CS 310 Operating Systems

Lecture 38: Input Output Concept, Buses, Processor Device Interaction

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References

- Book: Operating Systems: Three Easy Pieces, OSTEP, by Remzi H. Arpaci-Dusseau and Andrea C. Arpaci-Dusseau
- Book: Operating Systems: Principles and Practice: Thomas Anderson and Michael Dahlin, Part 4
- CS162, Operating Systems and Systems Programming, University of California, Berkeley
- CS4410, Operating Systems, Course, Cornell University, Spring 2019,

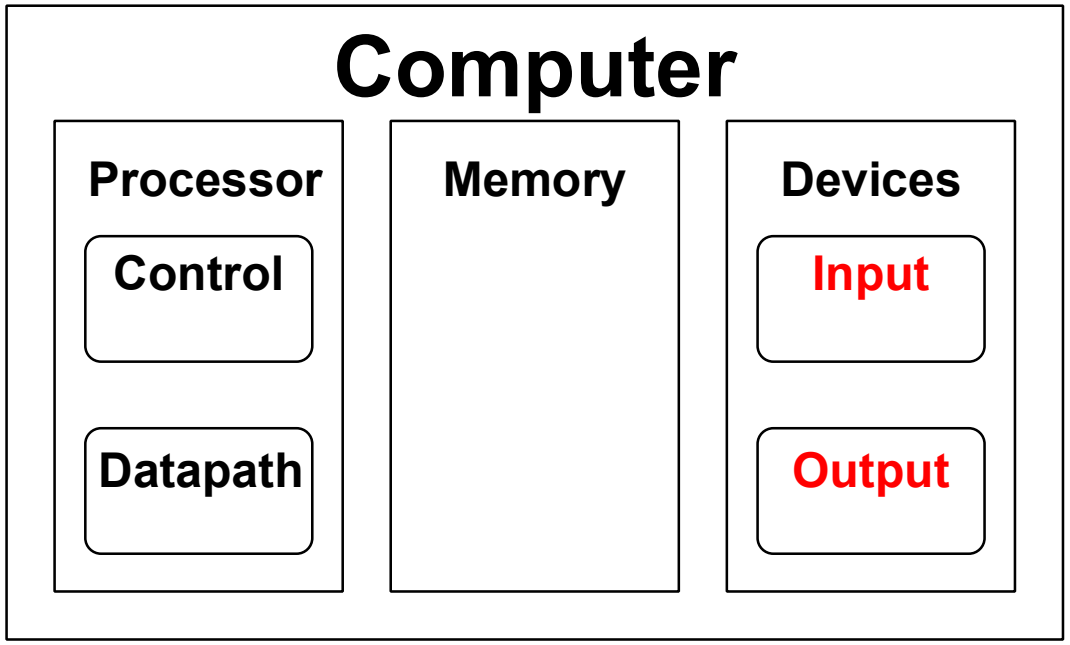
In this lecture, we will study

- Input-Output Concepts
- Buses
- Processor Device Interaction
  - I/O Instruction
  - Memory Mapped
- Programmed I/O (Polling), Interrupt Driven I/O, DMA

Input - Output Concepts

Recall: Five Components of a Computer

- Components a computer needs to work
  - Control
  - Datapath
  - Memory
  - **Input**
  - **Output**



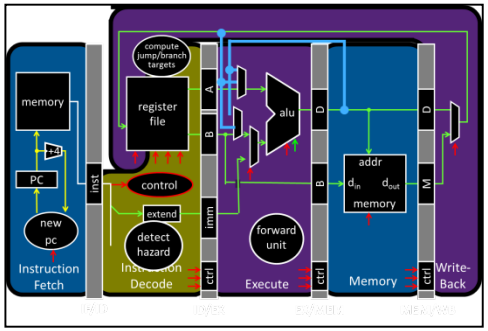
Ref: Morgan Rae Reschenberg, Course 61C, Univ of California, Berkeley

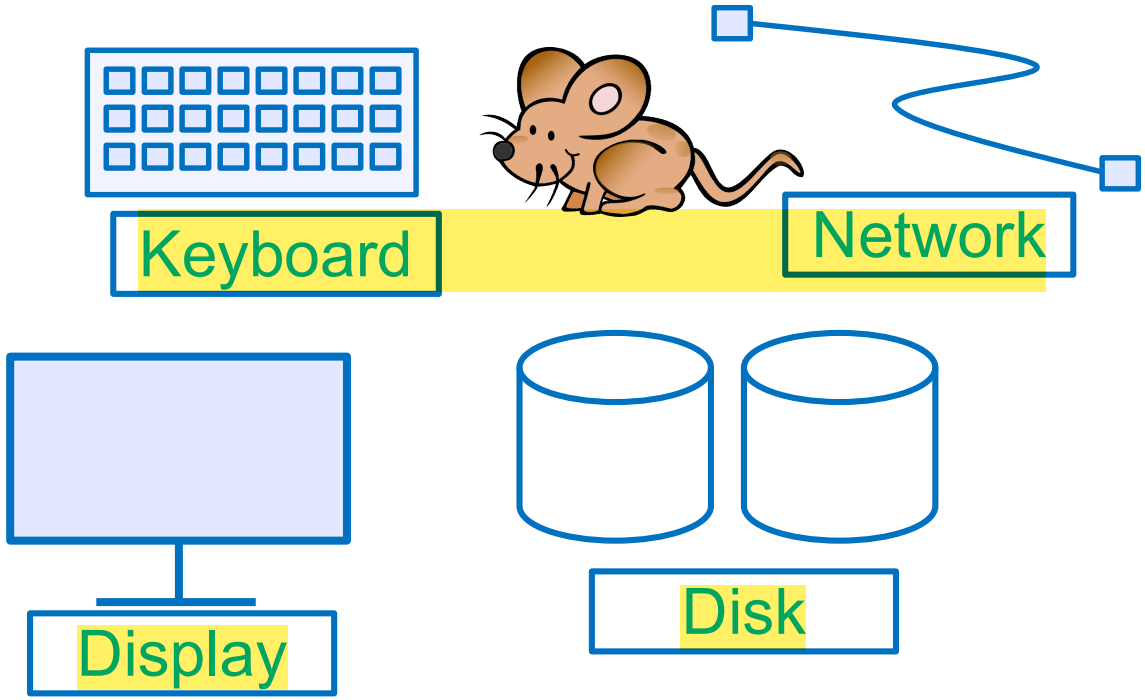
Recall: Big Picture: Input/Output (I/O)

How does a processor interact with its environment?

Computer System =

Memory + Datapath + Control **+ Input + Output**

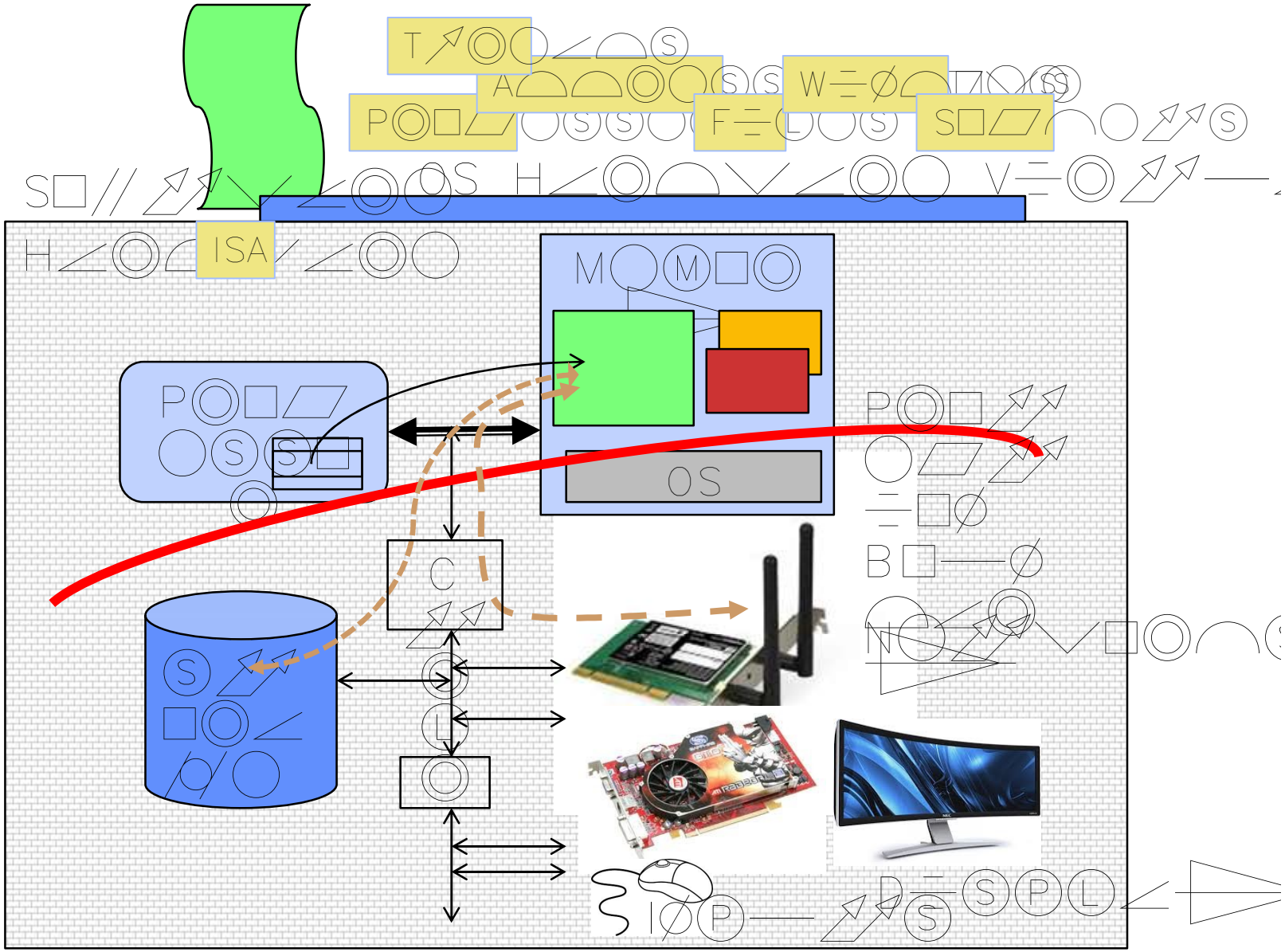




Ref: I/O lecture, Prof Hakim Weatherspoon, Cornell Univ

Recall: OS Basics: I/O

OS provides common services in the form of I/O



Adapted from lectures CS162 at UC Berkeley, 2020

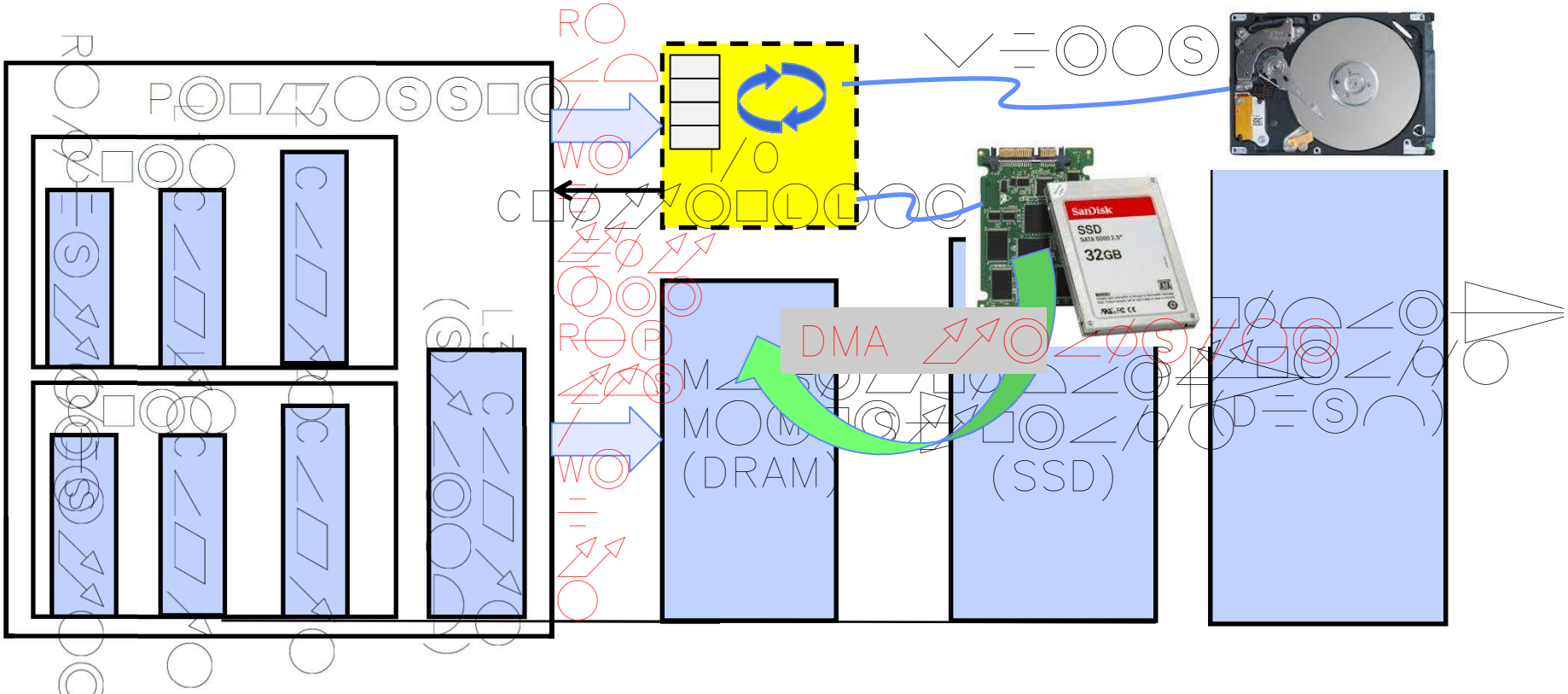
And Range of Timescales

L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	25 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	3,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns
Disk seek	10,000,000 ns
Read 1 MB sequentially from disk	20,000,000 ns
Send packet CA->Netherlands->CA	150,000,000 ns

Key Stroke / Click
100 ms

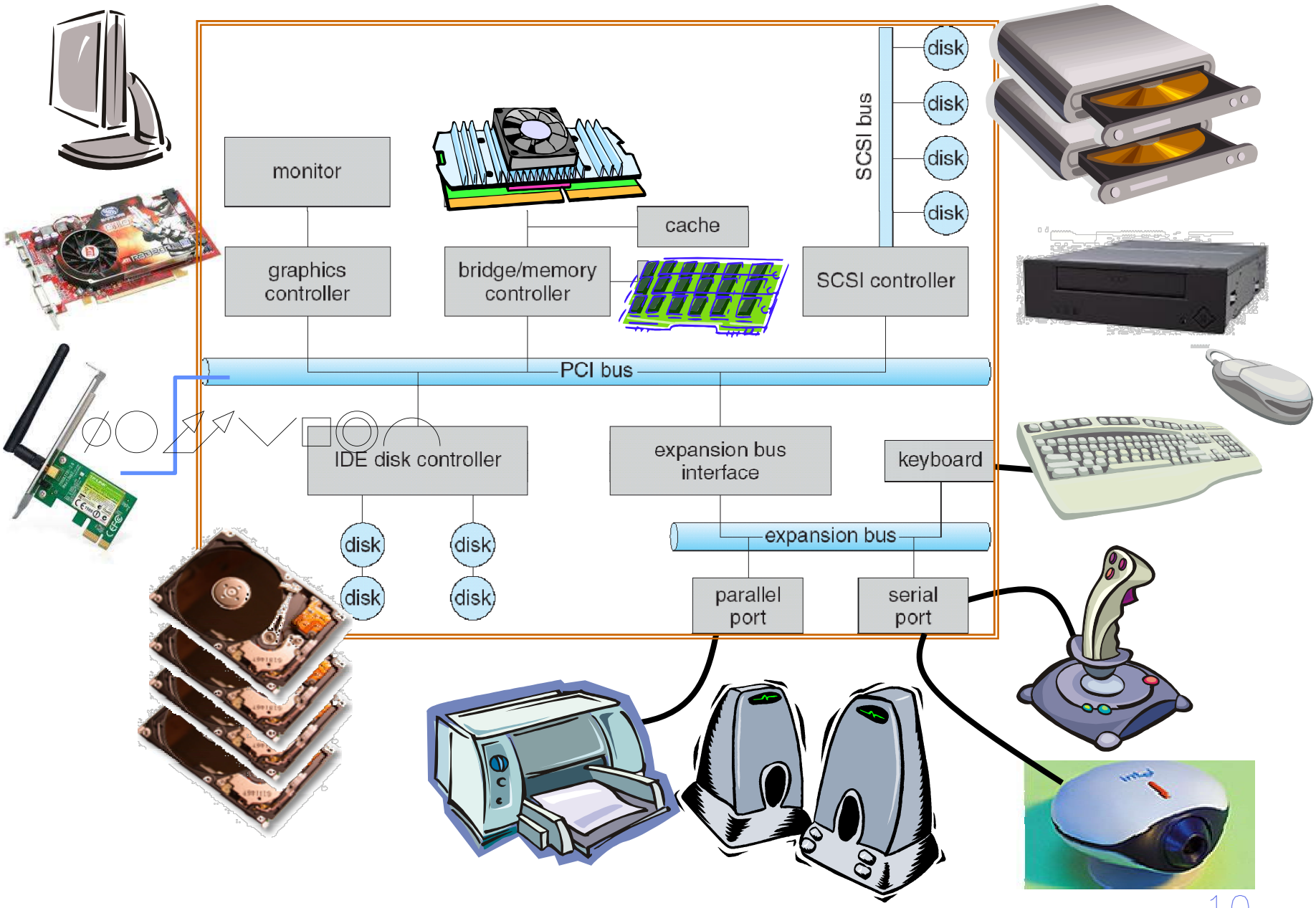
Adapted from lectures CS162 at UC Berkeley, 2020

In a Picture



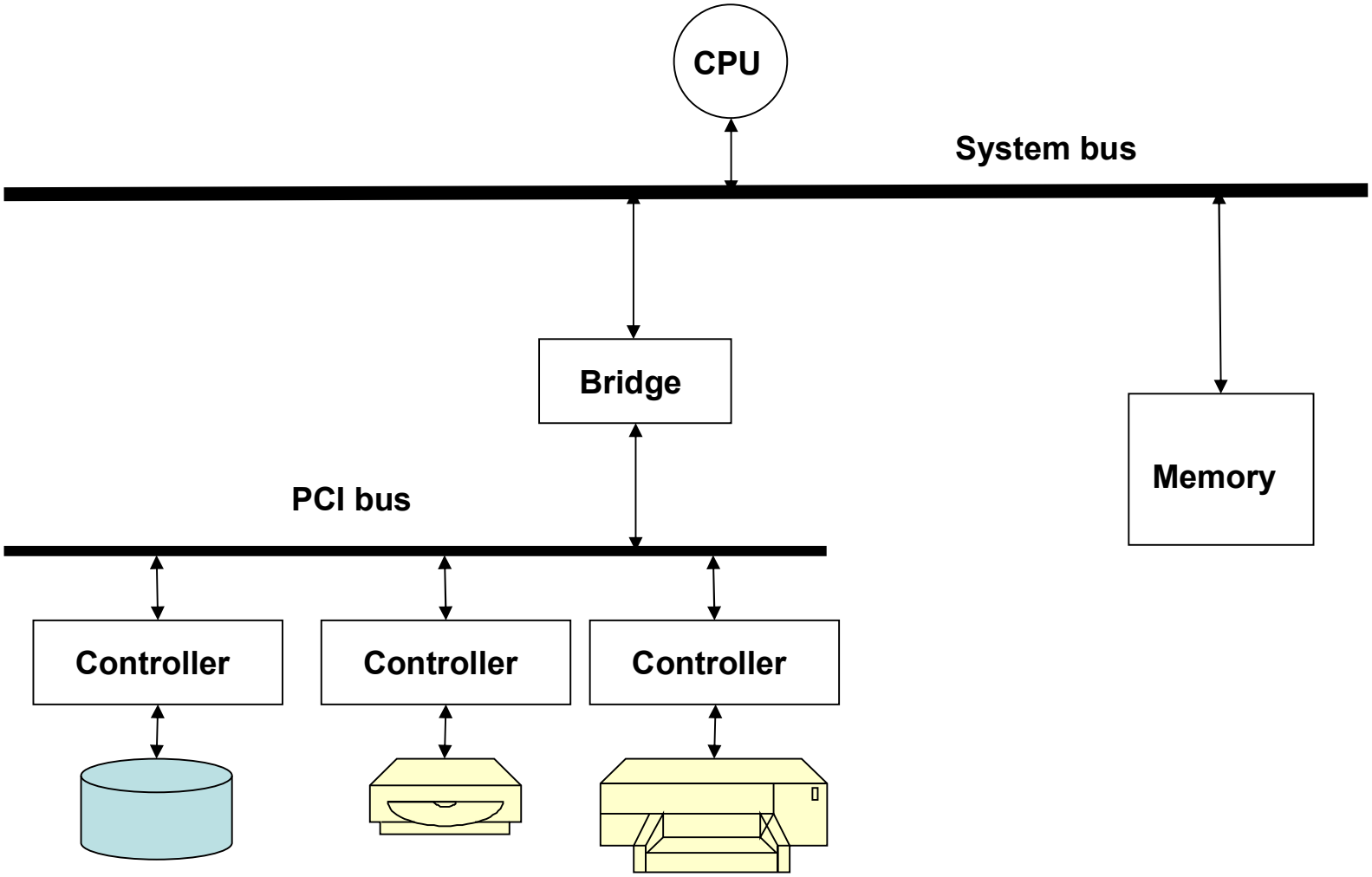
- I/O devices are supported by I/O Controllers
- Processors accesses them by reading and writing IO registers as if they were memory
  - Write commands and arguments, read status and results

Modern I/O Systems



Buses

Buses


CPU
System bus
Bridge
Memory
PCI bus
Controller
Controller
Controller

PCI Express Bus

- Serial, point-to-point, switched bus, non-shared connections between devices
  - Similar to switched Ethernet
  - Slow devices don't have to share with fast ones
  - No longer a parallel bus
  - Star like architecture

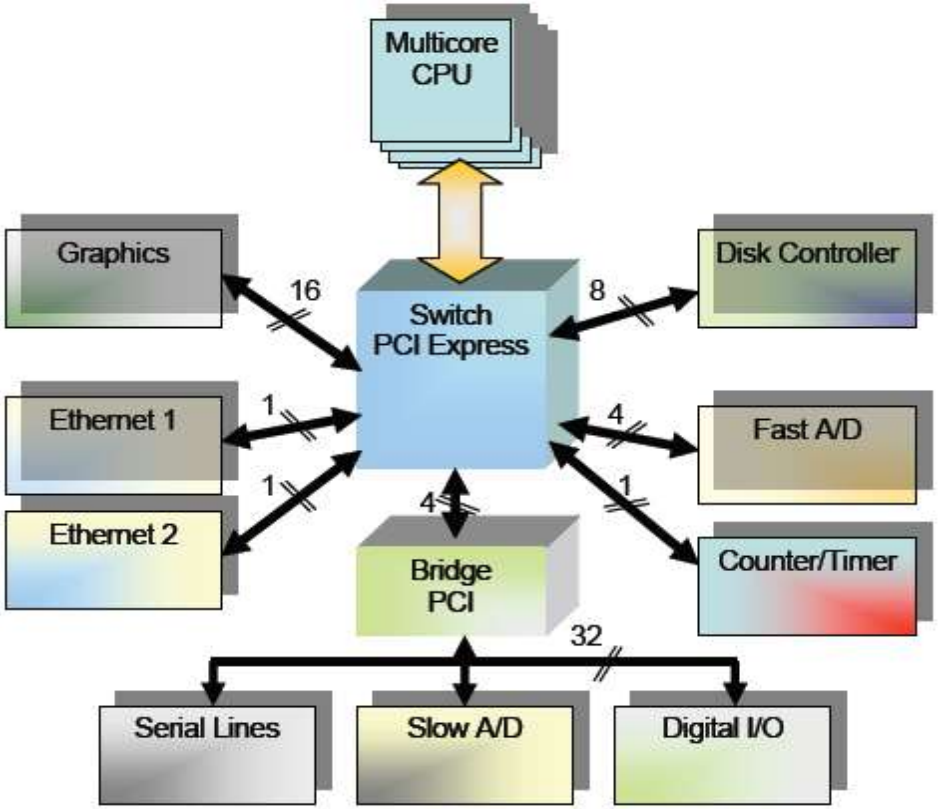


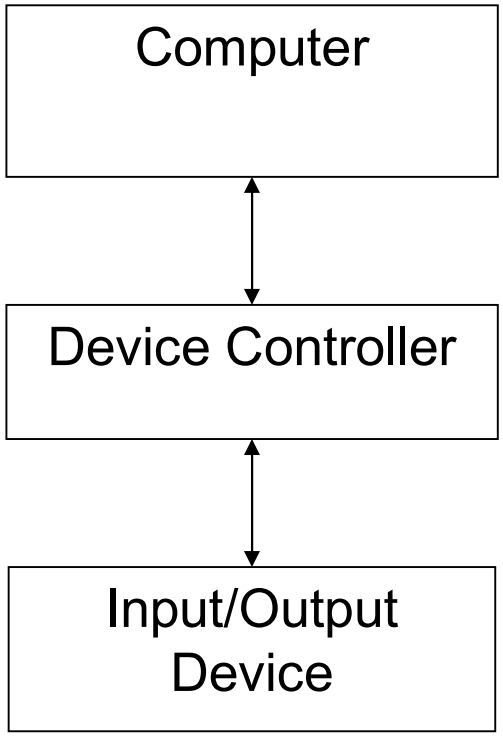
Figure 3: PCI Express switched fabric

Typical I/O system - Notes

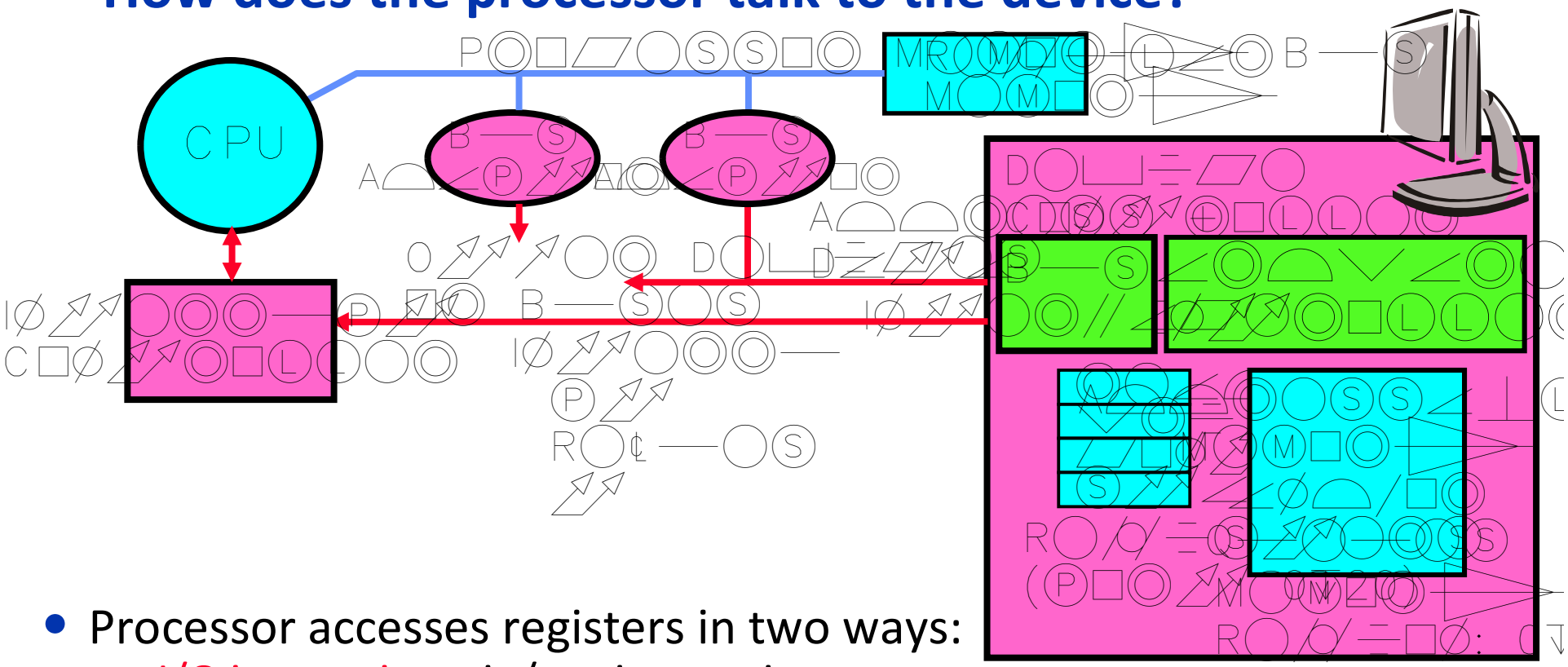
- Memory bus (system bus)
  - Proprietary, Fast, Small, costly, Very High Bandwidth
- General I/O Bus
  - Example PCI or similar
  - Connects Graphics and other high performance I/O devices
- Peripheral Bus
  - SCSI, SATA, USB etc
  - Connect slow devices such as disks, mice, keyboards
- Advantages of Hierarchical System
  - Slow devices don’t impact performance
  - Many slow devices can be connected

Processor – Devices Interaction

Communication between the CPU and the I/O devices



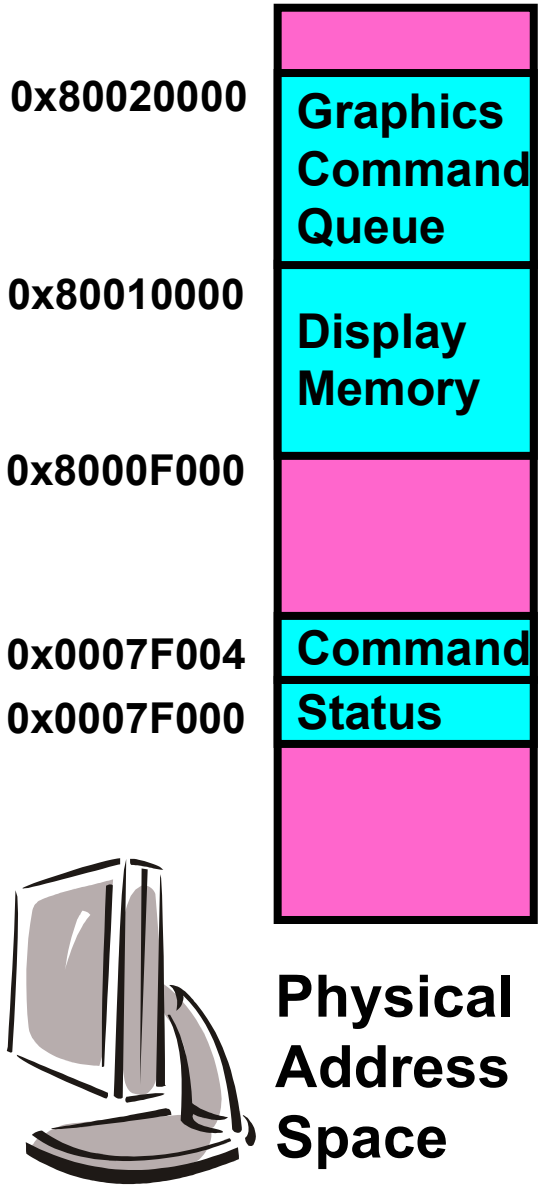
How does the processor talk to the device?



- Processor accesses registers in two ways:
  - I/O instructions: in/out instructions
    - Example from the Intel architecture: `out 0x21`
  - Memory mapped I/O: load/store instructions
    - Registers/memory appear in physical address space
    - I/O accomplished with load and store instructions
      - No extra instruction is required

Memory-Mapped I/O: Display Controller

- Memory-Mapped:
  - Hardware maps control registers and display memory into physical address space
    - Addresses set by HW jumpers or at boot time
  - Simply writing to display memory (also called the "frame buffer") changes image on screen
    - Addr: 0x8000F000 — 0x8000FFFF
  - Writing graphics description to cmd queue
    - Say enter a set of triangles describing some scene
    - Addr: 0x80010000 — 0x8001FFFF
  - Writing to the command register may cause on-board graphics hardware to do something
    - Say render the above scene
    - Addr: 0x0007F004



Programmed I/O, Interrupt Driven I/O, DMA

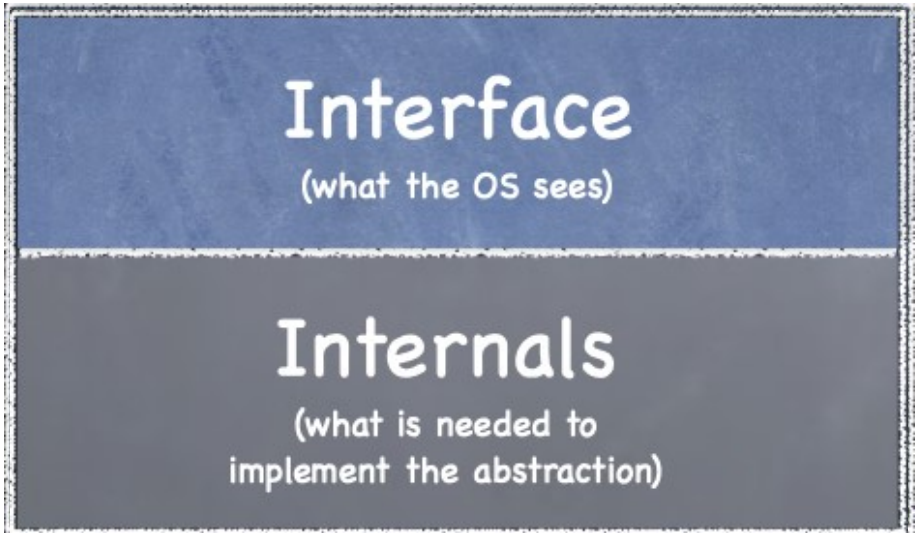
Interacting with a Device

What Users See

Abstraction

Interacting with a Device

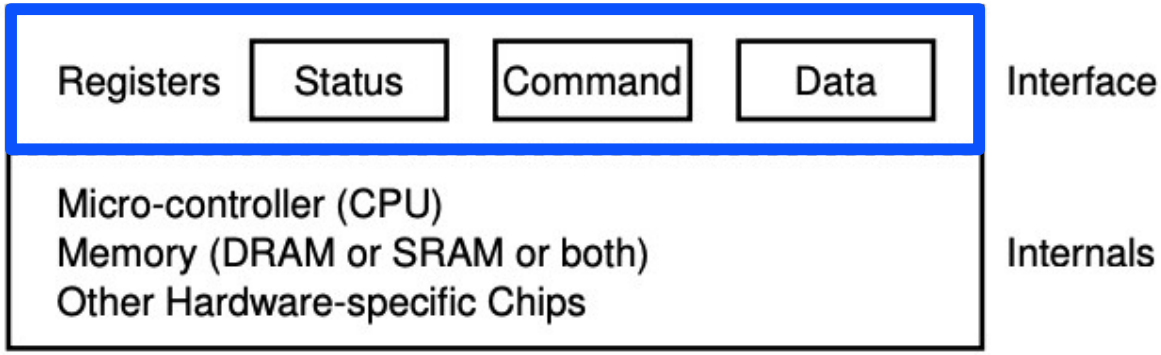
All devices have some specified interface and protocol for interaction



A Device

Interacting with a Device

All devices have some specified interface and protocol for interaction



- Device Interface: 3 registers
  - Status Register: to see the current status
  - Command Register: to tell device to perform a certain task
  - Data Register: to pass data to device or to receive data from device
- OS can control device behavior using these registers

Ref: OSTEP Book

Interacting with a Device – Programmed I/O

- CPU is repeatedly reading status register to check if the device is free - Polling
- OS sends some data down to the data register
  - Multiple such writes are needed to write a block (4KB) for disk
- Here, main CPU is involved with the data movement
  - Programmed I/O
- OS writes command to command register
  - It will lets the device know that both the data is present
  - it should begin working on the command
- OS waits for device to finish by polling it in a loop – waiting to see it it has finished

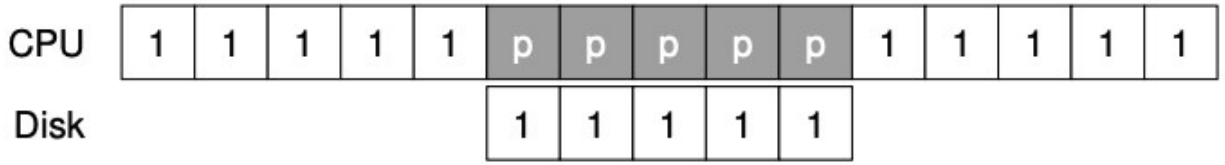
OS controls device by reading/writing registers

```
while (STATUS == BUSY)
    ; // wait until device is not busy
write data to DATA register
write command to COMMAND register
    // starts device and executes command
while (STATUS == BUSY)
  // wait until device is done with request
```

Simple but inefficient; Wastage of CPU time as OS keep polling

Ref: OSTEP Book

Interacting with a Device – Programmed I/O



- Process 1 runs on CPU for some time
- Issues I/O request to disk to read some data
- System simply spins –polling status repeatedly
  - Shown as p – polling
- The disk services the request and finally Process 1 can run again

Ref: OSTEP Book

Interrupt Driven I/O

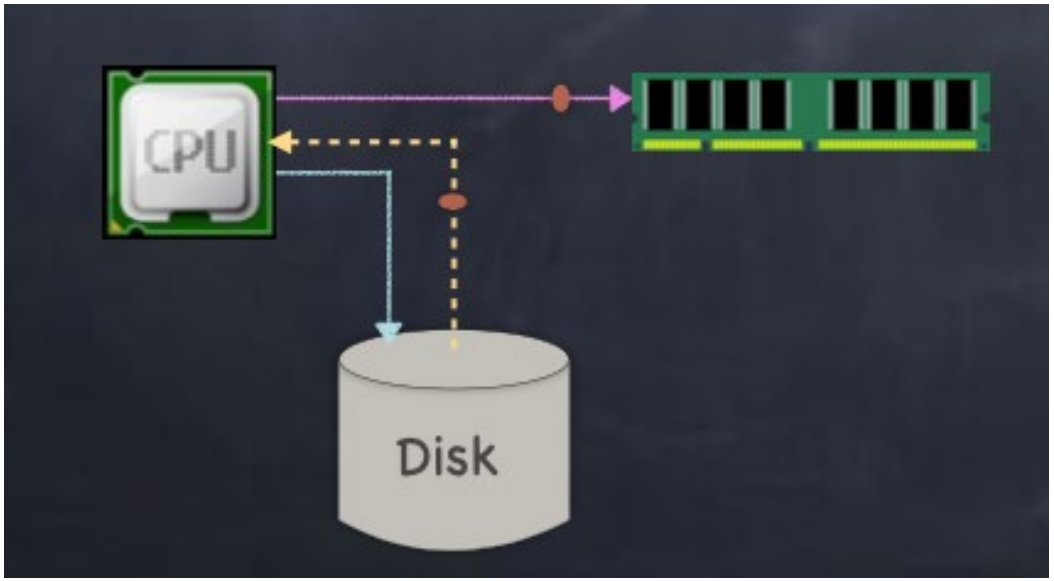
- Device ←→ CPU ←→ RAM

```
for (i = 1...n)
```

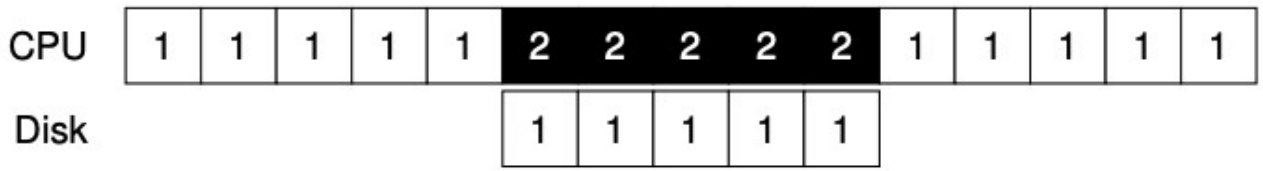
CPU issues read request

Device interrupts CPU with data

CPU writes data to memory



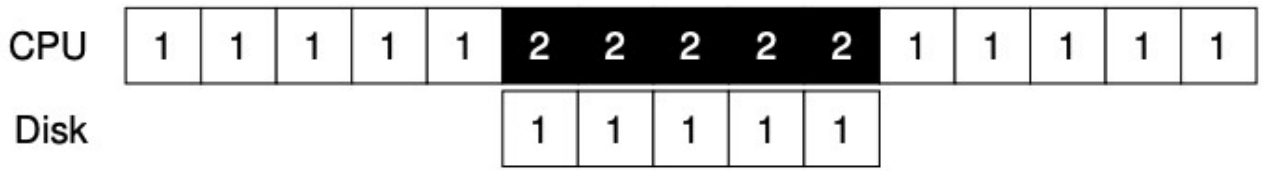
Interrupt Driven I/O



- OS runs Process 2 on CPU when disk is servicing Process 1's request
- When request is complete the interrupt occurs, OS wakes up process 1 and runs it again

- If device is fast, polling performs better than interrupt driven I/O
- If device is slow, interrupt driven I/O is faster than polling

Interrupt Driven I/O



- Livelock
  - A huge stream of incoming packets – each generating an interrupt
  - OS finds itself only processing interrupts
    - Not allowing a user process to run and actually service the request
  - It's better to use polling

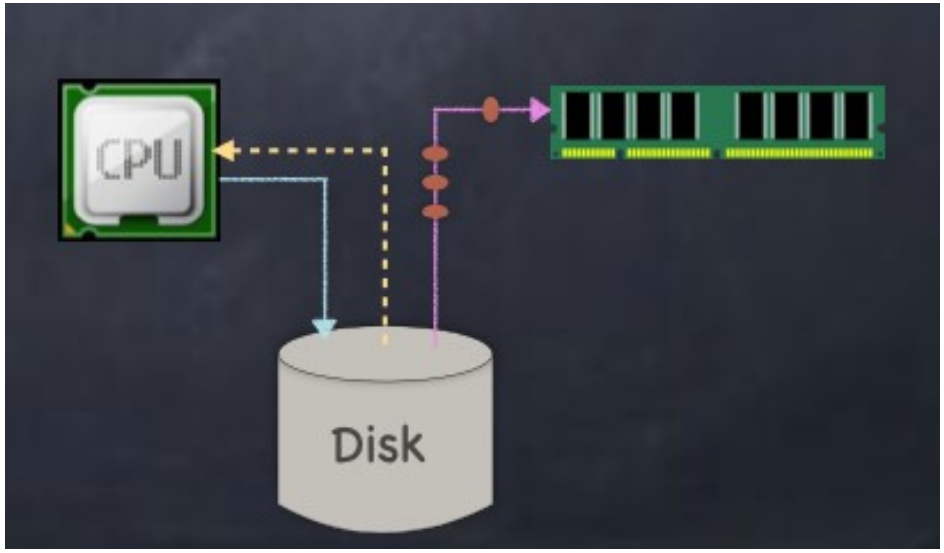
- Both Programmed I/O and Interrupt driven I/O are not efficient as CPU gets busy doing mundane task

In both cases, CPU time is wasted

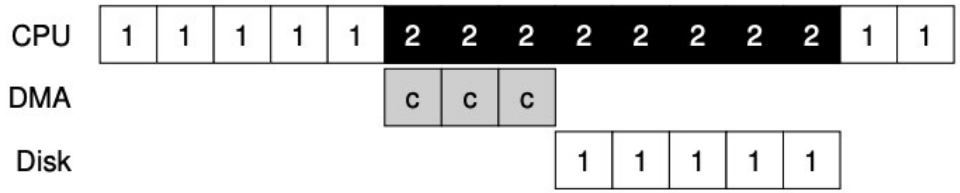
Direct Memory Access (DMA) I/O

- Device ←→ RAM

- CPU sets up DMA request
- Device puts data on bus & RAM accepts it
- Device interrupts CPU when done

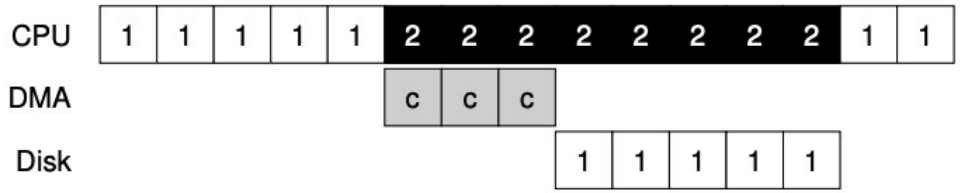


Direct Memory Access (DMA) I/O



- Process 1 is running and it wants to transfer some data to the disk
- It initiates I/O
  - Copy data from memory to the device explicitly
    - One word at a time (marked as c)
  - When copy is complete, I/O can begin on the disk
- CPU can be used for something else say process 2
- When transfer is complete, interrupt is raised and process 1 runs again

Direct Memory Access (DMA) I/O



- DMA engine
  - A very specific device within a system that can orchestrate transfer between devices and MM without CPU intervention
- To transfer data to device, OS programs DMA engine
  - Data location in the MM
  - How much data to copy
  - Which device to send it to
- When DMA is complete, DMA controller raises an interrupt and the OS knows that the transfer is complete

I/O Device Notifying the OS

- The OS needs to know when:
  - The I/O device has completed an operation
  - The I/O operation has encountered an error
- I/O Interrupt: Device generates interrupt when it needs service
  - Handles unpredictable events well, but high overhead
- Polling: OS periodically checks device-specific status register
  - Low overhead, but may waste cycles for infrequent or unpredictable I/O
- Actual devices combine both polling and interrupts
  - E.g., high-bandwidth network adapter

Performance Concepts

Basic Performance Concepts

- *Response Time* or *Latency*: Time to perform an operation(s)

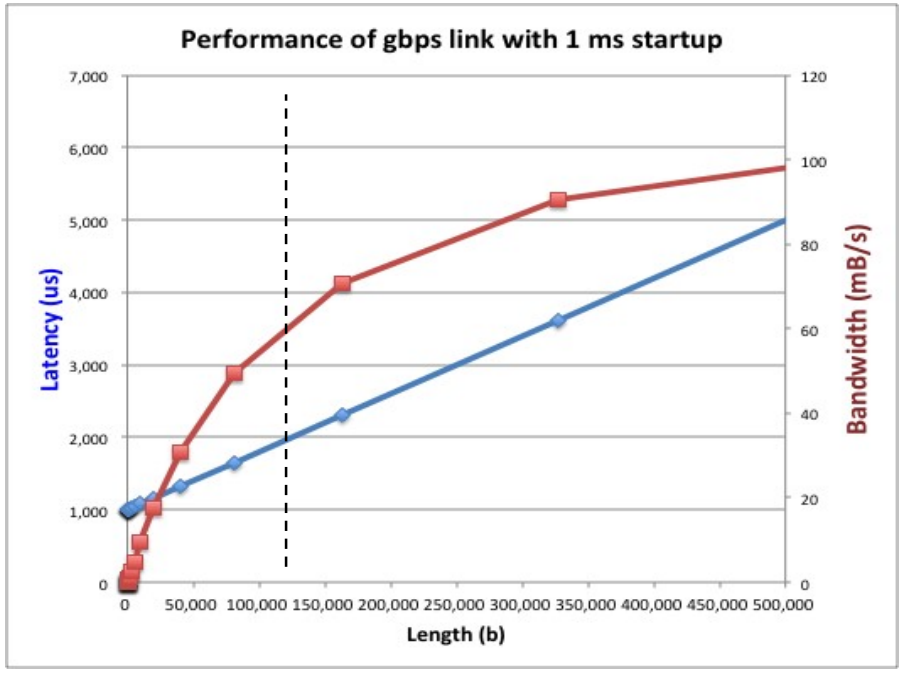
- *Bandwidth* or *Throughput*: Rate at which operations are performed (op/s)
  - Files: MB/s, Networks: Mb/s, Arithmetic: GFLOP/s

- *Start up* or "Overhead": time to initiate an operation

- Most I/O operations are roughly linear in *b* bytes
  - Latency(*b*) = Overhead + *b*/TransferCapacity

Example (Fast Network)

- Consider a 1 Gb/s link (BW = 125 MB/s)
  - With a startup cost S = 1 ms

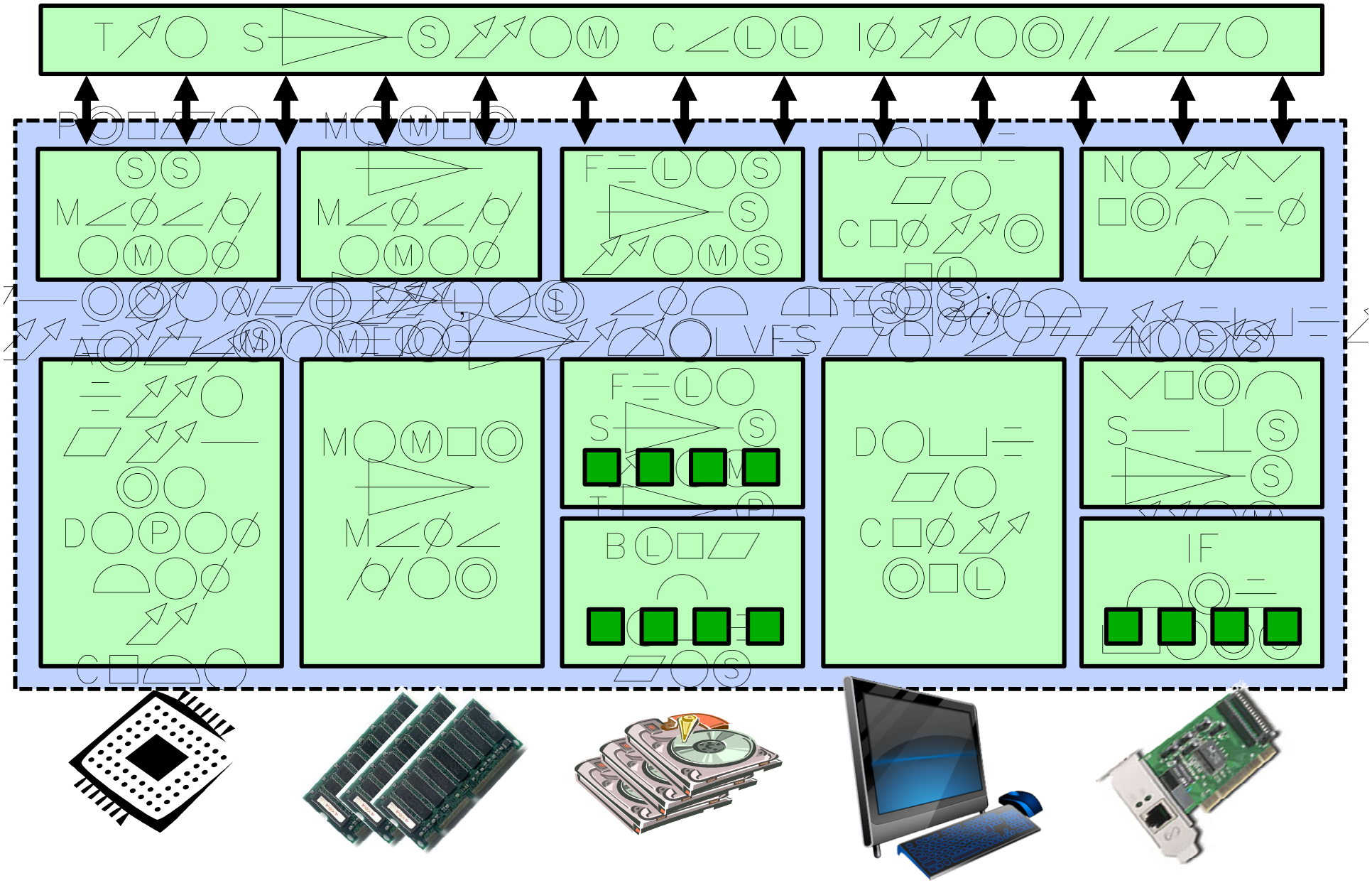


- Latency(b) = S + b/BW
- Bandwidth = b/(S + b/BW) = BW×b/(BW×S + b) = BW/(BW×S/b + 1)

Lecture Summary

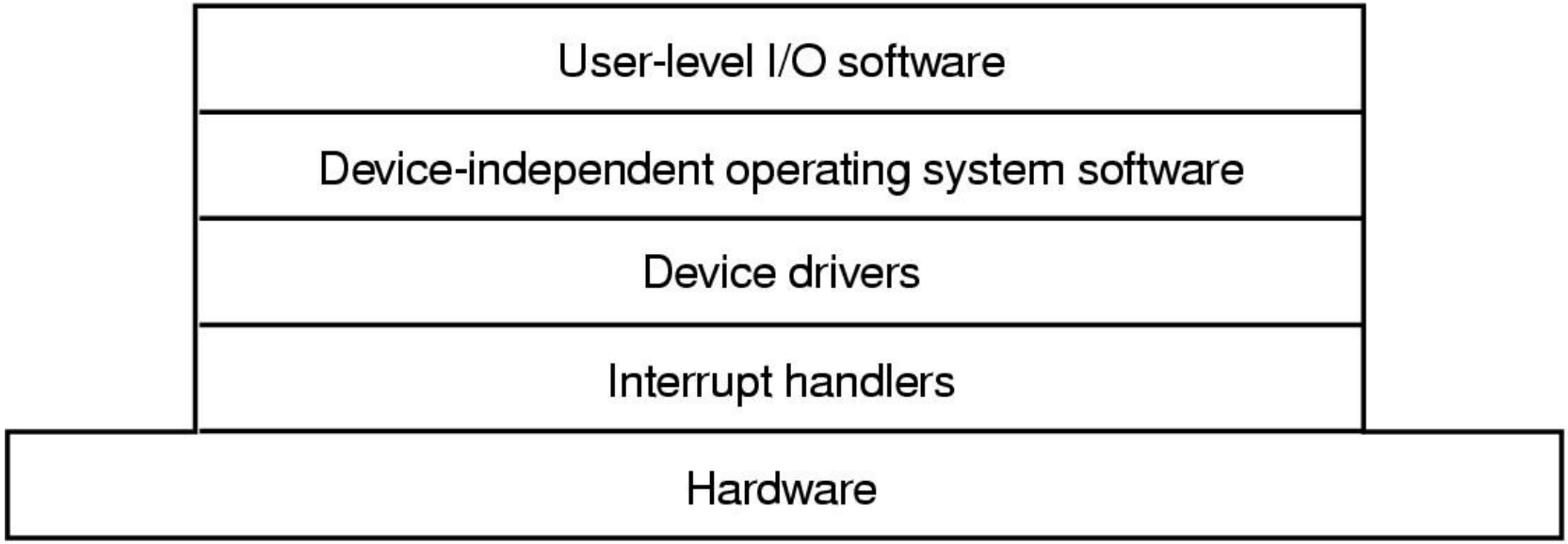
- Buses are evolving very fast – Shared → Switch
- Device Controllers are used to help in communication between Processor and device
- Processor accesses device registers (in controller) in two ways:
  - I/O Interrupt
  - Memory Mapped I/O
- Interacting with a device
  - Programmed I/O
  - Interrupt driven I/O
  - DMA

Kernel Device Structure



Lecture Summary

I/O Software Layers



Layers of the I/O Software System

Interrupt Handlers (Repeat)

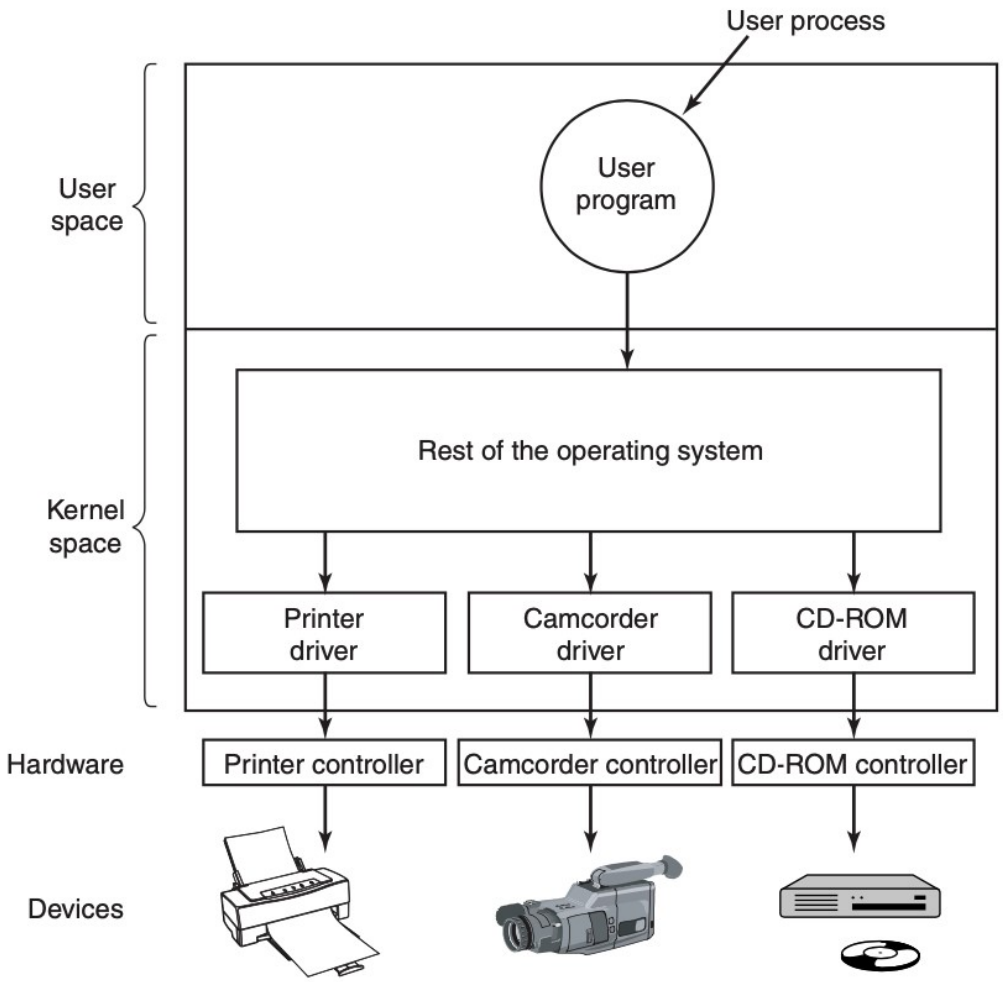
- Device drivers after starting an operation- blocks
- On receiving an interrupt, the driver unblocks
- Interrupt handling
  - Unlocks the driver (using semaphore)
- A lot of other activities are done as a part of interrupt handling
    - Register Saving
    - Set up context for Interrupt service routine
      - Setting up TLb, MMU, Page Table
    - Set up stack for interrupt service-procedure
    - Ack the interrupt controller
    - Copy registers
    - Run Interrupt service procedure
    - Choose the process to run next
    - Set up MMU context for the process to run next
    - Load and run new process

Device Driver

- The number of device registers and nature of commands vary radically from device to device
  - Mouse driver has to accept information from the mouse how far it has moved and which button is pressed
  - Disk driver have to know about sectors, track, cylinders, arm motion
- each I/O device attached to a computer needs some device-specific code for controlling it
  - This code is the device driver
- Device driver is generally written by the device's manufacturer and delivered along with the device
  - Device drivers are supplied for OS
- Each device driver usually handles one device type or class of closely related types

Device Driver

- Device driver has to be part of OS
  - to access device's hardware



- Oss classify device drivers in to number of categories
  - Block Devices: Disks
  - Character Devices: Keyboards and Printers
    - Generate and accept stream of characters
- Standard interface that all block drivers (and character drivers) must support
  - Number of procedures that rest of the OS can call eg read a block

- to accept abstract read and write requests from the device-independent software above it
- Execution of requests
- Power management and logs

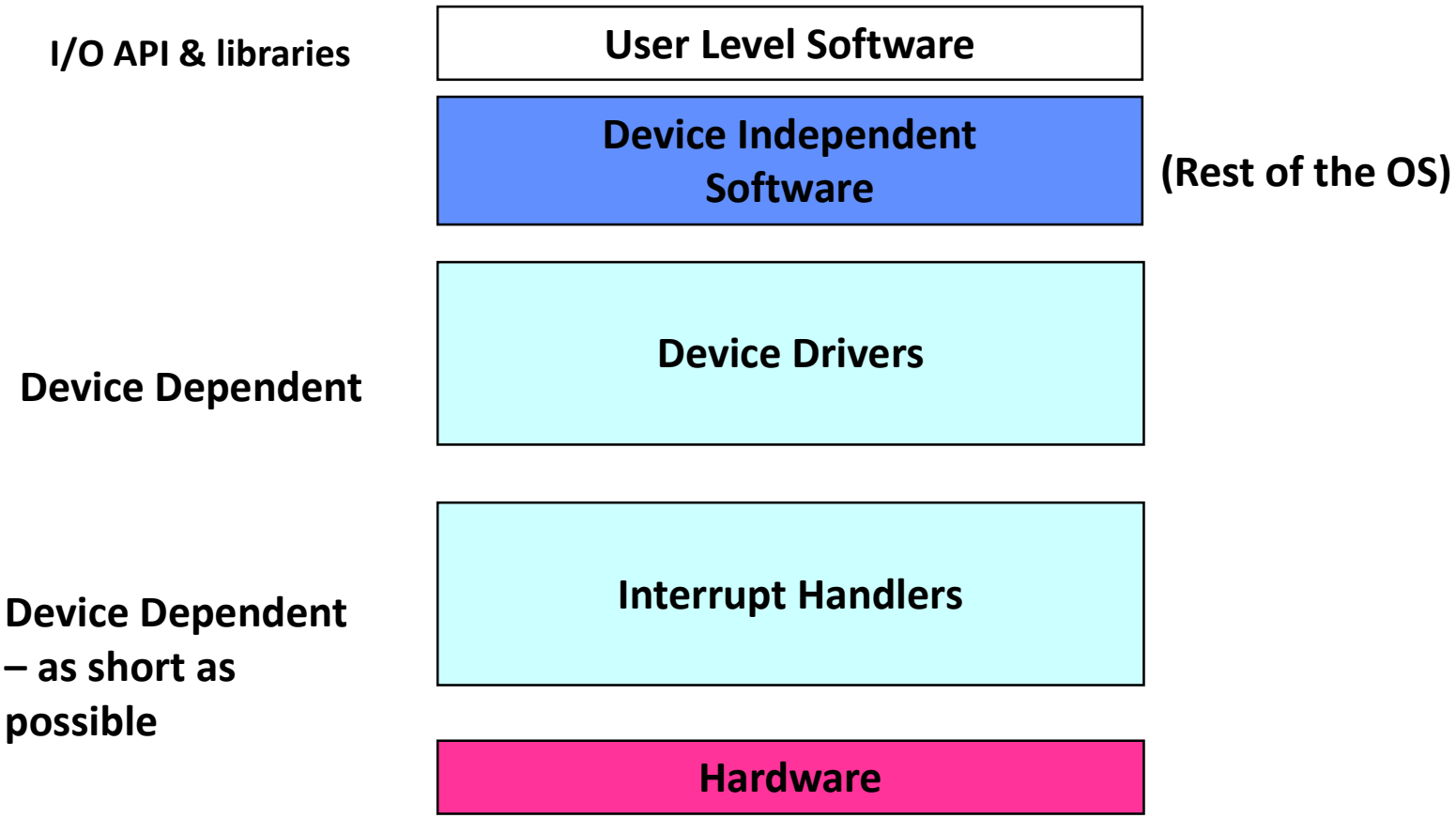
Device Driver – Functions (1)

- Initialize the device
- Check if input parameters are valid
  - If not error is generated
- If inputs are valid, translation from abstract to concrete term
  - For a disk driver
    - Convert a linear block number to head, track, sector, and cylinder numbers
- Check if the device is in use
  - If busy, the request is put in the queue
  - If Idle, hardware status is checked – if it can accept the request – there may be need to switch on the device etc
- When device is free, actual control can begin

Device Driver – Functions (2)

- Controlling a device -> issuing a sequence of commands
- Driver issues commands
- To drive a commend
  - Driver writes a command into device's control registers
    - Once the command is accepted by the device, the controller issue more commands
- Device driver waits until controller does some work on it
  - In some operations (eg screen scrolling), waiting is not required
- Blocked driver is awakened by the interrupt by the controller
- Driver checks for errors
  - If there is error, it passes it upwards
- If everything is all right, the driver may have data to pass on to the device-independent software (eg block just read)
- Selects next request for execution

I/O Software "Stack"



Device Independent I/O Software (1)

Uniform interfacing for device drivers
Buffering
Error reporting
Allocating and releasing dedicated devices
Providing a device-independent block size

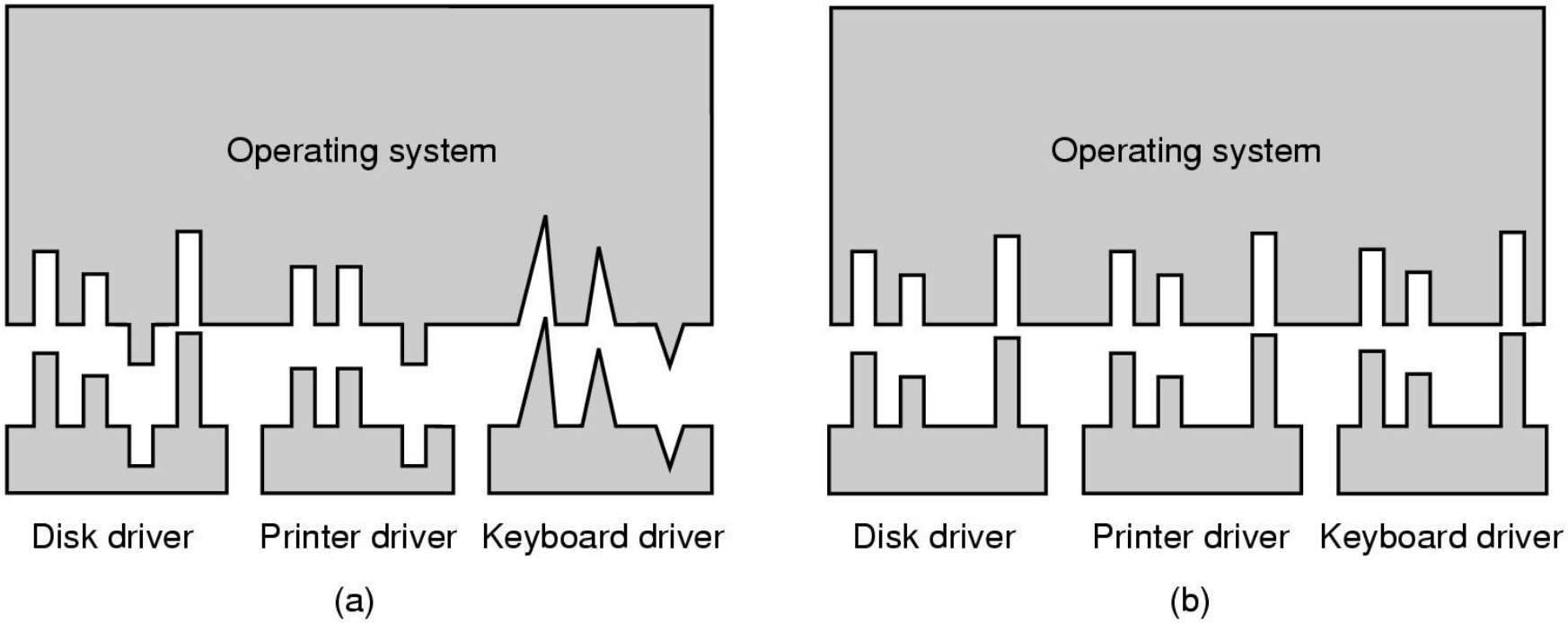
- Function of Device Independent I/O SW
  - to perform the I/O functions that are common to all devices
  - to provide a uniform interface to the user-level software

Device-Independent I/O Software (2) – Uniform Interfacing

Uniform interfacing for device drivers
Buffering
Error reporting
Allocating and releasing dedicated devices
Providing a device-independent block size

(a) Without a standard driver interface

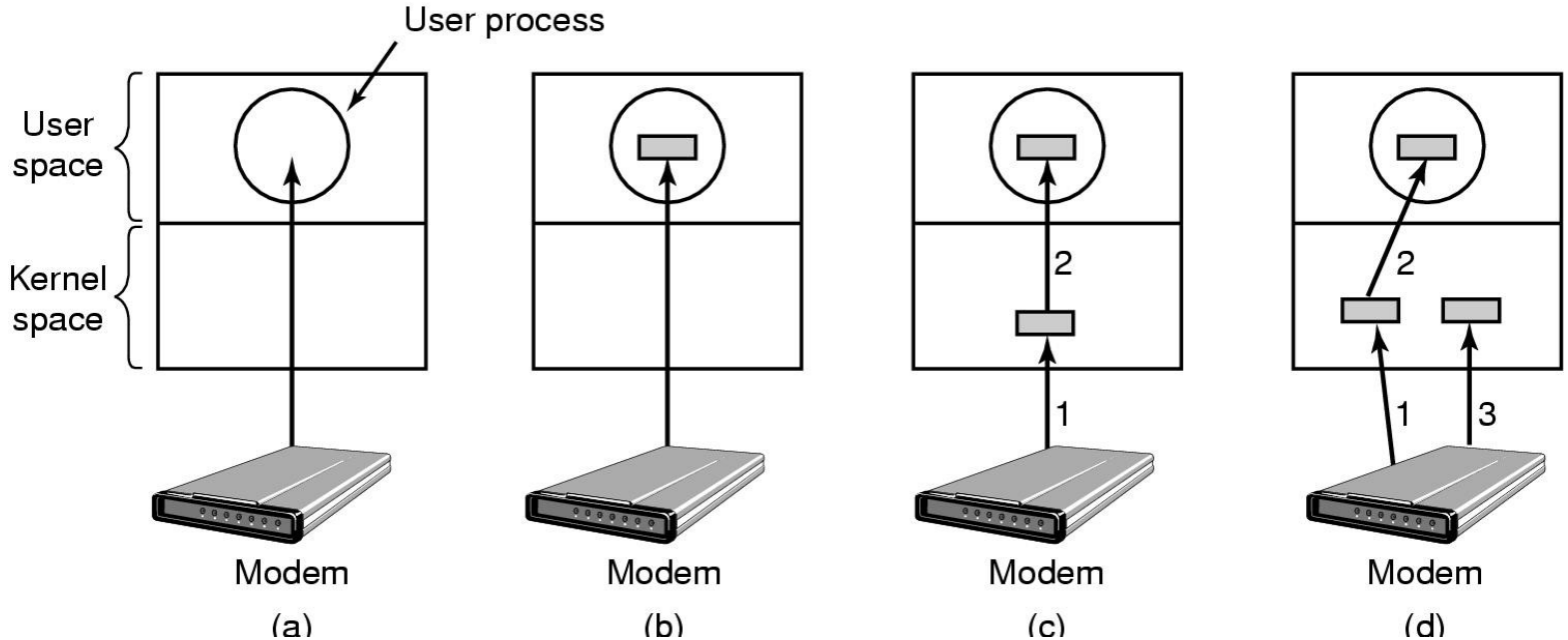
(b) With a standard driver interface



Device-Independent I/O Software (3) – Buffering

- Buffering improves efficiency

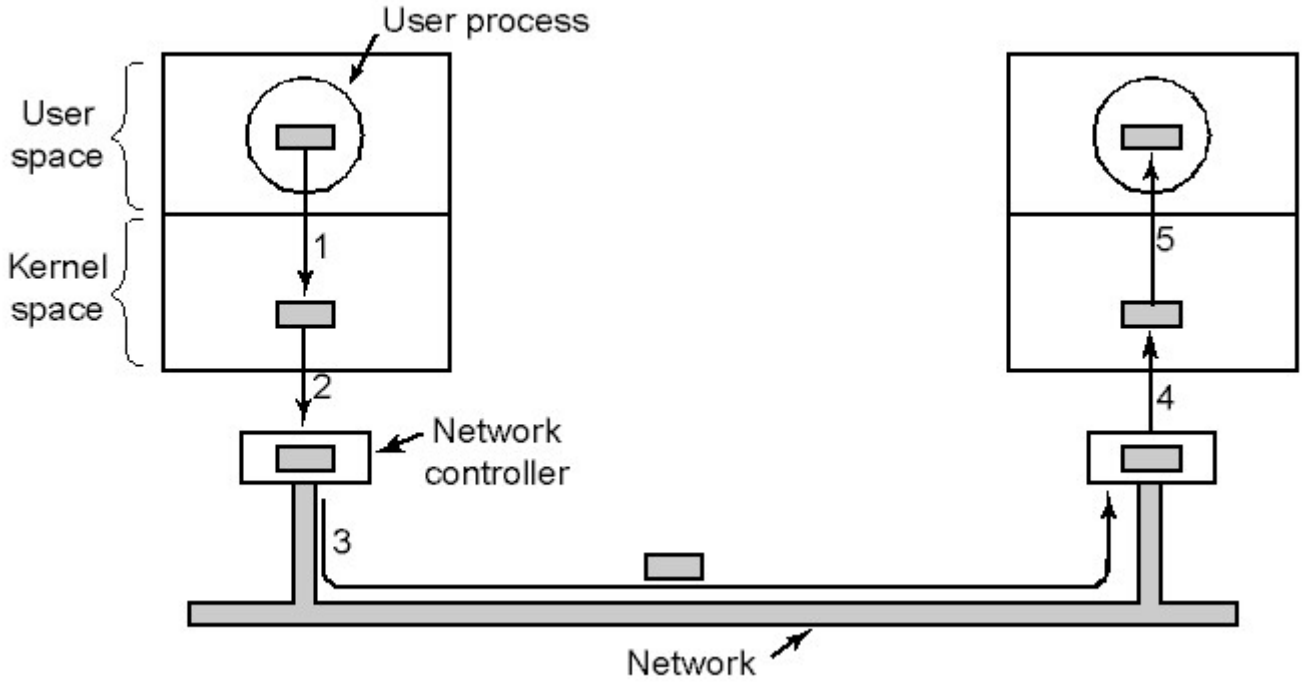
Uniform interfacing for device drivers
Buffering
Error reporting
Allocating and releasing dedicated devices
Providing a device-independent block size



(a) Unbuffered input
(b) Buffering in user space
(c) Buffering in the kernel followed by copying to user space
(d) Double buffering in the kernel

Device-Independent I/O Software – Sending packet on network – buffering

Uniform interfacing for device drivers
Buffering
Error reporting
Allocating and releasing dedicated devices
Providing a device-independent block size



Networking may involve many copies

Error Reporting

Uniform interfacing for device drivers
Buffering
Error reporting
Allocating and releasing dedicated devices
Providing a device-independent block size

- Framework for error reporting
  - Device independent
- Errors can happen in many ways
  - Programming Errors – eg writing to a keyboard etc
  - Trying to write to a disk block that has been damaged
  - Trying to read from a device that is switched off
- Device specific errors may be handled by Device Driver
  - If it is not able to handle the error, it passes problem to device independent software. Solutions:
    - This software may inform user about the problem – eg using dialog box
    - Ignoring the error
    - Retry
    - Killing the process
    - Call fail with error code

Allocating and Releasing Dedicated Devices

Uniform interfacing for device drivers
Buffering
Error reporting
Allocating and releasing dedicated devices
Providing a device-independent block size

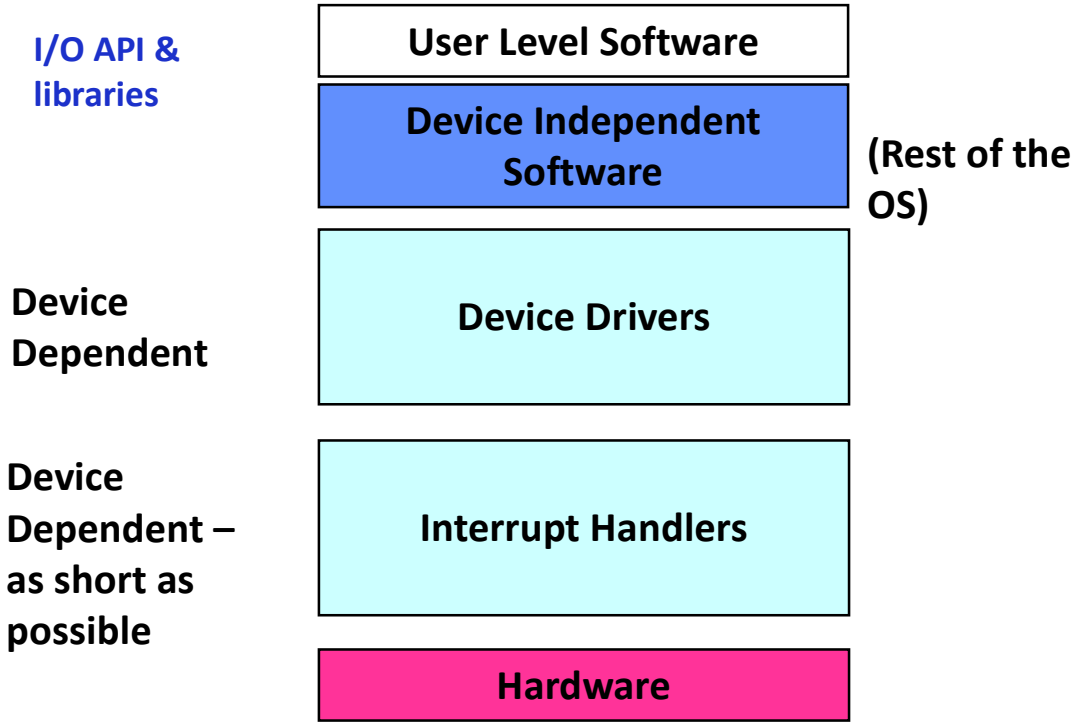
- Some devices can be used by a single process at a time
- OS must examine requests – accept or reject them
- There are many ways to do this
  - Perform open on a special file for the device directly
    - If device is unavailable – open fails
  - Special mechanisms for requesting and releasing dedicated devices
    - Block the caller process instead of failing – if device is busy
      - Put the process in the queue
    - When device is available, the first process in the queue is allowed to use it

Device Independent block size

Uniform interfacing for device drivers
Buffering
Error reporting
Allocating and releasing dedicated devices
Providing a device-independent block size

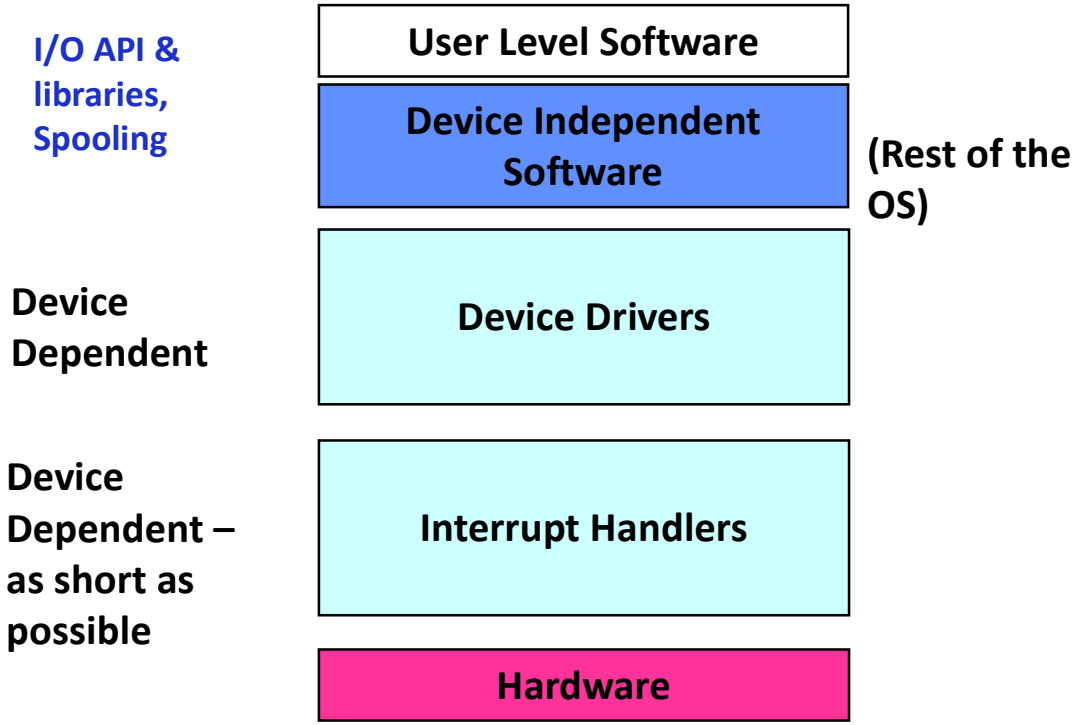
- Different disks may have different sector sizes
- Device independent software hides this
- It provides uniform block size to higher layers
- Example: Treating several sectors as a single logical block
  - Allows higher layers to deal with abstract devices

User Space I/O software - Libraries



- Libraries linked with user programs
- System calls (including I/O system calls) are made by library procedures
- Ex: printf("The square of %3d is %6d\n", i, i*i);

User Space I/O software - Spooling

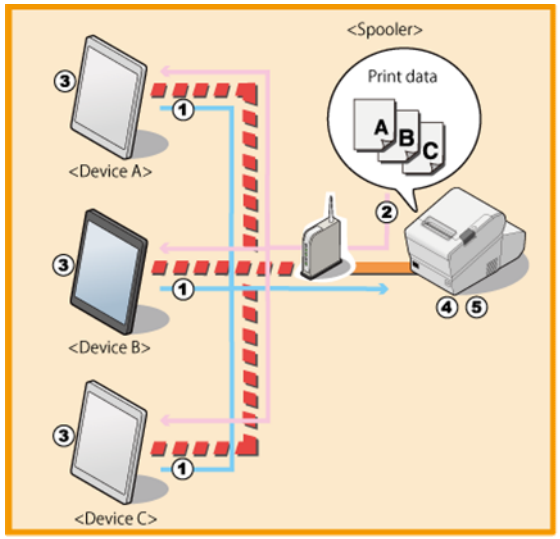


- A way of dealing with dedicated I/O devices in a multiprogramming system
  - Spooled device – Printer
- Consider a process opens a character special file associated with the printer and does nothing
  - Blocking other processes

Spooling

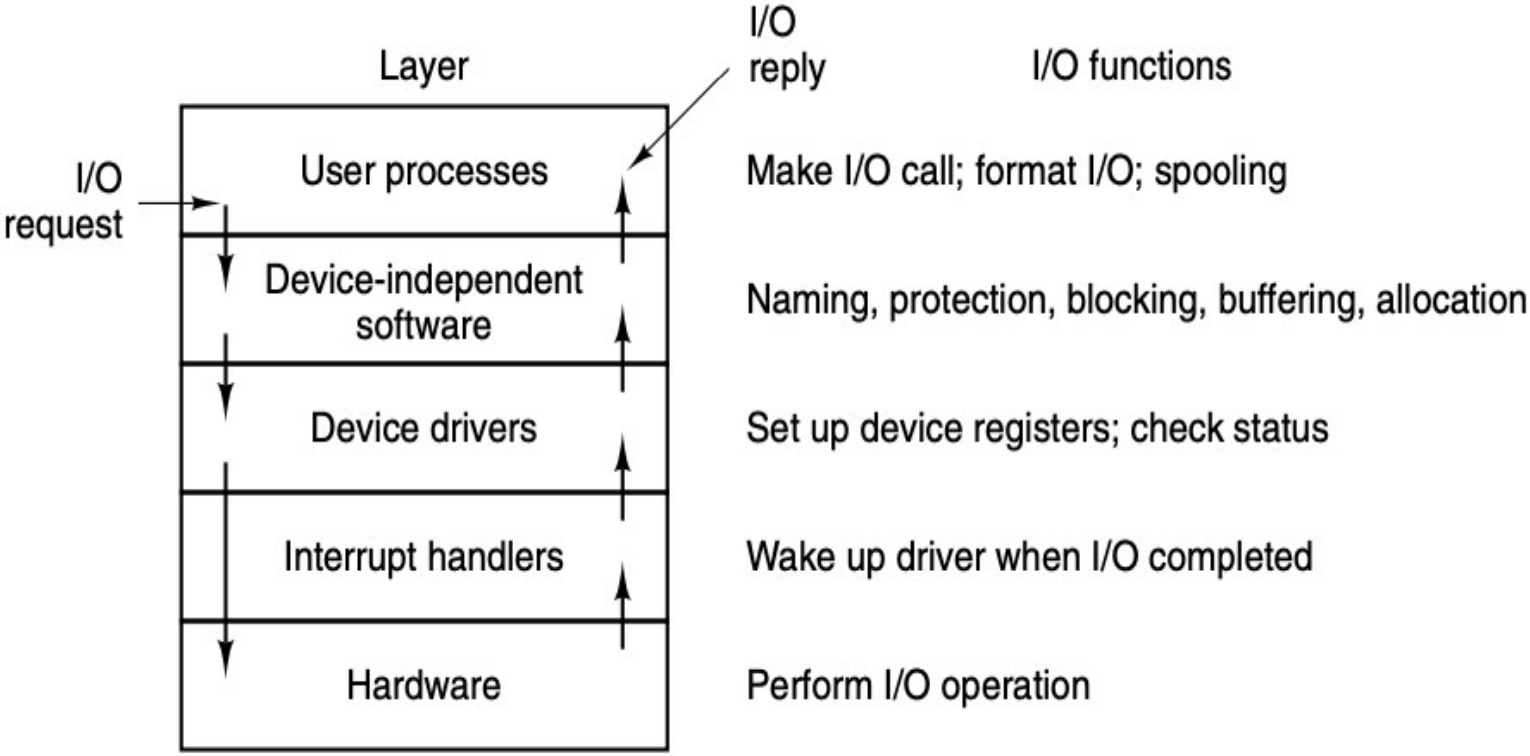
- Spooling is a method for queuing and holding data for input or output
- Uses special process called a daemon and special directory called spooling directory
- To print a file a process
  - first generates the entire file to be printed
  - Puts the file in the spooling directory
- Daemon is the only process that has permission to use printer's special file
  - to print the files in the directory
- It protects use of the special file directly by users

Spooling – Example (Aside)



- Devices A to C request printing of data A to C almost simultaneously.
- The spooler function saves the print data in the spooler in the order it receives it, and returns the printing results to each device.
- Each device application completes the printing process and executes the next operation.
- This product successively prints print data A to C.
- The spooler function saves the printing results in the log.

Main Functions of layers of I/O System



Lecture Summary

Device Drivers - USB

- Sometimes widely different devices are based on the same underlying technology
- Consider USB (Universal Serial Bus) Devices
  - Mouse, Keyboards, mini-fans, wireless network cards, keyboards, memory sticks, external disks, robots, credit card readers, bar code scanner etc
- They all use USB ..yet do different things
- USB drivers are stacked
  - Bottom layer – like Layer 2 of TCP/IP
  - Middle layer – handle packet transmission and reception
  - Higher layer = APIs such as mass storage, cameras etc
    - Separate device drivers

Device Drivers

- Device Driver: Device-specific code in the kernel that interacts directly with the device hardware
  - Supports a standard, internal interface
  - Same kernel I/O system can interact easily with different device drivers
  - Special device-specific configuration supported with the `ioctl()` system call

- Device Drivers typically divided into two pieces:
  - Top half: accessed in call path from system calls
    - implements a set of standard, cross-device calls like `open()`, `close()`, `read()`, `write()`, `ioctl()`, `strategy()`
    - This is the kernel's interface to the device driver
    - Top half will *start* I/O to device, may put thread to sleep until finished
  - Bottom half: run as interrupt routine
    - Gets input or transfers next block of output
    - May wake sleeping threads if I/O now complete

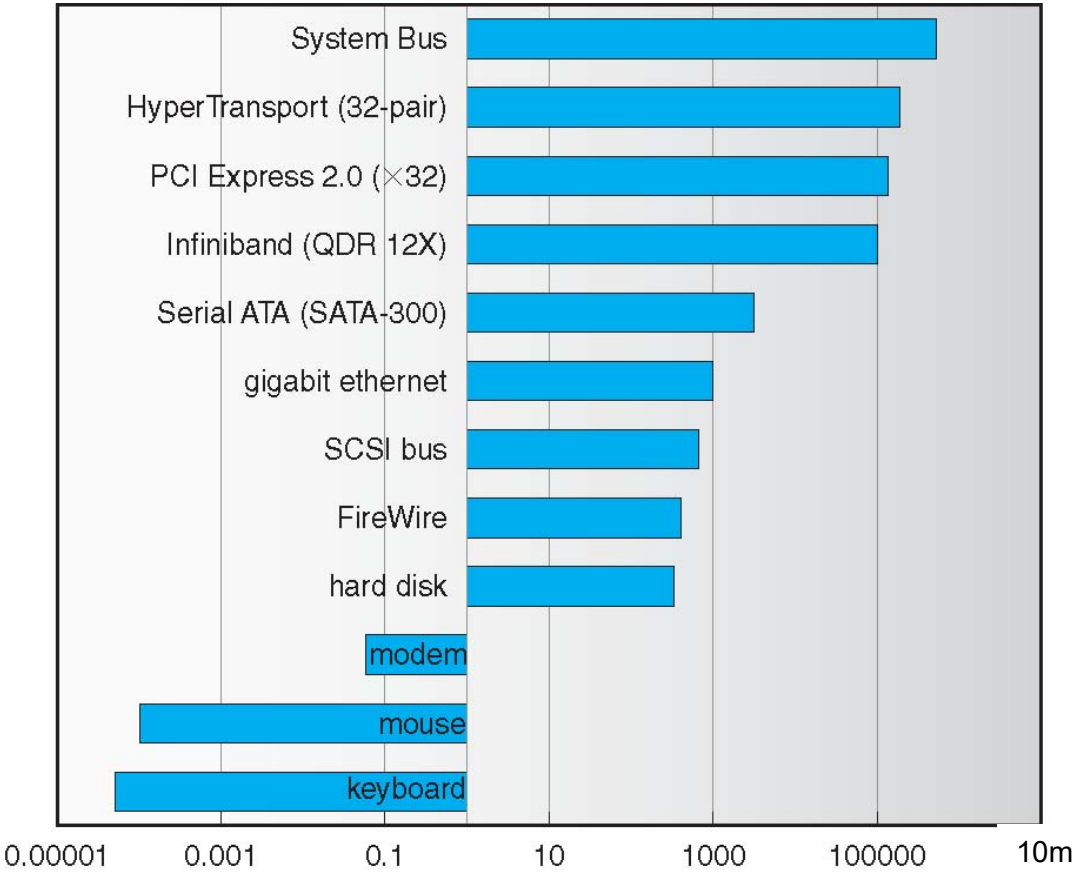
Operational Parameters for I/O

- Data granularity: Byte vs. Block
  - Some devices provide single byte at a time (e.g., keyboard)
  - Others provide whole blocks (e.g., disks, networks, etc.)

- Access pattern: Sequential vs. Random
  - Some devices must be accessed sequentially (e.g., tape)
  - Others can be accessed “randomly” (e.g., disk, cd, etc.)
    - Fixed overhead to start transfers
  - Some devices require continual monitoring
  - Others generate interrupts when they need service

- Transfer Mechanism: Programmed IO and DMA

Example Device-Transfer Rates in Mb/s (Sun Enterprise 6000)



- Device Rates vary over 12 orders of magnitude !!!
  - System better be able to handle this wide range
  - Better not have high overhead/byte for fast devices!
  - Better not waste time waiting for slow devices

Typical I/O system - Notes

- Memory bus
  - Proprietary, Fast, Small, costly, Very High Bandwidth
- General I/O Bus
  - Example PCI or similar
  - Connects Graphics and other high performance I/O devices
- Peripheral Bus
  - SCSI, SATA, USB etc
  - Connect slow devices such as disks, mice, keyboards
- Advantages of Hierarchical System
  - Slow devices don’t impact performance
  - Many slow devices can be connected