Efficient Performance Profiling for Virtual Machines

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AMD
together we advance_

Motivation

Performance profiling inside Virtual Machines (VMs) is no longer an afterthought

- Due to a high degree of cloud adoption

Inexpensive and accurate profiling are highly desirable

- Creates opportunities for both cloud vendors and users to optimize
  - Provisioning
  - Quality-of-service (QoS)
  - Capacity planning
  - Billing and costs

Performance Profiling

Running perf on a typical Linux system

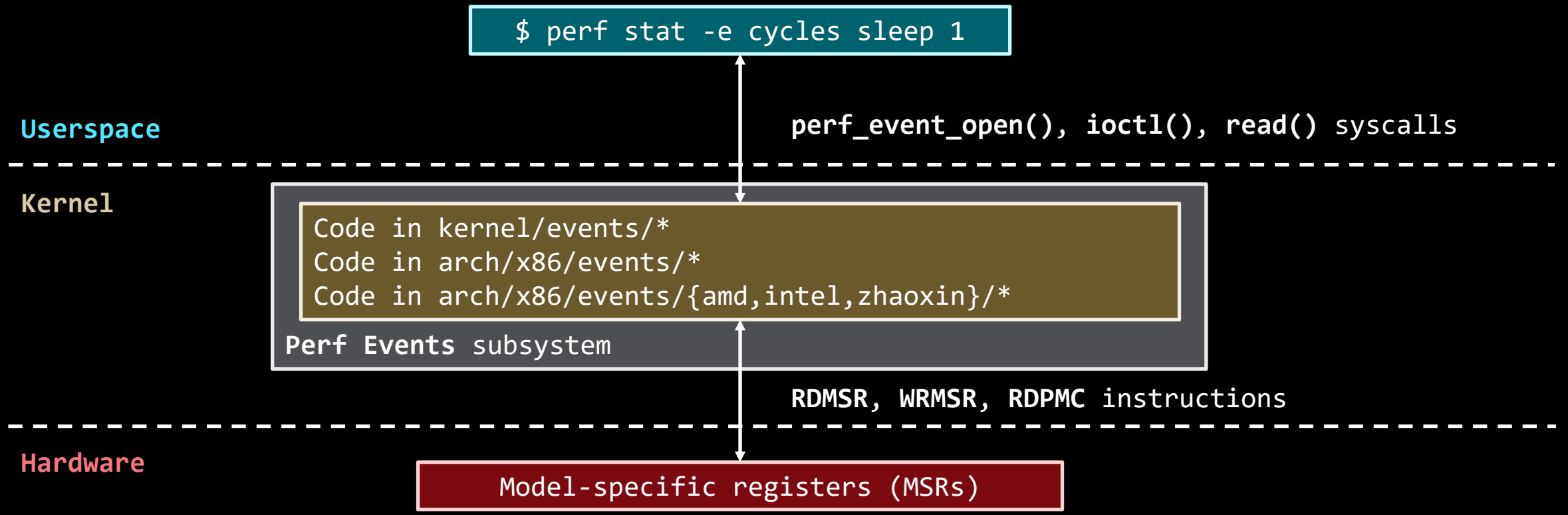
```
$ perf stat -e cycles sleep 1

 Performance counter stats for 'sleep 1':

         2,082,889      cycles:u

       1.002348165 seconds time elapsed

       0.000000000 seconds user
       0.002138000 seconds sys
```

Workload to be profiled

Event to be counted

Performance Profiling

Running perf on a typical Linux system



Performance Profiling

Dealing with multiple `perf` events

```
$ perf stat -e cpu-cycles,ref-cycles,branch-instructions,branch-misses,cache-misses sleep 1
```

Need for an event scheduling mechanism

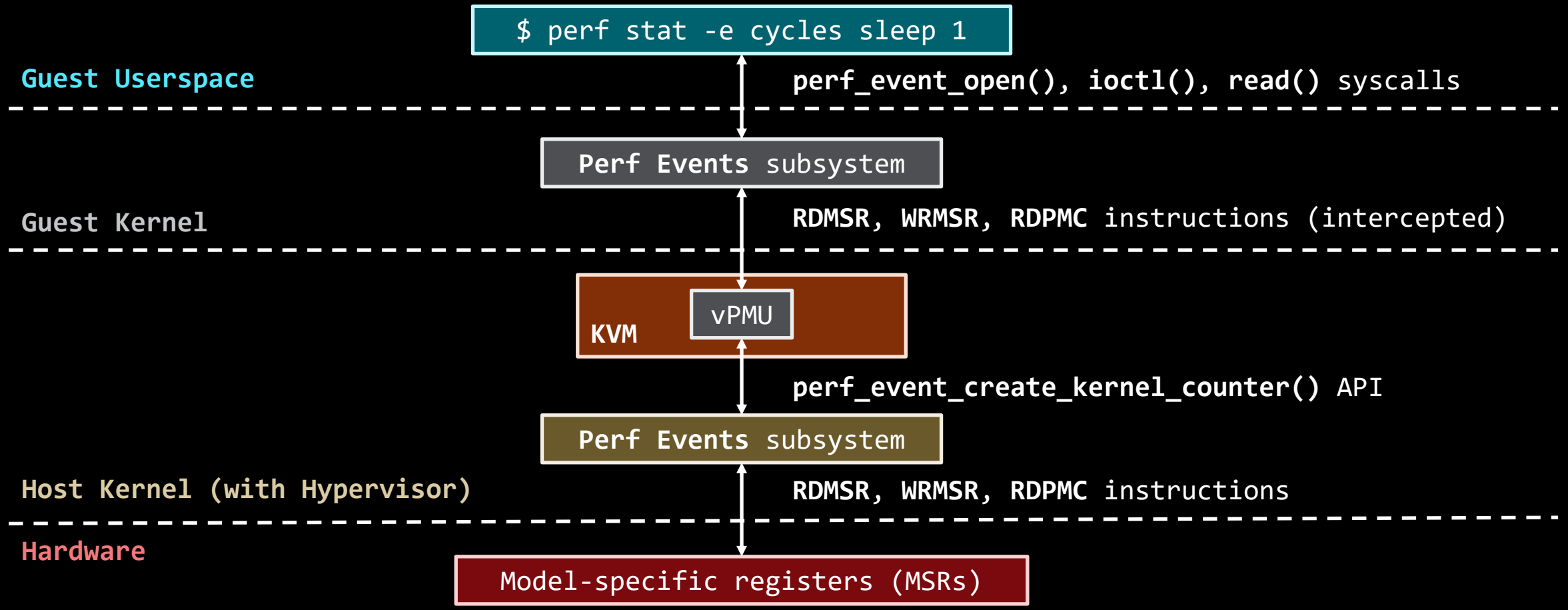
- The number of available hardware counters is limited, so they need to be rationed
- Some events may be programmable only on a specific subset of counters (events with constraints)
- Some events may be programmable only alongside other events (events that are grouped)
- Some events are tied to a process or thread (events that are task-specific)

The **Perf Events** subsystem has an event scheduler which

- Manages assignment of hardware counters to events and time-tracking
- Handles switching of event groups (time-based multiplexing)
- Switching of task-specific events during context switches (through scheduler hooks)

Performance Profiling – Inside Guests

Running perf inside a KVM guest



Performance Profiling – Inside Guests

Running `perf` inside a KVM guest

Guests do not have direct access to hardware

- MSR accesses are intercepted by KVM
- High overhead of world switches (transitions between host and guest contexts) due to interceptions

Backing events are created on behalf of the guest

- They exist alongside other host perf events (including the event used for the NMI watchdog)
- They may be silently disabled by the host due to unavailability of free hardware counters
- Guests have no control over how the host Perf Events subsystem is handling the backing events
- Guests do not know if their backing events are even getting hardware counters allotted

Performance Profiling – Conflicts between Host and Guest

Best Case – Running `perf` inside a KVM guest while `perf` is not running on the host

```
Guest instance
$ perf stat -e cycles,instructions,branches,cache-misses sleep 1


 Performance counter stats for 'sleep 1':

          377,066      cycles:u
          311,251      instructions:u
           69,108      branches:u
            6,206      cache-misses:u

      1.010779420 seconds time elapsed

      0.002668000 seconds user
      0.008005000 seconds sys
```

Performance Profiling – Conflicts between Host and Guest

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$ perf stat -e cycles,instructions,branches,cache-misses sleep 1

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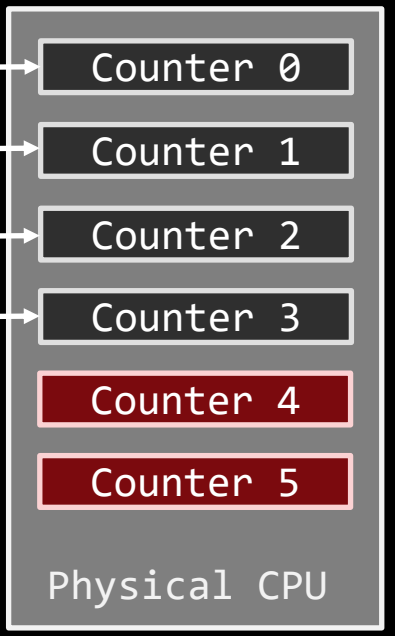
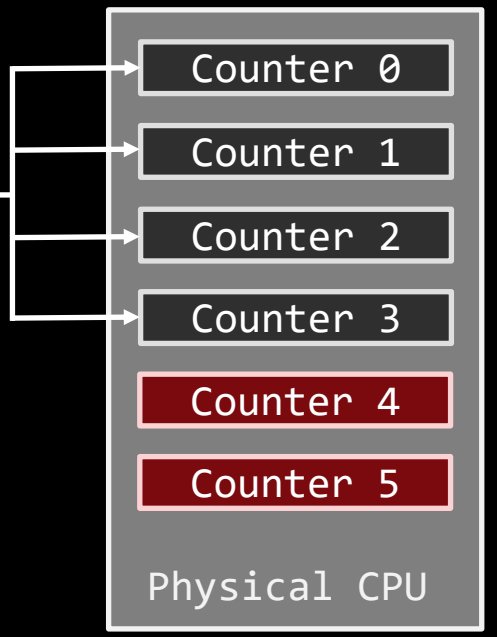


Performance Profiling – Conflicts between Host and Guest

Worst Case – Running `perf` inside a KVM guest while `perf` is also running on the host

```
Host instance
$ sudo perf stat -e cycles:D,instructions:D,branches:D,cache-misses:D -a
```

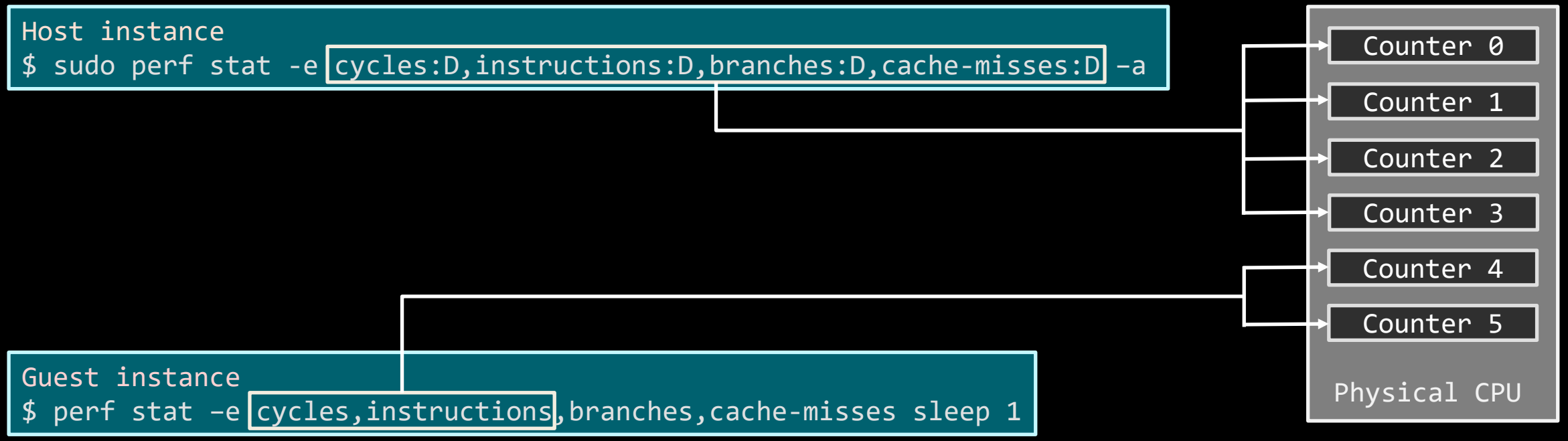


Pinning ensures that host events get permanent counter allotments

- No longer subject to time-based multiplexing
- Backing events for guests can no longer use these counters

Performance Profiling – Conflicts between Host and Guest

Worst Case – Running `perf` inside a KVM guest while `perf` is also running on the host



Performance Profiling – Conflicts between Host and Guest

Worst Case – Running `perf` inside a KVM guest while `perf` is also running on the host

```
Guest instance
$ perf stat -e cycles,instructions,branches,cache-misses sleep 1


 Performance counter stats for 'sleep 1':

          375,834      cycles:u
          311,372      instructions:u
                0      branches:u
                0      cache-misses:u

       1.010497211 seconds time elapsed

       0.000000000 seconds user
       0.010376000 seconds sys
```

vs. Best Case

```
377,066      cycles:u
311,251      instructions:u
 69,108      branches:u
  6,206      cache-misses:u
```

Performance Profiling – Conflicts between Host and Guest

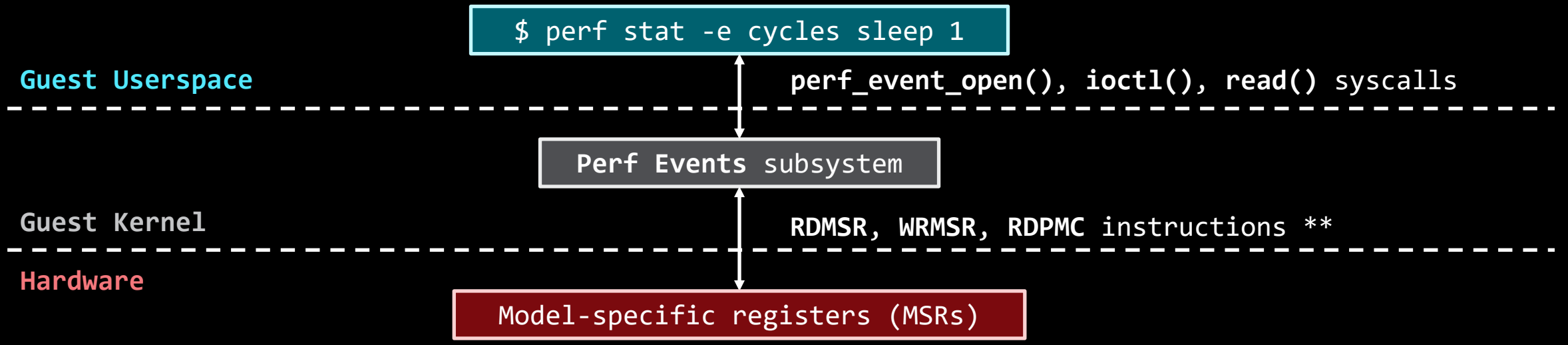
Solution – Mediated PMU

Switch the ownership and the state of hardware counters during world switches

- Before VM-Entry
  - Pause counting of host events and schedule them out; host perf events subsystem relinquishes control
  - Guest counter state is restored
- After VM-Exit
  - Guest counter state is saved
  - Schedule in host events and resume counting; host perf events subsystem regains control
- Guests get direct access to hardware (MSRs) in most cases

Performance Profiling – Inside Guests with Mediated PMU

Running perf inside a KVM guest



** Some MSRs like the Event Selectors are still intercepted for guest event filtering functionality

Performance Profiling – Overhead with Mediated PMU

Comparison – Typical workload analysis usage

```
Guest instance (single vCPU) – Perform a top-down analysis
$ sudo perf stat –M PipelineL1 true
```

```
Host instance – Count VM-Exits for hardware counter accesses
$ sudo perf stat –e kvm:kvm_msr --filter="((ecx >= 0xc0010000 && ecx <= 0xc0010007) || (ecx >=
0xc0010200 && ecx <= 0xc001020b) || (ecx >= 0xc0000300 && ecx <= 0xc0000303))" -e
probe:kvm_emulate_rdpmc –a
```

```
63      kvm:kvm_msr
11      probe:kvm_emulate_rdpmc
```

Legacy – 74 VM-Exits

```
22      kvm:kvm_msr
 0      probe:kvm_emulate_rdpmc
```

Mediated PMU – 22 VM-Exits

Performance Profiling – Overhead with Mediated PMU

Comparison – Typical performance dashboard usage

```
Guest instance (single vCPU) – Measure IPC every second for the next 10 seconds
$ sudo perf stat –e cycles,instructions –-interval-print 1000 –a sleep 10
```

```
Host instance – Count VM-Exits for hardware counter accesses
$ sudo perf stat –e kvm:kvm_msr --filter="((ecx >= 0xc0010000 && ecx <= 0xc0010007) || (ecx >=
0xc0010200 && ecx <= 0xc001020b) || (ecx >= 0xc0000300 && ecx <= 0xc0000303))" -e
probe:kvm_emulate_rdpmc –a
```

```
26      kvm:kvm_msr
23      probe:kvm_emulate_rdpmc
```

Legacy – 49 VM-Exits

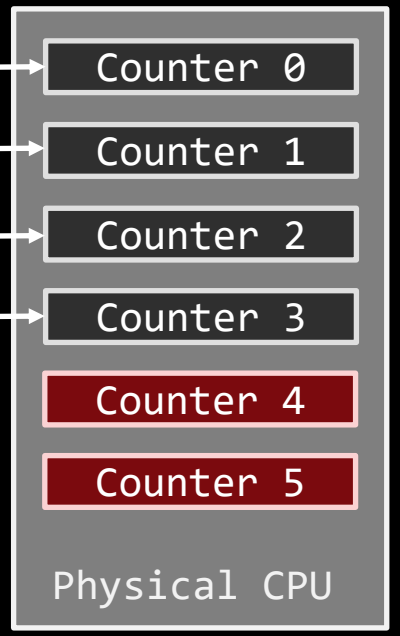
```
 6      kvm:kvm_msr
 0      probe:kvm_emulate_rdpmc
```

Mediated PMU – 6 VM-Exits

Performance Profiling – Accuracy with Mediated PMU

Worst Case – Running `perf` inside a KVM guest while `perf` is also running on the host

```
Host instance
$ sudo perf stat -e cycles:D,instructions:D,branches:D,cache-misses:D -a
```

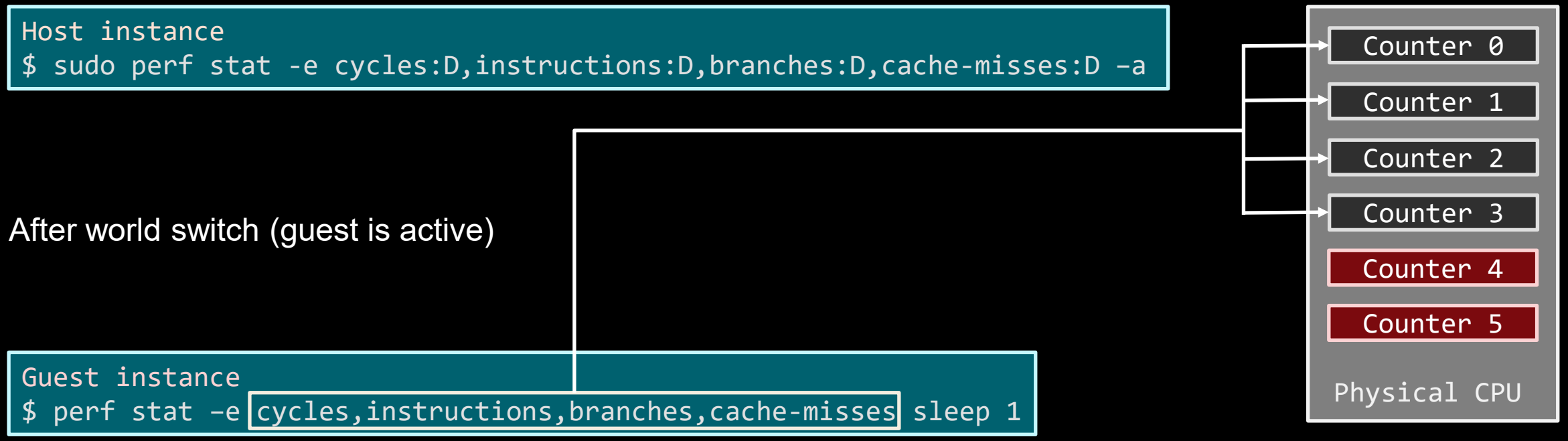


Before world switch (guest is inactive)

```
Guest instance
$ perf stat -e cycles,instructions,branches,cache-misses sleep 1
```

Performance Profiling – Accuracy with Mediated PMU

Worst Case – Running `perf` inside a KVM guest while `perf` is also running on the host



Performance Profiling – Accuracy with Mediated PMU

Worst Case – Running `perf` inside a KVM guest while `perf` is also running on the host

```
Guest instance
$ perf stat -e cycles,instructions,branches,cache-misses sleep 1


 Performance counter stats for 'sleep 1':

          375,852      cycles:u
          311,497      instructions:u
           69,157      branches:u
            6,233      cache-misses:u

      1.010792516 seconds time elapsed

      0.001689000 seconds user
      0.008446000 seconds sys
```

vs. Best Case

```
377,066      cycles:u
311,251      instructions:u
 69,108      branches:u
  6,206      cache-misses:u
```

Performance Profiling – Inside Guests with Mediated PMU

Pros

Low runtime overhead

- Direct access to most MSRs
- Avoid expensive VM-Exits caused by MSR interceptions and their side-effects

Native accuracy

- Avoid conflicts between host and guest perf events due to mutual exclusion
- Consistent results (guest events are not silently rejected due to scheduling conflicts)

Performance Profiling – Inside Guests with Mediated PMU

Cons

High world switch overhead

- The guest counter state has to be saved and restored for every world switch
- If a CPU mostly executes in guest context and runs for long uninterrupted stretches, like in the case of compute-bound cloud instances, the cost is amortized over a large period of guest runtime

Loss of host-side observability of guests

- Host perf events can no longer monitor guest activity due to mutual exclusion (design trade-off)
- Breaks tools like `perf kvm`

Performance Profiling – Inside Guests with Mediated PMU

Optimization and Future Work

Offload context switch of guest counter state to hardware

- Faster switching of host and guest states
- Reclaim part of the additional world switch overhead

Confidential compute requires mutual exclusion

- Prevent host from snooping guest performance metrics and potentially launching side-channel attacks
- Hardware can encrypt guest counter state and protect it from attacks

Adoption by other architectures

- Currently an x86-only feature

Other Takeaways

Patience

Multiple rounds of collaborative development, reviews and testing over a period of around 2 years to go from

```
Subject: [RFC PATCH 00/41] KVM: x86/pmu: Introduce passthrough vPMU
Date: Fri, 26 Jan 2024 16:54:03 +0800
Message-ID: <20240126085444.324918-1-xiong.y.zhang@linux.intel.com>
```

to

```
commit cb5573868ea85ddbc74dd9a917acd1e434d21390
Merge: c87c79345ea8 b1195183ed42
Author: Linus Torvalds <torvalds@linux-foundation.org>
Date: Fri Feb 13 11:31:15 2026 -0800

    Merge tag 'for-linus' of git://git.kernel.org/pub/scm/virt/kvm/kvm
```

Acknowledgements

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Manali Shukla
Xudong Hao
Yongwei Ma

…and more

References

Patch series

- RFC – https://lore.kernel.org/all/20240126085444.324918-1-xiong.y.zhang@linux.intel.com/
- Version 2 – https://lore.kernel.org/all/20240506053020.3911940-1-mizhang@google.com
- Version 3 – https://lore.kernel.org/all/20240801045907.4010984-1-mizhang@google.com
- Version 4 – https://lore.kernel.org/all/20250324173121.1275209-1-mizhang@google.com
- Version 5 – https://lore.kernel.org/all/20250806195706.1650976-1-seanjc@google.com
- Version 6 – https://lore.kernel.org/all/20251206001720.468579-1-seanjc@google.com/

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