Input/Output

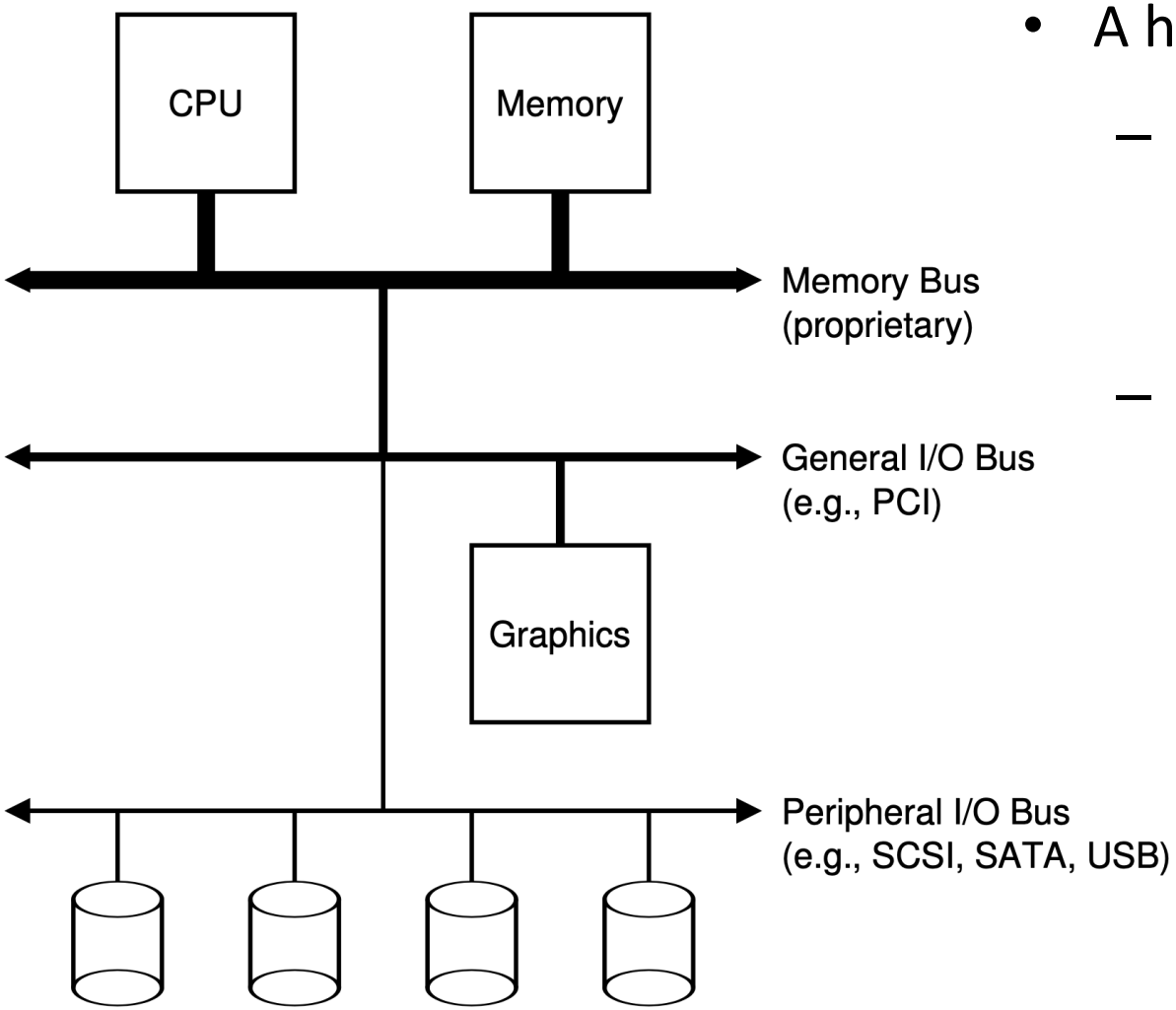
Chapter 5

Slides Borrowed from Modern Operating System, Operating System Concepts, OSPP, and OSTEP

Outline

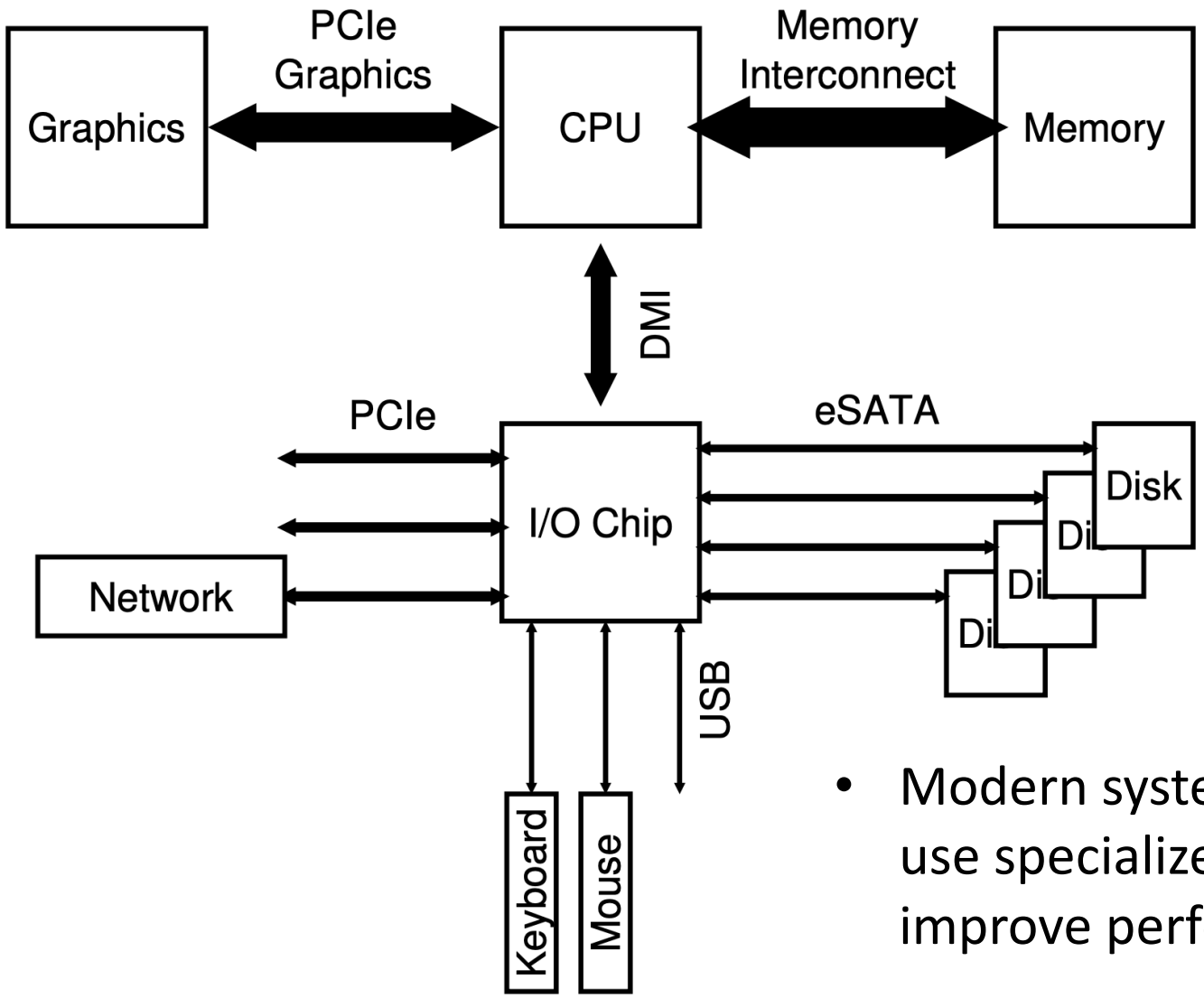
- Input/Output (I/O) devices
  - How should I/O be integrated into systems?
  - What are the general mechanisms?
- Hard disk drive
  - How is the data actually laid out and accessed?
  - How does disk scheduling improve performance?
- RAID
  - How can we make a large, fast, and reliable storage system?

A Typical System Architecture



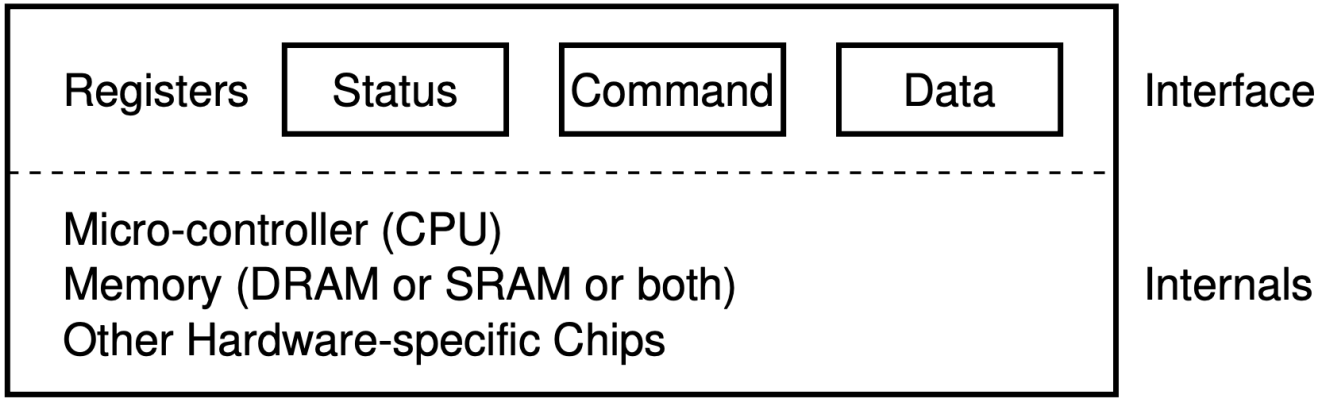
- A hierarchical structure
  - Physics and cost: the faster a bus is, the shorter it must be
  - Components that demand high performance are nearer the CPU

A Typical System Architecture



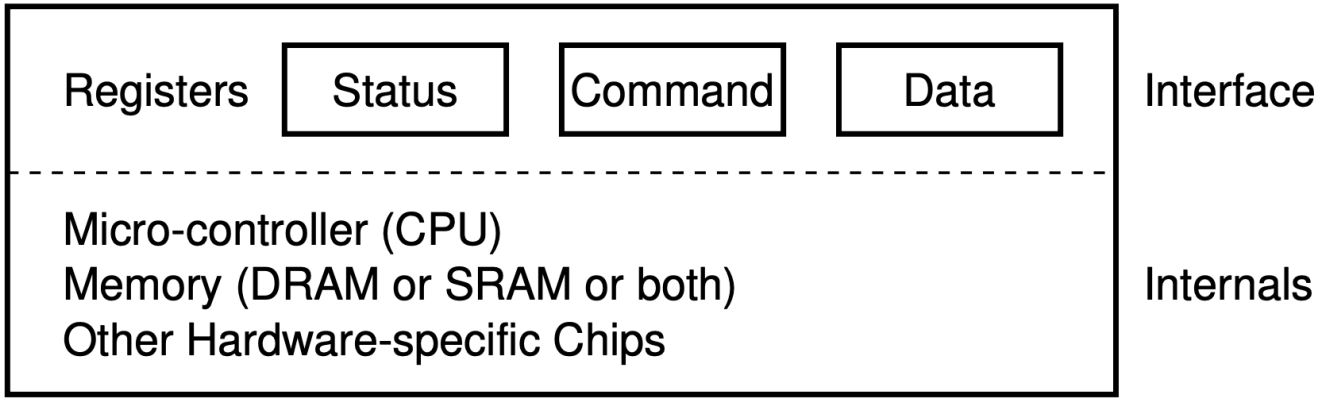
- Modern systems increasingly use specialized chipsets to improve performance

A Canonical Device



- A device has two important components
  - The **hardware interface** it presents to the rest of the system (allow OS to control its operation)
  - Its **internal structure** (implementation specific)

A Canonical Device



- Device interface is comprised of several registers
  - **Status Register**: read to see the current status of the device
  - **Command Register**: tell the device to perform a certain task
  - **Data Register**: pass data to the device, or get data from the device

Device Interaction

How should the CPU communicate with a device (specify a way for the OS to send data to specific device registers)?

- **I/O Instructions**
  - Each control register is assigned an **I/O port** number
  - Use special I/O instructions (on x86, `in` and `out`)
  - Such instructions are usually privileged

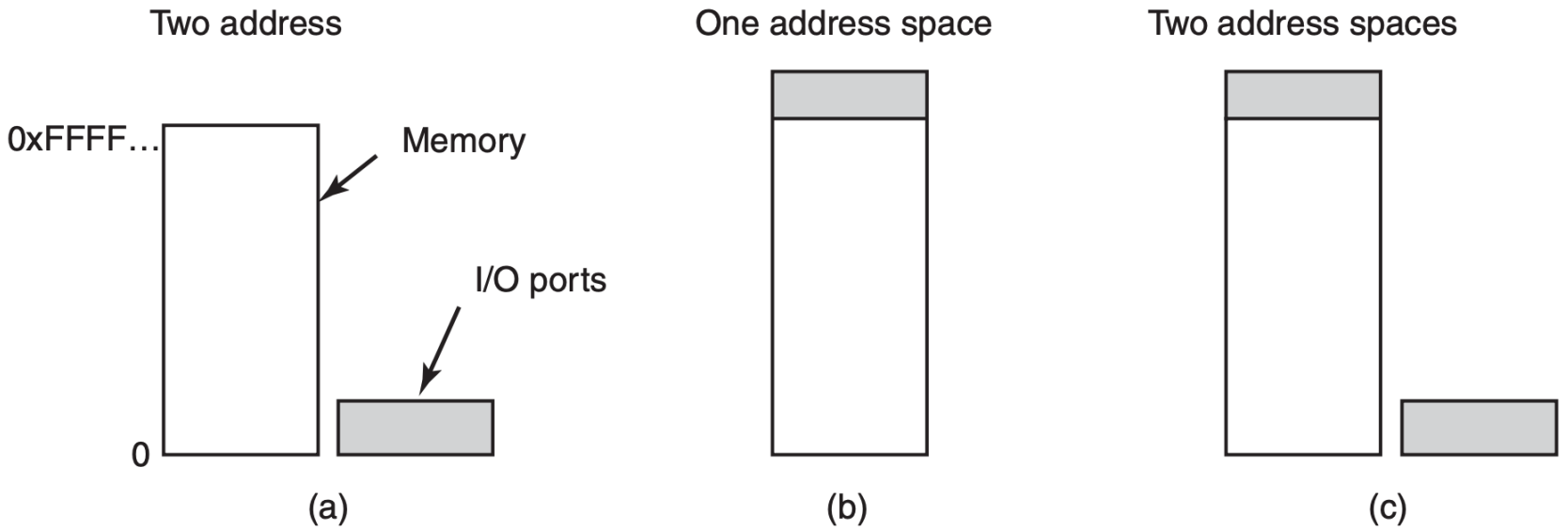
Device Interaction

How should the CPU communicate with a device (specify a way for the OS to send data to specific device registers)?

- **Memory Mapped I/O**: Map all the control registers into the memory space
  - Each control register is assigned a unique memory address
  - To access a particular register, the OS issues a load (to read) or store (to write) the address
  - The hardware then routes the load/store to the device instead of main memory

Device Interaction

How should the CPU communicate with a device (specify a way for the OS to send data to specific device registers)?



Separate I/O and memory space

Memory-mapped I/O

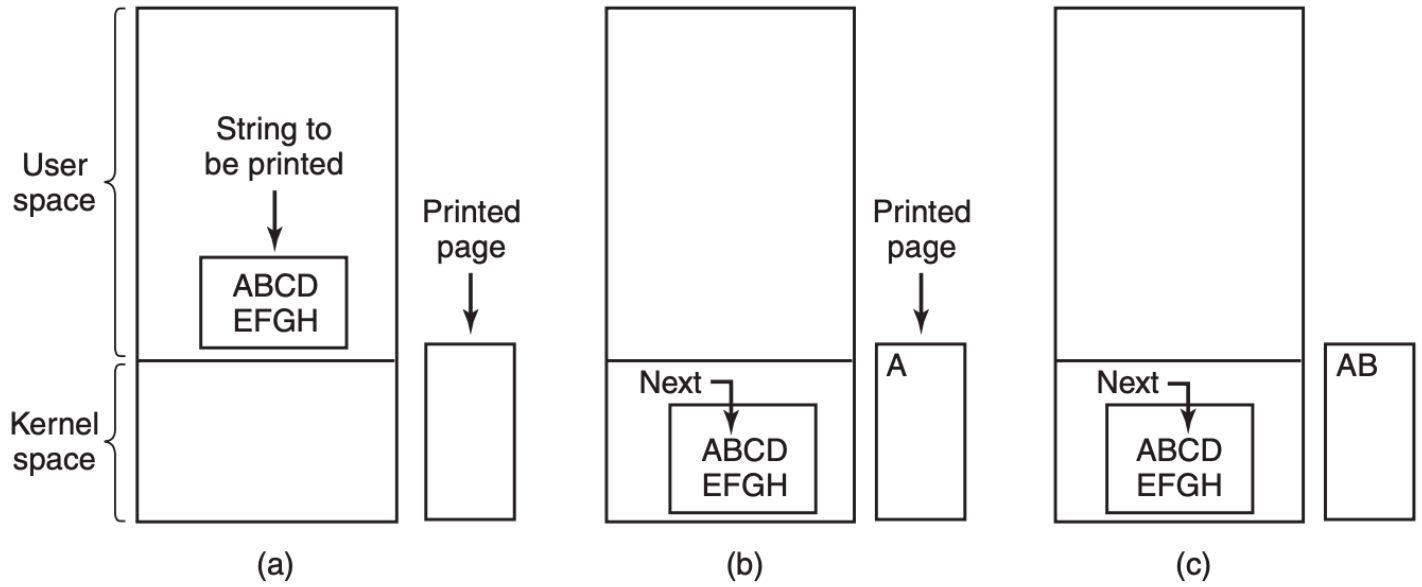
Hybrid

Programmed I/O

A basic interaction: **Polling** the device (busy waiting)

- OS waits until the device is ready to receive a command by repeatedly reading the status register
- OS sends some data down to the data register
- OS writes a command to the command register
- OS waits for the device to finish by again polling it in a loop, waiting to see if it is finished (it may then get an error code to indicate success or failure)

Programmed I/O




```
copy_from_user(buffer, p, count);          /* p is the kernel buffer */
for (i = 0; i < count; i++) {              /* loop on every character */
        while (*printer_status_reg != READY) ;   /* loop until ready */
        *printer_data_register = p[i];           /* output one character */
}
return_to_user( );
```

Interrupts

How to lower the CPU overhead required to manage the device?

- OS issues a request, puts the calling process to sleep, and context switch to another task
- When the device is finished with the operation, it will raise a hardware interrupt
- The interrupt causes CPU to jump into the OS at a pre-determined interrupt service routine **(interrupt handler)**
- The handler finishes the request (e.g., by reading data from the device) and wakes the process waiting for the I/O

Interrupts

```
copy_from_user(buffer, p, count);
enable_interrupts( );
while (*printer_status_reg != READY) ;
*printer_data_register = p[0];
scheduler( );
```

(a)

Code executed at the time the print system call is made

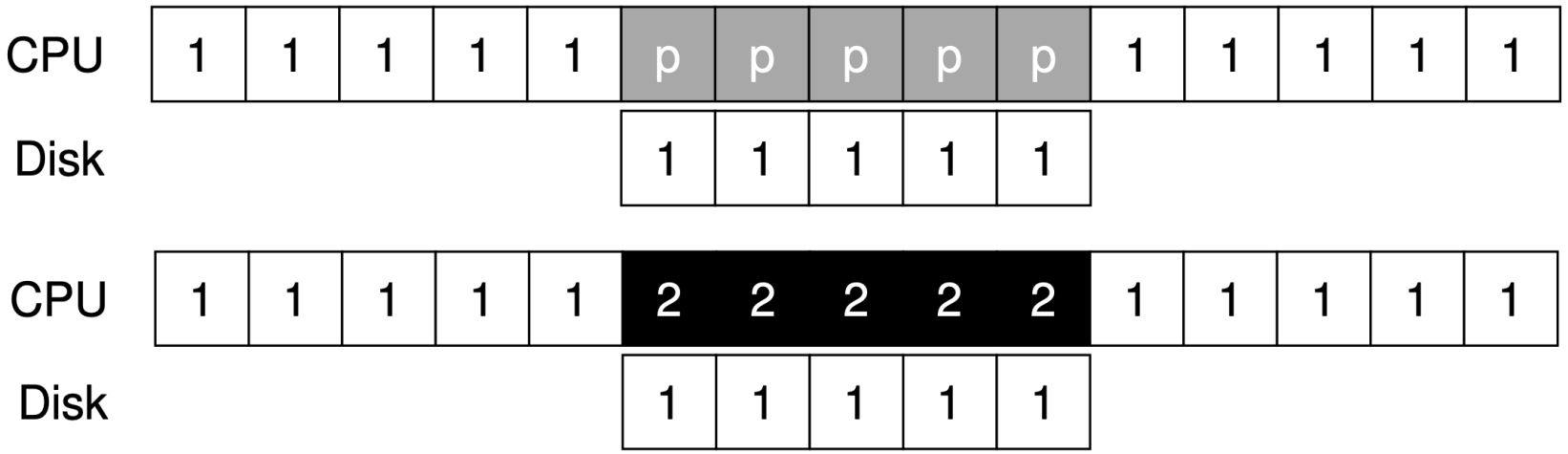
```
if (count == 0) {
    unblock_user( );
} else {
    *printer_data_register = p[i];
    count = count – 1;
     i = i + 1;
}
acknowledge_interrupt( );
return_from_interrupt( );
```

(b)

Interrupt service procedure for the printer

Interrupts

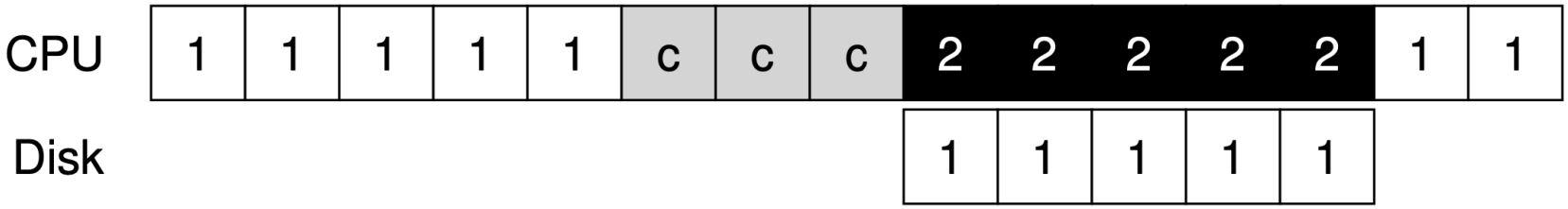
- Interrupts allow for **overlap** of computation and I/O



- The use of interrupts is not always the best solution
  - For example, a device that performs its tasks very quickly
  - Use a **hybrid** that polls for a little while and then, if the device is not yet finished, uses interrupts

Interrupts

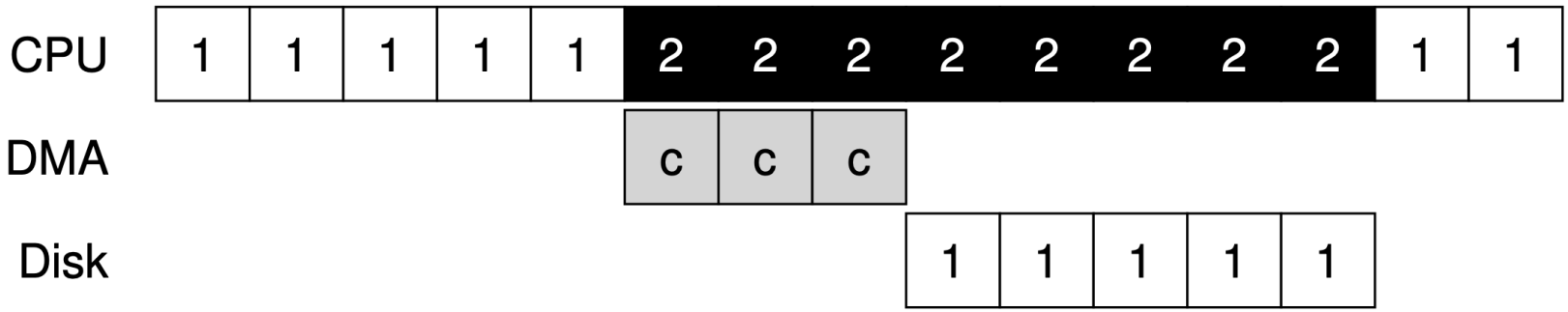
- **Interrupts take time**: To transfer a large chunk of data to a device, the CPU can be overburdened with a rather trivial task
  - When initiating the I/O, CPU must copy the data from memory to the device explicitly, one word at a time
  - Waste a lot of time and effort that could better be spent running other processes



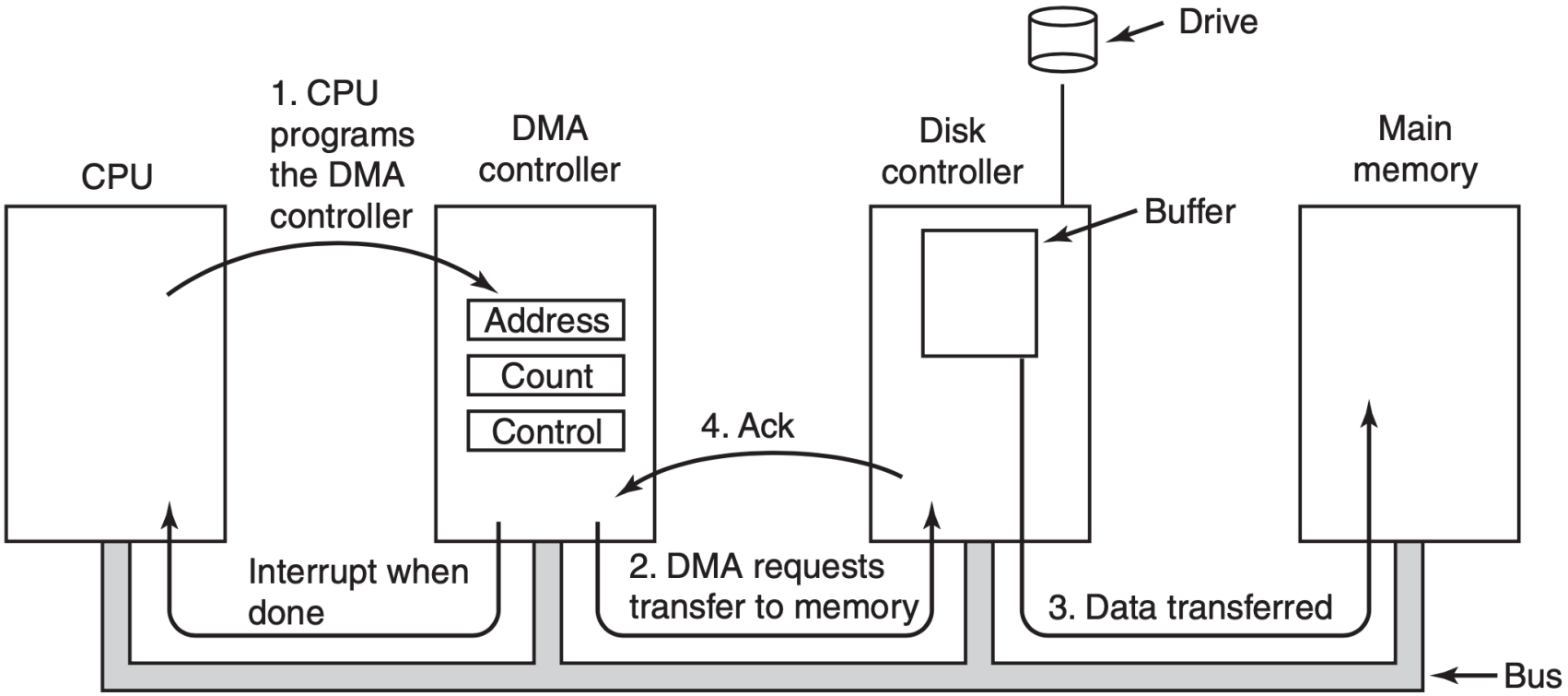
Direct Memory Access (DMA)

Direct Memory Access (DMA): A DMA controller is a specific device within a system that can orchestrate transfers between devices and main memory without much CPU intervention

- OS programs the DMA by telling it where the data lives in, how much data to copy, and which device to send it to
- When the DMA is complete, the DMA controller raises an interrupt



Direct Memory Access (DMA)




```
copy_from_user(buffer, p, count);
set_up_DMA_controller( );
scheduler( );
```

Code executed when the print system call is made

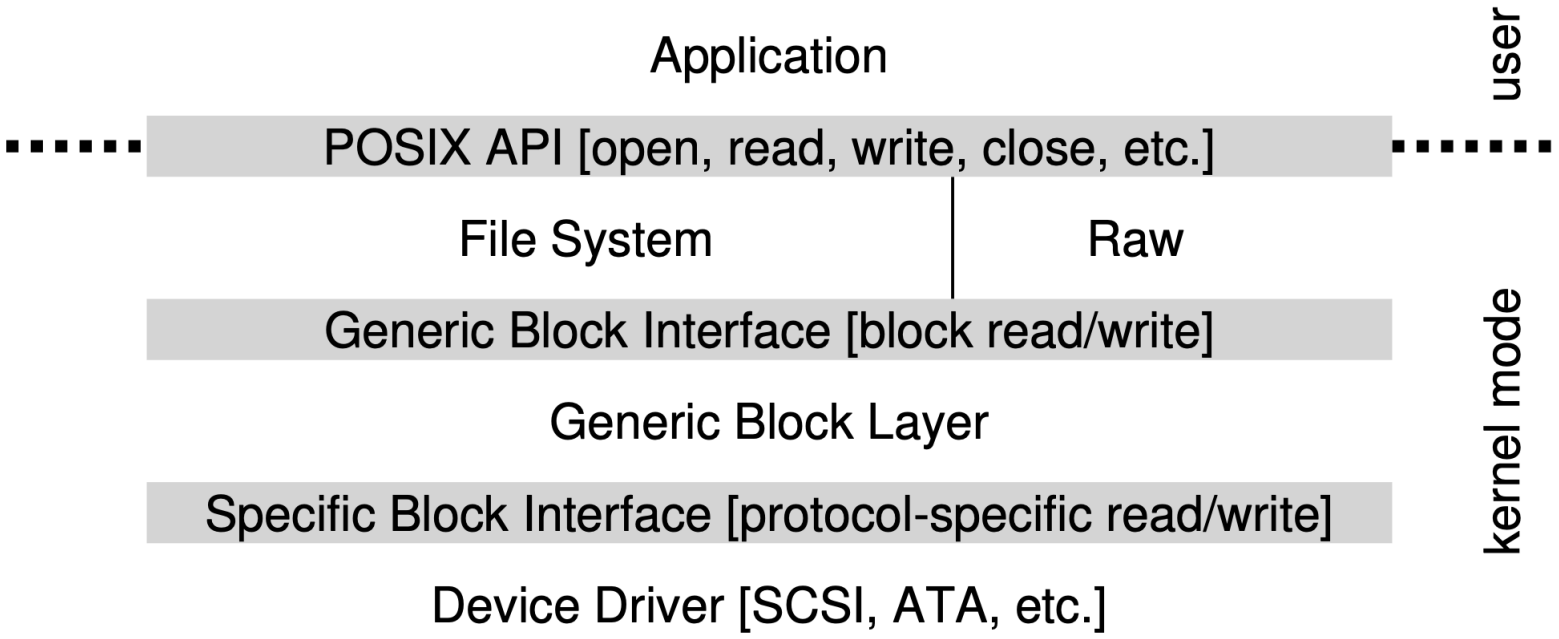
```
acknowledge_interrupt( );
unblock_user( );
return_from_interrupt( );
```

Interrupt-service procedure

Device Driver

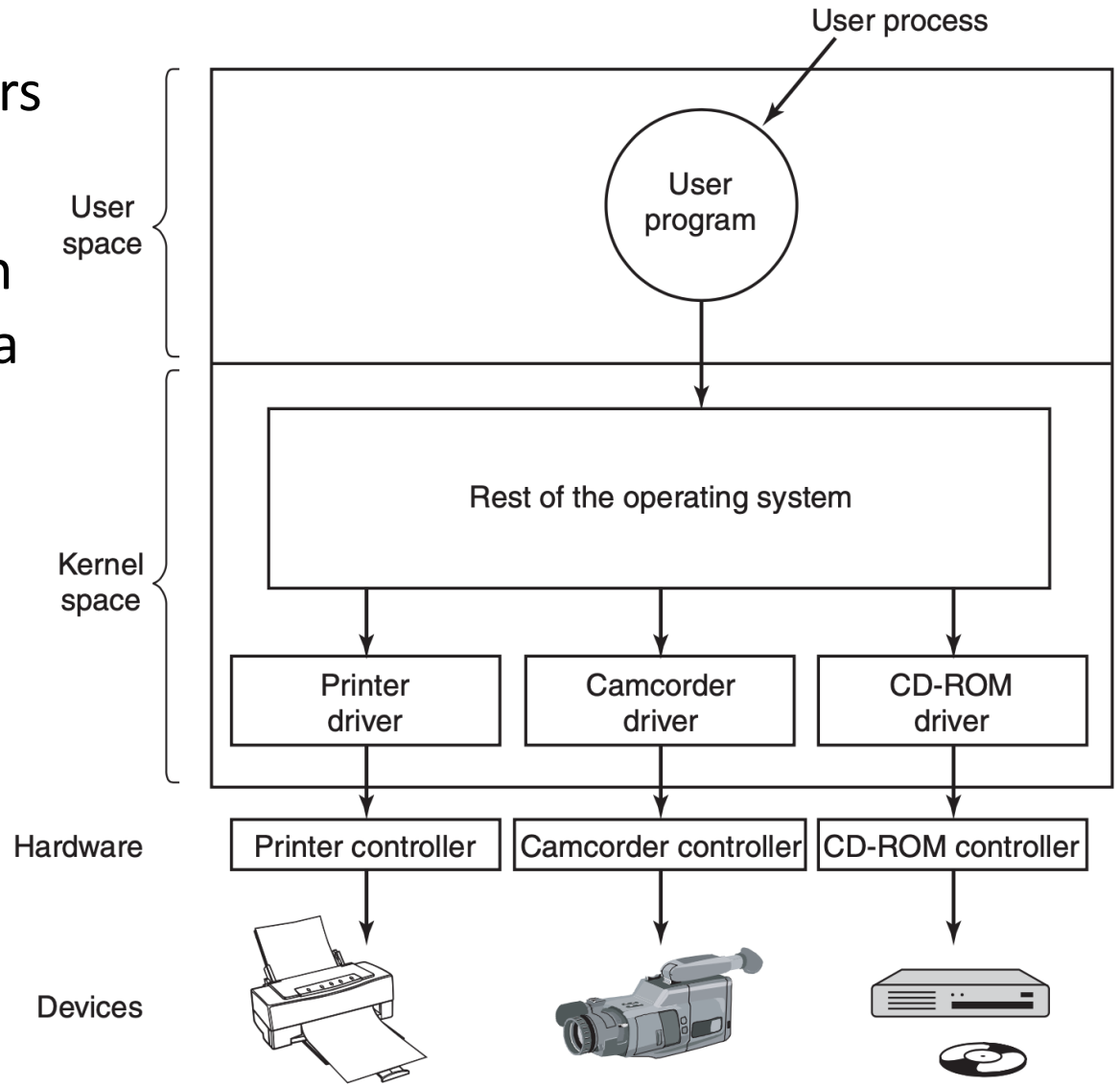
How to fit various devices (with specific interfaces) into the OS (keep as general as possible)?

- **Device driver**: A piece of software in OS, which knows in detail how a device works **(Abstraction)**



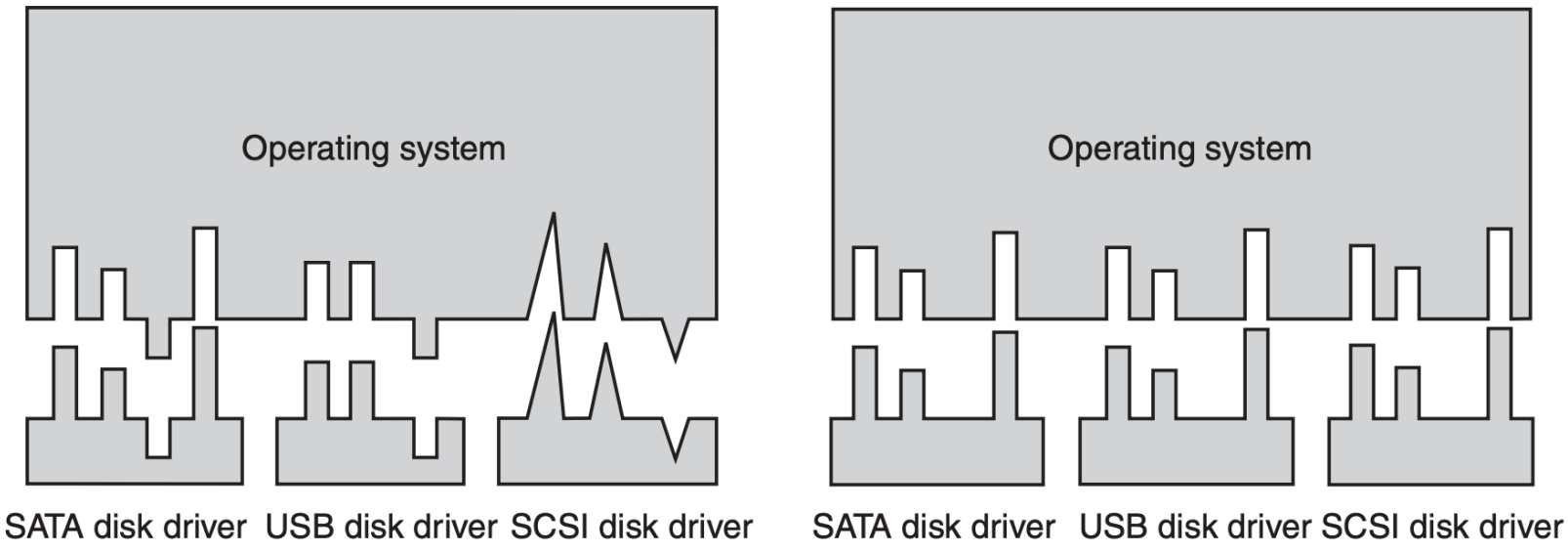
Device Driver

- OS often classifies drivers into categories:
  - **Block Devices**, which contain multiple data blocks (e.g., disk)
  - **Character Devices**, which generate or accept a stream of characters (e.g., keyboard)



Uniform Interfacing

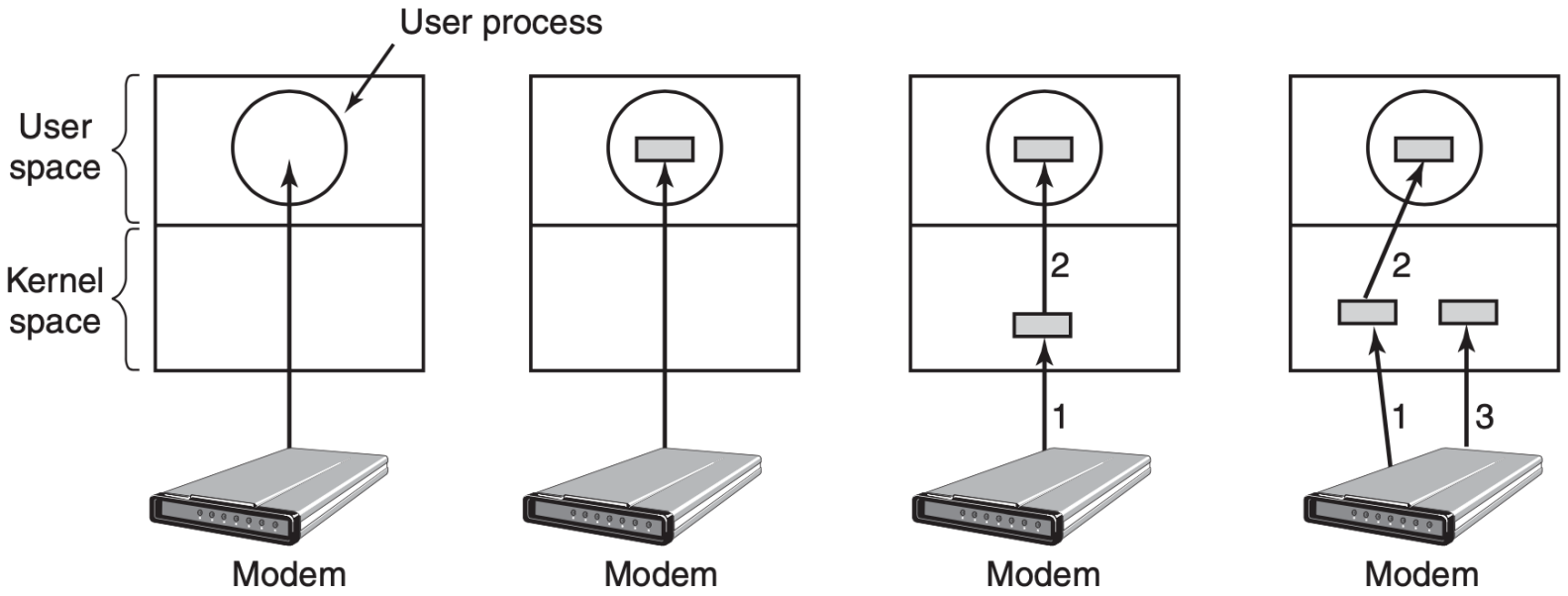
- Each device driver has a different interface to the OS (different driver functions and kernel functions)
- All drivers have the same interface
  - For each class of devices, OS defines a set of functions that the driver must supply



Uniform Interfacing

- Some common entry points
  - `init()`
    - Initialize hardware
  - `start()`
    - Boot time initialization
  - `open(dev, flag, id)` and `close(dev, flag, id)`
    - Initialization resources for read or write and release resources
  - `halt()`
    - Call before the system is shutdown
  - `intr(vector)`
    - Called by the kernel on a hardware interrupt
  - `read(...)` and `write()` calls
    - Data transfer
  - `poll(pri)`
    - Called by the kernel 25 to 100 times a second
  - `ioctl(dev, cmd, arg, mode)`
    - special request processing

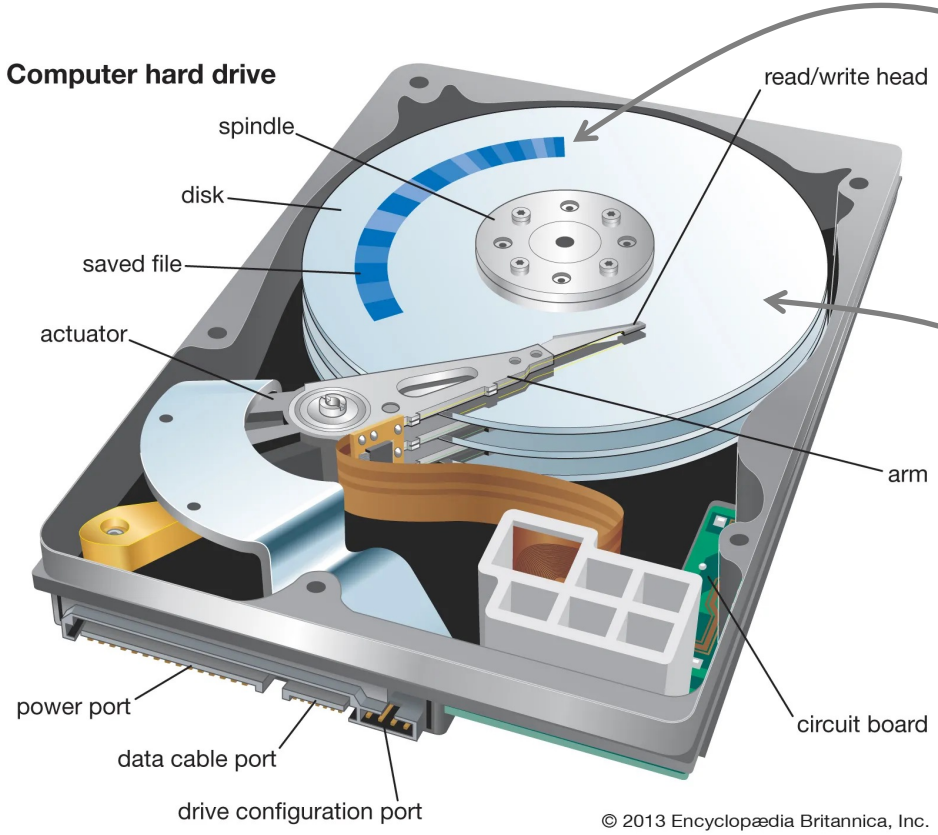
Buffering



- Unbuffered (user process has to be started up each time)
- Buffering in user space (what if the buffer is paged out)
- Buffering in the kernel
- Double buffering in the kernel

Hard Disk

- The main form of persistent data storage in computer systems



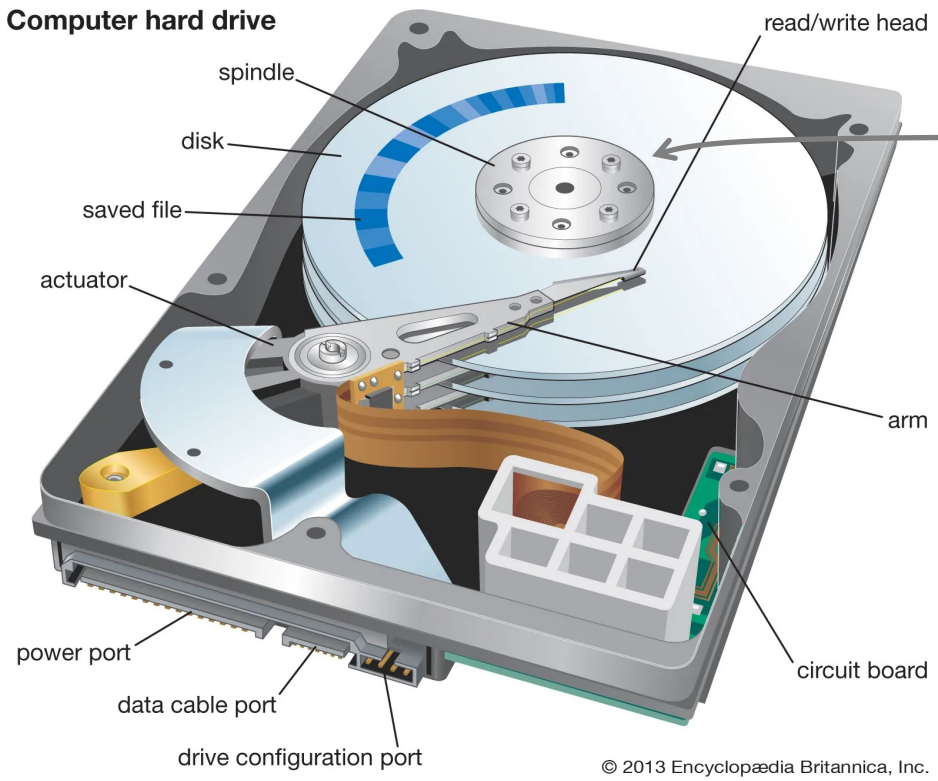
*Data is encoded on each surface in concentric circles of sectors, named **tracks***

*A **platter** is a circular hard surface on which data is stored persistently by inducing magnetic changes to it*

*Each platter has 2 sides, each of which is called a **surface***

Hard Disk

- The main form of persistent data storage in computer systems

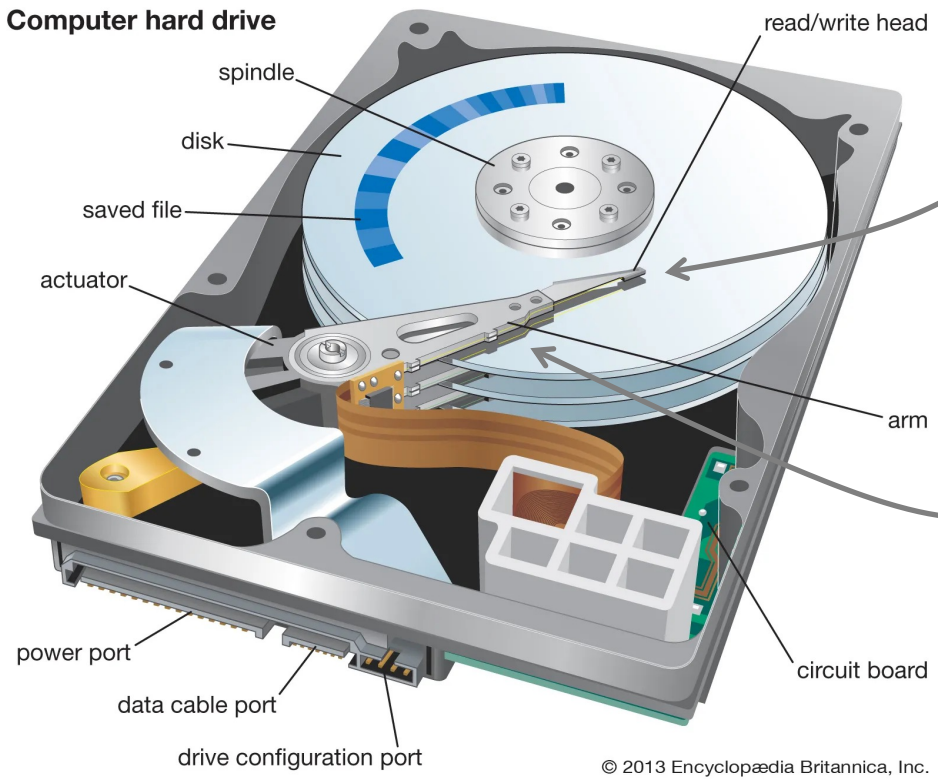


*The platters are all bound together around the **spindle**, which is connected to a motor that spins the platters around at a fixed rate*

*The rate of rotation is often measured in **rotations per minute (RPM)**, typically ranging from 7,200 to 15,000 RPM*

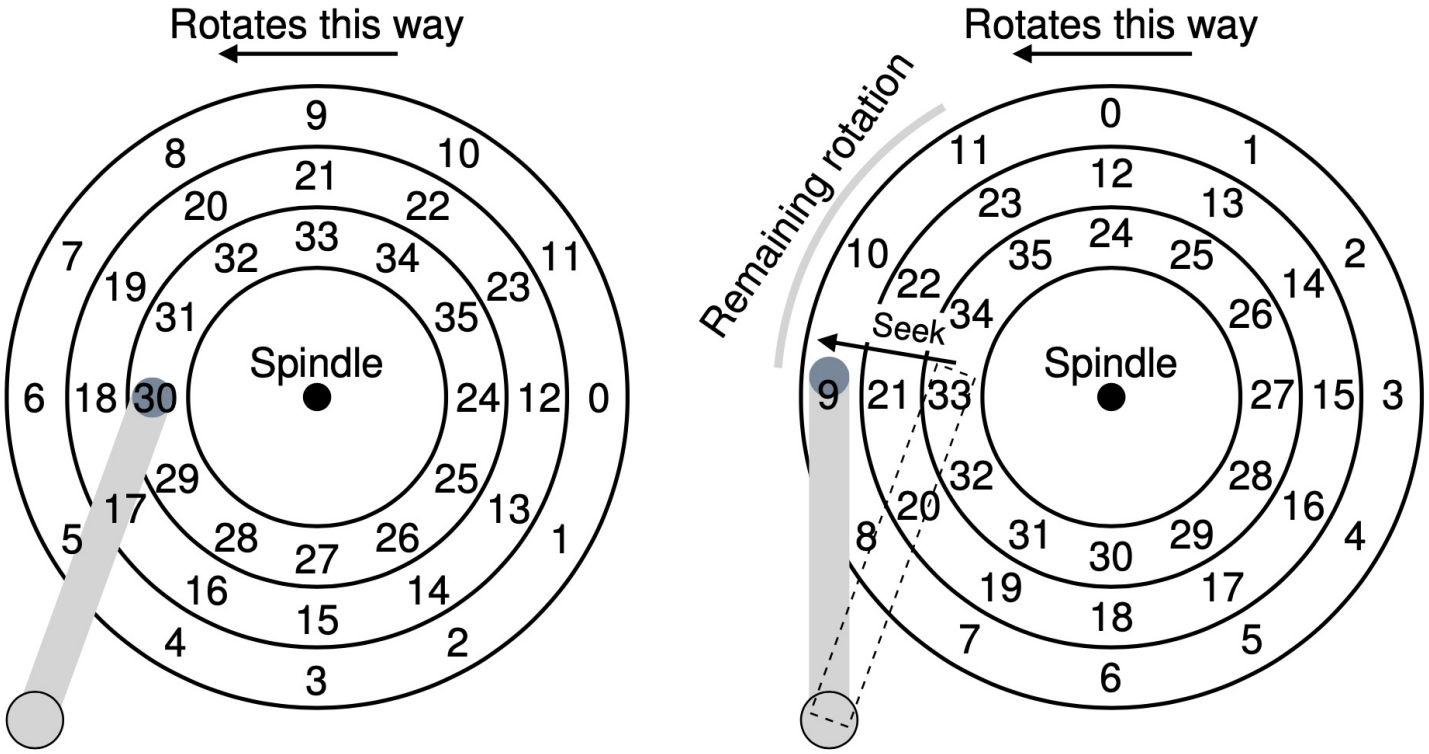
Hard Disk

- The main form of persistent data storage in computer systems



*The reading (sense the magnetic patterns) and writing (induce a change) is accomplished by the **disk head**, one per surface*

*The disk head is attached to a single **disk arm**, which moves across the surface to position the head over the desired track*



To service a request

- **Seek Time**: move the disk arm to the correct track
- **Rotational delay**: wait for the desired sector to rotate under the disk head
- **Transfer:** read or write data

- Seek and rotational times dominate the cost of small accesses
- To transfer a 4 KB block in a random workload (Cheetah)
  - T_{seek} = 4 ms
  - $T_{rotation}$ = 2 ms
  - $T_{transfer}$ = 0.03 ms
  - $R_{I/O}$ = 0.65 MB/s
- To transfer 100 MB in a sequential workload
  - A single seek and rotation before a very long transfer
  - $R_{I/O}$ is close to peak transfer rate

$$T_{I/O} = T_{seek} + T_{rotation} + T_{transfer}$$

$$R_{I/O} = \frac{Size_{Transfer}}{T_{I/O}}$$

	Cheetah 15K.5	Barracuda
Capacity	300 GB	1 TB
RPM	15,000	7,200
Average Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s
Platters	4	4
Cache	16 MB	16/32 MB
Connects via	SCSI	SATA

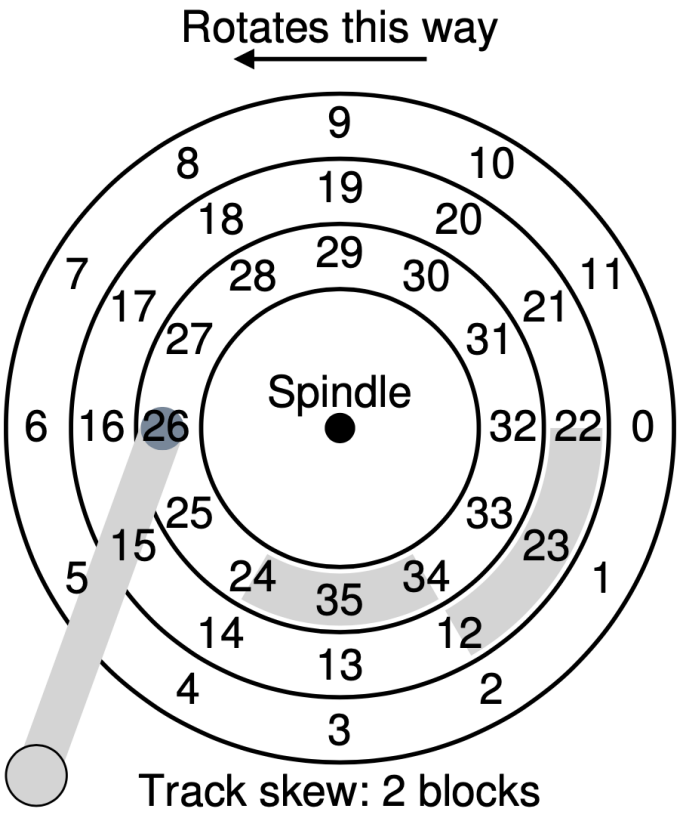
Hard Disk

- Disk parameters for the original IBM PC 360-KB floppy disk and a Western Digital WD 3000 HLFS hard disk (after 30 years)

Parameter	IBM 360-KB floppy disk	WD 3000 HLFS hard disk
Number of cylinders	40	36,481
Tracks per cylinder	2	255
Sectors per track	9	63 (avg)
Sectors per disk	720	586,072,368
Bytes per sector	512	512
Disk capacity	360 KB	300 GB
Seek time (adjacent cylinders)	6 msec	0.7 msec
Seek time (average case)	77 msec	4.2 msec
Rotation time	200 msec	6 msec
Time to transfer 1 sector	22 msec	1.4 μsec

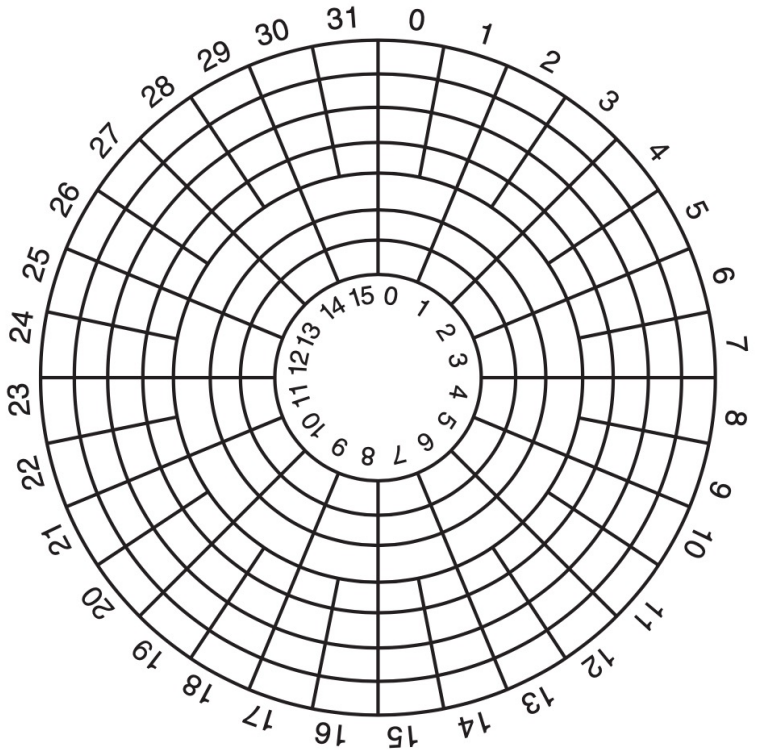
Hard Disk

- **Track (Cylinder) Skew:** make sure that sequential reads can be properly serviced when crossing track boundaries
  - When switching from one track to another, the disk needs time to reposition the head
  - Without such skew, the head would be moved to the next track but the desired next block would have already rotated under the head



Hard Disk

- **Multi-Zoned Disk Drives:** Outer zones have more sectors than inner zones
  - Disk is organized into multiple zones, each of which is a consecutive set of tracks on a surface
  - Each zone has the same number of sectors per track
  - Modern disks support logical block addressing (without regard to the disk geometry)



Hard Disk

- **Cache (Track Buffer):** Some small amount of memory (8 to 16 MB) which the drive can use to hold data read from or written to the disk
  - When reading a sector, reading in all sectors on that track
  - On write, acknowledge the write when it has put the data in its memory (write back), or after the write has actually been written to disk (write through)

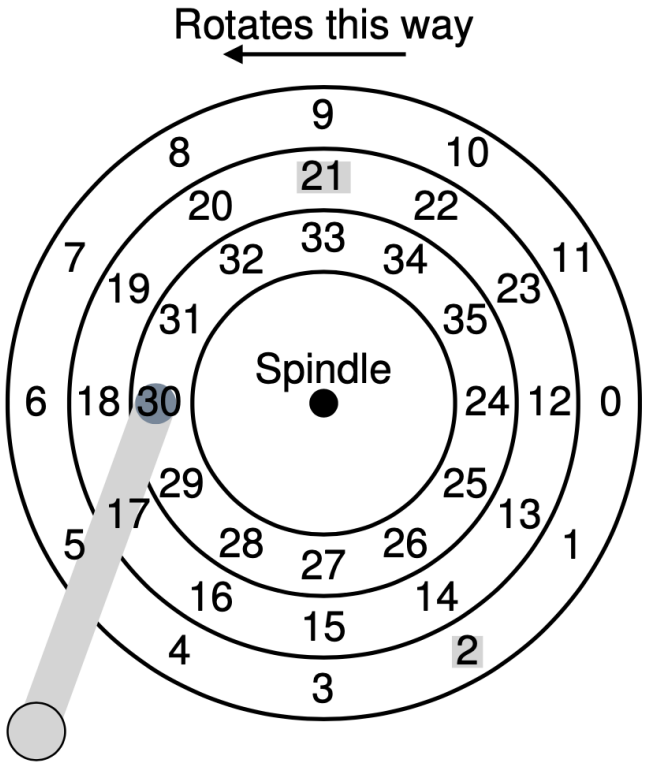
Disk Scheduling

- Because of the high cost of I/O, the OS has historically played a role in deciding the order of I/Os issued to the disk
- Given a set of I/O requests, the **disk scheduler** examines the requests and decides which one to schedule next
  - We can make a good guess at how long a disk request will take (unlike job scheduling)
  - Try to follow the principle of **shortest job first (SJB)**

Shortest Seek First (SSF)

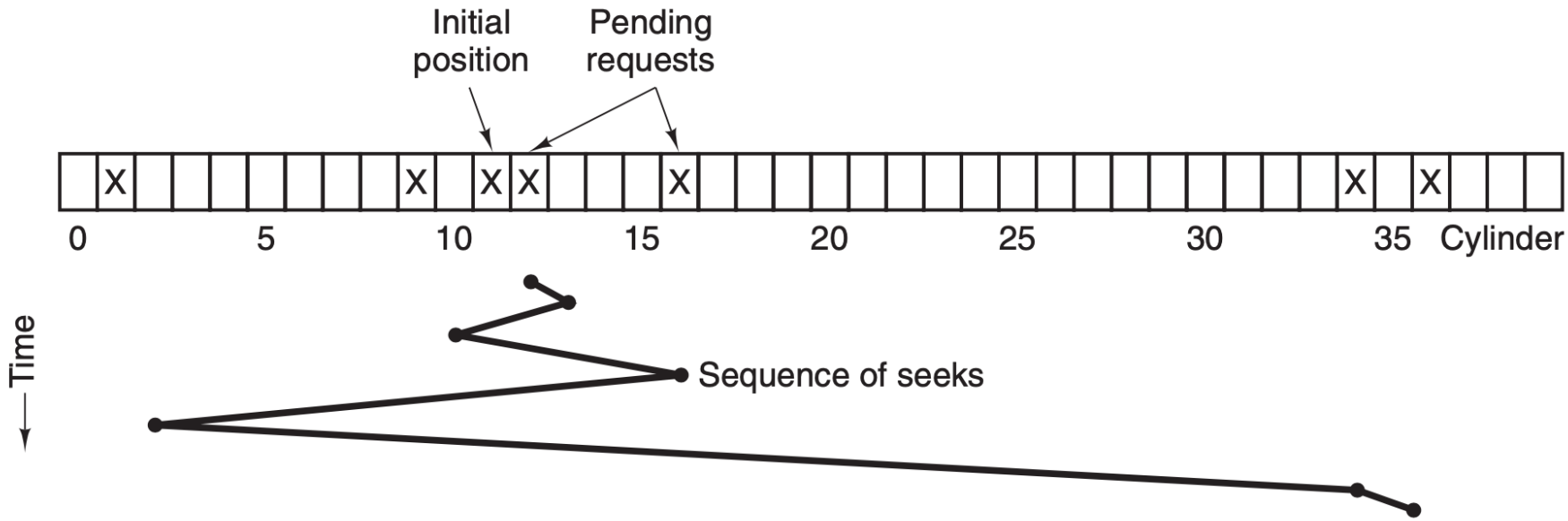
Order the queue of I/O requests by track, picking requests on the **nearest track** to complete first

- **Minimize the seek time**
- Assume the current head position is over the inner track, then issue request 21 (middle) → 2 (outer)



Shortest Seek First (SSF)

- Assume the first request is for track (cylinder) 11, and new requests come in for tracks 1, 36, 16, 34, 9, and 12, in order
  - **First Come First Service**: arm motions of 10 + 35 + 20 + 18 + 25 + 3 = 111 tracks
  - **SSF**: 1 + 3 + 7 + 15 + 33 + 2 = 61 tracks



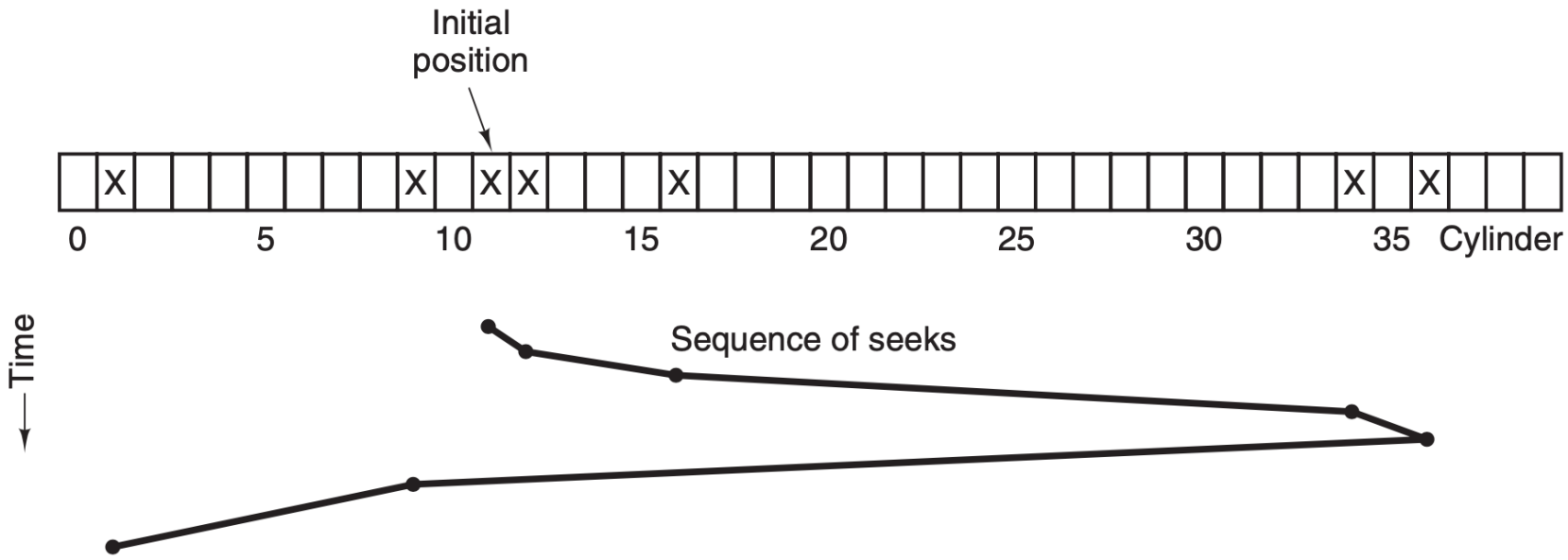
Shortest Seek First (SSF)

- Assume the first request is for track (cylinder) 11, and new requests come in for tracks 1, 36, 16, 34, 9, and 12, in order
  - **First Come First Service**: arm motions of 10 + 35 + 20 + 18 + 25 + 3 = 111 tracks
  - **STF**: 1 + 3 + 7 + 15 + 33 + 2 = 61 tracks
- **Starvation**: what if there is a steady stream of requests to the middle tracks?

Elevator (SCAN)

Simply **move back and forth** across the disk servicing requests in order across the tracks (behaves like an elevator)

- A single pass across the disk (from outer to inner tracks, or inner to outer) is called a *sweep*
- Arm motions of 1 + 4 + 18 + 2 + 27 + 8 = 60 tracks



Elevator (SCAN)

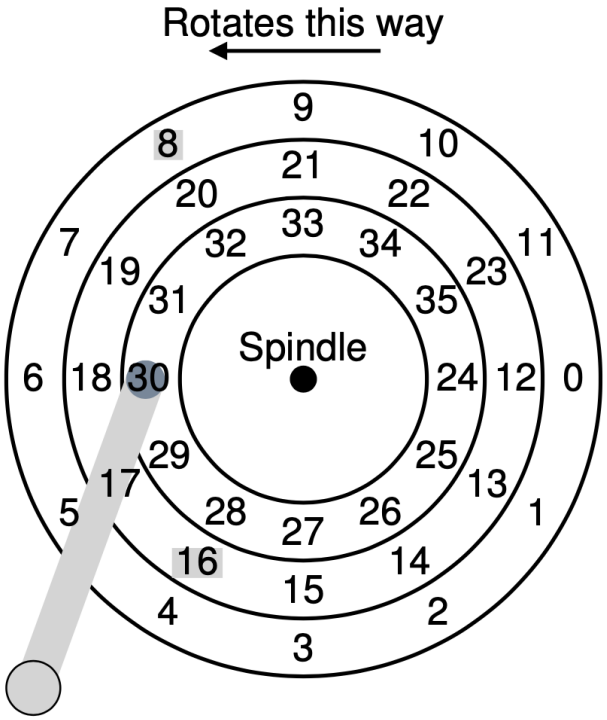
Simply **move back and forth** across the disk servicing requests in order across the tracks (behaves like an elevator)

- A single pass across the disk (from outer to inner tracks, or inner to outer) is called a *sweep*
- A number of variants available
  - *F-SCAN*: freeze the queue to be serviced when it is doing a sweep (avoid starvation of far-away requests)
  - *C-SCAN*: only sweeps from outer-to-inner, and then resets at the outer track to begin again (a bit more fair to inner and outer tracks)

Shortest Positioning Time First (SPTF)

Take both seek and rotation time into account

- Assume the current head position is over sector 30 (inner), then issue request 16 (middle), or 8 (outer) ?
  - If seek time is much higher than rotational delay, then SSF is good
  - If seek is quite a bit faster than rotation, then service 8 first
- Difficult to implement in OS, which generally does not have a good idea where track boundaries are or where the disk head currently is



Disk Scheduling

- Where is disk scheduling performed on modern systems?
  - In older systems, OS did all the scheduling
  - In modern systems, disks accommodate multiple requests, and have sophisticated internal schedulers (like SPTF)
    - OS usually picks what it thinks the best few requests are (say 16) and issues them all to disk
    - Wait for a bit, then a new and “better” request may arrive
    - Some requests can be merged (e.g., merge requests for blocks 33 and 34 into a single two-block request)

RAID

Redundant Array of Inexpensive Disks (RAID): use multiple disks in concert to build a ***faster***, ***bigger***, and ***more reliable*** disk system

- **Capacity**: Large data sets demand large disks
- **Reliability**: Spread data across multiple disks makes the data vulnerable to the loss of a single disk (redundancy)
- **Performance**: Use multiple disks in parallel can greatly speed up I/O times
- RAIDs provide these advantages transparently to systems that use them
  - To a file system above, a RAID just looks like a single disk (an array of blocks)

RAID

Redundant Array of Inexpensive Disks (RAID): use multiple disks in concert to build a ***faster***, ***bigger***, and ***more reliable*** disk system

- RAID level 0: Striping
- RAID level 1: Mirroring
- RAID level 4: Saving Space With Parity
- RAID level 5: Rotating Parity

RAID-0: Striping

- Spread the blocks across the disks in a round-robin fashion
  - Blocks in the same row are referred to as a **stripe**
- Extract the most parallelism when requests are made for contiguous chunks

Disk 0	Disk 1	Disk 2	Disk 3
0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

4-disk array

RAID-0: Striping

- **Capacity**: Given *N* disks each of size *B* blocks, deliver *N*B* blocks of useful capacity
- **Reliability**: Any disk failure will lead to data loss
- **Performance**
  - For sequential and random workloads, $R_{I/O}$ = *N*X* MB/s (as all disks are utilized in parallel)

RAID-1: Mirroring

- Make more than one copy of each block in the system (each copy should be placed on a separate disk)
  - Tolerate disk failures
- Read either copy; On write, must update both copies (take place in parallel)

Disk 0	Disk 1	Disk 2	Disk 3
0	0	1	1
2	2	3	3
4	4	5	5
6	6	7	7

Keep two physical copies of each logical block

RAID-1: Mirroring

- **Capacity**: With mirroring level = 2, useful capacity is *(N*B)/2*
- **Reliability**: Tolerate 1 disk failure for certain, and up to *N/2* failures depending on which disks fail (e.g., disks 1 and 3)
- **Performance**
  - Each logical write must result in two physical writes, $R_{I/O}$ = (*N/2*) * *X* MB/s
  - Random read is the best case, $R_{I/O}$ = *N*X* MB/s
  - For sequential read, disk is rotating over skipped blocks (e.g., block 2 in disk 0), $R_{I/O}$ = (*N/2*) * *X* MB/s

RAID-4: Saving Space With Parity

- For each stripe of data, add a single **parity** block that stores the redundant information for that stripe of blocks
  - Withstand the loss of any one block from the stripe

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	1	2	3	P0
4	5	6	7	P1
8	9	10	11	P2
12	13	14	15	P3

RAID-4: Saving Space With Parity

- Use the XOR function: the number of 1s in any row, including the parity bit, must be an even number
- To reconstruct the lost value: XOR the data bits and the parity bits together

C0	C1	C2	C3	P
0	0	1	1	XOR(0,0,1,1) = 0
0	1	0	0	XOR(0,1,0,0) = 1

Block0	Block1	Block2	Block3	Parity
00	10	11	10	11
10	01	00	01	10

blocks of size 4 bits

RAID-4: Saving Space With Parity

- Use the XOR function: the number of 1s in any row, including the parity bit, must be an even number
- To reconstruct the lost value: XOR the data bits and the parity bits together
- When overwriting a bit, compare the old data and the new data; if they are different, then flip the old parity bit (perform based on each block)

$$P_{new} = (C_{old} \oplus C_{new}) \oplus P_{old}$$

RAID-4: Saving Space With Parity

- **Capacity**: Use 1 disk for parity information, useful capacity is *(N - 1)*B* blocks
- **Reliability**: Tolerate 1 disk failure
- **Performance**
  - Sequential read and write (full-stripe write) can utilize all of the disks except for the parity disk, $R_{I/O}$ = (*N - 1*) * *X* MB/s
  - Random read can be spread across the data disks, $R_{I/O}$ = (*N - 1*) * *X* MB/s
  - Random write ?

RAID-4: Saving Space With Parity

- Small write problem, $R_{I/O} = X / 2$ MB/s
  - Each write will generate 4 physical I/Os (2 reads + 2 writes)

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	1	2	3	P0
*4	5	6	7	+P1
8	9	10	11	P2
12	*13	14	15	+P3

  - Read and write to disks 0 and 1 can happen in parallel, while both have to read the related parity disk (a **bottleneck** that prevents parallelism)

RAID-5: Rotating Parity

- Rotate the parity block across drives
  - Remove the parity-disk bottleneck

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	1	2	3	P0
5	6	7	P1	4
10	11	P2	8	9
15	P3	12	13	14
P4	16	17	18	19

RAID-5: Rotating Parity

- **Capacity**: *(N - 1)*B* blocks
- **Reliability**: Tolerate 1 disk failure
- **Performance**
  - For sequential read and write, $R_{I/O}$ = (*N - 1*) * *X* MB/s
  - Random read is little better as all disks can be utilized, $R_{I/O}$ = *N* * *X* MB/s
  - Random write now allows for parallelism across requests (keep all disks about evenly busy), $R_{I/O}$ = (*N/4*) * *X* MB/s

RAID

The tradeoffs across RAID levels

- Strictly want performance and do not care about reliability
  → RAID-0 (striping)
- Want random I/O performance and reliability
  → RAID-1 (mirroring)
- Capacity and reliability are the main goals
  → RAID-5