Pointers

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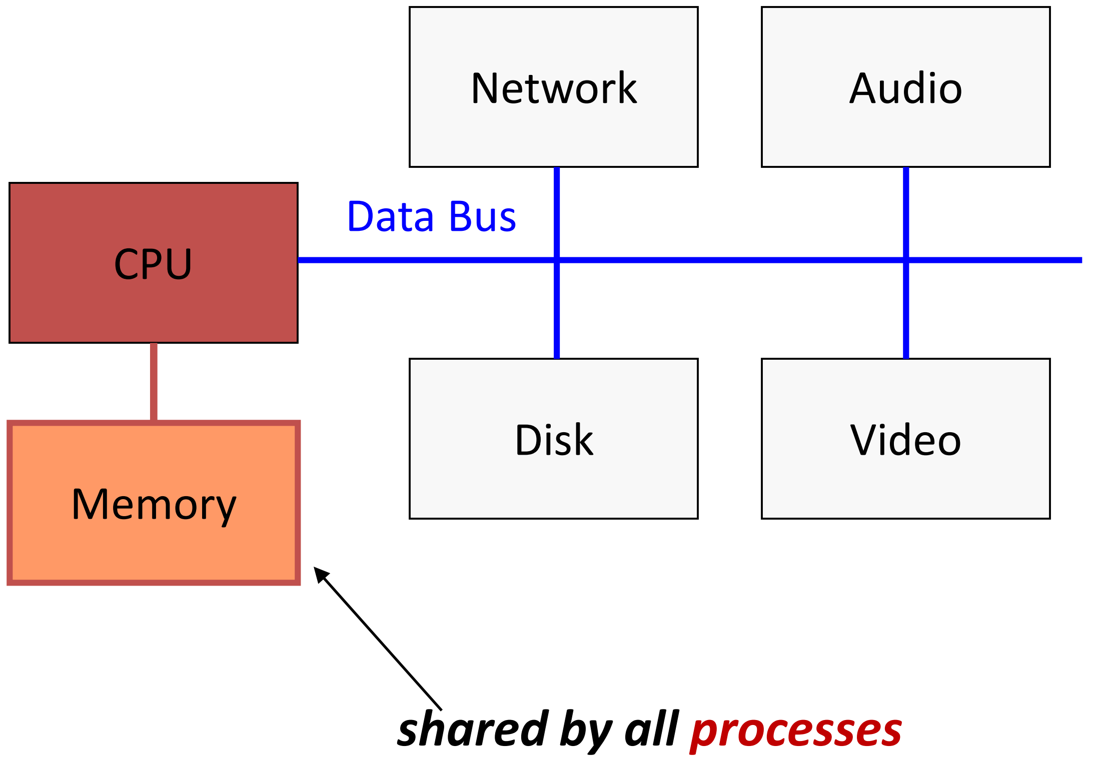
Main Memory

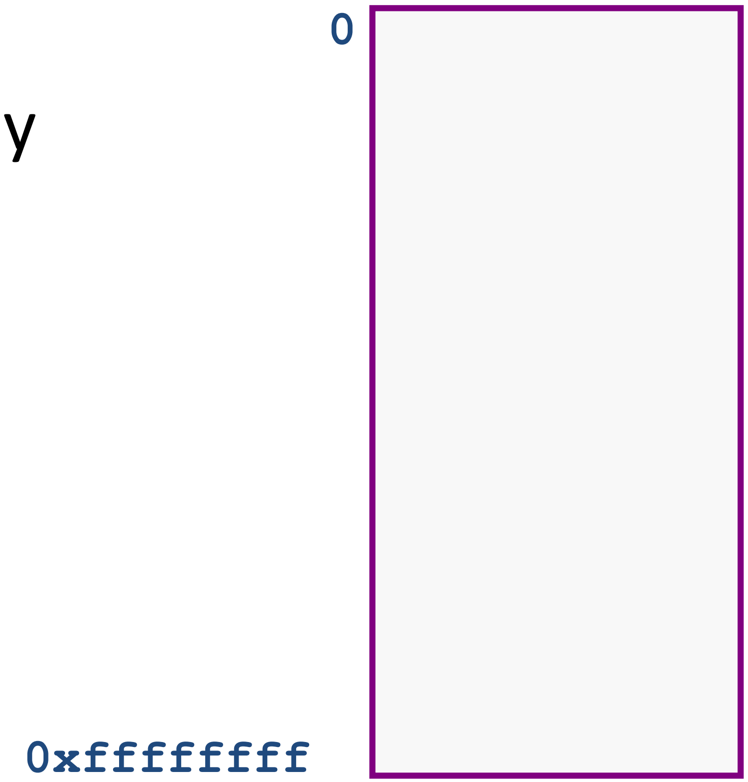


What is a process?

An executing program (loaded in memory) is called process…

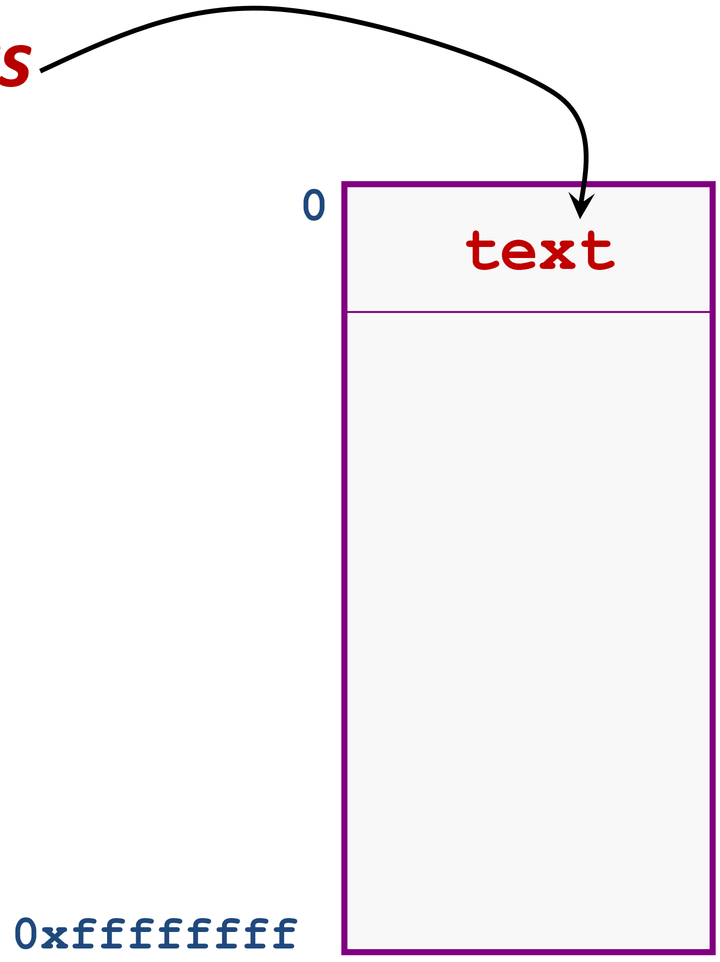
Virtual Memory
(How a CPU see's a Process?)

- **Continuous memory space for all process:**
  - **Set of locations** as **needed** by a **process**



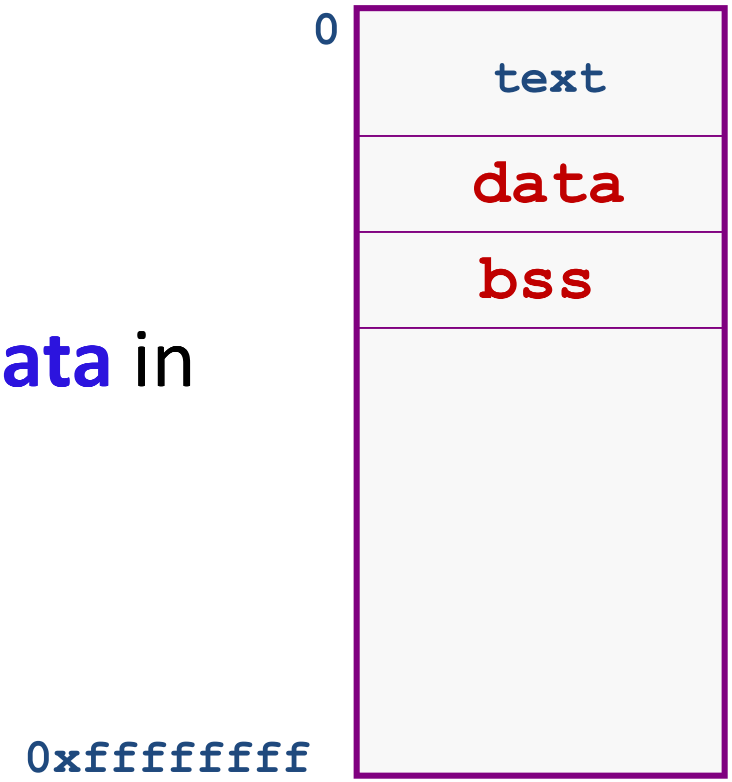
Organization of Virtual Memory: .text

- ***Program code*** and ***constants***
  - binary form
  - loaded libraries
  - code instructions
  - space calculated at compile-time



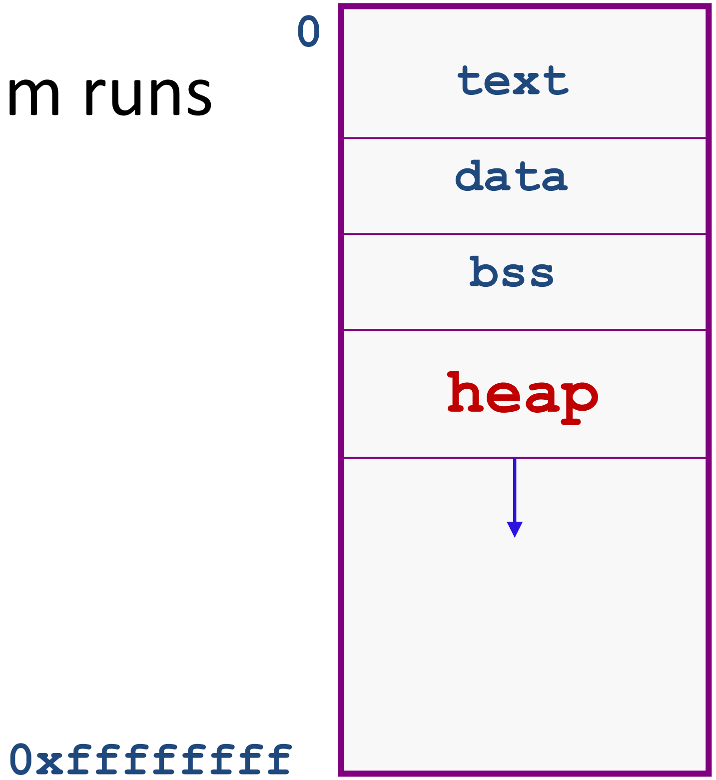
Organization of Virtual Memory: .data

- **Data**: **initialized global data** in the program
  - Ex: `int size = 100;`
- **BSS**: **un-initialized global data** in the program
  - Ex: `int length;`



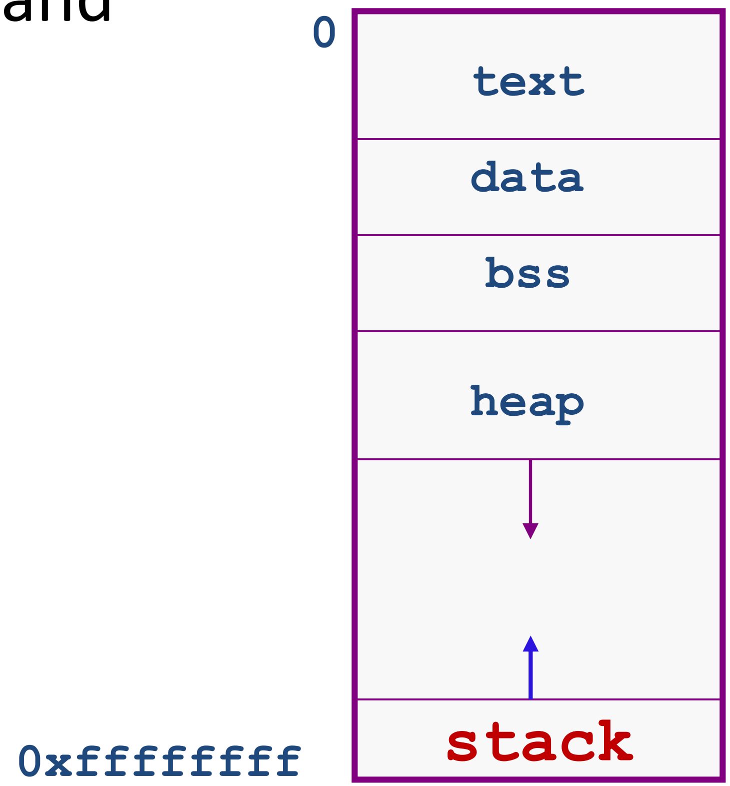
Organization of Virtual Memory: heap

- **Heap**: **dynamically-allocated spaces**
  - Ex: **new**, **delete**
  - **dynamically grows** as program runs



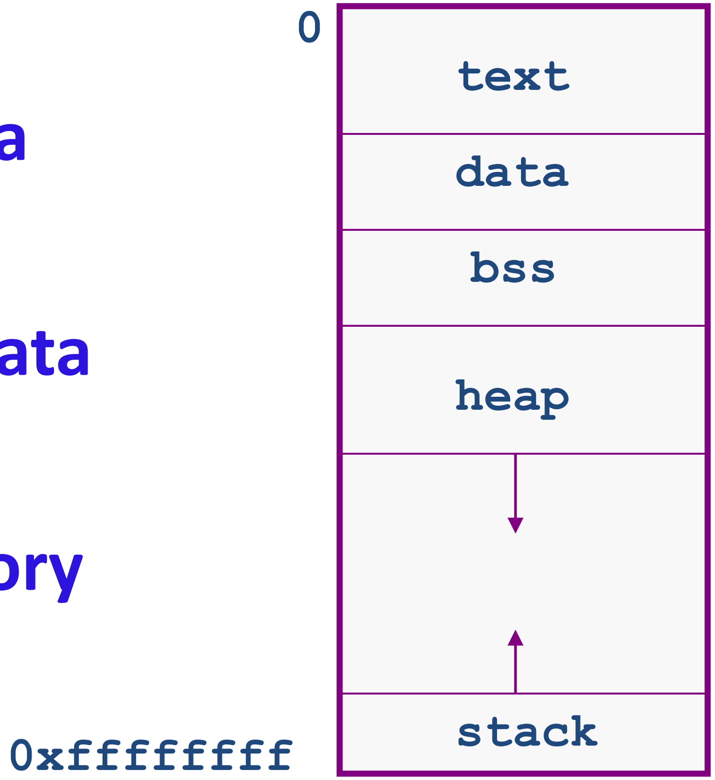
Organization of Virtual Memory: stack

- **Stack**: **local variables** in **functions**
  - **support function call/return** and **recursive functions**
  - **grow** to **low address**



Summary: Process Address Space

- **text**: program text/code and constants
- **data**: initialized global & static data
- **bss**: un-initialized global & static data
- **heap**: dynamically managed memory
- **stack**: function's local variables

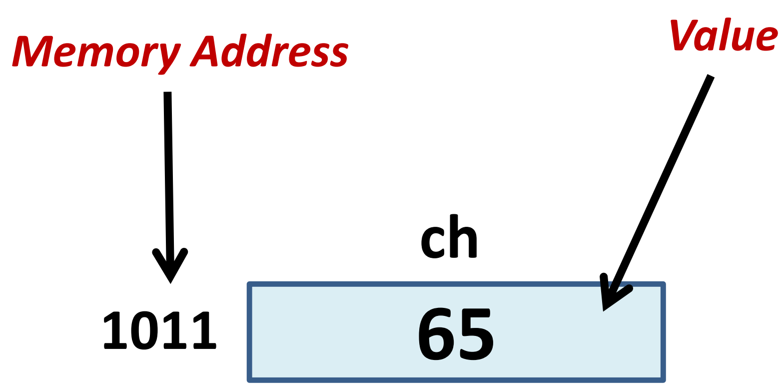


Introduction to Pointers

- When we **declare** a **variable,** some **memory** is **allocated** for it.

- Thus, we have **two properties** for any **variable**:
  1. Its **Address**
  2. and its **Data value**

E.g., char ch = ‘A’;



Introduction to Pointers

- **How to get** the **memory-address** of a **variable**?

- **Address** of a **variable** can be **accessed** through the **referencing operator** “**&**”
  - Example: **&i** ➔ will return **memory location** where the **data value** for “**i**” is stored.

➢ A **pointer is a variable**

➢ **Pointer stores only address**

Creating a Pointer Variable

Type* <variable Name>;

<u>Example:</u>

```
int* P;
float* P2;
```

- creates a ***pointer variable*** named **"P"**, that will ***store address*** (memory location) of some **int type** variable.

The address of Operator &

- The **&** operator can be used to **determine** the **address of** a **variable**, which can be **assigned to** a **pointer variable**

Examples:

Dereferencing Operator *

- **C++ uses** the * **operator** in yet **another way with pointers**
  - "The **variable values pointed to by p**" → ***p**
  - Here the * is the **dereferencing operator**

    p is said to be **dereferenced**

```
int v1=99;
int* p= &v1;
cout<<" P points to the value: "<<*p;
```

Dereferencing Pointer Example

```
int v1 = 0;
int* p1 = &v1;
*p1 = 42;
cout << v1 << endl;
cout << *p1 << endl;
```

v1 and *p1 now refer to the same variable

Output:

```
42
42
```

Pointer Assignment and Dereferencing

- **Assignment operator** (**=**) is used to assign value of one **pointer** to another

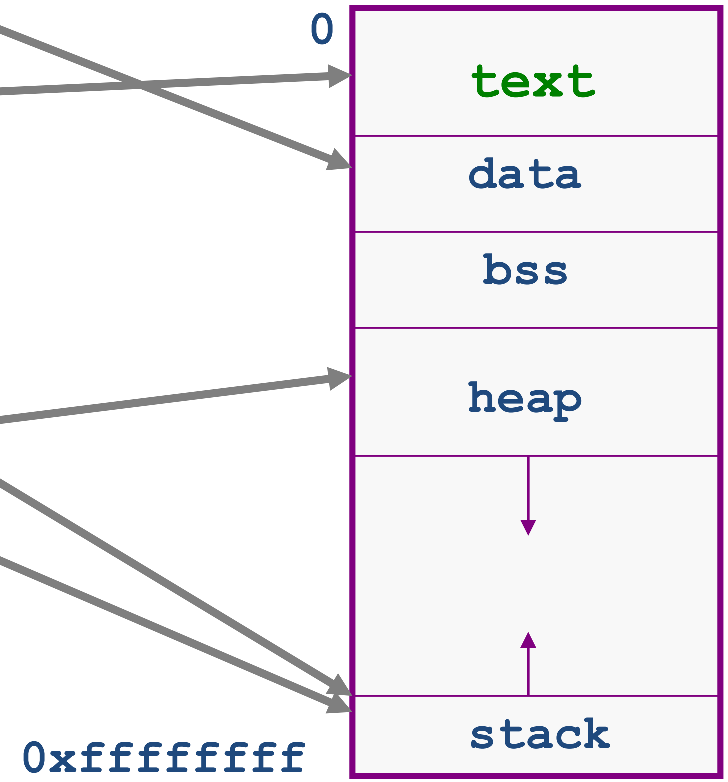
- **Pointer stores addresses** so **p1=p2** copies **an address value** into another pointer

```
int v1 = 55;
int* p1 = &v1;
int* p2;
p2=p1;
cout << *p1 << endl;
cout << *p2 << endl;
```

```
Output:

55
55
```

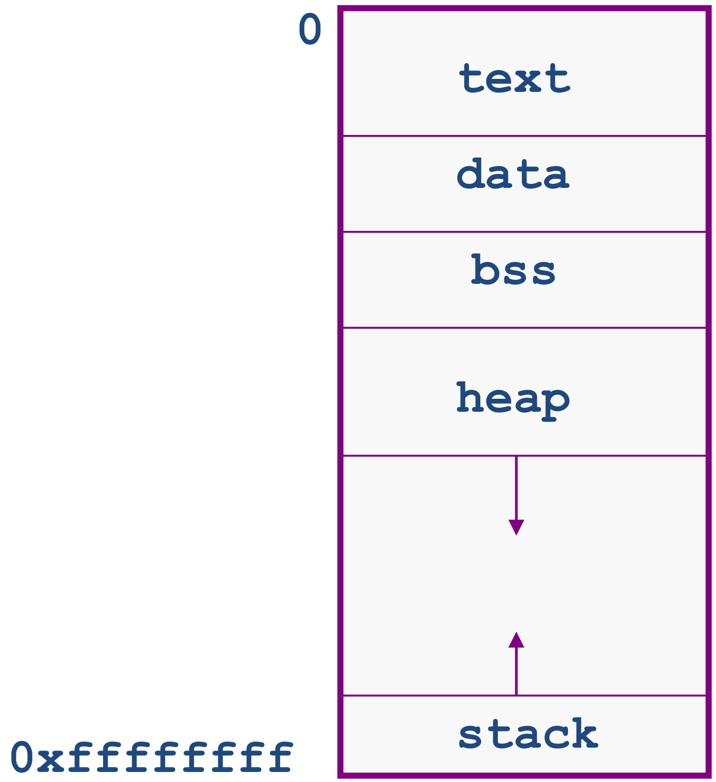
Storage and Data Allocation of C++ Program

```
char *str = "hello";

const int iSize=8;

char* f(int x)
{
  char *p;

  p = new char[iSize];

  return p;
}
```



Variables' Lifetime

- **text:**
  - program startup
  - program finish
- **data, bss:**
  - program startup
  - program finish
- **heap:**
  - dynamically allocated
  - de-allocated (free)
- **stack:**
  - function call
  - function return



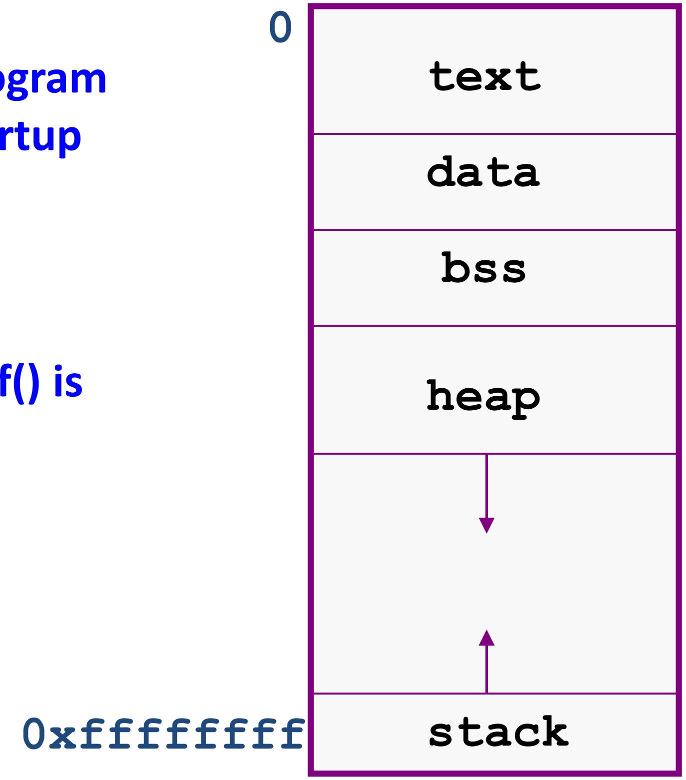
Example

```
char *string = "hello";

const int iSize=8;

char *f (int x)
{
  char *p;

  p = new char[iSize];

  return p;
}
```

program startup

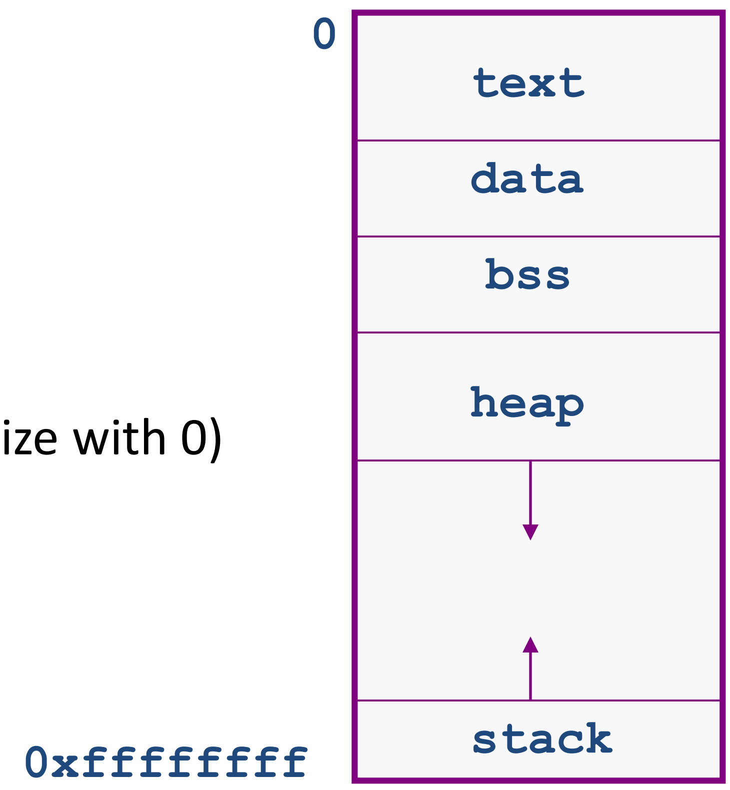
when f() is called

Live after allocation; till *delete* or program finish



Variables' Initialization

- **text:**
  - **Read-only (once; e.g., constants)**
- **data**
  - **on program startup**
- **bss:**
  - **un-initialized** (though some systems initialize with 0)
- **heap:**
  - **un-initialized**
- **stack:**
  - **un-initialized**



Pointer Assignments (Aliasing)

- Some **care is required** making **assignments to pointer** variables:

```
p1 = p2;       // changes the location that p1 "points" to

*p1 = *p2;   // changes the value at location that
             // p1 "points" to
```

Another Pointer Example

```
int i = 1;
int j = 2;
int* ptr;
ptr = &i; // ptr points to location of i
*ptr = 3; // contents of i are updated
ptr = &j; // ptr points to location of j
*ptr = 4; // contents of j are updated
cout << i << " " << j << endl;
```

```
Output:
        3  4
```

Swapping variables using Pointers

```
void main()  {
   char a = 'A';
   char b = 'Z';
   char *Ptr1= &a;
   char *Ptr2= &b;

   char temp = *Ptr1;
   *Ptr1 = *Ptr2;
   *Ptr2 = temp;

   cout << a << b << endl;
}
```

Dynamic Memory Allocation

- Used when space requirements are unknown at compile time

- Most of the time the amount of space required is unknown at compile time

- Dynamic Memory Allocation (DMA):-
  - With Dynamic memory allocation we can allocate/deletes memory (elements of an array) at runtime or execution time.

Static VS. Dynamic Memory Allocation

- **Dynamically allocated memory** is kept on the **memory heap** (also known as the **free store**)
- **Dynamically allocated memory** **cannot have a "name"**, it must be referred to (using address)
- **Declarations** are used to **statically allocate memory**
- The ***new*** **operator** is used to **dynamically allocate memory**

Dynamic Memory Allocation

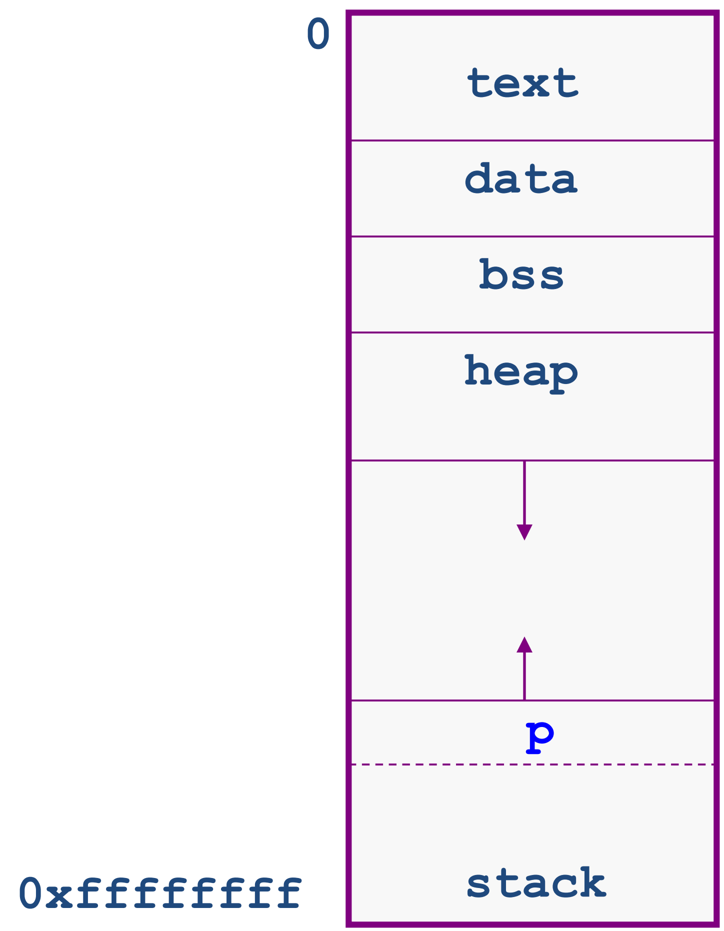
Heap management in C++ is explicit:

```
ptr = new data-type;
//allocte memory for one element

ptr = new data-type [ size ];
//allocte memory for fixed number of element
```

```
delete ptr;
//deallocte memory for one element

delete[] ptr;
//deallocte memory for array
```

Dynamic Allocation - Example

```
int main()
{
    int *p;

    p = new int;
    *p = 99;

    return 0;
}
```



Dynamic Allocation - Example

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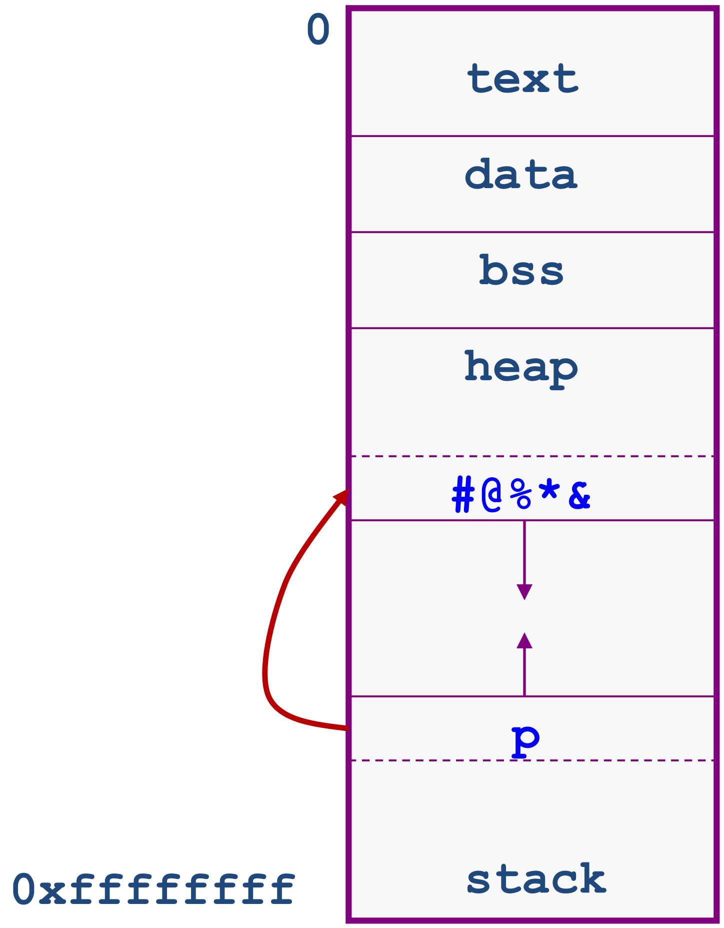
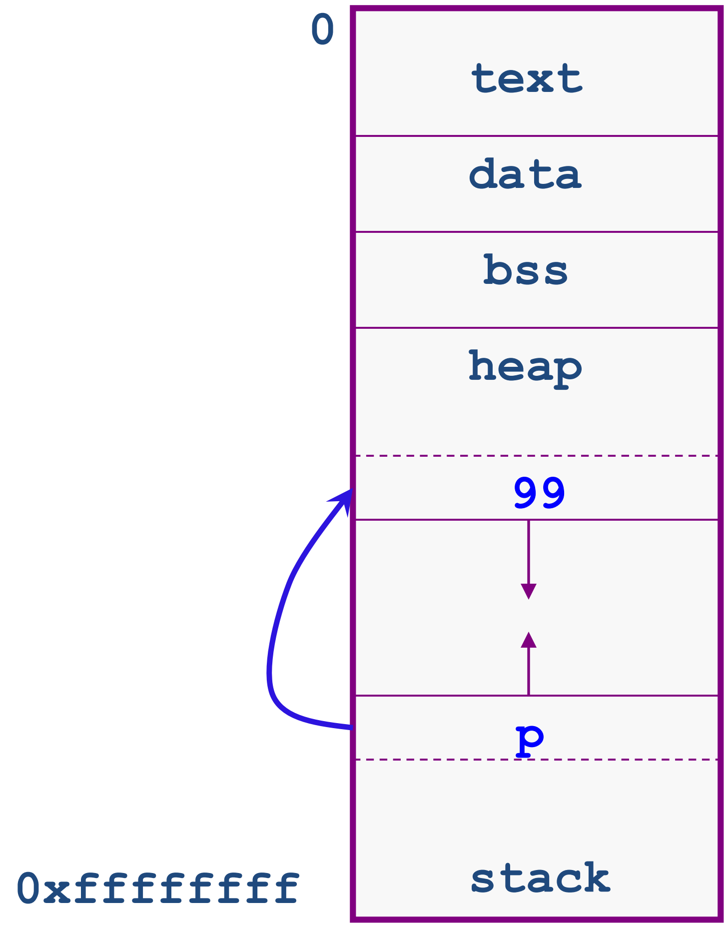


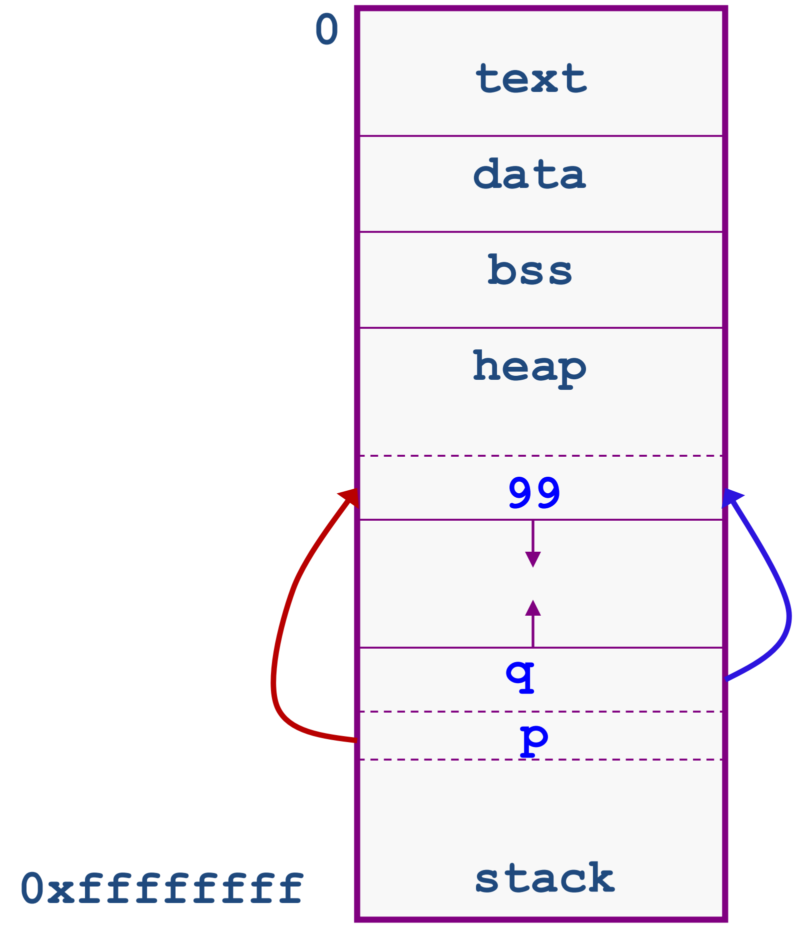
Dynamic Allocation - Example

```
int main()
{
  int *p;

  p = new int;
  *p = 99;

  return 0;
}
```



Pointer Aliasing

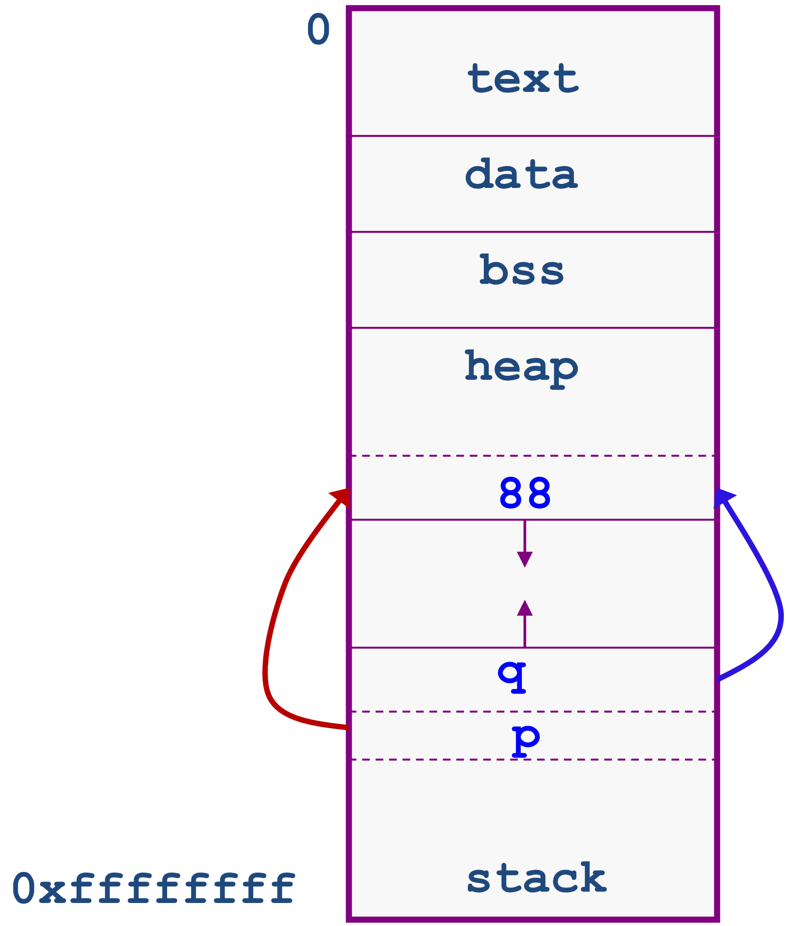
```
int main()
{
    int *p, *q;

    p = new int;
   *p = 99;
    q = p;

    return 0;
}
```



Pointer Aliasing: same memory location can be accessed using different names.

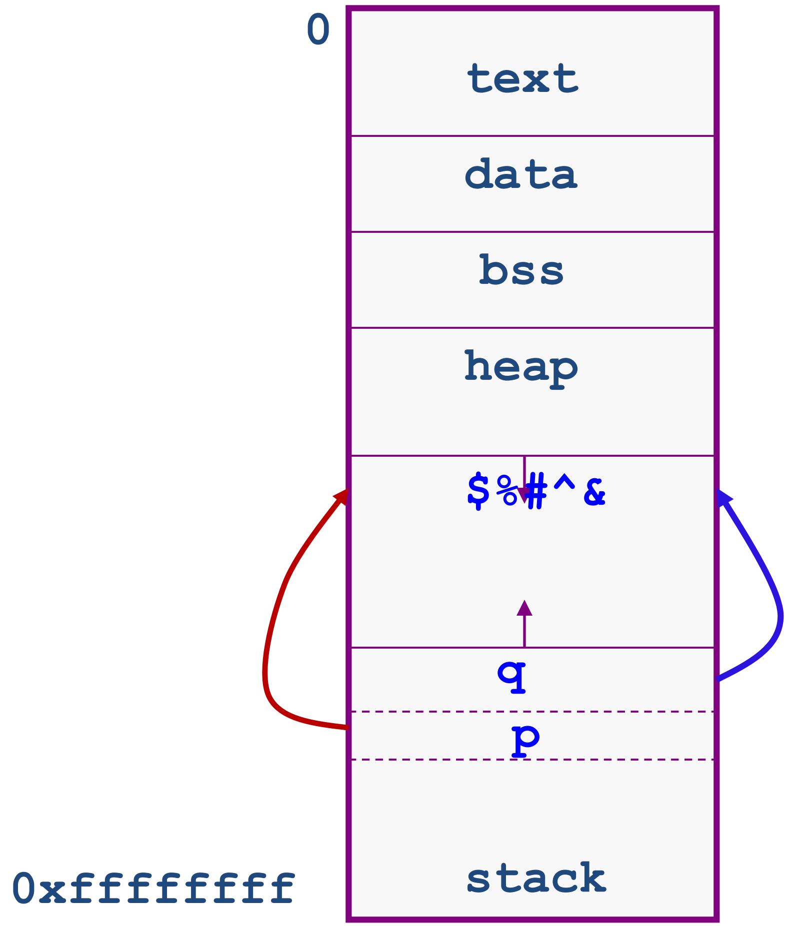
Pointer Aliasing

```
int main()
{
    int *p, *q;

    p = new int;
    *p = 99;
    q = p;

    *q = 88;

    return 0;
}
```



Pointer Aliasing

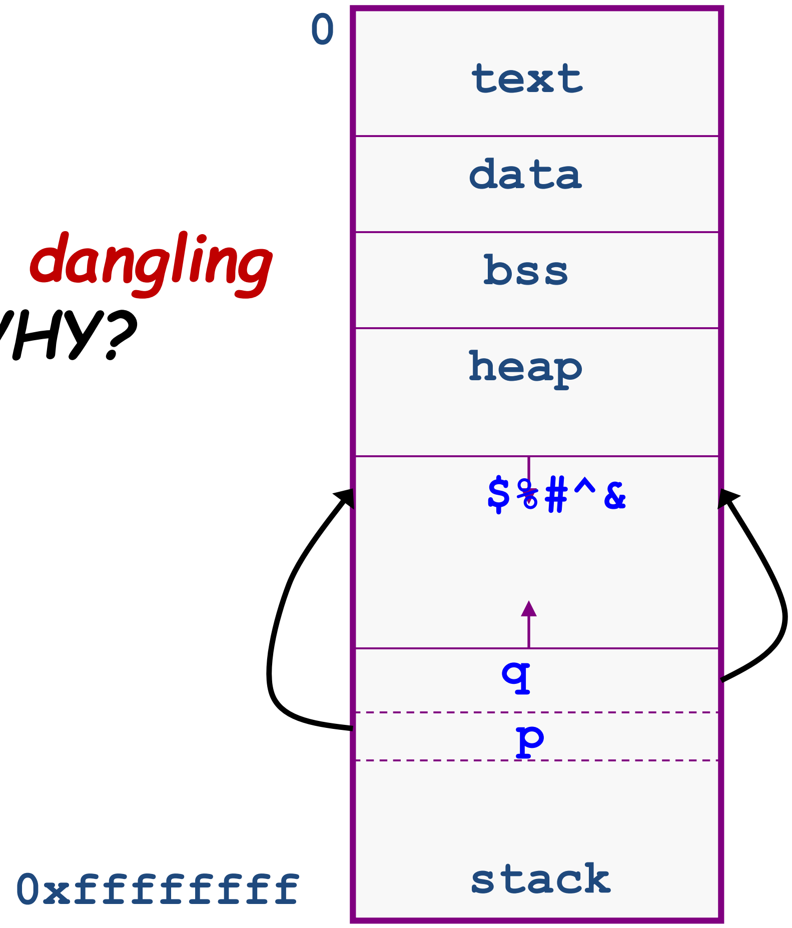
```
int main()
{
    int *p, *q;

    p = new int;
    *p = 99;
    q = p;

    *q = 88;

    delete q;

    return 0;
}
```



Dangling Pointers

```
int main()
{
    int *p, *q;

    p = new int;
   *p = 99;
    q = p;

    *q = 88;

    delete q;

    *p = 77;

    return 0;
}
```

P and q are dangling pointers, WHY?



Dangling Pointers

- The **delete operator** **does not delete the pointer**, it takes the **memory being pointed** to and **returns** it **to the heap**

- It **does not even change the contents** of the **pointer**

- Since the memory **being pointed to is no longer available** (and **may even be given to another application**), such a **pointer is said to be dangling**

Avoiding a Dangling Pointer

- **For Variables:**

```
delete v1;
v1 = NULL;
```

- **For Arrays:**

```
delete[ ] arr;
arr = NULL;
```

Returning Memory to the Heap

- **Remember:**
  - Return **memory to the heap before *undangling* the pointer**

- What's wrong with the following code:

```
ptr = NULL;
delete ptr;
```

Memory Leaking

```
int main()
{

    int *p;

    p = new int;

    // make the above space unreachable; How?
    p = new int;


    // even worse…; WHY?
    while (1)
        p = new int;

    return 0;
}
```

Memory Leaking

```
void f ( )
{
    int *p;
    p = new int;

    return;
}



int main ( )
{
    f ( );
    return 0;
}
```

Memory Leaks

- Memory ***leaks*** when it is **allocated from the heap** using the **new** operator but **not returned to the heap** using the **delete operator**

Memory Leaking and Dangling Pointers

- **Dangling pointers** and **memory leaking** are **evil sources of bugs**:
  - **hard to debug**
    - may appear after a long time of run
    - may far from the bug point
  - **hard to prevent**

What should be the good programming practices while using Pointers?

Null Address

- Like a **local variable**, a **pointer** is assigned a **random value (i.e., address)** if not initialized
- **0** is a **pointer constant** that represents the **empty** or **Null address**
- **Should be used to avoid dangling pointers**
  - **Cannot Dereference a Pointer whose value is Null:**

```
int *ptr = 0; OR int *ptr=NULL;

cout<< *ptr << endl;  // ERROR: ptr
                      // does not point to
                      // a valid address
```

Pointers Data-Type

- **Question:**

Why is it important to declare the type of the variable that a pointer points to?

Aren't **all memory addresses of the same length**?

Pointers Type

- **Answer:**

  - **All memory addresses are of the same length**,
    - However, with **operation "p++"** where **"p"** is a **pointer** → the **compiler needs to know** the **data type** of the **variable "p"** (**to jump at next memory location**)

  Examples:

  - If **"p"** is a **character-pointer** then **"p++"** will increment **"p"** by **one byte** **(next location)**
  - if **"p"** is an **integer-pointer** its value on **"p++"** would be incremented by **4 bytes** **(next loc.)**

Relationship Between Pointers and Arrays

- **Arrays** and **pointers** are **closely related**
  - **Array name** is **like** **constant pointer**
  - ***All arrays elements are placed in the consecutive locations***.
    - **Example:- int List [10];** ***List is the start address of array***

  - **Pointers can do array subscripting operations**
    We can access array elements using pointers.
    - **Example:-   int value = List [2];** //value assignment
      int* p = List; //address assignment

Relationship Between Pointers and Arrays

Effect:-

- **List is an address, no need for &**
- The **bPtr pointer** will contain the **address of the first element** of **array List**.
- Element **List[2]** can be accessed by **`*(bPtr+2)`**

Relationship between Arrays and Pointers

- **Arrays** and **pointers** are ***closely related:***

```
void main()
{
   int numbers[]={10,20,30,40,50};
   cout<<numbers[0]<<endl;        10
   cout<<numbers<<endl;           Address e.g., &34234
   cout<<*numbers<<endl;          10
   cout<<*(numbers+1);            20
}
```

Arrays and Pointers

Expression	Assuming p is a pointer to a…	… and the size of *p is…	Value added to the pointer
p+1	char	1	1
p+1	short	2	2
p+1	int	4	4
p+1	double	8	8
p+2	char	1	2
p+2	short	2	4
p+2	int	4	8
p+2	double	8	16

Warning: These byte increments are based on 32-bit architecture, adjust according to the machine architecture.

Pointer Arithmetic

Only two types of arithmetic operations allowed:

1) **Addition :** only integers can be added
2) **Subtraction:** only integers be subtracted

Which of the following are valid/invalid?

I. pointer + integer (ptr+1) ✓
II. integer + pointer (1+ptr) ✓
III. pointer + pointer (ptr + ptr) ✗
IV. pointer – integer (ptr – 1) ✓
V. integer – pointer (1 – ptr) ✗
VI. pointer – pointer (ptr – ptr) ★
VII. compare pointer to pointer (ptr == ptr) ✓
VIII. compare pointer to integer (1 == ptr) ✗
IX. compare pointer to 0 (ptr == 0) ✓
X. compare pointer to NULL (ptr == NULL) ✓

Comparing Pointers

- If one address comes before another address in memory, the ***first address*** is considered ***less than*** the ***second address.***

- Two pointer variables can be compared using C++ relational operators: **<**, **>**, **<=**, **>=**, **==**

- In an array, elements are stored in consecutive memory locations, E.g., *address of* **Arr[2]** *will be smaller than the address of* **Arr[3]** *etc.*

Void Pointer

- `void*` is a **pointer** to **no type** at all:
  - ***Any pointer type*** *may be* ***assigned*** *to* ***void ****

```
int iVar=5;
```

This is a great advantage…
So, What are the limitations/challenges?

```
p1 = &iVar;   // Allowed
p1 = &fvar;   // Not Allowed
P1 = &cVar;   // Not Allowed
vp2 = &fvar; // Allowed
vp2 = &cVar; // Allowed
vp2 = &iVar; // Allowed
```

Accessing 1-Demensional Array

```
….
….
    int List [50];
    int *p;
    p = List;
    p = p + 3;
    *P = 293;

}
```

Address	Data
980	Element 0
984	Element 1
988	Element 2
992	293
996	Element 4
1000	Element 5
1004	Element 6
1008	Element 7
1012	Element 8
…	
…	
1180	Element 49

Accessing 1-Demensional Array

```
…
…
    int List [ 50 ];
    int *Pointer;
    Pointer = List;
    for ( int i = 0; i < 50; i++ )
    {
        cout << *Pointer;
        Pointer++; //Address of next element

    }
```

This is Equivalent to

```
    for (int loop = 0; loop<50; loop++)
        cout<<Array[loop];
```

Address	Data
980	Element 0
984	Element 1
988	Element 2
992	293
996	Element 4
1000	Element 5
1004	Element 6
1008	Element 7
1012	Element 8
…	
…	
1180	Element 49

Accessing 2-Demensional Array

- **In 1D array if we use:**

```
int *Pointer;
Pointer = &List[3]; //accessing the
                    // address of 4th slot.
```

- **In 2-Demensional array:**

```
int main()
{
    int A[3][3]={{1,2,3},{4,5,6},{7,8,9}};
    int *p;
    p=A[2];
    cout<<"\nvalue of p= "<<*p<<endl; //outputs 7
    return 0;
}
```

Demo Code: pointersArrays1.cpp

Addres	Data
980	Element 0
984	Element 1
988	Element 2
992	293
996	Element 4
1000	Element 5
1004	Element 6
1008	Element 7
1012	Element 8
…	
…	
1180	Element 49

Accessing 2-Demensional Array

Full array traversal of 2D array:

```
int main()
{
    int A[3][3]={{1,2,3},{4,5,6},{7,8,9}};
    int *p;
    p=A;
    for(int i=0;i<9;i++)
    {
        cout<<"\nValue of p= "<<*p<<endl;
        p++; // or just cout<<*(p+i)
    }

    return 0;
}
```

- Pointer access is faster as compared to 2D array notation (one address calculation as compared to [ ][ ] row and col addresses)

Casting pointers

- **Pointers** have **types**, so **<u>you cannot do</u>**

```
int *pi; double *pd;
pd = pi;
```

- C++ will let you change the type of a pointer with an **explicit cast:**

```
int *pi; double *pd;
pd = (double*) pi;
```

<u>Warning:</u> Values dereferenced after the cast are undermined (because of possibly difference in memory size)

Creating Dynamic 2D Arrays

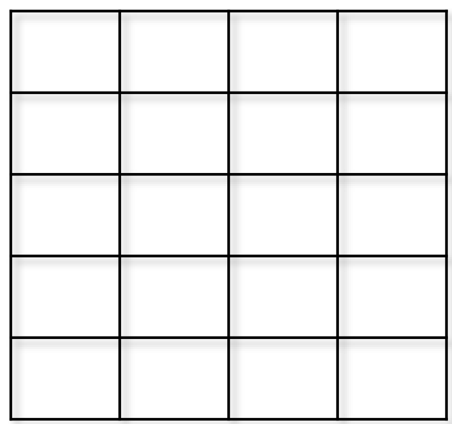
- Two basic methods:
  1. Using a single Pointer
  2. Using a Array of Pointers

Dynamic two dimensional arrays

1. Using a single Pointer

- Total elements in a 2D Array:
  - m * n (i.e., rows * cols)

5 rows * 4 columns
= 20 elements



Target Approach=

- allocate 20 elements using dynamic allocation
- Use a single pointer to point and access those items.

Dynamic 2D Arrays

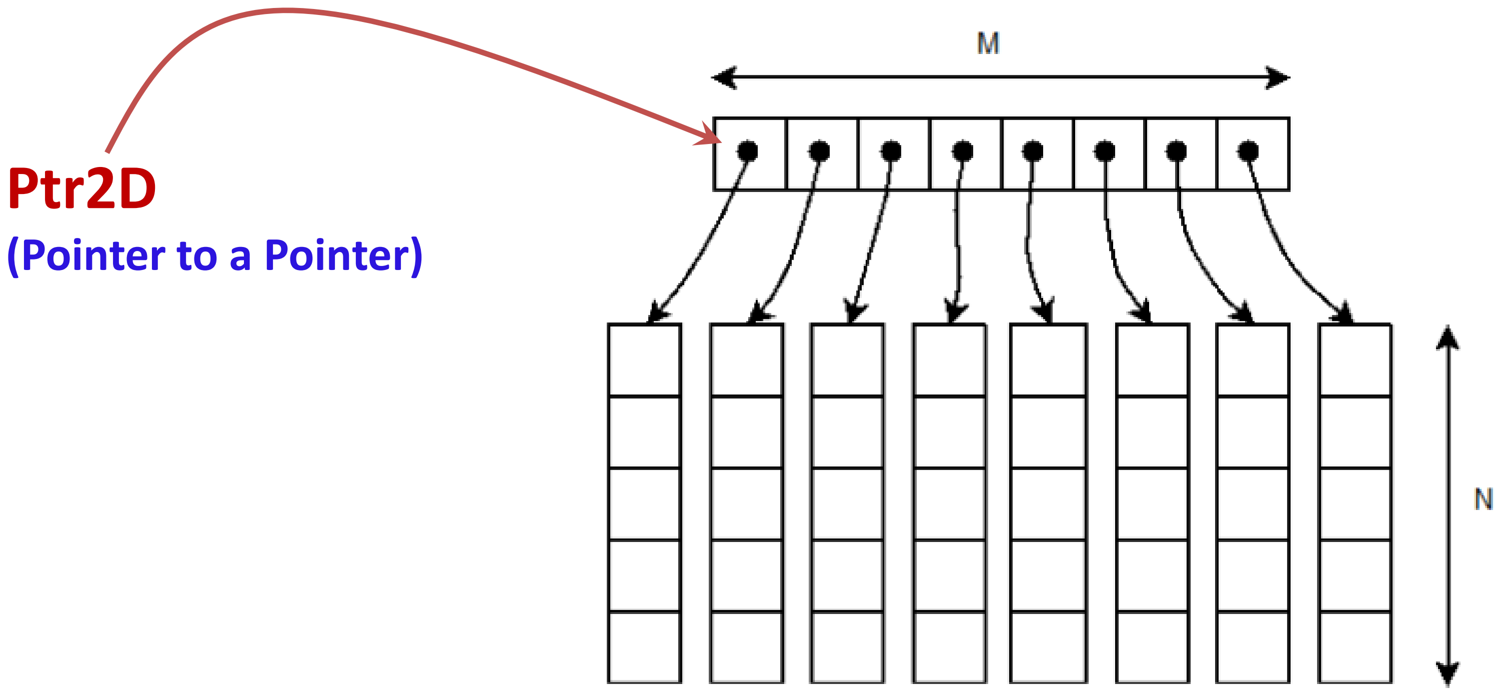
```
#include<iostream>
#include <stdlib.h>
#include<time.h>
using namespace std;
int main()
{
   int M=4; int N=5;
   int* Arr=new int[M*N];
   srand(time(0));

   //set values
   for(int i=0;i<M;i++)
        for(int j=0;j<N;j++)
               *(Arr + i*M+j) = rand()%100;

   //display values
   for(int i=0;i<M;i++) {
       for(int j=0;j<N;j++) {
           cout<<*(Arr + i*M+j)<<"   ";
           //cout<<(Arr+i*M)[j]<<"   ";
       }
     cout<<endl;
    }
    delete[] Arr;
   return 0; }
```

Demo Code:
pointersArrays2.cpp

Dynamic 2D Array – Double Pointer

2. Using a Pointer that points to Array of Pointer

- Total elements in a 2D Array: M_rows * N_coulmns



Dynamic 2D Array – Double Pointer

```
int **dynamicArray = 0;

//memory allocated for elements of rows.


dynamicArray = new int *[ROWS] ;

//memory allocated for  elements of each column.


for( int i = 0 ; i < ROWS ; i++ )
dynamicArray[i] = new int[COLUMNS];

//free the allocated memory


for( int i = 0 ; i < ROWS ; i++ )
delete [] dynamicArray[i] ;
delete [] dynamicArray ;
```

Dynamic 2D Arrays

Demo Code: pointersArrays3.cpp

```
int main() {
   int M=4; int N=6;
   int** A=new int*[M]; srand(time(0));

   for(int i=0;i<M;i++) /*Allocate subarrays */
       A[i]=new int[N];

   for(int i=0;i<M;i++)
        for(int j=0;j<N;j++)
                A[i][j] = rand()%100;

   //display values
   for(int i=0;i<M;i++) {
       for(int j=0;j<N;j++) {
           cout<<A[i][j]<<"   ";
       }
     cout<<endl;
    }

    //deallocate memory
    for(int i=0;i<M;i++)
       delete[] A[i];

    delete[] A;
    return 0;
}
```

- **A** → start of array of pointers
- ***A** → First Address pointed by first row (sub-array)
- ***(*A)** → First value of first array
- **(*A)++** → Move to next address in the first array
- **A++** → Move to Next row (second sub-array)

Can we vary size of each column in Dynamic 2D Array (using double pointer)

Dynamic 2D Array

(Varying Row Size)

```
// Dynamically Allocate Memory for 2D Array in C++
int main()
{
    // dynamically create array of pointers of size M
    int** A = new int*[M];

    // dynamically allocate memory of size N for each row
    for (int i = 0; i < M; i++)
        A[i] = new int[N+i];

    // assign values to allocated memory
    for (int i = 0; i < M; i++)
        for (int j = 0; j < N+i; j++)
            A[i][j] = rand() % 100;

    // print the 2D array
    for (int i = 0; i < M; i++)
    {
        for (int j = 0; j < N+i; j++)
            std::cout << A[i][j] << " ";

        std::cout << std::endl;
    }

    // deallocate memory using delete[] operator
    for (int i = 0; i < M; i++)
        delete[] A[i];

    delete[] A;

    return 0;
}
```

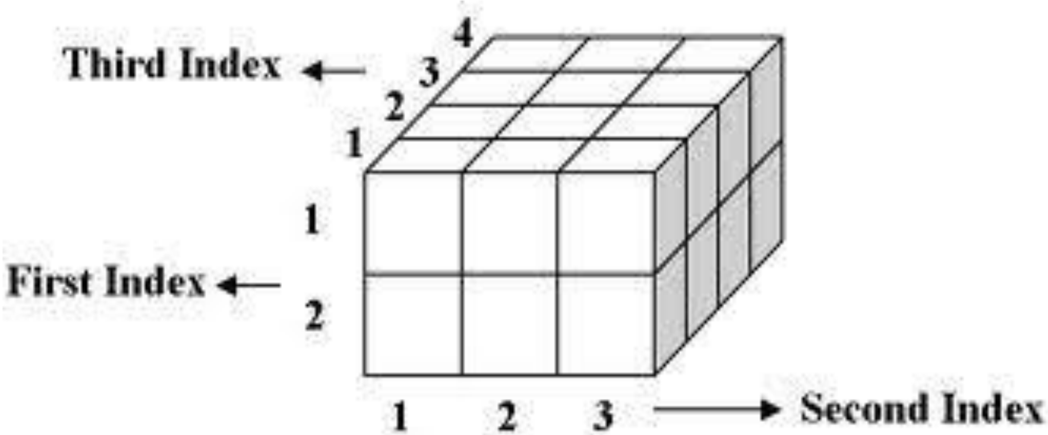
Output

```
83 86 77 15 93
35 86 92 49 21 62
27 90 59 63 26 40 26
72 36 11 68 67 29 82 30
```

Home Work

- Manipulating a 3D Array

1. Using a single pointer
2. Using a triple pointer



Three-dimensional array with twenty four elements

Constant Pointer

- A **constant pointer** is a **pointer** that is **constant**, such that we **cannot change** the **location** (**address**) to which the pointer points to:

```
char c = 'c';
char d = 'd';
char* const ptr1 = &c;
ptr1 = &d;  // Not Allowed
int v1=90;
int* const ptr2=&v1;
```

Pointer to Constant 1/2

- we **cannot** set a **non-const pointer** to a **const data-item**

```
const int value = 5; // value is const
int *ptr = &value; // compile error: cannot convert
                   // const int* to int*
// To avoid such operations→ *ptr = 6;

const int value = 5;
const int *ptr = &value; // this is okay,
*ptr = 6; // not allowed,
          // we cannot change a const value
```

Pointer to Constant 2/2

- A **pointer** through which we **cannot change** the **value** of **variable** it **points** is known as a **pointer to constant**.
- These type of pointers **can change** the **address** they point to but **cannot change** the **value** kept at those address.

```
int var1 = 0;
const int* ptr = &var1;
*ptr = 1;  // Not Allowed
 cout<<*ptr;
```

Home-Work: char* and const

- `const char *ptr` : This is a pointer to a constant character. **You** cannot change the value pointed **by ptr, but you** can change the pointer **itself**.

- `char* const ptr` : This is a constant pointer to **non-constant character**. **You** cannot change the pointer p, **but** can change the value pointed **by ptr.**

- `const char* const ptr` : This is a constant pointer to constant character. **You** can neither change the value pointed by ptr nor the pointer ptr.

C-String and Char Pointer

- A **String:** is simply defined as **an array of characters**

  char* s;

  // **s** is the **address** of the **first character** (byte) of the **string**

- A **valid C string ends** with the **null character** **'\0'**

- **Direct initialization** char* <string Literal>;

```
char* s="FAST";
cout<<s<<sizeof(s);
cout<<++s<<sizeof(s);
```

char [ ] VS. char *

```
char A[20]="FAST";
```

1) A is an Array

2) A++; //invalid

3) sizeof(A) → 20 Characters or bytes

4) A and &A points to same memory address

5) A="PAKISTAN"; //invalid
A is an address, "PAKISTAN" is the start address where "PAKISTAN" string is stored in memory.

6) A[0]='p'; //Valid

7) A is stored in stack

```
char* P="FAST";
```

1) P is a pointer variable

2) P++; //Valid

3) Sizeof(P) → 4 Characters or bytes

4) P points to start address where characters are stored, and &P points to address of pointer variable.

5) P="PAKISTAN" //valid

6) P[0]='p'; //inValid

7) P is stored in Stack, "FAST" is stored in "Text" section (Read-only)

C-String and Char Pointer - Example

```
// Copying string using Pointers

char* str1 = “Self-conquest is the greatest victory.”;
char str2[80]; //empty string
char* src = str1;
char* dest = str2;

while( *src ) //until null character,
      *dest++ = *src++; //copy chars from src to dest

*dest = ‘\0’; //terminate dest

cout << str2 << endl; //display str2
```

Functions→ Pass by using Reference Pointer

- **Pass-by-reference with pointer** arguments
    - Use pointers as formal parameters and addresses as actual parameters

- **Pass address** of **argument** using **&** operator
    – **Arrays not passed with &** because array name already an address
    – Pointers variable are used inside function

Pass by Reference Pointers– Example1

```
void func(int  *num)
{
      cout<<"num = "<<*num<<endl;
      *num = 10;
      cout<<"num = "<<*num<<endl;
}

void main()
{
    int n = 5;
    cout<<"Before call: n = "<<n<<endl;
    func(&n);
    cout<<"After call: n = "<<n<<endl;
}
```

Pass by Reference Pointers– Example2

```
void compDouble(int* Ar)
{
    for(int i=0;i<10;i++)
    {       *Ar=(*Ar)*2;
             Ar++;
    }
}
void main()
{   int Arr[10]={0,1,2,3,4,5,6,7,8,9};
    compDouble(Arr);
    for(int i=0;i<10;i++)
            cout<<Arr[i]<<endl;
}
```

Any Questions!