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Original Project Contributions and Credits goes to

Faculty of Computer and Information Sciences

Ain Shams University

Second Semester

2024 - 2025

Operating Systems

FOS KERNEL
MEMORY MANAGEMENT PROJECT

Milestone 2

Contents

***LOGISTICS:* refer to power point presentation in the project materials**

Delivery:

1. ***Dropbox-based***
2. ***Milestone 1**: THU **(17 APRIL till 10:00 PM)** ➔ kernel heap functions*
3. ***Milestone 2:** Saturday of Week#14 **(10 MAY till 10:00 PM)** ➔ fault handler, user heap, env free*

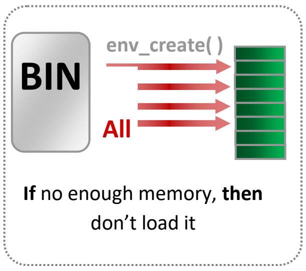
For Milestone1 & 2:

- *It's **FINAL** delivery*
- ***MUST** deliver the required tasks and **ENSURE** they're worked correctly.*
- ***Code**: Make sure you are working on the **FOS_PROJECT_2023_template.zip** provided to you*

Introduction

What's new?!

Previously: all segments of the program binary plus the stack page should be loaded in the main memory. If there's no enough memory, the program will not be loaded. See the following figure:

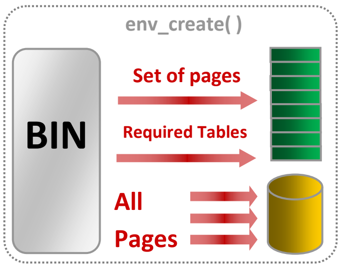


But, wait a minute…

This means that you may not be able to run one of your programs if there's no enough main memory for it!! This is not the case in real OS!! In windows for example, you can run any program you want regardless the size of main memory… do you know WHY?!

YES… it uses part of secondary memory as a virtual memory. So, the loading of the program will be distributed between the main memory and secondary memory.

NOW in the task: when loading a program, only part of it will be loaded in the main memory while the whole program will be loaded on the secondary memory (H.D.D.). See the following figure:



This means that a "Page Fault" can occur during the program run. (i.e. an exception thrown by the processor to indicate that a page is not present in main memory). The kernel should handle it by loading the faulted page back to the main memory from the secondary memory (H.D.D.).

Project Specifications

In the light of the studied memory management system, you are required add new features for your FOS memory manager, these new features are:

1- **Kernel heap:** allow the kernel to dynamically allocate and free memory space at run-time (for user directory, page tables …etc.)
2- Handle **page faults** during execution by applying **MODIFIED CLOCK replacement algorithm.**
3- **User heap:** Allow user program to dynamically allocate and free memory space at run-time (i.e., ***malloc*** and ***free*** functions) by applying **BEST FIT strategy.**

For loading only part of a program in main memory, we use the **working set** concept; the working set is the set of all pages loaded in main memory of the program at run time at any instant of time.

Each **program environment** is modified to hold its working sets information. The working sets are a **FIXED** size array of virtual addresses corresponding to pages that are loaded in main memory.

The virtual space of any loaded user application is as described in lab 6, see **Figure 1**.

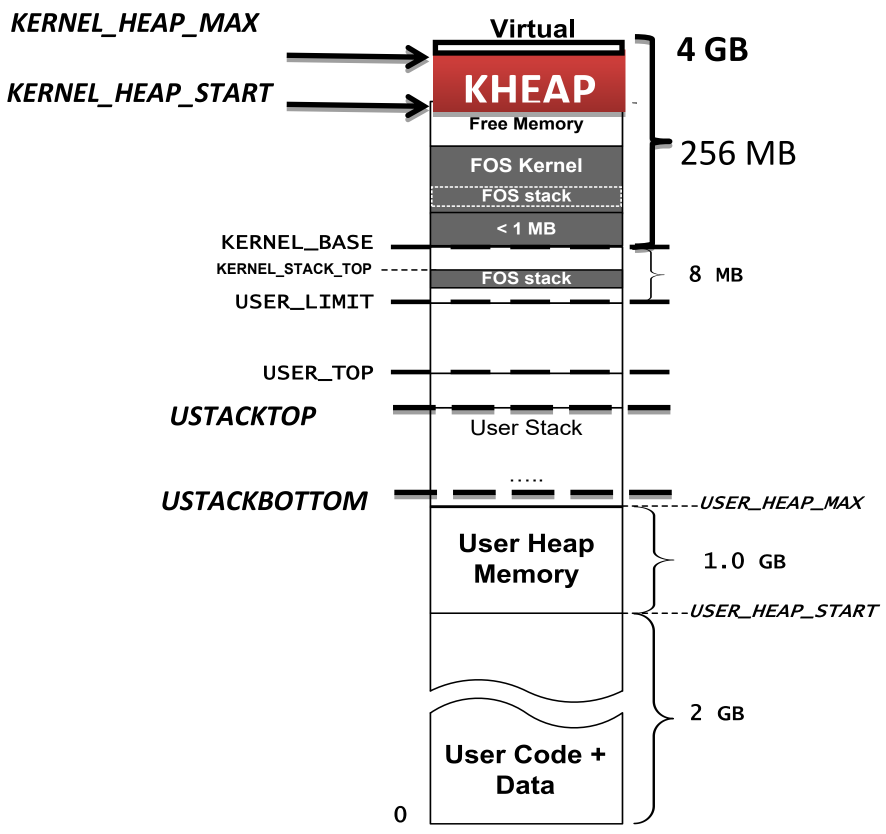


Figure 1: Virtual space layout of single user loaded program

There are three important concepts you need to understand in order to implement the project; these concepts are the **Working Set**, **Page File** and **System Calls.**

New Concepts

FIRST: Working Sets

We have previously defined the working set as the set of all pages loaded in main memory of the program at run time which is implemented as a **FIXED** size array of virtual addresses corresponding to pages that are loaded in main memory.

See Appendix II for description about the working sets data structure and helper functions.

Although it's a fixed size array, but its size is differ from one program to another. It's max size is specified during the env_create() and is set inside the "struct Env", let's say ***N*** pages, when the program needs memory (*either when the program is being loaded or by dynamic allocation during the program run*) FOS must allow maximum ***N*** pages for the program in main memory.

So, when page fault occur during the program execution, the page should be loaded from the secondary memory (the **PAGE FILE** as described later) to the **WORKING SET** of the program. If the working set is complete, then one of the program environment pages from the working set should be replaced with the new page. This is called **LOCAL** replacement since each program should replace one of its own loaded pages. This means that our working sets are **FIXED size with LOCAL replacement facility**.

FOS must maintain the working sets during the run time of the program, when new pages from PAGE FILE are loaded to main memory, the working set must be updated.

*The initialization of the working set by the set of pages during the program loading is already implemented for you in **"env_create()",** and you will be responsible for maintaining the working set during the run time of the program.*

Therefore, the working sets of any loaded program must always contain the correct information about the pages loaded in main memory.

SECOND: Page File

The page file is an area in the secondary memory (H.D.D.) that is used for saving and loading programs pages during runtime. Thus, for each running program, there is a storage space in the page file for ***ALL*** pages needed by the program, this means that user code, data, stack and heap sections are ***ALL*** written in page file. (Remember that not all these pages are in main memory, only the working set). You might wonder why we need to keep all pages of the program in secondary memory during run!!

The reason for this is to have a copy of each page in the page file. So, we don't need to write back each swapped out page to the page file. Only **MODIFIED** pages are written back to the page file.

But wait a minute… Did we have a file manager in FOS?!!

NO…! Don't panic, we wrote some helper functions for you that allow us to deal with the page file. ***See Appendix I for description about these helper functions.***

*The loading of **ALL** program binary segments plus the stack page to the page file is already implemented for you in **"env_create()",** you will need to maintain the page file in the rest of the project.*

THIRD: Page Buffering

An interesting strategy that can improve paging performance is page buffering. A replaced page is not lost but rather is assigned to one of two lists:

1. the free frame list if the page has not been modified, or
2. the modified page list if it has.

See Appendix IV for description about the page buffering structures and helper functions.

Note that the page is not physically moved about in main memory; instead, the PRESENT bit for this page is set to 0 and its "Frame_Info" is placed in the **tail** of either the free or modified list.

Buffering a Page:

To indicate whether or not this page is buffered in the memory, we use the following two values:

1- **BUFFERED bit**: one of the available bits in the page table is used to indicate whether the frame of certain virtual address is buffered or not

2- **isBuffered**: Boolean defined inside the "Frame_Info" structure to indicate whether the corresponding frame is buffered or not.

IMPORTANT NOTE: These two values should be set/reset together inside the code

If we buffer the page, then we should set its BUFFERED bit to 1 inside the page table **together** with the "isBuffered" variable inside its "Frame_Info" structure. (Refer to ***Appendix IV*** for more details)

When a page is to be allocated, the frame at the head of the free frame list is used, destroying the page that was there.

When an unmodified page is to be replaced, it remains in memory and its "Frame_info" is added to the tail of the free frame list. Similarly, when a modified page is to be written out and replaced, its "Frame_info" is added to the tail of the modified page list.

Freeing the Buffer

The pages on the modified list can periodically be written out in batches when their count reaches "*MAX_MODIFIED_LIST_COUNT*" (defined in “inc/environment_definitions.h”) and moved to the tail of free frame list. This page (on the free frame list) is then either reclaimed if it is referenced or lost when its frame is assigned to another page.

There are two important aspects of these maneuvers

1. The page to be replaced remains in memory. Thus, if the process references that page, it is returned to the working set of that process at little cost (by setting its PRESENT bit to 1).

2. Modified pages are written out in clusters rather than one at a time. This significantly reduces the number of I/O operations and therefore the amount of disk access time.

FOURTH: System Calls

- You will need to implement a dynamic allocation function (and a free function) for your user programs to make runtime allocations (and frees).
- The user should call the kernel to allocate/free memory for it.
- But wait a minute…!! remember that the user code is not the kernel (i.e., when a user code is executing, the processor runs **user mode** (less privileged mode), and to execute kernel code the processor needs to go from user mode to **kernel mode**)
- The switch from user mode to kernel mode is done by a **software interrupt** called “**System Call**”.
- All you need to do is to call a function prefixed “**sys_**” from your user code to call the kernel code that does the job, (e.g. from user function malloc(), call ***sys_allocateMem()*** which then will call kernel function **allocateMem()** to allocate memory for the user) as shown in figure:

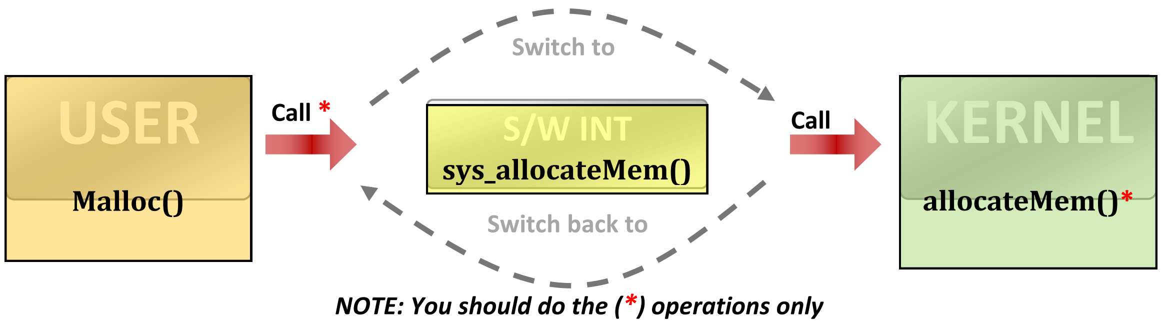
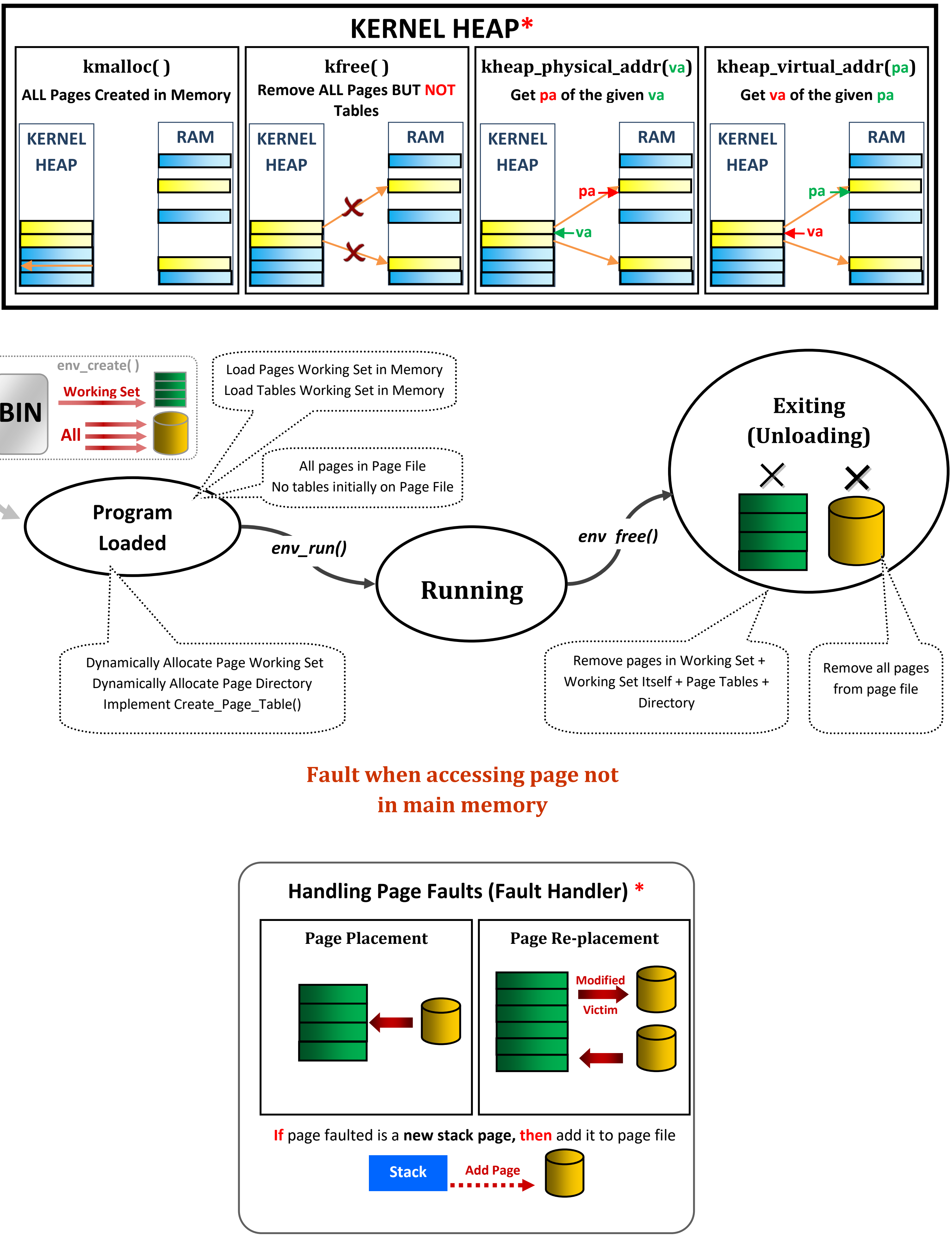


Figure 2: Sequence diagram of dynamic allocation using malloc()

Overall View

The following figure shows an overall view of all project components together with the interaction between them. The components marked with **(*)** should be written by you, the unmarked components are already implemented.



KERNEL HEAP*
kmalloc( )
ALL Pages Created in Memory
KERNEL HEAP
RAM
kfree( )
Remove ALL Pages BUT NOT Tables
kheap_physical_addr(va)
Get pa of the given va
pa
va
kheap_virtual_addr(pa)
Get va of the given pa
env_create( )
BIN
Working Set
All
Load Pages Working Set in Memory
Load Tables Working Set in Memory
All pages in Page File
No tables initially on Page File
Program Loaded
env_run()
Running
env free()
Exiting (Unloading)
Dynamically Allocate Page Working Set
Dynamically Allocate Page Directory
Implement Create_Page_Table()
Remove pages in Working Set + Working Set Itself + Page Tables + Directory
Remove all pages from page file
Fault when accessing page not in main memory
Handling Page Faults (Fault Handler) *
Page Placement
Page Re-placement
Modified
Victim
If page faulted is a new stack page, then add it to page file
Stack
Add Page

Figure 3: Interaction among components in project

Details

FIRST: Fault Handler

IMPORTANT: Refer to the ppt inside the project materials for more details and examples

In function fault_handler() , " kern/trap.c"

- **Fault:** is an exception thrown by the processor (MMU) to indicate that:
  - **A page** can't be accessed due to either it's not present in the main memory OR
  - **A page table** is not exist in the main memory (i.e. new table). (see the following figure)

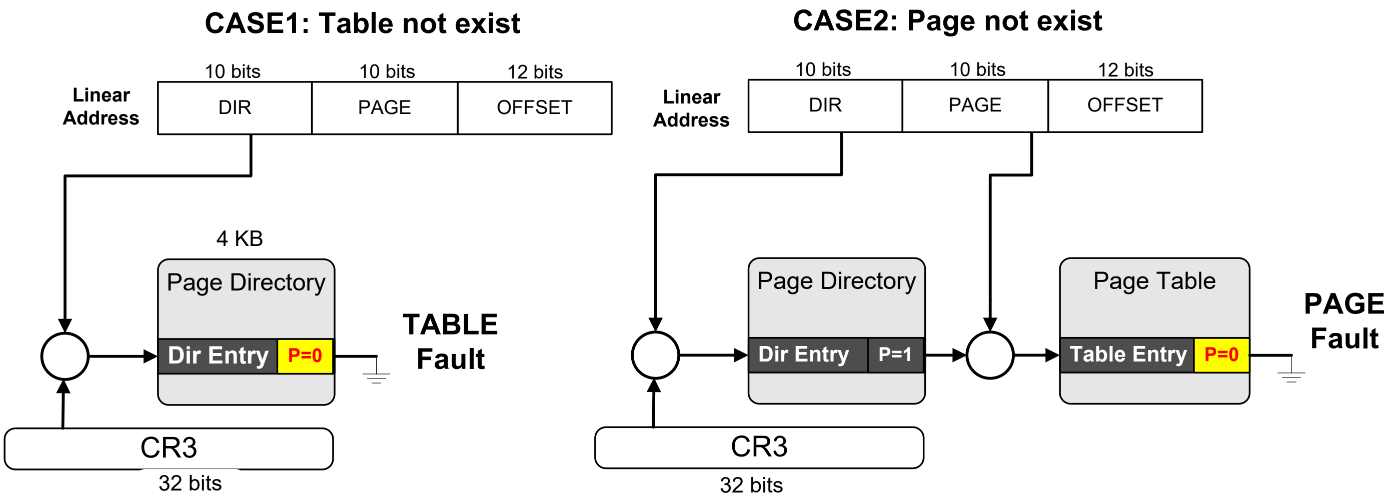


Figure 4: Fault types (table fault and page fault)

- The first case (Table Fault) is **already handled** for you by allocating a new page table if it not exists
- You **should handle** the page fault in FOS kernel by:
  a. Allocate a new page for this faulted page in the main memory
  b. Loading the faulted page back to main memory from page file if the page exists. Otherwise (i.e. new page), add it to the page file (for new stack pages only).
- You can handle the page fault in **function "page_fault_handler()"** in "trap.c".
- In **replacement** part, it's required to apply **MODIFIED CLOCK** algorithm.
  You need to check which algorithm is currently selected using the given functions, as follows

```
//Page Replacement
If isPageReplacmentAlgorithmModifiedCLOCK()
      Apply MODIFIED CLOCK algorithm to choose the victim
```

- **PAGE FAULT HANDLER** should work as follows:

1. if the size of the page working set < ***PAGE_WS_MAX_SIZE*** then do

   Placement:

   1. check if required page is buffered (***see Appendix III***), if true, do the following:
      1. Just reclaim the page by setting PRESENT bit to 1, and BUFFERED bit to 0, and set its ***frame_info->isBuffered*** to **0**. (***See Appendix III*** and ***Appendix IV***)
      2. Remove its Frame_Info from: "**modified_frame_list**" if the page was modified (MODIFIED bit = 1), or from "**free_frame_list**" if the page was not modified (MODIFIED bit = 0) (*see* ***Appendix III*** and ***Appendix IV***)
   - else
      1. allocate and map a frame for the faulted page.
      2. read the faulted page from page file to memory.
      3. If the page **does not exist** on page file, then **CHECK if it is a stack page**. If so this means that it is a new stack page, add a **new empty page** with this faulted address to page file *(refer to* ***Appendix I*** and ***Appendix II****)*, else panic with invalid virtual address.
   2. update the page working set.

- else, do

   Replacement:

   3. implement the **modified clock** algorithm to find victim virtual address from page working set to replace *(refer to* ***Appendix V*** *to see how the modified clock works)*

   4. for the victim page:

      - Prepare its **Frame_Info** by
         i. flagging it as buffered,
         ii. setting the environment inside it,
         iii. setting the victim virtual address inside it.
      - Set the BUFFERED bit to 1 in the victim page table.
      - Set the PRESENT bit to 0 in the victim page table.

   5. If the victim page was not modified, then:

      - Add the victim frame to "**free_frame_list**" at the tail (***see Appendix IV***)

      Else

      - Add the victim frame to "**modified_frame_list**" at the tail (***see Appendix IV***)
        Then, check the count of modified pages in "**modified_frame_list**" (***see Appendix IV***), if it reaches ***its maximum capacity (check this by calling getModifiedBufferLength())***, do the following:

        For each modified frames in this list (either belong to this environment or other environments), do (***see Appendix IV***)

        . update its page in page file (***see Appendix I***),
        a. set the MODIFIED bit of its page in its page table to 0 (***see Appendix III***)
        b. add it to the tail of the "**free_frame_list**".

   2. Apply **Placement** steps that are described before.

- Refer to helper functions to deal with flags of Page Table entries (***Appendix III***)
- Refer to the basic and helper memory manager functions (***Appendix VII***)

SECOND: User Heap ➔Dynamic Allocation and Free

IMPORTANT: Refer to the ppt inside the project materials for more details and examples

- You should implement function **"`malloc()`"** (allocates user memory) and **"`free()`"** (frees user memory) functions in the USER side **"lib/uheap.c"**
- You should use THIRD: Page Buffering
- You should use FOURTH: System Calls to switch from user to kernel.
- Your kernel code will be in "**`allocateMem()`**" and "**`freeMem()`**" functions in "**memory_manager.c**"

Dynamic Allocation

User Side (malloc)

1. Implement assigned strategy (**NEXTFIT, FIRSTFIT, BESTFIT, WORSTFIT)** to search the heap for suitable space to the required allocation size (space should be on **4 KB BOUNDARY**)
2. if no suitable space found, return NULL, else,
3. Call `sys_allocateMem` to invoke the Kernel for allocation.
4. Return pointer containing the virtual address of allocated space.

Kernel Side (allocateMem)

In allocateMem(), all pages you allocate will **not be added** to the working set (not exist in main memory). Instead, they **should be added** to the page file, so that when this page is accessed, a page fault will load it to memory.

Dynamic De-allocation

User Side (free)

1. Frees the allocation of the given virtual address in the user Heap
2. Need to call "`sys_freeMem`" inside.

Kernel Side (_freeMem_with_buffering)

1. **For each BUFFERED** page in the given range inside the **given environment**
   a) If the buffered page is MODIFIED, then
      - Get its "**`Frame_info`**" pointer (see ***Appendix VII***)
      - Remove it from the "**`modified_frame_list`**"
      - Flag it as a free frame (setting **`isBuffered`** to 0, **`environment`** to NULL)
      - Add it to the head of "**`free_frame_list`**" (by calling **`free_frame()`**)

   b) Else
      - Just flag its "**`Frame_Info`**" as free frame (setting **`isBuffered`** to 0, **`environment`** to NULL)
      - Remove frame from the end of the "**`free_frame_list`**".
      - Bring it to the head of the "**`free_frame_list`**".

   c) Set its entry in the page table to **NULL** to indicate that this page is no longer exists (see ***Appendix III***).

2. **Remove ONLY working set pages** that are located in the given user virtual address range. **REMEMBER** to
    - Clear the entry inside the page table to indicate that the page is no longer exists (see Appendix III).
    - Update the working sets after removing.
3. **Remove ONLY the EMPTY page tables** in the given range (i.e., no pages are mapped in it)
4. **Remove ALL pages** in the given range **from the page file** (see *Appendix I*).

THIRD: Free the entire environment (exit)

- **For each BUFFERED page in the User Space**
    - If the buffered page is MODIFIED then
        - Get its "Frame_info" pointer (see ***Appendix X***)
        - Remove it from the "**modified_frame_list**"
        - Flag it as a free frame (setting **isBuffered** to 0, **environment** to NULL)
        - Add it to the head of "**free_frame_list**" (by calling **free_frame()**)
    - Else
        - Just flag its "Frame_Info" as free frame (setting **isBuffered** to 0, **environ.** to NULL)
        - Bring it to the head of the "**free_frame_list**"
- ***Then, you should free:***
    1. All pages in the page working set.
    2. The working set itself.
    3. All page tables in the entire user virtual memory.
    4. The directory table.
    5. All pages from page file, and the env itself and this code ***is already*** written for you ☺

Enjoy developing your own OS

☺ GOOD LUCK ☺

APPENDICES

Testing

A- How to test your project

TESTS are available inside the Project Folder

APPENDIX I: Page File Helper Functions

There are some functions that help you work with the page file. They are declared and defined in "kern/file_manager.h" and "kern/file_manager.c" respectively. Following is brief description about those functions:

Pages Functions

Add a new environment page to the page file

Function declaration:

```
int pf_add_empty_env_page( struct Env* ptr_env, uint32 virtual_address, uint8
                                             initializeByZero);
```

Description:

Add a new environment page with the given virtual address to the page file and initialize it by zeros.

Parameters:

`ptr_env`: pointer to the environment that you want to add the page for it.

`virtual_address`: the virtual address of the page to be added.

`initializeByZero`: indicate whether you want to initialize the new page by ZEROs or not.

Return value:

= 0: the page is added successfully to the page file.

= E_NO_PAGE_FILE_SPACE: the page file is full, can't add any more pages to it.

Example:

In dynamic allocation: let for example we want to dynamically allocate 1 page at the beginning of the heap (i.e. at address USER_HEAP_START) without initializing it, so we need to add this page to the page file as follows:

```
int ret = pf_add_empty_env_page(ptr_env, USER_HEAP_START, 0);

if (ret == E_NO_PAGE_FILE_SPACE)

      panic("ERROR: No enough virtual space on the page file");
```

Read an environment page from the page file to the main memory

Function declaration:

```
int pf_read_env_page(struct Env* ptr_env, void *virtual_address);
```

Description:

Read an existing environment page at the given virtual address from the page file.

Parameters:

ptr_env: pointer to the environment that you want to read its page from the page file.

virtual_address: the virtual address of the page to be read.

Return value:

= 0: the page is read successfully to the given virtual address of the given environment.

= E_PAGE_NOT_EXIST_IN_PF: the page doesn't exist on the page file (i.e. no one added it before to the page file).

Example:

In placement steps: let for example there is a page fault occur at certain virtual address, then, we want to read it from the page file and place it in the main memory at the faulted virtual address as follows:

```
int ret = pf_read_env_page(ptr_env, fault_va);

if (ret == E_PAGE_NOT_EXIST_IN_PF)

{     ...    }
```

Update certain environment page in the page file by contents from the main memory

Function declaration:

```
int pf_update_env_page(struct Env* ptr_env, void *virtual_address, struct
Frame_Info* modified_page_frame_info));
```

Description:

Updates an existing page in the page file by the given frame in memory

Parameters:

ptr_env: pointer to the environment that you want to update its page on the page file.

virtual_address: the virtual address of the page to be updated.

modified_page_frame_info: the Frame_Info* related to this page.

Return value:

= 0: the page is updated successfully on the page file.

= E_PAGE_NOT_EXIST_IN_PF: the page to be updated doesn't exist on the page file (i.e. no one add it before to the page file).

Example:

```
struct Frame_Info *ptr_frame_info = get_frame_info(…);

int ret = pf_update_env_page(environment, virtual_address, ptr_frame_info);
```

Remove an existing environment page from the page file

Function declaration:

```
void pf_remove_env_page(struct Env* ptr_env, uint32 virtual_address);
```

Description:

Remove an existing environment page at the given virtual address from the page file.

Parameters:

ptr_env: pointer to the environment that you want to remove its page (or table) on the page file.

virtual_address: the virtual address of the page to be removed.

Example:

Let's assume for example we want to free 1 page at the beginning of the heap (i.e. at address USER_HEAP_START), so we need to remove this page from the page file as follows:

```
pf_remove_env_page(ptr_env, USER_HEAP_START);
```

APPENDIX II: Working Set Structure & Helper Functions

Working Set Structure

As stated before, each environment has a working set that is dynamically allocated at the env_create() with a given size and holds info about the currently loaded pages in memory.

It holds two important values about each page:

1. User virtual address of the page
2. Time stamp since the page is last referenced by the program (to be used in **LRU** replacement algorithm)

The working set is defined as a pointer inside the environment structure "`struct Env`" located in "inc/environment_definitions.h". Its size is set in "**`page_WS_max_size`**" during the env_create(). "**`page_WS_last_index`**" will point to the next location in the WS after the last set one.

```
struct WorkingSetElement {
	uint32 virtual_address;  // the virtual address of the page
	uint8 empty; // if empty = 0, the entry is valid, if empty=1, entry is empty
	uint32 time_stamp ; // time stamp since this page is last referenced
};

struct Env {
	.
	.
	.
	//page working set management
	struct WorkingSetElement* ptr_pageWorkingSet;
	unsigned int page_WS_max_size;
	// used for modified clock algorithm, the next item (page) pointer
	uint32 page_WS_last_index;
};
```

Figure 5: Definitions of the working set & its index inside `struct Env`

Working Set Functions

These functions are declared and defined in "kern/memory_manager.h" and "kern/ memory_manager.c" respectively. Following are brief description about those functions:

Get Working Set Current Size

Function declaration:

`inline uint32 env_page_ws_get_size(struct Env *e)`

Description:

Counts the pages loaded in main memory of a given environment

Parameters:

`e`: pointer to the environment that you want to count its working set size

Return value:

Number of pages loaded in main memory for environment "**e**",(i.e. **"e"** working set size)

Set Virtual Address of Page in Working Set

Function declaration:

```
inline void env_page_ws_set_entry(struct Env* e, uint32 entry_index, uint32
                                                 virtual_address)
```

Description:

Sets the entry number "entry_index" in **"e"** working set to given virtual address after **ROUNDING it DOWN** to the start of page

Parameters:

`e`: pointer to an environment

`entry_index`: the working set entry index to set the given virtual address

`virtual_address`: the virtual address to set (should be ROUNDED DOWN)

Clear Entry in Working Set

Function declaration:

```
inline void env_page_ws_clear_entry(struct Env* e, uint32 entry_index)
```

Description:

Clears (make empty) the entry at “entry_index” in **“e”** working set.

Parameters:

`e`: pointer to an environment

`entry_index`: working set entry index

Check If Working Set Entry is Empty

Function declaration:

```
inline uint32 env_page_ws_is_entry_empty(struct Env* e, uint32 entry_index)
```

Description:

Returns a value indicating whether the entry at “entry_index” in env “e” working set is empty

Parameters:

`e`: pointer to an environment

`entry_index`: working set entry index

Return value:

0: if the working set entry at “entry _index” is NOT empty

1: if the working set entry at “entry _index” is empty

Print Working Set

Function declaration:

```
inline void env_page_ws_print(struct Env* e)
```

Description:

Print the page working set together with the used, modified and buffered bits + time stamp. It also shows where the **`last_WS_index`** of the working set is point to.

Parameters:

`e`: pointer to an environment

APPENDIX III: Manipulating permissions in page tables and directory

Permissions in Page Table

Set Page Permission

Function declaration:

```
inline void pt_set_page_permissions(struct Env* ptr_env, uint32 virtual_address,
                uint32 permissions_to_set, uint32 permissions_to_clear)
```

Description:

Sets the permissions given by "**`permissions_to_set`**" to "1" in the page table entry of the given page (virtual address), and **Clears** the permissions given by "**`permissions_to_clear`**". The environment used is the one given by "`ptr_env`"

Parameters:

`ptr_env`: pointer to environment that you should work on

`virtual_address`: any virtual address of the page

`permissions_to_set`: page permissions to be set to 1

`permissions_to_clear`: page permissions to be set to 0

Examples:

1. to set page PERM_WRITEABLE bit to 1 and set PERM_PRESENT to 0

```
pt_set_page_permissions(environment, virtual_address,
PERM_WRITEABLE, PERM_PRESENT);
```

2. to set PERM_MODIFIED to 0

```
pt_set_page_permissions(environment, virtual_address, 0,
PERM_MODIFIED);
```

Get Page Permission

Function declaration:

```
inline uint32 pt_get_page_permissions(struct Env* ptr_env, uint32 virtual_address )
```

Description:

Returns all permissions bits for the given page (virtual address) in the given environment page directory (ptr_pgdir)

Parameters:

`ptr_env`: pointer to environment that you should work on

`virtual_address`: any virtual address of the page

Return value:

Unsigned integer containing all permissions bits for the given page

Example:

To check if a page is modified:

```
uint32 page_permissions = pt_get_page_permissions(environment, virtual_address);
if(page_permissions & PERM_MODIFIED)
{
	. . .
}
```

Clear Page Table Entry

Function declaration:

`inline void pt_clear_page_table_entry(struct Env* ptr_env, uint32 virtual_address)`

Description:

Set the entry of the given page inside the page table to **NULL**. This indicates that the page is no longer exists in the memory.

Parameters:

`ptr_env`: pointer to environment that you should work on

`virtual_address`: any virtual address inside the page

Permissions in Page Directory

Clear Page Dir Entry

Function declaration:

`inline void pd_clear_page_dir_entry(struct Env* ptr_env, uint32 virtual_address)`

Description:

Set the entry of the page table inside the page directory to **NULL**. This indicates that the page table, which contains the given virtual address, becomes no longer exists in the whole system (memory and page file).

Parameters:

`ptr_env`: pointer to environment that you should work on

`virtual_address`: any virtual address inside the range that is covered by the page table

Check if a Table is Used

Function declaration:

`inline uint32 pd_is_table_used(Env* ptr_environment, uint32 virtual_address)`

Description:

Returns a value indicating whether the table at "`virtual_address`" was used by the processor

Parameters:

`ptr_environment`: pointer to environment

`virtual_address`: any virtual address inside the table

Return value:

0: if the table at "`virtual_address`" is not used (accessed) by the processor

1: if the table at "`virtual_address`" is used (accessed) by the processor

Example:

```
if(pd_is_table_used(faulted_env, virtual_address))
{
        …
}
```

Set a Table to be Unused

Function declaration:

```
inline void pd_set_table_unused(Env* ptr_environment, uint32 virtual_address)
```

Description:

Clears the “Used Bit” of the table at `virtual_address` in the given directory

Parameters:

`ptr_environment`: pointer to environment

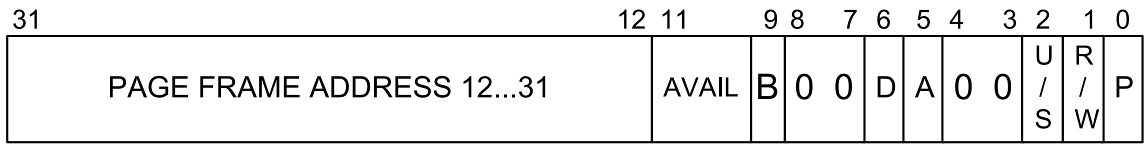
`virtual_address`: any virtual address inside the table

APPENDIX IV: Page Buffering

Structures

In order to keep track of the buffered frames, the **following changes were added to FOS**:

1- We use one of the available bits in the page table as a BUFFERED bit (Bit number 9) to indicate whether the **frame of this page** is buffered or not.



P:	Present bit ***(PERM_PRESENT)***
R/W:	Read/Write bit ***(PERM_WRITABLE)***
U/S:	User/Supervisor bit ***(PERM_USER)***
A:	Accessed bit ***(PERM_USED)***
D:	Dirty bit ***(PERM_MODIFIED)***
B:	Buffered bit ***(PERM_BUFFERED)***
AVAIL:	Available for system programmers use
NOTE:	0 indicates Intel reserved. Don't define.

2- Add the following information to the "***Frame_Info***" structure:

a- **`isBuffered`**: to indicate whether **this frame** is buffered or not

b- **`va`**: virtual address of the page that was mapped to this buffered frame

c- **`environment`**: the environment that own this virtual address

3- Create a new list called "**modified_frame_list**"

A new Frame_Info* linked list is added to FOS to keep track of buffered modified page frames,(see memory_manager.c):

```
struct Linked_List modified_frame_list;
```

Functions

Add Frame to the Tail of a Buffered List

Description:

Adds the given frame (ptr_frame_info) to the **TAIL** of the given list (bufferList)

Function declaration:

```
inline void bufferList_add_page(struct Linked_List* bufferList,struct Frame_Info
                                    *ptr_frame_info)
```

Parameters:

`bufferList`: pointer to a linked list of Frame_Info* elements (either F.F.L or Modified List)

`ptr_frame_info`: a pointer to Frame_Info object that will be added

Example:

```
struct Frame_Info* ptr_victim_frame;
. . .
bufferList_add_page(&modified_frame_list, ptr_victim_frame);
```

Remove Frame from a Buffered List

Description:

Removes the given frame (ptr_frame_info) from the given list (bufferList)

Function declaration:

```
inline void bufferlist_remove_page(struct Linked_List* bufferList, struct Frame_Info
                                   *ptr_frame_info)
```

Parameters:

`bufferList`: pointer to a linked list of Frame_Info* elements (either F.F.L or Modified List)

`ptr_frame_info`: a pointer to Frame_Info object that will be removed

Example:

```
struct Frame_Info* ptr_victim_frame;
. . .
bufferList_add_page(&modified_frame_list, ptr_victim_frame);
```

Get Current Size of a Buffered List

Description:

Return the size of the given list (bufferList)

Function declaration:

```
LIST_SIZE(struct Linked_List* bufferList)
```

Parameters:

`bufferList`: pointer to a linked list of Frame_Info* elements (either F.F.L or Modified List)

Example:

```
//Get size of modified frame list
uint32 size = LIST_SIZE(&modified_frame_list);
```

Get Maximum Length of the Modified Buffered List

Description:

Return the maximum length of the modified buffered list

Function declaration:

```
uint32 getModifiedBufferLength()
```

Parameters:

No parameters

Example:

```
//Get maximum length of modified buffer list
uint32 max_len = getModifiedBufferLength();
```

Iterate on ALL Elements of a Buffered List

Description:

Used to loop on all frames in the given list

Function declaration:

```
LIST_FOREACH (Frame_Info* iterator, Linked_List* list)
```

Parameters:

`list`: pointer to the linked list to loop on its elements (of type Frame_Info*)

`iterator`: pointer to the current element in the list (of type Frame_Info*)

Example:

```
//Check which modified frame belongs to the current environment
struct Frame_Info *ptr_fi ;
LIST_FOREACH(ptr_fi, &modified_frame_list)
{
      if (ptr_fi->environment == curenv)
      {
            ...
      }
}
```

APPENDIX V: Modified CLOCK Replacement Algorithm

Modified clock replacement is a slightly modified version of normal clock algorithm you already studied, instead of working only on 1 "**used bit**", another bit is also used called "**modified bit**"

Algorithm Description

Starting with current pointer position in the working set:

Try 1*: (search for a "not used, not modified" victim page)*

- Search for page with used bit = 0 and modified bit = 0
  - If a page is found, it will be the victim. **Replace it** and then update the pointer to point the next page to the victim in the working set, and algorithm is finished
- If the pointer reaches its first position again without finding a victim, goto **Try 2**

Try 2: ***(normal clock: search for a "not used, (regardless of the value of modified bit)" victim page)***

- Search for page with used bit = 0, regardless the value of modified bit, **and setting the used bit value of any page in the way to 0**
  - If a page is found, it will be the victim, **Replace it** and then update the pointer to point the next page to the victim in the working set, and algorithm is finished
- If the pointer reaches its first position again without finding a victim, goto **Try 1**

Example

Pointer	Page	used	modified
*	**P1**	0	1
	P2	1	0
	P3	1	0

A
New Page:
P5 (write)

Pointer	Page	used	modified
*	**P1**	0	1
	P2	1	0
	P3	1	0

B
P1 is victim found in Try 2

Pointer	Page	used	modified
	P5	1	1
*	**P2**	1	0
	P3	1	0

C
requested P5 is placed

Pointer	Page	used	modified
	P5	1	1
*	**P2**	1	**1**
	P3	1	0

D
P2 is modified
New Page:
P7 (read)

Pointer	Page	used	modified
	P1	**0**	1
	P2	**0**	1
*	**P3**	**0**	0

E
P3 is victim found in second Try 1

Pointer	Page	used	modified
*	**P1**	**0**	1
	P2	**0**	1
	P7	**1**	0

F
P7 is placed

Figure 6: Example on modified clock algorithm

Appendix VI: Command Prompt

NEW Command Prompt Features

The following features are newly added to the FOS command prompt. They are originally developed by ***Mohamed Raafat & Mohamed Yousry, 3rd year student, FCIS, 2017***, thanks to them. Edited and modified by TA\ Ghada Hamed.

First: DOSKEY

Allows the user to retrieve recently used commands in (FOS>_) command prompt via UP/DOWN arrows. Moves left and right to edit the written command via LEFT/RIGHT arrows.

Second: TAB Auto-Complete

Allow the user to auto-complete the command by writing one or more initial character(s) then press "TAB" button to complete the command. If there're 2 or more commands with the same initials, then it displays them one-by-one at the same line.

The same feature is also available for auto-completing the "Program Name" after "load" and "run" commands.

Appendix VII: Basic and Helper Memory Management Functions

Basic Functions

The basic **memory manager functions** that you may need to use are defined in "`kern/memory_manager.c`" file:

Function Name	**Description**
`allocate_frame`	Used to allocate a free frame from the free frame list
`free_frame`	Used to free a frame by adding it to free frame list
`map_frame`	Used to map a single page with a given virtual address into a given allocated frame, simply by setting the directory and page table entries
`get_page_table`	Used by "`map_frame`" to get a pointer to the page table if exist
`unmap_frame`	Used to un-map a frame at the given virtual address, simply by clearing the page table entry
`get_frame_info`	Used to get both the page table and the frame of the given virtual address

Helpers Functions

There are some **helper functions** that we may need to use them in the rest of the course:

Function	**Description**	**Defined in…**

`LIST_FOREACH (Frame_Info*, Linked_List *)`	Used to traverse a linked list.
	Example: to traverse the modified list
	struct Frame_Info* ptr_frame_info = NULL;
	LIST_FOREACH(ptr_frame_info, &modified_frame_list)
	{
		`inc/queue.h`

	…. }	
`to_frame_number (Frame_Info *)`	Return the frame number of the corresponding Frame_Info element	`Kern/memory_manager.h`
`to_physical_address (Frame_Info *)`	Return the start physical address of the frame corresponding to Frame_Info element	`Kern/memory_manager.h`
`to_frame_info (uint32 phys_addr)`	Return a pointer to the Frame_Info corresponding to the given physical address	`Kern/memory_manager.h`

Function	**Description**	**Defined in…**
`PDX (uint32 virtual address)`	Gets the page directory index in the given virtual address (10 bits from 22 – 31).	`Inc/mmu.h`
`PTX (uint32 virtual address)`	Gets the page table index in the given virtual address (10 bits from 12 – 21).	`Inc/mmu.h`
`ROUNDUP (uint32 value, uint32 align)`	Rounds a given "value" to the nearest upper value that is divisible by "align".	`Inc/types.h`
`ROUNDDOWN (uint32 value, uint32 align)`	Rounds a given "value" to the nearest lower value that is divisible by "align".	`Inc/types.h`
`tlb_invalidate (uint32* page_directory, uint32 virtual address)`	Refresh the cache memory (TLB) to remove the given virtual address from it.	`Kern/helpers.c`
`rcr3()`	Read the physical address of the current page directory which is loaded in CR3	`Inc/x86.h`
`lcr3(uint32 physical address of directory)`	Load the given physical address of the page directory into CR3	`Inc/x86.h`

Have a nice & useful project

☺ GOOD LUCK ☺