Splitting the Linux Kernel for Fun & Profit

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‘ How to hack a Micro-Kernel interface into Linux’

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‘ How to hack a Micro-Kernel interface into Linux’

OR

‘Adding Intra-Kernel protection to Linux using silicon-based Virtualization Extensions’

(Without needing a Hypervisor)

Outline

- Part 1: Motivation for the work
  - If I wanted a secure OS I wouldn't start from Linux…but what if that was all you had?
- Part 2: Background
  - Ways to structure Operating Systems
  - Linux Kernel Weaknesses & Split-Kernel Demo Video
- Part 3: Splitting the Kernel
  - Restructuring Linux using HW Virtualization Support
  - High-level & Some code details
  - Performance & Invasiveness
- Part 4: Current Status, Opportunities & Futures
  - Open Source Links

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Part 1: Original motivation for the work

- Containers offer alternative to using Hypervisors for SW deployments
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  - Only one underlying OS to manage
  - Plus better integration opportunities

Original Motivation for the Work

- Containers offer alternative to using Hypervisors for SW deployments
  - Docker, CoreOS / Rkt, etc
- Upside: Lighter-weight than using VMs
  - Only one underlying OS to manage
  - Plus better integration opportunities
- Downside: Shared ‘host’ kernel a significant vulnerability
  - Currently Linux has no ‘**intra-kernel**’ protection
  - All bets are off if you manage to get into the kernel

Getting into the kernel is not that hard!

E.g. Malware triggering buffer overflows / stack / heap attacks, un-authorized module loading, User-space kernel hijack via code & data redirection (ROP), DMA attacks, etc. even with SMAP / SMEP / PXN support

And of course more recent Spectre / Meltdown / L1TF attacks

What did we want to do?

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Reduce the consequences of a Kernel compromise by introducing a degree of **Intra-kernel** Protection into the Linux Kernel

How?

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Restructure kernel into Outer and Inner region based on MMU access

Inner Region can access the MMU directly

Outer Region needs to go through a virtual MMU interface to modify page mappings, etc.

Inner/Outer region separation enforced through CPU HW support for virtualization

Related Research

- ‘Nested Kernel: An Operating System Architecture for Intra-Kernel Privilege Separation’ (Dautenhahn, et al.)
  - Looks at implementing a vMMU for FreeBSD
  - Relies on privileged instruction removing from kernel binary and code scanning for enforcement not VT-x extensions
- ‘Dune: Safe User-level Access to Privileged CPU Features’ (Belay et al.)
  - Uses Intel Vt-x extensions to safely expose HW to user-space processes (e.g. each process has access to cpu rings 0-3)
- ‘Address space isolation Inside the Linux Kernel’ (Rapoport, et al 2019)
  - Tries to achieve similar properties and capabilities to our work
  - Uses restricted page table mappings and kernel direct map modifications not VT-x extensions

What does this buy us?

- Strong control over the integrity of kernel code and core data
  - No ‘un-authorized’ code gets to run in kernel mode
  - Can protect the integrity of data even against malicious kernel mode code
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- Guard against cross-process code + data compromise
  - Enhanced risk when running multiple ‘isolated’ containers

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Constraints

- What no Hypervisor??
  - Strategic control point for others in the Industry (Dell, VMWare, etc)
- Is it still Linux?
  - Can’t afford long-term engineering support
  - Needs to be upstream-able
  - Minimize performance overhead c.f. Hypervisors
  - Minimize intrusiveness c.f. L4Linux
  - But still has to offer significant security improvements over ‘normal’ Linux

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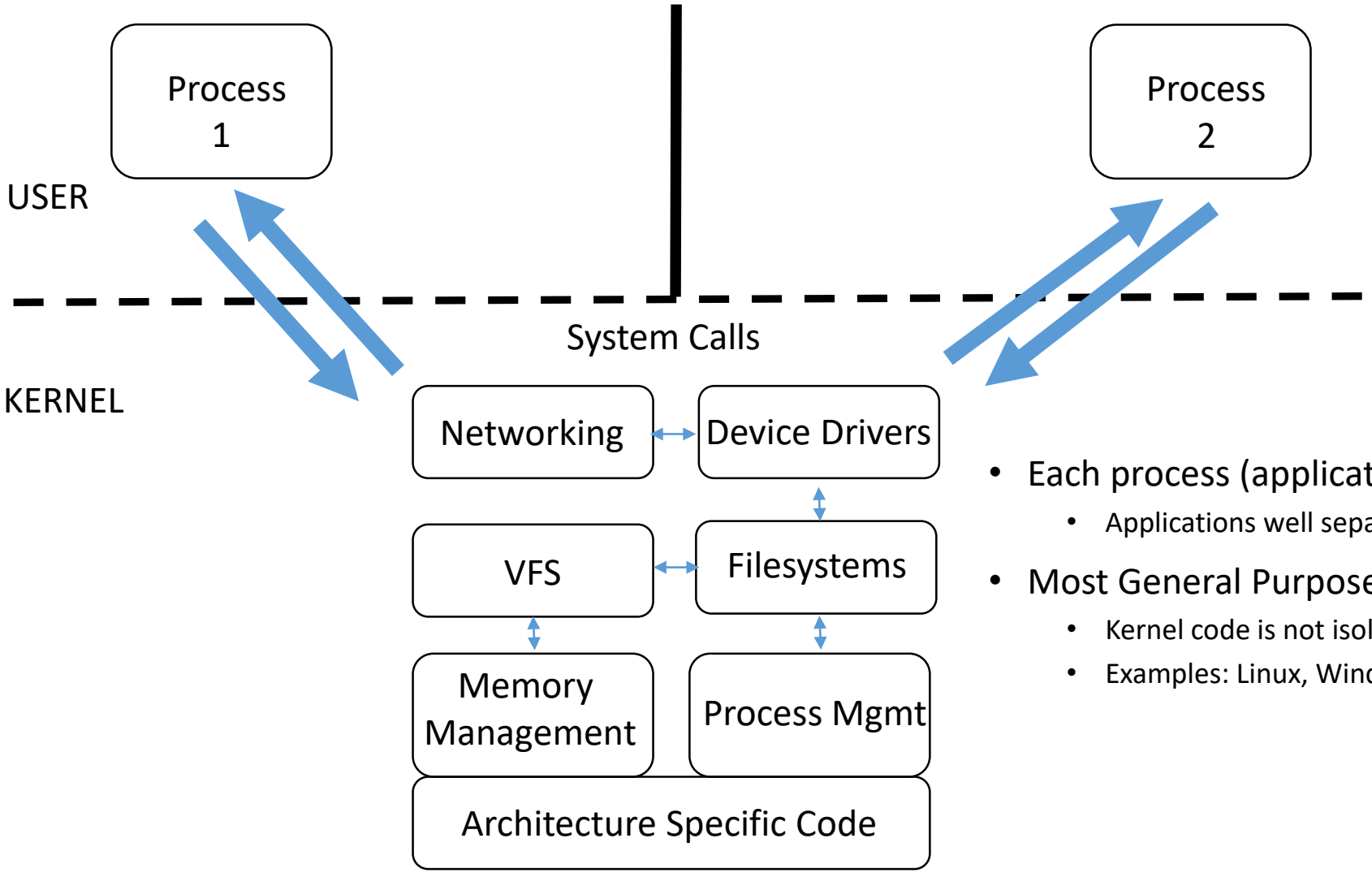
Part 2: Operating Systems Background

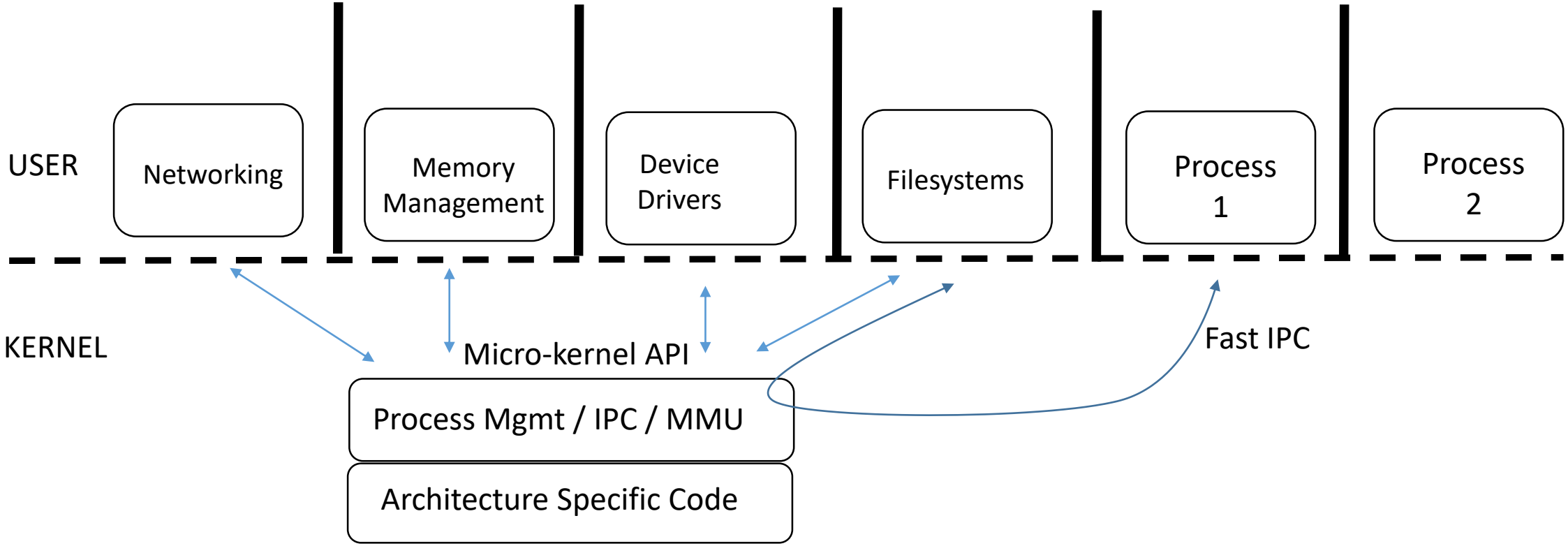
(Monolithic) Operating Systems



- Each process (application) has its own isolated space
  - Applications well separated
- Most General Purpose Operating Systems are ‘Monolithic’
  - Kernel code is not isolated from itself
  - Examples: Linux, Windows

Diagram adapted from Mauerer.

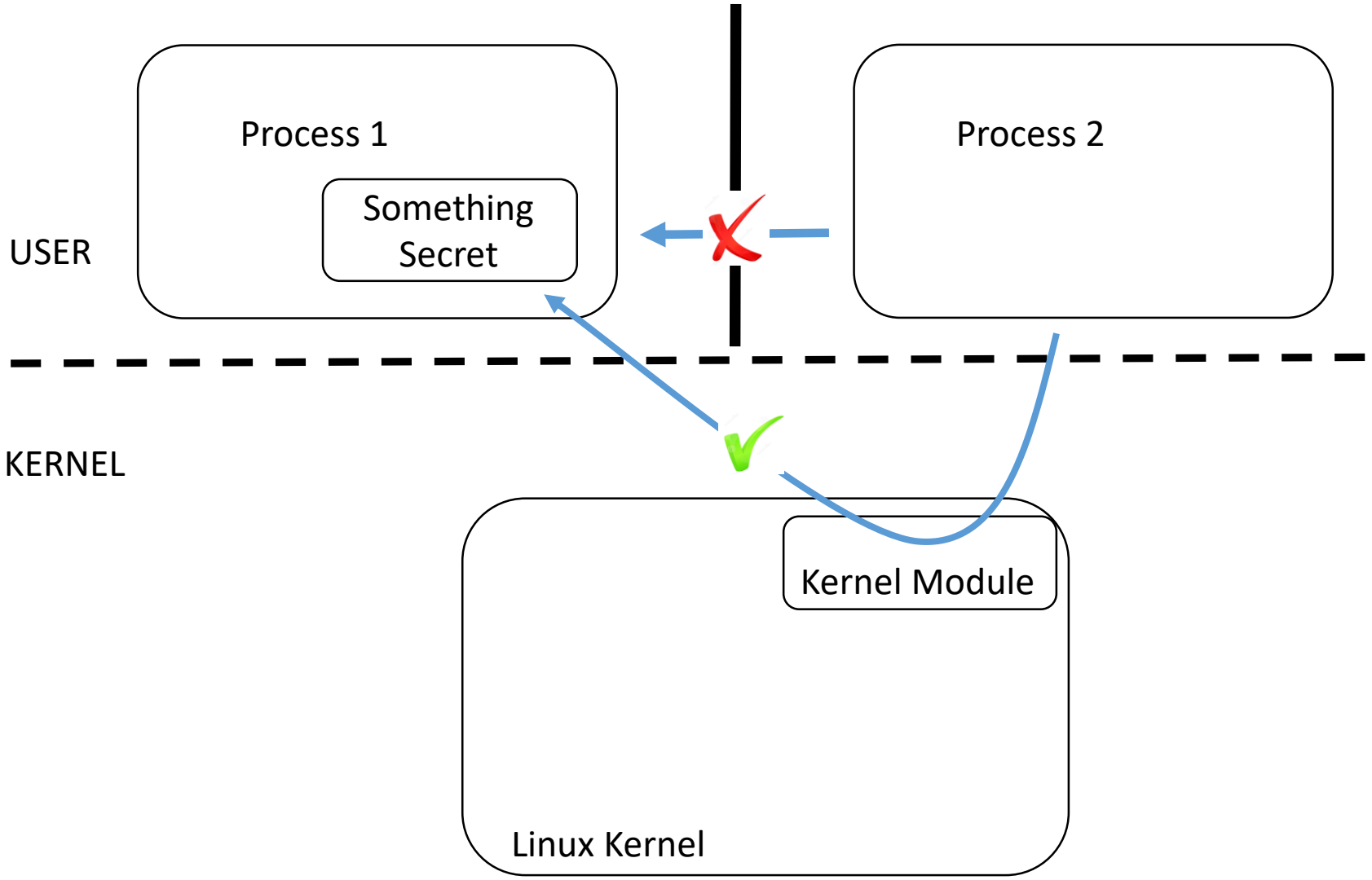
(Micro-Kernel) Operating Systems



- Examples: Fiasco.OC (L4 Micro-kernel), Composite
- Google Fuscia/Zircon

Part 3: Monolithic Linux Kernel (In-)Security Demo

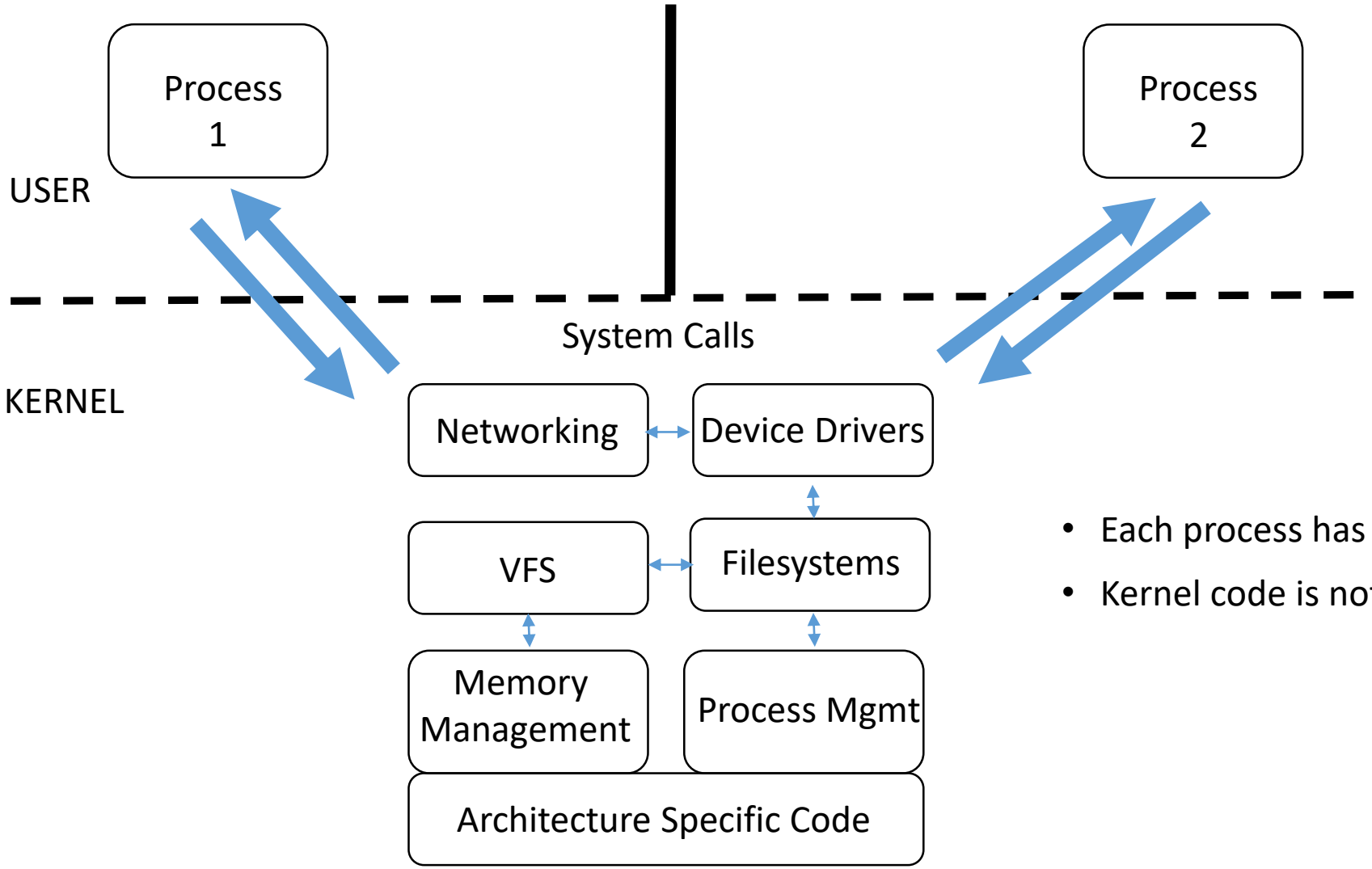
Demo: Attack Scenario



Part 4: Splitting the Kernel

(Hacking a Micro-Kernel interface into Linux)

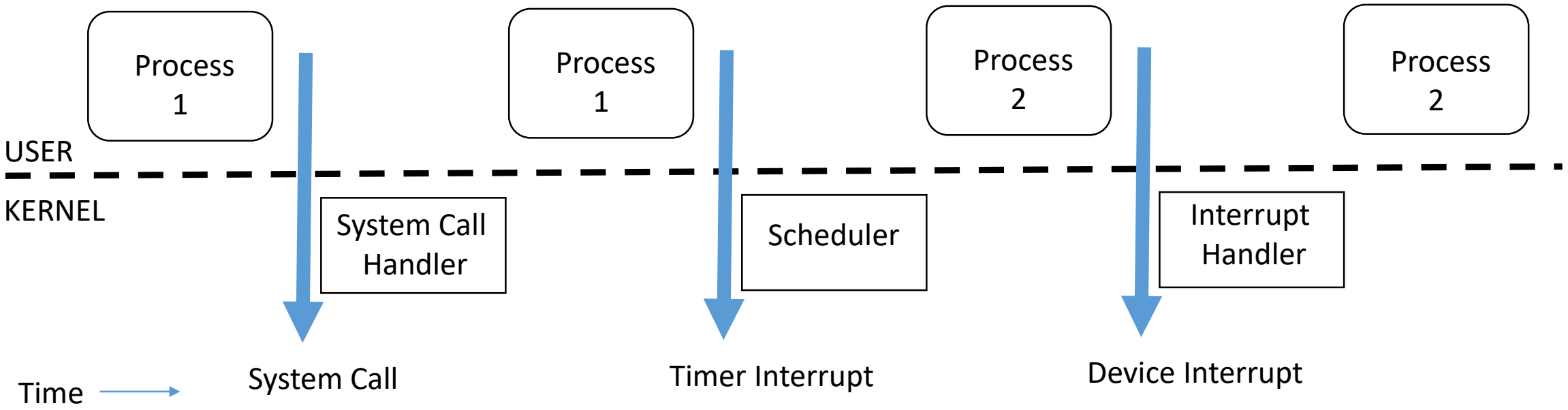
Linux Kernel



- Each process has its own isolated user space
- Kernel code is not isolated from itself

Diagram adapted from Mauerer.

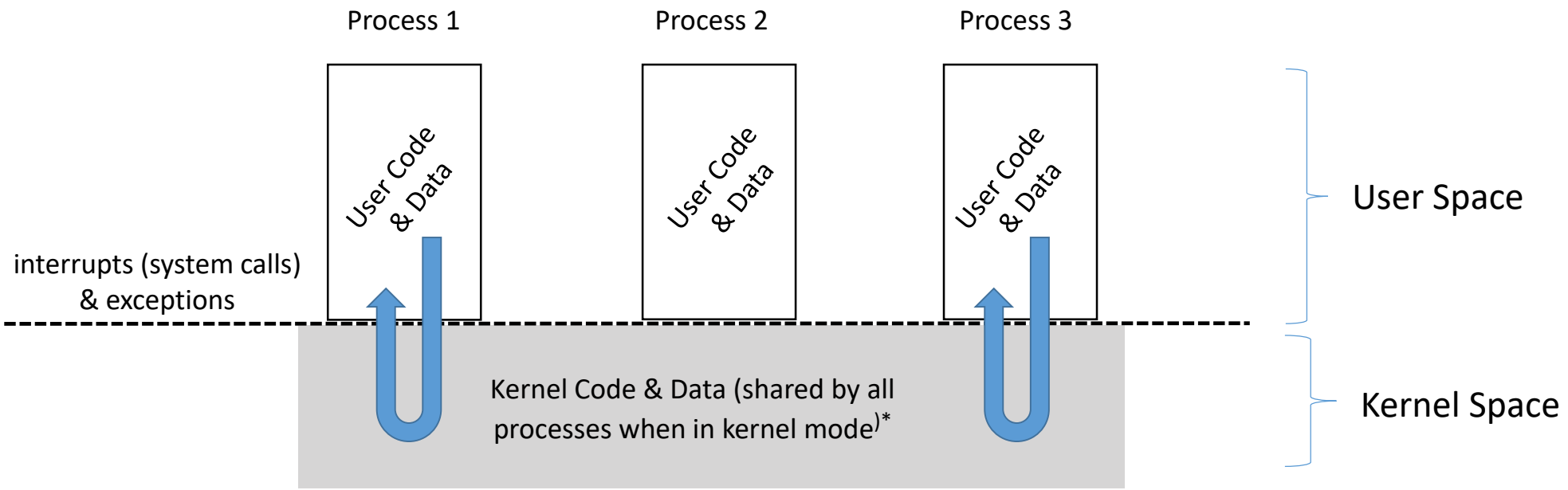
Some More Linux Kernel Background



- Each process has its own user space Page table mappings
  - Ignoring process cloning/threads
- Shares kernel mapping (synced from init_mm.pgd)
- Separate kernel stack per process
- Kernel entered through process context
  - It is not a separate 'thing' that runs concurrently
  - Does support the notion of kernel services via kthreads though

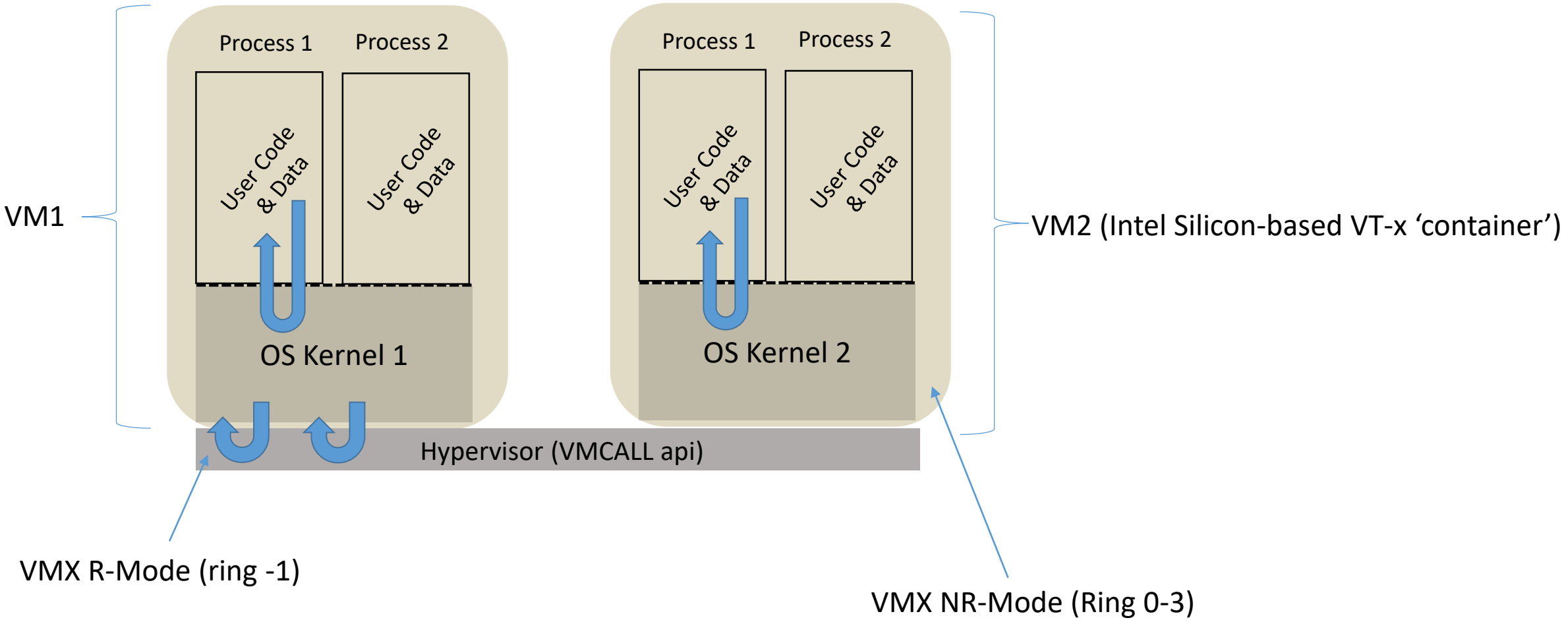
Diagram from Bovet,et al.

Linux Kernel Design



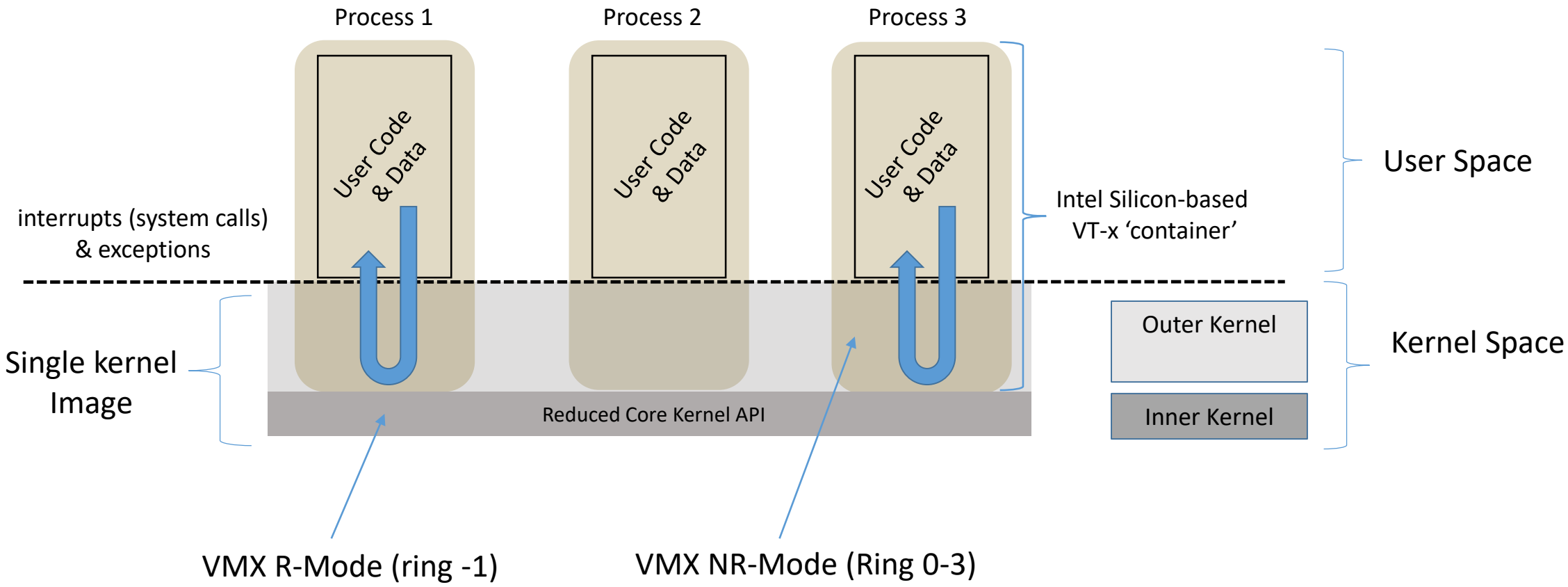
*separate kernel stack per process

Intel Virtualization HW support for VMMs

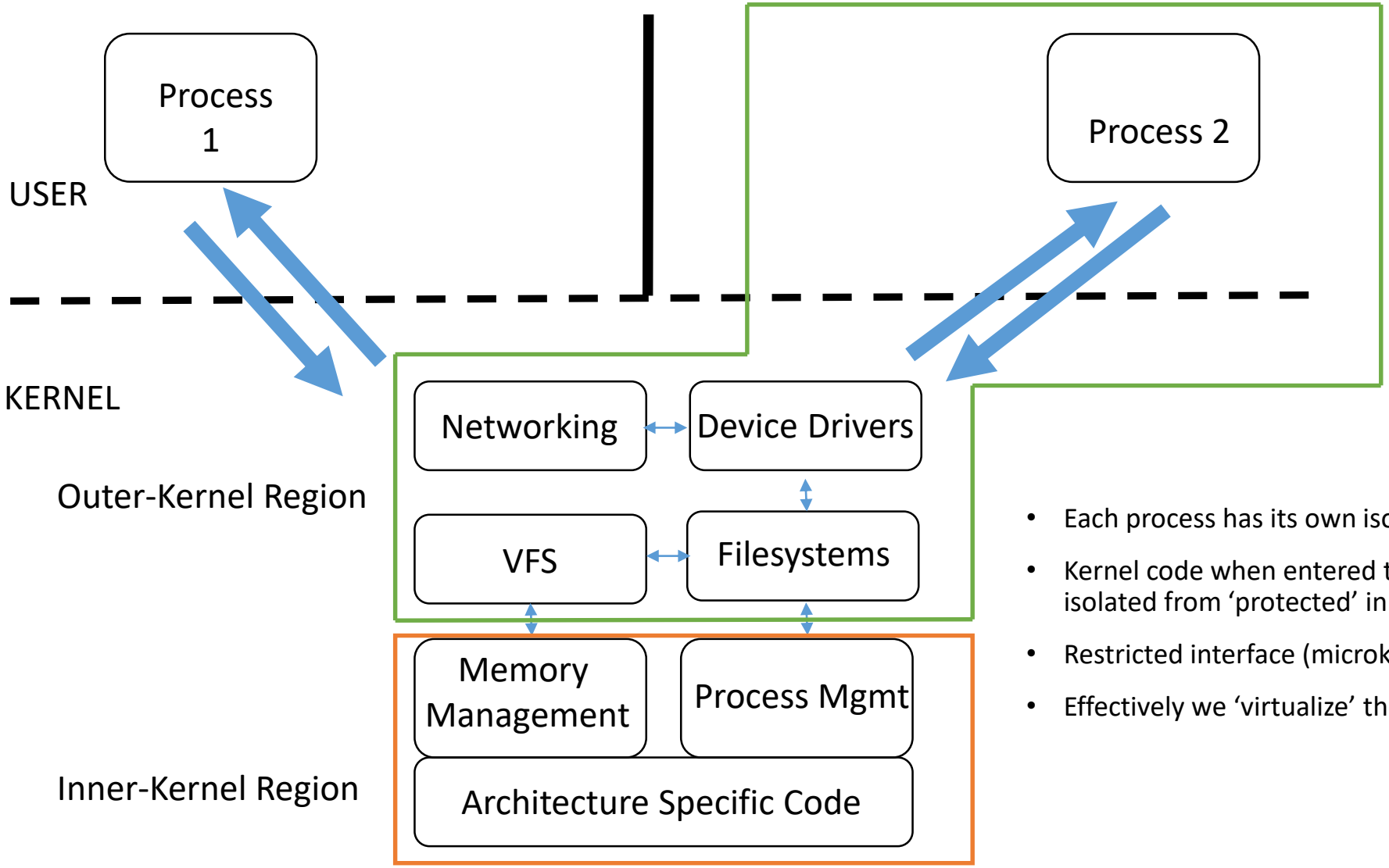


Separate Kernel Code & Data per VM

Linux Split-Kernel Design using Virtualization HW

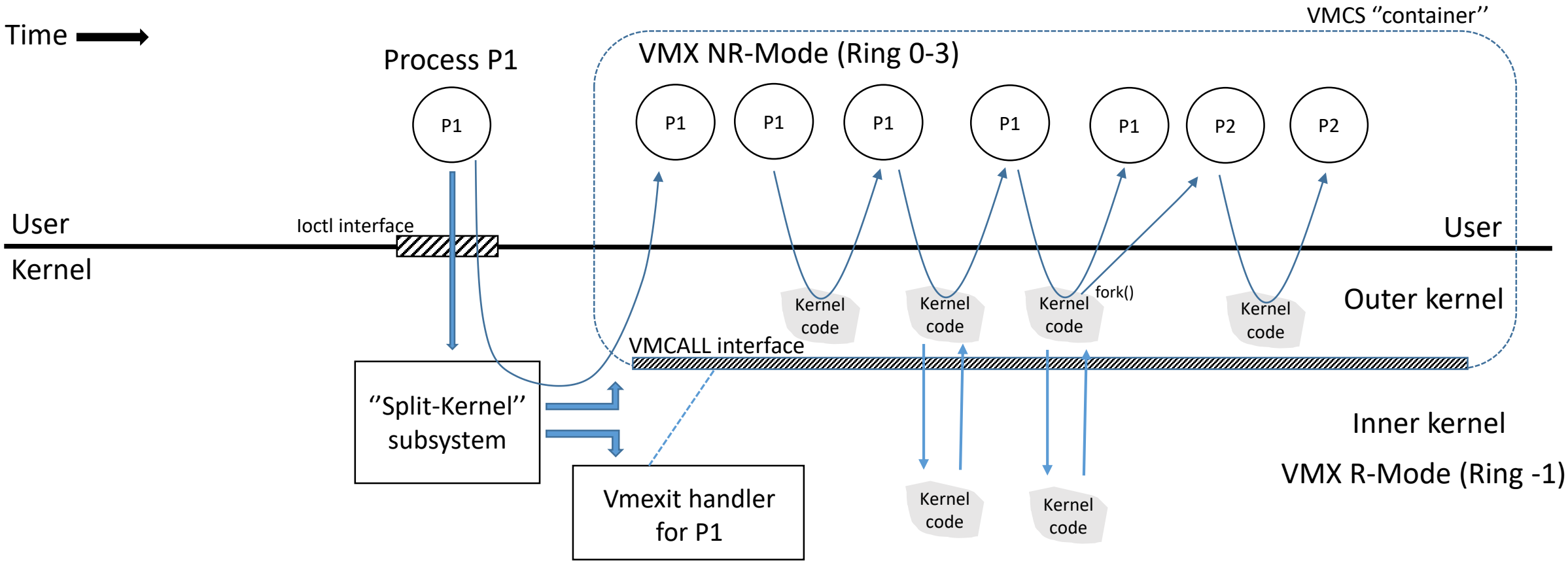


Split-Kernel (logical view)



- Each process has its own isolated user space
- Kernel code when entered through ‘containerized’ process is isolated from ‘protected’ inner kernel code & data
- Restricted interface (microkernel-like) to inner-kernel
- Effectively we ‘virtualize’ the kernel

Split-Kernel Process Lifecycle



Split-Kernel Architecture (x86_64)

- Use Intel VMX/EPT interposed on the normal linux kernel path
  - Allows vMMU interface for kernel entered through userspace-process to be enforced
  - Split the single shared kernel into an **Outer** region and an **Inner** region
  - Same kernel image but detects during execution whether in outer-kernel or inner-kernel mode
- X86: Each (container) process runs in vmx non-root mode within an EPT 'Container'
  - State defined by its own VMCS record
  - Each VMCS has its EPT pointer set to the same top-level table
  - Direct map 1:1 'host' physical memory except for 'protected' or 'private' memory regions
  - 'Protected' memory regions mapped RO, 'private' regions not mapped unless owned by that process
- do_schedule() from outer-kernel does VMCALL into inner-kernel
  - R-mode side of the process is scheduled / de-scheduled
- Inner-kernel needs to provide a VMEXIT handler
  - Need to maintain VMCS state across time-slices

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Some Code: Entering Outer-Kernel Mode

```
long ok_device_ioctl(struct file *filp, unsigned int cmd, unsigned long arg)
{
        switch(cmd)
        {
        case OKERNEL_ON_CMD:
                /* do okernel_enter() here... */
                HDEBUG("About to go into okernel on mode via okernel_enter() for pid (%d)\

                current->okernel_status = OKERNEL_ON;

                if(is_in_vmx_nr_mode()){
                        printk(KERN_CRIT "NR: Calling okernel_enter in  NR mode kernel...s
                }

                ret = okernel_enter(OKERNEL_ENTER_IOCTL);

                if(is_in_vmx_nr_mode()){
                        BXMAGICBREAK;
                        HDEBUG("Returning from okernel_enter (IOCTL_LAUNCH).\n");
                        BXMAGICBREAK;
                        goto nr_exit;
                }
                current->okernel_status = OKERNEL_OFF;

                if(ret){
                        printk(KERN_ERR "okernel_enter failed for pid <%d> ret (%d)\n", cu
                }
                HDEBUG("outer kernel off for <%d>\n", current->pid);
                unset_vmx_r_mode();
                break;
        default:
                printk(KERN_ERR "okernel invalid IOCTL cmd.\n");
                return -ENODEV;
}
nr_exit:
        return 0;
}
```

```
        HDEBUG("About to enter vmx handler while loop...\n");

        while(1){
                HDEBUG("Entering vmxit handler loop...\n");

                /* Use this instead of local_irq_disable() to save getting tangled in irq on/off
                native_irq_disable();

                /************************** GO FOR IT **************************/
                ret = vmx_run_vcpu(vcpu);
                /************************** GONE FOR IT! ***********************/

                if((vmcs_readl(GUEST_RFLAGS) & RFLAGS_IF_BIT)){
                        native_irq_enable();

                }

                HDEBUG("Returned from vmx_run_vcpu...handling exit condition...\n");

                if(ret==VMX_EXIT_REASONS_FAILED_VMENTRY){
                        HDEBUG("vmentry failed (%#x)\n", ret);
                        break;
                } else if (ret == EXIT_REASON_EPT_VIOLATION){
                        qual = vmcs_readl(EXIT_QUALIFICATION);
                        gp_addr = vmcs_readl(GUEST_PHYSICAL_ADDRESS);

                        HDEBUG("ept violation exit - qualification=%#lx gpa=%#lx\n",
                                qual, gp_addr);
                        /* Grant access to protected pages lazily */
                        if(__ok_protected_phys_addr(gp_addr)){
                                HDEBUG("ok: EPT vmexit on protected address:=(%#lx)\n", gp_addr);
                                if(ok_allow_protected_access(gp_addr)){
                                        (void)add_ept_page_perms(vcpu, gp_addr);

                                } else {
                                        /*
                                           Map in 'dummy' page for now  - need to be careful not
                                           create another vulnerability.
                                        */
                                        (void)remap_ept_page(vcpu, gp_addr, ok_get_protected_dumm
                                }
                                continue;
                        }
                HDEBUG("Done handling exit condition, looping...\n");
        }

        /* something went wrong - legitimate exit would have been through the
```

Some Code: Scheduling

```
asmlinkage __visible void __sched schedule(void)
{
        struct task_struct *tsk = current;
#if defined(CONFIG_OKERNEL)
#ifdef HPE_DEBUG
        volatile struct thread_info *ti;
        int cpu = smp_processor_id();
        struct tss_struct *tss = &per_cpu(cpu_tss, cpu);
        unsigned long fs;
        int orig_cpu = 0;
        int new_cpu = 0;
#endif

        if(is_in_vmx_nr_mode()){
                /* Return control to the original process running in root-mode VMX */
                /* shouldn't be holding locks at this point? */
#ifdef HPE_DEBUG
                ti = current_thread_info();
                rdmsrl(MSR_FS_BASE, fs);
                HDEBUG("called (pid=%d)  cpu_cur_tos (%#lx) flgs(%#x) MSR_FS_BASE=%#lx\n",
                        current->pid, (unsigned long)tss->x86_tss.sp0, ti->flags, fs);
                BXMAGICBREAK;
                HDEBUG("in_atomic(): %d, irqs_disabled(): %d, pid: %d, name: %s\n",
                       in_atomic(), irqs_disabled(), current->pid, current->comm);
                HDEBUG("preempt_count (%#x) rcu_preempt_depth (%#x)\n",
                       preempt_count(), rcu_preempt_depth());
#if defined(CONFIG_TRACE_IRQFLAGS) && defined(CONFIG_PROVE_LOCKING)
                HDEBUG("current->h_irqs_en (%d)\n",
                       current->hardirqs_enabled);
#endif /* CONFIG_TRACE_IRQFLAGS */
#endif /* HPE_DEBUG */
                sched_submit_work(tsk);
                (void)vmcall(VMCALL_SCHED);
        } else {
                sched_submit_work(tsk);
                do {
                        preempt_disable();
                        okernel_schedule(false);
                        sched_preempt_enable_no_resched();
                } while (need_resched());
        }
```

```
void vmx_handle_vmcall(struct vmx_vcpu *vcpu, int nr_irqs_enabled)
{
        struct vmx_vcpu *cpu_ptr;
        /* do_fork_fixup args */
        struct task_struct *p;

        cmd = vcpu->regs[VCPU_REGS_RAX];

        if(cmd == VMCALL_DO_EXEC_FIXUP_HOST){
                /* Next time we take a vmexit we will return using these page tables - should val
                h_cr3 = vcpu->regs[VCPU_REGS_RBX];
                HDEBUG("excec_fixup: Setting saved HOST CR3 to (%#lx) __pa (%#lx)\n",
                       (unsigned long)h_cr3, __pa(h_cr3));
                vmx_get_cpu(vcpu);
                vmcs_writel(HOST_CR3, __pa(h_cr3));
                vmx_put_cpu(vcpu);
                BXMAGICBREAK;
                ret = 0;
        } else if (cmd == VMCALL_SCHED){
                unset_vmx_r_mode();
                /* This is the only place we should be swapping CPUs */
                /* There is redunancy here: don't need to do all this flushing */
                vpid_sync_vcpu_global();
                ept_sync_global();
                barrier();

                schedule_r_mode();

                vpid_sync_vcpu_global();
                ept_sync_global();

                /* We may come back here on a different CPU...*/
                set_vmx_r_mode();

                cpu = smp_processor_id();
                tss = &per_cpu(cpu_tss, cpu);

                HDEBUG("ret schedule_r (pid %d) cpu_cur_tos (%#lx) tss.sp0 (%#lx) flgs (%#x)\n",
                       current->pid, current_top_of_stack(), (unsigned long)tss->x86_tss.sp0, r_t
                HDEBUG("ret from sched in_atomic(): %d, irqs_disabled(): %d, pid: %d, name: %s\n"
                       in_atomic(), irqs_disabled(), current->pid, current->comm);
                HDEBUG("ret from preempt_count (%d) rcu_preempt_depth (%d)\n",
                       preempt_count(), rcu_preempt_depth());
                BXMAGICBREAK;
        } else if(cmd == VMCALL_DOEXIT){
                code = (long)vcpu->regs[VCPU_REGS_RBX];
                HDEBUG("calling do_exit(%ld)...\n", code);
                vmx_destroy_vcpu(vcpu);
```

Performance and Invasiveness

- Still surprised it works at all…
  - Largest test machine 2 physical CPUS with 24 cores & 256 GB memory
  - Focus on functionality not performance or upstream optimization
  - Docker a good testcase for use of obscure Linux kernel features BTW
  - Initial debugging really,really hard
  - Can’t use printk(), etc but Bochs is really useful ☺
- Benchmarking
  - Linux kernel build, Apache Phoronix, etc.
  - Overhead around 2-5% depending upon number of processor cores
  - Depends on approach to handling process migration across CPU cores
- Invasiveness
  - Core code around 1000-2000 new lines in separate (static) kernel module
  - Plus maybe 100-200 lines of other Linux kernel modifications
  - Does still look like Linux!

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  - Processor scaling depends on approach to handling process migration across CPU cores
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Current Status / Opportunities / Futures

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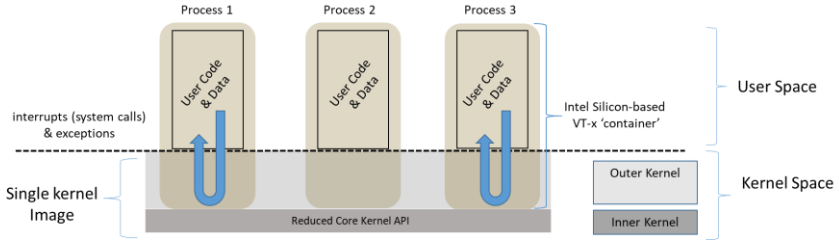

- We do mention some of the concepts in our HOTOS paper
  - 'Separating Translation from Protection in Address Spaces with Dynamic Remapping', HOTOS 17
- Worth considering for general Linux use
  - Not just container deployments
  - Can run light-dm in outer-kernel mode (e.g. full desktop)
  - Need to fill-out ARM v8.1 implementation
- Good vehicle for kernel malware tracing on top of enhanced security
  - What else?

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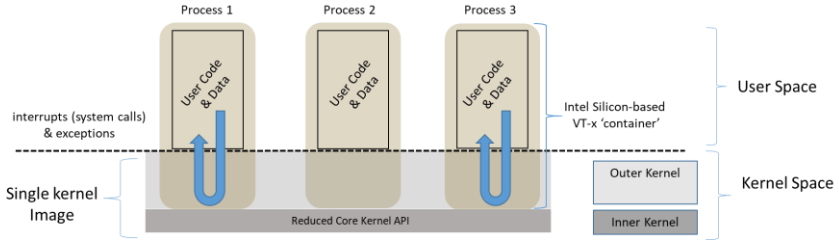

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- Worth considering for general Linux use
  - Not just container deployments
  - Can run light-dm in outer-kernel mode (e.g. full desktop)
  - Need to fill-out ARM v8.1 implementation
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  - What else?

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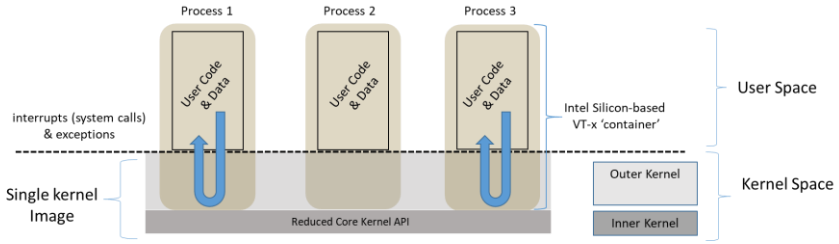

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