EI338 Computer Systems Engineering

Project 8 Designing a Virtual Memory Manager

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The environment used in this project is **Deepin 15.11**, the latest version of an open source operating system based on Debian's stable branch. The kernel version is **Linux version 4.15.0**.

Exercise

This project consists of writing a program that translates logical to physical addresses for a virtual address space of size $2^16 = 65,536$ bytes. Out program will read from a file containing logical addresses and, using a TLB and a page table, will translate each logical address to its corresponding physical address and output the value of the byte stored at the translated physical address. The learning goal here is to use simulation to understand the steps involved in translating logical to physical addresses. This will include resolving page-faults using demand paging, managing a TLB, and implementing a page-replacement algorithm.

Basic Structure

Our program will read a file containing several 32-bit integer numbers that represent logical addresses. Our program is only concerned with reading logical addresses and translating them into physical addresses. Some specifics include the following:

- 2^8 entries in the page table
- Page size of 2^8 bytes
- 16 entries in the TLB
- Frame size of 2^8 bytes
- 256 frames
- Physical memory of $65,536$ bytes (256 frames $\times$ 256-byte frame size)

Implementation

A visual representation of the address-translation process is shown in 1. Three main issues should be dealed with:

1. How to extract the page number and offset from logical addresses?
2. How to consult the TLB to obtain the frame number?
3. If the page table must be consulted, how to handle page faults?

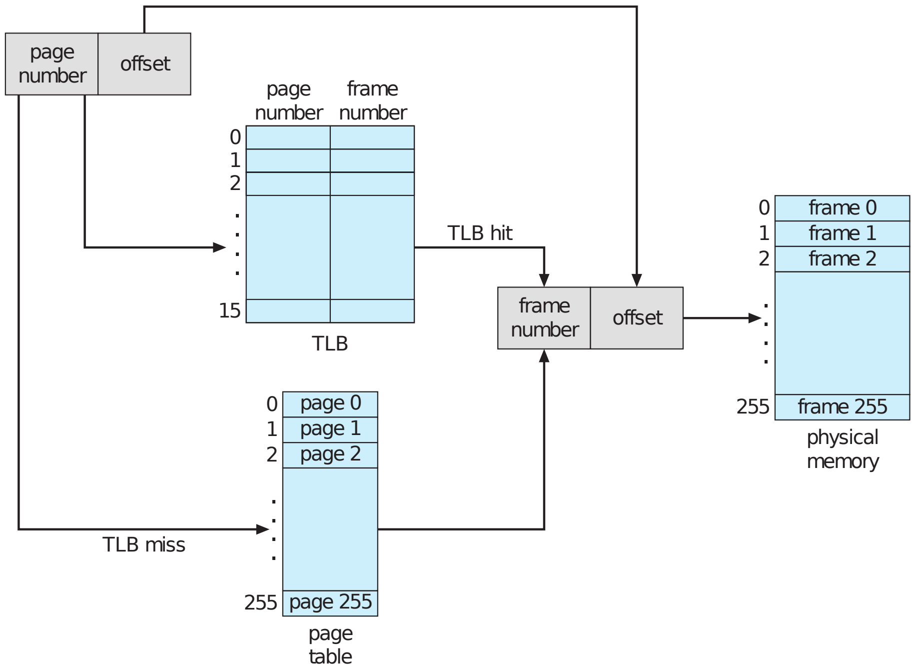


Figure 1: Address-translation Process

extract_page_num() & extract_offset()

To address the first issue, we use bit-masking and bit-shifting. **PAGE_MASK** and **OFFSET_MASK** are masking bits.

```
#define PAGE_MASK 0xFF00
#define PAGE_NUM_BIT 8
#define FRAME_NUM_BIT 8
#define OFFSET_MASK 0xFF

// ...

unsigned extract_page_num(unsigned logical_addr) {
    return (logical_addr & PAGE_MASK) >> PAGE_NUM_BIT;
}

unsigned extract_offset(unsigned logical_addr) {
    return logical_addr & OFFSET_MASK;
}
```

Listing 1: extract_page_num() & extract_offset()

0.0.1 get_frame_num_from_TLB()

get_frame_num_from_TLB() is to address the second issue, translating a page number into a frame number by consulting the TLB.

We first check whether the specific page is already in the TLB.

```
for (int i = 0; i < tlb_capacity; ++i) {
    if (tlb[i].page_num == page_num) {
        ++TLB_hit_num;
```

```
        return tlb[i].frame_num;
    }
}
```

Listing 2: TLB Hit

If a TLB miss occurs, we call *get_frame_num_from_pt()* to consult the page table, and then update the TLB. If the TLB is not full, we directly add the new page into the TLB. Otherwise, we update it by applying the simplest FIFO policy.

```
// TLB is not full
if (tlb_capacity < TLB_ENTRY_NUM) {
    tlb[tlb_capacity].frame_num = frame_num;
    tlb[tlb_capacity].page_num = page_num;

    ++tlb_capacity;
}

// TLB is full
else {
    tlb[tlb_first_index].frame_num = frame_num;
    tlb[tlb_first_index].page_num = page_num;

    tlb_first_index = (tlb_first_index + 1) % TLB_ENTRY_NUM;
}
```

Listing 3: TLB Miss

get_frame_num_from_pt()

consulting the page table is similar to consulting the TLB. Again, we first try to obtain the frame number by checking whether the corresponding valid bit is set.

```
if (pt[page_num].valid_bit)
    return pt[page_num].frame_num;
```

Listing 4: Consulting the Page Table

If a page fault occurs, we need to find a free-frame in the free frame list. If the page table is full, we select a victim with the FIFO policy and replace it. A new frame is swapped in from **BACKING_STORE**.

```
unsigned frame_num;

// find a free frame
if (free_frame_index < FRAME_NUM) {
    pt[page_num].frame_num = frame_num = free_frame_index++;
    pt[page_num].valid_bit = 1;
    frame_to_page[frame_num] = page_num;
}

// replace a page
else {
    pt[page_num].frame_num = frame_num = victim_frame_index;
    pt[page_num].valid_bit = 1;
    pt[frame_to_page[frame_num]].valid_bit = 0; // erase
    victim_frame_index = (victim_frame_index + 1) % FRAME_NUM; // circular array
    frame_to_page[frame_num] = page_num;
}
```

```
// swap
fseek(backing_store_fp, page_num * PAGE_SIZE, SEEK_SET);
fread(memory + frame_num * FRAME_SIZE, FRAME_SIZE, 1, backing_store_fp);
```

Listing 5: Page Fault

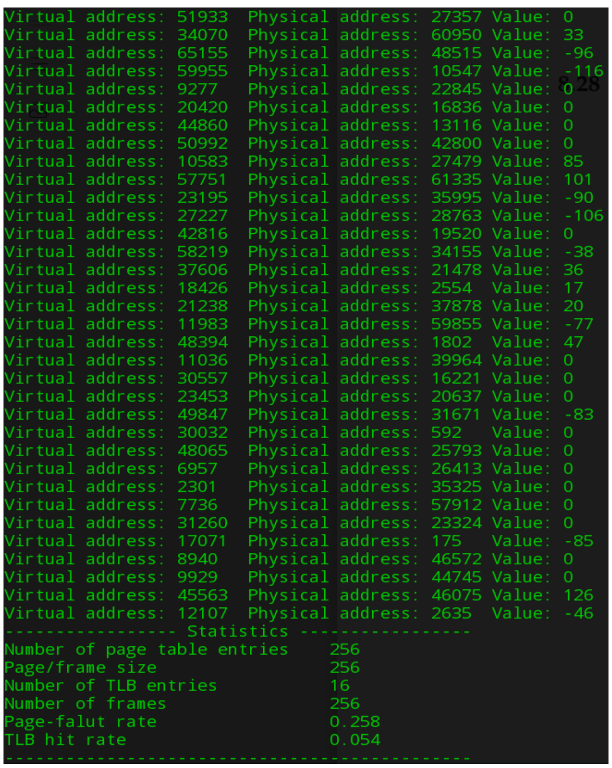
Result

To check whether our program is correct, we conduct an experiment with the test file **address.txt**, which contains 1000 integer values representing logical addresses ranging from 0 to 65535 (the size of the virtual address space). The translation is validated by consulting the ground truth.

Further more, two statistics are to reported:

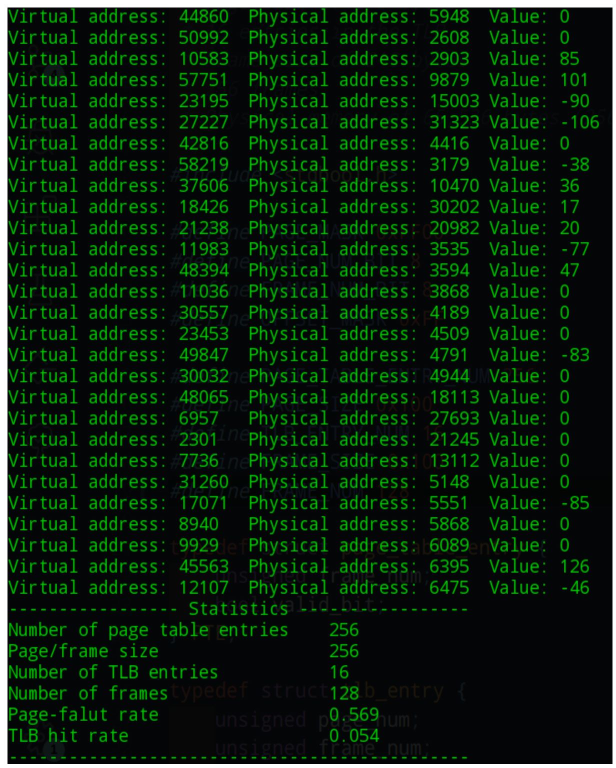
1. **Page-fault rate**–The percentage of address references that resulted in page faults.
2. **TLB hit rate**–The percentage of address references that were resolved in the TLB .

Our program reports the statistics under two circumstances: **FRAME_NUM** = 128 and **FRAME_NUM** = 256. The results seem reasonable.



```
Virtual address: 51933  Physical address: 27357 Value: 0
Virtual address: 34070  Physical address: 60950 Value: 33
Virtual address: 65155  Physical address: 48515 Value: -96
Virtual address: 59955  Physical address: 10547 Value: -116
Virtual address: 9277   Physical address: 22845 Value: 0
Virtual address: 20420  Physical address: 16836 Value: 0
Virtual address: 44860  Physical address: 13116 Value: 0
Virtual address: 50992  Physical address: 42800 Value: 0
Virtual address: 10583  Physical address: 27479 Value: 85
Virtual address: 57751  Physical address: 61335 Value: 101
Virtual address: 23195  Physical address: 35995 Value: -90
Virtual address: 27227  Physical address: 28763 Value: -106
Virtual address: 42816  Physical address: 19520 Value: 0
Virtual address: 58219  Physical address: 34155 Value: -38
Virtual address: 37606  Physical address: 21478 Value: 36
Virtual address: 18426  Physical address: 2554  Value: 17
Virtual address: 21238  Physical address: 37878 Value: 20
Virtual address: 11983  Physical address: 59855 Value: -77
Virtual address: 48394  Physical address: 1802  Value: 47
Virtual address: 11036  Physical address: 39964 Value: 0
Virtual address: 30557  Physical address: 16221 Value: 0
Virtual address: 23453  Physical address: 20637 Value: 0
Virtual address: 49847  Physical address: 31671 Value: -83
Virtual address: 30032  Physical address: 592   Value: 0
Virtual address: 48065  Physical address: 25793 Value: 0
Virtual address: 6957   Physical address: 26413 Value: 0
Virtual address: 2301   Physical address: 35325 Value: 0
Virtual address: 7736   Physical address: 57912 Value: 0
Virtual address: 31260  Physical address: 23324 Value: 0
Virtual address: 17071  Physical address: 175   Value: -85
Virtual address: 8940   Physical address: 46572 Value: 0
Virtual address: 9929   Physical address: 44745 Value: 0
Virtual address: 45563  Physical address: 46075 Value: 126
Virtual address: 12107  Physical address: 2635  Value: -46
----------------- Statistics -----------------
Number of page table entries    256
Page/frame size                 256
Number of TLB entries           16
Number of frames                256
Page-falut rate                 0.258
TLB hit rate                    0.054
----------------------------------------------
```

(a) FRAME_NUM = 128



```
Virtual address: 44860  Physical address: 5948  Value: 0
Virtual address: 50992  Physical address: 2608  Value: 0
Virtual address: 10583  Physical address: 2903  Value: 85
Virtual address: 57751  Physical address: 9879  Value: 101
Virtual address: 23195  Physical address: 15003 Value: -90
Virtual address: 27227  Physical address: 31323 Value: -106
Virtual address: 42816  Physical address: 4416  Value: 0
Virtual address: 58219  Physical address: 3179  Value: -38
Virtual address: 37606  Physical address: 10470 Value: 36
Virtual address: 18426  Physical address: 30202 Value: 17
Virtual address: 21238  Physical address: 20982 Value: 20
Virtual address: 11983  Physical address: 3535  Value: -77
Virtual address: 48394  Physical address: 3594  Value: 47
Virtual address: 11036  Physical address: 3868  Value: 0
Virtual address: 30557  Physical address: 4189  Value: 0
Virtual address: 23453  Physical address: 4509  Value: 0
Virtual address: 49847  Physical address: 4791  Value: -83
Virtual address: 30032  Physical address: 4944  Value: 0
Virtual address: 48065  Physical address: 18113 Value: 0
Virtual address: 6957   Physical address: 27693 Value: 0
Virtual address: 2301   Physical address: 21245 Value: 0
Virtual address: 7736   Physical address: 13112 Value: 0
Virtual address: 31260  Physical address: 5148  Value: 0
Virtual address: 17071  Physical address: 5551  Value: -85
Virtual address: 8940   Physical address: 5868  Value: 0
Virtual address: 9929   Physical address: 6089  Value: 0
Virtual address: 45563  Physical address: 6395  Value: 126
Virtual address: 12107  Physical address: 6475  Value: -46
---------------- Statistics ----------------
Number of page table entries    256
Page/frame size                 256
Number of TLB entries           16
Number of frames                128
Page-falut rate                 0.569
TLB hit rate                    0.054
--------------------------------------------
```

(b) FRAME_NUM = 256

Figure 2: Result