Module 8 Guidance Notes

# Pointers, Dynamic Memory & Linked Lists

ENGG1340

Computer Programming II

COMP2113

Programming Technologies

**Estimated Time of Completion: 3 Hours**

# Outline

Part I

# POINTERS

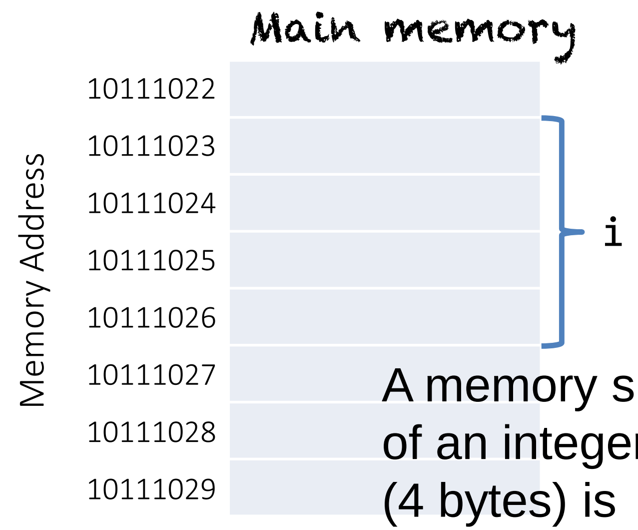
# What are we going to learn?

- Memory addresses and pointers
- Pointers and arrays
- Pass-by-reference with pointers

# Memory Address

- The main memory of a computer can be regarded as a collection of consecutively numbered memory cells.
- Each memory cell has a minimal size that the computer can manage (e.g., one byte).

- The unique number assigned to each memory cell is called its address, which is used to locate the memory cell in main memory.




A memory space of an integer size (4 bytes) is allocated by the variable declaration

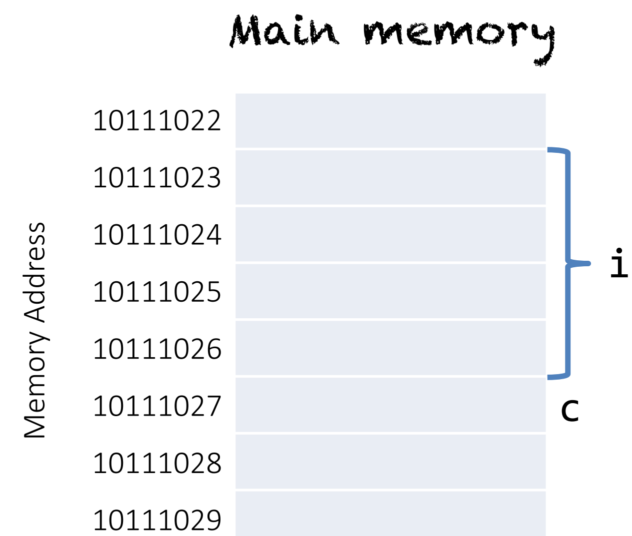
`int i;`

The address of `i` is `10111023`.

# Address-of Operator

- The memory address of a variable can be obtained by placing the address-of operator & in front of the variable

```
int i;
char c;

cout << &i << ' ' << &c;
```




```
10111023 10111027
```

This is just the conceptual output, as memory addresses are by default output as hex. Check addressof.cpp

# The & Operator

Note that the & operator in C++ have two meanings:

- If it is used in an expression, then it is the address-of operator as in the example in the previous slide.

```
int i;
cout << &i;
```

- When it is used in a declaration, it serves as the reference operator to provide a reference of an alias to a variable.

```
void swap( int & x, int & y);
```

An example you've seen before is when it is used in the function formal parameters for pass-by-reference

# Pointer Variable

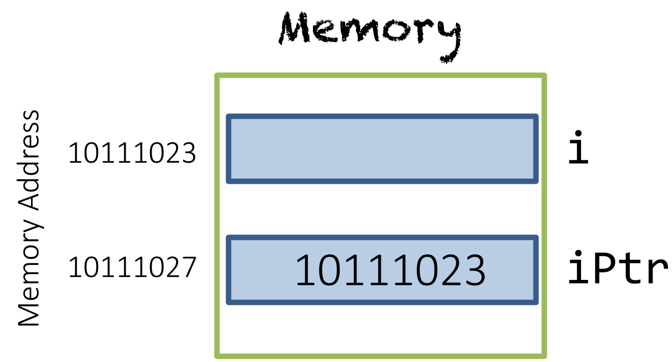
- We may declare a pointer variable to store the address of a variable

Creating a variable named `i` of type `int` that stores an integer

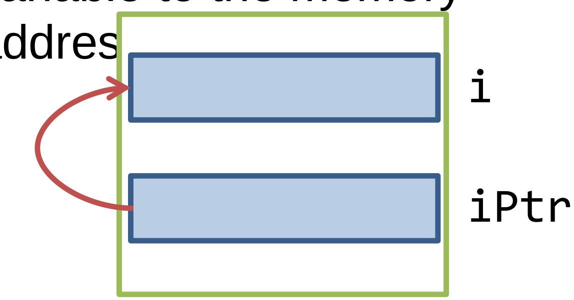
```
int i;
int * iPtr = &i;
```

Creating a variable named `iPtr` of type `int *` that stores the address of another integer variable.

address of `i`

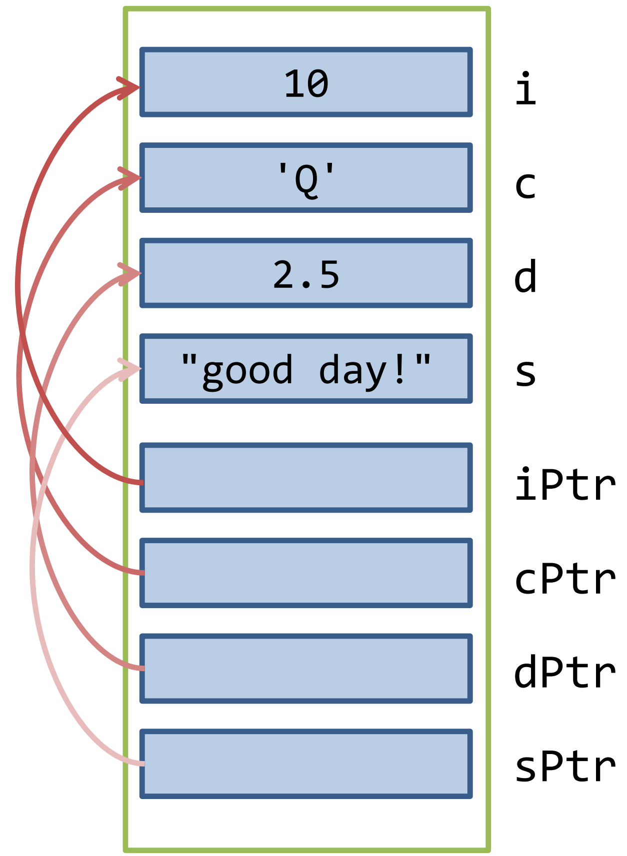



Usually represented as a diagram with an arrow pointing from the pointer variable to the memory addres



# Pointer Variable

```
int i = 10;
char c = 'Q';
double d = 2.5;
string s = "good day!";

int * iPtr;
char * cPtr;
double * dPtr;
string * sPtr;

iPtr = &i;
cPtr = &c;
dPtr = &d;
sPtr = &s;
```



# Pointer Variable

```
int * iPtr;
char * cPtr;
double * dPtr;
string * sPtr;
```

These are all pointers that point to variables of different types, and therefore the pointers are of different types.

Hence, it is an error to assign to a pointer variable of one type with an address of another variable of a different type.

```
int * iPtr;
char c;

iPtr = &c;
```

Compilation error!
`&c` is of type `char *`

# Pointer Variable

- We can declare pointer variables and regular variables together in the same declaration statement:

```
int i, * iPtr;
char c, * cPtr;
double d, * dPtr;
string s, * sPtr;
```

How may we declare multiple pointers of the same type in a single statement?

```
int * iPtr1, * iPtr2, * iPtr3;
```

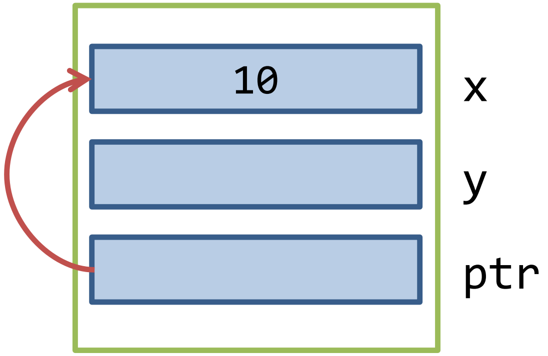
We need to place an asterisk * in front of each variable to indicate that each of them is a pointer.

# Dereference Operator

- The memory location that a pointer points to can be accessed or modified using the dereference operator *.

```
int x = 10, y;
int * ptr = &x;

y = *ptr;
*ptr = 20;
cout << x << ' ' << y << endl;
cout << *ptr << endl;

ptr = &y;
(*ptr)++;
cout << x << ' ' << y << endl;
cout << *ptr << endl;
```

dereference.cpp



# Dereference Operator

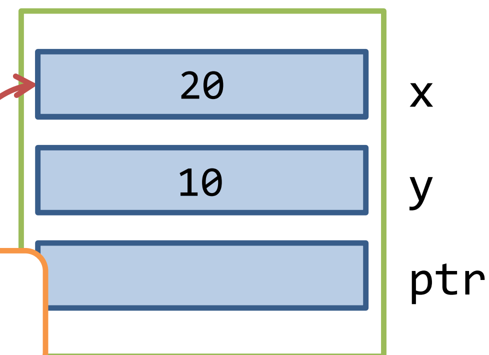
- The memory location that a pointer points to can be accessed or modified using the dereference operator *.

```
int x =
int * p

y = *ptr;
*ptr = 20;
cout << x << ' ' << y << endl;
cout << *ptr << endl;

ptr = &y;
(*ptr)++;
cout << x << ' ' << y << endl;
cout << *ptr << endl;
```

Accessing the contents of the memory location pointed to by ptr

Modifying the contents of the memory location pointed to by ptr

dereference.cpp




Screen output

```
20 10
20
```

# Dereference Operator

- The memory location that a pointer points to can be accessed or modified using the dereference operator *.

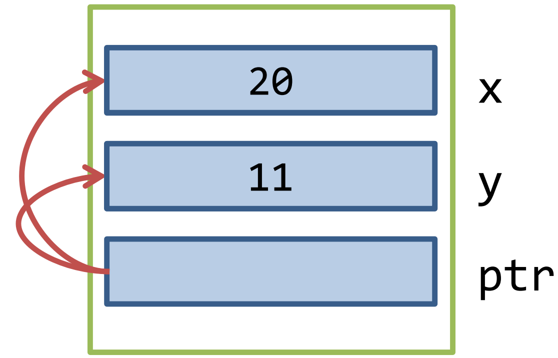
*ptr can be viewed as an alias (i.e., another name) of the variable that the pointer ptr points to.

Note that * is both used (1) to declare a pointer and (2) to dereference a pointer. It has different meanings in the two cases.

The parentheses are necessary since the ++ operator takes high precedence over *

```
cout << x <<
cout << *pt

ptr = &y;
(*ptr)++;
cout << x << ' ' << y << endl;
cout << *ptr << endl;
```

dereference.cpp




Screen output

```
20 10
20
20 11
11
```

```
int x = 10, y = 20;
string s = "abc";

int * ptr1, * ptr2;
int * ptr3;
string * ptr4;
```

What are the results of the followings?

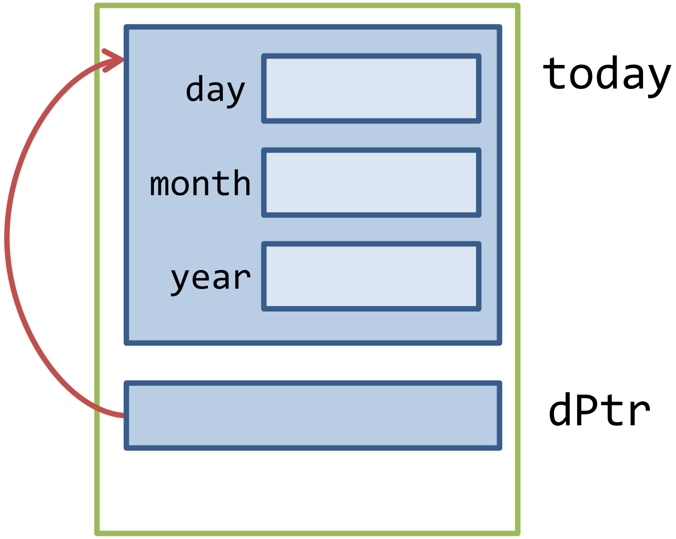
- `ptr1 = &x;` — ptr1 points to x
- `ptr2 = &y;` — ptr2 points to y
- `ptr3 = &y;` — ptr3 also points to y
- `ptr4 = &y;` — Error! A pointer to string cannot store the address of an int
- `*ptr1 = *ptr2;` — x now stores 20
- `*ptr3 = *&x - 10;` — y now stores 10
- `cout << *ptr3;` — 10

& and * are inverse of each other

# Member Access Operator

- Consider a pointer that points to a compound data (e.g., a structure or a class):

```
struct Date
{
    int day;
    int month;
    int year;
};

Date today;

Date * dPtr = &today;
```




Declare a pointer to a structure of type `Date` and assign the address of `today` to it.

# Member Access Operator

- Now we may access the members of the structure in the following ways:

```
today.year = 2015;
```

By using the dot operator of a structure

```
(*dPtr).year = 2015;
```

By first dereferencing the pointer to obtain a structure, then using the dot operator. Note that the parentheses are necessary here, as . (dot) takes higher precedence over * (star)

```
dPtr->year = 2015;
```

By using the `->` shorthand (which means member of pointer)

Check `pointer_date.cpp`

# Member Access Operator

- Member functions of a class can also be accessed in the same ways.

```
string s = "good day!";
string * sPtr = &s;

cout << s.length() << endl;

cout << "1st word: " << (*sPtr).substr(0, 4) << endl;
cout << "2nd word: " << sPtr->substr(5, 3) << endl;

cout << "sixth letter: " << (*sPtr)[5] << endl;
```

pointer_string.cpp

*sPtr is like an alias to s

# Dangling Pointers

- A pointer that does not point to a valid object is called a dangling pointer.
- Dereferencing a dangling pointer will lead to unpredictable result and sometimes may crash your program.

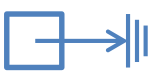
```
int * dangling_ptr;
cout << *dangling_ptr << endl;
```

What is the result?

Since `dangling_ptr` is not initialized, it stores an address which is just some garbage value.
The result of the statement depends on where `dangling_ptr` points to.

# Null Pointer

- We may assign a zero value (using the keyword `nullptr`) to a pointer which means that the pointer points to nothing.
- The pointer is then called a null pointer or a zero pointer.

ptr 

```
int * ptr = nullptr;
cout << *ptr << endl;
```

Dereferencing a null pointer will crash the program

```
if ( ptr != nullptr )
    cout << *ptr << endl;
```

Check if a pointer is null before using it

null_pointer.cpp

`nullptr` is a constant that equals `0`, so we may use either `nullptr` or `0`. (Prior to C++11, the constant NULL is used instead.)

## What's wrong with the following statements?

```
Date today;
Date * dPtr;

cout << dPtr->month;
```

`dPtr` is a dangling pointer. Accessing `dPtr->month` is error prone.

## How to fix it?

Trial 1

```
Date today;
Date * dPtr = 0;

cout << dPtr->month;
```

`dPtr` is a null/zero pointer. Accessing `dPtr->month` will crash the program.

Trial 2

```
Date today;
Date * dPtr = &today;

cout << dPtr->month;
```

Trial 3

```
Date today;
Date * dPtr = 0;

if (dPtr != 0)
    cout << dPtr->month;
```

# Pointers and Arrays

- The name of an array is indeed a pointer pointing to the first element of the array
- Hence, we may assign an array name to a pointer, and use the pointer to access the array elements

```
int x[10], i;

for ( i = 0; i < 10; ++i )
    x[i] = 2 * i;

int * p = x;

for ( i = 0; i < 10; ++i )
    cout << p[i] << ' ';
cout << endl;
```

Assigning an array name to a pointer of the same type as the array element

The pointer variable can be used
just as an array name

However, it is invalid to assign a pointer to an array name (e.g., `x = p`), since an array name is a constant pointer variable.

# Pointers and Arrays

```
int a[10], i;

for ( i = 0; i < 10; ++i )
    a[i] = 2 * i;

int * p = a;
for ( i = 0; i < 10; ++i )
    cout << p[i] << ' ';
cout << endl;

int * q = &a[0];
for ( i = 0; i < 10; ++i )
    cout << q[i] << ' ';
cout << endl;

p = &a[2];
cout << p[3] << endl;
```

Screen output

```
0 2 4 6 8 10 12 14 16 18
0 2 4 6 8 10 12 14 16 18
10
```

pointer_array.cpp

# Exercise 1

- Write a function that takes an integer array and its size, and returns a pointer to the largest element in the array

Solution: ex1.cpp

# Pass-by-reference with Reference Arguments

- We have learned pass-by-value and pass-by-reference for passing arguments to a function.
- Pass-by-reference enables the called functions to modify the values of the arguments passed from the caller.

```
void swap( int & x, int & y)
{
    int temp = x;
    x = y;
    y = temp;
}
```

Reference arguments

In the caller (e.g., the main function)

```
int a = 2, b = 3;

swap(a, b);
```

The values in a and b will be swapped after calling `swap()` because x and y are just aliases of a and b, respectively (i.e., they share the same memory locations)

# Pass-by-reference with Pointers

- We can also achieve pass-by-reference by passing pointers as arguments.

```
void swap( int * x, int * y)
{
    int temp = *x;
    *x = *y;
    *y = temp;
}
```

Pointer arguments

swap_by_pointers.cpp

In the caller (e.g., the main function)

```
int a = 2, b = 3;

swap(&a, &b);
```

Here we explicitly pass the memory addresses of a and b to swap(), so that swap() operates on these memory locations directly.

The values in a and b will be swapped after calling `swap()`.

# Exercise 2

- Write a function void addOne(int &p) which adds 1 to the integer referenced by p
- Write a function void addOne(int *p) which adds 1 to the integer pointed to by p
- Note the difference in the function parameter. For each of the above, write the appropriate function call in the main body of your program.

Part II

# DYNAMIC MEMORY MANAGEMENT

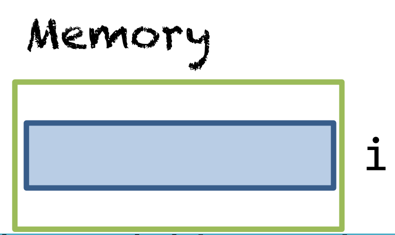
# What are we going to learn?

- Dynamic variables
- Dynamic arrays
- Pointer operations

# Static Variables

- We have used only static variables in our programs so far, which means that:
  - The number of variables is fixed.
  - The life span of variable is determined by its scope; it is created (i.e., storage space is allocated) when it is declared and it is destroyed (i.e., storage space is released) when execution is out of scope.
  - Each variable is given a name when it is declared.

```
for (int i = 0; i < 10; ++i)
{
    cout << i << ' ';
}
```




The variable `i` only exists in the memory during the execution of the `for` loop.

# Dynamic Variables

- Very often the number of variables that we need in a program is not known in advance.   For example, processing student records without knowing the number of students beforehand.
- We can create **dynamic variables** in our program so that memory storage is dynamically allocated or released at runtime.

Unlike static variables, dynamic variables have no names!

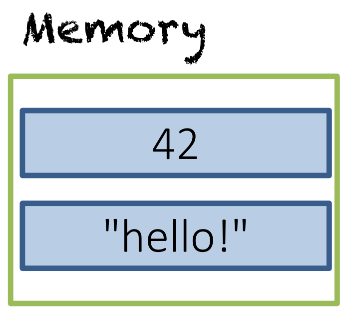
So how may we access dynamic variables?

Pointers!!!

# Creating Dynamic Variables

- We use the **new** operator to create a dynamic variable:

```
new int (42);
new string ("hello!");
```

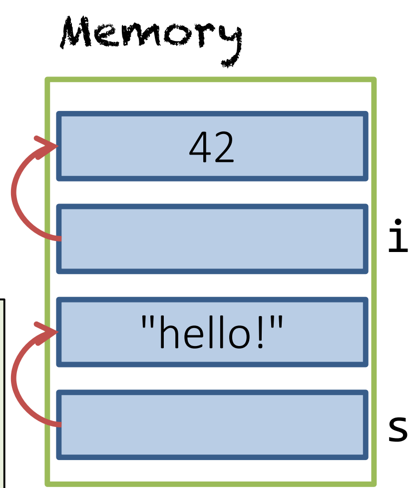



No names for these memory locations, and there's no way that you can access them

```
int * i = new int (42);
string * s = new string ("hello!");
```

this is equivalent to

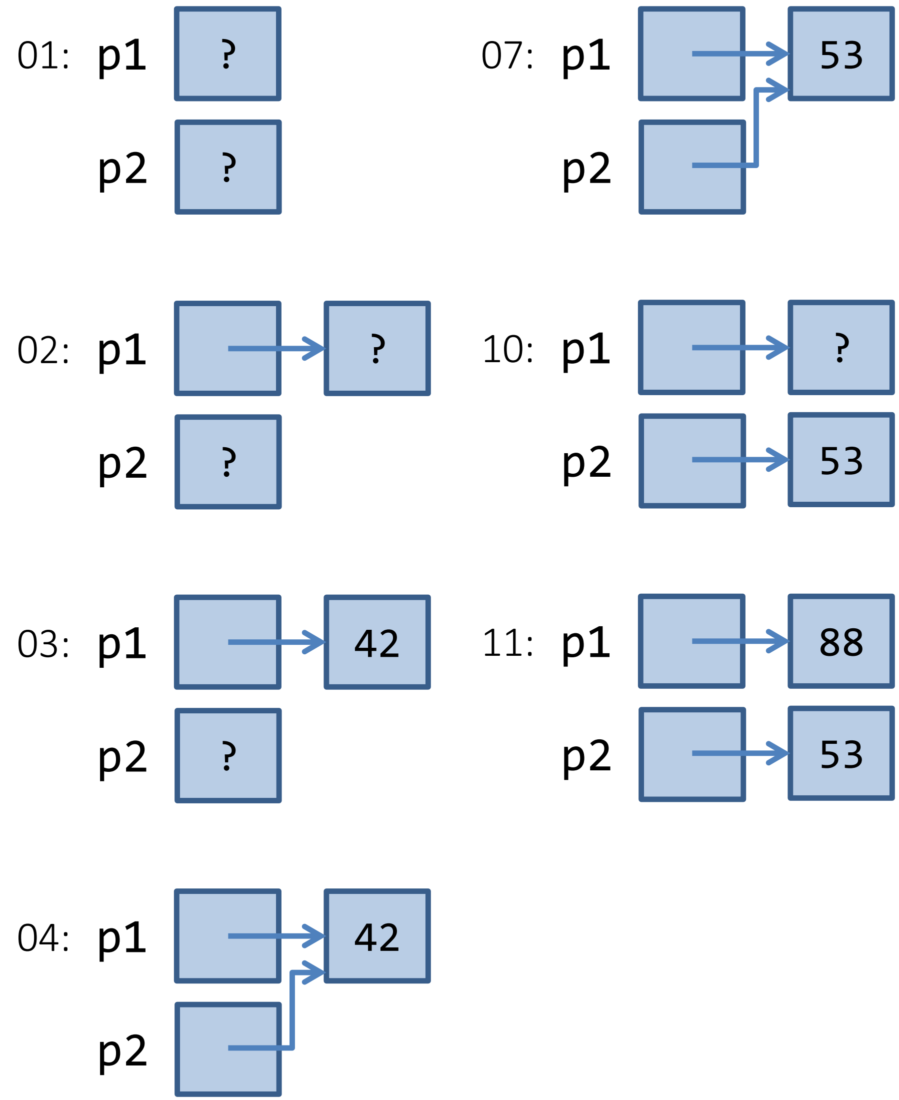
```
int * i = new int;
*i = 42;
string * s = new string;
*s = "hello!";
```




Now we may access these memory locations via the pointers `i` and `s`.

dynamic.cpp

```
01: int *p1, *p2;
02: p1 = new int;
03: *p1 = 42;
04: p2 = p1;

05: cout << "*p1 = " << *p1 << ", ";
06: cout << "*p2 = " << *p2 << endl;

07: *p2 = 53;
08: cout << "*p1 = " << *p1 << ", ";
09: cout << "*p2 = " << *p2 << endl;

10: p1 = new int;
11: *p1 = 88;
12: cout << "*p1 = " << *p1 << ", ";
13: cout << "*p2 = " << *p2 << endl;
```




Screen output

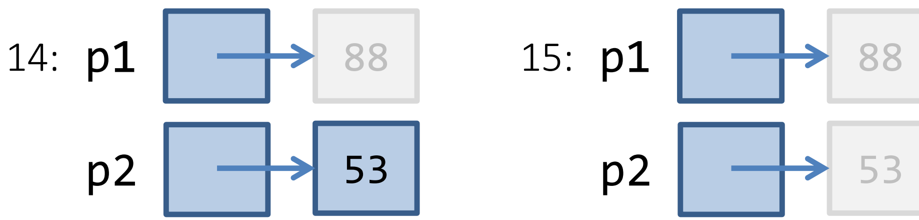
```
*p1 = 42, *p2 = 42
*p1 = 53, *p2 = 53
*p1 = 88, *p2 = 53
```

# Destroying Dynamic Variables

- Memory allocated to dynamic variables can be freed using the delete keyword:

```
14: delete p1;
15: delete p2;
```

The pointer pointing to the memory location that needs to be freed.




The freed memory space can be re-used by the system.

# Destroying Dynamic Variables

- It's a good practice to reset a pointer to zero after the memory location that it points to is freed.

```
int * p1 = new int (42);
cout << *p1;
delete p1;
p1 = 0;
```

- It's the programmer's responsibility to free up all dynamic variables that are no longer in use.

Failing to do so will lead to memory leak, i.e., having memory space that the system cannot reclaim, and the system may gradually run out of memory

# Common Mistakes with Pointers

Dereferencing a pointer before it is initialized

```
int * p;
*p = 88;
```

Dereferencing a dangling pointer

```
int * p = new int;
*p = 88;
delete p;
cout << *p;
```

```
int * p1, * p2;
p1 = new int;
p2 = p1;
delete p1;
cout << *p2;
```

Deleting a pointer that does not point to a valid memory location

```
int * p1, * p2;
p1 = new int;
p2 = p1;
delete p1;
delete p2;
```

```
int * p;
p = new int;
…
delete p;
…
delete p;
```

Memory leak

```
int * p1, *p2;
p = new int;
q = new int;
q = p;
```

# Dynamic Arrays

Recall

```
int a[10];
```

This declares an array of 10 integers. The size of the array is determined at compilation time.

What if we need more elements in the array during execution or the size of the array can only be known during runtime?

We may dynamically create an array at runtime using the new operator:

```
new int [10];
```

This allocates a dynamic array of 10 integers at runtime.

However, the dynamic array is without a name. So what's next?

# Dynamic Arrays

- An example for the full cycle of a dynamic array

```
int n;
cin >> n;

int * a = new int [n];

for (int i = 0; i < n; ++i)
  a[i] = i;

…

delete [] a;
```

dynamic_array.cpp

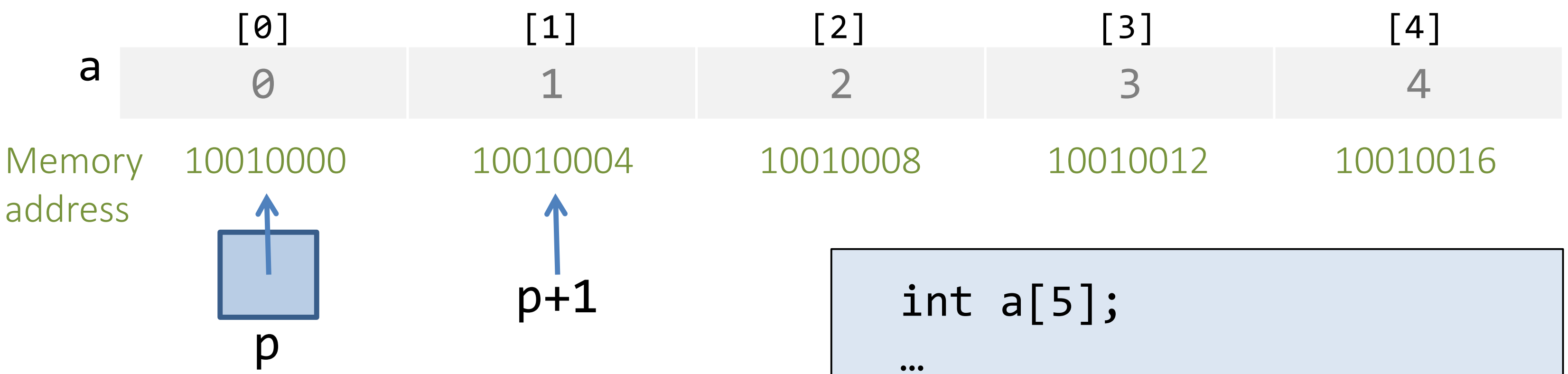
Create a dynamic array and use a pointer to point to it. Note that the value of n is only known at runtime.

Use the array pointer a to access the elements

Use delete [] to free the dynamic array pointed to by a

# Pointer Operations

- We may carry out addition and subtraction on pointers.
- Since they are actually memory addresses, the unit of addition and subtraction depends on the size of the data type to which they point.




```
int a[5];
…
int * p = a;
cout << *p << ' ';
cout << *(p+1) << endl;
```

Screen output

```
0 1
```

# Pointer Operations

- We may also compare if two pointers are the same, i.e., if they point to the same memory location:

```
int a[5];
…

int * p = a, * q = a + 5;

while ( p != q ) {
  cout << *p << ' ';
  ++p;
}
```

pointer_operation.cpp

What does this program do?

# TUTORIAL

*Did you find the concept of dynamic memory management too complicated? Don't worry! Let's have a tutorial.*

# Phonebook Manager

- We are going to work on a program that manages a phonebook that stores phone records. Functions provided by the phonebook are:
  - Load a phonebook from an external file
  - Print the records in a phonebook
  - Sort the records in a phonebook
  - Search in a phonebook
  - Save a phonebook to an external file
  - Add a record

*No worry, most of these functions are implemented. But it is recommended that you take time (could be after the tutorial) to go through the codes and learn more about them.*

`phonebook_incomplete.cpp` *and* `phonebook.txt` *(a file containing phone records) are given to you.*

phonebook.cpp provides the completed version of this tutorial problem. You may compile and run it to see the expected results first.

# Phonebook Manager

- We focus ONLY on maintaining a dynamic array that stores the phone records so that the phonebook manager can handle as many phonebook records as the user requires, in a time/space efficient manner.
- You will be implementing a function called `grow_phonebook()` which enlarges the size of the dynamic array *(i.e., the size of phonebook)* when necessary.
- The phonebook is initially of size 3, i.e., it can hold 3 records at most:

In main():

```
int phonebook_size = 3;
PhoneRec * phonebook = new PhoneRec[phonebook_size];
```

# Phonebook Manager

- Compile and run `phonebook_incomplete.cpp`.

Since we have not implemented grow_phonebook(), the program can only read in 3 records. (Note that there are 10 records in phonebook.txt.)

```
******************************
* Welcome to Phonebook Manager *
******************************
1. Load a phonebook.
2. Print all records.
3. Sort the records by ascending order of the name.
4. Search the records by partial match of the name.
5. Save the phonebook.
6. Add a new record.
0. Quit.
Please enter your choice: 1

Please enter the filename: phonebook.txt
--->phonebook size enlarged to hold a maximum of 3 records.
--->phonebook size enlarged to hold a maximum of 3 records.
--->phonebook size enlarged to hold a maximum of 3 records.
--->phonebook size enlarged to hold a maximum of 3 records.
--->phonebook size enlarged to hold a maximum of 3 records.
--->phonebook size enlarged to hold a maximum of 3 records.
--->phonebook size enlarged to hold a maximum of 3 records.

3 record(s) loaded.
```

# Phonebook Manager

- After implemented **`grow_phonebook()`** correctly, the result should look like:

```
*******************************
* Welcome to Phonebook Manager *
*******************************
1. Load a phonebook.
2. Print all records.
3. Sort the records by ascending order of the name.
4. Search the records by partial match of the name.
5. Save the phonebook.
6. Add a new record.
0. Quit.
Please enter your choice: 1

Please enter the filename: phonebook.txt
---> phonebook size enlarged to hold a maximum of 6 records.
---> phonebook size enlarged to hold a maximum of 9 records.
---> phonebook size enlarged to hold a maximum of 12 records.

10 record(s) loaded.
```

# When will `grow_phonebook()` be called?

- In **`load_phonebook()`** when the number of records read in exceeds the phonebook size.

```
int load_phonebook(...)
{
        ...
        if (i >= phonebook_size)
            grow_phonebook(...);

        ...
}
```

*The variable `i` keeps track of the number of records read in so far, and `phonebook_size` stores the capacity of the phonebook, i.e., the size of the dynamic array for holding the records*

- Before calling **`add_record()`** when the phonebook is already full.

```
int main()
{
        ...
        case '6':
            if (num_records >= phonebook_size)
                grow_phonebook(...);
        ...
}
```

*The variable `num_records` stores the number of records that are kept in the dynamic array*

# What does `grow_phonebook()` do?

*function prototype*

```
void grow_phonebook(PhoneRec * &pb, int &pb_size, int n);
```

`pb` *points to the dynamic array storing the phonebook*

`pb_size` *is the current size of the dynamic array*

`n` *is the size by which to increase the dynamic array. Hence, the new size of the array is* `pb_size + n` *after calling this function*

*Example:*

phonebook `phonebook_size = 5`

`phonebook_size` *is modified and hence it is passed as a reference parameter*

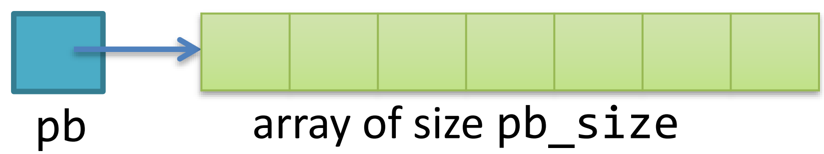
After calling
`grow_phonebook( phonebook, phonebook_size, 2 );`

phonebook `phonebook_size = 7`

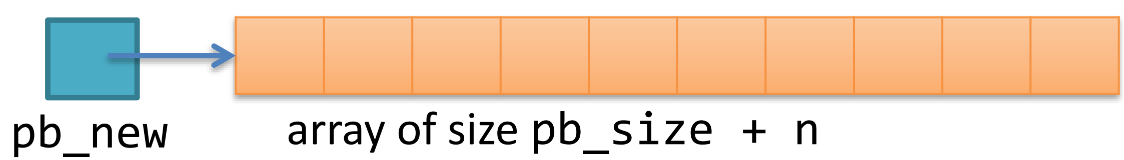
*the new array occupies a new chunk of memory and hence the pointer* `phonebook` *needs also be modified; it is therefore passed as a reference parameter*

# Implementing `grow_phonebook()`

```
void grow_phonebook(PhoneRec * &pb, int &pb_size, int n);
```




- Now, let's do the following steps for `grow_phonebook()`
- **Step 1:** create a new dynamic array with a new size equals `pb_size + n` dynamic array, pointed to by a pointer

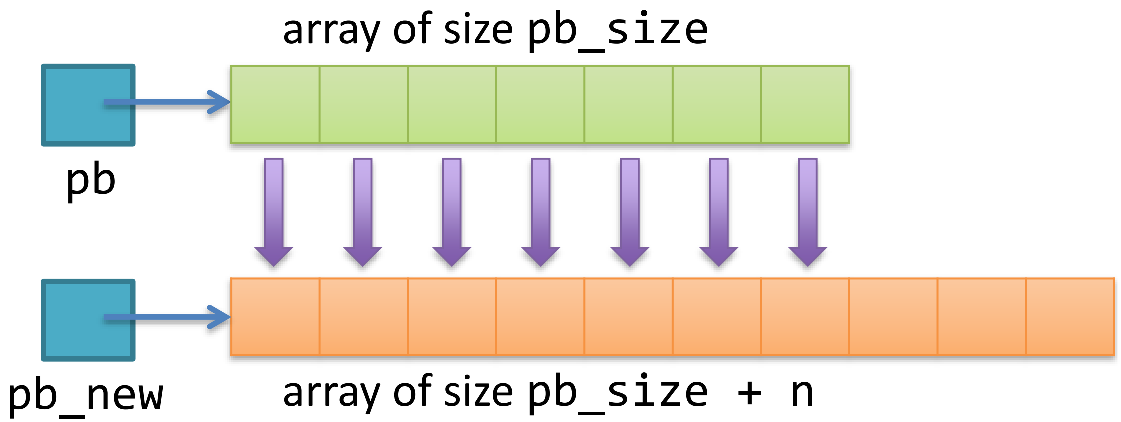



*What is the data type of pb_new?*

*How to create a dynamic array?*

# Implementing `grow_phonebook()`

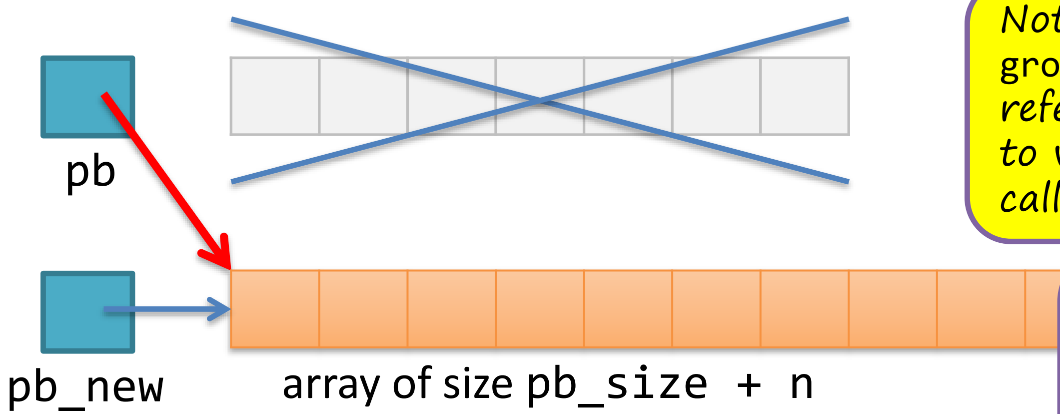
- **Step 2:** Copy all the records from the original array to the new array




*You just need to treat it as ordinary copying of array elements. Remember that a pointer to array can be used as an array name for accessing the elements, e.g., you may write* `pb[i]`, `pb_new[i]`

# Implementing `grow_phonebook()`

- **Step 3:** Now that the new array is ready, we should deal with releasing the memory occupied by the old array. Delete the old dynamic array and points **pb** to the new array.




*Note that pb_new is only local to grow_phonebook() and pb is the reference parameter that points to where the new array is in the calling function (i.e., main())*

*If we forgot to update pb to point to the new array, the new array cannot be accessed in the main function and there is memory leak. Also, the pointer phonebook in the main function will become a dangling pointer.*

- **Step 4:** update the phone book size `pb_size` to the new size and we are done!

*Try the program with the add record option from the main menu and see the result.*

# A Question

- The program now works in such a way that the phonebook will grow whenever it is full, and we can control the size that it should grow every time (the parameter n in `grow_phonebook()`). But by how much?
- In this program, we just simply increase the size by a constant amount (now 3), independent of the original array size.
- What if we set a large `n`?
- What if we set a small `n`?
- Think about it first before turning to the next page for some suggestions.

# A Question

- Having an `n` too large will result in wasted space in most of the time.
- Having an `n` too small will result in calling `grow_phonebook()` too frequently which is not time efficient, since it involves array copying.
- There is no right choice for `n` which works optimally in all cases, but a general practice is to double the array size every time when it needs to grow.

Part III

# LINKED LISTS

# What are we going to learn?

- Modes of data access
  - Random access
  - Sequential access
- Linked lists
- Linked list operations
  - Traversing a linked list
  - Building a linked list
  - Inserting an item into a linked list
  - Deleting an item from a linked list

# Mode of data access – Random Access

- Array is a container which allows random access to the items stored in it.

| | [0] | [1] | [2] | [3] | [4] | [5] | [6] | [7] | [8] | [9] |
|---|---|---|---|---|---|---|---|---|---|---|
| `data` | 23 | 56 | 92 | 38 | 12 | 76 | 35 | 89 | 10 | 62 |

*We can directly access the 5th item by writing* `data[4]`

What if we want to access the 5th smallest item?

| | [0] | [1] | [2] | [3] | [4] | [5] | [6] | [7] | [8] | [9] |
|---|---|---|---|---|---|---|---|---|---|---|
| `data` | 10 | 12 | 23 | 35 | 38 | 56 | 62 | 76 | 89 | 92 |

*Sort the array, and then access* `data[4]` *directly*

*Search can also be made fast (with a binary search) with a sorted array*

# Mode of data access – Random Access

What if we want to insert an item into a sorted array so that the array remains sorted?

| | [0] | [1] | [2] | [3] | [4] | [5] | [6] | [7] | [8] | [9] |
|---|---|---|---|---|---|---|---|---|---|---|
| data | 10 | 12 | 23 | 35 | 38 | 56 | 62 | 76 | 89 | 92 |

For example, to insert 15 into data:

*Step 1: Increase the array capacity if necessary*

| | [0] | [1] | [2] | [3] | [4] | [5] | [6] | [7] | [8] | [9] | [10] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| data | 10 | 12 | 23 | 35 | 38 | 56 | 62 | 76 | 89 | 92 | |

*Step 2: Shift all items larger than 15 to the right*

*What if this is a very very large array?*

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| data | 10 | 12 | | 23 | 35 | 38 | 56 | 62 | 76 | 89 | 92 |

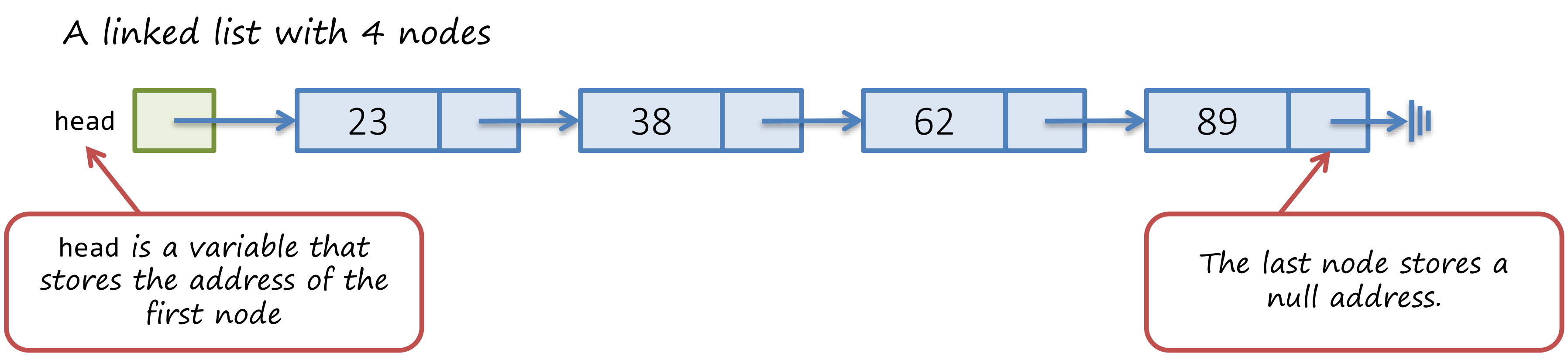
*Step 3: Put 15 into the empty slot*

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| data | 10 | 12 | 15 | 23 | 35 | 38 | 56 | 62 | 76 | 89 | 92 |

***Insertion*** *and* ***deletion*** *using array is* ***not efficient****, because these involve data movement.*
*Imagine how many data you would need to move if working on a very big array.*

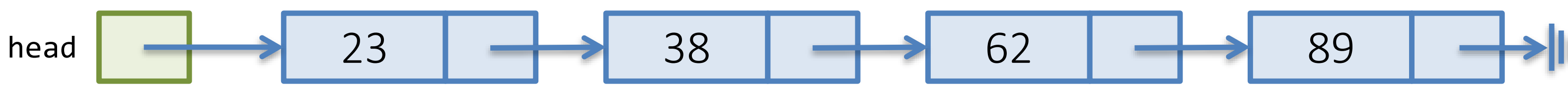
# Linked Lists

- We need a data structure that can support efficient data insertion and deletion.
- Linked list is a collection of items called nodes.
- Each node stores a piece of data, as well as the address of the next node (except for the last node).

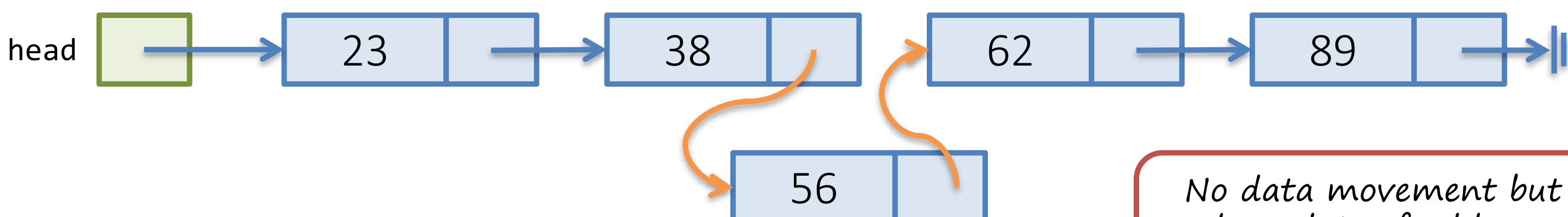


# Linked Lists

- Linked list is a sequential access data structure
  - i.e., to go to a specific item in a linked list, you have to start from the head of the list and go through the item one by one until you hit that item you need.
- However, **insertion** and **deletion** of items can be done efficiently.




For example, to insert 56 into the linked list:




*No data movement but only update of addresses (i.e., pointers) are needed.*

# Linked Lists vs. Arrays

## Linked Lists

- Items need not be stored contiguously in memory
- Sequential access from the head of list for an item
- Insertion & deletion of items can be done efficiently (in constant time, i.e., independent of the number of items)

## Arrays

- Items are stored contiguously in memory
- Random access that allows fast direct access to an item
- Insertion & deletion of items can be time consuming (in linear time in the number of items)

# Implementation

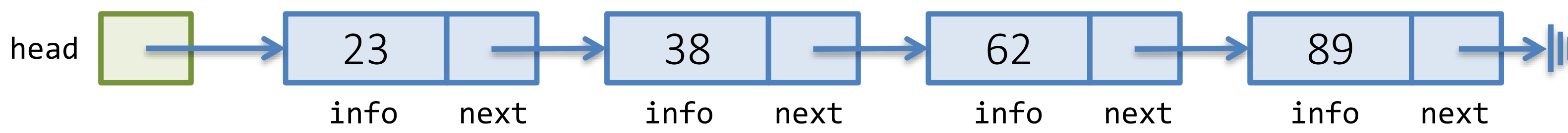
- A node can be implemented using a struct in C++.

```
struct Node
{
    int info;
    Node * next;
};
```

- The linked list is given as a pointer that points to the first node.

```
    Node * head;
```

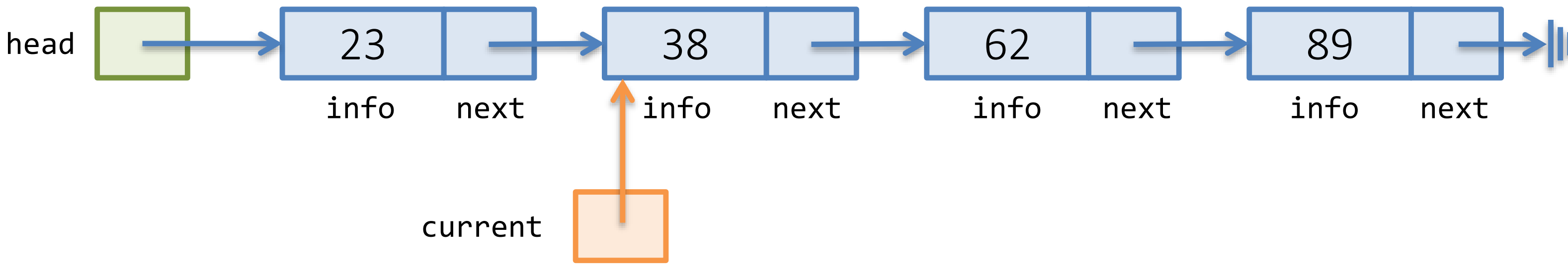
# Implementation




*What do the following expressions evaluate to?*

| | |
|---|---|
| head | address of the 1st node of the list |
| head->info | 23 |
| head->next | address of the 2nd node |
| head->next->info | 38 |
| head->next->next->info | 62 |
| head->next->next->next->info | 89 |
| head->next->next->next->next | 0 |
| head->next->next->next->next->info | does not exist, error! |

# Implementation




*What do the following expressions evaluate to?*

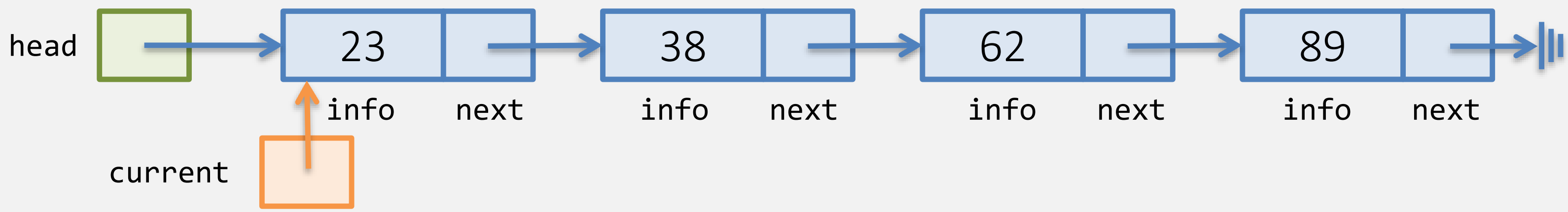
| | |
|---|---|
| current | address of the 2nd node of the list |
| current->info | 38 |
| current->next | address of the 3rd node |
| current->next->info | 62 |
| current->next->next->info | 89 |
| current->next->next->next | 0 |
| current->next->next->next->next | does not exist, error! |

***A question:*** *how may we move the current pointer to point to the previous node?*

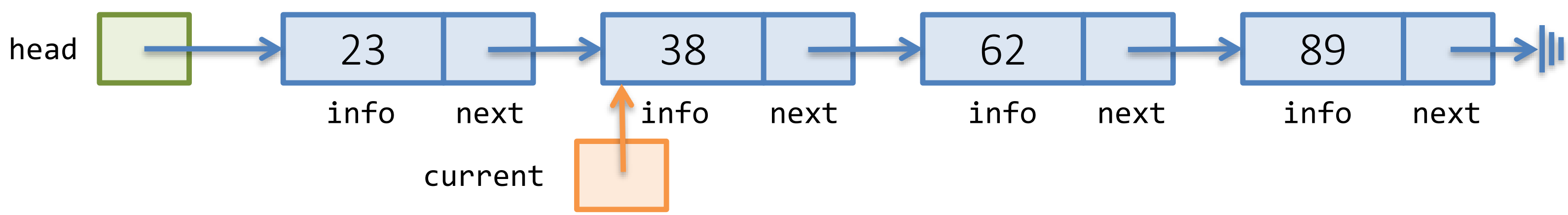
# Traversing a Linked List

- Traversing: to go through the nodes in a linked list one-by-one, starting from the first node.

```
Node * current = head;
```

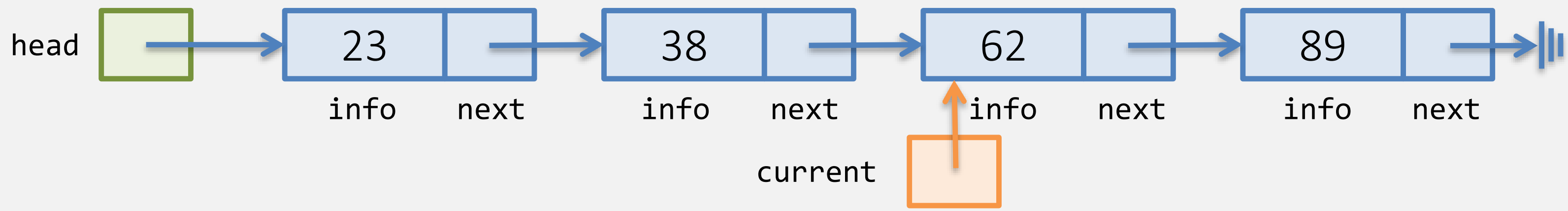



```
current = current->next;
```



# Traversing a Linked List

```
current = current->next;
```




By advancing **current** to the next node repeatedly in this way, we may visit the nodes in the link list one by one.

*How do we know the end of the linked list is reached and stop advancing to the next?*

*A standard while loop for traversing a linked list*

```
Node * current = head;
while (current != NULL)
{
    // process the current node, e.g., print the content
    current = current->next;
}
```

print_list() function in build_list_backward.cpp

# Traversing a Linked List

*Why not traversing a list using the* head *pointer?*

```
while (head != NULL)
{
     cout << head->info << endl;
     head = head->next;
}
```

*NO!!! You should never do this.*

*If you modify the head pointer, the first node and therefore the entire linked list will be lost.*

*What happens if we forgot to advance the* current *pointer?*

```
while (current != NULL)
{
     cout << current->info << endl;
}
```

*This will go into an infinite loop, since current will never be equal to NULL, unless head points to an empty linked list initially.*

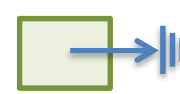
# Building a Linked List

- Starting from an empty list, new nodes may be created and inserted into the linked list.
- To build a linked list in a forward manner:
  - Always insert a new node at the end of the linked list
- To build a linked list in a backward manner:
  - Always insert a new node at the beginning of the linked list

*We start by defining an **empty list**, i.e., a list without any node*

```
Node * head = NULL;
```

head

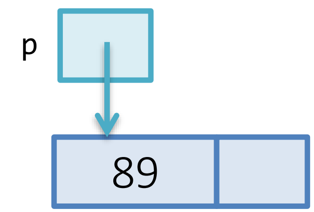


# Building a Linked List Backward

- We now build a linked list in a backward manner by always inserting a new node at the beginning of the list.

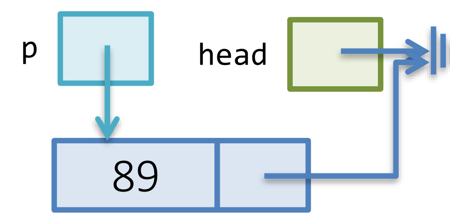
1. *Create a new node and fill in the required info*

```
Node * p = new Node;
p->info = 89;
```



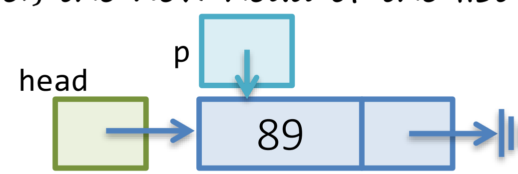

2. *Have the next pointer of the new node points to the beginning of the list*

```
p->next = head;
```




3. *Update the head pointer to point to the new node, i.e., the new head of the list*

```
head = p;
```



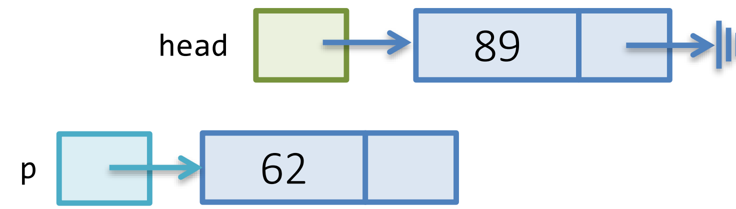

*Now we have a list with one node.*

# Building a Linked List Backward

- Repeating the steps to insert one more node at the beginning:

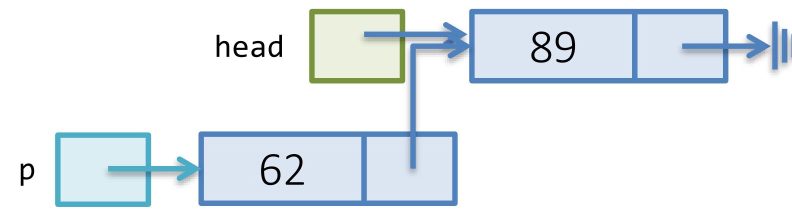
1.

```
Node * p = new Node;
p->info = 62;
```



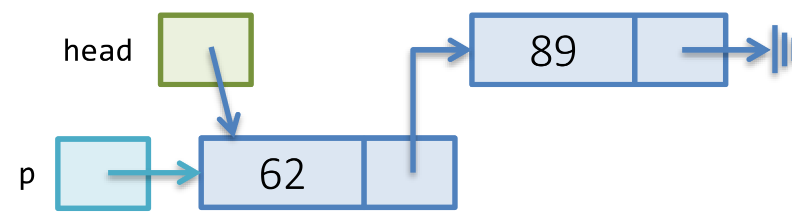

2.

```
p->next = head;
```




3.

```
head = p;
```




*Now we have a list with two nodes.*

# Building a Linked List Backward

- **Example**: Suppose we want to build a linked list of numbers input by the user until he enters -999.

```
Node * head = NULL;
int num = 0;

cin >> num;
while ( num != -999 ) {
     head_insert(head, num);
     cin >> num;
}
```

build_list_backward.cpp

```
void head_insert(Node * & head, int num)
{
     Node * p = new Node;
     p->info = num;
     p->next = head;
     head = p;
}
```

*The* head *pointer needs to be updated and hence is passed by reference*

```
input integers (-999 to end): 23 56 14 45 98 -999

98 -> 45 -> 14 -> 56 -> 23 -> NULL
```

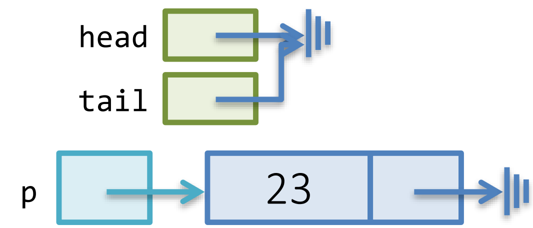
build_list_backward.cpp

# Building a Linked List Forward

- To build a linked list in a forward manner, we always insert a new node at the end of the list.

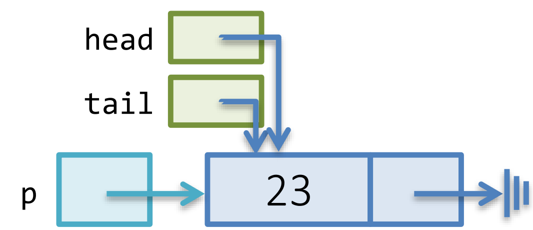
1. *Create a new node and fill in the required info. Since this will be the last node, set the next pointer to NULL.*

```
Node * p = new Node;
p->info = 23;
p->next = NULL;
```




2. *If this is going to be the first node of the list, we point both head and last to it.*

```
head = p;
tail = p;
```



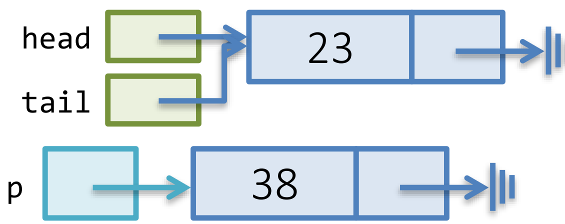

*Since a new node is always inserted at the end, we need to maintain where the last node is using the pointer* `tail`.

# Building a Linked List Forward

- Repeating the steps to insert one more node at the end:

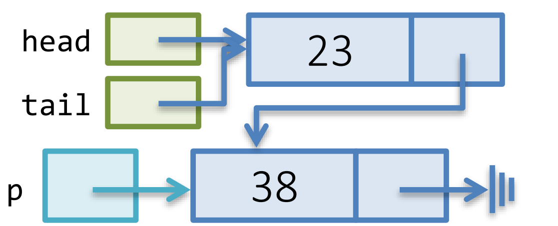
*1. Create a new node and fill in the required info. Since this will be the last node, set the next pointer to NULL.*

```
Node * p = new Node;
p->info = 38;
p->next = NULL;
```



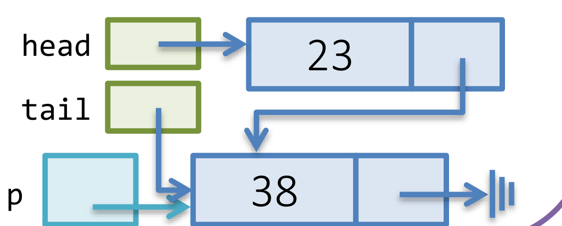

*2. If this is **NOT** going to be the first node of the list, we link the last node of the list to the new node:*

```
tail->next = p;
```




*and set the last pointer to point to the new node:*

```
tail = p;
```



# Building a Linked List Forward

- **Example**: Suppose we want to build a linked list of numbers input by the user until he enters -999.

```
Node * head = NULL, * tail = NULL;
int num = 0;

cin >> num;
while ( num != -999 ) {
     tail_insert(head, tail, num);
     cin >> num;
}
```

build_list_forward.cpp

```
void tail_insert(Node * & head,
     Node * & tail, int num)
{
     Node * p = new Node;
     p->info = num;
     p->next = NULL;

     if (head == NULL) {
          head = p;
          tail = p;
     }
     else {
          tail->next = p;
          tail = p;
     }
}
```

```
input integers (-999 to end): 23 56 14 45 98 -999

23 -> 56 -> 14 -> 45 -> 98 -> NULL
```

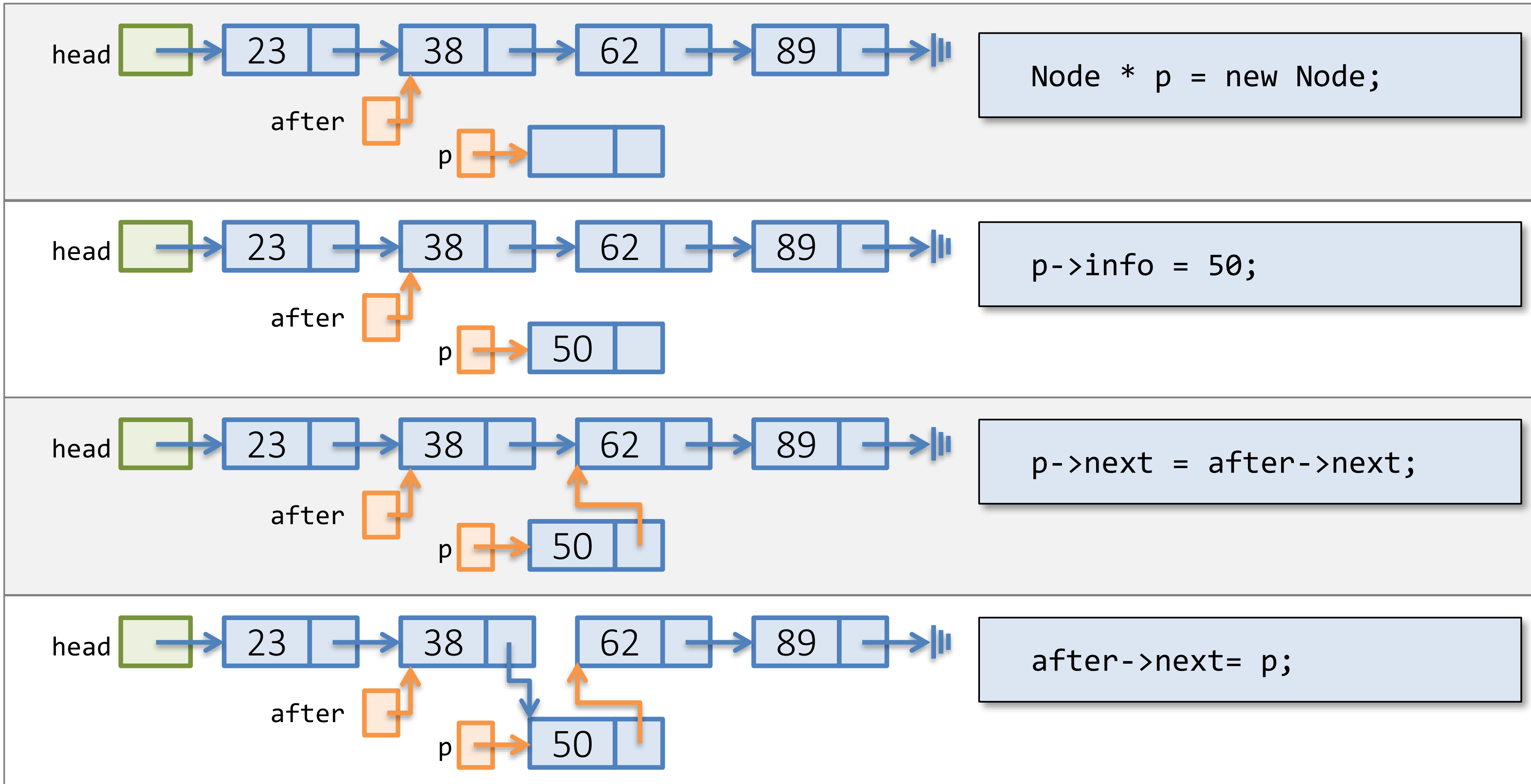
*Compare this list with that produced by build_list_backward.cpp*



build_list_forward.cpp

# Inserting a Node

- Suppose the pointer `after` points to the node 38, and we want to insert 43 after it.



# Inserting a Node

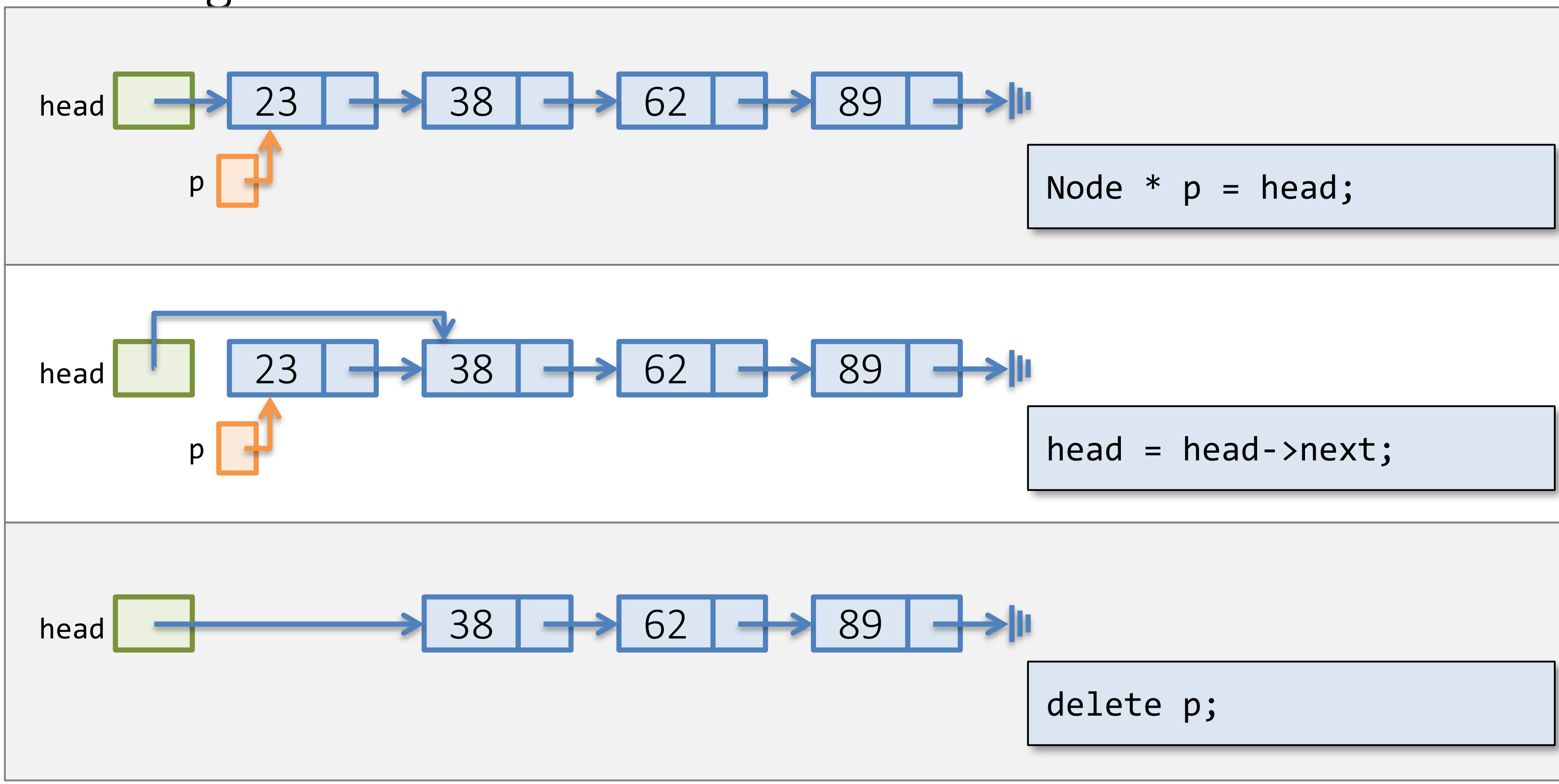
- A function to insert a number after the node pointed to by `after` in a linked list

```
// assume that after points to a node
// i.e., after not equals null
void insert( Node * after, int num )
{
    Node * p = new Node;
    p->info = num;
    p->next= after->next;
    after->next = p;
}
```

build_list_sorted.cpp

# Deleting a Node

- Deleting the first node:



# Deleting a Node

- A function to delete the first node in a linked list:

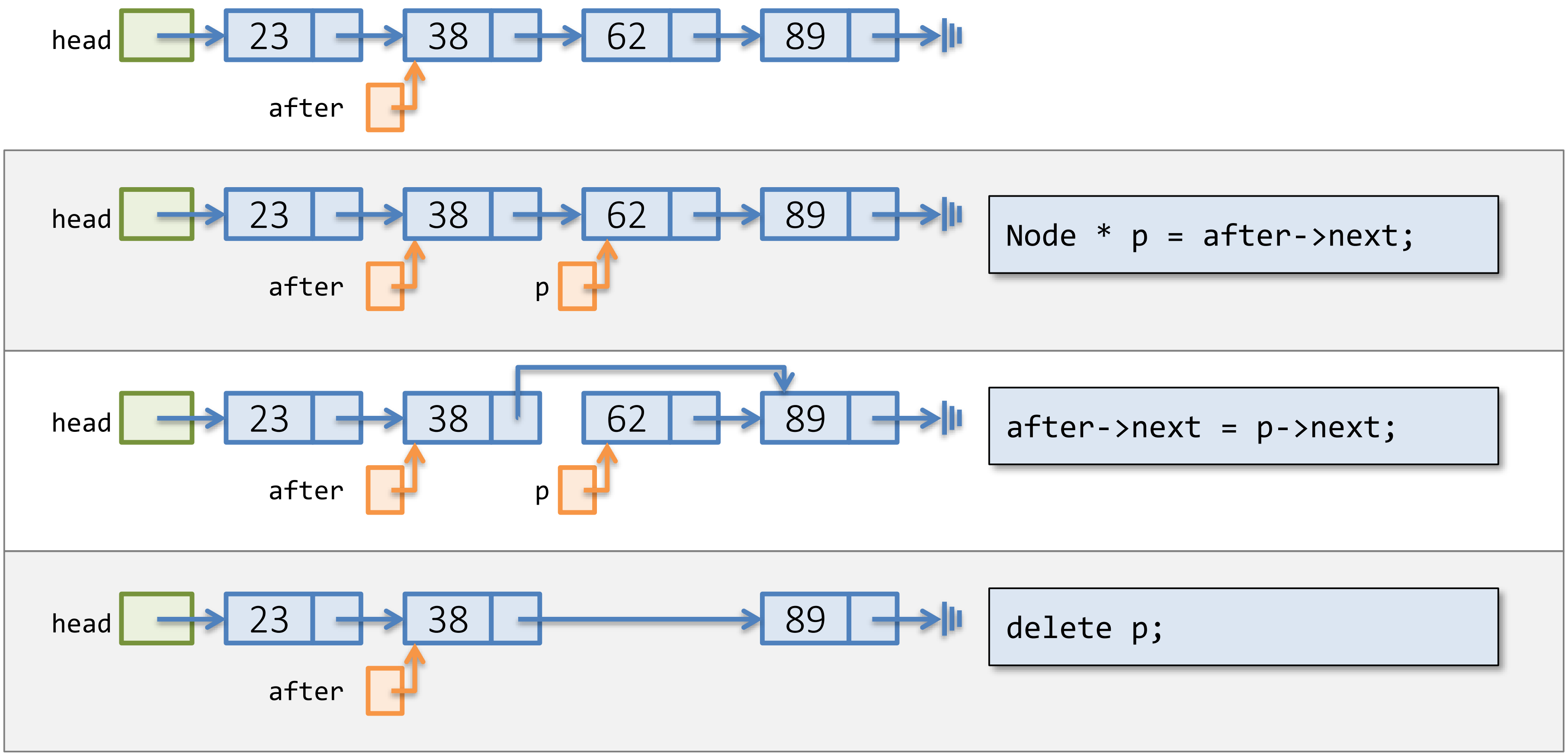
```
void delete_head( Node * & head)
{
    if (head != NULL) {
        Node * p = head;
        head = head->next;
        delete p;
    }
}
```

Make sure the list is not empty

build_list_sorted.cpp

# Deleting a Node

- To remove a node after the node pointed to by **`after`**, i.e., the node with number 62



# Deleting a Node

- A function to delete a number after the node pointed to by `after` in a linked list

```
// assume that after points to a node and is //
i.e., after not equals null
void delete_node( Node * after)
{
    Node * p = after->next;
    after->next = p->next;
    delete p;
}
```

build_list_sorted.cpp

# Searching for a Node

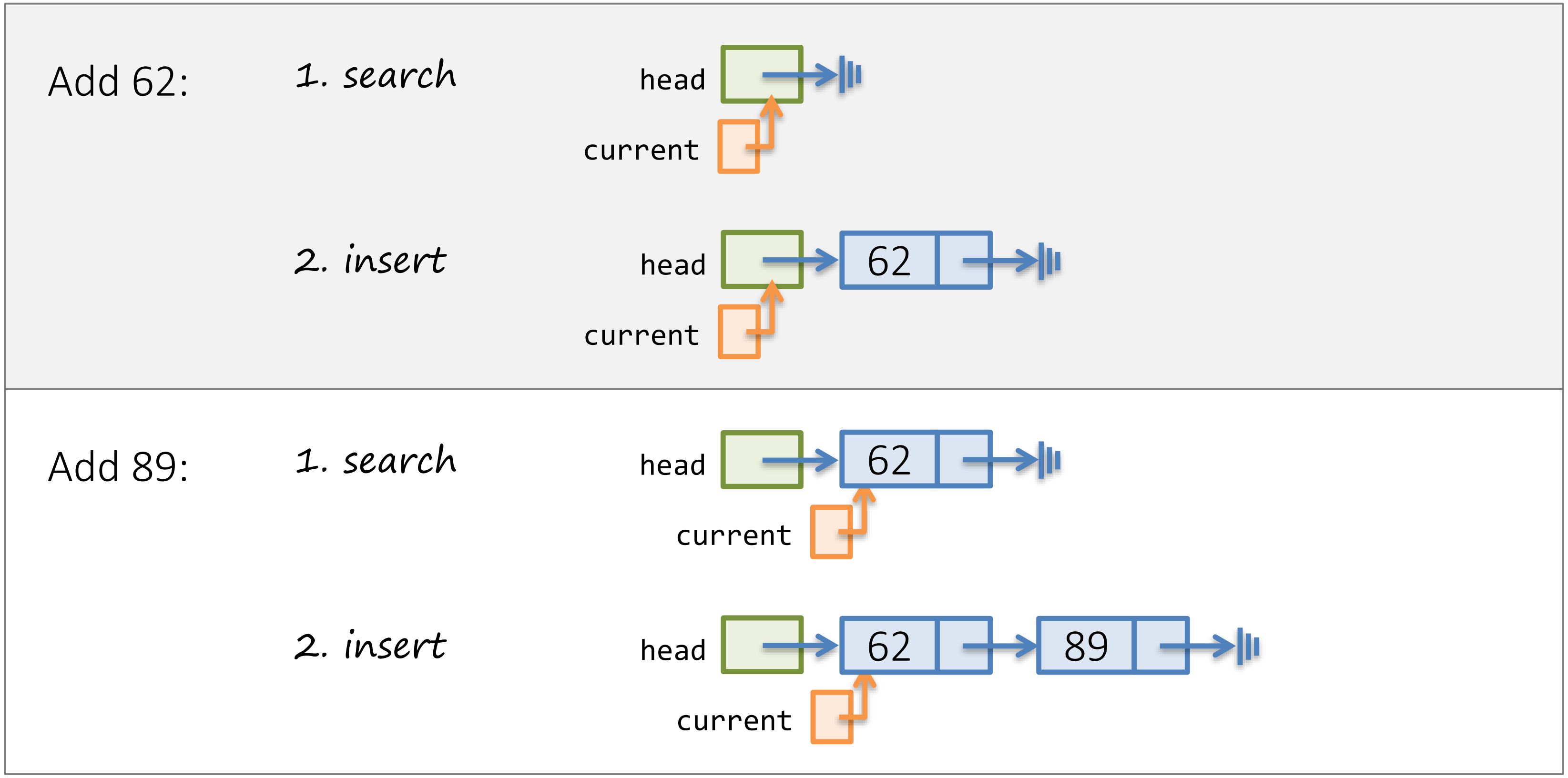
- To search for an item in a linked list is similar to traversing a list:
  - starting from the first node, we go through the items one by one
  - return the pointer to a found item, if found; or
  - return NULL if we reach the end of a list and the item is not found

```
Node * find( Node * head, int num )
{
    Node * current = head;

    while (current != NULL) {
        if (current->info == num)
            return current;
        else
            current = current->next;
    }

    return NULL;
}
```

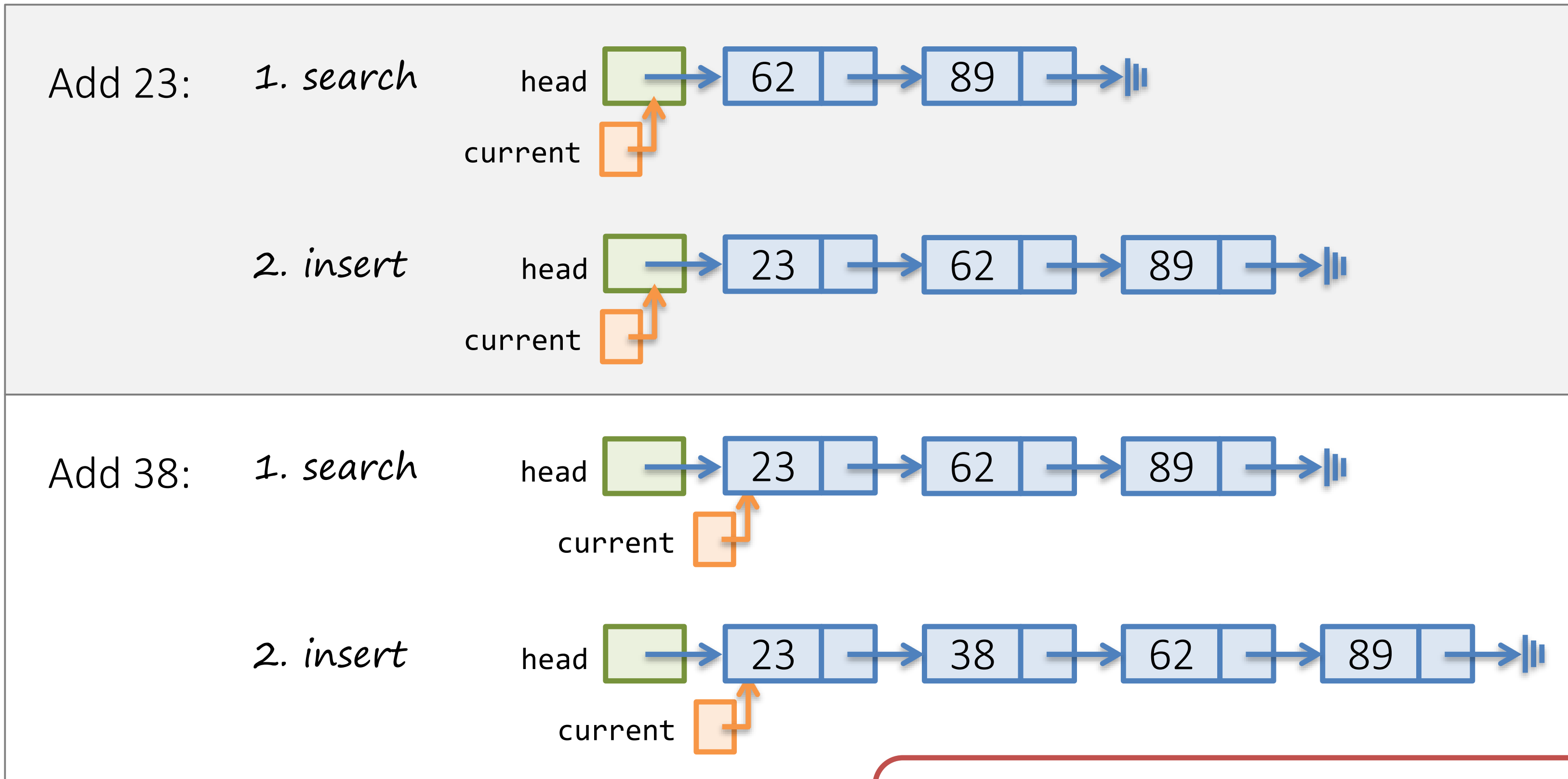
build_list_sorted.cpp

# Building a Sorted Linked List

- To build a sorted linked list in which the items are always maintained in order, we need to search for an appropriate location to insert before adding any new item to the list



# Building a Sorted Linked List




Note that current should always point to the previous node of where the new node is supposed to be

# Building a Sorted Linked List

```
// return the node which is the last one in
// the list that is smaller than num
Node * find_prev( Node * head, int num )
{
    if (head == NULL || head->info >= num)
        return NULL;

    // at least one node in the list now
    Node * current = head;

    while (current->next != NULL) {
        if (current->next->info >= num)
            return current;
        else
            current = current->next;
    }

    return current;
}
```

build_list_sorted.cpp

*Return NULL if the list is empty or the first item is not smaller than num*

*Compare the next item with num, >= makes sure that all items after current is larger than num*

*Execution reaches this point only when num is larger than all the existing items in the list*

*Compare this with the find() function*

# Building a Sorted Linked List

```
Node * head = NULL, * after_this;
int num = 0;

cin >> num;
while ( num != -999 ) {
    after_this = find_prev(head, num);

    if (after_this == NULL)
        head_insert(head, num);
    else
        insert(after_this, num);
    cin >> num;
}
```

The comparison in find_prev() determines whether the resulting list is in increasing order or in decreasing order

build_list_sorted.cpp

# Deleting an Entire List

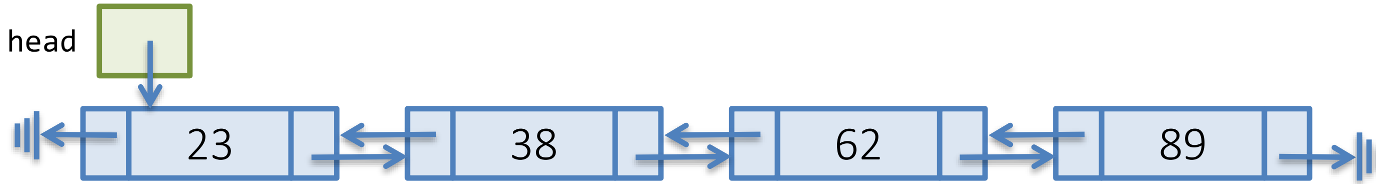
- To delete an entire linked list, we may iteratively delete the head node from it.

```
void delete_list(Node * & head)
{
    while ( head != NULL ) {
        delete_head(head);
    }
}
```

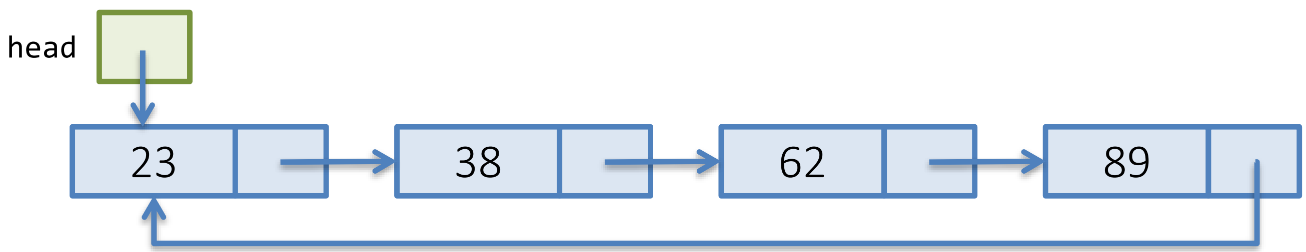
build_list_sorted.cpp

# Variations of Linked Lists

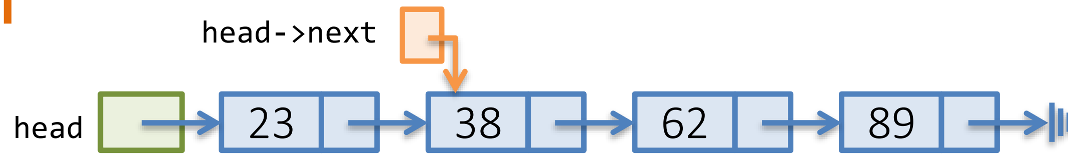
- Doubly-linked list




- Circularly-linked list



# Printing a Linked List in Reverse
## using Recursion




*Recursive algorithm*

To print a linked list pointed to by **head** in reverse

1. If linked list is empty, print nothing.
2. Otherwise,
   a) Print the linked list pointed to by **head->next** in reverse
   b) Print the node pointed to by **head**

```
void print_list_reverse(Node * head)
{
      if (head == NULL)
          cout << "NULL" << endl;

      else {
          print_list_reverse( head->next );
          cout << " <- " << head->info;
      }
}
```

print_list_reverse.cpp

Compare this to the iterative function for traversing a linked list here.

# Exercise 3

How to sort a linked list?

Idea: remove a node from the given list one by one, and built a new sorted linked list. You should have all the functions ready from the previous discussions.

Change the program build_list_backward.cpp and build_list_forward.cpp so that after a list is built, sort the list and output the contents

# Exercise 4

Add a function `reverse()` to `build_list_sorted.cpp` to reverse a linked list. Add a user option in the main function to test this new function. A sample call of the function is (where head is the pointer to the first node of a linked list:

```
reverse(head);
```

Solution: ex4ex5.cpp

# Exercise 5

Add a function **`get_item()`** to **`build_list_sorted.cpp`** to return the pointer to the k$^{th}$ item in the linked list. If no such item exists, return `NULL`. Add a user option in the main function to test this new function. A sample call of the function is:

```
Node * p = get_item(head, k);
if (p != NULL)
    cout << p->info << endl;
else
    cout << "Item does not exist." << endl;
```

Solution: ex4ex5.cpp

# Exercise 6

Add a function to `build_list_forward.cpp` to divide the linked list into two sublists of almost equal sizes. For example, if a list points to the elements `1 -> 2 -> 3 -> 4 -> 5 -> NULL`, after division, the first list should be `1 -> 2 -> 3 -> NULL` and the second list should be `4 -> 5 -> NULL`. Modify the main function to call this new function and print out the two resulting lists. A sample call of the function is:

```
divide(head, second);
```

where `head` points to a linked list to be divided, and after completion of the function, `head` points to the first sublist, and `second` points to the second sublist.

Solution: ex6.cpp

# We are happy to help you!

"Are the concepts too difficult? If you face any problems in understanding the materials, **please feel free to contact me, our TAs or student TAs**. **We are very happy to help you!**
We wish you enjoy learning programming in this class ☺."