Announcements

- Midterm #1 was returned
- project #3 is due Friday!

Midterm #1 Results

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>70</td>
</tr>
<tr>
<td>Min</td>
<td>29</td>
</tr>
<tr>
<td>Max</td>
<td>95</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>15</td>
</tr>
</tbody>
</table>
X86 Segmentation + Paging

Stored in Segment Register

Virtual Address

Seg Descriptor

selector Offset

directory page offset

Page Directory Page Table Page Frame
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
      - $4 \times 9 = 36$ bits via 4-level page tables
    - 2MB pages
      - 21 bits page
      - $3 \times 9 = 27$ bits via 3-level page tables
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
Inverted Page Table Example (PPC)

Virtual Address

16 Segment Registers (per process)

4 16 12
Seg Page # Byte

24

Hash Function

40

Virtual Segment ID

Status bits

40
VS ID

20
Physical page

Page Table Entry (PTE)

Page Table Group
8 page table entries

Page Table (variable size)
one per system

Main Memory