Address Space Isolation (ASI)

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Why ASI ?
Context

- Data can leak between CPU threads from the same CPU core
  - Leak through shared hardware (micro)architecture via speculative attacks
  - Example: L1TF and MDS speculative attacks

- A VM can control the leak and spy on its sibling CPU thread
  - Guest can spy on another guest running on the same CPU core
  - Guest can spy on the host running on the same CPU core

- Major issue for virtual machines and cloud providers
  - Allow Guest-to-Guest attacks and Guest-to-Host attacks
Mitigations

- Basic mitigation: disable CPU hyper-threading
  - Most complete and reliable solution
  - Significant impact on performances and capacity
- Mitigation for Guest-to-Guest attacks
  - Pin VMs to different dedicated CPU cores
  - Core scheduling
- Mitigation for Guest-to-Host attacks
  - Synchronize VM entry and VM exit for all CPU threads on a CPU core
  - KVM Address Space Isolation (ASI)
KVM ASI

- Address space with limited kernel and VM mappings
  - Only has mappings required to enter VM and handle VM exit

- Goal: run VM and handle (most) VM exits without exiting ASI

- Only map data from a single VM in the same ASI
  - Prevent VM running on same CPU core to steal data from host kernel or from another VM

- Synchronize on VM entry only if sibling CPU thread is not running ASI
  - No need to synchronize if all CPU threads are running with ASI
  - Core scheduling helps having the same VM ASI run on all CPU threads
ASI Overview
ASI Overview

• Define a restricted address space
  - Define a page table with limited data
  - Contain no sensitive or secret data

• Prevent a sub-system from accessing the entire memory or unrelated data

• Sub-system explicitly enters/exits ASI

• ASI is interrupted/resumed on interrupt, exception, context switch
ASI Lifecycle

- Create an ASI
  - Each ASI has its own page-table
- Populate the ASI page-table
- Enter ASI = switch to the ASI page-table
- Interrupt/Resume ASI on interrupt/exception/fault/context switch
  - interrupt ASI = switch to the kernel page-table
  - resume ASI = switch back to the ASI page-table
- Exit ASI = switch to the kernel page-table
- Destroy the ASI page-table
ASI Applications

• KVM ASI
  - Protect against guest-to-host attack

• User ASI
  - Implement kernel/user page-table switch with ASI
  - Refactor KPTI to use ASI

• Userland ASI?
  - Provide multiple user address spaces to a user process
  - Isolate user virtual environment (JVM, containers...)
  - To be investigated
ASI and Page-Table
ASI Page Table

• An ASI page table (PGD) is allocated in a buffer at offset 0x1000
  - Used to identify ASI page-table vs kernel page-table
  - Mechanism already used for PTI page-tables

• Page-table is populated by adding VA range mappings
  - Copy mappings from the kernel page-table
  - Copy mapping entries at a specified level (e.g. PTE)
  - Can create cross-reference to the kernel page-table (if level != PTE)

• Need to keep track of pages used in the ASI page-table structure
  - To only modify/free entries effectively belonging to the ASI page-table
ASI VA Range Mappings

- Mapping VA range can leak adjacent data
  - Mapping size and alignment constrained by the page-table level (e.g. 4K at PTE level)
  - Mapping range can be larger than VA range and map (leak) adjacent data
  - Example: mapping a 8 bytes buffer at PTE level will leak at least one page (4K)

- Need to keep track of VA range mapped in the ASI page-table
  - To handle VA/mapping range overlap
  - Required for safely removing a mapping
  - Example: map different buffers from the same page => same mapping
Decorated Page Table (DPT)

• Encapsulate a native page-table (e.g. a PGD)
  - There is currently no generic function for creating/populating a page-table
  - Specific functions for mm, pti..

• Provide convenient page-table management functions
  - Track pages used in page-table structure
  - Track VA ranges mapped
  - Functions to add/remove VA range mapping
  - Handle VA ranges mapping overlap

• Used for building ASI page-table for KVM ASI and Test ASI
  - Could probably be used for PTI too
ASI Page-Table Switching
ASI Page Table Switching Logic

- On x86, just update the CR3 control register to switch the page-table
  - But also need to use Process-Context Identifiers (PCIDs) for efficiency

- PCIDs are used to limit TLB flushing on context (mm) switch
  - 6 PCIDs (0x001 to 0x006) are used to identify recently used mm kernel page-table
  - PCIDs are reused in a round-robin way for non-recently used mm

- Also used for user page-table (with PTI)
  - 6 PCIDs (0x801 to 0x806) are used to identify the corresponding mm user page-table
  - Switch between kernel and user → mask/unmask 0x800 in PCID
ASI and PCIDs

- Extend PCIDs usage to ASI as done with PTI
  - Change PTI implementation to use ASI (PTI → user ASI)

- Each ASI has a type with an associated PCID prefix (value between 1 and 255)
  - ASI PCID = (PCID prefix) << 4 | (kernel PCID)
  - User ASI → PCID prefix = 0x80 => user ASI PCID = [0x801, 0x806]
  - KVM ASI → PCID prefix = 0x01 => KVM ASI PCID = [0x011, 0x016]

- Track recently used ASI PCID (per ASI type)
  - Similar to mm context tracking for kernel PCID
  - Used to figure out if TLB flushing is required when switching to ASI page-table
ASI Page Table Switch Logic

- **ASI Enter**
  - Save the original CR3 value (CR3 value for the kernel page-table)
  - Get the kernel PCID used
  - Compute ASI PCID = (ASI PCID prefix << 4) | (kernel PCID)
  - Set flushing = FLUSH or NOFLUSH depending if ASI PCID is being reused or not
  - Update CR3 = flushing | PA(ASI page table) | ASI PCID

- **ASI Exit**
  - Update CR3 = saved original CR3 value | NOFLUSH
ASI, Interrupts and Friends
ASI and Interrupts/Exceptions

- Switch to kernel page-table to handle interrupts/exceptions
  - ASI Interrupt: logic similar to ASI Exit but keep track of the ASI being used
- Switch back to the ASI page-table after interrupt/exception has been handled
  - ASI Resume: logic similar to ASI Enter but return to the ASI used
- Track interrupt nesting depth
  - Interrupt/Resume ASI on the outermost interrupt
- ASI Enter/Exit runs with interrupts disabled
  - To prevent conflict with ASI Interrupt/Resume
ASI and Page Fault

• Should we return to the ASI after a page fault on ASI?
  - It depends on the ASI type
  - User ASI → yes, return to the ASI page-table
  - KVM ASI → no, return to the kernel page-table (ASI abort)

• Configurable option, specific to each ASI type
  - Either abort the ASI and ASI Resume won’t switch back to the ASI page-table
  - Or continue regular processing and ASI resume will switch back to the ASI page-table

• Optionally, log the fault (+ stack)
  - Useful for tracking missing mapping in ASI page-table
ASI and Context Switch

- Task using ASI is scheduled out → interrupt ASI
  - ASI Exit + save ASI information in task

- Task using ASI is scheduled in → resume ASI
  - ASI Enter with ASI information saved in task

- If context switch occurs in interrupt/exception
  - ASI has already been interrupted
  - Only need to save/restore ASI session information
ASI and Non-Maskable Interrupt (NMI)

- NMI can interrupt any code
  - In particular ASI Enter/Exit/Interrupt/Resume sequence

- Special processing on NMI Entry
  - Save CR3 value
  - Check if ASI is active based on CR3 value (ASI page table is at offset 0x1000)
  - If ASI is enabled then switch to the kernel page-table

- Special processing on NMI return
  - Check if ASI was active based on the saved CR3 value
  - If ASI was active then check if flushing is needed
  - Restore the saved CR3 value with flushing if needed
ASI Lockdown
ASI Lockdown

• Force all CPU threads from a CPU core to use a specified ASI

• If sibling CPU thread is already running the ASI
  - CPU thread continues to run uninterrupted
  - CPU thread will wait in idle loop if it tries to exit ASI

• If sibling CPU thread is not running the ASI
  - CPU thread is requested to reschedule
  - If next task is using the ASI then enter the ASI and run the task
  - If next task is not using the ASI then enter the ASI and wait in idle loop

• ASI lockdown tag allows different ASIs to be locked down together
  - Lockdown together ASIs which have the same lockdown tag
  - By default, each ASI has a unique lockdown tag
ASI Lockdown and Interrupt/Exception/NMI

- On ASI lockdown
  - Interrupt/Exception/NMI need to interrupt ASI
  - Interrupt/Exception/NMI will cause all sibling CPU threads to interrupt

- One CPU thread receives an interrupt/exception/NMI

- That CPU thread forces all sibling CPU threads to interrupt

- Then each CPU thread will:
  - Wait for all sibling CPU threads to be interrupted
  - Interrupt ASI → switch to kernel page-table
  - Do interrupt processing
  - Wait for interrupt processing to be done on all sibling CPU threads
  - Resume ASI → switch to ASI page-table
  - Resume from interrupt
ASI Lockdown and Fault

• Fault on ASI can cause ASI to exit
  - For example with KVM ASI

• If fault happens during ASI lockdown then lockdown is breached
  - Security mitigation might not be effective anymore

• Ideally we should then run single-threaded on the impacted CPU core
  - Certainly complex to implement
  - Probably easier to define ASI page-table so it doesn’t fault during lockdown

• Instead just log a warning
  - Provide information about the fault so that ASI page-table can be augmented not to fault
  - Lockdown sequences are expected to be short so finding required mapping should be simple
KVM ASI
KVM ASI

• Goal: run VM and handle (most) VM exits without exiting ASI

• Create one KVM ASI per vcpu
  - KVM ASI from the same VM uses the same ASI lockdown tag

• KVM ASI page-table mappings
  - kvm and kvm-intel modules
  - various kernel structures (context_tracking, irq_stat, rcu_data, hrtimer_bases...)
  - kvm_vmx and vcpu_vmx structures
  - KVM IO buses and memslots
KVM ASI Usage

- KVM ASI is used when running a guest VCPU
  - KVM_RUN ioctl
  - Enter KVM ASI
  - Start KVM ASI lockdown
    - VMEnter
    - VMExit
    - Stop KVM ASI lockdown
    - Run (most) VMExit handlers with KVM ASI
    - vcpu_run loop

- Early test (from RFCv2) showed that:
  - Most of loop iterations are done without exiting ASI
  - Most common VMExits are almost always processed without exiting ASI
ASI Test Driver
ASI Test Driver

- Kernel module and CLI for testing
- Create a Test ASI
- Test sequences:
  - Simple ASI enter/exit
  - Using printk() with ASI
  - Access a mapped or unmapped buffer in ASI
  - Receive an interrupt or NMI (or a NMI in an interrupt) in ASI
  - Scheduling a task using ASI in and out
  - ASI lockdown
ASI Introspection

• Driver/CLI can also be used to introspect and interact with an ASI
  - List ASI faults
  - Clear ASI faults
  - Toggle reporting of stack trace on ASI fault
  - List ASI mappings
  - Add ASI mapping
  - Clear ASI mapping

• By default actions are applied to the test ASI

• Actions can also be applied to a specified target ASI such as KVM ASI
  - Option available to list KVM ASIs
ASI printk() Test Example (1/2)

- Test printk() in ASI:

  ```
  # asicmd printk
  Test printk (sequence 1)
  - rv = 0 ; result = 0 ; asi inactive
  - expect = asi active
  TEST FAILED - unexpected ASI state
  ```

- Test has failed because of an ASI fault:

  ```
  # asicmd fault
  ADDRESS         COUNT  SYMBOL
  0xffffffff8110b5a1  1  vprintk_func+0x11/0xbc
  ```

- Debugger shows that the fault is due to printk_context not being mapped:

  ```
  0xffffffff8110b5a1: mov %gs:0x7ef106f8(%rip),%eax  # 0x1bca0 <printk_context>
  ```
ASI printk() Test Example (2/2)

- Add missing mapping: (printk_context is a percpu buffer of size 4)

```c
# asicmd mapadd percpu:0x1bca0:4
mapadd 1bca0/4/0 percpu
```

- Run the test again:

```c
# asicmd printk
Test printk (sequence 1)
   - rv = 0 ; result = 0 ; asi inactive
   - expect = asi active
TEST FAILED - unexpected ASI state
```

- Test is still failing but because of a new fault: (cpu_number is not mapped)

```c
# asicmd fault
ADDRESS   COUNT SYMBOL
0xffffffff8110b5a1   1  vprintk_func+0x11/0xbc
0xffffffff811081f3   1  log_store.constprop.27+0x1f3/0x280
```
KVM ASI Introspection Example (1/2)

● List target ASIs

```
# asicmd target
TARGET
kvm/1502/vcpu0
kvm/1502/vcpu1
```

● Dump KVM ASI Faults

```
# asicmd -t kvm/1502/vcpu0 fault
ADDRESS   COUNT   SYMBOL
0xffffffff8111b026  20878  rcu_qs+0x6/0x60
```
## KVM ASI Introspection Example (2/2)

- Dump KVM ASI Mapping

```bash
# aicmd -t kvm/1502/vcpu0 map
<p>|</p>
<table>
<thead>
<tr>
<th>ADDRESS</th>
<th>SIZE</th>
<th>LEVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0xffffffff888033e88800</td>
<td>0x5c8</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffff8880349c0a00</td>
<td>0x1e8</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffff8880343ea000</td>
<td>0x468</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffff88807d623ec8</td>
<td>0x20</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffff88807d623f18</td>
<td>0x20</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffff88807ce65a80</td>
<td>0x80</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffff88806e662a40</td>
<td>0x50</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffffc9000064c000</td>
<td>0x4000</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffff88807d5c0000</td>
<td>0x2480</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffff88806edc7000</td>
<td>0x1000</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffff88806edd000</td>
<td>0x1000</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffff88806edda000</td>
<td>0x1000</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffff88807c34b268</td>
<td>0x1000</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffffea0001ed2dc0</td>
<td>0x40</td>
<td>PMD</td>
</tr>
<tr>
<td>0xffffffff888079dc0000</td>
<td>0xa70</td>
<td>PTE</td>
</tr>
<tr>
<td>0xffffffff88807b4ad000</td>
<td>0x1000</td>
<td>PTE</td>
</tr>
</tbody>
</table>
```

...
ASI Status
ASI Status

- 4 RFCs already submitted
- RFCv5 in preparation, with 5 parts:
  - ASI Infrastructure and PTI
  - ASI Lockdown [NEW]
  - Decorated Page Table (DPT)
  - KVM ASI [NEW]
  - ASI Driver and CLI
- Core ASI code looks stable since RFCv3
- But need more testing of ASI Lockdown and KVM ASI
- Need to measure performance impact on KPTI and KVM
Thank You

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