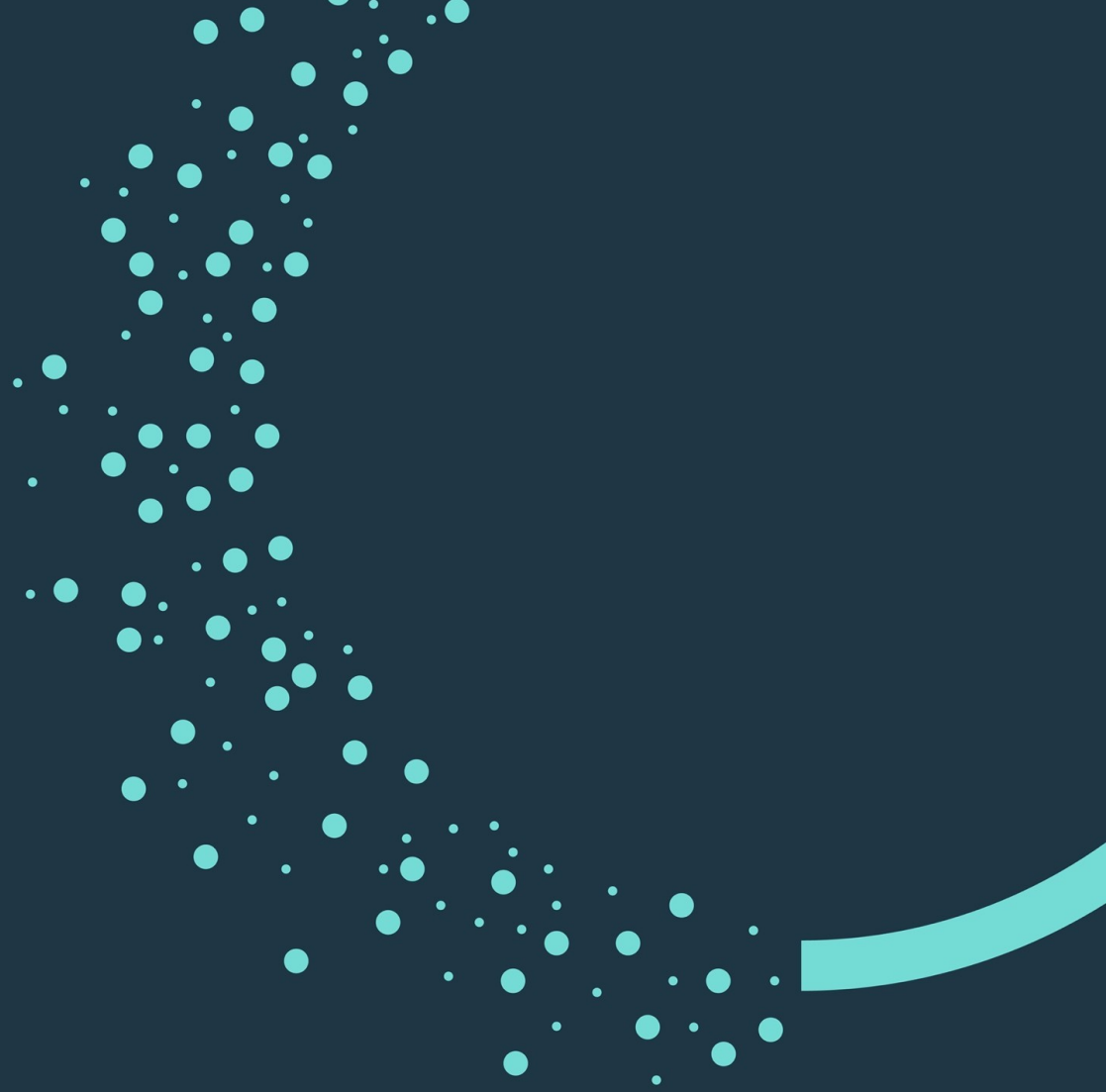

seL4 VMs with virtio à la KVM/QEMU

Hannu Lyytinen, Markku Ahvenjärvi
seL4 summit 2022 – Munich, Germany

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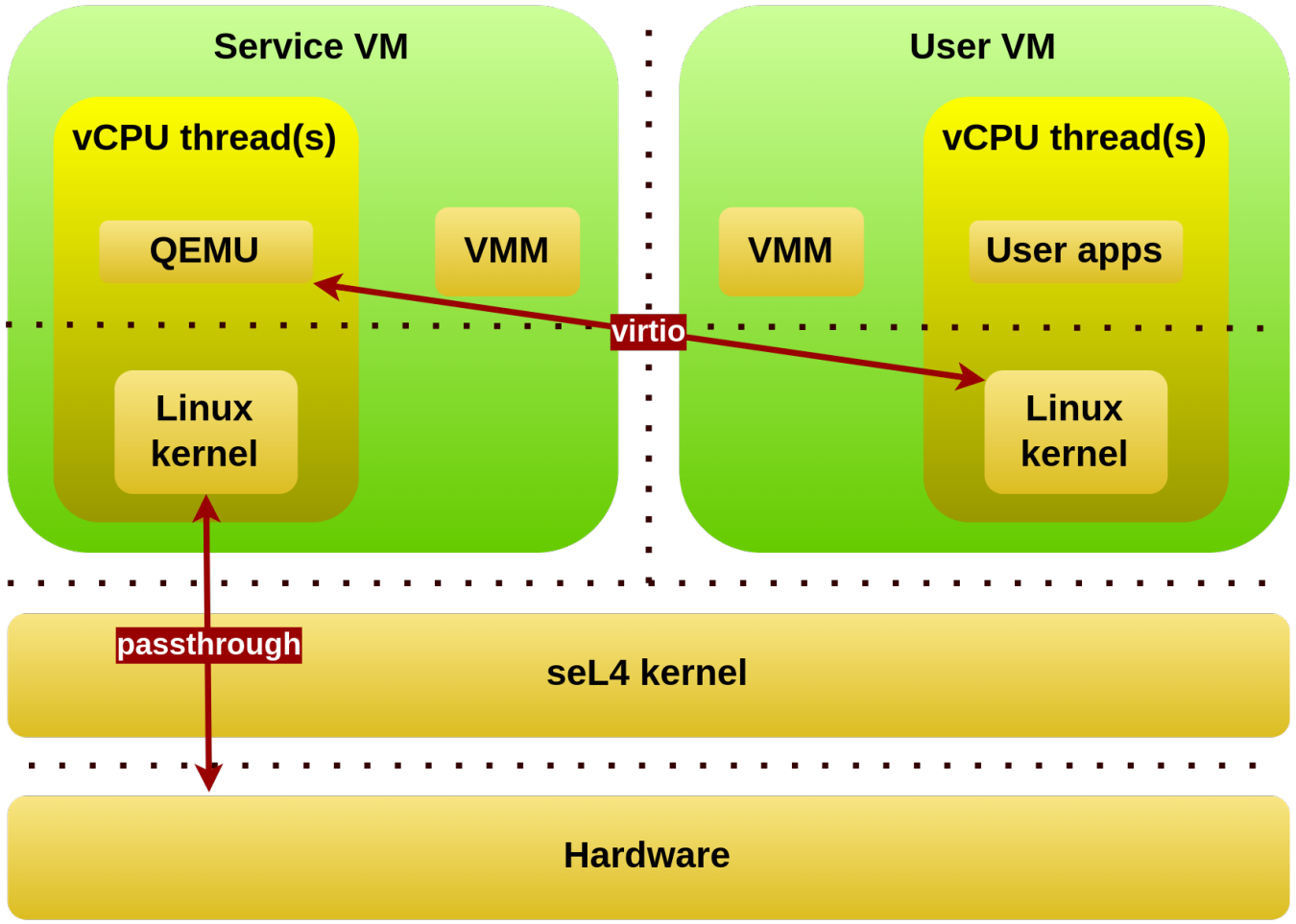
Why?

- Internal virtualization projects which use KVM
- Type-1 hypervisor better, no huge TCB
- Could we replace KVM with seL4?
- How to bring QEMU's (KVM's "little helper") virtio to seL4?
- Could we use CrosVM instead of QEMU (virtio-wayland)?

Our seL4 idea



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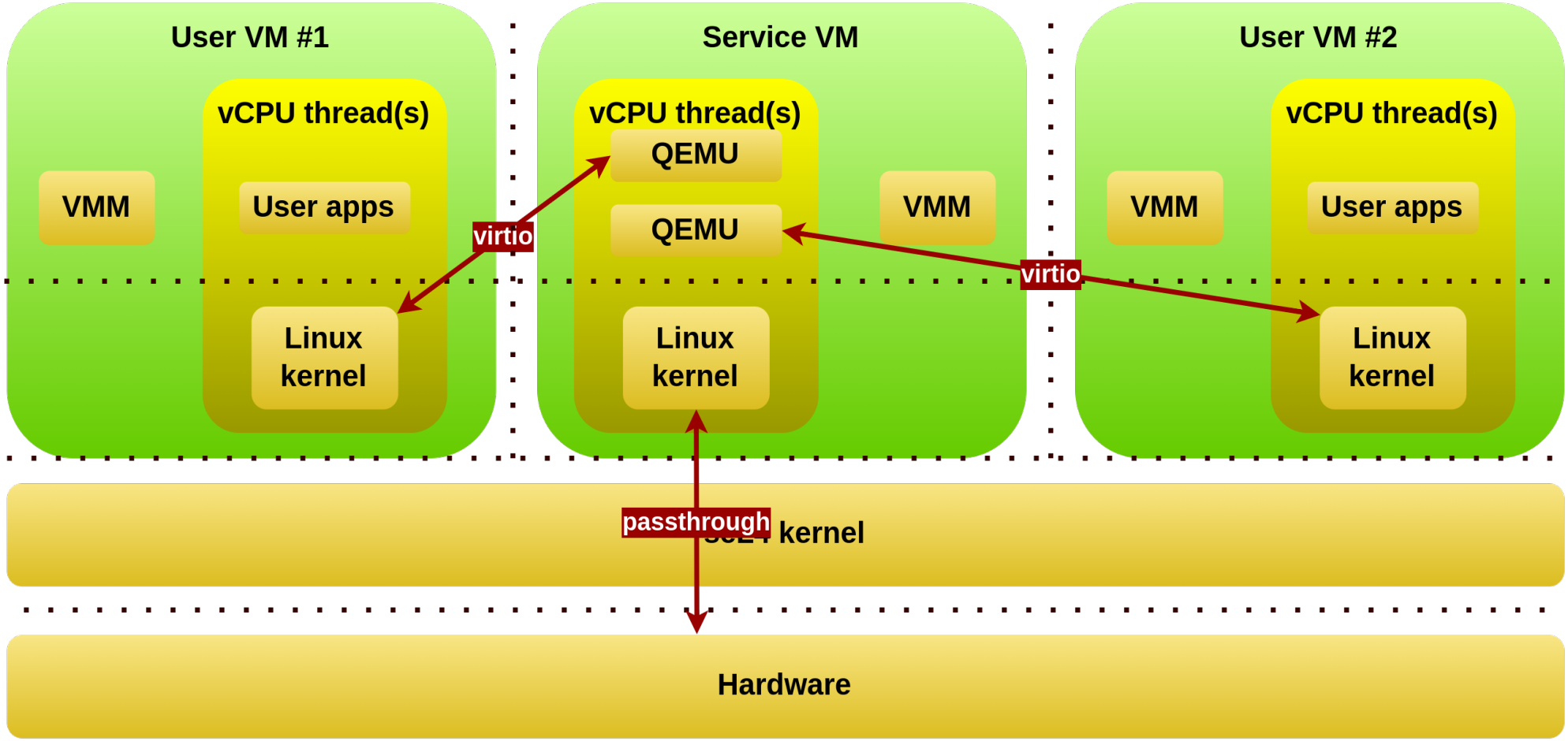
Our seL4 idea



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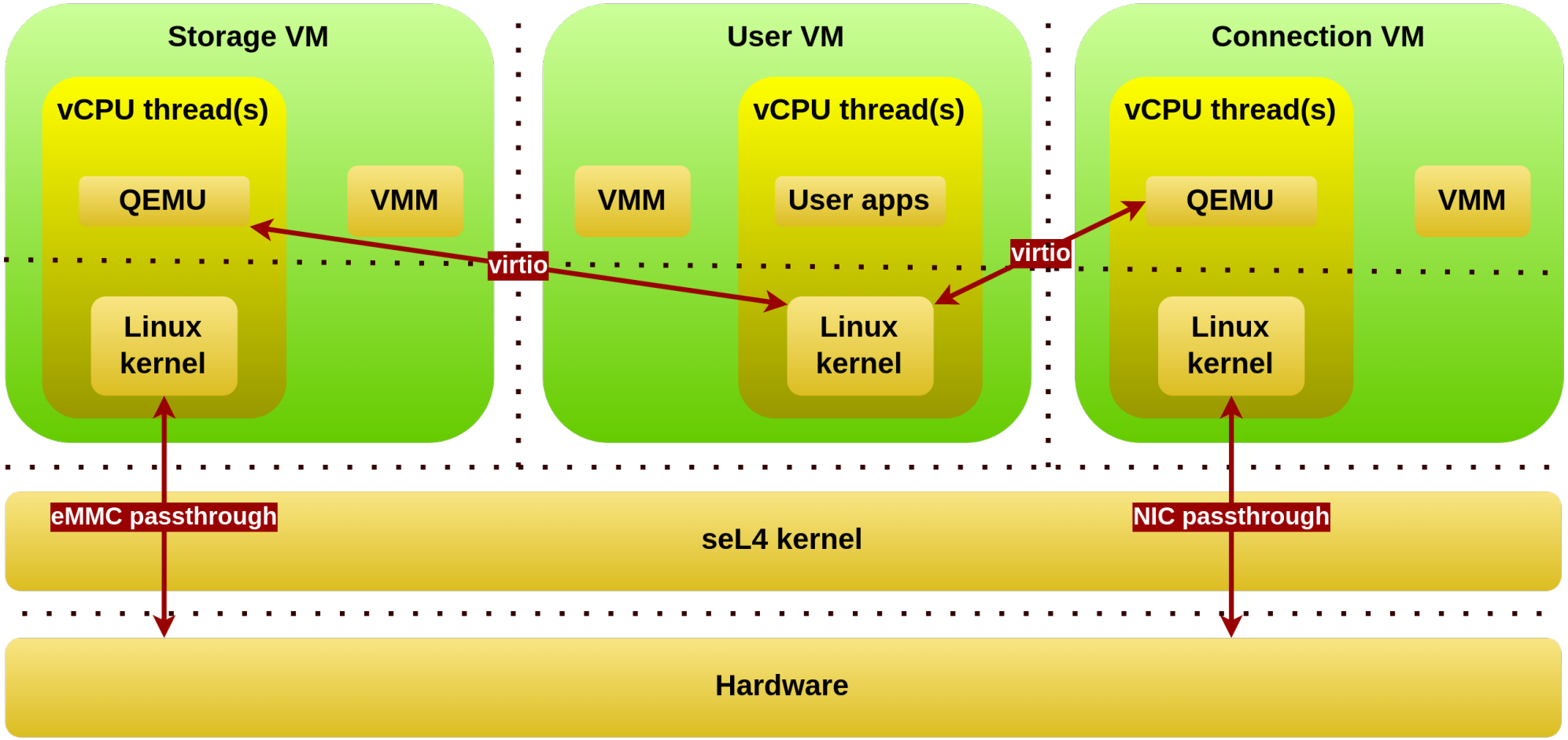
Multihost



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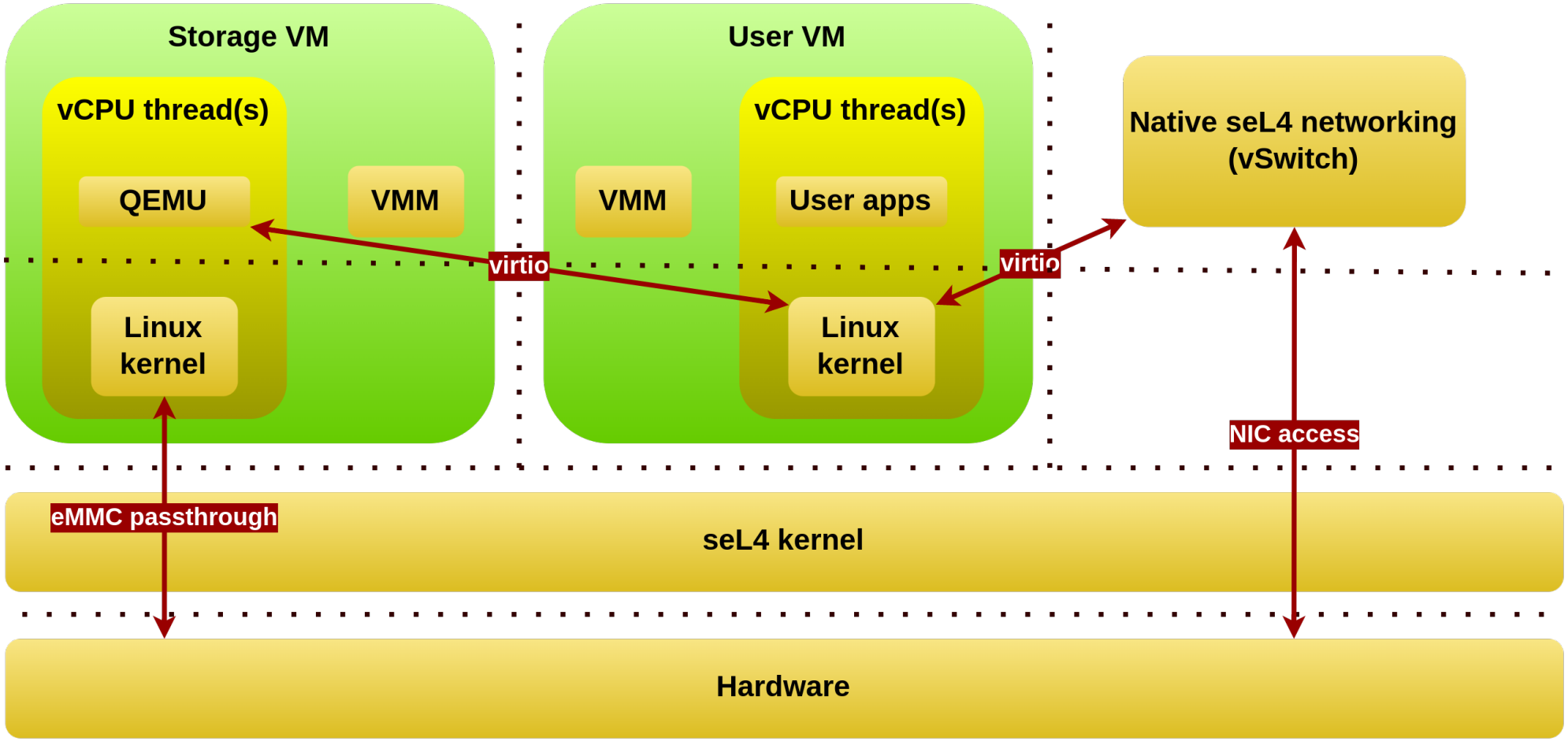
Mixed VM/native



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Where are we now

- “modern” virtio 1.0 supported
- virtio-console, virtio-blk, virtio-net, virtfs
- virtio-display, virtio-gpu, virtio-input (mouse, keyboard)
- PCI transport; no need to configure anything in guest
- Some preliminary results
- rpi4 virtio-blk 70 MB/s
- rpi4 virtio-net 1 MB/s (3% of native, ouch)
- rpi4 virtio-gpu glx-gears 45 fps @ 720p
- One service VM / one user VM
- Host sees all of guest’s memory

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What we are working on

- System-wide ftrace (kernel, VMMs, guests)
- Traces absolutely required to understand all interactions
- vhost should help with inferior virtio-net performance
- Minimize context switches
- Hypervisor/guest scheduler options study
- 1:1 service/user → M:N service/user
- Restrict guest memory visibility to host
- Dynamic VMs (pure virtio, no need for IOMMU/SMMU)
- CrosVM and its derivatives

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VMs with RPi4

- Docker container to build it all
- seL4 kernel, vm_qemu_virtio example, guest Yocto Linux root filesystems
- Boot from network with DHCP / TFTP
- First VM uses NIC passthrough and mounts root from NFS
- Second VM mounts root from virtio-blk provided by QEMU in first VM
- So effectively both root filesystems served from development desktop
- Quick iteration cycle, no need to play with SD cards
- ”screen” to multiplex VM consoles onto RPi4’s physical UART
- QEMU’s debug monitor also in the screen session
- Try it out: https://github.com/tiiuae/tii_sel4_build

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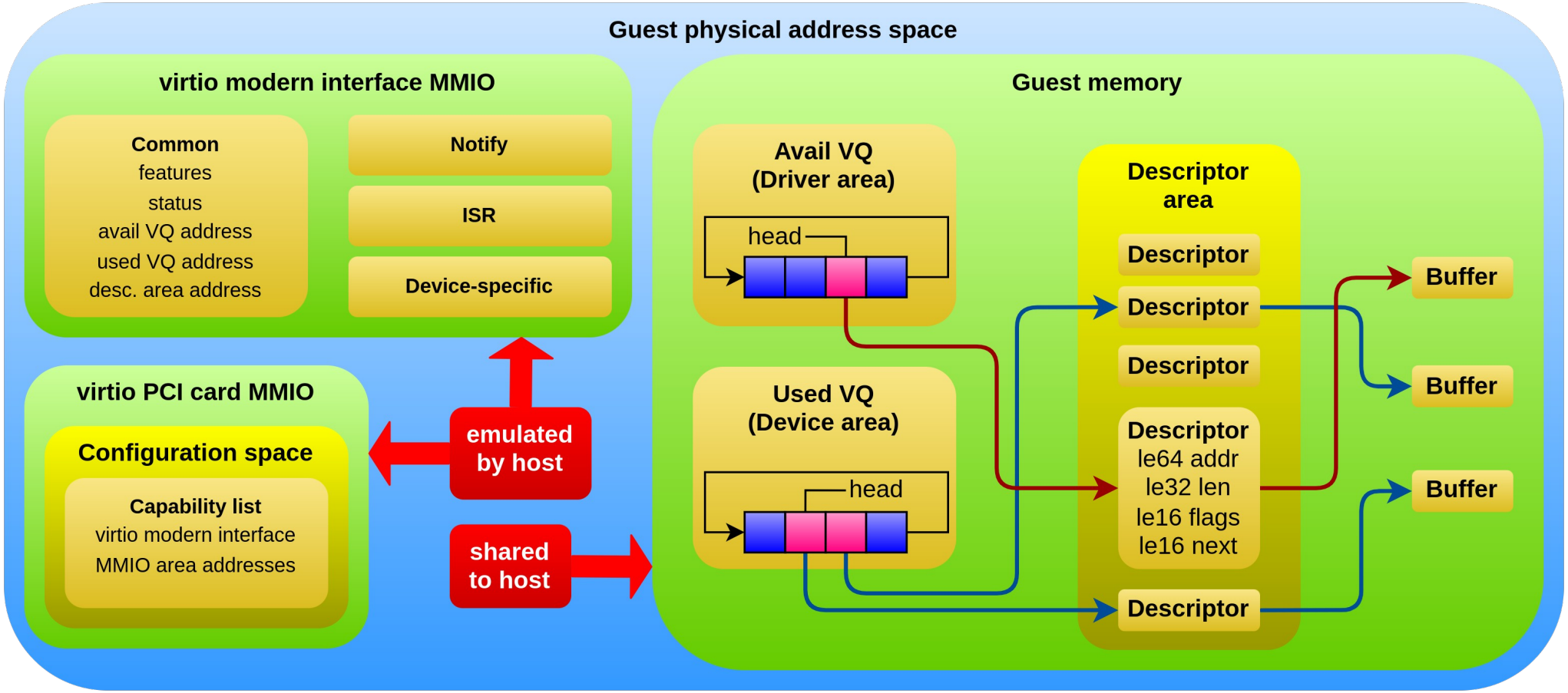
Virtio recap



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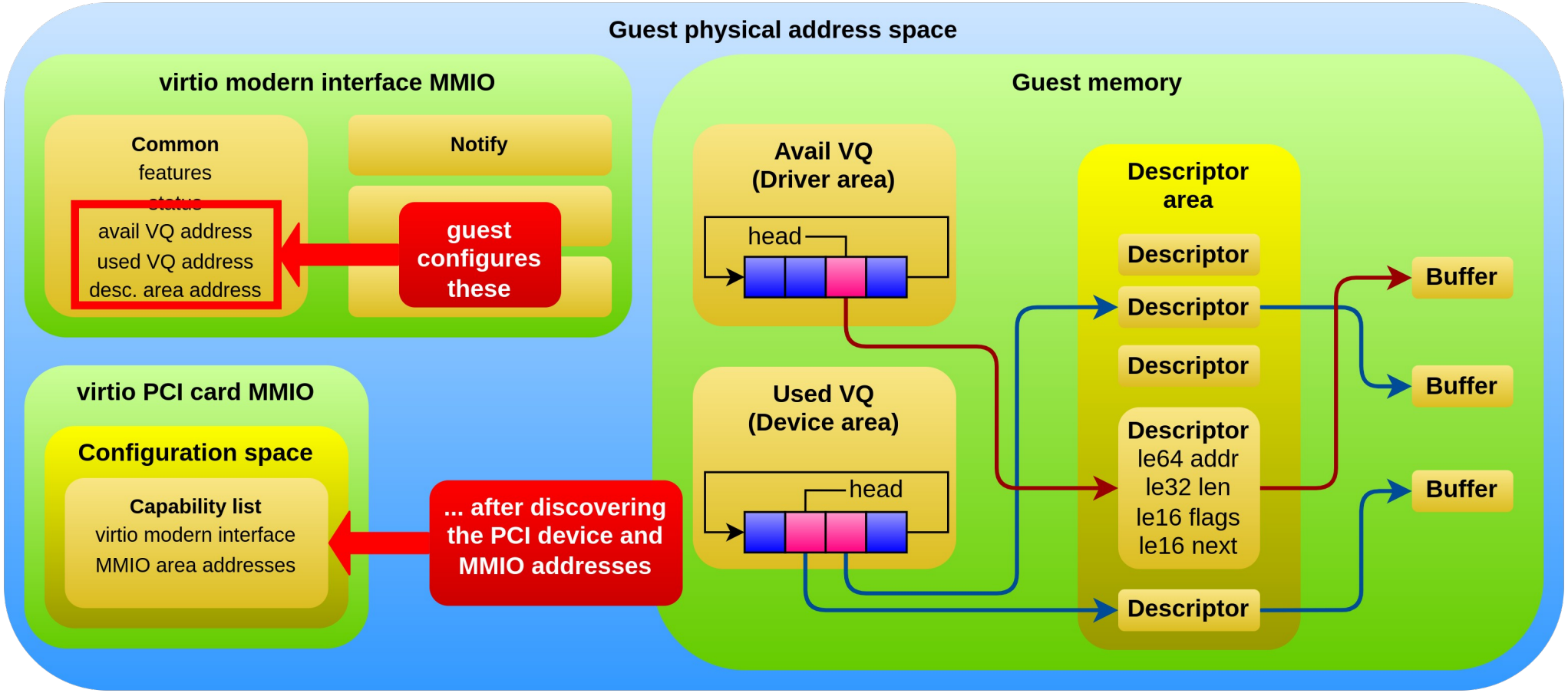
Virtio recap



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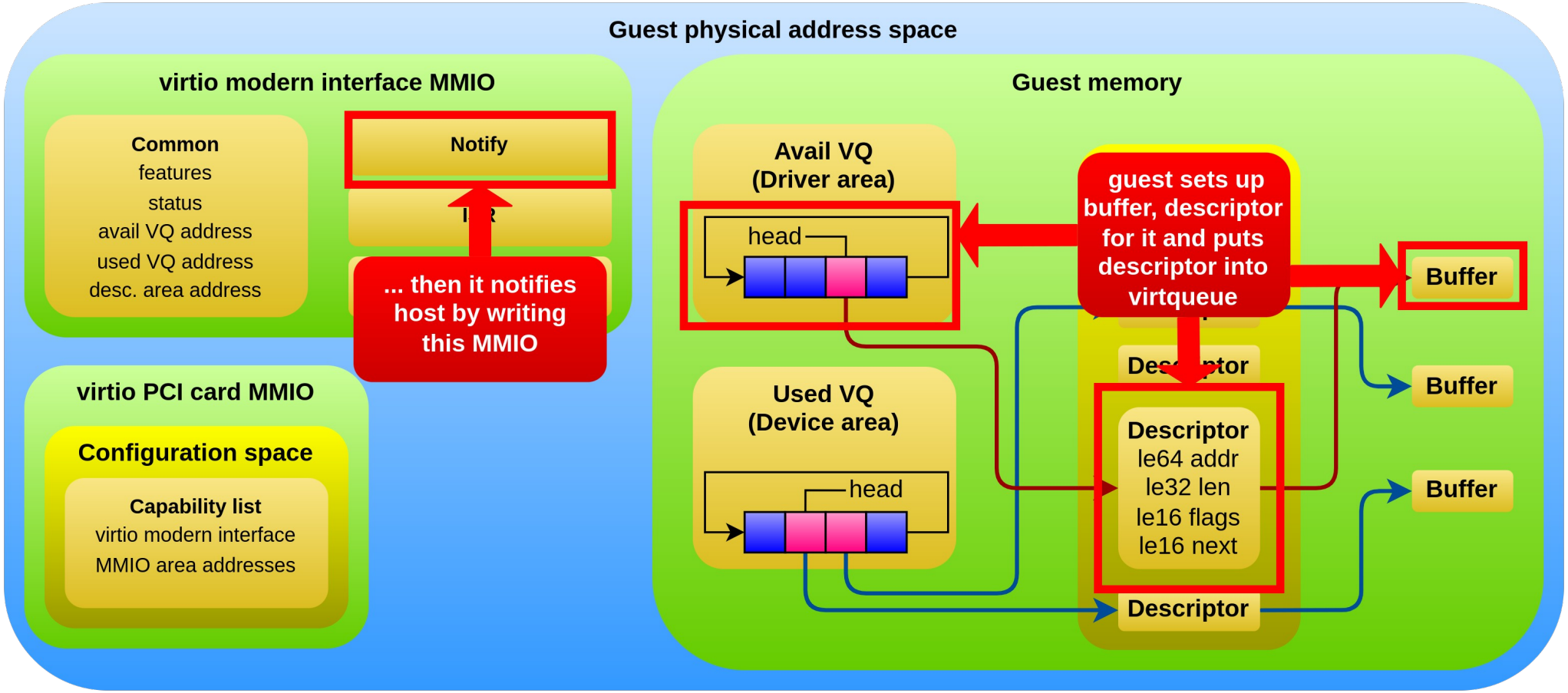
Virtio recap



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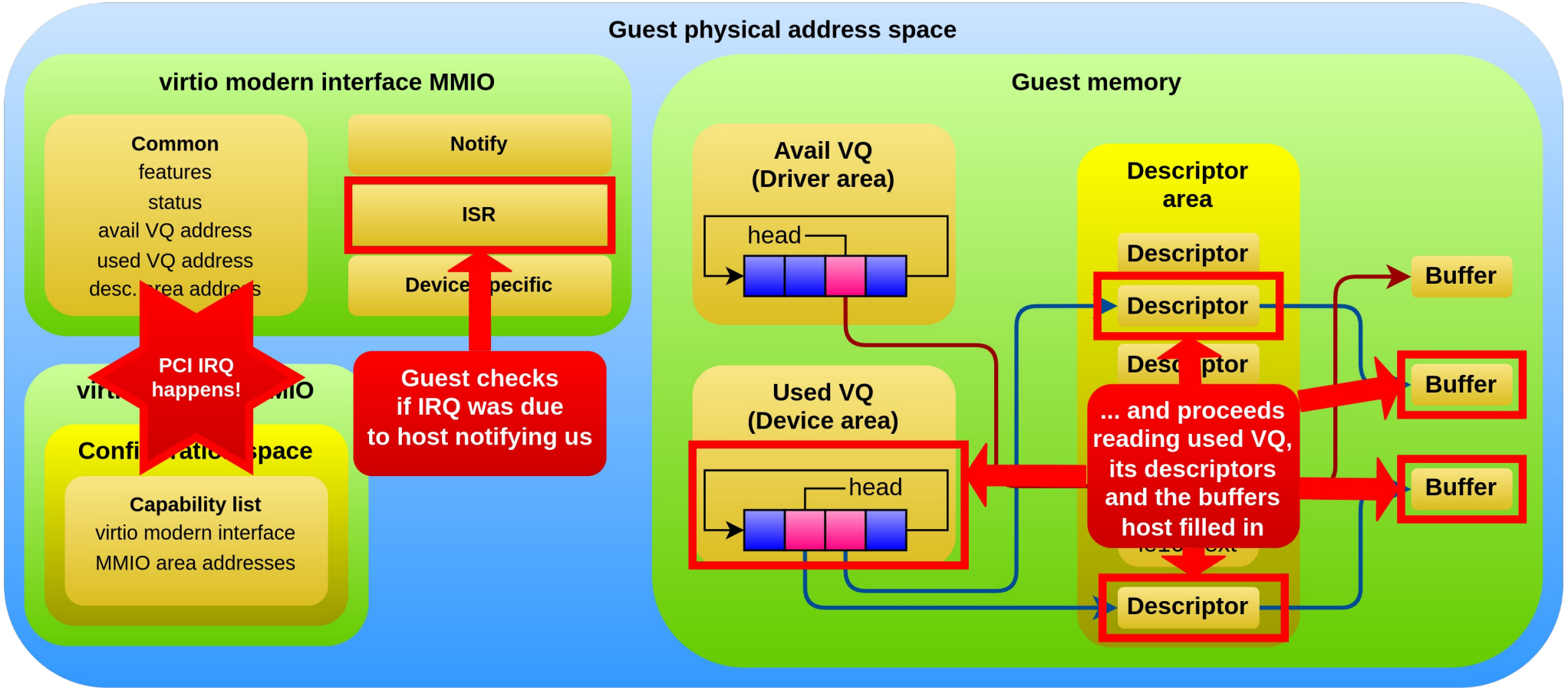
Virtio recap



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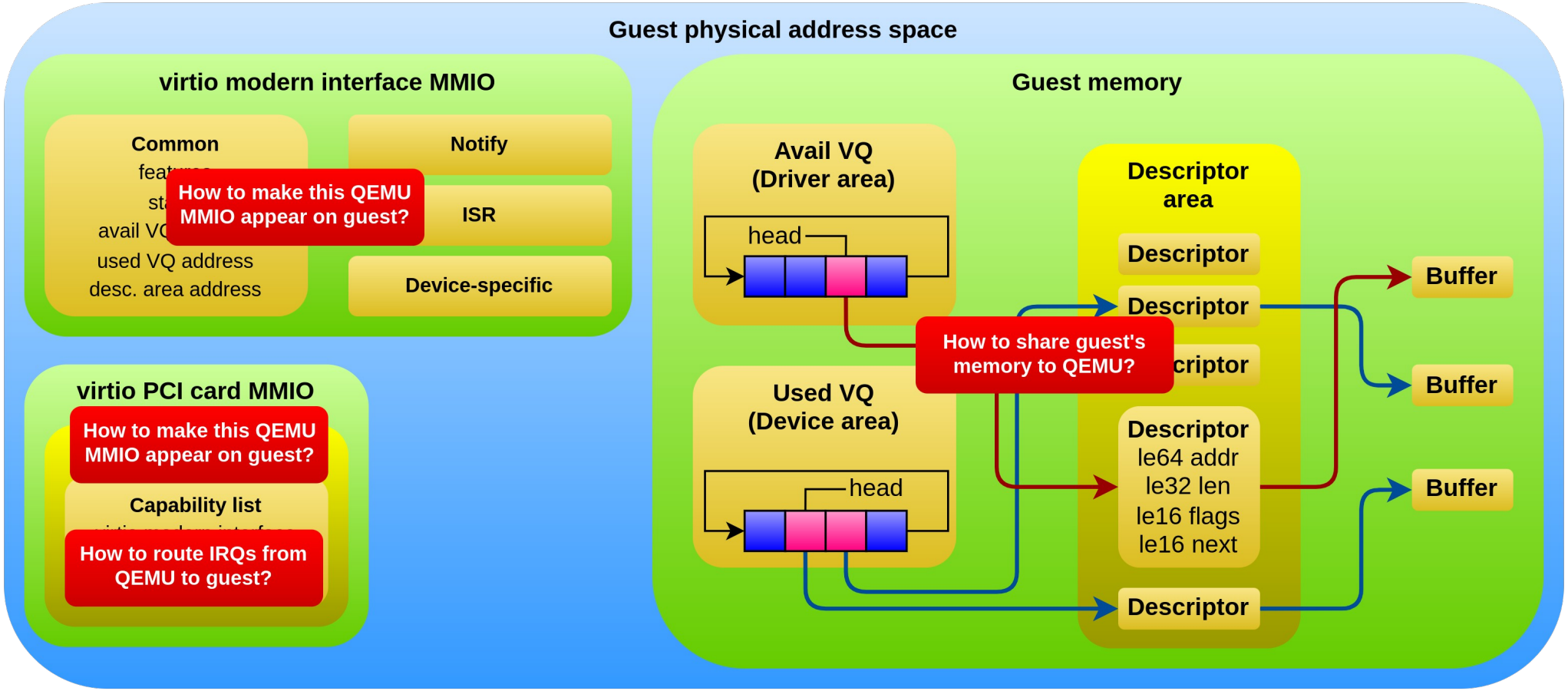
Virtio recap



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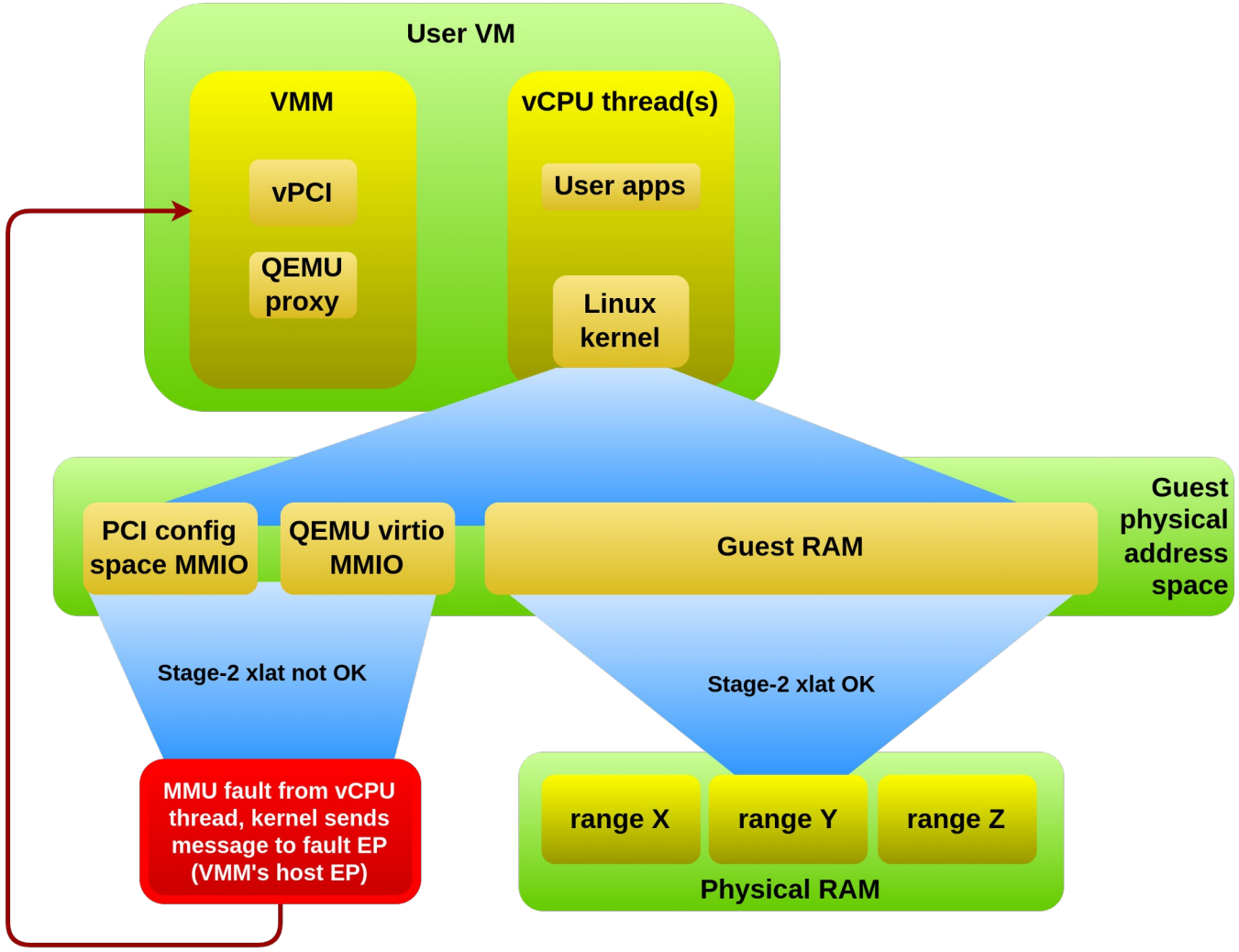
MMIO emulation



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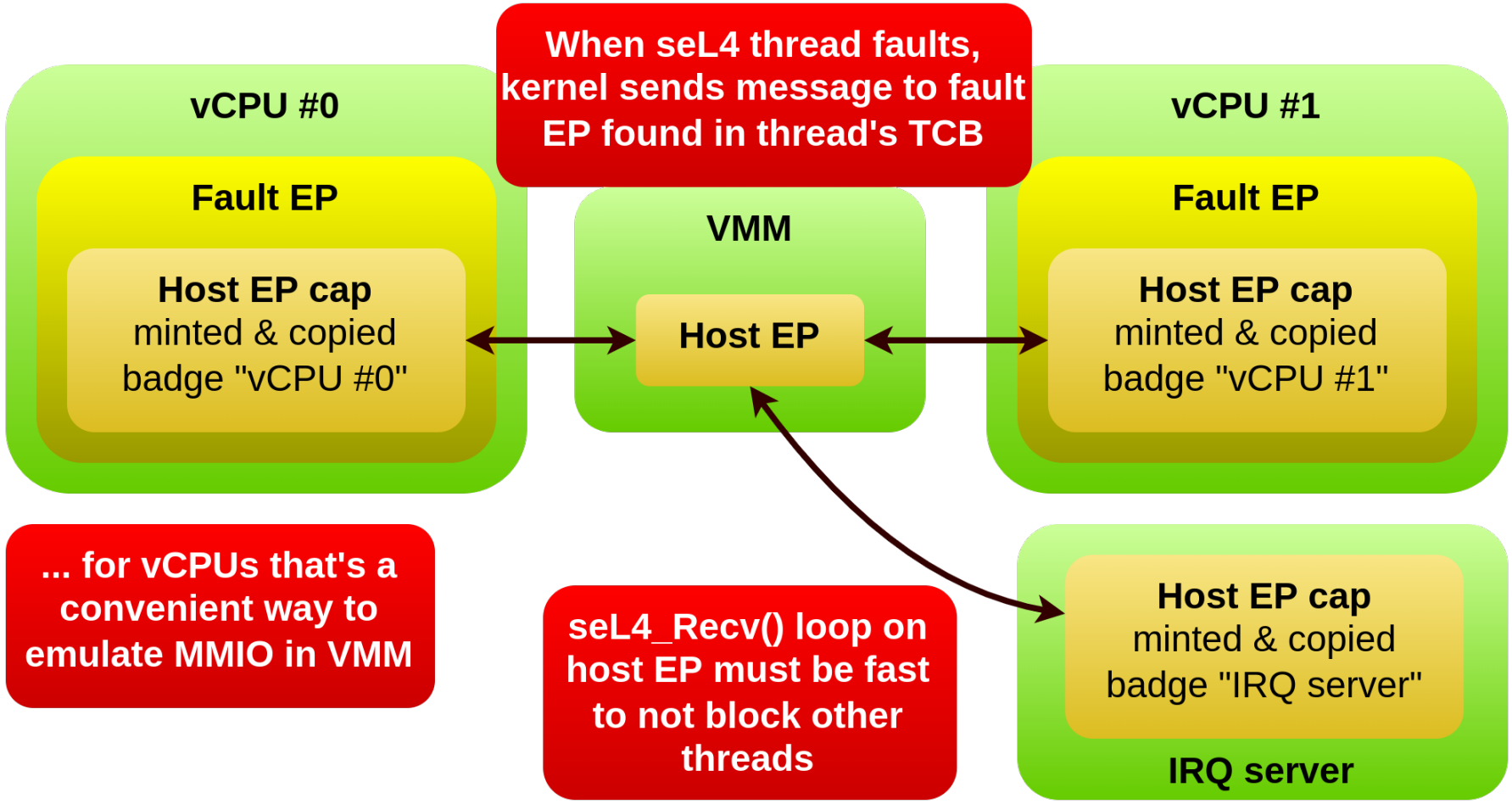
virtio MMIO



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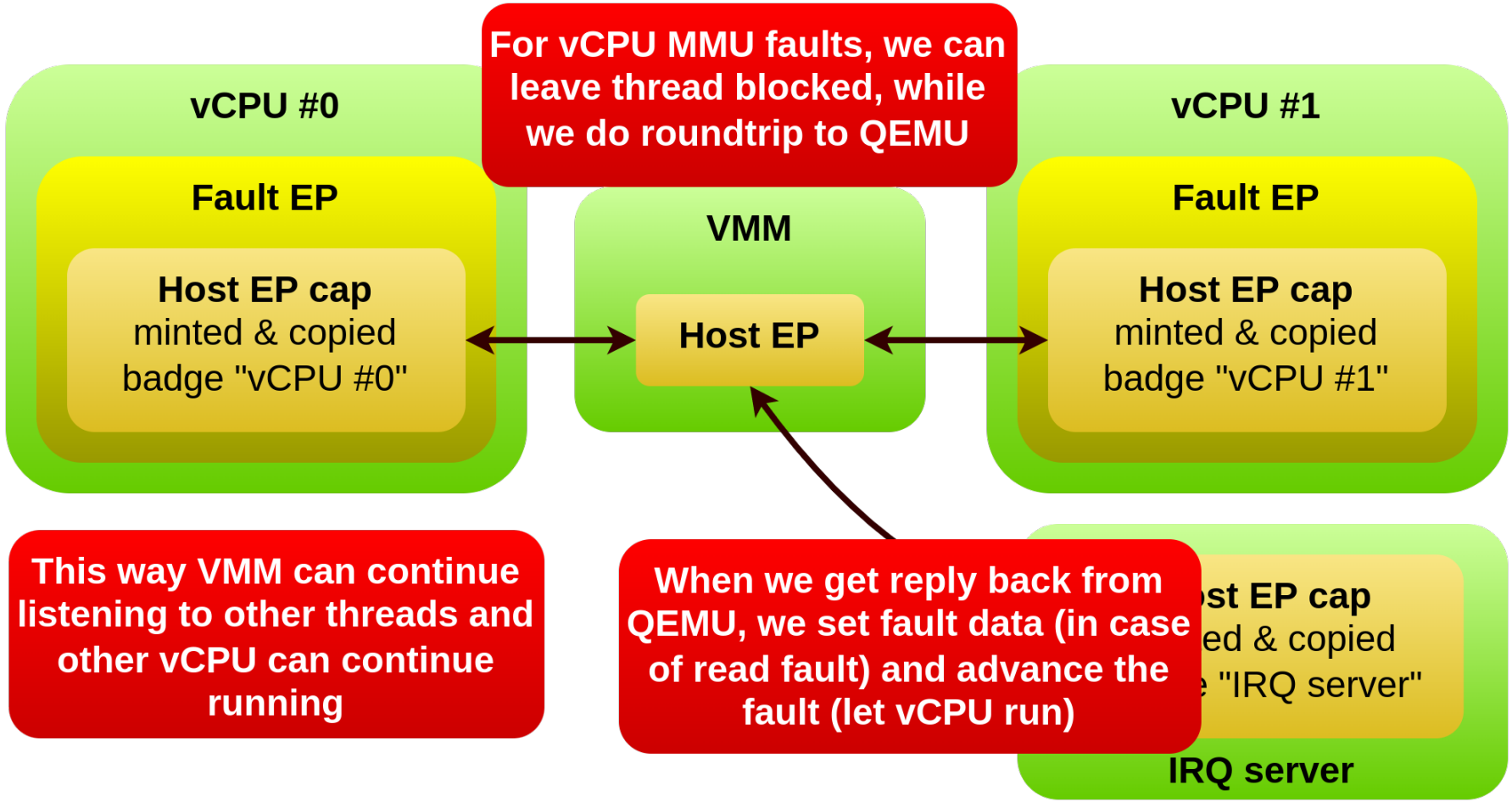
virtio MMIO



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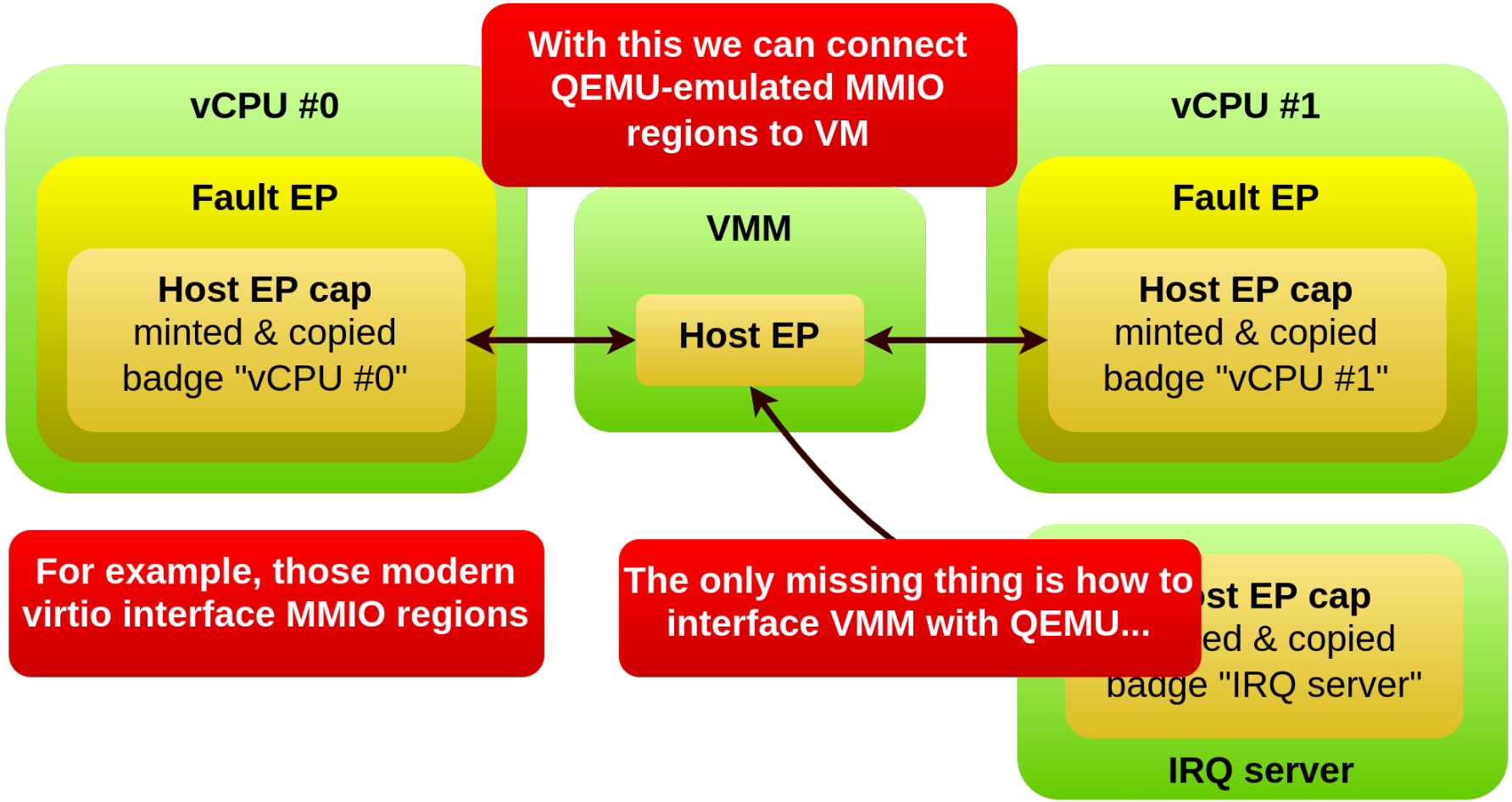
virtio MMIO



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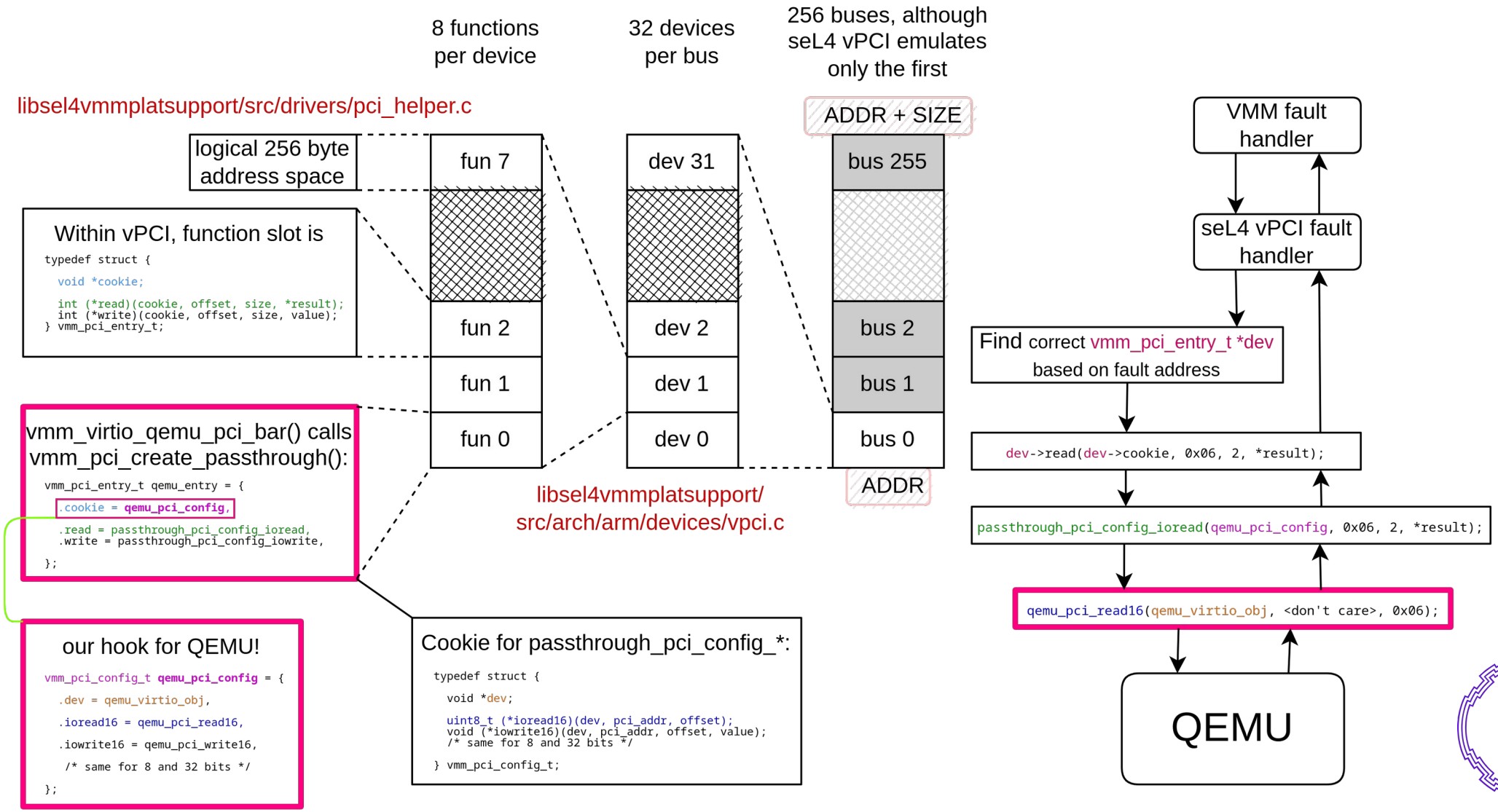
Virtual PCI in seL4



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RPC

- To proxy faults to QEMU we need RPC
- Ring buffers on shared memory & doorbells
- On native side with seL4 threads everything is easy
- Shared memory is just (minted & copied) capabilities to frames
- Doorbells are just notifications

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QEMU shared memory

- Static configuration
- VMM maps shared memory to VM's vspace (stage-2 mapping)
- VMM adds vPCI device whose BAR points to GPA of this mapping
- PCI driver kernel module is added to guest Linux
- Maps shared memory to userland via UIO (stage-1 mapping)
- We can map guest memory to QEMU's address space easily:

```
qemu-system-aarch64
  -object memory-back-end-file,\
    id=virt.ram,size=128M,mem-path=/dev/uio1,offset=4096,share=on\
  -machine memory-backend=virt.ram
```

- We had to add "offset" support
- Offset of 1 * PAGE_SIZE or 4096 selects dataport mapping instead of event BAR

QEMU doorbells (recv)

- Event BAR of cross-connector PCI device is the doorbell
- Mapped to QEMU via page 0 of /dev/uioX
- QEMU VMM thread blocks on UIO fd
- Host-VMM receives specially badged notification from guest-VMM
- Cross-connector increase event count in event BAR
- Injects IRQ to host VM
- Host’s guest Linux forwards IRQ to UIO
- UIO asks cross-connector whether this IRQ is for it
- Kernel module sets event count to zero (MMU fault)
- UIO unblocks QEMU thread doing poll() on fd

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QEMU doorbells (send)

- Host Linux writes to event BAR emit register (MMU fault)
- Cross-connector sends seL4 notification
- Guest VMM notification wait thread unblocks
- Thread asynchronously (to VMM thread) handles ring buffer
- Async handler might post semaphore for ops than wait synchronously

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Sharing VM RAM to QEMU

- Tweak init_ram_module() for user-VM
- Put shared memory frames where guest RAM frames used to be
- Those were unity mapping for ”untyped_mmios”
- We don’t really need unity mapping if we don’t use DMA
- Use shared memory frame caps to map memory to VM’s vspace

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Level-triggered IRQs

- CAmkES VMM supports only edge-triggered IRQs
- QEMU’s virtio-pci needs level-triggered IRQs
- We added support for them
- Inject another IRQ if any external IRQ line still active

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WFI / seL4_Yield()

- Important to get thread priorities right
- ”Host” threads should have higher priority than ”guest”
- VMM threads should have higher priority than vCPU threads
- Host continues to execute after QEMU has served the guest
- Host just executes WFI (Wait For Interrupt) until its timeslice is consumed
- Our modification to seL4 kernel does yield when it traps WFI from user threads
- virtio-blk benchmark shows 25 % – 40 % improvement in throughput

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seL4/guest schedulers

- Two levels of schedulers
- One in seL4 kernel (for each CPU)
- Guests running their own schedulers
- Nasty interactions
- Big field of research

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Tracing

- Essential for improving performance
- sel4bench good for kernel and native threads
- We need also traces from guest VMs (Linux kernel / QEMU)
- seL4 kernel / VMM tracing easy
- Guest tracing is more complex since there can be multiple vCPUs
- Hard to implement atomic writes to trace buffer
- Let’s avoid “not invented here” and use Linux ftrace instead

Tracing

- We intend to convert seL4 kernel and VMM traces into ftrace format
- Merging kernel, VMM and guest traces into one
- Possibly existing work from KVM community can be used
- We need to record virtual timer offsets on vCPU thread switches to do that
- After that we can use kernelshark, FlameGraphs, etc.
- The whole system will be visualized
- ”Doing nothing” or ”doing context switches” more easily pinpointed

ioeventfd

- Every QEMU hypervisor backend has to implement memory listeners
- Configures callbacks that get called when given region is accessed
- Our prototype uses custom code
- Similar thing exists in KVM, called ioeventfd
- ioeventfds configured on /dev/kvm with proper ioctl()
- Better change our code to adhere to this API
- Prepares us for other KVM-compatible VMMs
- Hides the memory listener details from VMM

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irqfd

- QEMU needs a way to raise IRQ in guest
- Once again, our code is one-off hack
- Glues the injection code to QEMU’s gpex PCI host
- KVM has irqfd concept
- When you write to fd, IRQ gets injected to guest
- Supporting irqfds gives us even more KVM compatibility

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Dynamic RAM allocation

- With pure virtio VMs we don’t need DMA capability
- No need for unity stage 2 mapping
- We can allocate RAM from VM anywhere
- GPA range stays the same due to stage 2 mapping
- Idea: create a ”mallocator” seL4 application
- Has a pool of untyped memory
- VMMs request memory from mallocator
- It copies/mints capabilities and transfers them to VMM
- VMM maps these caps as VM’s RAM

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Dynamic VMs

- ioeventfd and irqfd simplifies VMM porting
- Dynamic RAM allocation doable
- Some more bits from KVM API need to be provided
- We need to provide means to create vCPUs, route IRQs etc.
- Most probably we won’t be able to be 100% pin-compatible…
- … but not sure if that’s even desirable
- The important point is to minimize the VMM porting effort
- CrosVM, firecracker, etc.

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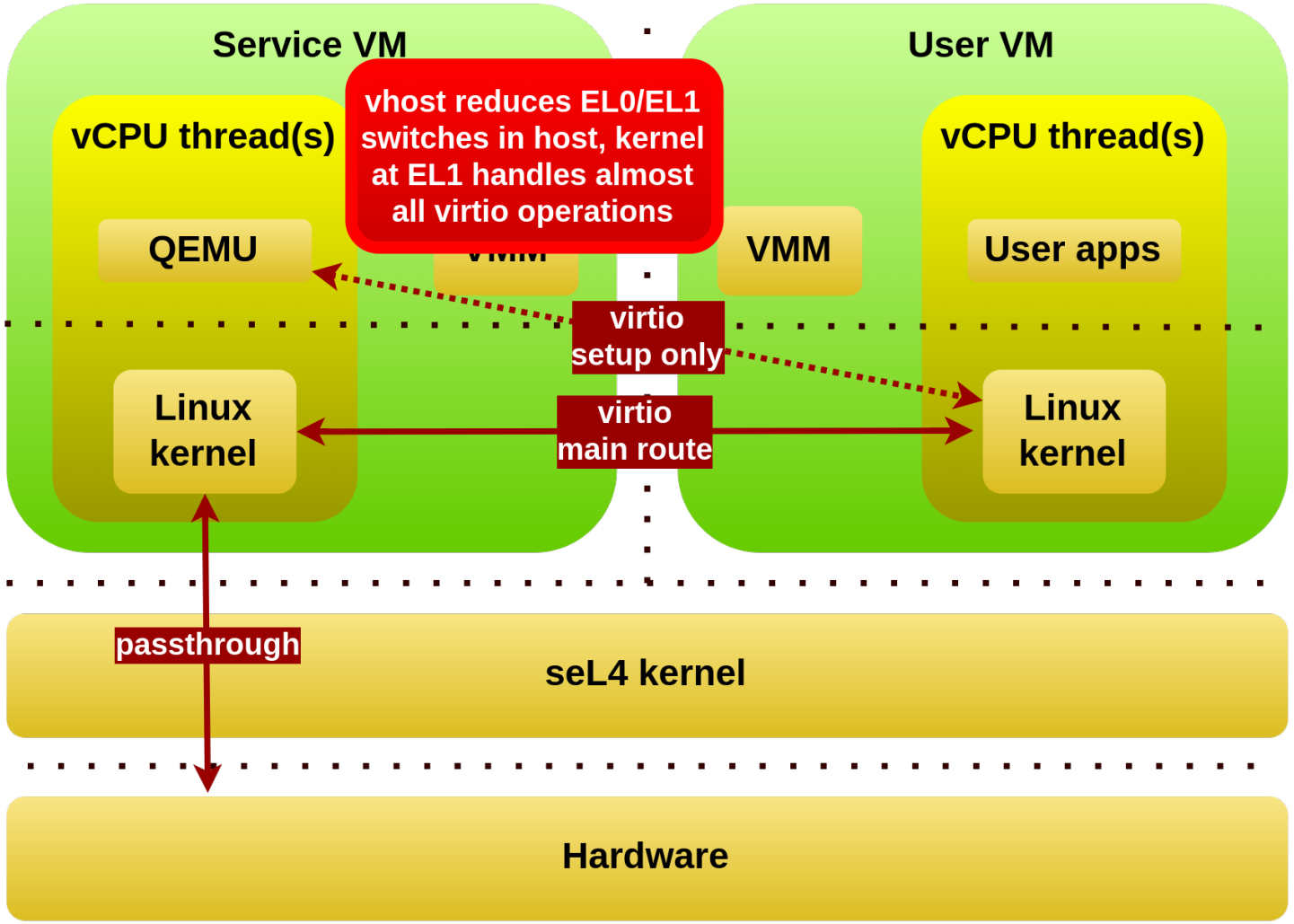
Host blinding

- Right now host sees all of the guest's RAM
- Only pages involved with virtio needed
- Idea: use mallocator to restrict host access
- Mallocator intercepts notifications between host and guest
- Tracks which pages guest wants to share to host
- Host VMM can ask mallocator to give caps to virtio pages

vhost



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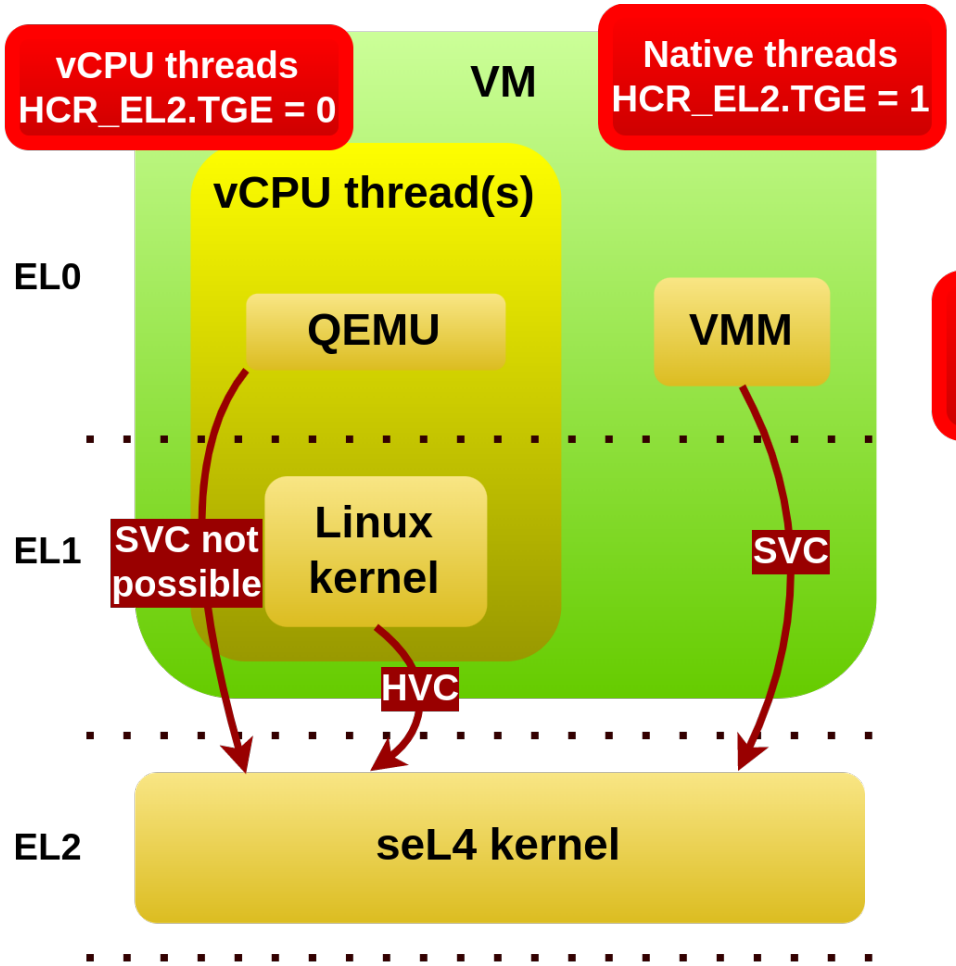
seL4 virtio transport



QEMU can call seL4_Send() only
a) via Linux kernel
b) via VMM-handled MMU fault

Either way, needless
context switch

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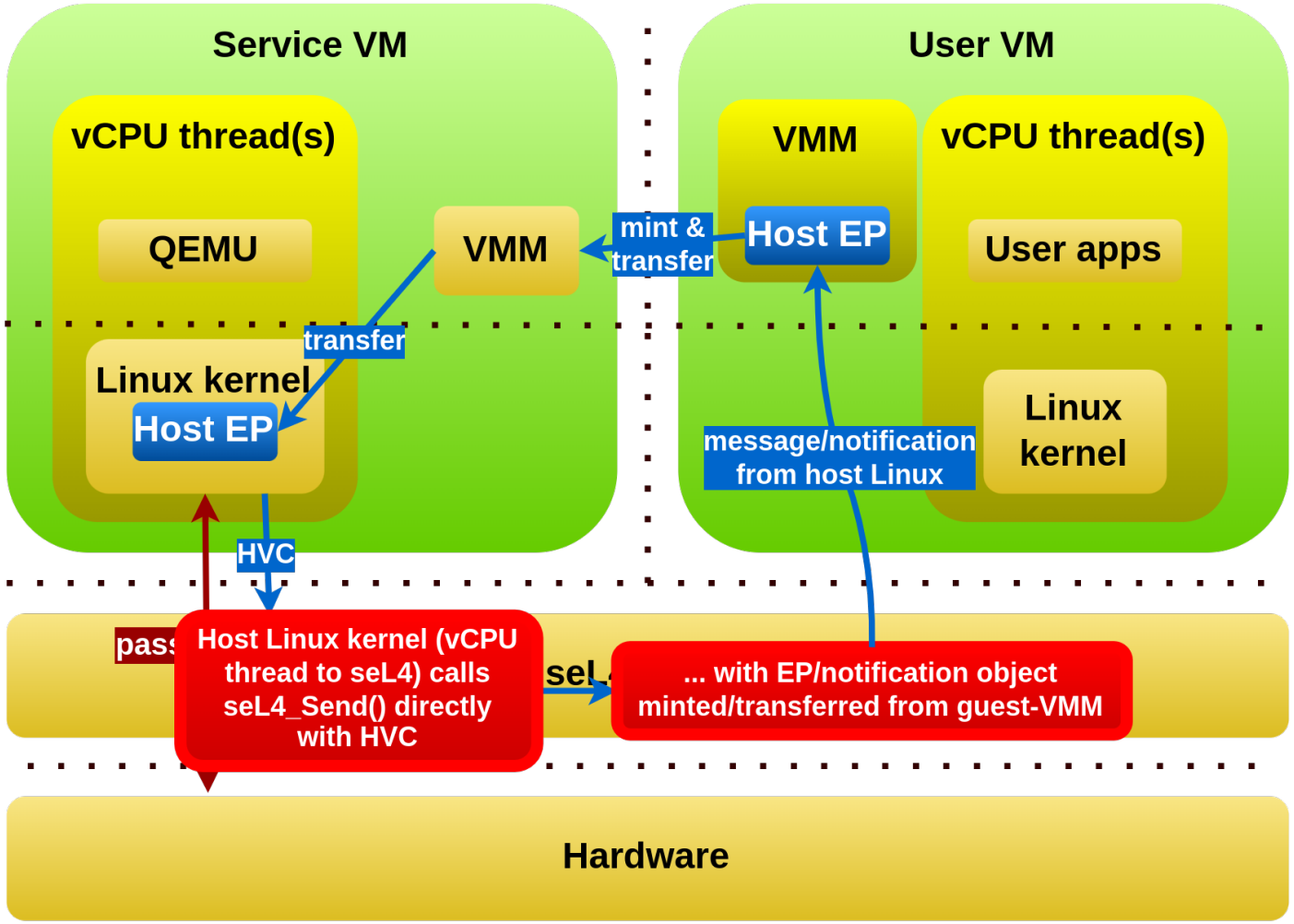
seL4 virtio transport



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