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

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• 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 #15: Lab 4, due week 14
  – Handout #16: HW 5 solutions
  – Midterm 2, Wed, 4/6

• Readings
  – Synthesis Lecture: Architectural and Operating System Support for Virtual Memory (optional)
  – start on P&H Ch 6
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 mapped only lower 44 bits
- PA space size set by implementation, $2^{28}$ max pgs
- 64 entry fully associative I-TLB and D-TLB

Unlike caches, TLB specifics are architectural; TLB misses have effects visible to kernel SW!!
SPARC TLB Miss Handling

• 32-bit V8 used a 3-level hierarchical page table for HW MMU page-table walk
  
  - L1 Table: 256 descriptors (1024-byte)
  - L2 Table: 64 descriptors (256-byte)
  - L3 Table: 64 PTEs (256-byte)

• 64-bit V9 switched to Translation Storage Buffer
  - a software managed, in-DRAM direct-mapped “cache” of PTEs (think hashed pg table or SW TLB)
  - 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_{24}
- seg offset_{16}
- page offset_{12}
- seg#_{4}
- segments 256MB regions

128 2-way ITLB and DTLB

PPN_{20}

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 2nd **PTEG**, trap to software handler

- Hashed table structure also used for 64-bit **EA→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 \ ASID</th>
<th>PPN</th>
<th>ndvg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0_20</td>
<td>0_6</td>
<td>0_8</td>
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</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

- **VPN**: Virtual Page Number
- **PO**: Page Offset
- **PTEBase**: Pointer to Page Table Base
- **VPN**: Virtual Page Number
- **0s**: Base Address
- **mem load**: Memory Load
- **PPN**: Physical Page Number
- **status**: Page Status

**VA on TLB Miss, trap**
- **VA of PTE**: Value Address of Page Table Entry (generated automatically by HW after TLB miss)
- **PTE loaded from mem**: Page Table Entry loaded from memory

**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,tlbctxt  # 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 $\rightarrow$ 96b VA (global) $\rightarrow$ 64b PA
• Variable sized segmented EA $\rightarrow$ 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 (PIDs) 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
Two-level address translation:

segmented $EA \rightarrow$ global $VA \rightarrow$ $PA$

User-private 48-bit $EA$
- 16-bit $SN$ (implicit) + 32-bit $SO$
- 6 user-controlled registers hold active $SN$s; 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

- 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, \(0 \sim (2^{32}-1)\)
  - 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

TLB lookup

VA

hit

no

yes

PT walk

10~100 pclk

page in DRAM

not in DRAM

found

don’t exist

allocate TLB

“page fault” allocate or bring from disk (10 ms)

“seg fault” now what?

“protection violation”

protection check

okay

no

yes

PA to cache

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

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

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- 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 on configuration B if 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

[a fundamental tenet that ISA does not care about time]

[We've seen ...]

[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

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

Cache invisible architecturally, but performance “side-effect” easily detectable using timer
MIPS R10K

- 64-bit virtual address
  - 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 physical address

Translation - 64-bit VA and 8-bit ASID \( \rightarrow \) 40-bit PA

simplified example from 32-bit VA in R2000/3000

\[ X: \]
- 1 GB mapped (kseg)
- 0.5 GB unmapped uncached
- 0.5 GB unmapped cached

\[ Y:\]
- bottom 2 GB mapped (normal)

Read addr \( Y+C, Y+2C, Y+3C \ldots \) so addr \( Y \) is not in cache; then attempt to execute:

\[ I_1: lw \ t0, 0(r"X") \]
\[ I_2: andi \ t0, t0, 0x1 \]
\[ I_3: sli \ t0, t0, \"log_2\)(blocksize)" \]
\[ I_4: add \ t0, t0, r"Y" \]
\[ I_5: lw \ x0, 0(t0) \]

\( I_1 \) is an exception so \( I_1 \sim I_5 \) not observed architecturally; nevertheless addr \( Y \) is cached if LSB of mem[\( X \)] is 0
Control Speculation: PC+4

Inst_h is a taken branch
- 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!!*

We've seen...

control flow "restitched"
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—ISA disallows spurious read if PTE says “uncacheable” or “side-effect”

*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?