7

**Question 1:** Given the shown page table and assuming 256-bytes pages

a) What is the value of N (the number of entries in the PT) assuming that the virtual address space consists of 128KB?

$2^{17}$ bytes / $2^{8}$ (bytes/page) = $2^{9}$ pages

b) How long (in bits) is the virtual byte address and the virtual page number?

Virtual byte address = 17 bits
Virtual page number = 9 bits

c) What is the size of the physical memory?

5-bit physical page # → 32 pages → 32 * 256 = $2^{5}$ * $2^{8}$ = 8 Kbytes

d) Calculate the physical address for the following virtual byte address:

0 0000 0100 0011 1100 → 10011 0011 1100
0 0000 1001 1010 1111 → 11010 1010 1111
0 0000 0001 1000 1110 → Page fault

e) Assuming that physical page 10111 is the least recently used page in memory, what will be the content of the page table after the above three memory reference (after servicing any page fault)?

| | valid | Physical page # |
|---|---|---|
| 0 | 0 | |
| 1 | 0 1 | 10111 |
| 2 | 1 | 11000 |
| 3 | 0 | |
| 4 | 1 | 10011 |
| 5 | 0 | |
| 6 | 1 | 00010 |
| 7 | 0 | |
| 8 | 1 | 01110 |
| 9 | 1 | 11010 |
| 10 | 1 | 10101 |
| 11 | | |
| 12 | . | . |
| 13 | . | . |
| | . | . |
| N-1 | | |

7

**Question 2:** Consider a virtual memory system with a 40-bit virtual byte address, 8KB pages and 512 MB of physical memory.

a) What is the minimum number of bytes needed to store each entry of the page table assuming that the Valid, Protection, Dirty and LRU/Use bits take a total of one byte per entry?

512MB Physical memory and page size $2^{13}$ Bytes → $2^{29}$ / $2^{13}$ = $2^{16}$ physical pages

Each page table entry has 8(Valid, Protection, …) + 16 (Physical Page #) = 24 bits (3 bytes)

b) What is the total size of the page table (in bytes) for each process on this machine, assuming that all the virtual pages are in use (assume that disk addresses are not stored in the page table)?

40-bit virtual byte address and page size $2^{13}$ Bytes → $2^{40}$ / $2^{13}$ = $2^{27}$ virtual pages

Page table has $2^{27}$ entries → Total # of byte in the page table = 3* $2^{27}$ =384MB

c) Express the size of the page table in terms of number of memory pages it will occupy

The entire page table can be stored in 3* $2^{27}$ / $2^{13}$ = 3* $2^{14}$ = 48 Kilo pages.

5

**Question 3:** Consider a virtual memory system with a 40-bit virtual byte address, 512 MB of physical memory and 2MB superpages.

a) What is the minimum number of bytes needed to store each entry of the page table assuming that the Valid, Protection, Dirty and LRU/Use bits take a total of one byte per entry?

For superpages, page size = $2^{21}$ Bytes → Physical memory = $2^{29}$ / $2^{21}$= $2^{8}$ physical pages
Each page table entry has 8(Valid, …) +8 (Physical Page #) = 16 bits (needs 2bytes)

b) What is the total size of the page table (in bytes) for each process on this machine, assuming that all the virtual pages are in use (assume that disk addresses are not stored in the page table)?

$2^{40}$ byte virtual space and page size = $2^{21}$ Bytes → $2^{40}$/ $2^{21}$= $2^{19}$ virtual pages

Total # of byte in the page table = 2* $2^{19}$ = 1MB (can fit in one superpage).

**Question 4:** Assume that the entries of the shown 32-entries Page Table are cached into a 4-entry direct mapped cache specifically used to cache the frequently used page table entries (called the TLB). Show the content of the TLB after caching entries 00010 and 01000 of the page table.

Entry 00010 of the page table is cached at entry 10 of the TLB with tag 000

Entry 01000 of the page table is cached at entry 00 of the TLB with tag 010

| | V | tag | valid | Physical page number |
|---|---|---|---|---|
| 00 | 1 | 010 | 1 | 01110 |
| 01 | | | | |
| 10 | 1 | 000 | 1 | 11000 |
| 11 | | | | |

| | valid | Physical page # |
|---|---|---|
| 00000 | 0 | |
| 00001 | 1 | 10111 |
| 00010 | 1 | 11000 |
| 00011 | 0 | |
| 00100 | 1 | 10011 |
| 00101 | 0 | |
| 00110 | 1 | 00010 |
| 00111 | 0 | |
| 01000 | 1 | 01110 |
| 01001 | 1 | 11010 |
| 01010 | 1 | 10101 |
| 01011 | | |
| 01100 | . | . |
| 01101 | . | . |
| | . | . |
| 11111 | | |