# KVM

Florent Gluck - Florent.Gluck@hesge.ch

March 21, 2023

# TODO

- Describe how to handle PMIO and MMIO VMexits
- PMIO: describe how to detect read or write
    - read: describe how to retrieve port and inject value
    - write: describe how to retrieve port and retrieve written value
- MMIO: describe how to detect read or write
    - read: describe how to retrieve address and inject value
    - write: describe how to retrieve address and retrieve written value

# Kernel modules

# Linux kernel modules

**Module = kernel code that can be loaded/unloaded at runtime**

- Allows to add/remove kernel features while system is running
- Modules have **full privileges** and control of the system → buggy modules may crash the kernel!
- Make it easy to develop drivers without rebooting
- Help keep kernel image size to a minimum
- Help reduce boot time: avoid spending time initializing devices and kernel features that will only be needed later
- Modules installed in `/lib/modules/<kernel_version>/kernel` and have the `.ko` extension

# Loading modules

- To load a single module **without** its dependencies:

```
sudo insmod <module_path>.ko
```

- To load a module **with** its dependencies:

```
sudo modprobe <module_name>
```

- `modprobe` reads `/lib/modules/<kernel_version>/modules.dep.bin` to determine:
  - each module's location (path)
  - each module's dependencies

# Module utilities

- To get information about a module (parameters, license, description, dependencies, etc.):

```
modinfo <module_name>
modinfo <module_path>.ko
```

- To display all loaded modules (see /proc/modules):

```
lsmod
```

- To remove a module (and its depedencies with -r):

```
rmmod <module_name>
```

# KVM

# What is KVM?

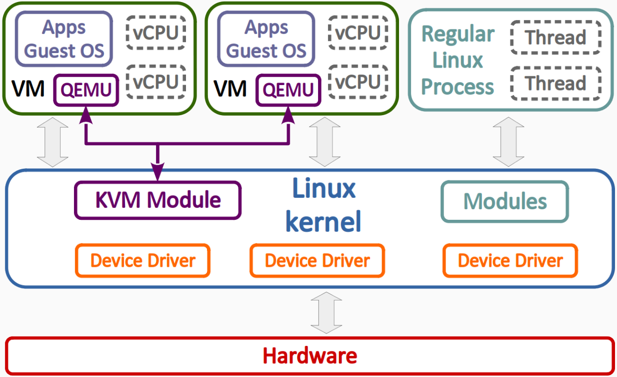
- **KVM** stands for **K**ernel based **V**irtual **M**achine
- Linux kernel module providing hardware-assisted virtualization
- **Provide a virtualization API** for hypervisors
- **Requires** Intel VT-x or AMD-V
- Originally, KVM virtualized only CPU and memory
  - devices (I/O) had to be emulated by QEMU
- Nowadays, KVM supports device virtualization (PIC and probably more)
- Being part of Linux, KVM is open-source software

# Evolution of KVM

- Introduced to make VT-x/AMD-V available to user space
  - expose virtualization features securely
  - interface: `/dev/kvm`
- Quickly merged into Linux mainline
  - available since kernel 2.6.20 (2006)
  - from first LKML posting to kernel merge: only 3 months!
  - 7300 lines of C code! (as of Linux 5.8.12)
- Evolved significantly since 2006
  - ported to other architectures: RAM, s390, PowerPC, IA64
  - became recognized & driving part of Linux kernel
  - quick support of latest virtualization features

# KVM model

- User processes can create VMs → VMs are just user space processes
- Virtual CPUs (vCPUs) mapped to kernel threads



# Architectural benefits of KVM model

- **Proximity of guest and user space hypervisor**
  - Only one address space switch: guest ↔ host
  - Both run in user space → lighter context switch
- **Massive Linux kernel reuse**
  - Memory management
  - Scheduler
  - I/O stacks, power management, host CPU hot-plugging, etc.
- **Massive Linux user space reuse**
  - Network configuration
  - Handling of VM images
  - Logging, tracing, debugging

# KSM (Kernel Samepage Merging)

- Linux kernel feature that deduplicates “identical” pages found across user processes
  - **benefit: massive gain in memory usage!**
  - drawback: security (theoretical)
- Spawn `ksmd` daemon which inspects pages for possible merges
- Kernel must be compiled with `CONFIG_KSM=y` (> 2.6.32)
- KSM controled[1] by writing to `/sys/kernel/mm/ksm/run`:
  - 0: stop `ksmd` from running but keep merged pages
  - 1: run `ksmd`
  - 2: stop `ksmd` and unmerge all pages currently merged
- Article on KSM "Increasing memory density by using KSM"[2]

[1] https://www.kernel.org/doc/Documentation/vm/ksm.txt

[2] https://www.kernel.org/doc/ols/2009/ols2009-pages-19-28.pdf

# Can a host run KVM?

- Check for hardware virtualization support (Intel or AMD):

```
$ lscpu|grep Flags|grep "vmx\|svm"
Flags:  fpu vme de pse tsc msr pae mce cx8 apic sep
    mtrr pge mca cmov pat pse36 clflush dts acpi mmx
    fxsr sse sse2 ss ht tm pbe syscall nx pdpe1gb rdtscp
     lm constant_tsc arch_perfmon pebs bts rep_good nopl
     xtopology nonstop_tsc cpuid aperfmperf pni
    pclmulqdq dtes64 monitor ds_cpl vmx smx est tm2
    ssse3 sdbg fma cx16 xtpr pdcm ...
```

- Check the kvm module is loaded in the kernel:

```
$ lsmod|grep kvm
kvm_intel          282624  0
kvm                663552  1 kvm_intel
```

# Accessing KVM

- To access the KVM device, `/dev/kvm`, one **must** either (depends on the Linux distro):
  - be in the `kvm` group[3]
  - have the proper ACL permissions[4]

- Typical examples of KVM API use:
  - QEMU when launched with `-enable-kvm`
  - Any other Linux-based hypervisor using KVM
  - Any application using `/dev/kvm`, typically a custom VMM

[3] https://linuxize.com/post/how-to-add-user-to-group-in-linux/

[4] https://www.redhat.com/sysadmin/linux-access-control-lists

# KVM API

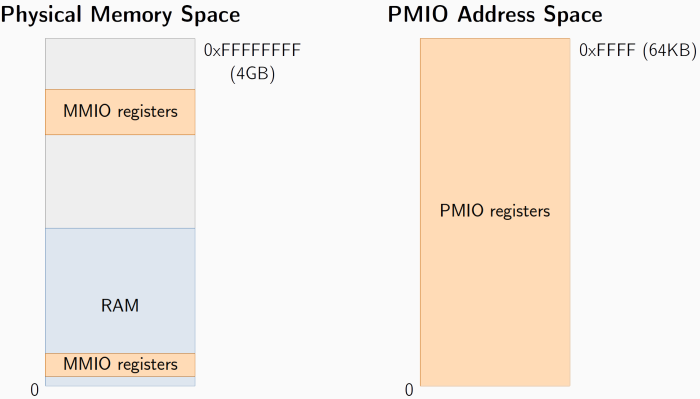
# Overview

- Device `/dev/kvm` provides access to the KVM API
  - `kvm` module must be loaded!
- Requests performed through `ioctl` calls
- Provide 3 types of resources, accessed by file descriptors:
  - system (KVM): VM creation, memory mapping, etc.
  - VM: vCPU creation, interrupts, etc.
  - vCPU : access to registers, etc.

# Devices: MMIO vs PMIO

- **Memory-Mapped I/O devices (MMIO)**
  - device registers are mapped into the physical memory space
  - **RAM and devices share the same address space!**
  - read/write to/from these devices happen exactly like memory
  - all instructions dealing with memory operands can interact with these devices
    - e.g. `mov` instruction (x86) → `mov al,[42]`
- **Port-Mapped I/O devices (PMIO)**
  - device registers are mapped into a specific memory space, **distinct** from the physical memory space
  - require **specific** instructions to access these devices
    - e.g. `in` and `out` instructions (x86) → `in al,42`

# Device address spaces



- MMIO address space, accessed using regular memory instructions (`mov`)
- Distinct memory space, **only** accessed using specific assembly instructions (`in`, `out`)

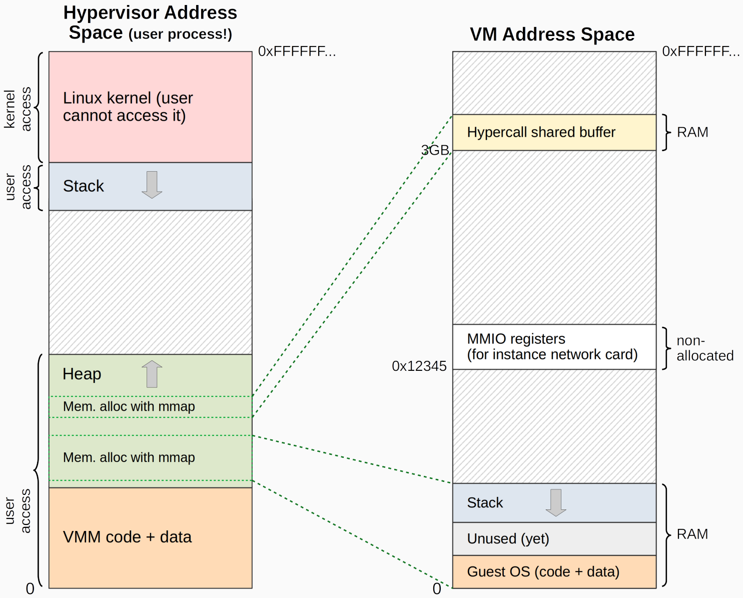
# KVM workflow from the VMM's perspective

1. Create a KVM device
2. Create a VM
3. Allocate RAM for the VM
4. Map allocated RAM into the VM's address space
5. Load guest OS binary blob into the VM's RAM
6. Create a vCPU and setup its registers
7. Run the vCPU on the guest OS' code until a `VMexit` is triggered
   - handle `VMexit` to emulate the guest OS' expected behavior
   - resume vCPU execution

# vCPU execution and VMexits

- **vCPU execution happens at native speed**, without interruption until guest OS code generates a `VMexit`
- A `VMexit` occurs when guest OS code:
  - reads from or writes to an I/O port (PMIO)
  - writes to a physical address that has no mapping (MMIO)
  - triggers some special operation (including errors)
- After a `VMexit` is handled, the VMM resumes the vCPU's execution

# VM memory mapping example



# (1) Create a KVM device

- To obtain a file descriptor on the kvm device and check the stable version of the API is available:

```
int kvmfd = open("/dev/kvm", O_RDWR | O_CLOEXEC);
if (kvmfd < 0) err(1, "%s", "/dev/kvm");

int version = ioctl(kvmfd, KVM_GET_API_VERSION, NULL);
if (version < 0) err(1, "KVM_GET_API_VERSION");
if (version != KVM_API_VERSION) err(1, "Unsupported
    version of the KVM API");
```

# (2) Create a VM

- To obtain a file descriptor on a newly created VM:

```
int vmfd = ioctl(kvmfd, KVM_CREATE_VM, 0);
if (vmfd < 0) err(1, "KVM_CREATE_VM");
```

# (3) Allocate RAM for the VM

- Memory allocated for the guest **must** be:
    - a multiple of a page size (4KB)
    - aligned to a page boundary (4KB)
- **Must** use mmap to allocate pages (not malloc!)

```
// Alloc 4KB for the guest
u_int ram_size = 4096;
uint8_t *mem = mmap(NULL, ram_size, PROT_READ|
    PROT_WRITE, MAP_SHARED|MAP_ANONYMOUS, -1, 0);
if (!mem) err(1, "Allocating guest memory");
```

# (4) Map allocated RAM into the VM's address space

- Define where in the VM, the memory is physically mapped
- Below code maps `mem` at physical address 0 in the VM
- Each memory mapping (*region* in KVM lingo) must be associated to a different slot, here 0

```c
struct kvm_userspace_memory_region memreg = {
  .slot = 0,
  .guest_phys_addr = 0,     // MUST be aligned to a page boundary (4KB)
  .memory_size = ram_size,  // MUST be a multiple of a page size (4KB)
  .userspace_addr = (uint64_t)mem,
  .flags = 0
};
if (ioctl(vmfd, KVM_SET_USER_MEMORY_REGION, &memreg) < 0) err(1, "
     KVM_SET_USER_MEMORY_REGION");
```

# (5) Load guest OS into VM's RAM

- Guest OS must be "loaded" into the guest address space
- Simplest guest OS = mini bare-metal OS
- Simply perform the following operations:
  1. read the binary file generated from compiling/linking the guest OS' code + data
  2. read the file into the pages allocated for the guest RAM
  3. easiest is to load it at address 0 in guest physical memory
     - later on, we'll set the CPU instruction pointer to 0 as well

# (6) Create a vCPU

- A vCPU is referenced through a file descriptor, `vcpufd` below
- The vCPU is represented as a memory-mapped file
    - the memory-mapped area is a `kvm_run` structure, `run` below

```c
int vcpufd = ioctl(vmfd, KVM_CREATE_VCPU, 0);
if (vcpufd < 0) err(1, "KVM_CREATE_VCPU");

int vcpu_mmap_sz = ioctl(kvmfd, KVM_GET_VCPU_MMAP_SIZE, NULL);
if (vcpu_mmap_sz < 0) err(1, "KVM_GET_VCPU_MMAP_SIZE");
if (vcpu_mmap_sz < sizeof(struct kvm_run)) err(1, "KVM_GET_VCPU_MMAP_SIZE
     unexpectedly small");

struct kvm_run *run = mmap(NULL, vcpu_mmap_sz, PROT_READ | PROT_WRITE,
     MAP_SHARED, vcpufd, 0);
if (!run) err(1, "mmap vcpu");
```

# (6) Setup the vCPU registers (1/2)

- Initialize segment registers to zero:

```c
struct kvm_sregs sregs;
if (ioctl(vcpufd, KVM_GET_SREGS, &sregs) < 0) err(1, "KVM_GET_SREGS");
sregs.cs.base = 0;  sregs.cs.selector = 0;
sregs.ds.base = 0;  sregs.ds.selector = 0;
sregs.es.base = 0;  sregs.es.selector = 0;
sregs.ss.base = 0;  sregs.ss.selector = 0;
if (ioctl(vcpufd, KVM_SET_SREGS, &sregs) < 0) err(1, "KVM_SET_SREGS");
```

# (6) Setup the vCPU registers (2/2)

- Initialize instruction pointer rip to point to the beginning of the OS' code (0)
- Initialize stack pointer rsp to point to top of the RAM (ram_size)
- Initialize flags register rflags (bit 1 is reserved: must be 1)

```
struct kvm_regs regs;
memset(&regs, 0, sizeof(regs));
regs.rip = 0;
regs.rsp = ram_size;
regs.rflags = 0x2;
if (ioctl(vcpufd, KVM_SET_REGS, &regs) < 0) err(1, "
    KVM_SET_REGS");
```

# (7) Run the vCPU

- Use the KVM_RUN ioctl on the vCPU file descriptor to run it
- This ioctl **blocks** until the vCPU triggers a VMexit!

```
bool done = false;
while (!done) {
    // Runs the vCPU until encoutering a VM_EXIT (blocking call)
    if (ioctl(vcpufd, KVM_RUN, NULL) < 0) err(1, "KVM_RUN");
    switch (run->exit_reason) {  // See struct kvm_run in "(6) Create a vCPU"
        case KVM_EXIT_IO:
            ...  // handle PMIO VMexits
        case KVM_EXIT_MMIO:
            ...  // handle MMIO VMexits
        case KVM_EXIT_HLT:
            printf("Encounterd HLT instruction\n");
            done = true;
            break;
        case KVM_EXIT_SHUTDOWN:
        case KVM_EXIT_FAIL_ENTRY:
        case KVM_EXIT_INTERNAL_ERROR:
        default:
            fprintf(stderr, "KVM error");
            done = true;
            break;
    }
}
```

# (8) Handle VMexits to emulate desired behavior

- There are many types of `VMexits`, but these 2 are especially interesting:
    - `KVM_EXIT_IO`: the vCPU executed a port I/O instruction (PMIO) that can't be satisfied by KVM
        - means the guest wrote to or read from a port
    - `KVM_EXIT_MMIO`: the vCPU executed a memory-mapped I/O (MMIO) instruction that can't be satisfied by KVM
        - means the guest wrote to or read from an address that has no RAM mapping
- Note that `KVM_EXIT_IO` is **significantly faster** than `KVM_EXIT_MMIO`
- VMM must then emulate the desired behavior expected by the guest OS

# KVM_EXIT_IO: retrieving data written by the guest

## Guest wrote to an I/O port (PMIO)

```c
if (run->io.direction == KVM_EXIT_IO_OUT) {  // See struct kvm_run in "(6) Create a vCPU"
    uint8_t *addr = (uint8_t *)kvm_run + run->io.data_offset;
    uint32_t value;
    switch (run->io.size) {
        case 1:  // Retrieve the 8-bit value written by the guest
            value = *(uint8_t *)addr;
            break;
        case 2:  // Retrieve the 16-bit value written by the guest
            value = *(uint16_t *)addr;
            break;
        case 4:  // Retrieve the 32-bit value written by the guest
            value = *(uint32_t *)addr;
            break;
        default:
            fprintf(stderr, "Unsupported size in KVM_EXIT_IO\n");
            value = 0;
    }
    printf("PMIO guest write: size=%d port=0x%x value=0x%x\n", run->io.size, run->io.port, value);
}
```

# KVM_EXIT_IO: injecting data into the guest

## Guest read from an I/O port (PMIO)

```c
if (run->io.direction == KVM_EXIT_IO_IN) {  // See struct kvm_run in "(6) Create a vCPU"
  uint32_t injected_val;
  uint8_t *addr = (uint8_t *)kvm_run + run->io.data_offset;
  switch (run->io.size) {
    case 1: { // Guest is reading 8 bits from the port
      injected_val = 0x12;  // dummy 8-bit value injected into the guest
      *addr = injected_val;
      } break;
    case 2: { // Guest is reading 16 bits from the port
      injected_val = 0x1234;  // dummy 16-bit value injected into the guest
      *((uint16_t *)addr) = injected_val;
      } break;
    case 4: { // Guest is reading 32 bits from the port
      injected_val = 0x12345678;  // dummy 32-bit value injected into the guest
      *((uint32_t *)addr) = injected_val;
      } break;
    default:
      fprintf(stderr, "Unsupported size in KVM_EXIT_IO\n");
  }
  printf("PMIO guest read: size=%d port=0x%x [value injected by VMM=0x%x]\n",
       run->io.size, run->io.port, injected_val);
}
```

# KVM_EXIT_MMIO: retrieving data written by the guest

Guest wrote to an address that has no RAM mapping (MMIO)

```
if (run->mmio.is_write) {  // See struct kvm_run in "(6) Create a vCPU"
    int bytes_written = run->mmio.len;
    uint32_t value;
    switch (bytes_written) {
        case 1:  // Retrieve the 8-bit value written by the guest
            value = *((uint8_t *)run->mmio.data);
            break;
        case 2:  // Retrieve the 16-bit value written by the guest
            value = *((uint16_t *)run->mmio.data);
            break;
        case 4:  // Retrieve the 32-bit value written by the guest
            value = *((uint32_t *)run->mmio.data);
            break;
        default:
            fprintf(stderr, "Unsupported size in KVM_EXIT_MMIO\n");
            value = 0;
    }
    printf("MMIO guest write: len=%d addr=0x%llx value=0x%x\n", bytes_written,
         run->mmio.phys_addr, value);
}
```

# KVM_EXIT_MMIO: injecting data into the guest

Guest read from an address that has no RAM mapping (MMIO)

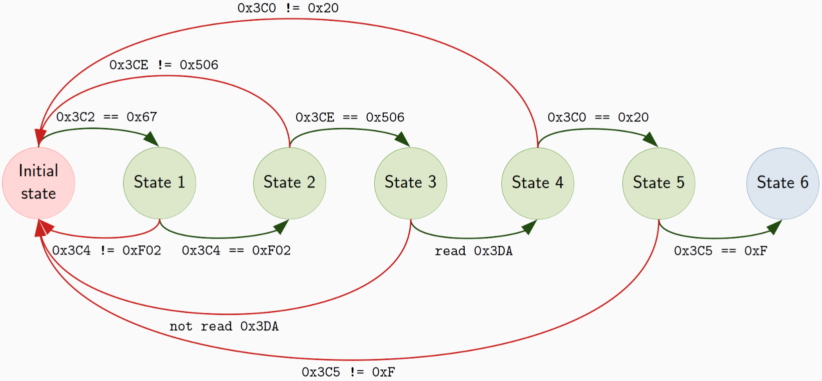
```
if (!run->mmio.is_write) {  // See struct kvm_run in "(6) Create a vCPU"
  int bytes_read = run->mmio.len;
  uint32_t injected_val;
  switch (bytes_read) {
    case 1: { // Guest is reading 8 bits
      uint8_t *addr = (uint8_t *)run->mmio.data;
      injected_val = 0x12;  // dummy 8-bit value injected into the guest
      *addr = injected_val;
      } break;
    case 2: { // Guest is reading 16 bits
      uint16_t *addr = (uint16_t *)run->mmio.data;
      injected_val = 0x1234;  // dummy 16-bit value injected into the guest
      *addr = injected_val;
      } break;
    case 4: { // Guest is reading 32 bits
      uint32_t *addr = (uint32_t *)run->mmio.data;
      injected_val = 0x12345678;  // dummy 32-bit value injected into the guest
      *addr = injected_val;
      } break;
    default:
      fprintf(stderr, "Unsupported size in KVM_EXIT_MMIO\n");
  }
  fprintf(stderr, "MMIO guest read: len=%d addr=0x%llx injected=0x%x\n",
       bytes_read, run->mmio.phys_addr, injected_val);
}
```

# Device emulation

- Emulating a real device allows a guest OS implementing a driver for the real hardware to use it
- OS implements drivers to support various physical devices, for instance:
  - VGA display, mouse, keyboard, SATA drive, etc.
- Device drivers write and read to specific device registers
  - either MMIO or PMIO or both
- How does an hypervisor emulate a device?

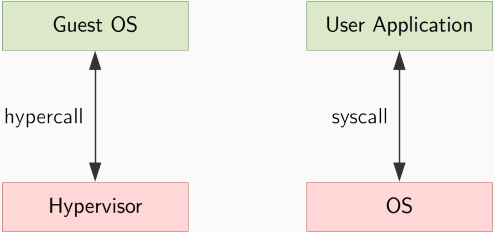
# Device emulation: state machine

```
// Code excerpt of init. sequence for VGA X-mode 400x300
// This code writes and reads to ports (PMIO) only
outb(0x3C2, 0x67);
outw(0x3C4, 0x0F02);  // enable writing to all planes
outw(0x3CE, 0x0506);  // graphic mode
inb(0x3DA);
outb(0x3C0, 0x20);   // enable video
outb(0x3C5, 0x0F);
```



# Hypercalls

- Mechanism for the guest to request the help of the hypervisor
- Similar to a system call between an application and an OS

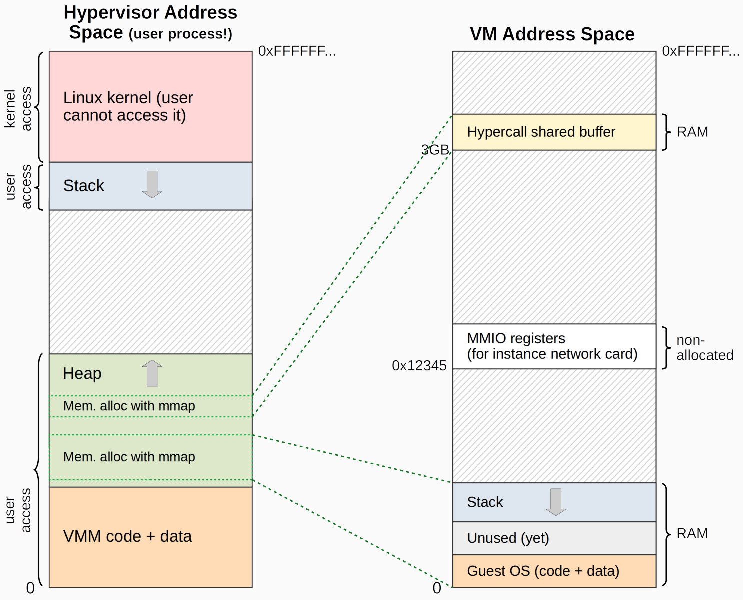


- Benefits
  - **much simpler drivers** → no need to emulate the real hardware!
  - **much better performance!**

# Hypercalls: simple implementation example

- **Guest**
  - write hypercall arguments in shared memory (buffer) between guest ↔ hypervisor
  - write hypercall request to an unused port, e.g. `0xABBA`
- **Hypervisor**
  - when `KVM_EXIT_IO` encountered, check whether it's an hypercall
  - if hypercall, then extract its arguments and emulate the expected behavior
    - possibly write an output to the shared buffer

# Hypercalls: shared buffer



# Gracefully exit the VM (1/2)

**Case 1: guest OS explicitely stops the CPU**

- Guest: executes the `hlt` machine instruction to stop the CPU
- Hypervisor: `hlt` triggers the `KVM_EXIT_HLT` VMexit
- Do not forget to deallocate the VM's resources!

# Gracefully exit the VM (2/2)

**Case 2: execution of the guest OS never stops** (infinite loop)

→ `KVM_RUN ioctl` never stops either!

- How to handle a graceful exit initiated on the host?
  - run the vCPU in a dedicated thread
  - configure the thread to be **asynchronously interruptible** with:

```
pthread_setcanceltype(PTHREAD_CANCEL_ASYNCHRONOUS, NULL);
```

  - when the VM must be stopped, cancel the vCPU thread with:

```
pthread_cancel(vcpu_thread);
```

# Cleanup the VM’s data structures

- Do not forget to deallocate the VM’s resources:
  - close the KVM device using the file descriptor previously returned by `open`(/dev/kvm`, ...`)
  - free all memory regions (RAM, ) allocated with `mmap` by calling `munmap`

# Resources

- KVM
  http://linux-kvm.org
- KVM API reference
  https://www.kernel.org/doc/html/latest/virt/kvm/api.html
- Using the KVM API
  https://lwn.net/Articles/658511/
- Kernel module (Arch Linux documentation)
  https://wiki.archlinux.org/index.php/Kernel_module