## Virtual Memory

1. Name three specific benefits of using virtual memory:
2. What should happen to the TLB when a new entry is loaded into the page table base register?
3. Fill in the formulas below using descriptions, not variables:

Page offset bits $=\log _{2}($ $\qquad$ _)

Virtual address bits $=$ $\qquad$ + page offset bits

Physical address bits = physical page number bits + $\qquad$
Virtual page number bits $=\log _{2}($ $\qquad$
Entries in a page table $=$ $\qquad$
4. Fill in the following table:

| VA width <br> $(n)$ | PA width <br> $(m)$ | Page size <br> $(P)$ | VPN <br> width | PPN <br> width | Bits in PTE <br> (assume V, D, R, W, X) |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 32 | 32 | 16 KiB |  |  |  |
| 32 | 26 |  |  | 13 |  |
|  | 32 |  | 21 |  | 22 |
|  |  | 32 KiB | 25 |  | 26 |
| 64 |  |  | 48 |  | 29 |

5. Processor: 16-bit addresses, 256-byte pages

TLB: 8-entry fully associative with LRU replacement

- Track LRU (shown in decimal) using 3 bits to encode the order in which pages were accessed, with 0 being the most recent
At some time instant, the TLB for the current process is in the initial state given below.
Assume that all page table entries that are not in the initial TLB have read and write permissions, but no execute permission (i.e. $\mathrm{R}=1, \mathrm{~W}=1, \mathrm{X}=0$ ).
- OS will assign new pages starting at PPN 0x20, with read and write permissions but no execute permission (i.e. $R=1, W=1, X=0$ ).
Fill in the final state of the TLB according to the access pattern below. For each access, indicate if it leads to a:
a) TLB hit? b) TLB miss? c) Page fault? d) Protection fault?

Initial TLB:

| TLBT | PPN | Valid | R | W | X | Dirty | LRU |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $0 \times 01$ | $0 \times 11$ | 1 | 1 | 1 | 0 | 1 | 0 |
| $0 \times 02$ | $0 \times 18$ | 1 | 1 | 0 | 0 | 0 | 6 |
| $0 \times 10$ | $0 \times 13$ | 1 | 1 | 1 | 1 | 1 | 1 |
| $0 \times 20$ | $0 \times 12$ | 1 | 0 | 1 | 0 | 0 | 5 |
| $0 \times 00$ | $0 \times 00$ | 0 | 0 | 0 | 0 | 0 | 7 |
| $0 \times 11$ | $0 \times 14$ | 1 | 1 | 0 | 0 | 0 | 4 |
| $0 \times A C$ | $0 \times 15$ | 1 | 1 | 0 | 0 | 0 | 2 |
| $0 \times 34$ | $0 \times 16$ | 1 | 1 | 1 | 0 | 1 | 3 |

Page Table (partial):

| VPN | Valid | PPN |
| :--- | :---: | :---: |
| $0 \times 0$ | 0 | $0 \times 00$ |
| $0 \times 1$ | 1 | $0 \times 19$ |
| $0 \times 2$ | 1 | $0 \times 18$ |
| $0 \times 3$ | 1 | $0 \times 17$ |
| $0 \times 4$ | 0 | - |
| $0 \times 5$ | 0 | - |
| $0 \times 6$ | 1 | $0 \times 1 \mathrm{~A}$ |
| $0 \times 7$ | 0 | - |
|  |  |  |


| VPN | Valid | PPN |
| :---: | :---: | :---: |
| $0 \times 8$ | 1 | $0 \times 1 \mathrm{C}$ |
| $0 \times 9$ | 1 | $0 \times 1 \mathrm{D}$ |
| $0 \times \mathrm{A}$ | 0 | $0 \times 1 \mathrm{E}$ |
| $0 \times B$ | 1 | $0 \times 1 \mathrm{~F}$ |
| $0 \times \mathrm{C}$ | 0 | - |
| $0 \times \mathrm{D}$ | 1 | $0 \times 09$ |
| $0 \times \mathrm{E}$ | 0 | - |
| $0 \times \mathrm{F}$ | 1 | $0 \times 1 \mathrm{~B}$ |
|  |  |  |

## Access pattern:

1) Read $0 x 11 F 0$
2) Write $0 \times 0301$
3) Write $0 \times 20 \mathrm{AE}$
4) Write $0 \times 0532$
5) Read 0x0E15
6) Write $0 x A C F F$

Final TLB:

| TLBT | PPN | Valid | R | W | X | Dirty | LRU |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
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