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Who Watches the Watcher?

Detecting Hypervisor Introspection from Unprivileged Guests

Overview

"The Cloud"

- Numerous organizations are moving en masse to **the cloud**
  - It's easier to manage
  - It's easier to scale
- This results in a loss of control of **physical hardware** and **privileges on the system**
  - Everything is tied to guest virtual machines

Overview

Hypervisors (Virtual Machine Monitors)

- The root-of-trust is the hypervisor (virtual machine monitor)
  - It can introspect on guests with **few restrictions**
  - It can introspect on guests with **little evidence of apparent action**

Overview

Hypervisors (Virtual Machine Monitors)

- This trade-off puts organizations and individuals in a difficult situation
  - They have **sensitive data and processes**
  - Compromises are **expensive and dangerous**

Overview

Related Work

- **Compromise of** or **introspection by** a hypervisor has been a known issue
- Previous work on hypervisor detection has focused on **hardware or software artifacts**
  - This is more oriented towards **detection** of past events rather active **introspection**

Motivation

- A hypervisor's activities are **not entirely invisible** to its guests
- **System performance is impacted** as the hypervisor seeks to provides an environment which is functionally equivalent to native hardware
- Increases in an instruction's **execution time and/or cache artifacting** can provide evidence of a hypervisor's intervention

Implementation

- A **test framework** emulates inappropriate introspection
- A **monitoring module** on the guest employs a set of sensors to detect malicious behavior

Test Framework

- The *Xen Project* was used as the hypervisor
- Modifications were made to support hypercalls which would toggle introspection capabilities
- Modifications were made to support instructions that *Xen Project* does not support VM-exiting for

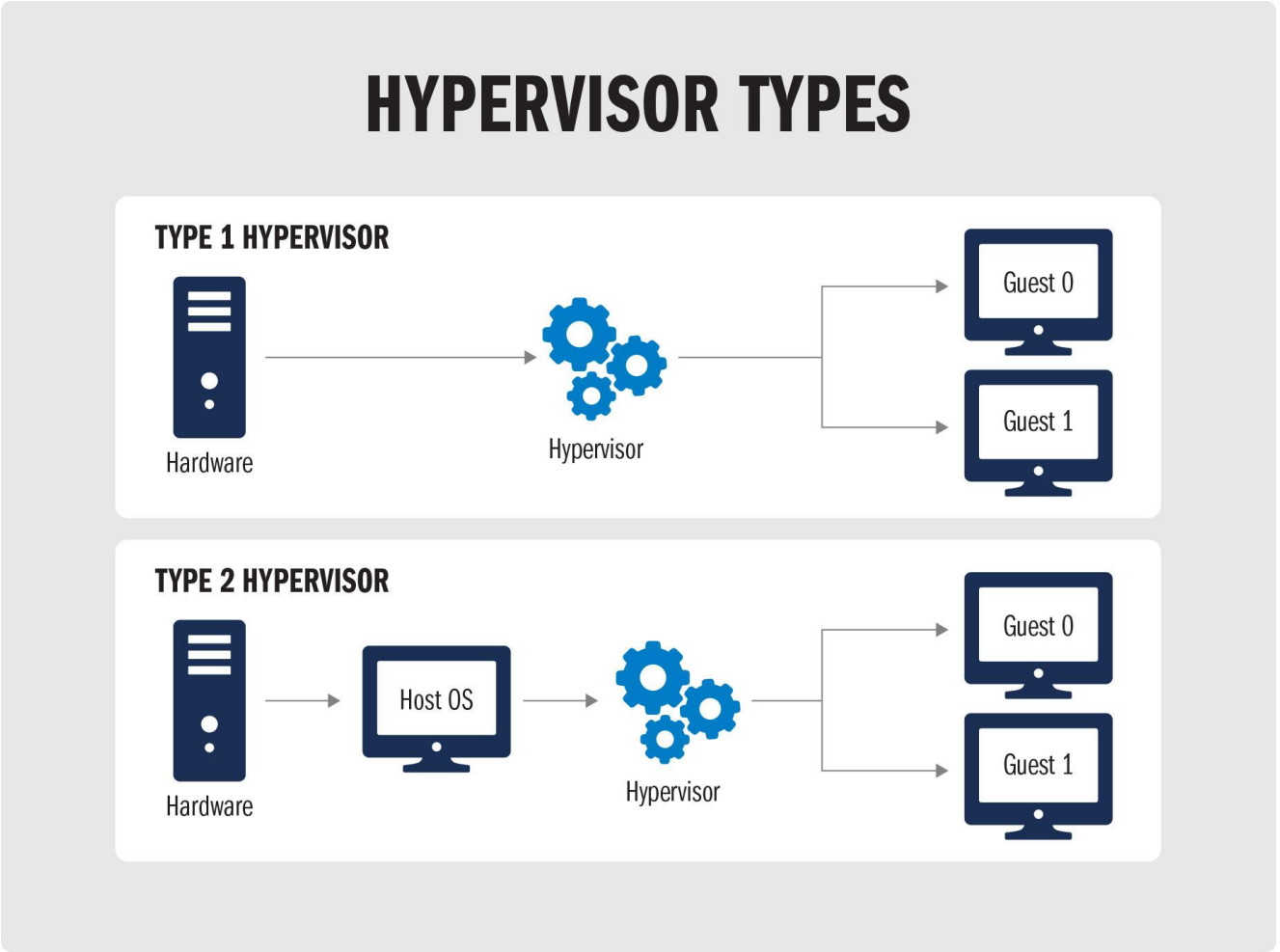
Monitoring Module and Sensors

- **Instruction intercession sensors** detect intercession of instruction execution using intercession timing
- **Active memory intercession sensors** detect the hypervisor actively interceding in memory access operations
- **Passive memory monitoring sensors** detect when a hypervisor accesses memory externally to a guest
- **Non-temporal access sensors** are not completed, but could be used to detect hypervisor introspection via non-caching page mappings or non-temporal instructions

Background

Hypervisor

- Privileged software that handles **execution** and **isolation** of guest virtual machines



Background

Virtual Machine Exits (VM-Exits)

- A hypervisor must be able to intercede in guest execution as necessary
- Guest execution is **paused** and execution is **handed to the hypervisor**
- Guest state information is stored in the Virtual Machine Control Structure (VMCS)
  - Resides in memory
  - Exits require that **state information is saved off during transition**
  - As such, an exit incurs significant overhead

Background

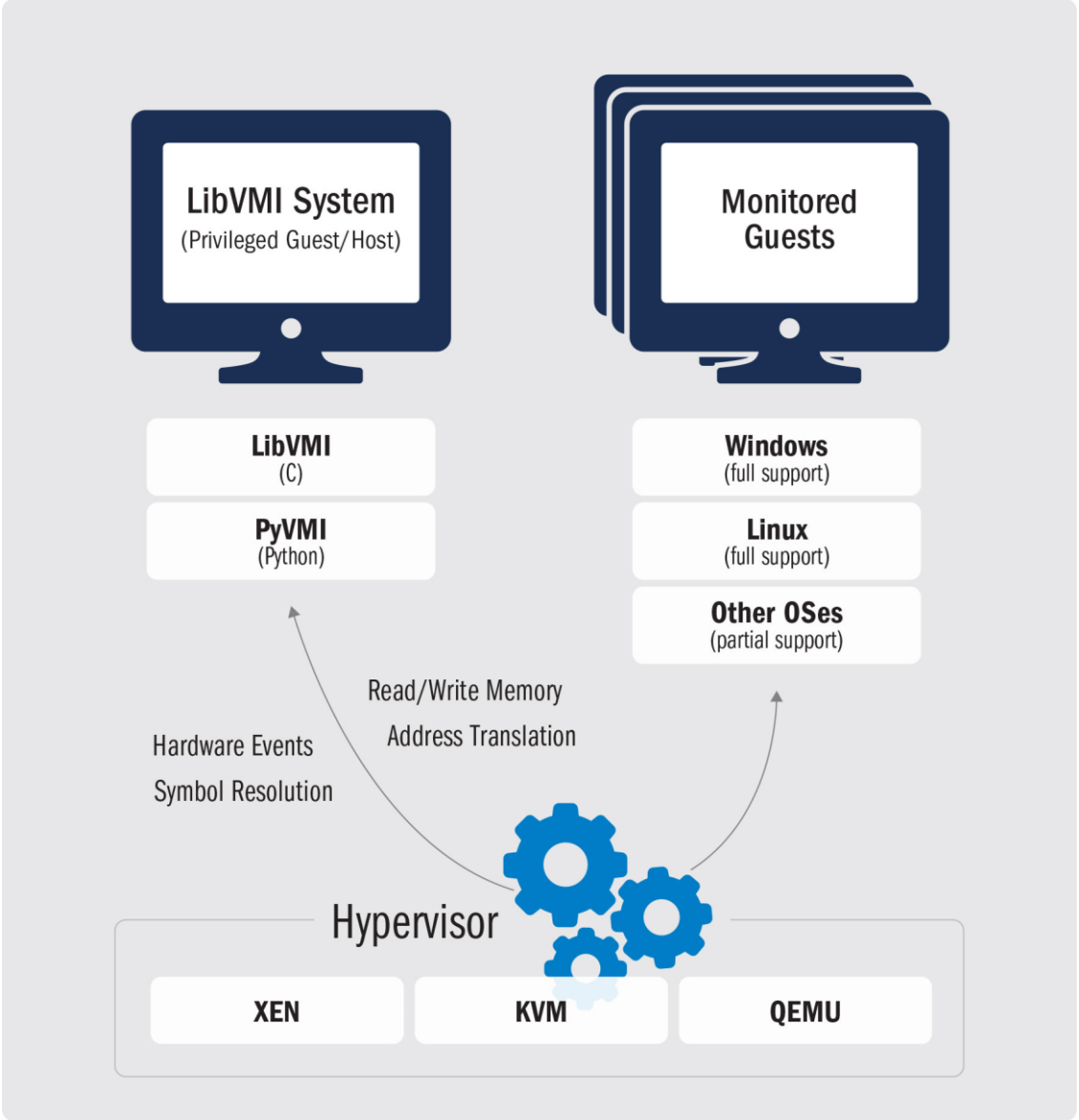
Timers & Timing Methods

- Time Stamp Counter (TSC)
- High Precision Event Timer (HPET)
- Thread racing

Background

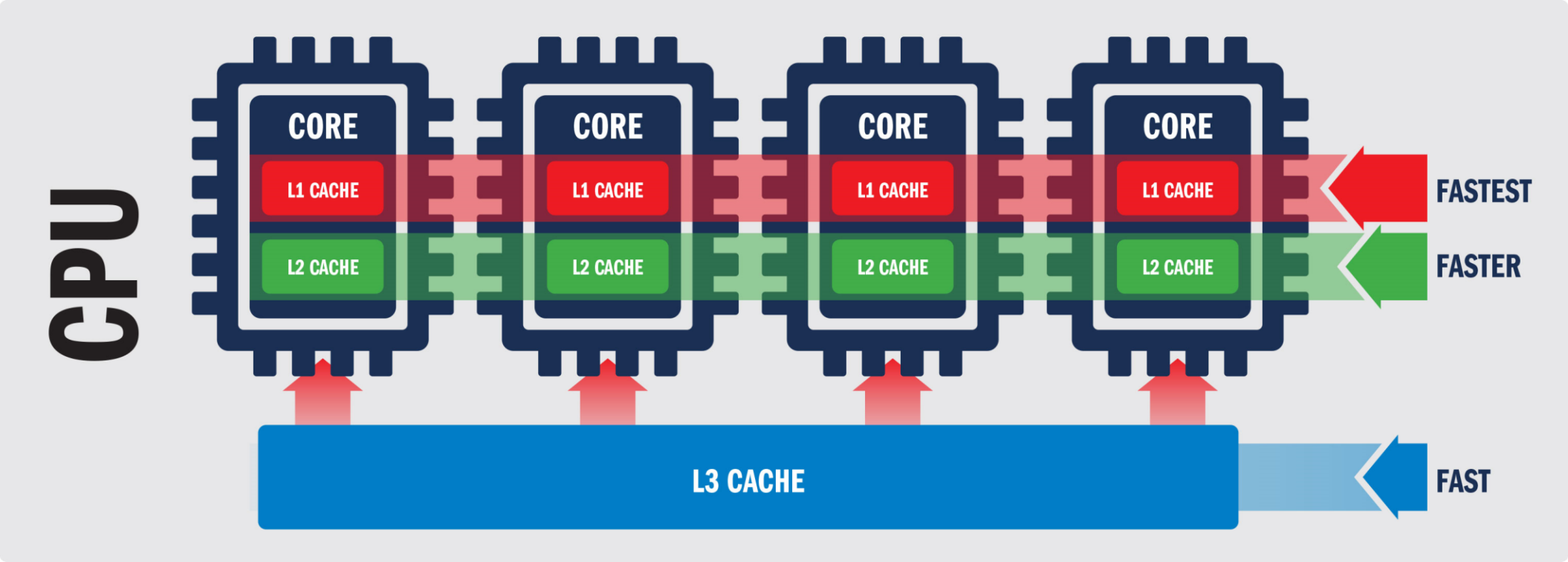
LibVMI

- C and Python library that enables introspection on virtual machines



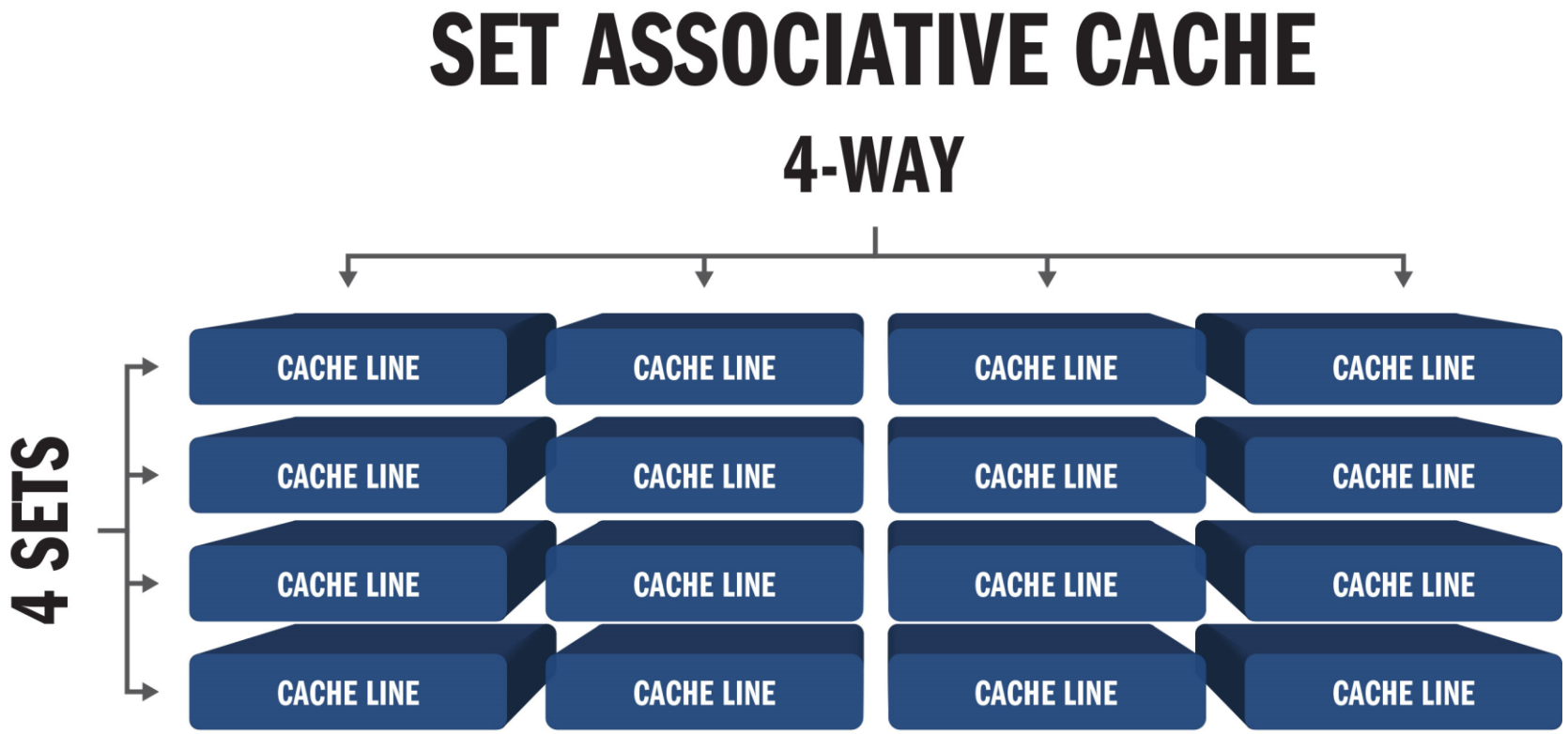
Background

Cache



Background

Cache



Instruction Intercession Sensors

- A hypervisor can trap on certain instructions to:
  - **Modify** the guest's execution behavior
  - Determine when a guest **performs** various operations
  - **Extraction** of information
- Timing can be used to determine that this is happening, and how much work the hypervisor performed while trapping

Instruction Intercession Sensors

- Wall timing via the HPET
  - Manipulation of the HPET would result in **noticeable interruptions** in operations to the observer
- Thread racing
  - Parallel threads run, one of which executes NOPs, with number of executions counted upon completion

Active Memory Intercession Sensors

- Virtual to physical memory mappings can be marked to **cause a VM-exit** (using LibVMI)

- VM-exit incurs a **sizable overhead**, and resultant **large timing increase**

Passive Memory Monitoring Sensors

- A more stealthy hypervisor can choose to **map the guest's physical pages** into other contexts
- Time required to access a memory line can be used
- Using Flush+Reload:
  - The memory line of interest is flushed from the cache
  - A period of time passes to allow for potential access to the memory region to occur
  - The memory line is reloaded, and the access is timed
- An **decrease in timing** is indicative of introspection

Non-Temporal Access Experimentation

- Non-temporal, streaming, and vector instructions have cache-coherence side-effects, despite bypassing the cache
  - A non-temporal instruction reading/writing a populated page **triggers a cache flush**
- Intel's Page Attribute Table (PAT) allows specifying per-page caching behavior
  - Passive mappings can become **non-cache-interacting**

Analysis & Classification of Results

- A variety of machines are used which had different processor generations
- For instruction intercession, a baseline is derived from non-exiting instructions
  - Adequately high values can be flagged as potentially exiting, or of interest
- For memory intercession, baselines are observable from adjacent non-introspected memory

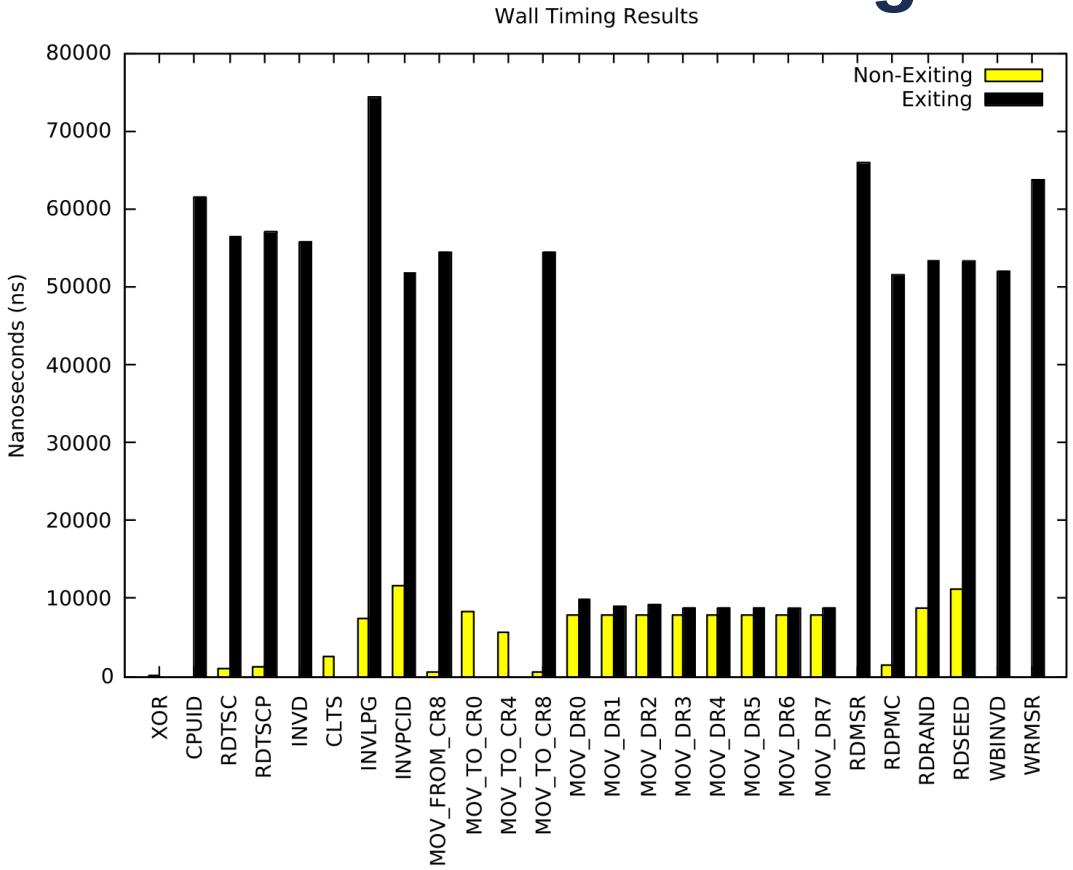
Results

Instruction Intercession

- Trapping by the hypervisor immediately returns, thus delivering the minimal possible impact on timing

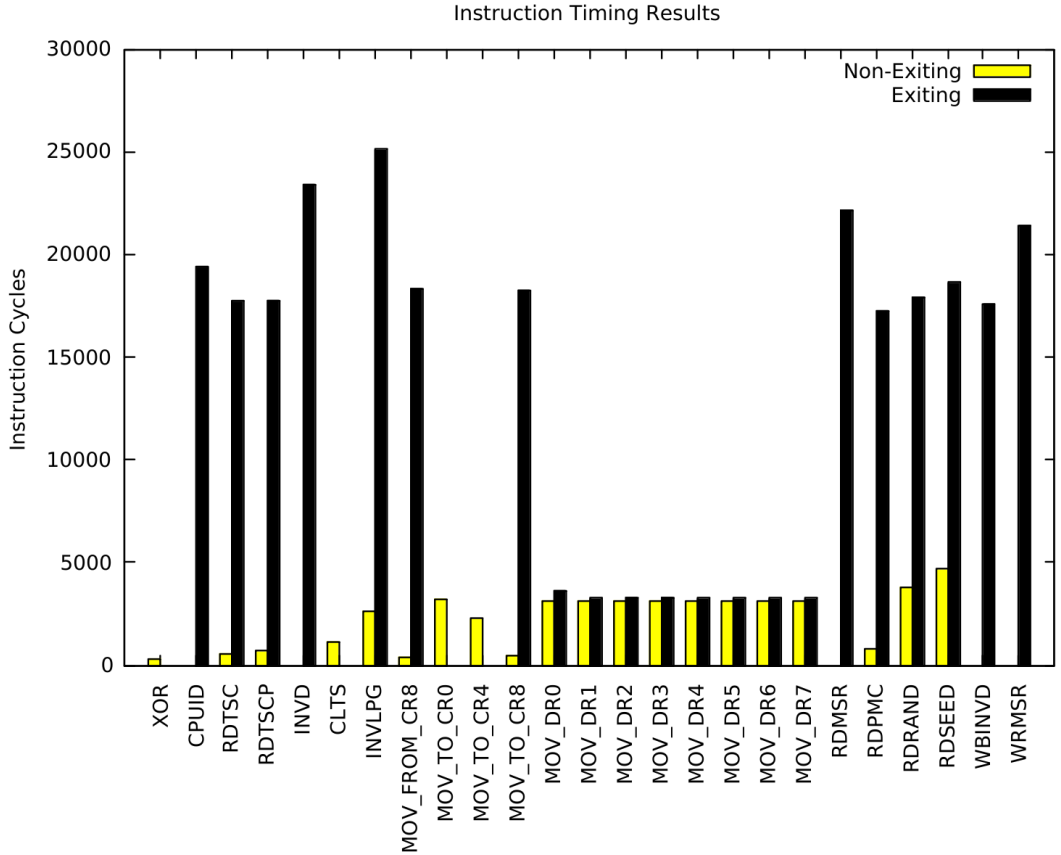
Results

Instruction Intercession – Wall Timing



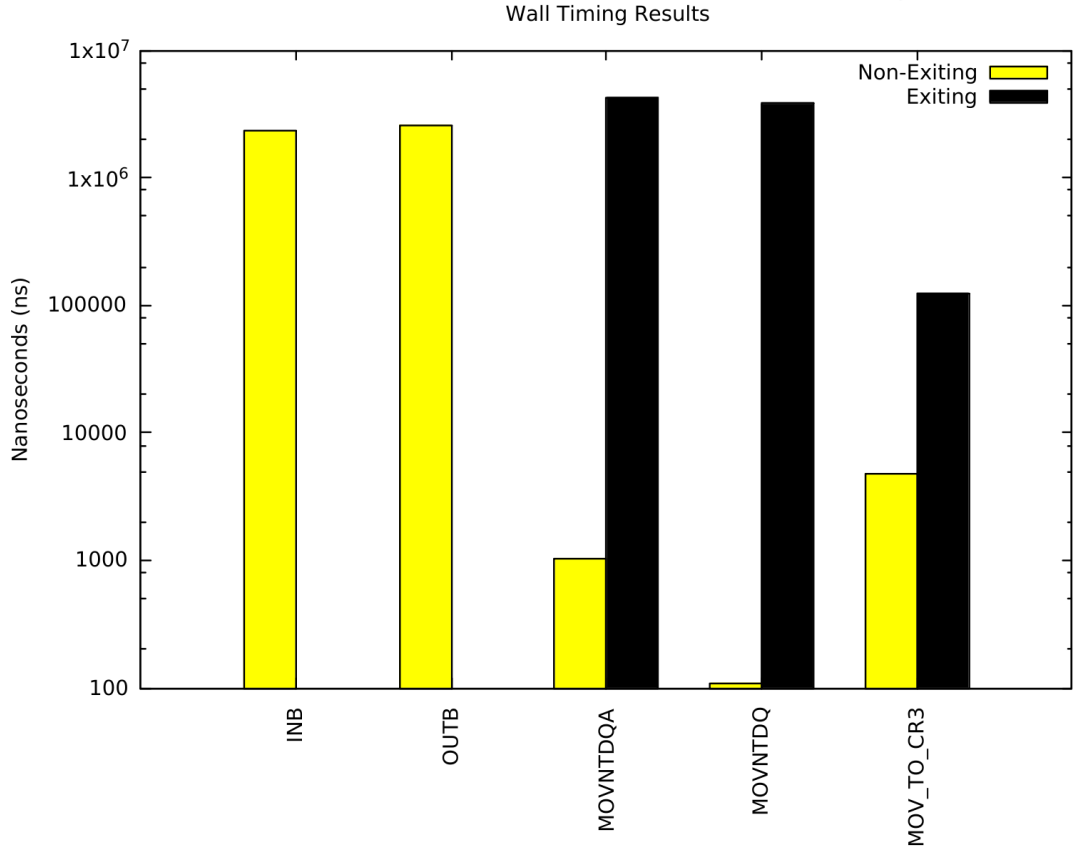
Results

Instruction Intercession – Instruction Timing



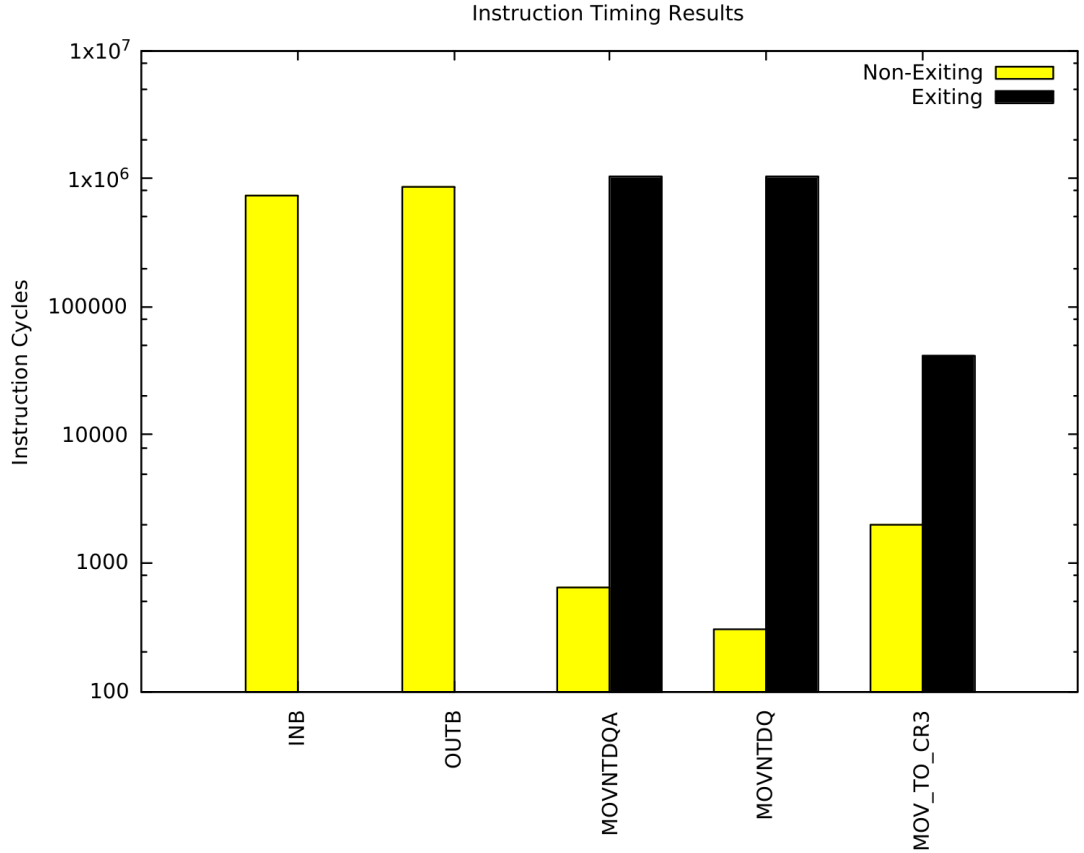
Results

Instruction Intercession – Wall Timing



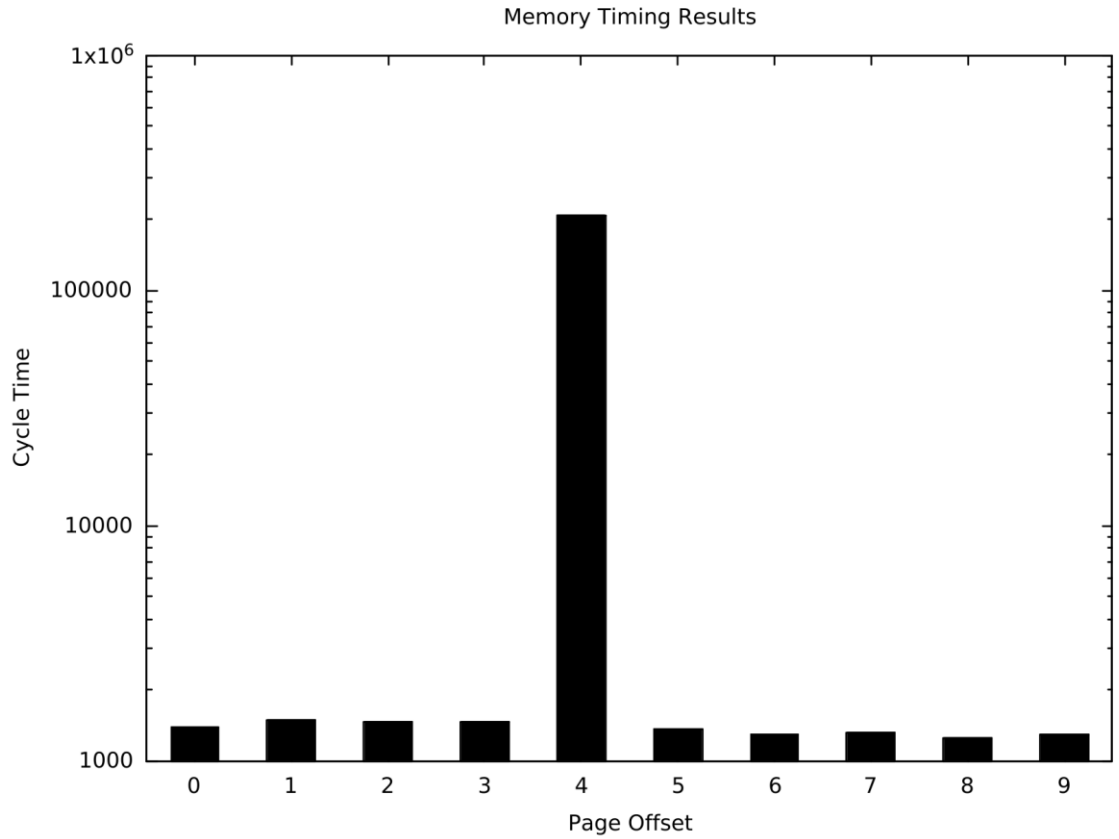
Results

Instruction Intercession – Instruction Timing



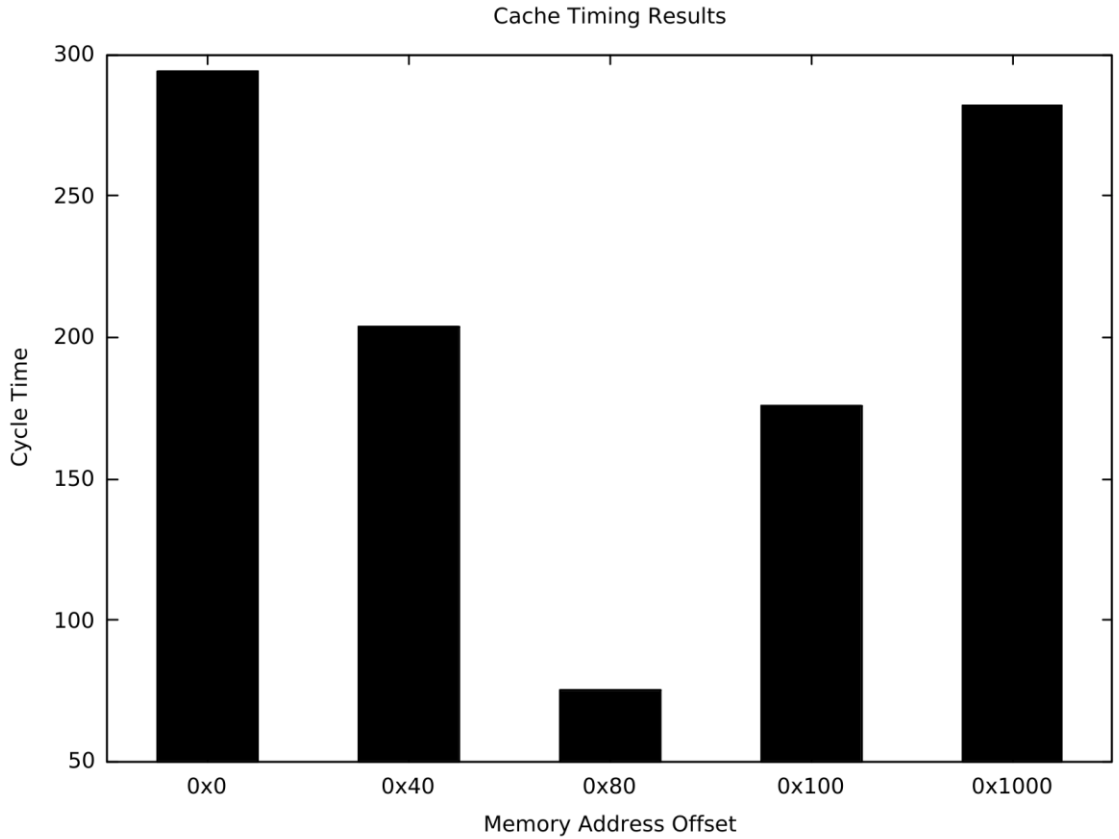
Results

Active Memory Intercession



Results

Passive Memory Intercession



Future Work

Next Steps

- This is a **first look** into hypervisor detection technology
- A **continuous detection environment** could implemented
- Full **binary classification** could better categorize introspection
- A **response strategy** when introspection is discovered

Future Work

Technology on the Horizon

- New virtualization extensions limit detection via timing since they **reduce overhead**
  - *Virtualization Exceptions (#VE)*
  - *VMFUNC*
- Sub-page permissions permit **memory protections at a 128-byte granularity**

Conclusion

- Detection of instruction intercession is possible
- Active and passive memory monitoring is possible
  - Isolating a memory region to a specific process may be necessary
  - Active and passive monitoring used in conjunction could obfuscate results of timing techniques
- This work establishes the **limitations of hypervisor introspection detection**

Questions?

- We intend to open-source this work [whenever we get around to it]

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