CS 422/522 Design & Implementation of Operating Systems

Lecture 2:The Kernel Abstraction

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Today's lecture

- An overview of HW functionality
  - read the cs323 textbook
- How to bootstrap ?
- An overview of OS structures
  - OS components and services
  - how OS interacts with IO devices ? **interrupts**
  - how OS interacts with application program ? **system calls**

What makes a "computer system" ?

- **Hardware**
  - motherboard (cpu, buses, I/O controllers, memory controller, timer); memory; hard disk & flash drives, CD&DVDROM; keyboard, mouse; monitor & graphics card; printer, scanner, sound board & speakers; modem, networking card; case, power supply.
  - all connected through buses, cables, and wires
- **Software**
  - *a bunch of 0/1s; stored on a hard disk or a usb drive or a DVD*
    - * operating system (e.g., Linux, Windows, Mac OS)
    - * application programs (e.g., gcc, vi)
- **User (it is "you")**

How a "computer" becomes alive?

Step 0: connect all HWs together, build the computer

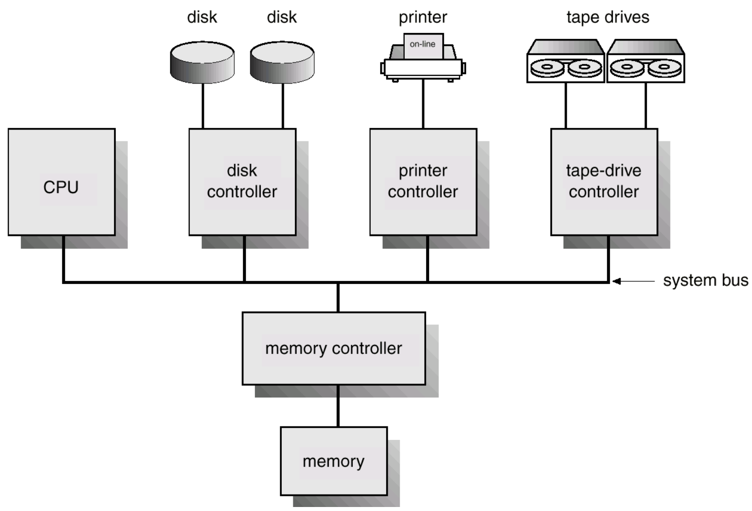
Step 1: power-on and bootstrap
assuming that OS is stored on the boot drive
(e.g., USB drive, hard disk, or CDROM)

Step 2: OS takes over and set up all of its services

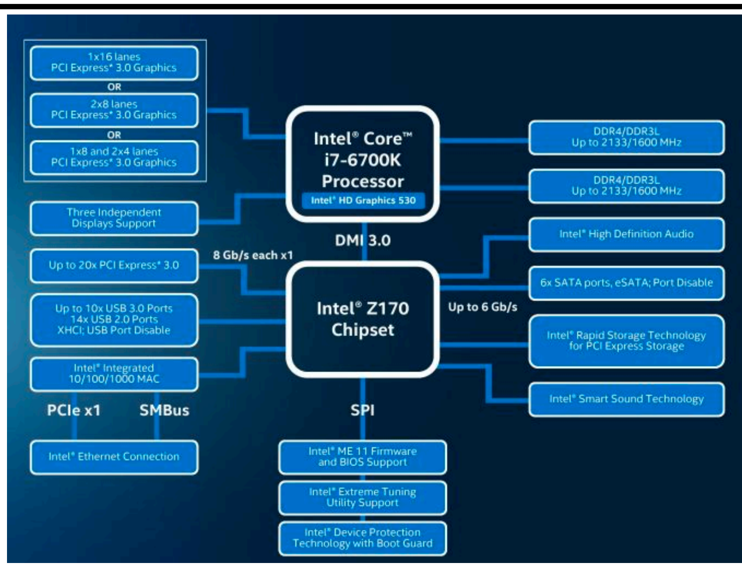
Step 3: start the window manager and the login prompt

Step 4: user logs in; start the shell; run applications

Computer-system architecture (1980)



Computer-system architecture (Intel Skylake 2015)



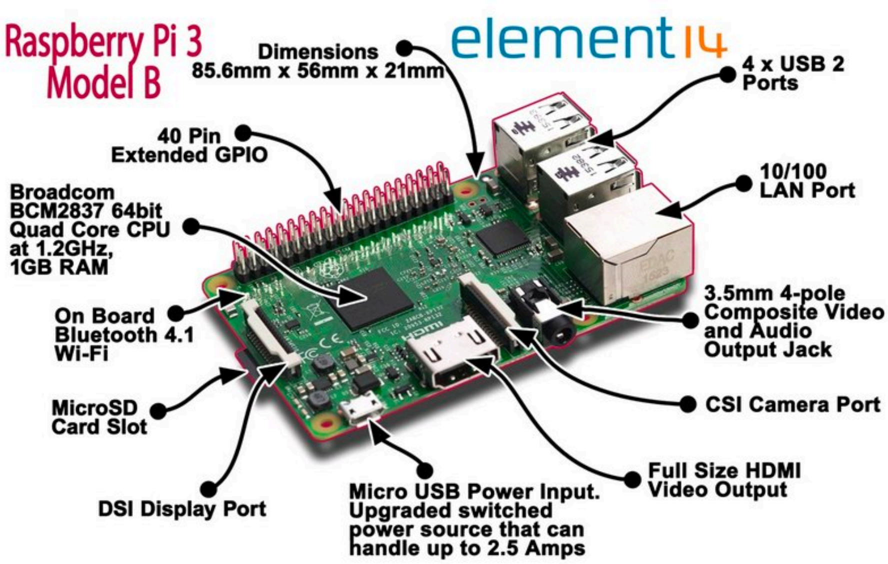
http://images.anandtech.com/doci/9483/Z170%20Platform.jpg?_ga=1.245977734.363736712.1473128269

Computer-system architecture (Intel Skylake 2015)

Intel Z170 Motherboard
(Asrock Z170 Extreme6)

http://www.techspot.com/photos/article/1073-intel-z170-motherboard-roundup/#Asrock_02

Computer-system architecture (Raspberry Pi3)



http://www.rlocman.ru/i/Image/2016/02/29/RaspberryPi_3_1.jpg

An overview of HW functionality

- **Executing the machine code** (cpu, cache, memory)
  - instructions for ALU-, branch-, and memory-operations
  - instructions for communicating with I/O devices
- **Performing I/Os**
  - I/O devices and the CPU can execute concurrently
  - Each device controller in charge of one device type
  - Each device controller has a local buffer
  - CPU moves data btw. main memory and local buffers
  - I/O is from the device to local buffer of controller
  - Device controller uses **interrupt** to inform CPU that it is done
- **Protection hardware**
  - timer, paging HW (e.g. TLB), mode bit (e.g., kernel/user)

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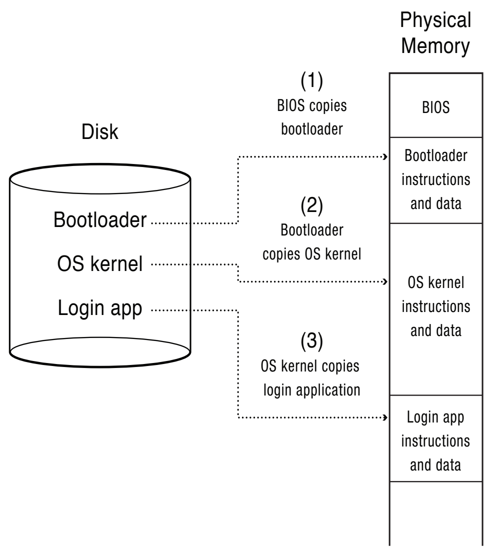
How to bootstrap?

- Power up a computer
- Processor reset
  - Set to known state
  - Jump to ROM code (for x86 PC, this is **BIOS**)
- Load in the boot loader from stable storage
- Jump to the boot loader
- Load the rest of the operating system
- Initialize and run



System boot

- Power on (processor waits until Power Good Signal)
- On an Intel PC, processor jumps to address $FFFF0_h$ (maps to $FFFFFFF0_h = 2^{32}-16$)
  - $1M = 1{,}048{,}576 = 2^{20} = FFFFF_h+1$
  - $FFFFF_h = FFFF0_h+15$ is the end of the (first 1MB of) system memory
  - The original PC using Intel 8088 (in 1970's) had 20-bit address lines :-)
- ($FFFFFFF0_h$) is a JMP instruction to the BIOS startup program

BIOS startup (1)

- POST (Power-On Self-Test)
  - If pass then AX:=0; DH:=5 (Pentium);
  - Stop booting if fatal errors, and report
- Look for video card and execute built-in BIOS code (normally at C000h)
- Look for other devices ROM BIOS code
  - IDE/ATA disk ROM BIOS at C8000h (=819,200d)
  - SCSI disks may provide their own BIOS
- Display startup screen
  - BIOS information
- Execute more tests
  - memory
  - system inventory

BIOS startup (2)

- Look for logical devices
  - Label them
    - Serial ports: COM 1, 2, 3, 4
    - Parallel ports: LPT 1, 2, 3
  - Assign each an I/O address and IRQ
- Detect and configure PnP devices
- Display configuration information on screen

BIOS startup (3)

- Search for a drive to BOOT from
  - Hard disk or USB drive or CD/DVD
  - Boot at cylinder 0, head 0, sector 1
- Load code in boot sector
- Execute boot loader
- Boot loader loads program to be booted
  - If no OS: "Non-system disk or disk error - Replace and press any key when ready"
- Transfer control to loaded program
  - Which maybe another feature-rich bootloader (e.g., GRUB), which then loads the actual OS

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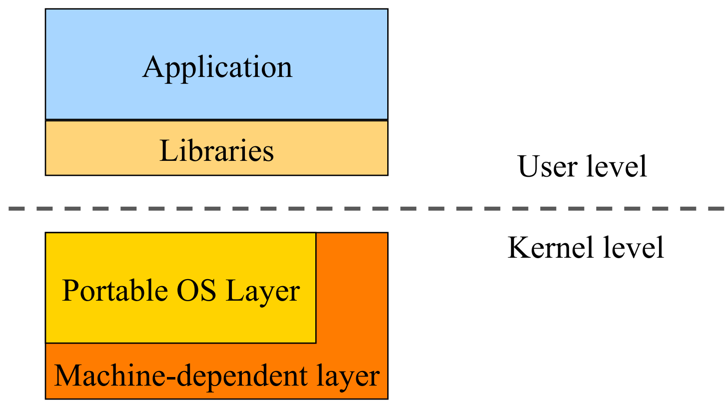
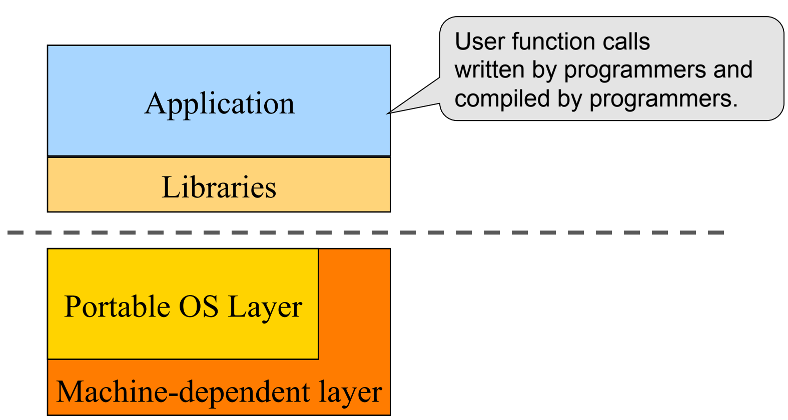
Typical Unix OS structure



Typical Unix OS structure



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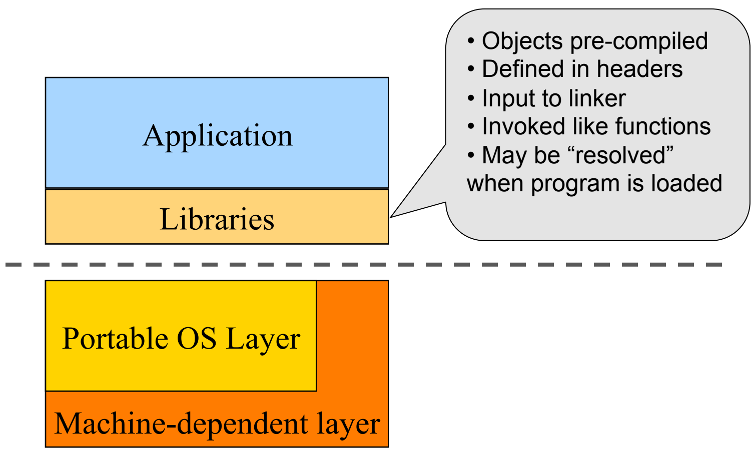
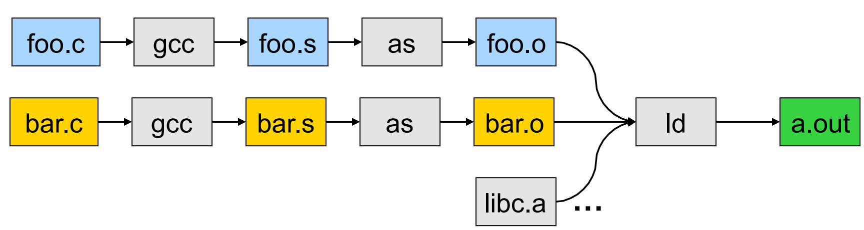


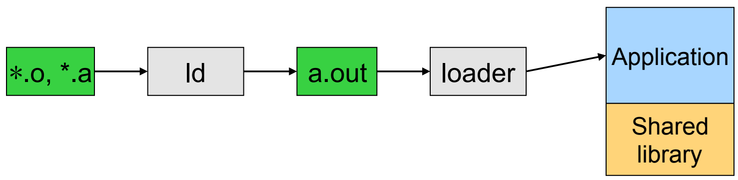
Pipeline of creating an executable file



- gcc can compile, assemble, and link together
- Compiler part of gcc compiles a program into assembly
- Assembler compiles assembly code into relocatable object file
- Linker links object files into an executable
- For more information:
  - Read man page of a.out, elf, ld, and nm
  - Read the document of ELF

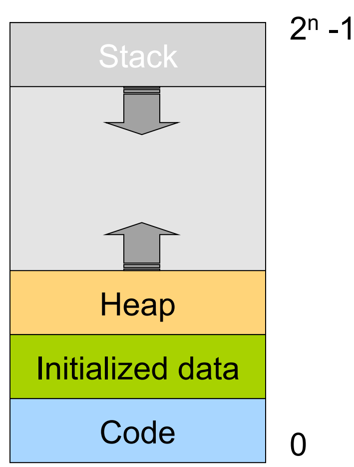
Execution (run an application)

- On Unix, "loader" does the job
  - Read an executable file
  - Layout the code, data, heap and stack
  - Dynamically link to shared libraries
  - Prepare for the OS kernel to run the application



What's an application?

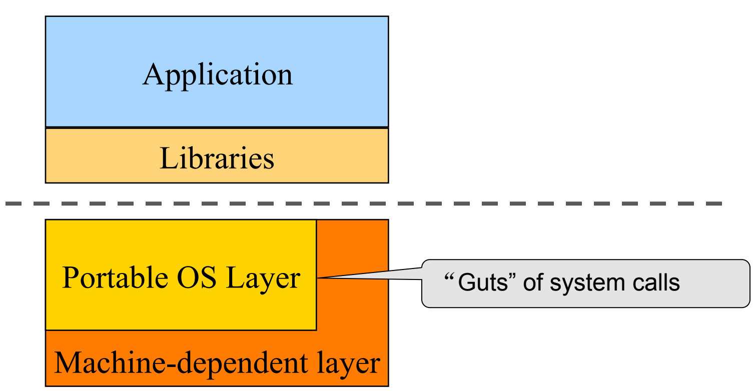
- Four segments
  - Code/Text – instructions
  - Data – initialized global variables
  - Stack
  - Heap
- Why?
  - Separate code and data
  - Stack and heap go towards each other



Responsibilities

- Stack
  - Layout by compiler
  - Allocate/deallocate by process creation (fork) and termination
  - Local variables are relative to stack pointer
- Heap
  - Linker and loader say the starting address
  - Allocate/deallocate by library calls such as malloc() and free()
  - Application program use the library calls to manage
- Global data/code
  - Compiler allocates statically
  - Compiler emits names and symbolic references
  - Linker translates references and relocates addresses
  - Loader finally lays them out in memory

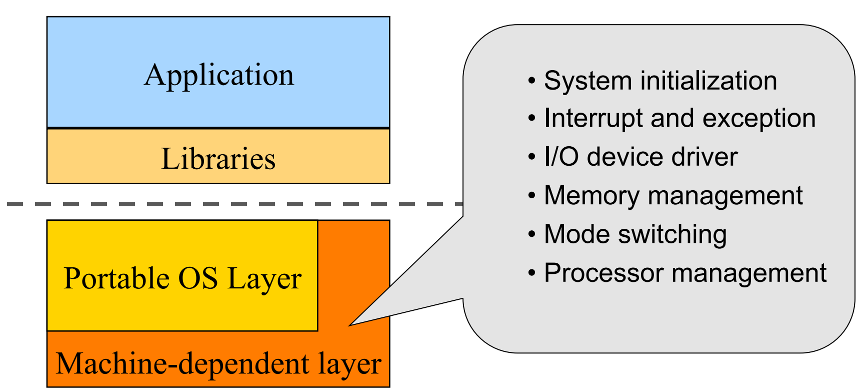
Typical Unix OS structure



OS service examples

- Examples that are not provided at user level
  - System calls: file open, close, read and write
  - Control the CPU so that users won't stuck by running
    - while (1) ;
  - Protection:
    - Keep user programs from crashing OS
    - Keep user programs from crashing each other
- Examples that can be provided at user level
  - Read time of the day
  - Protected user level stuff

Typical Unix OS structure

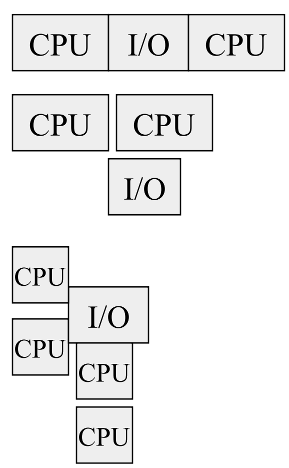


OS components

- Resource manager for each HW resource
  - processor management (CPU)
  - memory management
  - file system and secondary-storage management
  - I/O device management (keyboards, mouse, …)
- Additional services:
  - networking
  - window manager (GUI)
  - command-line interpreters (e.g., shell)
  - resource allocation and accounting
  - **protection**
    - Keep user programs from crashing OS
    - Keep user programs from crashing each other

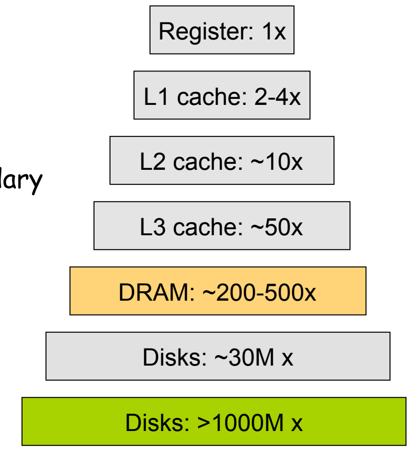
Processor management

- Goals
  - Overlap between I/O and computation
  - Time sharing
  - Multiple CPU allocations
- Issues
  - Do not waste CPU resources
  - Synchronization and mutual exclusion
  - Fairness and deadlock free



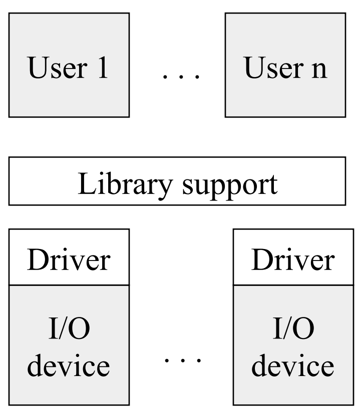
Memory management

- Goals
  - Support programs to run
  - Allocation and management
  - Transfers from and to secondary storage
- Issues
  - Efficiency & convenience
  - Fairness
  - Protection



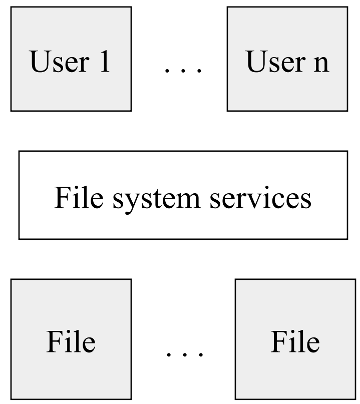
I/O device management

- Goals
  - Interactions between devices and applications
  - Ability to plug in new devices
- Issues
  - Efficiency
  - Fairness
  - Protection and sharing



File system

- A typical file system
  - open a file with authentication
  - read/write data in files
  - close a file
- Efficiency and security
- Can the services be moved to user level?



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Device interrupts

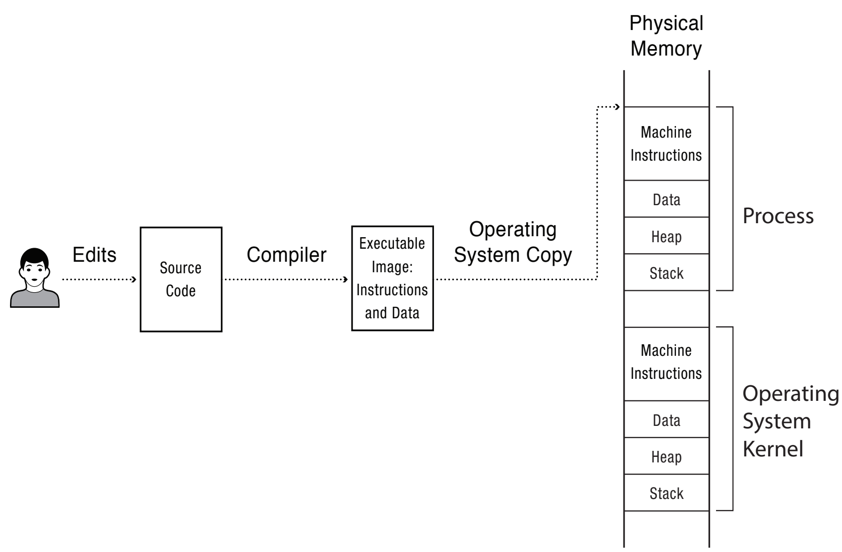
How does an OS kernel communicate with physical devices?

- Devices operate *asynchronously* from the CPU
  - Polling: Kernel waits until I/O is done
  - Interrupts: Kernel can do other work in the meantime
- Device access to memory
  - Programmed I/O: CPU reads and writes to device
  - Direct memory access (DMA) by device
- How do device interrupts work?
  - Where does the CPU run after an interrupt?
  - What is the interrupt handler written in?
  - What stack does it use?
  - Is the work the CPU had been doing before the interrupt lost?
  - If not, how does the CPU know how to resume that work

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 user program running on top of an OS
  - A third party device driver running within an OS
  - 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

A problem



Main points

- 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?

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
  - 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)

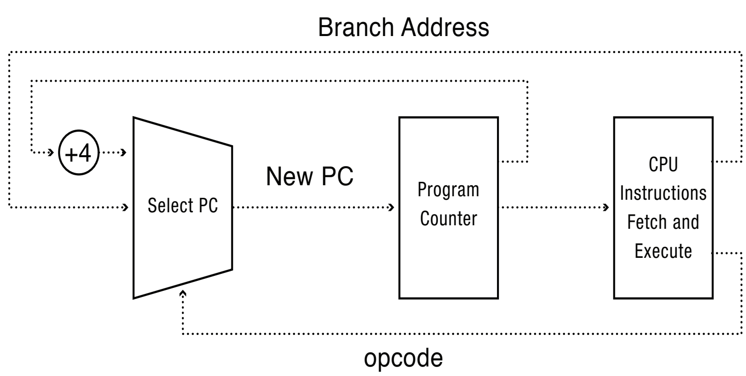
Thought experiment

- How can we implement execution with limited privilege?
  - Execute each program instruction in a simulator
  - If the instruction is permitted, do the instruction
  - Otherwise, stop the process
  - Basic model in Javascript and other interpreted languages
- How do we go faster?
  - Run the unprivileged code directly on the CPU!

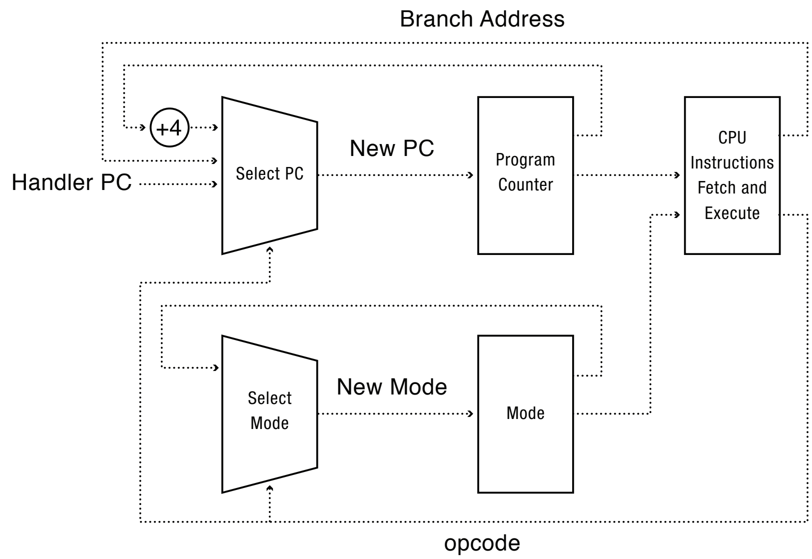
Hardware support: dual-mode operation

- **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



A CPU with dual-mode operation



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

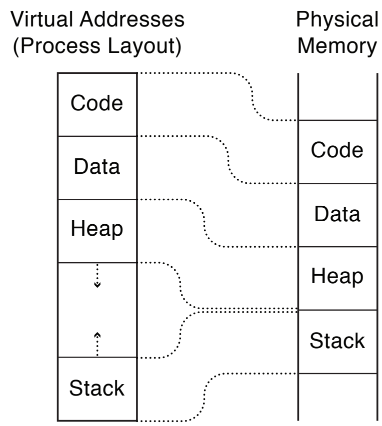
Privileged instruction examples

- Memory address mapping
- Cache flush or invalidation
- Invalidating TLB entries
- Loading and reading system registers
- Changing processor modes from kernel to user
- Changing the voltage and frequency of processor
- Halting a processor
- I/O operations

What should happen if a user program attempts to execute a privileged instruction?

Virtual addresses

- Translation done in hardware, using a table
- Table set up by operating system kernel



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

"User ⇔ Kernel" model switch

An interrupt or exception or system call (INT)

User mode
- Regular instructions
- Access user-mode memory

Kernel (privileged**) mode**
- All instructions
- Access all memory

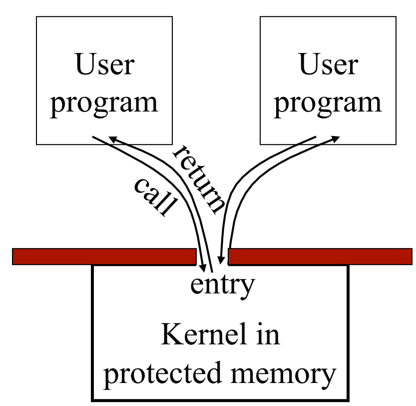
A special instruction (IRET)

Mode switch

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

System calls

- User code can be arbitrary
- User code cannot modify kernel memory
- Makes a system call with parameters
- The call mechanism switches code to kernel mode
- Execute system call
- Return with results



They are like **"local" remote procedure calls (RPCs)**

Interrupts and exceptions

- Interrupt sources
  - Hardware (by external devices)
  - Software: INT n
- Exceptions
  - Program error: faults, traps, and aborts
  - Software generated: INT 3
  - Machine-check exceptions
- See Intel document volume 3 for details

Interrupt and exceptions (1)

Vector #	Mnemonic	Description	Type
0	#DE	Divide error (by zero)	Fault
1	#DB	Debug	Fault/trap
2		NMI interrupt	Interrupt
3	#BP	Breakpoint	Trap
4	#OF	Overflow	Trap
5	#BR	BOUND range exceeded	Trap
6	#UD	Invalid opcode	Fault
7	#NM	Device not available	Fault
8	#DF	Double fault	Abort
9		Coprocessor segment overrun	Fault
10	#TS	Invalid TSS	

Interrupt and exceptions (2)

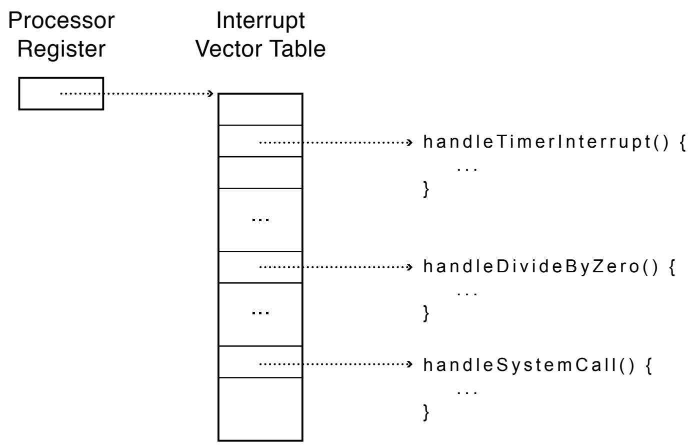
Vector #	Mnemonic	Description	Type
11	#NP	Segment not present	Fault
12	#SS	Stack-segment fault	Fault
13	#GP	General protection	Fault
14	#PF	Page fault	Fault
15		Reserved	Fault
16	#MF	Floating-point error (math fault)	Fault
17	#AC	Alignment check	Fault
18	#MC	Machine check	Abort
19-31		Reserved	
32-255		User defined	Interrupt

How to take interrupt & syscall safely?

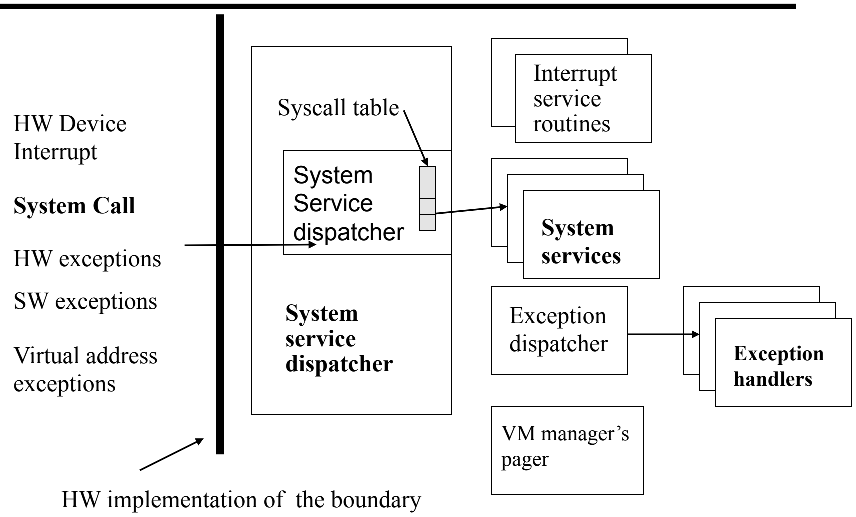
- Interrupt & trap & syscall vector
  - Limited number of entry points into kernel
- Atomic transfer of control
  - Single instruction to change:
    - Program counter
    - Stack pointer
    - Memory protection
    - Kernel/user mode
- Transparent restartable execution
  - For HW interrupts: user program does not know interrupt occurred
  - For system calls: it is just like return from a function call

Interrupt & trap & syscall vector

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

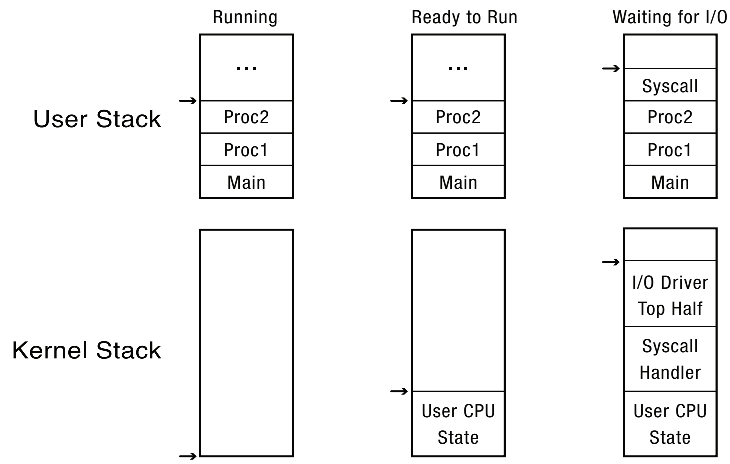


Interrupt & trap & syscall vector (cont'd)



Interrupt stack

Per-processor, located in kernel memory. Why can't the interrupt handler run on the stack of the interrupted user process?



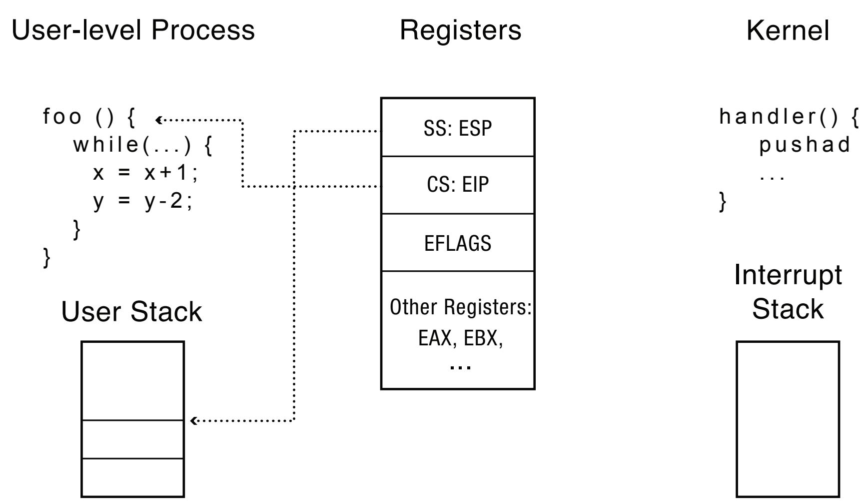
Interrupt handler & interrupt masking

- Interrupt handler often non-blocking (with interrupts off), run to completion (then re-enable interrupts)
  - 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
- Interrupt masking: OS kernel can also turn interrupts off
  - Eg., when determining the next process/thread to run
  - On x86
    - CLI: disable interrupts
    - STI: enable interrupts
    - Only applies to the current CPU (on a multicore)

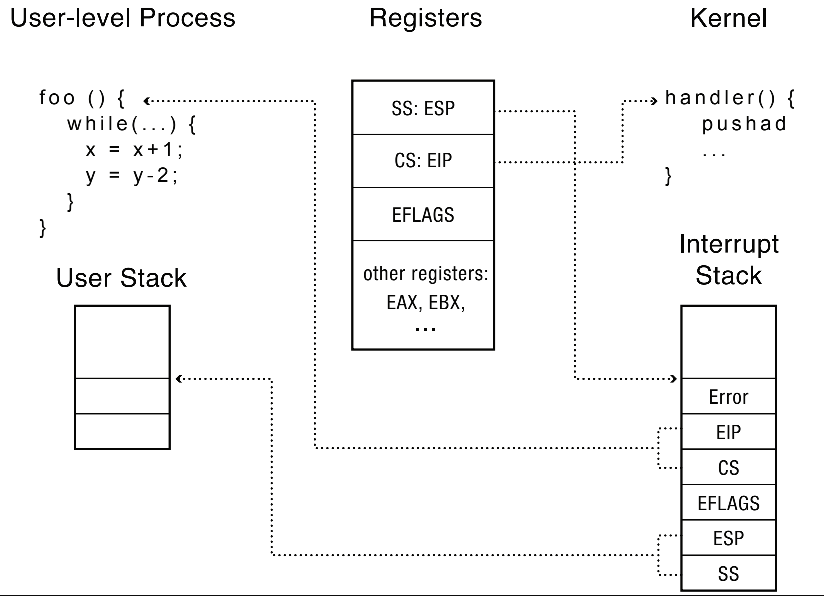
Case study: x86 interrupt & syscall

- 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

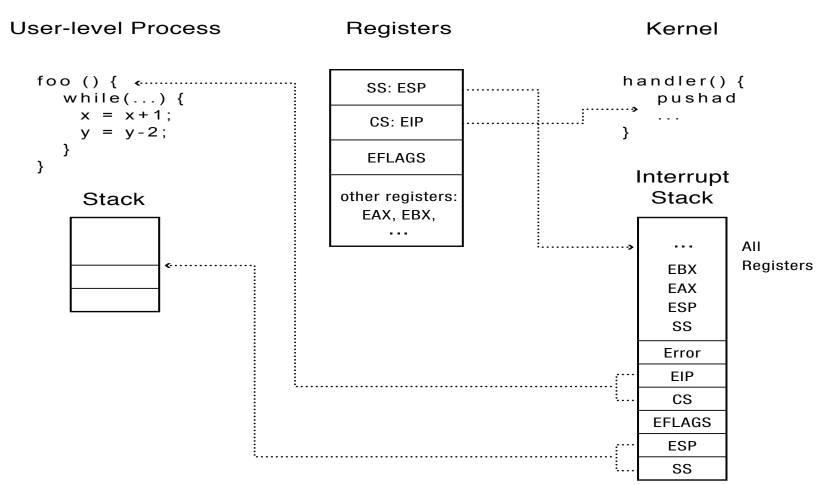
Before interrupt



During interrupt



After interrupt



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

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

System call stubs

User Program

```
main () {
  file_open(arg1, arg2);
}
```

(1) (6)

User Stub

```
file_open(arg1, arg2) {
  push #SYSCALL_OPEN
  trap
  return
}
```

(2)
Hardware Trap

Trap Return
(5)

Kernel

```
file_open(arg1, arg2) {
    // do operation
}
```

(3) (4)

Kernel Stub

```
file_open_handler() {
  // copy arguments
  //   from user memory
  //   check arguments
  file_open(arg1, arg2);
  // copy return value
  //   into user memory
  return;
}
```

User-level system call stub

```
// We assume that the caller put the filename onto the stack,
// using the standard calling convention for the x86.

open:
// Put the code for the system call we want into %eax.
    movl #SysCallOpen, %eax

// Trap into the kernel.
    int #TrapCode

// Return to the caller; the kernel puts the return value in %eax.
    ret
```

Kernel-level system call stub

```
int KernelStub_Open() {
    char *localCopy[MaxFileNameSize + 1];

// Check that the stack pointer is valid and that the arguments are stored at
// valid addresses.

    if (!validUserAddressRange(userStackPointer, userStackPointer + size of arguments))
        return error_code;

// Fetch pointer to file name from user stack and convert it to a kernel pointer.

    filename = VirtualToKernel(userStackPointer);

// Make a local copy of the filename.  This prevents the application
// from changing the name surreptitiously.

// The string copy needs to check each address in the string before use to make sure
// it is valid.

// The string copy terminates after it copies MaxFileNameSize to ensure we
// do not overwrite our internal buffer.

    if (!VirtualToKernelStringCopy(filename, localCopy, MaxFileNameSize))
        return error_code;

// Make sure the local copy of the file name is null terminated.

    localCopy[MaxFileNameSize] = 0;

// Check if the user is permitted to access this file.

    if (!UserFileAccessPermitted(localCopy, current_process)
        return error_code;

// Finally, call the actual routine to open the file.  This returns a file
// handle on success, or an error code on failure.

    return Kernel_Open(localCopy);
}
```