VIETNAM NATIONAL UNIVERSITY, HO CHI MINH CITY
UNIVERSITY OF TECHNOLOGY
FACULTY OF COMPUTER SCIENCE AND ENGINEERING

OPERATING SYSTEM (CO2017)

Assignment

"Simple Operating System"

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Member list & Workload

No.	Fullname	Student ID	Problems	% done
1	Nguyễn Thái Học	2311100	- Implement memory section - Answering memory questions - Put it all together	100%
2	Lê Nguyễn Kim Khôi	2311671	- Implement memory section - Explaining the memory implementation - Put it all together	100%
3	Huỳnh Đức Nhân	2312420	- Implement sheduling, syscall section - Explaining schedule, syscall implementation - Answering syscall questions	100%
4	Hồ Anh Dũng	2310543	- Implement sheduling and syscall section - Shedule, syscall testcase - Answering schedule, syscall questions	100%
5	Nguyễn Thiện Minh	2312097	- Implement memory section - Create, explain Memory Testcase - Put it all together	100%

Table 1: Member list & workload

Introduction

This report presents our work on the "Simple Operating System" assignment for the CO2017 Operating Systems course. The main goal of this project was to gain a hands-on understanding of how fundamental operating system concepts work by building and simulating several key components. Through this process, we aimed to learn more about their internal mechanisms, how they interact with each other, and some of the challenges involved in OS development.

For this assignment, our team focused on implementing and integrating three main modules that are essential for an operating system:

- **Scheduler:** We designed and implemented a scheduler to manage how processes get to use the CPU. Our approach uses a Multi-Level Queue (MLQ) policy to prioritize and schedule processes.

- **Memory Management:** This part involved simulating how an OS handles memory. We focused on a paging-based virtual memory system, including how memory is allocated and deallocated, how virtual addresses are translated to physical ones, and basic page swapping.

- **System Call Interface:** We built a basic interface that allows user programs to request services from our OS kernel. As part of this, we implemented a custom system call, `killall`, to demonstrate process control functionality.

We also included basic synchronization mechanisms to handle situations where different parts of our OS might try to access shared data at the same time, which is important in systems with multiple CPUs or concurrent operations.

To help you navigate our work, this report is organized as follows:

- We start by explaining our **Queue Implementation Strategy**, as queues are a basic building block for our scheduler.

- Next, the **Scheduling Logic and Design Decisions** section describes how our MLQ scheduler works, including how processes are managed and terminated.

- The **Memory Implementation** section covers our approach to virtual and physical memory, including details on allocation, deallocation, and read/write operations in our paging system.

- We then discuss the **Design of the `killall` System Call**, which was a specific task in the assignment.

- A key part of our report is the **Test Cases** section. Here, we show the setup, logs, and our analysis for different tests we ran on the scheduler, memory manager, and system calls to check if they work correctly and to show how they behave.

- Finally, in the **Answering Questions** section, we address specific questions from the assignment, discussing our design choices, the pros and cons of the algorithms we used, and other OS design considerations.

Our aim with this project was to meet the assignment's requirements and, more importantly, to better understand how operating systems perform their complex but essential functions in making a computer usable and efficient. We hope this report clearly shows what we've learned and accomplished.

1 Queue Implementation Strategy

In our project, the queue is implemented as a fixed-size array (`MAX_QUEUE_SIZE = 10`), with two main operations: `enqueue`, which adds a process to the queue, and `dequeue`, which removes the process with the highest priority (i.e., the lowest `prio` value).
There are three general strategies to implement this queue:

1. **Simple Enqueue + Min-Priority Dequeue:** Insert the new process at the end of the queue. During `dequeue`, scan the entire array to find the process with the minimum priority, remove it, and shift the remaining elements to fill the gap.

2. **Sorted Enqueue + Fast Dequeue:** Insert the new process while maintaining the array sorted in descending priority order. This allows `dequeue` to simply remove the last element.

3. **Hybrid Enqueue + Dequeue:** Depending on the scheduler type (`#ifdef MLQ_SCHED` for MLQ or `#else` for a single shared queue), different strategies are used. In MLQ mode, each queue contains processes of the same priority, so we can simply append the new process during `enqueue` and take the first process during `dequeue`. In single-queue mode, strategy (2) offers optimal performance.

Although strategies (2) and (3) offer better asymptotic performance for `dequeue`, they introduce additional implementation complexity, such as maintaining a sorted structure or handling dynamic memory. Given that our queue is small (size = 10) and fixed, the overhead of scanning and shifting elements in strategy (1) is negligible in practice.

Therefore, I chose to implement the queue using strategy (1). This decision is motivated by the simplicity and clarity of the approach, as well as its consistency across both scheduling modes: `#ifdef MLQ` (multi-level queues with same-priority processes in a queue) and `#else` (a single queue shared across all priorities). Using a unified queue logic also improves modularity and reusability of the queue structure, which may benefit future extensions beyond process scheduling.

```c
void enqueue(struct queue_t * q, struct pcb_t * proc) {
    if (q == NULL || proc == NULL || q->size >= MAX_QUEUE_SIZE) {
        printf("Queue is full or NULL\n");
        return;
    }
    q->proc[q->size] = proc;
    q->size++;
}
struct pcb_t * dequeue(struct queue_t * q) {
    if (q == NULL || q->size == 0) return NULL;
    int MAX_INDEX = 0;
    #ifdef MLQ_SCHED
        uint32_t MAX = q->proc[0]->prio;
        for (int i = 1; i < q->size; i++) {
            if (q->proc[i]->prio < MAX) {
                MAX = q->proc[i]->prio;
                MAX_INDEX = i;
            }
        }
    #else
        uint32_t MAX = q->proc[0]->priority;
        for (int i = 1; i < q->size; i++) {
```

```
23            if (q->proc[i]->priority < MAX) {
24                MAX = q->proc[i]->priority;
25                MAX_INDEX = i;
26            }
27        }
28    #endif
29    struct pcb_t * ret_proc = q->proc[MAX_INDEX];
30    for (int i = MAX_INDEX; i < q->size - 1; i++) {
31        q->proc[i] = q->proc[i + 1];
32    }
33    q->size--;
34    return ret_proc;
35 }
```

We also implement an extra function, `remove_proc`, which removes a specified process from the queue.

2 Scheduling Logic and Design Decisions

The core of the scheduler implementation consists of several key functions that manage the selection and movement of processes for execution. While some functions are relatively straightforward, the primary complexity lies in the logic of `get_proc`, particularly under the multi-level queue (MLQ) model.

2.1 Process Management Functions

Basic functions such as `put_proc` and `add_proc` are implemented with minimal logic:

- `add_proc`: This function is called by `ld_routine`, meaning it is used when a process is loaded. The process is simply enqueued into either `mlq_ready_queue` or `ready_queue`, and the process's pointer is set accordingly.

- `put_proc`: After `cpu_routine` retrieves a process from `get_proc`, it calls `put_proc` to reinsert the previously running process into the appropriate queue. This function removes the process from `running_list` (using `remove_proc`) and enqueues it into the ready queue.

```
1  void put_proc(struct pcb_t * proc) {
2      proc->ready_queue = &ready_queue;
3      proc->mlq_ready_queue = mlq_ready_queue;
4
5      pthread_mutex_lock(&queue_lock);
6      enqueue(&mlq_ready_queue[proc->prio], proc);
7      remove_proc(&running_list, proc);
8      proc->running_list = NULL;
9      pthread_mutex_unlock(&queue_lock);
10
11     return;
12 }
13
14 void add_proc(struct pcb_t * proc) {
15     proc->ready_queue = &ready_queue;
16     proc->mlq_ready_queue = mlq_ready_queue;
```

```
17
18      return add_mlq_proc(proc);
19  }
```

Additionally, the `running_list` is used to track processes that are currently running. So if a process is in ready queue, running_list pointer must be NULL.

Depending on the scheduling mode (controlled via `#ifdef MLQ`), `get_proc` returns a process from the appropriate queue. In non-MLQ mode, this is done by simply dequeuing the highest-priority process from the `ready_queue`. In MLQ mode, the logic is more involved:

- The scheduler maintains an array of queues, one for each priority level up to `MAX_QUEUE = 140`.

- Each queue has an associated `time_slot`, calculated as `MAX_QUEUE - prio`, meaning that higher-priority queues are allowed more execution slots.

- The `get_proc` function iterates through the queues in order of priority and attempts to retrieve a process from the first queue that has remaining time slots.

A critical design decision was determining when to reset the time slots. Several options were considered:

- Reset only when all time slots are exhausted (which may lead to starvation if processes only exist in a few priority levels).

- Reset when there are no runnable processes available (i.e., all queues are empty or blocked).

To balance safety and fairness, our implementation resets time slots under either of the following conditions:

1. All time slots have reached zero.

2. No process is runnable in the currently selected queue (i.e., `proc == NULL`).

```
1   struct pcb_t * get_mlq_proc(void) {
2       static int reset_slot = 0;
3       struct pcb_t * proc = NULL;
4
5       pthread_mutex_lock(&queue_lock);
6       for (int i = 0; i < MAX_PRIO; i++) {
7           if (slot[i] == 0) continue;
8           proc = dequeue(&mlq_ready_queue[i]);
9           if (proc != NULL) {
10              int proc_time_slot = proc->code->size - proc->pc;
11
12              if (proc_time_slot > slot[i]) proc_time_slot = slot[i];
13              if (proc_time_slot > time_slot) proc_time_slot = time_slot;
14
15              slot[i] -= proc_time_slot;
16              proc->time_slot = proc_time_slot;
17              reset_slot = 1;
18              break;
19          }
```

```
20        }
21
22        if (proc != NULL) {
23            enqueue(&running_list, proc);
24            proc->running_list = &running_list;
25        }
26        else if (reset_slot == 1) {
27            for (int i = 0; i < MAX_PRIO; i++)
28                slot[i] = MAX_PRIO - i;
29            reset_slot = 0;
30            //Re-get process
31            //.............
32        }
33        pthread_mutex_unlock(&queue_lock);
34
35        return proc;
36 }
```

Before returning a process from `get_proc`, it is added to the `running_list`, and its pointer is updated accordingly too. To avoid premature or unnecessary resets, a flag `reset_slot` is introduced to detect changes in the slot states. This ensures that time slot resets occur only after actual usage begins, and not immediately after initialization when all time slots are still untouched.

2.2 Process Termination Functions

Since the initial codebase lacks functionality for terminating a process, we implement such functionality for use in `syscall killall`. The main function we introduce is `remove_pcb`, which removes a process from all relevant queues and deallocates its memory (delegated to the helper function `delete_pcb`).

Because our operating system does not support forcibly terminating a running process, this function is implemented to terminate only ready or finished process. If we want to terminate a process, we need to make that process finishes its job first (we will dicuss about this case in killall implementation). Function `remove_pcb` simply dequeued from all relevant queues and passed to `delete_pcb` for memory deallocation.

```
1 void delete_pcb(struct pcb_t *proc)
2 {
3     if (proc->page_table != NULL) free(proc->page_table);
4     if (proc->code != NULL) {
5         if (proc->code->text != NULL) free(proc->code->text);
6         free(proc->code);
7     }
8     #ifdef MM_PAGING
9         if (proc->mm != NULL) {
10            if (proc->mm->pgd != NULL) free(proc->mm->pgd);
11            struct vm_rg_struct* head = proc->mm->mmap->vm_freerg_list;
12            while (head != NULL) {
13                struct vm_rg_struct* tmp = head;
14                head = head->rg_next;
15                free(tmp);
16            }
17            if (proc->mm->mmap != NULL) free(proc->mm->mmap);
```

```
18              free(proc->mm);
19          }
20      #endif
21  }
22
23  void remove_pcb(struct pcb_t *proc) {
24      if (proc->running_list != NULL) {
25          remove_proc(proc->running_list, proc);
26      }
27      else {
28          #ifdef MLQ_SCHED
29              remove_proc(&mlq_ready_queue[proc->prio], proc);
30          #else
31              remove_proc(&ready_queue, proc);
32          #endif
33      }
34      delete_pcb(proc);
35      free(proc);
36  }
```

3   Memory Implementation

In the Memory Management design of this simple OS implementation, the design is divided into smaller modules as follows: Libmem acts as an interface that allows users to interact with the OS; the mm-vm layer is responsible for managing virtual memory; the mm layer directly handles the interaction between the virtual memory layer and the physical memory layer; and finally, the mm-memphy layer manages the physical memory regions within the OS.
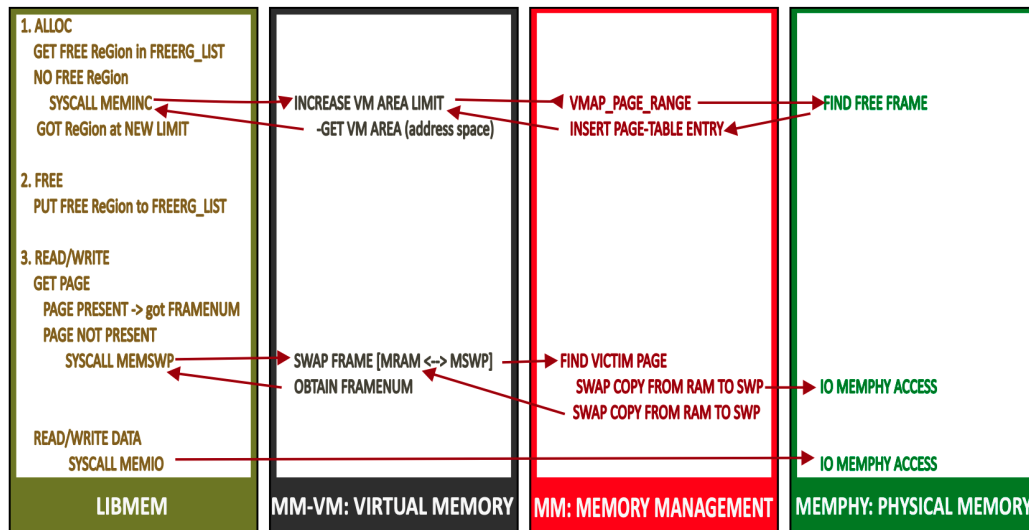

Figure 1: Memory System Modules

In order to gather the requirements from the design, it is necessary to reiterate the design

assumptions that were mentioned in the problem statement for designing a basic operating system as follows.

- ALLOC: user call the library functions in libmem and in most cases, it fits into data segment area. If there is no suitable space, we need to expand the memory space by lift up the barrier set by sbrk. Since it have never been touched, it may needs to leverage some MMU systemcalls to obtains physical frames and then map them using Page Table Entry.

- FREE: user call the library functions in libmem to revoke the storage space associated with the given region id. Since we cannot reclaim the taken physical frame which might cause memory holes, we just keep the collected storage space in a free list for future alloc request, all are embedded in libmem library.

- READ/WRITE: requires to get the page to be presented in the main memory. The most resource consuming step is the page swapping. If the page is in the MEMSWAP device, it needs to be brought back to MEMRAM device (swapping in) and if there is a lack of space, we need to give back some pages to MEMSWAP device (swapping out) to make more rooms.

3.1 Alloc Implementation

```c
int __alloc(struct pcb_t *caller, int vmaid, int rgid, int size, int *
    alloc_addr)
{
  if (rgid < 0 || rgid > PAGING_MAX_SYMTBL_SZ)
    return -1;
  /*Allocate at the toproof */
  pthread_mutex_lock(&mmvm_lock);
  struct vm_rg_struct rgnode;

  /* TODO: commit the vmaid */
  // rgnode.vmaid

  if (get_free_vmrg_area(caller, vmaid, size, &rgnode) == 0)
  {
    caller->mm->symrgtbl[rgid].rg_start = rgnode.rg_start;
    caller->mm->symrgtbl[rgid].rg_end = rgnode.rg_end;

    *alloc_addr = rgnode.rg_start;

    pthread_mutex_unlock(&mmvm_lock);
    return 0;
  }

  /* TODO get_free_vmrg_area FAILED handle the region management (Fig.6)
      */

  /* TODO retrieve current vma if needed, current comment out due to
      compiler redundant warning*/
  /*Attempt to increate limit to get space */
  struct vm_area_struct *cur_vma = get_vma_by_num(caller->mm, vmaid);
  if(cur_vma == NULL){
```

```
29    pthread_mutex_unlock(&mmvm_lock);
30    return -1;
31  }
32
33  /* TODO INCREASE THE LIMIT as invoking systemcall
34   * sys_memap with SYSMEM_INC_OP
35   */
36  struct sc_regs regs;
37  regs.a1 = SYSMEM_INC_OP;
38  regs.a2 = vmaid;
39  regs.a3 = size;
40  /* SYSCALL 17 sys_memmap */
41  syscall(caller, 17, &regs);
42
43  /* TODO: commit the limit increment */
44  if (get_free_vmrg_area(caller, vmaid, size, &rgnode) == 0){
45    caller->mm->symrgtbl[rgid].rg_start = rgnode.rg_start;
46    caller->mm->symrgtbl[rgid].rg_end = rgnode.rg_end;
47
48    *alloc_addr = rgnode.rg_start;
49
50    pthread_mutex_unlock(&mmvm_lock);
51    return 0;
52  }
53  /* TODO: commit the allocation address */
54  pthread_mutex_unlock(&mmvm_lock);
55  return -1;
56 }
```

Listing 1: Function `__alloc`

The `__alloc` function acts as a middleware interface between user processes and the virtual memory management system, allowing a process to request a memory region within a specified segment (e.g., heap or data). It receives parameters such as the calling process (PCB), virtual memory area ID (`vmaid`), region ID (`rgid`), requested size, and a pointer to store the allocated address. Initially, it validates input parameters—especially ensuring `rgid` is within bounds. A mutex is used to lock the memory resource, preventing race conditions. The system first attempts to find an existing free region; if found, it updates the allocation info in the `symrgtbl` and returns the base address. If no suitable space is available, it invokes the system call `sys_memmap` with `SYSMEM_INC_OP` to expand memory limits. The allocation attempt is then retried. If it still fails, the function returns `-1`. This two-step strategy (search–expand–retry) improves efficiency by avoiding unnecessary memory expansion and ensures proper synchronization and memory reuse, thereby enhancing system performance.

```
1 int inc_vma_limit(struct pcb_t *caller, int vmaid, int inc_sz)
2 {
3   struct vm_rg_struct * newrg = malloc(sizeof(struct vm_rg_struct));
4   int inc_amt = PAGING_PAGE_ALIGNSZ(inc_sz);
5   int incnumpage =  inc_amt / PAGING_PAGESZ;
6   struct vm_rg_struct *area = get_vm_area_node_at_brk(caller, vmaid,
        inc_sz, inc_amt);
7   struct vm_area_struct *cur_vma = get_vma_by_num(caller->mm, vmaid);
8
9   int old_end = cur_vma->vm_end;
```

```
10
11    if (area == NULL) return -1;
12
13    /*Validate overlap of obtained region */
14    if (validate_overlap_vm_area(caller, vmaid, area->rg_start, area->
          rg_end) < 0){
15      free(area);
16      return -1; /*Overlap and failed allocation */
17    }
18
19    /* TODO: Obtain the new vm area based on vmaid */
20    // cur_vma->vm_end += inc_amt;
21    // cur_vma->sbrk += inc_amt;
22    // // inc_limit_ret...
23
24    if (vm_map_ram(caller, area->rg_start, area->rg_end,
25                     old_end, incnumpage , newrg) < 0){
26      free(area);
27      return -1; /* Map the memory to MEMRAM */
28    }
29
30    cur_vma->vm_end += inc_amt;
31    cur_vma->sbrk += inc_amt;
32    enlist_vm_rg_node(&caller->mm->mmap->vm_freerg_list, newrg);
33    free(area);
34    return 0;
35  }
```

Listing 2: Function `inc_vma_limit`

The `inc_vma_limit` function is responsible for safely expanding the size limit of a virtual memory area (VMA) within a process, typically used when regions like the heap or data segment run out of allocatable space. It takes the calling process, the target VMA ID, and the requested increment size in bytes. The size is first aligned to the system's page size for compatibility with paging. The function then seeks a free memory region adjacent to the current VMA end to maintain continuity. It verifies that the proposed extension does not overlap with any existing memory areas. If the region is valid, the function maps it into physical RAM. If the mapping fails, the expansion is aborted. Upon success, control structures are updated: `vm_end` is moved to the new boundary, and if applicable, `sbrk` is adjusted. Any surplus memory is added to the free region list for reuse. Overall, `inc_vma_limit` bridges logical allocation needs and physical memory mapping, ensuring expansion is safe, non-overlapping, and well-integrated into memory management.

```
1  int get_free_vmrg_area(struct pcb_t *caller, int vmaid, int size, struct
       vm_rg_struct *newrg)
2  {
3    struct vm_area_struct * vma = get_vma_by_num(caller->mm, vmaid);
4    if (vma == NULL) return -1;
5    for (struct vm_rg_struct ** p_rgit = &vma->vm_freerg_list; *p_rgit;
         p_rgit = &((*p_rgit)->rg_next)) {
6      struct vm_rg_struct * rgit = *p_rgit;
7      if (rgit->rg_start + size == rgit->rg_end) {
8        newrg->rg_start = rgit->rg_start;
9        newrg->rg_end = rgit->rg_end;
```

```
10        *p_rgit = rgit->rg_next;
11        free(rgit);
12        return 0;
13      }
14      if (rgit->rg_start + size < rgit->rg_end) {
15        newrg->rg_start = rgit->rg_start;
16        newrg->rg_end = rgit->rg_start += size;
17        return 0;
18      }
19    }
20    return -1;
21 }
```

Listing 3: Function `get_free_vmrg_area`

The `get_free_vmrg_area` function is a key component in managing a process's virtual memory regions (VMRs), responsible for locating a free memory region within a specified virtual memory area (VMA). It receives the requesting process, the VMA ID, the aligned size to allocate, and a reference to `newrg` which will hold the resulting region if successful. First, it retrieves the corresponding `vm_area_struct`. If not found, the function returns `-1`. It then iterates over the `vm_freerg_list`, checking whether any free region is large enough for the requested size. If a region matches exactly, it is removed from the list and returned. If larger, the region is split—`newrg` receives the front portion, and the leftover remains in the free list. If no suitable region exists, the function returns `-1`, signaling the need to expand the VMA using `inc_vma_limit`. This strategy optimizes memory reuse, avoids unnecessary expansions, and enhances performance by leveraging existing free space within the virtual memory area.

```
1  int vmap_page_range(struct pcb_t *caller,      // process call
2                      int addr,                  // start address
                         which is aligned to pagesz
3                      int pgnum,                 // num of mapping
                         page
4                      struct framephy_struct *frames, // list of the mapped
                          frames
5                      struct vm_rg_struct *ret_rg)   // return mapped
                         region, the real mapped fp
6  {                                              // no guarantee all
      given pages are mapped
7    // struct framephy_struct *fpit = malloc(sizeof(struct framephy_struct)
       );
8    struct framephy_struct *fpit;
9    int pgit = 0;
10   int pgn = PAGING_PGN(addr);
11
12   /* TODO: update the rg_end and rg_start of ret_rg */
13   ret_rg->rg_start = addr;
14   ret_rg->rg_end = addr + pgnum * PAGING_PAGESZ;
15   // ret_rg->vmaid = ;
16
17   /* TODO map range of frame to address space
18    *      [addr to addr + pgnum*PAGING_PAGESZ
19    *      in page table caller->mm->pgd[]
20    */
21
```

```
22    if( frames == NULL)  return -1;
23    fpit = frames;
24    for (; pgit < pgnum; ++pgit)
25    {
26      pte_set_fpn(&caller->mm->pgd[pgn + pgit], fpit->fpn);
27      enlist_pgn_node(&caller->mm->fifo_pgn, pgn + pgit);
28
29      fpit = fpit->fp_next;
30      free(frames);
31      frames = fpit;
32    }
33
34    return 0;
35 }
```

<div align="center">Listing 4: Function <code>vmap_page_range</code></div>

The `vmap_page_range` function plays a crucial role in mapping a contiguous range of virtual memory pages to corresponding physical frames and updating the process's page table. It takes the calling process, the starting address (aligned to page size), the number of pages to map, the list of allocated physical frames, and a pointer `ret_rg` to store the mapped region. The function calculates the end address of the mapping, validates the input, and checks if the frame list is empty. It then iterates over the requested pages, updating the page table entry for each page, mapping the virtual address to the physical frame, and adding the virtual page number to the FIFO queue for future page replacement policies. If all mappings succeed, the function returns 0. This process is integral for managing virtual memory and physical memory mappings, ensuring the system's memory management operates efficiently and correctly.

3.2   Free Implementation

```
1  int __free(struct pcb_t *caller, int vmaid, int rgid)
2  {
3    struct vm_rg_struct *rgnode;
4
5    // Dummy initialization for avoiding compiler dummy warning
6    // In incomplete TODO code rgnode will be overwritten through
        implementing
7    // the manipulation of rgid later
8
9    if(rgid < 0 || rgid > PAGING_MAX_SYMTBL_SZ)
10     return -1;
11   pthread_mutex_lock(&mmvm_lock);
12
13   rgnode = &caller->mm->symrgtbl[rgid];
14   if(rgnode->rg_start >= rgnode->rg_end){
15     pthread_mutex_unlock(&mmvm_lock);
16     return -1;
17   }
18
19   /* TODO: Manage the collect freed region to freerg_list */
20
21   /* Enlist the obsoleted memory region */
22   enlist_vm_freerg_list(caller->mm, rgnode);
```

```
23    pthread_mutex_unlock (&mmvm_lock);
24
25    return 0;
26  }
```

<div align="center">Listing 5: Function __free</div>

The `__free` function is responsible for freeing previously allocated memory. It removes a memory region, identified by `rgid`, from the process's memory symbol table and adds it to the free memory list (`freerg_list`) for future reuse. The function checks the validity of `rgid`, and if invalid, returns `-1`. It then locks the memory manager mutex (`mmvm_lock`) to ensure thread safety. After retrieving the corresponding memory region from the symbol table, it checks whether the region's start address is valid. If valid, it adds the region to the free memory list and unlocks the mutex before returning `0`, signaling successful memory deallocation. This function helps optimize memory reuse and ensures safe concurrent access by using mutex locking.

3.3 Read and Write Implementation

```
1  int pg_getpage (struct mm_struct *mm, int pgn, int *fpn, struct pcb_t *
       caller)
2  {
3    uint32_t pte = mm->pgd[pgn];
4
5    if (!PAGING_PAGE_PRESENT(pte))
6    { /* Page is not online, make it actively living */
7      int vicpgn, swpfpn;
8      int vicfpn;
9      uint32_t vicpte;
10
11     int tgtfpn = PAGING_PTE_SWP(pte); // the target frame storing our
           variable
12
13     /* TODO: Play with your paging theory here */
14     /* Find victim page */
15     if(find_victim_page(caller->mm, &vicpgn) != 0)  return -1;
16
17     /* Get free frame in MEMSWP */
18     vicfpn = PAGING_PTE_FPN(caller->mm->pgd[vicpgn]);
19     MEMPHY_get_freefp(caller->active_mswp, &swpfpn);
20
21     /* TODO: Implement swap frame from MEMRAM to MEMSWP and vice versa */
22     struct sc_regs regs;
23     regs.a1 = SYSMEM_SWP_OP;
24     regs.a2 = vicfpn;
25     regs.a3 = swpfpn;
26
27     /* SYSCALL 17 sys_memmap */
28     syscall(caller, 17, &regs);
29
30     /* Swap target frame from SWAP to MEMRAM */
31     __swap_cp_page(caller->active_mswp, tgtfpn, caller->mram, vicfpn);
32
33     /* Update page table */
```

```
34      pte_set_swap (&mm->pgd[vicpgn], caller ->active_mswp_id, swpfpn);
35      pte_set_fpn (&mm->pgd[pgn], vicfpn);
36
37      enlist_pgn_node (&caller ->mm->fifo_pgn, pgn);
38    }
39
40    *fpn = PAGING_FPN (mm ->pgd[pgn]);
41
42    return 0;
43  }
```

Listing 6: Function `pg_getpage`

The `pg_getpage` function is responsible for retrieving a specific page from RAM, identified by the Page Number (`pgn`). If the page is not present in RAM, it performs actions to swap the page from swap memory into RAM. The function first checks the page's status in the page table (`pgd[pgn]`) and if the page is not present, it initiates a page replacement process. A victim page is selected and swapped out to swap memory using syscall 17 (`sys_memmap`) with swap operation. The required page is then swapped into RAM. The page table is updated to reflect these changes, including pointing the victim page to swap memory and the new page to the corresponding physical frame. Finally, the page is added to the FIFO queue of accessed pages and the function returns the physical frame number (FPN) of the requested page.

```
1  int pg_getval(struct mm_struct *mm, int addr, BYTE *data, struct pcb_t *
       caller)
2  {
3    int pgn = PAGING_PGN(addr);
4    int off = PAGING_OFFST(addr);
5    int fpn;
6    pthread_mutex_lock(&mmvm_lock);
7
8    /* Get the page to MEMRAM, swap from MEMSWAP if needed */
9    if (pg_getpage(mm, pgn, &fpn, caller) != 0)
10     return -1; /* invalid page access */
11
12   int phyaddr = (fpn << PAGING_ADDR_FPN_LOBIT) + off;
13
14   /* SYSCALL 17 sys_memmap with SYSMEM_IO_READ */
15   struct sc_regs regs;
16   regs.a1 = SYSMEM_IO_READ;
17   regs.a2 = phyaddr;
18
19   syscall(caller, 17, &regs);
20
21   /* Update data */
22   *data = (BYTE)regs.a3;
23   pthread_mutex_unlock(&mmvm_lock);
24   return 0;
25 }
```

Listing 7: Function `pg_getval`

The `pg_getval` function is responsible for reading a value from a virtual address in a process's memory space and returning it. If the page for that address is not present in RAM, the function

performs a swap operation to load the page from swap memory into RAM. The function first extracts the page number (PGN) and the offset from the virtual address using `PAGING_PGN(addr)` and `PAGING_OFFST(addr)`. It then locks the memory mutex (`mmvm_lock`) to prevent race conditions. The page is fetched from RAM, and if not found, it is swapped in from swap memory using the `pg_getpage` function. Once the physical page frame number (FPN) is obtained, the physical address is calculated and the value is read from memory using syscall 17 (SYSMEM_IO_READ). The value read is returned via the `data` pointer. Finally, the mutex is unlocked and the function returns successfully.

```c
int pg_setval(struct mm_struct *mm, int addr, BYTE value, struct pcb_t *
    caller)
{
  pthread_mutex_lock(&mmvm_lock);
  int pgn = PAGING_PGN(addr);
  int off = PAGING_OFFST(addr);
  int fpn;

  /* Get the page to MEMRAM, swap from MEMSWAP if needed */
  if (pg_getpage(mm, pgn, &fpn, caller) != 0)
    return -1; /* invalid page access */

  int phyaddr = (fpn << PAGING_ADDR_FPN_LOBIT) + off;

  /* SYSCALL 17 sys_memmap with SYSMEM_IO_WRITE */
  struct sc_regs regs;
  regs.a1 = SYSMEM_IO_WRITE;
  regs.a2 = phyaddr;
  regs.a3 = value;

  syscall(caller, 17, &regs);

  pthread_mutex_unlock(&mmvm_lock);
  return 0;
}
```

Listing 8: Function `pg_setval`

The `pg_setval` function is responsible for writing a value to a specific virtual address in a process's memory. If the page for that address is not present in RAM, the function performs a swap operation to load the page from swap memory into RAM. First, it extracts the page number (PGN) and offset from the virtual address using `PAGING_PGN(addr)` and `PAGING_OFFST(addr)`. It then locks the memory mutex (`mmvm_lock`) to ensure safe access and prevent race conditions. The function uses `pg_getpage` to fetch the physical memory frame (FPN) from the page table. If the page is not found, the function returns an error. Once the physical frame is obtained, the physical address is calculated and the value is written to memory using syscall 17 (SYSMEM_IO_WRITE). After the operation, the mutex is unlocked and the function returns success.

4 System Call `killall` Design

To support bulk process termination by name, we implement a new system call named `killall`. Given the simplicity of our operating system's architecture, this syscall is designed to terminate

all processes whose names match a specified target string.

The name of the target process to be terminated is passed via a predefined memory region identified by `REGIONID`, and is retrieved using the utility function `libread`, which has already been implemented in the memory module.

Each process in our system stores its executable name within the `path[]` field of its `pcb_t` structure. Using this field, we compare against the target name to identify matching processes. To ensure that no matching processes are missed, we scan all relevant queues:

- The `running_list`, which contains processes currently executing.

- Either `mlq_ready_queue[]` (in MLQ mode) or the single `ready_queue` (in non-MLQ mode).

Since the logic for scanning a queue and terminating matching processes is common across these queues, we define a helper function, `kill_in_queue()`, to encapsulate this functionality. It iterates over a given queue, compares each process's name with the target, and invokes `remove_pcb()` for each match in ready queue. If process is running, we only make its pc go to the end of code to notice the CPU that the process is finished and it's time to kill the process. The total number of terminated processes is accumulated and returned by the syscall.

```c
int kill_in_queue(struct queue_t *proc_queue, char *proc_name)
{
    int count = 0, i = 0;

    while (i < proc_queue->size) {
        struct pcb_t *proc = proc_queue->proc[i];
        if (proc == NULL) {
            ++i;
            continue;
        }

        int same_name = check_name(proc_name, proc->path);
        if (same_name == 1) {
            printf("Process %s with PID: %2d is killed\n", proc_name,
                proc->pid);
            if (proc->running_list != NULL) {
                remove_proc(proc->running_list, proc);
                proc->running_list = NULL;
                proc->pc = proc->code->size;
            }
            else {
                remove_pcb(proc);
            }
            ++count;
        }
        else ++i;
    }

    return count;
}
```

An important design decision was to place the `remove_pcb()` function within `sched.c`. This is due to the potential concurrency issues that may arise when removing a process that is currently running or being accessed by other components (e.g., via `get_proc()`).

To mitigate such risks, `remove_pcb()` includes appropriate mutex locking mechanisms to ensure thread-safe access to all queues, including `running_list`, `mlq_ready_queue[]`, and `ready_queue`. Centralizing process removal logic in the scheduler improves synchronization and helps maintain the integrity of the scheduling subsystem.

The steps performed by the `killall` syscall are as follows:

1. Read the target process name using `libread()` from `REGIONID`.

2. Call `kill_in_queue()` for each relevant queue (including `running_list` and the ready queue).

3. Return the total number of processes successfully terminated.

```c
int __sys_killall(struct pcb_t *caller, struct sc_regs* regs)
{
    pthread_mutex_lock(&queue_lock);
    char proc_name[100];
    uint32_t data;
    uint32_t memrg = regs->a1;

    int i = 0;
    data = 0;
    while(data != -1){
        libread(caller, memrg, i, &data);
        proc_name[i]= data;
        if(data == -1) proc_name[i]='\0';
        i++;
    }
    printf("The procname retrieved from memregionid %d is \"%s\"\n",
        memrg, proc_name);

    int killed_count = 0; // Expected output

    struct queue_t *running_list = caller->running_list;
    if (running_list != NULL) {
        killed_count += kill_in_queue(running_list, proc_name);
    }

    #ifdef MLQ_SCHED
        struct queue_t *mlq_ready_queue = caller->mlq_ready_queue;
        if (mlq_ready_queue != NULL) {
            for (int i = 0; i < MAX_PRIO; ++i) {
                struct queue_t *queue = &(mlq_ready_queue[i]);
                if (queue != NULL) {
                    killed_count += kill_in_queue(queue, proc_name);
                }
            }
        }
    #else
        struct queue_t *ready_queue = caller->ready_queue;
        if (ready_queue != NULL) {
            killed_count += kill_in_queue(ready_queue, proc_name);
        }
```

```
40    #endif
41    pthread_mutex_unlock(&queue_lock);
42    return killed_count; // Expected output
43 }
```

This modular approach ensures clarity, code reuse, and synchronization safety within the scheduling system.

5 Testcase

5.1 Scheduler Testcases

This section details the execution and results of the scheduler test cases, demonstrating the Multi-Level Queue (MLQ) scheduling policy implemented in the Simple Operating System, considering the updated scheduler logic in `sched.c`.

5.1.1 Testcase: `sched`

Configuration: The simulation is configured using the `input/sched` file:

```
1 4 2 3
2 1048576 16777216 0 0 0
3 0 p1s 1
4 1 p2s 0
5 2 p3s 0
```

<div align="center">Listing 9: Content of input/sched</div>

This specifies:

- Global Time Slice (`time_slot` in `sched.c`): 4 time units

- CPUs: 2

- Processes: 3

- Process `p1s` (PID 1): Load at time 0, Priority 1

- Process `p2s` (PID 2): Load at time 1, Priority 0

- Process `p3s` (PID 3): Load at time 2, Priority 0

Output Log:

```
1  Time slot   0
2  ld_routine
3    Loaded a process at input/proc/p1s, PID: 1 PRIO: 1
4  Time slot   1
5    CPU 1: Dispatched process  1
6    Loaded a process at input/proc/p2s, PID: 2 PRIO: 0
7  Time slot   2
8    CPU 0: Dispatched process  2
9    Loaded a process at input/proc/p3s, PID: 3 PRIO: 0
10 Time slot   3
11 Time slot   4
```

```
12    CPU 1: Put process   1 to run queue
13    CPU 1: Dispatched process   3
14 Time slot    5
15 Time slot    6
16    CPU 0: Put process   2 to run queue
17    CPU 0: Dispatched process   2
18 Time slot    7
19 Time slot    8
20    CPU 1: Put process   3 to run queue
21    CPU 1: Dispatched process   3
22 Time slot    9
23 Time slot    10
24    CPU 0: Put process   2 to run queue
25    CPU 0: Dispatched process   2
26 Time slot    11
27 Time slot    12
28    CPU 1: Put process   3 to run queue
29    CPU 1: Dispatched process   3
30 Time slot    13
31 Time slot    14
32    CPU 0: Processed   2 has finished
33    CPU 0: Dispatched process   1
34 Time slot    15
35    CPU 1: Processed   3 has finished
36 Time slot    16
37    CPU 1 stopped
38 Time slot    17
39 Time slot    18
40    CPU 0: Put process   1 to run queue
41    CPU 0: Dispatched process   1
42 Time slot    19
43 Time slot    20
44    CPU 0: Processed   1 has finished
45    CPU 0 stopped
```

Listing 10: Output log: res_sched.txt

Execution Analysis: The simulation executes with two CPUs, a global time slice of 4, and the MLQ scheduler prioritizing lower numerical priority values.

- **T=0-1:** PID 1 (p1s, Prio 1) loads. At T=1, CPU 1 dispatches it. The scheduler (`get_mlq_proc`) grants it a time slice (`proc->time_slot`) of min(instructions_left, slot[1], 4) = 4.

- **T=1-2:** PID 2 (p2s, Prio 0) loads. At T=2, CPU 0 dispatches it with a time slice of min(instr, slot[0], 4) = 4.

- **T=2-3:** PID 3 (p3s, Prio 0) loads.

- **T=4:** PID 1 completes its slice on CPU 1. `put_proc` enqueues it to `mlq_ready_queue[1]`. CPU 1 calls `get_mlq_proc`, finds PID 3 (Prio 0), grants slice=4, and dispatches it.

- **T=6:** PID 2 completes its slice on CPU 0. `put_proc` enqueues it to `mlq_ready_queue[0]`. CPU 0 calls `get_mlq_proc`, finds PID 2 (Prio 0), grants slice=4, and dispatches it (RR within Prio 0).

- **T=8:** PID 3 completes its slice on CPU 1. `put_proc`. CPU 1 gets PID 3 again (RR), grants slice=4, dispatches it.

- **Execution Continues:** PIDs 2 and 3 continue running on CPUs 0 and 1 respectively, preempting PID 1 and executing in RR within their priority level, each receiving slices of 4 units.

- **T=14:** PID 2 finishes execution. The `cpu_routine` calls `remove_pcb` to clean up its resources. CPU 0 calls `get_mlq_proc`. Priority 0 queue is empty. It finds PID 1 (Prio 1), grants slice=4, and dispatches it.

- **T=15:** PID 3 finishes execution. `remove_pcb` is called. CPU 1 calls `get_mlq_proc`, finds no ready processes, and enters its termination sequence.

- **T=16:** CPU 1 prints `CPU 1 stopped`.

- **T=18:** PID 1 completes its slice on CPU 0. `put_proc`. CPU 0 gets PID 1 again, grants slice=4, dispatches it.

- **T=20:** PID 1 finishes execution. `remove_pcb` is called. CPU 0 finds no ready processes and stops.

The analysis confirms the MLQ scheduler correctly implements priority-based scheduling, Round-Robin within the same priority level, and proper process termination handling via `remove_pcb`. The time slice calculation in `get_mlq_proc` determines the duration each process runs before yielding or finishing.
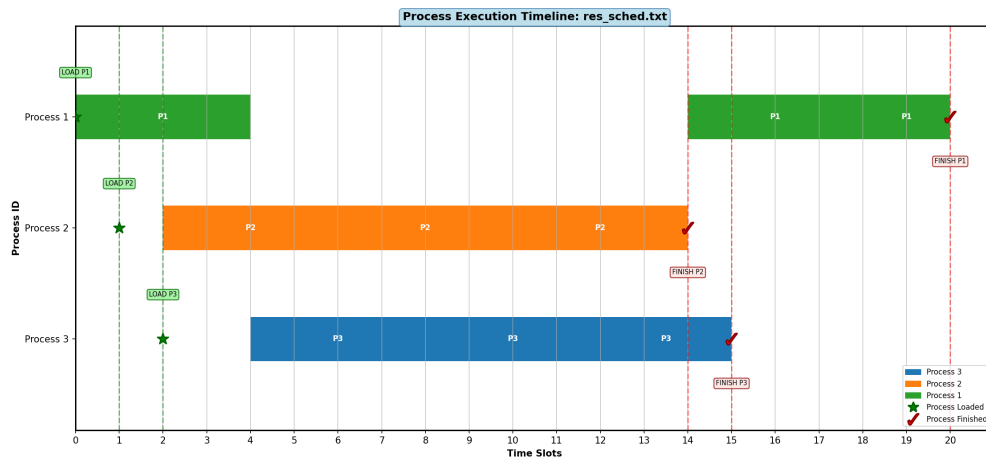
Gantt Chart:

Figure 2: Gantt chart for the `sched` test case.

5.1.2 Testcase: sched_0

Configuration:

```
2 1 2
1048576 16777216 0 0 0
0 s0 4
```

```
4  4 s1 0
```

Listing 11: Content of input/sched_0

This specifies:

- Global Time Slice: 2 time units

- CPUs: 1

- Processes: 2

- Process `s0` (PID 1): Load at time 0, Priority 4

- Process `s1` (PID 2): Load at time 4, Priority 0

Output Log:

```
1  Time slot    0
2  ld_routine
3    Loaded a process at input/proc/s0, PID: 1 PRIO: 4
4  Time slot    1
5    CPU 0: Dispatched process  1
6  Time slot    2
7  Time slot    3
8    CPU 0: Put process  1 to run queue
9    CPU 0: Dispatched process  1
10   Loaded a process at input/proc/s1, PID: 2 PRIO: 0
11 Time slot    4
12 Time slot    5
13   CPU 0: Put process  1 to run queue
14   CPU 0: Dispatched process  2
15 Time slot    6
16 Time slot    7
17   CPU 0: Put process  2 to run queue
18   CPU 0: Dispatched process  2
19 Time slot    8
20 Time slot    9
21   CPU 0: Put process  2 to run queue
22   CPU 0: Dispatched process  2
23 Time slot   10
24 Time slot   11
25   CPU 0: Put process  2 to run queue
26   CPU 0: Dispatched process  2
27 Time slot   12
28   CPU 0: Processed  2 has finished
29   CPU 0: Dispatched process  1
30 Time slot   13
31 Time slot   14
32   CPU 0: Put process  1 to run queue
33   CPU 0: Dispatched process  1
34 Time slot   15
35 Time slot   16
36   CPU 0: Put process  1 to run queue
37   CPU 0: Dispatched process  1
38 Time slot   17
```

```
39 Time slot   18
40   CPU 0: Put process   1 to run queue
41   CPU 0: Dispatched process   1
42 Time slot   19
43 Time slot   20
44   CPU 0: Put process   1 to run queue
45   CPU 0: Dispatched process   1
46 Time slot   21
47 Time slot   22
48   CPU 0: Put process   1 to run queue
49   CPU 0: Dispatched process   1
50 Time slot   23
51   CPU 0: Processed   1 has finished
52   CPU 0 stopped
```

<div align="center">Listing 12: Output log: res_sched_0.txt</div>

Execution Analysis: This test demonstrates priority preemption on a single CPU with a global time slice of 2.

- **T=0-1:** PID 1 (`s0`, Prio 4) loads. At T=1, CPU 0 dispatches it with slice=min(instr, slot[4], 2)=2. Runs T=1, T=2.

- **T=3:** PID 1 slice ends. `put_proc`. CPU 0 gets PID 1 again, grants slice=2. Dispatched. Runs T=3, T=4.

- **T=4:** PID 2 (`s1`, Prio 0) loads.

- **T=5:** PID 1 slice ends. `put_proc`. CPU 0 calls `get_mlq_proc`. Finds PID 2 (Prio 0), grants slice=min(instr, slot[0], 2)=2. Dispatches PID 2, preempting PID 1. Runs T=5, T=6.

- **T=7, 9, 11:** PID 2 continues running, being dispatched repeatedly with slice=2 as it's the highest priority.

- **T=12:** PID 2 finishes execution. `remove_pcb`. CPU 0 calls `get_mlq_proc`. Finds PID 1 (Prio 4), grants slice=2. Dispatches PID 1. Runs T=12, T=13.

- **T=14-23:** PID 1 continues running, receiving slices of 2, until it finishes at T=23. `remove_pcb`. CPU 0 stops.

The arrival of the higher-priority PID 2 correctly preempts the lower-priority PID 1.
Gantt Chart:
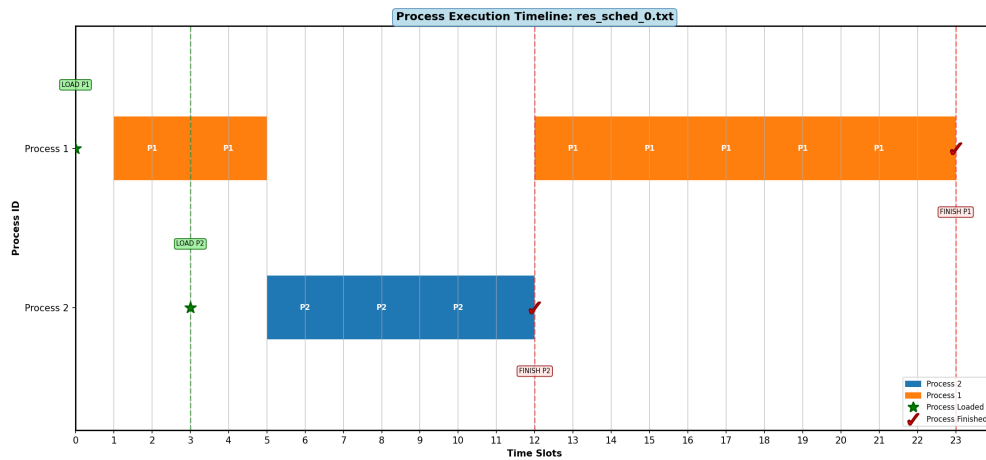
Figure 3: Gantt chart for the `sched_0` test case.

5.1.3 Testcase: sched_1

Configuration:

```
2 1 4
1048576 16777216 0 0 0
0 s0 4
4 s1 0
6 s2 0
7 s3 0
```

Listing 13: Content of input/sched_1

This specifies:

- Global Time Slice: 2 time units

- CPUs: 1

- Processes: 4

- PIDs (Load Time, Name, Priority): 1(0, s0, 4), 2(4, s1, 0), 3(6, s2, 0), 4(7, s3, 0)

Output Log:

```
Time slot    0
ld_routine
  Loaded a process at input/proc/s0, PID: 1 PRIO: 4
Time slot    1
  CPU 0: Dispatched process  1
Time slot    2
Time slot    3
  CPU 0: Put process  1 to run queue
  CPU 0: Dispatched process  1
  Loaded a process at input/proc/s1, PID: 2 PRIO: 0
Time slot    4
Time slot    5
```

```
13    CPU 0: Put process  1 to run queue
14    CPU 0: Dispatched process  2
15    Loaded a process at input/proc/s2, PID: 3 PRIO: 0
16  Time slot   6
17  Time slot   7
18    CPU 0: Put process  2 to run queue
19    CPU 0: Dispatched process  3
20    Loaded a process at input/proc/s3, PID: 4 PRIO: 0
21  Time slot   8
22  Time slot   9
23    CPU 0: Put process  3 to run queue
24    CPU 0: Dispatched process  2
25  Time slot  10
26  Time slot  11
27    CPU 0: Put process  2 to run queue
28    CPU 0: Dispatched process  4
29  Time slot  12
30  Time slot  13
31    CPU 0: Put process  4 to run queue
32    CPU 0: Dispatched process  3
33  Time slot  14
34  Time slot  15
35    CPU 0: Put process  3 to run queue
36    CPU 0: Dispatched process  2
37  Time slot  16
38  Time slot  17
39    CPU 0: Put process  2 to run queue
40    CPU 0: Dispatched process  4
41  Time slot  18
42  Time slot  19
43    CPU 0: Put process  4 to run queue
44    CPU 0: Dispatched process  3
45  Time slot  20
46  Time slot  21
47    CPU 0: Put process  3 to run queue
48    CPU 0: Dispatched process  2
49  Time slot  22
50    CPU 0: Processed  2 has finished
51    CPU 0: Dispatched process  4
52  Time slot  23
53  Time slot  24
54    CPU 0: Put process  4 to run queue
55    CPU 0: Dispatched process  3
56  Time slot  25
57  Time slot  26
58    CPU 0: Put process  3 to run queue
59    CPU 0: Dispatched process  4
60  Time slot  27
61  Time slot  28
62    CPU 0: Put process  4 to run queue
63    CPU 0: Dispatched process  3
64  Time slot  29
65  Time slot  30
```

```
66    CPU 0: Put process   3 to run queue
67    CPU 0: Dispatched process   4
68  Time slot   31
69  Time slot   32
70    CPU 0: Put process   4 to run queue
71    CPU 0: Dispatched process   3
72  Time slot   33
73  Time slot   34
74    CPU 0: Processed   3 has finished
75    CPU 0: Dispatched process   4
76  Time slot   35
77    CPU 0: Processed   4 has finished
78    CPU 0: Dispatched process   1
79  Time slot   36
80  Time slot   37
81    CPU 0: Put process   1 to run queue
82    CPU 0: Dispatched process   1
83  Time slot   38
84  Time slot   39
85    CPU 0: Put process   1 to run queue
86    CPU 0: Dispatched process   1
87  Time slot   40
88  Time slot   41
89    CPU 0: Put process   1 to run queue
90    CPU 0: Dispatched process   1
91  Time slot   42
92  Time slot   43
93    CPU 0: Put process   1 to run queue
94    CPU 0: Dispatched process   1
95  Time slot   44
96  Time slot   45
97    CPU 0: Put process   1 to run queue
98    CPU 0: Dispatched process   1
99  Time slot   46
100   CPU 0: Processed   1 has finished
101   CPU 0 stopped
```

Listing 14: Output log: res_sched_1.txt

Execution Analysis: This test demonstrates Round-Robin scheduling among multiple high-priority processes arriving at different times on a single CPU with a global time slice of 2.

- **T=0-4:** PID 1 (`s0`, Prio 4) runs for two time slices.

- **T=4:** PID 2 (`s1`, Prio 0) loads.

- **T=5:** PID 1 slice ends, put back. PID 2 (Prio 0) is dispatched (slice=2).

- **T=6:** PID 3 (`s2`, Prio 0) loads.

- **T=7:** PID 2 slice ends → enqueued. PID 3 (Prio 0) dispatched (slice=2). PID 4 (`s3`, Prio 0) loads.

- **T=9:** PID 3 slice ends → enqueued. PID 2 (first in Prio 0 queue) dispatched (slice=2).

- **T=11:** PID 2 slice ends → enqueued. PID 4 (next in Prio 0) dispatched (slice=2).

- **T=13:** PID 4 slice ends → enqueued. PID 3 (next in Prio 0) dispatched (slice=2).

- **Execution Continues:** PIDs 2, 3, and 4 (all Prio 0) execute in Round-Robin order (2 → 3 → 4 → 2...), each getting a slice of 2, until completion. PID 2 finishes first (T=22), then PID 3 (T=34), then PID 4 (T=35). The processes finish before exhausting their initial time slots, so the slot reset logic in `get_mlq_proc` is not triggered in this test.

- **T=35:** All Prio 0 processes are finished. CPU 0 dispatches the waiting PID 1 (Prio 4), granting slice=2.

- **T=35-46:** PID 1 runs until completion, being put back and re-dispatched every 2 time slots. `remove_pcb` cleans it up at T=46. CPU 0 stops.

This test confirms preemption of lower priorities and effective Round-Robin scheduling among multiple processes within the highest priority level.
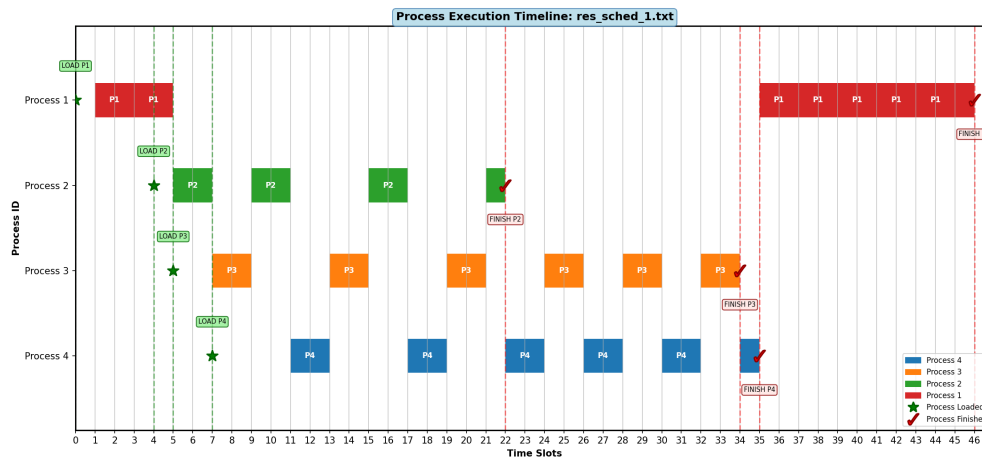
Gantt Chart:

Figure 4: Gantt chart for the `sched_1` test case.

5.2 Memory Management

5.2.1 Testcase 1: Basic Process Loading and Page Table Management

Input Files

- `mem_test_1`

```
1  10 1 1
2  1048576 0 0 0 0
3  0 mem_proc_1 1
```

- `mem_proc_1`

```
1  1 3
2  alloc 300 0
3  alloc 200 1
4  alloc 200 2
```

Output Content

```
1  Time slot    0
2  ld_routine
3          Loaded a process at input/proc/mem_proc_1, PID: 1 PRIO: 1
4          CPU 0: Dispatched process  1
5  ===== PHYSICAL MEMORY AFTER ALLOCATION =====
6  PID=1 - Region=0 - Address=0 - Size=300 byte
7  print_pgtbl: 0 - 512
8  00000000: 80000001
9  00000004: 80000000
10 Page Number: 0 -> Frame Number: 1
11 Page Number: 1 -> Frame Number: 0
12 ================================================================
13 Time slot    1
14 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
15 PID=1 - Region=1 - Address=300 - Size=200 byte
16 print_pgtbl: 0 - 512
17 00000000: 80000001
18 00000004: 80000000
19 Page Number: 0 -> Frame Number: 1
20 Page Number: 1 -> Frame Number: 0
21 ================================================================
22 Time slot    2
23 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
24 PID=1 - Region=2 - Address=512 - Size=200 byte
25 print_pgtbl: 0 - 768
26 00000000: 80000001
27 00000004: 80000000
28 00000008: 80000002
29 Page Number: 0 -> Frame Number: 1
30 Page Number: 1 -> Frame Number: 0
31 Page Number: 2 -> Frame Number: 2
32 ================================================================
33 Time slot    3
34         CPU 0: Processed  1 has finished
35         CPU 0 stopped
```

Explanation

This testcase demonstrates the loading and memory allocation process for a single user process using paging-based virtual memory management.

The file `mem_proc_1` contains information for one process:

- The first line indicates there is only 1 process.

- The second line shows its priority is 1.

- The next three lines correspond to the sizes of its three memory regions: 300, 200, and 200 bytes.

In time slot 0, the loader routine starts by creating the process (PID = 1). It assigns 300 bytes for Region 0 starting from address 0. Since each page is 256 bytes, Region 0 spans across two virtual pages. The page table maps:

- Page 0 to Frame 1

- Page 1 to Frame 0

In time slot 1, Region 1 (200 bytes) is allocated from address 300. This region is still within the bounds of the first two pages, so no new frame is needed, and the page table remains unchanged. In time slot 2, Region 2 (200 bytes) begins at address 512, which lies in a new page. Therefore, a new mapping is created:

- Page 2 to Frame 2

The page table now covers addresses up to 768 bytes, reflecting the additional mapping.
By time slot 3, the process finishes execution, and CPU 0 becomes idle.
This testcase is useful for verifying:

- The loader correctly splits memory across pages.

- Proper frame allocation based on virtual address range.

- The incremental update of the page table as more regions are allocated.

- Clean termination and memory release behavior (implied after final time slot).
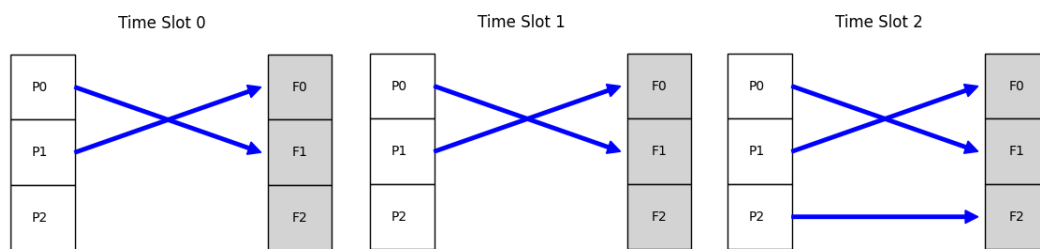

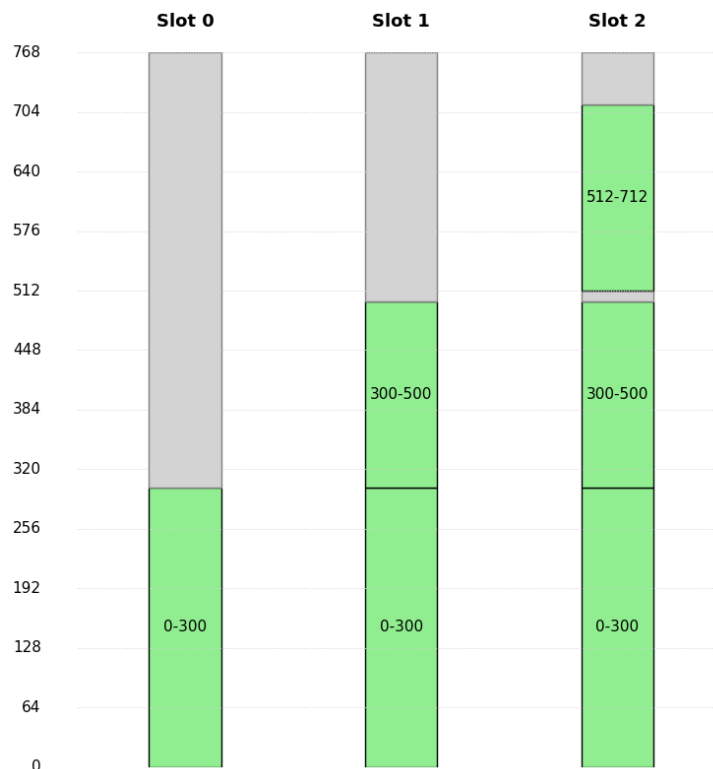Figure 5: Virtual memory mapping across time slots.

Figure 6: Physical memory state over time.

5.2.2 Testcase 2: Dynamic Allocation and Deallocation with Page Table Reuse

Input Files

- `mem_test_2`

```
10 1 1
1048576 0 0 0 0
0 mem_proc_2 1
```

- `mem_proc_2`

```
1 6
alloc 100 0
alloc 100 1
free 0
alloc 50 0
alloc 25 2
alloc 50 3
```

Output Content

```
Time slot   0
```

```
2  ld_routine
3         Loaded a process at input/proc/mem_proc_2, PID: 1 PRIO: 1
4         CPU 0: Dispatched process   1
5  ===== PHYSICAL MEMORY AFTER ALLOCATION =====
6  PID=1 - Region=0 - Address=0 - Size=100 byte
7  print_pgtbl: 0 - 256
8  00000000: 80000000
9  Page Number: 0 -> Frame Number: 0
10 ================================================================
11 Time slot    1
12 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
13 PID=1 - Region=1 - Address=100 - Size=100 byte
14 print_pgtbl: 0 - 256
15 00000000: 80000000
16 Page Number: 0 -> Frame Number: 0
17 ================================================================
18 Time slot    2
19 ===== PHYSICAL MEMORY AFTER DEALLOCATION =====
20 PID=1 - Region=0
21 print_pgtbl: 0 - 256
22 00000000: 80000000
23 Page Number: 0 -> Frame Number: 0
24 ================================================================
25 Time slot    3
26 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
27 PID=1 - Region=0 - Address=0 - Size=50 byte
28 print_pgtbl: 0 - 256
29 00000000: 80000000
30 Page Number: 0 -> Frame Number: 0
31 ================================================================
32 Time slot    4
33 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
34 PID=1 - Region=2 - Address=50 - Size=25 byte
35 print_pgtbl: 0 - 256
36 00000000: 80000000
37 Page Number: 0 -> Frame Number: 0
38 ================================================================
39 Time slot    5
40 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
41 PID=1 - Region=3 - Address=200 - Size=50 byte
42 print_pgtbl: 0 - 256
43 00000000: 80000000
44 Page Number: 0 -> Frame Number: 0
45 ================================================================
46 Time slot    6
47         CPU 0: Processed  1 has finished
48         CPU 0 stopped
```

Explanation

This testcase demonstrates the dynamic behavior of memory allocation and deallocation using paging. A process is loaded, memory is allocated to different regions, and one region is explicitly deallocated and reused.

The file `mem_proc_2` describes a process that performs six memory-related operations:

- It allocates 100 bytes in region 0.

- It then allocates another 100 bytes in region 1.

- Region 0 is freed, releasing the associated memory.

- It reallocates 50 bytes in region 0 (smaller size).

- It allocates 25 bytes in region 2.

- It allocates 50 bytes in region 3.

In time slot 0, the process is loaded, and 100 bytes are allocated for region 0 starting from address 0. Since one page is 256 bytes, all data fits within one page, and a single page-to-frame mapping is made.

Time slot 1 continues with another 100-byte allocation at address 100 for region 1. The data still fits within the first page, so no additional frame is needed. The mapping remains unchanged.

Time slot 2 frees region 0. Although the virtual address space is unaffected, the associated memory block becomes available for reuse.

In time slot 3, the program reuses the freed space to allocate a smaller region of 50 bytes at address 0. The system reuses the same frame (frame 0), showing efficiency in page management.

Time slot 4 allocates a 25-byte region at address 50, still within the same page and frame.

Finally, in time slot 5, 50 bytes are allocated at address 200 for region 3, which again fits within the same page. The entire process's memory footprint lies within the 256-byte range of one page, thus requiring only one frame.

By time slot 6, the process finishes execution, and the CPU stops.

This testcase is useful for verifying:

- Memory deallocation and reallocation on the same page.

- Efficient reuse of freed memory frames.

- Handling of multiple small allocations within a single page.

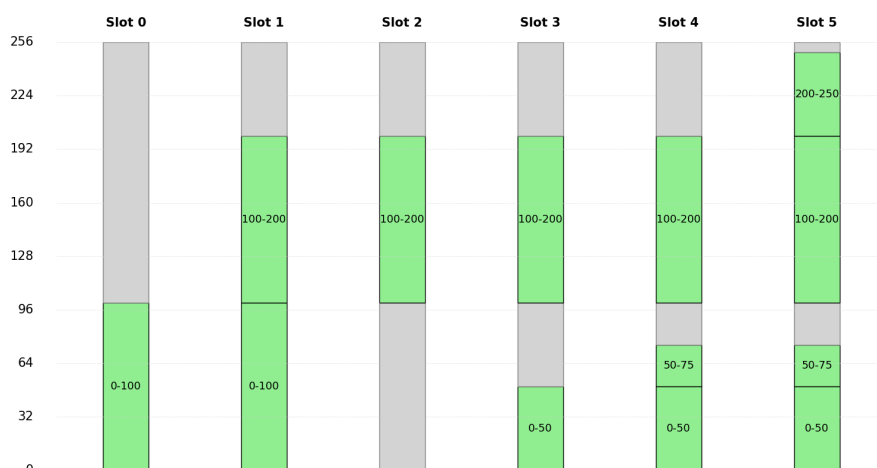- Correctness of page table consistency across changes.

Figure 7: Physical memory state over time.

5.2.3   Testcase 3: Memory Access with Paging - Read/Write Across Pages

Input Files

- mem_test_3

```
1  10 1 1
2  1048576 0 0 0 0
3  0 mem_proc_3 1
```

- mem_proc_3

```
1  1 8
2  alloc 200 0
3  alloc 500 1
4  write 12 1 200
5  read 1 200 10
6  write 34 1 400
7  read 1 400 10
8  write 56 1 400
9  read 1 400 10
```

Output Content

```
1  Time slot   0
2  ld_routine
3         Loaded a process at input/proc/mem_proc_3, PID: 1 PRIO: 1
4  Time slot   1
5         CPU 0: Dispatched process  1
6  ===== PHYSICAL MEMORY AFTER ALLOCATION =====
7  PID=1 - Region=0 - Address=0 - Size=200 byte
8  print_pgtbl: 0 - 256
9  00000000: 80000000
10 Page Number: 0 -> Frame Number: 0
11 ================================================================
12 Time slot   2
13 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
14 PID=1 - Region=1 - Address=256 - Size=500 byte
15 print_pgtbl: 0 - 768
16 00000000: 80000000
17 00000004: 80000002
18 00000008: 80000001
19 Page Number: 0 -> Frame Number: 0
20 Page Number: 1 -> Frame Number: 2
21 Page Number: 2 -> Frame Number: 1
22 ================================================================
23 Time slot   3
24 ===== PHYSICAL MEMORY AFTER WRITING =====
25 write region=1 offset=200 value=12
26 print_pgtbl: 0 - 768
27 00000000: 80000000
28 00000004: 80000002
29 00000008: 80000001
30 ================================================================
```

```
31 ===== PHYSICAL MEMORY DUMP =====
32 BYTE 000002c8: 12
33 ===== PHYSICAL MEMORY END-DUMP =====
34 ===============================================================
35 Time slot   4
36 ===== PHYSICAL MEMORY AFTER READING =====
37 read region=1 offset=200 value=12
38 print_pgtbl: 0 - 768
39 00000000: 80000000
40 00000004: 80000002
41 00000008: 80000001
42 ===============================================================
43 ===== PHYSICAL MEMORY DUMP =====
44 BYTE 000002c8: 12
45 ===== PHYSICAL MEMORY END-DUMP =====
46 ===============================================================
47 Time slot   5
48 ===== PHYSICAL MEMORY AFTER WRITING =====
49 write region=1 offset=400 value=34
50 print_pgtbl: 0 - 768
51 00000000: 80000000
52 00000004: 80000002
53 00000008: 80000001
54 ===============================================================
55 ===== PHYSICAL MEMORY DUMP =====
56 BYTE 00000190: 34
57 BYTE 000002c8: 12
58 ===== PHYSICAL MEMORY END-DUMP =====
59 ===============================================================
60 Time slot   6
61 ===== PHYSICAL MEMORY AFTER READING =====
62 read region=1 offset=400 value=34
63 print_pgtbl: 0 - 768
64 00000000: 80000000
65 00000004: 80000002
66 00000008: 80000001
67 ===============================================================
68 ===== PHYSICAL MEMORY DUMP =====
69 BYTE 00000190: 34
70 BYTE 000002c8: 12
71 ===== PHYSICAL MEMORY END-DUMP =====
72 ===============================================================
73 Time slot   7
74 ===== PHYSICAL MEMORY AFTER WRITING =====
75 write region=1 offset=400 value=56
76 print_pgtbl: 0 - 768
77 00000000: 80000000
78 00000004: 80000002
79 00000008: 80000001
80 ===============================================================
81 ===== PHYSICAL MEMORY DUMP =====
82 BYTE 00000190: 56
83 BYTE 000002c8: 12
```

```
84  ===== PHYSICAL MEMORY END-DUMP =====
85  ================================================================
86  Time slot   8
87  ===== PHYSICAL MEMORY AFTER READING =====
88  read region=1 offset=400 value=56
89  print_pgtbl: 0 - 768
90  00000000: 80000000
91  00000004: 80000002
92  00000008: 80000001
93  ================================================================
94  ===== PHYSICAL MEMORY DUMP =====
95  BYTE 00000190: 56
96  BYTE 000002c8: 12
97  ===== PHYSICAL MEMORY END-DUMP =====
98  ================================================================
99  Time slot   9
100         CPU 0: Processed  1 has finished
101         CPU 0 stopped
```

Explanation

This testcase verifies the correctness of virtual memory management using paging. It demonstrates:

- Proper page-to-frame mappings during multiple region allocations.

- Accurate translation of virtual addresses to physical addresses during memory operations.

- Consistency of page table entries through successive memory accesses.

- Correctness of read/write operations with updated data values.

The memory operations in `mem_proc_3` involve:

- **Region 0** is allocated 200 `bytes`, starting at virtual address 0. It fits entirely within page 0.

- **Region 1** is allocated 500 `bytes`, starting at virtual address 256. This region spans across **three pages**, because `256 + 500 = 756`, which exceeds one and two page boundaries (each page is 256 bytes).

The virtual-to-physical mapping after allocations is:

- Page 0 → Frame 0

- Page 1 → Frame 2

- Page 2 → Frame 1

Specific memory operations:

- A **write** operation at `offset` 200 in region 1.

    - Virtual address = `base address (256) + offset (200)` = 456.

    - Virtual address 456 belongs to page 1 (`page number = 456 / 256 = 1`).

- Page 1 is mapped to frame 2.
- Physical address = `frame 2 * 256 + (456 mod 256)` = 2*256 + 200 = 712 (000002C8).

- A **read** operation at the same offset confirms the value `12` is correctly retrieved from physical address 712.

- A **write** at `offset 400` in region 1.

    - Virtual address = `256 + 400 = 656`.
    - Virtual address 656 belongs to page 2 (`page number = 656 / 256 = 2`).
    - Page 2 is mapped to frame 1.
    - Physical address = `frame 1 * 256 + (656 mod 256)` = 1*256 + 144 = 400 (00000190).

- A **read** at the same offset confirms the written value (`34` initially, later updated to `56`) is correctly stored and retrieved from physical address 400.

The page table remains consistent throughout all time slots, and memory dumps validate that the data is properly written, updated, and read according to the virtual-to-physical mappings.

5.2.4 Testcase 4: Multi-Process Memory Allocation and Paging Consistency

Input Files

- `mem_test_4`

```
1  10 3 3
2  1048576 0 0 0 0
3  0 mem_proc_4_1 1
4  1 mem_proc_4_2 1
5  2 mem_proc_4_3 1
```

- `mem_proc_4_1`

```
1  1 6
2  alloc 200 0
3  calc
4  calc
5  alloc 200 1
6  calc
7  calc
```

- `mem_proc_4_2`

```
1  1 4
2  alloc 200 0
3  calc
4  calc
5  alloc 200 1
```

- `mem_proc_4_3`

```
1  1 5
2  alloc 200 0
3  calc
4  calc
5  alloc 200 1
6  calc
```

Output Content

```
1  Time slot    0
2  ld_routine
3          Loaded a process at input/proc/mem_proc_4_1, PID: 1 PRIO: 1
4          CPU 2: Dispatched process  1
5  ===== PHYSICAL MEMORY AFTER ALLOCATION =====
6  PID=1 - Region=0 - Address=0 - Size=200 byte
7  print_pgtbl: 0 - 256
8  00000000: 80000000
9  Page Number: 0 -> Frame Number: 0
10 ================================================================
11 Time slot    1
12         Loaded a process at input/proc/mem_proc_4_2, PID: 2 PRIO: 1
13         CPU 1: Dispatched process  2
14 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
15 PID=2 - Region=0 - Address=0 - Size=200 byte
16 print_pgtbl: 0 - 256
17 00000000: 80000001
18 Page Number: 0 -> Frame Number: 1
19 ================================================================
20 Time slot    2
21         Loaded a process at input/proc/mem_proc_4_3, PID: 3 PRIO: 1
22 Time slot    3
23 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
24 PID=1 - Region=1 - Address=256 - Size=200 byte
25 print_pgtbl: 0 - 512
26 00000000: 80000000
27 00000004: 80000002
28 Page Number: 0 -> Frame Number: 0
29 Page Number: 1 -> Frame Number: 2
30 ================================================================
31         CPU 0: Dispatched process  3
32 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
33 PID=3 - Region=0 - Address=0 - Size=200 byte
34 print_pgtbl: 0 - 256
35 00000000: 80000003
36 Page Number: 0 -> Frame Number: 3
37 ================================================================
38 Time slot    4
39 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
40 PID=2 - Region=1 - Address=256 - Size=200 byte
41 print_pgtbl: 0 - 512
42 00000000: 80000001
43 00000004: 80000004
44 Page Number: 0 -> Frame Number: 1
```

```
45  Page Number: 1 -> Frame Number: 4
46  ================================================================
47  Time slot    5
48  Time slot    6
49          CPU 2: Processed  1 has finished
50          CPU 2 stopped
51  ===== PHYSICAL MEMORY AFTER ALLOCATION =====
52  PID=3 - Region=1 - Address=256 - Size=200 byte
53          CPU 1: Processed  2 has finished
54          CPU 1 stopped
55  print_pgtbl: 0 - 512
56  00000000: 80000003
57  00000004: 80000005
58  Page Number: 0 -> Frame Number: 3
59  Page Number: 1 -> Frame Number: 5
60  ================================================================
61  Time slot    7
62          CPU 0: Processed  3 has finished
63          CPU 0 stopped
```

Explanation

This testcase demonstrates consistent memory allocation and virtual-to-physical mapping in a multi-core and multi-process paging system. It ensures the following:

- Each process independently allocates memory in two separate regions.

- The virtual pages are correctly mapped to distinct physical frames.

- Frame reuse is avoided across processes to preserve isolation and correctness.

- Page tables reflect accurate mappings for each PID, confirming region-wise paging.

Detailed process activity includes:

- Process 1 (PID=1) is dispatched on CPU 2 and allocates 200 bytes in Region 0, then another 200 bytes in Region 1 (total 2 frames used).

- Process 2 (PID=2) runs on CPU 1 and similarly allocates 200 bytes in Region 0, then another 200 bytes in Region 1 (2 frames).

- Process 3 (PID=3) starts on CPU 0 slightly later and performs identical allocations, with unique frame mappings.

By Time slot 7, all three processes have terminated, and the memory state shows six separate frame allocations corresponding to three processes, each with two memory regions. The output validates that the memory manager correctly maintains separation and mapping for all processes in a concurrent environment.
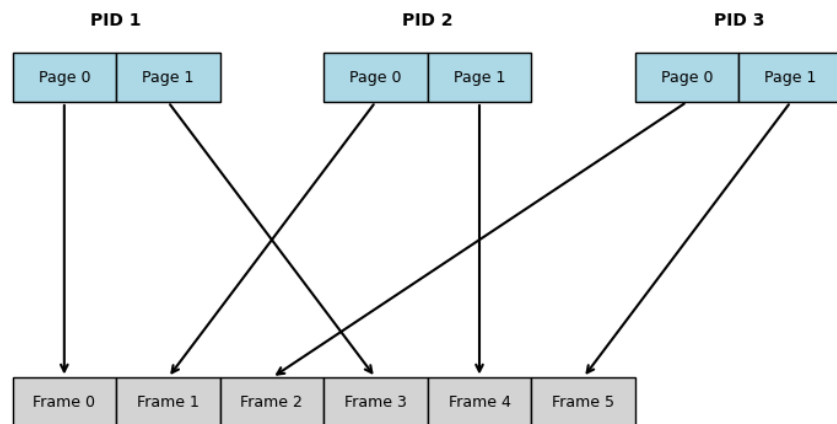
Figure 8: Virtual memory mapping at time slot 6.

5.3 System Call Testcases

This section verifies the implementation and interaction of system calls within the Simple Operating System, considering the updated scheduling logic and build process.

5.3.1 Testcase: `os_syscall_list`

Configuration:

```
1 2 1 1
2 2048 16777216 0 0 0
3 9 sc1  15
```

Listing 15: Content of input/os_syscall_list

```
1 20 1
2 syscall 0
```

Listing 16: Content of input/proc/sc1

System Call Tested: Syscall number 0 (`sys_listsyscall`)

Output Log:

```
1 Time slot   0
2 ld_routine
3 Time slot   1
4 Time slot   2
5 Time slot   3
6 Time slot   4
7 Time slot   5
8 Time slot   6
9 Time slot   7
10 Time slot   8
11   Loaded a process at input/proc/sc1, PID: 1 PRIO: 15
12 Time slot   9
13   CPU 0: Dispatched process  1
```

```
14  0-sys_listsyscall
15  17-sys_memmap
16  101-sys_killall
17  440-sys_xxxhandler
18  Time slot   10
19    CPU 0: Processed   1 has finished
20    CPU 0 stopped
```

Listing 17: Output log: res_os_syscall_list.txt

Execution Analysis:

- **T=0-8:** System initializes.

- **T=9:** PID 1 (sc1, Prio 15) loads.

- **T=10:** CPU 0 dispatches PID 1. Scheduler grants slice=min(1 instr left, slot[15], global_slice=2)=1. PID 1 executes syscall 0.

- The system call mechanism invokes __sys_listsyscall. The handler prints the list of registered system calls (lines 14-17 in log). Handler returns 0.

- Syscall completes within T=10. pc advances.

- **T=11:** OS detects PID 1 finished. remove_pcb. CPU 0 stops.

This confirms syscall 0 is correctly mapped and executed. Interaction Flow: User Process → CPU → libsyscall → Kernel syscall Dispatcher → __sys_listsyscall Handler → Standard Output → Process Completion.

5.3.2 Testcase: os_syscall

Configuration:

```
1  2 1 1
2  2048 16777216 0 0 0
3  9 sc2   15
```

Listing 18: Content of input/os_syscall

```
1  20 5
2  alloc 100 1
3  write 80 1 0
4  write 48 1 1
5  write -1 1 2
6  syscall 101 1
```

Listing 19: Content of input/proc/sc2

System Call Tested: Syscall number 101 (sys_killall)
Output Log:

```
1  Time slot    0
2  ld_routine
3  Time slot    1
4  Time slot    2
```

```
 5 Time  slot    3
 6 Time  slot    4
 7 Time  slot    5
 8 Time  slot    6
 9 Time  slot    7
10 Time  slot    8
11   Loaded a process at input/proc/sc2, PID: 1 PRIO: 15
12 Time  slot    9
13   CPU 0: Dispatched process   1
14 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
15 PID=1 - Region=1 - Address=00000000 - Size=100 byte
16 print_pgtbl: 0 - 256
17 00000000: 80000000
18 Page Number: 0 -> Frame Number: 0
19 ================================================================
20 Time  slot   10
21 ===== PHYSICAL MEMORY AFTER WRITING =====
22 Time  slot   11
23   CPU 0: Put process   1 to run queue
24   CPU 0: Dispatched process   1
25 ===== PHYSICAL MEMORY AFTER WRITING =====
26 Time  slot   12
27 ===== PHYSICAL MEMORY AFTER WRITING =====
28 Time  slot   13
29   CPU 0: Put process   1 to run queue
30   CPU 0: Dispatched process   1
31 ===== PHYSICAL MEMORY AFTER READING =====
32 ===== PHYSICAL MEMORY AFTER READING =====
33 ===== PHYSICAL MEMORY AFTER READING =====
34 The procname retrieved from memregionid 1 is "P0"
35 Time  slot   14
36   CPU 0: Processed   1 has finished
37   CPU 0 stopped
```

Listing 20: Output log: res_os_syscall.txt

Execution Analysis: This analysis uses the updated log for `os_syscall`, with global time slice 2.

- **T=0-8:** System initializes.

- **T=9:** Loader loads PID 1 (`sc2`, Prio 15).

- **T=10:** CPU 0 dispatches PID 1. Scheduler grants slice=min(5 instr left, slot[15], 2)=2. Executes `alloc 100 1`. Memory allocation message printed.

- **T=11:** PID 1 continues. Executes `write 80 1 0`. Memory write message printed. Time slice (2 units) ends.

- **T=12:** CPU 0 puts PID 1 back. Gets PID 1 again. Grants slice=min(3 instr left, slot[15], 2)=2. Dispatches PID 1. Executes `write 48 1 1`.

- **T=13:** PID 1 continues. Executes `write -1 1 2`. Time slice ends.

- **T=14:** CPU 0 puts PID 1 back. Gets PID 1 again. Grants slice=min(1 instr left, slot[15], 2)=1. Dispatches PID 1. Executes `syscall 101 1`.

- libsyscall sets `regs.a1 = 1` and calls kernel `syscall`.
- Dispatcher invokes `__sys_killall`.
- Handler uses `regs->a1` (value 1) as region ID. Reads `P0` via `libread`. Prints confirmation `The procname retrieved from memregionid 1 is "P0"`.
- Scans process lists for `P0`; finds none. Returns 0.

- The syscall instruction completes within T=14. `pc` advances.

- **T=15:** OS detects PID 1 finished (`pc == code->size`). Prints `Processed 1 has finished`. `remove_pcb`. CPU 0 stops.

The test confirms `killall` receives the REGIONID via `regs->a1`, retrieves the name (`P0`), and completes. The timing reflects the scheduler granting slices up to the global limit or remaining instructions.
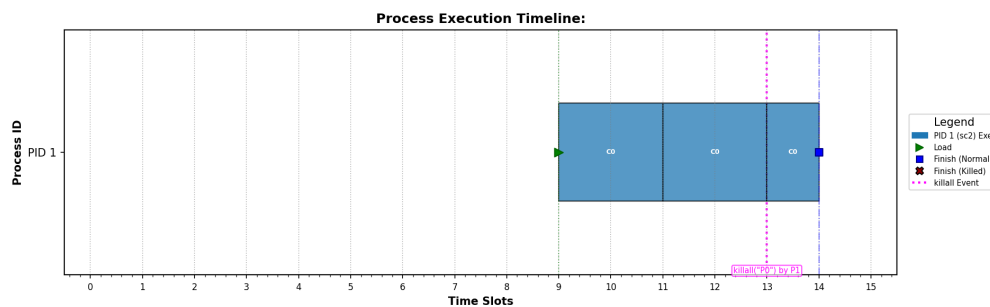
Gantt Chart:

Figure 9: Gantt chart for the `os_syscall` test case.

5.3.3 Testcase: os_sc

Configuration:

```
1  2 1 1
2  2048 16777216 0 0 0
3  9 sc3   15
```

Listing 21: Content of input/os_sc

```
1  20 1
2  syscall 440 1
```

Listing 22: Content of input/proc/sc3

System Call Tested: Syscall number 440 (Implemented as `sys_first_handler`)

Output Log:

```
1   Time slot    0
2   ld_routine
3   Time slot    1
4   Time slot    2
5   Time slot    3
6   Time slot    4
7   Time slot    5
8   Time slot    6
9   Time slot    7
10  Time slot    8
11    Loaded a process at input/proc/sc3, PID: 1 PRIO: 15
12  Time slot    9
13    CPU 0: Dispatched process  1
14  The first system call parameter 1
15  Time slot   10
16    CPU 0: Processed  1 has finished
17    CPU 0 stopped
```

Listing 23: Output log: res_os_sc.txt

Execution Analysis:

- **T=0-8:** System initializes.

- **T=9:** PID 1 (`sc3`, Prio 15) loads.

- **T=10:** CPU 0 dispatches PID 1. Scheduler grants slice=min(1 instr left, slot[15], global_slice=2)=1. Executes `syscall 440 1`.

- `libsyscall` sets `regs.a1 = 1` and calls kernel `syscall`.

- Kernel dispatcher finds `case 440:` (based on `syscall.tbl` and `Makefile`) and invokes `__sys_first_handler`.

- `__sys_first_handler` retrieves argument from `regs->a1` and prints `The first system call parameter 1`. Handler returns 0.

- Syscall completes within T=10. `pc` advances.

- **T=11:** OS detects PID 1 finished. Prints `Processed 1 has finished.` remove_pcb. CPU 0 stops.

This test demonstrates the successful implementation, registration, and invocation of the custom system call 440, including argument passing.

5.3.4 Testcase: `os_killall_complex`

Configuration:

```
2 2 8
2048 16777216 0 0 0
0 s0 5
3 s1 10
5 s1 15
8 s1 20
12 s2 8
15 s3 12
20 killer 1
25 s1 5
```
Listing 24: Content of input/os_killall_complex

- Global Time Slice: 2 units, CPUs: 2, Processes: 8.

- PIDs (Load Time, Name, Priority): 1(0,s0,5), 2(3,s1,10), 3(5,s1,15), 4(8,s1,20), 5(12,s2,8), 6(15,s3,12), 7(20,killer,1), 8(25,s1,5).

```
20 5
alloc 100 1
write 115 1 0
write 49 1 1
write -1 1 2
syscall 101 1
```
Listing 25: Content of input/proc/killer

System Call Tested: `sys_killall` (101) invoked by PID 7 targeting `s1`.
Output Log:

```
Time slot    0
ld_routine
  Loaded a process at input/proc/s0, PID: 1 PRIO: 5
  CPU 1: Dispatched process  1
Time slot    1
Time slot    2
  Loaded a process at input/proc/s1, PID: 2 PRIO: 10
  CPU 1: Put process  1 to run queue
  CPU 1: Dispatched process  1
Time slot    3
  CPU 0: Dispatched process  2
Time slot    4
  Loaded a process at input/proc/s1, PID: 3 PRIO: 15
  CPU 1: Put process  1 to run queue
```

```
15  CPU 1: Dispatched process  1
16 Time slot    5
17  CPU 0: Put process  2 to run queue
18  CPU 0: Dispatched process  2
19 Time slot    6
20  CPU 1: Put process  1 to run queue
21  CPU 1: Dispatched process  1
22 Time slot    7
23  CPU 0: Put process  2 to run queue
24  CPU 0: Dispatched process  2
25  Loaded a process at input/proc/s1, PID: 4 PRIO: 20
26 Time slot    8
27  CPU 1: Put process  1 to run queue
28  CPU 1: Dispatched process  1
29 Time slot    9
30  CPU 0: Put process  2 to run queue
31  CPU 0: Dispatched process  2
32 Time slot   10
33  CPU 0: Processed  2 has finished
34  CPU 0: Dispatched process  3
35  CPU 1: Put process  1 to run queue
36  CPU 1: Dispatched process  1
37 Time slot   11
38  Loaded a process at input/proc/s2, PID: 5 PRIO: 8
39 Time slot   12
40  CPU 0: Put process  3 to run queue
41  CPU 0: Dispatched process  5
42  CPU 1: Put process  1 to run queue
43  CPU 1: Dispatched process  1
44 Time slot   13
45 Time slot   14
46  CPU 0: Put process  5 to run queue
47  CPU 0: Dispatched process  5
48  Loaded a process at input/proc/s3, PID: 6 PRIO: 12
49  CPU 1: Put process  1 to run queue
50  CPU 1: Dispatched process  1
51 Time slot   15
52  CPU 1: Processed  1 has finished
53 Time slot   16
54  CPU 0: Put process  5 to run queue
55  CPU 1: Dispatched process  6
56  CPU 0: Dispatched process  5
57 Time slot   17
58  CPU 1: Put process  6 to run queue
59 Time slot   18
60  CPU 1: Dispatched process  6
61  CPU 0: Put process  5 to run queue
62  CPU 0: Dispatched process  5
63 Time slot   19
64  Loaded a process at input/proc/killer, PID: 7 PRIO: 1
65  CPU 1: Put process  6 to run queue
66  CPU 1: Dispatched process  7
67 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
```

```
68  PID=7 - Region=1 - Address=00000000 - Size=100 byte
69  Time slot   20
70  print_pgtbl: 0 - 256
71  00000000: a8000000
72  Page Number: 0 -> Frame Number: 0
73  ================================================================
74    CPU 0: Put process   5 to run queue
75    CPU 0: Dispatched process   5
76  Time slot   21
77  ===== PHYSICAL MEMORY AFTER WRITING =====
78  Time slot   22
79    CPU 1: Put process   7 to run queue
80    CPU 1: Dispatched process   7
81  ===== PHYSICAL MEMORY AFTER WRITING =====
82    CPU 0: Put process   5 to run queue
83    CPU 0: Dispatched process   5
84  ===== PHYSICAL MEMORY AFTER WRITING =====
85  Time slot   23
86    CPU 1: Put process   7 to run queue
87    CPU 1: Dispatched process   7
88  Time slot   24
89  ===== PHYSICAL MEMORY AFTER READING =====
90  ===== PHYSICAL MEMORY AFTER READING =====
91  ===== PHYSICAL MEMORY AFTER READING =====
92  The procname retrieved from memregionid 1 is "s1"
93  Process s1 with PID:   3 is killed
94  Process s1 with PID:   4 is killed
95    CPU 0: Processed   5 has finished
96    CPU 0: Dispatched process   6
97    Loaded a process at input/proc/s1, PID: 8 PRIO: 5
98    CPU 1: Processed   7 has finished
99  Time slot   25
100   CPU 1: Dispatched process   8
101 Time slot   26
102   CPU 0: Put process   6 to run queue
103   CPU 0: Dispatched process   6
104   CPU 1: Put process   8 to run queue
105 Time slot   27
106   CPU 1: Dispatched process   8
107 Time slot   28
108   CPU 0: Put process   6 to run queue
109   CPU 0: Dispatched process   6
110   CPU 1: Put process   8 to run queue
111   CPU 1: Dispatched process   8
112 Time slot   29
113 Time slot   30
114   CPU 0: Put process   6 to run queue
115   CPU 0: Dispatched process   6
116   CPU 1: Put process   8 to run queue
117   CPU 1: Dispatched process   8
118 Time slot   31
119   CPU 0: Processed   6 has finished
120   CPU 0 stopped
```

```
121  Time slot   32
122    CPU 1: Processed   8 has finished
123    CPU 1 stopped
```

Listing 26: Output log: res_os_killall_complex.txt (Updated)

Execution Analysis: This analysis reflects the updated output log for the complex `killall` scenario.

- **T=0-19:** PIDs 1-6 load and execute according to MLQ rules across 2 CPUs. Key events: PID 2 (Prio 10) finishes T=10. PID 1 (Prio 5) finishes T=15. PID 3 (Prio 15) and PID 4 (Prio 20) load but are preempted or wait due to PID 5 (Prio 8) and PID 6 (Prio 12). PID 7 (`killer`, Prio 1) loads at T=19 (log message appears at T=20, but loading happens before the slot starts).

- **T=19 (Dispatch):** At the end of T=19, CPU 1 finishes its slice for PID 6 (Prio 12). It enqueues PID 6 and immediately dispatches the newly loaded, highest-priority PID 7 (Prio 1). Scheduler grants slice=min(5, slot[1], 2)=2.

- **T=20-21:** PID 7 runs on CPU 1, executing `alloc 100 1` and the first `write`. CPU 0 runs PID 5. PID 7 yields at the end of T=21.

- **T=22-23:** CPU 1 gets PID 7 again, grants slice=2. PID 7 executes the remaining two `write` instructions. CPU 0 continues with PID 5. PID 7 yields at the end of T=23.

- **T=24:** CPU 1 gets PID 7 again, grants slice=min(1, slot[1], 2)=1. PID 7 executes `syscall 101 1`.

  - `__sys_killall` retrieves the name `s1` from region 1.
  - Handler scans process lists. It identifies PID 3 (from `input/proc/s1`) and PID 4 (from `input/proc/s1`) as matching the target name `s1`.
  - Prints kill messages for PIDs 3 and 4 (Lines 89-90). Calls `remove_pcb` for both, effectively terminating them and removing them from scheduler consideration.
  - Handler returns 0.

- Syscall completes within T=24. PID 7's `pc` advances.

- **T=25 (Post-Kill):**

- PID 8 (`s1`, Prio 5) loads (message appears at T=25, loaded before slot starts).

- CPU 0 finishes PID 5 (`s2`). Prints `Processed 5...`. Calls `get_mlq_proc`. PIDs 3 and 4 no longer exist. The next available is PID 6 (`s3`). CPU 0 dispatches PID 6.

- CPU 1 detects PID 7 finished (`pc == code->size`). Prints `Processed 7...`. Calls `remove_pcb`. Calls `get_mlq_proc`. Finds newly loaded PID 8 (`s1`, Prio 5). Dispatches PID 8.

- **T=25-32:** Remaining processes PID 6 (Prio 12) and PID 8 (Prio 5) run concurrently on CPUs 0 and 1, respectively, until completion (PID 6 finishes T=31, PID 8 finishes T=32). CPUs stop.

This complex test accurately demonstrates the `killall` syscall's functionality within the MLQ scheduling environment. PID 7 successfully retrieves the target name `s1` and the subsequent log confirms that PIDs 3 and 4 (both originating from `s1`) are terminated, as they are no longer scheduled after time slot 24. The scheduler correctly proceeds with the remaining and newly loaded processes (PID 6 and PID 8).
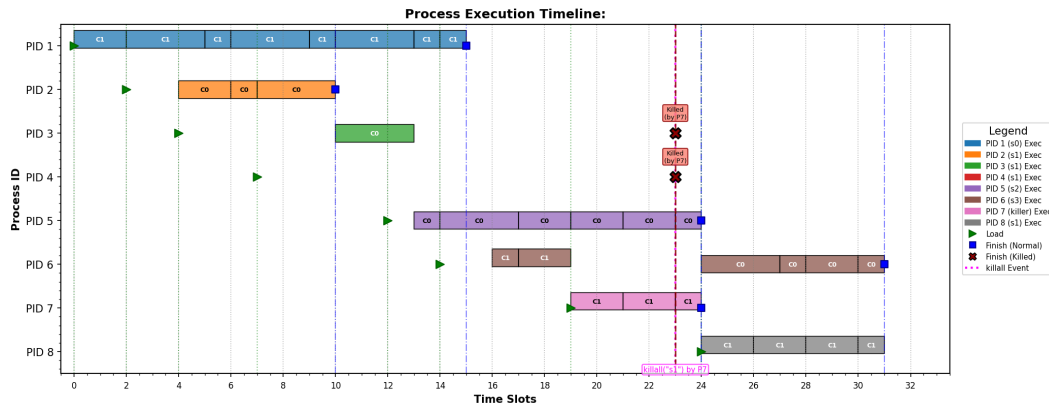
Gantt Chart:

Figure 10: Gantt chart for the `os_killall_complex` test case.

6   Answering questions

Question1: What is the mechanism to pass a complex argument to a system call using the limited registers?

System calls bridge user processes and the kernel. While simple arguments fit directly into registers (like `a1`, `a2`, `a3` in `struct sc_regs`), complex data like strings requires an indirect mechanism due to the limited number of registers.

1. Common OS Approach: Passing Virtual Address Pointers

   Most general-purpose operating systems (e.g., Linux, Windows) handle complex arguments by passing **virtual memory pointers**.

   - **User Setup:** The process allocates memory in its virtual address space and stores the complex data (e.g., a string for a filename, a buffer for reading data) there.
   - **Syscall Invocation:** The process places the starting **virtual address** of this data buffer into one of the argument registers when invoking the system call.
   - **Kernel Operation:** The kernel retrieves the virtual address from the register. It performs essential **validation** (checking if the address range is valid and accessible for the process) and **translation** (using page tables to find the physical address) before accessing the user's data buffer. This is typical for calls like `read()` or `write()`.

2. Assignment's `killall` Approach: Passing Region ID for Program Name

The `killall` system call (syscall 101) in this assignment uses a specific variation tailored to its function: it passes a **Memory Region Identifier (REGIONID)** that references the location of the **target program name string**.

- **User Setup:** A user process (like `sc2`) uses instructions like `alloc 100 1` to associate memory region ID `1` with a buffer, and then uses `write` to store the target program name (e.g., "P0") into that region.
- **Syscall Invocation:** The process calls `syscall 101 1`, passing the `REGIONID` (`1`) as the argument.
- **Kernel Argument Handling:** `libsyscall` packages this ID into `regs.a1 = 1`.
- **Kernel Name Retrieval:** The `__sys_killall` handler receives the ID via `regs->a1`. It knows this ID refers to a region containing a program name. It uses the ID (`memrg = regs->a1`) with kernel memory functions (`libread(caller, memrg, ...)`) to read the actual program name string (e.g., "P0") from the calling process's specified memory region.
- **Purpose & Subsequent Action:** The purpose of retrieving this target name ("P0") is for the kernel handler to then iterate through the system's process lists (like `running_list` and `mlq_ready_queue`). For each process found, the kernel extracts the base program name from its `proc->path` field and compares it to the retrieved target name ("P0"). If the names match, the kernel terminates that process (as described by the instructor's clarification, although the termination code itself might be simplified or partially implemented in the provided skeleton). If the names don't match, the kernel bypasses that process and continues the search.

This method uses the system call argument as a specific identifier for the program name's location, leveraging the simulation's memory region management (`libread` handling the lookup based on ID) rather than passing a raw, general-purpose pointer. This allows `killall` to target processes based on the name stored in a designated region.

Question 2: In this simple OS, we implement a design of multiple memory segments or memory areas in source code declaration. What is the advantage of the proposed design of multiple segments?

Segmentation is the mechanism where a process is divided into variable-sized segments according to their purposes , such as text, data, stack, heap, etc. These segments are managed and mapped to the physical memory though Segment Table.

This design provides security and protection among segments. When a segment is attached, it is isolated to other, avoiding unauthorized access from other segments. Additionally, segmentation enhances Inter-process communication, allowing processes sharing segments without worrying about security. when other process acquire the memory in a certain segment, we can give access to that exact segment without splitting or duplicating data.

Also, segmentation offer flexibility when the segments is varying in size. We can allocate the segments in different size and contiguously.This improves CPU utilization, because we don't have to jump between pages for a segment, unlike in paging technique.

Logical View of Segmentation
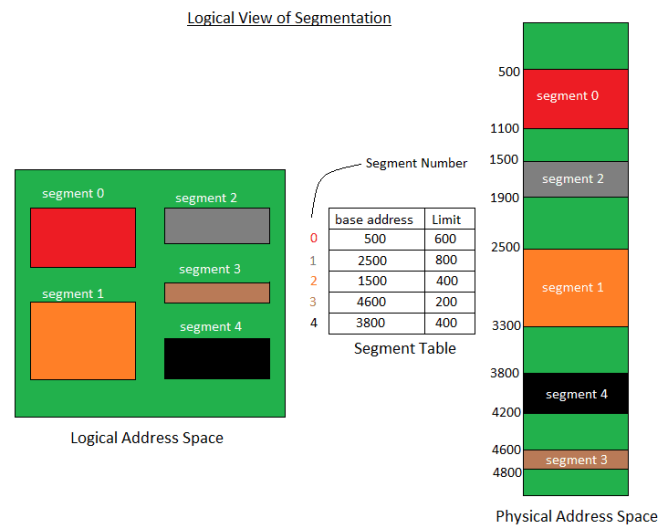
Beside that, the Segment Table consume less memory compared to Page Table. We can briefly search for a certain segment also.

Question 3: What will happen if we divide the address to more than 2 levels in the paging memory management system?

Multilevel-Paging is the memory management mechanism in which it breaks down the virtual address space into smaller pieces so that easier to manage through Page Table. Each entry of the page table represent the index of the frame mapped or the index of the entry in lower level. Then we combining the physical address of the frame with the offset in virtual address to get the real address of the instruction wanted.

Here is the example of splitting the 22-bits virtual address space into multilevel bits:

1. Three level: 5 bits for level 1 + 5 bits for level 2 + 4 bits for level 3 + 8 bits offset
2. Four level: 4 bits for level 1 + 4 bits for level 2 + 3 bits for level 3 + 3 bits for level 4 + 8 bits offset

Advantages:

1. Lookup faster:We do not need to traverse n entries to access the n-th page.
2. Less memory overhead for each Page Table: Less entry to hold for each table.
3. Suitable for large address space
4. Only a portion of entries in the system is created to manage the process.
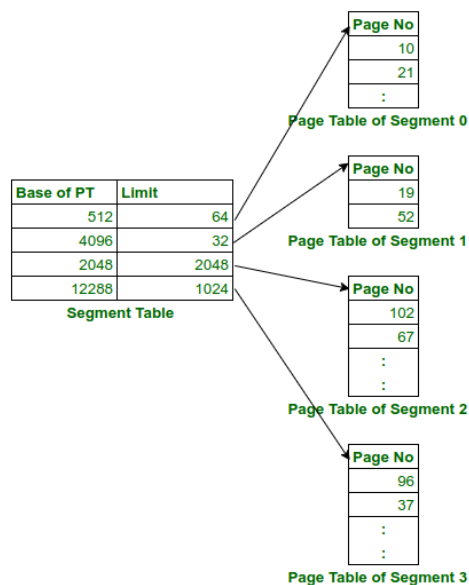
Disadvantages:

1. Increase overhead for page table lookup: We have to go through multiple step/level the get the physical address
2. More space needed to create high-level page tables, even when we need less space for each page table
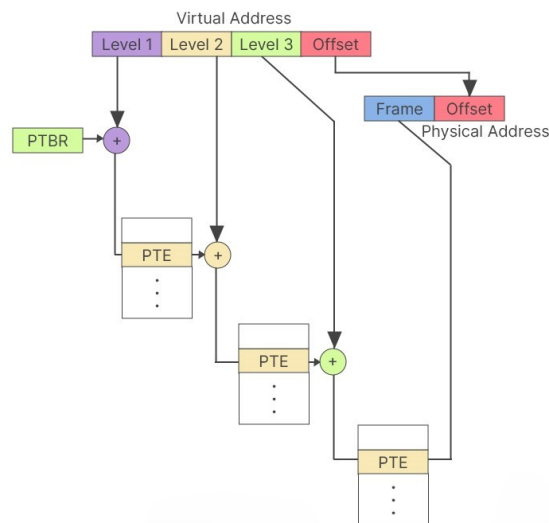
3. Harder to create and debug

Question 4: What are the advantages and disadvantages of segmentation with paging?

As i explained about paging and segmentation above, we have a few knowledge about these technique. Each of them have pros and cons that are opposite to the opposite one. So, there is a mixed mechanism to lessen the disadvantages of them, Segmentation with Paging. The process is firstly divided into segments according to their purposes. Then these segments is divided into fixed-size pages and mapped to frames in physical devices.

Advantage

- A large segment can be divided into multiple pages, so that it can fit in ram without necessarily having a large sequential segment within.
- Decrease the effect of external fragmentation.
- Optimize memory usage and more logical due to grouping data according to their purposes (stack,heap, data, ...)
- Easier to share pages and segments between processes.
- Decrease page table size, because it only need to represent the data according to that segment.
- More secure between segments since it has its own regions, and limits other segment's fault access

Disadvantages:

- Still have internal fragmentation since the size of a frame is alligned.
- Need to handle multiple pages and segments, increase overhead for lookup
- Storing page directory for processes is expensive for system that has limited size.

Question 5: What are the advantages of using the scheduling algorithm described in this assignment compared to other scheduling algorithms?

The scheduling algorithm implemented in this assignment is Multi-Level Queue (MLQ) scheduling with the following characteristics:

- **Fixed Priority Levels:** Processes are assigned priorities (0-139) when loaded, based on their type or configuration
- **Multiple Ready Queues:** One queue exists for each priority level
- **Priority-Based Inter-Queue Scheduling:** The scheduler always selects processes from the highest-priority non-empty queue
- **Round-Robin Intra-Queue Scheduling:** Within a single priority queue, processes are scheduled using Round-Robin with fixed time slices (implemented by the slot mechanism)
- **Preemption:** Higher-priority process arrivals preempt currently running lower-priority processes

Comparative advantages of MLQ against other common scheduling algorithms:

- MLQ vs. First-Come, First-Served (FCFS): MLQ provides significantly better responsiveness for high-priority processes. It eliminates the "convoy effect" where short or important tasks get blocked behind long-running, low-priority tasks that arrived earlier. MLQ ensures critical processes gain CPU access promptly based on their assigned priority.
- MLQ vs. Shortest Job First (SJF)/Shortest Remaining Time First (SRTF): MLQ does not require predicting future CPU burst times, which is a major practical limitation of SJF/SRTF. Instead, MLQ relies on fixed priorities that can be determined in advance, making it more feasible to implement in real systems where future behavior is unknown. It also generally prevents the starvation problem inherent in pure SJF/SRTF where long jobs might never execute during continuous streams of short jobs.

- MLQ vs. Simple Priority Scheduling: By incorporating Round-Robin scheduling within each priority level, MLQ prevents CPU monopolization by a single high-priority process. This introduces fairness among processes of equal priority, ensuring that all processes at a given priority level receive CPU time. Simple priority scheduling might allow one high-priority process to run indefinitely until completion, even when other equally important processes are waiting.
- MLQ vs. Simple Round Robin (RR): MLQ allows for differentiation between process types and importance levels. Critical or interactive processes can receive higher priorities to ensure prompt CPU allocation, resulting in better overall system responsiveness. Simple RR treats all processes equally regardless of their importance or requirements, which fails to optimize system performance across diverse workloads.

Question 6: What happens if the syscall job implementation takes too long execution time?

In the context of system call (`syscall`) implementation, one important consideration is the duration of execution. While most syscalls are expected to complete quickly, a long-running syscall can negatively impact the responsiveness and stability of the operating system, such as:

- **Kernel Blocking:** In non-preemptive kernel architectures (as simplified OS designs), a syscall holds control over the entire kernel until it finishes. This means no other syscall or scheduling operation can proceed, effectively stalling the whole system.
- **Responsiveness Issues:** Since all other processes are blocked during the syscall execution, user interaction and background tasks are delayed, leading to a poor user experience. In extreme cases, this can result in system "freezes".
- **Scheduling Delays and Starvation:** A lengthy syscall can delay process switching and cause starvation for other runnable processes. This is especially problematic in real-time systems where timing guarantees are critical.
- **Concurrency Hazards:** If the syscall acquires locks (e.g., mutexes on queues or lists), holding them for too long increases the risk of deadlocks and race conditions. This is particularly dangerous if other kernel components rely on the same resources.

To address the risks of long-running syscalls, several mitigation strategies can be employed:

- **Task Chunking:** Break the operation into smaller pieces, allowing multiple calls or yield points between chunks.
- **Asynchronous Processing:** Defer the heavy work to a background task and return from the syscall quickly.
- **Timeout or Bounded Execution:** Limit execution time or steps per syscall invocation to avoid monopolizing CPU time.

In our simplified OS, due to the limited number of processes and small-scale scheduling queues, we assume all syscalls complete in a short, bounded time. However, we remain cautious and avoid long-running loops within syscall implementations to prevent system hangs.

Question 7: What happens if the synchronization is not handled in your Simple OS? Illustrate the problem of your simple OS (assignment outputs) by example if you have any.

Synchronization is an attempt to handle the order of process's execution to avoid common errors like data race, race condition, etc.

Race condition occurs when multiple process access to the shared memory in an undesirable order, resulting in the fault result after a sequence of operations. Otherwise, data race happens if multiple processes did not wait other processes complete their execution, they apply several operation on the same space at the same time, leading to the unexpected result.

To solve these problems, many methods like mutex lock, semaphores, monitors, have been applied to ensure the synchronization of the program.

Example 1:

Expected Behavior:

```
...
Time slot    3
        CPU 0: Dispatched process   1
        CPU 1: Dispatched process   2
Time slot    4
Time slot    5
  CPU 0: Put process   1 to run queue
        CPU 1: Put process   2 to run queue
...
```

In the expected behavior, CPU 0 and CPU 1 independently dispatch two different processes. Each CPU tracks its own context and handles scheduling appropriately, and each process is returned to the run queue after execution.

Faulty Behavior Due to Missing Synchronization:

```
...
Time slot    3
        CPU 0: Dispatched process   1
        CPU 1: Dispatched process   1
Time slot    4
Time slot    5
  CPU 0: Put process   1 to run queue
        CPU 1: Put process   1 to run queue
...
```

In this case, both CPU 0 and CPU 1 dispatch the same process (Process 1) at the same time. This duplication implies that the run queue or scheduler is being accessed simultaneously without any mutual exclusion, allowing the same process to be scheduled on two CPUs. This can result in memory corruption, state inconsistency, and undefined behavior in user or kernel space due to duplicated execution contexts.

Example 2:

Expected Behavior:

```
1  ...
2  Time slot   3
3         CPU 0: Dispatched process   1
4         CPU 1: Dispatched process   2
5  Time slot   4
6  ===== PHYSICAL MEMORY AFTER ALLOCATION =====
7  PID=1 - Region=1 - Address=00000000 - Size=100 byte
8  print_pgtbl: 0 - 256
9  00000000: 80000000
10 Page Number: 0 -> Frame Number: 0
11 ================================================================
12 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
13 PID=2 - Region=1 - Address=00000000 - Size=100 byte
14 print_pgtbl: 0 - 256
15 00000000: 80000000
16 Page Number: 0 -> Frame Number: 1
17 ================================================================
18 Time slot   5
19   CPU 0: Put process  1 to run queue
20         CPU 1: Put process  2 to run queue
21 ...
```

This output shows correct memory allocation behavior. Each process is given a unique physical memory frame. Process 1 gets Frame 0, and Process 2 gets Frame 1. The page table and address translation are consistent and isolated.

Faulty Behavior Due to Missing Synchronization:

```
1  ...
2  Time slot   3
3         CPU 0: Dispatched process   1
4         CPU 1: Dispatched process   2
5  Time slot   4
6  ===== PHYSICAL MEMORY AFTER ALLOCATION =====
7  PID=1 - Region=1 - Address=00000000 - Size=100 byte
8  print_pgtbl: 0 - 256
9  00000000: 80000000
10 Page Number: 0 -> Frame Number: 0
11 ================================================================
12 ===== PHYSICAL MEMORY AFTER ALLOCATION =====
13 PID=2 - Region=1 - Address=00000000 - Size=100 byte
14 print_pgtbl: 0 - 256
15 00000000: 80000000
16 Page Number: 0 -> Frame Number: 0
17 ================================================================
18 Time slot   5
19   CPU 0: Put process  1 to run queue
20         CPU 1: Put process  2 to run queue
21 ...
```

In this faulty scenario, both processes receive the same physical frame (Frame 0), which breaks the isolation between processes. Since each process thinks it owns Frame 0, their memory writes may interfere with each other. This is a direct result of a

data race in the memory allocator, where two CPUs allocate memory simultaneously without synchronizing access to the frame table.

References