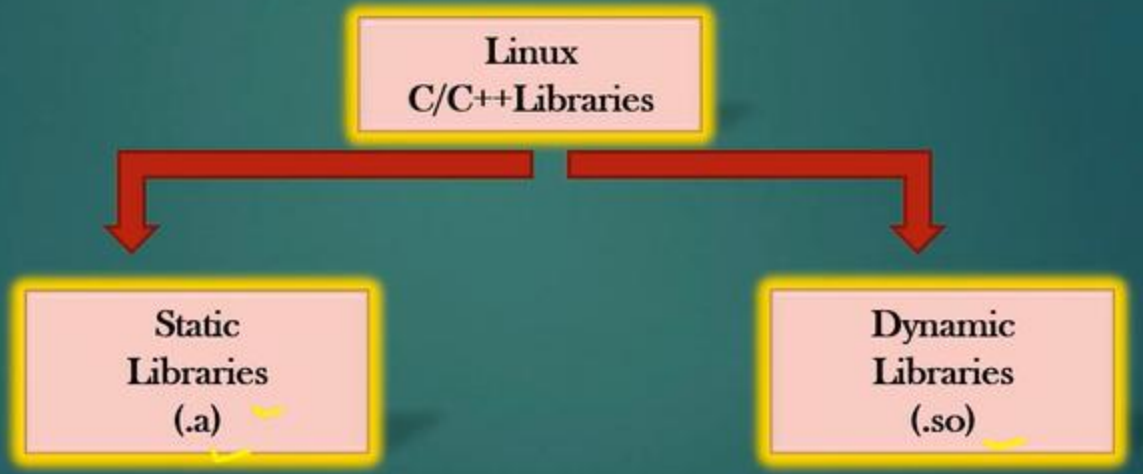
Library

- C/C++ source files can be compiled to form two flavors of Libraries on Linux Platform
- Libraries are collection of compiled object files (.o)



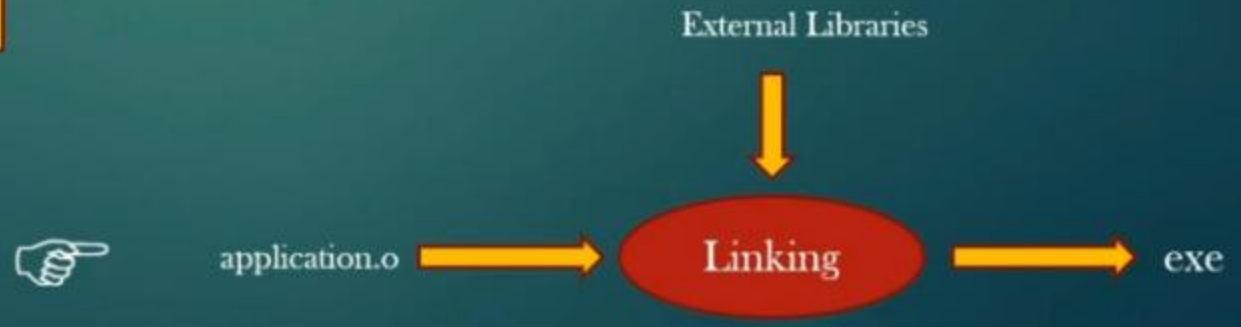
- We shall learn the process of creation of two types of libraries, and how they internally work

Library Integration - Static

- Some developer wrote DLL library and provide you dll.h and libdll.a (Or libdll.so). Note that you don't have direct access to dll.c/dll_util.c file now
- You have written your application *application.c* which uses DLL
- How will you create your final executable now ?

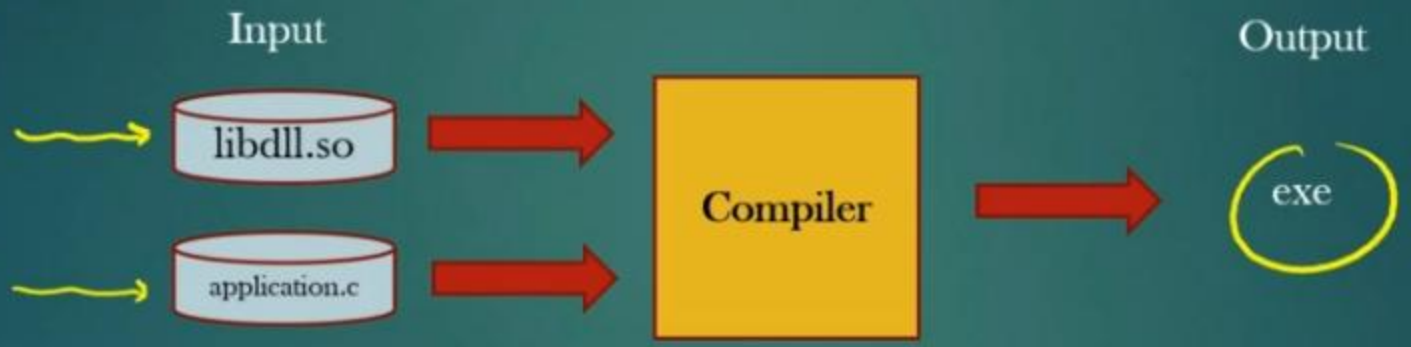
Steps :

1. gcc -c application.c -o application.o
2. gcc application.o -o exe -L . -ldll
3. Run executable : ./exe



Library Integration - Dynamic

- How will you create your final executable when we have Shared library file ?

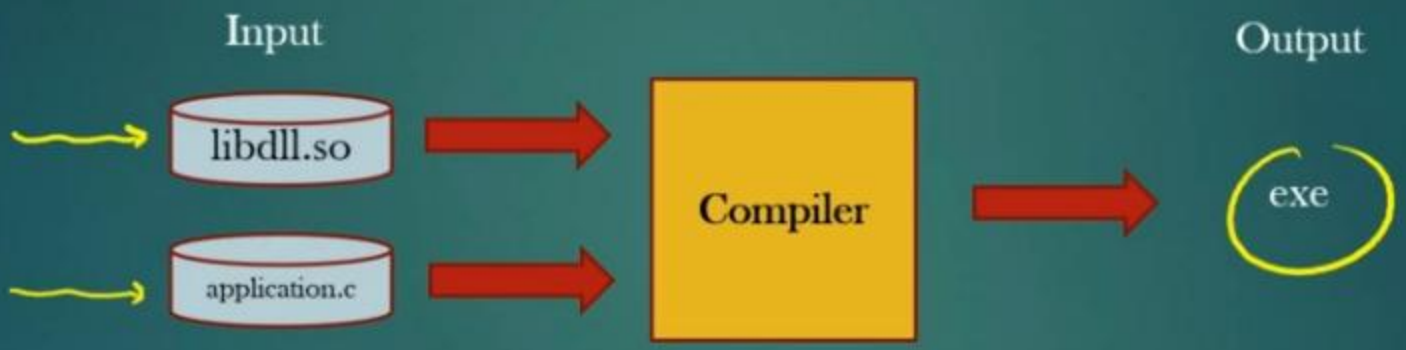


Steps :

1. gcc -c application.c -o application.o
2. Place the libdll.so file in default location in /usr/lib and run *sudo ldconfig* command
3. gcc application.o -o exe -ldll *(Linking)*
4. Run executable : ./exe

Library Integration - Dynamic

- How will you create your final executable when we have Shared library file ?

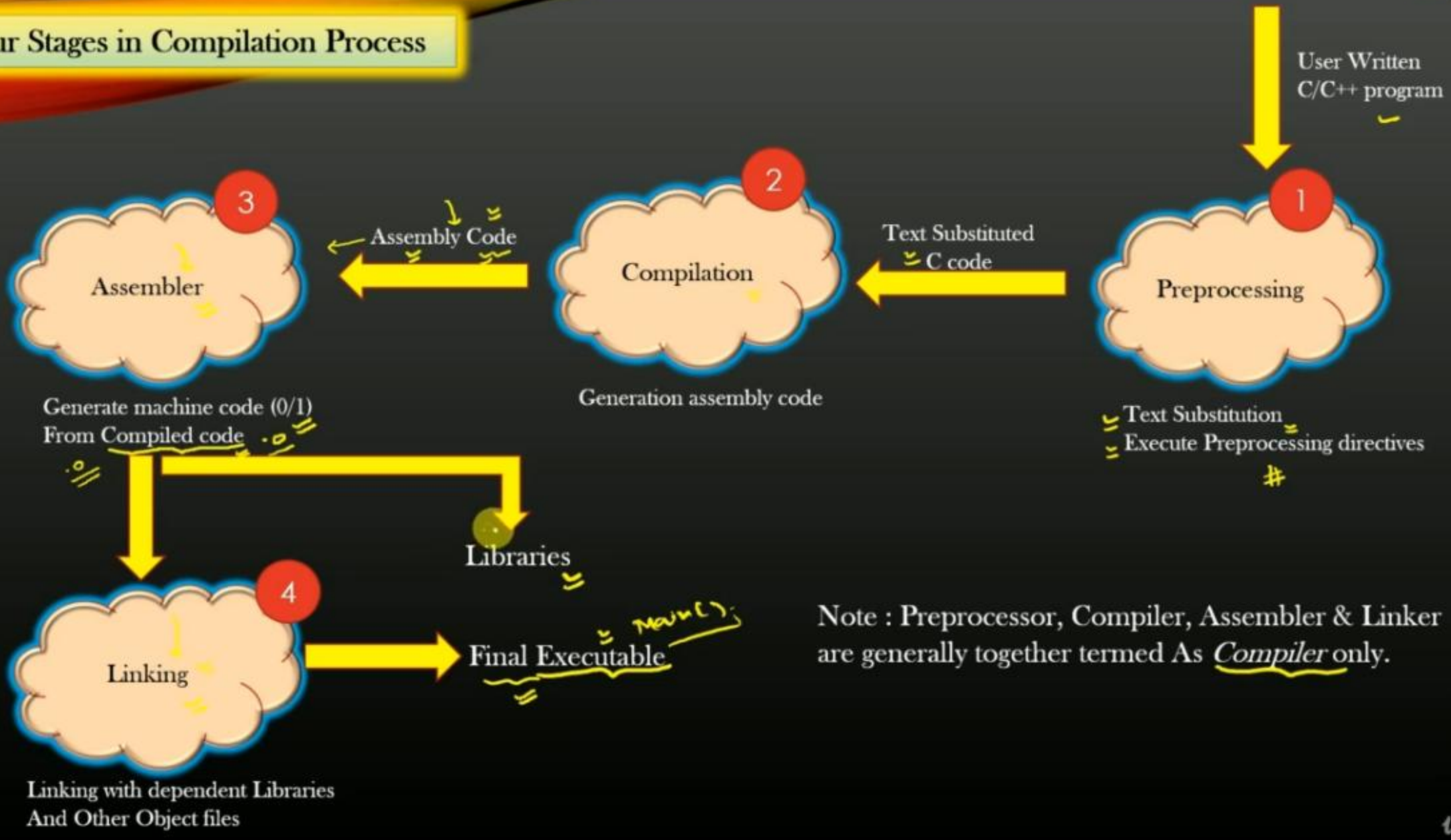


Steps :

1. gcc -c application.c -o application.o
2. Place the libdll.so file in default location in /usr/lib and run *sudo ldconfig* command
3. gcc application.o -o exe -ldll *(Linking)*
4. Run executable : ./exe

4 stages of Compilation

Four Stages in Compilation Process



Note : Preprocessor, Compiler, Assembler & Linker are generally together termed As *Compiler* only.

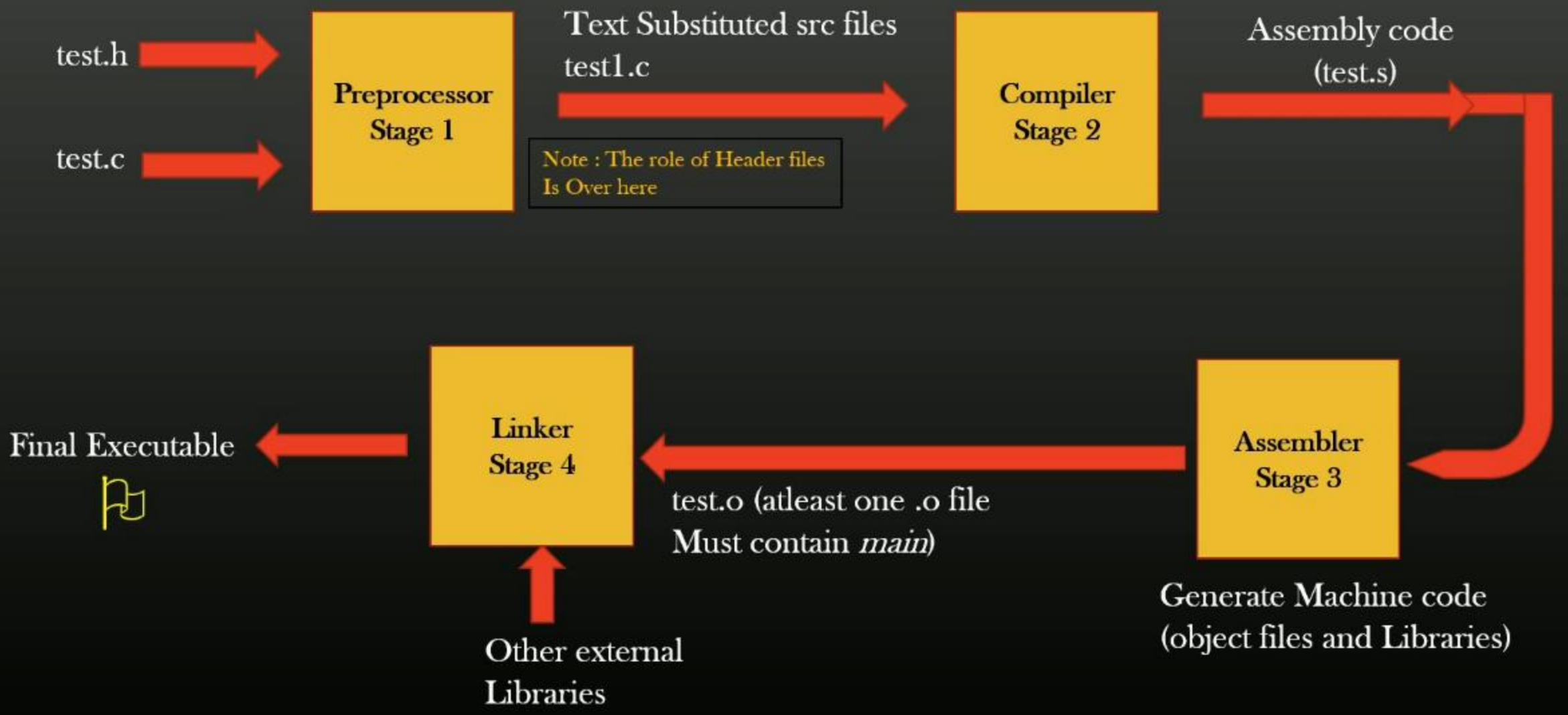
Four Stages in Compilation Process

Preprocessing stage :

All #includes<abc.h> are replaced by contents of abc.h recursively

All #defines are applied in src file code and then #defines themselves are removed

Four Stages in Compilation Process



Makefile

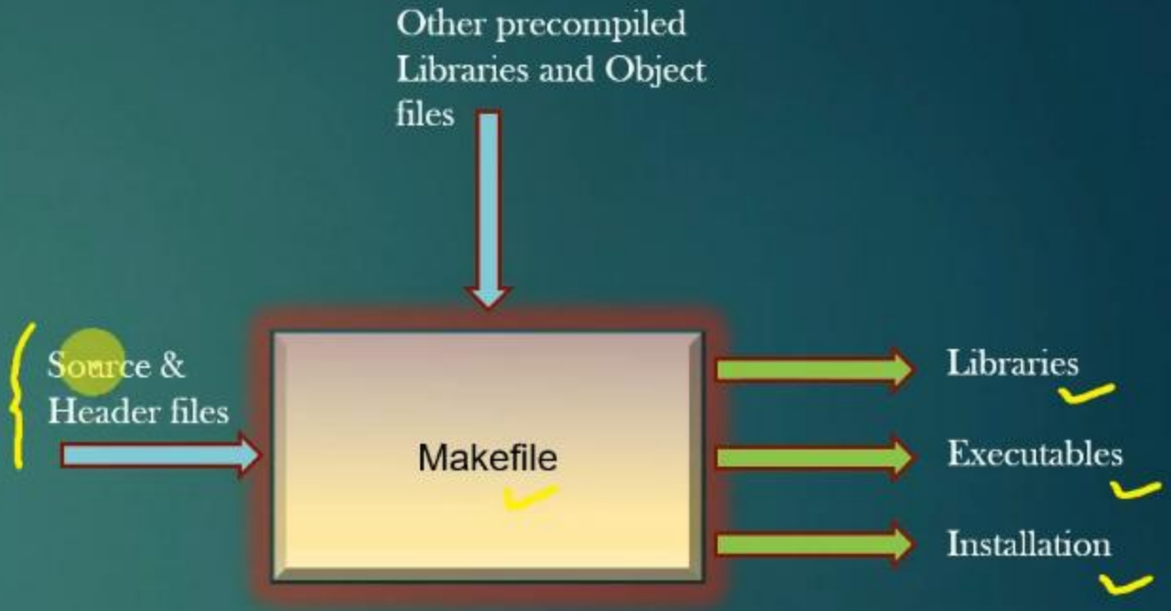
- Makefile is a *program building tool* which runs on Unix, Linux, and their flavors.
- It aids in simplifying building the software program that may dependent on various other libraries
- For example, if you have a software program which has
  - 200 source files
  - 20 header files

  And you need to create below dishes from above Raw material :
  - 10 static libraries
  - 5 shared libraries
  - 3 executable
- Then, you need to make use of Makefile. You will go mad if you do it one by one !
- Makefile contains all the commands required to build all the Dishes you need
- 99% students never make use of Makefiles to build and compile their C/C++ programs !! ☹ Sad !!

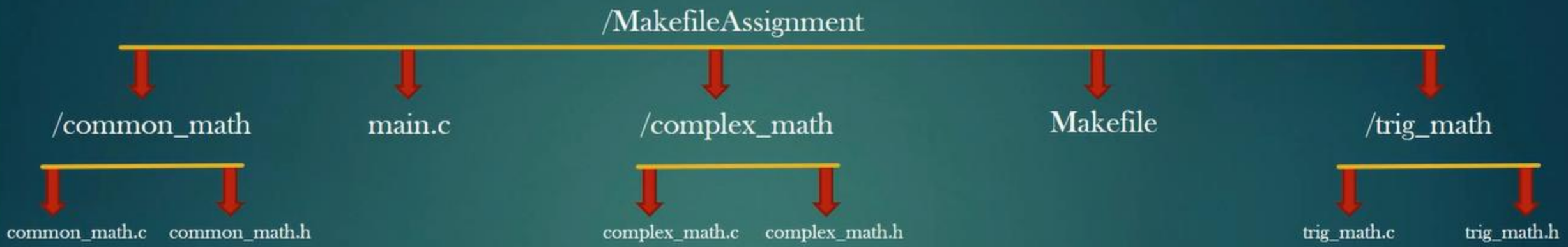
Makefile

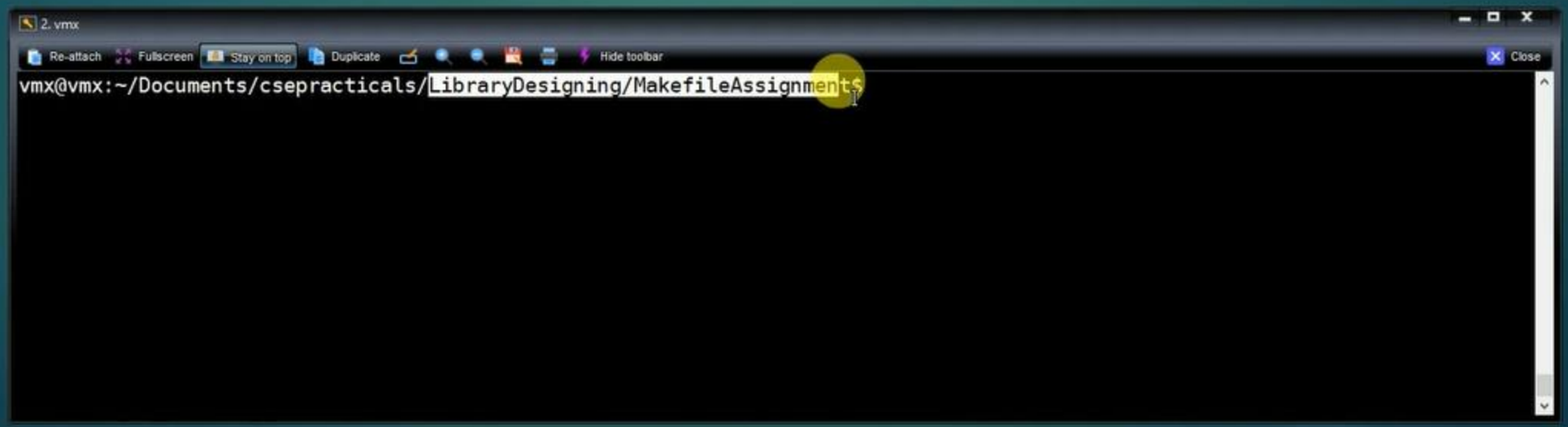
- Functions of Makefile :

1. Compiling
2. Linking
3. Creating required libraries – static and Dynamic
4. Create required Executables
5. Installation of Libraries & executables
6. Update dependencies



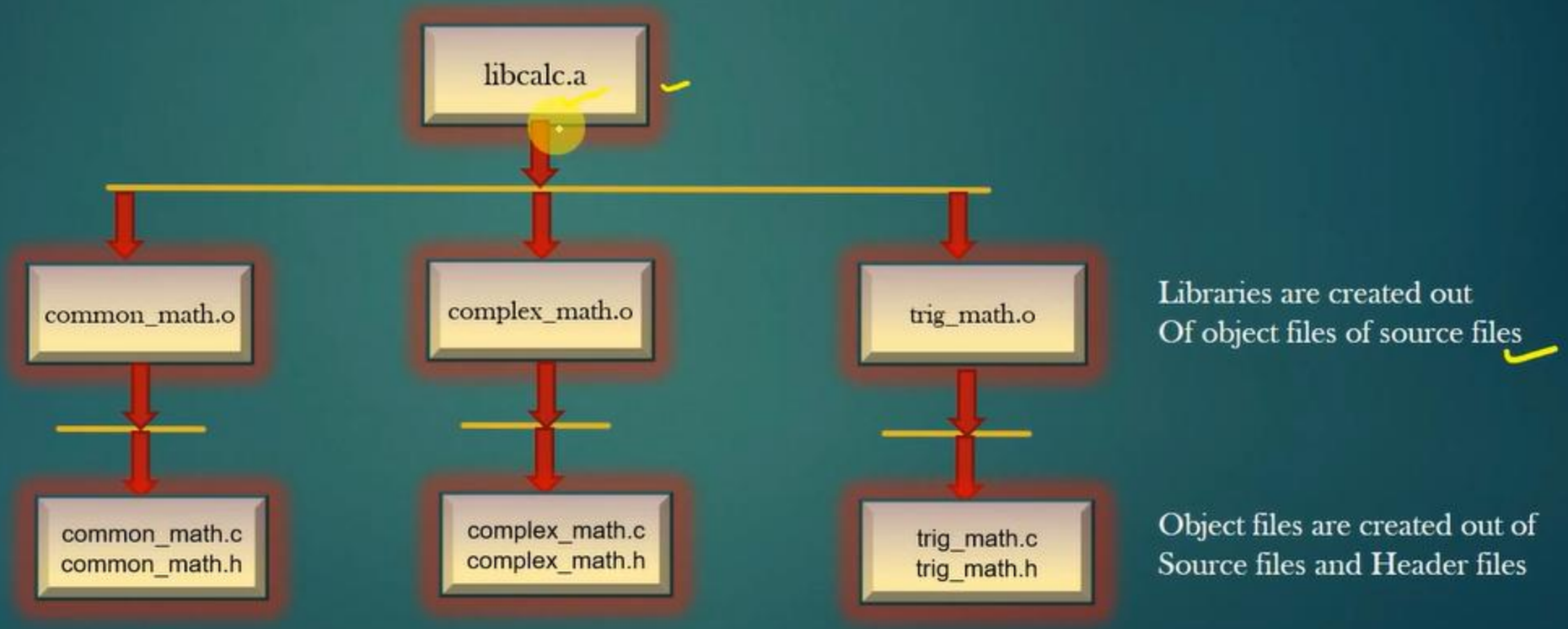
Makefile Example





Makefile Example

- Let us suppose we want to create a Library libcalc.a which will be a collection of all Mathematical functions defined in *common_math.c, complex_math.c and trig_math.c*



Makefile Example

- In Makefile we write *rules* which have the following syntax as follows :

<What we want to prepare (Final Dish)>:<What are raw materials we need to prepare the final dish>
<Action – Steps to prepare>

Example :

```
common_math.o:common_math/common_math.c
    gcc -c -I common_math common_math/common_math.c -o common_math/common_math.o
```

Note : *-I <path>* is used to specify the location of header files

```
complex_math.o:complex_math/complex_math.c
    gcc -c -I complex_math complex_math/complex_math.c -o complex_math/complex_math.o

trig_math.o:trig_math/trig_math.c
    gcc -c -I trig_math trig_math/trig_math.c -o trig_math/trig_math.o
```

So, as per the dependency tree, now we have all the L1 elements ready which are required to prepare *libcalc.a*

Makefile Example

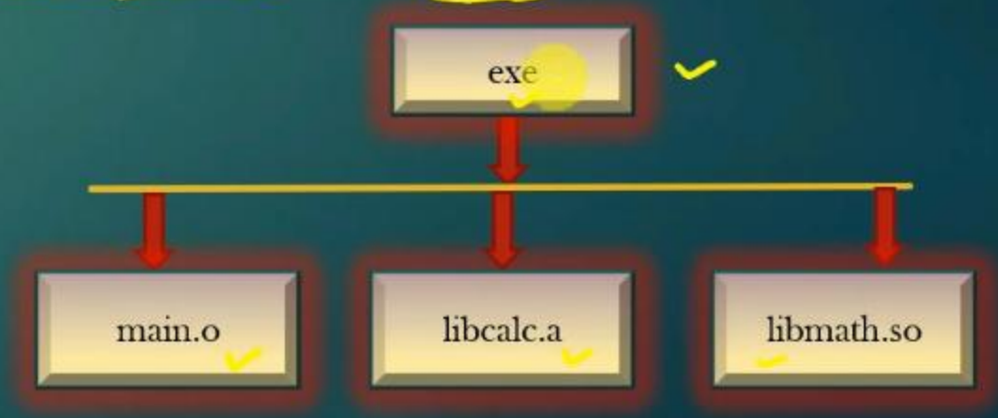
- In Makefile we write *rules* which have the following syntax as follows :

<What we want to prepare (Final Dish)>:<What are raw materials we need to prepare the final dish>
<Action – Steps to prepare>

Building libcalc.a

```
libcalc.a : trig_math/trig_math.o common_math/common_math.o complex_math/complex_math.o
    ar rs mylibmath.a common_math/common_math.o complex_math/complex_math.o trig_math/trig_math.o
```

Congrats , We have now created our library, Next we also want to create an executable because we have main.c



Makefile Example

- In Makefile we write *rules* which have the following syntax as follows :

<What we want to prepare (Final Dish)>:<What are raw materials we need to prepare the final dish>
<Action – Steps to prepare>

Building libcalc.a

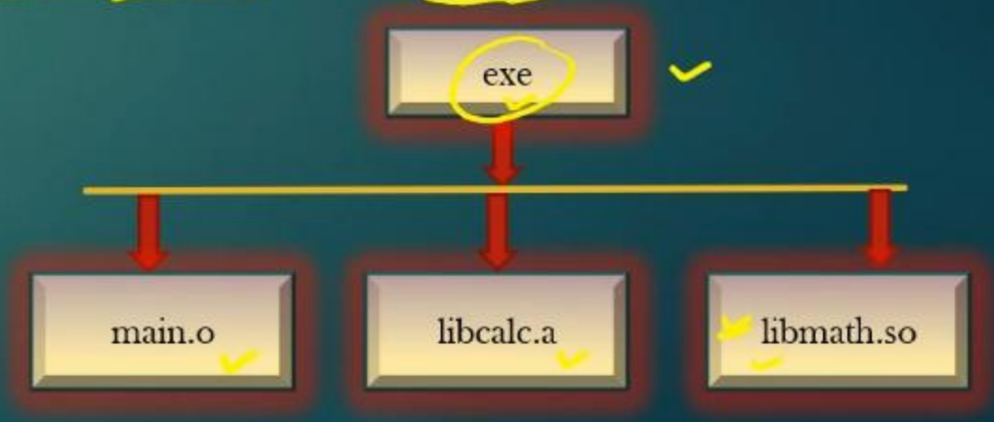
```
libcalc.a : trig_math/trig_math.o common_math/common_math.o complex_math/complex_math.o
    ar rs mylibmath.a common_math/common_math.o complex_math/complex_math.o trig_math/trig_math.o
```

Congrats , We have now created our library, Next we also want to create an executable because we have main.c

```
exe : main.o libcalc.a
    gcc main.o -o exe -L . libcalc.a -lm

main.o : main.c
    gcc -c -I common_math -I complex_math -I trig_math main.c -o main.o
```

Now , putting it altogether in one single Makefile



Makefile Example

- In Makefile we write *ru*

<What we want

<Action – .

Building libcalc.a

libcalc.a : trig_math/trig_m

ar rs mylibmath.a co

Congrats , We have now

exe : main.o libcalc.a

gcc main.o -o exe -L . libcalc.a -lm

main.o : main.c

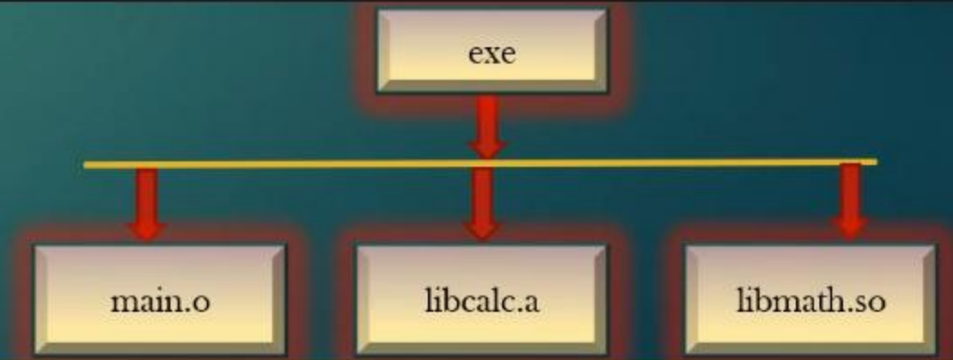
gcc -c -I common_math -I complex_math -I trig_math main.c -o main.o

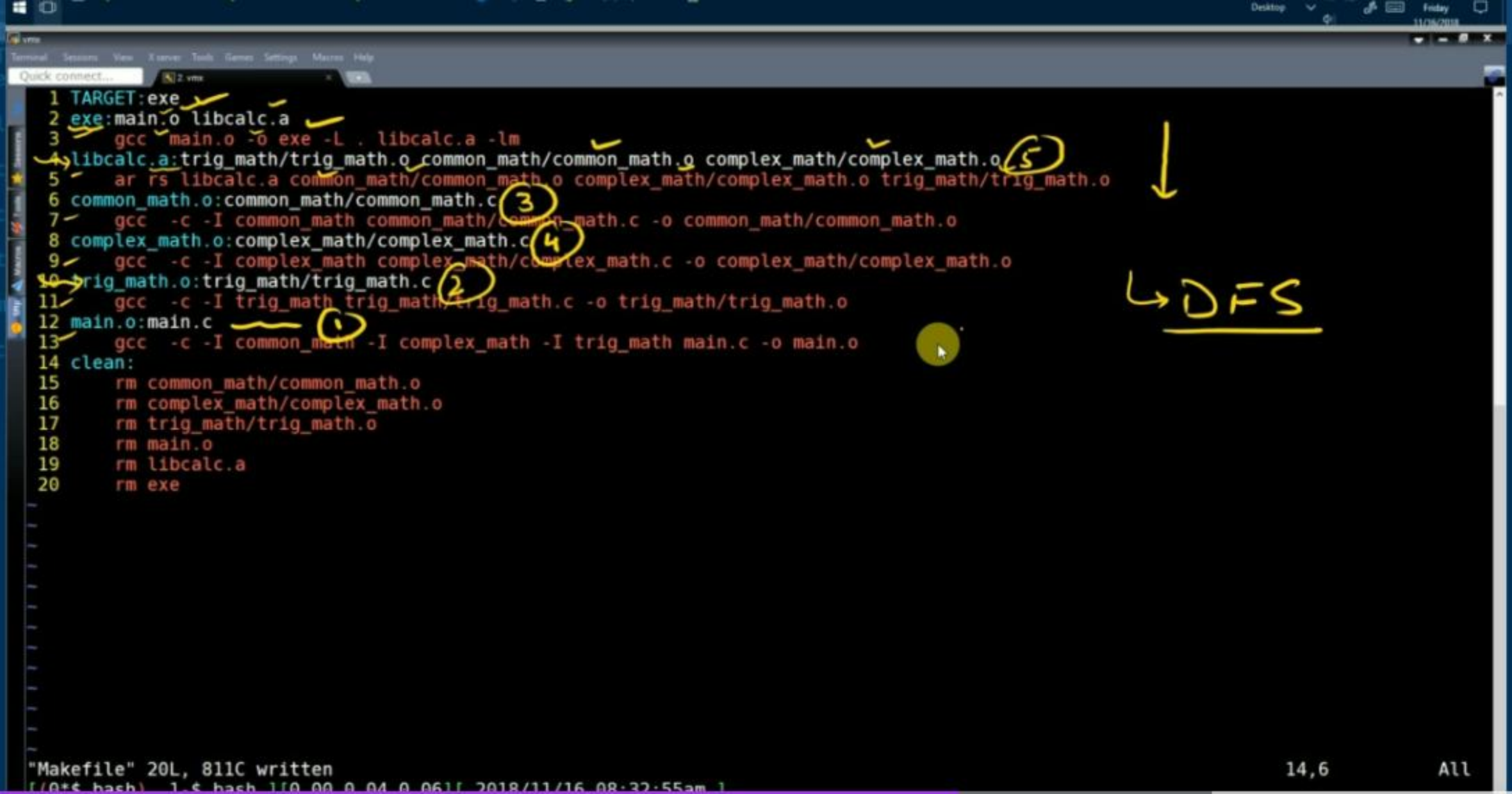
Now , putting it altogether in one single Makefile

2.vmx

Re-attach | Fullscreen | Stay on top | Duplicate | Hide toolbar | Close

```
1 TARGET:exe
2 common_math.o:common_math/common_math.c
3     gcc  -c -I common_math common_math/common_math.c -o common_math/common_math.o
4 complex_math.o:complex_math/complex_math.c
5     gcc  -c -I complex_math complex_math/complex_math.c -o complex_math/complex_math.o
6 trig_math.o:trig_math/trig_math.c
7     gcc  -c -I trig_math trig_math/trig_math.c -o trig_math/trig_math.o
8 libcalc.a:trig_math/trig_math.o common_math/common_math.o complex_math/complex_math.o
9     ar rs libcalc.a common_math/common_math.o complex_math/complex_math.o trig_math/trig_math.o
10 exe:main.o libcalc.a
11     gcc  main.o -o exe -L . libcalc.a -lm
12 main.o:main.c
13     gcc  -c -I common_math -I complex_math -I trig_math main.c -o main.o
14 clean:
15     rm common_math/common_math.o
16     rm complex_math/complex_math.o
17     rm trig_math/trig_math.o
18     rm main.o
19     rm libcalc.a
20     rm exe
~
~
~
~
~
1 more line; before #1  16:30:31                                    20,1-4        All
[0-$ bash  (1*$ bash) ][0.00 0.10 0.13][ 2018/11/27 05:02:38pm ]
```




TARGET:exe
exe:main.o libcalc.a
gcc main.o -o exe -L . libcalc.a -lm
libcalc.a:trig_math/trig_math.o common_math/common_math.o complex_math/complex_math.o
ar rs libcalc.a common_math/common_math.o complex_math/complex_math.o trig_math/trig_math.o
common_math.o:common_math/common_math.c
gcc -c -I common_math common_math/common_math.c -o common_math/common_math.o
complex_math.o:complex_math/complex_math.c
gcc -c -I complex_math complex_math/complex_math.c -o complex_math/complex_math.o
trig_math.o:trig_math/trig_math.c
gcc -c -I trig_math trig_math/trig_math.c -o trig_math/trig_math.o
main.o:main.c
gcc -c -I common_math -I complex_math -I trig_math main.c -o main.o
clean:
rm common_math/common_math.o
rm complex_math/complex_math.o
rm trig_math/trig_math.o
rm main.o
rm libcalc.a
rm exe
1
2
3
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5
DFS
"Makefile" 20L, 811C written
14,6
All

Search by key Callbacks

Step 1 : Callback Implementation

```
int /*return 0 if matches, return -1 if do not match */
    match_student_rec_by_key(void *data, void *key);

int /*return 0 if matches, return -1 if do not match */
    match_employee_rec_by_key(void *data, void *key);
```

Note that : Signature of these two functions must be generic – that is should not application specific

Step 2 : Now, Next we will going to define a callback fn pointer in DLL library

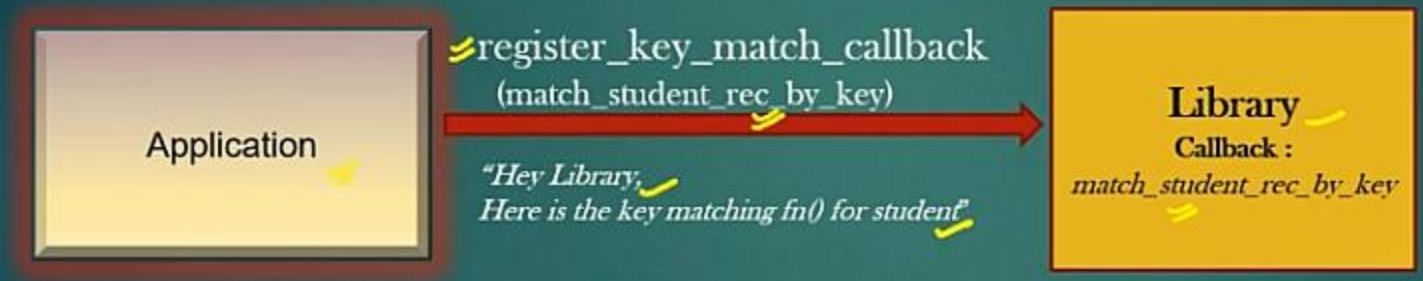
```
typedef struct dll_{
    dll_node_t *head;
    int (*key_match)(void *, void *);  /*Function Pointer Added*/
} dll_t;
```

Search by key Callbacks

Step 3 : Search Callbacks Registration

*/*Add a new function to DLL library* and provide its implementation in source file*/*

```
void
register_key_match_callback(dll_t *dll, int (*key_match)(void *, void *));
```



Step 4 : Add a new generic Search function in Library. This function can be used to search any application data hold by DLL

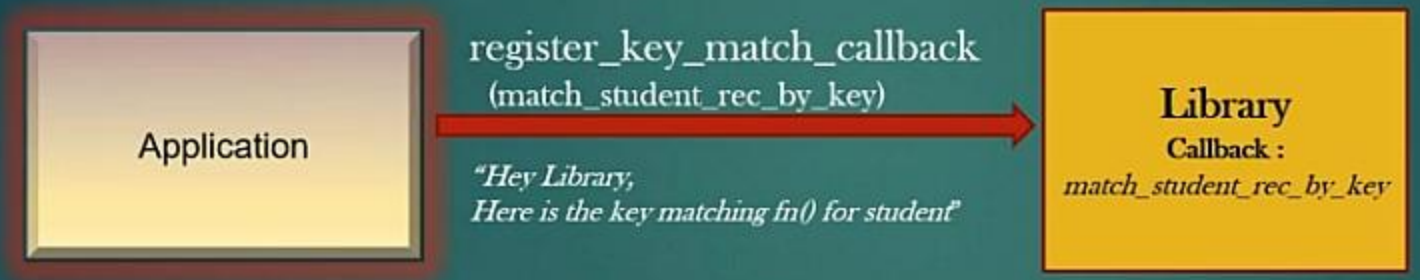
```
void *
dll_search_by_key (dll_t *dll, void *key);
```

Search by key Callbacks

Step 3 : Search Callbacks Registration

*/*Add a new function to DLL library* and provide its implementation in source file */*

```
void
register_key_match_callback(dll_t *dll, int (*key_match)(void *, void *));
```



Step 4 : Add a new generic Search function in Library. This function can be used to search any application data hold by DLL

```
void *
dll_search_by_key (dll_t *dll, void *key);
```

Step 5 : After creating a DLL in application, register the appropriate callback function with DLL

Step 6 : Done !!

Search by key Callbacks -> Summary

- We have just taught the DLL Library by registering the key match callback to how to search the application data hold by the DLL depending on the key
- All Application developer need is to write a key match callback for the data type which will be maintained by DLL library
- We have nicely delegated the search operation onto Library
- Library performs application specific operations by invoking the application specific functions through generic Callbacks
- Have we written any application specific code in dll.h/dll.c ? NO
  - Libraries are suppose to be application agnostic, we have not violated this rule
- In Industry, you will find this technique everywhere !!
- Let us use the same concept to provide intelligence to our DLL library so that it can insert the data in sorted order using *comparison callback Next . . .*

Comparison Callback

- A Developer wants, whenever he inserts the data in the DLL, the data should be inserted in sorted order
- Of-course, this requirement needs to compare the data being inserted with the data elements already present in the DLL so as to find the appropriate position in DLL
- So, DLL should be intelligent to compare two application specific data objects of same type being maintained by DLL
- We can achieve this using comparison callback, let us do it step by step (Same steps as before) . . .

Dir : LibraryDesigning/ProgrammableLib/comparison_callbacks

Step 1 : Callback Implementation in application.c

```
/*      Return 0 if equal,
 *      -1 if stud1 < stud2
 *       1 if stud1 > stud2*/
static int
student_comparison_fn(void *stud1, void *stud2);
```

< Note that, function signature is again generic

Comparison Callback

Step 2 : Now, Next we will going to define a callback fn pointer in DLL library

```
typedef struct dll_{
   dll_node_t *head;
   int (*key_match)(void *, void *);
   int (*comparison_fn)(void *, void *); /*Function Pointer Added*/
} dll_t;
```

Step 3 : Comparison Callbacks Registration

```
/*Add a new function to DLL library* and provide its implementation in source file*/

void
register_comparison_callback(dll_t *dll, int (*comparison_cb)(void *, void *));
```

Step 4 : Add a new generic insert function in Library. This function can be insert the new appln data in DLL in a sorted order

```
int /*0 on success, -1 on failure*/
dll_priority_insert_data (dll_t *dll, void *data);
```

Comparison Callback

Step 5 : After creating a DLL in application, register the appropriate comparison callback function with DLL using *register_comparison_callback()* API

Step 6 : Done !!

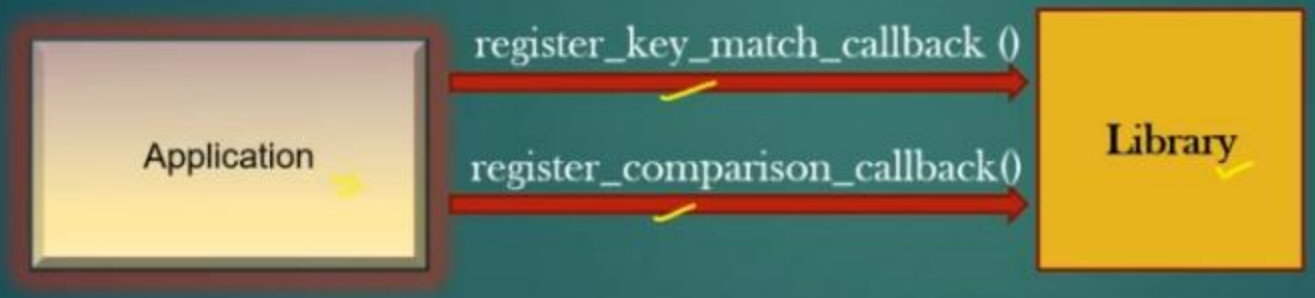
Now, insert the elements in the DLL using dll_priority_insert_data and verify the output.

DLL Must insert the data into DLL as per the comparison function

Programmable Libraries -> Summary

- We can always Program our general purpose libraries using Callbacks to how to
  1. Search based on key (key_match_cb)
  2. Compare two data elements (comparison_cb)

- Application Developer need to specify key_match and Comparison_fn and register with Library



- Library uses registered application specific Callbacks to perform application specific operations on app data
- Library code stays generic and application agnostic all the time
- C++/JAVA provides *Generics* as an equivalent feature

Iterative Macros

- To iterate data structures such as Linked lists, Trees etc we need to write Iterative macros
- We need to iterate over common data structures in our application many times
- Iterative macros makes Iteration over these DS very easy and handy

Iterating over a Linked List
Using traditional approach

```
dll_node_t *current = dll->head;
while (current){
        /*process current node*/
        current = current->next;
}
```

Iterating over a Linked List
Using a Macro

```
dll_node_t *current = NULL;
ITERATE_LIST_BEGIN ( listptr, current ) {
        /*process current node */
} ITERATE_LIST_END ( listptr, current ) ;
```

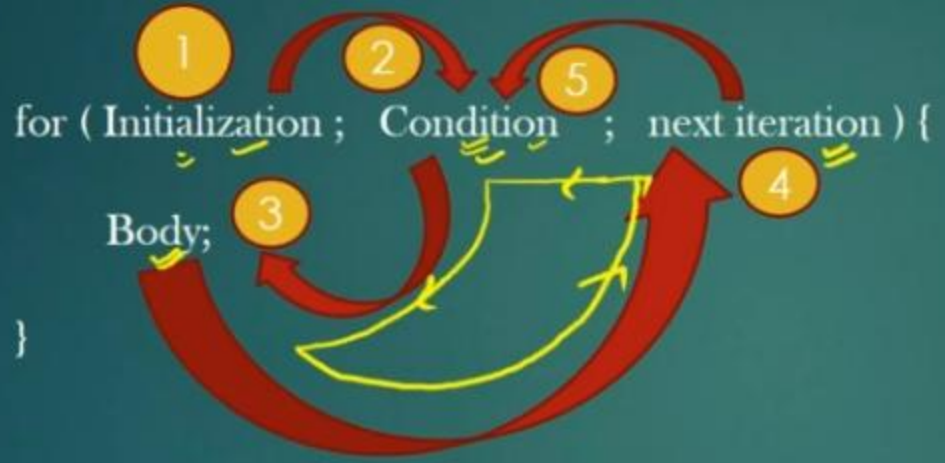
- More readable
- No error prone
- Handy and easy
- Soon, with complex DS such as tree or graph, you cannot survive without writing Iterative macros

Summary

- Iterative macros makes it easy and handy to iterate over data structures
- With complex data structures, Iterative macros becomes a necessity
- Iterative macros are a wrapper over for/while loops
- You must ensure that all parenthesis are balanced for iterative macros, else compiler error
- Apply text substitution to see, what C code Iterative macros translates to in Source files
- In C++/Java, equivalent is class iterators
- In Industry, you will see Iterative macros all over the code base. You are not allowed to iterate over Data-structures using traditional ways
- Your Library must provide delete-safe Iterative macros
- Exercises !!

for loop semantics

- Let us revise the syntax of the for loop



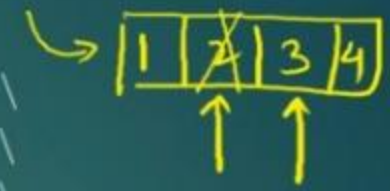
- We will write our Iterative macros over the for loops

Writing an Iterative Macro for a List

```
#define ITERATE_LIST_BEGIN( list_ptr, node_ptr)
{
    dll_node_t *_node_ptr = NULL;
    node_ptr = list_ptr->head;
    for(; node_ptr != NULL ; node_ptr = _node_ptr ){
        _node_ptr = node_ptr->right;
```

```
#define ITERATE_LIST_END }}
```

This is used to balance the parentheses



Code : LibraryDesigning/IterativeMacros/dll.h

☆ If you apply text substation carefully, you will see that this Iterative macro expands into mere *for loop* in source file to iterate over our DLL. Do this as an exercise.

Also, note that, it is delete safe loop !
The highlighted line is responsible to make this loop delete safe.

Writing an Iterative Macro for a BST

Let us take one more example of how to iterate (In-order traversal) over a BST using iterative macro. This will make you realize that how powerful and necessary is writing iterative macros for walking over data structures

- First, you should know the algorithm to iterate over a BST in inorder sequence.
- Assume, each node of the Tree has a pointer to its parent
- Because of above assumption, there is no need (and you are not suppose to) to write any recursive function
- Recursive logic performs very poorly as compared to equivalent iterative logic

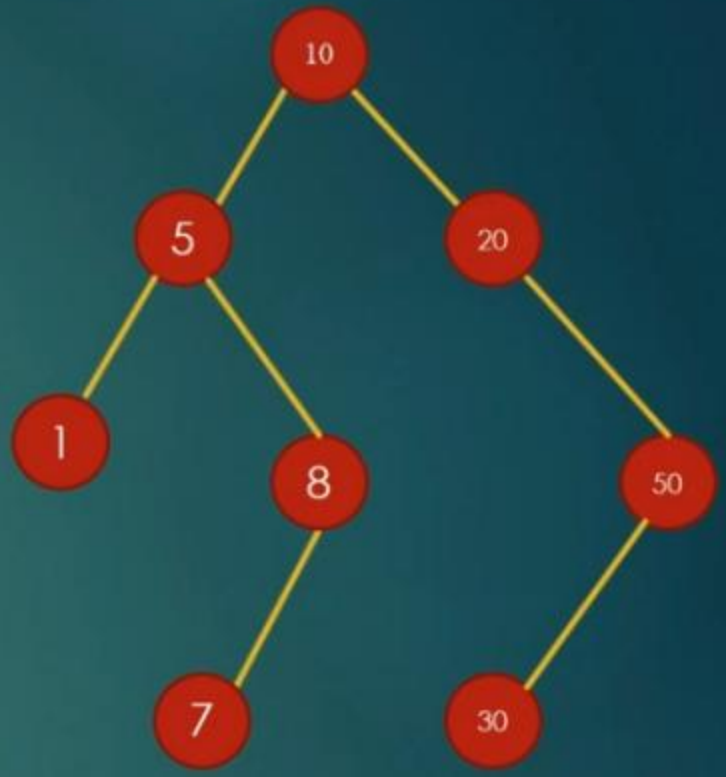
```
typedef struct tree_node {
        struct tree_node *left;
        struct tree_node *right;
        struct tree_node *parent;
        int data;
} tree_node_t;
```

```
typedef struct tree {
    tree_node_t *root;
} tree_t;
```

- I expect you that you at-least know already how to insert a node in a BST

- Now, we need to do some homework before we could write an iterative macro

Writing an Iterative Macro for a BST



Goal : Given a BST, Write a macro to iterate in in-order sequence over all nodes Of a BST

Constraints :

- You are not allowed to write any recursive logic
- You should be able to start Iteration from any starting node
- Every node in a BST also has pointer to its parent
- We need to implement below macro

```
tree_node_t *treenodeptr = NULL;
ITERATE_BST_BEGIN(tree, treenodeptr) {

    do_something(treenodeptr->data);

} ITERATE_BST_END;
```

Want to Try before we discuss the approach ??

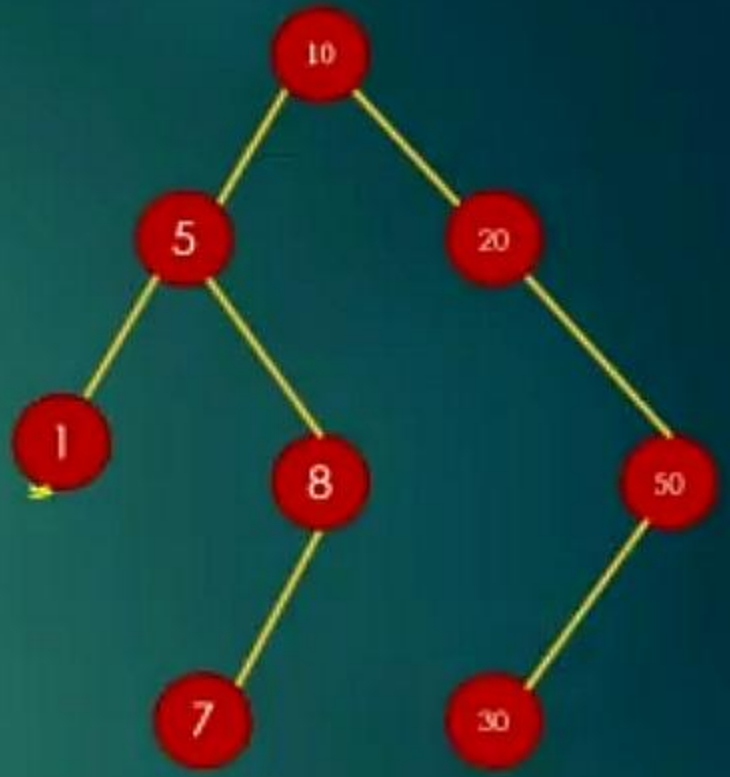
Writing an Iterative Macro for a BST

We Need to Write two pre-requisite functions :

```
tree_node_t *
get_left_most (tree_node_t *root);

tree_node_t *
get_next_inorder_succ (tree_node_t *node);
```

Inorder ->



- Again, it is my expectation that you know how to implement above two functions
- This is not a Data structure Course ! I am sorry ! 😊
- Henceforth, I assume, you have correctly implemented above two functions
- Code : LibraryDesigning/IterativeMacros/tree.c & tree.h

Glue Concept

- Let me introduce you to a new way of using Standard Data structures - *the Glue way*
- We shall redefine our DLL library in a new way altogether
- You will realize the benefits of using Glued Libraries over Traditional Library
- Just FYI, Linux kernel code uses GLUEd version of standard data structures such as Trees, Linked List etc
- Even in industry, it is easier to find glue libraries being used instead of traditional libraries
- Let us call our GLUEd Doubly linked list as *glthreads* - Just a name change, it is still a doubly linked list
- The GLUE concept that you will learn with DLL as an example are applicable to any other Data structures
- Code : https://github.com/.../DevelopLibrary/glthreads
  files : glthread.h , glthread.c

Glthreads – Glued Doubly Linked List

```
typedef struct dll_node_ {
    void *data;
    struct dll_node_ *left;
    struct dll_node_ *right;
} dll_node_t;
```

```
typedef struct glthread_node_ {
    struct glthread_node_ *left;
    struct glthread_node_ *right;
} glthread_node_t;
```

```
tyepdef struct dll_ {
    dll_node_t *head;
    int (*key_match)(void *, void *);
    int (*comparison_fn)(void *, void *);
} dll_t;
```

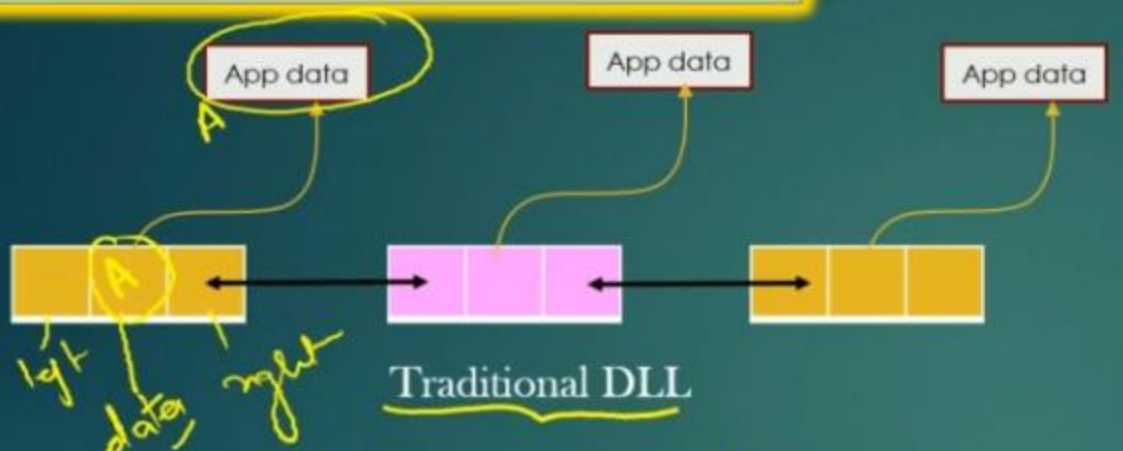
Traditional DLL

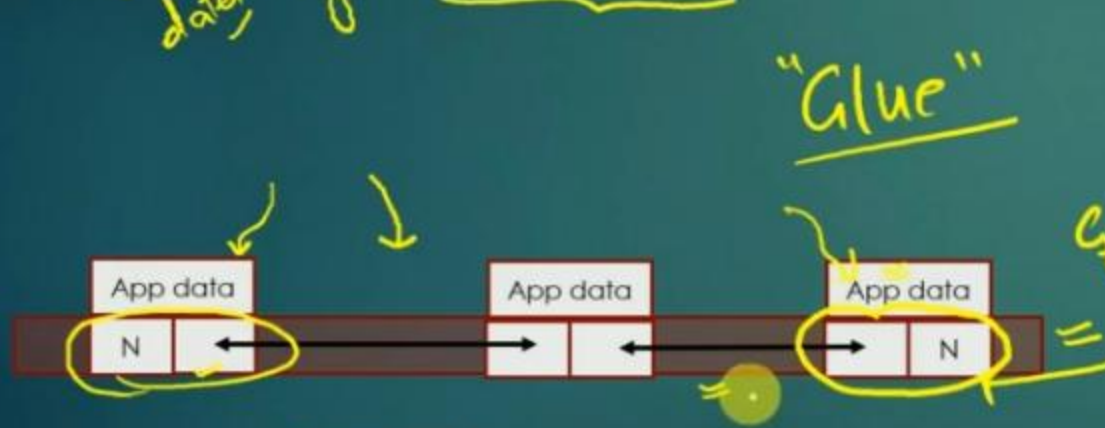
```
typedef struct gldll_
    glthread_node_t *head;
    int (*key_match)(void *, void *);
    int (*comparison_fn)(void *, void *);
    unsigned int offset;
} gldll_t;
```

Glthreads DLL

- Glthread nodes do not have *void *data* member
- Then how do glthreads hold the application data ?
- Before Jumping into this point, let us learn some more C
- Looks like you are very Curious to know now !!

Pictorial difference : Glthreads Vs Traditional DLL





GLthreads 'glnode'

glthread_node_t glue;

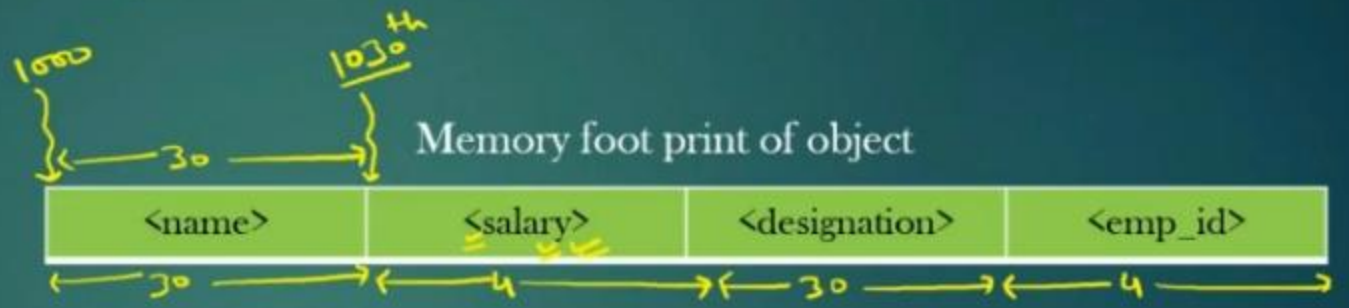
Offset manipulation in C structures

Q. Write a C macro which computes the offset of a given field in a given C structure ?

For example :

```
typedef struct emp_ {

        char name[30];
        unsigned int salary;
        char designation[30];
        unsigned int emp_id;
} emp_t ;
```



Fields	Size	offset
name	30	0
salary	4	30
designation	30	34
emp_id	4	64

```
#define offsetof(struct_name, field_name) \
        (unsigned int)&((struct_name *)0)->field_name
```

```
int x = offsetof(emp_t, emp_id);
```

= 64

Offset manipulation in C structures

Q. Print the Employee details.

```
emp_t  *emp = <pointer to emp_t object>
print_emp_details (&emp->glnode);

void print_emp_details(glthread_node_t *glnode){

        /* print employee details */

}
```

```
typedef struct emp_ {

    char name[30];
    unsigned int salary;
    char designation[30];
    unsigned int emp_id;
    glthread_node_t glnode;
} emp_t ;
```

Hint :

Memory Layout of the object of type emp_t

Glthreads – Node insertion

```
typedef struct emp_ {

    char name[30];
    unsigned int salary;
    char designation[30];
    unsigned int emp_id;
    glthread_node_t glnode;
} emp_t ;
```

```
/*An API to insert a new glthread node after the current node*/

void
glthread_add (glthread_t *lst, glthread_node_t *new);

/* Code to insert elements in glthread DLL*/
/*The first node is the head of glthread DLL*/
```

Memory Layout of Objects Hold by the glthread DLL

Glthreads – Iteration

```
typedef struct emp_ {

    char name[30];
    unsigned int salary;
    char designation[30];
    unsigned int emp_id;
    glthread_node_t glnode;
} emp_t ;
```

Iterating over glthread DLL

```
void print_emp_db (glthread_node_t *head) {

    emp_t *data = NULL;
    if(!head) return;
    while(head){
        data = (emp_t *)((char *)head - offsetof(emp_t, glnode));
        printf_emp_details(data);
        head = head->right;
    }
}
```

Memory Layout of Objects
Hold by the glthread DLL

Glthreads – Node Removal

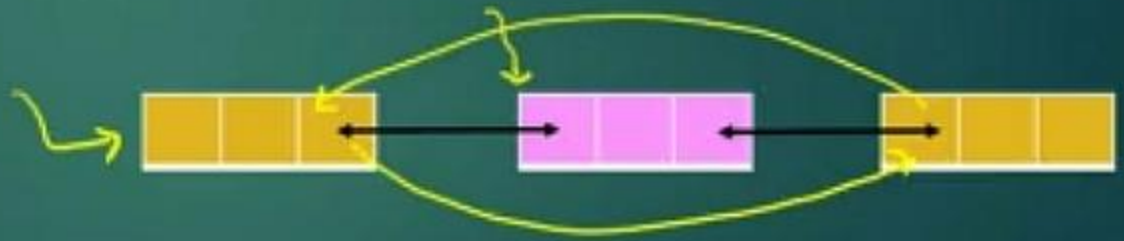
```
typedef struct emp_ {

    char name[30];
    unsigned int salary;
    char designation[30];
    unsigned int emp_id;
    glthread_node_t glnode;
} emp_t ;
```

Removing a Node from DLL

```
void glthread_remove(glthread_node_t *glnode) {

    /*Simply remove like you delete a middle node
        from traditional DLL
    TC : O(1)
    */
}
```



Glthreads – Code Walk

- Code : https://github.com/csepracticals/DevelopLibrary/glthreads
  files : glthread.h , glthread.c, main.c, Makefile

Glthreads – Benefits

- Why we have twisted things a little if we are accomplishing the same end goals before by traditional DLL ?
- Let us discuss the benefits of glthread DLL over traditional DLL
- Let us see the problem with traditional DLL. This problem applies to traditional Trees, Queues etc

```
typedef struct emp_ {

    char name[30];
    unsigned int salary;
    char designation[30];
    unsigned int emp_id;
} emp_t ;
```

empt_t *empx = <pointer to emp_t object>

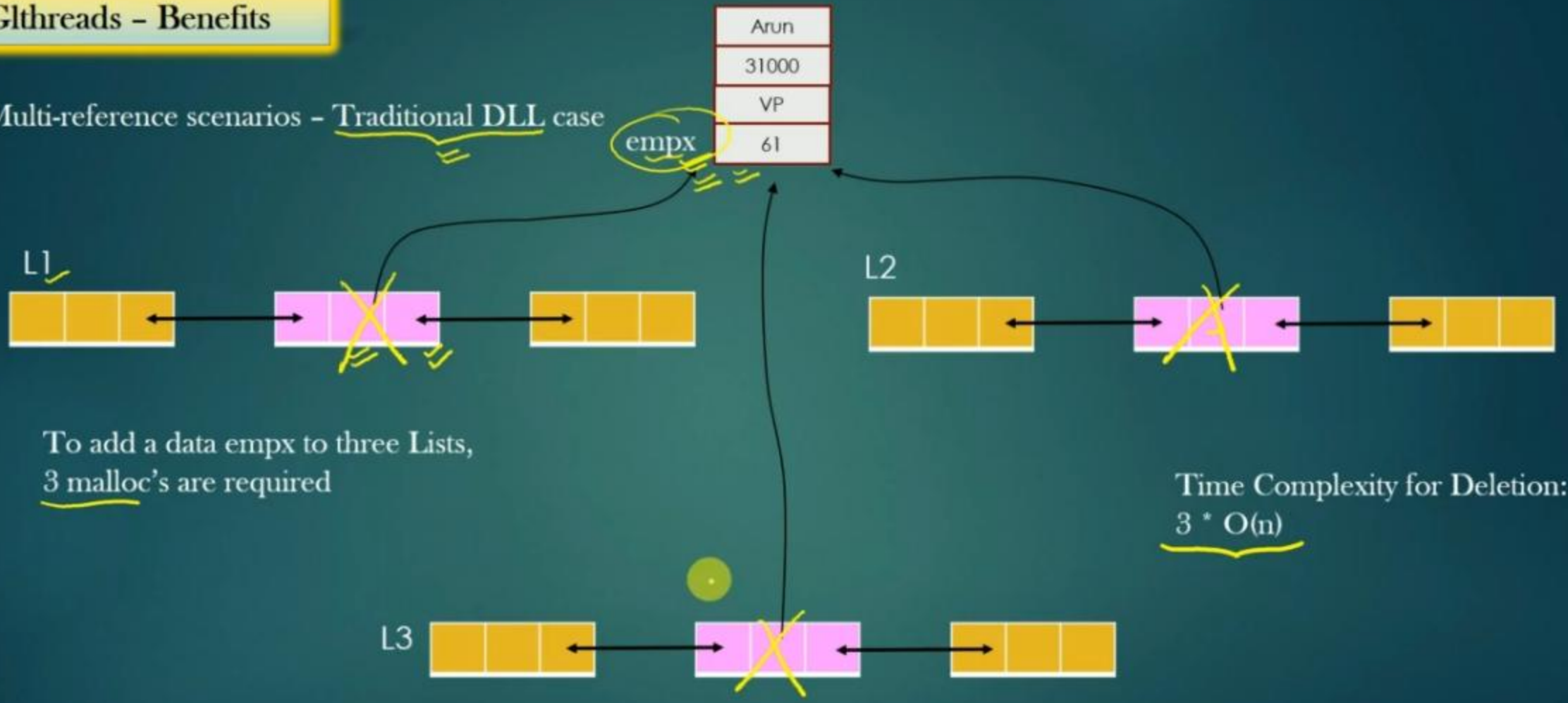
Your application is maintaining three DLL :

1. L1 : DLL to maintain the records of employees
2. L2 : DLL to maintain records of employees above Mgr level
3. L3 : DLL to maintain the records of employees whose promotions are due

Let us suppose, our favorite employee empx qualifies all three criteria, therefore empx record need to be inserted into all three DLLs

Glthreads – Benefits

Multi-reference scenarios – Traditional DLL case



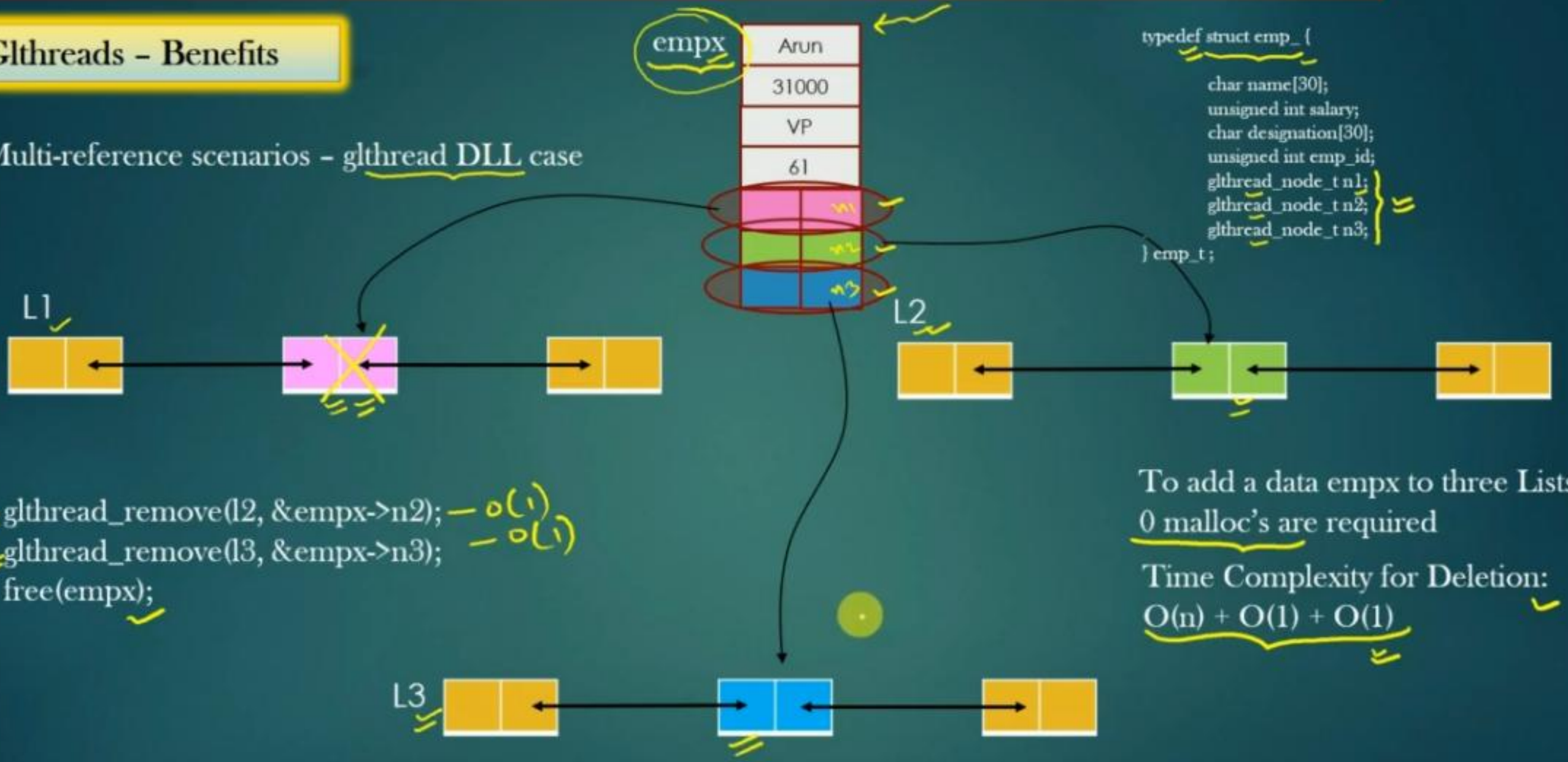
To add a data empx to three Lists,
3 malloc's are required

Time Complexity for Deletion:
3 * O(n)

- Now suppose, Arun leaves the company, and you need to remove his record from all Lists
- So, Iterate over all Lists one by one , find the record matching with Arun, and un-reference it from all Lists
- Finally free(empx)

Glthreads – Benefits

Multi-reference scenarios – glthread DLL case




```
typedef struct emp_ {
    char name[30];
    unsigned int salary;
    char designation[30];
    unsigned int emp_id;
    glthread_node_t n1;
    glthread_node_t n2;
    glthread_node_t n3;
} emp_t;
```

```
glthread_remove(l2, &empx->n2);
glthread_remove(l3, &empx->n3);
free(empx);
```

O(1)
O(1)

To add a data empx to three Lists, 0 malloc's are required

Time Complexity for Deletion: O(n) + O(1) + O(1)

- Now suppose, Arun leaves the company, and you need to remove his record from all Lists
- So, Iterate over List L1 (or any one), find the record matching with Arun, and un-reference it from L1
- Now you have pointer to empx object

Opaque Pointers

- Opaque Pointers are very extensively used in the industry
- Opaque pointers are a way to isolate one code with another , while at the same time, ensure seamless integration between them
- In OOPs Terminology , A class with all its instance variables private is an Opaque Class

```
class LinkedListNode {

    private int data;
    private LinkedListNode left;
    private LinkedListNode right;
};

LinkedListnode L1 = new LinkedListNode( );
```

- L1 is an Opaque Object

- How to define opaque pointers in C ?
- What's the use ?
- Let's explore ...

linkedlist.h

```
typedef struct ll_node_ {

    int data;
    struct ll_node_ *left;
    struct ll_node_ *right;
} ll_node_t;

/*public APIs*/

void
linkedlist_insertion (
    ll_node_t *current_node,
    ll_node_t *new_node);
```

linkedlist.c

```
#include <linkedlist.h>

void
linkedlist_insertion (
    ll_node_t *current_node,
    ll_node_t *new_node){

 if (!current_node->right){
    current_node->right = new_node;
    new_node->left = current_node;
    return;
  }

  glthread_t *temp = current_node->right;
  current_node->right = new_node;
  new_node->left = current_node;
  new_node->right = temp;
  temp->left = new_node;
}
```

application.c

```
#include <linkedlist.h>

int
Main(){

ll_node_t *node1 = malloc ...

/*You can access */
node1->data;

node1->left;

node1->right;
}
```

linkedlist.h

```
typedef struct ll_node_ {

    int data;
    struct ll_node_ *left;
    struct ll_node_ *right;
} ll_node_t;

/*public APIs*/

void
linkedlist_insertion (
        ll_node_t *current_node,
        ll_node_t *new_node);
```

linkedlist.c

```
#include <linkedlist.h>

void
linkedlist_insertion (
        ll_node_t *current_node,
        ll_node_t *new_node){

 if (!current_node->right){
        current_node->right = new_node;
        new_node->left = current_node;
        return;
    }

    glthread_t *temp = current_node->right;
    current_node->right = new_node;
    new_node->left = current_node;
    new_node->right = temp;
    temp->left = new_node;
}
```

application.c

```
#include <linkedlist.h>

int
Main(){
```

What if somebody tries to re-invent the wheel, and try to Write his own node insertion code in his application, which is buggy !!

He was able to introduce a bug because he was spoiled child, Had privileges to all wealth (node's members) and he exploited them because he didn't know how to use wealth wisely

```
}
```

linkedlist.h

```
typedef struct ll_node_ {

    int data;
    struct ll_node_ *left;
    struct ll_node_ *right;
} ll_node_t;

/*public APIs*/

void
linkedlist_insertion (
    ll_node_t *current_node,
    ll_node_t *new_node);
```

linkedlist.c

```
#include <linkedlist.h>

void
linkedlist_insertion (
    ll_node_t *current_node,
    ll_node_t *new_node){

 if (!current_node->right){
    current_node->right = new_node;
    new_node->left = current_node;
    return;
  }

  glthread_t *temp = current_node->right;
  current_node->right = new_node;
  new_node->left = current_node;
  new_node->right = temp;
  temp->left = new_node;
}
```

application.c

```
#include <linkedlist.h>

int
Main(){
```

To prevent this problem, if we take away access of all wealth from spoiled brad, he can't misuse the wealth, even if he wants to !

If we restrict the access the node's member's in this file, nobody shall be able to write any new code which requires access to node's internal members

```
}
```

linkedlist.h

```
typedef struct ll_node_ {

    int data;
    struct ll_node_ *left;
    struct ll_node_ *right;
} ll_node_t;

/*public APIs*/

void
linkedlist_insertion (
    ll_node_t *current_node,
    ll_node_t *new_node);
```

linkedlist.c

```
#include <linkedlist.h>

void
linkedlist_insertion (
    ll_node_t *current_node,
    ll_node_t *new_node){

 if (!current_node->right){
    current_node->right = new_node;
    new_node->left = current_node;
    return;
  }

  glthread_t *temp = current_node->right;
  current_node->right = new_node;
  new_node->left = current_node;
  new_node->right = temp;
  temp->left = new_node;
}
```

application.c

```
#include <linkedlist.h>

int
Main(){

node1->data ;  /*Compilation error*/

node->left;    /*Compilation error*/

node1->right;  /*Compilation error*/

sizeof (node_t);  /*Compilation error*/

linklist_insertion (node1, node2); ✓
}
```

Goal : But how to achieve it !

Opaque Pointers -> Defining Opaque Pointers

- To define the structure (ll_node_t) as opaque to external world (application.c), define the structure definition in library's source files rather than header files
- The intent is not to expose the structure definition to outside world, so outside world would never know its internal members details

Opaque Pointers -> Defining Opaque Pointers

linkedlist.h

```
typedef
struct ll_node_ ll_node_t;

/*public APIs*/
void
linkedlist_insertion (
        ll_node_t *current_node,
        ll_node_t *new_node);

ll_node_t *
malloc_new_node();
```

linkedlist.c

```
#include <linkedlist.h>

typedef struct ll_node_ {

        int data;
        struct ll_node_ *left;
        struct ll_node_ *right;
};

void
linkedlist_insertion (
        ll_node_t *current_node,
        ll_node_t *new_node){

        ...
}
```

application.c

```
#include <linkedlist.h>

int
Main(){

sizeof(__)
malloc(_____);

}
```

Compiler never sees the internal member Of ll_node_t , Hence direct access to any Internal member of ll_node_t is prevented.

Opaque Pointers -> Defining Opaque Pointers

linkedlist.h

```
typedef
struct ll_node_ ll_node_t;

/*public APIs*/
void
linkedlist_insertion (
        ll_node_t *current_node,
        ll_node_t *new_node);

ll_node_t *
malloc_new_node();
```

linkedlist.c

```
#include <linkedlist.h>

typedef struct ll_node_ {

    int data;
    struct ll_node_ *left;
    struct ll_node_ *right;
};

void
linkedlist_insertion (
        ll_node_t *current_node,
        ll_node_t *new_node){

        ...
}

ll_node_t *
malloc_new_node( ){
  return malloc(sizeof(ll_node_t));
}
```

application.c

```
#include <linkedlist.h>

int
Main(){

ll_node_t *node =
malloc_new_node();

ll_node_t *node2 =
malloc_new_node();

linklist_insertion (node1, node2);
}
```

Compiler never sees the internal member Of ll_node_t , Hence direct access to any Internal member of ll_node_t is prevented.

linkedlist.h

```
typedef
struct ll_node_ ll_node_t;


/*public APIs*/
void
linkedlist_insertion (
        ll_node_t *current_node,
        ll_node_t *new_node);

ll_node_t *
malloc_new_node();
```

application.c

```
#include <linkedlist.h>

int
Main(){


ll_node_t *node =
malloc_new_node();


ll_node_t *node2 =
malloc_new_node();

linklist_insertion (node1, node2);
}
```

- Simple ! Stick to basics to know why Opaque pointers work
- Apply text substitution On application.c
- Compiler never sees the definition of ll_node_t
- Hence, compiler nevers knew what Members are there in ll_node_t
- Neither compiler knows the sizeof (ll_node_t)

→ "Incomplete definition"

Opaque Pointers -> Benefits

- The production Code base is huge, millions of lines of code across thousands of files and hundreds of libraries in use and tens of teams working on them independently
- Opaque Pointers ensure Code Isolation across component while seamless integration
- Opaque library is like a black box to external world, application owners can use it through exposed public APIs but must not bother about its internal design and implementation
- If public exposed API gives wrong result in application.c , application developer can say – *there is something wrong with library code* and blame the team owning the library maintenance/development work ☺ ('Bug')
- Library owning team can enhance the library functionality independent of applications using the library public APIs as long as public APIs in-and-out is not impacted.
- Opaque pointers ensure that you are the mere user of Library
- They way you write a code shows your maturity/experience as a programmer !

BIT Manipulation

- Most programming language provide developer to manipulate memory at the finest granularity level of 1 Byte (char data type)

- In C/C++/Java etc , you cannot have a data type smaller than 1B
- Meaning, your program cannot manipulate memory less than 1 Byte using primitive/inbuilt data types

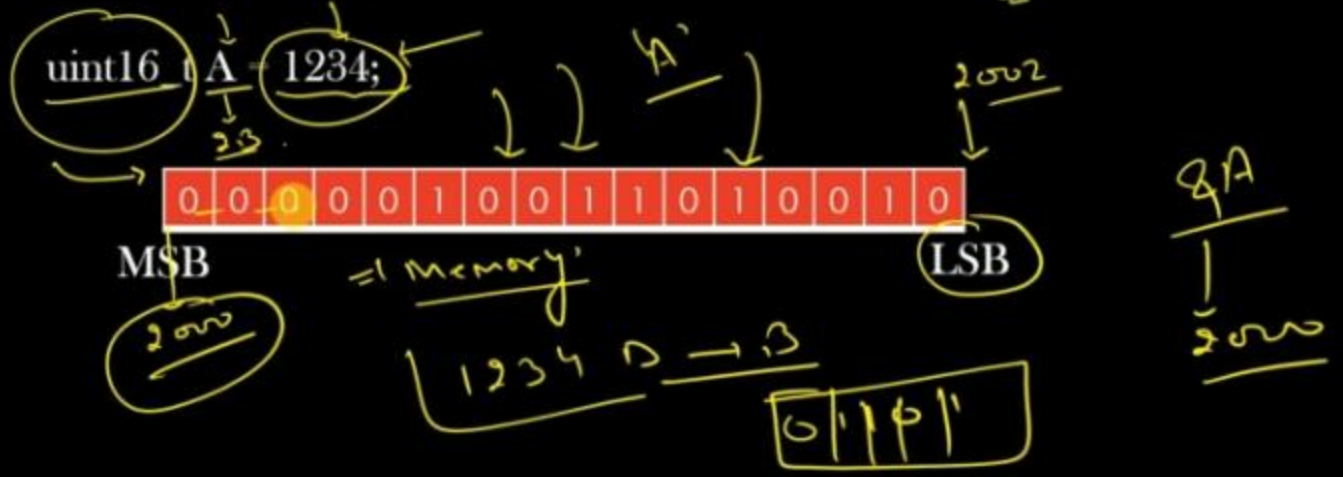
- But some problem statement requires to manipulate memory at a bit level

- A Bit is 0 or 1

- We use Logical operators to manipulate memory at a bit level

- Use case and relevance :
  - Boolean is used to say yes or no
  - Size of Boolean is 4B on most compilers
  - Why not just use a bit to track Boolean status since bit also have two states – yes or no
  - Bit manipulation makes tracking of a set of Booleans very easy
  - Very important from interview perspective
  - We will do some interview questions as an exercise on bit manipulation
  - Pre-requisite : Memorize basics of Boolean algebra (And , OR and NOT Operators)

- Every data type is stored in computer memory in bits



BIT Manipulation → Inbuilt BitWise Operators

- AND Operator : &

  a & b

- Or Operator : |

  a | b

- Complement Operator : ~

  ~a

- XOR Operator

  a ^ b

- Shift Operators
  - >> Right shift (divide by 2)

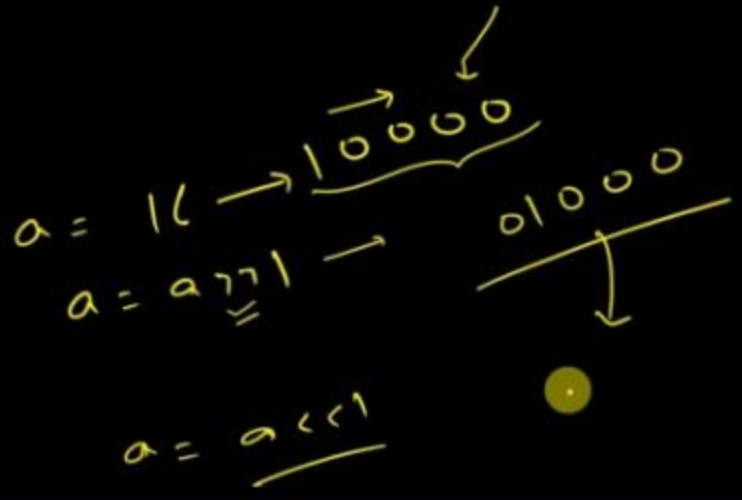
    a = a >> n

  - << Left shift (Multiply by 2)

    a = a << n

- Every data type is stored in computer memory in bits

uint16_t A = 1234;



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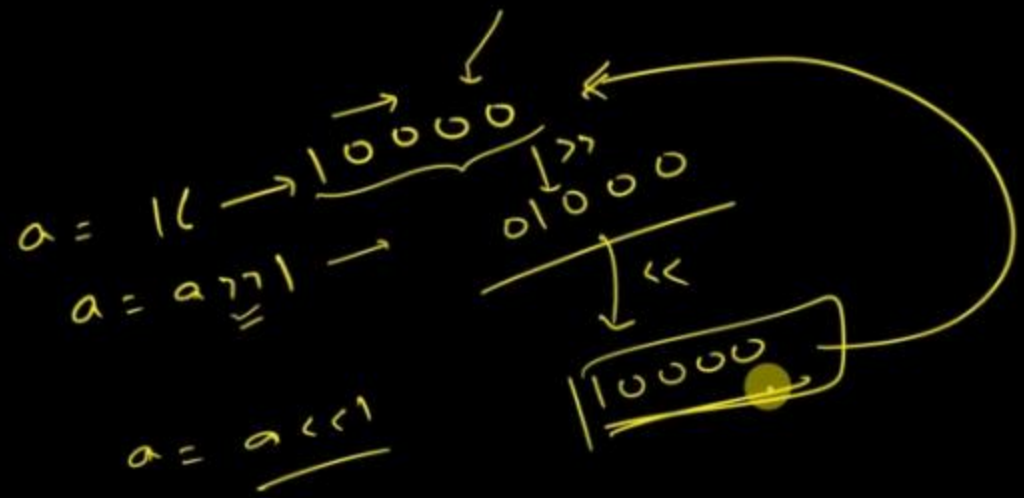

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  >> Right shift (divide by 2)

  a = a >> n

  << Left shift (Multiply by 2)

  a = a << n

- Every data type is stored in computer memory in bits

uint16_t A = 1234;

Homework :

- Pls browse internet and learn about these operators if you are not familiar
- We shall be going to learn some advanced learning in this course
- Write a Truth table for C = a XOR b

- XOR has a supernatural power to segregate the mixture of two things :
  - like separating milk from water
  - Separating dissolved sugar from water

R = A xor B
R xor A = B
R xor B = A

```
struct list_node {

    int data;
    struct list_node *next;
};
```

< Implement a doubly linked list using this struct list_node structure !

BIT Manipulation → XOR specialty

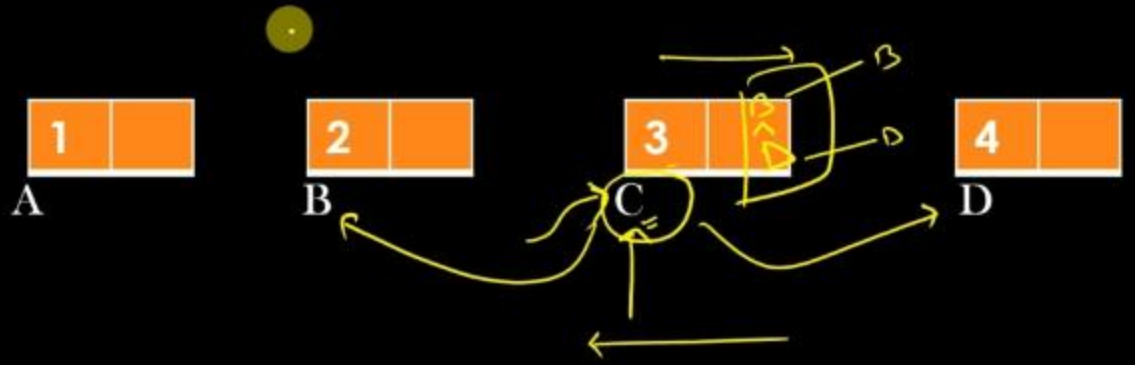
- XOR has a supernatural power to segregate the mixture of two things :
  - like separating milk from water
  - Separating dissolved sugar from water

R = A xor B
R xor A = B
R xor B = A

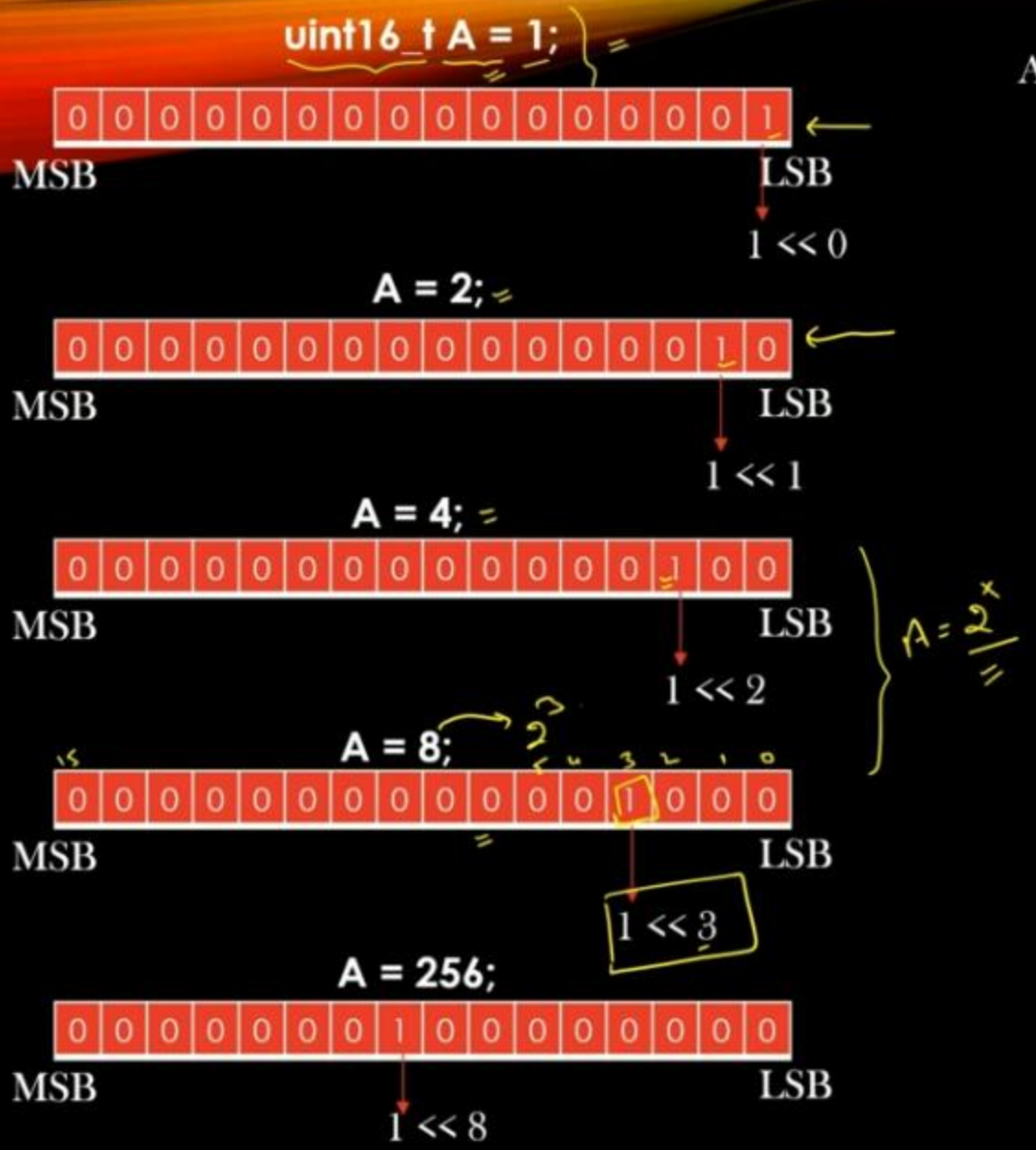
```
struct list_node {

    int data;
    struct list_node *next;
};
```

< Implement a doubly linked list using this struct list_node structure !



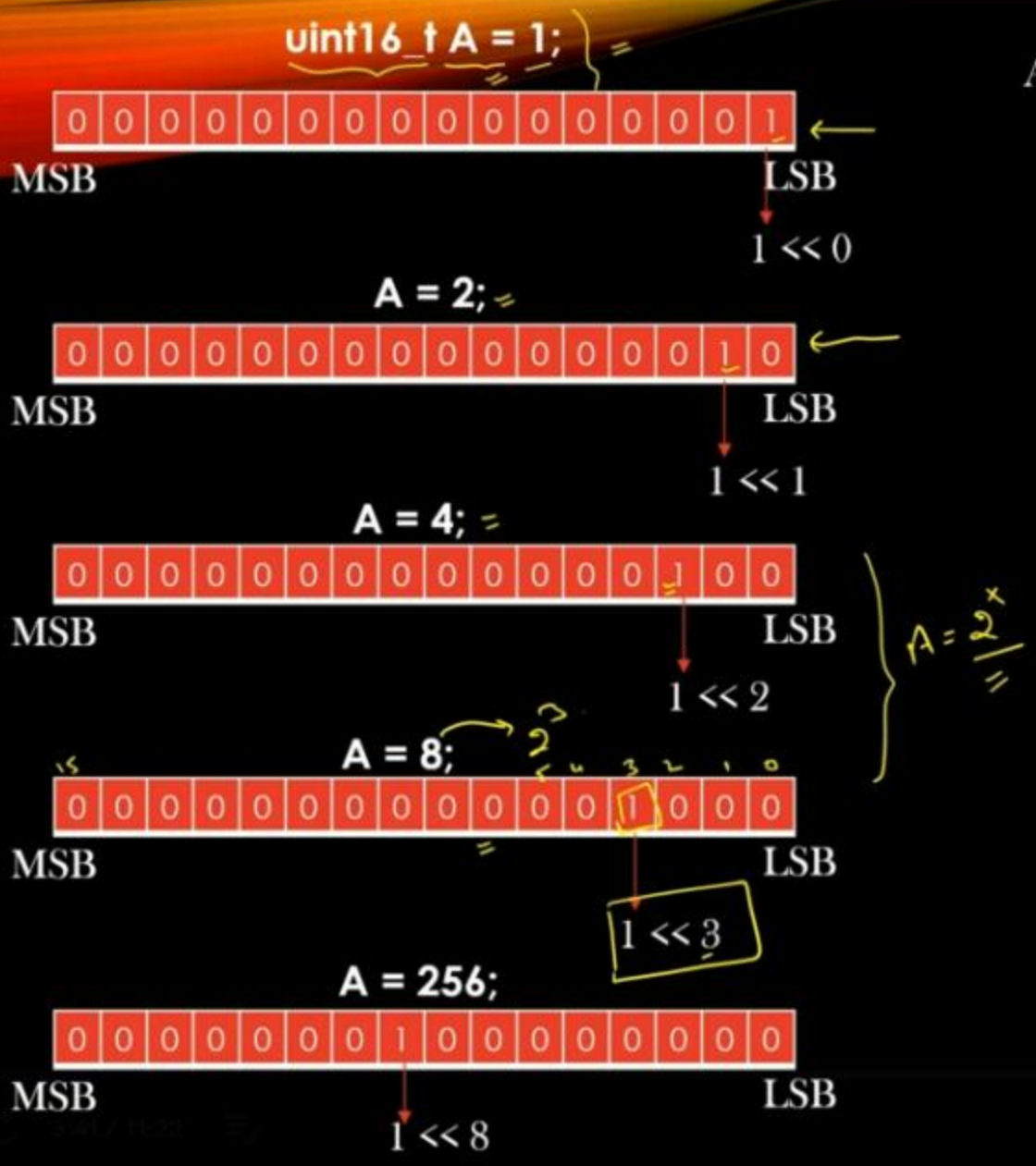
- You need to cache the address of Prev node in local variable to compute address of next node during traversals (In either direction)



Attributes of a Student :

1. Is Student a native citizen ?
   #define STUD_NATIVE_CITIZEN_F (1 << 0)
2. Is student male ?
3. Is student graduate ?
4. Is Student Post-graduate ?
5. Has student avail any prev scholarship ?
6. Is Student born after 1 Jan 2020 ?
7. Does Student posses dual citizen ship ?

BIT Manipulation → Using Bits as Boolean Flags



Attributes of a Student :

1. Is Student a native citizen ?
   `#define STUD_NATIVE_CITIZEN_F (1 << 0)`
2. Is student male ?
   `#define STUD_MALE_F (1 << 1)`
3. Is student graduate ?
   `#define STUD_GRAD_F (1 << 2)`
4. Is Student Post-graduate ?
   `#define STUD_POST_GRAD_F (1 << 3)`
5. Has student avail any prev scholarship ?
   `#define STUD_PREV_SCHOL_F (1 << 4)`
6. Is Student born after 1 Jan 2020 ?
   `#define STUD_BIRTH_F (1 << 5)`
7. Does Student posses dual citizen ship ?
   `#define STUD_DUAL_CZN_F (1 << 6)`

BIT Manipulation → Using Bits as Boolean Flags

Attributes of a Student :

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   `#define STUD_NATIVE_CITIZEN_F (1 << 0)`
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   `#define STUD_PREV_SCHOL_F (1 << 4)`
6. Is Student born after 1 Jan 2020 ?
   `#define STUD_BIRTH_F (1 << 5)`
7. Does Student posses dual citizen ship ?
   `#define STUD_DUAL_CZN_F (1 << 6)`

uint8_t / uint32_t

```
uint16_t alex_f ; = 0
...
```

Alex is Native USA Citizen.

```
alex_f = alex_f | STUD_NATIVE_CITIZEN_F ;
```

Alex is Male

```
alex_f |= STUD_MALE_F;
```

Alex has dual Membership

```
alex_f |= STUD_DUAL_CZN_F ;
```

Alex is not post-graduate

```
alex_f &= ~STUD_POST_GRAD_F
```

BIT Manipulation → Using Bits as Boolean Flags

Attributes of a Student :

1. Is Student a native citizen ?
   `#define STUD_NATIVE_CITIZEN_F (1 << 0)`
2. Is student male ?
   `#define STUD_MALE_F (1 << 1)`
3. Is student graduate ?
   `#define STUD_GRAD_F (1 << 2)`
4. Is Student Post-graduate ?
   `#define STUD_POST_GRAD_F (1 << 3)`
5. Has student avail any prev scholarship ?
   `#define STUD_PREV_SCHOL_F (1 << 4)`
6. Is Student born after 1 Jan 2020 ?
   `#define STUD_BIRTH_F (1 << 5)`
7. Does Student posses dual citizen ship ?
   `#define STUD_DUAL_CZN_F (1 << 6)`

uint8_t / uint32_t ...

`uint16_t alex_f; = 0`

Alex is Native USA Citizen.
```
alex_f = alex_f | STUD_NATIVE_CITIZEN_F ;
```

Alex is Male
```
alex_f |= STUD_MALE_F;
```

Alex has dual Membership
```
alex_f |= STUD_DUAL_CZN_F ;
```

Alex is not post-graduate
```
alex_f &= ~STUD_POST_GRAD_F
```

Macros

```
#define SET_BIT(n, BIT_F)        \
    (n |= BIT_F)
#define UNSET_BIT(n, BIT_F)      \
    (n &= ~BIT_F)
#define IS_BIT_SET(n, BIT_F)     \
    (n & BIT_F)
```

BIT Manipulation → Using Bits as Boolean Flags

uint16_t n = 0xFFFF;


```
#define TOGGLE_BIT(n, BIT_F)                \
        <provide definition>

#define COMPLEMENT16(n)                     \
        (n ^ 0xFFFF) OR (~n)
```

BIT Manipulation → Using Enums as bit Flags

Sometimes, it make sense ~~sometimes~~ to define enums in power of 2 so that :

- We can use enums like constants
- We can use enums like BITs

```
typedef enum col_ {
    RED     = 1 << 0,
    GREEN   = 1 << 1,
    BLACK   = 1 << 2,
    BLUE    = 1 << 3,
    COL_MAX = 1 << 4
} COL;
```

```
uint8_t col_av = 0;

col_av |= RED;
col_av |= BLUE;

if (col_av & RED) {
 printf ("RED color Available");
}
else if (col_av & BLUE) {
  printf ("BLUE color Available");
}
```

- Disadvantage : it shall be memory inefficient to use enums as index of arrays

```
COL col_available[COL_MAX];
```

BIT Manipulation → Bit pattern matching

Input Binary String	Base Bit Pattern	Result
1101	1XX1	match
1110	1XX1	no match
1101	1XX1	match
1011	1XX1	match
0101	1XX1	no match

X – don't care bit

Real world use case :

Block all traffic with Dest IP Address : 100.100.X.X

m-trie - A data structure based on bit pattern matching, used to implement ACLs in Firewalls

BIT Manipulation → Bit pattern matching

Input Binary String	Base Bit Pattern	Result
1101	1XX1	match
1110	1XX1	no-match

X – don't care bit

Mask :
1001

- Replace all bits to be matched by 1
- Represent all X by 0

Template :
1001

- Represent all X by 0

```
if (Input & Mask == Template )
        match
else
        no match
```

Ex 2 :

0000 10xx 10xx xxx0

Mask:
1111 1100 1100 0001

template:
0000 1000 1000 0000

Input String : 0000 1011 1010 1100 (match)
Input String : 0010 1011 1101 1100 (no match)

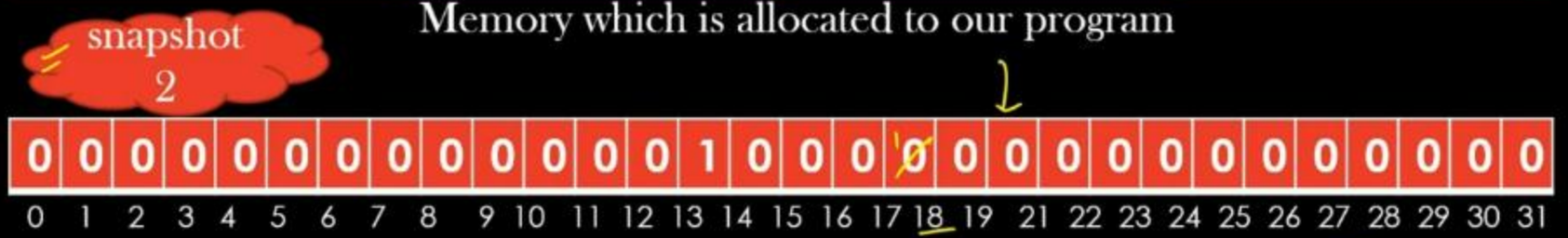
BitMap - Array of Bits

- Person comes with a theatre tkt having seat no 13 (between 1 to 28 inclusive)
- Mark the corresponding seat no as reserved

Not used

Memory is always allocated in units of bytes, and not bits !
So, you need to create wrapper APIs which work on Byte-Addressable memory but able to perform operation at bit level

Memory which is allocated to our program



Memory snapshot which our program suppose to see (Illusion)

Q. How to create bit arrays of size n bits ?

```
typedef struct bitmap_ {
        char *bit_arr;
        int arr_size;
} bitmap_t;
```

```
int N_bytes = n / 8 + (n % 8) ? 1 : 0;
Bitmap_t*bitmap = (bitmap_t *)calloc (1, sizeof(bitmap_t) );
bitmap->bit_arr = (char *) calloc(N_bytes, sizeof(char));
bitmap->arr_size = n;
```

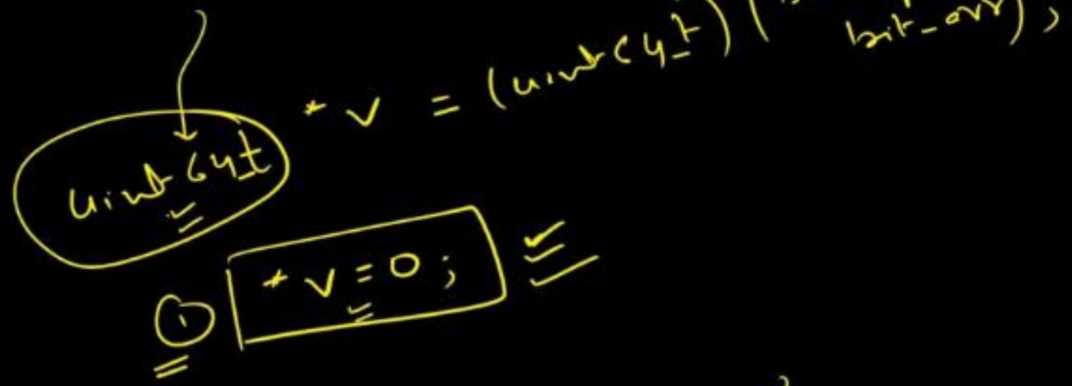
Ex : if n = 45
Create a char array by mallocing 6 Bytes
But access bits only in index range : [0, 44]

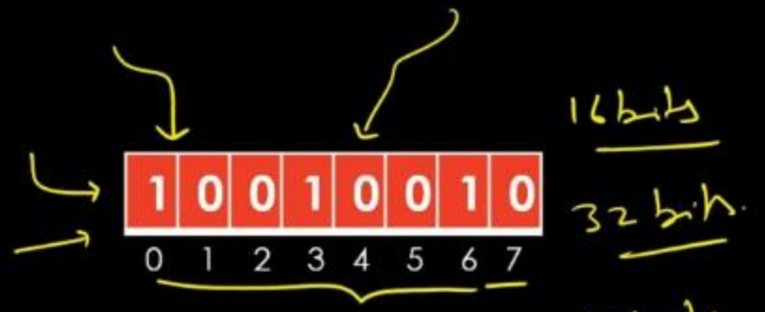
Q. Write a bitmap library :
bitmap.c/.h

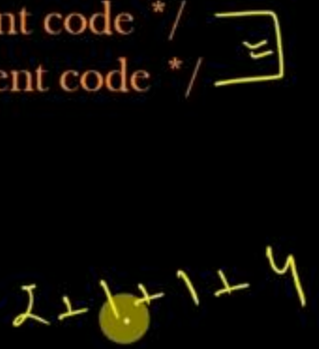
```
typedef struct bitmap_ {
    char *bit_arr;
    int arr_size;
} bitmap_t;
```

APIs :

```
bitmap_t * bitmap_create (int n_bits);
void bitmap_print (bitmap_t *bitmap);
void bitmap_set_bit (bitmap_t *bitmap, int index);
void bitmap_unset_bit (bitmap_t *bitmap, int index);
bool bitmap_is_bit_set (bitmap_t *bitmap, int index);
void bitmap_clear (bitmap_t *bitmap);  /* Write efficient code */
void bitmap_set_all (bitmap_t *bitmap); /* Write efficient code */
void bitmap_free (bitmap_t *bitmap);
```







BitMap – Array of Bits

Q. Write a bitmap library :
bitmap.c/.h

```
typedef struct bitmap_ {
        char *bit_arr;
        int arr_size;
} bitmap_t;
```

```
#define SET_BIT(n, r)    (n = n | r)

void
bitmap_set_bit(bitmap_t *bitmap, int index) {

    assert (index >= 0 && index < bitmap->arr_size);
    int byte_no = index / 8;
    uint8_t bit_no = 7 - (index % 8);
    uint8_t temp = 1 << bit_no;
    SET_BIT (  *(bitmap->bit_arr + byte_no)  , temp);
}
```

Q. Write a bitmap library :
bitmap.c/.h

```
typedef struct bitmap_ {
        char *bit_arr;
        int arr_size;
} bitmap_t;
```

APIs :

```
bitmap_t * bitmap_create (int n_bits);
void bitmap_print (bitmap_t *bitmap);
void bitmap_set_bit (bitmap_t *bitmap, int index);
void bitmap_unset_bit (bitmap_t *bitmap, int index);
bool bitmap_is_bit_set (bitmap_t *bitmap, int index);
void bitmap_clear (bitmap_t *bitmap);  /* Write efficient code */
void bitmap_set_all (bitmap_t *bitmap); /* Write efficient code */
void bitmap_free (bitmap_t *bitmap);
```

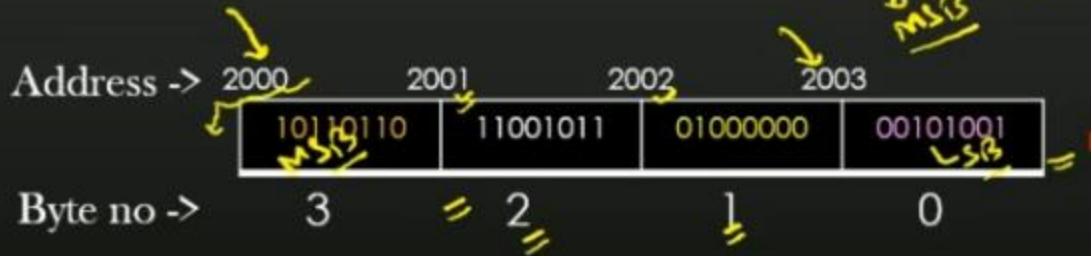
Endian-ness of Machines

What are big-Endian and Little-Endian machines

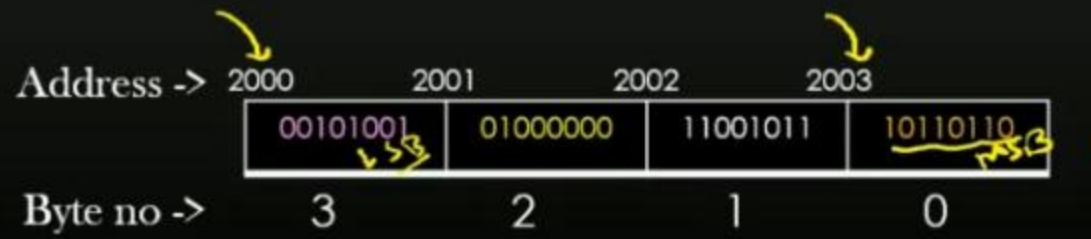
- Endianness refers to the sequential order in which bytes of data are stored in computer memory
- Best understood with the help of example
- Let's us you have a number : 3066773545

Binary representation of this number is : (10110110 11001011 01000000 00101001)

B3 B2 B1 B0 — MSB — LSB



This is big endian representation
(Least significant byte at higher address)
Network Byte Order



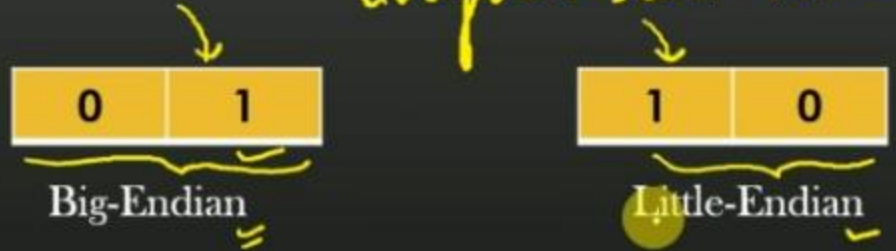
This is little endian representation
(Least significant byte at lower address)
Host Byte Order

What are big-Endian and Little-Endian machines

- Interview Question :

Write a C program which determines whether your machine is big endian or little endian ?

unsigned short int a = 1




```
/* return 0 - Big endian, 1 for Little endian*/

int
machine_endianness_type() {

        unsigned short int a = 1;
        char ist_byte = *((char *)&a);
        if ( ist_byte == 0 )
                return 0;
        else if ( ist_byte == 1 )
                return 1;
}
```

The Concept of TLVs

- TLV – Type Length Value
- Let us first try to understand the problem which TLV solves, and then we shall discuss What TLVs are and how they are used
- It is a very common scenario in Networking that Machines often exchange messages with each other. Many Internet routing protocols necessitate Machines to exchange various messages with each other periodically.
- For example, If you remember, Interior Gateway protocols such as OSPF exchange their Link state packets with other routers in the network for their proper functioning.
- To understand the problem, Let's say Machines A, B and C are exchanging the following msg with other as a part of hypothetical functionality P

```
struct xmsg{
        uint loopbck_ip;
        char router_name[32];
        uint if_addr1;
        uint if_addr2;
        uint link1_bw;
        uint link2_bw;
}
```

The Concept of TLVs

```
struct xmsg{
        uint loopbck_ip;
        char router_name[32];
        uint if_addr1;
        uint if_addr2;
        uint link1_bw;
        uint link2_bw;
}
```


```
struct xmsg{
        100.100.1.1
        A
        10.1.1.1
        12.1.1.1
        100
        200
}
```

A

```
struct xmsg{
        100.100.1.2
        B
        11.1.1.1
        12.1.1.2
        110
        220
}
```

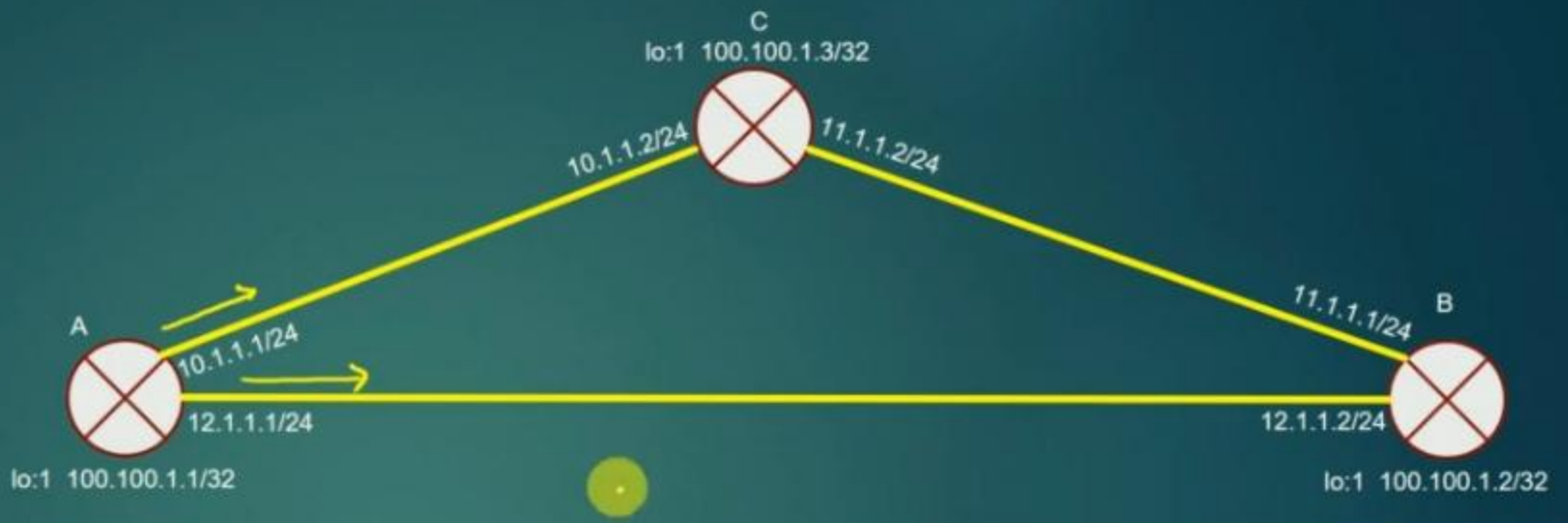
B

```
struct xmsg{
        100.100.1.3
        C
        10.1.1.2
        11.1.1.2
        90
        190
}
```

C

The Concept of TLVs

```
struct xmsg{
        uint loopbck_ip;
        char router_name[32];
        uint if_addr1;
        uint if_addr2;
        uint link1_bw;
        uint link2_bw;
}
```



- So, When machine B/C when receive this msg from machine A over the network, B/C can simply read the msg as as usual :

```
struct xmsg *recv_msg = (struct xmsg *)buffer;
recv_msg->uint_loopback_ip;
recv_msg->router_name;
recv_msg->if_addr1;
recv_msg->if_addr2;
recv_msg->link1_bw;
recv_msg->link2_bw;
```

So ?? What's the problem ?

The Concept of TLVs

- The problem in such exchange of messages arises due to heterogeneity of communicating machines
- Heterogeneity reasons could be mannnyyy ….
  - Different manufacturing vendors
  - Using different Hardware and Technologies
  - Using Different C compilers
  - And so on . . .

- We cannot ask all the vendors around the world to manufacture their network equipment's using Identical technologies and hardware !

The Concept of TLVs

- So let us try to understand the technical glitches that arises due to heterogeneity of the communicating machines in the network

We will discuss two scenarios :

- When machines are distinct and incompatible
- When selective machines in the network are upgraded

The Concept of TLVs

Ok, before going forward , let us revise our C knowledge a bit …

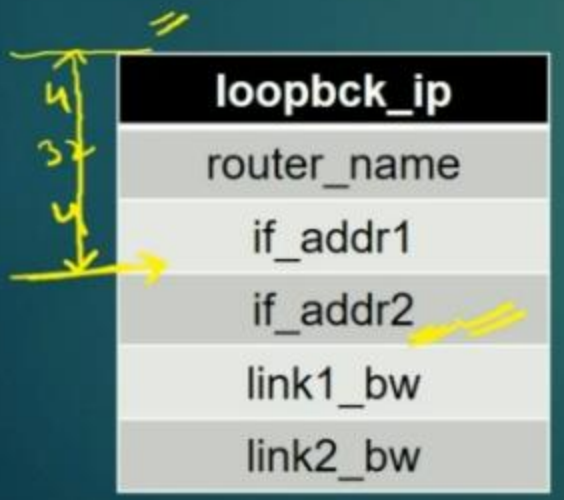
```
struct xmsg{
    uint loopbck_ip;
    char router_name[32];
    uint if_addr1;
    uint if_addr2;
    uint link1_bw;
    uint link2_bw;
}
```

On a 32 bit system ⇒ '4 bytes'

Fields	Size	offset
loopbck_ip	4	0
router_name	32	4
if_addr1	4	36
if_addr2	4	40
link1_bw	4	44
link2_bw	4	48

A = 2000

2040



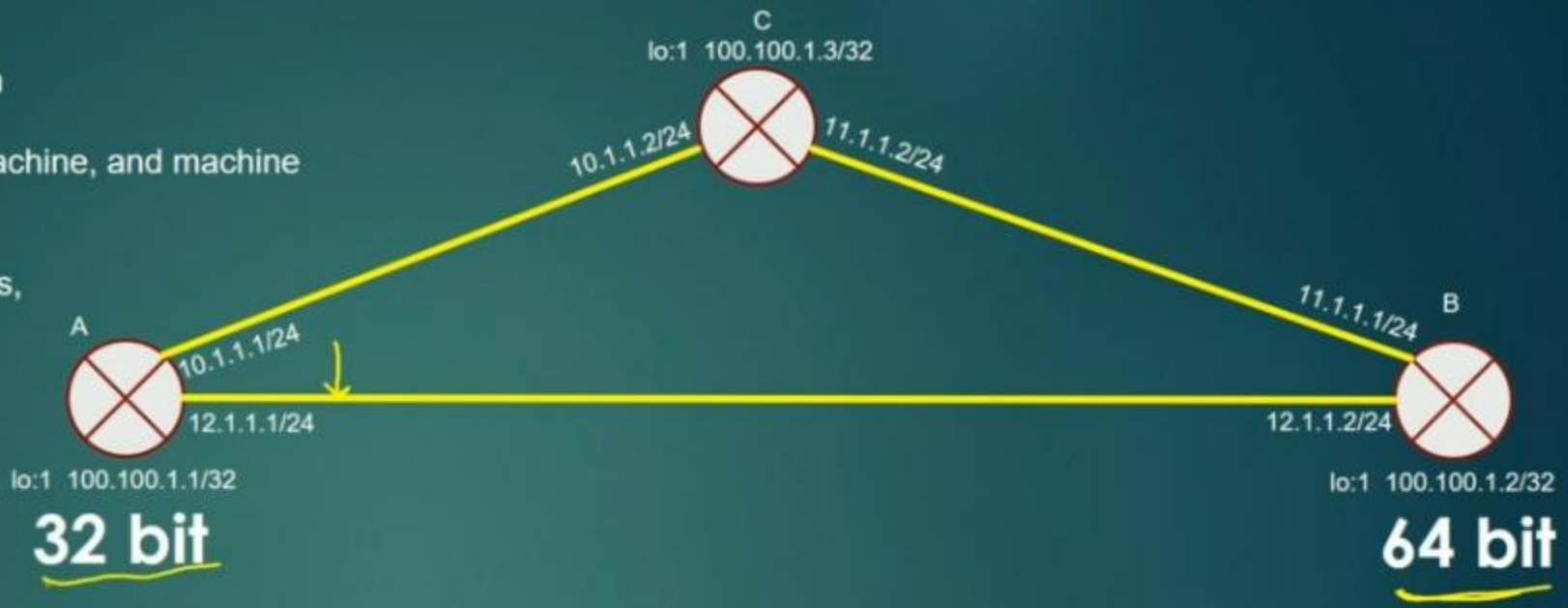
Struct xmsg *ptr;

ptr->if_addr2 – reading/writing 4 bytes @40th byte from starting address

2040

The Concept of TLVs

- Ok, now let us see the real problem
- Let us Say Machine A is a 32 bit machine, and machine B is a 64 bit machine.
- It means, sizeof(uint) on A is 4 bytes, whereas it is 8 bytes on B
- Now, let see the xmsg layout on wire when they are generated by machine A and B respectively.




```
struct xmsg{
        uint loopbck_ip;
        char router_name[32];
        uint if_addr1;
        uint if_addr2;
        uint link1_bw;
        uint link2_bw;
}
```

A

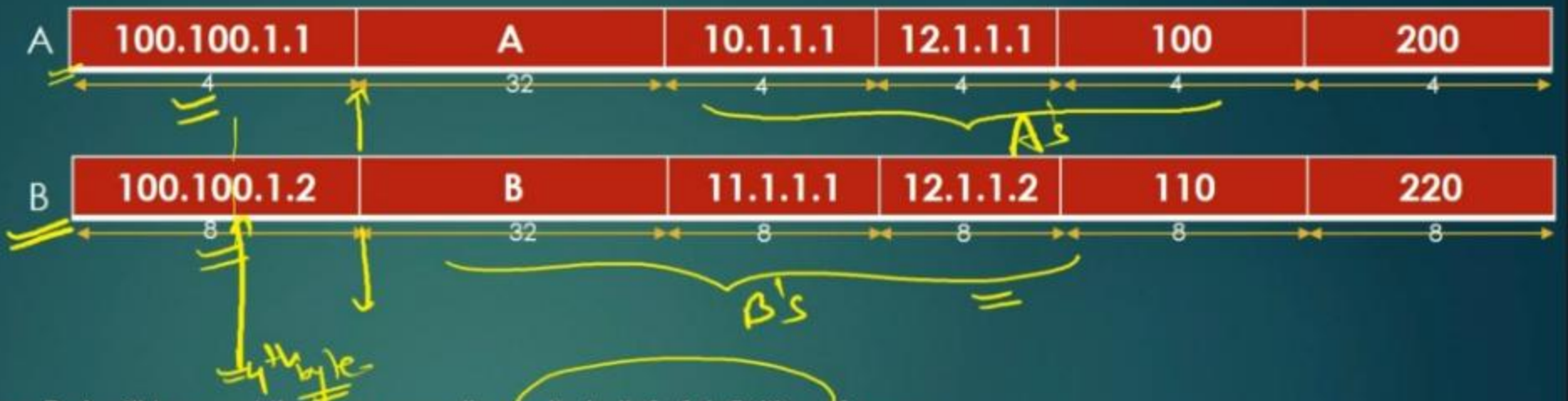
100.100.1.1	A	10.1.1.1	12.1.1.1	100	200
4	32	4	4	4	4

B

100.100.1.2	B	11.1.1.1	12.1.1.2	110	220
8	32	8	8	8	8

The Concept of TLVs

```
struct xmsg{
        uint loopbck_ip;
        char router_name[32];
        uint if_addr1;
        uint if_addr2;
        uint link1_bw;
        uint link2_bw;
}
```



When A receives xmsg from B, A will typecast the msg according to its belief of definition of xmsg:

- So, When machine A receive the xmsg from machine B over the network, A will type cast the msg according to its own definition of struct xmsg :

```
struct xmsg *recv_msg = (struct xmsg *)buffer;
recv_msg->uint_loopback_ip;   /*Instead of reading 8 bytes, A will read only 4 bytes*/
recv_msg->router_name;        /*From B's perspective, it is 8th byte from start of msg, from A's perspective it is 4th byte from start of msg*/
recv_msg->if_addr1;
recv_msg->if_addr2;
recv_msg->link1_bw;
recv_msg->link2_bw;
```

"Spanish"
English

The Concept of TLVs

```
struct xmsg{
        uint loopbck_ip;
        char router_name[32];
        uint if_addr1;
        uint if_addr2;
        uint link1_bw;
        uint link2_bw;
}
```

When A receives xmsg from B, A will typecast the msg according to its belief of definition of xmsg:

- So, When machine A receive the xmsg from machine B over the network, A will type cast the msg according to its own definition of struct xmsg :

```
struct xmsg *recv_msg = (struct xmsg *)buffer;
recv_msg->uint_loopback_ip;   /*Instead of reading 8 bytes, A will read only 4 bytes*/
recv_msg->router_name;        /*From B's perspective, it is 8th byte from start of msg, from A's perspective it is 4th byte from start of msg*/
recv_msg->if_addr1;
recv_msg->if_addr2;
recv_msg->link1_bw;
recv_msg->link2_bw;
```

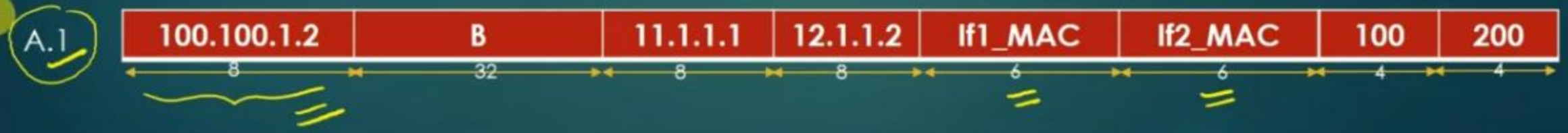
"Spanish" English

So, A ends up in reading a Garbage, leading to Data corruption on A. It happened because size of Data types on B is different from that of A.

The Concept of TLVs

- Lets see the same problem due to other reason.
- Let us Say Machine A's software is upgraded such that it introduces a new member in the structure.

```
struct xmsg{
        uint loopbck_ip;
        char router_name[32];
        uint if_addr1;
        uint if_addr2;
        char if_mac1[6];
        char if_mac2[6];
        uint link1_bw;
        uint link2_bw;
}
```



The Concept of TLVs

A.1

```
struct xmsg{
        uint loopbck_ip;
        char router_name[32];
        uint if_addr1;
        uint if_addr2;
        char if_mac1[6];
        char if_mac2[6];
        uint link1_bw;
        uint link2_bw;
}
```

B and C

```
struct xmsg{
        uint loopbck_ip;
        char router_name[32];
        uint if_addr1;
        uint if_addr2;
        uint link1_bw;
        uint link2_bw;
}
```

Machines B and C, when receives the new msg A.1 generated by machine A, they will try to read the msg according to their own definition of struct xmsg. Again Data corruption !

So many problems !! Vendor manufacturer has invented his new patented technology but he cannot upgrade his software with new technology because other machines in the network wont work with his new version of Software ! Competitors are happy ! Funny !!

The Concept of TLVs

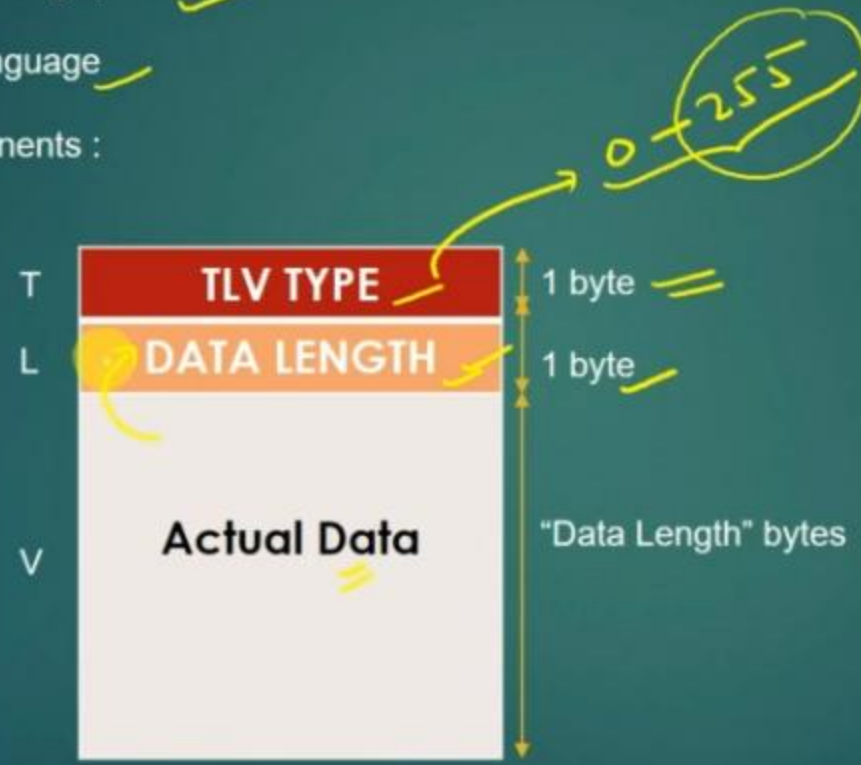
- Networking is a field where various network equipment's being manufactured by various vendors, need to work In complete cooperation and harmony with each other for the network protocol to work.

- Machines need to comply with each other for the network functionality to work correctly, yet at the same time Network Vendors should be free to innovate/upgrade/update their software without breaking the existing compliance with the other Machines deployed in the network.

The concept of TLVs Solves these problems very easily

The Concept of TLVs

- TLV (Type length value)
  - Is a mechanism to encode the data in the format that is independent of
    - Machine Architecture
    - Underlying Operating system
    - Compiler
    - Programming language
  - TLVs has three components :



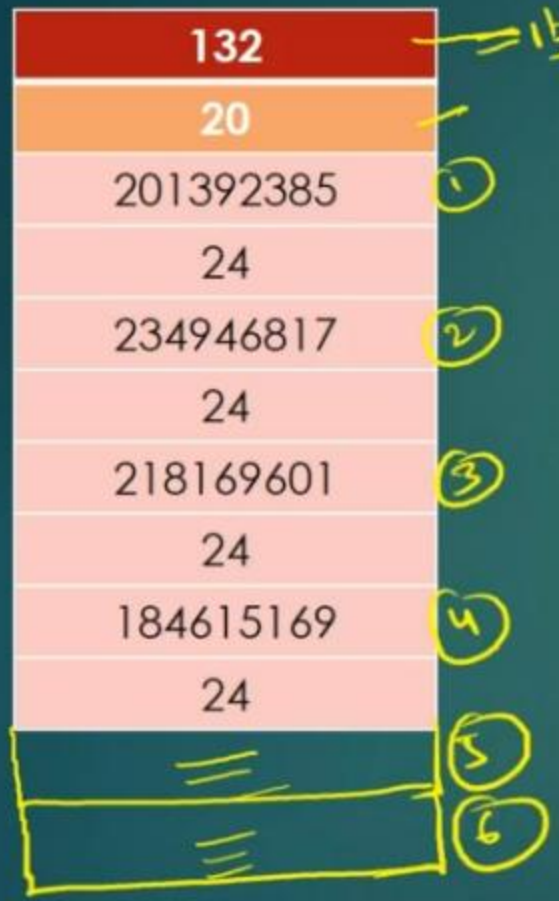
The Concept of TLVs

- Example :
  - Suppose Machine A wants to send machine B, the set of all IP addresses which is configured on all its interfaces

- We can take any number as TLV type. Let's take it as 132.
- Next we need to define the definition of TLV 132 :
  - 4 byte integer number (which is ip address)
  - 1 byte mask value
  - This is called *TLV definition*
- Any machine which is suppose to process this TLV when received, us suppose to be aware of TLV definition.

132
20
201392385
24
234946817
24
218169601
24
184615169
24

The Concept of TLVs

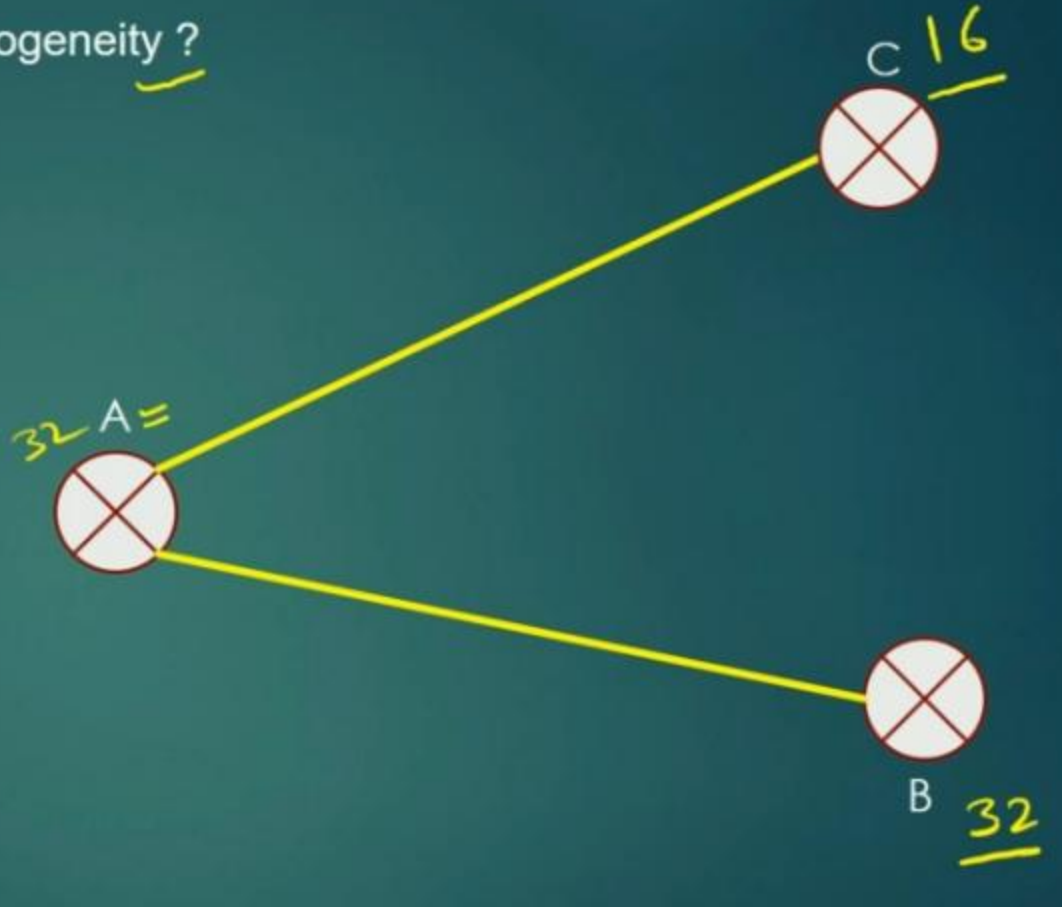


- When receiving machine receives this TLV :
  - It reads first byte
  - Now it knows that it is TLV 132
  - It means, its unit data size is 5 bytes,
    4 bytes of ip address followed by 1 byte of mask value
  - Read next 1 byte which is 20
  - Divide 20 by 5 = 4
  - Now, machine knows it has four occurrence of unit data type
  - Iterate over rest of the data and read all units of data

The Concept of TLVs

How TLVs solve the problem of machine heterogeneity ?

132
20
201392385
24
234946817
24
218169601
24
184615169
24



Let us suppose, machine A sends this TLV to machine B and C
Let say, machine B is 32 bit machine, and C is 16 bit machine

Let us see, how B and C decode this TLV . . .

The Concept of TLVs

Had we sent the data as simple C structure on the wire as below :

```
struct tlv132{
        unsigned int ip_address;
        char mask;
}
```

Then it would have been problem for receiving machines, if their hardware architecture differs from sending machine.

For 32 bit machine : structure size is 5 bytes
For 16 bit machine : structure size is 3 bytes

Receiving Machines which are non compliant with sending machine would end up reading garbage !

```
struct tlv132 *ptr = (struct tlv132 *)recv_msg;   /*recv_msg us 4 byte ip address, and 1 byte mask*/

ptr->ip_address ;  /*This line would read 4 bytes on 32 bit machine, and 2 bytes on 16 bit machine*/
```

To Sum up : TLVs are all about *Send and Read data byte by byte*, and every machine MUST know TLV TYPE definition

The Concept of TLVs

How TLVs solve the problem of Software Upgrade ?

132
20
201392385
24
234946817
24
218169601
24
184615169
24
222
12
08:00:27:3e:97:62
08:00:27:ce:90:78

TLV definition :

- 6 bytes (which is mac address)

We have just learned, how TLVs solves the problem of software Upgrade !!

The Concept of TLVs

Streams

- Design a Data structure to create (serialize) and read (De-serialize) TLVs
- Data structure : *Stream*
- It resembles to type writer – start with the next line when there is no space left in the current line

The Concept of TLVs

Coding Assignment

- Streams (also called serialize-buffer)

```
typedef struct serialized_buffer{
  char *b;
  int size;
  int next;
} ser_buff_t;
```

The Concept of TLVs

Coding Assignment

- Streams (also called serialize-buffer)

```
typedef struct serialized_buffer{
    char *b;
    int size;
    int next;
} ser_buff_t;
```

```
void
init_serialized_buffer (ser_buff_t **b){
    (*b) = (ser_buff_t *)calloc(1, sizeof(ser_buff_t));
    (*b)->b = calloc(1, SERIALIZE_BUFFER_DEFAULT_SIZE); /*const , say 100*/
    (*b)->size = SERIALIZE_BUFFER_DEFAULT_SIZE;
    (*b)->next = 0;
}
```

Usage :

```
ser_buff_t *stream;
init_serialized_buffer(&stream);
```

The Concept of TLVs

Coding Assignment

- Streams (also called serialize-buffer)

```
void serialize_data (ser_buff_t *buff, char *data, int nbytes){
    int available_size = buff->size - buff->next;
    char isResize = 0;

    while(available_size < nbytes){
        buff->size = buff->size * 2;
        available_size = buff->size - buff->next;
        isResize = 1;
    }

    if(isResize == 0){
        memcpy((char *)buff->b + buff->next, data, nbytes);
        buff->next += nbytes;
        return;
    }

    // resize of the buffer
    buff->b = realloc(buff->b, buff->size);
    memcpy((char *)buff->b + buff->next, data, nbytes);
    buff->next += nbytes;
    return;
}
```

The Concept of TLVs

Coding Assignment

- Streams (also called serialize-buffer)

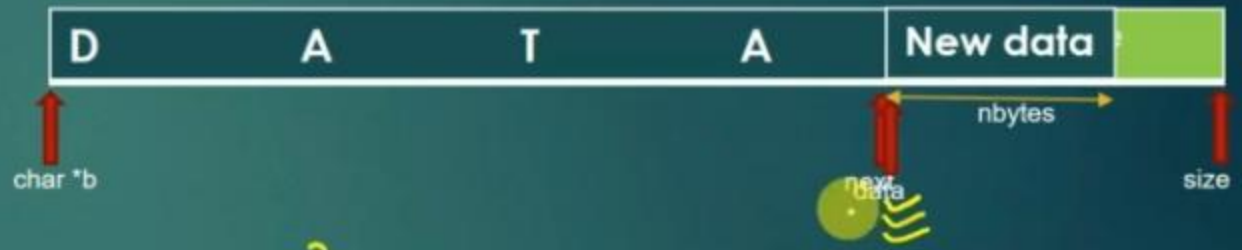
```
void serialize_data (ser_buff_t *buff, char *data, int nbytes){

    int available_size = buff->size - buff->next;
    char isResize = 0;

    while(available_size < nbytes){
        buff->size = buff->size * 2;
        available_size = buff->size - buff->next;
        isResize = 1;
    }

    if(isResize == 0){
        memcpy((char *)buff->b + buff->next, data, nbytes);
        buff->next += nbytes;
        return;
    }

    // resize of the buffer
    buff->b = realloc(buff->b, buff->size);
    memcpy((char *)buff->b + buff->next, data, nbytes);
    buff->next += nbytes;
    return;
}
```



The Concept of TLVs

Coding Assignment

- Streams (also called serialize-buffer)

```
void serialize_data (ser_buff_t *buff, char *data, int nbytes){

    int available_size = buff->size - buff->next;
    char isResize = 0;

    while(available_size < nbytes){
        buff->size = buff->size * 2;
        available_size = buff->size - buff->next;
        isResize = 1;
    }

    if(isResize == 0){
        memcpy((char *)buff->b + buff->next, data, nbytes);
        buff->next += nbytes;
        return;
    }

    // resize of the buffer
    buff->b = realloc (buff->b, buff->size);
    memcpy((char *)buff->b + buff->next, data, nbytes);
    buff->next += nbytes;
    return;
}
```

If there is no space to accommodate new data,
Double the size of entire buffer while preserving the
Exiting content

The Concept of TLVs

Coding Assignment

- Serializing the TLVs

```
ser_buff_t *stream;
init_serialized_buffer(&stream);

char data = 132;
serialize_data (stream, &data, 1 );

data = 20;
serialize_data (stream, &data, 1 );

unsigned int ip = 201392385;
serialize_data (stream, &ip, 4 );

char mask = 24;
serialize_data (stream, &mask, 1 );

ip = 234946817;
serialize_data (stream, &ip, 4 );

mask = 24;
serialize_data (stream, &mask, 1 );

ip = 218169601;
serialize_data (stream, &ip, 4 );

mask = 24;
serialize_data (stream, &mask, 1 );

ip = 184615169;
serialize_data (stream, &ip, 4 );

mask = 24;
serialize_data (stream, &mask, 1 );
```

```
char data = 222;
serialize_data (stream, &data, 1 );

data = 12;
serialize_data (stream, &data, 1 );

char mac1[6] = {8, 0, 27, 3e, 97, 62};
serialize_data (stream, mac1, 6 );

char mac2[6] = {8, 0, 27, ce, 90, 78};
serialize_data (stream, mac2, 6 );
```

Data to be send as TLV :
stream->b with size stream->next

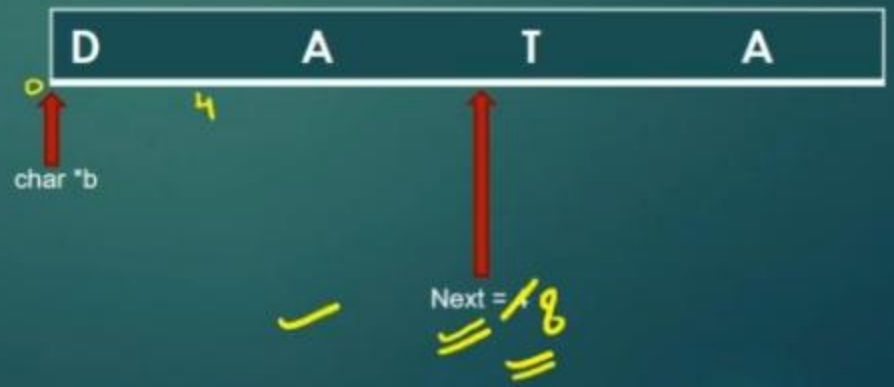
The Concept of TLVs

Coding Assignment

- De-Serializing the TLVs

```
void
de_serialize_data (char *dest, ser_buff_t *b, int size){
    memcpy(dest, b->b + b->next, size);
    b->next += size;
}
```


```
unsigned int dest;
de_serialize_data ((char *)&dest, b, 4);
```




```
de_serialize_data ((char *)&dest, b, 4);
```

Agenda and Pre-requisites

- After this section, you will be able to :
  - Create, Update, Delete Linux Timers
  - Restart, Pause, Resume, Reschedule Timers
  - Fire Periodic Or One Shot or Exponential back off timers
  - Create an application using Timers
  - Implement Timer biased Algorithms and state machines
  - Build your own Custom Timer Library (libtimer)

Pre-requisites :

1. Linux OS
2. Callbacks / Function Pointers
3. C Programming Skills

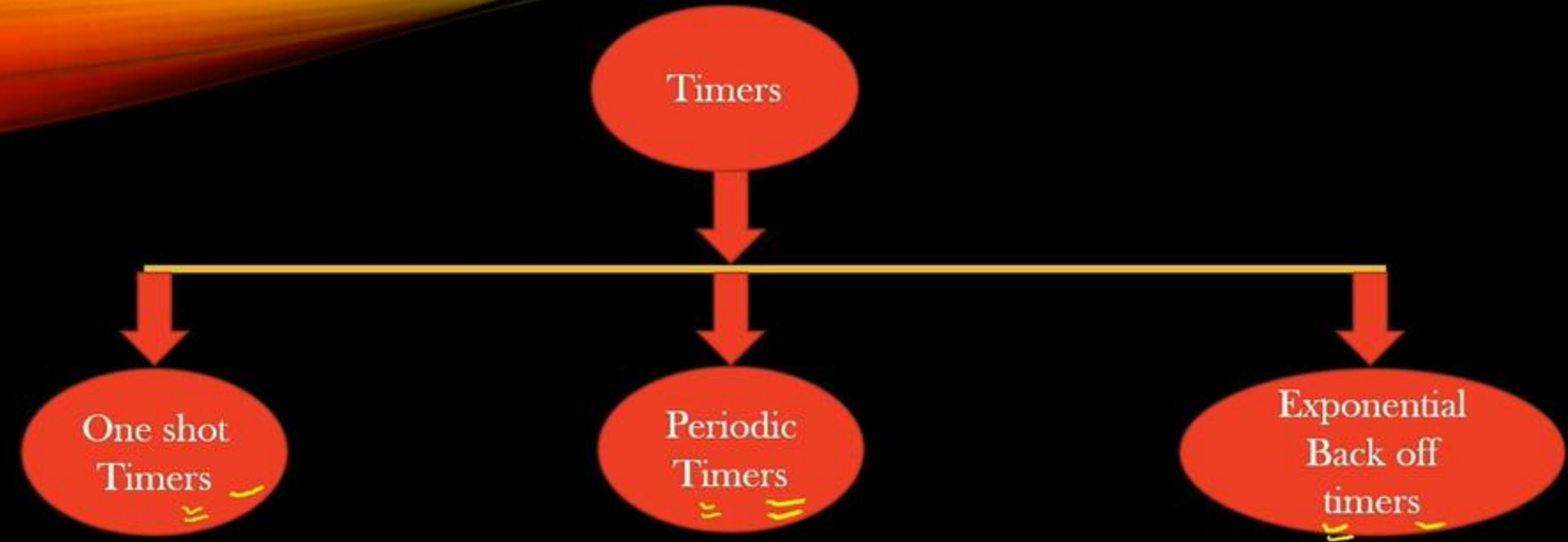
Note that :

We are learning programming concepts, not programming Language Or linux !

Timers Relevance

- One of the most common programming concept that you would come across is the Timers
- Timers helps in scheduling the events in future Or periodically
- Timers are extensively used in many domain of Computer science, especially in Networking
  - TCP Timers
  - OTP Time outs
  - Session log out
  - Periodically sending out Network packets
  - Deferring/Scheduling the computation
- In this Section, We shall Study Linux Inbuilt Posix Compliant Timer APIs and built our own custom more controllable timers on top of those

Timers Types



- We will use Linux In-built API to create Timers, and use those to implement all three type of timers

Timers -> POSIX APIs

- POSIX provides four basic APIs to manipulate timers on Unix compliance platforms

- timer_create( )
  - Create a Timer Data structure (but do not fire it)
- timer_settime ( )
  - Used to start / stop the timers depending on the arguments
- timer_gettime ( )
  - Returns the time remaining for the timer to fire
- timer_delete( )
  - Delete the timer data structure

☞ We will use the above 4 APIs as building blocks to build our custom timer library

Terminologies ☞

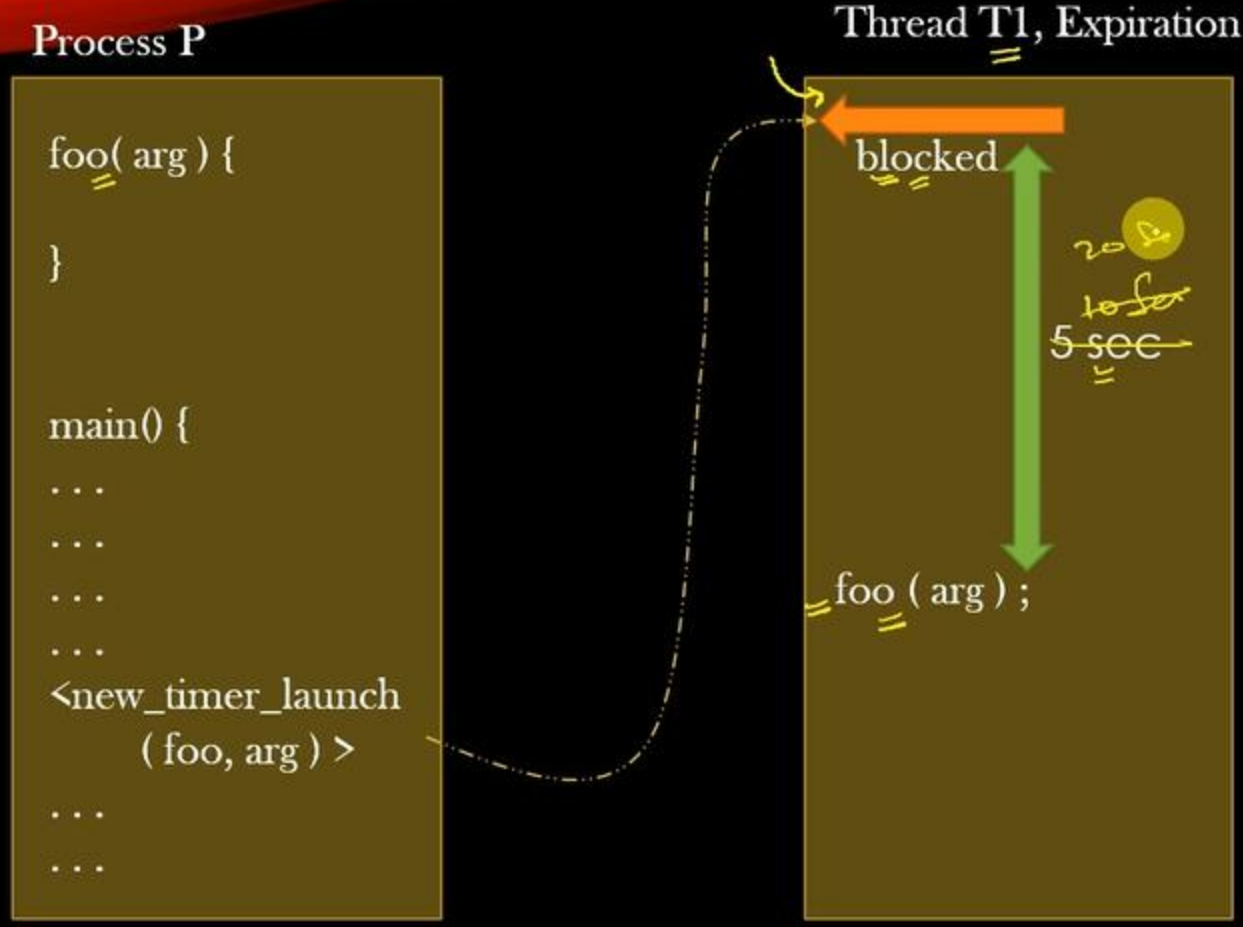
Suppose you want to send a network packet after 10 seconds

At t = 0, you start or Alarm the timer

At t = 10 , timer fires Or timer Expires

Linux Timers -> How timer Works

- Timer Works in the context of separate code flow (thread or process)



When foo() has completed its execution in the Context of timer thread, Timer is tuned off (timer thread is killed by kernel)

Application (P) should free all Resources that were occupied by timer (In the end of foo ( ) only

foo() is called timer callback

Same mechanics for :

- One shot timer
- Periodic Timer
- Exponential back off timer

```
int timer_create ( <Type of Timer >,
                   < Timer Controlling Parameters >,
                   < Timer pointer > );
```

Returns 0 on success, -1 on error, and errno (errno.h) is set to errcode

```
struct sigevent evp;

evp.sigev_notify_function = <ptr to callback fn >
evp.sigev_value.sival_ptr = < address of argument to callback( arg >
evp.sigev_notify = SIGEV_THREAD ; / * asking the kernel to launch a timer thread to invoke callback >
```

timer_callback () is actually

A generic wrapper over
Application callback

```
void timer_callback (union sigval arg ){
    foo(arg.sival_ptr);
}
```

- We need a way to specify expiration time of the timer
- For this, POSIX standard provide a data structure :

```
struct itimerspec ts;

ts.it_value.tv_sec = 5;
ts.it_value.tv_nsec = 0;    /*nano sec granularity*/
```

```
struct itimerspec {
        struct timespec it_interval; /* next value */
        struct timespec it_value;  /* current value */
};

struct timespec {
        time_t tv_sec;  /* seconds */
        long tv_nsec;   /* nanoseconds */
};
```

- And final step is to arm the timer (start the timer)

```
int timer_settime( <timer > ,  0,  &ts, NULL ) ;
```

- We need a way to specify expiration time of the timer
- For this, POSIX standard provide a data structure :

```
struct itimerspec ts;

ts.it_value.tv_sec = 5;
ts.it_value.tv_nsec = 0;    /*nano sec granularity*/
```

```
struct itimerspec {
        struct timespec it_interval; /* next value */
        struct timespec it_value;  /* current value */
};

struct timespec {
        time_t tv_sec;  /* seconds */
        long tv_nsec;   /* nanoseconds */
};
```

- And final step is to arm the timer (start the timer)

```
int timer_settime( <timer > ,  0,  &ts, NULL ) ;
```

Now, let us put all pieces together and write our timer demo program

- Demo for first Timer implementation

  WheelTimer/WheelTimer/libtimer/Course/timerExampleDemo1.c

- Converting one shot timer into periodic timer

Linux Timers -> POSIX APIs -> Demo 1

vm

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```
27 #include <stdlib.h>
28 #include <stdio.h>
29 #include <memory.h>
30 #include <unistd.h> /* for pause() */
31 #include <stdint.h>
32 #include <stdbool.h>
33
34 static void
35 print_current_system_time(){
36
37     time_t t;
38     time(&t);   /*  Get the current system time */
39
40     /* Print the current system time,
41      * Will insert one \n character */
42     printf("%s ",ctime(&t));
43 }
44
45 /* Example */
46 typedef struct pair_{
47
48     int a;
49     int b;
50 } pair_t;
51
52 pair_t pair = { 10, 20 };
53
54 /* The Timer callback function which will be called every
55  * time the timer expires. The signature of the function would be :
56  * void <fn-name>(union sigval)
57
```

```
int timer_create ( <Type of Timer >,
                   < Timer Controlling Parameters >,
                   < Timer pointer > );
```

Returns 0 on success, -1 on error, and errno (errno.h) is set to errcode

```
struct sigevent evp;
```

```
evp.sigev_notify_function = <ptr to callback fn >
evp.sigev_value.sival_ptr = < address of argument to callback arg >
evp.sigev_notify = SIGEV_THREAD ; / * asking the kernel to launch a timer thread to invoke callback >
```

timer_callback () is actually

A generic wrapper over
Application callback

```
void timer_callback (union sigval arg ){

  foo(arg.sival_ptr);
}
```

arg.sival_ptr gives the actual Argument to callback foo

Linux Timers -> POSIX APIs -> timer_create ( )

```
44
45 /* Example */
46 typedef struct pair_{
47
48     int a;
49     int b;
50 } pair_t;
51
52 pair_t pair = { 10, 20 };
53
54 /* The Timer callback function which will be called every
55  * time the timer expires. The signature of the function would be :
56  * void <fn-name>(union sigval)
57  * */
58 void
59 timer_callback(union sigval arg){
60
61     print_current_system_time();
62
63     pair_t *pair = (pair_t *) arg.sival_ptr; /*Extract the user data structure*/
64
65     printf("pair : [%u %u]\n", pair->a, pair->b);
66 }
67
68
69
70
71
72
73
74
```

Linux Timers -> POSIX APIs -> timer_create ( )

vm

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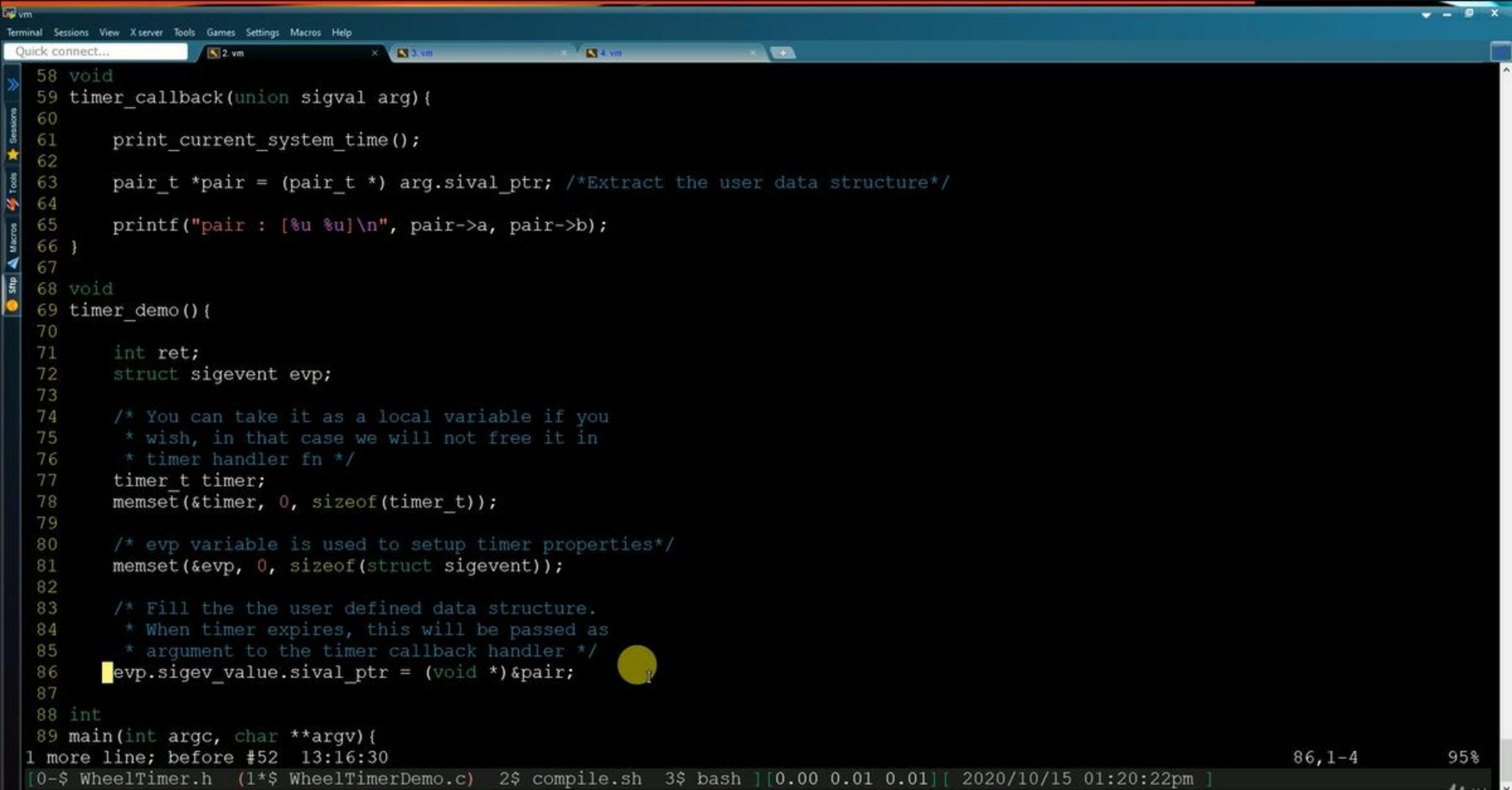
```
58 void
59 timer_callback(union sigval arg){
60
61     print_current_system_time();
62
63     pair_t *pair = (pair_t *) arg.sival_ptr; /*Extract the user data structure*/
64
65     printf("pair : [%u %u]\n", pair->a, pair->b);
66 }
67
68 void
69 timer_demo(){
70
71     int ret;
72     struct sigevent evp;
73
74 int
75 main(int argc, char **argv){
76
77     return 0;
78 }
```


vm
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58 void
59 timer_callback(union sigval arg){
60
61 print_current_system_time();
62
63 pair_t *pair = (pair_t *) arg.sival_ptr; /*Extract the user data structure*/
64
65 printf("pair : [%u %u]\n", pair->a, pair->b);
66 }
67
68 void
69 timer_demo(){
70
71 int ret;
72 struct sigevent evp;
73
74 /* You can take it as a local variable if you
75 * wish, in that case we will not free it in
76 * timer handler fn */
77 timer_t timer;
78 memset(&timer, 0, sizeof(timer_t));
79
80 /* evp variable is used to setup timer properties*/
81 memset(&evp, 0, sizeof(struct sigevent));
82
83 /* Fill the the user defined data structure.
84 * When timer expires, this will be passed as
85 * argument to the timer callback handler */
86 evp.sigev_value.sival_ptr = (void *)&pair;
87
88 int
89 main(int argc, char **argv){
1 more line; before #52 13:16:30
86,1-4 95%
[0-$ WheelTimer.h (1*$ WheelTimerDemo.c) 2$ compile.sh 3$ bash][0.00 0.01 0.01][2020/10/15 01:20:22pm]

```
72      struct sigevent evp;
73
74      /* You can take it as a local variable if you
75       * wish, in that case we will not free it in
76       * timer handler fn */
77      timer_t timer;
78      memset(&timer, 0, sizeof(timer_t));
79
80      /* evp variable is used to setup timer properties*/
81      memset(&evp, 0, sizeof(struct sigevent));
82
83      /* Fill the the user defined data structure.
84       * When timer expires, this will be passed as
85       * argument to the timer callback handler */
86      evp.sigev_value.sival_ptr = (void *)&pair;
87
88      /* On timer Expiry, We want kernel to launch the
89       * timer handler routine in a separate thread context */
90      evp.sigev_notify = SIGEV_THREAD;
91
92      /* Register the timer hander routine. This routine shall
93       * be invoked when timer expires*/
94      evp.sigev_notify_function = timer_callback;
95
96      /* Create a timer. It is just a timer initialization, Timer
97       * is not fired (Alarmed)  */
98      ret = timer_create (CLOCK_REALTIME,
99                          &evp,
100                         &timer);
101
102 int
103 main(int argc, char **argv){
1 more line; before #38  13:16:26                                    100,1-4       95%
[0-$ WheelTimer.h  (1*$ WheelTimerDemo.c)  2$ compile.sh  3$ bash ][0.00 0.00 0.00][ 2020/10/15 01:22:41pm ]
```

```
 94      evp.sigev_notify_function = timer_callback;
 95
 96      /* Create a timer. It is just a timer initialization, Timer
 97       * is not fired (Alarmed)  */
 98      ret = timer_create (CLOCK_REALTIME,
 99                          &evp,
100                          &timer);
101
102      if ( ret < 0) {
103
104          printf("Timer Creation failed, errno = %d\n", errno);
105          exit(0);
106      }
107
108      /* Let us setup the time intervals */
109
110      struct itimerspec ts;
111
112      /* I want the timer to fire for the first time after 5 seconds
113       * and 0 nano seconds*/
114      ts.it_value.tv_sec = 5;
115      ts.it_value.tv_nsec = 0;
116
117  int
118  main(int argc, char **argv){
119
120      return 0;
121  }
~
~
~
~
1 more line; before #23  13:16:18                                    115,1-4       Bot
[0-$ WheelTimer.h  (1*$ WheelTimerDemo.c)  2$ compile.sh  3$ bash ][0.00 0.00 0.00][ 2020/10/15 01:25:15pm ]
```

```
                        &evp,
                        &timer);

    if ( ret < 0) {

        printf("Timer Creation failed, errno = %d\n", errno);
        exit(0);
    }

    /* Let us setup the time intervals */

    struct itimerspec ts;

    /* I want the timer to fire for the first time after 5 seconds
     * and 0 nano seconds*/
    ts.it_value.tv_sec = 5;
    ts.it_value.tv_nsec = 0;

    ts.it_interval.tv_sec = 0;
    ts.it_interval.tv_nsec = 0;

    /* Now start the timer*/
    ret = timer_settime (timer,
                         0,
                         &ts,
                         NULL);

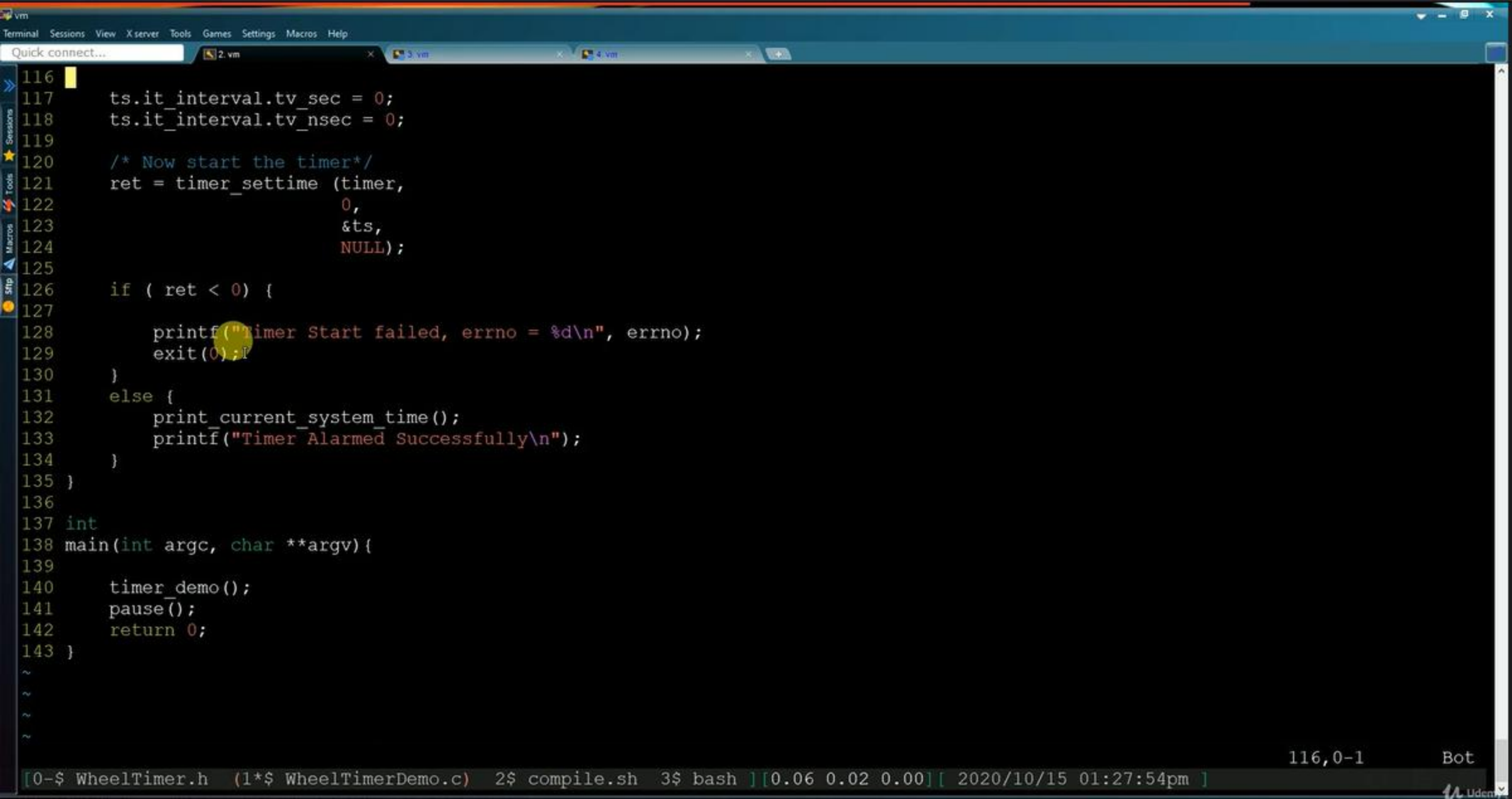
int
main(int argc, char **argv){

    return 0;
}
```

130,1 Bot

[0-$ WheelTimer.h (1*$ WheelTimerDemo.c) 2$ compile.sh 3$ bash][0.00 0.00 0.00][2020/10/15 01:26:38pm]

```
116
117     ts.it_interval.tv_sec = 0;
118     ts.it_interval.tv_nsec = 0;
119
120     /* Now start the timer*/
121     ret = timer_settime (timer,
122                          0,
123                          &ts,
124                          NULL);
125
126     if ( ret < 0) {
127
128         printf("Timer Start failed, errno = %d\n", errno);
129         exit(0);
130     }
131     else {
132         print_current_system_time();
133         printf("Timer Alarmed Successfully\n");
134     }
135 }
136
137 int
138 main(int argc, char **argv){
139
140     return 0;
141 }
```


vm
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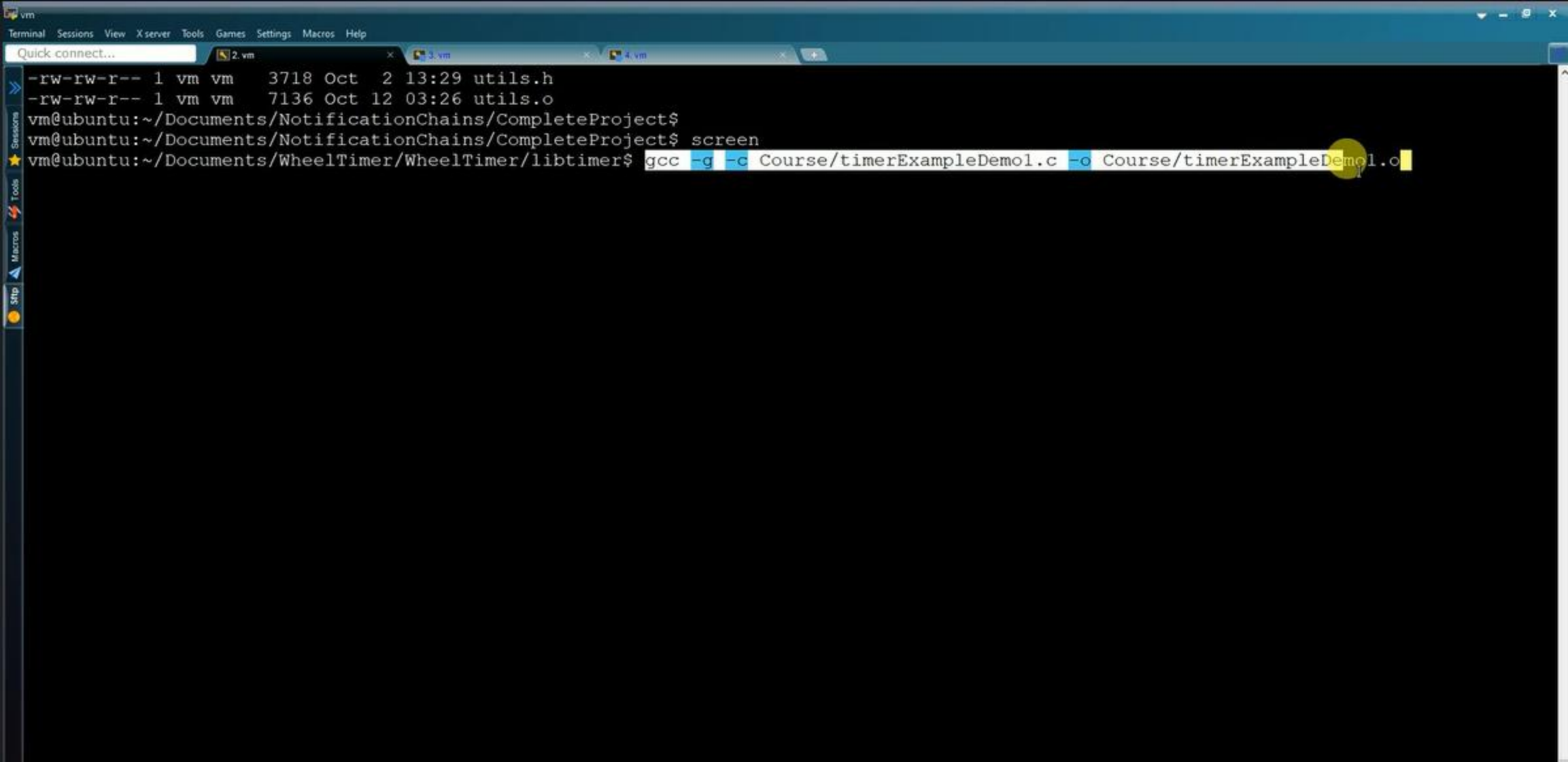
Sftp
116
117 ts.it_interval.tv_sec = 0;
118 ts.it_interval.tv_nsec = 0;
119
120 /* Now start the timer*/
121 ret = timer_settime (timer,
122 0,
123 &ts,
124 NULL);
125
126 if (ret < 0) {
127
128 printf("Timer Start failed, errno = %d\n", errno);
129 exit(0);
130 }
131 else {
132 print_current_system_time();
133 printf("Timer Alarmed Successfully\n");
134 }
135 }
136
137 int
138 main(int argc, char **argv){
139
140 timer_demo();
141 pause();
142 return 0;
143 }
~
~
~
~
116,0-1 Bot
[0-$ WheelTimer.h (1*$ WheelTimerDemo.c) 2$ compile.sh 3$ bash][0.06 0.02 0.00][2020/10/15 01:27:54pm]


vm
Terminal Sessions View X server Tools Games Settings Macros Help
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2. vm
3. vm
4. vm
-rw-rw-r-- 1 vm vm 3718 Oct 2 13:29 utils.h
-rw-rw-r-- 1 vm vm 7136 Oct 12 03:26 utils.o
vm@ubuntu:~/Documents/NotificationChains/CompleteProject$
vm@ubuntu:~/Documents/NotificationChains/CompleteProject$ screen
vm@ubuntu:~/Documents/WheelTimer/WheelTimer/libtimer$ gcc -g -c Course/timerExampleDemo1.c -o Course/timerExampleDemo1.o
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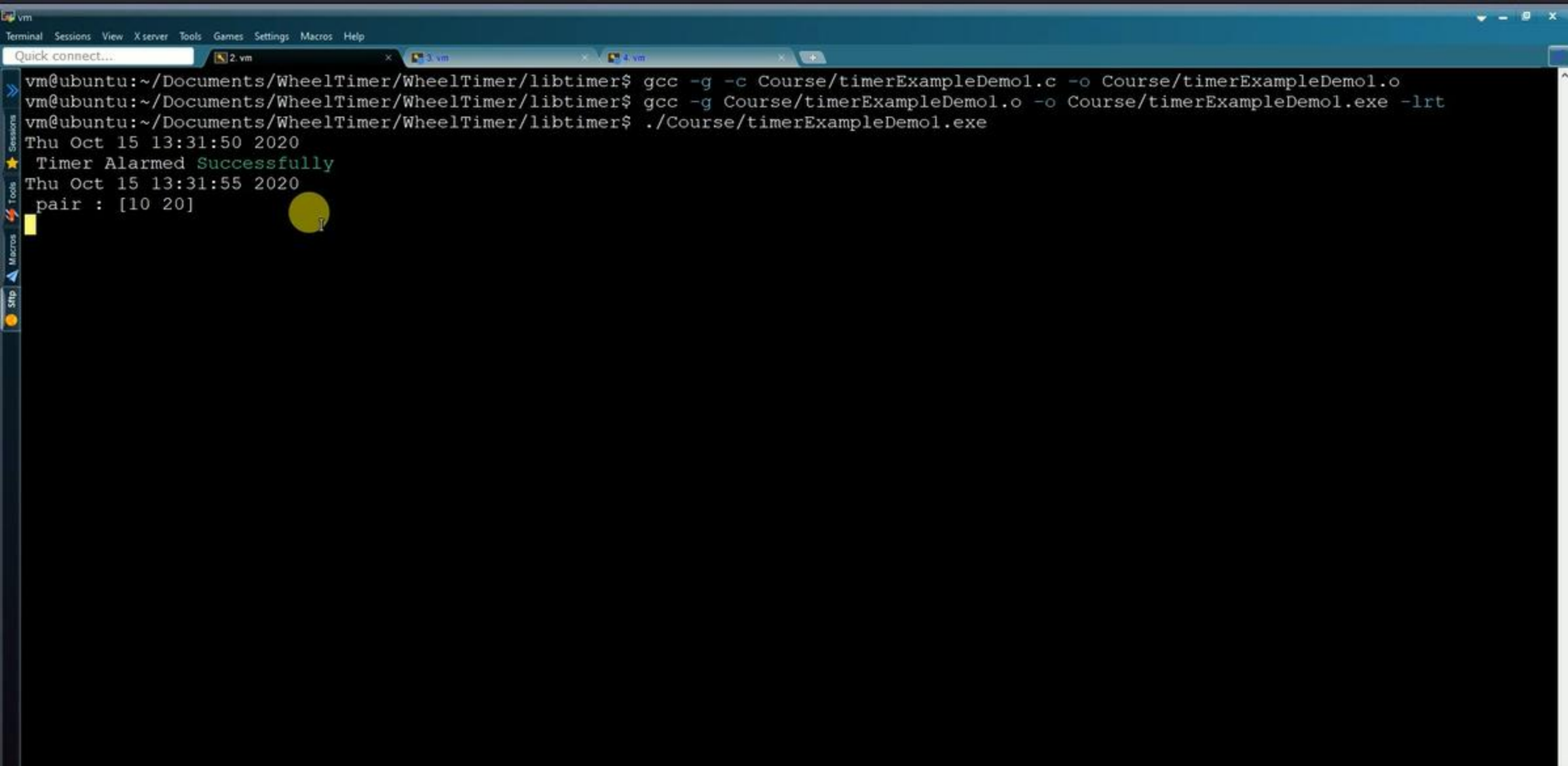

vm
Terminal Sessions View X server Tools Games Settings Macros Help
Quick connect...
2. vm
3. vm
4. vm
vm@ubuntu:~/Documents/WheelTimer/WheelTimer/libtimer$ gcc -g -c Course/timerExampleDemo1.c -o Course/timerExampleDemo1.o
vm@ubuntu:~/Documents/WheelTimer/WheelTimer/libtimer$ gcc -g Course/timerExampleDemo1.o -o Course/timerExampleDemo1.exe -lrt
vm@ubuntu:~/Documents/WheelTimer/WheelTimer/libtimer$ ./Course/timerExampleDemo1.exe
Thu Oct 15 13:31:50 2020
Timer Alarmed Successfully
Thu Oct 15 13:31:55 2020
pair : [10 20]
Sessions
Tools
Macros
Sftp

```
vm@ubuntu:~/Documents/WheelTimer/WheelTimer/libtimer$ gcc -g -c Course/timerExampleDemo1.c -o Course/timerExampleDemo1.o
vm@ubuntu:~/Documents/WheelTimer/WheelTimer/libtimer$ gcc -g Course/timerExampleDemo1.o -o Course/timerExampleDemo1.exe -lrt
vm@ubuntu:~/Documents/WheelTimer/WheelTimer/libtimer$ ./Course/timerExampleDemo1.exe
Thu Oct 15 13:31:50 2020
 Timer Alarmed Successfully
Thu Oct 15 13:31:55 2020
 pair : [10 20]
^C
vm@ubuntu:~/Documents/WheelTimer/WheelTimer/libtimer$ gcc -g -c Course/timerExampleDemo1.c -o Course/timerExampleDemo1.o
vm@ubuntu:~/Documents/WheelTimer/WheelTimer/libtimer$ gcc -g Course/timerExampleDemo1.o -o Course/timerExampleDemo1.exe -lrt
vm@ubuntu:~/Documents/WheelTimer/WheelTimer/libtimer$ ./Course/timerExampleDemo1.exe
Thu Oct 15 13:34:33 2020
 Timer Alarmed Successfully
Thu Oct 15 13:34:38 2020
 pair : [10 20]
Thu Oct 15 13:34:41 2020
 pair : [10 20]
Thu Oct 15 13:34:44 2020
 pair : [10 20]
Thu Oct 15 13:34:47 2020
 pair : [10 20]
```

Memory Management in Linux

Agenda

- Concepts like Paging, Demand paging etc are out of scope of this course
- Pls check for pure OS courses for this purpose

Pre-requisite knowledge

- To understand the Linux Memory Management, we first need to understand some basics :
  - Virtual Address Space
  - Virtual Memory
  - Memory layout of a process

Virtual Address space & Virtual Memory

What exactly is Virtual Memory and Virtual Address space ?

- Virtual Memory is the total amount of memory your system has for a process.
- It is different from physical memory and is computer architecture dependent

For example :

For a 32 bit system, Total virtual memory is 2^32 bytes (Fixed), and it is per process (Not for all processes combined !)
Whereas You can extend physical memory to 4GB, 8GB or 16GB (Variable) (Upper limit)

- 2^32 bytes !! Every byte has an address. Therefore, there are 2^32 Virtual addresses in a 32 bit system.
- Computer Programs works with Virtual Memory only, means, your program access only virtual addresses
- Your Program never knows anything about physical memory , all it knows that it has 2 ^ 32 bytes of virtual memory to store its data
- Each process in execution is allotted virtual memory for its usage, which can grow to maximum of 2^32 bytes = 4GB
- The Memory assigned to a process is called process's virtual address space
- Every process running on a 32 bit system, can use maximum of 2 ^ 32 bytes of Virtual memory

Memory Layout of a Process

- It is a diagrammatic representation of the of the Process's memory layout in Linux/Unix OS
- MLoP helps us to understand how process's virtual memory works during the course of execution of a process
- Let us see how Memory Layout of a process looks like for a linux process . . .

But windows is not open source, therefore, World do not talks about it :p

Memory Layout of a Process

argc & argv[i]

Memory assigned for process execution. It cannot grow beyond a certain limit.
Content : All local variables, arguments passed, Return address, Caller's info

Total System Available memory. The Heap region expands or shrinks When the process malloc Or free the memory

Dynamic memory assigned to a process

Memory which stores the process uninitialized global and static variables, fixed

Memory which stores the process initialized global and static variables, fixed

Memory which stores the compiled process assembly code in text format, fixed

Memory Layout of a Process


```
int global_var = 10;
int global_var2;

int
main(int argc, char **argv){
    int i = 0;
    char *my_name = "Abhishek";
    static int j = 5;
    int *k;
    k = malloc(100);
    foo(j);
    return 0;
}
```

VAS = Code + Data + Heap + Stack + CLA

Memory Layout of a Process

Summary :

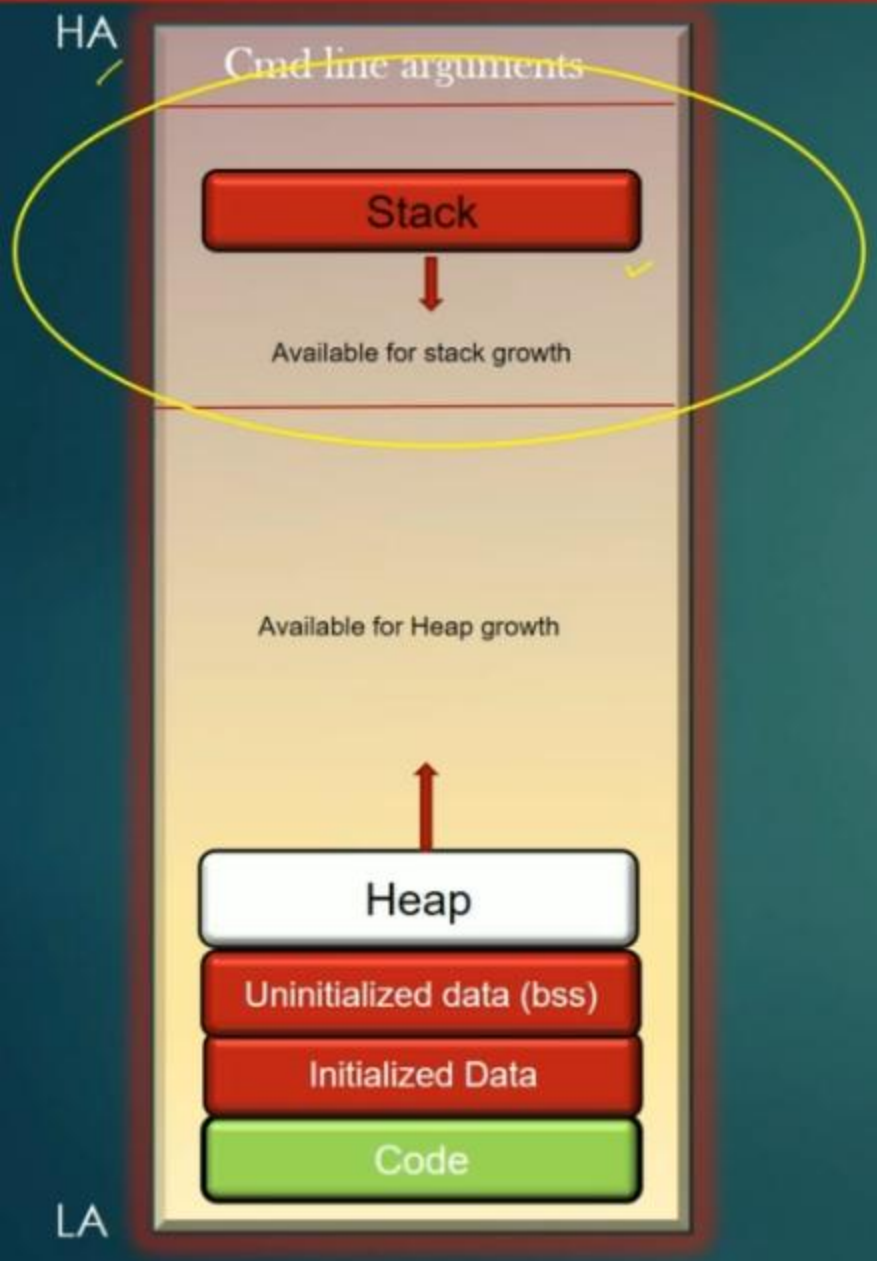
- Heap: When program allocate memory at runtime using calloc and malloc function, then memory gets allocated in heap. when some more memory need to be allocated using calloc and malloc function, heap grows upward as shown in diagram

- Stack: Stack is used to store your local variables, passed arguments to the functions along with the return address of the instruction which is to be executed after the function call is over. When a new stack frame needs to be added (as a result of a newly called function), the stack grows Downward. Stack Memory supports procedure calls and procedure returns.

- Data Segment : Global and Static variables

- Stack-Memory grows from HA to LA, Heap Memory grows from LA to HA

Very Important for interview perspective
Asked from fresher's to 10 yrs of experience, every time !



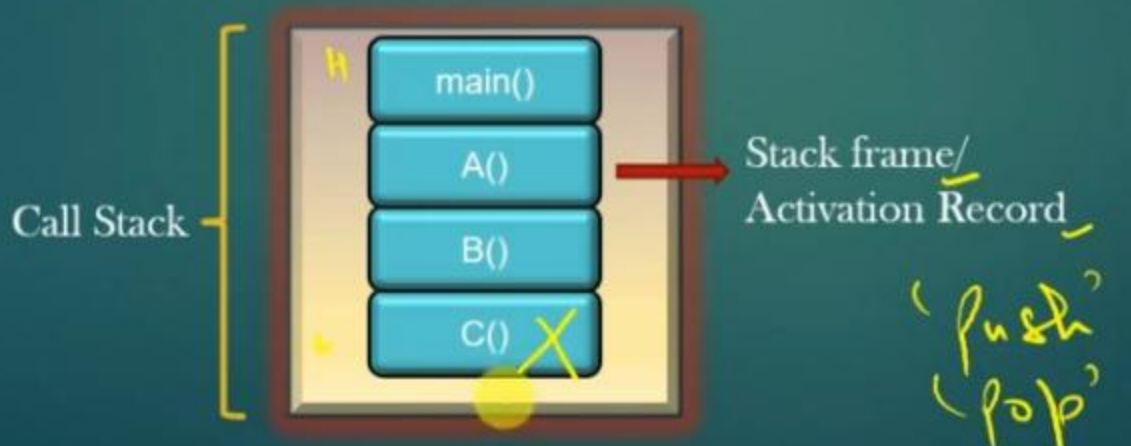
Stack Memory

- What is stack Memory ?
- What is the purpose ?
- How it is organized by OS ?

Stack Memory

- Region of Memory in process's Virtual address space where data is added or removed in Last-in-first-out manner
- When a new function call is invoked, Data is added to stack memory and when a current fn call returns, data is removed from stack Memory. This "Data" is called a stack-frame. Thus every fn has its stack frame.
  main() -> A() -> B() -> C()
- Any data which is stored in Stack Memory is said to reside on a stack
- Every process has its own fixed (configurable) stack memory. When process terminates, stack memory is reclaimed back by OS
- For the F() to execute, its stack frame should be setup up first on the stack memory. This is joint effort of Caller and Callee.

f1() → f2()
Caller
Callee

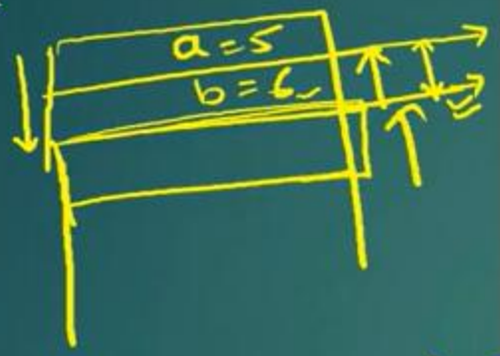


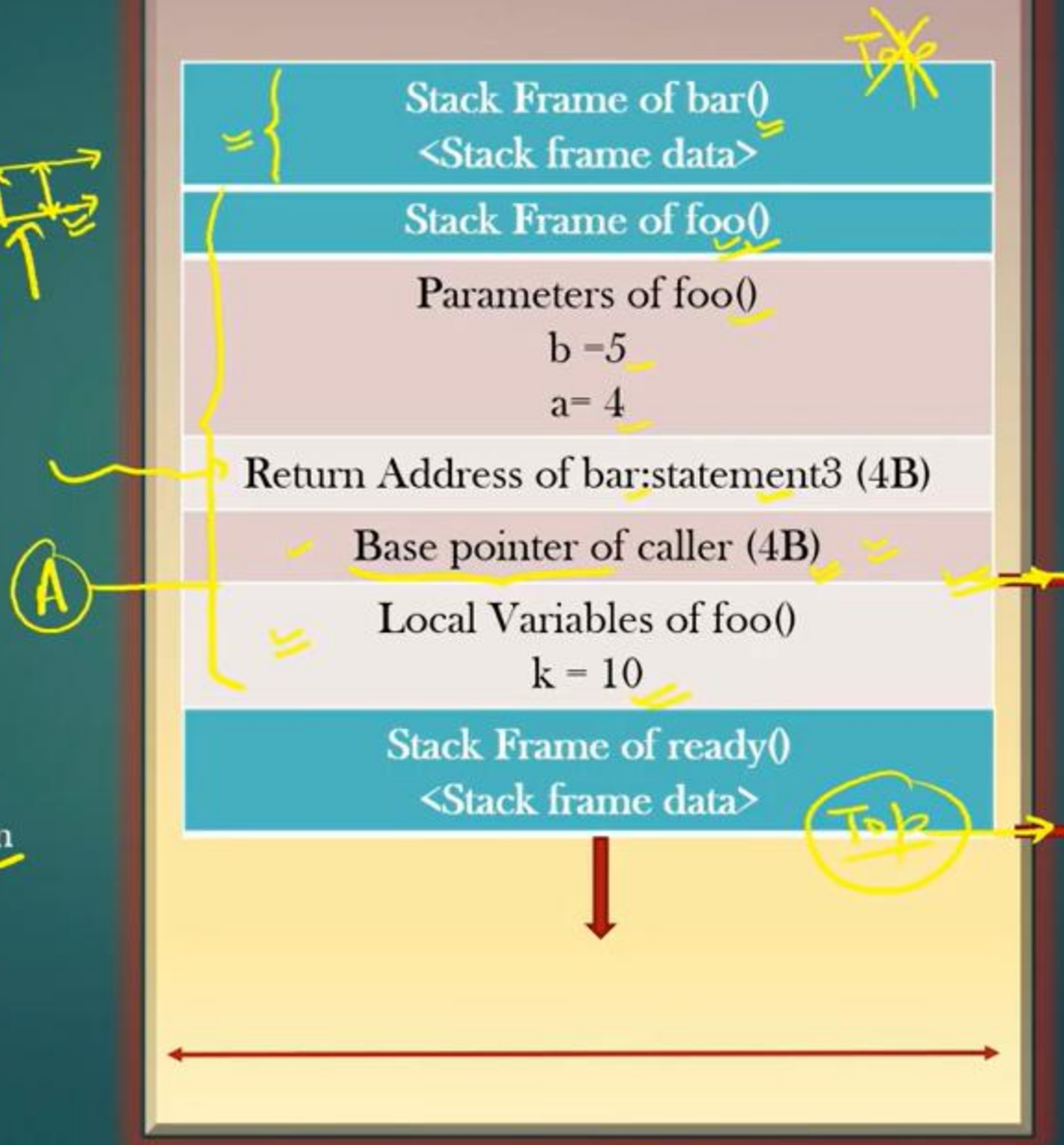
Stack Memory contents

```
void foo (int a, int b){
        int k = 10;
        . . .
        . . .
        ready();
}

void bar (int c) {

        statement 1;
        statement 2;
        foo (4, 5) ;
        statement 3;
}
```





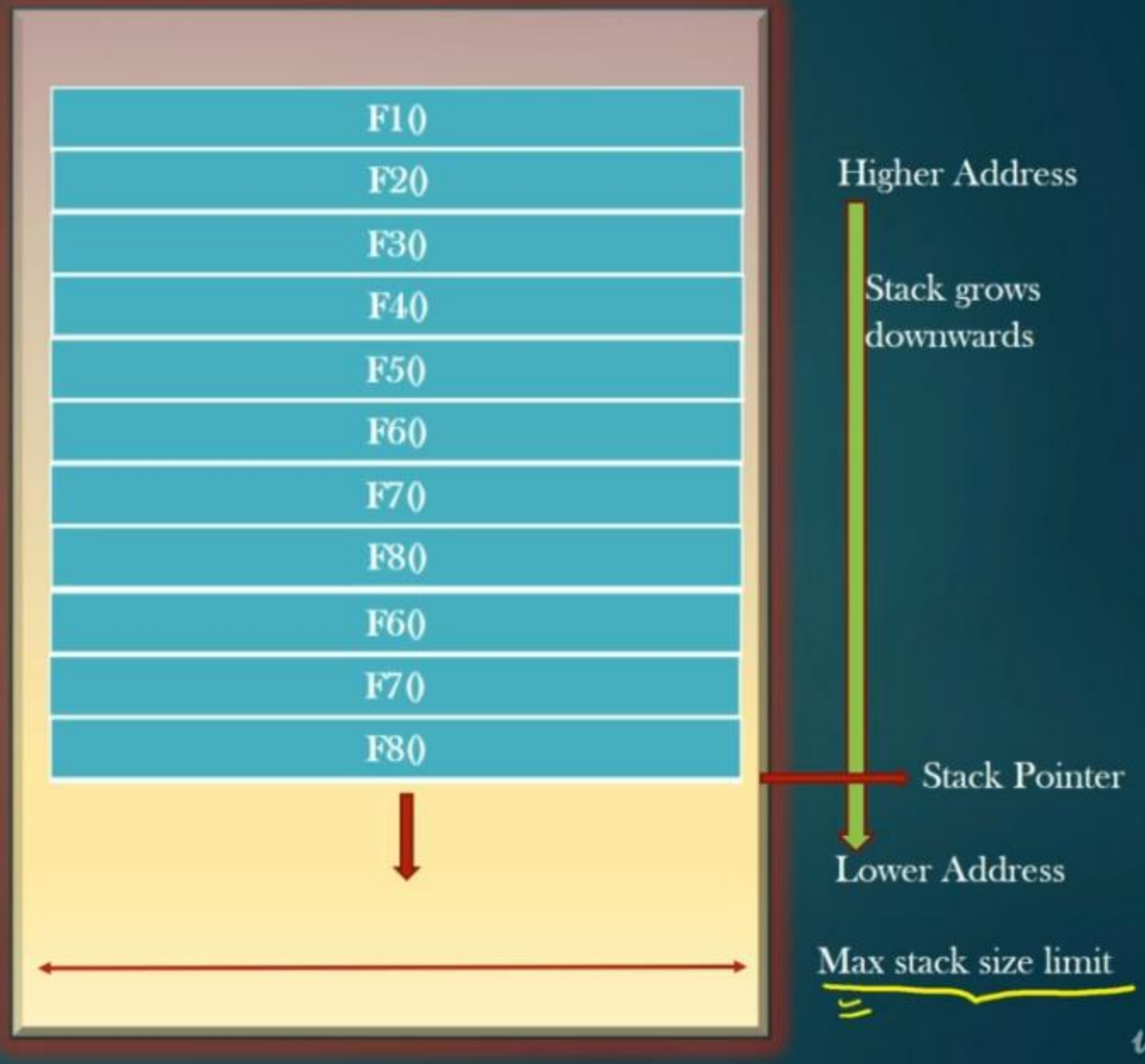
- Stack frame contains four types of information
  1. Parameter Passed to the callee
  2. Return Address of the caller fn – 4B
  3. Base pointer – 4B
  4. Local Variables of a function

Stack Overflow

- If you write a program such that there are is a long chain of function calls, you can cause stack overflow
- Stack overflow is a situation where program stack grows beyond the maximum stack fixed size
- Recursive functions often cause stack overflow

```
int add(int n) {
        return n + add(n+1);
}
```

- You are discouraged to write recursive functions in Industry
- To see stack memory max size on your machine ulimit -s (shows in MB)



Stack Corruption

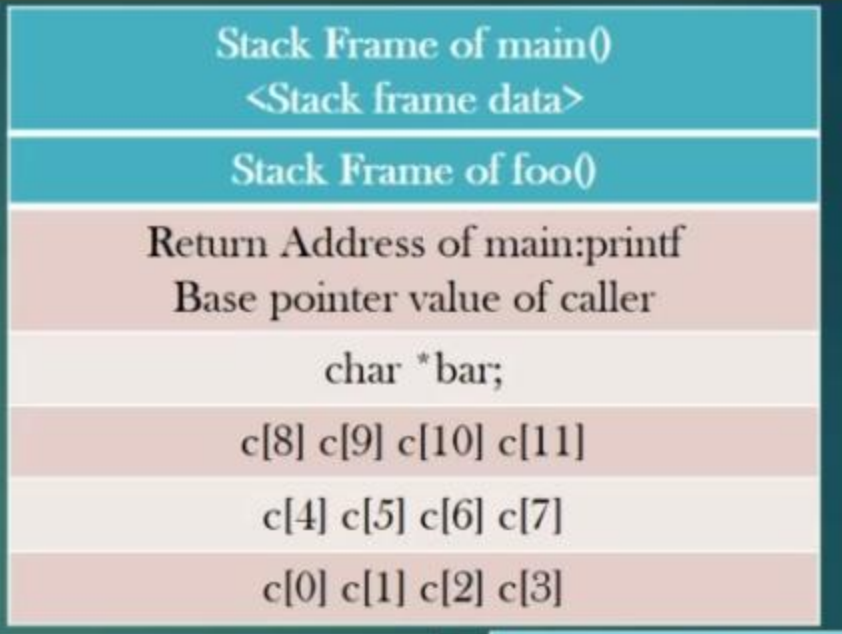
Stack Corruption

- Stack corruption is a situation where we corrupt the stack data by copying the data more than the memory limits

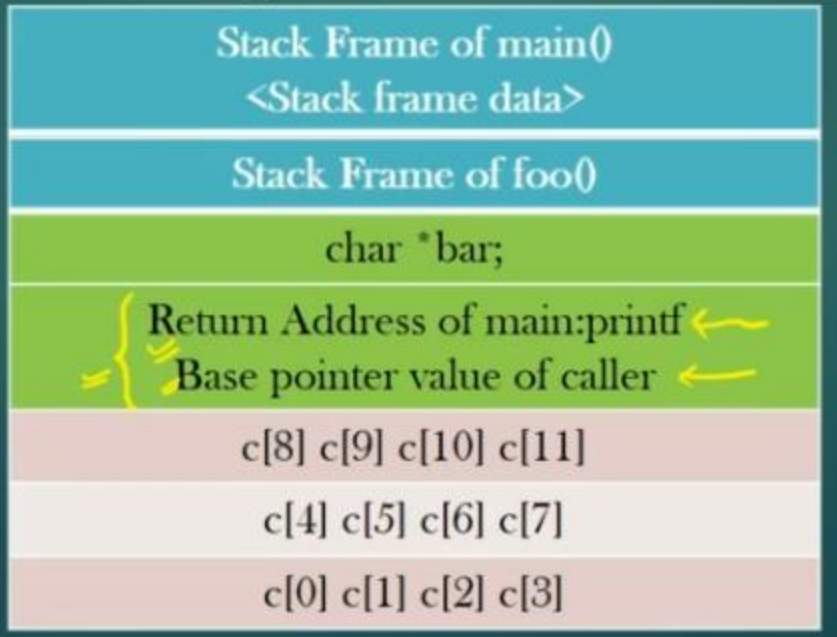
```
void foo (char *bar)
{
char c[12];
strcpy(c, bar); // no bounds checking...
}

int main (int argc, char **argv)
{
foo(argv[1]);
printf("exiting...");
}
```

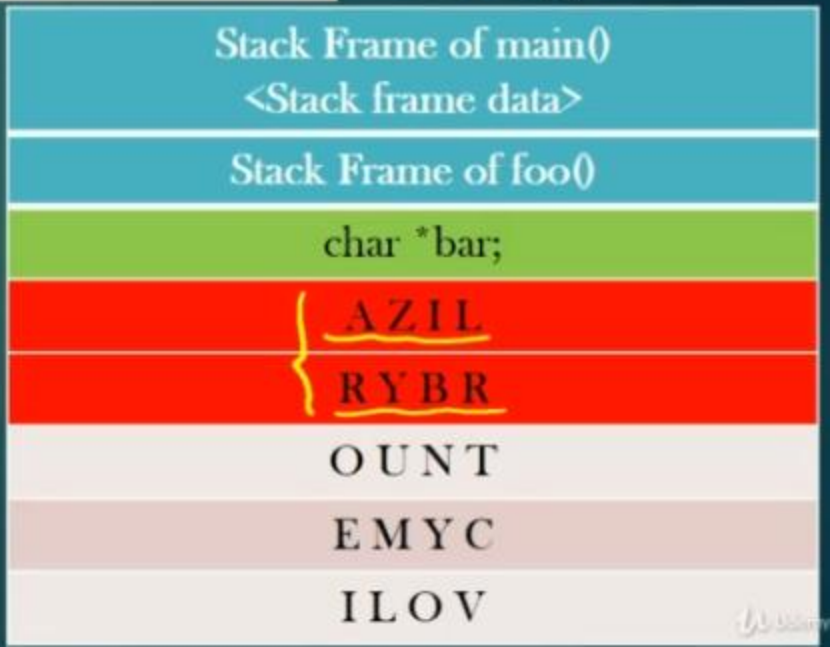
Call using :
ILOVEMYCOUNTRYBRAZIL



Before copy



After copy



Procedure Call & Return - Basics

Procedure Call and Return

- Let us understand how Function Call is implemented in Linux OS using Stack Memory

- Goal :
  - When Caller makes a call to Callee, Callee should start execute from beginning
  - When Callee finishes Or returns, Caller resumes from the point where it left
  - Return Value by Callee, if any, should be available to Caller

- Let us understand at the low level how to achieve the above stated Goals

Procedure Call and Return

- *Terminologies :*
- *Call Stack* is a collection of stack frames, each function when called in program create a new frame in stack
- A frame that is being executed is always the topmost frame of stack, pointer to top most frame in the stack is called *frame pointer* also called *base pointer*
- Pointer to the top of *stack is called the stack pointer.* In other words, stack pointer points to the end of the top-most frame in the stack
- Now, let us see in depth how function calls happen, how values are returned from Callee and how caller resume its execution when Callee returns
- Program Counter (PC) is a pointer which always pointes to the current instruction to be executed, also called Instruction pointer
- We understand already that Stack Memory is Managed by Data structure called *Stack* on which two basic operation are supported – Push & Pop
- We Use Push when we need to store the new data into the stack. Increment the Stack Pointer after Push Operation
- We Pop when we need to remove data from top of stack. Decrement the Stack Pointer after Pop Operation

Procedure Call and Return

Let's divide our discussion into two parts :

1. Procedure Call : Caller calling the callee, control transfer to callee
2. Procedure Return : Callee terminates and control return back to Caller

We will see the mechanism behind each of the above two Scenarios in detail.

Lets gather some basics first . . .

Understanding CPU Registers

- We need to understand the purpose of three registers which are used to implement the mechanism of procedure call and return

- eip - Instruction pointer register which stores the address of very next instruction to be executed
- esp - Stack pointer register, always stores the address of top of stack (lowest address)
- ebp - Base pointer register, stores the starting address in callee's stack frame where caller's base pointer value is copied (record's history)

Just, have the definition of these in mind, Now Let us understand how these register values are used.
Note : these registers are per cpu, not per frame.

Registers Usage In case of Procedure Call : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

```
f1(arg1, arg2){
.....
.....
f2(arg3, arg4); 0x1002
}
```

```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

Stack frame of f1()

Stack frame of f2()

Stack frame of f3()

- eip stores the address of instruction in execution, since f1() is executing, hence eip will store the address of instruction being executed. eip keeps on incrementing as subsequent instructions are executed.
- Green and Orange slabs are 4 bytes each, and are used to store historical data (Caller's frames information). This information helps the caller to resume its execution when callee returns.
- When Caller invokes the Callee, the current value of ebp and eip are saved in Callee's stack frame, and ebp and eip registers are updated as per the Callee's stack frame.

Use of ebp register

Stack frame of f20

- For a frame in execution, ebp register value is used as a reference to access all local variables and local arguments of the frame

Example :

84 =
ebp + 0 = address where caller's base pointer is saved
ebp + 4 = address where caller's next instruction address is saved
ebp + 8 = arg1
ebp + 12 = arg2
ebp - 4 = var2
ebp - 8 = var1

- CPU accesses all of the data of current stack frame in execution through ebp register value.
- This for a frame to execute its instruction, ebp value must be set
- ebp by definition, is the address where caller's base pointer address is saved in Callee's stack frame
- When Callee returns, Caller's must restore the value of ebp register to point to locn where Caller's Caller's base pointer address is stored in Caller's Stack frame :p

Procedure Call Algorithm

- When Caller Calls the Callee f, following steps take place on most common linux system architectures

1. Caller : Push the Argument list in reverse order
   push y
   push x . . .

2. Caller : Push the address of next instruction in caller as *Return Address* in the callee's stack frame
   push %eip

3. Callee : Push the Previous frame's base pointer and copy esp to ~~eab~~ ebp
   push %ebp
   mov %ebp %esp << ebp now stores the address where caller;s ebp's Value is stored

4. Callee : Set PC = next instruction in callee to be executed
   mov %eip , <address of first instruction in callee>

5. Callee : Push the local Variables of Callee
   push temp1
   push temp2

6. Callee : Execute the Callee

- With every push, esp is decremented
- With every pop, esp is incremented

Registers Usage In case of Procedure Return : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

```
f1(arg1, arg2){
.....
.....
f2(arg3, arg4); 0x1002
}
```

```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

Stack frame of f1()

Stack frame of f2()

Stack frame of f3()

- At the moment when f3() returns, ebp = 36, eip = <*return* instruction in f3>, esp = 28
- Now, for f2() to resume its execution, Stack frame of f3() should be popped out of stack
- Also, Value of esp should be restored to 52, ebp = 60, and eip = 0x2004

Registers Usage In case of Procedure Return : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

```
f1(arg1, arg2){
.....
.....
f2(arg3, arg4); 0x1002
}
```

```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

Stack frame of f1()

Stack frame of f2()

Stack frame of f3()

Registers Usage In case of Procedure Return : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

```
f1(arg1, arg2){
.....
.....
f2(arg3, arg4); 0x1002
}
```

```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

Stack frame of f1()

Stack frame of f2()

Stack frame of f3()

- Step 1 : Pop out all local variables

Registers Usage In case of Procedure Return : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

```
f1(arg1, arg2){
.....
.....
f2(arg3, arg4); 0x1002
}
```

```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

Stack frame of f1()

Stack frame of f2()

Stack frame of f3()

- Step 1 : Pop out all local variables

Registers Usage In case of Procedure Return : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

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f1(arg1, arg2){
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.....
f2(arg3, arg4); 0x1002
}
```

```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

Stack frame of f1()

Stack frame of f2()

Stack frame of f3()

- Step 1 : Pop out all local variables

Registers Usage In case of Procedure Return : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

```
f1(arg1, arg2){
.....
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f2(arg3, arg4); 0x1002
}
```

```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

Stack frame of f1()

Stack frame of f2()

Stack frame of f3()

- Step 2 : copy Caller's base address into ebp register
  mv %ebp %esp
  pop

Registers Usage In case of Procedure Return : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

```
f1(arg1, arg2){
.....
.....
f2(arg3, arg4); 0x1002
}
```

```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

Stack frame of f1()

Stack frame of f2()

Stack frame of f3()

- Step 2 : copy Caller's base address into ebp register

```
mv %ebp %esp
pop
```

Registers Usage In case of Procedure Return : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

```
f1(arg1, arg2){
.....
.....
f2(arg3, arg4); 0x1002
}
```

```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

Stack frame of f1()

Stack frame of f2()

Stack frame of f3()

- Step 2 : copy Caller's base address into ebp register
  - mv %ebp %esp
  - pop

Registers Usage In case of Procedure Return : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

```
f1(arg1, arg2){
.....
.....
f2(arg3, arg4); 0x1002
}
```

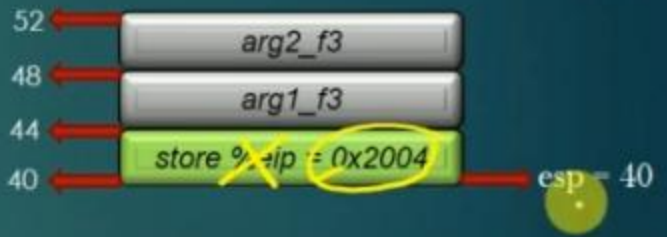
```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

eip

Stack frame of f1()

Stack frame of f2()



Stack frame of f3()

- Step 3 : Restore the Caller's last instruction address into eip register

```
mv %eip %esp
pop
```

Registers Usage In case of Procedure Return : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

```
f1(arg1, arg2){
.....
.....
f2(arg3, arg4); 0x1002
}
```

```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

eip

Stack frame of f1()

Stack frame of f2()

Stack frame of f3()

- Step 4 : Pop all arguments

Registers Usage In case of Procedure Return : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

```
f1(arg1, arg2){
.....
.....
f2(arg3, arg4); 0x1002
}
```

```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

eip

Stack frame of f1()

Stack frame of f2()

Stack frame of f3()

- Step 4 : Pop all arguments

Registers Usage In case of Procedure Return : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

```
f1(arg1, arg2){
.....
.....
f2(arg3, arg4); 0x1002
}
```

```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

eip

Stack frame of f1()

Stack frame of f2()

Stack frame of f3()

- Step 4 : Pop all arguments
- Stack frame 3 is completely destroyed now

Registers Usage In case of Procedure Return : eip, ebp and esp

- Let us suppose , f1() -> f2() -> f3()

```
f1(arg1, arg2){
.....
.....
f2(arg3, arg4); 0x1002
}
```

```
f2(arg1, arg2){
.....
.....
f3(arg3, arg4); 0x2004
}
```

```
f3(arg1, arg2){
.....
.....
}
```

eip +1

Stack frame of f1()

Stack frame of f2()

Stack frame of f3()

- Step 4 : Pop all arguments
- Stack frame 3 is completely destroyed now
- Now, stack frame f2 is restored, f2() can resume its execution as normal

Procedure Return Algorithm

- When Callee f returns, following steps take place

1. Callee : Set the return value of the Callee in *eax* register
2. Callee : "Increase" the stack pointer by the amount = size of all local variables of the frame
   (This releases the local stack memory assigned to local variables)
3. Callee : Restore %ebp to point to caller's stack frame and POP the previous frame's base pointer from the stack
   mov %ebp %esp << Caller's base pointer is restored, now caller can access all its local variables and arguments using ebp as a reference
   pop
4. Callee : set %eip = "Return address" saved in the callee's stack, and POP the saved "Return Address" from the stack
   (This gives control back to calling function)
   mov %eip , %esp
   pop
5. Caller : POPs all the argument it had passed onto the stack
6. Caller : reads the value stored in eax register, and resumes execution from %eip + 1 (Next instruction)

Assignment instructions

60 minutes to complete | 30 student solutions

Please Answer the Question as Asked.

Questions are based on following short C program:

In below program code, Address of instructions at line no 15 and 22 are also given.

Assume the function B() is currently executing on CPU.

Also, given that the base address (also called frame pointer) of the stack frame of function A is **0xbffff0c8.**

Assume, the program runs on a 32 bit system - which means size of interger data type is 4Bytes, and 4Bytes of memory is used to store any address.

You Should use above Inputs and assumptions to answer the Questions.

3 int B (int a , int b , int c) {

Next

```
4
5  int res = 0;
6  res = a + b + c;
7  return res;
8 }

11 int A (int a, int b) {
12
13  int c = 0 ;
14  c = a + b;
15  int d = B (c, a, b);  /*l3 0x8048440 */
16  return d;
17 }

19 int main (int argc, char **argv) {
20
21   int res = 0;
22 res = A (4, 5);  /* l1 : 0x8048469*/
```

Next

Course content

```
21  int res = 0;
22 res = A (4, 5);  /* I1 : 0x8048469*/
23 return 0;
24 }
```

Questions for this assignment

1. How many stack frames are present in the stack memory ?
2. What is the Return address saved in the stack frame of function A in stack memory ?

   What is the stack memory address where this Return address is saved, and this Return Address is the address of which instruction (express in term of Line no in the program) ?
3. What is the address of third argument (int c) passed to function B ?
4. What is the Return address saved in the stack frame of function B in stack memory ?

   What is the stack memory address where this Return address is saved ?
5. When function A is executing, What is the value of esp & ebp registers ?
6. When function B is executing, What is the value of esp & ebp registers ?
7. When function B is executing, what is the combined total size of stack frame of function A and function B ?
8. What will be the value of esp, eip and ebp register, when function B has returned ?
9. What is the lowest address (that is top of stack Memory) the stack memory ever grows

Next

Instructions | Submission | Instructor example | Give feedback

Questions for this assignment

1. How many stack frames are present in the stack memory ?
2. What is the Return address saved in the stack frame of function A in stack memory ?

   What is the stack memory address where this Return address is saved, and this Return Address is the address of which instruction (express in term of Line no in the program) ?
3. What is the address of third argument (int c) passed to function B ?
4. What is the Return address saved in the stack frame of function B in stack memory ?

   What is the stack memory address where this Return address is saved ?
5. When function A is executing, What is the value of esp & ebp registers ?
6. When function B is executing, What is the value of esp & ebp registers ?
7. When function B is executing, what is the combined total size of stack frame of function A and function B ?
8. What will be the value of esp, eip and ebp register, when function B has returned ?
9. What is the lowest address (that is top of stack Memory) the stack memory ever grows throughout the execution of the program ?
10. When function B returns, what is the content of eax register ?

Next

Course content

Heap Memory Management In Linux

Goals :

1. How malloc() and free() works ?
2. Internal management of Heap Memory by Linux OS
3. Understanding the problem of fragmentation and its Solution
4. System calls related to Heap Memory Mgmt
5. Prepare Technical Interview Questions

Fasten your Seat Belts for another drive !! ☺

Heap Memory Management - >Introduction

- Heap Memory of the process is the continuous part of Virtual Address space of the process from which a process claims and reclaims Memory during runtime (Dynamic Memory Allocation)
- *glibc* APIs to harness the functionality of Heap :
  - malloc, calloc, free, realloc,
  - System Calls : brk, sbrk
- Unlike Stack memory which is reclaimed back upon procedure return automatically, it is programmer's responsibility to free the dynamic memory after usage
- malloc/calloc are used to allocate a block of memory from heap segment of the process
- free is used to release the memory back to heap segment which was claimed by malloc/calloc
- As a System Programmer, you must know how dynamic memory allocation works

Very Important
For Interviews, Mind it !!

Heap Memory Management - > malloc ?

- You must have used malloc/calloc in your program to assign memory chunks dynamically to your process
- malloc is a Standard C Library function that allocates (i.e. reserves) memory chunks from process Virtual Address Space, particularly from, Heap memory segment
- malloc allocates at least the number of bytes requested
- The pointer returned by malloc points to an allocated space i.e. a space where the program can read or write successfully
- No other call to malloc will allocate the reserved space or any portion of it, unless the space has been freed before.
- malloc should also provide resizing and freeing. realloc
- In this section we shall explore the science behind malloc and free.

Heap Memory Management - > malloc ?

- You must have used malloc/calloc in your program to assign memory chunks dynamically to your process
- malloc is a Standard C Library function that allocates (i.e. reserves) memory chunks from process Virtual Address Space, particularly from, Heap memory segment
- malloc allocates at least the number of bytes requested
- The pointer returned by malloc points to an allocated space i.e. a space where the program can read or write successfully
- No other call to malloc will allocate the reserved space or any portion of it, unless the space has been freed before.
- malloc should also provide resizing and freeing. realloc
- In this section we shall explore the science behind malloc and free.

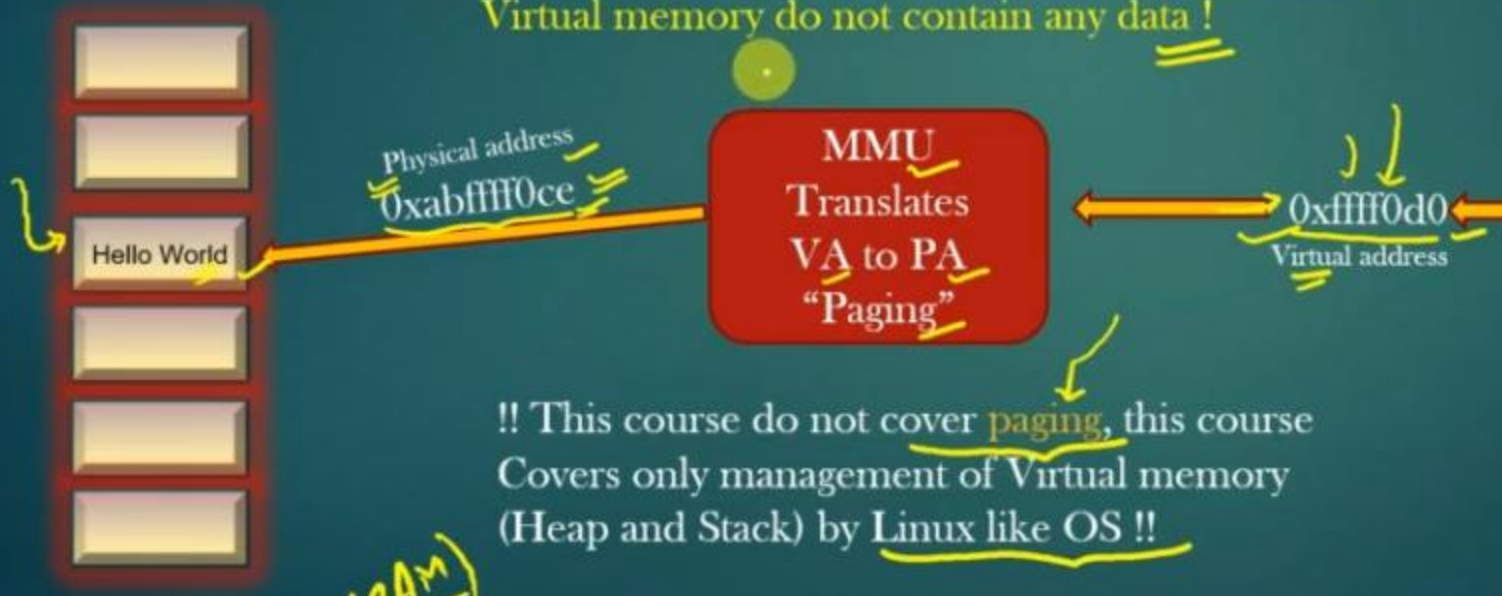
Heap Memory Management - > malloc ?

```
void *ptr = malloc (20);
```

- if ptr points to address location, say, 0xffff0d0, then this address will be some address in Heap Segment of the process Virtual address space

```
strncpy (ptr, "Hello", 5);
```

Actual Data/Content is written on physical memory
Virtual memory do not contain any data !



!! This course do not cover paging, this course Covers only management of Virtual memory (Heap and Stack) by Linux like OS !!

Higher Address

Lower Address

Heap Memory Management - > *break* pointer

- **Break** is the pointer maintained by OS per process, it points to top of Heap Memory segment
- Any memory above break pointer is not a Valid memory to be used by the process
- Break pointer moves towards higher address, increasing the Heap region, as process claims more Heap memory
- Break pointer moves back towards lower address as process frees the Heap memory

break

Point upto which heap memory is being used by process

Start of the Heap

Higher Address

Lower Address

Heap Memory Management - > brk and sbrk

- Linux OS provide two system calls – *brk and sbrk* using which we can claim more memory from Heap segment

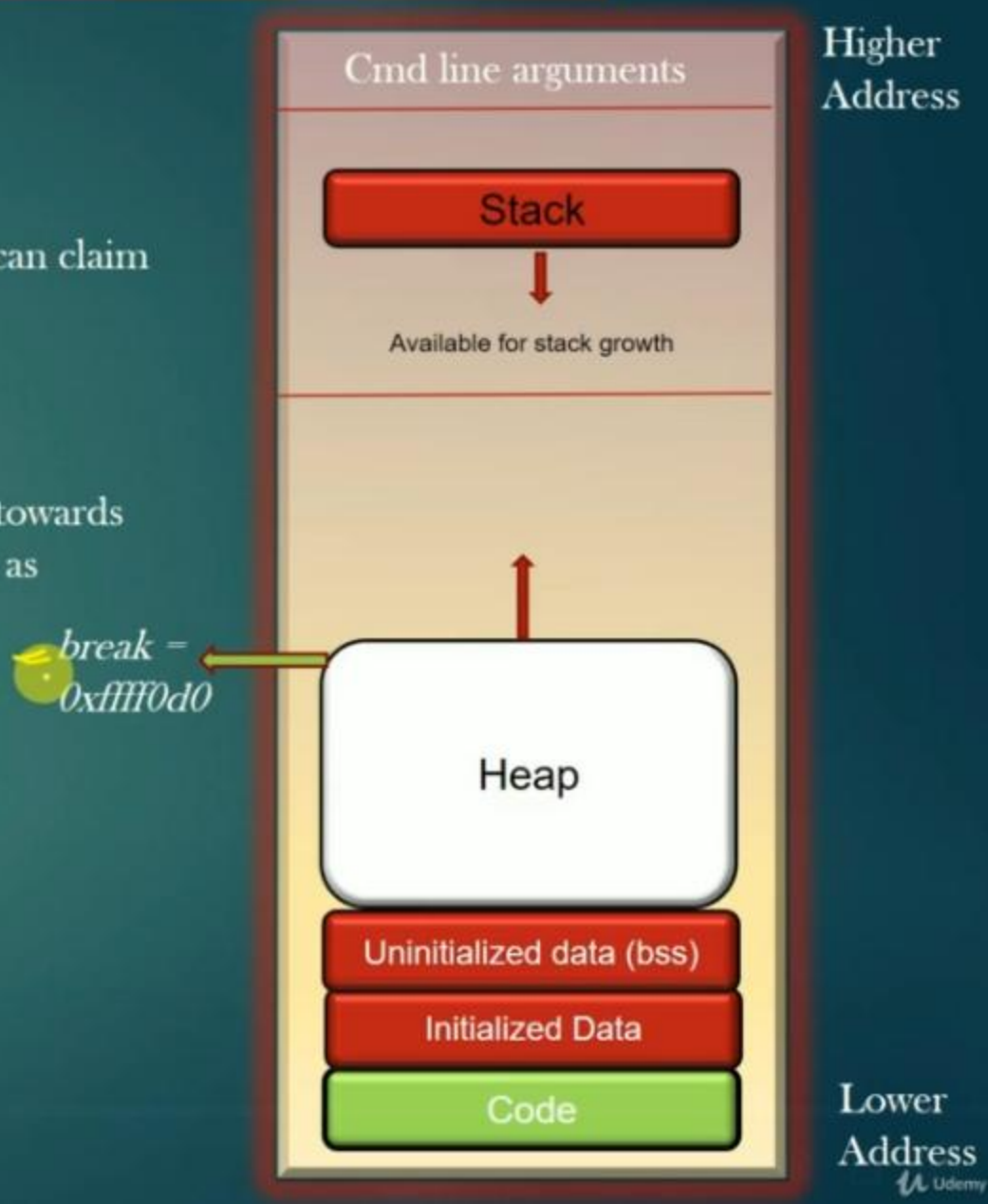
- *brk* Synopsis :

  *int brk(const void *addr);*

  brk() expands the heap memory segment such that *break* moves towards higher memory address and points to the *addr which is p*rovided as argument. *addr* should be valid address.

  Return : 0 on success and -1 on failure

  int rc = brk (0xffff0d0);



Heap Memory Management - > brk and sbrk

- Linux OS provide two system calls – *brk and sbrk* using which we can claim more memory from Heap segment

- *sbrk* Synopsis :

  *void *sbrk(intptr_t incr);*

  sbrk() expands the heap memory segment such that *break* moves towards higher memory by incr vytes w*hich is p*rovided as argument.

  Return : old break pointer address on success and NULL on failure

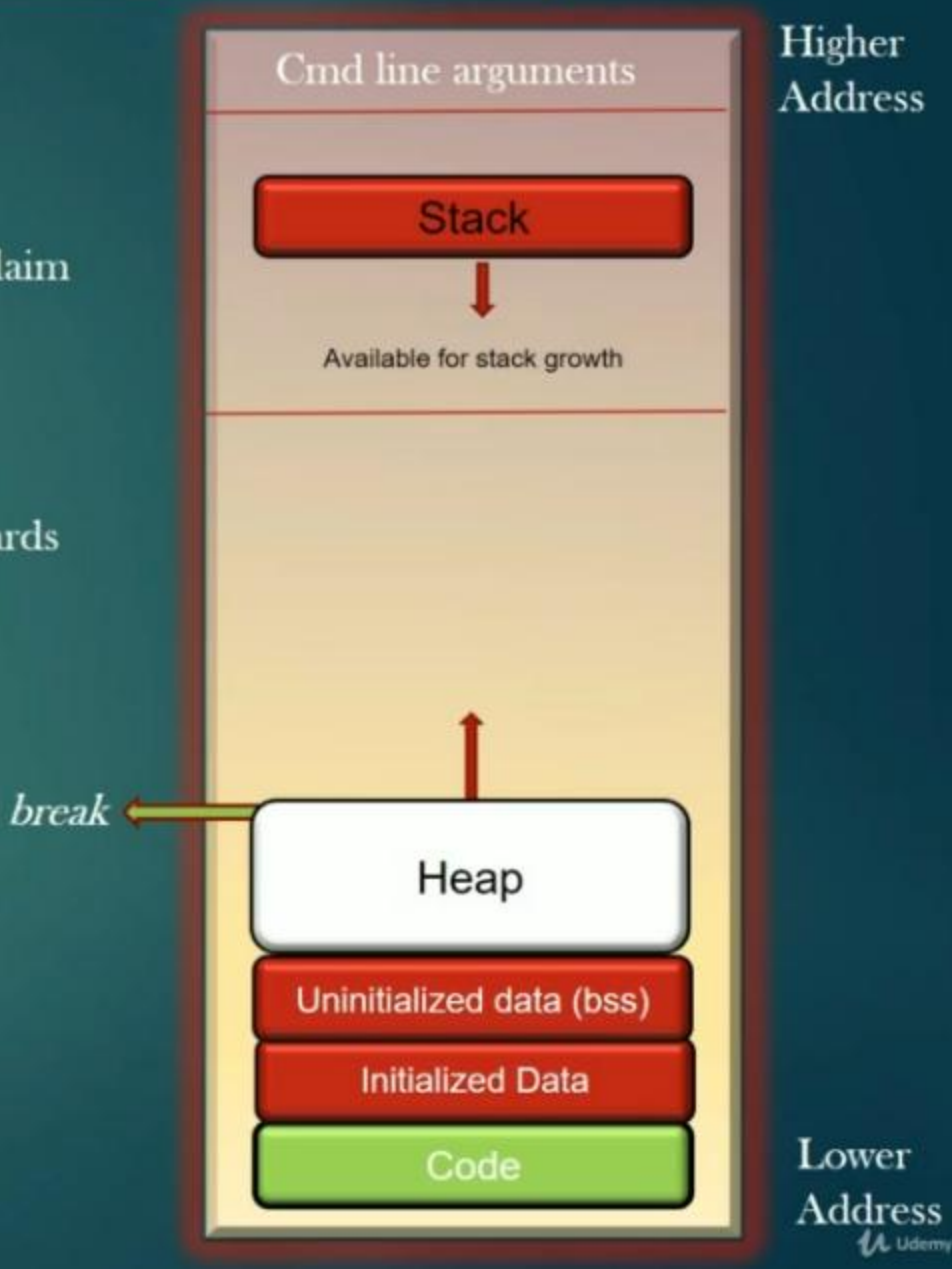
  Ex : void *ptr = sbrk(10);

  /*ptr = break (old break pointer address)*/

  /*break' is the new value of break pointer*/

  Special case :

  sbrk(0) – returns the value of break pointer



Heap Memory Management - > brk and sbrk

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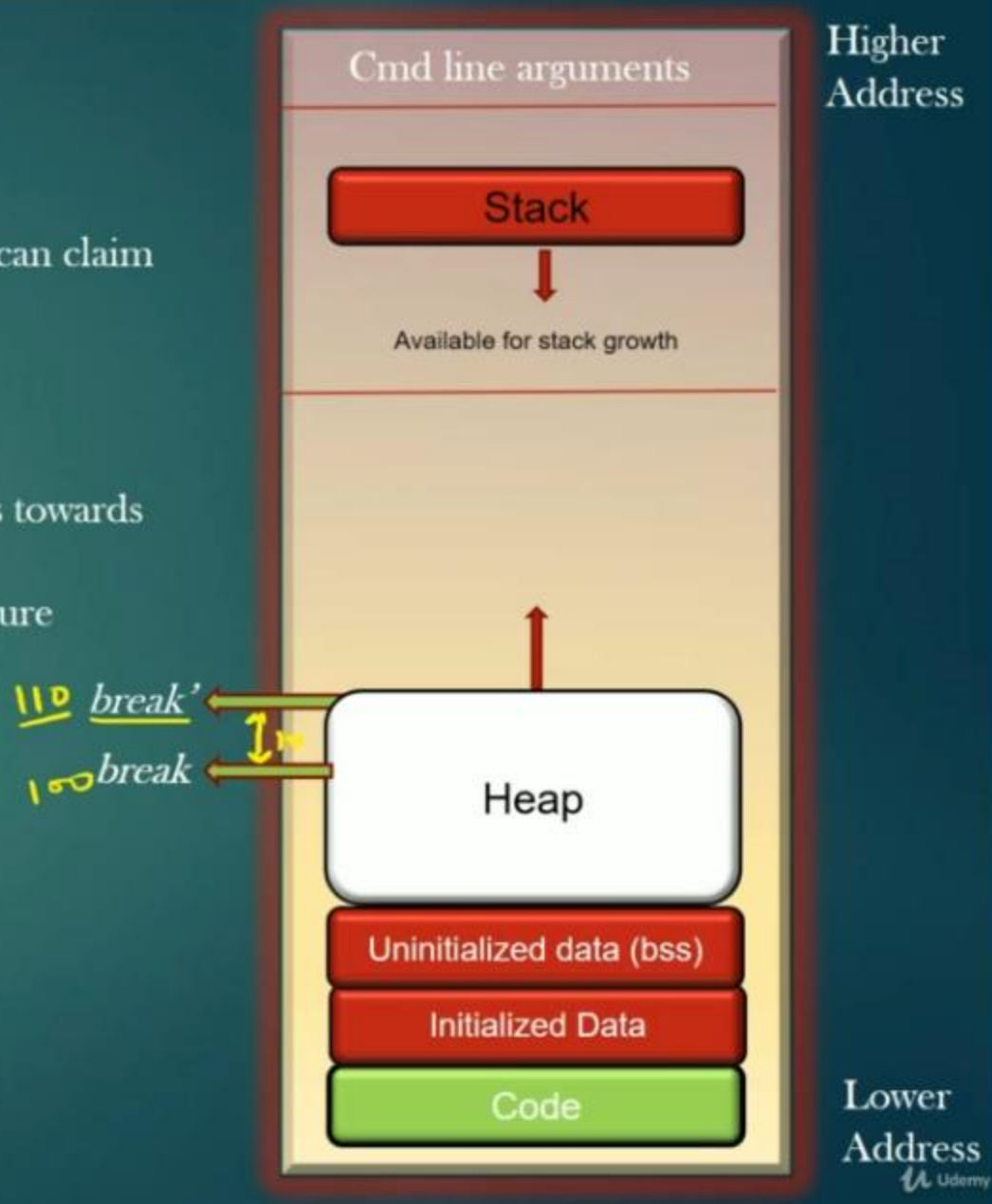


Heap Memory Management - > malloc basic Implementation

- Now, We know that we use malloc/calloc to allocate dynamic memory to our program from Heap Region
- malloc/calloc are actually not a system calls , but they are functions provided by standard C library
- They are wrapper over *sbrk()* system call. Malloc/calloc internally invoke sbrk() to claim the memory from heap segment. The returned *break pointer address* is what is returned by malloc/calloc
- A very simple implementation of malloc could be written as below :

```
void *malloc (int size) {
        void *p;
        p = sbrk(0);

        if (sbrk(size) == NULL)
                return NULL;
        return p;
}
```

```c
#include <stdio.h>
#include <string.h>
#include <memory.h>
#include <assert.h>

void *xmalloc (int size) {
    void *p;
    p = sbrk(0);

    if (sbrk(size) == NULL)
        return NULL;
    return p;
}

void
xfree(int nbytes){

    assert(nbytes > 0);
    sbrk(nbytes * -1);
}

int
main(int argc, char **argv){

    char *p = (char *)xmalloc(20);
    strncpy(p, "Hello", strlen("Hello"));
    printf("p = %s\n", p);
    xfree(20);
    return 0;
}
```

Heap Memory Management - > Problem Statement

```
void *p1 = malloc (20);
void *p2 = malloc (10);
void *p3 = malloc (10);
void *p4 = malloc (15);
void *p5 = malloc (20);
free(p3);
```

Q1. How OS would know how much memory to free on invoking *free(p3)* ?

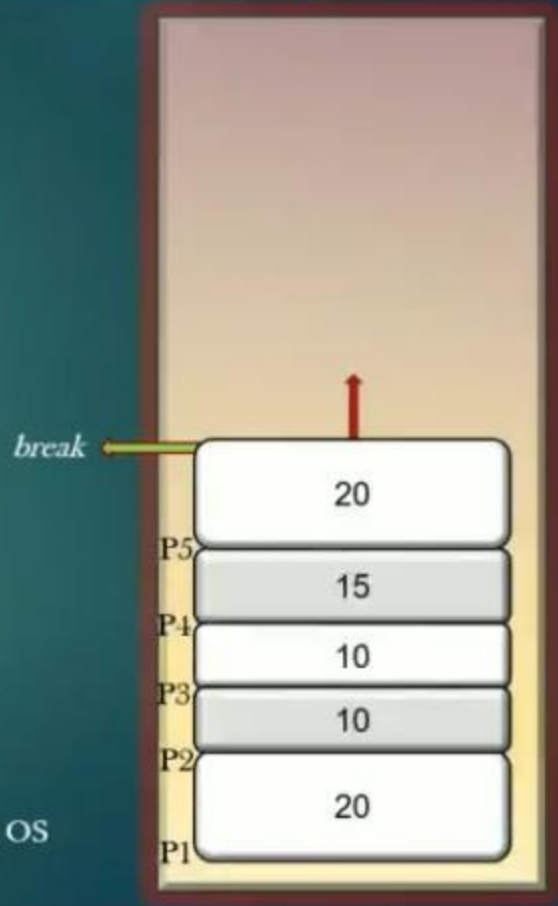
Q2. How, OS organizes the memory blocks assigned by malloc ?

OS need to know that p3 is associated with 10 bytes of block of memory and free(p3) should release only 10 bytes of memory

Q3. How, OS ensures that p3 is a valid memory address, and memory pointed by p3 is occupied and is not freed already ?

Let us understand the concept of *Memory Block Management* to find our Answers !

Basically we want to understand how Heap Memory Management is done by Linux OS



Heap Memory Management

- Let us suppose, you are given a huge chunk of contiguous memory, which represents the Process's Virtual address space

- Process should be able to allocate smaller chunks of memory as per the requested size from this heap segment memory when needed
- Process should be able to return back those smaller chunks of memory it had requested back to heap segment
- You are not allowed to use any supporting data structures, as your DS would in-turn need separate memory which is not available to you
- Let us see how can we implement this scheme . .

Heap Memory Management - > Metablock and Datablock

```
void *ptr1 = malloc (14);
```

Actual memory to be used by the process

ptr1

Meta information

```
struct meta_block_t {
    int size;  /*= 14*/
    struct meta_block_t *next; /*= NULL*/
    bool is_free; /*= FALSE*/
}
```

Enhanced malloc

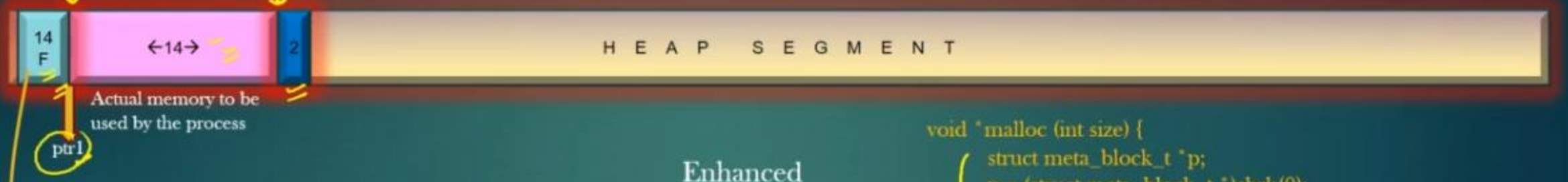
```
void *malloc (int size) {
    struct meta_block_t *p;
    p = (struct meta_block_t *)sbrk(0);
    if (sbrk (size + sizeof(meta_block_t)) == NULL)
        return NULL;
    p->size = size;
    p->next = NULL;
    p->is_free = FALSE;
    return p + 1;
}
```

Note that, OS inserts additional padding bytes at the end to make the total block size (Meta block + Data block) integer multiple of 4. This is called 4 bytes alignment.

But Process should use only 14 bytes of memory starting from address ptr1

Heap Memory Management - > Metablock and Datablock

```
void *ptr1 = malloc (14);
```



Meta information

```
struct meta_block_t {
    int size;  /*= 14*/
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Enhanced malloc

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```

Note that, OS inserts additional padding bytes at the end to make the total block size (Meta block + Data block) integer multiple of 4. This is called 4 bytes alignment.

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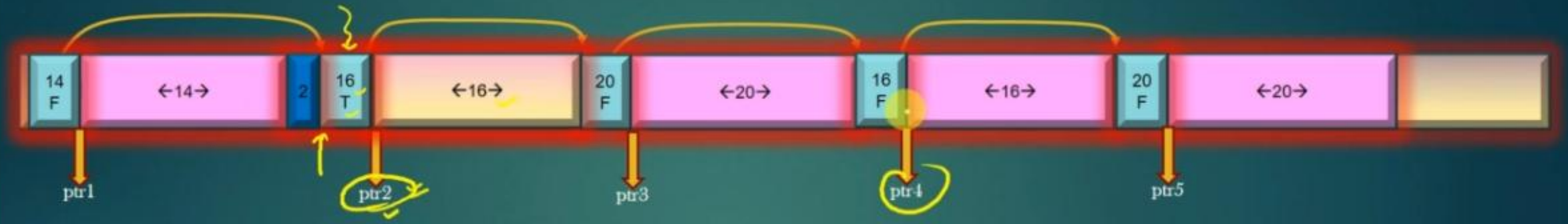
Allocations & DeAllocations

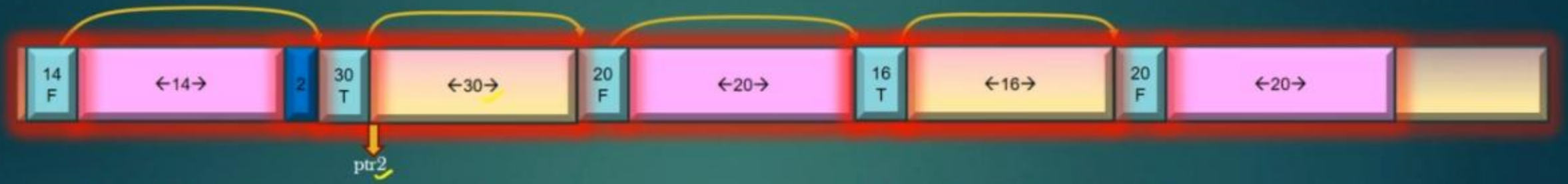
Heap Memory Management - > Memory Allocations and Deallocations

```
void *ptr1 = malloc (14);
```



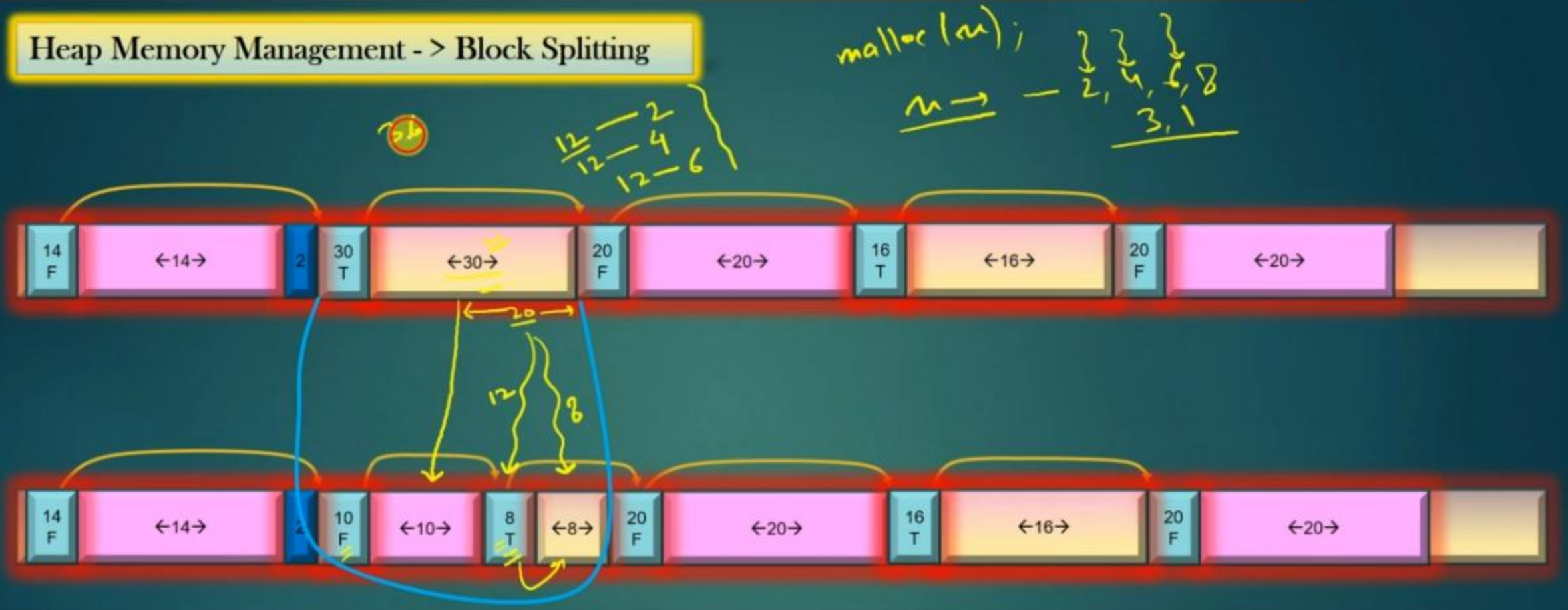

```
void *ptr2 = malloc (16);
void *ptr3 = malloc (20);
void *ptr4 = malloc (16);
void *ptr5 = malloc (20);
free(ptr2);
free(ptr4);
```

Heap Memory Management - > Block Splitting



- Now, Given the snapshot of the heap memory segment as above, What should happen if Process issues the request : void *ptr = malloc (10);
- Our malloc should search the block from the list which could satisfy the request of 10 bytes
- Such a block is pointed to by ptr2
- Common Sense says ptr2 block should be reused to assign 10B of memory, whereas remaining 20 bytes should still be maintained as free block in the block list
- We achieve this by splitting the 30B block into two blocks - 10B and 20B respectively. 10B block should be marked as is_free = FALSE, and 20B block should be marked as is_free = TRUE

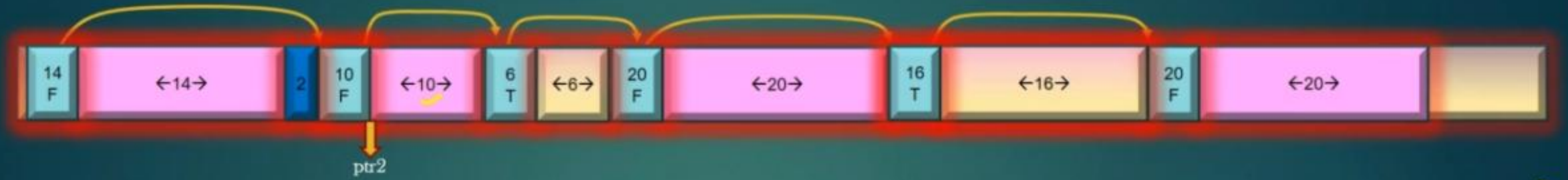
Heap Memory Management - > Block Splitting

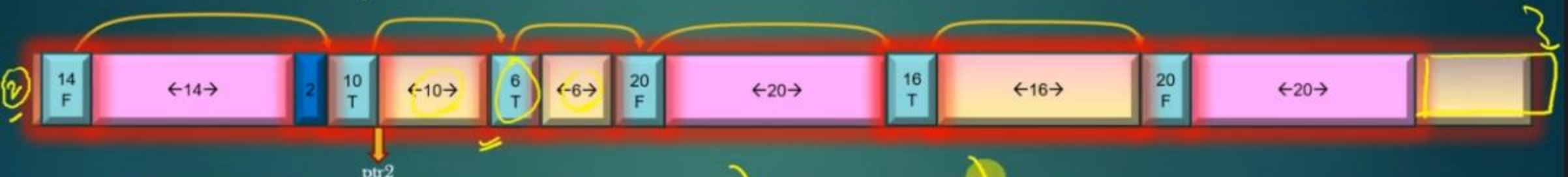


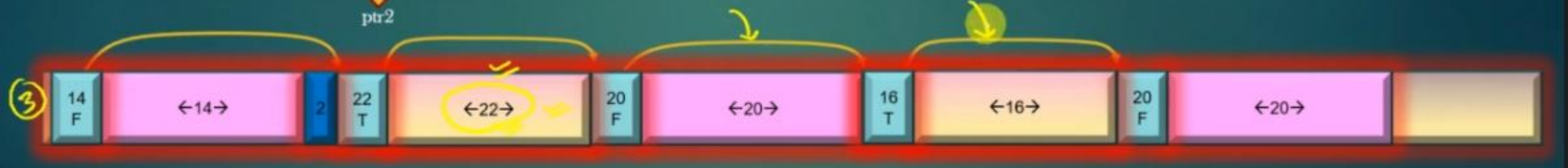
- Total No of Blocks increased from 5 to 6 in block list
- Our malloc function should be enhanced to split the block large enough to provide the requested memory.
- Just for simplicity , I am not ignoring taking care of 4 byte alignment

Heap Memory Management - > Block Merging

malloc (20);



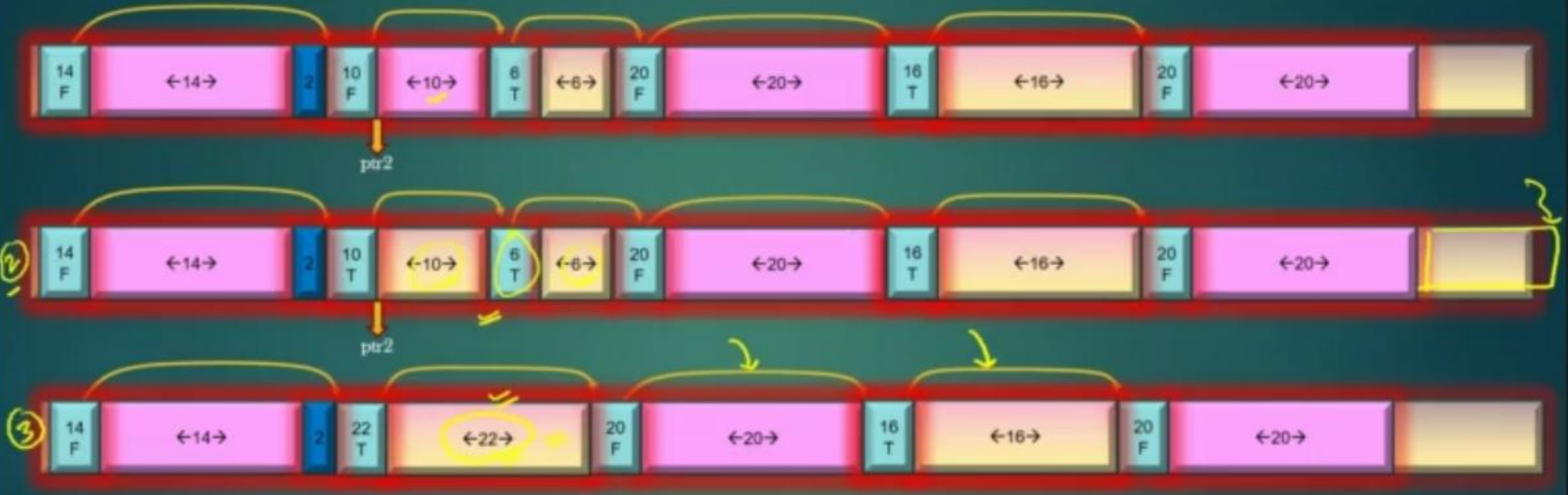




- Consider the snapshot of the Heap memory segment as shown in the above diagram
- Suppose the process issues free(ptr2). OS knows from meta info that it has to free 10B of memory
- All consecutive free blocks must be merged together to form a bigger free block
- 10B block pointed by ptr2 is freed and merged with 6B free block to form one single 22B free block
- Total no of blocks are reduced from 6 to 5 in the block list

Heap Memory Management - > Block Merging

malloc (20);

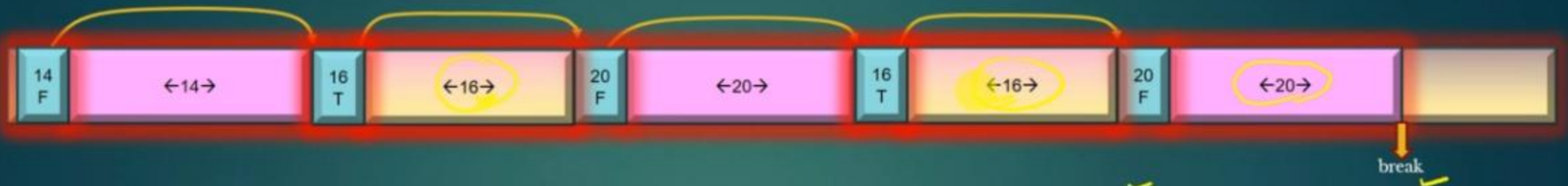


- Consider the snapshot of the Heap memory segment as shown in the above diagram
- Suppose the process issues free(ptr2). OS knows from meta info that it has to free 10B of memory
- All consecutive free blocks must be merged together to form a bigger free block

So Your malloc and free fn() should handle all these scenarios

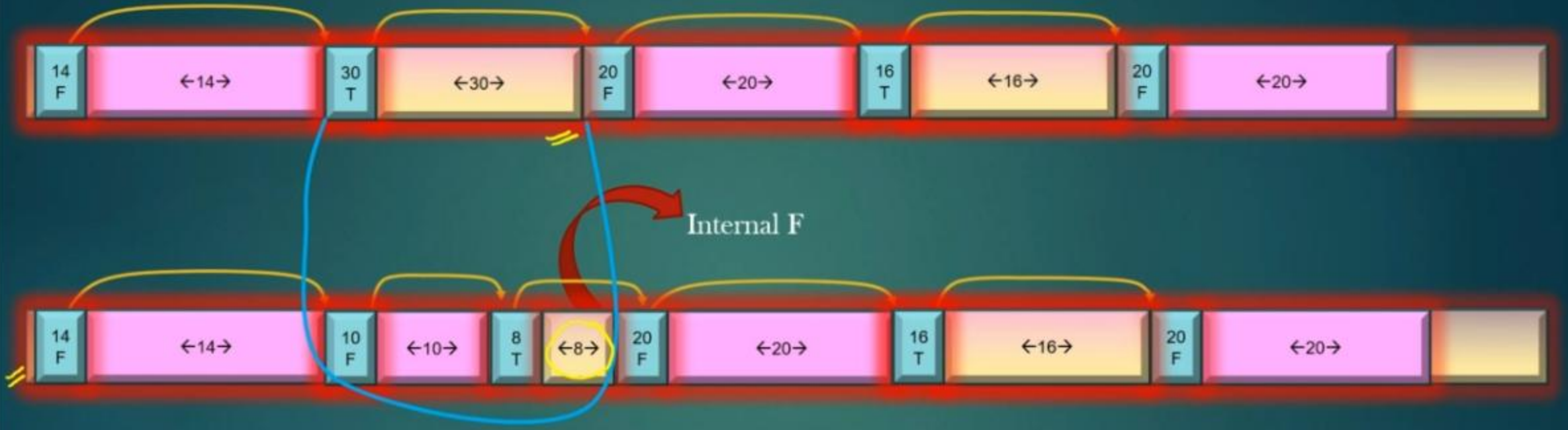
- Total no of blocks are reduced from 6 to 5 in the block list

Heap Memory Management - > Fragmentation



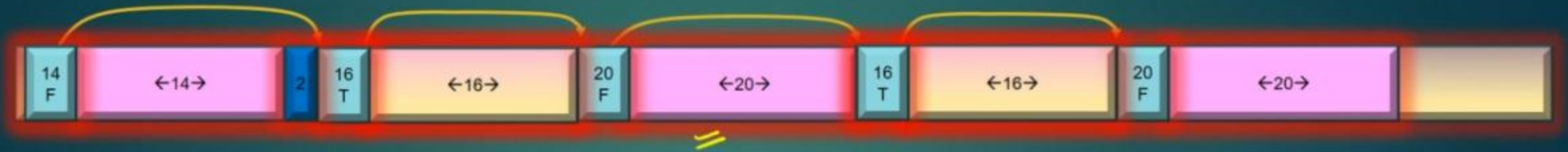
- Consider a snapshot of the heap memory segment as shown above
- Suppose process issues malloc(20);
- Now there are two free blocks of 16B each, together they can satisfy this new malloc request, but since they are not consecutive blocks, these blocks together cannot be used to provide 20B of requested memory
- This is called the problem of Memory fragmentation. Despite having enough free memory already, we still need to extend the heap region further to satisfy the new memory request

Heap Memory Management - > Internal Fragmentation



- Suppose malloc(10) request is issued by the process, 30B free block will undergo split
- 8B block in the second diagram, which results from block splitting, is unusable memory for all malloc(x) requests, where x > 8.
- In other words, 8B of memory is internally fragmented which results from block splitting

Heap Memory Management - > External Fragmentation



- Consider a process issues a request of malloc(20)
- We have two free 16B blocks of memory which is suffice to satisfy request of 20 B,
  but still we cannot allocate this requests because 16B are non-contiguous and hence cannot be merged
- These free blocks are said to be externally fragmented memory which is unusable by virtue of being non-contiguous
- So, our Heap Memory Management suffers from Fragmentation Problems !

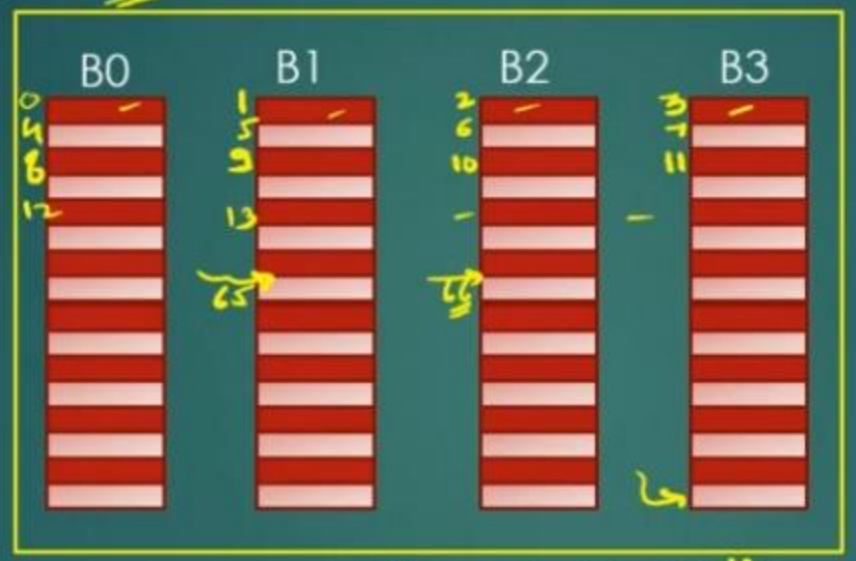
Introduction to Paging !!

Memory Management in Linux -> Paging

- Paging is one of the most discussed concepts in the world of OS
- It is the backbone of all modern OS today
- There are not one, but many benefits of paging :
  - On a 32 bit system with RAM size of 4GB, Paging create the illusion to a *process in execution* as if system has 2^32 bytes (4GB) of physical memory for its execution, whereas actually total system memory is 4GB for all processes
    - Allows the process to store its data in non-contiguous addresses in physical memory
    - Allows, Multiple processes to re-use the same physical memory addresses to store its data, one process at a time
- Paging is implemented by a special hardware unit called MMU (Memory Management Unit)
- Let us dive deep into concepts of Paging Step by Step

Memory Management in Linux -> Byte Addressable Memory

- A Memory in which every BYTE has an address



Virtual and Physical Memory are byte addressable memory

- char *ptr = <some location>
- ptr++;

- Byte is the lowest unit of Memory that can be accessed
- That is why we need to perform Boolean operation in order to manipulate memory at BIT level

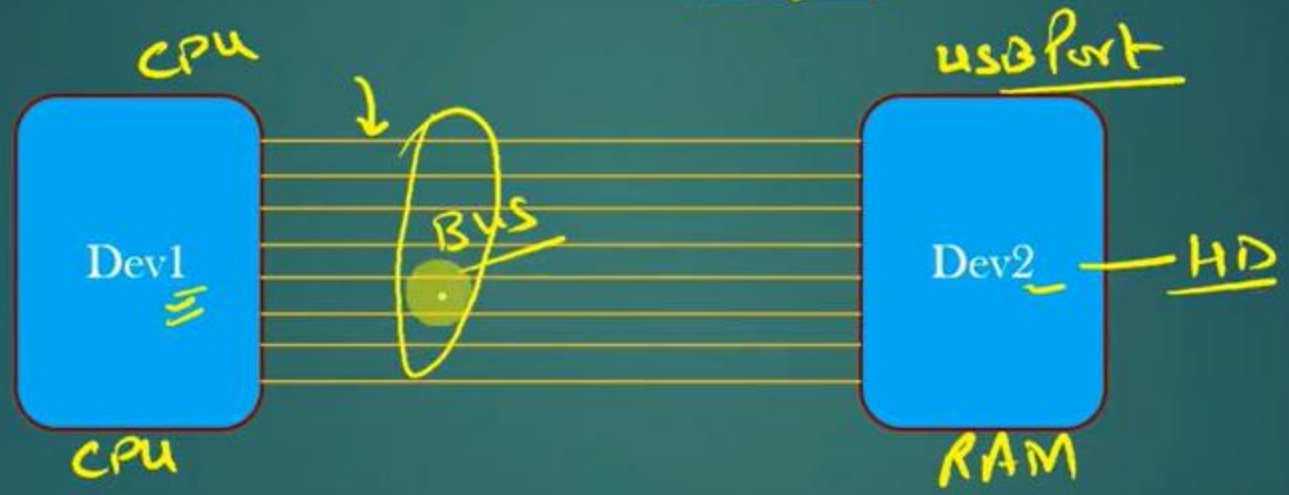
Memory Management in Linux -> 32 | 64 bit System

- What is meant when we say my system is 32|64 bit system ?
  - 32 bit system simply means :
    - All processes in execution have theoretically 2^32 virtual addresses in its process VAS
    - Addresses are 32 bit integers which identifies memory locations
    - Size of Data bus is 32 bits
    - Size of Address bus is 32 bits

<data type> a = <value>;
printf ("address of a = %p", &a); << prints virtual address of a

Memory Management in Linux -> What is a Bus ?

- A bus is a collection of Hard Metal Wires connecting devices, used to transfer data from one device to other
- Each Wire changes its voltage level to represent a bit is set or not
- Such a System of Metal wires permanently fabricated on a board connecting devices is called a Bus



- In Computer Architecture, different hardware components exchange data with each other through buses

Memory Management in Linux -> What is a Bus ?

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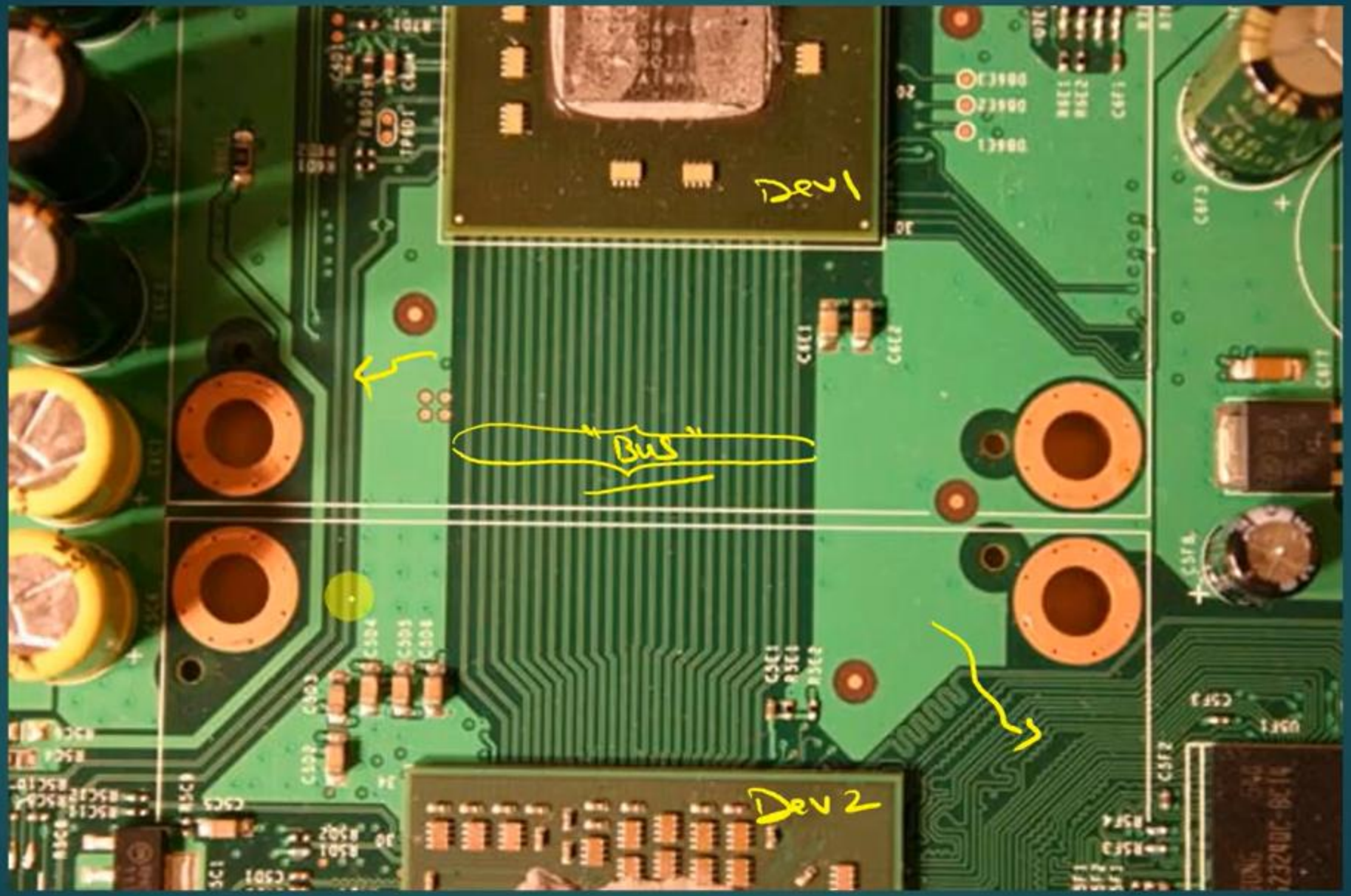
Memory Management in Linux -> What is a Bus ?



CPU Generates Virtual Addresses

Memory Management in Linux -> CPU generates only Virtual Addresses

- Variables in the programs are just symbolic names of addresses
- Variables are there for our convenience so that we can read and write computer instruction in human readable format
- At the lowest level, programs are translated into Machine code which only deals with virtual addresses, not with variables names. Variable names are replaced by their actual virtual address locations
- Your Program translates into machine code after compilation
  - In Machine code, variable names are replaced by their virtual addresses
  - Machine code executes and perform read and write operations using addresses of variables instead of variable names
    - int a = 10 would look like mov %ebp+4 10 in assembly code, that is talking in terms of addresses only
  - Machine code is not aware of int a, int b etc . . .
- We have already learnt that, all local variables and arguments of a function are accessed by CPU by adding or subtracting to base pointer register *ebp* of the current stack frame
- Let us recap in the next slide ...

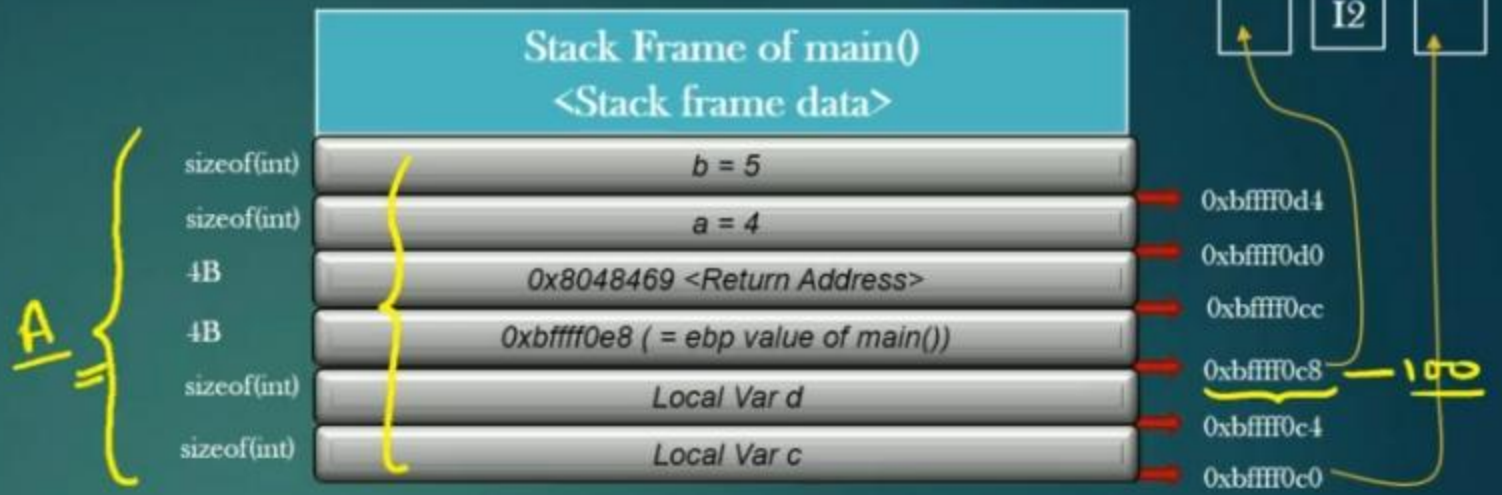
Memory Management in Linux -> CPU generates only Virtual Addresses

Recap

```
3 int B (int a , int b , int c ) {
4
5       int res = 0; /*I4*/
6       res = a + b + c;
7       return res;
8 }
```

```
11 int A (int a, int b) {
12
13      int c = 0 ; /*I2*/
14      c = a + b;
15      int d = B (c, a, b);
16      return d;
17 }
```

```
19 int main (int argc, char **argv) {
20
21   int res = 0;
22   res = A (4, 5); /* I1 : 0x8048469*/
23   return 0;
24 }
```



- *ebp register stores* 0xbffff0c8 which is the address of old ebp's value
- ebp register value is used by the processor to reference arguments and local variables of the current stack in execution

(-4)%ebp -- address of local variable d — 96
(-8)%ebp -- address of local variable c — 92
%ebp - Address of prev frame ebp's value
(4)%ebp - Address where *Return address* is saved
(8)%ebp -- address of argument a — 108
(12)%ebp -- address of argument b — 112

Memory Management in Linux -> CPU generates only Virtual Addresses

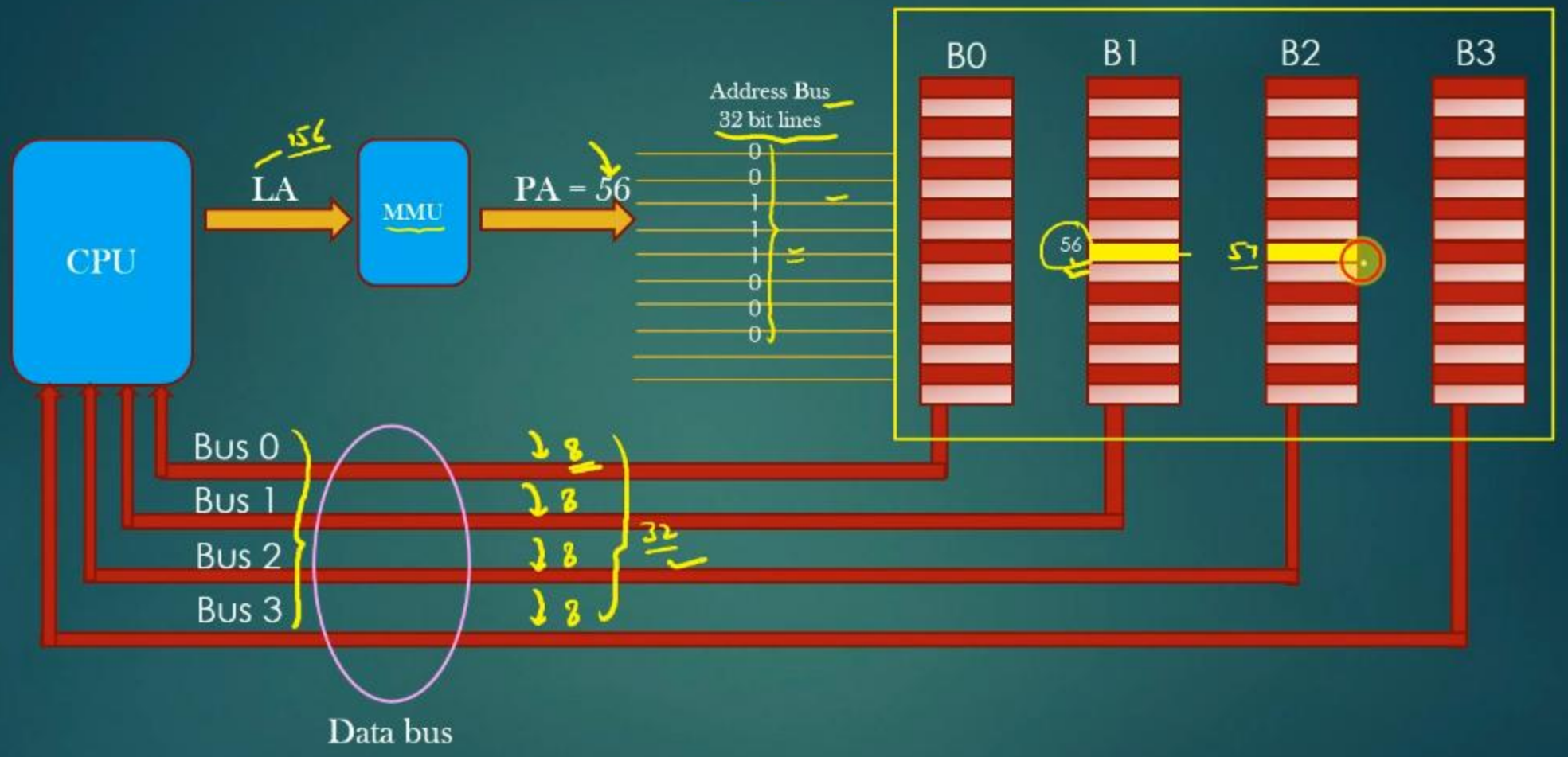
- Hence, CPU generates millions of Virtual addresses during the course of execution of a process

- These generated Virtual addresses are then mapped to corresponding physical addresses by MMU using concept called Paging (We are about to dive into this)

- CPU then issue the instruction to either read or write the data on the mapped physical addresses

- Let us understand the picture in totality . . .

Memory Management in Linux -> Address and Data Bus on a 32 bit system



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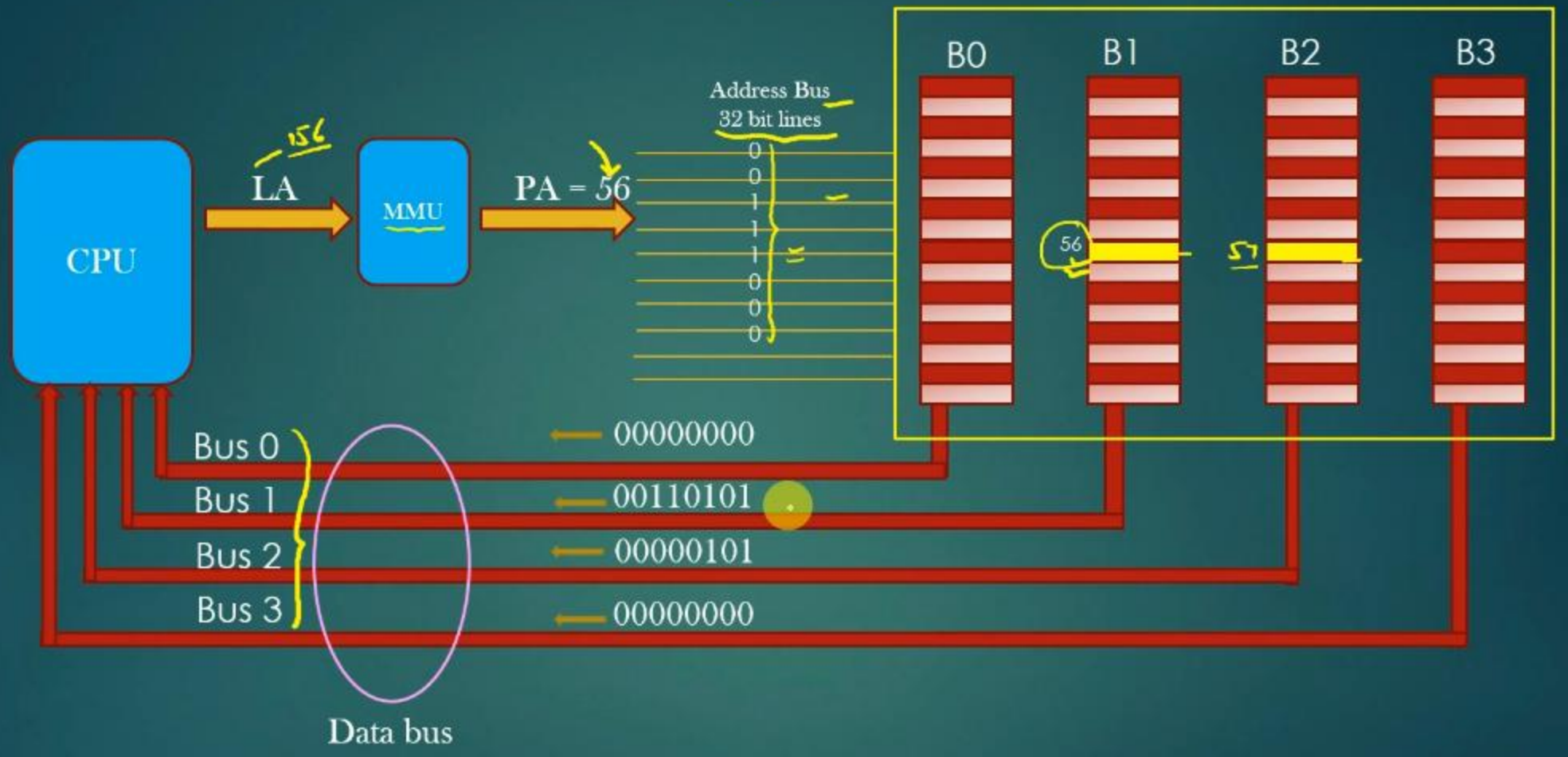
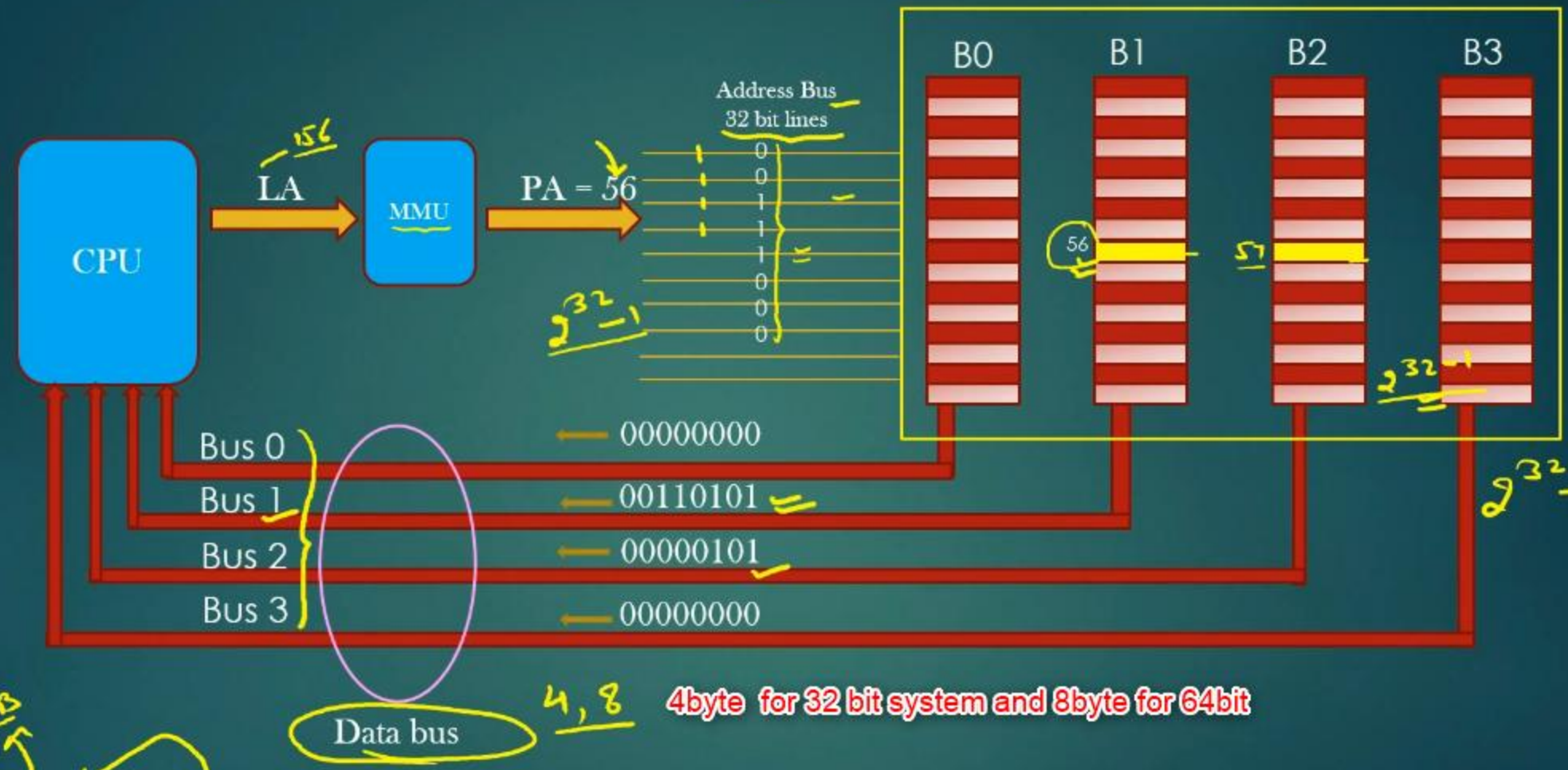
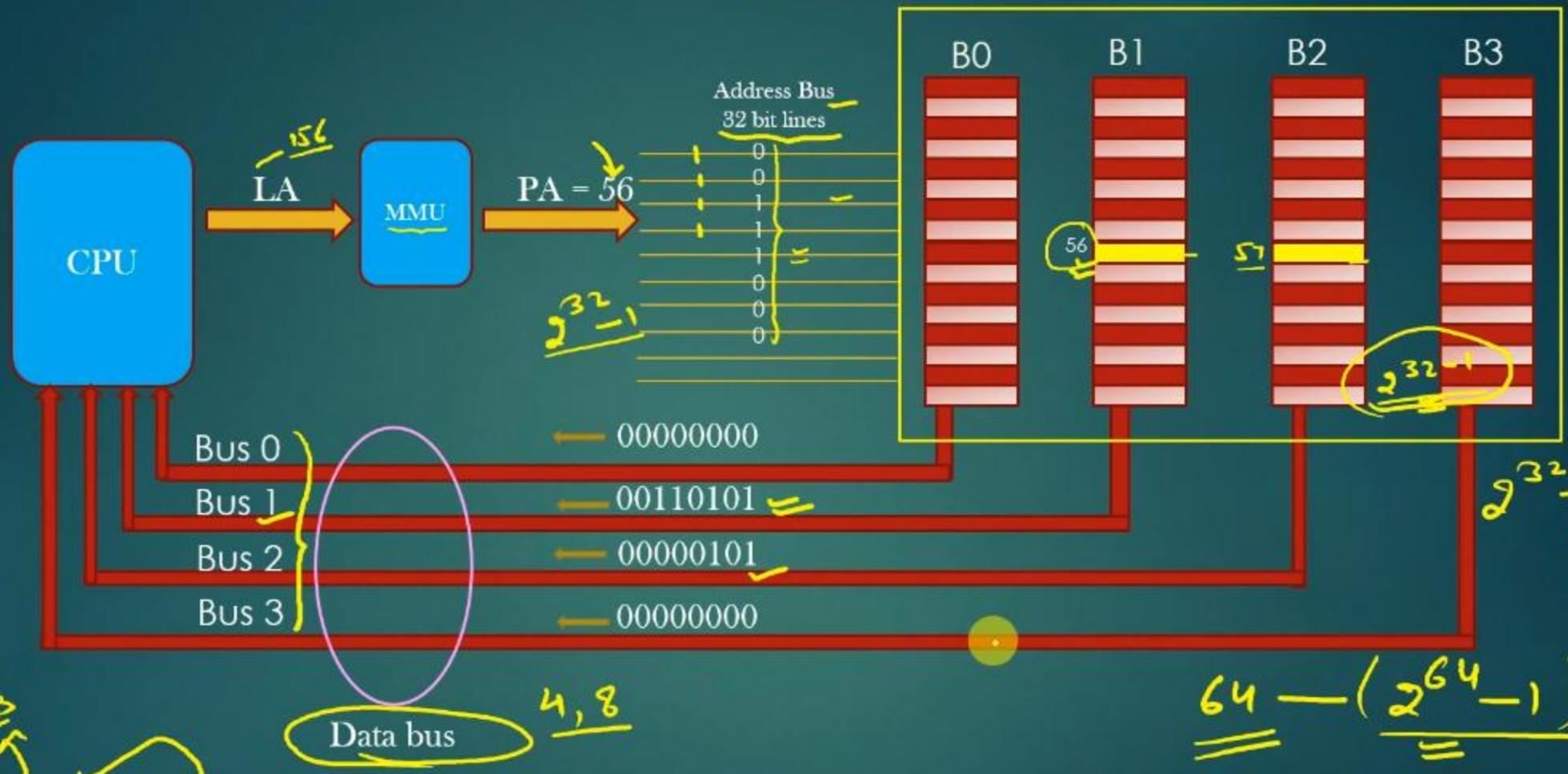


Memory Management in Linux -> Address and Data Bus on a 32 bit system



long var1 = 567; /*will take 2 cpu clock cycles to store data in physical memory on 32 bit System, and 1 cpu clock cycle on 64 bit OS*/

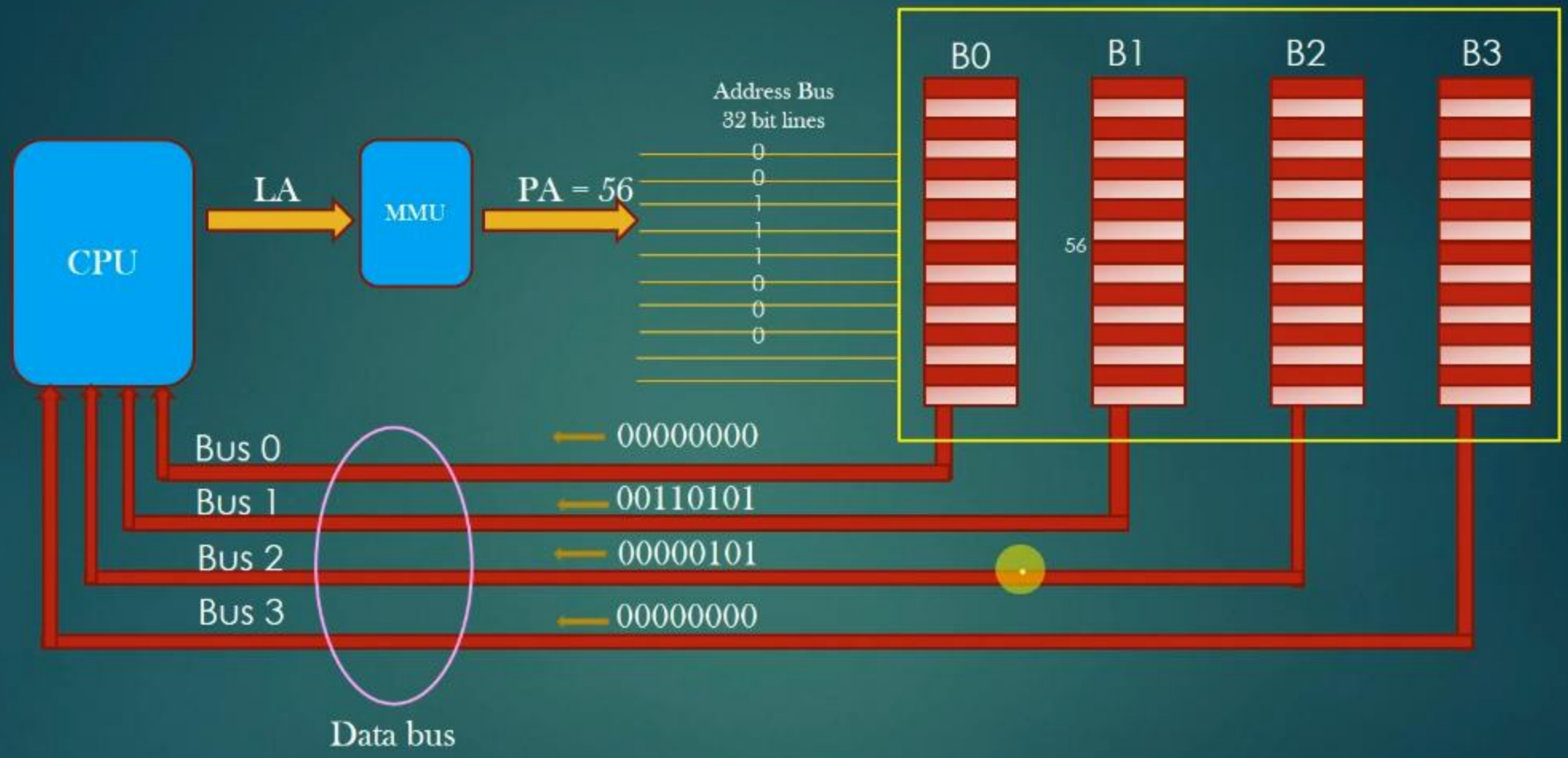
Memory Management in Linux -> Address and Data Bus on a 32 bit system



long var1 = 567; /*will take 2 cpu clock cycles to store data in physical memory on 32 bit System, and 1 cpu clock cycle on 64 bit OS*/

Note : You must learn these diagram (through out the course) to in order to explain concepts in interviews

Memory Management in Linux -> Word Size



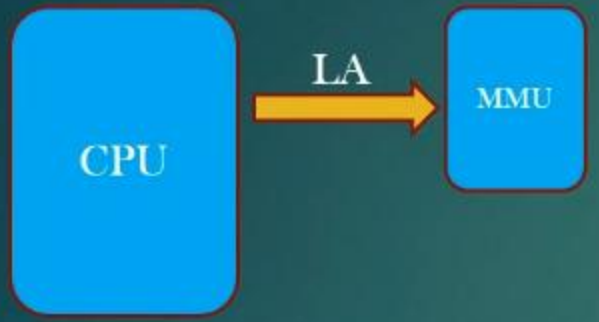
Word Size : No of bytes a CPU can read and write into physical memory in one clock cycle

For 32 bit system , word size = 4B

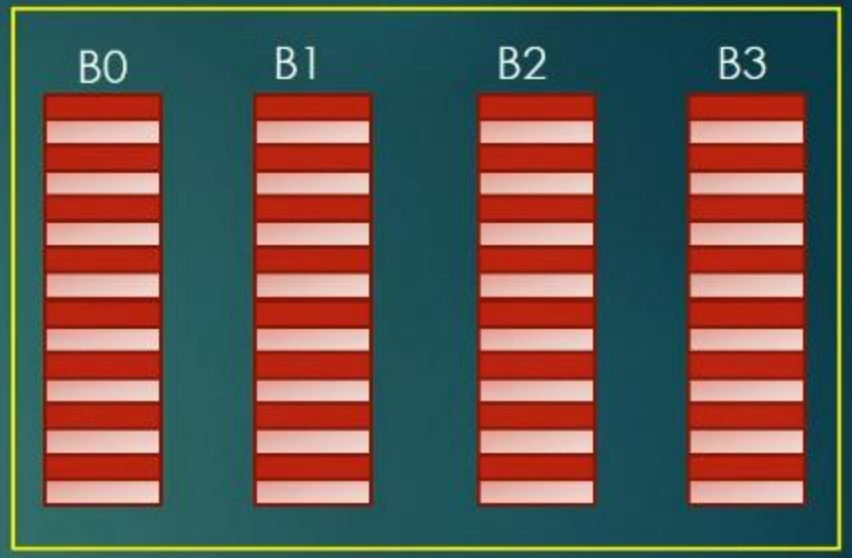
For 64 bit system, word size = 8B

No of Metal wires in Data bus/8 = Word size in Bytes

Memory Management in Linux -> Address and Data Bus on a 32 bit system



Address bus



long var1 = 10.0; /*will take 2 cpu clock cycles to store data in physical memory on 32 bit System, and 1 cpu clock cycle on 64 bit OS*/

Assignment 9: Check your understanding

Questions for this assignment

1. Why we felt the need for a 64 bit system architecture ?

   What is the maximum byte address in physical memory in 64 bit system architecture ?

   How many Bit lines are there in address and data bus for 64 bit architectures ?

2. Ramesh has a 32 bit System running 32 bit OS with 4GB of physical memory. He feels his system is running slow, and he install more RAM chips in his system. But he do not see any improvement in multi-tasking and speed of system ? Why ?

3. A CPU performs the following operation on a 32 bit system architecture.

   memcpy(ptr, buffer, 35);

   How many times CPU has to access the main memory to complete the copy of data from "buffer" to memory location pointed by "ptr" ?

   How many times CPU has to access the main memory for the same operation on a 64 bit system ?

   (Note : memcpy copies data to target memory location byte by byte)

4. Now that you know what is Data bus and Address bus and how does it work , read this article to understand atomic operations. I will going to add complete section on this soon.

   [Added on 10 Feb 2022]

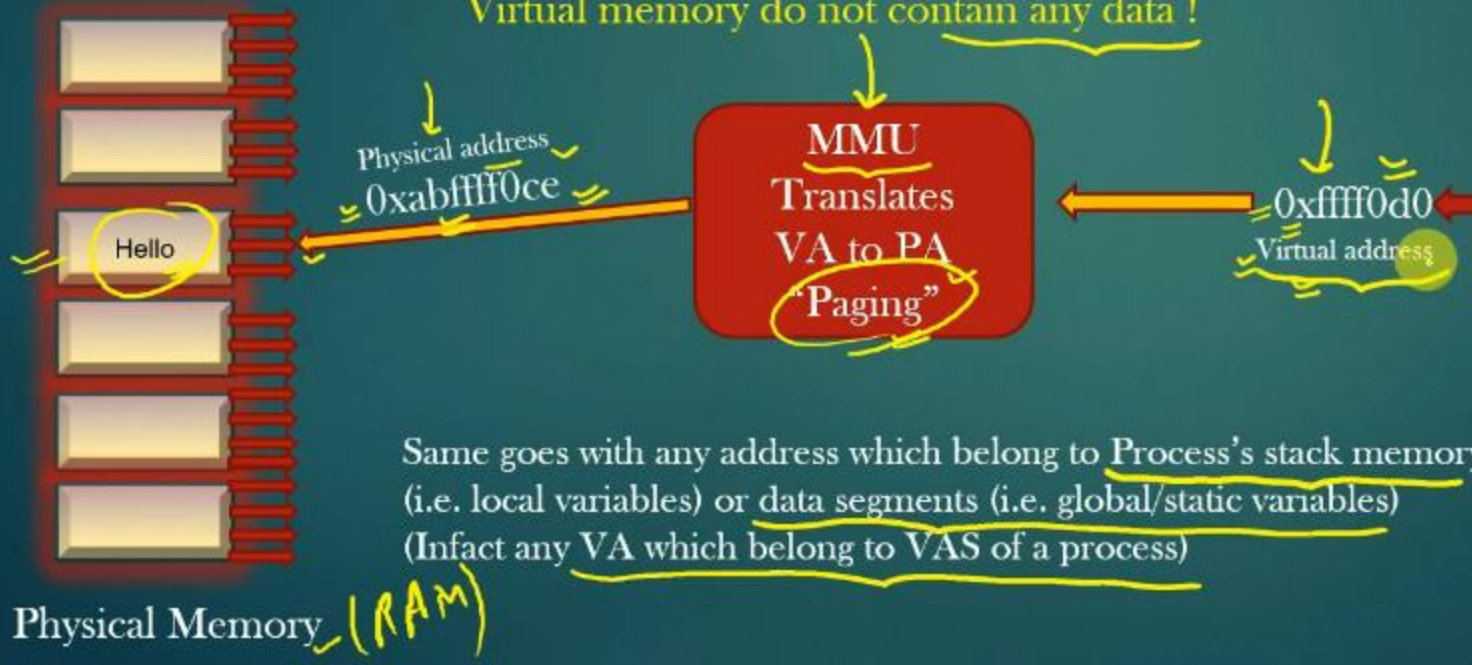
Memory Management in Linux -> Virtual Addresses to physical address Mapping

void *ptr = malloc (20);

- if ptr points to address location, say, 0xffff0d0, then this address will be some address in Heap Segment of the process Virtual address space

strncpy (ptr, "Hello", 5);

Actual Data/Content is written on physical memory
Virtual memory do not contain any data !



Same goes with any address which belong to Process's stack memory (i.e. local variables) or data segments (i.e. global/static variables) (Infact any VA which belong to VAS of a process)

Memory Management in Linux -> Virtual Addresses to physical address Mapping

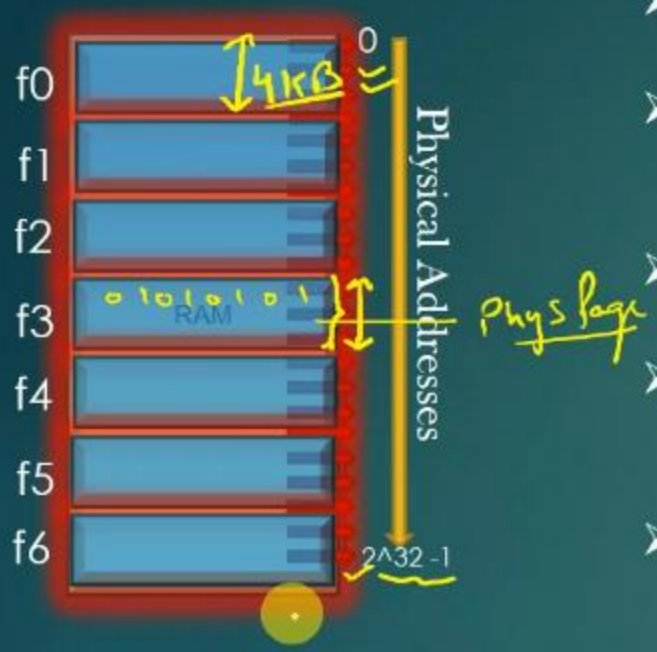
Which Key belongs to which Locker

MMU "Paging"

Consider Keys As Virtual Addresses

Consider Lockers as Actual storage On Physical Memory where Data is kept

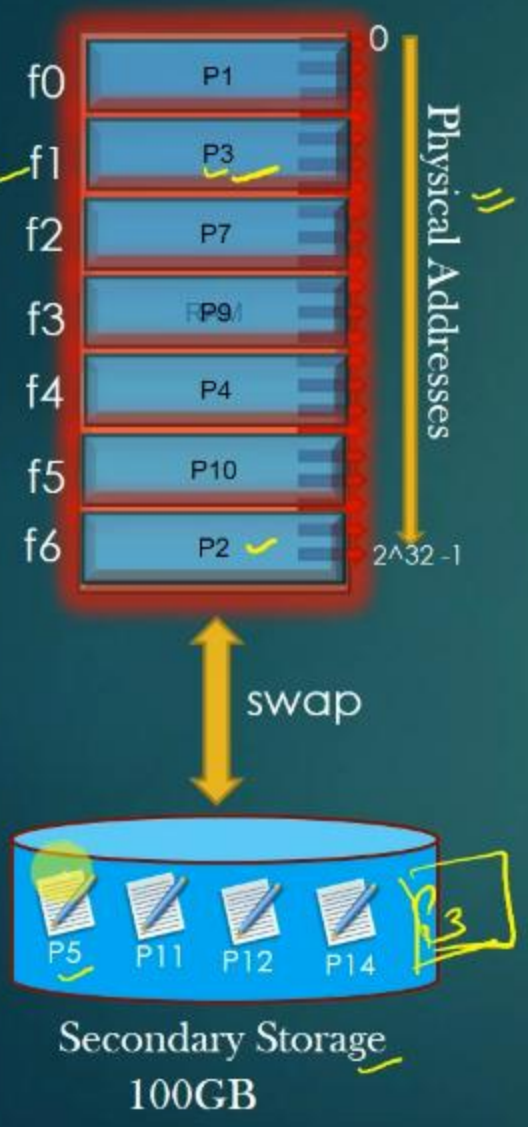
Memory Management in Linux -> Physical Pages & Physical Frames



- Shown is the System's Main Memory whose size is 4GB
- If we fragment this main memory in blocks of equal size, each block is called a frame
- On Most System architectures, size of frames is taken as 4KB (4096B)
- So, how many frames are there in 4GB of physical memory ?
  = size of physical memory / size of Frame = 2^32 / 2 ^ 12 = 2^ 20 frames
- The SNAPSHOT of the data stored in a frame of physical memory is called a Physical page
- Obviously, size of page = size of Frame
- Think frames as container of pages

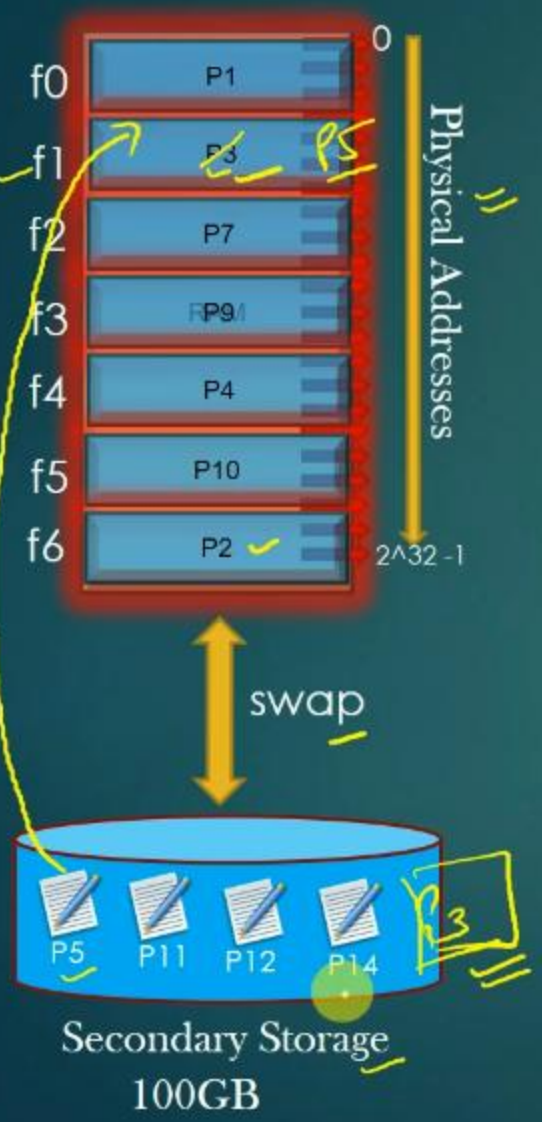
Analogy : You have a container (Main Memory) which can contain max of 3 apples (max 3 frames), and you have to carry 9 apples (9 physical)from one place to another

Memory Management in Linux -> Page swapping



- Consider the snapshot of the main memory at some random time when it has some pages in its frames
- Swap is the operation in which Main memory saves the page in one of its frame to the secondary storage and reload other page from secondary storage into the frame
- When Main Memory do not left with a free frame it may chose to temporarily store the pages on secondary storage
- For example, MM can save Page P3 in frame f1 to swap it with ~~frame~~ P5

Memory Management in Linux -> Page swapping



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- When Main Memory do not left with a free frame it may chose to temporarily store the pages on secondary storage
- For example, MM can save Page P3 in frame f1 to swap it with frame P5
- Main Memory uses various page replacement algorithm to choose which page to be chosen to be replaced with new page from disk, its not random Algorithms : LRU, FIFO etc

- Just like Main Memory is divided into frames which store pages, Virtual Memory of the process is also fragmented into pages of same size (4096B). These pages are called Virtual pages.

Virtual Memory Page

Memory Management in Linux -> Virtual Memory Pages

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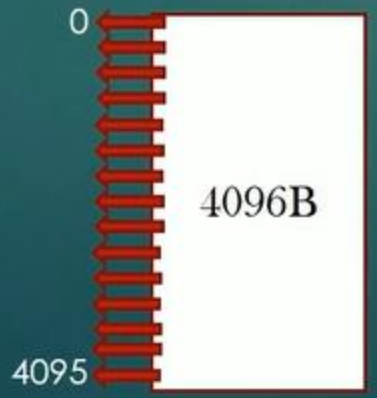
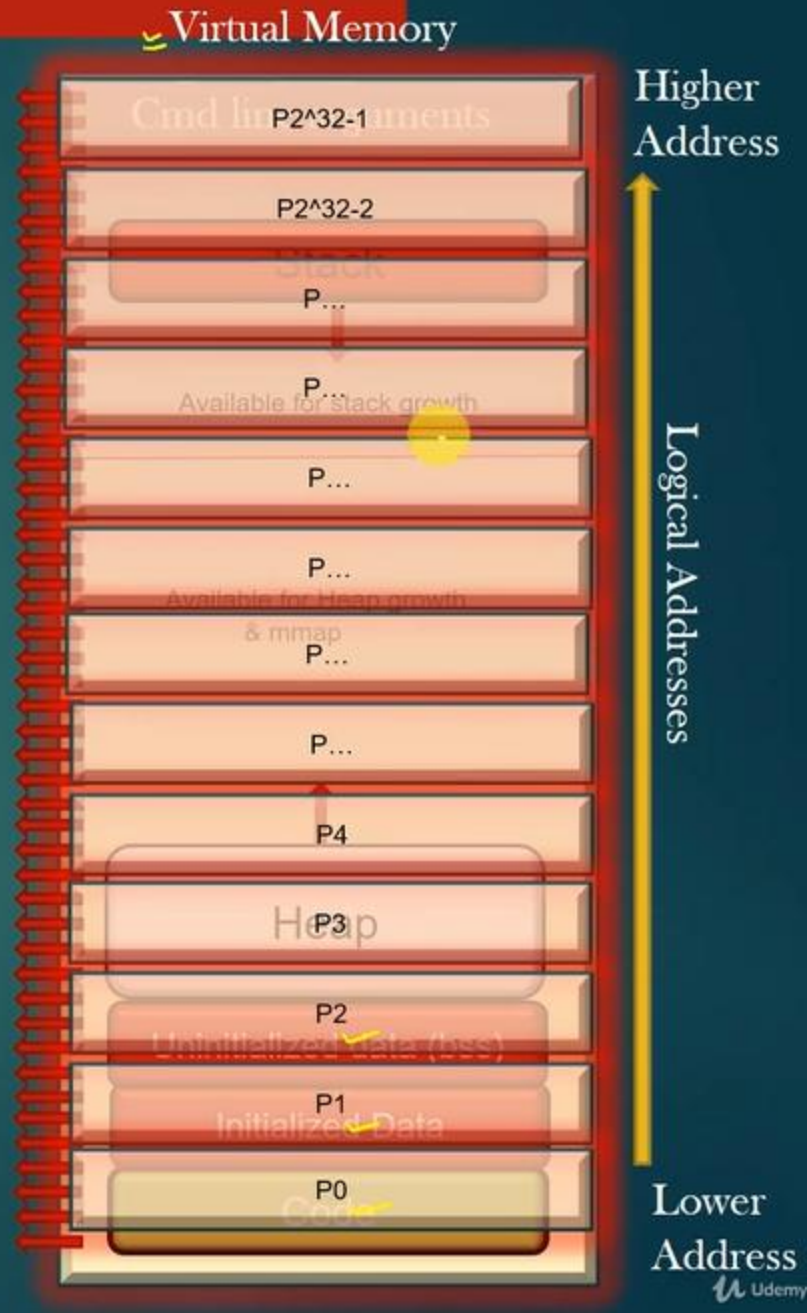
Correction : Upto Page no 2 ^ 20 - 1



Virtual Memory Page



Memory Management in Linux -> Virtual Memory Pages

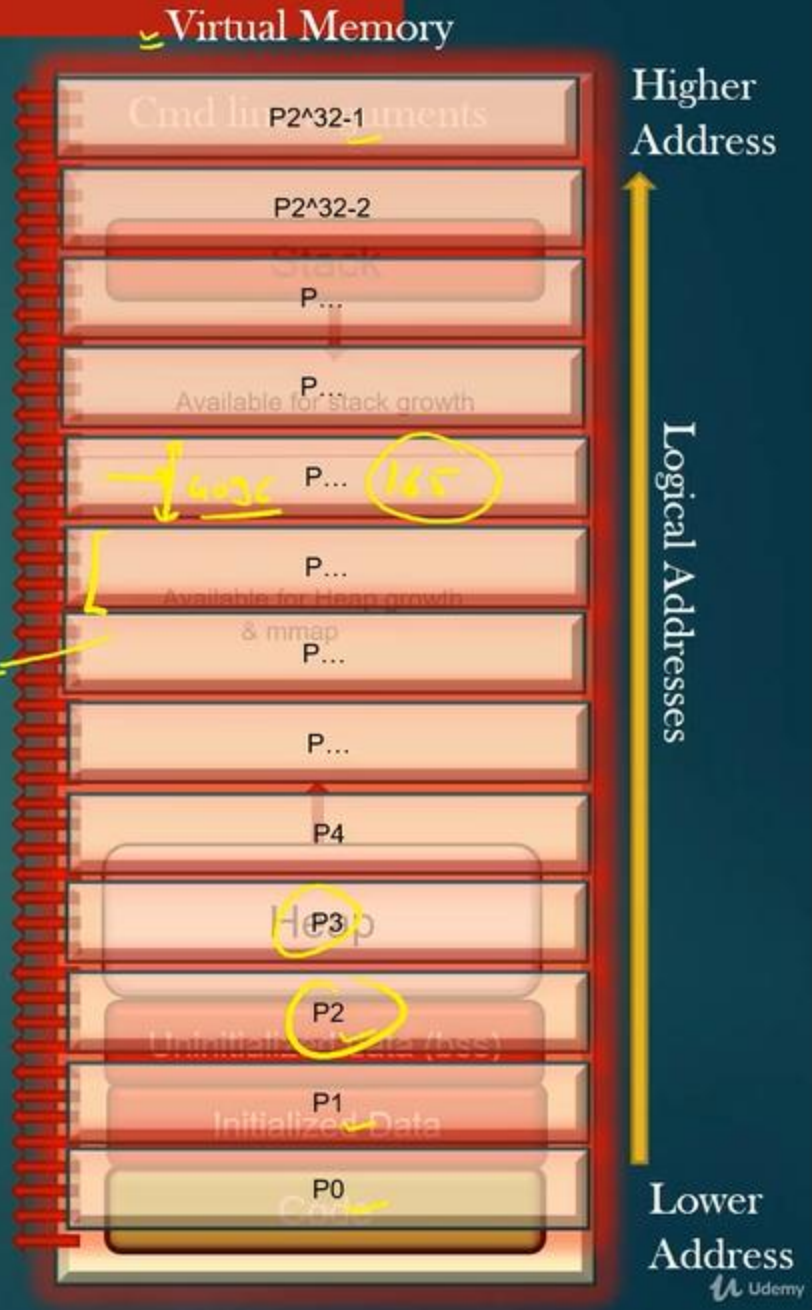
- Just like Main Memory is divided into frames which store pages, Virtual Memory of the process is also fragmented into pages of same size (4096B). These pages are called Virtual pages.

- So, if size of Virtual Memory of a process is 2^32 B, and page size is 4096B, then total no of pages into which VAS of a process is divided are 2^20 pages

- To uniquely identify a page in VAS of a process we need 20 bits !

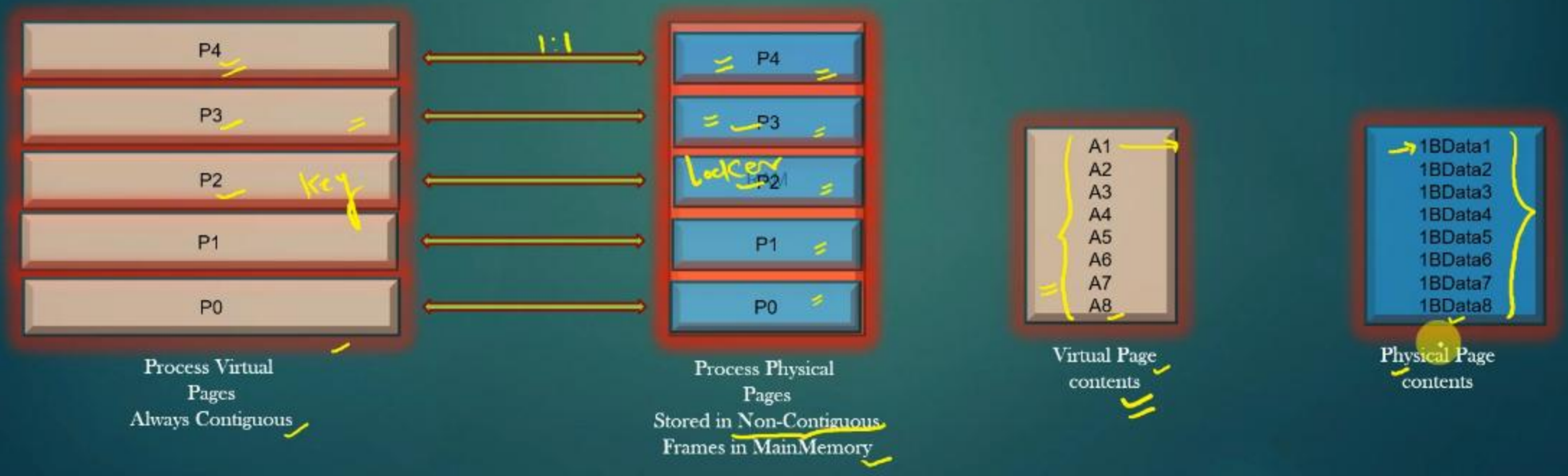
- Since size of each page is 4096B (2^12B), 12 bits are required to uniquely assign an address to a Byte with in a page (Remember every Byte is supposed to have an address)

Virtual Memory Page



Memory Management in Linux -> 1:1 relationship between Physical and Virtual page

- Remember, We equate Virtual addresses as a key and Physical addresses as lockers
- A Virtual page is a collection of 4096 keys, each key unlocks one byte of data in physical memory, means, each VA provide an access to 1B of data present at some physical address in main memory
- If there is a key, then there has to be a locker, precisely saying, if there is a Virtual page, there exists a corresponding physical page (may be on disk on in main memory)



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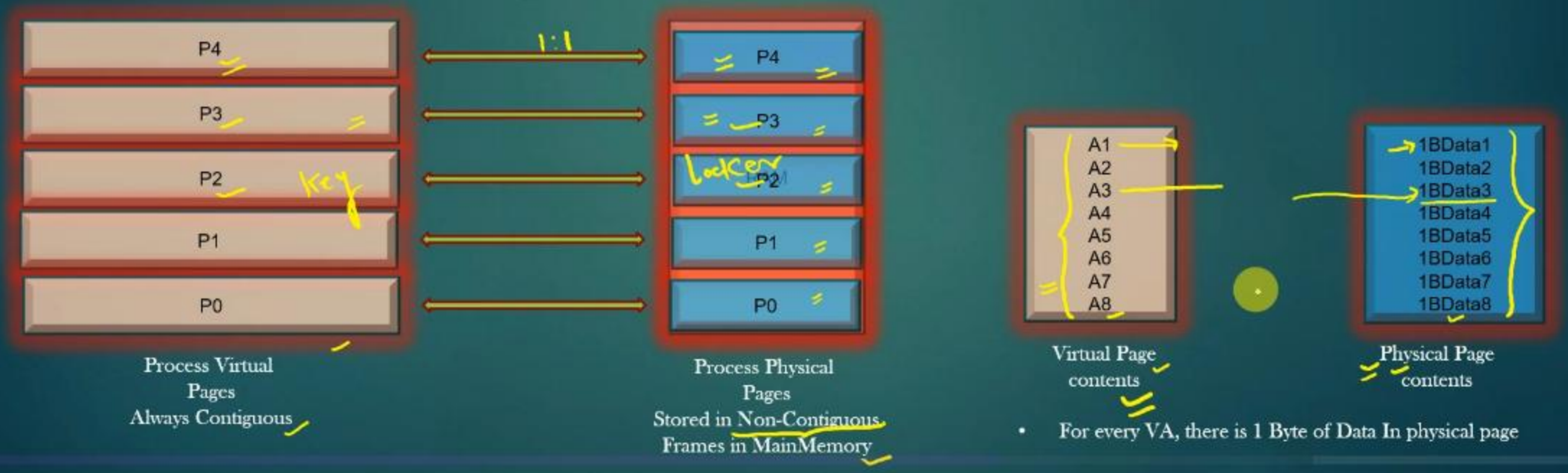
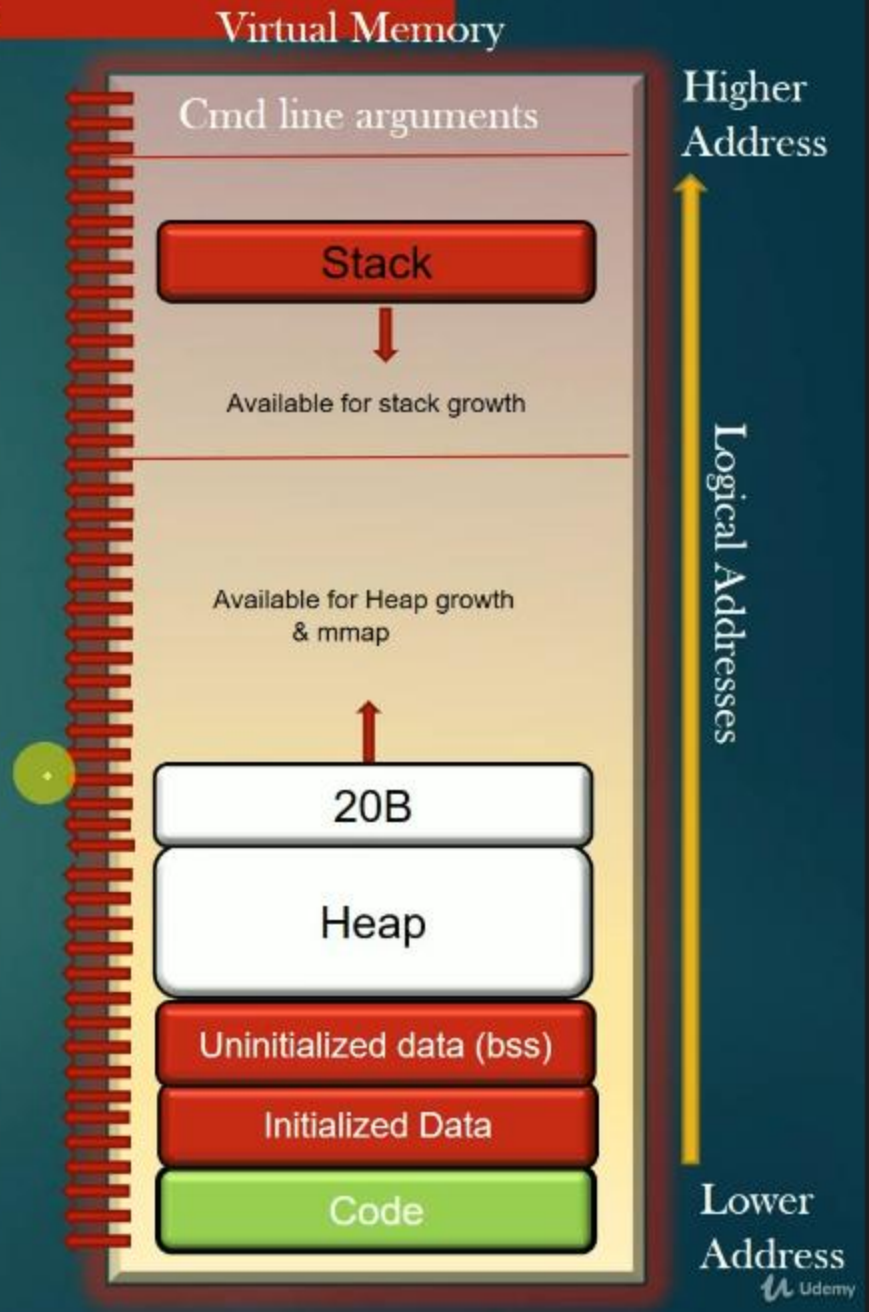


Memory Management in Linux -> 1:1 relationship between Physical and Virtual page

- Physical Pages are created Or destroyed as process uses or frees corresponding virtual pages during the course of execution



Memory Management in Linux -> 1:1 relationship between Physical and Virtual page

- Physical Pages are created Or destroyed as process uses or frees corresponding virtual pages during the course of execution

Physical Pages

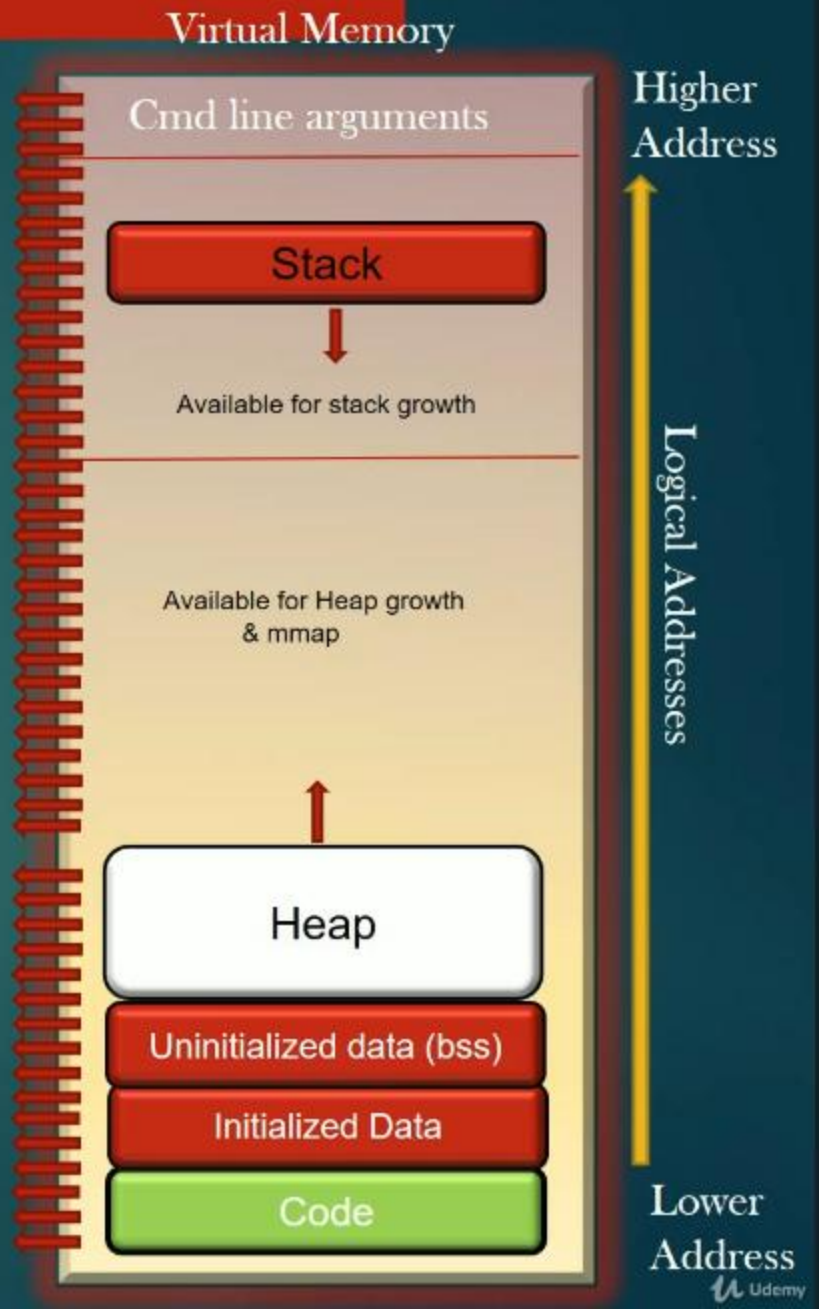
Memory Management in Linux -> 1:1 relationship between Physical and Virtual page

- Physical Pages are created Or destroyed as process uses or frees corresponding virtual pages during the course of execution
- OS allocates or releases the Virtual Memory (hence Physical Pages also) in units of PAGE SIZE (4096 Bytes)
- Thus malloc(10) , will not result in creation of new physical/Virtual page if top-most V.page in Heap Segment of Process's VAS has 10 spare bytes to satisfy malloc request

Memory Management in Linux -> Virtual Address Composition

- Suppose, during the course of execution of the process, CPU generates a virtual address of 32 bits, ex, 0xffff0d00
- These 32 bits is split into two parts

- Thus the Virtual address means 0xffff0d00 simply means an address which is within page no 1048560, at offset 3328



Memory Management in Linux -> Virtual Address Composition

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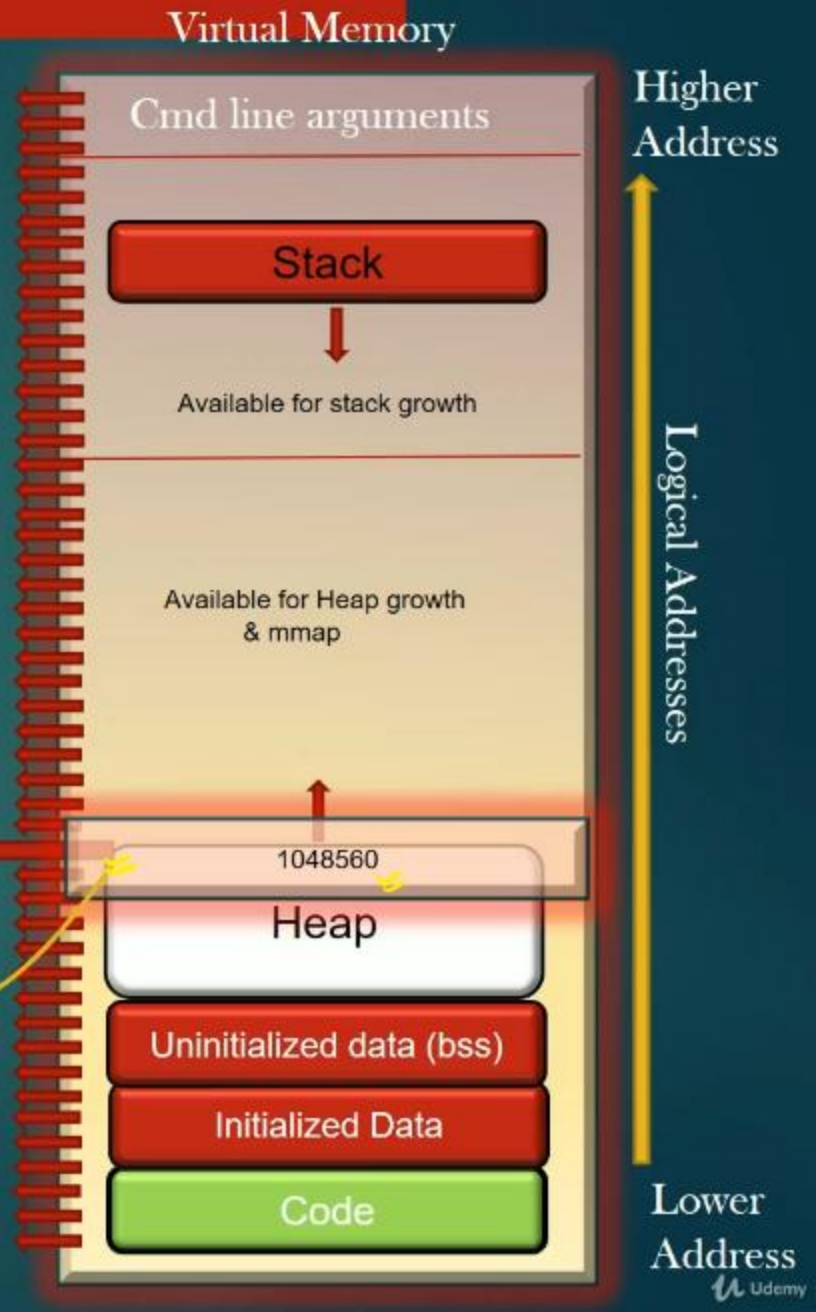

Memory Management in Linux -> Virtual Address Composition

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Memory Management in Linux -> Page Table

- Page Table is a Data structure maintained by OS for every process running on the system
- Page Table is used to MAP the virtual address of process's VAS to a physical address of RAM

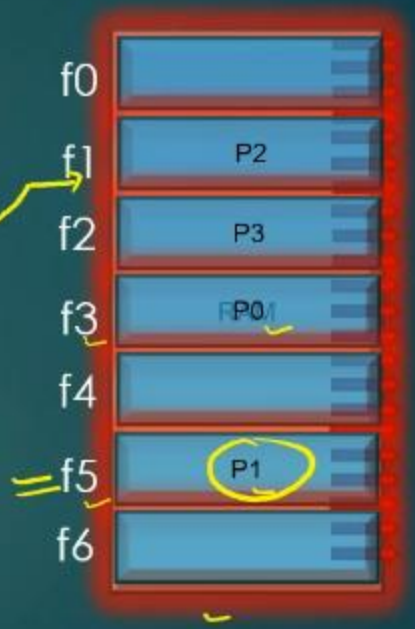
VP = 3
PP = 3 (2)

Virtual Memory
Pages (Contiguous)

2^{20}
$2^{20}-1$

Page Table

V. Page No	Phy Page No	Frame no
0	0	3
1	1	5
2	2	1
3	3	2
4	4	-



Physical Memory
Pages (Non-Contiguous)

- No of rows in page table = No of pages in process VAS
- Let us now take an example to illustrate how address mapping from Virtual address to physical address happens !

Assignment instructions

30 minutes to complete | 28 student solutions

Pls follow the instructions given in the Question.

Questions for this assignment

1. A computer system implements a 36 bit virtual address. Page size is 4KB and size of physical memory address is 30 bits. The approximate size of page table in the system is ___ MB ?

   Assume the size of single page table entry = no of bits required to represent a frame no of physical memory.

2. A computer system implements 8 kilobyte pages and a 32-bit physical address space. Each page table entry contains a valid bit, a dirty bit, three permission bits, and the translation. If the maximum size of the page table of a process is 24 magabytes, the length of the virtual address supported by the system is _____ bits.

   Note : Translation means, no of bits to represent a frame no.

Instructor example

Abhishek CSEPracticals

1. A computer system implements a 36 bit virtual address. Page size is 4KB and size of physical memory address is 30 bits. The approximate size of page table in the system is ___ MB ?

   Assume the size of single page table entry = no of bits required to represent a frame no of physical memory.

   Size of Page table = No of entries in Page table * size of one entry of page table

   No if entries in a Page table of a process = No of Virtual Pages into which Process's VAS is fragmented

   = 2 ^ 36 / 4KB = 2 ^ 24

   Physical Memory size = 2 & 30 Bytes

   No of Physical Memory Frames = Physical Memory Size / Size of Physical Frame

   = 2 ^ 30 Bytes / 4KB = 2 ^ 18

   18 bits are required to represent a physical memory frame.

   Thus, as per Assumption in Question, size of single page table entry = 18 bits.

   Size of Page table = (2 ^ 24) * 18 bits = ~36 MB

2. A computer system implements 8 kilobyte pages and a 32-bit physical address space. Each page table entry contains a valid bit, a dirty bit, three permission bits, and the translation. If the maximum size of the page table of a process is 24 magabytes, the length of the virtual address supported by the system is _____ bits.

Note : Translation means, no of bits to represent a frame no.

32 bit Physical address space means, size of physical address is 32 bits. It means, No of Physical addresses on RAM is 2 ^ 32. Since, RAM is byte addressable memory, every byte has an address. Therefore, size of RAM is = 2 ^ 32 Bytes.

Page Size = 8KB (Given)

Therefore no of frames into which Physical memory is fragmented = 2 ^ 32 / (8 * 1024) = 2 ^ 19 frames.

Thus 19 bits are required to represent a frame no.

Page table entry size = valid bit + dirty bit + 3 permission bits + translation

= 1 + 1 + 3 + 19 = 24 bits.

No of entries in a page table = 24MB/24 = 2 ^ 23

Since, no of entries in a page table = No of Virtual pages into which Process VAS is fragmented, therefore

No of Virtual Pages = 2 ^ 23.

Process Total Virtual Memory = 2 ^ 23 * PAGE_SIIZE

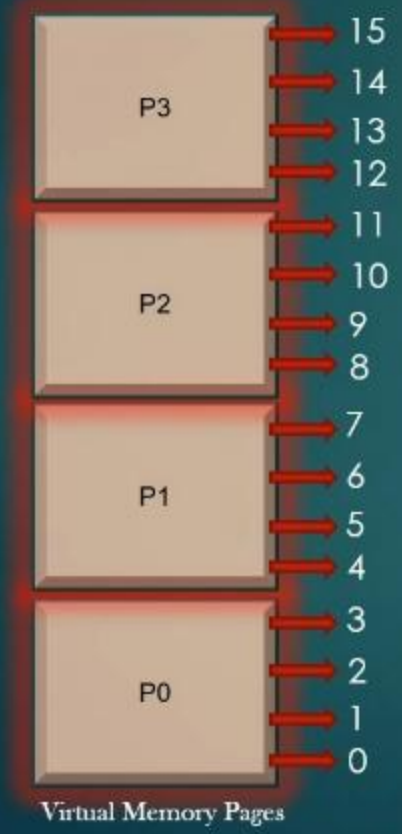
= 2 ^ 23 * 8KB = 2 ^ 36 Bytes

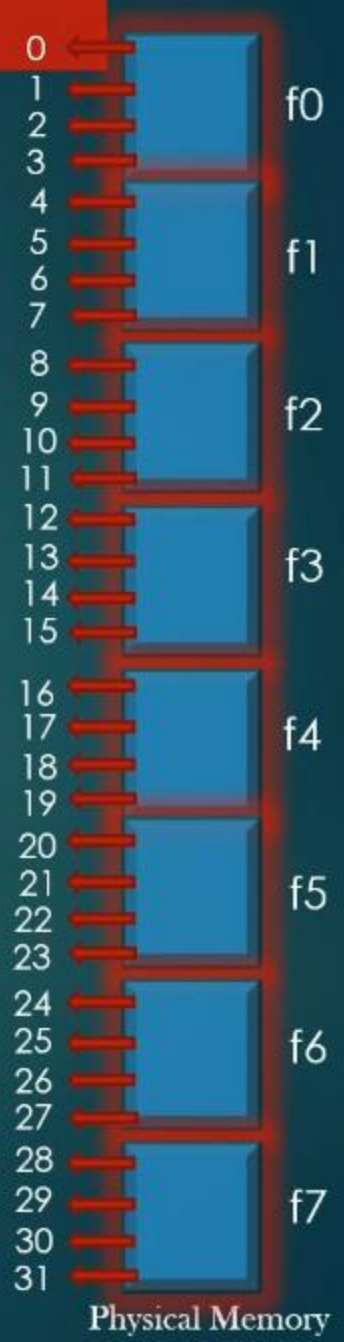
Since, Virtual Memory is also Byte addressable, therefore, 36 bits are required to represent a Byte in Virtual Memory.

Therefore, length of Virtual address supported is 36 bits.

Memory Management in Linux -> Paging In Action

- In our example, consider the following configuration of the system
  - Size of Virtual address space of a process = 16B = 2 ^ 4
  - Virtual address is of 4 bits
  - Page size = 4B
  - Main Memory Size = 32B
  - No of Bits to represent a V page uniquely = 2bits
  - No of Bits to represent an address with in V page uniquely = 2bits





Memory Management in Linux -> Paging In Action

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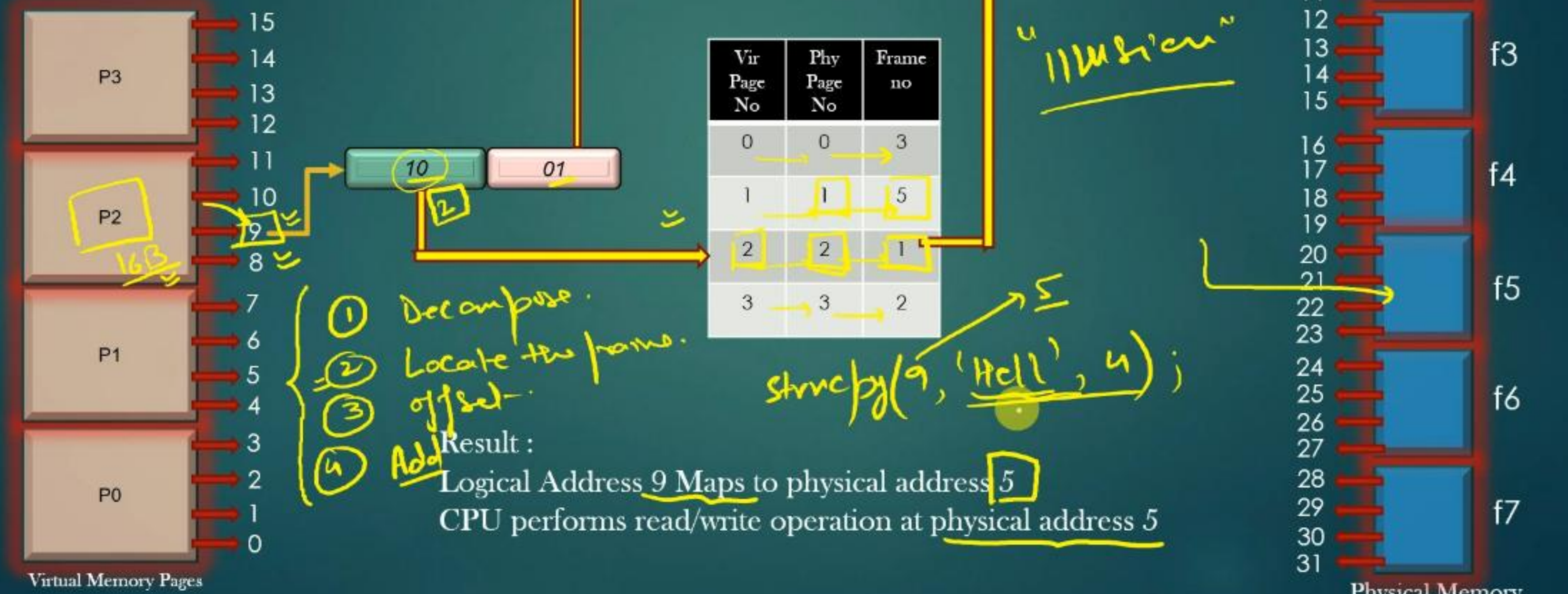

Result :

Logical Address 9 Maps to physical address 5

CPU performs read/write operation at physical address 5

Memory Management in Linux -> Paging In Action

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  - Size of Virtual address space of a process = 16B = 2 ^ 4
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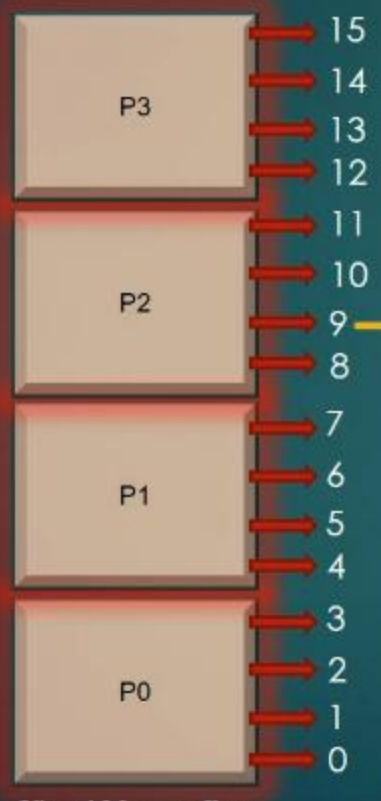


Virtual Memory Pages

Vir Page No	Phy Page No	Frame no
0	0	3
1	1	5
2	2	1
3	3	2

Physical Memory

Similarly, LA 6 (0110) maps to 22 PA
LA 13 (1101) maps to 9 PA
LA 15 (1111) maps to 11 PA
LA 3 (0011) maps to 15 PA

Instructions | Submission | Instructor example | Give feedback

Assignment instructions

60 minutes to complete | 24 student solutions

Answer as per the instruction mentioned in the Question.

Questions for this assignment

1. Given a Virtual address generated by the process P, and given a page table, what is the time complexity of looking up the page table and locate the correct frame number ? Explain.

Next

Course content

Instructions Submission **Instructor example** Give feedback

How did you do?

Compare the instructor's example to your own

Instructor example

Abhishek CSEPracticals

1. Given a Virtual address generated by the process P, and given a page table, what is the time complexity of looking up the page table and locate the correct frame number ? Explain.

   O(1).

   Page tables are usually maintained as arrays since they have fixed size. No of entries in page table = VAS size / Page size.

   Page tables are arrays whose indices are virtual page number. We already know, arrays data structure are random access data structures in which given can access any element in O(1) given an index.

Course content

11min

Assignment 11: Test your Understanding

134. Multiple Process Scenario
3min

135. Resolve External Fragmentation
2min

136. Page Allocation to a Process - Part1
6min

137. Page Allocation to a Process - Part2
6min

138. Shared Physical Pages
10min

139. Page tables Problems
2min

140. Page Table Problem 1 - Large Page Table Size Matters
5min

141. Page Table Problem 2 - Need for Contiguous Main Memory
3min

Memory Management in Linux -> Multiple Processes Scenario

- Physical Memory frames are shared between processes running on the system

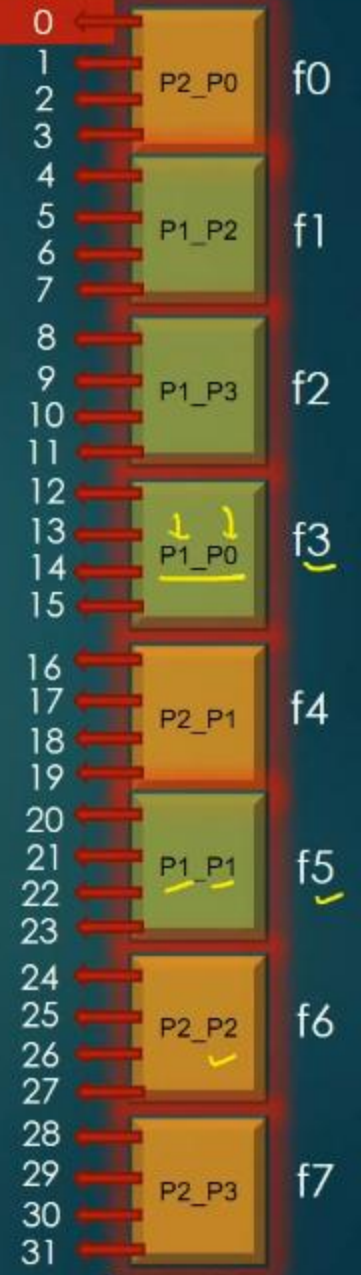
Vir Page No	Phy Page No	Frame no
0	0	3
1	1	5
2	2	1
3	3	2

Process 1

Vir Page No	Phy Page No	Frame no
0	0	0
1	1	4
2	2	6
3	3	7

Process 2

- Physical Pages need not be contiguous in physical memory
  - Ex, Page 0 and page 1 of Process 1 are in frames f3 and f5 respectively
- Any free frame can be allocated to a process's physical page (Depending on Page replacement algorithms)



Memory Management in Linux -> No External Fragmentation

- Why Frame size = Physical Page Size ?
  4KB 4KB
- A Physical Page is always loaded at the frame Boundary

Course content

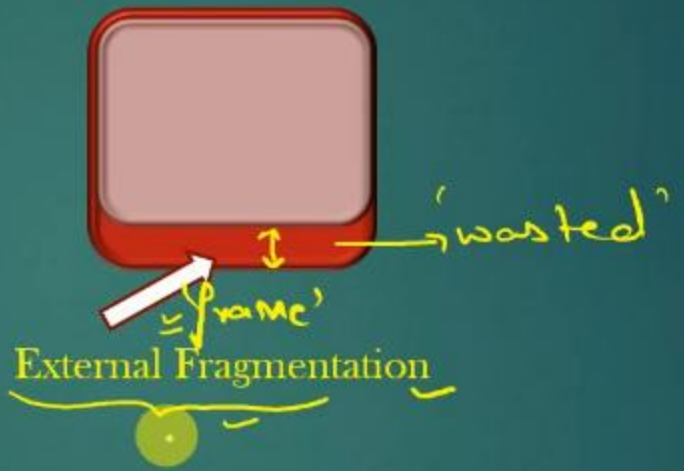
Section 20: Multi Level Paging

Memory Management in Linux -> No External Fragmentation

- Why Frame size = Physical Page Size ?
- A Physical Page is always loaded at the frame Boundary

Memory Management in Linux -> No External Fragmentation

- Why Frame size = Physical Page Size ?
- A Physical Page is always loaded at the frame Boundary



Heap Memory Management - > Metablock and Datablock

```
void *ptr1 = malloc (14);
```

Actual memory to be used by the process

ptr1

Meta information

```
struct meta_block_t {
        int size;  /*= 14*/
        struct meta_block_t *next; /*= NULL*/
        bool is_free; /*= FALSE*/
}
```

Enhanced malloc

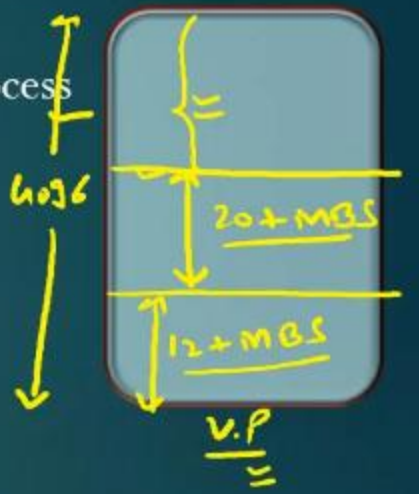
```
void *malloc (int size) {
        struct meta_block_t *p;
        p = (struct meta_block_t *)sbrk(0);

        if (sbrk (size + sizeof(meta_block_t)) == NULL)
                return NULL;
        p->size = size;
        p->next = NULL;
        p->is_free = FALSE;
        return p + 1;
}
```

Note that, OS inserts additional padding bytes at the end to make the total block size (Meta block + Data block) integer multiple of 4. This is called 4 bytes alignment.

But Process should use only 14 bytes of memory starting from address ptr1

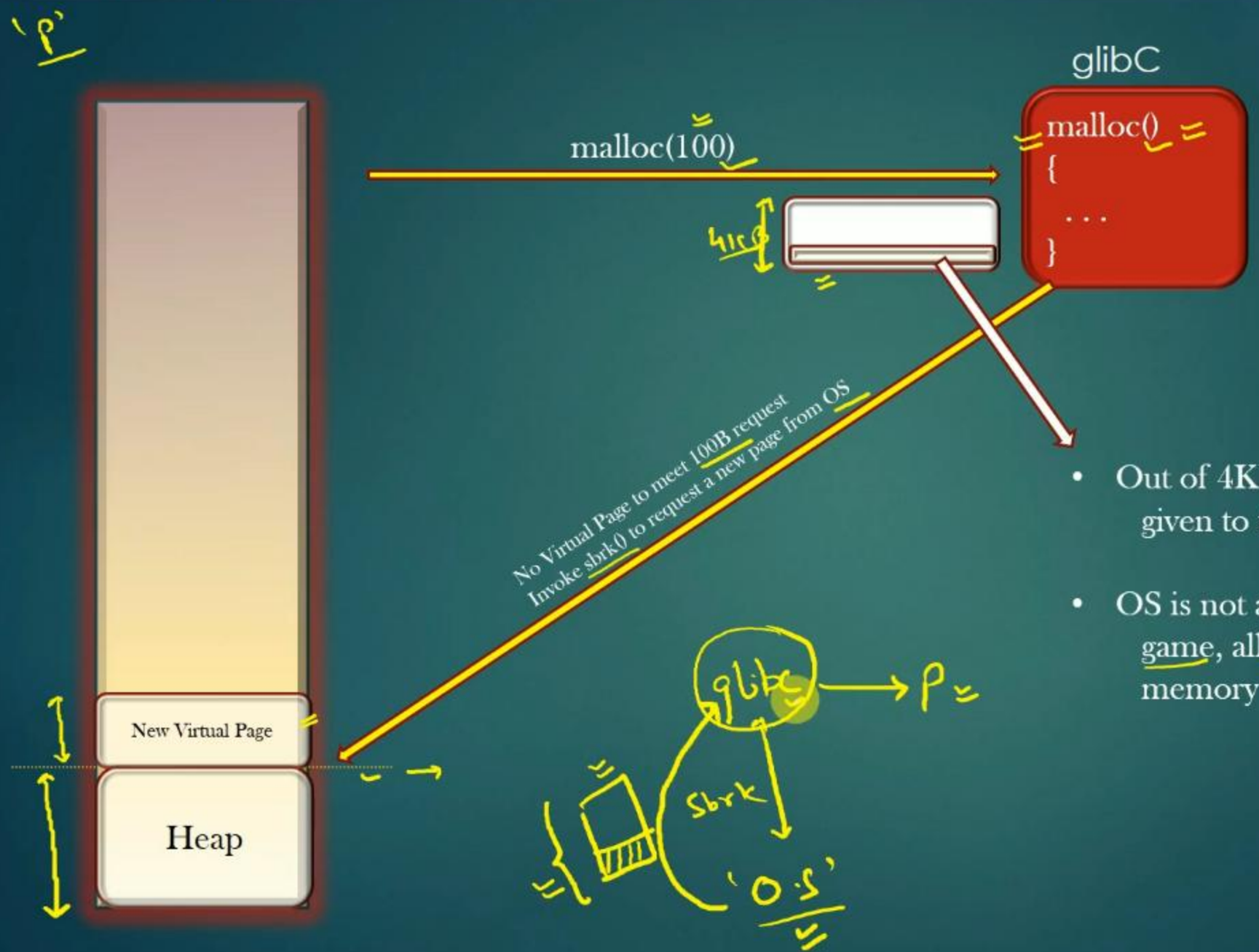
Memory Management in Linux -> Memory Allocation to a Process

- OS allocates/frees memory to/from a process in units of PAGE_SIZE (4096B)
- So, if your process invokes malloc(12) for example, does OS allocates (12 + MBS) bytes or PAGE_SIZE bytes of memory to a process , where MBS – size of meta data block (recall !)
- Answer is Both :
  - OS allocates PAGE_SIZE bytes of virtual memory to your process (and creates a corresponding physical page), out of those PAGE_SIZE bytes, (12 + MBS) bytes is assigned to your process



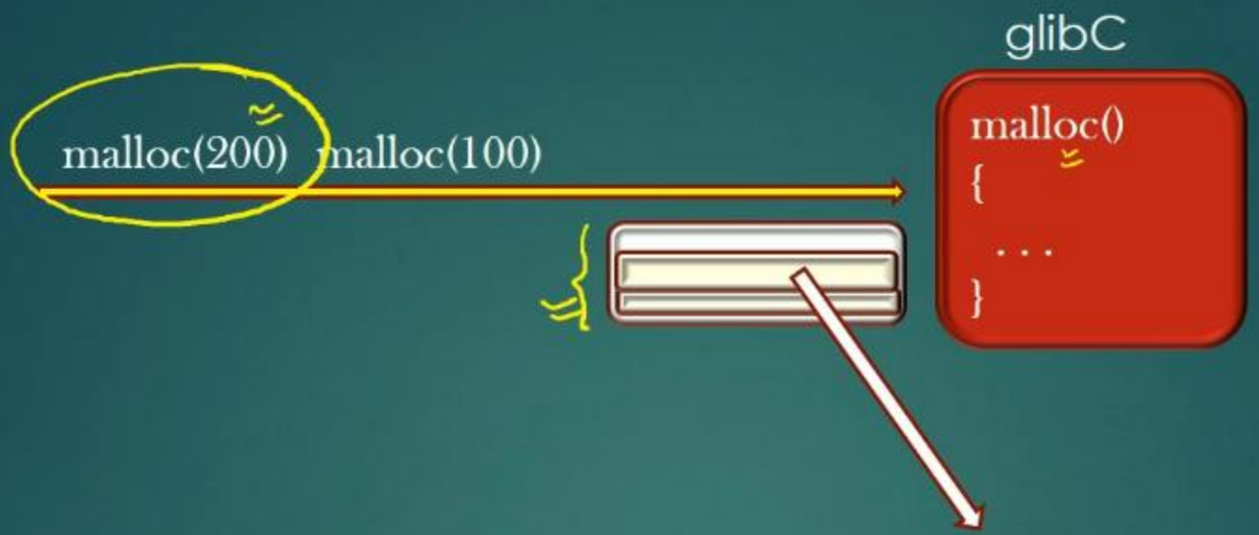
  - > Remaining (PAGE_SIZE – (12 + MBS)) Virtual Memory is cached by glibC malloc implementation
  - > Next time when process request, say 20, bytes of memory, malloc checks if it has a virtual page which has unassigned virtual addresses to meet the new request, if yes, then (20 + MBS) bytes are assigned from remaining portion of the virtual page.
  - > Memory remaining now : (PAGE_SIZE – 12 – 20 – 2 * MBS) Bytes in a virtual page
  - > In case Virtual page do not have enough memory left to satisfy the process request, malloc request OS to assign another brand new virtual page altogether
  - > A Diagram worth 1000 words . . .

Memory Management in Linux -> Memory Allocation to a Process



- Out of 4KB, only (100 + MBS) Bytes are given to the process to use
- OS is not aware that glibC is playing this efficient game, all it believes that it has assigned 4KB of memory to a requesting process

Memory Management in Linux -> Memory Allocation to a Process



- Out of 4KB - 100 -MBS , only (200 + MBS) Bytes are given to the process to use from cached Virtual page
- OS is not disturbed again !

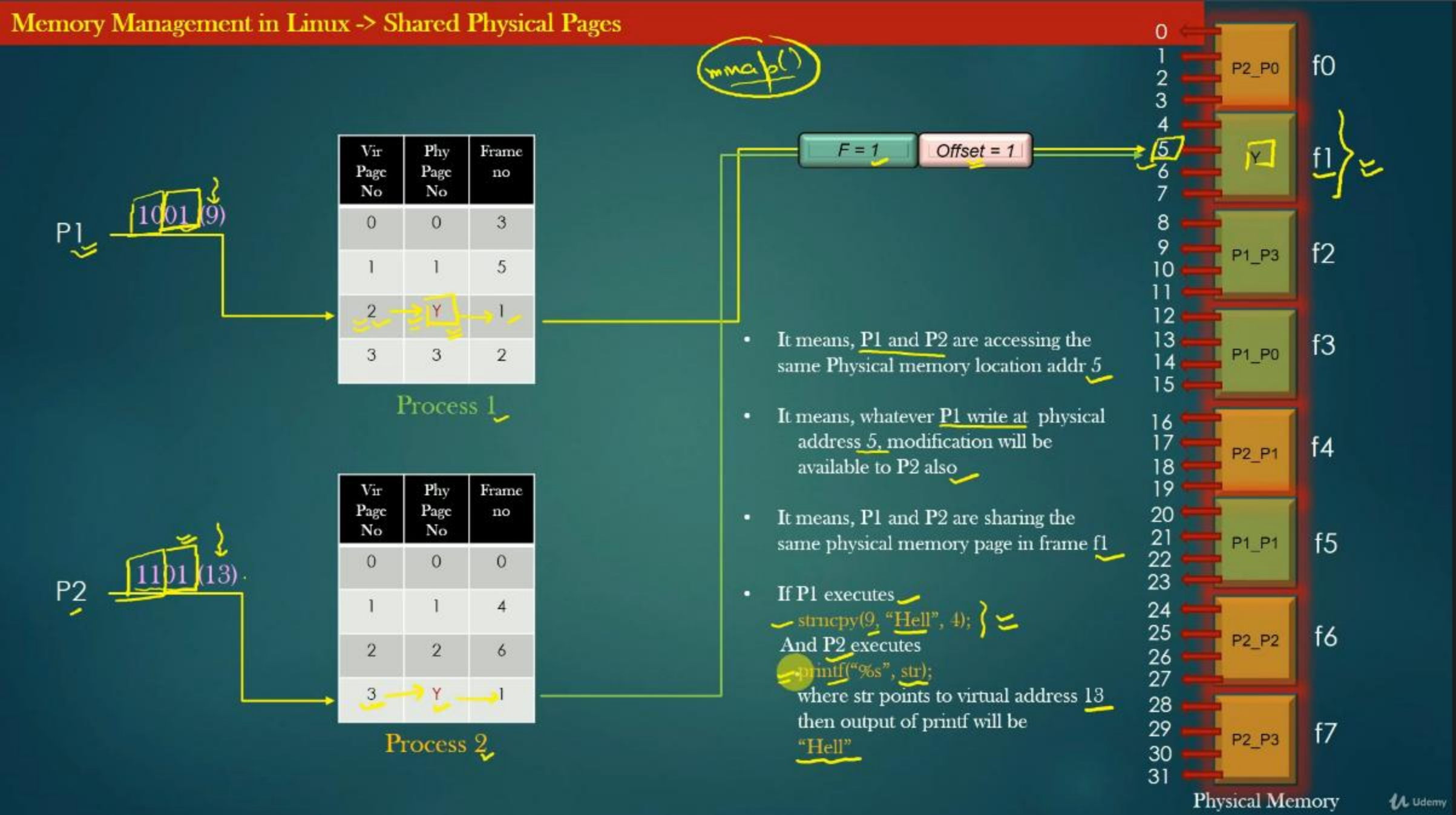
Why this Game by malloc ?

- To Minimize no of System Calls invocation (sbrk()) for every memory requests by a process

Memory Management in Linux -> Shared Physical Pages

- A Shared physical page is a physical page which is shared by two or more running processes
- A Physical page is said to be shared, if it is present in page tables of two or more processes
- In our example, We shall continue with the same configuration of the system
  - Size of Virtual address space of a process = 16B = 2 ^ 4
  - Virtual address is of 4 bits
  - Page size = 4B
  - Main Memory Size = 32B
  - No of Bits to represent a V page uniquely = 2bits
  - No of Bits to represent an address with in V page uniquely = 2bits

Memory Management in Linux -> Shared Physical Pages



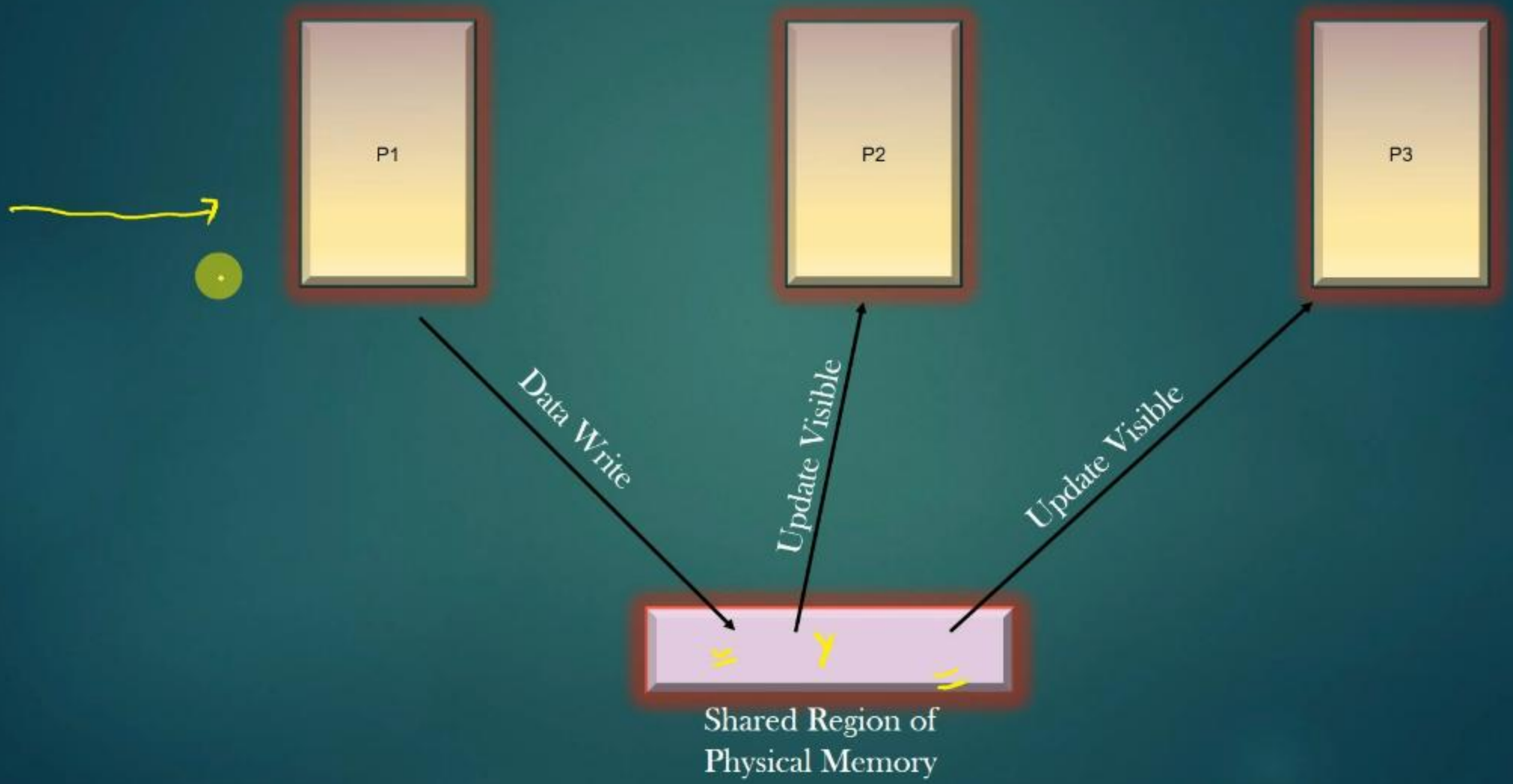
Vir Page No	Phy Page No	Frame no
0	0	3
1	1	5
2	Y	1
3	3	2

Vir Page No	Phy Page No	Frame no
0	0	0
1	1	4
2	2	6
3	Y	1

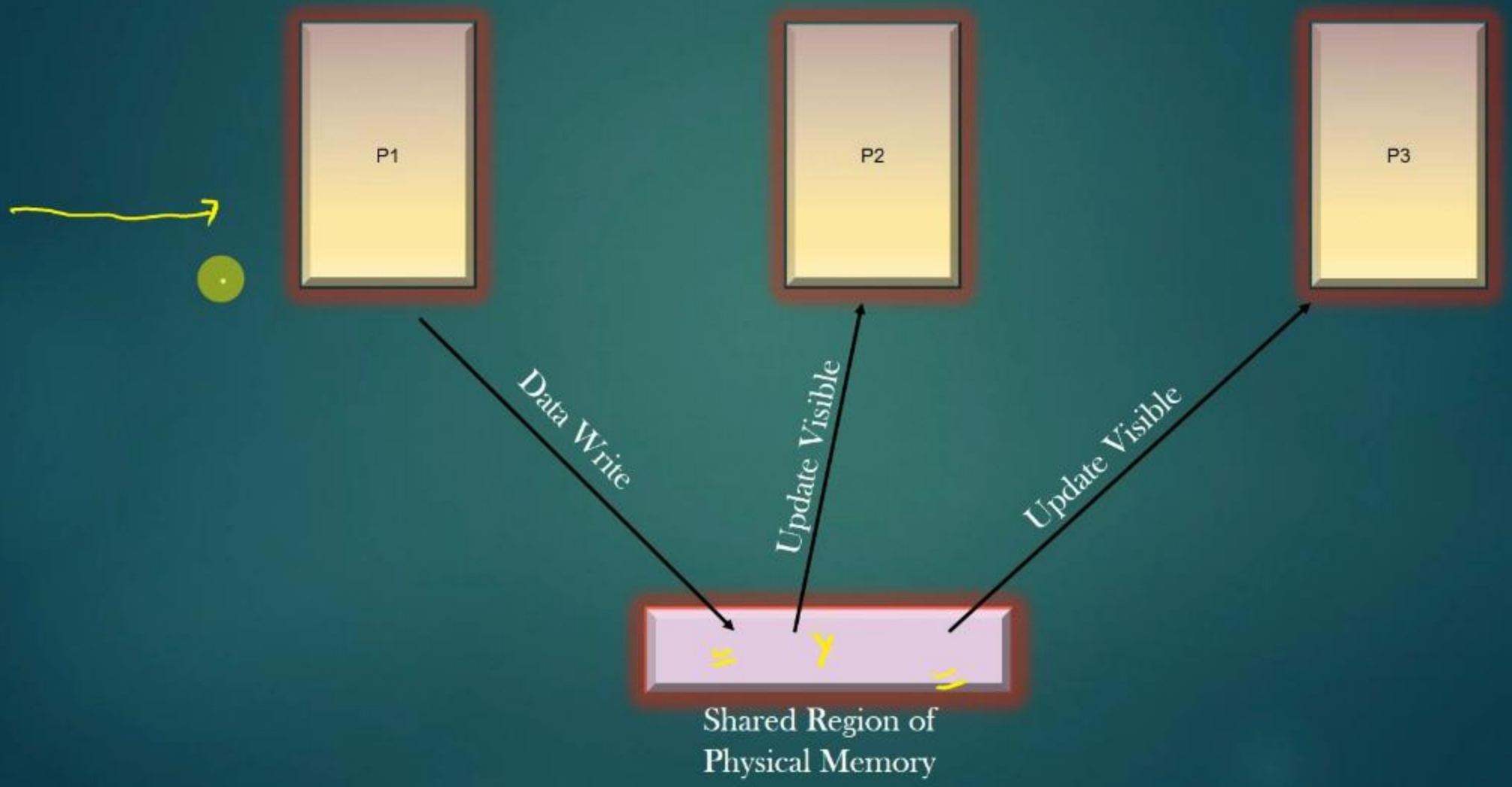
- It means, P1 and P2 are accessing the same Physical memory location addr 5
- It means, whatever P1 write at physical address 5, modification will be available to P2 also
- It means, P1 and P2 are sharing the same physical memory page in frame f1
- If P1 executes
  strncpy(9, "Hell", 4);
  And P2 executes
  printf("%s", str);
  where str points to virtual address 13 then output of printf will be "Hell"

Memory Management in Linux -> Shared Physical Pages

Shared Memory End Goal :



Shared Memory End Goal :



Summary on Shared Pages

- So, if Virtual Page of multiple processes maps to same physical Page, that particular physical page is shared by multiple processes
- Linux/Unix OS officially calls this concepts as *"shared Memory"*
- *Shared Memory* is one of the IPC (Inter process Communication) technique
- Linux/Unix OS provide a system call using which a Multiple process can create a shared memory region and exchange data through it ~~using~~
- We have learnt the concepts behind shared memory, we shall learn later how to write programs using shared memory

Summary on Shared Pages

- So, if Virtual Page of multiple processes maps to same physical Page, that particular physical page is shared by multiple processes
- Linux/Unix OS officially calls this concepts as *"shared Memory"*
- *Shared Memory* is one of the IPC (Inter process Communication) technique
- Linux/Unix OS provide a system call using which a Multiple process can create a shared memory region and exchange data through it ~~using~~
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Problems With Page Tables

Now That we have learnt the core concept of Paging and Page tables, Let us see what are the challenges and problems we come across with Page Tables/Paging

There are basically three problems with Page tables :

1. Page Table Size Matters !!

2. Contiguous Main Memory allocation

3. Page Tables Hollowness for small processes

Soln : Multi Level Paging

Let us discus each one by one , and try to analyze how MLP addresses each of these problems

1. Page Table Size Matters

Scenario 1 :

32 bit System, Main Memory size 4GB, page size 4KB, Page table entry size = 4B

- Size of Page Table = 2 ^ 22 B = 4MB per process.
- Looks Ok

100 P → 4 * 100 = 400 MB

Scenario 2 :

64 bit System, Main Memory size 8GB, page size 4KB, Page table entry size = 4B

- Size of Page Table = 2 ^ 22 B = 2 ^ 34 MB , and this is for each Process , lol !!
- Not feasible !

Thus, Problem of Page table size grows more aggrieved as Virtual address size supported by the system increases

Remember, 32 bit system cannot access RAM beyond 4GB, therefore, today we have 64 bit systems so as to access more RAM And hence enhances the speed and multi-tasking ability of the system

But , with 64 bit system, Having a Page table of this giant size is also not feasible !

Problem 2 - Continguous Memory need

2. Contiguous Main Memory Allocation

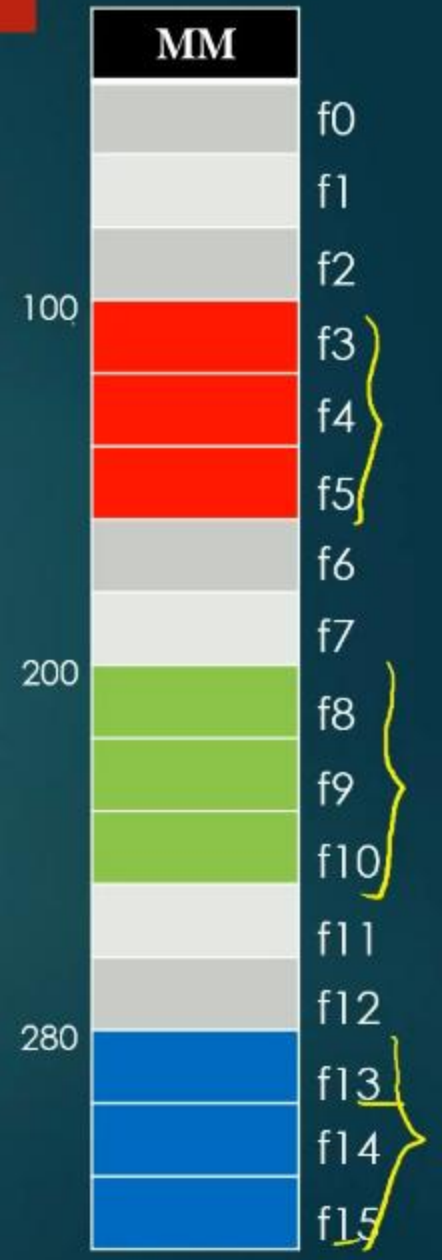
- Page tables, like Physical Pages, are not fragmented and need a contiguous region in Main Memory
  - > For ex : 4MB of Page table would need 4MB of contiguous region in Main Memory

- With the increase in the size of Virtual Address support , Page table size tends to increase drastically
  - Finding the continuous region in Main Memory becomes more and more challenging to load the page Tables of increased size

Memory Management in Linux -> Problems With Page Tables

- Let us suppose, there are three processes in the system whose page tables needs 3 frames each to be stored in main memory
- Process P1
- Process P2
- Process P3
- Page Tables of processes could be loaded in any 3 consecutive frames of MM
- With the increase in size of Page tables, chances to find more available consecutive frames grows more rare

Soln : Multi Level Paging !
Let us break the large page tables into smaller size, load it in non-contiguous Frames in Main-Memory !



3. Page Tables Hollowness for small processes

- 32 bit System, Main Memory size 4GB, page size 4KB, Page table entry size = 4B
  Size of Page Table = 2 ^ 22 B = 4MB per process.

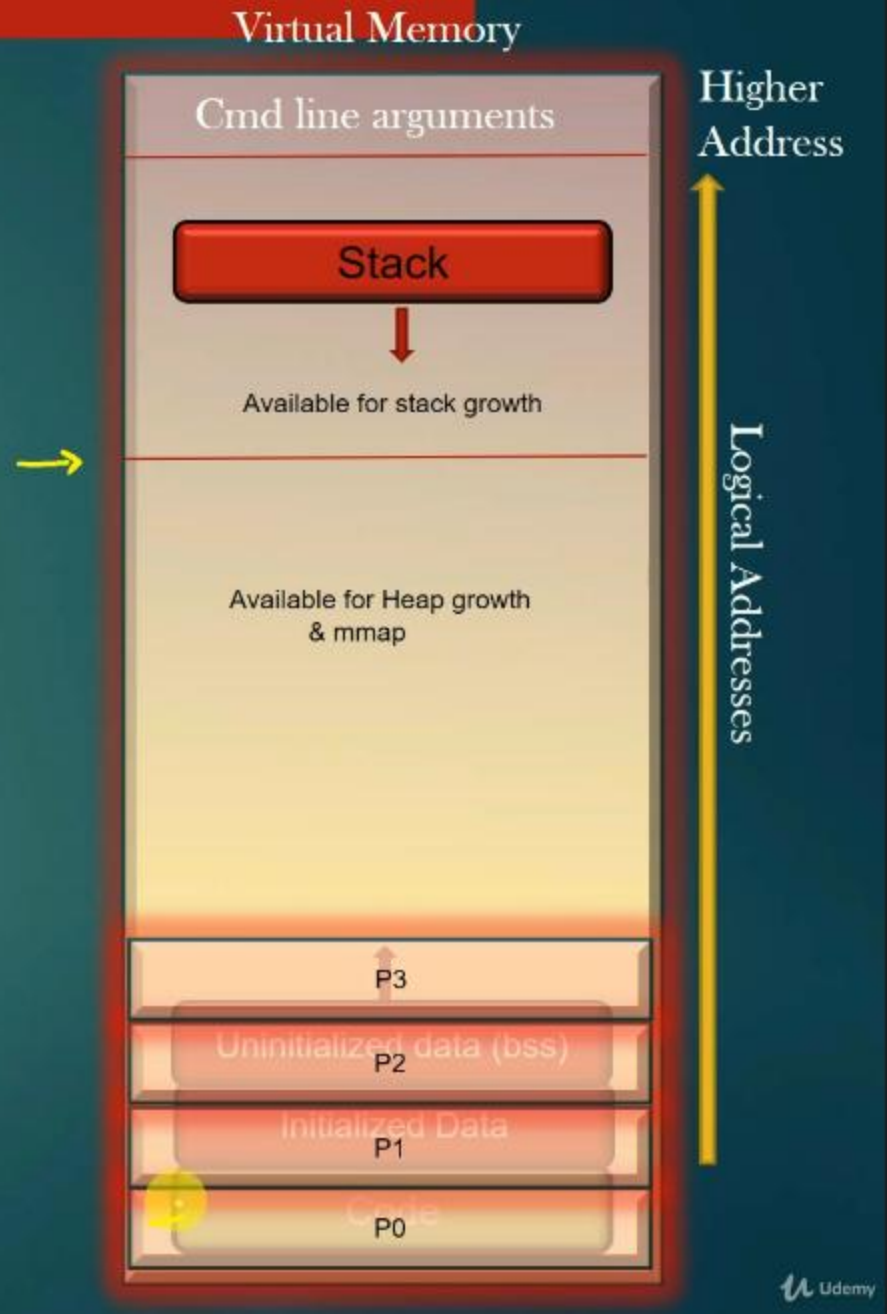
- As soon Process runs, OS creates its Page table of size 4MB and load in Main Memory, irrespective whether process has malloc'd any memory or not

- Not all Processes running on the system are memory intensive, in-fact most of them are not

- Let us visualize how does the Memory Look like when you run your favorite hello-world program which consume almost no memory from heap or stack segment

or

3. Page Tables Hollowness for small processes



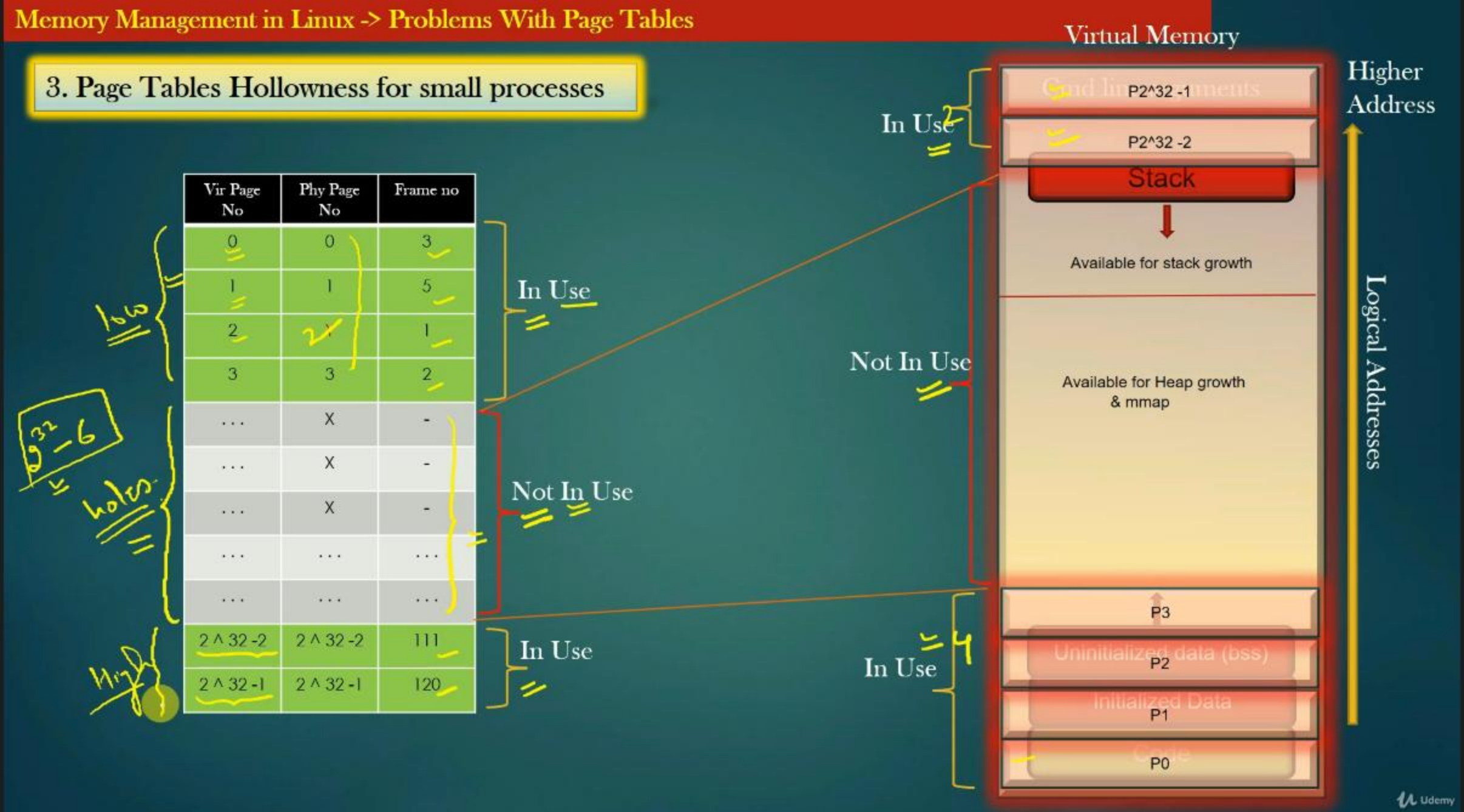
3. Page Tables Hollowness for small processes

Vir Page No	Phy Page No	Frame no
0	0	3
1	1	5
2	X	1
3	3	2
...	X	-
...	X	-
...	X	-
...	...	...
...	...	...
2 ^ 32 -2	2 ^ 32 -2	111
2 ^ 32 -1	2 ^ 32 -1	120

In Use

Not In Use

In Use



3. Page Tables Hollowness for small processes

- Thus, For small Processes, more than 99% of the page table is wasted
- Wastage of Main-Memory
- Soln :
  - Multi Level Paging

Memory Management in Linux -> Multi Level Paging

- We already discussed the problems of Page tables
- Let us see how Multi-Level Paging address the problems of Page tables :
  - Larger size of Page tables
  - Need for contiguous Main Memory
  - Hollow region of Page tables
- The end goal of page tables is : Given a virtual address, locate the physical frame, and then locate the exact physical address In Main Memory

Table of Content

- Multi level Page tables is like a Book with multi-level Indexing of TOC :
  - Section 1
    - Unit 3
      - Chapter 5
        - Topic 6
          - Page-No 5
            - <topic of interest>
- In Multi-Level Paging, each *Section, Unit, Chapter, Topic , Page-No* in-turn are a Page table, and data item of our interest, i.e. *topic of interest* is the main-memory frame-no

Memory Management in Linux -> Multi Level Paging

- The main Idea behind Multi-level paging scheme is to break the large page tables into smaller sizes and fit each individual smaller page tables at dispersed location in main memory
- Since, Main-Memory itself is logically fragmented into frames of size PAGE_SIZE, designers chose to fragmented PAGE_SIZE as the optimal size into which large page table must be fragmented. This would allow smaller fragmented page tables to fully occupy the entire physical frame of main-memory
- Thus, In Multi-Level Paging Scheme, each Page table must be of size PAGE_SIZE
- Multi-Level Paging scheme take the shape of Tree-Like Structure, we shall shortly witness this
- Let us See Multi-Level Paging in Action

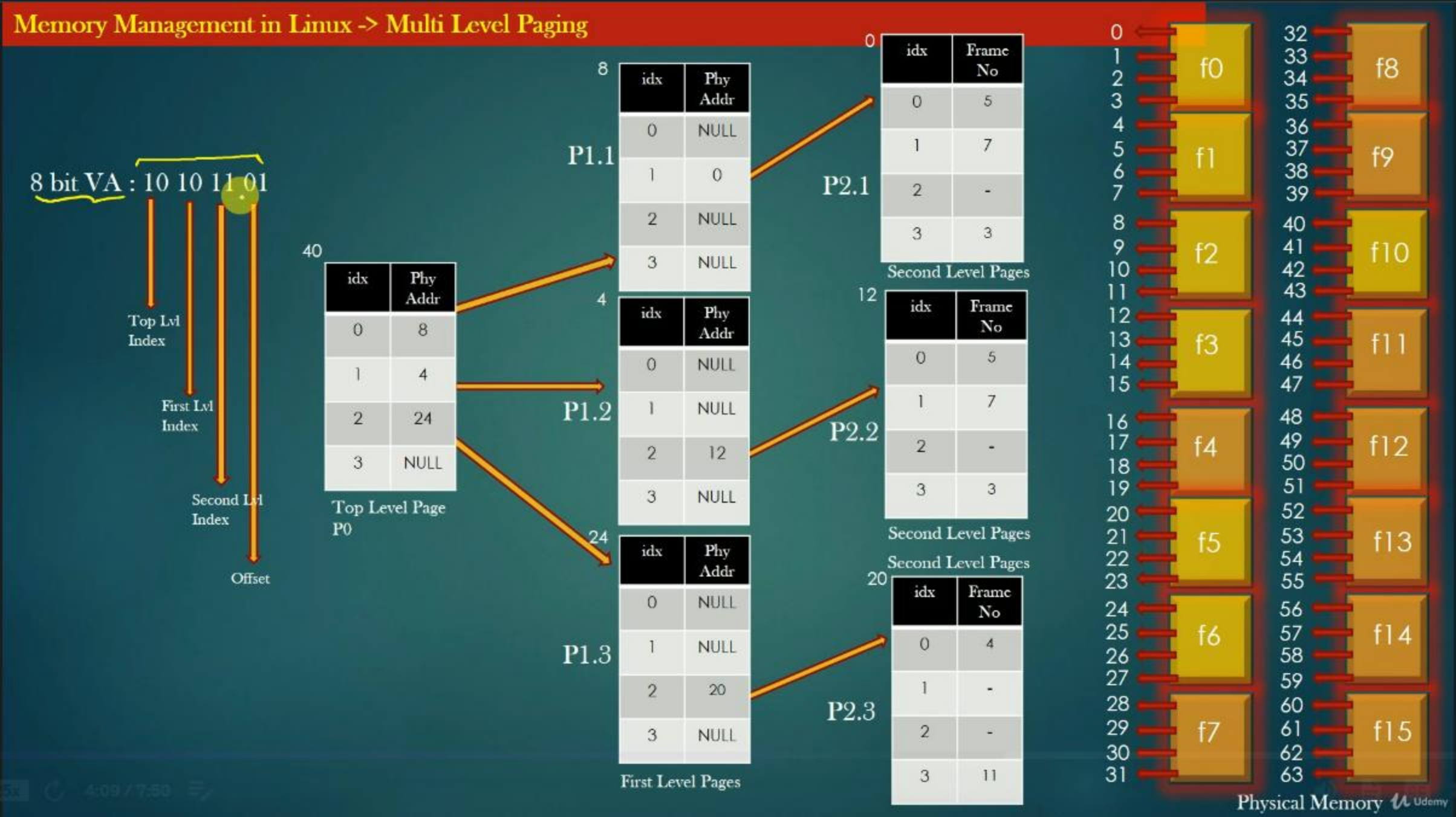
Memory Management in Linux -> Multi Level Paging

- Let us assume the following system configuration :
  - Size of Virtual address generated by CPU : 8bits
  - PAGE_SIZE = 4B
  - Main Memory = 64B = 16 f
  - Each page table entry size = 1B

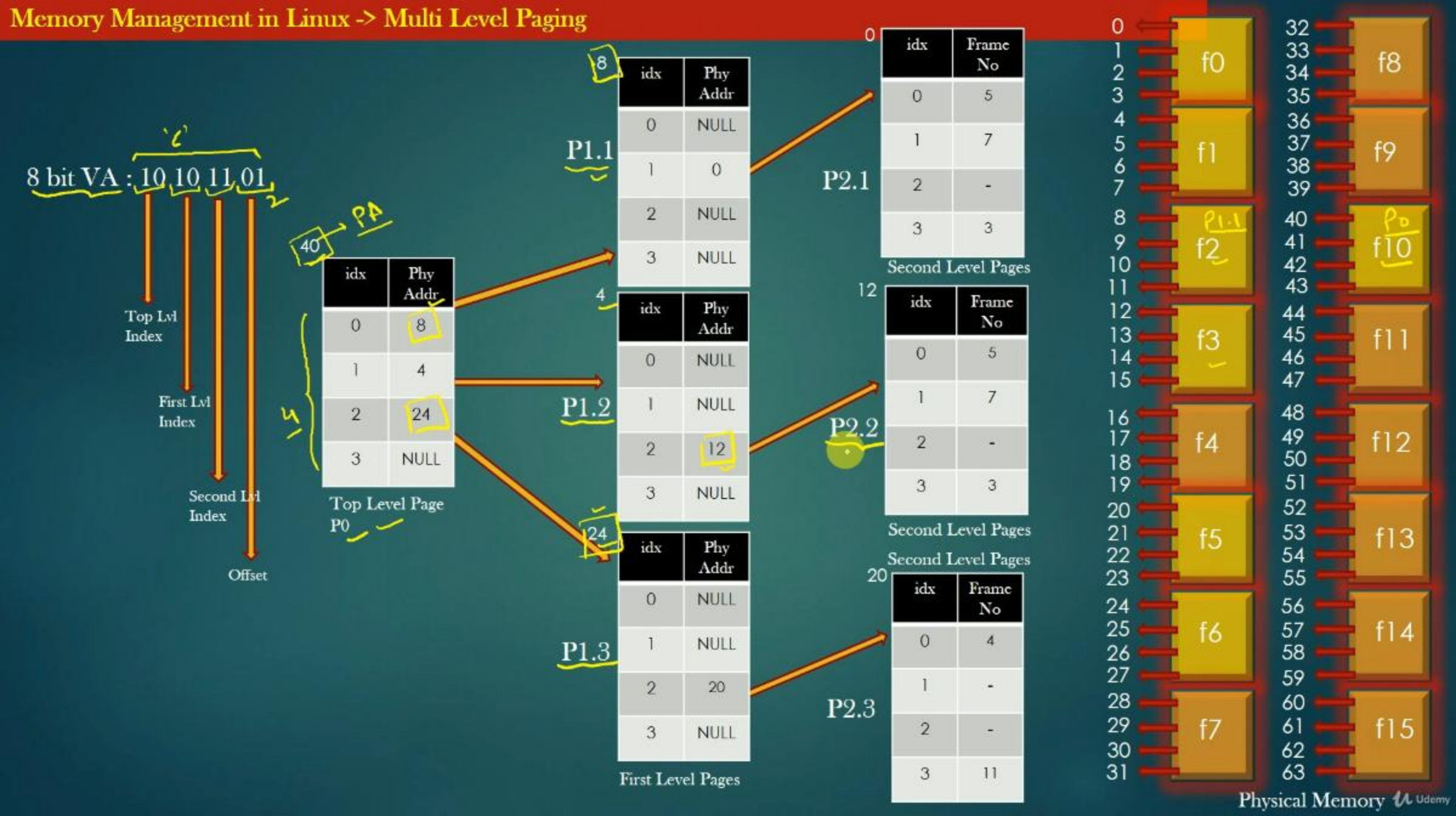
- Calculated Data :
  - Virtual address space size = 2 ^ 8 = 256B
  - Frame size = 4B — 4 PA = 2
  - Virtual Address composition = 6 + 2 bits
  - Page Table Size = PAGE_SIZE = 4B
  - No of entries in Page table = 4
  - No of bits required to index into a single page table = 2
  - Therefore : 6 = 2 (Ist level) + 2 (2nd level) + 2 (3rd level)
  - Physical Address size = 6 bits — 2^6 = 64

Thus, we need to map 8bit VA to 6bits PA
Let us see the above configuration pictorially

Memory Management in Linux -> Multi Level Paging



Memory Management in Linux -> Multi Level Paging

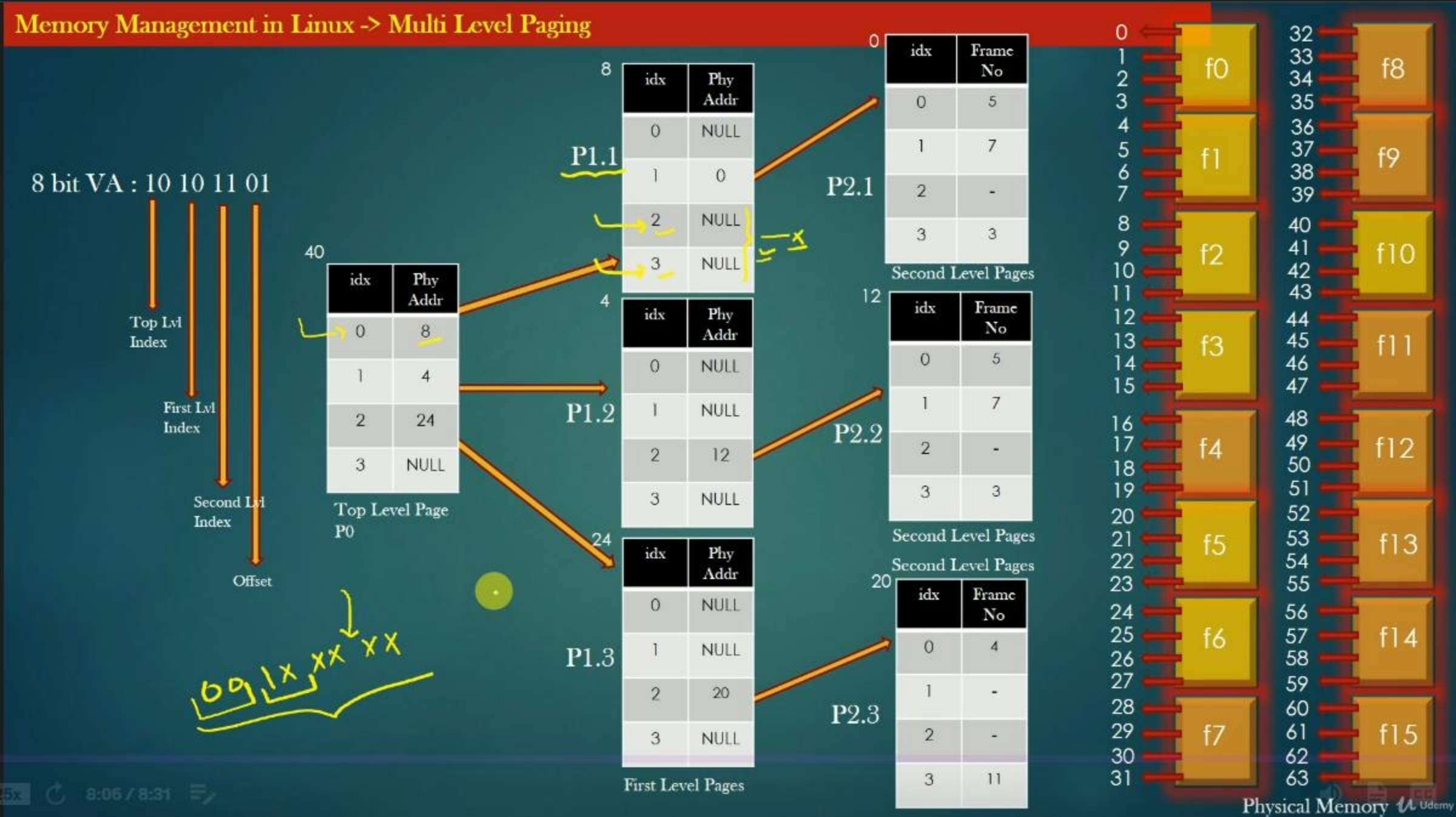


Memory Management in Linux -> Multi Level Paging

Memory Management in Linux -> Multi Level Paging

Single Level Paging Scheme	Multi Level Paging Scheme
Page table Size – PT Entry Size * No Of Virtual Pages of a Process	Page table Size – Frame Size
PT Size – 1B * ((2 ^ 8)/4) – 64B	PT Size – Frame Size – 4B
# of Page tables per process = 1	# of Page tables per process = 2 ^ 6 + 1= 65 Here, 1 is for Top level Page table
Memory references to map VA -> PA – 1	Memory references to map VA -> PA – 3 (Slow !!)
Most of the page table is empty	Create/Delete Page tables on demand Ex : VAS 0100XXXX is not being used by the process, hence no page tables created for VA->PA mapping for this range of VAs, where X = don't care Similarly, 001XXXXX

Memory Management in Linux -> Multi Level Paging



Assignment instructions

60 minutes to complete | 15 student solutions

Follow the instructions as given in the question

Questions for this assignment

1. If there is 2 or more level paging for processes, is it possible to have more than 1 page fault while accessing any single addressable Byte ?
2. Consider a byte addressable virtual memory system with 34-bit addresses where the first 23 bits are used as a page number, and the last 11 bits is the offset. Suppose the system using two-level paging, with first n bits of the address used as an index into the first-level page table. Assume that a typical program uses 16MB memory. An expression in terms of n that gives the number of second level page-tables used by the typical program is given by ?

   1. 2^(34−n−11) x 2^11

   2. 2^24 /2^(34−n−11)

   3. 2^24 / 2^(34−n)

   4. 2^(n−11) x 2^11

4. 2^(n−1) x 2^11

3. Consider a machine with byte addressable memory 32 bits virtual addresses, 32 bits physical addresses and 4 KB page size. If a two-level page table system is used where each page table occupies one page and page table entries of 4 B each.

   Calculate the total main-memory size required to store all page tables for a process ?

4. In multi-level paging, a big page table is divided into smaller pages and for those pages (of main page table) a new page table is created. So what be basically did is broke down the main page table into small pieces (usually so to reduce the size of parts to page size). But, the overall size of the main page table remain same, right? Then what actually is the benefit of multilevel paging?

5. In a 32-bit machine we subdivide the virtual address into 4 segments as follows:

   10 bits | 8 bits | 6 bits | 10 bits

   We use a 3-level page table, such that the first 10-bit are for the first level (top-level)and so on.

   1. What is the page size in such a system?

   2. What is the size of a page table for a process that has 256K of memory starting at address 0?

   3. What is the size of a page table for a process that has a code segment of 48K starting at address 0x1000000, a data segment of 600K starting at address 0x80000000 and a stack segment of 64K starting at address 0xf0000000 and growing upward ?

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   Assume page table entry size = 2B bytes.

6. Do more questions from this link. Search for more and practice it out. There are so many questions all over the internet.

   https://gatepoint.org/questions-paging-operating-system/

Instructor example

Abhishek CSEPracticals

1. If there is 2 or more level paging for processes, is it possible to have more than 1 page fault while accessing any single addressable Byte ?

   No. Because page table access never page faults. All the page tables belonging to all levels are always be in main memory.

   But a single instruction can cause multiple page faults if it involves multiple memory operands, for example, c = a + b, where a and b memory locations are in different pages and both pages are currently swapped out of main memory.

2. Consider a byte addressable virtual memory system with 34-bit addresses where the first 23 bits are used as a page number, and the last 11 bits is the offset. Suppose the system using two-level paging, with first n bits of the address used as an index into the first-level page table. Assume that a typical program uses 16MB memory. An expression in terms of n that gives the number of second level page-tables used by the typical program is given by ?

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Let us split the 34 bit Virtual address as follows : n|23-n|11, where

n bits - are used for indexing into Ist level page tables

23 - n bits - are used for indexing into IInd level page tables

11 - bits are used as an offset into physical frame.

The size of the program covered by one Page table (assuming page table has all entries) of second level = No of entries in IInd level page table * Frame size

= 2 ^ (23 -n) * 2 ^ 11

16MB size of a process = 16MB / ((2 ^ (23 -n)) * 2 ^ 11)

= 2^24 / 2^(34−n)

Hence, (3) is correct.

3. Consider a machine with byte addressable memory 32 bits virtual addresses, 32 bits physical addresses and 4 KB page size. If a two-level page table system is used where each page table occupies one page and page table entries of 4 B each.

Calculate the total main-memory size required to store all page tables for a process ?

Page size = 4KB which is equal to main memory frame size.

No of bits used for offset = no of bits required to represent 4096B

= 12 bits

No of bits remaining = 32 - 12 = 20

These 20 bits are decomposed into two parts for indexing into Ist level (top-level) page table and and 2nd level page tables.

There is always only 1 top level page table.

No of entries in top-level page tables = PAGE_SIZE / Entry size

= 4KB/4B = 1024

Therefore, no of bits required for indexing into first level page table = 10 bits (because 2 ^ 10 = 4096)

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No of bits required for indexing into second level page table = 20 - 10 = 10 bits.

We need to compute : Total size occupied by all page tables = total no of page tables * PAGE_SIZE

Total No of page tables = # top-level page table + # second level page table

= 1 + 2 ^ 10

Therefore, **Total size occupied by all page tables = (1 + 2^10) * 4KB**

= 1025 * 4KB = **4100 KB**

4. In multi-level paging, a big page table is divided into smaller pages and for those pages (of main page table) a new page table is created. So what be basically did is broke down the main page table into small pieces (usually so to reduce the size of parts to page size). But, the overall size of the main page table remain same, right? Then what actually is the benefit of multilevel paging?

   Write your understanding !!

   There are several benefits.

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3. What is the size of a page table for a process that has a code segment of 48K starting at address 0x1000000, a data segment of 600K starting at address 0x80000000 and a stack segment of 64K starting at address 0xf0000000 and growing upward ?

Assume page table entry size = 2B bytes.

1. What is the page size in such a system?

8 bits (last segment) is used as an offset. Hence, page size = 2 ^ 8 = 256B.

2. What is the size of a page table for a process that has 256K of memory starting at address 0 ?

A process is using 256KB of virtual memory.

Therefore, Total no of VM pages = VM size / VM page size = 256KB/256B = 2 ^ 10 =

2. What is the size of a page table for a process that has 256K of memory starting at address 0 ?

A process is using 256KB of virtual memory.

Therefore, Total no of VM pages = VM size / VM page size = 256KB/256B = 2 ^ 10 = 1024.

Therefore, Total no of physical frames being used by the process = 1024.

These 1024 frames cumulatively must be referenced by 3rd level page tables.

No of Page table entries which have a valid frame no = 1024.

Max no of entries per 3rd level page table = 2 ^ 6 (because 6 bits are assigned to 3rd level Page tables)

Therefore, Total no of 3rd level Page table in use = 1024 / 2 ^ 6 = 16

No of entries in 2nd level page table = 2 ^ 8 = 256.

Therefore, just 1 second level page table is enough to hold a reference to 16 3rd level page tables.

And, just 1 first level Page table (top level) is enough to hold a reference to 1 second level page table.

Therefore , total page tables of a process required = 1 + 1 + 16

Given, size of page table entry = 2B.

Therefore total size of all page tables combined = 2 * (1 * 2^10 + 1 * 2^8 + 16 *

Previous Next

And, just 1 first level Page table (top level) is enough to hold a reference to 1 second level page table.

Therefore , total page tables of a process required = 1 + 1 + 16

Given, size of page table entry = 2B.

Therefore total size of all page tables combined = 2 * (1 * 2^10 + 1 * 2^8 + 16 * 2^6) = **4608B.**

3. What is the size of a page table for a process that has a code segment of 48K starting at address 0x1000000, a data segment of 600K starting at address 0x80000000 and a stack segment of 64K starting at address 0xf0000000 and growing upward ?

In this case , A process is using total of 48 + 600 + 64 = 712 KB of virtual memory.

Now, this part is exactly same as IInd one.

6. Do more questions from this link. Search for more and practice it out. There are so many questions all over the internet.

https://gatepoint.org/questions-paging-operating-system/

Do yourself.

Demand Paging

- On a 32 bit system with PAGE_SIZE = 4KB, and Main Memory size = 4GB
- Max no of physical pages for each process = 2 ^ 32 / 2 ^ 12 = 2 ^ 20 (Max)
- No of Main Memory frames = 4GB / 4KB = 2 ^ 32 / 2 ^ 12 = 2 ^ 20
- So, in the worst case, Only one process would eat up entire main memory !
- No Multi-tasking !
- In-fact, OS also needs main-memory to run !

Demand Paging

- *Keep only required physical pages of a process in main-memory, rest swap them out to disk* } Goal
- Benefits :
  - Increase multi-tasking
  - Less main-memory is consumed per process
  - More Users

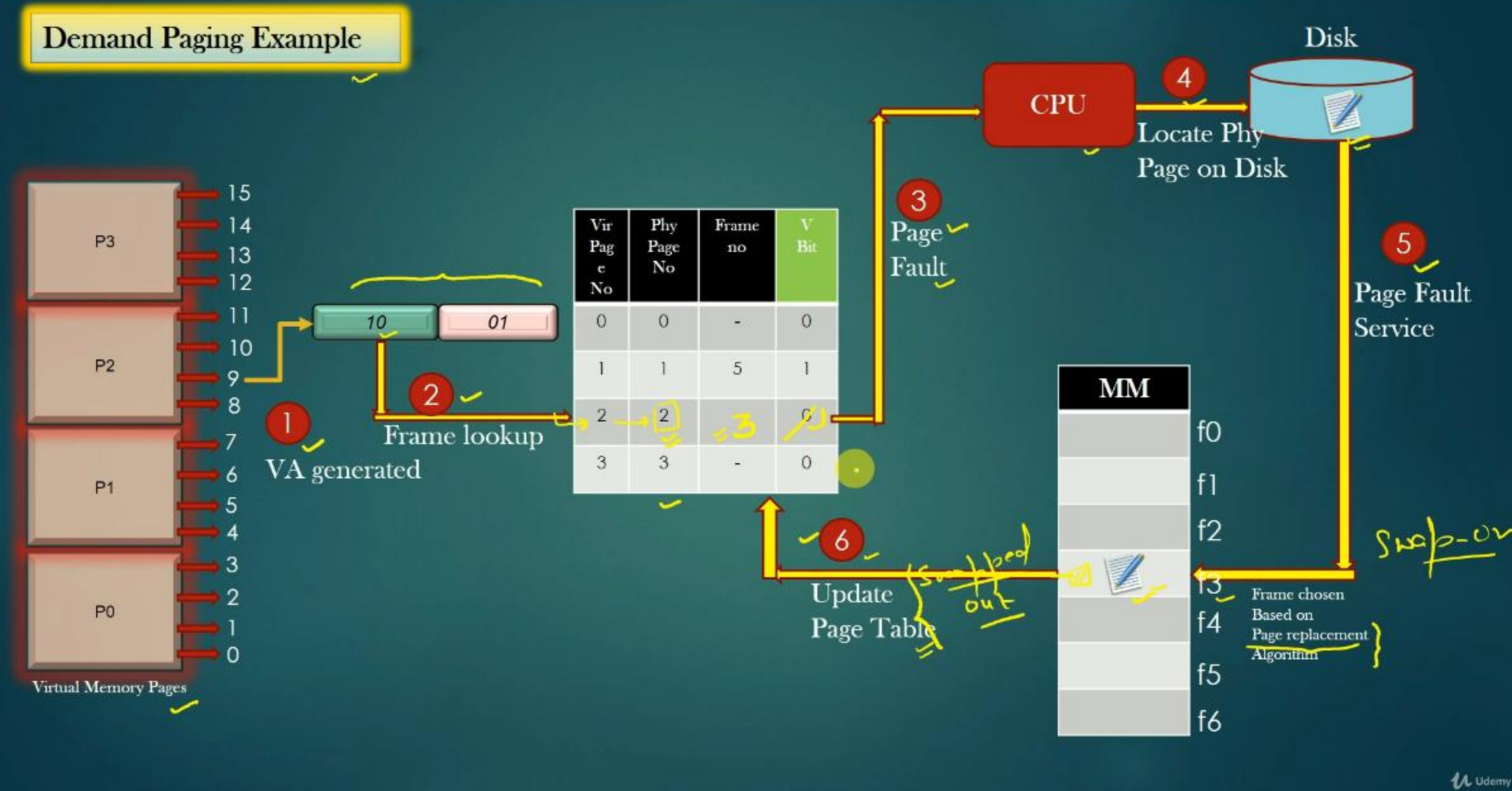
Vir Page No	Phy Page No	Frame no	V/I bit
0	0	3	0
1	1	0	1
2	2	1	1
3	3	2	0

There is a bit In page table which represents whether the Physical page is present in a frame Or has been swapped Out of physical memory to disk
If V bit set – Physical page is present in Frame
If V bit is not set – Physical page is not present in Frame

Page Fault

- When page table dictates that a physical page is not present in a frame, then a special signal is raised to CPU called trap, also called page fault
- Now let us see the Demand Paging scheme combined with the page fault in totality with the help of diagram
- Let us continue with the same configuration of the system:
  - Size of Virtual address space of a process = 16B = 2 ^ 4
  - Virtual address is of 4 bits
  - Page size = 4B
  - Main Memory Size = 32B
  - No of Bits to represent a V page uniquely = 2bits
  - No of Bits to represent an address with in V page uniquely = 2bits

Demand Paging Example



Demand Paging Performance

Page fault increase the memory access time by the CPU

If P is the probability of page fault occurrence, 0 <= p <= 1

if p = 0; no page fault

if p = 1; every memory access attempt is a page fault

EAT (Effective access time) for memory access :

EAT = (1 - p) x memory_access_time +
p x (Page fault overhead +
swap page out +
swap page in +
restart overhead)

Memory Management in Linux for Multi-threaded Processes

- A process can give birth to multiple threads, threads in-turn can generate more threads

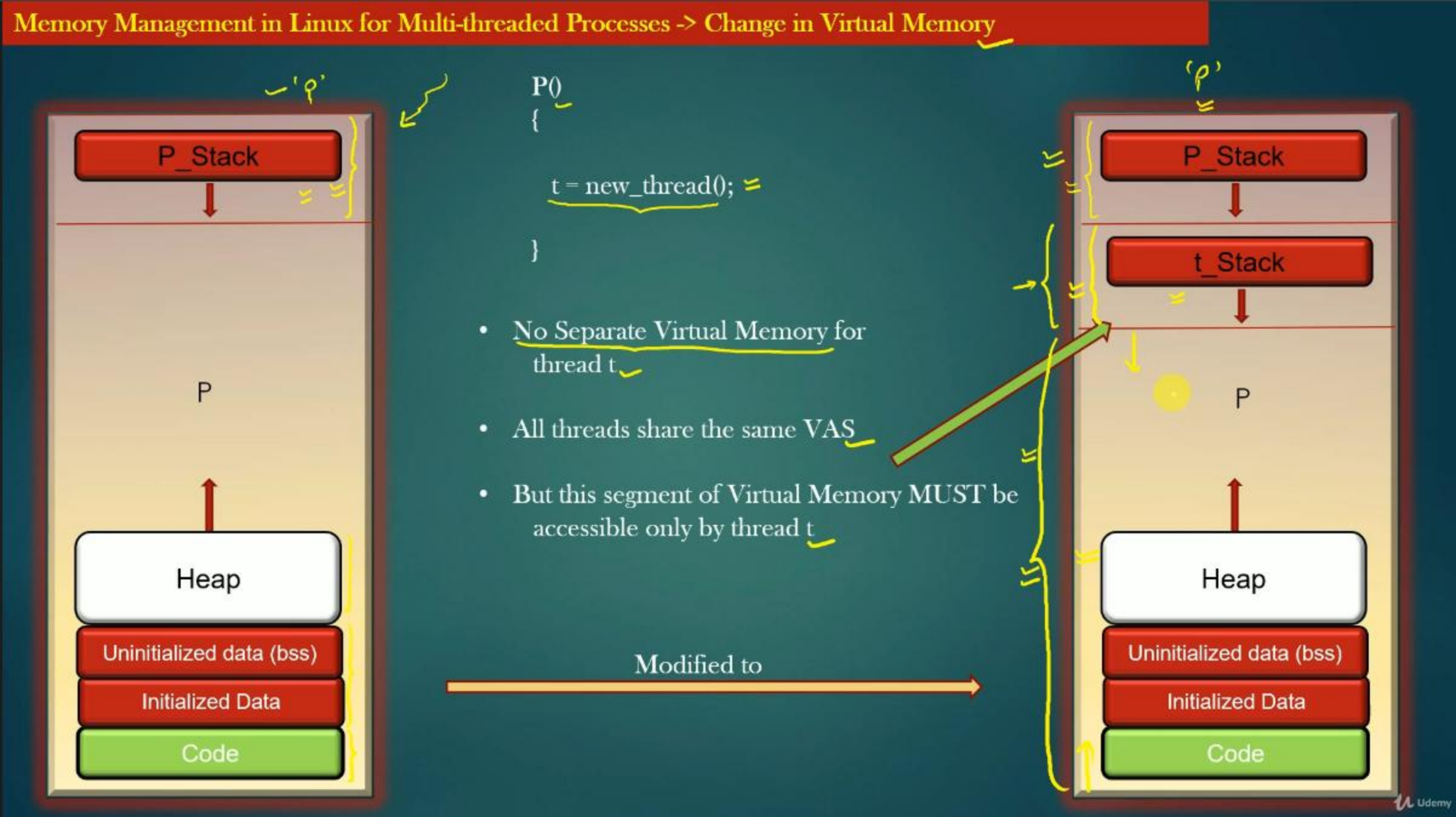
- Threads share almost every-thing amongst each other and with parent process
  - Code Segment
  - Data Segment (initialized and uninitialized)
  - Open File descriptors (sockets, msgQs, etc)
  - Heap Memory
  - BUT NOT STACK MEMORY

- Each thread has its own execution flow, hence, it is required that they have separate stack memory. It is the stack memory which is responsible for program execution (procedure call and returns)

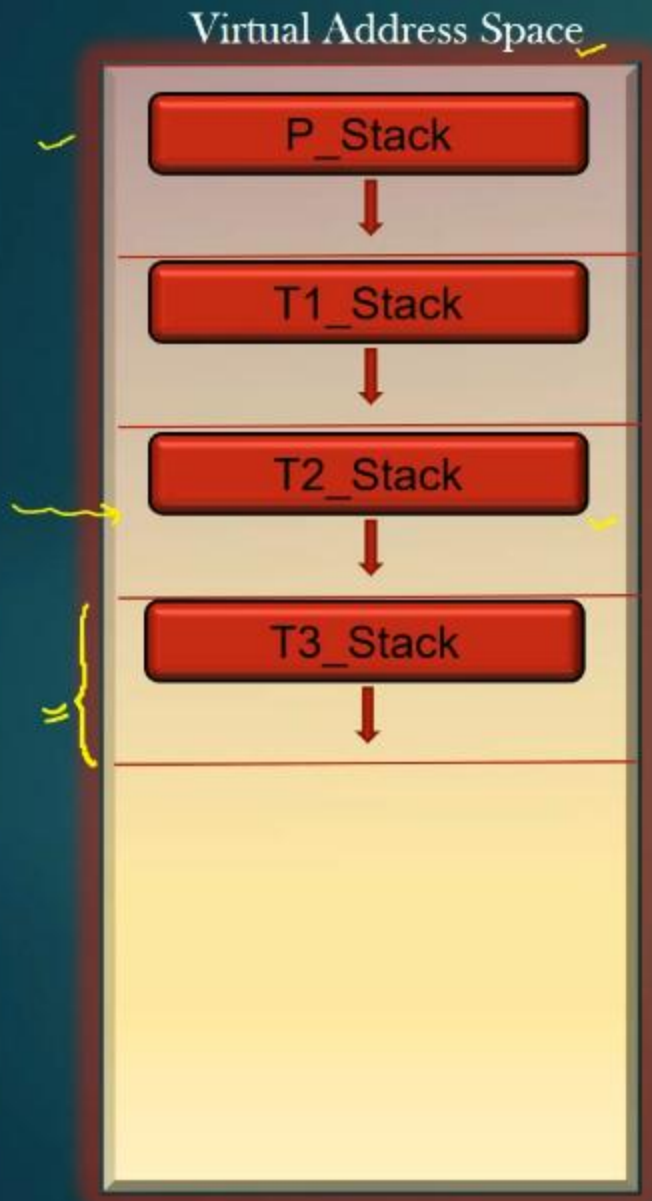
- Because threads share many things among themselves, Kernel/OS don't have to work too hard to create and destroy threads. That is why, they are also called light weight process

- Let us see what changes happen to process VAS and how page tables are setup when it creates a new thread !

Memory Management in Linux for Multi-threaded Processes -> Change in Virtual Memory



Memory Management in Linux for Multi-threaded Processes -> Change in Virtual Memory



Process P stack memory

Thread T1 thread memory

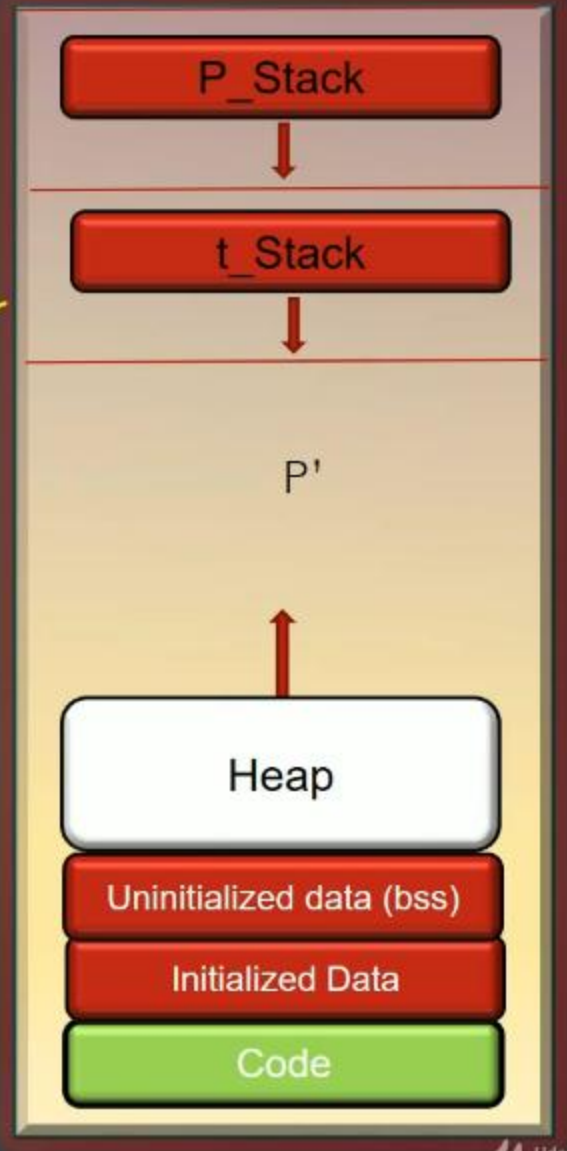
Thread T2 thread memory

Thread T3 thread memory

> Threads have their private stack Memory

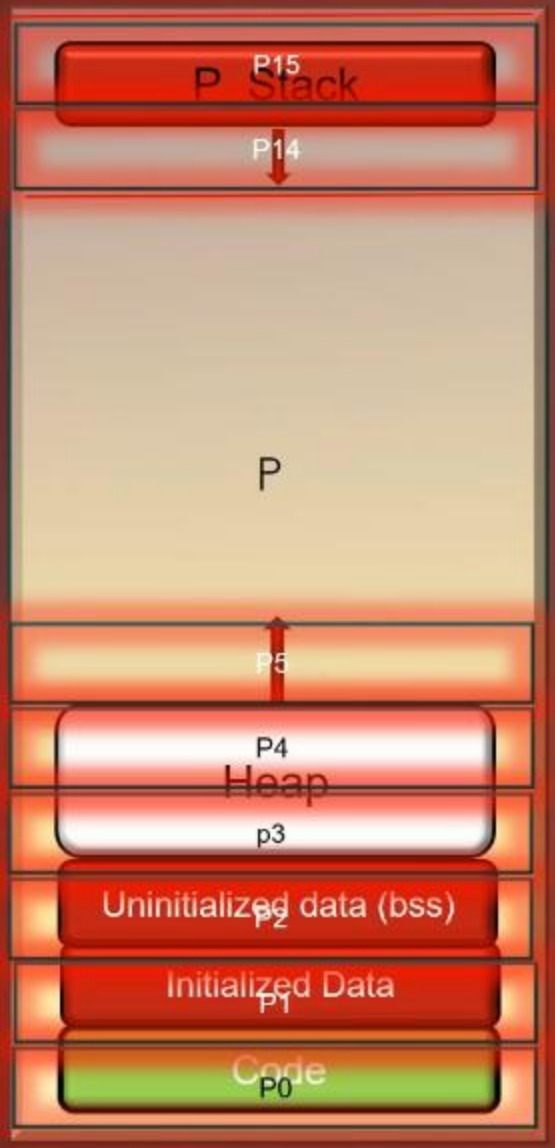
> Rest of the regions of VAS are shared By all threads

Memory Management in Linux for Multi-threaded Processes -> Change in Page Tables



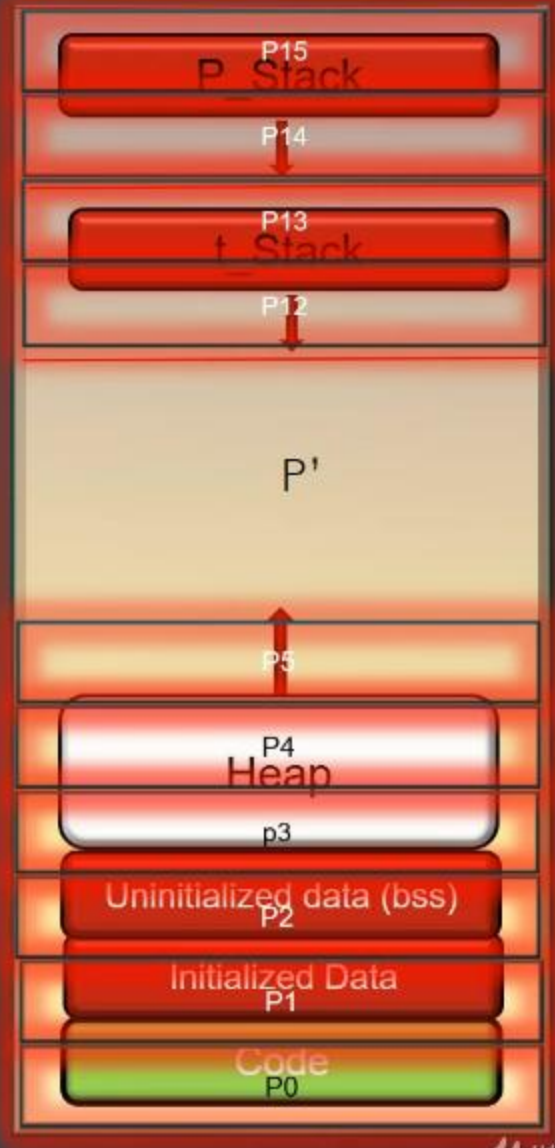
Memory Management in Linux for Multi-threaded Processes -> Change in Page Tables

Memory Management in Linux for Multi-threaded Processes -> Change in Page Tables

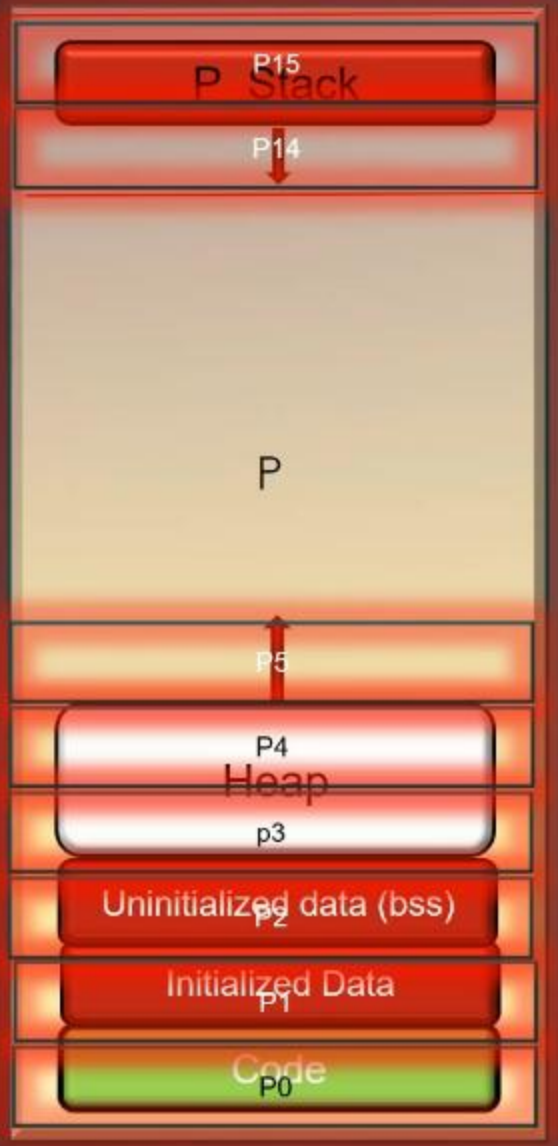


Page Table of P

V. Page No	Phy Page No	Frame no
0	0	X
1	1	X
2	2	X
3	3	X
4	4	X
5	5	X
6	-	-
7	-	-
. . .	. . .	. . .
. . .	. . .	. . .
12	-	-
13	-	-
14	14	X
15	15	X



Memory Management in Linux for Multi-threaded Processes -> Change in Page Tables

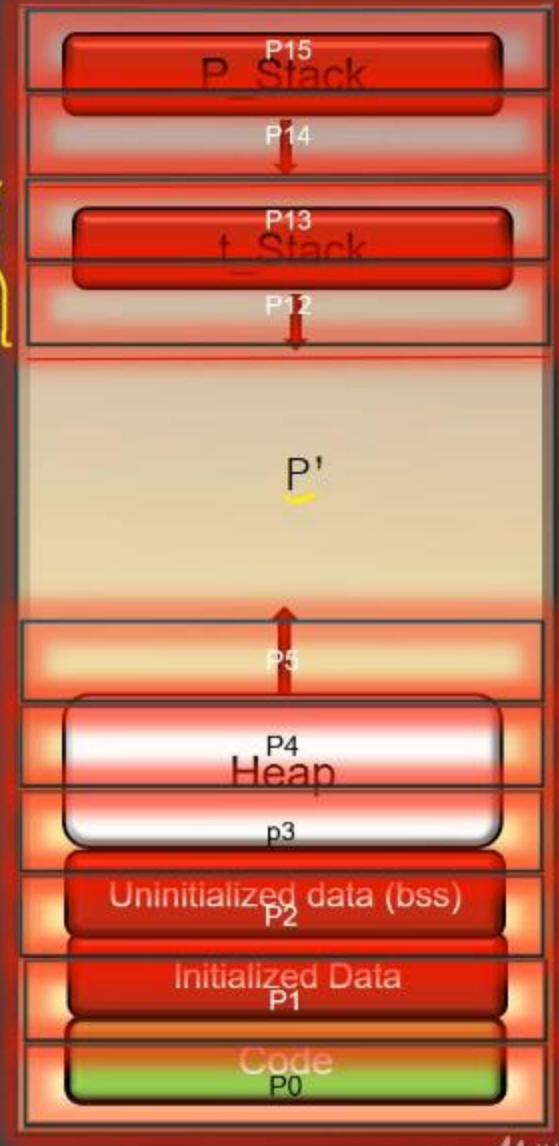


Page Table of P

V. Page No	Phy Page No	Frame no
0	0	X
1	1	X
2	2	X
3	3	X
4	4	X
5	5	X
6	-	-
7	-	-
. . .	. . .	. . .
. . .	. . .	. . .
12	-	-
13	-	-
14	14	X
15	15	X

Page Table of P after thread creation
Thread and P share same page table

V. Page No	Phy Page No	Frame no
0	0	X
1	1	X
2	2	X
3	3	X
4	4	X
5	5	X
6	-	-
7	-	-
. . .	. . .	. . .
. . .	. . .	. . .
12	12	X
13	13	X
14	14	X
15	15	X



Memory Management in Linux for Multi-threaded Processes

- A new thread shares the VAS of the parent process
- A new thread access the same page table , no new page table is created
- A thread T performs write operation at VA V, where V belongs to HEAP|DATA, same changes are visible to any other thread or parent process
- Virtual pages which belongs to new thread's stack memory are created. Corresponding physical pages are created and loaded in main-memory

Physical Page

- New thread shares the same page tables as that of a parent process P, except new VP -> PP mapping is created for new stack memory for a new thread

Virtual Page

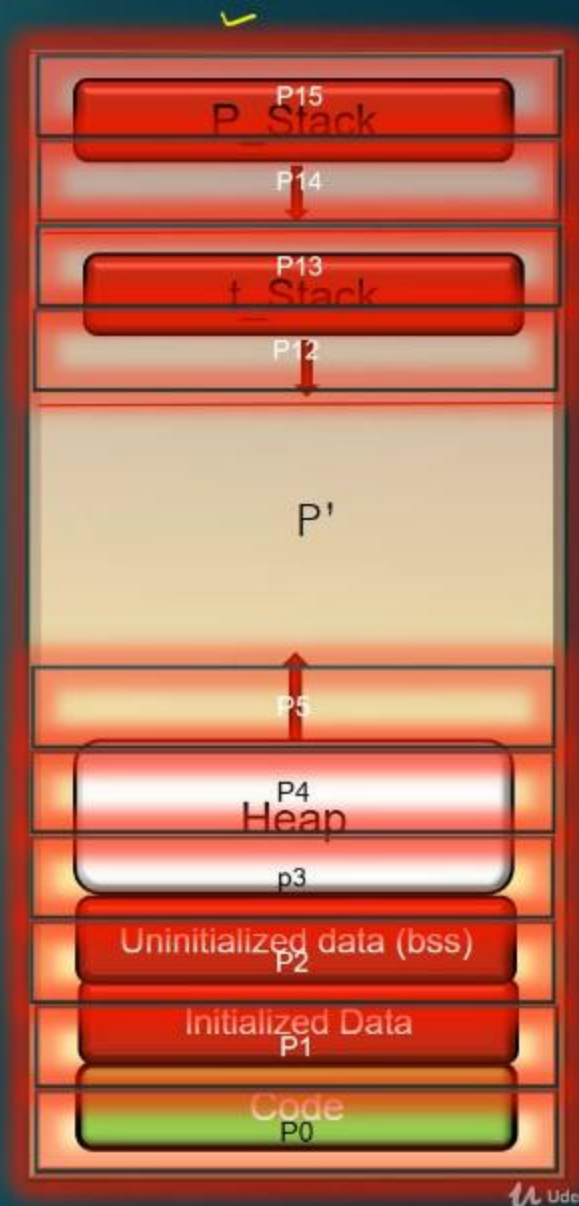
Thread Termination

Memory Management in Linux for Multi-threaded Processes -> Thread Termination

- When thread terminates its execution :
  - Only Virtual pages corresponding to stack memory are freed

Page Table of P after thread creation
Thread and P share same page table

V. Page No	Phy Page No	Frame no
0	0	X
1	1	X
2	2	X
3	3	X
4	4	X
5	5	X
6	-	-
7	-	-
. . .	. . .	. . .
. . .	. . .	. . .
12	12	X
13	13	X
14	14	X
15	15	X



Memory Management in Linux for Multi-threaded Processes -> Thread Termination

- When thread terminates its execution :
  - Only Virtual pages corresponding to stack memory are freed
  - Only Physical pages corresponding to stack memory are freed
  - Page table is updated to mark page table entries corresponding to virtual pages freed above as empty

Page Table of P after thread creation
Thread and P share same page table

V. Page No	Phy Page No	Frame no
0	0	X
1	1	X
2	2	X
3	3	X
4	4	X
5	5	X
6	-	-
7	-	-
. . .	. . .	. . .
. . .	. . .	. . .
. . .	. . .	. . .
. . .	. . .	. . .
14	14	X
15	15	X