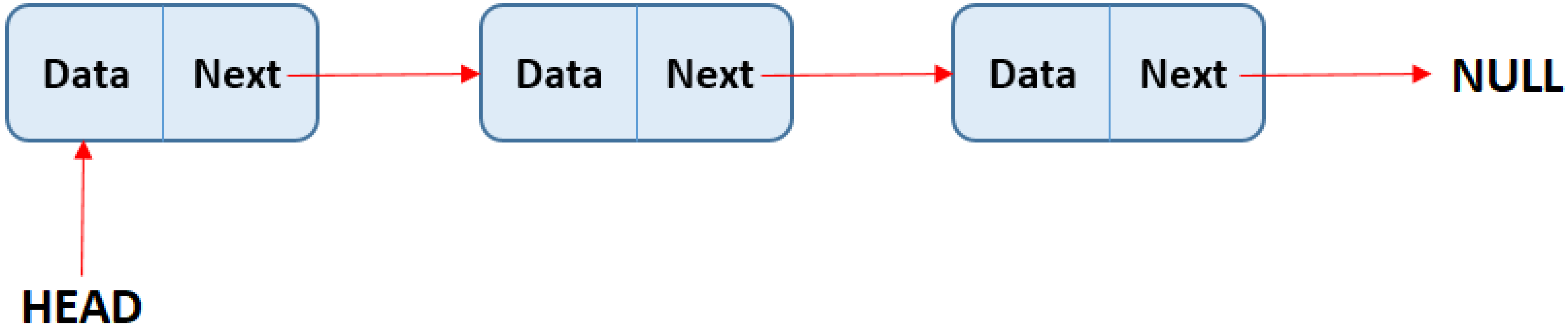
- Pros and Cons of using Arrays.
- Complexity
  - Storage Complexity: Amount of storage required by the data structure, relative to items stored
  - Computational Complexity: Number of CPU cycles required to perform each data structure operation
  - size(), set(), get(), indexOf()

Linked List

Linked List - Definitions and Terminologies

- A linked list is a sequence of data structures, which are connected together via links.
- Linked list is a sequence of links which contains items.
- Each link contains a connection to another link.
- Important terms to understand the concept of linked list.
  - Data − Each link of a linked list can store a data called an element
  - Next − Each link of a linked list contains a link to the next link called Next
  - List − A list contains the connection link to the first link called Head
- It can be visualized as a chain of nodes, where every node points to the next node.





Linked List - Definitions and Terminologies

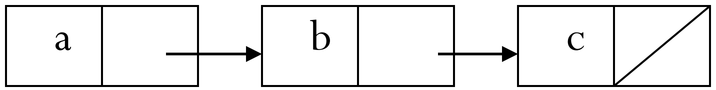
- A linked list is a data structure where each object is stored in a node
- As well as storing data, the node must also contains a reference/pointer to the node containing the next item of data.
- We must dynamically create the nodes in a linked list
- Thus, because new returns a pointer, the logical manner in which to track a linked lists is through a pointer
- A Node class must store the data and a reference to the next node (also a pointer)

Linked List in C

One or more of its components is a pointer to itself.

```
typedef  struct list {
            char data;
            list *link;
            }

list item1, item2, item3;
item1.data='a';
item2.data='b';
item3.data='c';
item1.link=item2.link=item3.link=NULL;
```

Construct a list with three nodes
item1.link=&item2;
item2.link=&item3;
malloc: obtain a node



Linked List in C

```
struct node {
        int data;
        struct node *next;
    };
```

- Linked list contains a link element called Head
- Each link carries a data field(s) and a link field called next
- Each link is linked with its next link using its next link
- Last link carries a link as null to mark the end of the list

Linked List Representation

- Problem with array:
  - Pre-defined capacity, under usage, cost to move items when full
- Solution:
  - Grow backing data structure dynamically when we add or remove node
    - Only use as much memory as required
- Linked lists use pointers to contiguous chain items
  - Node structure contains item and pointer to next node in List
- Add or remove nodes when setting or getting items

Linked List Operations

- First, create a linked list.
- Then, we are able to perform: insert into, access, and erase from the values stored in the linked list
- Operations on the first node of the linked list
- Adding, retrieving, or removing the value at the front of the linked list

```
void push_front( int );
int front() const;
void pop_front();
```

- To access the head of the linked list

```
Node *begin() const;
```

Node Class in C++

The node must store data and a pointer:

```
class Node {
        public: Node( int = 0, Node * = nullptr );

        int value() const;
        Node *next() const;

        private:
                int node_value;
                Node *next_node;
        };
```

Node Constructor in C++

```
class Node {
    public: Node( int = 0, Node * = nullptr );
    int value() const;
    Node *next() const;
    private:
        int node_value;
        Node *next_node;
};
```

The constructor assigns the two member variables based on the arguments

```
List::Node::Node( int e, Node *n ):
node_value( e )
next_node( n ) {// empty constructor}
```

The default values are given in the class definition:

Linked List Iterators in C++

General method of examining collections

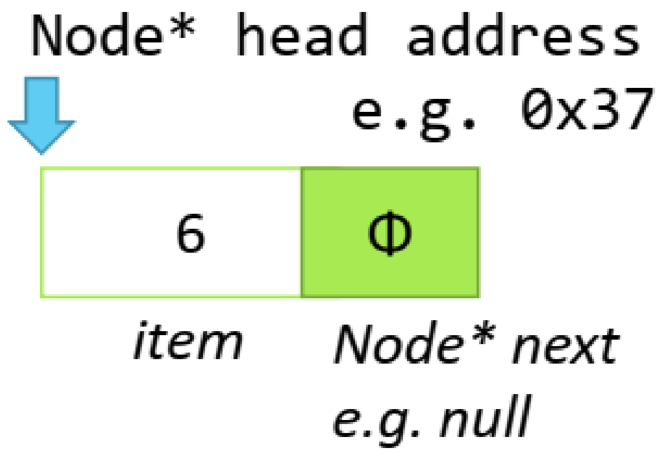
```
List<Object> *list;
Object x;
…
ListItr<Object> *i = list->first();
while ( i->hasNext() ) {
        x = i->next();
}
```

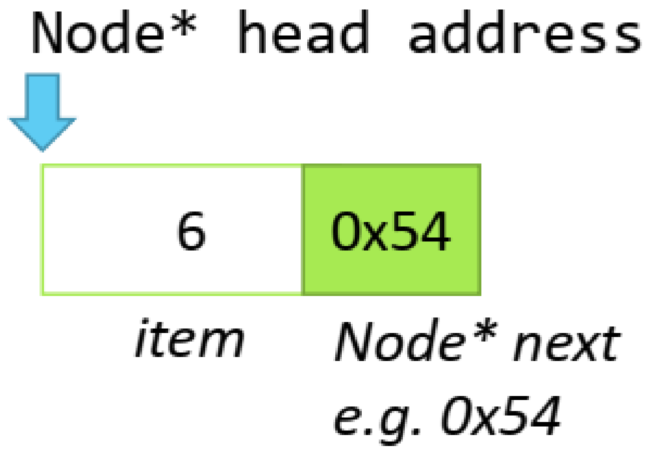
Linked List Operations

- Iteration operations:
  - ListItr<Object> first()
  - ListItr<Object> kth(int)
  - ListItr<Object> last()
- Main operations:
  - ListItr<Object> find(Object)
  - void insert(Object, listItr<Object>)
  - void remove(ListItr<Object>)
  - bool isEmpty()

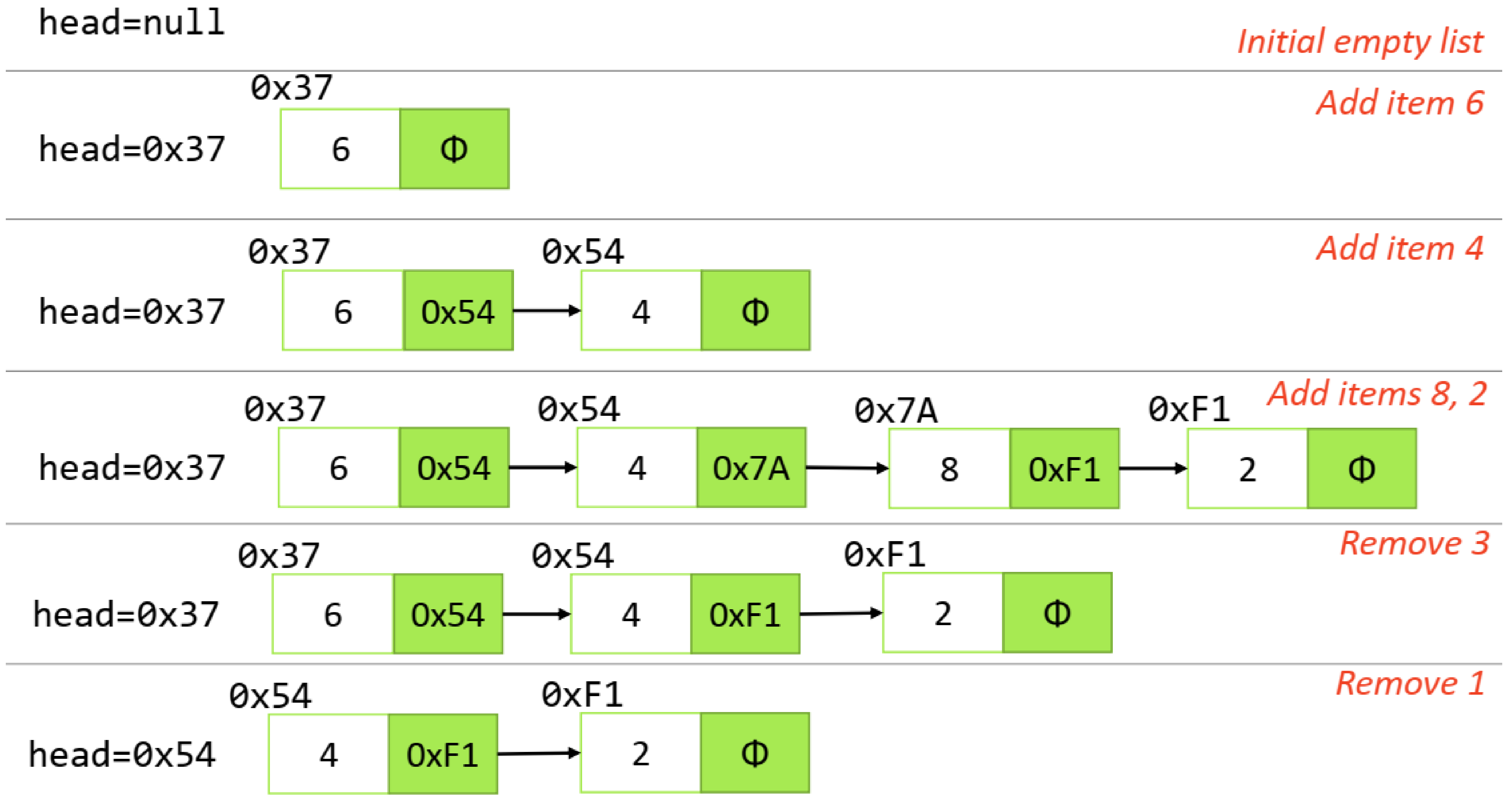
Linked List Operations in OOP (C++ or Java)

```
class LinkedList {
    Node* head;

    class Node* {
        int item
        Node* next
    }

    int size() {…}
    append() {…}
    get() {…}
    set() {…}
    remove {…}
}
```



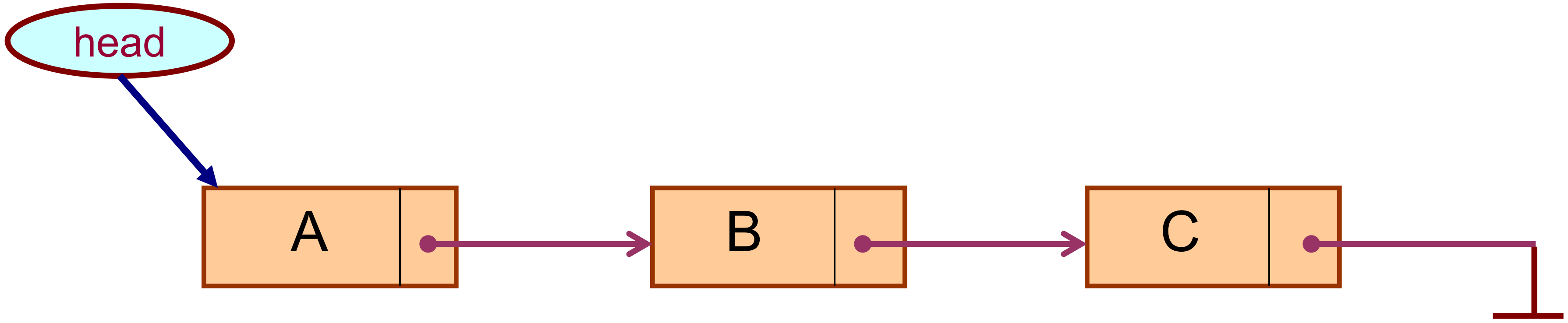


Linked List Operations



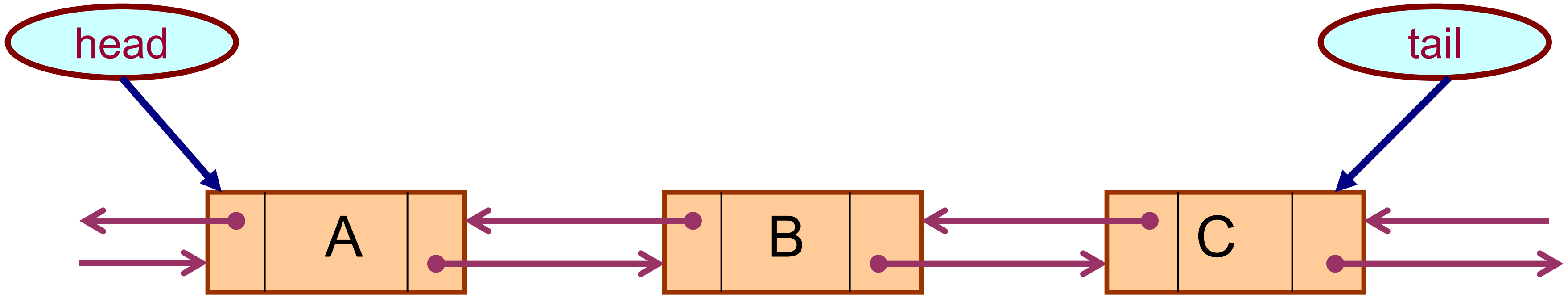
Types of Linked lists

- Depending on the way in which the links are used to maintain adjacency, several different types of linked lists are possible.
- Linear singly-linked list (or simply linear list)
  - One we have discussed so far.



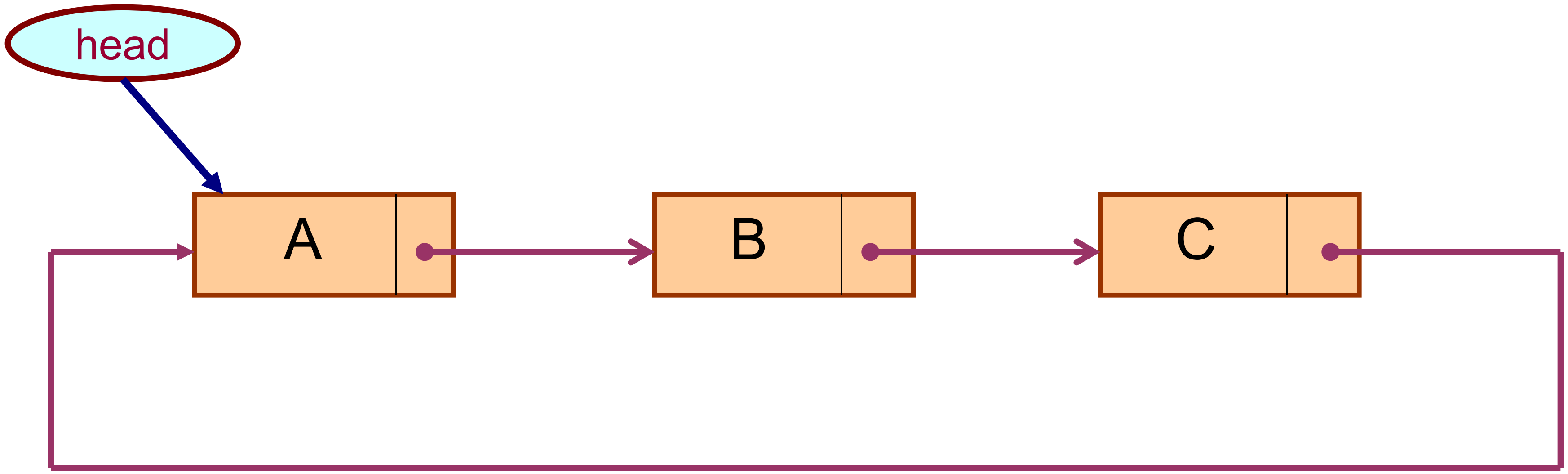
Types of Linked lists

- Doubly linked list
  - Pointers exist between adjacent nodes in both directions.
  - The list can be traversed either forward or backward.
  - Usually two pointers are maintained to keep track of the list, *head* and *tail*.



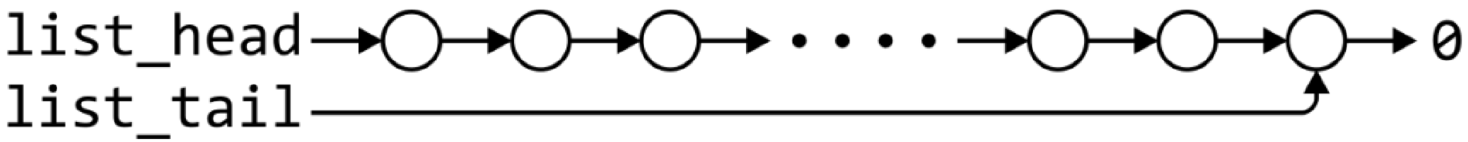
Types of Linked lists

- Circular linked list
  - The pointer from the last element in the list points back to the first element.

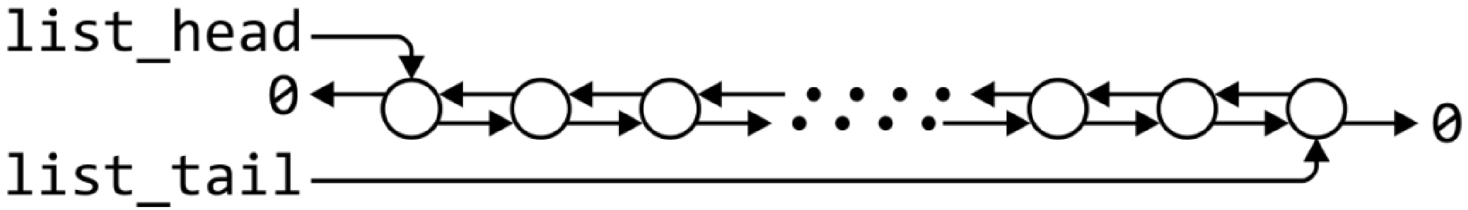


Types of Linked lists

- We will consider these for
  - Singly linked lists

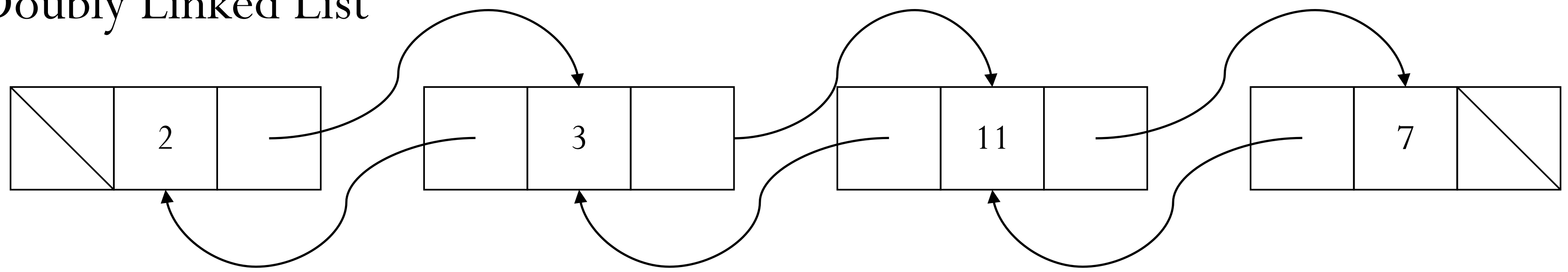


  - Doubly linked lists

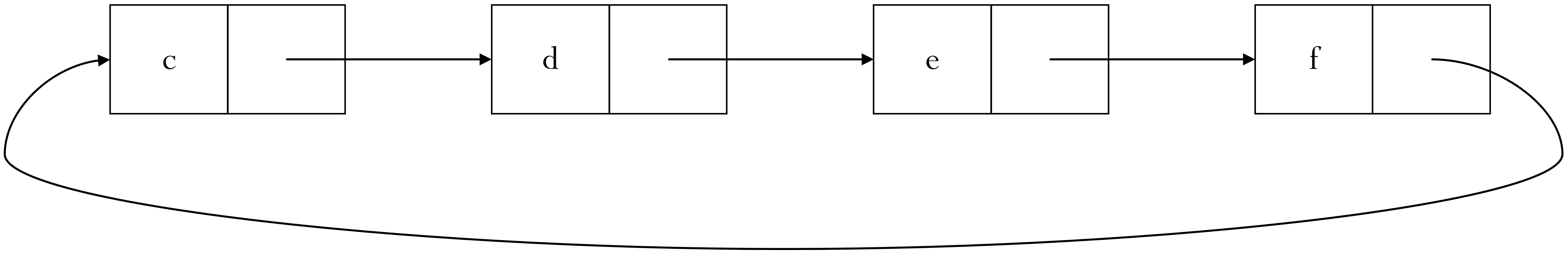


Types of Linked lists

- Doubly Linked List



- Circular List



Advantage of Linked List

- An Abstract List (or List ADT) is linearly ordered data where the programmer explicitly defines the ordering
- Most common operations and implementation uses either an Array or Linked list
- Arrays can be used to store linear data of similar types, with following limitations.
  - The size of the arrays is fixed
  - Inserting a new element in an array of elements is expensive
- Advantages over arrays
  - Dynamic size
  - Ease of insertion/deletion
- Drawbacks of linked list
  - Random access is not allowed. We cannot do binary search with linked lists.
  - Extra memory space for a pointer is required with each element of the list.

Dynamic Memory Management

Memory Allocation

The constructor is called whenever an object is created, either:

Static allocation,

```
List ls;
```

defines ls to be a linked list and the compiler deals with memory allocation

Dynamic allocation

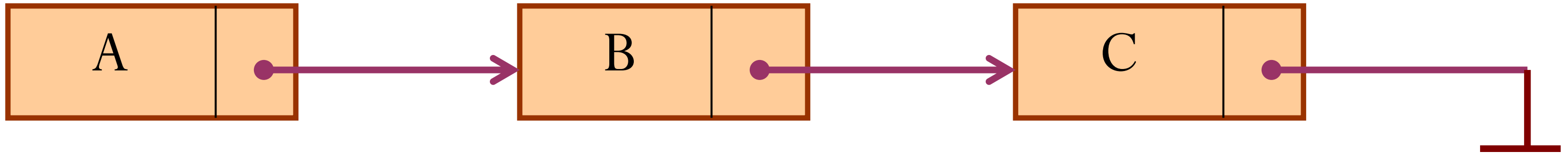
```
List *pls = new List();
```

requests sufficient memory from the OS to store an instance of the class

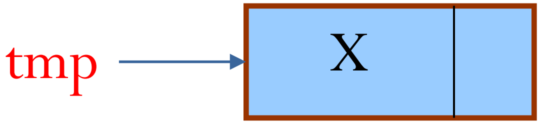
In both cases, the memory is allocated and then the constructor is called

Pseudo-code for insertion

```
typedef struct nd {
   struct item data;
   struct nd * next;
   } node;
```

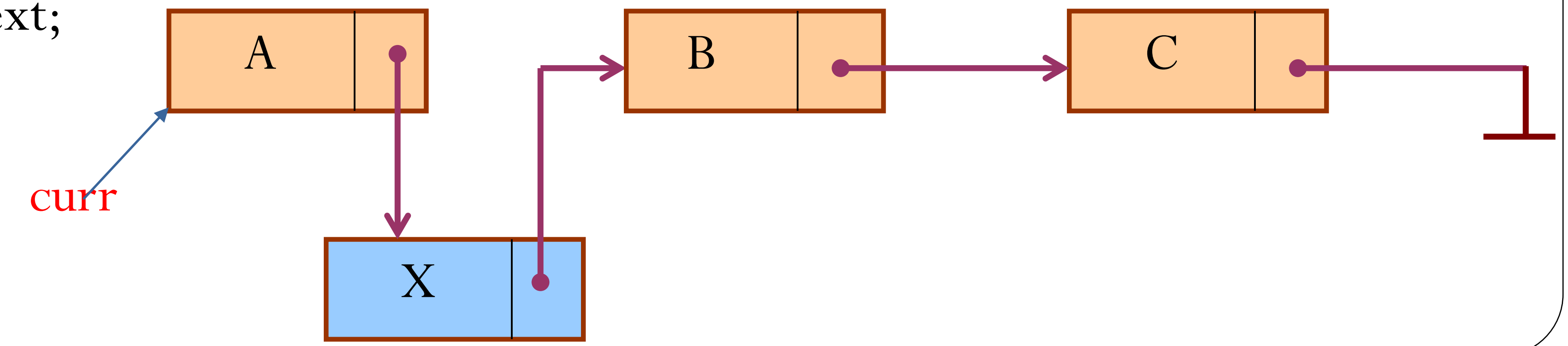



```
void insert(node *curr)
{
node * tmp;
```



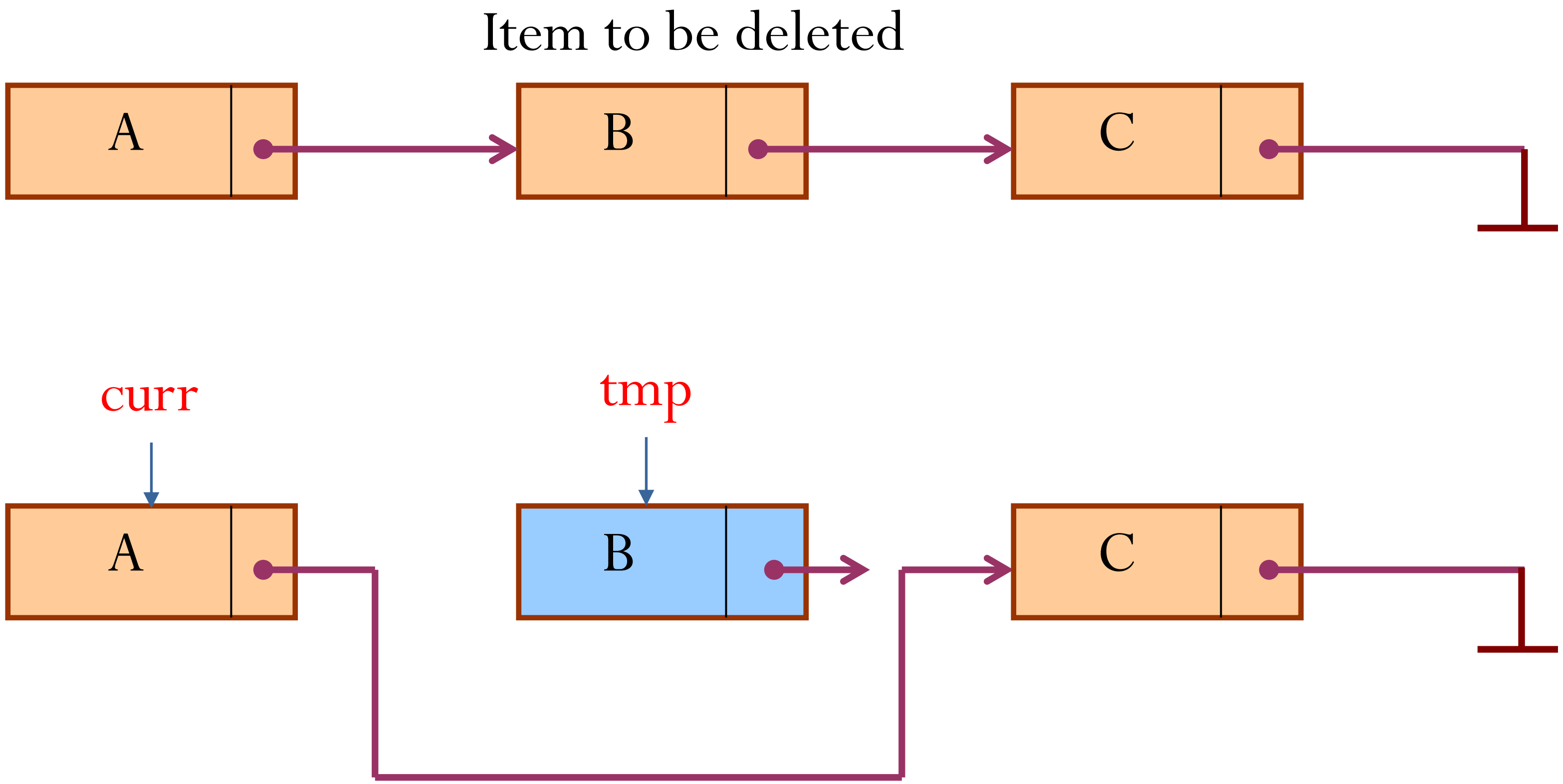
Item to be inserted

```
tmp=(node *) malloc(sizeof(node));
tmp->next=curr->next;
curr->next=tmp;
}
```



Pseudo-code for deletion

```
typedef struct nd {
   struct item data;
   struct nd * next;
   } node;

void delete(node *curr)
{
node * tmp;
tmp=curr->next;
curr->next=tmp->next;
free(tmp);
}
```



Pseudo-code

- For insertion:
  - A record is created holding the new item.
  - The next pointer of the new record is set to link it to the item which is to follow it in the list.
  - The next pointer of the item which is to precede it must be modified to point to the new item.
- For deletion:
  - The next pointer of the item immediately preceding the one to be deleted is altered, and made to point to the item following the deleted item.

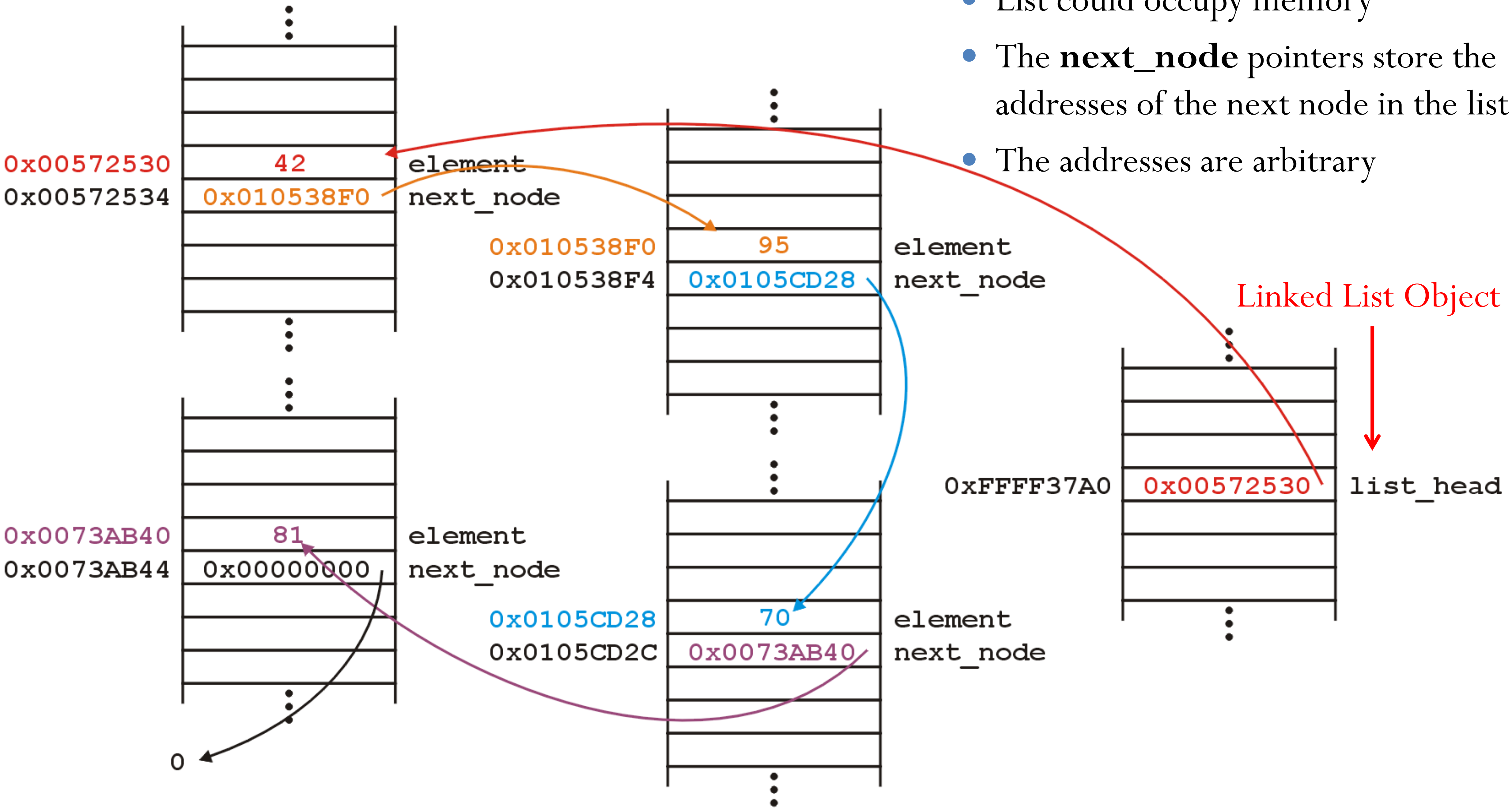
Dynamic Storage: Memory Management

A linked list uses linked allocation, and therefore each node may appear anywhere in memory

Assuming a 32-bit machine

Memory required for each node equals the memory required by the member variables

- 4 bytes for the linked list (a pointer)
- 8 bytes for each node (an **int** and a pointer)



- List could occupy memory
- The **next_node** pointers store the addresses of the next node in the list
- The addresses are arbitrary

Dynamic Storage: Memory Management

- Clean representation as follows:

- We do not specify the addresses because they are arbitrary and:
  - The contents of the circle is the value
  - The next_node pointer is represented by an arrow

Applications of Linked List

Ordered List Examples

- MONDAY, TUEDSAY, WEDNESDAY, THURSDAY, FRIDAY, SATURDAY, SUNDAY
- 2, 3, 4, 5, 6, 7, 8, 9, 10, Jack, Queen, King, Ace
- 1941, 1942, 1943, 1944, 1945
- a1, a2, a3, …, an-1, an
- ordered (linear) list: (item1, item2, item3, …, item*n*)

Applications

- Everything!
  - Class list
  - compilers: list of functions in a program, statements in a function
  - graphics: list of triangles to be drawn to the screen
  - operating systems: list of programs running
  - music: compose crazy hard transcendental études
  - other data structures: queues, stacks!

Application: Polynomial ADT

A_i is the coefficient of the x^{n-i} term:

$3x^2 + 2x + 5$	**(3 2 5)**
$8x + 7$	**(8 7)**
$x^2 + 3$	**(1 0 3)**

Problem?

$x^{2001} + 1$

(1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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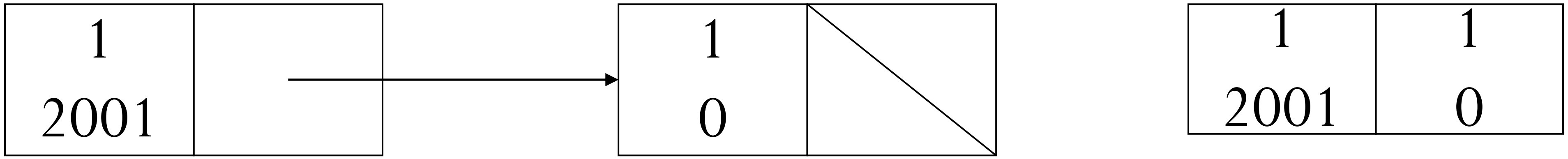
Sparse List Data Structure (?): $x^{2001} + 1$

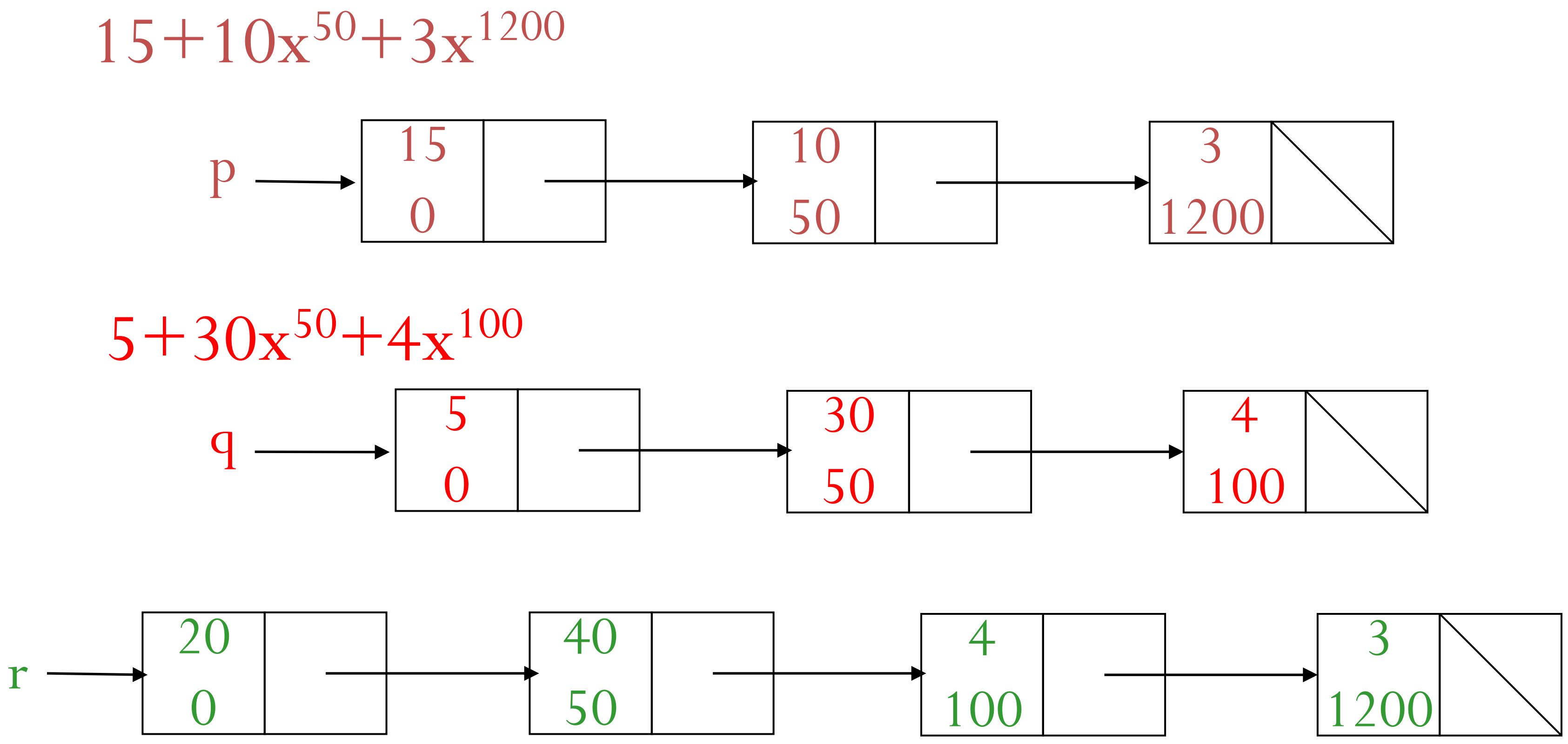
(<1 2001> <1 0>)

Linked List vs. Array



Addition of Two Polynomials

- Similar to merging two sorted lists



Multiple Linked Lists

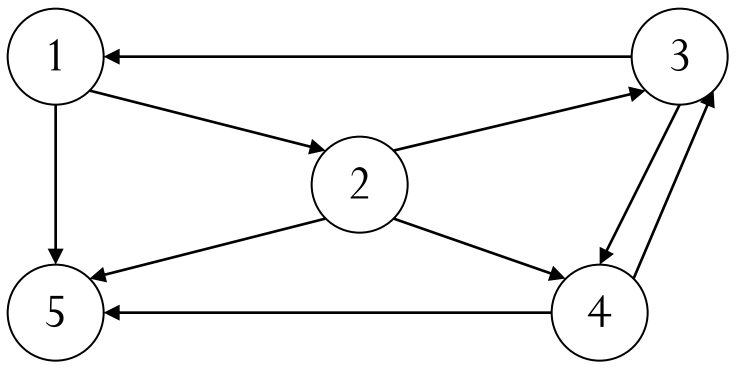
- Many ADTS such as graphs, relations, sparse matrices, multivariate polynomials use multiple linked lists

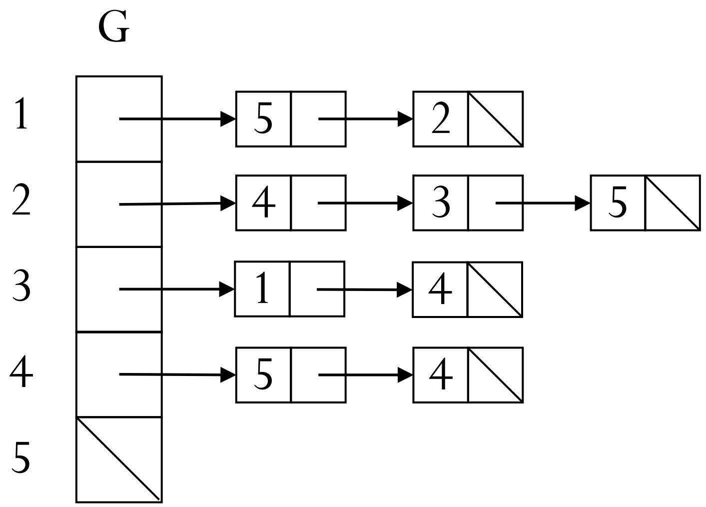
- Several options
  - array of lists
  - lists of lists
  - multi lists

- General principle: use one ADT to implement a more complicated one.

Array of Linked Lists: Adjacency List for Graphs

- Array G of unordered linked lists
- Each list entry corresponds to an edge in the graph





Reachability by Marking

- Suppose we want to mark all the nodes in the graph which are reachable from a given node **k**.
  - Let **G[1..n]** be the adjacency list rep. of the graph
  - Let **M[1..n]** be the mark array, initially all **false**s.

```
mark(int i){
 M[i] = true;
 x = G[i]
 while (x != NULL) {
  if (M[x->node] == false)
   mark(G[x->node])
  x = x->next
 }
}
```

Thoughts on Reachability

- The marking algorithm visits each node and each edge at most once.

- This marking algorithm uses Depth First Search. DFS uses a stack to track nodes. Where?

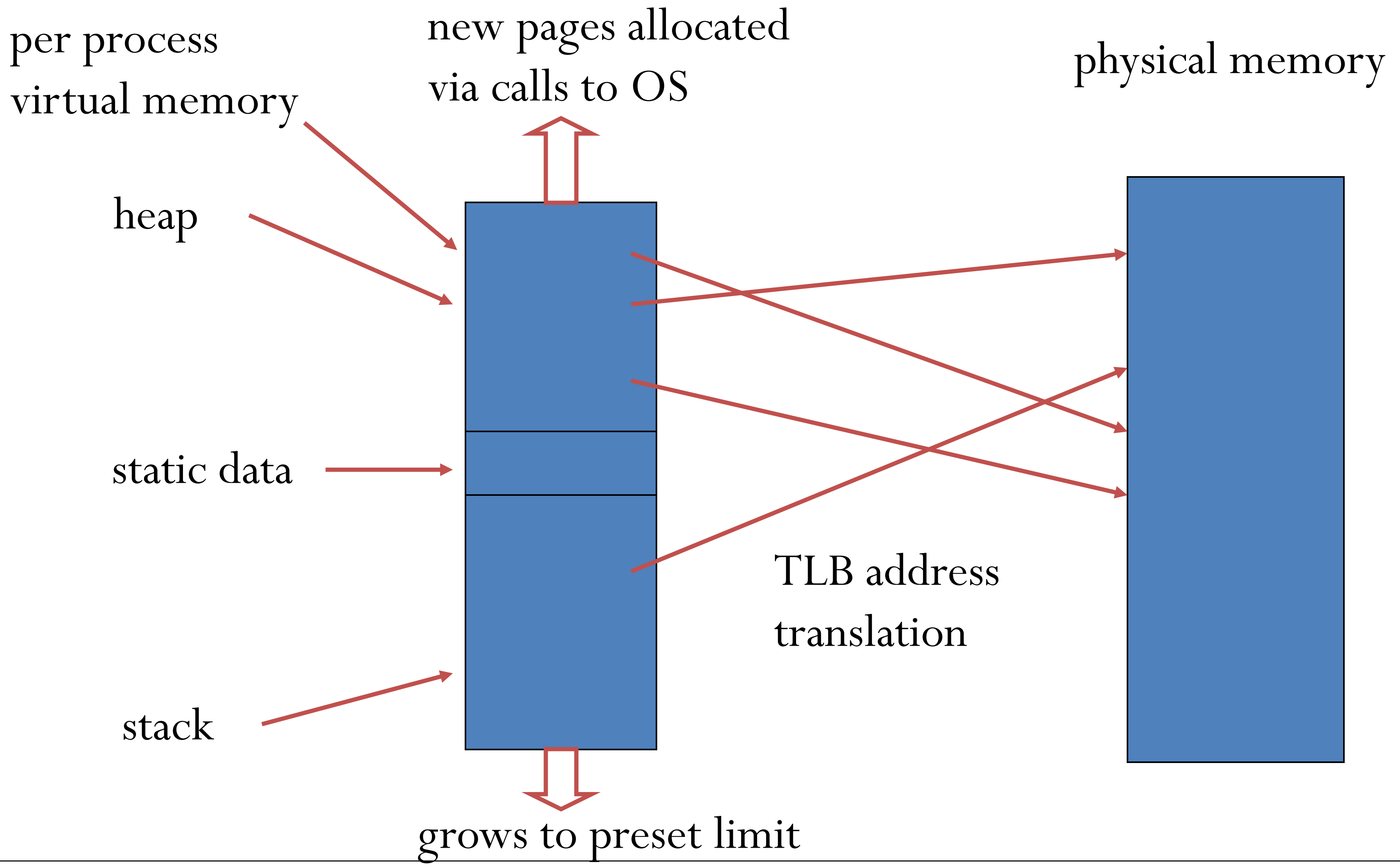
- Graph reachability is closely related to garbage collection
  - the nodes are blocks of memory
  - marking starts at all global and active local variables
  - the marked blocks are reachable from a variable
  - unmarked blocks are garbage

Garbage Collection

Garbage Collection

- Every modern programming language allows programmers to allocate new storage dynamically
  - New records, arrays, tuples, objects, closures, etc.
- Every modern language needs facilities for reclaiming and recycling the storage used by programs
- It's usually the most complex aspect of the run-time system for any modern language (Java, ML, Lisp, Scheme, Modula, …)

Memory layout



Garbage Collection

- What is garbage?
  - A value is garbage if it will not be used in any subsequent computation by the program

- Is it easy to determine which objects are garbage?
  - No. It's undecidable. Eg:

    if long-and-tricky-computation then use v

    else don't use v

Garbage Collection

- Since determining which objects are garbage is tricky, people have come up with many different techniques
  - It’s the programmers problem:
    - Explicit allocation/deallocation
  - Reference counting
  - Tracing garbage collection
    - Mark-sweep, copying collection
    - Generational Garbage Collection

Explicit Memory Management

- User library manages memory; programmer decides when and where to allocate and deallocate
  - void* malloc(long n)
  - void free(void *addr)
  - Library calls OS for more pages when necessary
  - Advantage: people are smart
  - Disadvantage: people are dumb and they really don't want to bother with such details if they can avoid it

Explicit Memory Management

- How does malloc/free work?
  - Blocks of unused memory stored on a freelist
  - malloc: search free list for usable memory block
  - free: put block onto the head of the freelist
- Drawbacks
  - malloc is not free: we might have to do a significant search to find a big enough block
  - As program runs, the heap fragments leaving many small, unusable pieces

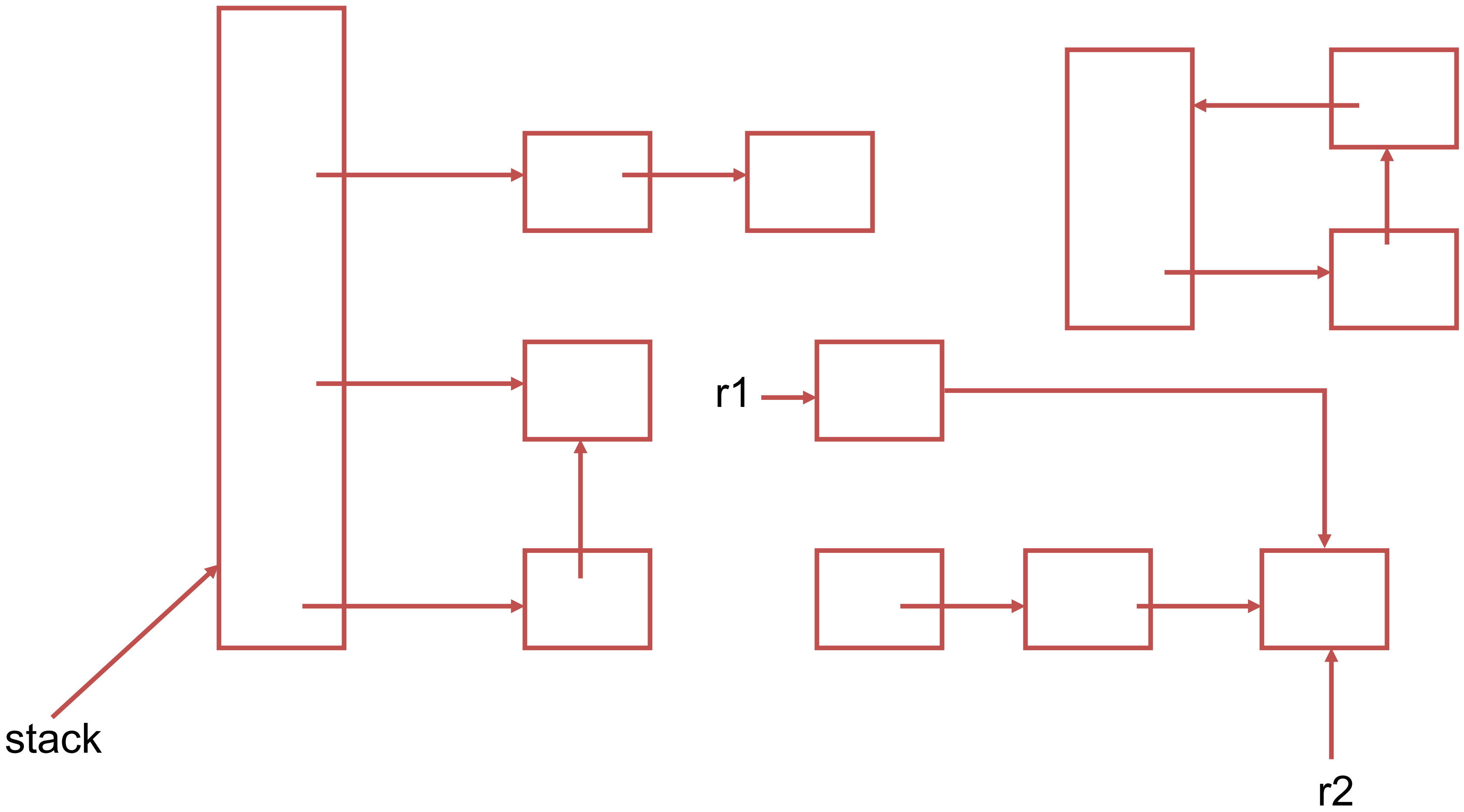
Automatic Memory Management (MM)

- Languages with Explicit MM are much harder to program than languages with Automatic MM
  - Always worrying about dangling pointers, memory leaks: a huge software engineering burden
  - Impossible to develop a secure system, impossible to use these languages in emerging applications involving mobile code
  - Soon, languages with unsafe, Explicit MM will all but disappear

Automatic Memory Management

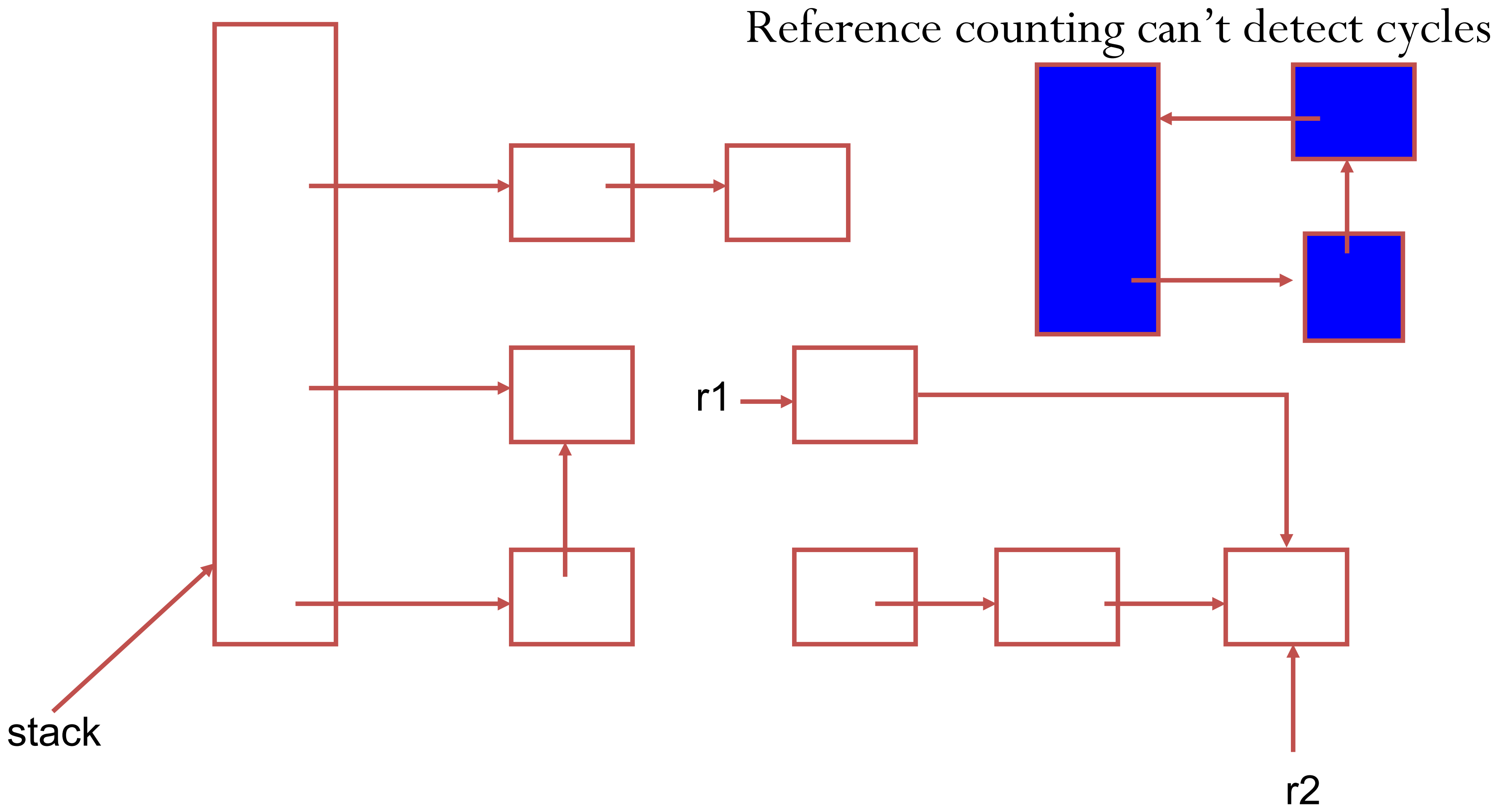
- Question: how do we decide which objects are garbage?
  - We conservatively approximate
  - Normal solution: an object is garbage when it becomes unreachable from the roots
    - The roots = registers, stack, global static data
    - If there is no path from the roots to an object, it cannot be used later in the computation so we can safely recycle its memory

Object Graph



- How should we test reachability?

Object Graph



- Keep track of the number of pointers to each object (the reference count).
- When the reference count goes to 0, the object is unreachable garbage

Copying Collection

- Basic idea: use 2 heaps
  - One used by program
  - The other unused until GC time
- Garbage Collection:
  - Start at the roots & traverse the reachable data
  - Copy reachable data from the active heap (from-space) to the other heap (to-space)
  - Dead objects are left behind in from space
  - Heaps switch roles

Student Linked List

Student Linked List

- Consider the structure of a node as follows:

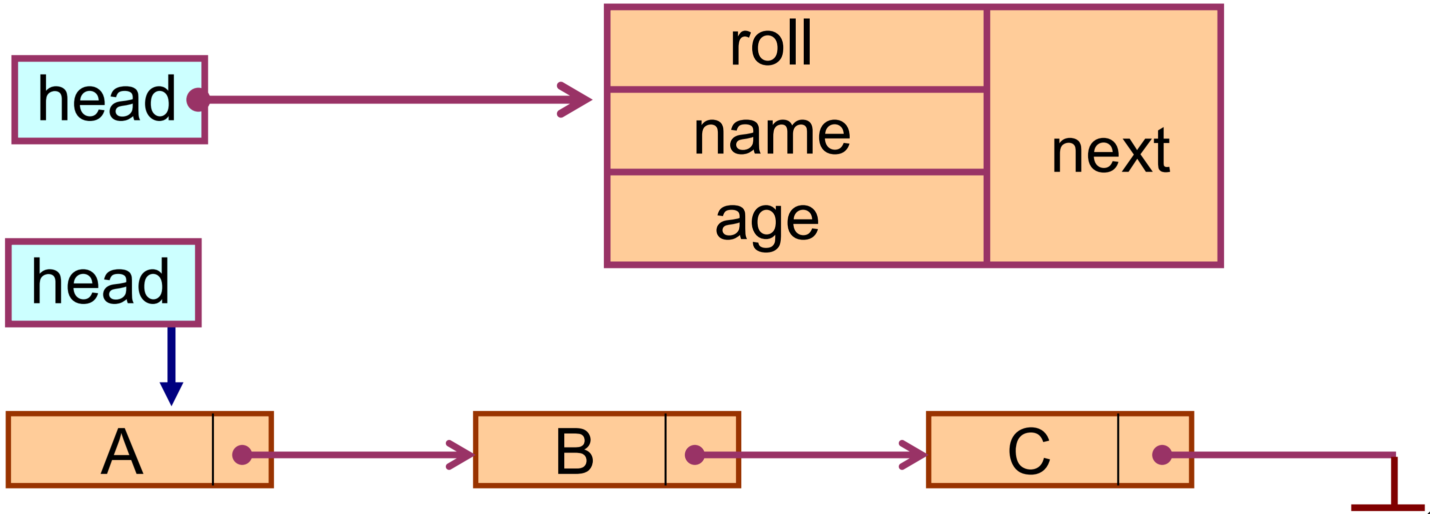
```
struct stud {
              int   roll;
              char  name[25];
              int   age;
              struct stud *next;
            };

  /* A user-defined data type called "node" */

typedef struct stud node;
node *head;
```

Student Linked List

- To start with, we have to create a node (the first node), and make `head` point to it

```
head = (node *) malloc(sizeof(node));
```

- If there are n number of nodes in the initial linked list:
  - Allocate n records, one by one.
  - Read in the fields of the records.
  - Modify the links of the records so that the chain is formed.



Create the Student Linked List

```
node *create_list()
{
    int  k, n;
    node  *p, *head;

    printf  ("\n How many elements to enter?");
    scanf ("%d", &n);

    for  (k=0; k<n; k++)
    {  if (k == 0) {
          head = (node *) malloc(sizeof(node));
          p = head;
       }
       else {
            p->next  = (node *) malloc(sizeof(node));
            p = p->next;
          }
       scanf ("%d %s %d", &p->roll, p->name, &p->age);
    }

    p->next  =  NULL;
    return (head);
}
```

To be called from `main()` function as:

```
node *head;
.........
head = create_list();
```

Traverse the Student Linked List

```
void display (node *head)
{
  int  count = 1;
  node  *p;

  p = head;
  while (p != NULL)
  { printf ("\nNode %d: %d %s %d", count, p->roll, p->name, p->age);
    count++;
    p = p->next;
  }
  printf ("\n");
}
```

- To be called from `main()` function

```
node *head;

    .........

display (head);
```

- After construction, *head* points to the first node of the list,
  - Follow the pointers.
  - Display the contents of the nodes as they are traversed.
  - Stop when the *next* pointer points to NULL.

Inserting a Node in a List

Inserting a Node in the Student Linked List

- The problem is to insert a node *before a specified node*.
  - Specified means some value is given for the node (called *key*).
  - In this example, we consider it to be `roll`.
- Convention followed:
  - If the value of roll is given as *negative*, the node will be inserted at the *end* of the list.

```
void insert (node **head)
{
    int  k = 0, rno;
    node *p, *q, *new;

    new = (node *) malloc(sizeof(node));

    printf ("\nData to be inserted: ");
      scanf ("%d %s %d", &new->roll, new->name, &new->age);
    printf ("\nInsert before roll (-ve for end):");
      scanf ("%d", &rno);

    p = *head;
```

- To be called from `main()` function

```
node *head;
.........
insert (&head);
```

Insert a Node in the Student Linked List

- When a node is added at the beginning,
  - Only one next pointer needs to be modified.
    - *head* is made to point to the new node.
    - New node points to the previously first element.
- When a node is added at the end,
  - Two next pointers need to be modified.
    - Last node now points to the new node.
    - New node points to NULL.
- When a node is added in the middle,
  - Two next pointers need to be modified.
    - Previous node now points to the new node.
    - New node points to the next node.
- The pointers q and p always point to consecutive nodes.

```
if (p->roll == rno)    /* At the beginning */
    {   new->next = p;
        *head = new;
    }
else
    {
  while ((p != NULL) && (p->roll != rno))
        {   q = p;
            p = p->next;
        }

        if  (p == NULL)    /* At the end */
        {   q->next = new;
            new->next = NULL;
        }
   else if  (p->roll == rno)
                        /* In the middle */
                {   q->next = new;
                    new->next = p;
                }
    }
}
```

Delete a Node in the Student Linked List

```
void  delete (node **head)
{    int  rno;
     node  *p, *q;

     printf ("\nDelete for roll :");
       scanf ("%d", &rno);

     p = *head;
```

- Required to delete a specified node.
  - Roll Number is given.
- Here also three conditions arise:
  - Deleting the first node.
  - Deleting the last node.
  - Deleting an intermediate node.

```
if   (p->roll == rno) /* Delete the first element */
     {    *head = p->next;
          free (p);
     }

else
     {   while  ((p != NULL) && (p->roll != rno))
         {    q = p;
              p  =  p->next;
         }

         if  (p == NULL)   /* Element not found */
           printf ("\nNo match deletion failed");

         else if (p->roll == rno)
                   /* Delete any other element */
               {   q->next  =  p->next;
                   free (p);
               }
     }
}
```

Exercises

- Write a function to:
  - Concatenate two given list into one big list.

    ```
    node  *concatenate (node *head1, node *head2);
    ```

  - Insert an element in a linked list in sorted order. The function will be called for every element to be inserted.

    ```
    void  insert_sorted (node **head,  node *element);
    ```

  - Always insert elements at one end, and delete elements from the other end (first-in first-out QUEUE).

    ```
    void  insert_q (node **head,  node *element)
    node  *delete_q (node **head)   /* Return the deleted node */
    ```

Linked Bag in Java

LinkedBag.java: Initialize

```
public class LinkedBag<Item> implements Iterable<Item> {
    private Node first;    // beginning of bag
    private int n;         // number of elements in bag

    // helper linked list class
    private class Node {
        private Item item;
        private Node next;
    }

  * Initializes an empty bag.
  */
public LinkedBag() {
    first = null;
    n = 0;
}
```

LinkedBag.java: Main

```
public static void main(String[] args) {
    LinkedBag<String> bag = new LinkedBag<String>();
    while (!StdIn.isEmpty()) {
        String item = StdIn.readString();
        bag.add(item);
    }

    StdOut.println("size of bag = " + bag.size());
    for (String s : bag) {
        StdOut.println(s);
    }
}
```

LinkedBag.java: Add item at First node

```java
/**
 * Adds the item to this bag.
 * @param item the item to add to this bag
 */
public void add(Item item) {
    Node oldfirst = first;
    first = new Node();
    first.item = item;
    first.next = oldfirst;
    n++;
}
```

LinkedBag.java: Other functions

```java
/**
 * Is this bag empty?
 * @return true if this bag is empty; false otherwise
 */
public boolean isEmpty() {
    return first == null;
}

/**
 * Returns the number of items in this bag.
 * @return the number of items in this bag
 */
public int size() {
    return n;
}
```

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ขอบคุณ
Thai

Grazie
Italian

תודה רבה
Hebrew

धन्यवादः
Sanskrit

ಧನ್ಯವಾದಗಳು
Kannada

Ευχαριστώ
Greek

Thank You
English

Gracias
Spanish

Спасибо
Russian

Obrigado
Portuguese

شكراً
Arabic

https://sites.google.com/site/animeshchaturvedi07

Merci
French

多謝
Traditional Chinese

धन्यवाद
Hindi

Danke
German

多谢
Simplified Chinese

நன்றி
Tamil

Tamil

ありがとうございました
Japanese

감사합니다
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