PROBLEM 1: BASICS OF SCHEDULING (page 4)

Scheduling policies can be easily depicted with some graphs. For example, let's say we run job A for 10 time units, and then run job B for 10 time units. Our graph of this policy might look like this:

```
    |
CPU |AAAAAAAAAABBBBBBBBBB
    |____________________

    0        10        20
```

In this question, you'll show your understanding of scheduling by drawing a few of these pictures.

(a) Draw a picture of Shortest Job First (SJF) scheduling with three jobs, A, B, and C, with run times of 5, 10, and 15 time units, respectively.

Make sure to LABEL the x-axis appropriately.

```
         TA          TB                    TC
    |
CPU |A AAAA| BBBBB|BBBBB| CCCCC|CCCCC|CCCCC|
    |____________________________________________
           5     10    15     20    25    30
```

(b) What is the average TURNAROUND TIME for jobs A, B, and C?

turnaround is $(Time_{end} - Time_{submit})$

$T_A = (5-0)$ $T_B = (15-0)$ $T_C = (30-0)$ $T_{avg} = \frac{5+15+30}{3} = \frac{50}{3}$

(c) Draw a picture of ROUND-ROBIN SCHEDULING for jobs A, B, and C, which each run for 6 time units, assuming a 2-time-unit time slice; also assume that the scheduler (S) takes 1 time unit to make a scheduling decision.

Make sure to LABEL the x-axis appropriately.

```
     RA    RB    RC                     TA   TB   TC
    |
CPU |SAA|SBB|SCC|SAA|SBB|SCC|SAA|SBB|SCC|
    |____________________________________________
        3   6   9   12  15  18  21  24  27
```

(d) What is the average RESPONSE TIME for round robin for jobs A, B, and C?

response time is $(Time_{first run} - Time_{submit})$

$R_A = 1$ $R_B = 4$ $R_C = 7$ $R_{AVG} = \frac{1+4+7}{3} = 4$

(e) What is the average TURNAROUND TIME for round robin for jobs A, B, and C?

$T_A = 21$ $T_B = 24$ $T_C = 27$

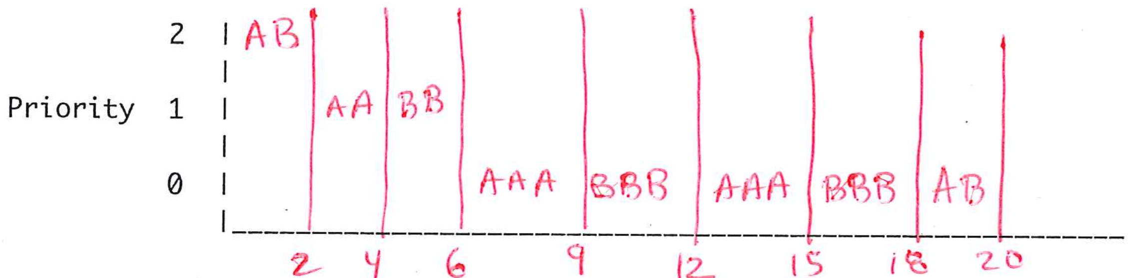
$T_{AVG} = 24$

Assume you have a multi-level feedback queue (MLFQ) scheduler.
In this question, we'll draw a picture of how it behaves over time.

Unlike the drawings in the previous problem (for SJF and RR), the y-axis will also be important for these pictures, as it will show the PRIORITY of the jobs over time.

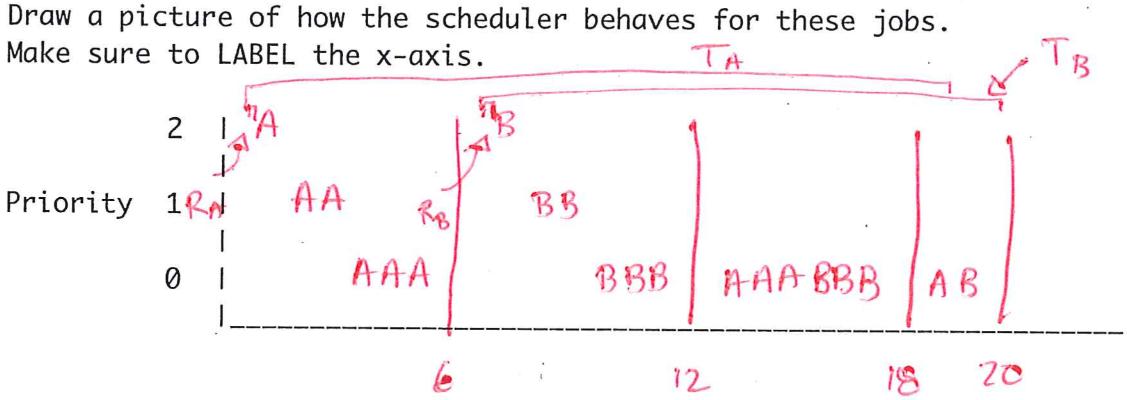
(a) Assume a 3-level MLFQ (high priority is 2, low priority is 0). Assume two jobs (A and B), both BATCH jobs (no I/O), each with a run-time of 10 time units, and both entering the system at T=0. Assume the quantum length at the highest priority level is 1, then 2 at the middle, and 3 for the lowest priority.

Draw a picture of how the scheduler behaves for these jobs.
Make sure to LABEL the x-axis.



(b) Assume the same scheduling parameters as above. Now the jobs are different; A and B both are BATCH jobs that each run for 10 time units (no I/O again), but this time A enters at T=0 whereas B enters the system at T=6.

Draw a picture of how the scheduler behaves for these jobs.
Make sure to LABEL the x-axis.



(c) Calculate the RESPONSE TIME and TURNAROUND TIME (in part b) for Job A

$R_A = 0$ $T_A = 19$

(d) Calculate the RESPONSE TIME and TURNAROUND TIME (in part b) for Job B

$R_B = 0$ $T_B = 20 - 6 = 14$

PROBLEM 3: MALLOC AND FREE

Assume you have a chunk of memory that you need to manage. When someone requests a chunk, you take the first available chunk and return it, starting at the lowest address in the space you are managing (i.e., a LOWEST-ADDRESS-FIRST policy, perhaps). The space is managed with a simple free list; when someone returns a chunk, you COALESCE the list, thus merging smaller allocated chunks back into a bigger free space.

Assuming you have 50 bytes of memory to manage, and that exactly one allocation has taken place (for 10 bytes), here is what memory would look like (with spaces in-between every 10 bytes for readability):

```
HHHHAAAAAA AAAAFFFFFF FFFFFFFFFF FFFFFFFFFF FFFFFFFFFF

(low)          Addresses of Managed Space          (high)
```

In the picture, A means allocated, F means free, and H is a 4-byte header that is REQUIRED before every allocated chunk.

(a) Assume a 50-byte free space. Draw what it would look like after these requests: allocate(10), allocate(10), and allocate(10).

2

HHHHAAAAAA | AAAAHHHHAA | AAAAAAAAHH | HHAAAAAAAA | AA FFFFFFFF

(b) Assume a 50-byte free space. Draw what it would look like after allocation requests of allocate(10), allocate(20), and allocate(20). ⟹ FAIL

2

$\underbrace{\text{HHHH AAAAAA | AAAA}}_{10}$ HHHH AA | $\underbrace{\text{A - - - - A | AAAAAAAA}}_{20}$ FF | $\underbrace{\text{F - - - F}}_{10}$

(c) Assume a 50-byte free space. Draw what it would look like after the following requests: x=allocate(10), y=allocate(10), z=allocate(10), free(y), w=allocate(24). ← FAIL

3

HHHH $\underbrace{\text{AAAAAA | AAAA}}_{x}$ $\underbrace{\text{FFFFFF | FFFFFFFFFF}}_{\text{where y was}}$ $\underbrace{\text{HH | HHAAAAAAAA | AA}}_{z}$ F . . . F

(d) Assume now that there is NO COALESCING of free space. Also assume that instead of allocating via the policy of LOWEST-ADDRESS-FIRST, you instead use a BEST-FIT policy. Assume a 50-byte free space. Draw what it would look like after the following requests: x=allocate(10), y=allocate(10), z=allocate(10), free(y), free(z), w=allocate(4).

3

$\underbrace{\text{HHHHAAAAAA | AAAA}}_{x}$ $\underbrace{\text{FFFFFF | FFFFFFFFFF}}_{\text{where y was}}$ $\underbrace{\text{FFFFFFFFFF | FF}}_{\text{where z was}}$ $\underbrace{\text{HHHHAAAA}}_{w}$

PROBLEM 4: SEGMENTATION (page 7)

Assume virtual memory hardware that uses segmentation, and divides the address space in two by using the top bit of the virtual address. Each segment is thus relocated independently.

What we'll be drawing in this question is what physical memory looks given some different parameters. We'll also label where a particular memory reference ends up.

For all questions, assume a virtual address space of size 16 bytes (yes tiny!) and a physical memory of size 64 bytes. Thus, if we had a virtual address space placed in physical memory, it might look like this (with spaces between every 8 physical bytes):

0000FFFF FFFFFFFF FFFFFFFF FFFFFFFF FFFFFFFF FFFFFFFF FFFFFFFF FFFF1111

In this example, the segment 0 base register is 0, segment 1 base is 64 (it grows backwards), and both length registers are 4. 0's are used to record where segment 0 is in memory; 1's are for segment 1; F means free.

(a) What would physical memory look like if we had the following values instead? (draw a picture below)

seg0 (base) : 12   seg0 (limit) : 6
seg1 (base) : 10   seg1 (limit) : 3

VA: 4 is here

seg1

FFFFFFF1 | 11FF0000 | 00 FFFFFF | F . . . . F

seg0

0 7 8 9 12 15 16 17 23 24 the rest

(b) In your picture above, CIRCLE which byte of memory is accessed when the process generates a byte load of virtual address 4
(or DRAW AN X on the physical-memory address if the access is illegal)

VA: 4 ⇒ seg 0
seg 0 base: 12
+ 4
16

(c) What would physical memory look like if we had the following values instead? (draw a picture below)

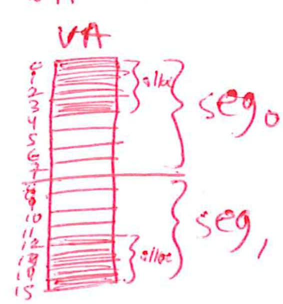
seg0 (base) : 40   seg0 (limit) : 4   40 ... 43
seg1 (base) : 50   seg1 (limit) : 4   46 ... 49

VA: 4 (fault)

seg0   seg1   VA: 14

F ... F | F ... F | F ... F | F ... F | F ... F | 0000 X F11 | 11 FFFFFF | F...

0 7 8 15 16 23 24 31 32 39 40 43 46 47 48 49



(d) In your picture above, CIRCLE which byte of memory is accessed when the process generates a byte load of virtual address 14
(or DRAW AN X on the physical-memory address if the access is illegal)

(e) In your picture above, CIRCLE which byte of memory is accessed when the process generates a byte load of virtual address 4
(or DRAW AN X on the physical-memory address if the access is illegal)

PROBLEM 5: SIMPLE PAGING

Which memory is accessed during the execution of an instruction? For this question, assume a linear page table, with a 1-byte page-table entry. Assume an address space of size 128 bytes with 32-byte pages. Assume a physical memory of size 128 bytes. The page-table base register is set to physical address 16. The contents of the page table are:

VPN	PFN
0	1
1	Not valid
2	3
3	Not valid

Now, finally assume we have the following instruction, which loads a SINGLE BYTE from virtual address 70 into register R1:

```
  10: LOAD 70, R1
```

This instruction resides at virtual address 10 within the address space of the process.

instruction fetch:
VA : 10 => VPN_0
⇓
translate by reading first entry of PT
42 => PA

In the diagram of physical memory below:

(a) Put a BOX around each valid virtual page (and label them)

(b) Put a BOX around the page table (and label it)

(c) CIRCLE the memory addresses that get referenced during the execution of the instruction, including both instruction fetch and data access (there is no TLB).

data fetch :
VA : 70 =>
read third entry of PT to xlate
PA : 102

(d) LABEL these addresses with a NUMBER that indicates the ORDER in which various physical addresses get referenced.

page table : base is 16, 4 entries each 1 byte in size

Physical Memory

0	1	2	3	4	5	6	7
8 1	9	10 3	11	12	13	14	15
16	17	18	19	20	21	22	23
24	25	26	27	28	29	30	31
32_0	33_1	34_2 2	35_3	36_4	37_5	38_6	39_7
40_8	41_9	42_{10}	43	44	45	46	47
48	49	50	51	52	53	54	55
56	57	58	59	60	61	62	63
64	65	66	67	68	69	70	71
72	73	74	75	76	77	78	79
80	81	82	83	84	85	86	87
88	89	90	91	92	93	94 4	95
96_{64}	97_{65}	98_{66}	99_{67}	100_{68}	101_{69}	102_{70}	103
104	105	106	107	108	109	110	111
112	113	114	115	116	117	118	119
120	121	122	123	124	125	126	127

phys page 1 — VPN_0 => PFN_1

phys page 3 — VPN_2 => PFN_3

PROBLEM 6: THE TLB, PAGE FAULTS, ETC. (page 9)

In this question, you will examine virtual memory reference traces. An access can be a TLB hit or a TLB miss; if it is a TLB miss, the reference can be a page hit (present) or a page fault (not present).

Assume a TLB with 4 entries, and a memory that can hold 8 pages. Assume the TLB and memory both are empty initially. Finally, assume LRU replacement is used for both the TLB and memory.

(a) What happens on each access in the following reference trace? a TLB hit, TLB miss/page hit, or TLB miss/page fault? (these can be abbreviated H, M, or PF)

0 PF
1 PF
2 PF
3 PF
0 H
1 H
2 H
3 H

after faulting in, all are in mem and mapped in TLB

(b) What happens on each access in the following reference trace? (write H, M, or PF)

0 PF
1 PF
2 PF
3 PF
4 PF
0 M
1 M
2 M
3 M
4 M

this time, pages are in memory, but TLB not big enough => TLB misses

(c) Now assume a memory that can only hold 3 pages. What happens on each access in the following reference trace? (H, M, PF)

LRU -> 0 1 2

0 PF
1 PF
2 PF
0 H — 1 2 0
1 H — 2 0 1
3 PF — 0 1 3
0 H — 1 3 0
3 H — 1 0 3
1 H — 0 3 1
2 PF — 3 1 2
1 H — 3 2 1

TLB: big enough to hold all mappings => no TLB misses

PROBLEM 7: MULTI-LEVEL PAGE TABLES (page 10)

In this question, we'll examine a multi-level page table, like that found in the (optional) homework. The parameters are the same:

- The page size is an unrealistically-small 32 bytes.
- The virtual address space for the process in question (assume there is only one) is 1024 pages, or 32 KB.
- Physical memory consists of 128 pages.

Thus, a virtual address needs 15 bits, 5 of which are the offset. A physical address requires 12 bits, also with 5 as the offset.

The system assumes a multi-level page table. Thus, the upper five bits of a virtual address are used to index into a page directory; the page directory entry (PDE), if valid, points to a page of the page table. Each page table page holds 32 page-table entries (PTEs). Each PTE, if valid, holds the desired translation (physical frame number, or PFN) of the virtual page in question.

The format of a PTE is thus:

VALID | ~~PFN7~~ PFN6 ... PFN0

and is thus 8 bits or 1 byte.

The format of a PDE is essentially identical:

VALID | ~~PT7~~ PT6 ... PT0

For this question, assume the PDBR (page-directory base register) is 73.

On the next page is the physical memory dump, where your answers will go.

(a) CIRCLE which bytes are accessed during a load from virtual address 0x3009.

VA: 011 0000 0000 1001 page index → Page Table Index = 0

PageDirIndex = 12 ⇒ 0x bf 7 page

valid → $\boxed{1|011\ 1111}$ ⇒ 63 +

\# 0x e7

valid ⇒ $\boxed{1|110\ 0111}$ ⇒ page 103

index: 01001 ⇒ 9

fetch ⇒ $\boxed{0d}$

(b) Put SQUARES around bytes accessed during a load from 0x7042.

11100 | 00010 | 00010

PD index | PT index | offset on page

```
page  0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page  1: 7f 7f a0 7f 7f 7f 7f 7f 7f 7f c5 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f
page  2: 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 8b 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f ff 7f 7f 7f 94 7f 7f 7f 7f
page  3: 1e 02 1e 10 18 0d 1e 17 11 1c 1a 10 17 0d 1a 08 03 0b 18 02 11 07 14 11 1e 16 0c 15 13 10 05 05
page  4: 08 00 1c 0f 01 0a 10 13 19 02 13 0a 1b 1c 12 0f 10 13 1b 1c 0a 05 1d 09 04 1e 07 0c 0e 01 18 17
page  5: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page  6: 0a 1c 01 14 0b 1a 19 0a 0a 1a 0c 14 02 0c 1c 0c 15 04 0e 13 17 11 08 05 08 07 04 13 0f 1d 0f 1e
page  7: 7f 7f 7f 7f 7f ee 7f 7f 7f 7f b6 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f a3 7f 7f 7f
page  8: 13 08 1c 0e 0b 0b 15 14 01 18 07 1c 00 1d 0f 00 08 08 0c 04 05 1a 0f 17 07 10 17 0a 16 17 17 10
page  9: 0b 1b 18 17 08 09 11 0a 03 01 04 06 0b 17 0e 12 12 01 1e 0d 0a 1c 09 09 02 0e 0a 1a 13 1d 06 0c
page 10: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 11: 05 04 04 11 0e 00 01 0b 0a 1b 14 17 0c 04 1c 0b 0e 15 11 09 14 1d 09 09 1a 0c 06 16 11 12 04 09
page 12: 15 08 1e 1c 0e 05 1d 04 18 19 0b 05 1b 1d 13 07 1c 0b 0a 1a 04 1b 01 11 10 0e 00 01 0a 12 1a 0c
page 13: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 14: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 15: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 16: 00 03 0f 10 0c 17 07 16 14 13 14 01 15 01 1e 10 17 01 0b 11 05 09 1e 1e 00 0d 1e 1b 0d 09 13 06
page 17: 16 13 1e 1e 05 01 1d 02 1d 16 12 0d 03 04 18 1e 16 18 00 02 08 0e 1b 01 13 07 16 11 11 1c 1a 13
page 18: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 19: 7f c8 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f
page 20: 01 1b 08 07 06 0c 00 00 05 05 1d 18 0a 06 17 08 1a 1e 1b 16 10 13 19 05 0e 0c 1a 17 1a 10 0a 02
page 21: 1a 0d 0f 0a 03 10 14 19 1a 13 04 05 08 08 0c 13 14 04 05 01 0b 05 03 1c 0e 1c 19 17 05 0f 1b 0c
page 22: 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f ec 7f 7f 7f ed 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f
page 23: 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 84 7f 7f 7f c6 7f aa 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f
page 24: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 25: 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 88 7f 7f 7f 7f 7f 7f 7f 7f f7 7f 7f
page 26: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 27: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 28: 03 16 16 09 13 1c 12 0d 0a 1a 10 00 0d 04 02 16 14 12 14 1d 0d 19 04 1b 14 04 11 11 06 08 07 05
page 29: 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 89 7f 7f 7f 7f 7f 7f b3 7f 7f 7f 7f 7f 7f 7f 7f 7f f8 7f 7f
page 30: 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f fa 7f 7f 7f 7f fc 7f 7f 7f 7f 7f bb 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f
page 31: 1b 19 17 0e 1a 1d 19 03 09 09 06 08 1a 05 0a 0e 17 11 00 13 13 02 0c 0c 18 19 10 12 04 06 16 19
page 32: 18 13 17 0f 06 12 1d 18 1c 04 01 1d 15 18 0b 14 13 1b 17 04 17 09 1e 11 1b 08 04 13 0e 03 0d 04
page 33: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 34: 7f 7f b5 7f a7 7f 7f 7f 7f 7f 7f 7f 7f ef 7f 7f bc 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f
page 35: 17 1a 19 05 16 1e 1b 1d 12 1c 03 15 02 0c 00 1e 19 06 19 16 18 1e 0a 16 01 0e 0f 12 13 07 16 07
page 36: 07 1e 05 02 0c 1c 02 17 01 19 06 03 0f 1b 13 1c 18 19 1a 1c 09 0e 0b 00 0e 19 19 12 06 0f 19 00
page 37: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 38: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 39: 1c 1a 0f 0f 13 16 10 16 00 11 0d 09 14 03 10 13 1a 0c 14 17 1b 03 0a 15 15 15 1a 18 17 13 17 0c
page 40: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 41: 11 0a 0a 15 0a 0a 09 1c 0a 04 04 01 04 18 02 18 16 1e 0b 10 03 13 14 04 19 08 17 03 01 0d 00 13
page 42: 1b 1d 12 15 08 05 03 19 12 01 01 00 02 0f 06 1b 04 03 1b 0d 06 14 1b 1a 1e 16 0b 18 1d 07 0a 00
page 43: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 44: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 45: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 46: 00 04 17 0a 0a 0f 13 09 18 0e 14 08 07 18 02 03 18 16 1d 10 10 01 0d 01 0f 03 13 1b 0b 1d 14 1d
page 47: 0e 0a 08 0d 19 0c 02 07 00 1e 1a 03 1e 0d 1e 0b 02 0d 08 16 1a 06 13 06 05 09 02 10 19 1d 15 07
page 48: 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f ca 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f
page 49: f5 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f d0
page 50: 00 13 14 1b 09 04 05 10 18 0b 08 09 11 18 1d 00 14 0e 07 12 08 1a 16 06 11 0f 16 1d 1b 01 14 15
page 51: 18 03 11 14 1d 05 15 07 0a 04 1e 14 0c 0b 1e 09 1d 0e 11 17 10 08 0f 09 12 1c 0c 0a 01 1a 1d 15
page 52: cb 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 9f 7f
page 53: 04 16 1c 1b 00 13 11 0c 01 06 11 1b 15 00 04 10 18 18 14 00 0b 03 0b 1a 02 1c 14 1b 12 1e 17 05
page 54: 1a 1e 0d 14 08 13 14 1d 13 10 0a 16 19 15 0d 10 04 11 04 0e 19 08 09 00 0c 0c 05 1b 0c 16 09 1a
page 55: 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f b2 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 83 7f 7f 7f 7f 7f de 7f
page 56: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 57: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 58: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page 59: 0e 1b 0d 1b 15 16 0f 00 1c 1a 09 00 01 14 05 1c 17 15 03 18 1a 0e 14 1e 12 18 17 01 03 12 1b 07
page 60: 04 03 0d 09 0e 07 03 08 06 0d 07 18 04 16 0f 12 1d 19 0b 08 0b 19 0d 0c 02 10 08 0d 12 00 10 0b
page 61: 06 03 07 18 1a 16 0e 03 09 19 1a 14 15 04 09 1a 05 06 07 18 12 0f 05 19 09 03 09 19 07 07 1c 01
page 62: 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f d1 7f 7f 7f
page 63: e7 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f
```

page of page table
for (a)

PD indexed entry for (a)

page dir

page 103 (part (a))

```
           0  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
page  64: 14 0b 15 14 01 18 05 00 17 0a 04 08 14 09 12 06 1d 02 0f 00 13 04 1d 0a 16 11 1e 0c 02 02 09 1c
page  65: 0d 0d 14 12 19 15 0f 10 14 08 0e 03 15 00 17 1e 14 17 1c 06 0c 19 1a 1a 13 1c 1c 05 10 00 0a 10
page  66: 7f 7f 7f 7f 7f 7f 7f 7f 91 df 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f a4 7f 7f 7f 7f 7f 7f 7f 7f 7f 7f ce
page  67: 7f 7f 7f 7f e1 7f 7f e9 7f 7f 7f 7f 7f 7f 7f 7f 90 7f 7f 7f 7f 7f 7f 7f c0 7f 7f c1 7f 7f 7f 7f
page  68: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page  69: 0a 1c 00 07 00 15 05 06 07 02 0b 08 1a 11 03 0d 00 15 01 16 1d 1c 19 13 03 16 11 17 02 0f 19 13
page  70: 17 07 08 07 0b 01 1e 09 14 17 17 0a 19 15 12 0d 04 05 0e 16 01 1e 18 04 1e 08 07 16 0e 0d 02 00
page  71: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
page  72: 19 0e 1a 1c 16 16 11 02 12 07 0e 1c 17 17 0c 11 0f 00 14 13 1c 16 01 1d 0e 10 1c 17 0d 03 03 11
page  73: a2 d2 97 96 d9 7f 87 b4 b7 f2 f4 82 bf 7f be 93 e8 9d 99 9e f1 7f 7f b0 d8 da eb b1 81 c3 c2 f6
page  74: 17 05 04 1e 03 0b 08 05 04 00 10 08 1b 0f 09 0b 13 13 12 0d 08 02 19 0d 16 05 06 19 13 0a 17 0c
page  75: 01 17 0a 15 19 0d 17 01 04 18 1b 01 0d 0c 07 1b 0c 0e 0a 0e 06 12 01 09 0a 11 0e 06 10 15 0a 19
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Ah, virtual machine monitors. You use them, and now (hopefully) you understand them (a little bit).

Assume in this question some hardware that has a software-managed TLB.

Assume we are running a virtual machine monitor (VMM), an operating system (OS) on top of the VMM, and a user process running on the OS.

Draw a picture of the control flow during a TLB miss generated by the user process. The picture should reflect a time-line of what happens during this miss, including when the user process, OS, and VMM run, and what they do when they run.