Effective multi-threading in QEMU

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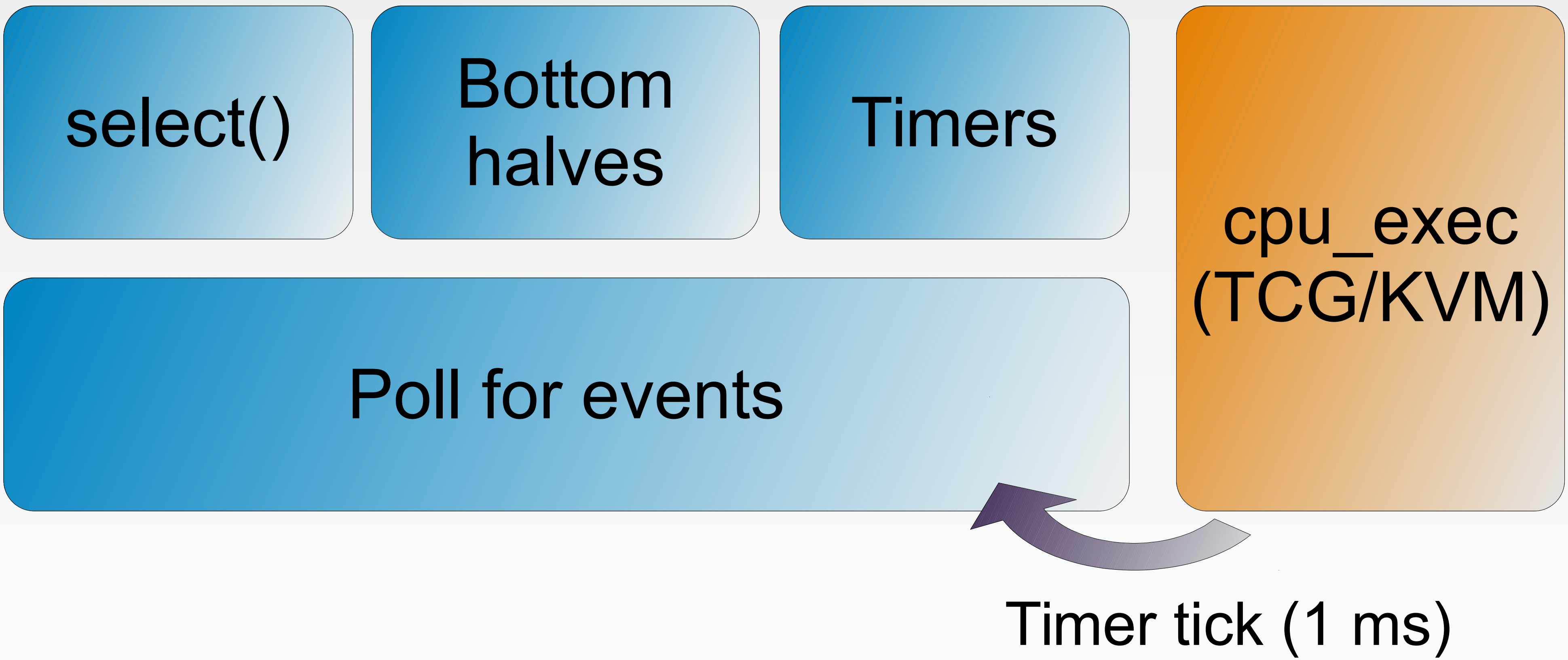
Why effective?

- Use well-known idioms and mechanisms
- Can be implemented in tiny steps
- Give some benefits *and* lay the groundwork for future improvements

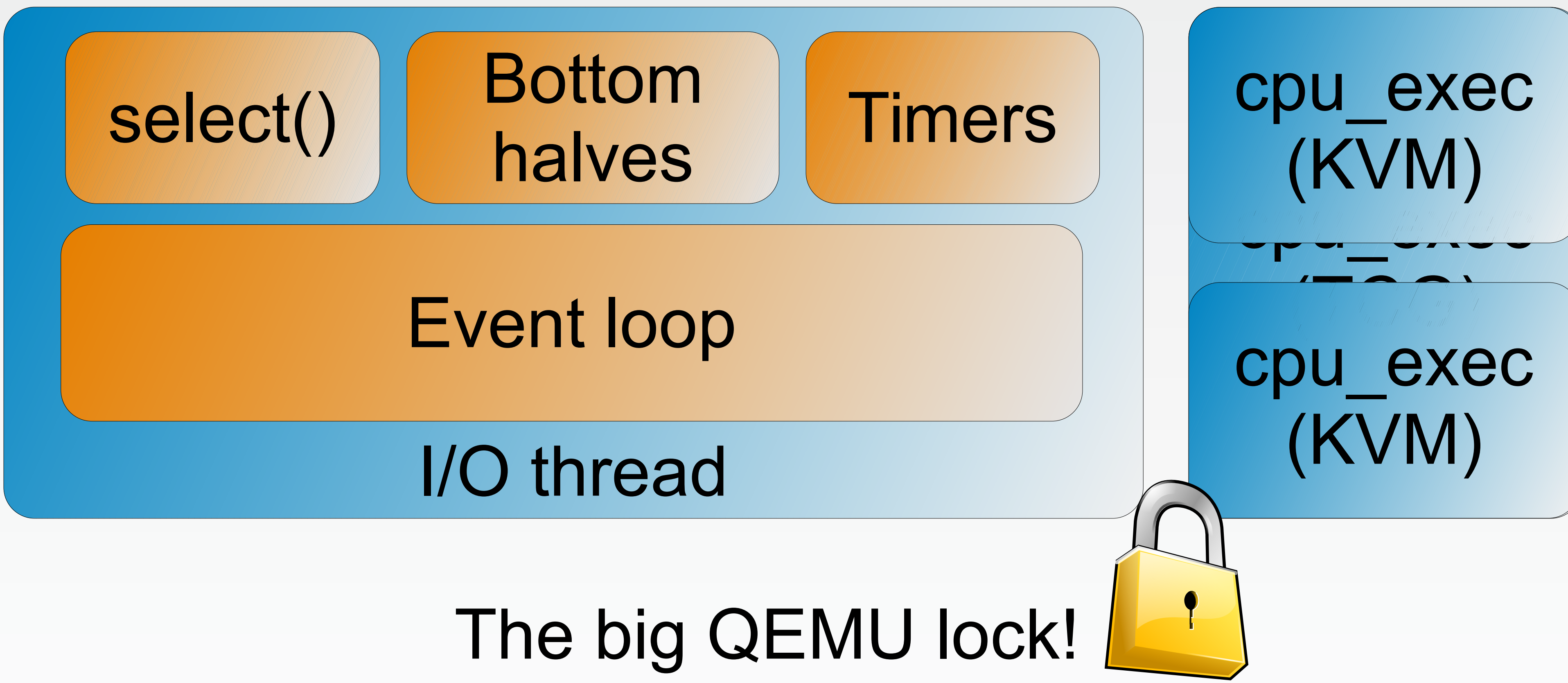
Outline

- QEMU architecture
- virtio-blk-dataplane architecture
- Unlocked memory dispatch
- Unlocked MMIO

QEMU architecture (up to 0.15)



QEMU architecture (1.0)

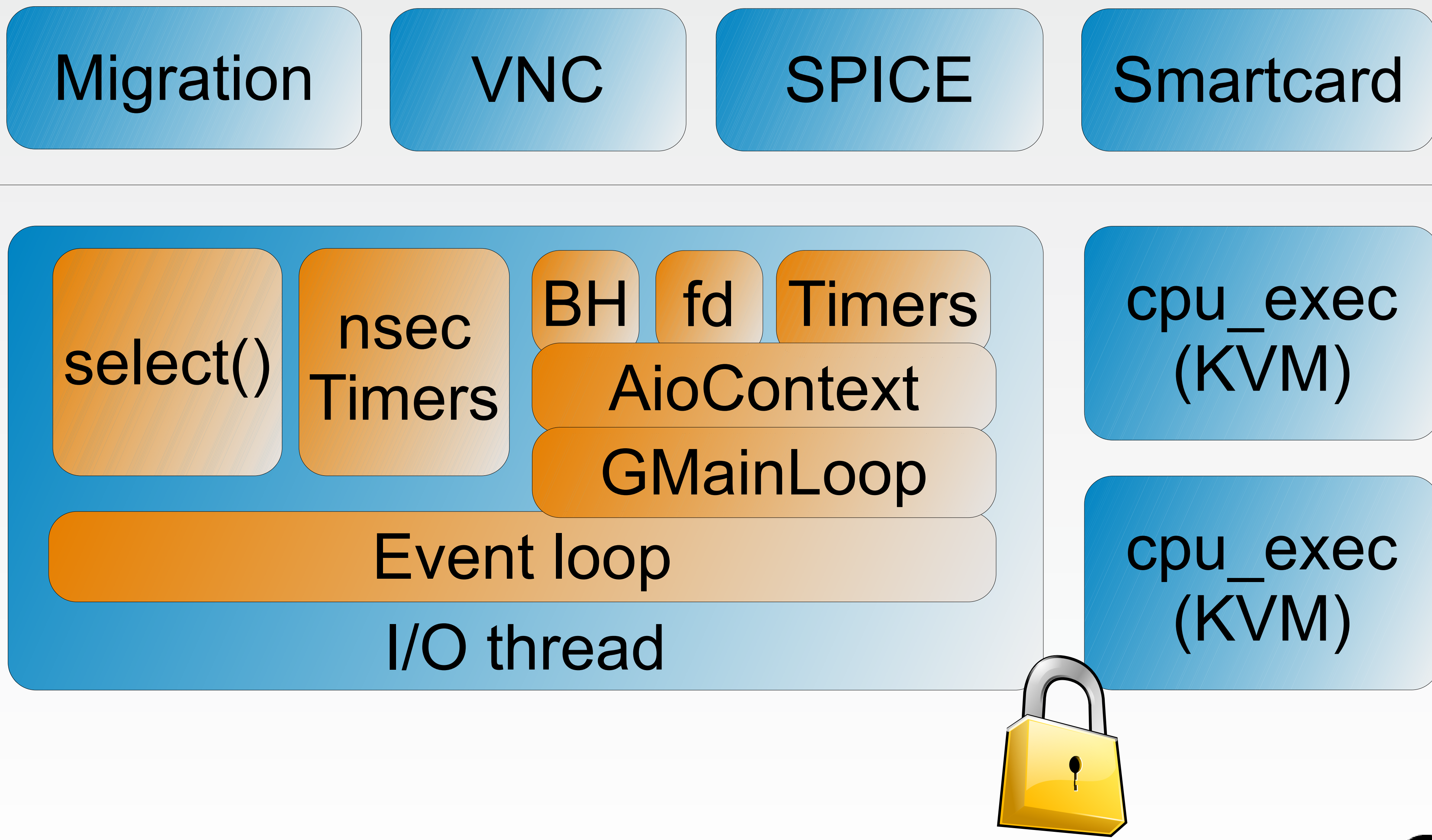


QEMU thread structure

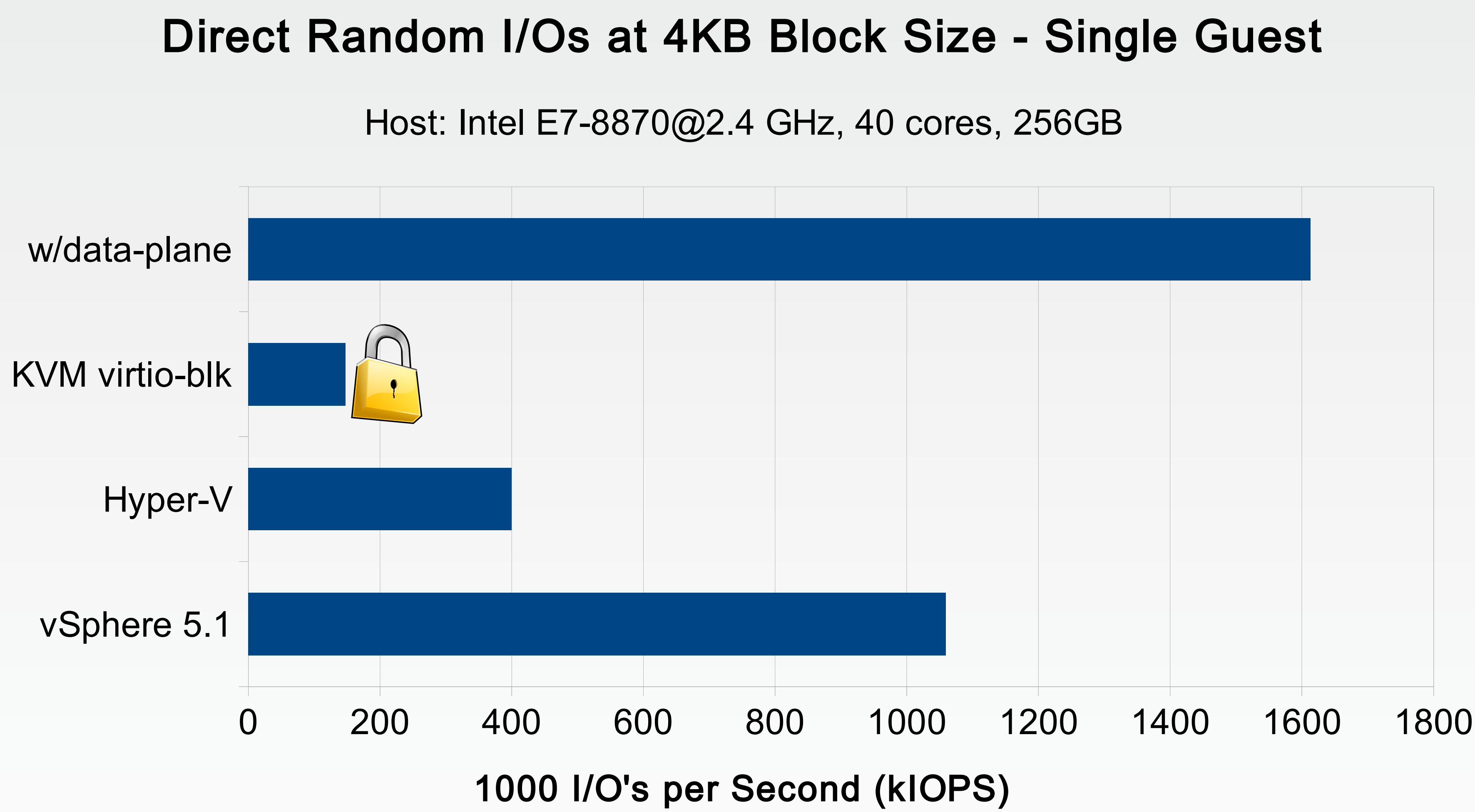
```
for (;;) {
   slirp_pollfds_fill();
   qemu_iohandler_fill();
   g_main_context_prepare();
   g_main_context_query();

   qemu_mutex_unlock_iothread();
   poll(...);
   qemu_mutex_lock_iothread();

   if (g_main_context_check()) {
      g_main_context_dispatch();
   }
   slirp_pollfds_poll();
   qemu_iohandler_poll();
}
```

```
for (;;) {
   kvm_arch_put_registers(cpu);
   kvm_arch_pre_run(cpu);


   qemu_mutex_unlock_iothread();
   kvm_vcpu_ioctl(cpu, KVM_RUN);
   qemu_mutex_lock_iothread();

   kvm_arch_post_run(cpu);
   switch(run->exit_reason) {
   case ...
   }

}
```

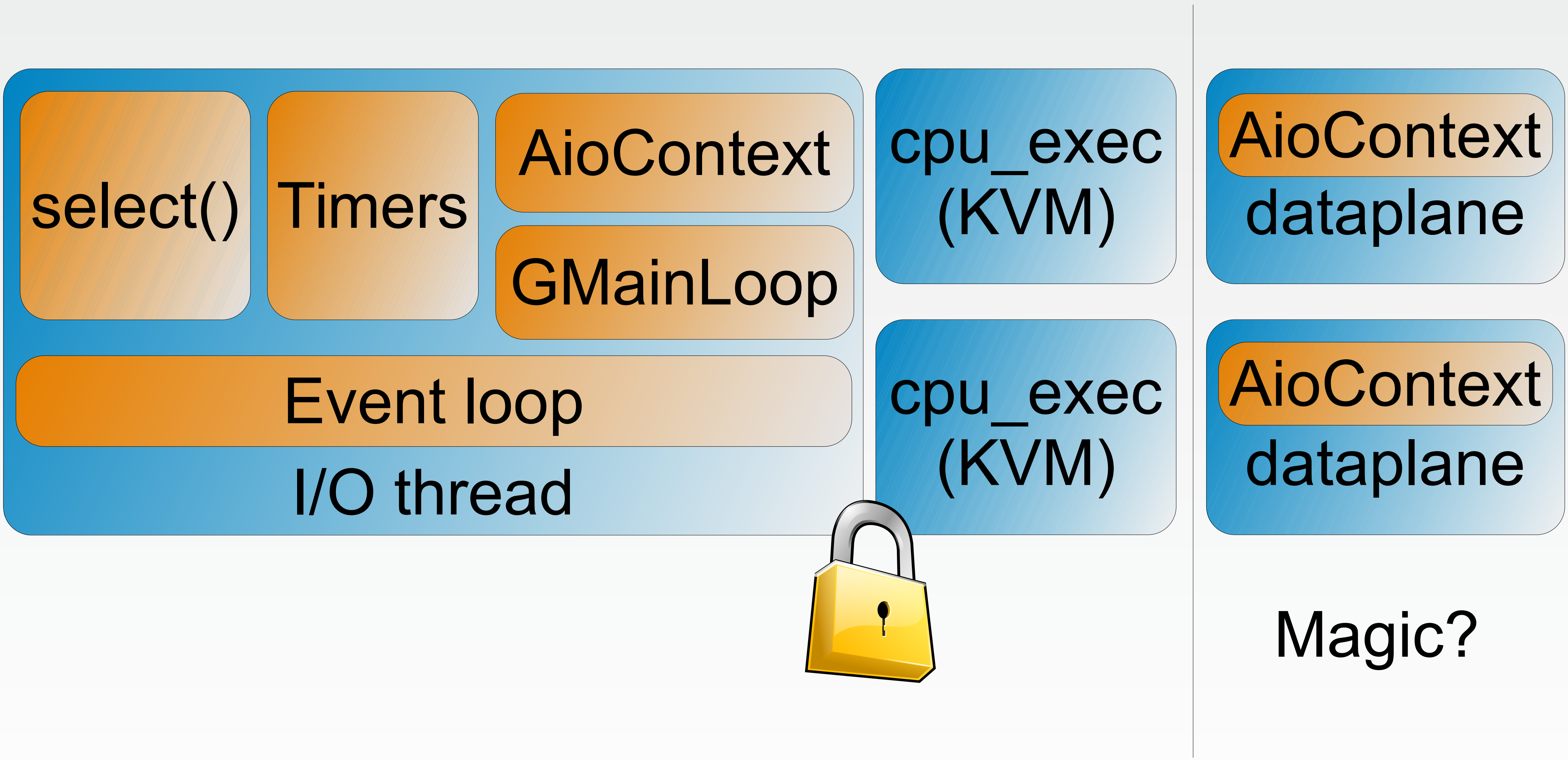
QEMU architecture (now)



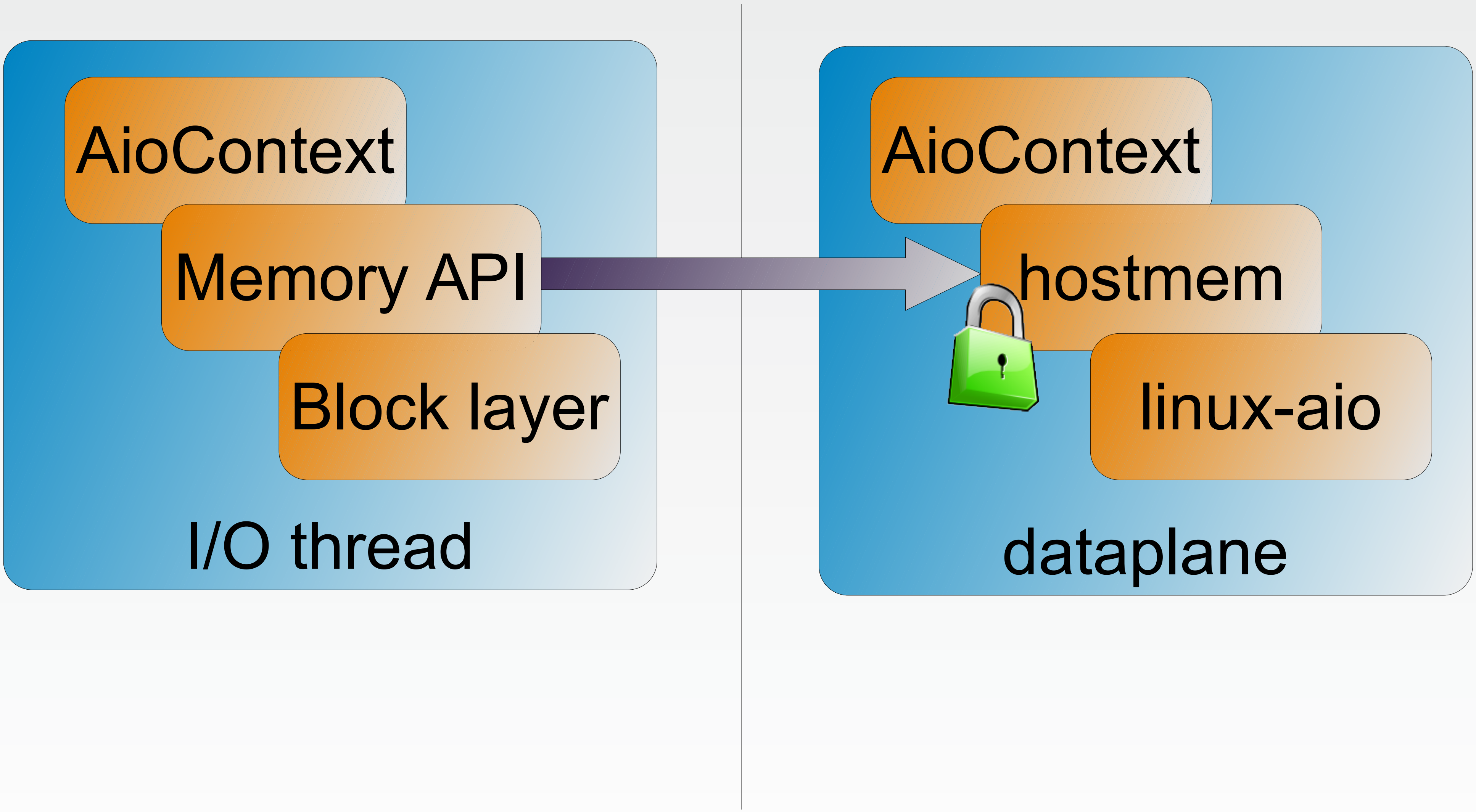
Enter virtio-blk-dataplane



Enter virtio-blk-dataplane



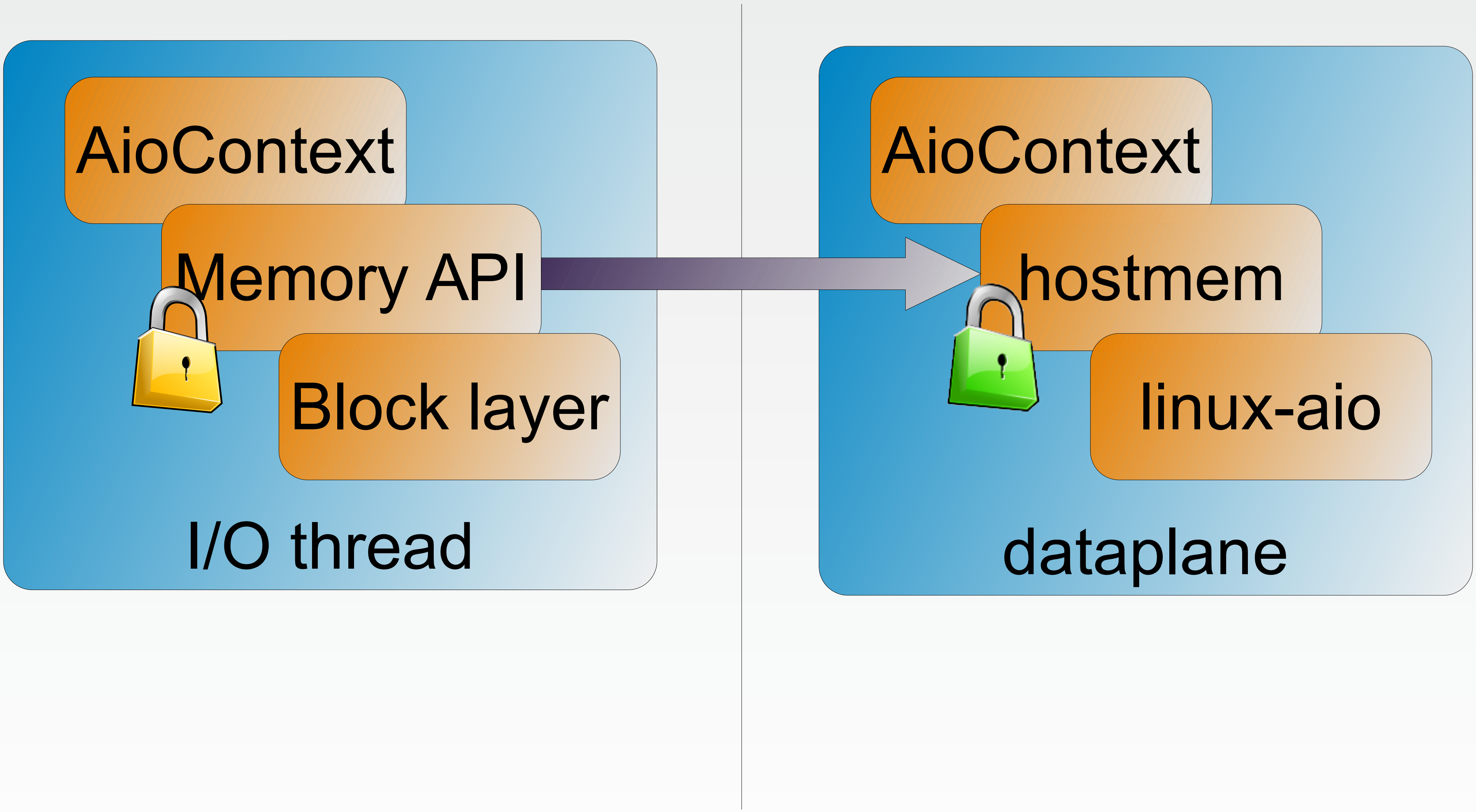
Dataplane architecture



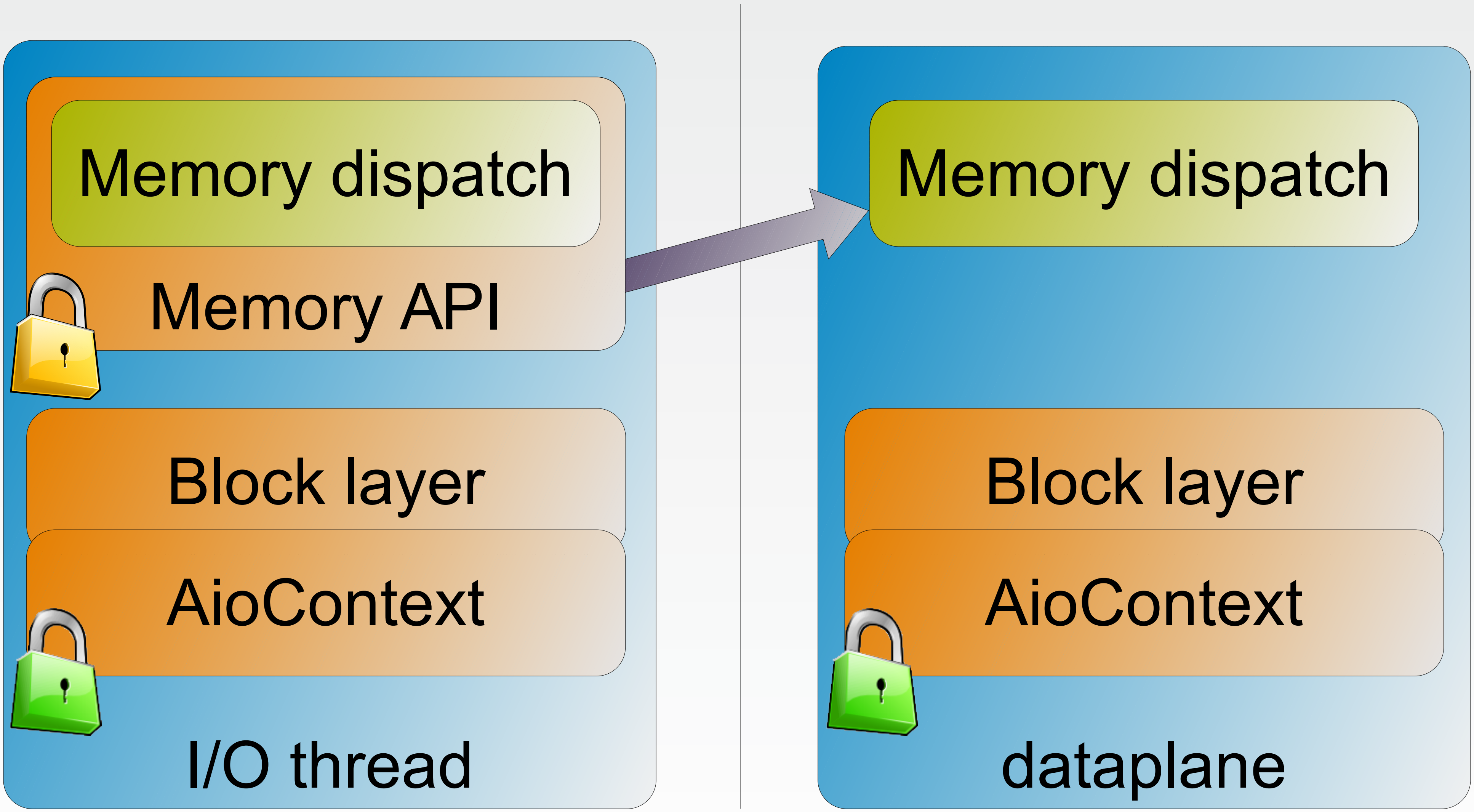
Lessons learned from dataplane

- Most of the time, the BQL is not a bottleneck
- Never take the BQL in “thread-centric” code
- Modularize existing code
  - Isolate data structures per thread
  - Avoid locks altogether
- Prototypes are great, but better have a plan

Dataplane architecture



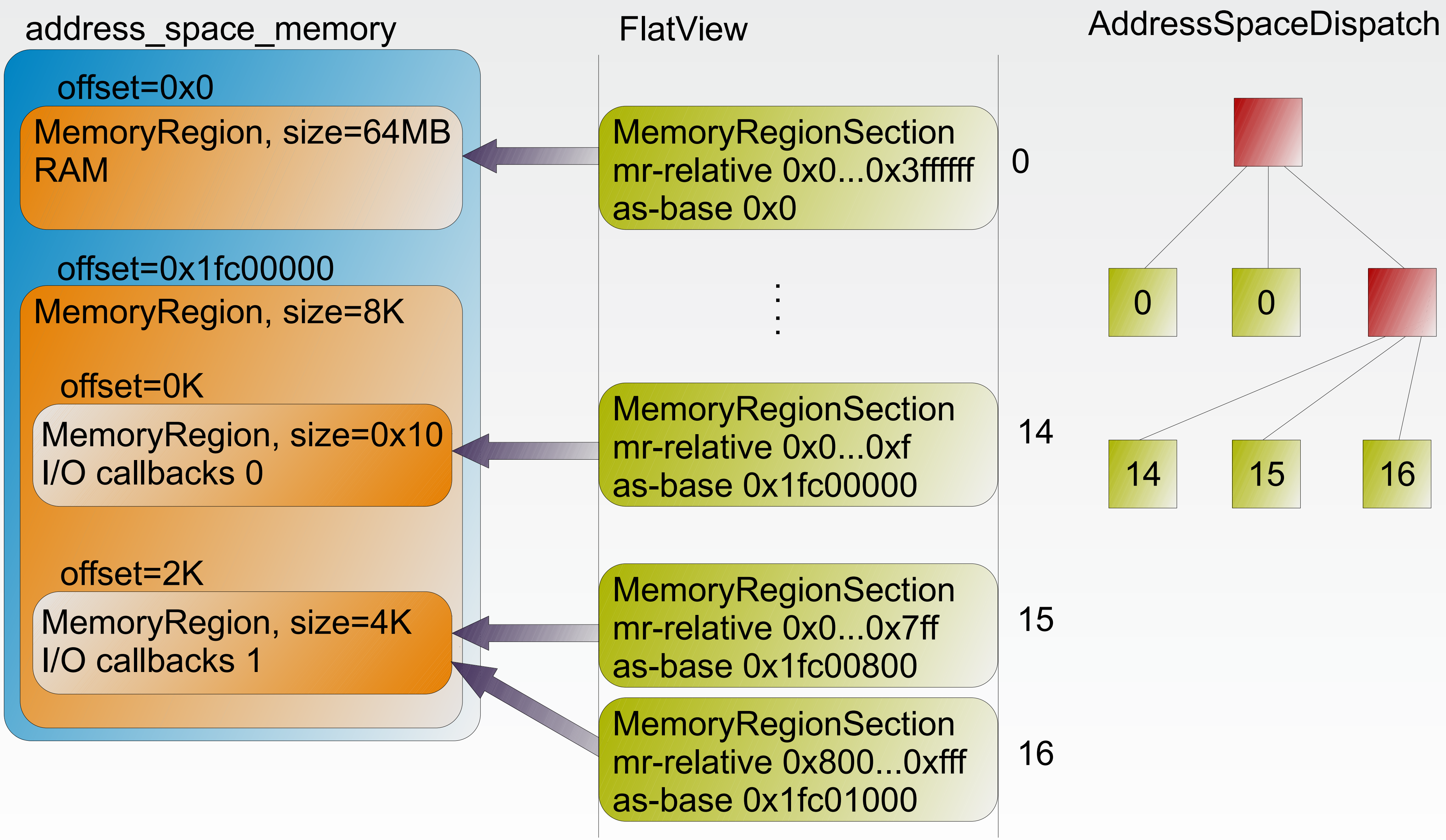
The plan


Memory dispatch
Memory API
Block layer
AioContext
I/O thread
Memory dispatch
Block layer
AioContext
dataplane

Lessons learned from dataplane

- Most of the time, the BQL is not a bottleneck
- Never take the BQL in “thread-centric” code
- Modularize existing code
- Prototypes are great, but better have a plan
- The BQL is going to stay for a long, long time

Memory API data structures



What's behind DMA?

address_space_map

- Visit radix tree
- If source is MMIO, call I/O read ops
- Return address of mapped memory

address_space_unmap

- Find MemoryRegion
- If source was MMIO, call I/O write ops
- If source was RAM, mark it as dirty

Dataplane (hostmem):

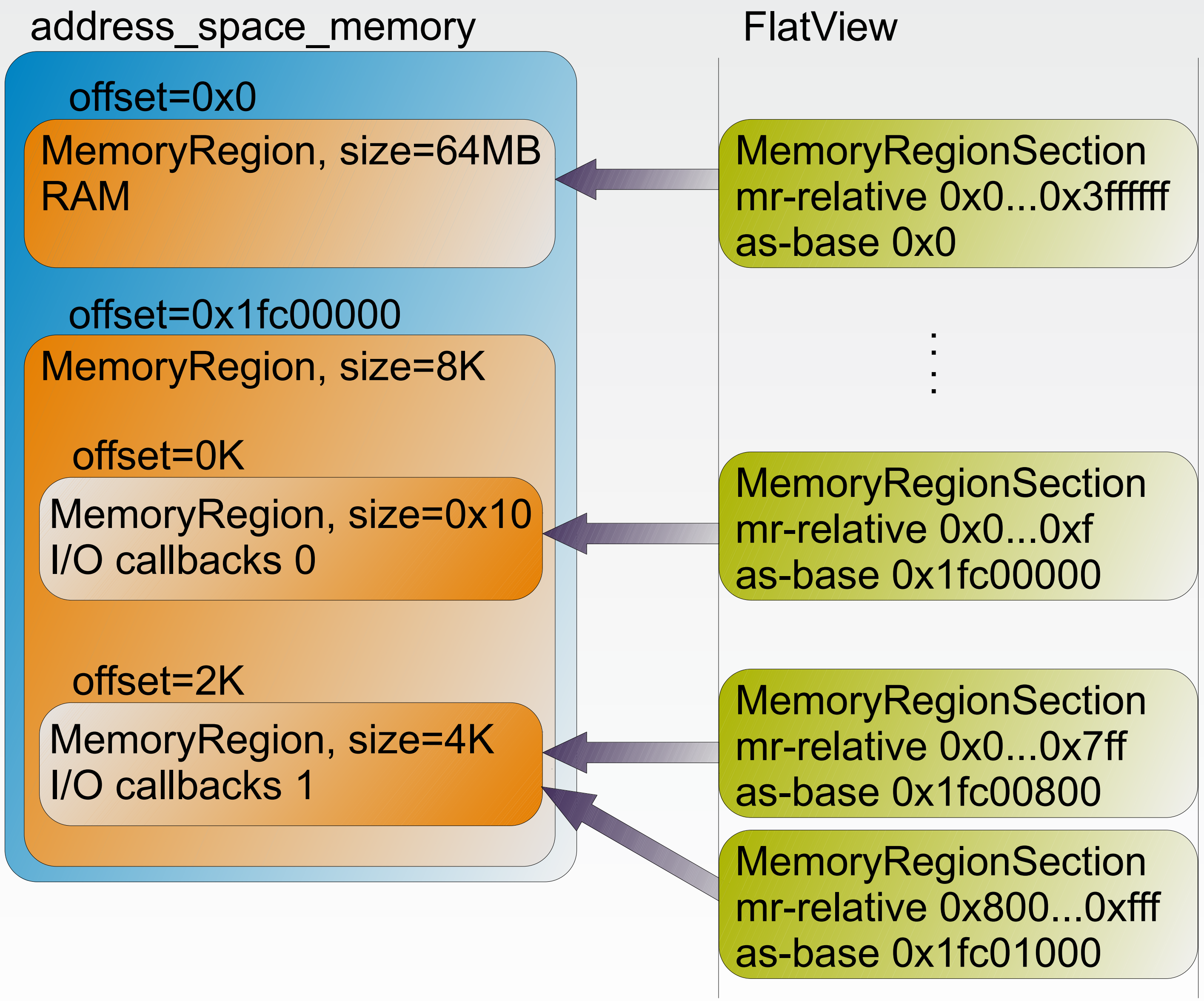
- Binary search list of RAM regions
- Return address

Dataplane (hostmem):

- Nothing :-)

  (Migration falls back to non-dataplane)

Memory API data structures



- Dataplane threads can use binary search on FlatView
- AddressSpaceDispatch is faster but not needed in the short term
- Still needed in the longer term for dirty bitmap/live migration

Immutable data structures

- Recreate FlatView from scratch on every update (cost: 1 extra malloc/free)
- Reference count FlatView, take reference while visiting

```
qemu_mutex_lock(&flat_view_mutex);
old_view = as->current_map;
as->current_map = new_view;
qemu_mutex_unlock(&flat_view_mutex);
flat_view_unref(old_view);
```

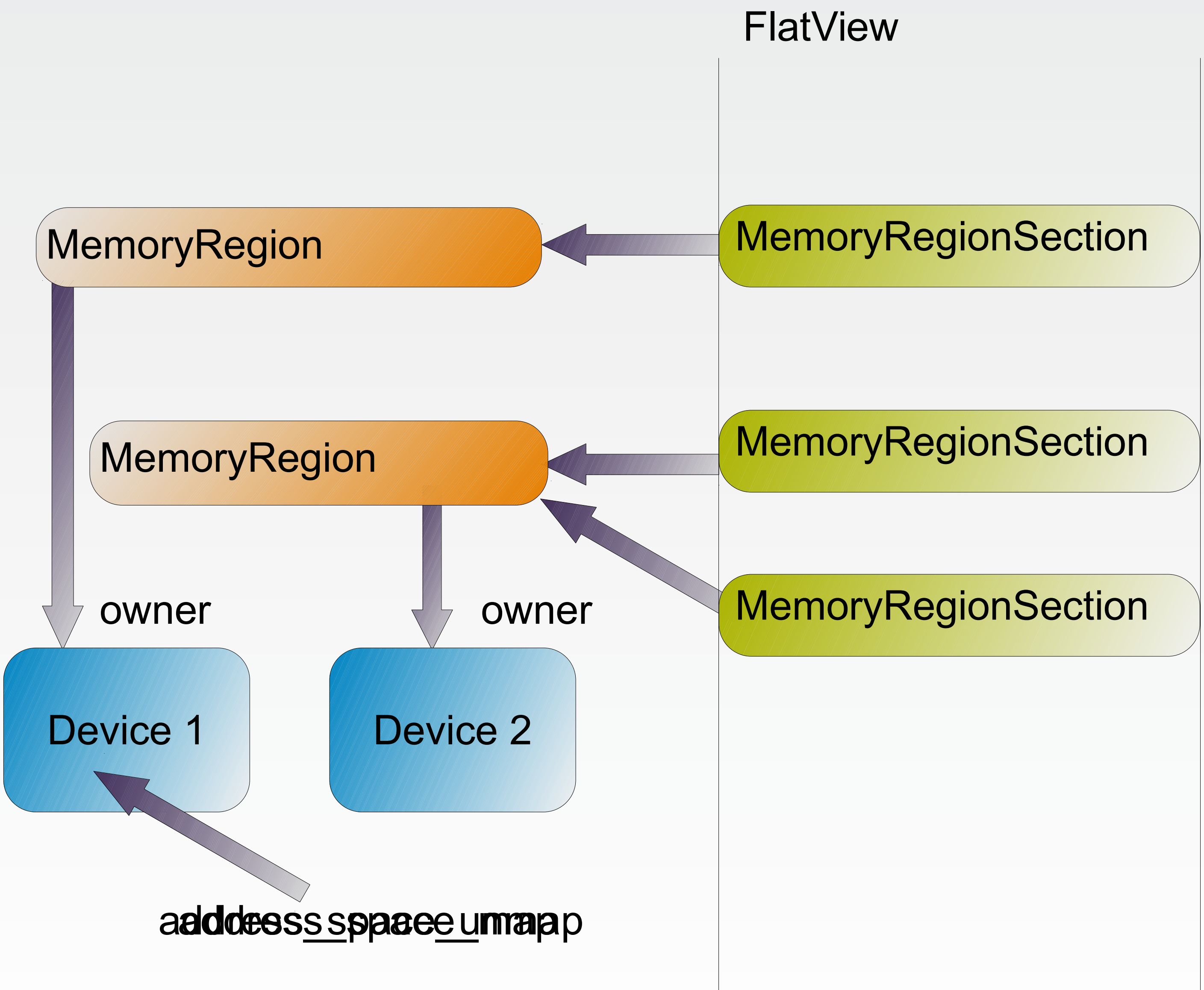
```
qemu_mutex_lock(&flat_view_mutex);
view = as->current_map;
flat_view_ref(view);
qemu_mutex_unlock(&flat_view_mutex);
...
flat_view_unref(view);
```

- Result: very small critical sections

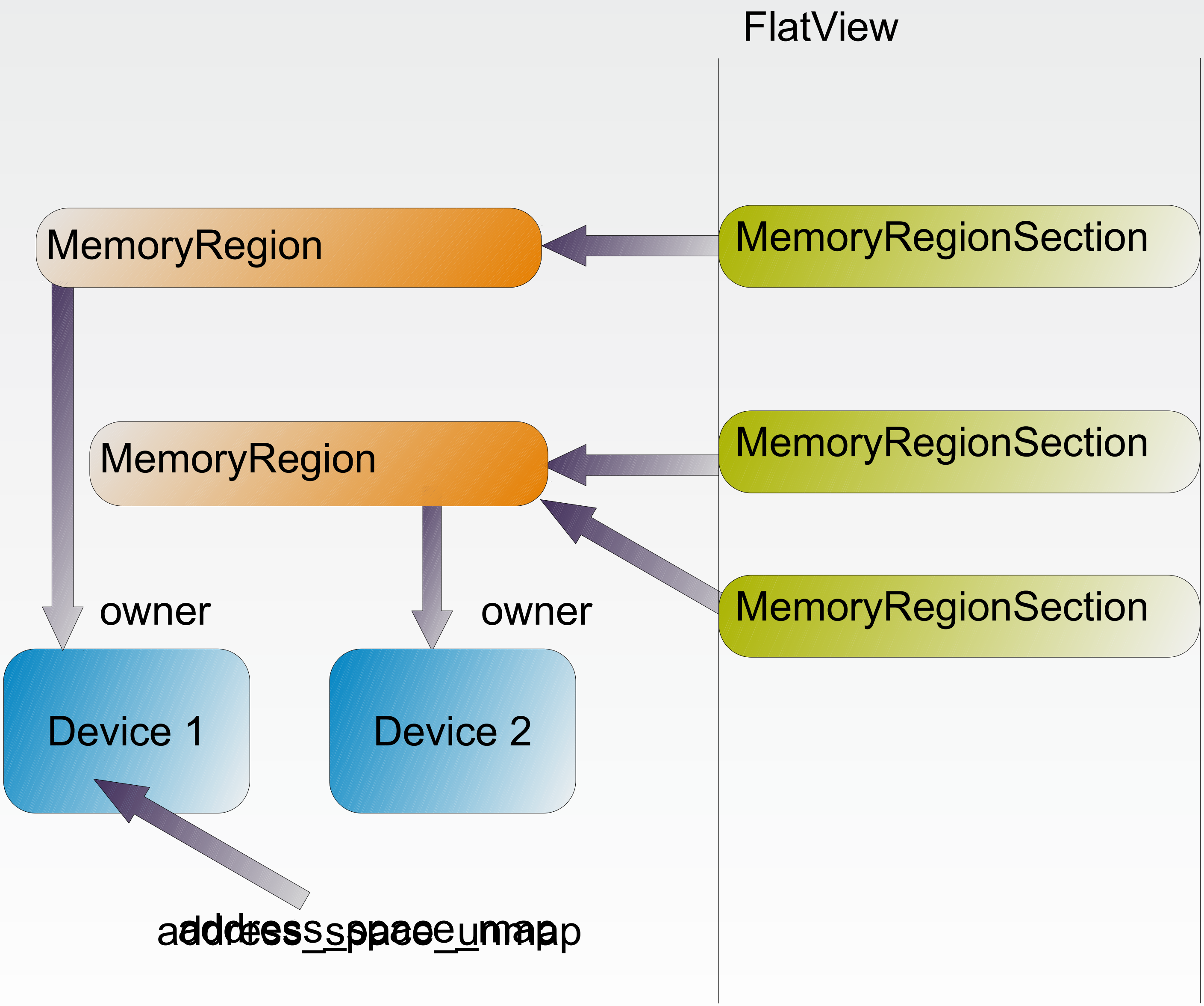
Extending reference counting

- Current memory API does not work well with hot-unplug
- If a device disappears while I/O is in progress:
  - MemoryRegions go away between address_space_map and address_space_unmap
  - QEMU can access dangling pointers
- Solution: add an *owner* to the MemoryRegion

Memory data structures lifetimes



Memory data structures lifetimes



Another problem: removal vs. reclamation

- Removal: remove references to data items within a data structure
- Reclamation: frees data items that are already removed from the data structure
- With reference counting, these two steps can happen at separate times
- QOM “unrealize” method currently does both!

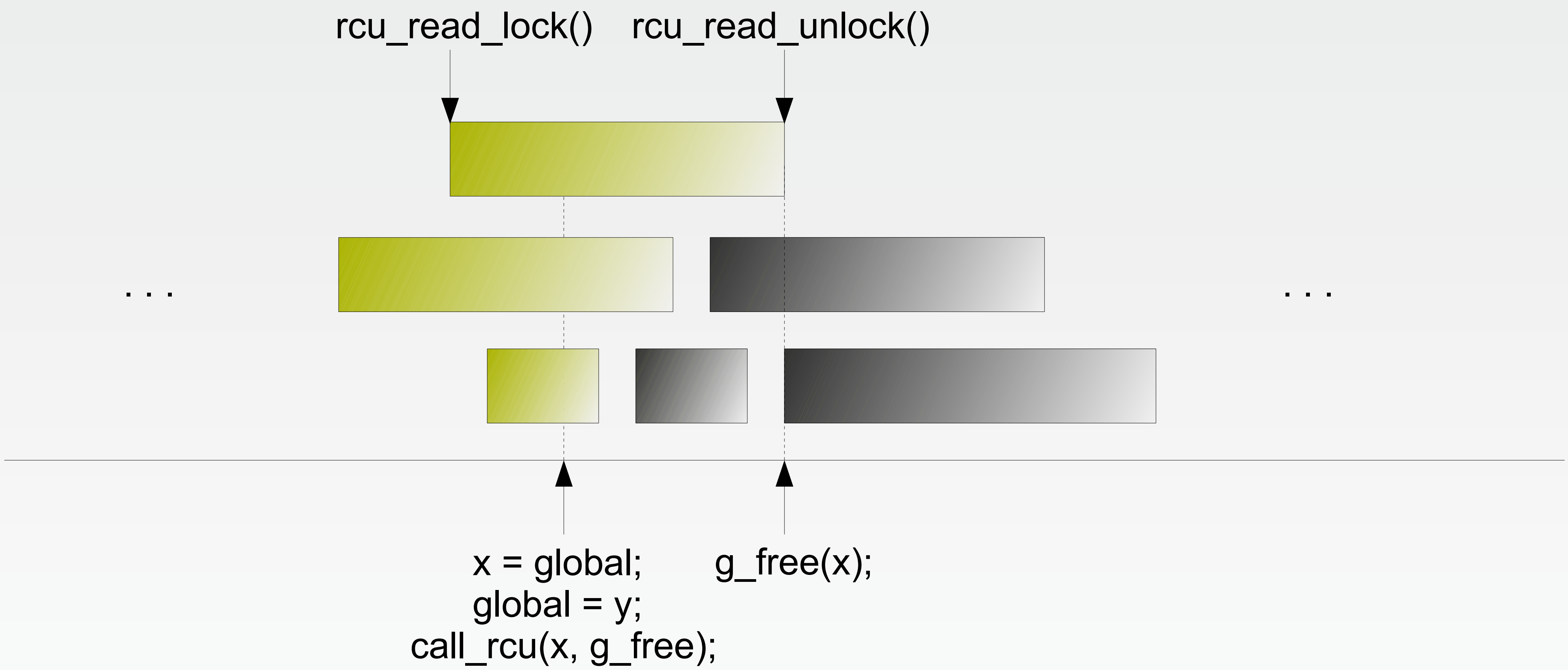
Separating removal and reclamation

- Removal: make device inaccessible from guest
  - memory_region_del_subregion
  - Corresponds to current “unrealize” time
- Reclamation: free the data items
  - memory_region_destroy
  - When last reference goes away (instance_finalize)
- Not just memory regions (e.g. NIC, block device, etc.)

From reference counting to RCU

- Immutable data structure are the basis of RCU (Read-Copy-Update) technique popular in Linux
- RCU runs removal concurrently with readers
- Reclamation only starts after readers no longer hold references

RCU basics



- RCU is a bulk reference-counting mechanism!

Why RCU?

- RCU avoids the need for fine-grained locking
  - The write side keeps using the BQL
  - Avoid reasoning about lock hierarchies
- RCU makes fast paths really fast
  - Little or no overhead on the read side
  - No need to take locks on hot TCG paths

Converting FlatView to RCU

```
qemu_mutex_lock(&flat_view_mutex);
old_view = as->current_map;
as->current_map = new_view;
qemu_mutex_unlock(&flat_view_mutex);
flat_view_unref(old_view);
```

```
old_view = as->current_map;
as->current_map = new_view;
call_rcu(old_view, flat_view_unref);
```

```
qemu_mutex_lock(&flat_view_mutex);
view = as->current_map;
flat_view_ref(view);
qemu_mutex_unlock(&flat_view_mutex);
...
flat_view_unref(view);
```

```
rcu_read_lock();
view = as->current_map;
flat_view_ref(view);
rcu_read_unlock();
...
flat_view_unref(view);
```

- The same technique can be applied to AddressSpaceDispatch

Implementation state

- MemoryRegion ownership: done
- Separate locking for FlatView: done
- Removing hostmem: patches posted
- RCU for FlatView: patches ready
- RCU for AddressSpaceDispatch: TCG?
- Lock-free address_space_rw/map/unmap: Missing dirty bitmap handling

A real-world trace

ACPI PM Timer

```
9439.144536: kvm_entry: vcpu 5
9439.144540: kvm_pio: pio_read at 0xb008 size 4 count 1
9439.144541: kvm_userspace_exit: reason KVM_EXIT_IO (2)
9439.144566: kvm_entry: vcpu 21
9439.144571: kvm_pio: pio_read at 0xb008 size 4 count 1
9439.144572: kvm_userspace_exit: reason KVM_EXIT_IO (2)
9439.144581: kvm_entry: vcpu 12
9439.144585: kvm_pio: pio_read at 0xb008 size 4 count 1
9439.144586: kvm_userspace_exit: reason KVM_EXIT_IO (2)
9439.144597: kvm_entry: vcpu 5
9439.144602: kvm_pio: pio_read at 0xb008 size 4 count 1
9439.144603: kvm_userspace_exit: reason KVM_EXIT_IO (2)
```

```
- 64.69%    _raw_spin_lock
  - 48.06%  futex_wait_setup
    - 99.32% [qemu-system-x86_64] __lll_lock_wait
  - 44.71%  futex_wake
    - 99.33% [qemu-system-x86_64] __lll_unlock_wake
```

The next step: lock-free MMIO/PIO?

```
for (;;) {
    kvm_arch_put_registers(cpu);
    kvm_arch_pre_run(cpu);

    kvm_vcpu_ioctl(cpu, KVM_RUN);

    kvm_arch_post_run(cpu);
    switch(run->exit_reason) {
    case KVM_EXIT_IO:
        address_space_rw(...);
        break;

    case KVM_EXIT_SHUTDOWN:
        qemu_mutex_lock_iothread();
        ...
        qemu_mutex_unlock_iothread();
        break;
    }
}
```

Q: Is it valid?

PCI in a nutshell

- PCI is a bus where you have reads and writes, interrupts are raised, etc.
- PCIe is a packet network that fakes the same
- PCIe packets go from the CPU to the devices and back
- Packets can be reordered only in limited ways

PCIe packets

- Packet types
  - Read
  - Read completion
  - Write to memory, including MSI
  - I/O or configuration write
  - I/O or configuration write completion
- Reordering packets must obey rules in the PCIe spec

Q: What kind of reordering would QEMU apply with unlocked MMIO?

A: For each CPU, everything is serialized

Multiple CPUs will not observe incorrect reordering *if accesses are atomic*

Atomicity (try 1)

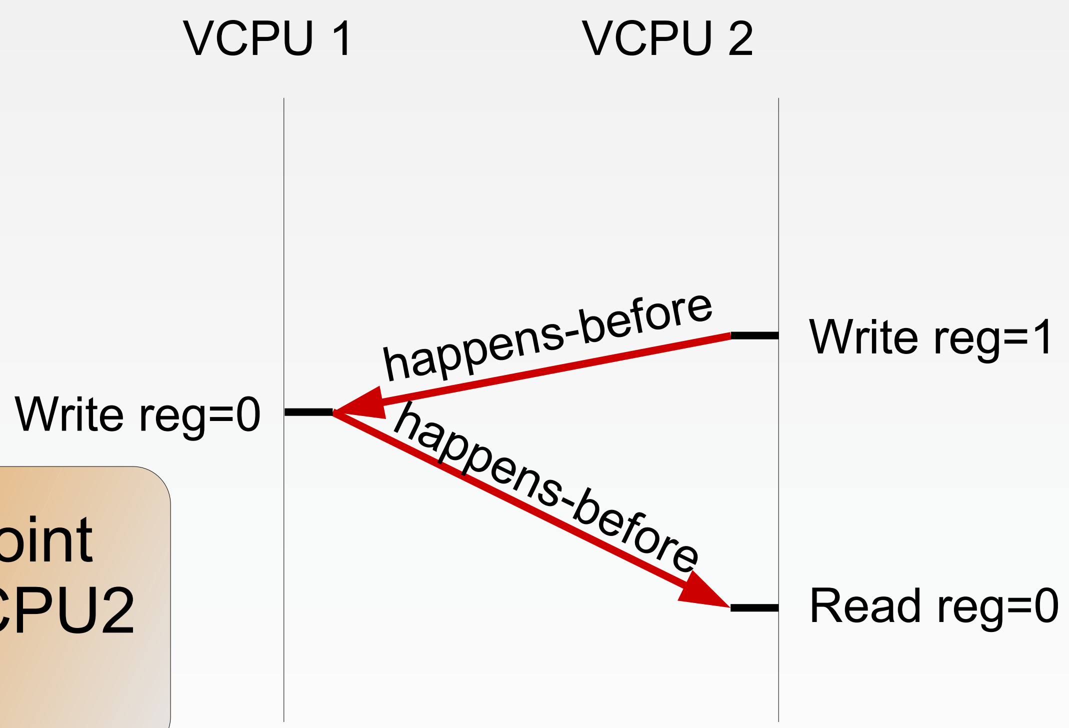
- An operation is *atomic* if it appears to the rest of the system to occur instantaneously.

Atomicity (try 2)

- All operations should have a *linearization point*
- All operations appear to occur instantly at their linearization point
- Linearizability == atomicity!

Observing atomic operations

- Causal relationships (“happens-before”) let an observer order the linearization points



Linearization point must be after VCPU2 writes 1!

Is MMIO linearizable?

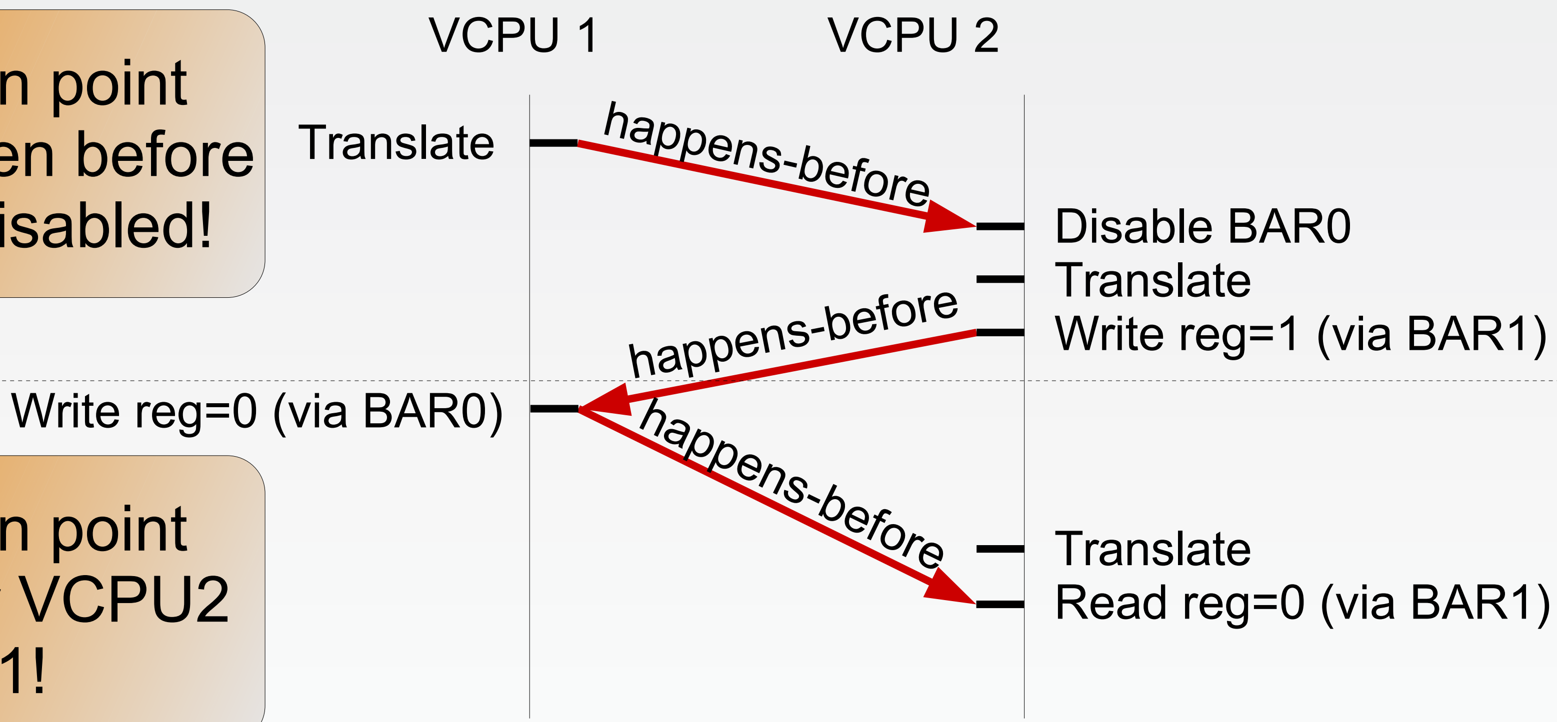
```
mr = address_space_translate(as, addr, &addr, &len, true);
memory_region_dispatch_write(mr, addr, val, 4);

mr = address_space_translate(as, addr, &addr, &len, false);
memory_region_dispatch_read(mr, addr, &val, 4);
```

- No locks taken: assume I/O callbacks are atomic and have their own linearization point
- address_space_translate's linearization point is where it fetches the AddressSpaceDispatch
- If the memory map is static, we can ignore it
- Otherwise, two linearization points are already one too many

Example

- Same register visible from two different BARs

Linearization point must have been before BAR0 was disabled!



Linearization point must be after VCPU2 writes 1!

- Contradiction: access not atomic!

(But we already get it wrong)

- Concurrency happens even with the BQL!
  - The BQL is released between address_space_map and address_space_unmap
- A translation returned by address_space_map can be used arbitrarily far in the future
- Example
  - address_space_map returns RAM address
  - bus-master DMA is disabled before unmap
  - Writes should be forbidden, but they happen!

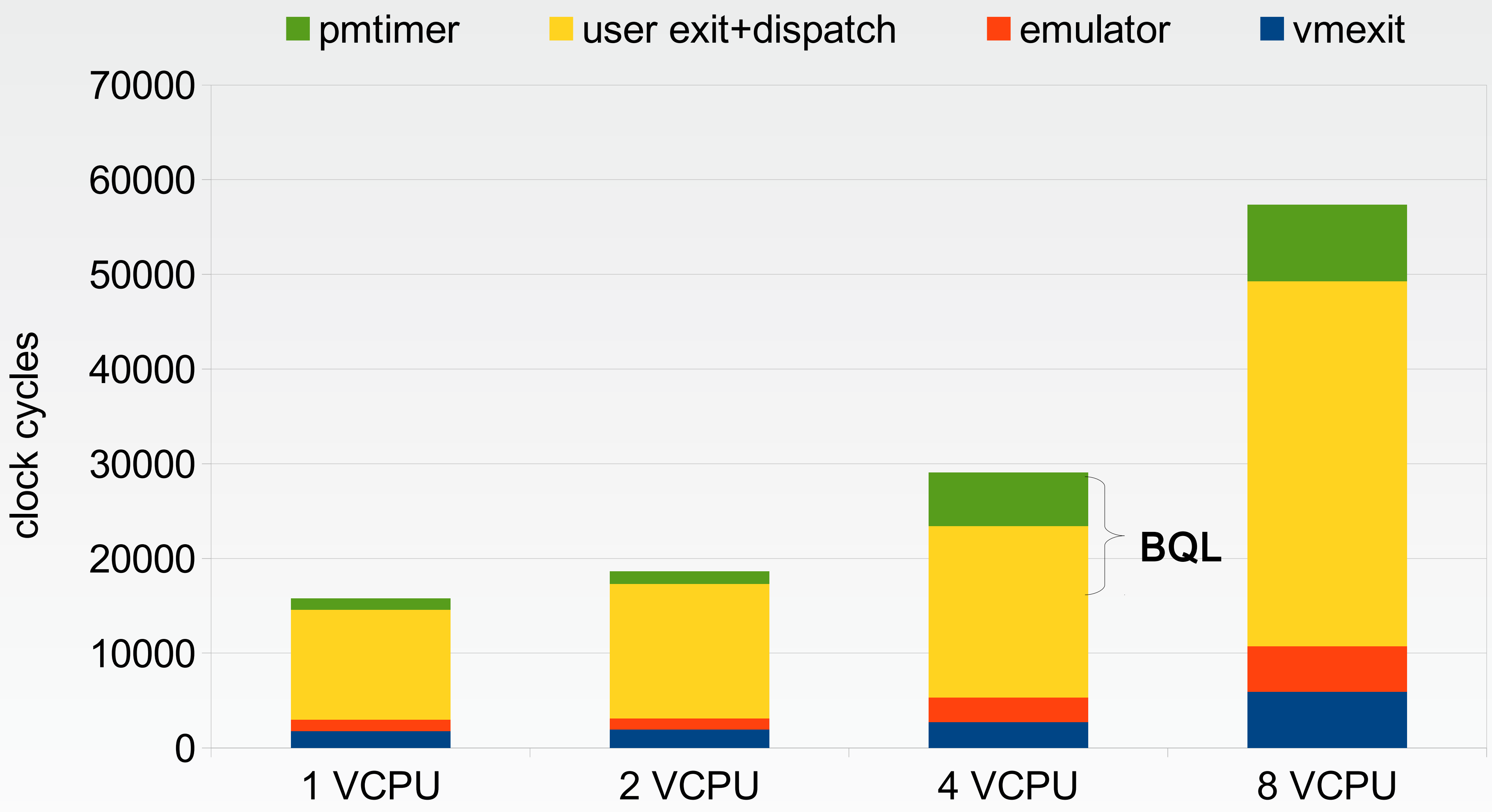
So, does it matter?

- “Unlocked” MMIO/PIO is opt-in behavior
  - Use it for paravirtual devices
  - Use it for devices with a static memory map
- Double-checked locking
  - Take fine-grained lock, check as->dispatch didn't change; if it did, release lock and retry dispatch
  - Prevents fully BQL-free MMIO/PIO
- OSes quiesce devices before disabling DMA
- Answer: no

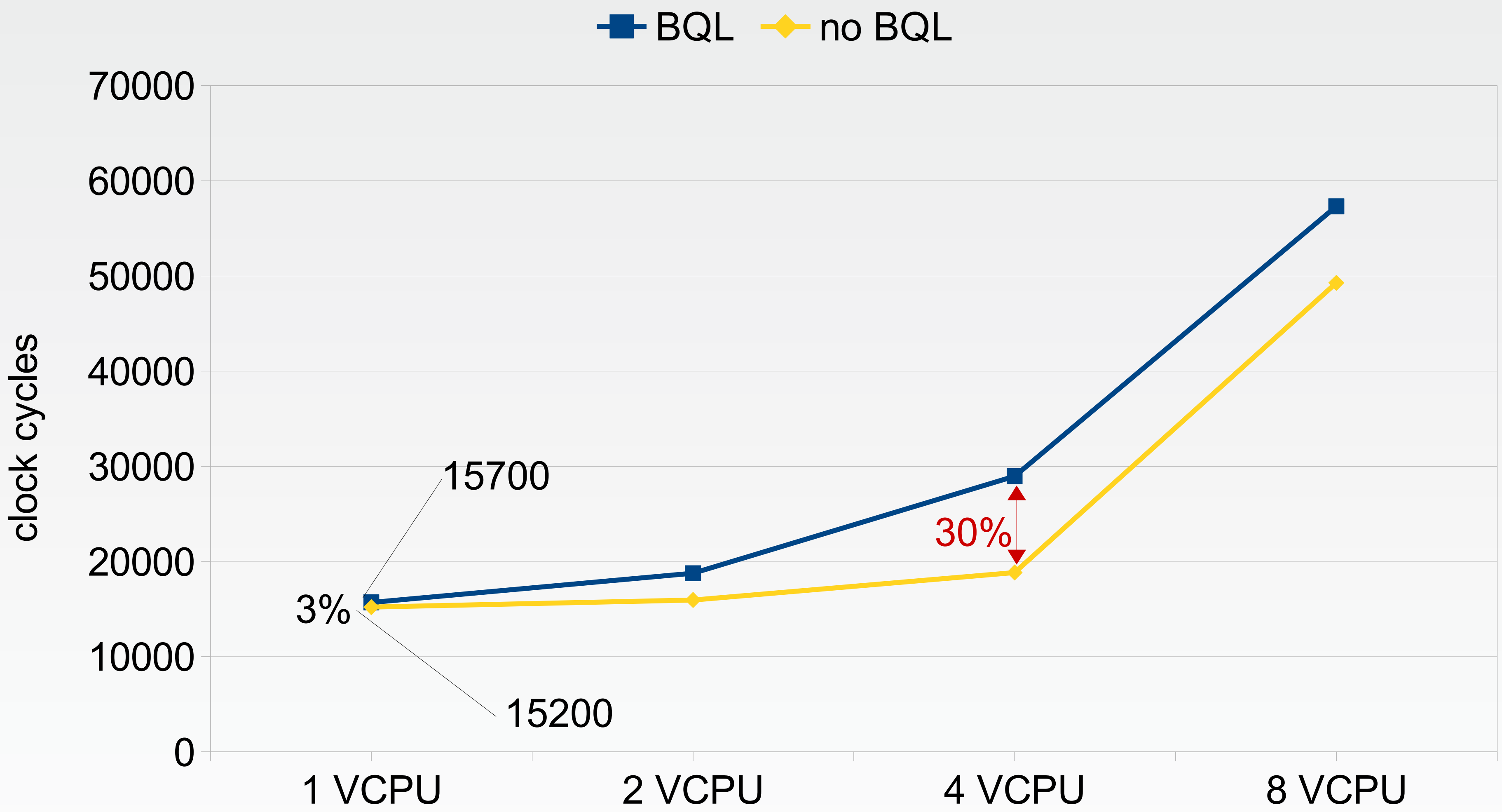
Experiments

- Microbenchmark using kvm-unit-tests
- Measure cost of accessing PM timer concurrently from multiple VCPUs
- Ivy Bridge processor with 4 CPUs
- Thanks to Jan Kiszka for the patches

MMIO cost breakdown (ACPI PM timer)



Effect of removing the BQL (ACPI PM timer)



What's next?

- Upstream patches
  - Unrealize vs. instance_finalize
  - RCU
  - Unlocked I/O
- Complete switch of virtio-blk-dataplane to block layer
- Make dirty bitmap access atomic
- ... Fine-grained locking for TCG? (2014?)

Questions?

Atomic operations API – C++11 vs. QEMU

- atomic_read(p) / atomic_set(p,v) →
  atomic_load(p,relaxed) / atomic_store(p,v,relaxed)
- atomic_mb_read(p) / atomic_mb_set(p,v) →
  atomic_load(p,seq_cst) / atomic_store(p,v,seq_cst)
- smp_mb() / smp_rmb() / smp_wmb() →
  atomic_thread_fence(seq_cst/acquire/release)
- atomic_fetch_add/sub/and/or(p,v) →
  atomic_fetch_add/sub/and(p,v,seq_cst)
- atomic_cmpxchg(p, old, new) →
  atomic_compare_exchange_strong(p,old,new)

RCU API – Linux vs. QEMU

- Threads need to report quiescent states
  - rcu_quiescent_state()
  - rcu_thread_offline()/rcu_thread_online()
  - Not needed for threads that use semaphores or condition variables
- rcu_dereference(p)➡atomic_rcu_read(&p)
- rcu_assign_pointer(p,v)➡atomic_rcu_set(&p,v)