# Operating Systems CS3500

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# I/O Systems

## Outline :

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

# Overview

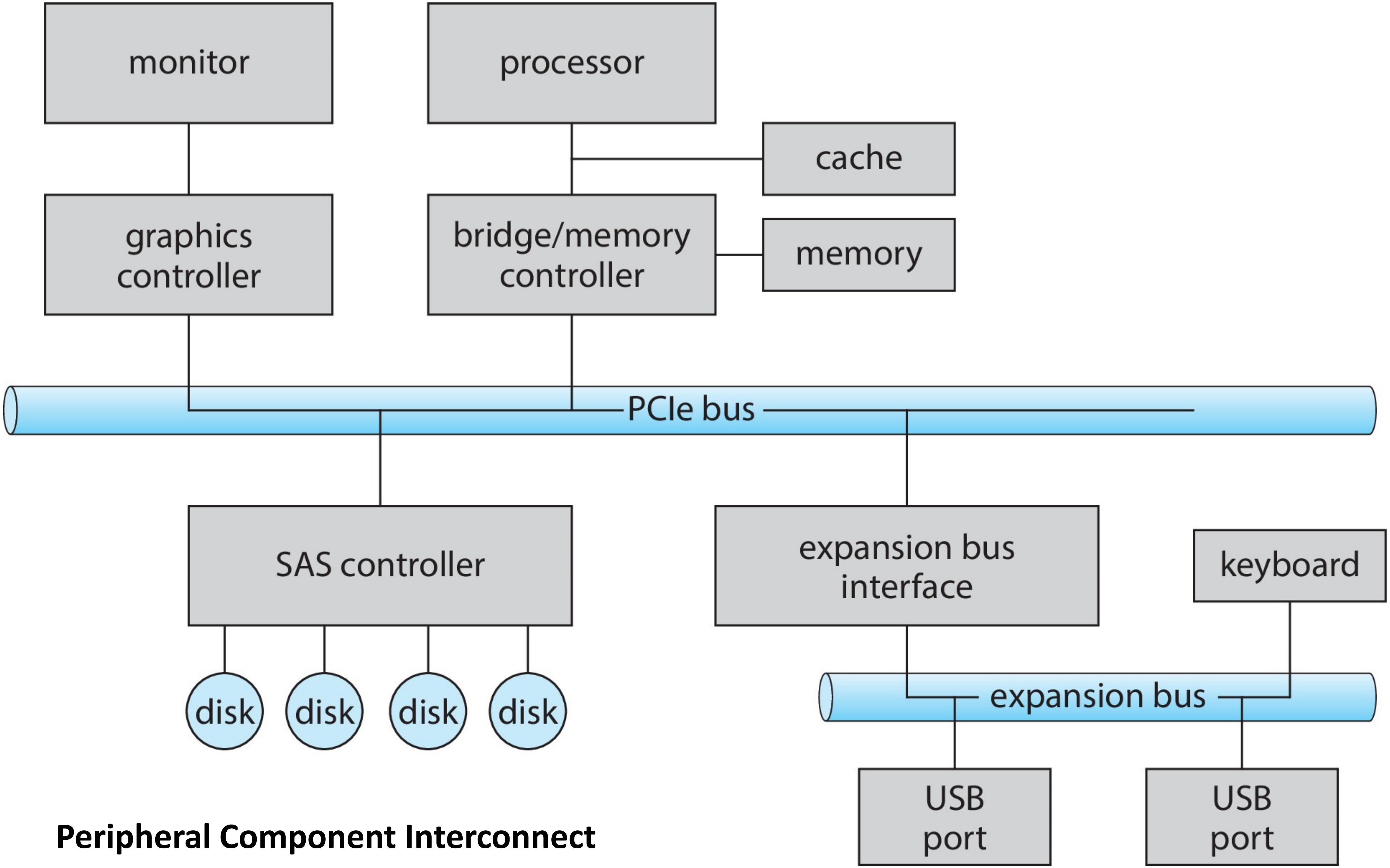
- I/O management is a major component of operating system design and operation
  - Important aspect of computer operation
  - I/O devices vary greatly
  - Various methods to control them
  - Performance management
  - New types of devices frequent

- Ports, busses, device controllers connect to various devices
- Device drivers encapsulate device details
  - Present uniform device-access interface to I/O subsystem

# I/O Hardware

- Incredible variety of I/O devices
  →Storage →Transmission, →Human-interface
- Common concepts – signals from I/O devices interface with computer
  - Port – connection point for device
  - Bus - daisy chain or shared direct access
    - PCI bus common in PCs and servers, PCI Express (PCIe)
    - expansion bus connects relatively slow devices
    - Serial-attached SCSI (SAS) common disk interface
  - Controller (host adapter) – electronics that operate port, bus, device
    - Sometimes integrated, sometimes separate circuit board (host adapter)
    - Contains processor, microcode, private memory, bus controller, etc.
      - Some talk to per-device controller with bus controller, microcode, memory, etc

# A Typical PC Bus Structure




**Peripheral Component Interconnect**

# I/O Hardware

- Fibre channel (FC) is complex controller, usually separate circuit board (host-bus adapter, HBA) plugging into bus
- I/O instructions control devices
- Devices usually have registers where device driver places commands, addresses, and data to write, or read data from registers after command execution
  - Data-in register, data-out register, status register, control register
  - Typically 1-4 bytes, or FIFO buffer
- Devices have addresses, used by
  - 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) |

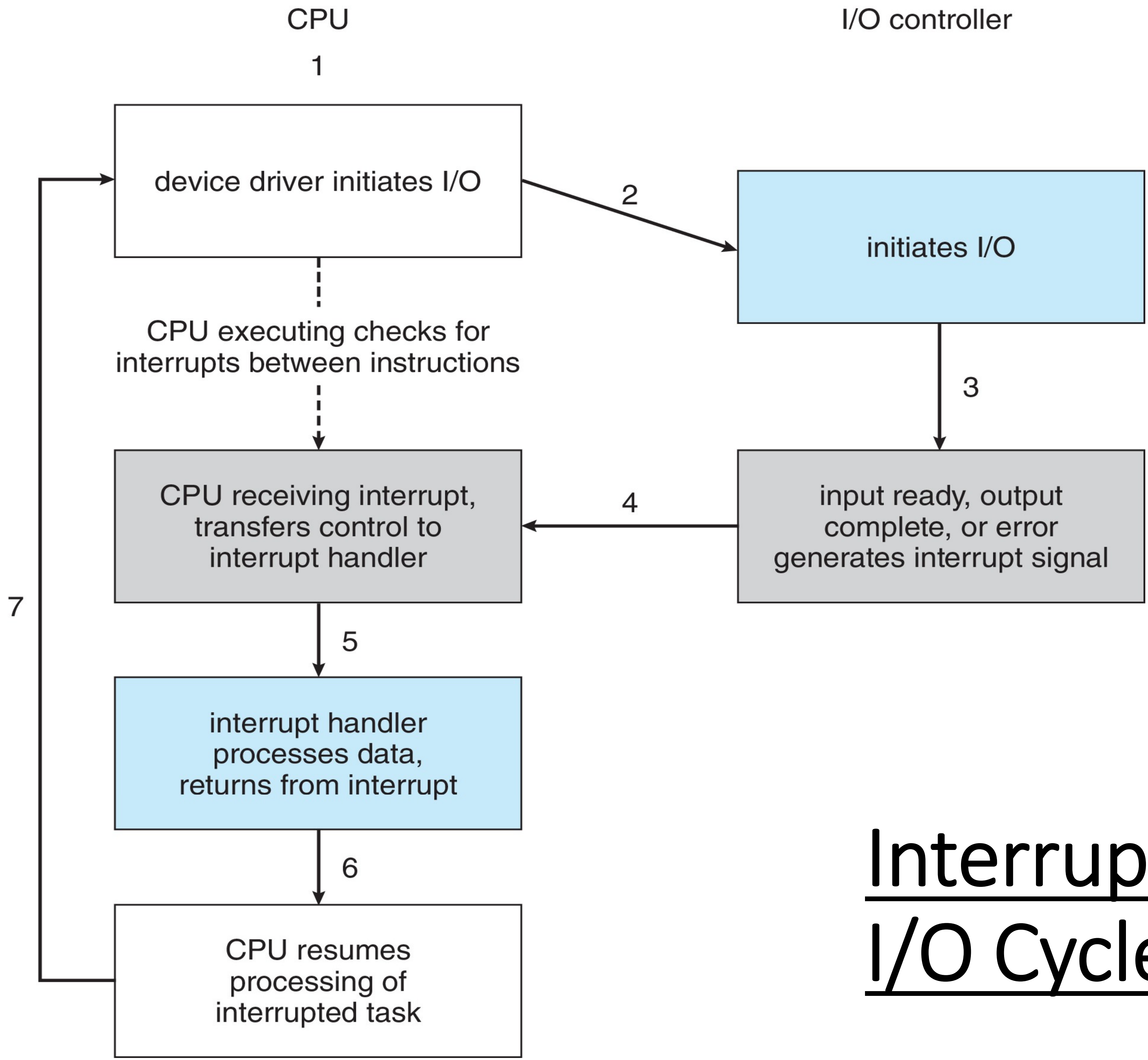
# Polling

- For each byte of 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?
    - But if miss a cycle data overwritten / lost

# Interrupts

- Polling can happen in 3 instruction cycles
  - Read status, logical-and to extract status bit, branch if not zero
  - How to be more efficient if non-zero infrequently?
- CPU Interrupt-request line triggered by I/O device
  - Checked by processor after each instruction
- Interrupt handler receives interrupts
  - Maskable 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

# Interrupts (Cont.)

- 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
- Used for time-sensitive processing, frequent, must be fast

# Latency

- Stressing interrupt management because even single-user systems manage hundreds or interrupts per second and servers hundreds of thousands
- For example, a quiet macOS desktop generated 23,000 interrupts over 10 seconds

```
Fri Nov 25 13:55:59                                        0:00:10
                              SCHEDULER      INTERRUPTS
---------------------------------------------
total_samples                        13           22998

delays <  10 usecs                   12           16243
delays <  20 usecs                    1            5312
delays <  30 usecs                    0             473
delays <  40 usecs                    0             590
delays <  50 usecs                    0              61
delays <  60 usecs                    0             317
delays <  70 usecs                    0               2
delays <  80 usecs                    0               0
delays <  90 usecs                    0               0
delays < 100 usecs                    0               0
total  < 100 usecs                   13           22998
```

# Intel Pentium Processor Event-Vector Table

A ***double fault*** exception occurs if the processor encounters a problem while trying to service a pending interrupt or exception. An example situation when a double fault would occur is when an interrupt is triggered but the segment in which the interrupt handler resides is invalid. If the processor encounters a problem when calling the double fault handler, a ***triple fault*** is generated and the processor shuts down.

| vector number | description |
|---|---|
| 0 | divide error |
| 1 | debug exception |
| 2 | null interrupt |
| 3 | breakpoint |
| 4 | INTO-detected overflow |
| 5 | bound range exception |
| 6 | invalid opcode |
| 7 | device not available |
| 8 | double fault |
| 9 | coprocessor segment overrun (reserved) |
| 10 | invalid task state segment |
| 11 | segment not present |
| 12 | stack fault |
| 13 | general protection |
| 14 | page fault |
| 15 | (Intel reserved, do not use) |
| 16 | floating-point error |
| 17 | alignment check |
| 18 | machine check |
| 19–31 | (Intel reserved, do not use) |
| 32–255 | maskable interrupts |

The events from 32 to 255, which are maskable, are used for purposes such as device-generated interrupts

# Direct Memory Access

- Used to avoid programmed I/O (one byte 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
  - Writes location of command block to DMA controller
  - Bus mastering of DMA controller – grabs bus from CPU
    - Cycle stealing from CPU but still much more efficient
  - When done, interrupts to signal completion
- Version that is aware of virtual addresses can be even more efficient - DVMA

| Parameter | Burst Mode of DMA | Cycle Stealing Mode of DMA |
|---|---|---|
| **Definition** | It is the DMA data transfer technique in which no. of data words are transferred continuously until whole data is not transferred. | It is the data transfer technique in which one data word is transferred and then control is returned to CPU. |
| **Data Transfer** | Data transfer Continues until whole data is not transferred. | Data is transferred Only when CPU is idle. |
| **Speed** | This is very fast data transfer technique and is used to transfer data for fast speed devices. | It is the slow data transfer technique as data is transferred only when CPU is idle |
| **CPU Utilization** | Low CPU Utilization because CPU remains idle until whole data is not transferred. | High CPU utilization because data is transferred when CPU has no task to perform. |
| **Extra Overhead** | No need to check CPU idleness | Extra Overhead because every time CPU has to be monitored for idle periods or slots. |

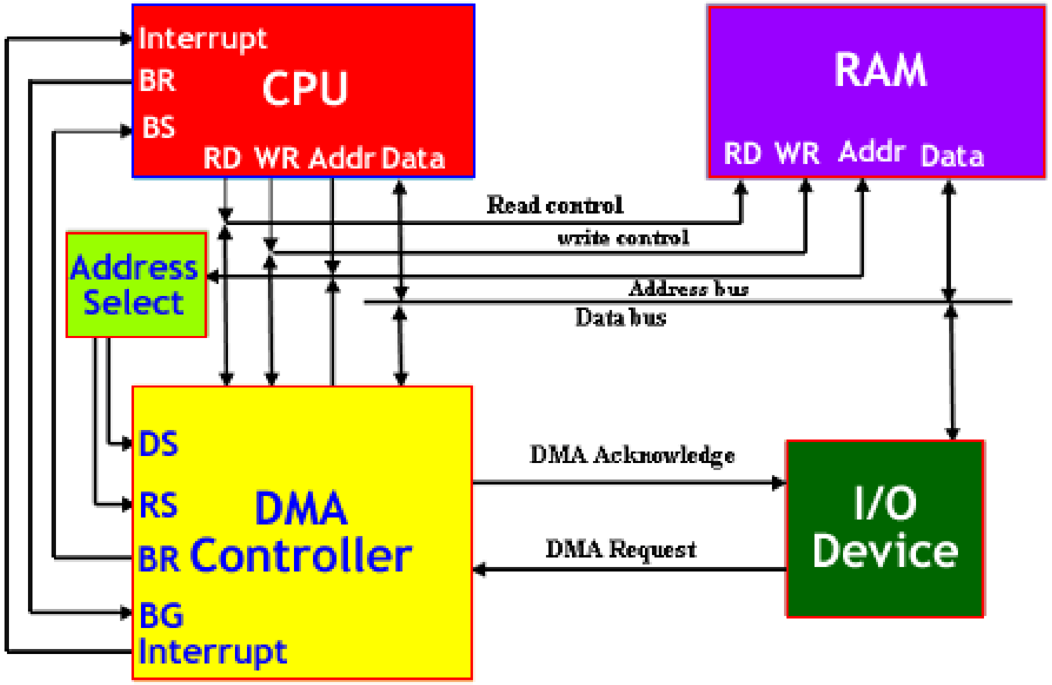



Fig: Showing DMA Mode of Data Transfer

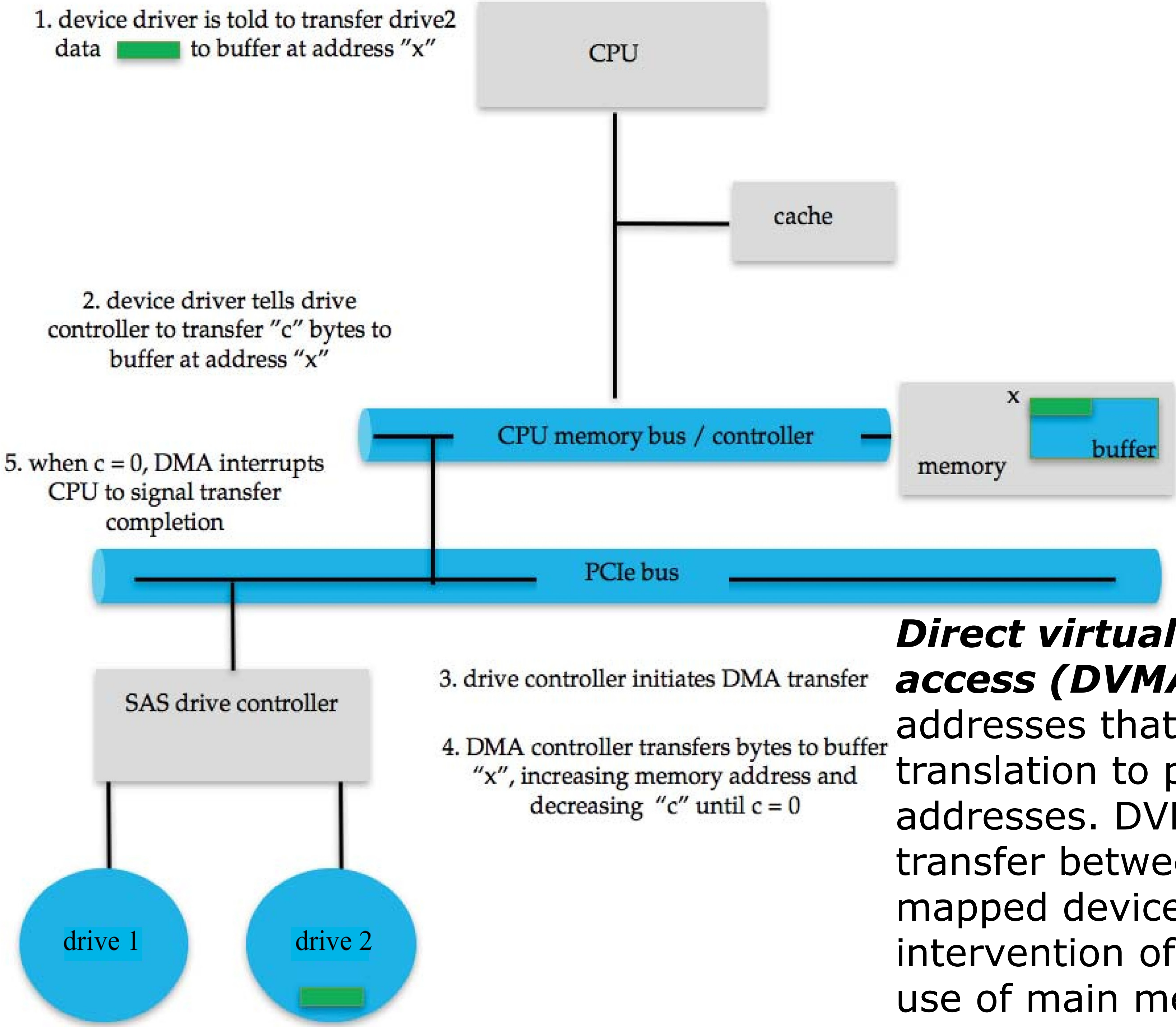
## Cycle Stealing

The DMA module takes control of the bus to transfer data to and from memory.

- it can either use the bus while the CPU is not using it.
- or it can force the CPU to temporarily suspend its operation.

The latter approach is called cycle stealing

# Six Step Process to Perform DMA Transfer



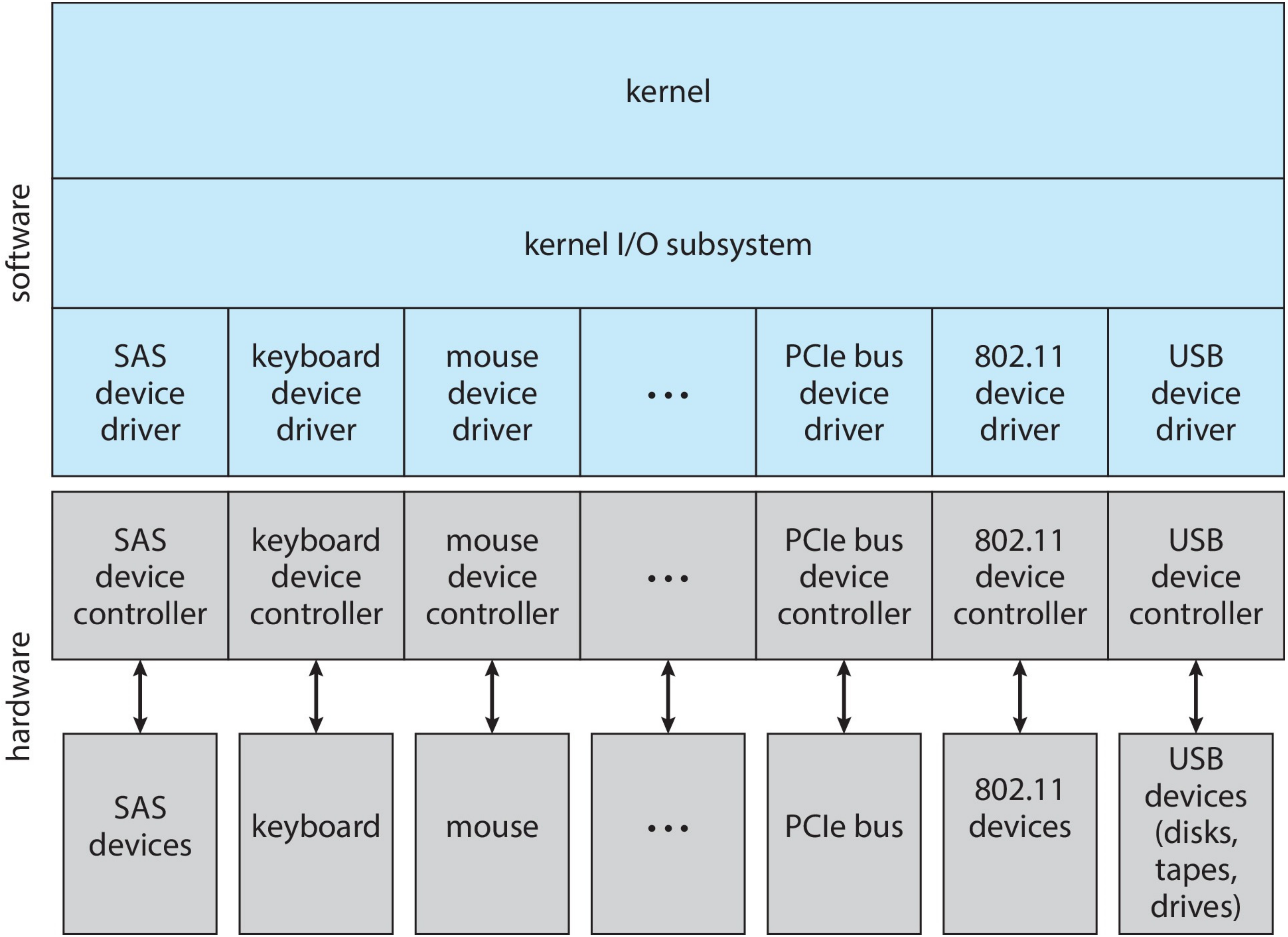

***Direct virtual memory access (DVMA),*** uses virtual addresses that undergo translation to physical addresses. DVMA can perform a transfer between two memory-mapped devices without the intervention of the CPU or the use of main memory.

# 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

- Devices vary in many dimensions
  - Character-stream or block
  - Sequential or random-access
  - Synchronous or asynchronous (or both)
  - Sharable or dedicated
  - Speed of operation
  - read-write, read only, or write only

# A Kernel I/O Structure



# Characteristics of I/O Devices

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

# Characteristics of I/O Devices (Cont.)

- Subtleties of devices handled by device drivers
- Broadly I/O devices can be grouped by the OS into
  - Block I/O
  - Character I/O (Stream)
  - Memory-mapped file access
  - Network sockets
- For direct manipulation of I/O device specific characteristics, using an escape / back door (Appcln Cmd → Dev. Drv)
  - Unix **`ioctl()`** call to send arbitrary bits to a device control register and data to device data register
- UNIX and Linux use tuple of "major" and "minor" device numbers to identify type and instance of devices (here major 8 and minors 0-4)

```
% ls -l /dev/sda*
brw-rw---- 1 root disk 8, 0 Mar 16 09:18 /dev/sda
brw-rw---- 1 root disk 8, 1 Mar 16 09:18 /dev/sda1
brw-rw---- 1 root disk 8, 2 Mar 16 09:18 /dev/sda2
brw-rw---- 1 root disk 8, 3 Mar 16 09:18 /dev/sda3
```

# Block and Character Devices

- Block devices include disk drives
  - Commands include read, write, seek
  - **Raw I/O**, **direct I/O**, or file-system access; *Direct*: a mode of operation on a file that disables buffering and locking; *Raw*: access a block device as a simple linear array of blocks.
  - Memory-mapped file access possible
    - File mapped to virtual memory and clusters brought via demand paging
  - DMA

- Character devices include keyboards, mice, serial ports
  - Commands include **get()**, **put()**
  - Libraries layered on top allow line editing

# Network Devices

- Varying enough from block and character to have own interface
- Linux, Unix, Windows and many others include socket interface
  - Separates network protocol from network operation
  - Includes `select()` functionality (manages a set of sockets).
- Approaches vary widely (pipes, FIFOs, streams, queues, mailboxes)

# Clocks and Timers

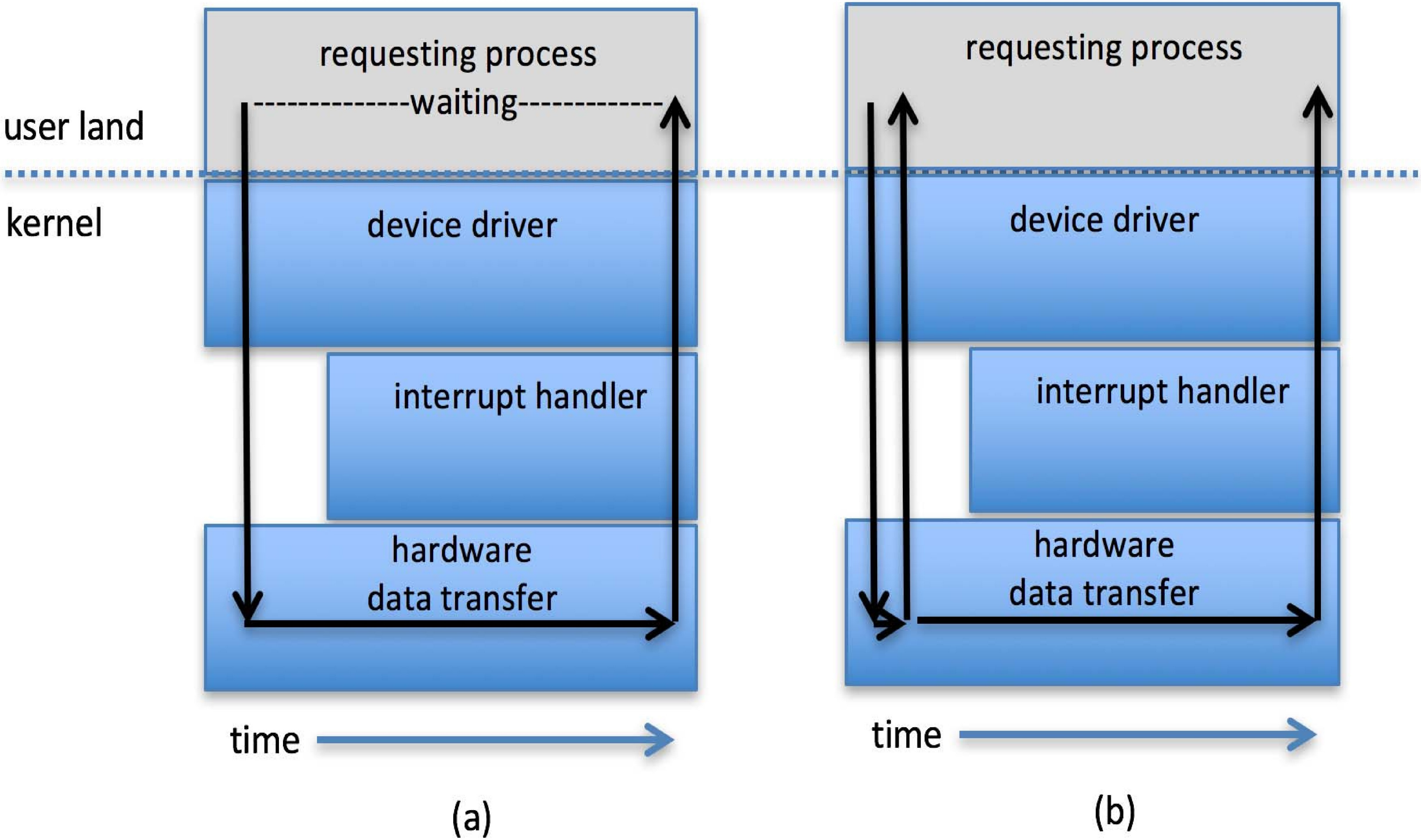
- Provide current time, elapsed time, tin
- Normal resolution about 1/60 second
- Some systems provide higher-resolutic
- Programmable interval timer used for t (for process scheduling)
- `ioctl()` (on UNIX) covers odd aspects of I/O such as clocks and timers

***High-performance event timer (HPET),*** runs at 10-MHz range. It has several comparators that can be set to trigger once or repeatedly when the value they hold matches that of the *HPET*. The trigger generates an interrupt, and the operating system's clock management routines determine what the timer was for and what action to take. Used to maintain the system time-of-day clock, if it drifts

# Nonblocking and Asynchronous I/O

- Blocking - process suspended until I/O completed
  - Easy to use and understand
  - Insufficient for some needs
- Nonblocking - I/O call returns as much as available
  - User interface, data copy (buffered I/O)
  - Implemented via multi-threading
  - Returns quickly with count of bytes read or written
  - **`select()`** - to find if data ready then **`read()`** or **`write()`** to transfer (select() returns information about which sockets have a packet waiting to be received and which sockets have room to accept a packet to be sent, how long to wait. The use of select() eliminates the polling and busy waiting that would otherwise be necessary for network I/O).
- Asynchronous - process runs while I/O executes
  - Difficult to use
  - I/O subsystem signals process when I/O completed

# Two I/O Methods




Synchronous

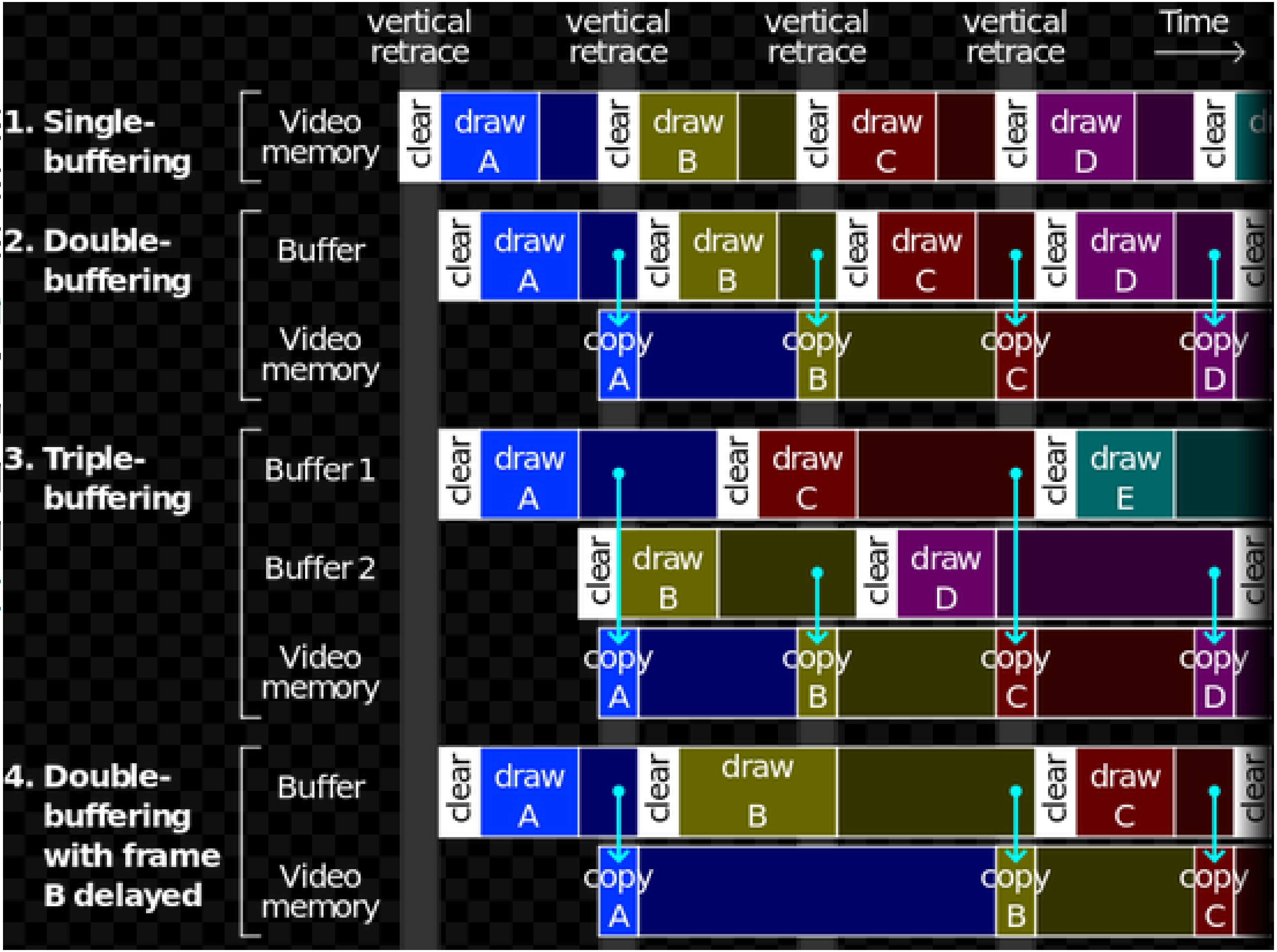
Asynchronous

# Vectored I/O

- Vectored I/O allows one system call to perform multiple I/O operations
- For example, Unix **`readve()`** accepts a vector of multiple buffers to read into or write from
- This scatter-gather method better than multiple individual I/O calls
  - Decreases context switching and system call overhead
  - Some versions provide atomicity
    - Avoid for example worry about multiple threads changing data as reads / writes occurring

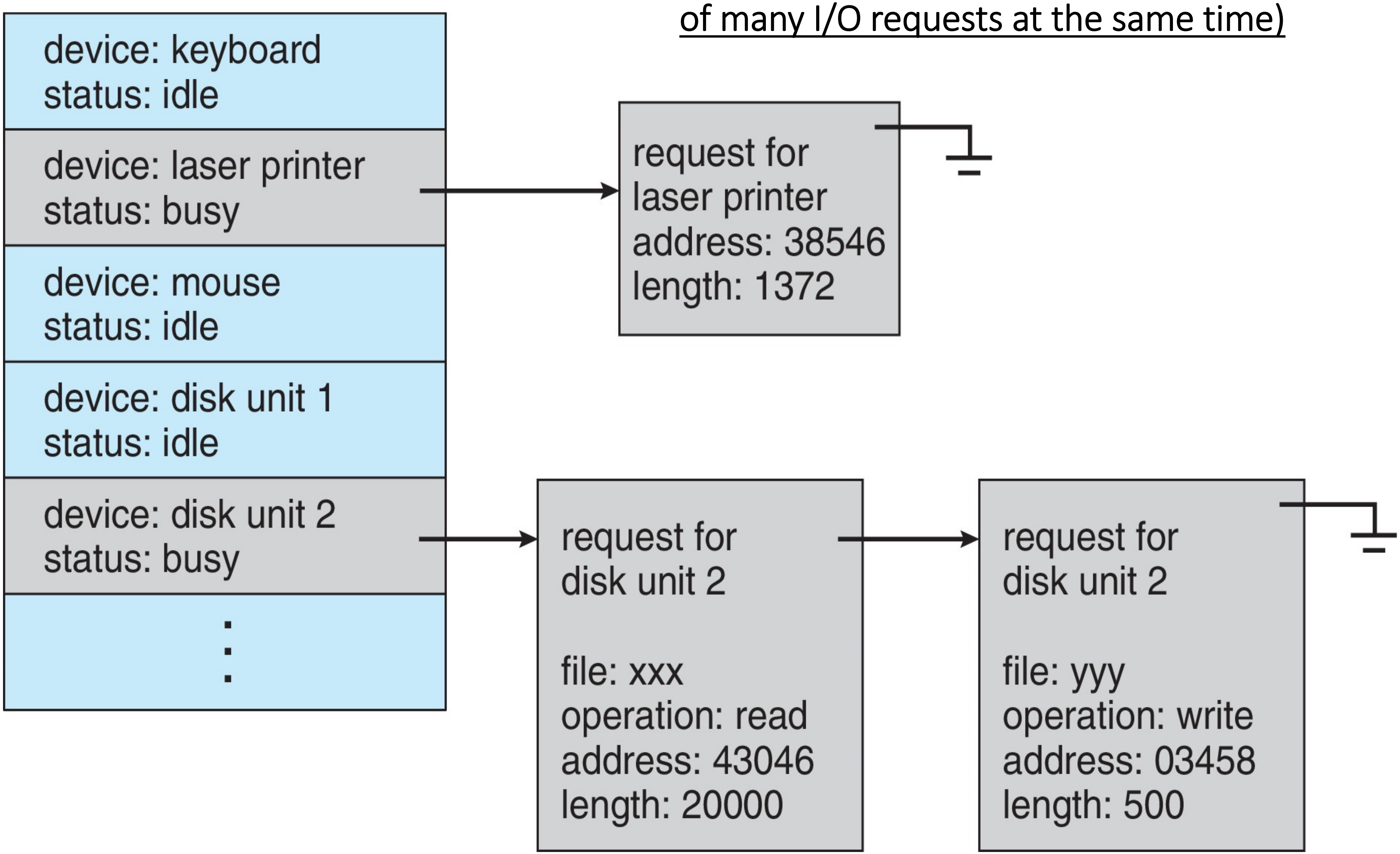
# Kernel I/O Subsystem

- Sch
  - S
  - S
  - S
- Buf
  dev
  - T
  - T
  - T
  - [

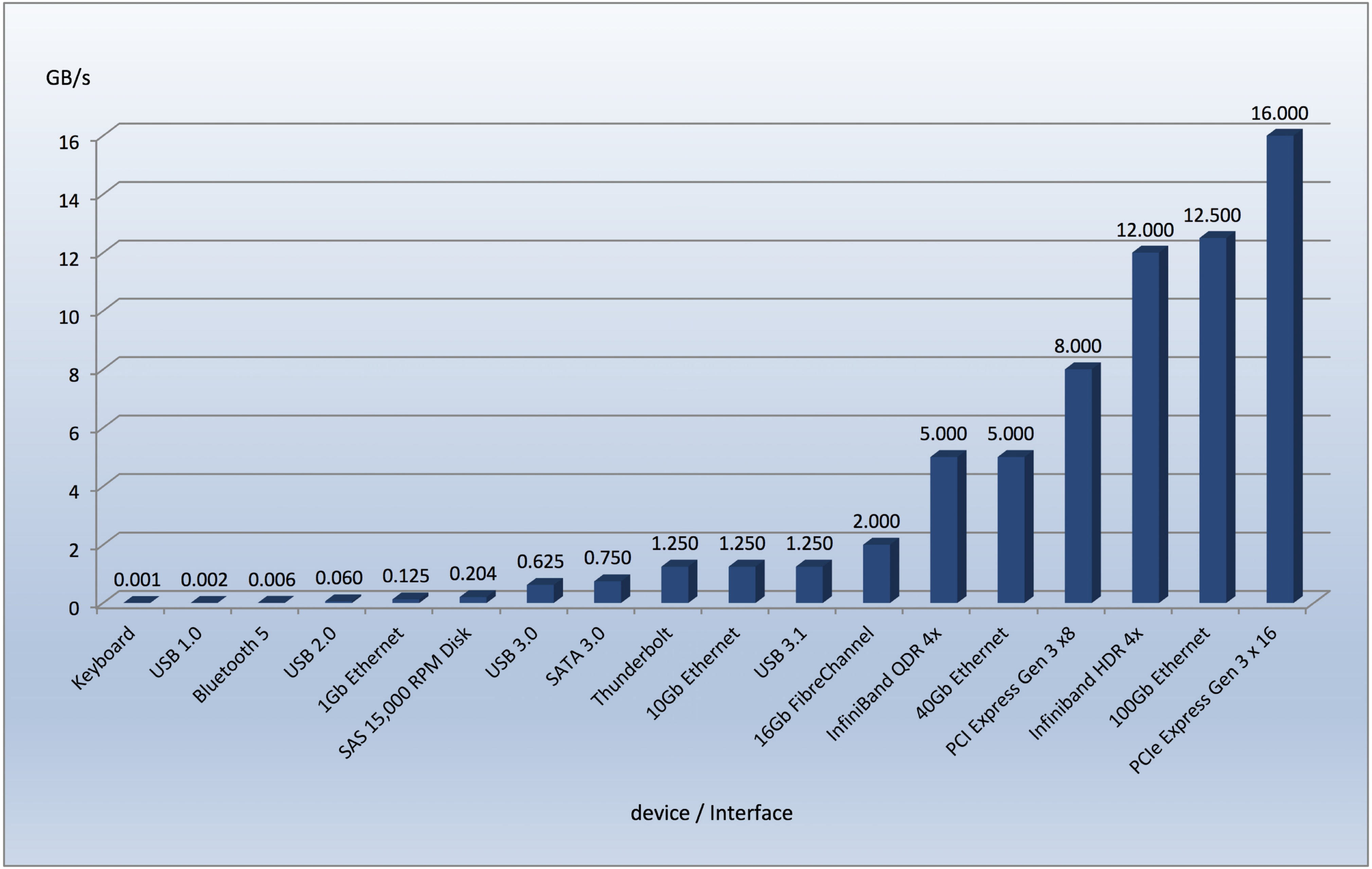


# Device-status Table

(to keep track
of many I/O requests at the same time)



# Common PC and Data-center I/O devices and Interface Speeds



# Kernel I/O Subsystem

- Caching - faster device holding copy of data
  - Always just a copy
  - Key to performance
  - Sometimes combined with buffering

- Spooling - hold output for a device
  - If device can serve only one request at a time
  - i.e., Printing

- Device reservation - provides exclusive access to a device
  - System calls for allocation and de-allocation
  - Watch out for deadlock

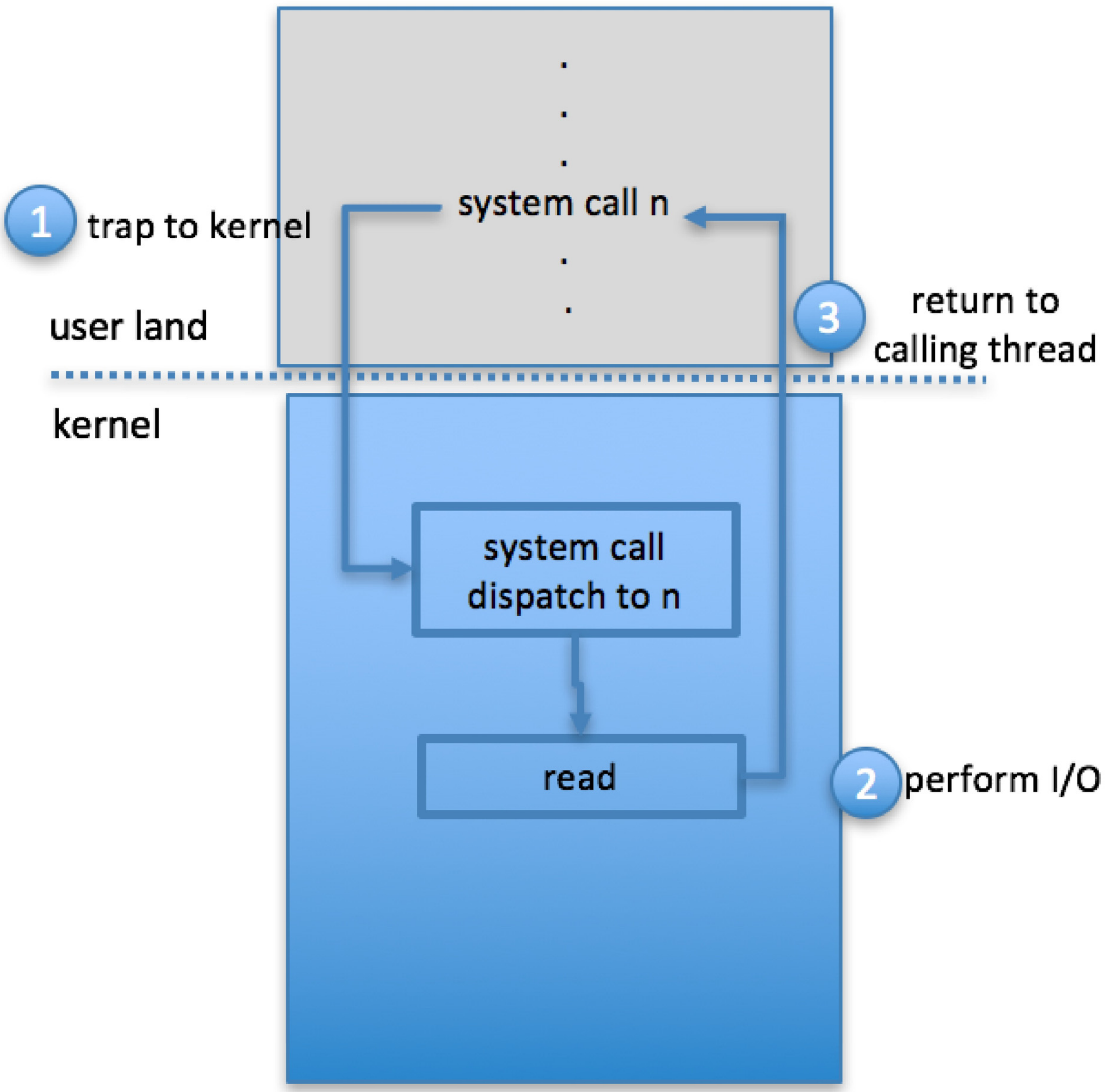
# Error Handling

- OS can recover from disk read, device unavailable, transient write failures
  - Retry a read or write, for example
  - Some systems more advanced – Solaris FMA, AIX
    - Track error frequencies, stop using device with increasing frequency of retry-able errors
- Most return an error number or code when I/O request fails
- System error logs hold problem reports

# 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
    - Memory-mapped and I/O port memory locations must be protected too

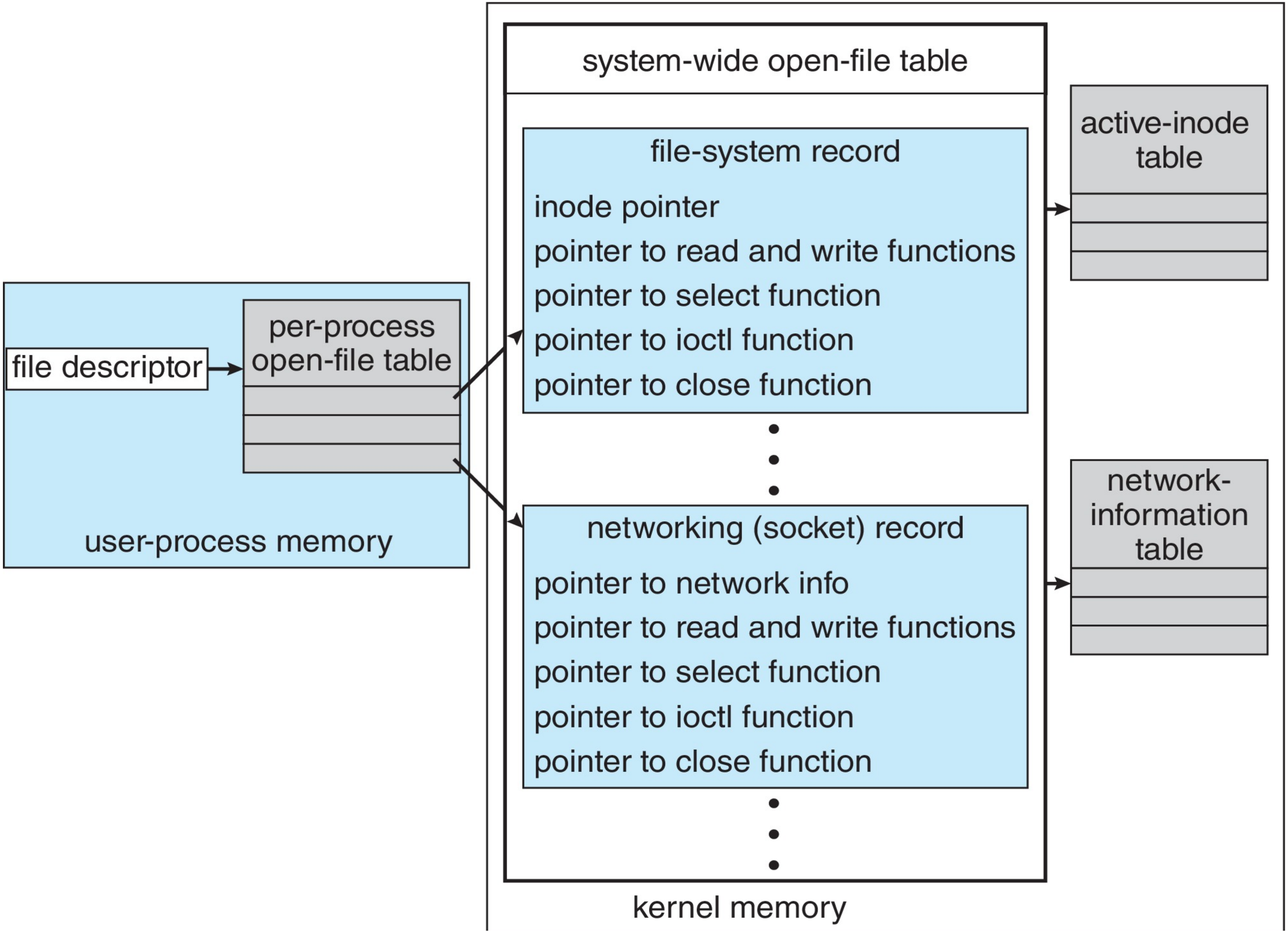
# Use of a System Call to Perform I/O



# Kernel Data Structures

- Kernel keeps state info for I/O components, including open file tables, network connections, character device state
- Many, many complex data structures to track buffers, memory allocation, "dirty" blocks
- Some use object-oriented methods and message passing to implement I/O
  - Windows uses message passing
    - Message with I/O information passed from user mode into kernel
    - Message modified as it flows through to device driver and back to process
    - Pros / cons? (flexibility, overhead, design…)

# UNIX I/O Kernel Structure



# Power Management

- Not strictly domain of I/O, but much is I/O related
- Computers and devices use electricity, generate heat, frequently require cooling
- OSes can help manage and improve use
  - Cloud computing environments move virtual machines between servers
    - Can end up evacuating whole systems and shutting them down
- Mobile computing has power management as first class OS aspect

# Power Management (Cont.)

For example, Android implements

- Component-level power management
  - Understands relationship between components
  - Build device tree representing physical device topology
  - System bus -> I/O subsystem -> {flash, USB storage}
  - Device driver tracks state of device, whether in use
  - Unused component – turn it off
  - All devices in tree branch unused – turn off branch
- Wake locks – like other locks but prevent sleep of device when lock is held
- Power collapse – put a device into very deep sleep
  - Marginal power use
  - Only awake enough to respond to external stimuli (button press, incoming call)

- Modern systems use advanced configuration and power interface (ACPI) firmware providing code that runs as routines called by kernel for device discovery, management, error and power management

# Kernel I/O Subsystem Summary

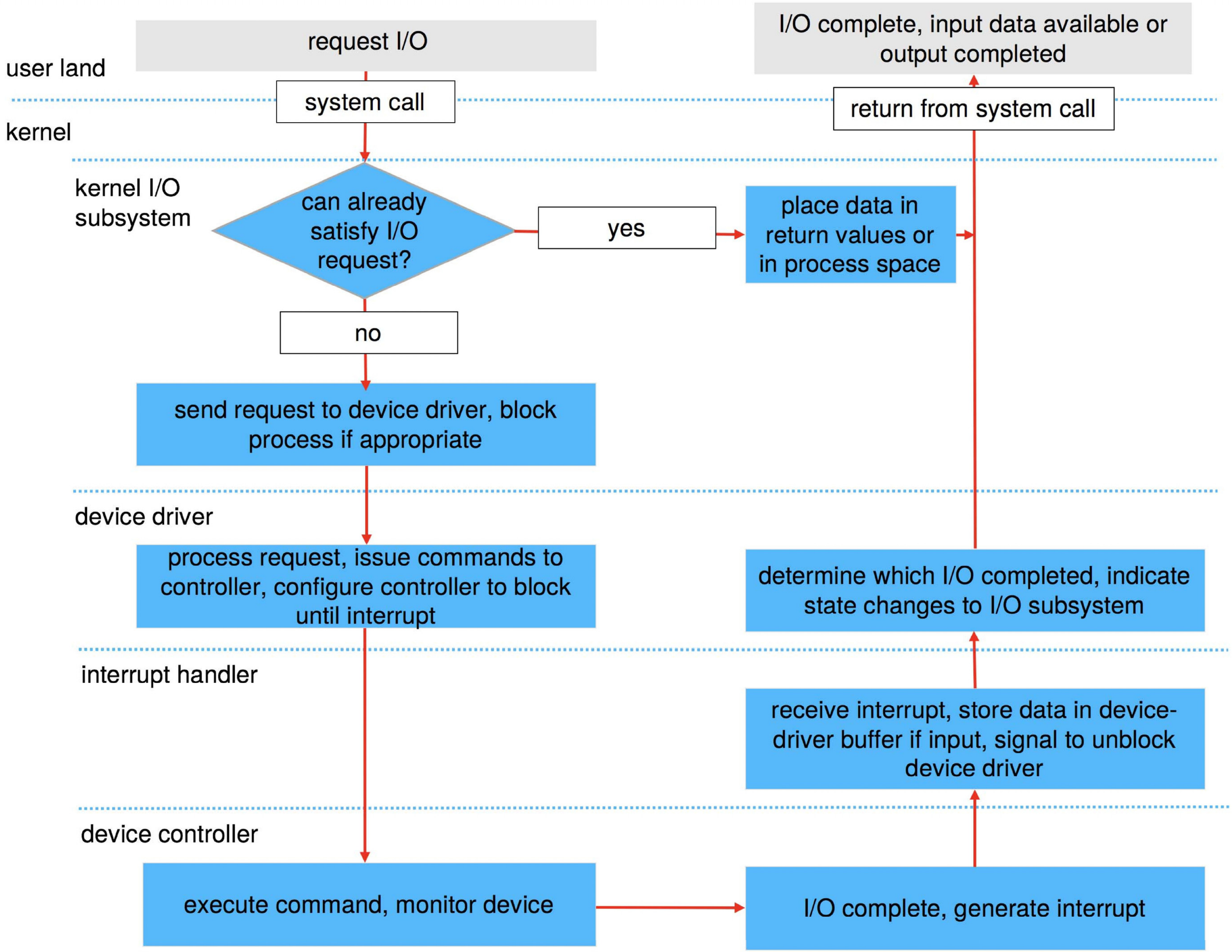
- In summary, the I/O subsystem coordinates an extensive collection of services that are available to applications and to other parts of the kernel
  - Management of the name space for files and devices
  - Access control to files and devices
  - Operation control (for example, a modem cannot seek())
  - File-system space allocation
  - Device allocation
  - Buffering, caching, and spooling
  - I/O scheduling
  - Device-status monitoring, error handling, and failure recovery
  - Device-driver configuration and initialization
  - Power management of I/O devices

- The upper levels of the I/O subsystem access devices via the uniform interface provided by the device drivers

# Transforming I/O Requests to Hardware Operations

- Consider reading a file from disk for a process:
  - Determine device holding file (FAT or inode, mount table)
  - Translate name to device representation
  - Physically read data from disk into buffer
  - Make data available to requesting process
  - Return control to process

# Life Cycle of An I/O Request



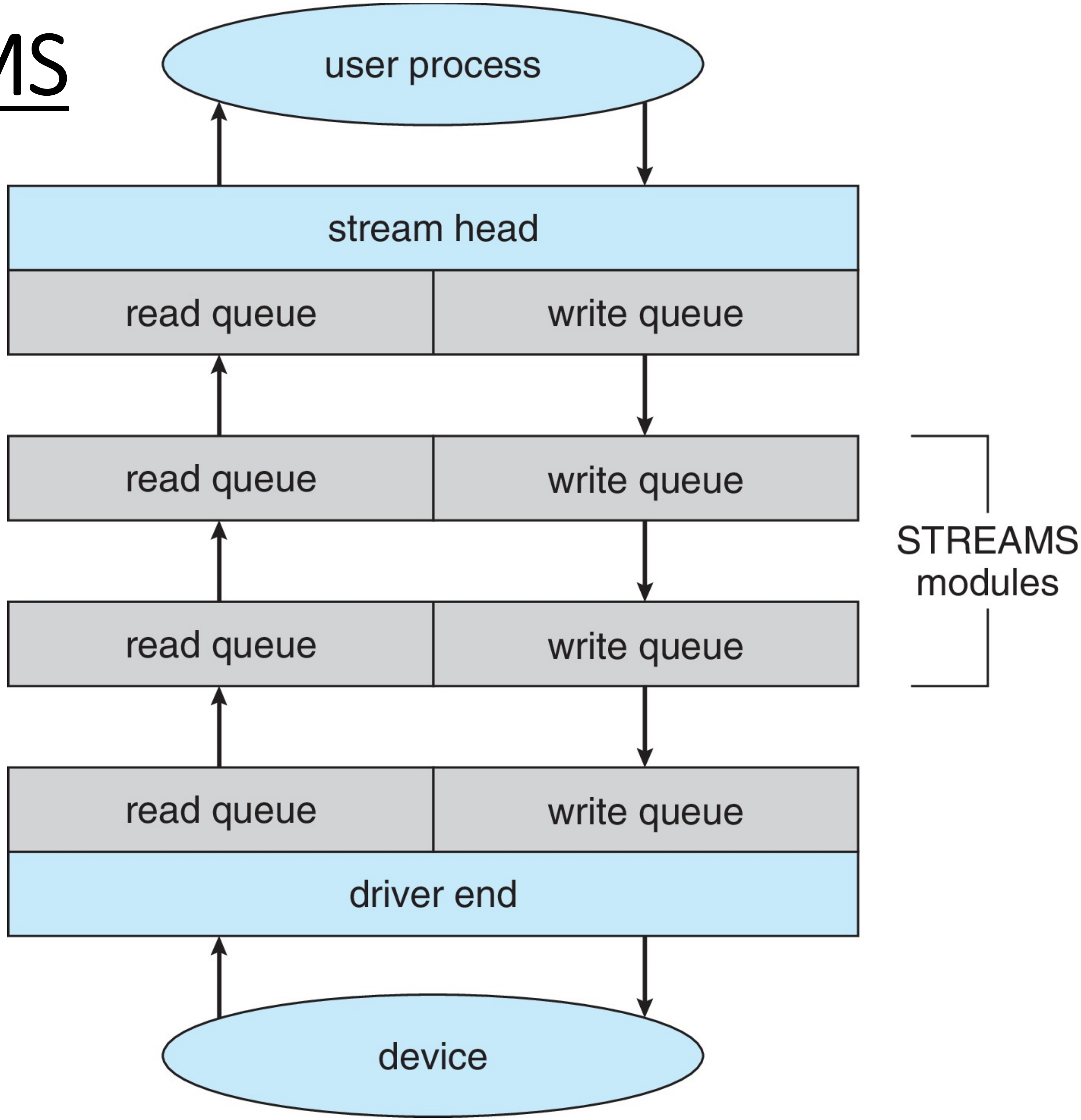
I/O operation requires a great many steps that together consume a tremendous number of CPU cycles.

**4.** The device driver allocates kernel buffer space to receive the data and schedules the I/O. Eventually, the driver sends commands to the device controller by writing into the device-control registers.
**5.** The device controller operates the device hardware to perform the data transfer.
**6.** The driver may poll for status and data, or it may have set up a DMA transfer into kernel memory. We assume that the transfer is managed by a DMA controller, which generates an interrupt when the transfer completes.
**7.** The correct interrupt handler receives the interrupt via the interrupt vector table, stores any necessary data, signals the device driver, and returns from the interrupt.
**8.** The device driver receives the signal, determines which I/O request has completed, determines the request's status, and signals the kernel I/O subsystem that the request has been completed.
**9.** The kernel transfers data or return codes to the address space of the requesting process and moves the process from the wait queue back to the ready queue.
**10.** Moving the process to the ready queue unblocks the process. When the scheduler assigns the process to the CPU, the process resumes execution at the completion of the system call.

# STREAMS

- STREAM – a full-duplex communication channel between a user-level process and a device in Unix System V and beyond
- A STREAM consists of:
  - *STREAM head* interfaces with the user process
  - *driver end* interfaces with the device
  - zero or more *STREAM modules* between them
- Each module contains a read queue and a write queue
- Message passing is used to communicate between queues
  - Flow control option to indicate available or busy, avoid overflow
  - Write() vs putmsg; read vs getmsg() functions
- Asynchronous internally, synchronous where user process communicates with stream head
- Driver end must respond to interrupts (with no blocking, like streams - the network card must simply drop further messages until there is enough buffer space to store incoming messages)

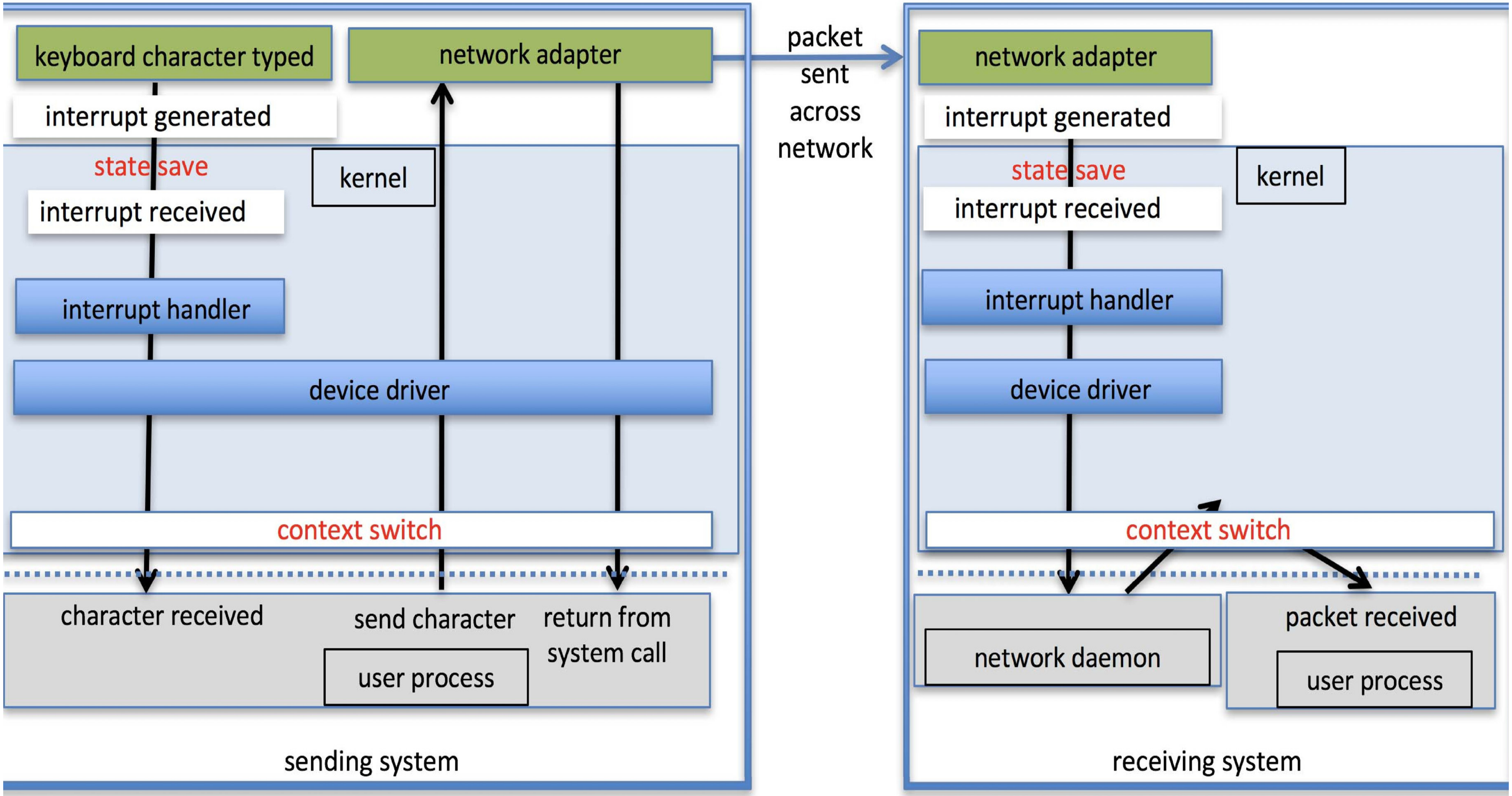
# The STREAMS Structure



# Performance

- I/O 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

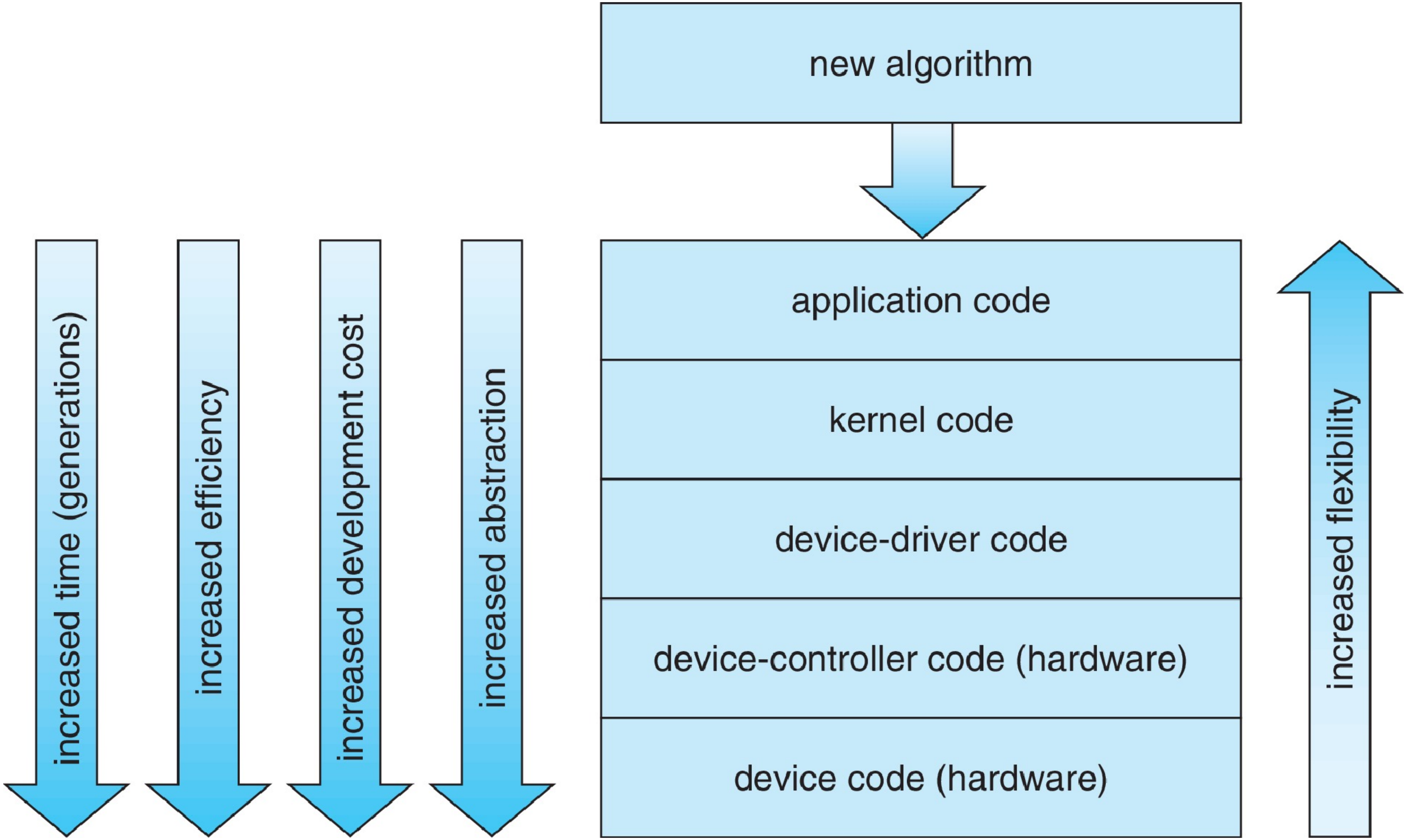
# Intercomputer Communications



# Improving 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



# I/O Performance of Storage (and Network Latency)