Guess What? Caching!

Translation-Lookaside Buffer (TLB)
- stores for future use a successful translation between a Virtual Page Number (VPN) and a Physical Frame Number (PFN)
- on a TLB hit, translation is achieved without accessing PT
- on a TLB miss
  - Page Table is accessed
  - if VA is invalid, exception (segmentation fault)
  - if VA is valid, but page is not present, load page (we'll talk about it soon)
  - if VA is valid and page is present, update TLB and retry op

Why Does it Work?

Spatial locality
- program is likely to access memory locations close to each other in VA space
  - only first access to a page causes a TLB miss and Page Table access

Temporal locality
- program is likely to quickly access again the same memory locations
  - if new access happens while translation still in TLB, no need to access Page Table

So Sorry I Missed You

TLB misses can be handled in Hardware
- HW updates TLB and retries instruction
- HW uses PTBR to find Page Table (PT)
- HW performs full address translation

TLB misses can be handled in Software
- TLB miss causes a trap
- HW raises an exception, moves to kernel mode, and jumps to trap handler
- Handler goes through PT and updates TLB
  - better not trigger a TLB miss while running the handler!
- HW returns from serving the miss with PC pointing to the instruction that caused the trap, so it is re-executed
Speeding things up: The TLB

Virtually Addressed Caches

Physically Addressed Caches

TLB Consistency – I

On context switch
- VAs of old process should no longer be valid
- Change PTBR — but what about the TLB?
TLB Consistency - I

On context switch
- VAs of old process should no longer be valid
- Change PTBR — but what about the TLB?
  - Option 1: Flush the TLB
  - Option 2: Add pid tag to each TLB entry

<table>
<thead>
<tr>
<th>TLB Entry</th>
<th>PID</th>
<th>VPN</th>
<th>PFN</th>
<th>Access</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>0x0053</td>
<td>0x0012</td>
<td>R/W</td>
</tr>
</tbody>
</table>

Ignore entries with wrong PIDs

TLB Consistency - II

What if OS changes permissions on a page?
- What if permissions are reduced?
  - OS must purge affected TLB entries (e.g., on copy-on-write)
- What if permissions are expanded?
  - either cause hardware to load new entries
  - or cause an exception, so handler can update TLB entry as necessary

What if we miss in the TLB?

- Suppose a 64-bit VAS, with 4KB page and a 512MB physical memory
  - Page table has $2^{52}$ entries
  - At 4 bytes/PTE, Page Table is 16 Petabytes!
    - per process!
  - For Page Table at each level to fit in a single page, each level should span at most 10 bits
    - 6 levels of paging!
  - But frames are few... only $2^{29}/2^{12} = 128K$

A different approach

- What if mapping size were proportional to the number of frames, instead of pages?
  - If PTE = 16 bytes, Page table size = 2MB
  - And since all processes share the same physical frames, just one global page table!

Inverted page tables
Page Registers  
(a.k.a. Inverted Page Tables)

- For each frame, a register containing:
  - Residence bit: is the frame occupied?
  - Page number of the occupying page
  - Id of the process currently mapping the frame
  - VAS of different processes may map the same page number to different frames!
  - Protection bits
- Searched by page number

Where have all the pages gone?

- Searching 128KB of registers on every memory reference is not fun
- If the number of frames is small, the page registers can be placed in an associative memory — but...
- Large associative memories are expensive
  - hard to access in a single cycle
  - consume lots of power

Basic Inverted Page Table Architecture

Hashed Inverted Page Tables

- Hash Anchor Table maps <pid, VPN> to an entry of the Inverted Page Table
- Collisions handled by chaining