Virtual Memory Summary

Page Table for each process:

- 4MB contiguous in physical memory, or multi-level, ...
- every load/store translated to physical addresses
- page table miss = *page fault*
  - load the swapped-out page and retry instruction, or kill program if the page really doesn’t exist, or tell the program it made a mistake
x86 Example: 2 level page tables, assume...
32 bit vaddr, 32 bit paddr
4k PDir, 4k PTTables, 4k Pages

Q: How many bits for a page number?
A: 20

Q: What is stored in each PageTableEntry?
A: ppn, valid/dirty/r/w/x/...

Q: What is stored in each PageDirEntry?
A: ppn, valid/?/...

Q: How many entries in a PageDirectory?
A: 1024 four-byte PDEs

Q: How many entries in each PageTable?
A: 1024 four-byte PTEs
x86 Example: 2 level page tables, assume...
32 bit vaddr, 32 bit paddr
4k PDir, 4k PTables, 4k Pages
PTBR = 0x10005000 (physical)

Write to virtual address **0x7192a44c**...

Q: Byte offset in page? PT Index? PD Index?

(1) PageDir is at 0x10005000, so...
   Fetch PDE from physical address 0x1005000+4*PDI
   • suppose we get {0x12345, v=1, ...}

(2) PageTable is at 0x12345000, so...
   Fetch PTE from physical address 0x12345000+4*PTI
   • suppose we get {0x14817, v=1, d=0, r=1, w=1, x=0, ...}

(3) Page is at 0x14817000, so...
   Write data to physical address 0x1481744c
   Also: update PTE with d=1
Virtual Memory Summary

PageTable for each process:

• 4MB contiguous in physical memory, or multi-level, ...
• every load/store translated to physical addresses
• page table miss: load a swapped-out page and retry instruction, or kill program

Performance?

• terrible: memory is already slow translation makes it slower

Solution?

• A cache, of course
Making Virtual Memory Fast
The Translation Lookaside Buffer (TLB)
Hardware **Translation Lookaside Buffer (TLB)**

A small, very fast cache of recent address mappings

- TLB hit: avoids PageTable lookup
- TLB miss: do PageTable lookup, cache result for later
<table>
<thead>
<tr>
<th>V</th>
<th>R</th>
<th>W</th>
<th>X</th>
<th>D</th>
<th>tag</th>
<th>ppn</th>
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</thead>
<tbody>
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**TLB Diagram**

- **V**: Validity bit
- **R**: Read bit
- **W**: Write bit
- **X**: Execute bit
- **D**:Dirty bit
- **tag**: Tag field
- **ppn**: Page table entry

The diagram illustrates the mapping of virtual to physical addresses using a translation lookaside buffer (TLB).

- The TLB contains a set of entries, each with a validity bit (V), read bit (R), write bit (W), execute bit (X), and dirty bit (D).
- Each entry also has a tag field (tag) and a page table entry (ppn).
-虚地址映射到物理地址的过程可以在图中看到，通过查找相应的表项来确定物理页的地址。
(1) Check TLB for vaddr (~ 1 cycle)

(2) TLB Hit
• compute paddr, send to cache

(2) TLB Miss: traverse PageTables for vaddr

(3a) PageTable has valid entry for in-memory page
• Load PageTable entry into TLB; try again (tens of cycles)

(3b) PageTable has entry for swapped-out (on-disk) page
• Page Fault: load from disk, fix PageTable, try again (millions of cycles)

(3c) PageTable has invalid entry
• Page Fault: kill process
TLB Coherency: What can go wrong?

A: PageTable or PageDir contents change
   - swapping/paging activity, new shared pages, ...

A: Page Table Base Register changes
   - context switch between processes
When PTE changes, PDE changes, PTBR changes....

Full Transparency: **TLB coherency in hardware**

- Flush TLB whenever PTBR register changes [easy – why?]
- Invalidate entries whenever PTE or PDE changes [hard – why?]

**TLB coherency in software**

If TLB has a no-write policy...

- OS invalidates entry after OS modifies page tables
- OS flushes TLB whenever OS does context switch
TLB parameters (typical)

- very small (64 – 256 entries), so very fast
- fully associative, or at least set associative
- tiny block size: why?

Intel Nehalem TLB (example)

- 128-entry L1 Instruction TLB, 4-way LRU
- 64-entry L1 Data TLB, 4-way LRU
- 512-entry L2 Unified TLB, 4-way LRU
Virtual Memory meets Caching

Virtually vs. physically addressed caches
Virtually vs. physically tagged caches
Q: Can we remove the TLB from the critical path?
A: Virtually-Addressed Caches
Q: What happens on context switch?
Q: What about virtual memory aliasing?
Q: So what’s wrong with physically addressed caches?
Physically-Addressed Cache
- slow: requires TLB (and maybe PageTable) lookup first

Virtually-Addressed Cache
- fast: start TLB lookup before cache lookup finishes
- PageTable changes (paging, context switch, etc.)
  \[\rightarrow\] need to purge stale cache lines (how?)
- Synonyms (two virtual mappings for one physical page)
  \[\rightarrow\] could end up in cache twice (very bad!)

Virtually-Indexed, Physically Tagged Cache
- \[\sim\] fast: TLB lookup in parallel with cache lookup
- PageTable changes \[\rightarrow\] no problem: phys. tag mismatch
- Synonyms \[\rightarrow\] search and evict lines with same phys. tag
Typical L1: On-chip *virtually* addressed, *physically* tagged

Typical L2: On-chip *physically* addressed

Typical L3: On-chip ...
Caches, Virtual Memory, & TLBs

Where can block be placed?
  • Direct, n-way, fully associative

What block is replaced on miss?
  • LRU, Random, LFU, ...

How are writes handled?
  • No-write (w/ or w/o automatic invalidation)
  • Write-back (fast, block at time)
  • Write-through (simple, reason about consistency)
## Summary of Cache Design Parameters

<table>
<thead>
<tr>
<th></th>
<th>L1</th>
<th>Paged Memory</th>
<th>TLB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size (blocks)</strong></td>
<td>1/4k to 4k</td>
<td>16k to 1M</td>
<td>64 to 4k</td>
</tr>
<tr>
<td><strong>Size (kB)</strong></td>
<td>16 to 64</td>
<td>1M to 4G</td>
<td>2 to 16</td>
</tr>
<tr>
<td><strong>Block size (B)</strong></td>
<td>16-64</td>
<td>4k to 64k</td>
<td>4-32</td>
</tr>
<tr>
<td><strong>Miss rates</strong></td>
<td>2%-5%</td>
<td>10^{-4} to 10^{-5}%</td>
<td>0.01% to 2%</td>
</tr>
<tr>
<td><strong>Miss penalty</strong></td>
<td>10-25</td>
<td>10M-100M</td>
<td>100-1000</td>
</tr>
</tbody>
</table>