Announcements

- Midterm #1 was returned
- Project #3 is due Friday
- Project #4 will be on the web later this week
  - It's a team project (will email partners)

Midterm #1 Summary

Question	Min	Max	Mean
1	7	20	17.8
2	3	20	14.2
3	6	16	12.5
4	4	12	8.2
5	0	18	12.9
6	4	14	10.5
Overall	52	94	76.1

Standard Dev: 11.5

Page State (hardware view)

- Page frame number (location in memory or on disk)
- *Valid Bit*
  - indicates if a page is present in memory or stored on disk
- A *modify* or *dirty* bit
  - set by hardware on write to a page
  - indicates whether the contents of a page have been modified since the page was last loaded into main memory
  - if a page has not been modified, the page does not have to be written to disk before the page frame can be reused
- *Reference bit*
  - set by the hardware on read/write
  - cleared by OS
  - can be used to approximate LRU page replacement
- Protection attributes
  - read, write, execute

Inverted Page Tables

- Solution to the page table size problem
- One entry per page frame of physical memory

  <process-id, page-number>

  – each entry lists process associated with the page and the page number

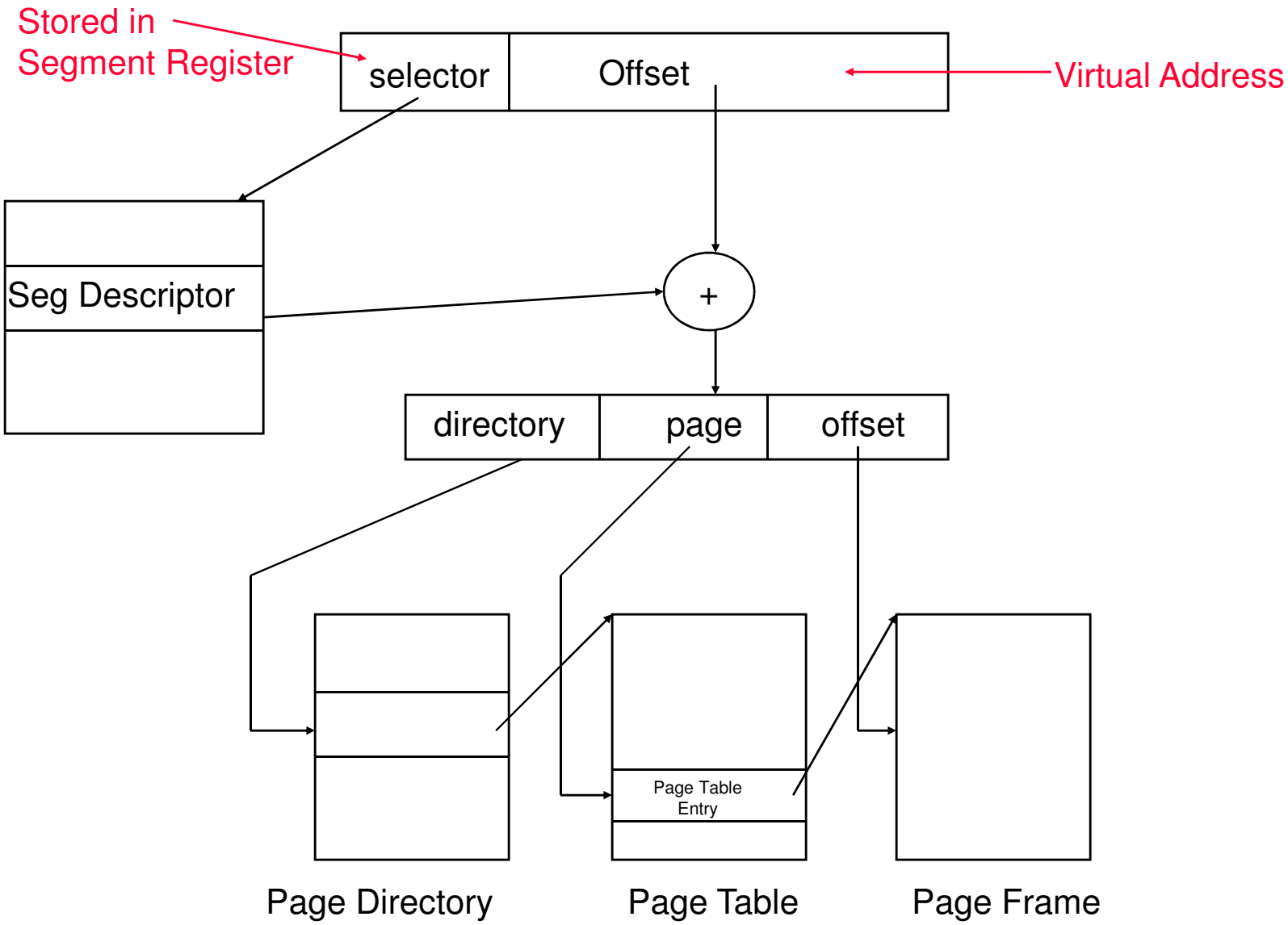
  – when a memory reference:

    - **<process-id,page-number,offset>**occurs, the inverted page table is searched (usually with the help of a hashing mechanism)
    - if a match is found in entry ***i*** in the inverted page table, the physical address **<i,offset>** is generated

  – The inverted page table does not store information about pages that are not in memory

    - page tables are used to maintain this information
    - page table need only be consulted when a page is brought in from disk

X86 Segmentation + Paging



64 bit processors

- Problem: 2 level page tables are too small
- Solution 1:
  - Use more levels & larger page size
    - Alpha:
      - 3 level
      - variable size pages
      - w8KB pages
        - 43 bits of virtual address
        - 13 bits page offset
        - 3x10=30 bits in page tables
      - w64KB pages
        - 55 bits of virtual address
        - 16 bits page offset
        - 3x13 = 39 bits in page tables

Sparc & IBM Power 64 bit processors

- Ultra Sparc 64 bit MMU
  - 8KB, 16KB, 512KB, 4MB pages supported
  - Software TLB miss handler
  - 44 bit virtual address
- Power 4
  - Variable sized pages up to 16MB
  - Inverted page tables
  - TLB
    - 1024 entry 4-way set associate
  - TLB cache
    - Called ERAT
      - 128 entry 2-way set associative

Other 64-bit Designs

- AMD-64
  - 54 bit physical memory
  - With 4KB pages
    - 48 bits of virtual address are used
    - 4KB pages
      - 12 bits page
      - 4x9 = 36 bits via 4-level page tables
    - 2MB pages
      - 21 bits page
      - 3x9 = 27 bits via 3-level page tables

Access Large Memory

- Problem:
  - Even with Super pages, limited TLB reach
- Solution:
  - Add one extra large segment in addition to VM
  - Can be any sized contiguous region of memory
  - Can map into any part of a processes address space
  - Consists of three fields:
    - Virtual base (starting addr in virtual memory, page aligned)
    - Physical base (starting addr in physical memory, page aligned)
    - Length (in multiple of machine's page size)
  - Hardware always consults this mapping regardless of TLB

Inverted Page Table Example (PPC)