18-447 Lecture 19: Survey of Commercial VM Arch + a Decomposition of Meltdown

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Housekeeping

• Your goal today
  – see the many realizations of “VM”, focusing on deviation from textbook-conceptual norms
  – put everything in 447 together in Meltdown

• Notices
  – Handout #13: Lab 4, due Friday 5/7 noon (no late)
  – Handout #14: HW 4 solutions (out on Friday)
  – Midterm 2, online during class time, Wed, 4/14

• Readings
  – start on P&H Ch 6
2 Parts to Modern VM

• In a multi-tasking system, \textit{virtual} memory supports the \textit{illusion} of a \textit{large}, \textit{private}, and \textit{uniform} memory space to each process

• Ingredient A: naming and protection
  – each process sees a large, contiguous address space without holes \textit{(for convenience)}
  – each process’s memory is private, i.e., protected from access by other processes \textit{(for sharing)}

• Ingredient B: demand paging \textit{(for hierarchy)}
  – capacity of secondary storage (swap space on disk)
  – speed of primary storage (DRAM)
SPARC V9 PTE/TLB Entry

- 64-bit VA + context ID
  - implementation can choose not to map high-order bits (require sign extension in unmapped bits)
  - e.g., UltraSPARC 1 maps only lower 44 bits
- PA space size set by implementation
- 64 entry fully associative I-TLB and D-TLB

Details fixed and exposed by privileged ISA

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SPARC TLB Miss Handling

- 32-bit V8 used a 3-level hierarchical page table for HW MMU page-table walk

- 64-bit V9 switched to Translation Storage Buffer
  - a software managed, in-DRAM direct-mapped “cache” of PTEs (think hashed page table)
  - HW assisted address generation on a TLB miss
  - TLB miss handler (SW) searches TSB. If TSB misses, a slower TSB-miss handler takes over
  - OS can use any page table structure after TSB
IBM PowerPC (32-bit)

16-entry segment table

seg ID\textsubscript{24} \quad seg offset\textsubscript{16} \quad page offset\textsubscript{12}

128 2-way ITLB and DTLB

PPN\textsubscript{20} \quad page offset\textsubscript{12}

segments 256MB regions

64-bit PowerPC = 64-bit EA \rightarrow 80-bit VA \rightarrow 64-bit PA

How many segments in 64-bit EA?
IBM PowerPC Hashed Page Table

- **HW table walk**
  - **VPN** hashes into a PTE group (**PTEG**) of 8
  - 8 **PTEs** searched sequentially for tag match
  - if not found in first **PTEG** search a second **PTEG**
  - if not found in 2\(^{nd}\) **PTEG**, trap to software handler

- **Hashed table structure** also used for 64-bit **EA\rightarrow VA**
MIPS R10K

- 64-bit VA
  - top 2 bits set kernel/supervisor/user mode
  - additional bits set cache and translation behavior
  - bit 61-40 not translate at all
    (holes and repeats in the VA??)

- 8-bit ASID (address space ID) distinguishes between processes

- 40-bit PA

- Translation -
  “64”-bit VA and 8-bit ASID → 40-bit PA
MIPS TLB

- 64-entry fully associative unified TLB
- Each entry maps 2 consecutive VPNs to independent respective PPNs
- Software TLB-miss handling *(exotic at the time)*
  - 7-instruction page table walk in the best case
  - TLB Write Random: chooses a random entry for TLB replacement
  - OS can exclude low TLB entries from replacement (some translations must not miss)

- TLB entry
  - N: noncacheable
  - V: valid
  - D: dirty *(write-enable!!)*
  - G: ignore ASID

<table>
<thead>
<tr>
<th>VPN_{20}</th>
<th>ASID_{6}</th>
<th>0_{6}</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPN_{20}</td>
<td>ndvg</td>
<td>0_{8}</td>
</tr>
</tbody>
</table>
MIPS Bottom-Up Hierarchical Table

- TLB miss vectors to a SW handler
  - page table organization is not hardcoded in ISA
  - ISA favors a chosen reference page table scheme by providing “optional” hardware assistance

- Bottom-Up Table
  - start with 2-level hierarchical table (32-bit case)
  - allocate all L2 tables for all VA pages (empty or not) linearly in the mapped kseg space
  - VPN is index into this linear table in VA

This table scales with VA size!! Is this okay?
### Bottom-Up Table Walk

<table>
<thead>
<tr>
<th>PTEBase</th>
<th>VPN</th>
<th>PO</th>
</tr>
</thead>
</table>

**VA** on TLB Miss, trap

**VA of PTE**
(generated automatically by HW after TLB miss)

Can this load miss in the TLB?
What happens if it misses?

**Notice translation also eats up TLB entries!**
# User TLB Miss Handling

- `mfc0 k0,tlbcxt` # move the contents of TLB context register into k0
- `mfc0 k1,.epc` # move PC of faulting memory instruction into k1
- `lw k0,0(k0)` # load thru address that was in TLB context register
- `mtc0 k0,entry_lo` # move the loaded value (a PTE) into the EntryLo register
- `tlbwr` # write PTE into the TLB at a random slot number
- `j k1` # jump to PC of faulting load instruction to retry
- `rfe` # restore privilege (in delay slot)
HP PA-RISC: PID and AID

- 2-level: 64b EA → 96b VA (global) → 64b PA
- Variable sized segmented EA → VA translation
- Rights-based access control
  - user controls segment registers (user can generate any VA it wants!!)
  
  *in contrast, everyone else controls translation to control what VA can be reached from a process*
  
  - each virtual page has an access ID (AID) assigned by OS
  
  - each process has 8 active protection IDs (PID) in privileged HW registers controlled by OS
  
  - a process can access a page only if one of the 8 PIDs matches the page’s AID
Intel 80386

• Two-level address translation:
  segmented EA → global VA → PA

• User-private 48-bit EA
  – 16-bit SN (implicit) + 32-bit SO
  – 6 user-controlled registers hold active SNs;
    selected according to usage: code, data, stack, etc

• Global 32-bit VA
  – 20-bit VPN + 12-bit PO

• An implementation defined paged PA space

What is very odd about this?
Living with the mistake

• 32-bit global VA too small to share by processes
  – per-process EA space oddly bigger than VA space
  – until 1990, no one cared  
    DOS and Windows
• Later multitasking OS ignore segment protection
  – time-multiplex **global** VA space for use by 1 process at a time
  – code, data, stack segments always map to entire VA space, 0~(2^{32}-1)
  – set MMU to use a different table on context switch
  – BUT! TLB for VA translation doesn’t have ASID; must flush TLB on context switch

  Later IA32e added PCID to TLB as fix
Meltdown in 18-447 Terms

*How to “know” the value at a memory location without permission to read it?*
VA to PA Translation Flow Chart

We’ve seen...

- TLB lookup
  - no → PT walk
  - yes → VA to PA

PT walk:
- page in DRAM
  - found → protection check
  - don’t exist → “page fault” allocate or bring from disk (10 ms)
- not in DRAM

Protection check:
- no → “seg fault” now what?
- yes → “protection violation”

“protection violation”

ISA says can’t “read” without permission
How should VM and Cache Interact?

- CPU
  - TLB
  - cache
  - lower hier.

- CPU
  - virtual cache
  - TLB

- CPU
  - cache
  - TLB
  - lower hier.

We've seen...

Actually you can “read” without permission; ISA (as an abstraction) only care you can’t “see” the read-value.

Only a question for L1 caches
“Flushing” a Pipeline

<table>
<thead>
<tr>
<th></th>
<th>$t_0$</th>
<th>$t_1$</th>
<th>$t_2$</th>
<th>$t_3$</th>
<th>$t_4$</th>
<th>$t_5$</th>
<th>$t_6$</th>
<th>$t_7$</th>
<th>$t_8$</th>
<th>$t_9$</th>
<th>$t_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IF</strong></td>
<td>$I_0$</td>
<td>$I_1$</td>
<td>$I_2$</td>
<td>$I_3$</td>
<td>$I_4$</td>
<td>bub</td>
<td>bub</td>
<td>bub</td>
<td>$I_h$</td>
<td>$I_{h+1}$</td>
<td>$I_{h+2}$</td>
</tr>
<tr>
<td><strong>ID</strong></td>
<td>$I_0$</td>
<td>$I_1$</td>
<td>$I_2$</td>
<td>$I_3$</td>
<td>bub</td>
<td>bub</td>
<td>bub</td>
<td>$I_h$</td>
<td>$I_{h+1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>EX</strong></td>
<td></td>
<td>$I_0$</td>
<td>$I_1$</td>
<td>$I_2$</td>
<td>$I_3$</td>
<td>bub</td>
<td>bub</td>
<td>bub</td>
<td>$I_h$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- can read without permission
- can even use read-value in dependent instructions
- as long as at the end can’t “see” any of it

100s of speculative instructions in flight in modern OOO CPUs
Key Idea 3: Inter-Model Compatibility

“a valid program whose logic will not depend implicitly upon time of execution and which runs upon configuration A, will also run upon the latter includes at least the required I/O devices ....”

• Invalid programs not constrained to yield same result
  – “invalid”==violating architecture manual
  – “exceptions” are architecturally defined

• The King of Binary Compatibility: Intel x86, IBM 360
  – stable software base and ecosystem
    performance scalability

[Amdahl, Blaauw and Brooks, 1964]
What cache is in your computer?

- How to figure out what cache configuration is in your computer:
  - capacity (C)
  - associativity (a)
  - block-size (B)
  - number of levels
  
- The presence or lack of a cache should not be detectable by functional behavior of software

- But you could tell if you measured execution time to infer the number of cache misses

Cache invisible architecturally, but performance “side-effect” easily detectable using timer

Infer read-value without “seeing” by running code to cause hit/miss based on unseen value
MIPS R10K

- 64-bit VA and 8-bit ASID → 40-bit PA

Read addr Y+C, Y+2C, Y+3C ... so addr Y is not in cache; then attempt to execute:

\[
\begin{align*}
    l_1: & \text{ lw } t0, 0(r"X") \\
    l_2: & \text{ andi } t0, t0, 0x1 \\
    l_3: & \text{ sli } t0, t0,"\log_2(\text{blocksize})" \\
    l_4: & \text{ add } t0, t0, r"Y" \\
    l_5: & \text{ lw } x0, 0(t0)
\end{align*}
\]

\(l_1\) is an exception so \(l_1 \sim l_5\) not observed architecturally; nevertheless addr Y is cached if LSB of mem[\(X\)] is 0

<table>
<thead>
<tr>
<th></th>
<th>1 GB mapped (kseg)</th>
<th>0.5 GB unmapped uncached</th>
<th>0.5 GB unmapped cached</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>bottom 2 GB mapped</td>
<td></td>
<td>(normal)</td>
</tr>
</tbody>
</table>
Control Speculation: PC+4

When inst_h branch resolves
- branch target (Inst_k) is fetched
- flush instructions fetched since inst_h ("wrong-path")

Train BTB so the previous executes as "wrong path" —
architecturally nothing illegal happened!!

Inst_h is taken branch
Idempotency and Side-effects

• Meltdown vulnerability not a bug but an ISA-allowed simplification—*no fast kill after exception as with BP miss*
• Same issue doesn’t arise with MMIO—because ISA disallow spurious read if TLB says “uncacheable”

*Not a “bug” but something is very wrong!!!*

*How to fix this . . . .*

• LW/SW to mmap locations can have side-effects
  – reading/writing mmap location can imply commands and other state changes
  – consider a FIFO example
    • SW to 0xffff0000 pushes value
    • LW from 0xffff0000 returns popped value

What happens if 0xffff0000 is cached?