The Kernel Abstraction

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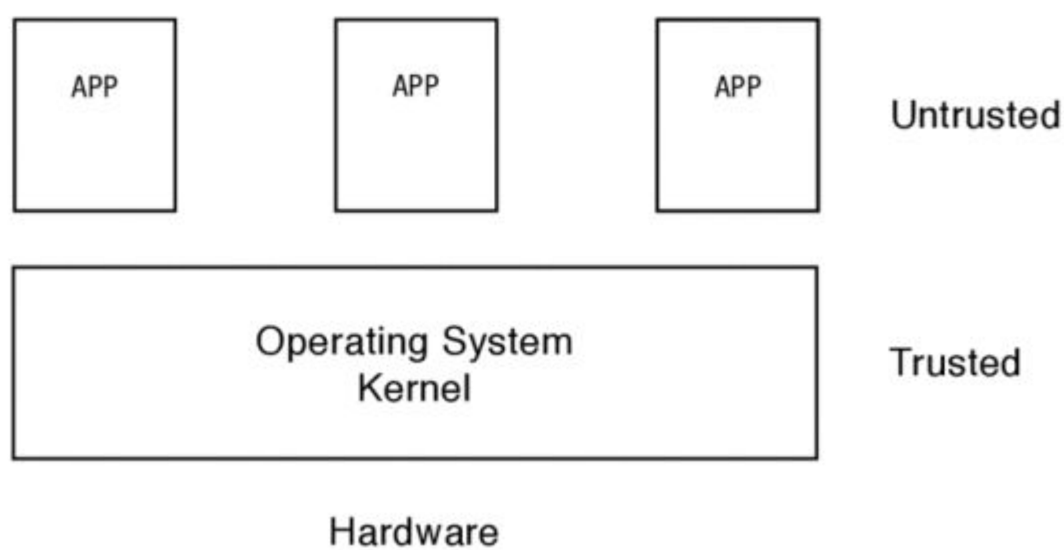
The Kernel Abstraction

A central role of operating systems is protection

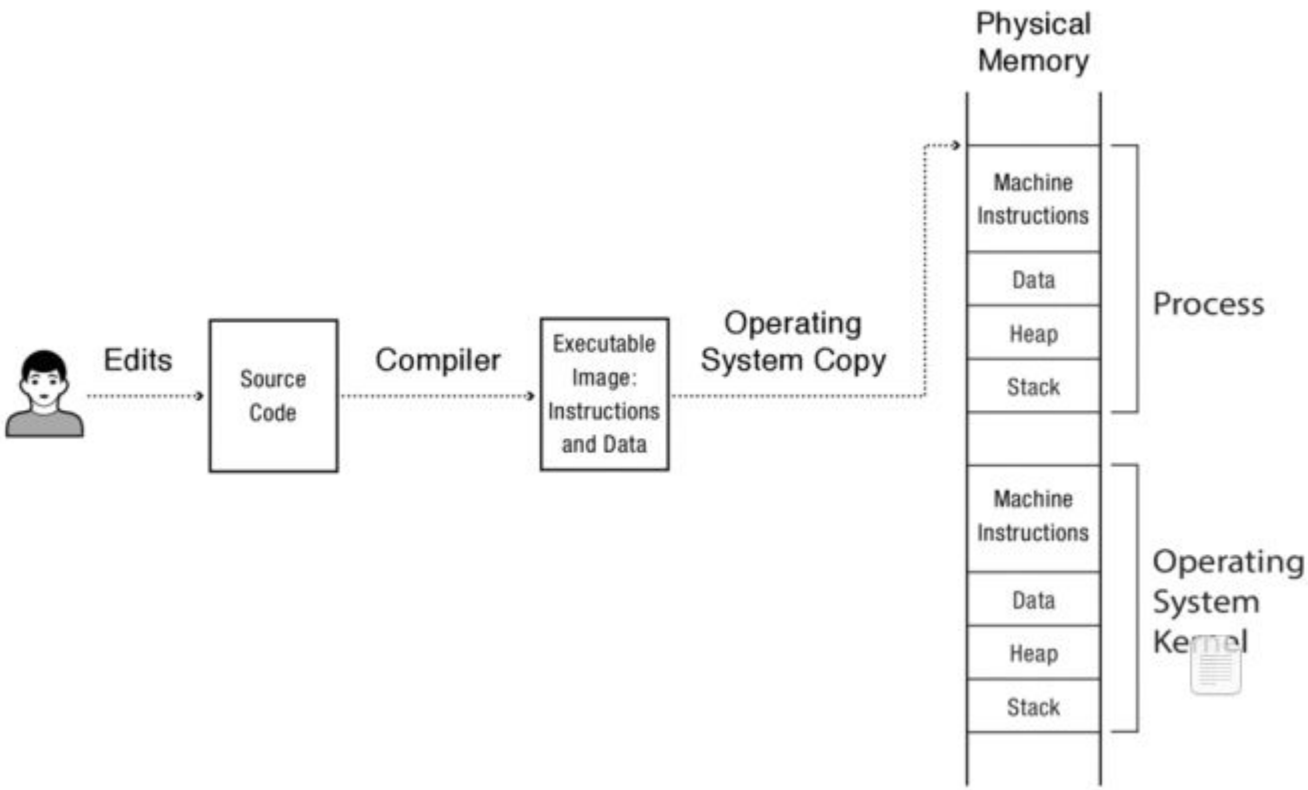
- **Reliability**. Protection prevents bugs in one program from causing crashes in other programs or in the operating system
- **Security**. Some users or applications on a system may be less than completely trustworthy; therefore, the operating system must limit the scope of what they can do.
- **Privacy**. On a multi-user system, each user must be limited to only the data that she is permitted to access
- **Fair resource allocation**. Protection is also needed for effective resource allocation.

Operating system kernel

- The kernel, the lowest level of software running on the system, has full access to all of the machine hardware
- Applications themselves often need to safely execute untrusted third party code



The Process Abstraction



Process Abstraction

- Process: an *instance* of a program, running with limited rights
  - Thread: a sequence of instructions within a process
    - Potentially many threads per process (for now 1:1)
  - Address space: set of rights of a process
    - Memory that the process can access
    - Other permissions the process has (e.g., which system calls it can make, what files it can access)

Challenge: Protection

- How do we execute code with restricted privileges?
  - Either because the code is buggy or if it might be malicious
- Some examples:
  - A script running in a web browser
  - A program you just downloaded off the Internet
  - A program you just wrote that you haven’t tested yet

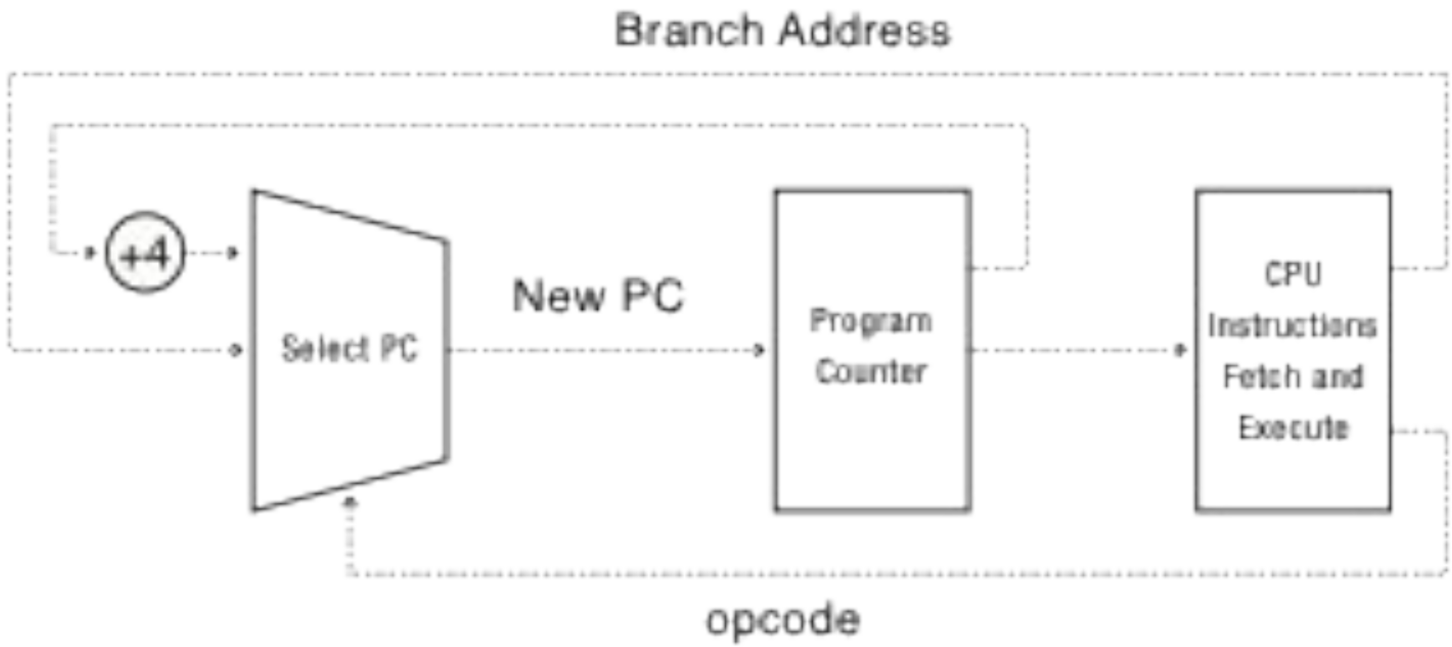
Dual-mode operation: user vs. kernel

- Process concept
  - A process is the OS abstraction for executing a program with limited privileges
- Dual-mode operation: user vs. kernel
  - Kernel-mode: execute with complete privileges
  - User-mode: execute with fewer privileges
- Safe control transfer
  - How do we switch from one mode to the other?

Hardware Support: Dual-Mode Operation

- Kernel mode
  - Execution with the full privileges of the hardware
  - Read/write to any memory, access any I/O device, read/write any disk sector, send/read any packet
- User mode
  - Limited privileges
  - Only those granted by the operating system kernel
- On the x86, mode stored in EFLAGS register
- On the MIPS, mode in the status register

A Model of a CPU



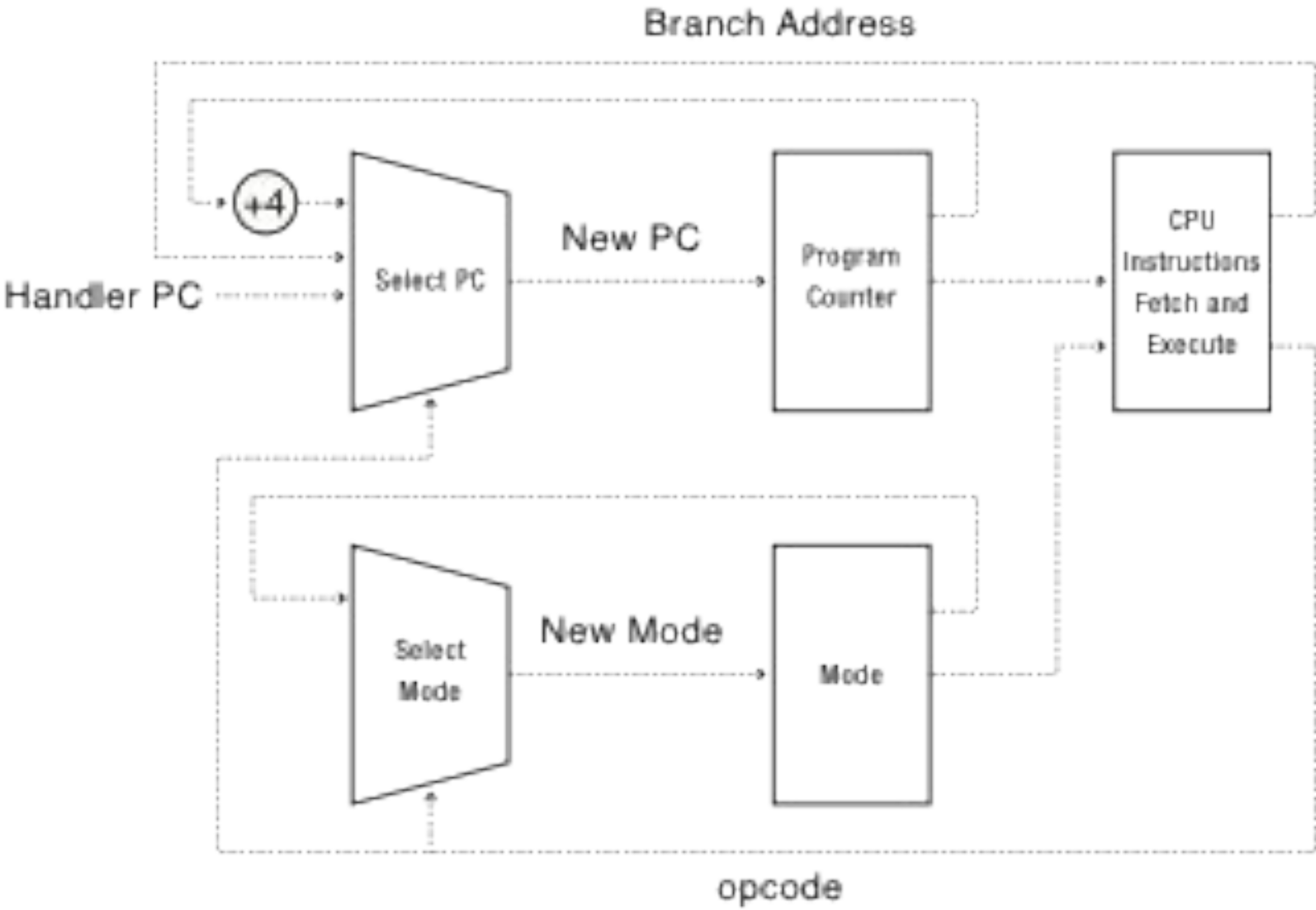
Hardware Support: Dual-Mode Operation

- Privileged instructions
  - Available to kernel
  - Not available to user code
- Limits on memory accesses
  - To prevent user code from overwriting the kernel
- Timer
  - To regain control from a user program in a loop
- Safe way to switch from user mode to kernel mode, and vice versa

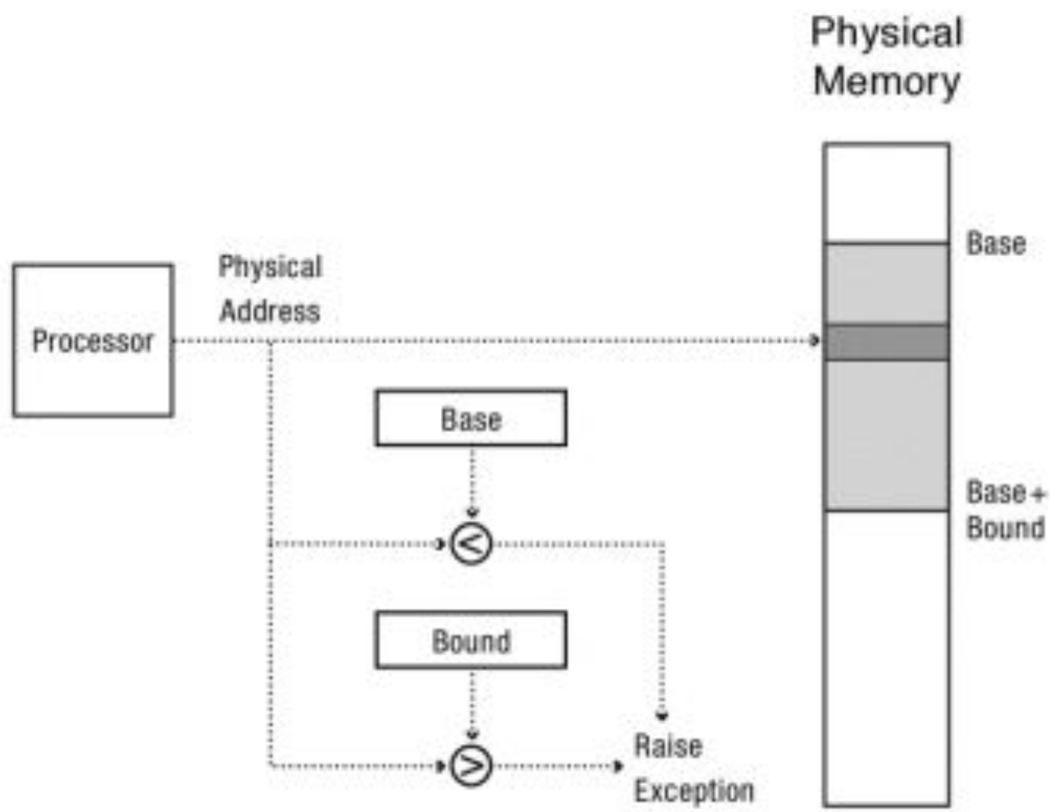
Privileged instructions

- Processes can indirectly change their privilege level by executing a special instruction, called a **system call**
- Instructions available in the kernel mode.
- If an application attempts to access restricted memory or attempts to change its privilege level cause a **processor exception**.

A CPU with Dual-Mode Operation



Example: Memory protection



Example

```
int staticVar = 0;      // a static variable
main() {
   staticVar += 1;
   sleep(10);  // sleep for x seconds
   printf ("static address: %x, value: %d\n", &staticVar,
                                                staticVar);
}
```

What happens if we run two instances of this program at the same time?

What if we took the address of a procedure local variable in two copies of the same program running at the same time?

Hardware Timer

- Hardware device that periodically interrupts the processor
  - Returns control to the kernel handler
  - Interrupt frequency set by the kernel
    - Not by user code!
  - Interrupts can be temporarily deferred
    - Not by user code!
    - Interrupt deferral crucial for implementing mutual exclusion

Mode Switch

- From user mode to kernel mode
  - Interrupts
    - Triggered by timer and I/O devices
  - Exceptions
    - Triggered by unexpected program behavior
    - Or malicious behavior!
  - System calls (aka protected procedure call)
    - Request by program for kernel to do some operation on its behalf (`trap` or `syscall`)
    - Only limited # of very carefully coded entry points

Mode Switch

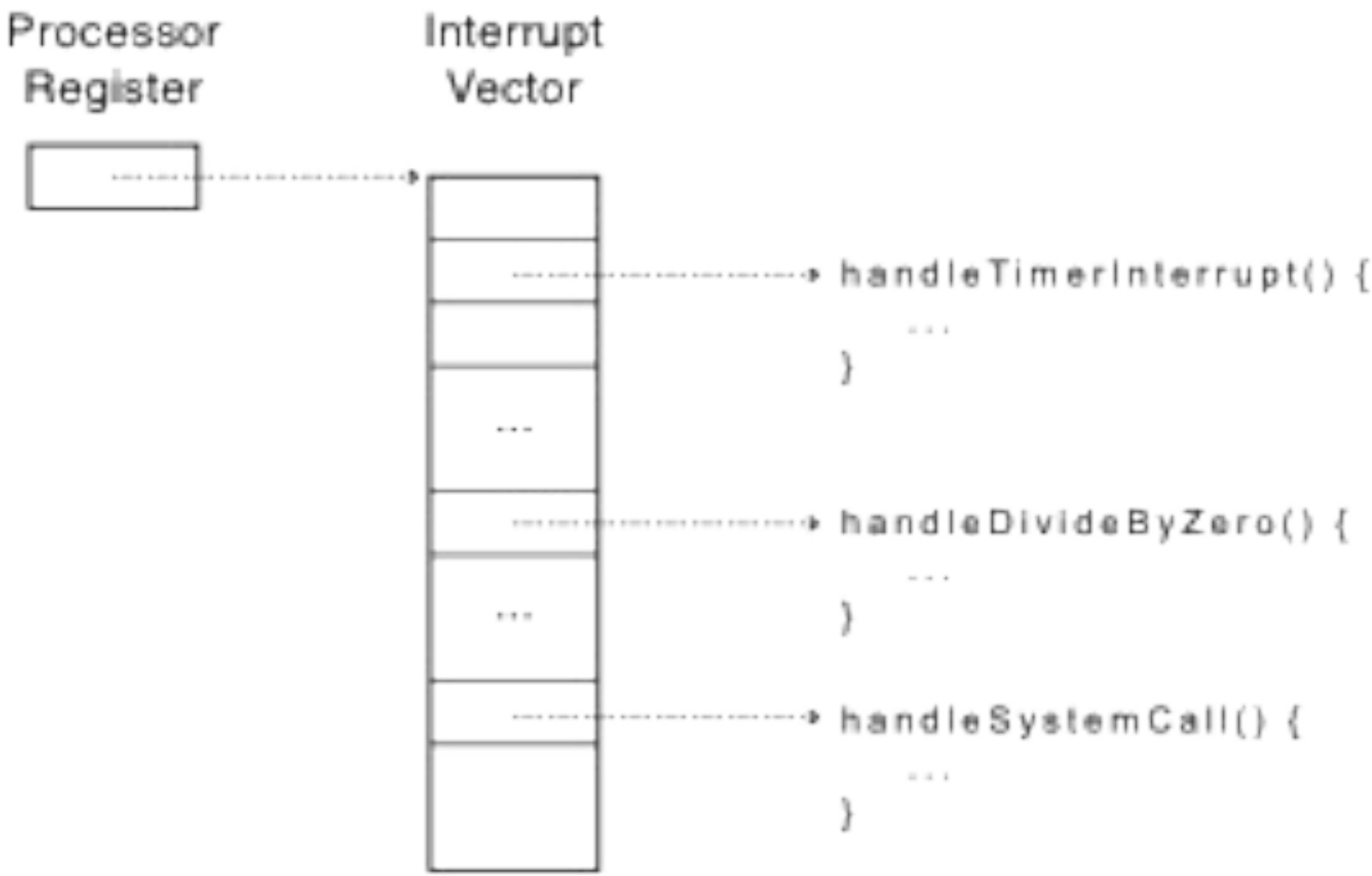
- From kernel mode to user mode
  - New process/new thread start
    - Jump to first instruction in program/thread
  - Return from interrupt, exception, system call
    - Resume suspended execution
  - Process/thread context switch
    - Resume some other process
  - User-level upcall (UNIX signal)
    - Asynchronous notification to user program

How do we take interrupts safely?

- Interrupt vector
  - Limited number of entry points into kernel
- Atomic transfer of control
  - Single instruction to change:
    - Program counter
    - Stack pointer
    - Memory protection
    - Kernel/user mode
- Transparent restartable execution
  - User program does not know interrupt occurred

Interrupt Vector

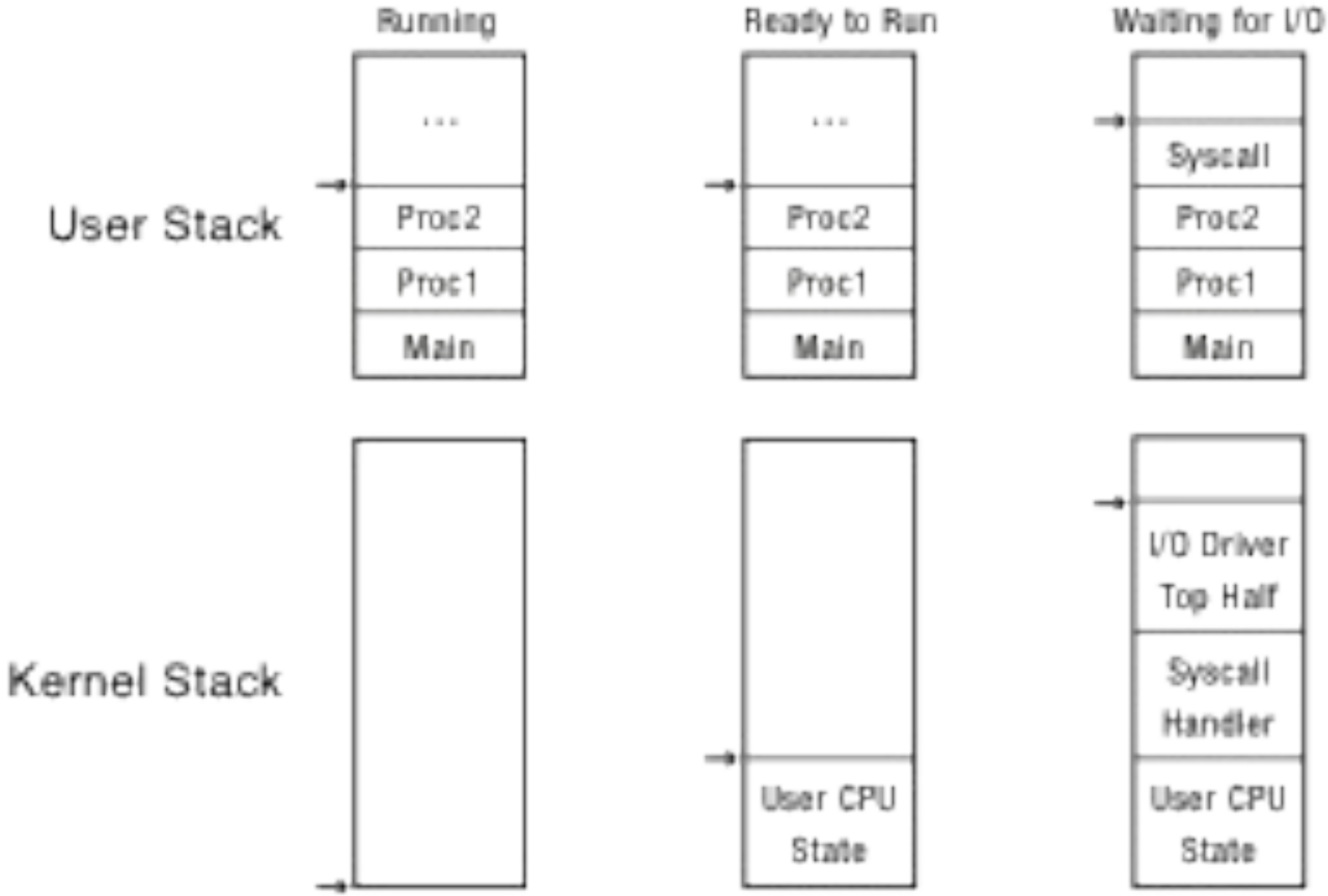
- Table set up by OS kernel; pointers to code to run on different events



Interrupt Stack

- Per-processor, located in kernel (not user) memory
  - Usually a process/thread has both: kernel and user stack
- Why can’t the interrupt handler run on the stack of the interrupted user process?

Interrupt Stack



Interrupt Masking

- Interrupt handler runs with interrupts off
  - Re-enabled when interrupt completes
- OS kernel can also turn interrupts off
  - Eg., when determining the next process/thread to run
  - On x86
    - CLI: disable interrrupts
    - STI: enable interrupts
    - Only applies to the current CPU (on a multicore)
- We'll need this to implement synchronization in chapter 5

Interrupt Handlers

- Non-blocking, run to completion
  - Minimum necessary to allow device to take next interrupt
  - Any waiting must be limited duration
  - Wake up other threads to do any real work
    - Linux: semaphore
- Rest of device driver runs as a kernel thread

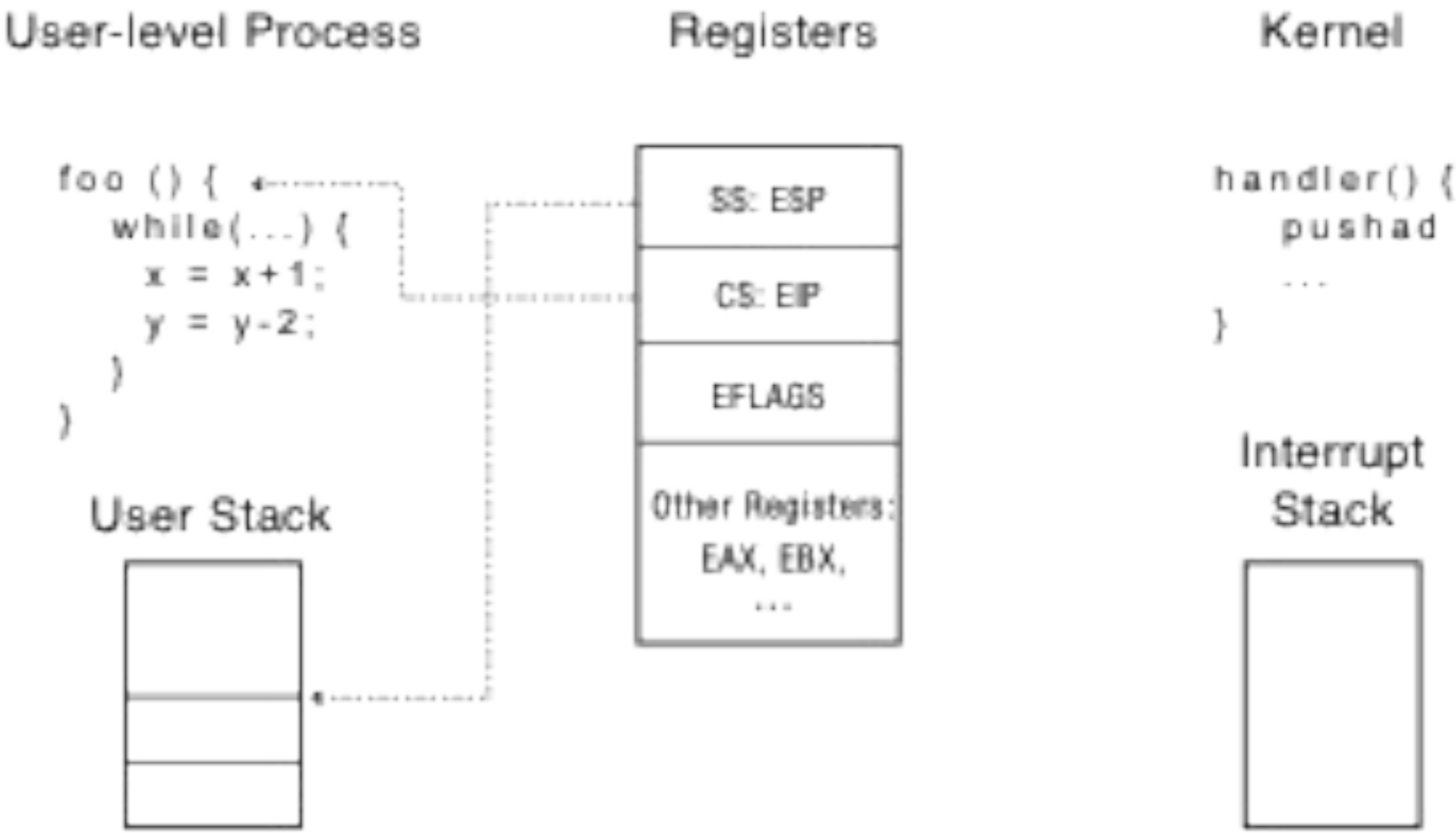
Case Study: MIPS Interrupt/Trap

- Two entry points: TLB miss handler, everything else
- Save type: syscall, exception, interrupt
  - And which type of interrupt/exception
- Save program counter: where to resume
- Save old mode, interruptable bits to status register
- Set mode bit to kernel
- Set interrupts disabled
- For memory faults
  - Save virtual address and virtual page
- Jump to general exception handler

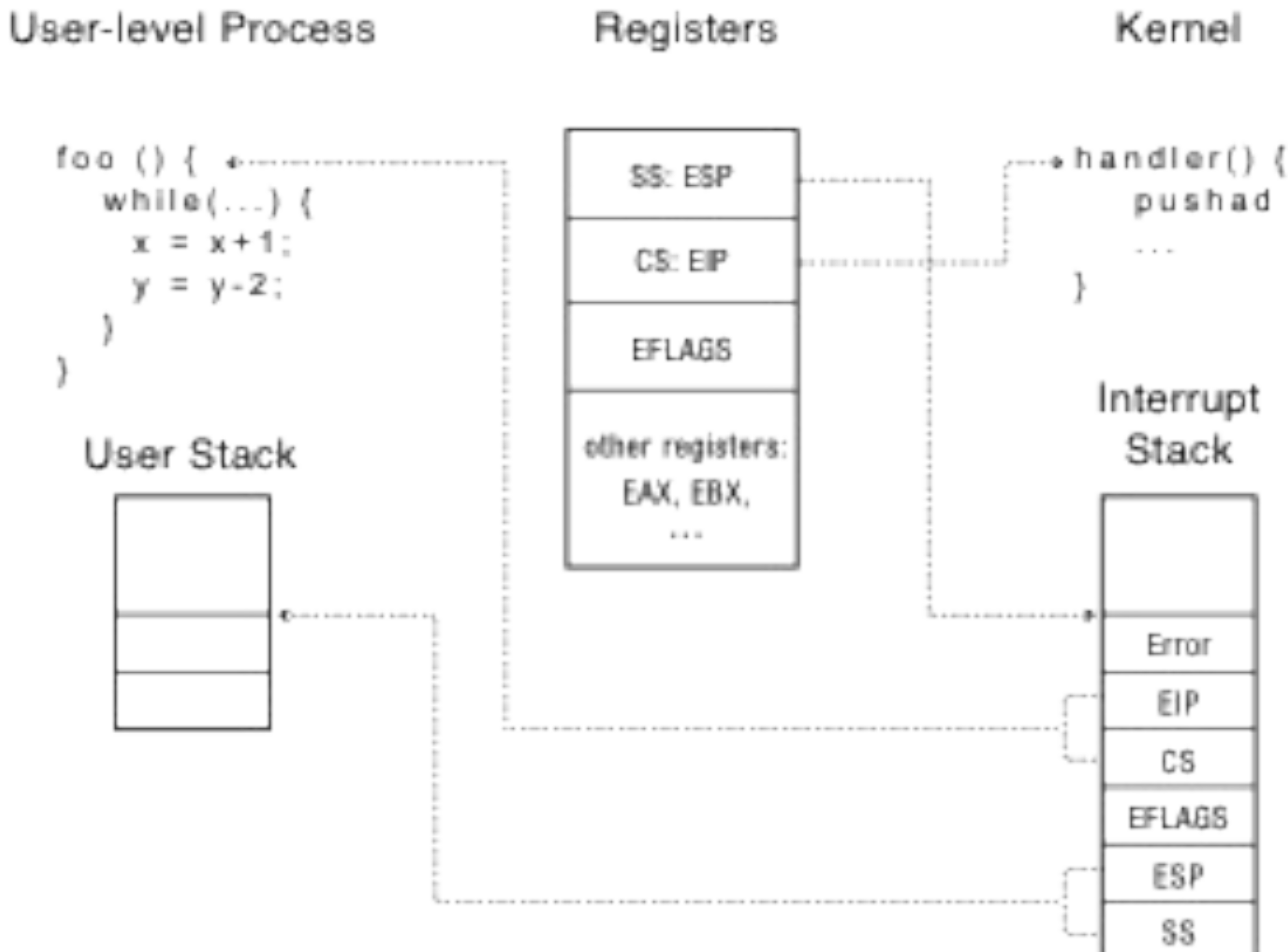
Case Study: x86 Interrupt

- Save current stack pointer
- Save current program counter
- Save current processor status word (condition codes)
- Switch to kernel stack; put SP, PC, PSW on stack
- Switch to kernel mode
- Vector through interrupt table
- Interrupt handler saves registers it might clobber

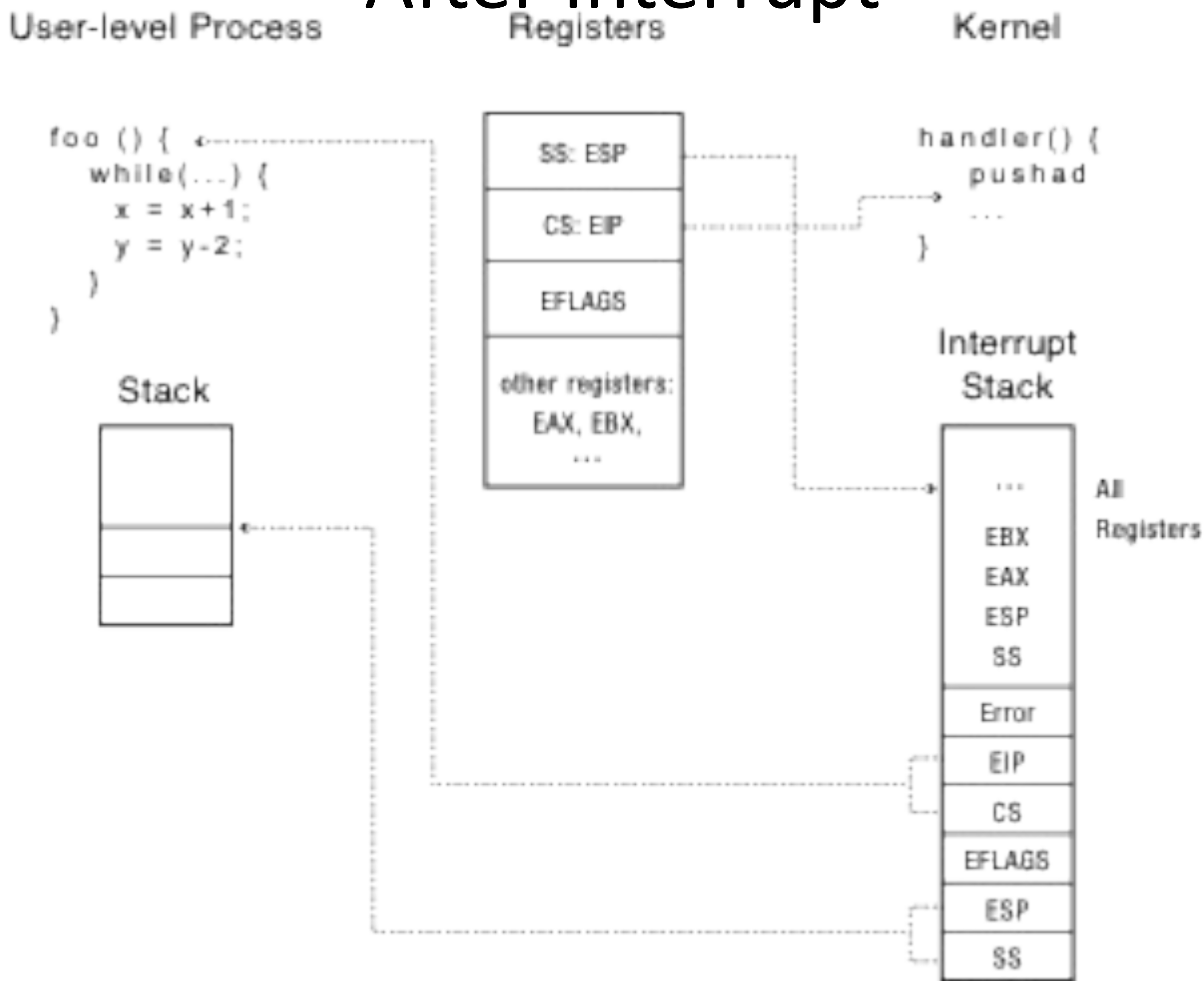
Before Interrupt



During Interrupt



After Interrupt



Question

- Why is the stack pointer saved twice on the interrupt stack?
  - Hint: is it the same stack pointer?

At end of handler

- Handler restores saved registers
- Atomically return to interrupted process/thread
  - Restore program counter
  - Restore program stack
  - Restore processor status word/condition codes
  - Switch to user mode

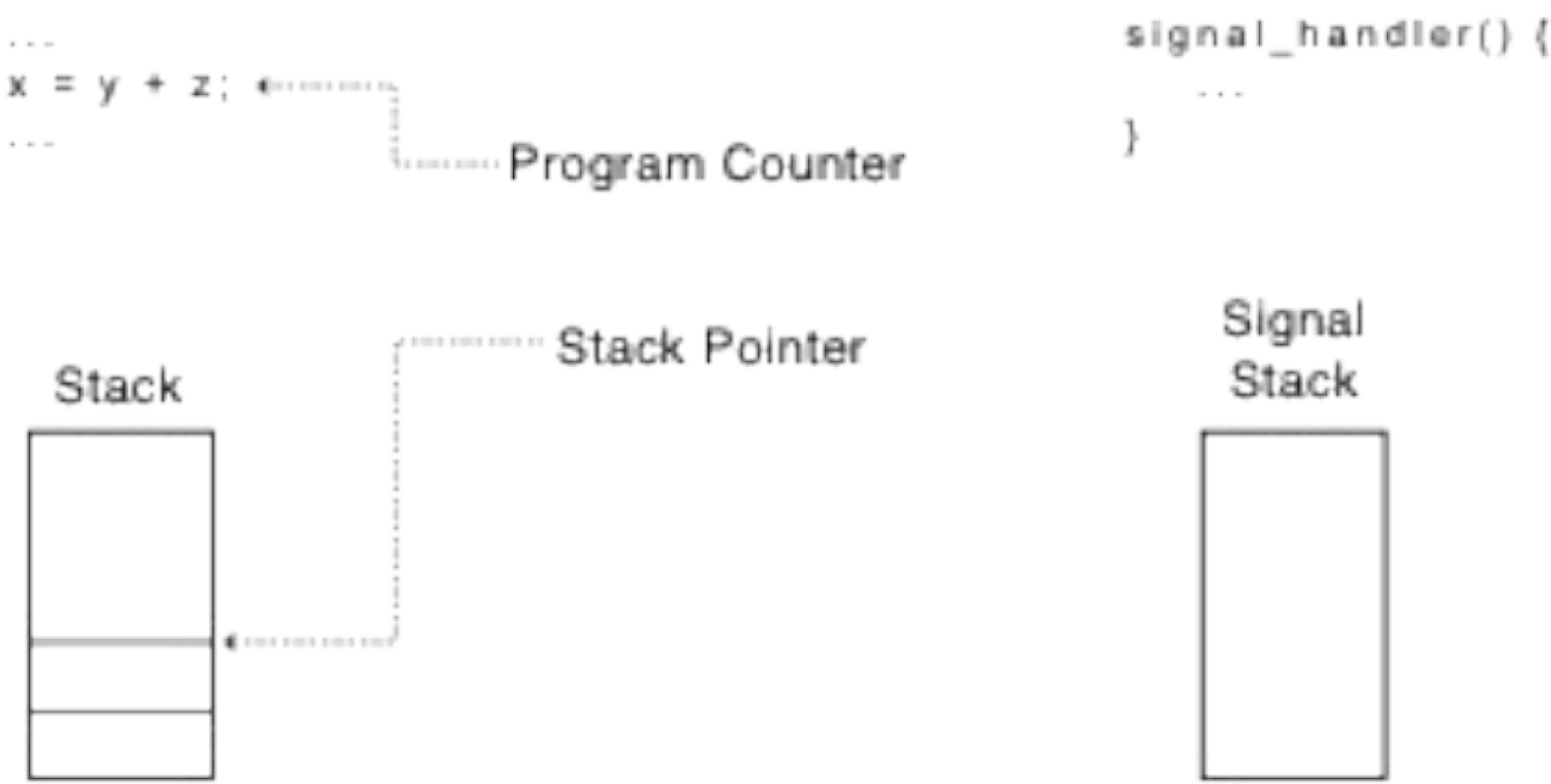
Upcall: User-level event delivery

- Notify user process of some event that needs to be handled right away
  - Time expiration
    - Real-time user interface
    - Time-slice for user-level thread manager
  - Interrupt delivery for VM player
  - Asynchronous I/O completion (async/await)
- AKA UNIX signal

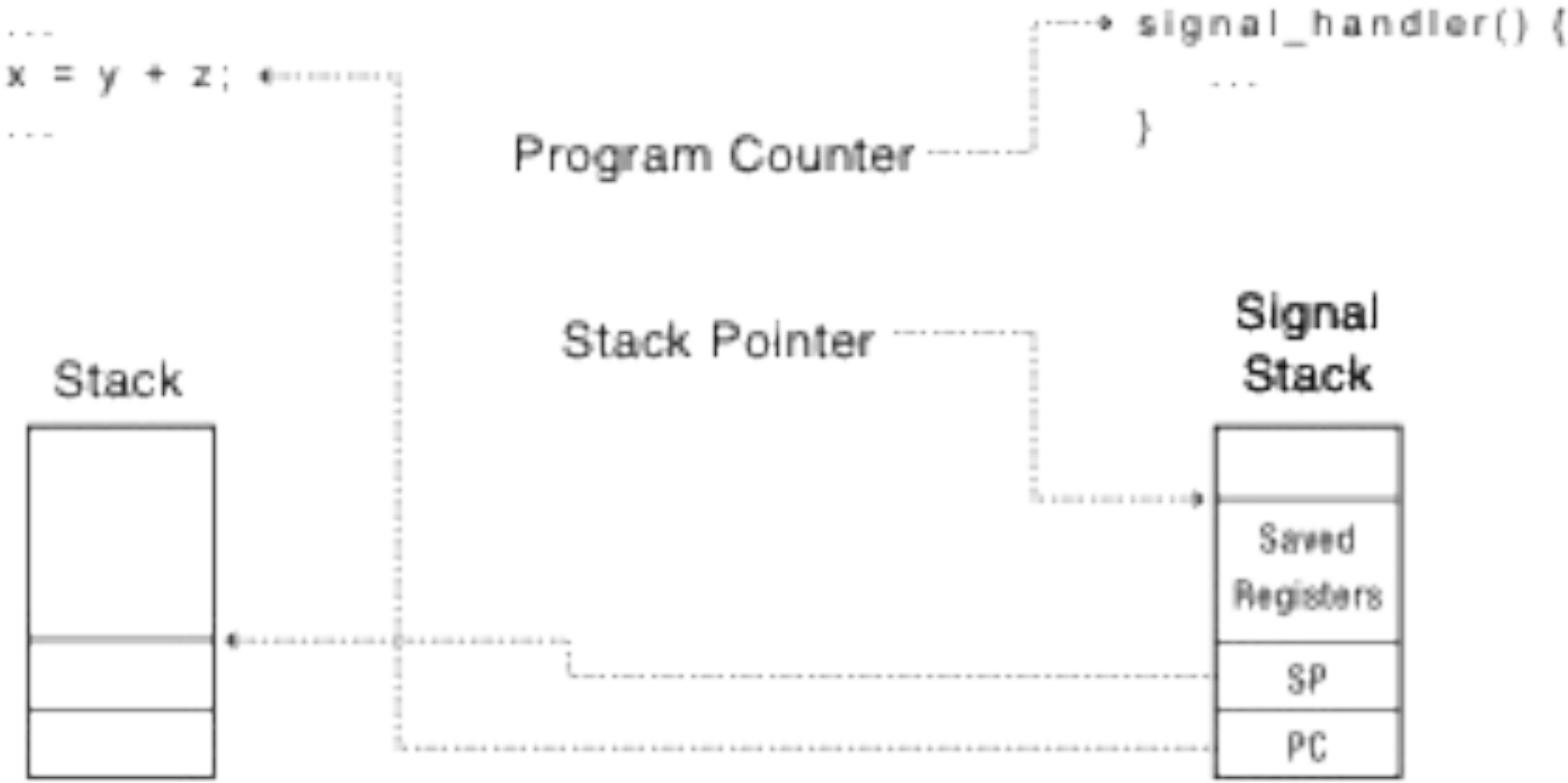
Upcalls vs Interrupts

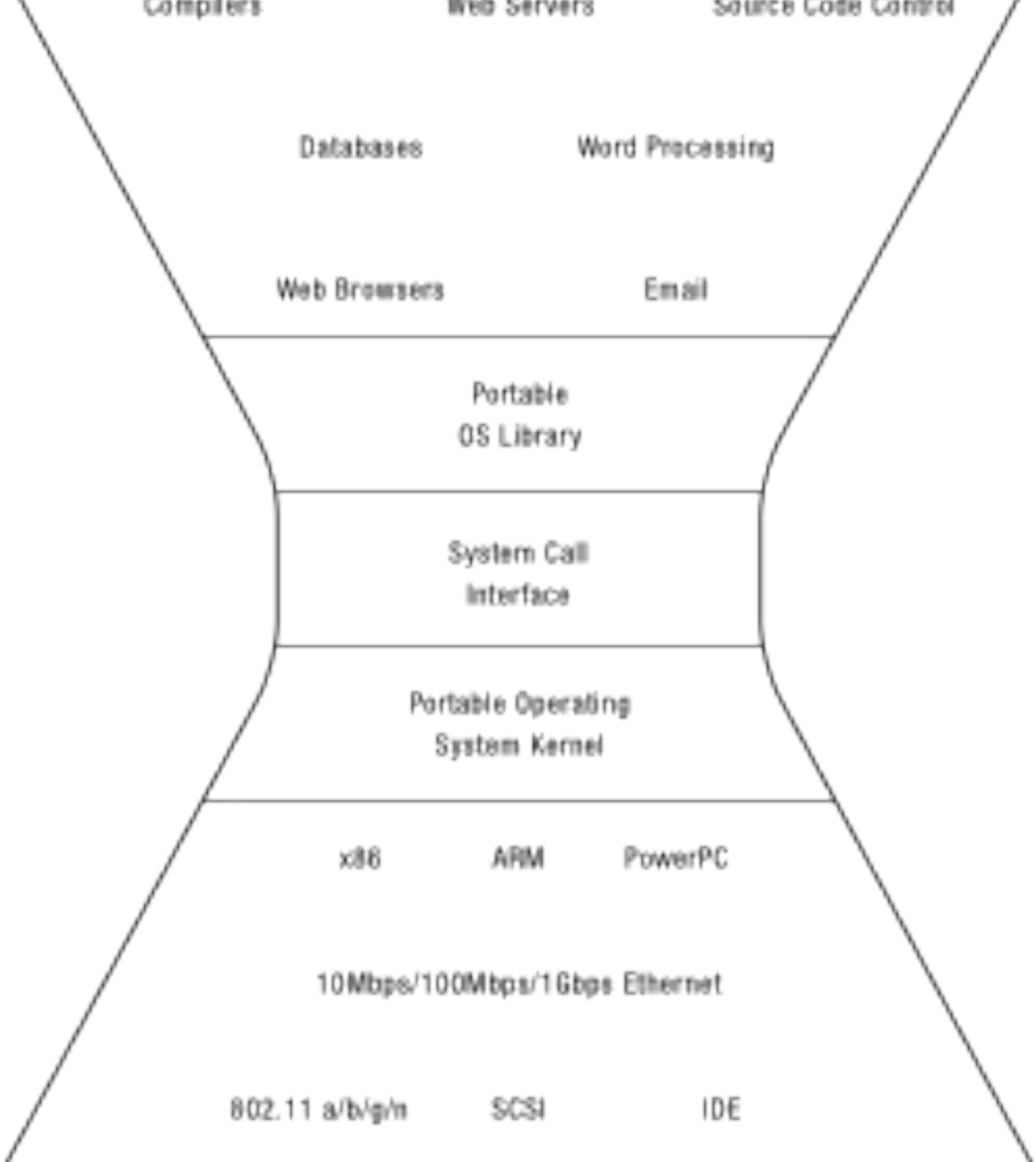
- Signal handlers = interrupt vector
- Signal stack = interrupt stack
- Automatic save/restore registers = transparent resume
- Signal masking: signals disabled while in signal handler

Upcall: Before

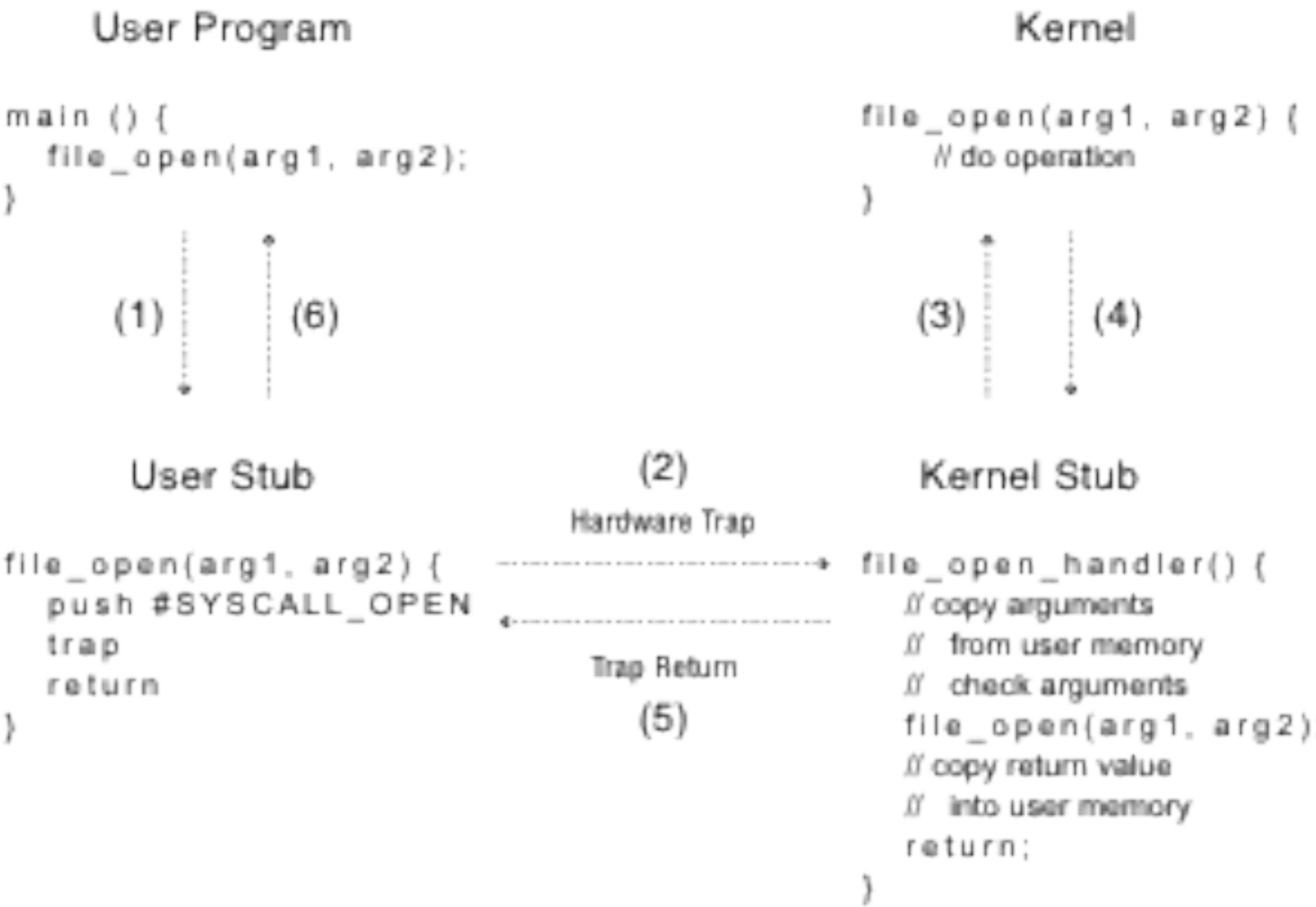


Upcall: During



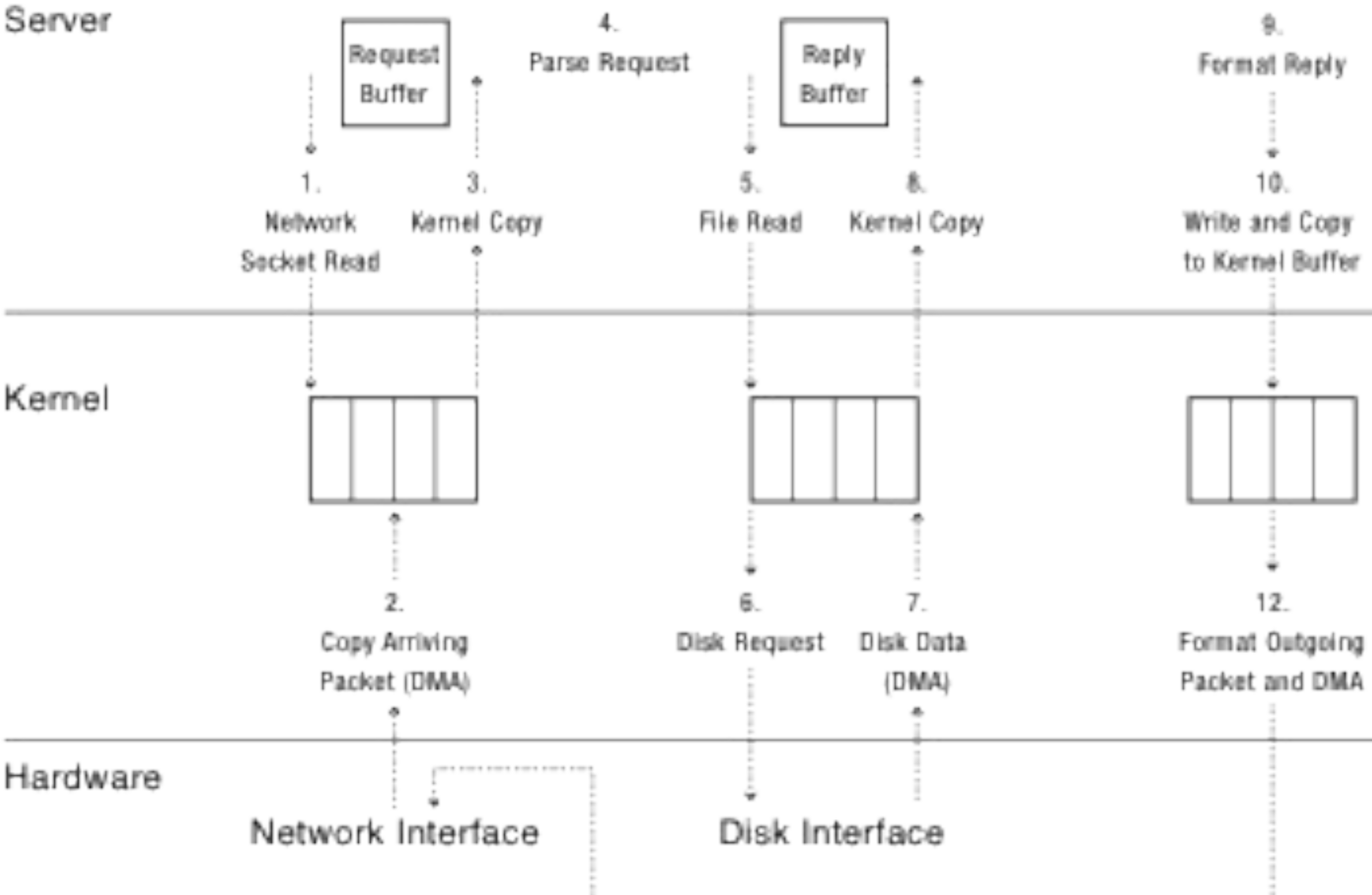


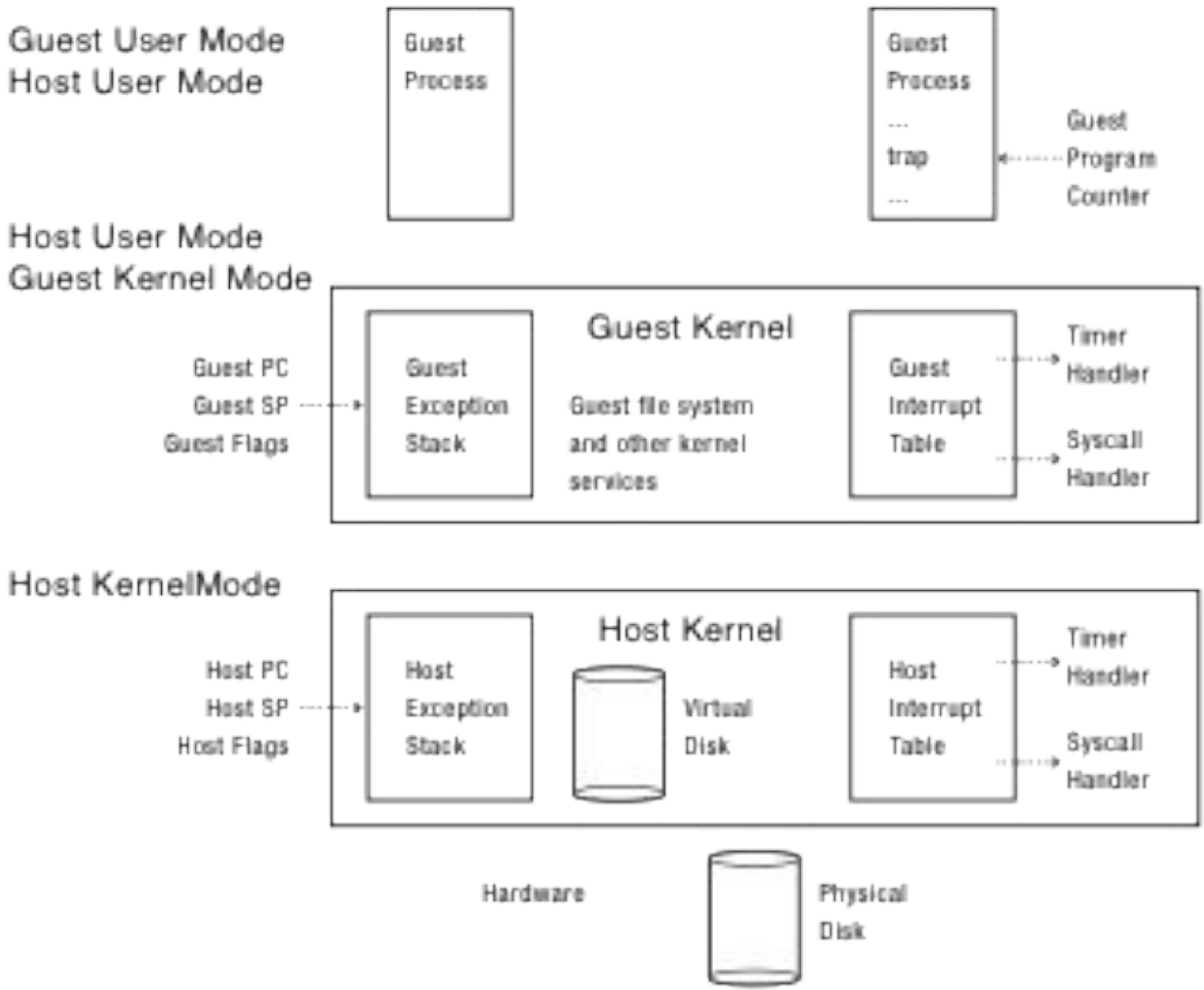
Compilers
Web Servers
Source Code Control
Databases
Word Processing
Web Browsers
Email
Portable
OS Library
System Call
Interface
Portable Operating
System Kernel
x86
ARM
PowerPC
10Mbps/100Mbps/1Gbps Ethernet
802.11 a/b/g/n
SCSI
IDE


User Program
Kernel
main () {
file_open(arg1, arg2);
}
file_open(arg1, arg2) {
// do operation
}
(1)
(6)
(3)
(4)
User Stub
(2)
Hardware Trap
Kernel Stub
file_open(arg1, arg2) {
push #SYSCALL_OPEN
trap
return
}
Trap Return
(5)
file_open_handler() {
// copy arguments
// from user memory
// check arguments
file_open(arg1, arg2);
// copy return value
// into user memory
return;
}

Kernel System Call Handler

- Locate arguments
  - In registers or on user stack
  - *Translate* user addresses into kernel addresses
- Copy arguments
  - From user memory into kernel memory
  - Protect kernel from malicious code evading checks
- Validate arguments
  - Protect kernel from errors in user code
- Copy results back into user memory
  - *Translate* kernel addresses into user addresses


Server
Request Buffer
4.
Parse Request
Reply Buffer
9.
Format Reply
1.
Network Socket Read
3.
Kernel Copy
5.
File Read
8.
Kernel Copy
10.
Write and Copy to Kernel Buffer
Kernel
2.
Copy Arriving Packet (DMA)
6.
Disk Request
7.
Disk Data (DMA)
12.
Format Outgoing Packet and DMA
Hardware
Network Interface
Disk Interface



Guest User Mode
Host User Mode
Guest Process
Guest Process
...
trap
...
Guest Program Counter
Host User Mode
Guest Kernel Mode
Guest Kernel
Guest PC
Guest SP
Guest Flags
Guest Exception Stack
Guest file system and other kernel services
Guest Interrupt Table
Timer Handler
Syscall Handler
Host KernelMode
Host Kernel
Host PC
Host SP
Host Flags
Host Exception Stack
Virtual Disk
Host Interrupt Table
Timer Handler
Syscall Handler
Hardware
Physical Disk

User-Level Virtual Machine

- How does VM Player work?
  - Runs as a user-level application
  - How does it catch privileged instructions, interrupts, device I/O?
- Installs kernel driver, transparent to host kernel
  - Requires administrator privileges!
  - Modifies interrupt table to redirect to kernel VM code
  - If interrupt is for VM, upcall
  - If interrupt is for another process, reinstalls interrupt table and resumes kernel