This page describes how virtio-blk latency can be measured. The aim is to build a picture of the latency at different layers of the virtualization stack for virtio-blk.

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Benchmarks

Single-threaded read or write benchmarks are suitable for measuring virtio-blk latency. The guest should have 1 vcpu only, which simplifies the setup and analysis.

The benchmark I use is a simple C program that performs sequential 4k reads on an `O_DIRECT` file descriptor, bypassing the page cache. The aim is to observe the raw per-request latency when accessing the disk.

Tools

Linux kernel tracing (ftrace and trace events) can instrument host and guest kernels. This includes finding system call and device driver latencies.

Trace events in QEMU can instrument components inside QEMU. This includes virtio hardware emulation and AIO. Trace events are not upstream as of writing but can be built from git branches:

http://repo.or.cz/w/qemu-kvm/stefanha.git/shortlog/refs/heads/tracing-dev-0.12.4 (http://repo.or.cz/w/qemu-kvm/stefanha.git/shortlog/refs/heads/tracing-dev-0.12.4)

This particular commit message (http://repo.or.cz/w/qemu-kvm/stefanha.git/commit/deaa69d19c14b0ce902c9f5f10455f9cbefeff5b) explains how to use the simple trace backend for latency tracing.

Instrumenting the stack

Guest

The single-threaded read/write benchmark prints the mean time per operation at the end. This number is the total latency including guest, host, and QEMU. All latency numbers from layers further down the stack should be smaller than the guest number.

Guest virtio-pci

The virtio-pci latency is the time from the virtqueue notify pio write until the vring interrupt. The guest performs the notify pio write in virtio-pci code. The vring interrupt comes from the PCI device in the form of a legacy interrupt or a message-signaled interrupt.

Ftrace can instrument virtio-pci inside the guest:

```
cd /sys/kernel/debug/tracing
echo 'vp_notify vring_interrupt' >set_ftrace_filter
echo function >current_tracer
cat trace_pipe >/path/to/tmpfs/trace
```

Note that putting the trace file in a tmpfs filesystem avoids causing disk I/O in order to store the trace.

Host kvm

The kvm latency is the time from the virtqueue notify pio exit until the interrupt is set inside the guest. This number does not include vmexit/entry time.

Events tracing can instrument kvm latency on the host:

```
cd /sys/kernel/debug/tracing
echo 'port == 0xc090' >events/kvm/kvm_pio/filter
echo 'gsi == 26' >events/kvm/kvm_set_irq/filter
echo 1 >events/kvm/kvm_pio/enable
echo 1 >events/kvm/kvm_set_irq/enable
cat trace_pipe >/tmp/trace
```

Note how `kvm_pio` and `kvm_set_irq` can be filtered to only trace events for the relevant virtio-blk device. Use `lspci -vv -nn` and `cat /proc/interrupts` inside the guest to find the pio address and interrupt.

QEMU virtio

The virtio latency inside QEMU is the time from virtqueue notify until the interrupt is raised. This accounts for time spent in QEMU servicing I/O.

- Run with 'simple' trace backend, enable virtio_queue_notify() and virtio_notify() trace events.
- Use ./simpletrace.py trace-events /path/to/trace to pretty-print the binary trace.
- Find vdev pointer for correct virtio-blk device in trace (should be easy because most requests will go to it).
- Use qemu_virtio.awk only on trace entries for the correct vdev.

QEMU paio

The paio latency is the time spent performing pread()/pwrite() syscalls. This should be similar to latency seen when running the benchmark on the host.

- Run with 'simple' trace backend, enable the posix_aio_process_queue() trace event.
- Use ./simpletrace.py trace-events /path/to/trace to pretty-print the binary trace.
- Only keep reads (`type=0x1` requests) and remove vm boot/shutdown from the trace file by looking at timestamps.
- Use qemu_paio.py to calculate the latency statistics.

Results

Host

The host is 2x4-cores, 8 GB RAM, with 12 LVM striped FC LUNs. Read and write caches are enabled on the disks.

The host kernel is kvm.git 37dec075a7854f0f550540bf3b9bbeef37c11e2a from Sat May 22 16:13:55 2010 +0300.

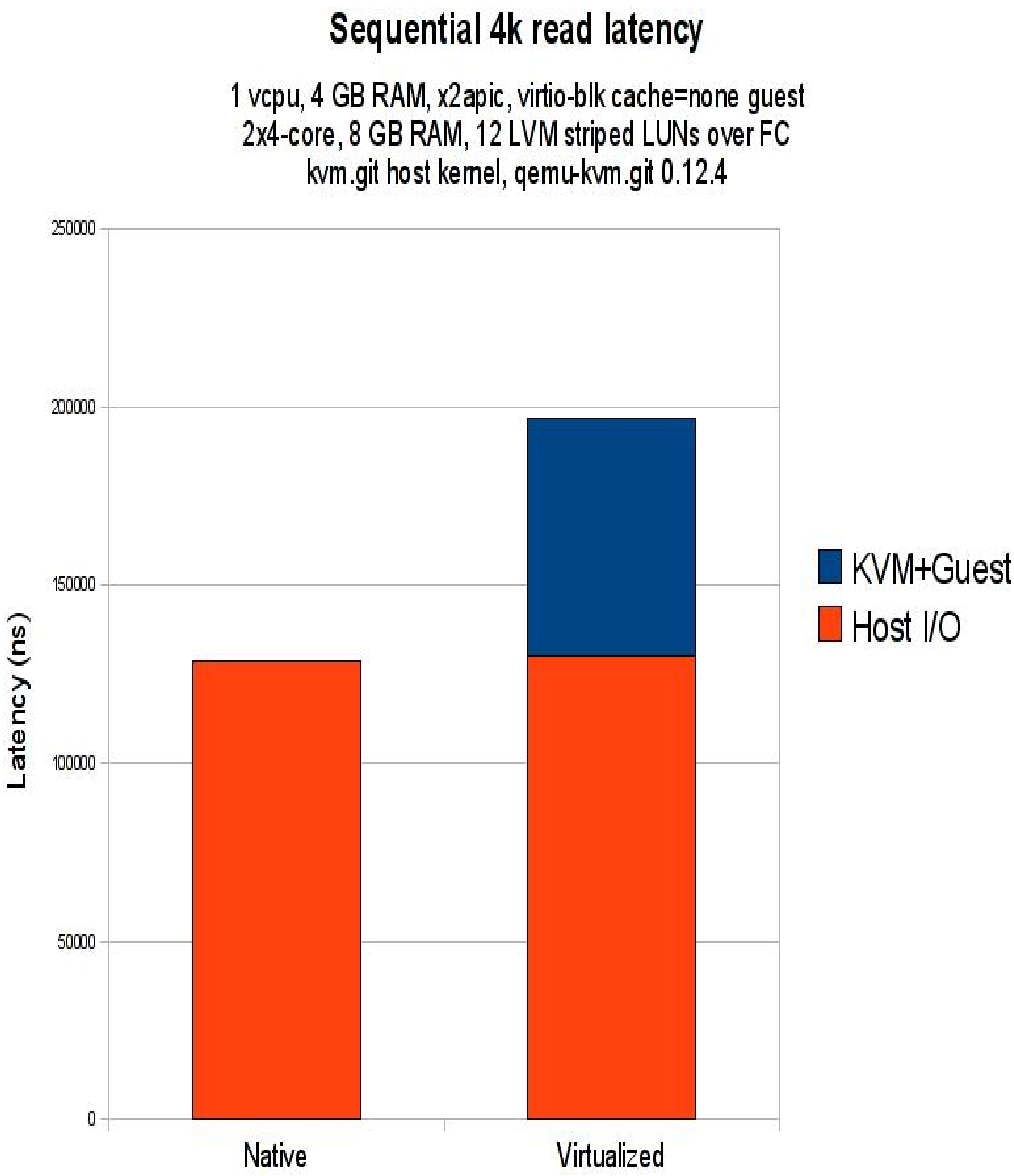
The qemu-kvm is 0.12.4 with patches as necessary for instrumentation.

Guest

The guest is a 1 vcpu, x2apic, 4 GB RAM virtual machine running a 2.6.32-based distro kernel. The root disk image is raw and the benchmark storage is an LVM volume passed through as a virtio disk with cache=none.

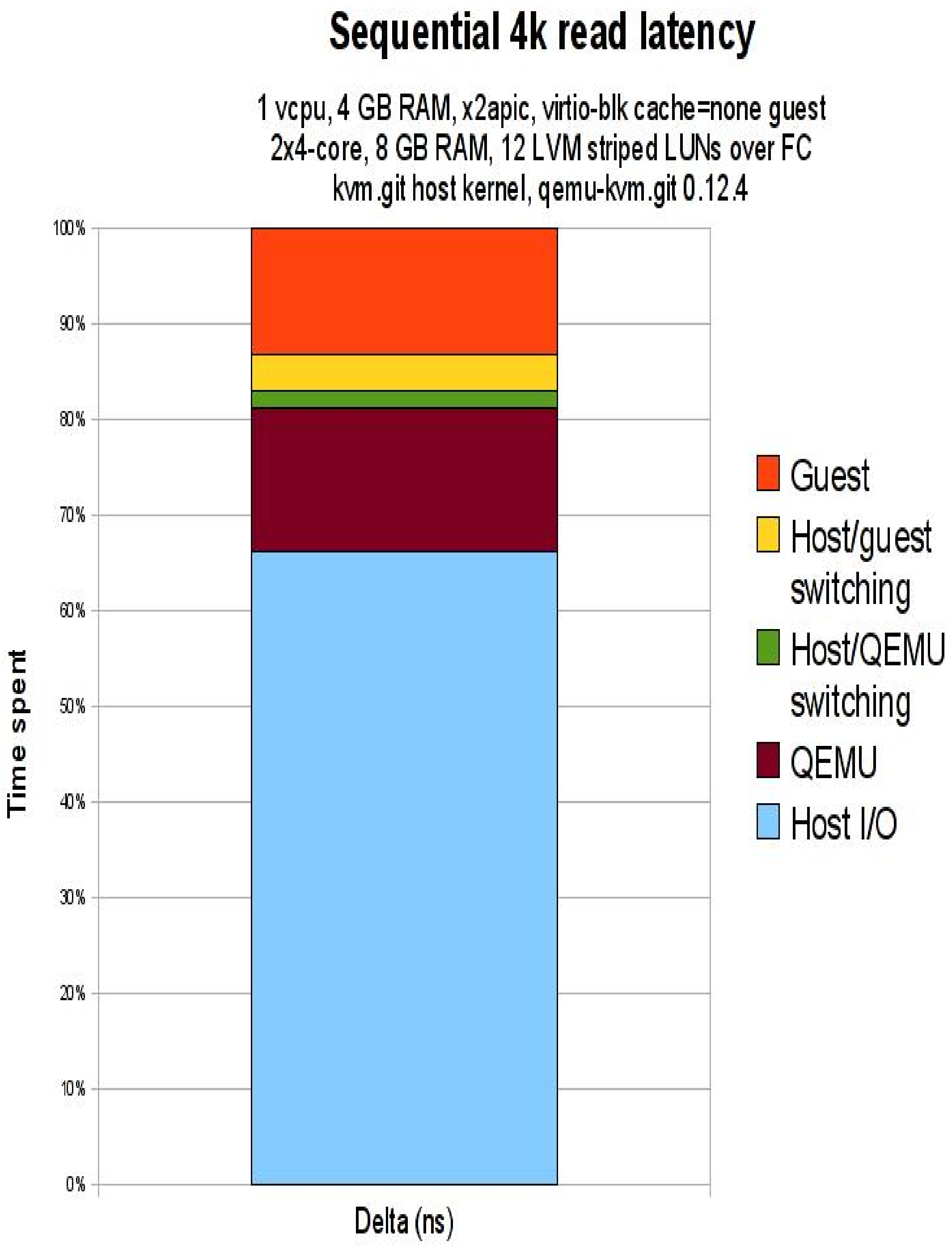
Performance data

The following diagram compares the benchmark when run on the host against run inside the guest:



(/page/File:Virtio-blk-latency-comparison.jpg)

The following diagram shows the time spent in the different layers of the virtualization stack:



(/page/File:Virtio-blk-latency-breakdown.jpg)

Here is the raw data used to plot the diagram:

Layer	Cumulative latency (ns)	Guest benchmark control (ns)
Guest benchmark	196528	
Guest virtio-pci	170829	202095
Host kvm.ko	163268	
QEMU virtio	159628	205165
QEMU paio	130235	202777
Host benchmark	128862	

The **Guest benchmark control (ns)** column is the latency reported by the guest benchmark for that run. It is useful for checking that overall latency has remained relatively similar across benchmarking runs.

The following numbers for the layers of the stack are derived from the previous numbers by subtracting successive latency readings:

Layer	**Delta (ns)**	**Delta (%)**
Guest	25699	13.08%
Host/guest switching	7561	3.85%
Host/QEMU switching	3640	1.85%
QEMU	29393	14.96%
Host I/O	130235	66.27%

The **Delta (ns)** column is the time between two layers, e.g. **Guest benchmark** and **Guest virtio-pci**. The delta time tells us how long is being spent in a layer of the virtualization stack.

Analysis

The sequential read case is optimized by the presence of a disk read cache. I think this is why the latency numbers are in the microsecond range, not the usual millisecond seek time expected from disks. However, read caching is not an issue for measuring the latency overhead imposed by virtualization since the cache is active for both host and guest measurements.

The results give a 33% virtualization overhead. I expected the overhead to be higher, around 50%, which is what single-process `dd bs=8k iflag=direct` benchmarks show for sequential read throughput. The results I collected only measure 4k sequential reads, perhaps the picture may vary with writes or different block sizes.

Guest

The `Guest` 202095 ns latency (13% of total) is high. The guest should be filling in virtio-blk read commands and talking to the virtio-blk PCI device, there isn't much interesting work going on inside the guest.

The `seqread` benchmark inside the guest is doing sequential `read()` syscalls in a loop. A timestamp is taken before the loop and after all requests have finished; the mean latency is calculated by dividing this total time by the number of `read()` calls.

The `Guest virtio-pci` tracepoints provide timestamps when the guest performs the virtqueue notify via a pio write and when the interrupt handler is executed to service the response from the host.

Between the `seqread` userspace program and `virtio-pci` are several kernel layers, including the vfs, block, and io scheduler. Previous guest oprofile data from Khoa Huynh showed `__make_request` and `get_request` taking significant amounts of CPU time.

Possible explanations:

- **Inefficiency in the guest kernel I/O path** as suggested by past oprofile data.
- **Expensive operations** performed by the guest, besides the pio write vmexit and interrupt injection which are accounted for by `Host/guest switching` and not included in this figure.
- **Timing inside the guest** can be inaccurate due to the virtualization architecture. I believe this issue is not too severe on the kernels and qemu binaries used because the guest latency stacks up with host latency. Ideally, guest tracing could be performed using host timestamps so guest and host timestamps can be compared accurately.

QEMU

The QEMU 29393 ns latency (~15% of total) is high. The QEMU layer accounts for the time between virtqueue notify until issuing the `pread64()` syscall and return of the syscall until raising an interrupt to notify the guest. QEMU is building AIO requests for each virtio-blk read command and transforming the results back again before raising an interrupt.

Possible explanations:

- **QEMU iothread mutex contention** due to the architecture of qemu-kvm. In preliminary futex wait profiling on my laptop, I have seen threads blocking on average 20 us when the iothread mutex is contended. Further work could investigate whether this is the case here and then how to structure QEMU in a way that solves the lock contention. See `futex.gdb` and `futex.py` for futex profiling using ftrace in my tracing branch (http://repo.or.cz/w/qemu-kvm/stefanha.git/tree/tracing-dev-0.12.4:/latency_scripts):

```
$ gdb -batch -x futex.gdb -p $(pgrep qemu) # to find futex addresses
# echo 'uaddr == 0x89b800 || uaddr == 0x89b9e0' >events/syscalls/sys_en
ter_futex/filter # to trace only those futexes
# echo 1 >events/syscalls/sys_enter_futex/enable
# echo 1 >events/syscalls/sys_exit_futex/enable
[...run benchmark...]
# ./futex.py </tmp/trace
```

Known issues

- **Mean average latencies** don't show the full picture of the system. I have copies of the raw trace data which can be used to look at the latency distribution.
- **Choice of I/O syscalls** may result in different performance. The `seqread` benchmark uses 4k `read()` syscalls while the qemu binary services these I/O requests using `pread64()` syscalls. Comparison between the host benchmark and QEMU paio would be more correct when using `pread64()` in the benchmark itself.

Zooming in on QEMU userspace virtio-blk latency

The time spent in QEMU servicing a read request made up 29 us or a 23% overhead compared to a host read request. This deserves closer study so that the overhead can be reduced.

The benchmark QEMU binary was updated to qemu-kvm.git upstream [Tue Jun 29 13:59:10 2010 +0100] in order to take advantage of the latest optimizations that have gone into qemu-kvm.git, including the virtio-blk memset elimination patch.

Trace events

Latency numbers can be calculated by recording timestamps along the I/O code path. The trace events work, which adds static trace points to QEMU, is a good mechanism for this sort of instrumentation.

The following trace events were added to QEMU:

Trace event	Description

virtio_add_queue	Device has registered a new virtqueue
virtio_queue_notify	Guest -> host virtqueue notify
virtqueue_pop	A buffer has been removed from the virtqueue
virtio_notify	Host -> guest virtqueue notify
virtio_blk_rw_complete	Read/write request completion
paio_submit	Asynchronous I/O request submission to worker threads
posix_aio_process_queue	Asynchronous I/O request completion
posix_aio_read	Asynchronous I/O completion events pending
qemu_laio_enqueue_completed	Linux AIO completion events are about to be processed
qemu_laio_completion_cb	Linux AIO request completion
laio_submit	Linux AIO request is being issued to the kernel
laio_submit_done	Linux AIO request has been issued to the kernel
main_loop_wait_entry	Iothread main loop iteration start
main_loop_wait_exit	Iothread main loop iteration finish
main_loop_wait_pre_select	Iothread about to block in the select(2) system call
main_loop_wait_post_select	Iothread resumed after select(2) system call
main_loop_wait_iohandlers_done	Iothread callbacks for select(2) file descriptors finished
main_loop_wait_timers_done	Iothread timer processing done
kvm_set_irq_level	About to raise interrupt in guest
kvm_set_irq_level_done	Finished raising interrupt in guest
pre_kvm_run	Vcpu about to enter guest
post_kvm_run	Vcpu has exited the guest
kvm_run_exit_io_done	Vcpu io exit handler finished

posix-aio-compat versus linux-aio

QEMU has two asynchronous I/O mechanisms: POSIX AIO emulation using a pool of worker threads and native Linux AIO.

The following results compare latency of the two AIO mechanisms. All time measurements in microseconds.

The seqread benchmark reports aio=threads 200.309 us and aio=native 193.374 us latency. The Linux AIO mechanism has lower latency than POSIX AIO emulation; here is the detailed latency trace to support this observation:

Trace event	aio=threads (us)	aio=native (us)
virtio_queue_notify	45.292	44.464
paio_submit/laio_submit	8.023	8.377
posix_aio_read/qemu_laio_completion_cb	**143.724**	**136.241**
posix_aio_process_queue/qemu_laio_enqueue_completed	1.965	1.754
virtio_blk_rw_complete	0.260	0.294
virtio_notify	1.034	1.342

The time between request submission and completion is lower with Linux AIO. paio_submit -> posix_aio_read takes 143.724 us while laio_submit -> qemu_laio_completion_cb takes only 136.241 us.

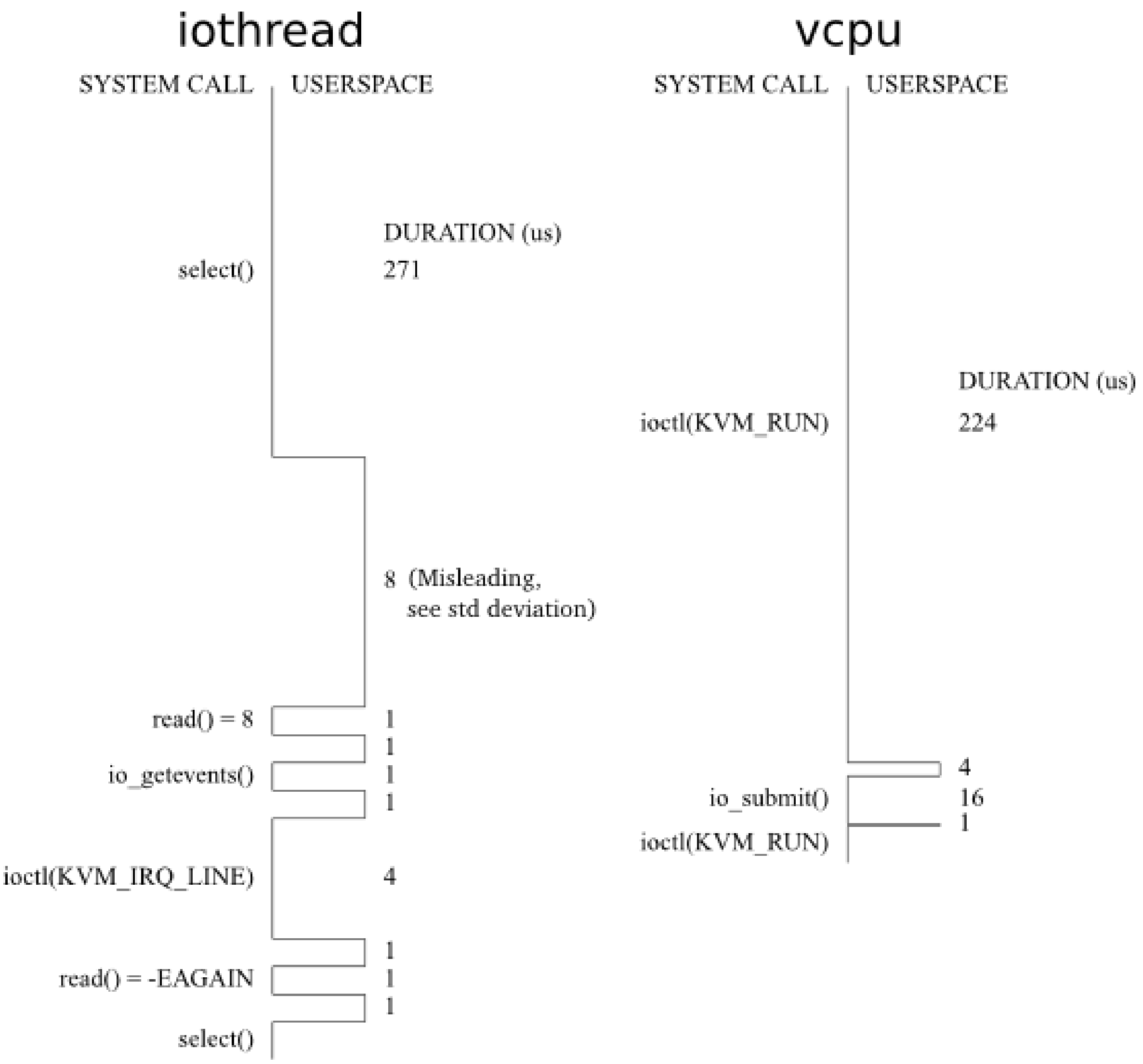
Note that the 8 us latency from virtio_queue_notify to submit is because the QEMU binary used to gather these results does not have the virtio-blk memset elimination patch.

Userspace and System Call times

Trace events inside QEMU have a hard time showing the latency breakdown between userspace and system calls. Because trace events are inside QEMU and the iothread mutex must be held, it is not possible to measure the exact boundaries of blocking system calls like select(2) and ioctl(KVM_RUN).

The ftrace raw_syscalls events can be used like strace to gather system call entry/exit times for threads.

The following diagram shows the userspace/system call times for the iothread and vcpu threads:



(/page/File:Threads.png)

The iothread latency statistics are as follows:

Event	Count	Mean (s)	Std deviation (s)	Minimum (s)	Maximum (s)	Total (s)
select()	210480	0.000271	0.001690	0.000002	0.030008	57.102602
select_post	209097	0.000009	0.000470	0.000001	0.030010	1.879496
read()	418439	0.000001	0.000000	0.000000	0.000021	0.325694
read_post	310035	0.000001	0.000001	0.000001	0.000052	0.459388
io_getevents()	204800	0.000001	0.000000	0.000000	0.000008	0.161967
io_getevents_post	204800	0.000002	0.000000	0.000001	0.000074	0.388233
ioctl(KVM_IRQ_LINE)	204829	0.000004	0.000001	0.000000	0.000025	0.807423

ioctl_post	204828	0.000001	0.000000	0.000001	0.000013	0.257511

The vcpu thread latency statistics are as follows:

Event	Count	Mean (s)	Std deviation (s)	Minimum (s)	Maximum (s)	Total (s)
ioctl(KVM_RUN)	224793	0.000224	0.011423	0.000000	1.991701	50.438935
ioctl_post	224785	0.000004	0.000001	0.000001	0.000054	0.994368
io_submit()	204800	0.000016	0.000001	0.000015	0.000111	3.303320
io_submit_post	204800	0.000002	0.000001	0.000001	0.000039	0.331057

The *_post statistics show the time spent inside QEMU userspace after a system call.

Observations on this data:

- The VIRTIO_PCI_QUEUE_NOTIFY pio has a latency of over 22 us! This is largely due to io_submit() taking 16 us. It would be interesting to using ioeventfd for VIRTIO_PCI_QUEUE_NOTIFY pio so that the iothread performs the io_submit() instead of the vcpu thread. This will increase latency but should reduce guest system time stealing.
- The Linux AIO eventfd() could be modified to reduce latency in the case where a single AIO request has completed. The read() = -EAGAIN could be avoided by not looping in qemu_laio_completion_cb(). The iothread select(2) call should detect that more AIO events have completed since the file descriptor is still readable next time around the main loop. This increases latency when AIO requests complete while still in qemu_laio_completion_cb().
- The standard deviation of the iothread return from select(2) is high. There is no complicated code in the path, I think iothread lock contention occassionally causes high latency here. Most of the time select_post only takes 1 us, not 8 us as suggested by the mean.

Read request lifecycle

The following data shows the code path executed in QEMU when the seqread benchmark runs inside the guest:

Trace event	Time since previous event (us)	Thread
main_loop_wait_entry	0.265	iothread
main_loop_wait_pre_select	0.422	iothread
post_kvm_run	35.678	vcpu
virtio_queue_notify	0.694	vcpu
virtqueue_pop	2.560	vcpu
laio_submit	1.012	vcpu
laio_submit_done	16.313	vcpu
kvm_run_exit_io_done	0.923	vcpu
pre_kvm_run	0.273	vcpu
main_loop_wait_post_select	118.307	iothread
qemu_laio_completion_cb	0.410	iothread
qemu_laio_enqueue_completed	1.624	iothread
virtio_blk_rw_complete	0.318	iothread
virtio_notify	1.282	iothread
kvm_set_irq_level	0.269	iothread
kvm_set_irq_level_done	3.626	iothread
main_loop_wait_iohandlers_done	1.337	iothread

main_loop_wait_timers_done	0.741	iothread
main_loop_wait_exit	0.211	iothread

Measure	**Time (us)**
Virtqueue notify to completion interrupt time [aio=native]	147.611
Virtqueue notify to completion interrupt time [aio=threads, old QEMU binary]	159.628
seqread latency figure from guest	190.229
seqread latency figure from host	128.862

Observations:

- virtqueue_pop 2.560 us is expensive, probably due to vring accesses. RAM API would make this faster since vring could be permanently mapped.
- Overhead at QEMU level is still 147.611 / 128.862 = 14.5%.