Faculty of Computer and Information Sciences

Ain Shams University

Third Year – Second Semester

2018 - 2019

Operating Systems

FOS KERNEL PROJECT

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Contents

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

Group Members: *3-5*

Group Registration:

- *3-5 members: you should* ***register your group here*** *due to* ***THR 11 APR till 23:59 PM***
- *6 members is asked to* ***implement one of the bonus tasks as MANDATORY****: register* ***here*** *due to* ***THR 11 APR 23:59***

Delivery:

1. ***Dropbox-based***
2. ***Milestone 1****: SUN of Week#12* ***(28 APR till 10:00 PM)*** ➔ *kernel heap functions, creation function, fault handler, semaphores*
3. ***Milestone 2:*** *SUN of Lab Exam Week* ***(12 MAY till 10:00 PM)*** ➔ *user heap, shared variables*

Support Dates: *WEEKLY Office Hours of Week#10 + MON(22/4) & WED(24/4) of Week#11 + WED(8/5) & THU(9/5) of Week#13*

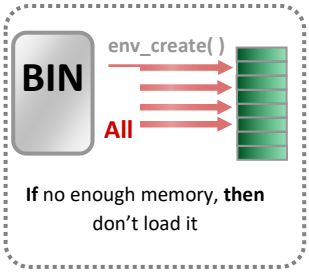
For Milestone1 & 2:

- *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_2019_template.zip*** *provided to you; Follow these steps to import the project folder into the eclipse*

Introduction

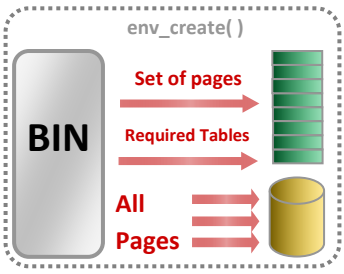
What's new?!

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 project: 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 to add new features for your FOS, 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- **Load and run** multiple user programs that are **partially** loaded in main memory and **fully** loaded in secondary memory **(H.D.D.) (*mostly DONE*)**
3- Handle **page faults** during execution by applying **MODIFIED CLOCK replacement algorithm**
4- **Semaphores**: OS-supported solution for concurrency problems (critical section & dependency)
5- **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**
6- **Shared variables:** Allow user programs to dynamically create and share variables at run-time 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**.

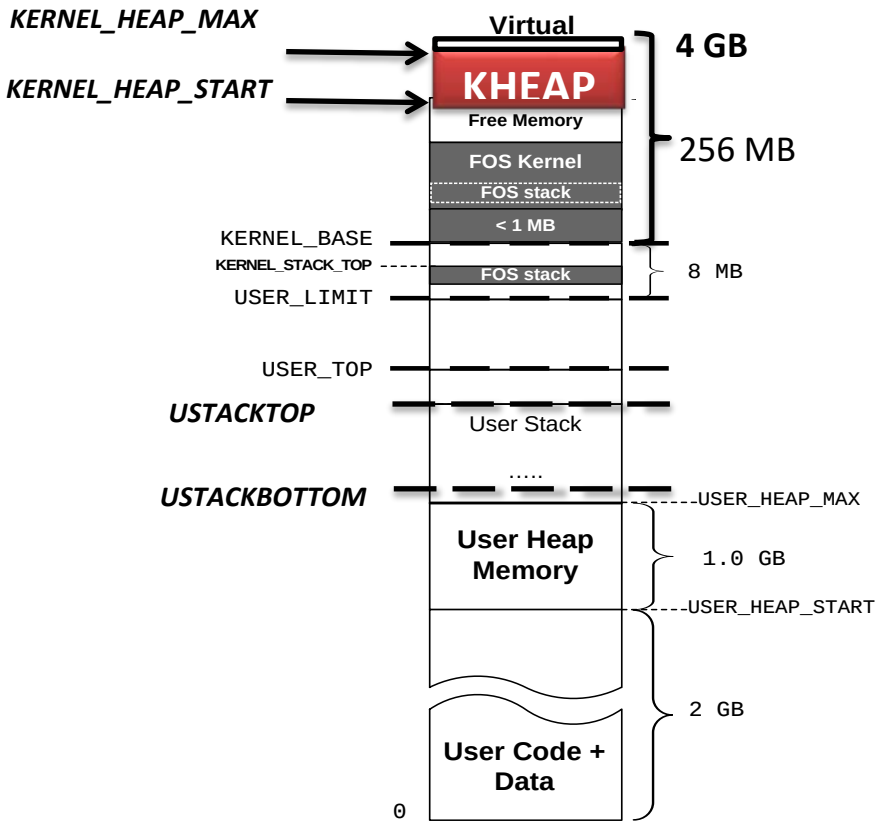


Figure 1: Virtual space layout of single user loaded program

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 differing 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 occurs 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.

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

> *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.*

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. These functions provide the following facilities:

1- Add a new environment empty page to the page file.

2- Read an environment page from the page file to the main memory.

3- Update certain environment page in the page file from the main memory.

4- Remove an existing environment page from 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 need 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:

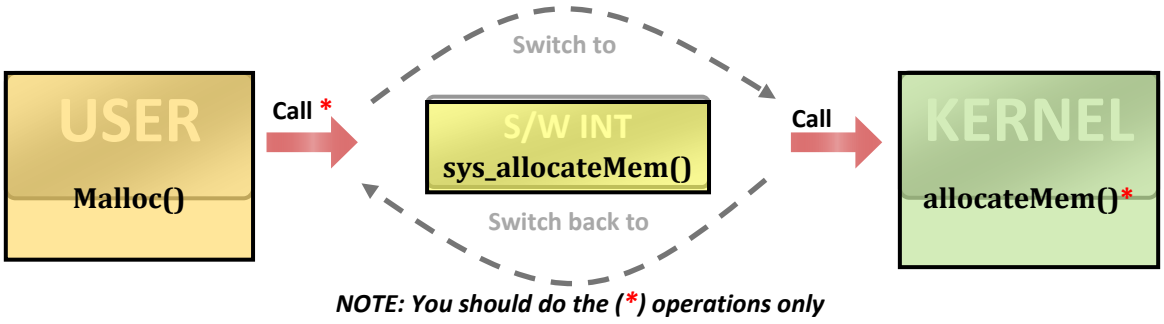
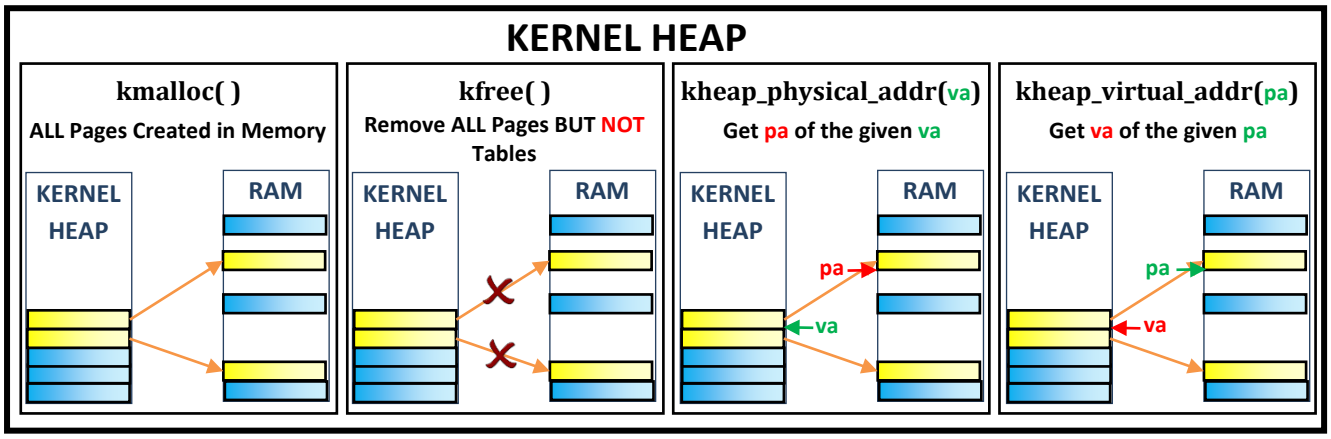


Figure 2: Sequence diagram of dynamic allocation using malloc()

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, **t**he unmarked components are already implemented.



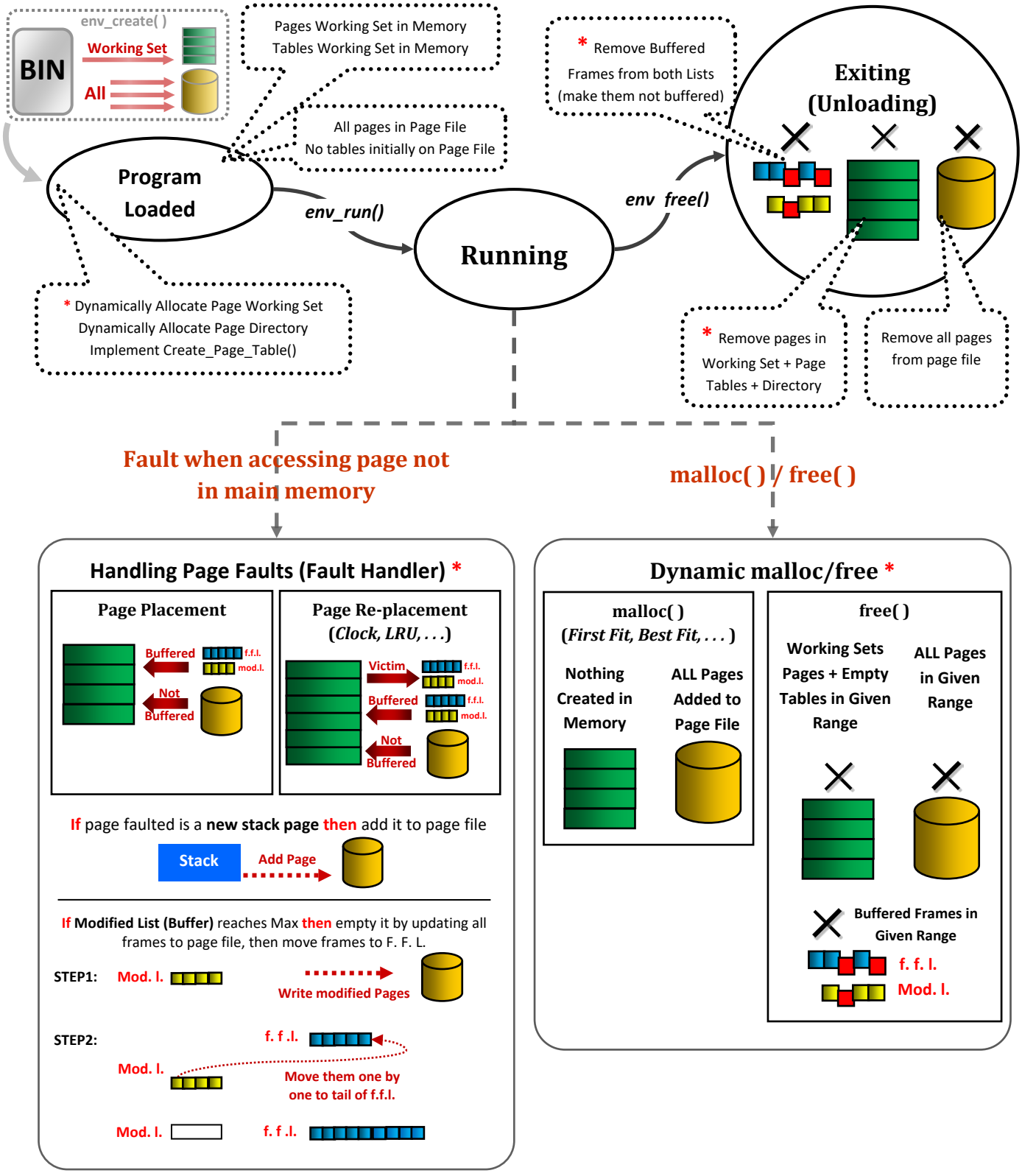


Figure 3: Interaction among components in project

Details

FIRST: Kernel Heap

Problem

The kernel virtual space [KERNEL_BASE, 4 GB) is **one-to-one** mapped to the physical memory [0, 256 MB), as shown in Figure 4. This limits the physical memory area for the kernel to 256 MB only. In other words, the kernel code can't use any physical memory after the 256 MB, as shown in Figure 5.

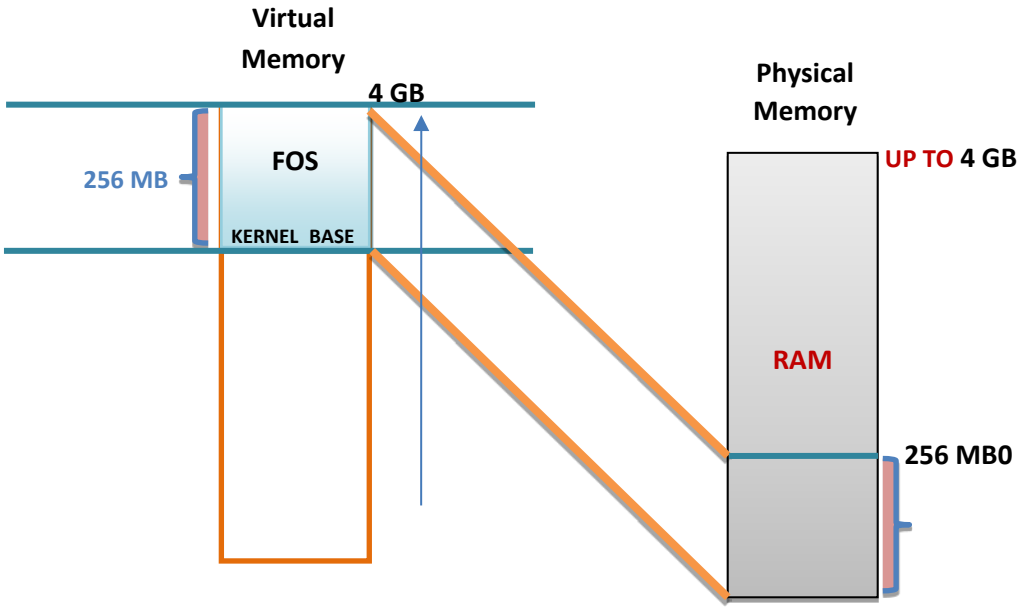


Figure 4: Mapping of the FOS VIRTUAL memory to the PHYSICAL memory [32 bit Mode]

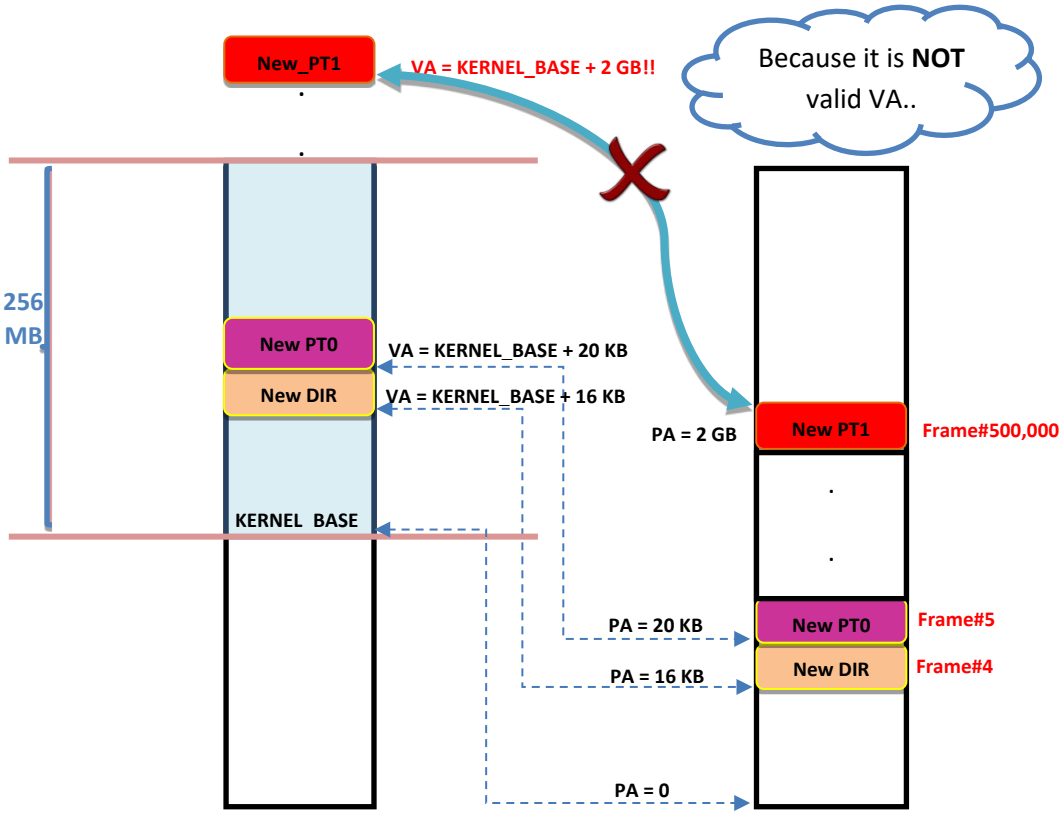


Figure 5: PROBLEM of ONE to ONE mapping's between the FOS VIRTUAL memory and its corresponding frames in the PHYSICAL memory

Solution

Replace the one-to-one mapping to an ordinary mapping as we did in the allocation of the user's space. This allows the kernel to allocate frames anywhere and reach it wherever it is allocated by saving its frame number in the page table of the kernel, as shown in **Figure 6**.

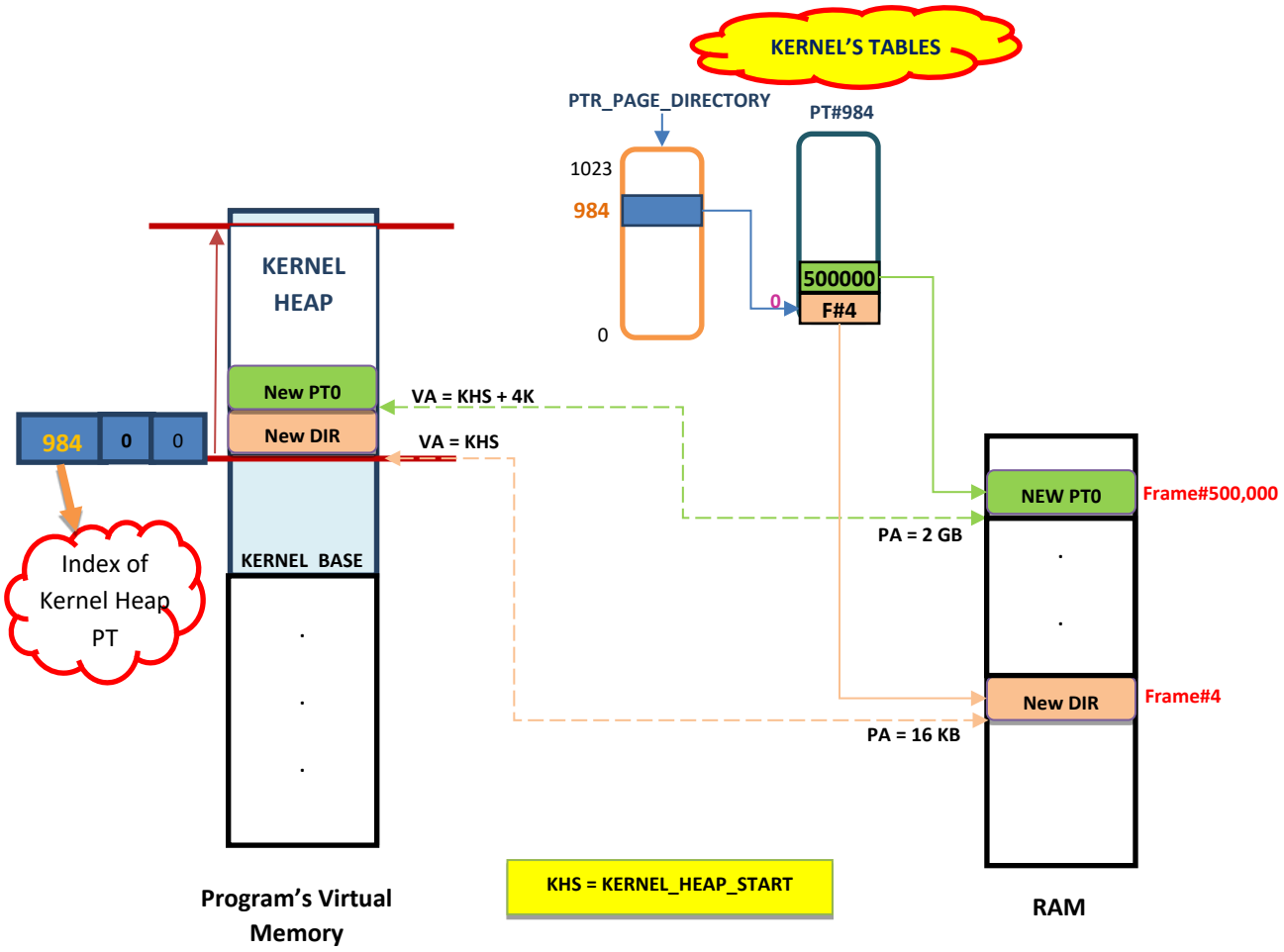


Figure 6: New Model to map kernel's VA of an allocated page in the KERNEL HEAP to pa

However, since the Kernel virtual space should be shared in the virtual space of all user programs, ALL page tables of the kernel virtual space (from table#960 to table#1023) are already created and linked to the Kernel directory. These tables **SHOULD NOT be removed** for any reason until the FOS is terminated.

You need to fill the following functions that serve the **Kernel's Heap**:

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

1. **Kmalloc():** dynamically allocate space size using **BEST FIT** Strategy and map it as shown in **Figure 6**. It should work as follows:

   Search for suitable place using the **BEST FIT** strategy, if found:

   1. Allocate free frame(s) for the required size
   2. Map the new frame(s) with the virtual page(s) starting from the found location.

   Else, return NULL

2. **Kfree():** delete a previously allocated space by removing all its pages from the Kernel Heap

   Q1) After calling kfree, if the page table becomes empty and all the entries within it are unmapped, i.e. cleared, **shall we delete this page table?**

   A1) No, take care this table is one of the kernel's table that are shared with ALL loaded user programs.

   Q2) Do you remember the first step we did in env_create to start creating a new environment for a program to be loaded in memory?

   A2) Yes we create new virtual by allocating a frame for the new directory then we copy the kernel's directory in the new directory to share the FOS kernel part.

   For this reason, if we take the decision to delete the page table, we shall delete it from all other programs and vice versa if it is allocated again at one process, it shall be created for all processes…

   So, take care we delete and **un-map PAGES ONLY not TABLES**.

   - Unmap each page of the previously allocated space at the given address by clearing its entry in the page table and free its frame.
   - **DO NOT remove** any table

3. **kheap_virtual_address():** find kernel virtual address of the given physical one.
   - For example, in **Figure 6**, if we call kheap_virtual_address() for physical address 16 KB, it should return KHS (KERNEL_HEAP_START).

4. **kheap_physical_address():** find physical address of the given kernel virtual address.
   - For example, in **Figure 6**, if we call kheap_physical_address() for virtual address KHS + 4 KB, it should return 2 GB.

SECOND: Load Environment by env_create( )

in "kern/user_environment.c" (mostly implemented, minor student codes are needed)

After env_create() is executed to load a program binary, the binary will partially loaded in main memory (part of segments + stack page) and FULLY loaded in page file (all segments + stack page)

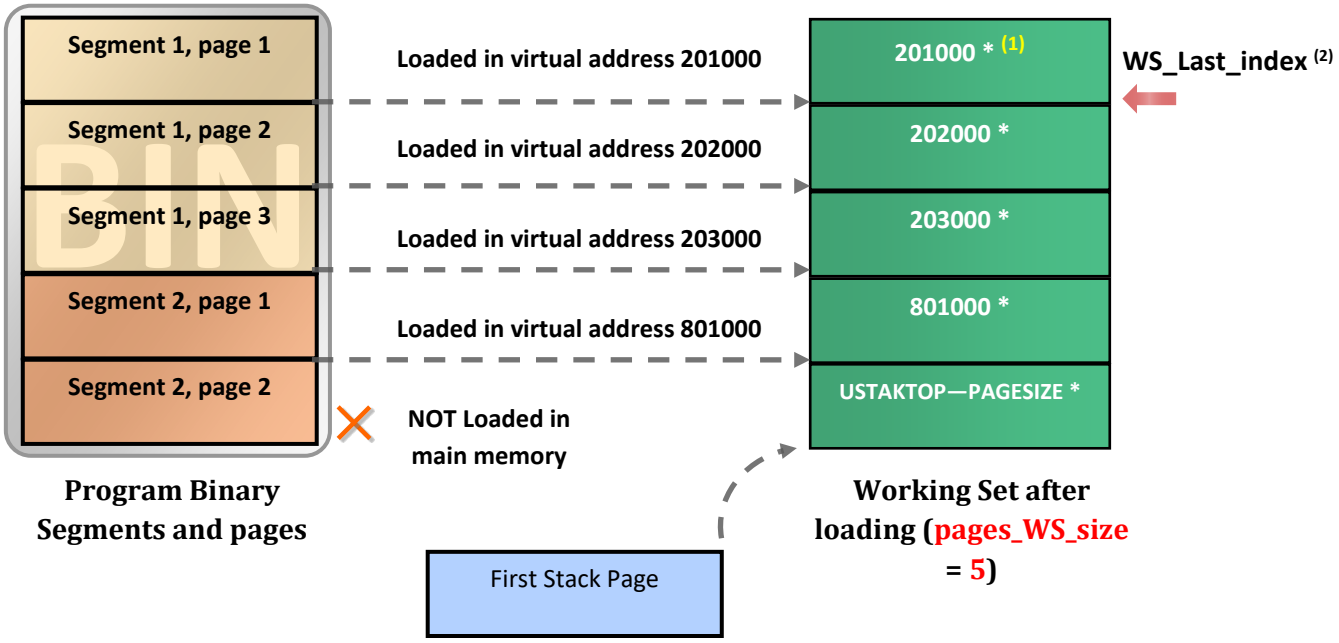


Figure 7: View of working set <u>after loading</u> a program binary with env_create(). [(1): * this asterisk means that "Used Bit" is set to 1 in page table for this virtual address, (2) "WS_Last_index": the WS index to start iterating from (used in FIFO and clock algorithms)]

The following functions are needed to **dynamically allocate** new data structures in the **Kernel Heap**:

1. **create_user_page_WS():** should create new array for pages WS with the given size **[DONE]**
2. **create_user_directory():** should create new user directory **[DONE]**
3. **create_page_table():** should create new page table and link it to the directory, for mapping the given user address. **[REQUIRED]** REMEMBER TO:
    a. clear all entries (as it may contain garbage data)
    b. clear the TLB cache (using "tlbflush()")

THIRD: Fault Handler

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)

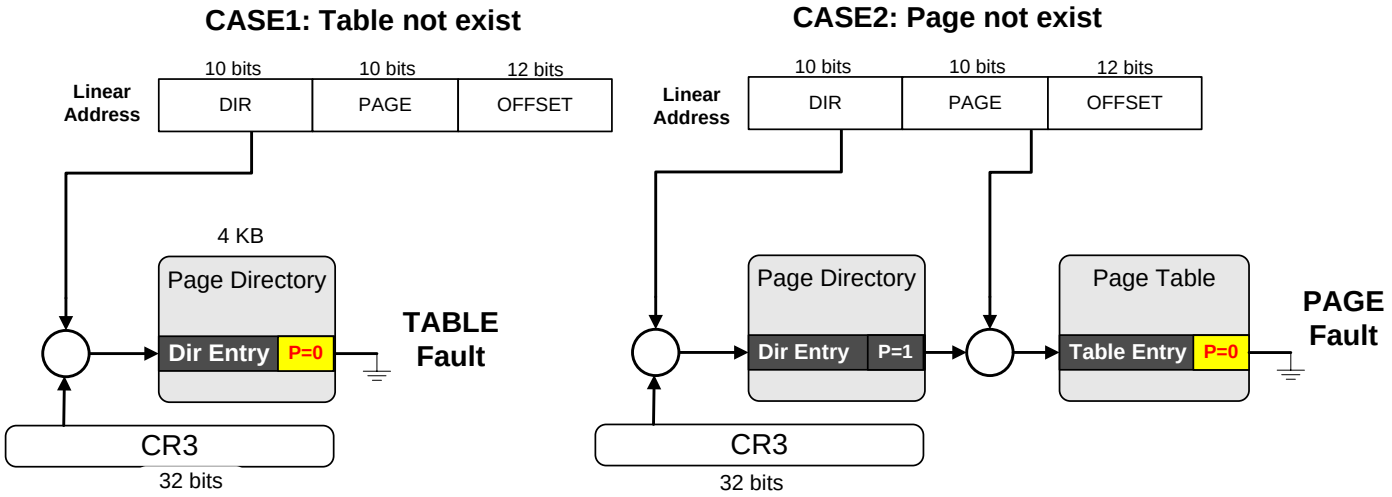


Figure 8: Fault types (table fault and page fault)

- 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 chose 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**)*
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***),
        - set the MODIFIED bit of its page in its page table to 0 (***see Appendix III***)
        - 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 X***)

FOURTH: Semaphores

> **IMPORTANT:** Refer to the ppt inside the project materials for more details and examples
>
> **APPENDIX VII**: Scheduler Helper Functions

- You should implement function **"createSemaphore()"**, **"waitSemaphore()"** and **"signalSemaphore()"** functions in the KERNEL **"kern/semaphore_manager.c"**

Create New Semaphore

1. If the semaphore with the given "ownerID" and "name" exists, return E_SEMAPHORE_EXISTS
2. Else, allocate a new semaphore object
3. If allocation succeed,
    1. initialize its members (ownerID, name, value)
    2. Return its ID (index in the array)
4. Else, return E_NO_SEMAPHORE

Wait Semaphore

1. Get the Semaphore with the given "ownerID" and "name"
2. Decrement its value
3. If negative, **block** the calling environment, by
    1. removing it from **ready queue** [refer to helper functions in doc]
    2. adding it to **semaphore queue** [refer to helper functions in doc]
    3. changing its status to **ENV_BLOCKED**
    4. set **curenv** with **NULL**
4. Call "**fos_scheduler()**" to continue running the remaining envs

Signal Semaphore

1. Get the Semaphore with the given "ownerID" and "name"
2. Increment its value
3. If less than or equal 0, **release** a blocked environment, by
    1. removing it from **semaphore queue** [refer to helper functions in doc]
    2. adding it to **ready queue** [refer to helper functions in doc]
    3. changing its status to **ENV_READY**

FIFTH: 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 BEST FIT strategy 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

You need to check which strategy is currently selected using the given functions.
[sys_isUHeapPlacementStrategyBESTFIT() …]

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 fil e, 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)

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 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()**)
    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
   a) Clear the entry inside the page table to indicate that the page is no longer exists (see Appendix III).
   b) 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*).

SIXTH: Shared Variables ➔Dynamic Allocation and Sharing

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

APPENDIX VIII: Shared Variables Data Structures & Functions

- Your should implement function **"smalloc()"** (allocates shared user memory) and **"sget()"** (share a previously allocated memory) functions in the USER side **"lib/uheap.c"**
- You should use FORUTH: SYSTEM CALLS to switch from user to kernel
- Your kernel code will be in "**createSharedObject()**" and "**getSharedObject()**" functions in "**shared_memory_manager.c**"

Dynamic Allocation

User Side (**smalloc**)

1. Implement **BEST FIT** strategy to search the heap for suitable space to the required allocation size (on **4 KB BOUNDARY**)
2. if no suitable space found, return NULL
3. Call **sys_createSharedObject**(...) to invoke the Kernel for allocation of shared variable
4. If the Kernel successfully creates the shared variable, return its virtual address
5. Else, return NULL

You need to check which strategy is currently selected using the given functions.
[sys_isUHeapPlacementStrategyBESTFIT() …]

Kernel Side (**createSharedObject**)

1. Allocate a new share object (use allocate_share_object())
2. Allocate ALL required space in the physical memory on a PAGE boundary
3. Map them on the given "virtual_address" on the current env. with writable permissions
4. Initialize the share object with the following:
   1. Set the data members of the object with suitable values (ownerID, name, size, ...)
   2. Set references to 1 (as there's 1 user environment that use the object now - OWNER)
   3. Store the object's isWritable flag for later use by getSharedObject()

4. Add all allocated frames to "frames_storage" of this shared object to keep track of them for later use (use: add_frame_to_storage())

5. If succeed: return the ID of the shared object (i.e. its index in the "shares" array)

6. Else, return suitable error

Getting a Shared Variable

User Side (**sget**)

4. Get the size of the shared variable (use **sys_getSizeOfSharedObject**())

5. If not exists, return NULL

6. Implement BEST FIT strategy to search the heap for suitable space (on 4 KB BOUNDARY)

7. if no suitable space found, return NULL

8. Call **sys_getSharedObject**(...) to invoke the Kernel for sharing this variable

9. If the Kernel successfully share the variable, return its virtual address

10. Else, return NULL

Kernel Side (**getSharedObject**)

1. Get the shared object from the "**shares**" array (use **get_share_object_ID**())

2. Get its physical frames from the "**frames_storage**" (use: **get_frame_from_storage**())

3. Share these frames with the current env. starting from the given "virtual_address"

4. use the flag **isWritable** to make the sharing either read-only or writable

5. Update references

6. If succeed: return the ID of the shared object (i.e. its index in the "shares" array)

7. Else, return suitable error

BONUSES

First: Strategies for Kernel Dynamic Allocation

- Beside the BEST FIT strategy, implement the **FIRST FIT** one to find the suitable space for allocation.
- Compare their performance!

Second: Kernel Realloc

- Attempts to resize the allocated space at given "virtual address" to "new size" bytes, possibly moving it in the kernel heap.
  - If successful: returns the new virtual address, in which case the old virtual address must no longer be accessed.
  - On failure: returns a null pointer, and the old virtual address remains valid.
- A call with "virtual address = null" is equivalent to kmalloc()
- A call with "new size = zero" is equivalent to kfree()

Third: User Realloc

- Attempts to resize the allocated space at given "virtual address" to "new size" bytes, possibly moving it in the user heap.
  - If successful: returns the new virtual address, in which case the old virtual address must no longer be accessed.
  - On failure: returns a null pointer, and the old virtual address remains valid.
- A call with "virtual address = null" is equivalent to malloc()
- A call with "new size = zero" is equivalent to free()

Fourth: Free Shared Object

1. Get the shared object from the shares array
2. Unmap it from the current environment
3. If page table(s) become empty, remove it
4. Update references
5. If this is the last share, delete the share object (use free_share_object())
6. Flush the cache

Fifth: 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. Shared variables [if any],
  4. Semaphores [if any],
  5. All page tables in the entire user virtual memory
  6. The directory table
  7. All pages from page file, this code ***is already*** written for you ☺

Sixth: Add "Program Priority" Feature to FOS

- Five different priorities can be assigned to any environment:
    1. Low
    2. Below Normal
    3. Normal **[default]**
    4. Above Normal
    5. High
- Kernel can set/change the priority of any environment
- Priority affects the working set (WS) size, as follows:

Priority	Effect on WS Size
Low	decrease WS size by its half **IMMEDIATELY** by removing half of it using replacement strategy
Below Normal	decrease WS size by its half **ONLY** when half of it become empty
Normal	**no change** in the original WS size
Above Normal	double the WS size when it becomes full (**1 time only**)
High	double the WS size **EACH TIME** it becomes full (until reaching half the RAM size)

CHALLENGES!!

FIRST: Stack De-Allocation

In the env_create, when loading the program, only ONE stack page is allocated and mapped in RAM and added as a copy on the page file (H.D.D). Later, page faults can occur for stack pages that are not allocated. In this case, the page fault is handled by YOU to allocate the required stack page(s) in RAM and add it in the program's page file. These stack pages will remain in page file until closing the program (EXIT).

The problem is that this may cause LEAK in both the Page File (H.D.D) and the memory as shown in **Figure 9**. Since these allocated pages will remain on the page file until the exit (even if there're no further need for them), this can filling up the page file and no further pages can be added.

So the challenge here is to handle this occurred leak by removing the UN-NEEDED stack pages every while from both memory and its copy on the page file as well.

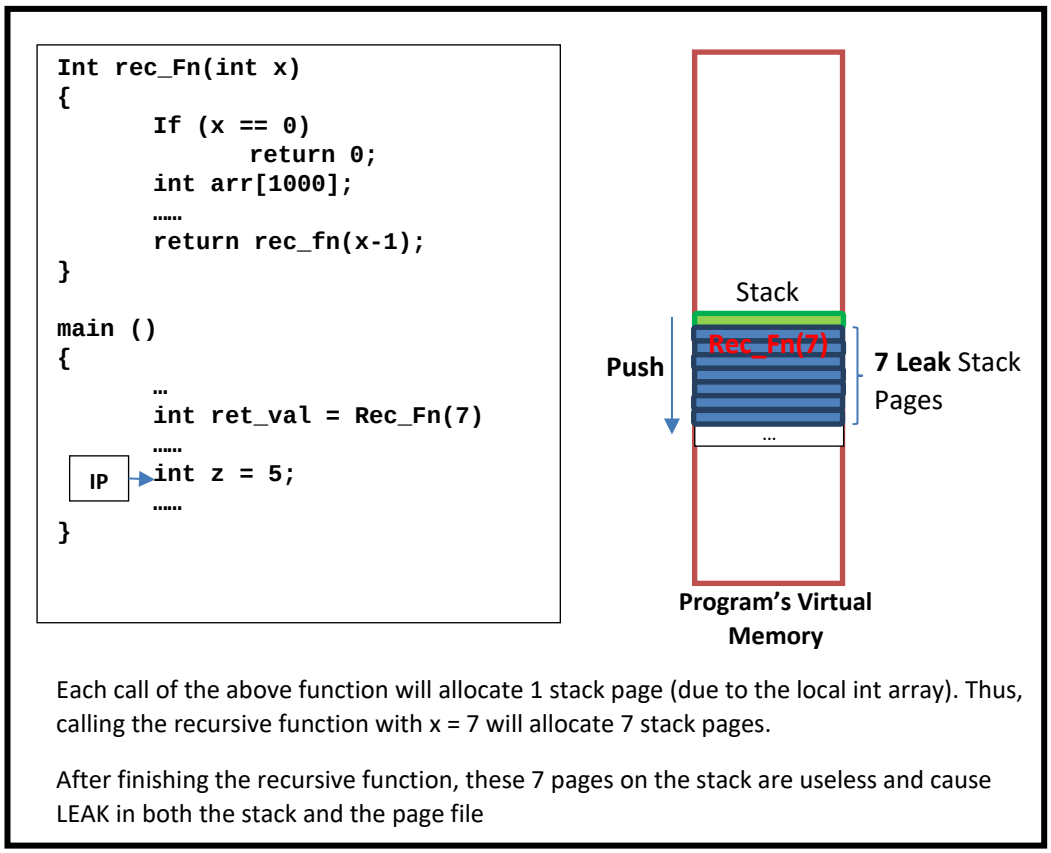


Figure 9: Memory leak due to the remaining part of the stack pages allocated in the memory during the execution of the recursive function

SECOND: System Hibernate

- Add a command to hibernate the system by:
    1. Saving the status of:
        - Main memory
        - Page file
    2. Close the system
- When opened again, without recompilation, the system is restored to its saved state.

SECOND: Dynamic Allocation, Local Scope Strategy

As you see, we give a fixed number of pages to each process (this is called Fixed Allocation). With this policy, it is necessary to decide ahead of time the amount of allocation to give to a process. The drawback to this approach is twofold:

1. If allocations tend to be too small, then there will be a high page fault rate, causing the entire multiprogramming system to run slowly.
2. If allocations tend to be unnecessarily large, then there will be too few programs in main memory and there will either be considerable processor idle time or considerable time spent in swapping.

To solve this problem, a **Dynamic Allocation** is used in which a process experiencing page faults will gradually grow in size, which should help reduce overall page faults in the system. But this growth is limited by Max Size that a process can't exceed (to avoid greedy process for allocating the whole memory).

The idea can be summarized as follows:

1. When a new process is loaded into main memory, allocate to it a certain number of page frames as its resident set, based on application type, program request, or other criteria.
2. When a page fault occurs, select the page to replace from among the resident set of the process that suffers the fault (Local Scope).
3. From time to time, reevaluate the allocation provided to the process, and increase or decrease it to improve overall performance.

With this strategy, the decision to increase or decrease a resident set size is a deliberate one and is based on an assessment of the likely future demands of active processes. Because of this evaluation, such a strategy may yield better performance.

The key elements of the dynamic-allocation, local-scope strategy are the criteria used to determine resident set size and the timing of changes. One specific strategy that has received much attention in the literature is known as the **working set strategy**. (For more details, refer to Textbook CH.8 starting from Page 377)

Challenge Description

Develop a dynamic-allocation, local-scope strategy that **minimizes** the number of page faults occur when running multi-programs in the FOS.

THIRD: Dynamic Allocation, Local Scope Strategy

As you see, we give a fixed number of pages to each process (this is called Fixed Allocation). With this policy, it is necessary to decide ahead of time the amount of allocation to give to a process. The drawback to this approach is twofold:

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2. If allocations tend to be unnecessarily large, then there will be too few programs in main memory and there will either be considerable processor idle time or considerable time spent in swapping.

To solve this problem, a **Dynamic Allocation** is used in which a process experiencing page faults will gradually grow in size, which should help reduce overall page faults in the system. But this growth is limited by Max Size that a process can't exceed (to avoid greedy process for allocating the whole memory).

The idea can be summarized as follows:

1. When a new process is loaded into main memory, allocate to it a certain number of page frames as its resident set, based on application type, program request, or other criteria.
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The key elements of the dynamic-allocation, local-scope strategy are the criteria used to determine resident set size and the timing of changes. One specific strategy that has received much attention in the literature is known as the **working set strategy**. (For more details, refer to Textbook CH.8 starting from Page 377)

Challenge Description

Develop a dynamic-allocation, local-scope strategy that **minimizes** the number of page faults occur when running multi-programs in the FOS.

In this CHALLENGE: Every effort is welcomed, search the books, ask faculty staff, search the internet or even invent your own algorithm.

Testing

A- How to test your project

To test your implementation, a bunch of test cases programs will be used.

You can test each part from the project independently. After completing all parts, you can test the whole project using the testing scenarios described below. User programs found in "**user/**" folder.

Note: *the corresponding entries in "user_environment.c" are* ***already added for you*** *to enable FOS to run these test programs just like the other programs in "user/" folder*.

TESTS ARE AVALIABLE NOW

Enjoy developing your own OS

☺ GOOD LUCK ☺

APPENDICES

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 FIFO & clock algorithm, the next item (page) pointer
	uint32 page_WS_last_index;
	//percentage of allocated pages that should be removed when RAM is scarce or
	WS becomes full
	uint32 percentage_of_WS_pages_to_be_removed;
};
```

Figure 10: 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)

Get Virtual Address of Page in Working Set

Function declaration:

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

Description:

Returns the virtual address of the page at entry "entry_index" in environment **"e"** working set

Parameters:

`e`: pointer to an environment

`entry_index`: working set entry index

Return value:

The virtual address of the page at entry "entry_index" in environment **"e"** working set

Get Time Stamp of Page in Working Set

Function declaration:

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

Description:

Returns the time stamp since the page at entry "entry_index" in environment **"e"** working set is last referenced (to be used in **LRU** algorithm)

Parameters:

`e`: pointer to an environment

`entry_index`: working set entry index

Return value:

The time stamp of the page at entry "entry_index" in environment **"e"** working set

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 environment "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

Flush certain Virtual Address from Working Set

Description:

Search for the given virtual address inside the working set of **"e"** and, if found, removes its entry.

Function declaration:

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

Parameters:

`e`: pointer to an environment

`virtual_address`: the virtual address to remove from working set

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

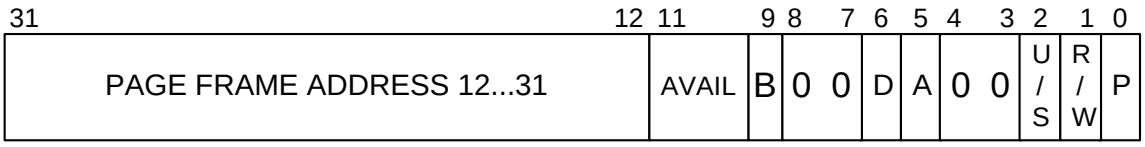
`virtual_address`: any virtual address inside the table

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 11: Example on modified clock algorithm

APPENDIX VI: Semaphore Data Structures & Helper Functions

They are declared and defined in “kern/semaphore_manager.h” and “kern/ semaphore_manager.c” respectively. Following is brief description about data structures and helper functions:

Data Structures

A struct is defined for each semaphore containing:

1. ID of the owner environment
2. Name
3. Value
4. Queue of blocked environments on it

Then, we dynamically allocate array of semaphores with size "MAX_SEMAPHORES",

```
struct Semaphore
{
	//owner environment ID
	int ownerID;
	//semaphore name
	char name[64];
	//queue of all blocked envs on this Semaphore
	struct Env_Queue env_queue;
	//semaphore value
	int value;
	//indicate whether this object is empty or used
	uint8 empty;
};
// Array of available Semaphores
struct Semaphore *semaphores ;
```

Figure 12: Semaphores data structures defined in "semaphore_manager.h"

Helper Functions

Create Semaphore Array

Function declaration:

```
void create_semaphores_array(int size)
```

Description:

Dynamically allocate the array of semaphore objects “**semaphores**” and initialize it by 0's. It set the empty flag = 1. [Already called for you ☺]

Parameters:

`size`: max number of semaphores.

Allocate Semaphore Object

Function declaration:

```
int allocate_semaphore_object(struct Semaphore **allocatedObject)
```

Description:

Allocates a new (empty) semaphore object from the “**semaphores**" array.

Parameters:

`allocatedObject`: return parameter containing a pointer to the allocated semaphore.

Return value:

= if succeed, **semaphoreObjectID** (its index in the array).

= Else, **E_NO_SEMAPHORE**: if the "semaphores" array is full.

Get Semaphore ID

Function declaration:

```
int get_semaphore_object_ID(int ownerID, char* name)
```

Description:

Get the array index of the given semaphore by searching the semaphores array with the given ownerID and name.

Parameters:

`ownerID`: ID of the owner environment of the required semaphore.

`name`: name of the semaphore to search for it.

Return value:

= **semaphoreObjectID** index in the array: if found.

= **E_SEMAPHORE_NOT_EXISTS**: if not found.

Free Semaphore Object

Description:

deletes the object with given "semaphoreObjectID" from the "**semaphores**" array (i.e. set its empty flag to 1 and clear all other members (name, value…)).

Function declaration:

```
int free_semaphore_object(int semaphoreObjectID)
```

Parameters:

`semaphoreObjectID`: ID of the semaphore to be removed (i.e. its index in the array).

Return value:

= 0: if found.

= **E_SEMAPHORE_NOT_EXISTS**: if not found.

Add environment to the Queue

Description:

Add the given environment into the tail of the given queue.

Function declaration:

```
void enqueue(struct Env_Queue* queue, struct Env* env);
```

Parameters:

queue: pointer (i.e. address) to the queue to insert on it.

env: pointer to the environment to be inserted.

Example: add current environment to myQueue

```
struct Env_Queue myQueue ;

...

enqueue(&myQueue, curenv);
```

Remove environment from the Queue

Description:

Get and remove the environment from the given queue.

Function declaration:

```
struct Env* dequeue(struct Env_Queue* queue);
```

Parameters:

queue: pointer (i.e. address) to the queue.

env: pointer to the environment to be inserted.

Return value:

pointer to the environment on the head of the queue (after removing it from the queue).

Example:

```
struct Env* env;

...

env = dequeue(&myQueue);
```

APPENDIX VII: Scheduler Helper Functions

They are declared and defined in “kern/sched.h” and “kern/sched.c” respectively. Following is brief description about these functions:

Helper Functions

Insert Environment to Ready Queue

Function declaration:

```
void sched_insert_ready(struct Env* env);
```

Description:

Insert the given environment to the tail of the ready queue, so, it'll be scheduled by the CPU.

Parameters:

env: pointer to the environment to be inserted.

Remove Environment from Ready Queue

Function declaration:

```
void sched_remove_ready(struct Env* env);
```

Description:

Remove the given environment from the ready queue, so, it'll be NOT scheduled by the CPU.

Parameters:

env: pointer to the environment to be removed.

Insert Environment to the NewEnv Queue

Function declaration:

```
void sched_insert_new(struct Env* env);
```

Description:

Insert the given environment to the tail of the new queue to indicate that it's loaded now.

Parameters:

env: pointer to the environment to be inserted.

Remove Environment from NewEnv Queue

Function declaration:

```
void sched_remove_new(struct Env* env);
```

Description:

Remove the given environment from the new queue.

Parameters:

env: pointer to the environment to be removed.

Insert Environment to the Exit Queue

Function declaration:

```
void sched_insert_exit(struct Env* env);
```

Description:

Insert the given environment to the tail of the exit queue to indicate that it's finished now.

Parameters:

env: pointer to the environment to be inserted.

Remove Environment from Exit Queue

Function declaration:

```
void sched_remove_exit(struct Env* env);
```

Description:

Remove the given environment from the exit queue.

Parameters:

env: pointer to the environment to be removed.

APPENDIX VIII: Shared Variables Data Structures & Functions

They are declared and defined in “kern/shared_memory_manager.h” and “kern/shared_memory_manager.c” respectively. Following is brief description about data structures and helper functions:

Data Structure

Each shared object has a struct that contains:

1. ID of the owner environment
2. Name of the shared variable
3. Size
4. All its frames [frames storage]
5. Sharing permissions (ReadOnly or Writable)
6. Number of environments that reference on it (share it).

Then, we dynamically allocate an array of allowed shared objects with size "MAX_SHARES".

```
int MAX_SHARES ;

///Struct that holds shared objects information
struct Share
{
	///ID of the owner environment
	int ownerID;
	///Shared object name
	char name[64];
	///Shared object size
	int size;
	///sharing permissions (0: Read-only, 1: Writeable)
	uint8 isWritable;
	///to store frames to be shared
	uint32 *framesStorage;
	///references, number of envs looking at this shared memory object
	uint32 references;
};

///Array of all shared objects
struct Share *shares;
```

Figure 13: Shared object data structures defined in "shared_memory_manager.h"

Helper Functions

Create Shares Array

Function declaration:

```
void create_shares_array(int size)
```

Description:

Dynamically allocate the array of shared objects “**shares**” and initialize it by 0's. It set the empty flag = 1. [Already called for you ☺]

Parameters:

`size`: max number of shared objects.

Allocate Shared Object

Function declaration: `int allocate_share_object(struct Share **allocatedObject)`

Description:

Allocates a new (empty) shared object from the "**shares**" array and dynamically creates its "**framesStorage**".

Parameters:

`allocatedObject`: return parameter containing a pointer to the allocated shared object.

Return value:

= if succeed, **shareObjectID** (its index in the array).

= Else, **E_NO_SHARE**: if the "shares" array is full.

Get Shared Object ID

Function declaration:

```
int get_share_object_ID(int ownerID, char * shareObjectName)
```

Description:

Get the array index of the shared object by searching the "shares" array with the given "ownerID" and "shareObjectName".

Parameters:

ownerID: ID of the owner environment of the required shared object

shareObjectName: name of the shared object to find

Return value:

= **shareObjectID** index in the array: if found.

= **E_SHARED_MEM_NOT_EXISTS**: if not found.

Free Shared Object

Function declaration:

```
int free_share_object(int semaphoreObjectID)
```

Description:

deletes the object with given "shareObjectID" from the "**shares**" array (i.e. set its empty flag to 1, delete "frames_storage" and clear all other members (name, value…)).

Parameters:

`shareObjectID`: ID of the shared object to be removed (i.e. its index in the array).

Return value:

= 0: if found.

= **E_SHARED_MEM_NOT_EXISTS**: if not found.

Store certain frame into shared object "frames storage"

Function declaration:

```
void add_frame_to_storage (uint32*  frames_storage , struct Frame_Info* ptr_frame_info,
                           uint32   index)
```

Description:

Store a **Frame_Info*** inside the shared object frames storage [**Share:: framesStorage**] associated with a frame index

Parameters:

frames_storage: the frames storage of a shared object [**Share:: framesStorage**]

ptr_frame_info: the Frame_Info* to store

index: the index desired to be given of the frame after adding to the storage

Example1: Add a first new allocated frame (index 0) to the storage of shared object number 0

Struct Frame_Info ptr_new_frame = 0*;

allocate_frame(&ptr_new_frame);

add_frame_to_storage(**shares**[0].framesStorage, *ptr_new_frame*, 0);

Example2: Add a second allocated frame to the storage of shared object number 0

add_frame_to_storage(**shares**[0].framesStorage, *ptr_new_frame*, 1);

Example3: Add a 3rd allocated frame to the storage of shared object number 1

add_frame_to_storage(**shares**[1].framesStorage, *ptr_new_frame*, 2);

Retrieves a certain frame from shared object "frames storage"

Function declaration:

struct Frame_Info* get_frame_from_storage (uint32* frames_storage , uint32 index)

Description:

Retrieves a **Frame_Info*** from the shared object frames storage [**Share:: framesStorage**] associated with a frame index

Parameters:

frames_storage: the frames storage of a shared object [**Share:: framesStorage**]

index: the index of the frame desired to be retrieved from the storage

Return value:

struct Frame_Info* : the retrieved frame at index from frames_storage

Example1:

Retrieve the first frame (index 0) of shared object 0 from the storage

struct Frame_Info ptr_new_frame* = **get_frame_from_storage** (**shares**[0].framesStorage, 0);

Example2:

Retrieve the 3rd frame of shared object 1 from the storage

struct Frame_Info ptr_new_frame* = **get_frame_from_storage** (**shares**[1].framesStorage, 2);

Removes all stored frames from shared object "frames storage"

Function declaration:

void get_frame_from_storage (uint32* frames_storage)

Description:

Removes all **Frame_Info*** instances from the shared object frames storage [**Share:: framesStorage**]

Parameters:

frames_storage: the frames storage of a shared object [**Share:: framesStorage**] to remove all its Frame_Info*

Get Size of a Shared Variable

Function declaration:

int getSizeOfSharedObject(int32 ownerID, char* shareName)

Description:

Returns the size of the given shared object with the given ownerID and name

Parameters:

ownerID: The ID of the owner environment

shareName: The shared variable name that its size needs to be known.

Appendix IX: Command Prompt

Ready-Made Commands

Run process

Name: **`run <program name> <page WS size> <percent of WS pages>`**

Arguments:

Program name: name of user program to load and run (should be identical to name field in UserProgramInfo array).

Page WS size: specify the max size of the page WS for this program

Percent of WS pages: specify the percentage of the allocated pages in WS that should be removed when the memory becomes scarce or the WS becomes full

Description:

Load the given program into the virtual memory (RAM & Page File) then run it.

Load process

Name: **`load <program name> <page WS size> <percent of WS pages>`**

Arguments:

Program name: name of user program to load it into the virtual memory (should be identical to name field in UserProgramInfo array).

Page WS size: specify the max size of the page WS for this program

Percent of WS pages: specify the percentage of the allocated pages in WS that should be removed when the memory becomes scarce or the WS becomes full

Description:

JUST Load the given program into the virtual memory (RAM & Page File) but **don't run** it.

Kill process

Name: **`kill <env ID>`**

Arguments:

Env ID: ID of the environment to be killed (i.e. freeing it).

Description:

Kill the given environment by calling env_free.

Run all loaded processes

Name: **`runall`**

Description:

Run all programs that are previously loaded by **"ld"** command using Round Robin scheduling algorithm.

Print all processes

Name: **printall**

Description:

Print all programs' names that are currently exist in new, ready and exit queues.

Kill all processes

Name: **killall**

Description:

Kill all programs that are currently loaded in the system (new, ready and exit queues. (by calling env_free).

Print current scheduler method (round robin, MLFQ, …)

Name: **sched?**

Description:

Print the current scheduler method with its quantum(s) (RR or MLFQ).

Change the Scheduler to Round Robin

Name: **schedRR** <quantum in ms>

Description:

Change the scheduler to round robin with the given quantum (in ms).

Change the Scheduler to MLFQ

Name: **schedMLFQ** <number of levels> <1st quantum> <2nd quantum> …

Description:

Change the scheduler to MLFQ with the given number of levels and their quantums (in ms).

Print current replacement policy (clock, LRU, …)

Name: **rep?**

Description:

Print the current page replacement algorithm (CLOCK, LRU, FIFO or modifiedCLOCK).

Changing replacement policy (clock, LRU, …)

Name: **clock** *(***lru, fifo, modifiedclock***)*

Description:

Set the current page replacement algorithm to CLOCK (LRU, FIFO or modifiedCLOCK).

Print current user heap placement strategy (NEXT FIT, BEST FIT, …)

Name: **uheap?**

Description:

Print the current USER heap placement strategy (NEXT FIT, BEST FIT, …).

Changing user heap placement strategy (NEXT FIT, BEST FIT, …)

Name: **uhnextfit** *(***uhbestfit***,* **uhfirstfit, uhworstfit***)*

Description:

Set the current user heap placement strategy to NEXT FIT (BEST FIT, …).

Print current kernel heap placement strategy (CONT ALLOC, NEXT FIT, BEST FIT, …)

Name: **kheap?**

Description:

Print the current KERNEL heap placement strategy (CONT ALLOC, NEXT FIT, BEST FIT, …).

Changing kernel heap placement strategy (NEXT FIT, BEST FIT, …)

Name: **khcontalloc** *(***khnextfit, khbestfit***,* **khfirstfit, khworstfit***)*

Description:

Set the current KERNEL heap placement strategy to NEXT FIT (BEST FIT, …).

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 X: 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 ☺