Operating System Practice

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Advanced Operating System Concepts

- Chapter 10: File System
- Chapter 11: Implementing File-Systems
- Chapter 12: Mass-Storage Structure
- ➡ Chapter 13: I/O Systems
- Chapter 14: System Protection
- Chapter 15: System Security

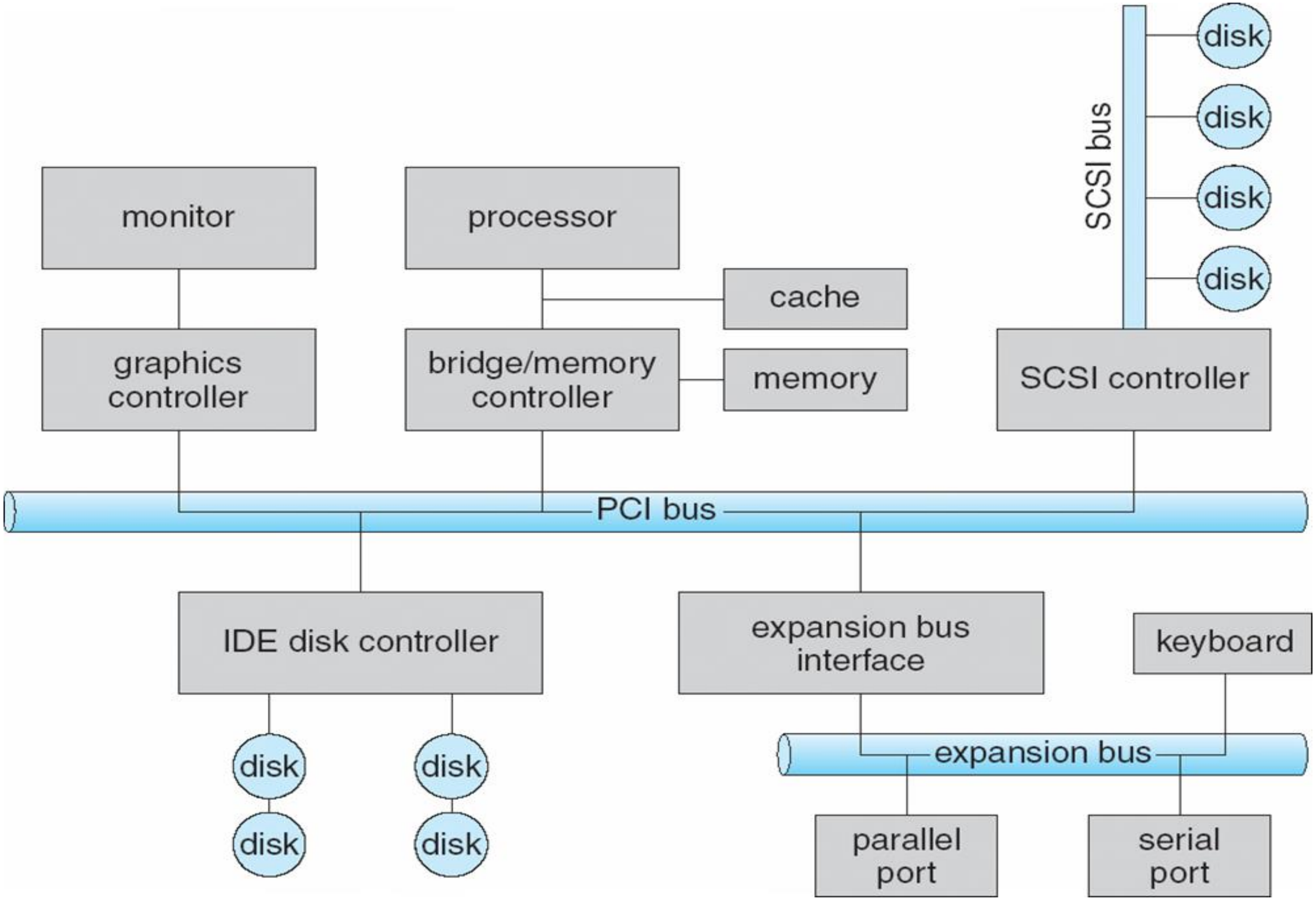
Study Items

- I/O Hardware
- Application I/O Interface
- Kernel I/O Subsystem
- Transforming I/O Requests to Hardware Operations
- Performance

I/O Hardware

- Incredible Variety of I/O Devices
  - Storage
  - Transmission
  - Human-interface
- Common Concepts
  - Port: connection point for device
  - Bus: daisy chain or shared direct access
  - Controller (host adapter): electronics that operate port, bus, device

A Typical PC Bus Structure

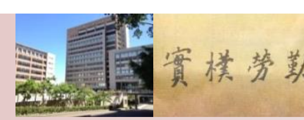


Access to I/O Hardware

- Device registers which can be accessed by the host
  - The data-in register is read by the host to get input
  - The data-out register is written by the host to send output
  - The status register contains bits which indicate device states
  - The control register is written by the host to send command
- Methods to access devices with their addresses
  - Direct I/O instructions
  - Memory-mapped I/O
    - Device data and command registers mapped to processor address space
    - Especially for large address spaces (graphics)

Device I/O Port Locations on PCs (Partial)

I/O address range (hexadecimal)	device
000–00F	DMA controller
020–021	interrupt controller
040–043	timer
200–20F	game controller
2F8–2FF	serial port (secondary)
320–32F	hard-disk controller
378–37F	parallel port
3D0–3DF	graphics controller
3F0–3F7	diskette-drive controller
3F8–3FF	serial port (primary)



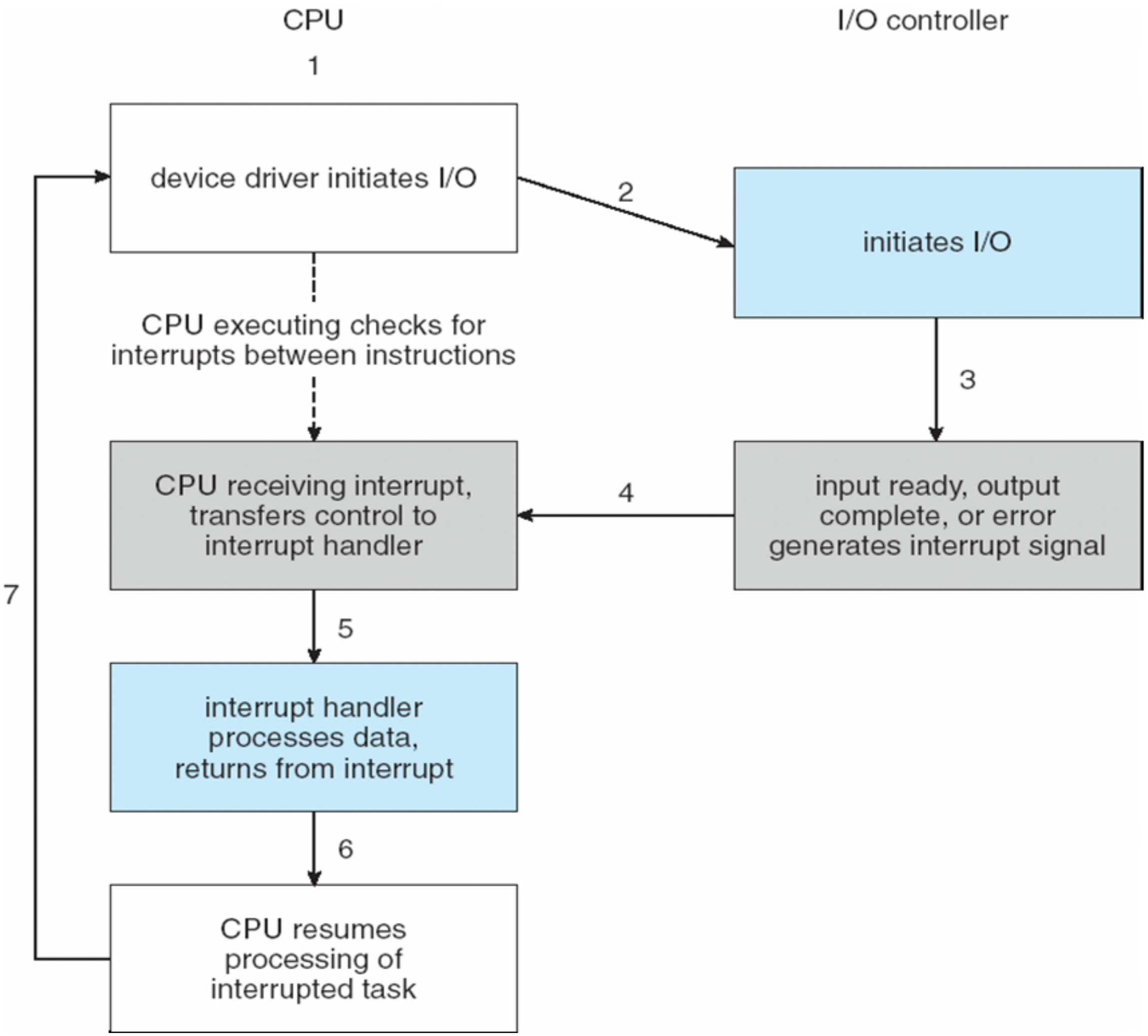
Polling

- An example of Polling I/O
  1. Read busy bit from status register until 0
  2. Host sets read or write bit and if write copies data into data-out register
  3. Host sets command-ready bit
  4. Controller sets busy bit, executes transfer
  5. Controller clears busy bit, error bit, command-ready bit when transfer done
- Step 1 is busy-wait cycle to wait for I/O from device
  - Reasonable if device is fast
  - But inefficient if device slow
    - CPU switches to other tasks?
      - Might miss some data

Interrupts

- CPU Interrupt-request line triggered by I/O device
  - Checked by processor after each instruction
- Interrupt handler receives interrupts
  - Masked to ignore or delay some interrupts
- Interrupt vector to dispatch interrupt to correct handler
  - Context switch at start and end
  - Based on priority
  - Some nonmaskable
  - Interrupt chaining if more than one device at same interrupt number

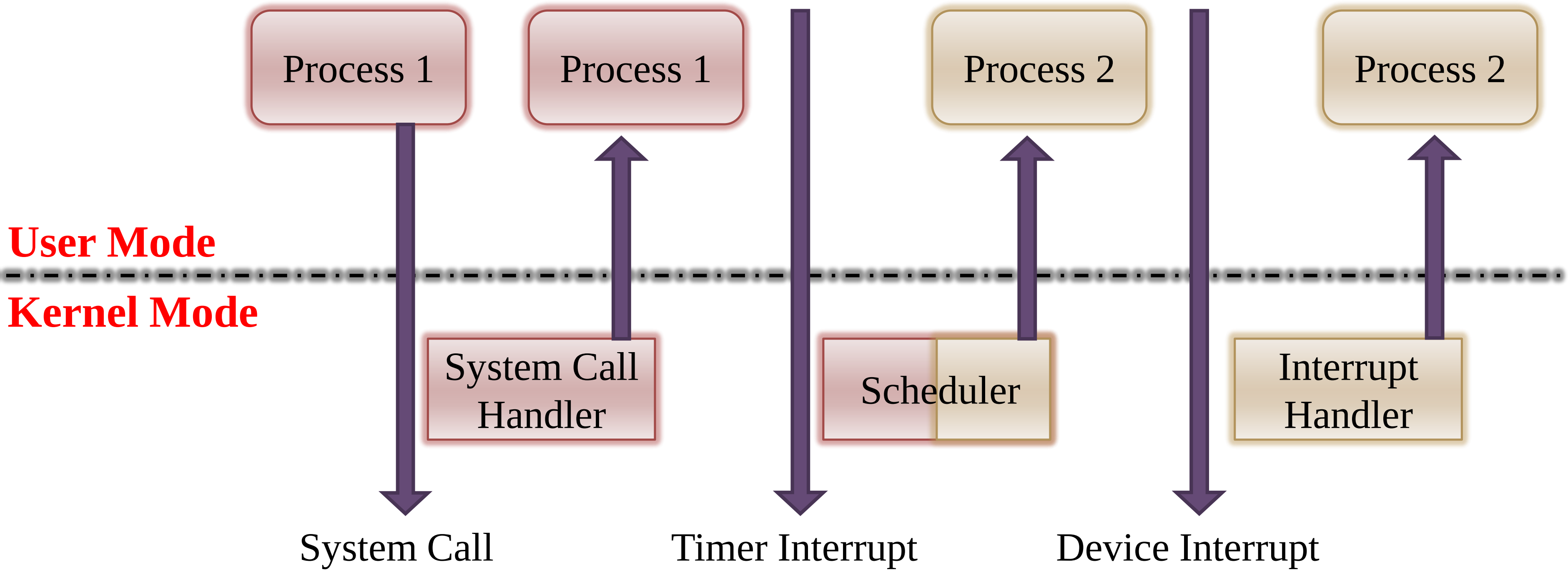
Interrupt-Driven I/O Cycle



Interrupt Usage

- Interrupt vector table is used to identify which device sent out the interrupt
  - When multiple devices share an interrupt number, the handlers are checked one by one
- Interrupt mechanism also used for exceptions
  - Terminate process, crash system due to hardware error
  - Page fault executes when memory access error
  - System call executes via trap to trigger kernel to execute request
- Multi-CPU systems can process interrupts concurrently
  - If operating system designed to handle it

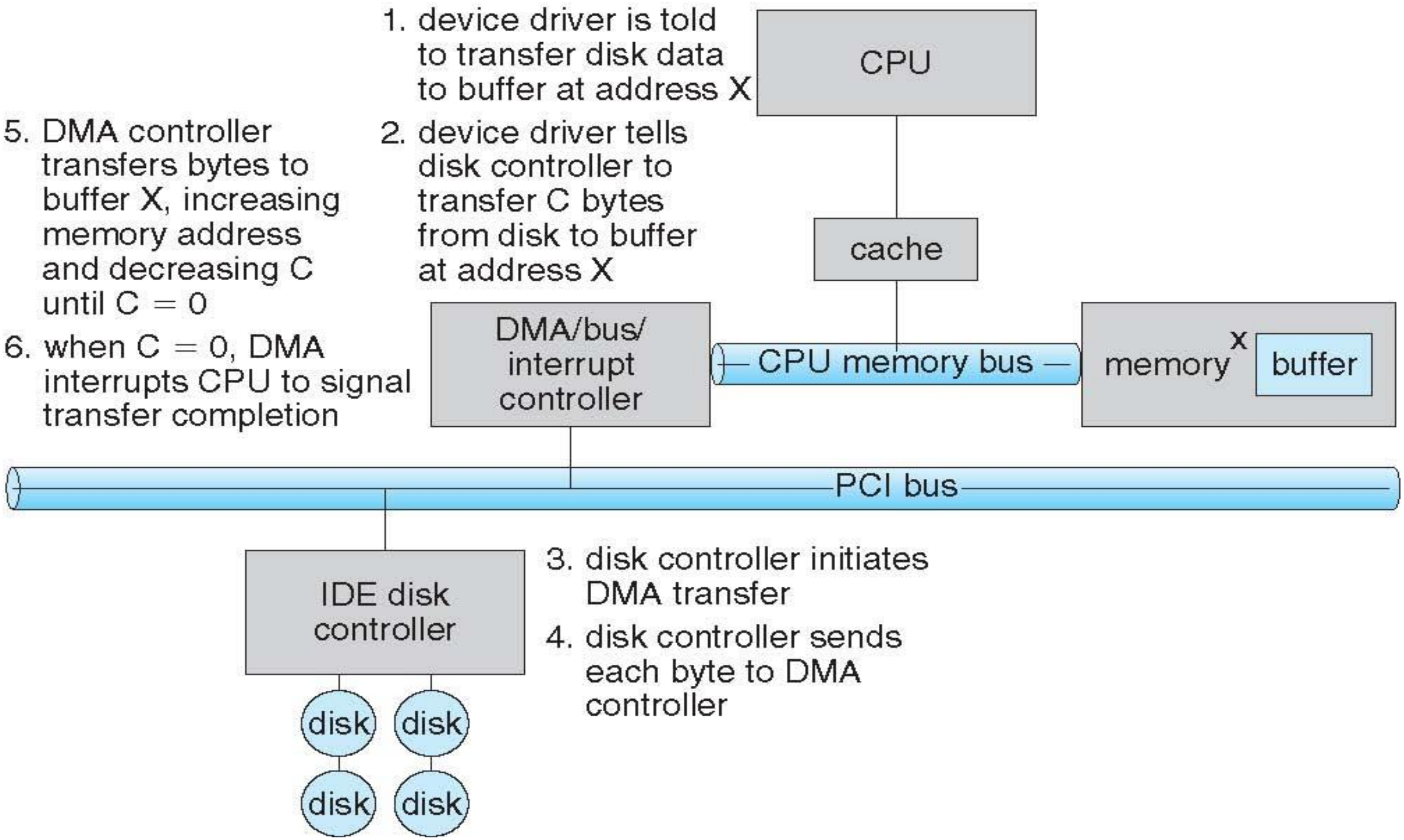
Transitions between User and Kernel Modes in Linux



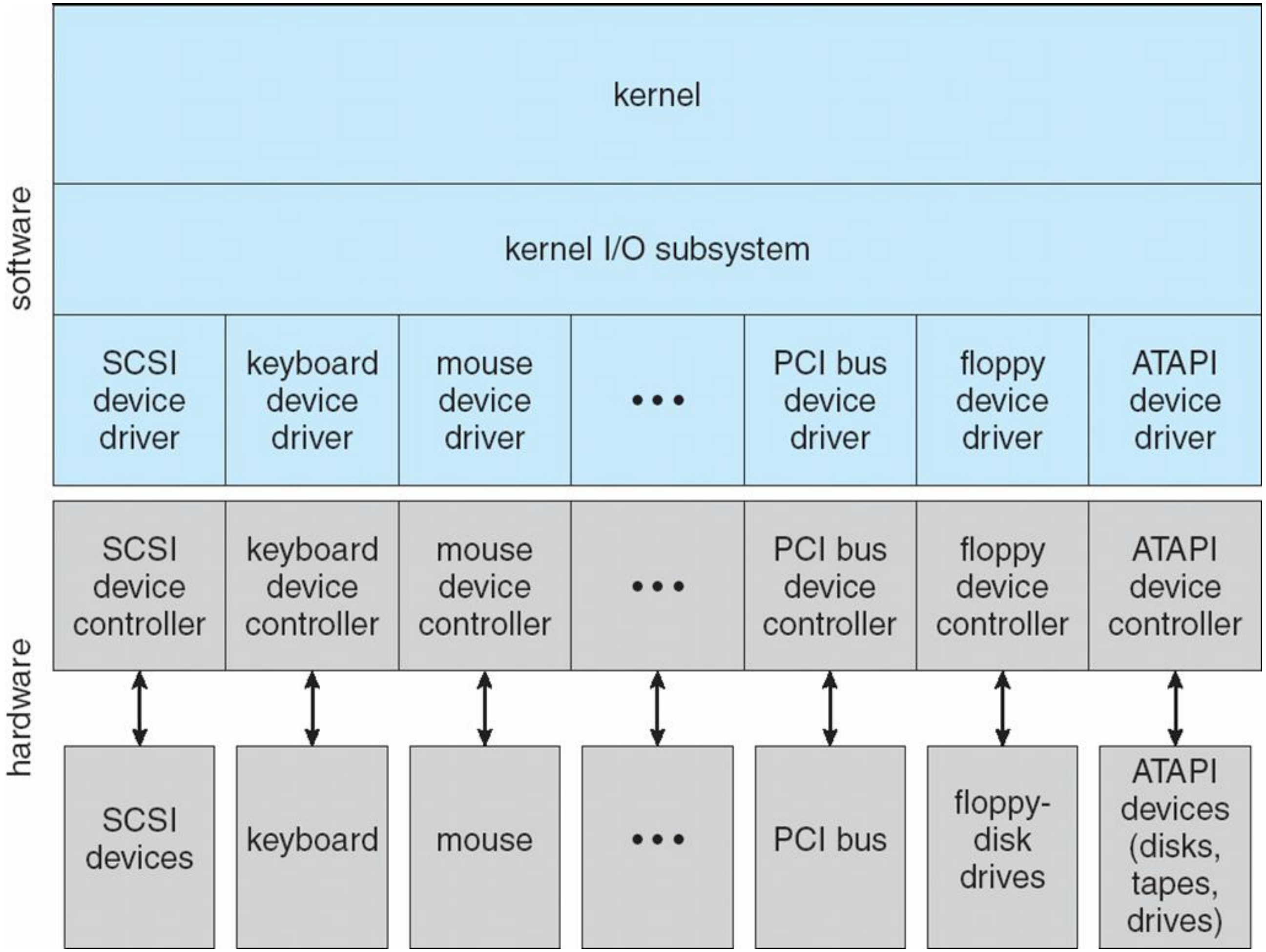
Direct Memory Access

- Used to avoid programmed I/O (one or few bytes at a time) for large data movement
- Requires DMA controller
- Bypasses CPU to transfer data directly between I/O device and memory
- OS writes DMA command block into memory
  - Source and destination addresses
  - Read or write mode
  - Count of bytes
  - For each read/write:
    - Device ready → DMA-request
    - DMA controller complete → DMA-acknowledge
  - When done, interrupts to signal completion

DMA Transfer



Kernel I/O Structure



Application I/O Interface

- I/O system calls encapsulate device behaviors in generic classes
- Device-driver layer hides differences among I/O controllers from kernel
- New devices talking already-implemented protocols need no extra work
- Each OS has its own I/O subsystem structures and device driver frameworks
- Unix ioctl() call to send arbitrary bits to a device control register and data to device data register (called escape or back door)
  - Which device
  - Which command
  - The pointer to the data
- Device characteristics vary in many dimensions

Characteristics of I/O Devices

aspect	variation	example
data-transfer mode	character block	terminal disk
access method	sequential random	modem CD-ROM
transfer schedule	synchronous asynchronous	tape keyboard
sharing	dedicated sharable	tape keyboard
device speed	latency seek time transfer rate delay between operations	
I/O direction	read only write only read–write	CD-ROM graphics controller disk

Block and Character Devices

- Character Devices
  - Sequential access
  - Commands include `get(), put()`
  - Examples include printer, sound board, terminal
  - The same device may have both block and character oriented interfaces
- Block Devices
  - Commands include read, write, seek
  - Raw I/O, direct I/O, or file-system access
    - Raw I/O: no file system support, manage the device directly
    - Direct I/O: with file system support but without buffering and locking
  - Block size is from 512B to 4KB
  - For example, disks are commonly implemented as block devices

Network Devices

- Varying enough from block and character to have own interface
- Unix and Windows have socket (e.g., IP + port) interface
  - Separates network protocol from network operation
  - Includes `select()` functionality
    - `select()` returns that which sockets have data to be received and which sockets are available for sending data now
- Approaches vary widely

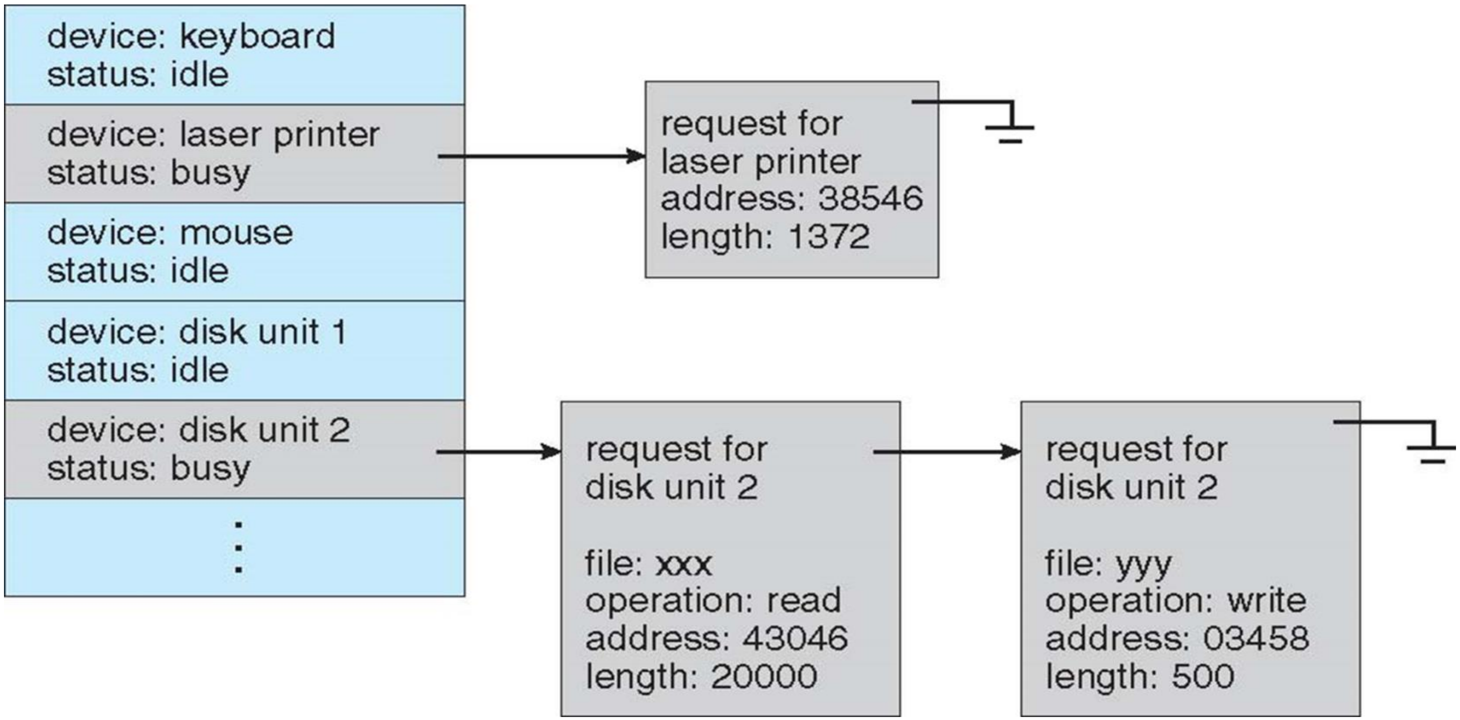
Clocks and Timers

- Hardware clocks and timers provide three basic functions:
  - Give the current time
  - Give the elapsed time
  - Set a timer to trigger operation X at time T
- Some high-frequency counters do not generate interrupts, but they offers accurate measurements of time intervals

Blocking, Nonblocking, and Asynchronous I/O

- Blocking I/O
  - The execution of the application is suspended until the expected results are provided
- Nonblocking I/O
  - Nonblocking call returns quickly, with a return value that indicates how many bytes were transferred
- Asynchronous I/O
  - Asynchronous call returns immediately, without waiting for the I/O to complete
  - The completion of the I/O at some future time is communicated to the application

Device-Status Table



This information is used for the disk I/O scheduling in Chapter 12

Buffering

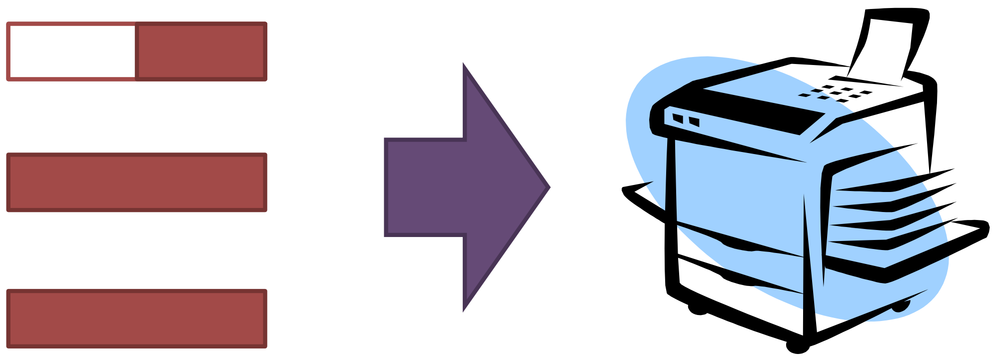
- Buffering — store data in memory while transferring between devices
  - To cope with device speed mismatch
  - To cope with device transfer size mismatch
  - To maintain “copy semantics”
    - The data might be modified after the copy is issued and before it completes
- Double buffering – two data buffers
  - It decouples the producer of data from the consumer, thus relaxing timing requirements between them

Caching

- A cache is a region of fast memory that holds copies of data
- Access to the cached copy is more efficient than access to the original
- The difference between a buffer and a cache is that a buffer may hold the only existing copy of a data item, whereas a cache, by definition, holds a copy on faster storage of an item that resides elsewhere.
- Caching and buffering are distinct functions, but sometimes a region of memory can be used for both purposes

Spooling

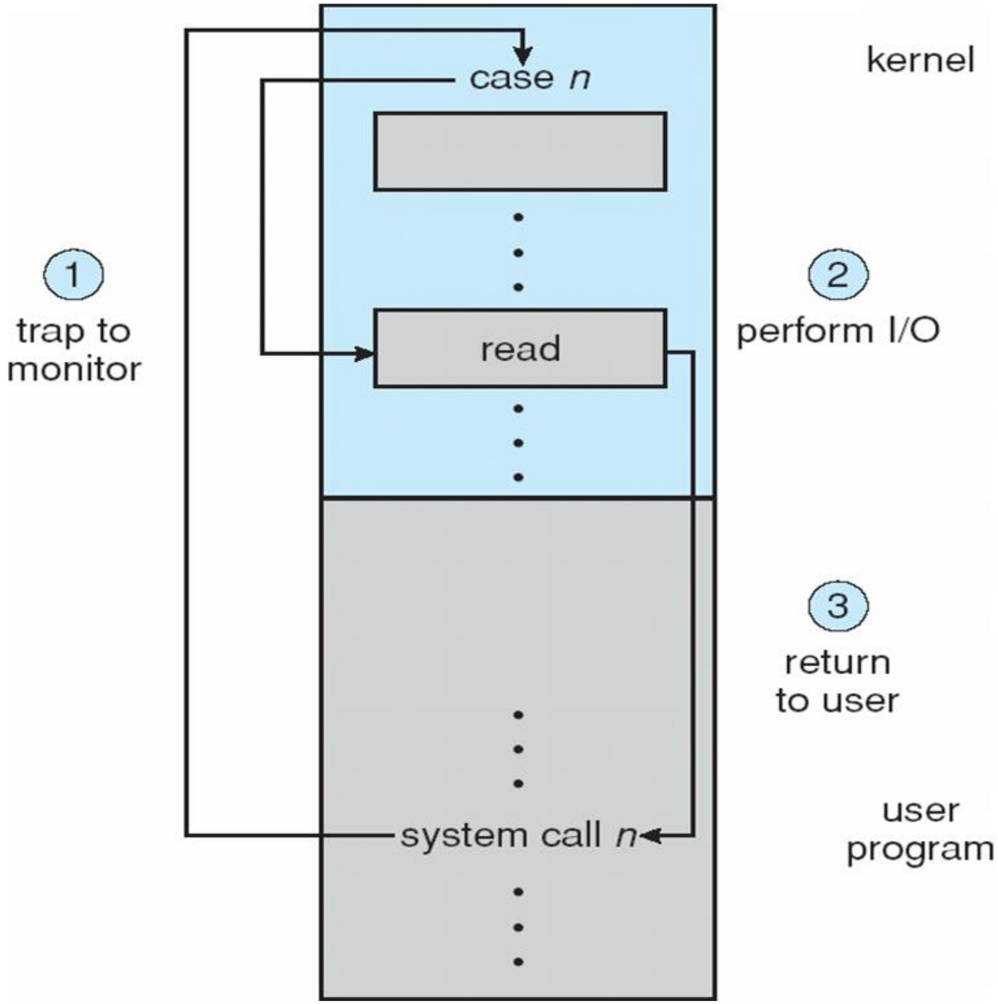
- A spool is a buffer that holds multiple outputs for a device, such as a printer, that cannot accept interleaved data streams



Error Handling

- OS can recover from disk read failures, device unavailable, transient write failures
  - Retry a read or write, for example
  - Some systems more advanced – SCSI
    - An additional sense code that states the category of failure
- Return an error number or code when I/O request fails
- I/O Protection:
  - User process may accidentally or purposefully attempt to disrupt normal operation via illegal I/O instructions
  - All I/O instructions defined to be privileged
  - I/O must be performed via system calls

System Call for I/O



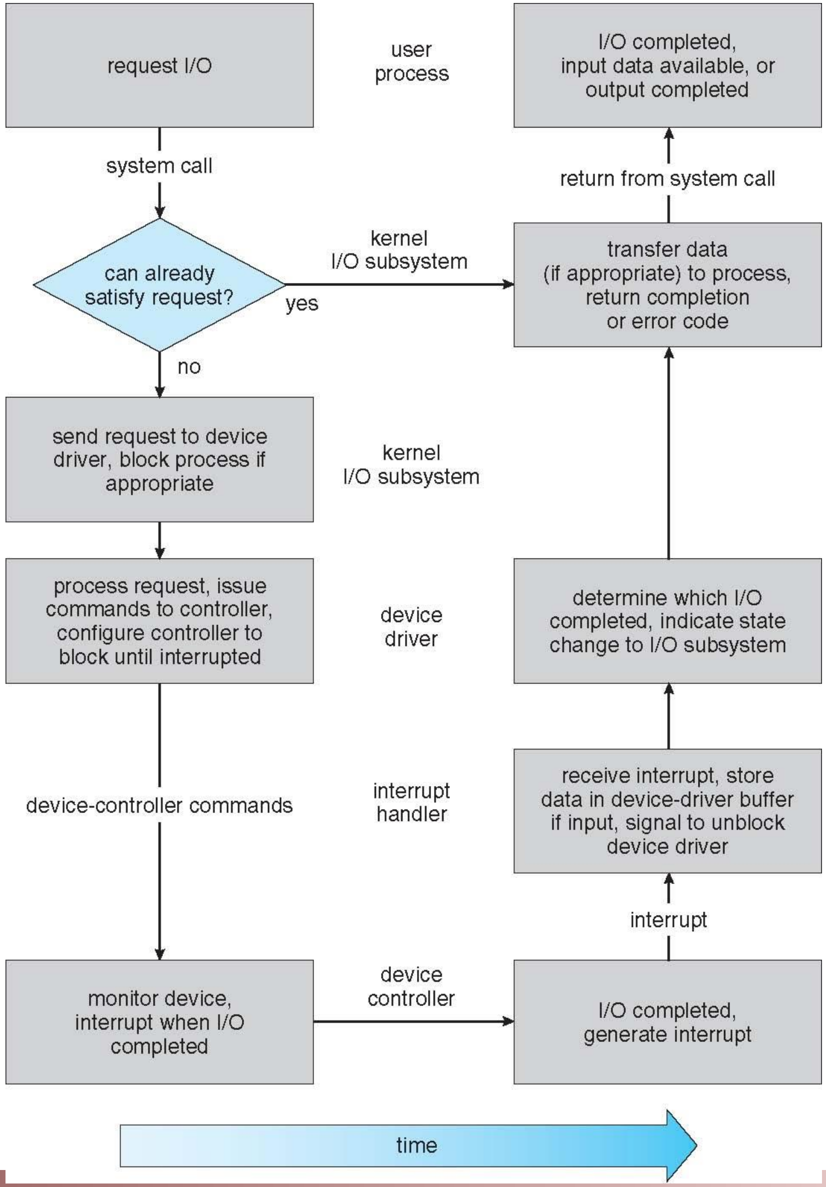
Build a System Call in Linux

- Set system call table
  - At /arch/x86/kernel/ for older version, or at /arch/x86/syscalls for new version
  - Use assembly to map the name of a new system call to a number and the vector
- Set header file to define the system call number
  - For example, at unistd.h
  - Let the C code know the mapping information of the system call
- Define system call prototype
  - For example, at syscall.h
- Implement the system call
- Modify Makefile to compile the kernel with the changes

Transforming I/O Requests to Hardware Operations

- Consider reading a file from disk for a process:
  - Determine which device is holding the file
    - Mount table → which device (major number, minor number)
  - Translate name to device representation
    - File system → where is the file in the disk
  - Physically read data from disk into buffer
  - Make data available to requesting process
  - Return control to process
- Major number
  - Each device driver is identified by a unique major number
- Minor number
  - This uniquely identifies a particular instance of a device

Life Cycle of An I/O Request



I/O Performance

- I/O is a major factor in system performance:
  - Demands CPU to execute device driver, kernel I/O code
  - Context switches due to interrupts
  - Data copying
  - Network traffic especially stressful
- Improving I/O performance
  - Reduce number of context switches
  - Reduce data copying
  - Reduce interrupts by using large transfers, smart controllers, polling
  - Use DMA
  - Use smarter hardware devices
  - Balance CPU, memory, bus, and I/O performance for highest throughput
  - Move user-mode processes/daemons to kernel threads

Device-Functionality Progression