CS 318 Principles of Operating Systems

Fall 2021

Lecture 14: I/O & Disks

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of ENGINEERING

Administrivia

Lab 3 overview session this Friday 5-6pm EDT

Next Tuesday (10/26) is project hacking day

- No class, work on lab 3a

In-class Quiz 4 for Lecture 6&7 next Thursday (10/28)

Overview

We've covered OS abstractions for CPU and memory so far

Virtualization
Processes
Scheduling
Virtual Memory

Concurrency
Threads
Synchronization
Semaphores and Monitors

Persistence
I/O
Disks
File Systems

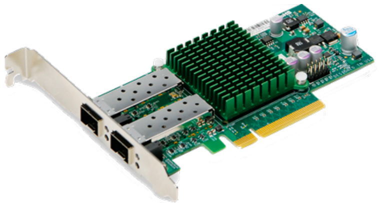
I/O management is another major component of OS

- Important aspect of computer operation
- I/O devices vary greatly: various methods to control them
- New types of devices

I/O Devices





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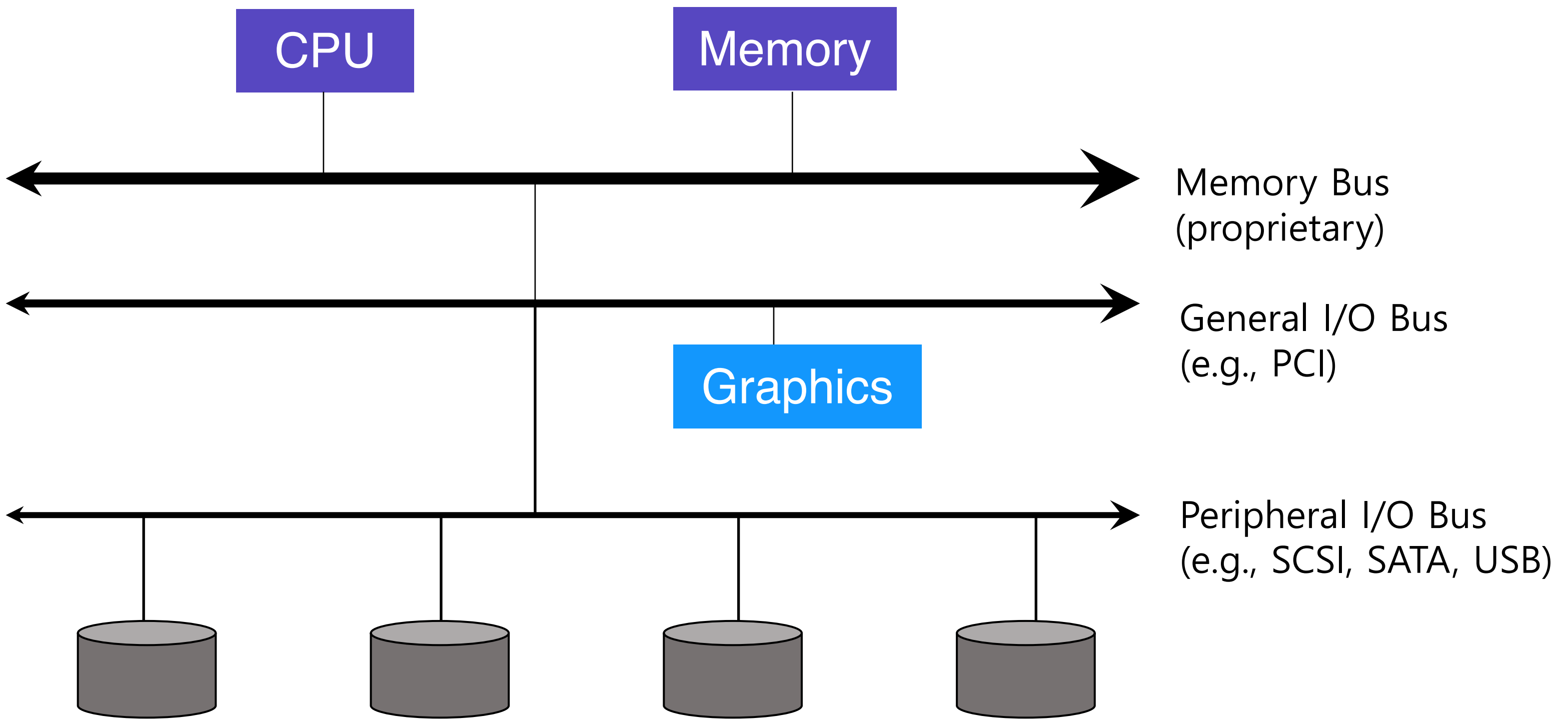
Issues to address:

- How should I/O be integrated into systems?
- What are the general mechanisms?
- How can we manage them efficiently?

Structure of Input/Output (I/O) Device



I/O Device Interfaces

Port – connection point for device

- serial port

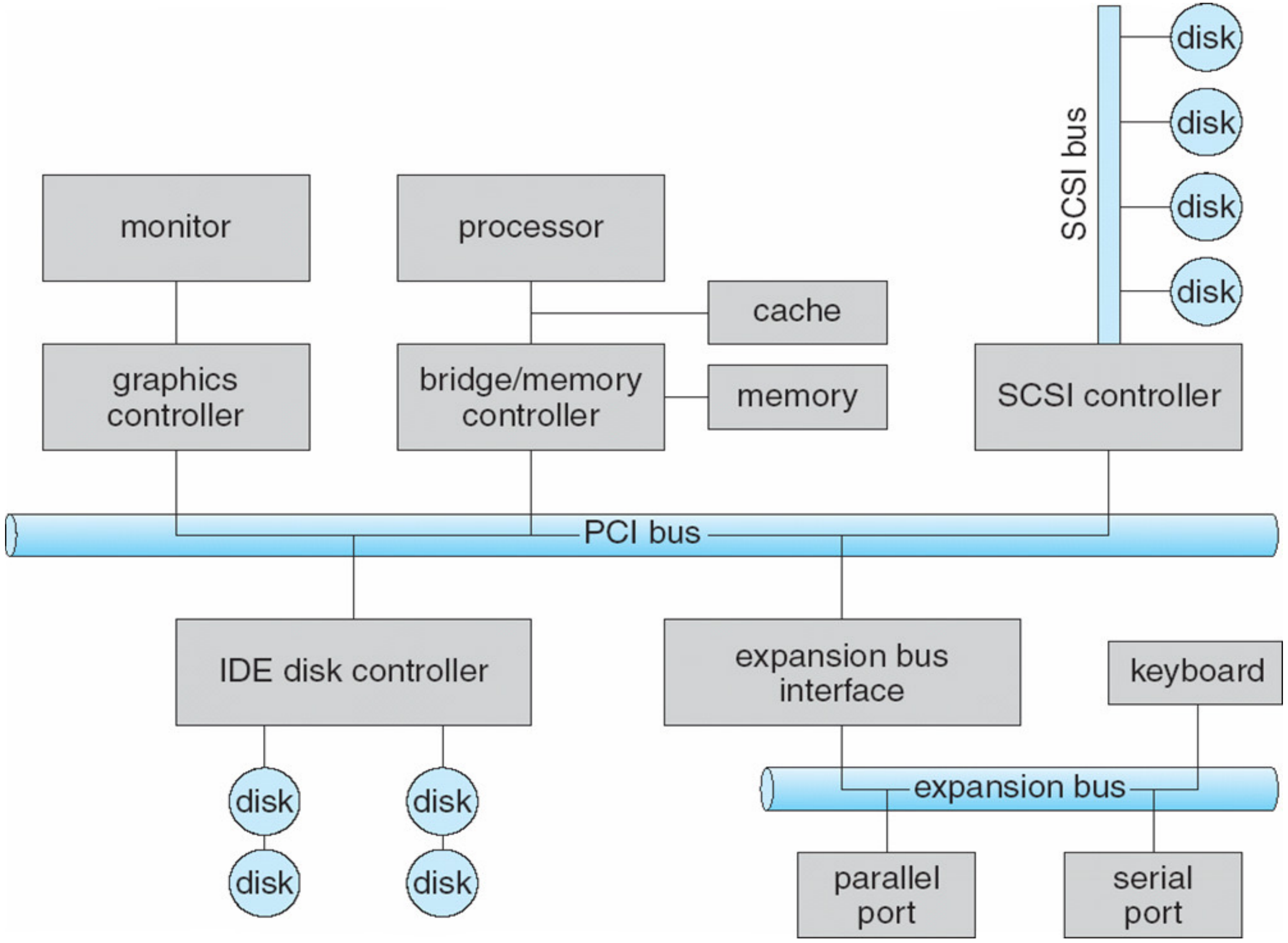
Bus – daisy chain for devices sharing a common set of wires

- PCI bus common in PCs and servers, PCI Express (PCIe)
- expansion bus connects relatively slow devices

Controller – 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.

What Is I/O Bus? E.g., PCI



Device Interaction

How the OS communicates with the device?

I/O instructions control devices

- `in` and `out` instructions on x86
- Devices usually have registers
  - device driver places commands, addresses, and data there to read/write

Memory-mapped I/O

- Device registers available as if they were memory locations.
- OS `load` (to read) or `store` (to write) to the device instead of main memory.

Device I/O Port Locations on PCs

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)

x86 I/O instructions

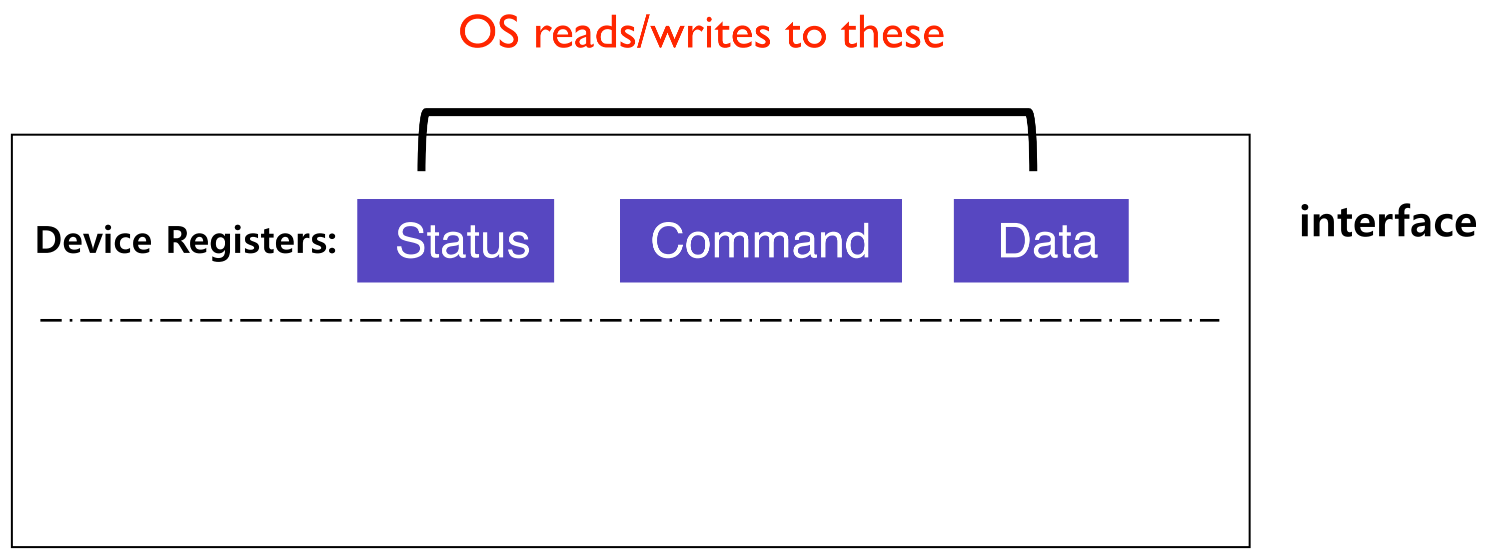
```
static inline uint8_t inb (uint16_t port)
{
  uint8_t data;
  asm volatile ("inb %w1, %b0" : "=a" (data) : "Nd" (port));
  return data;
}

static inline void outb (uint16_t port, uint8_t data)
{
  asm volatile ("outb %b0, %w1" : : "a" (data), "Nd" (port));
}

static inline void insw (uint16_t port, void *addr, size_t cnt)
{
  asm volatile ("rep insw" : "+D" (addr), "+c" (cnt)
                : "d" (port) : "memory");
}
```

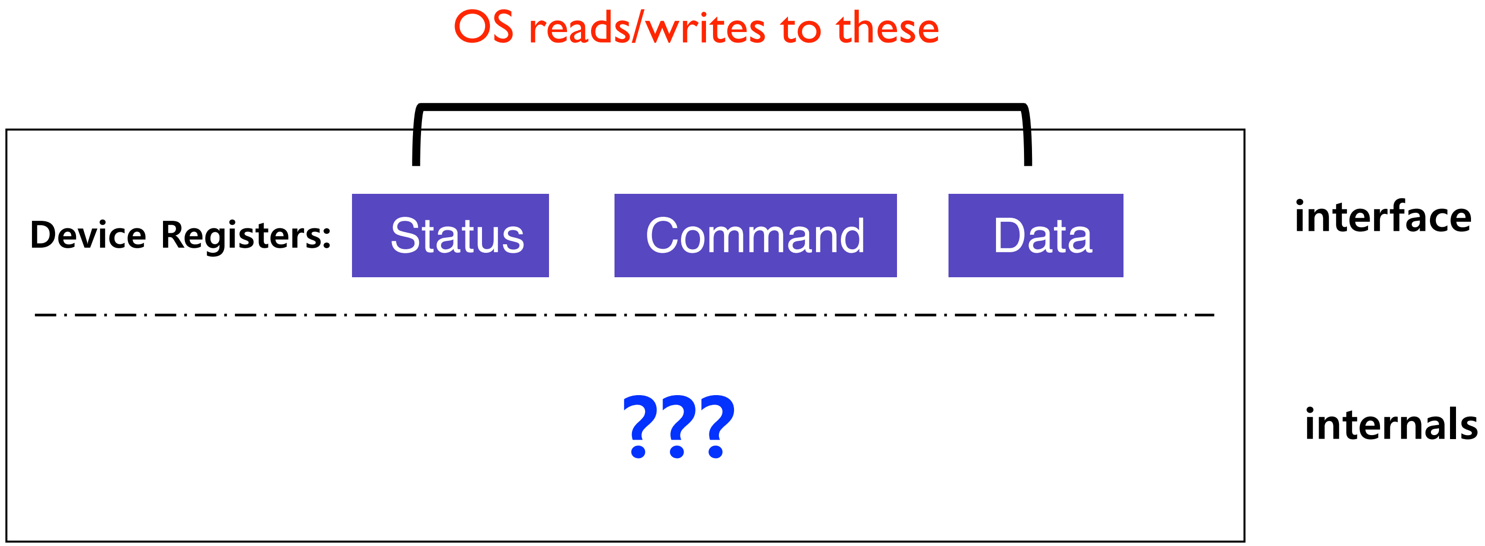
Pintos `threads/io.h`

Canonical I/O Device



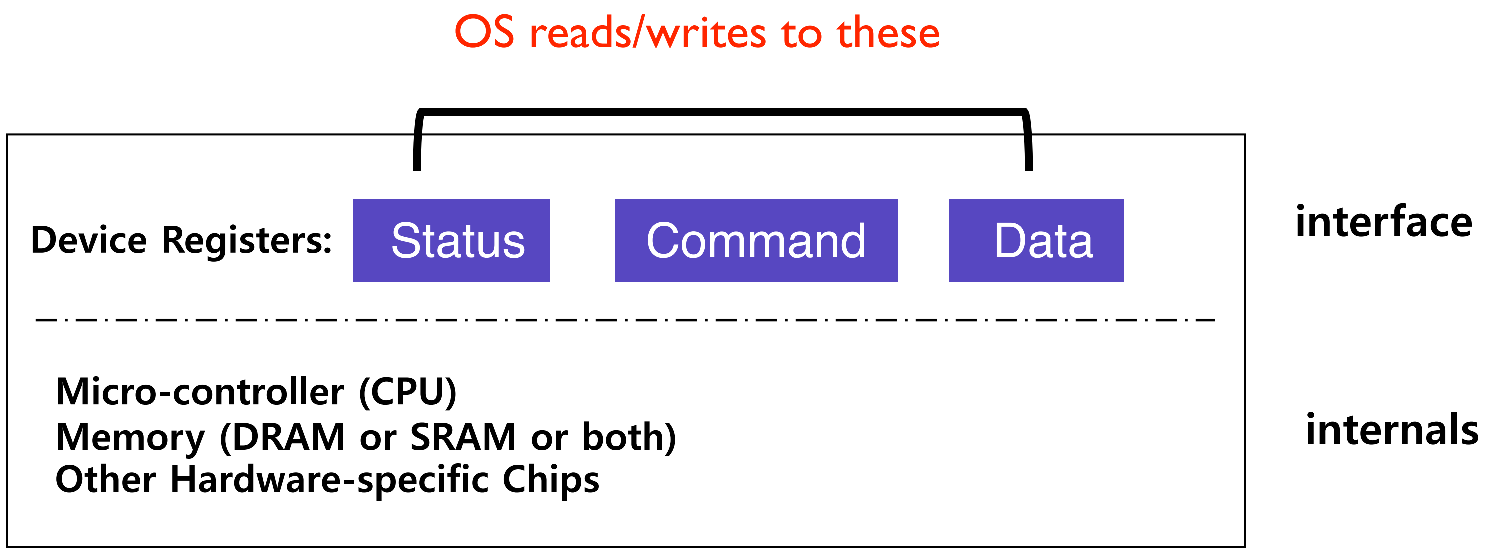
Canonical Device

Canonical I/O Device



Canonical Device

Canonical I/O Device



Canonical Device

Hardware Interface Of Canonical Device

status register

- 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

By reading or writing the three registers, OS controls device behavior

Hardware Interface Of Canonical Device

Typical interaction example

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

IDE Disk Driver

```
void IDE_ReadSector(int disk, int off,
     void *buf)
{
  // Select Drive
  outb(0x1F6, disk == 0 ? 0xE0 : 0xF0);
  IDEWait();
  // Read length (1 sector = 512 B)
  outb(0x1F2, 1);
  outb(0x1F3, off); // LBA low
  outb(0x1F4, off >> 8); // LBA mid
  outb(0x1F5, off >> 16); // LBA high
  outb(0x1F7, 0x20); // Read command
  insw(0x1F0, buf, 256); // Read 256 words
}
```

```
void IDEWait()
{
  // Discard status 4 times
  inb(0x1F7); inb(0x1F7);
  inb(0x1F7); inb(0x1F7);
  // Wait for status BUSY flag to clear
  while ((inb(0x1F7) & 0x80) != 0);
}
```

Memory-mapped IO

`in/out` instructions slow and clunky

- Instruction format restricts what registers you can use
- Only allows 2^{16} different port numbers
- Per-port access control turns out not to be useful (any port access allows you to disable all interrupts)

Devices can achieve same effect with physical addresses, e.g.:

```
volatile int32_t *device_control
   = (int32_t *) (0xc0100 + PHYS_BASE);
*device_control = 0x80;
int32_t status = *device_control;
```

- OS must map physical to virtual addresses, ensure non-cachable

Polling

- **OS waits until the device is ready by repeatedly reading the status register**
  - Positive aspect is simple and working.
  - However, it wastes CPU time just waiting for the device
    - Switching to another ready process is better utilizing the CPU.

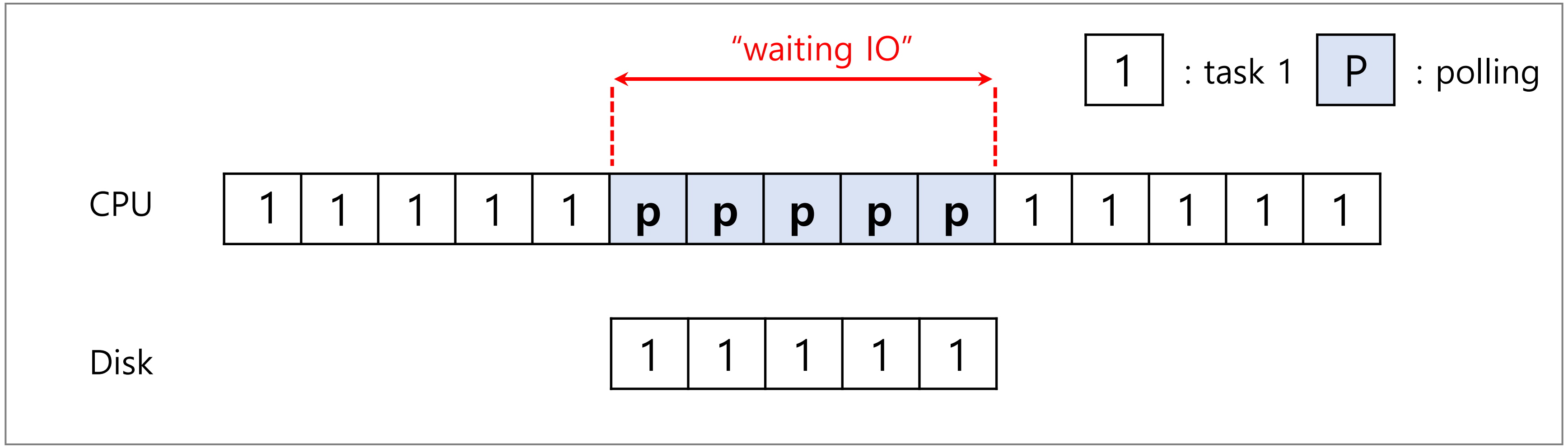


Diagram of CPU utilization by polling

Interrupts

Put the I/O request process to sleep and context switch to another

When the device is finished, wake the process by interrupt

- CPU and the disk are properly utilized

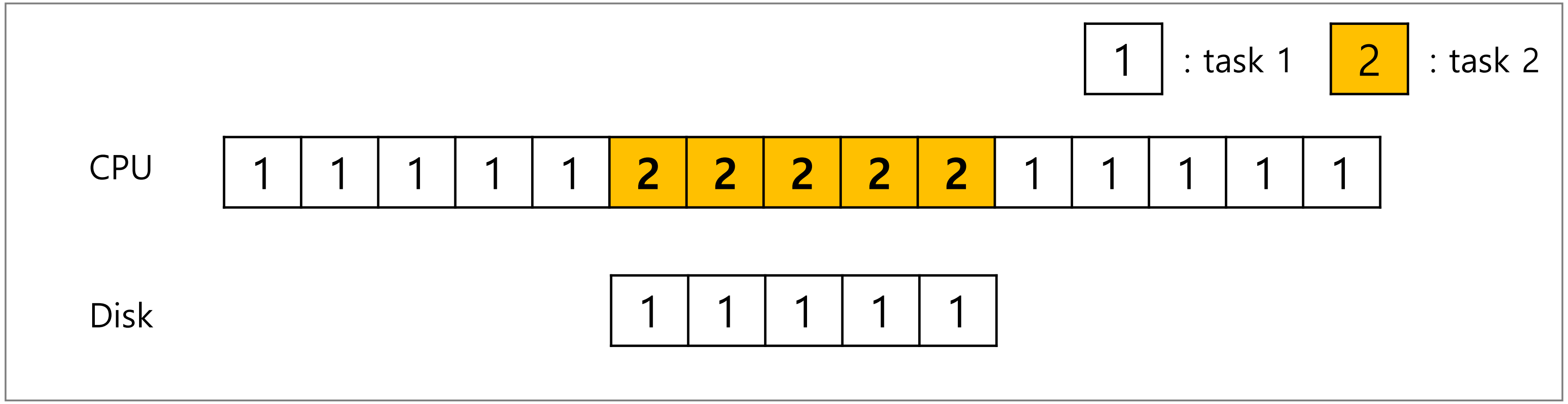


Diagram of CPU utilization by interrupt

Polling vs Interrupts

However, **"interrupts is not always the best solution"**

- If, device performs very quickly, interrupt will "slow down" the system.

E.g., high network packet arrival rate

- Packets can arrive faster than OS can process them
- Interrupts are very expensive (context switch)
- Interrupt handlers have high priority
- In worst case, can spend 100% of time in interrupt handler and never make any progress – *receive livelock*
- Best: Adaptive switching between interrupts and polling

If a device is fast → poll is best.
If it is slow → interrupt is better.

Protocol Variants

Device Registers: Status Command Data

Micro-controller (CPU)
Memory (DRAM or SRAM or both)
Other Hardware-specific Chips

Status checks: *polling* vs. *interrupts*

Data: *programmed I/O* (PIO) vs. *direct memory access* (DMA)

Control: *special instructions* vs. *memory-mapped I/O*

Variety Is a Challenge

Problem:

- many, many devices
- each has its own protocol

How can we avoid writing a slightly different OS for each H/W?

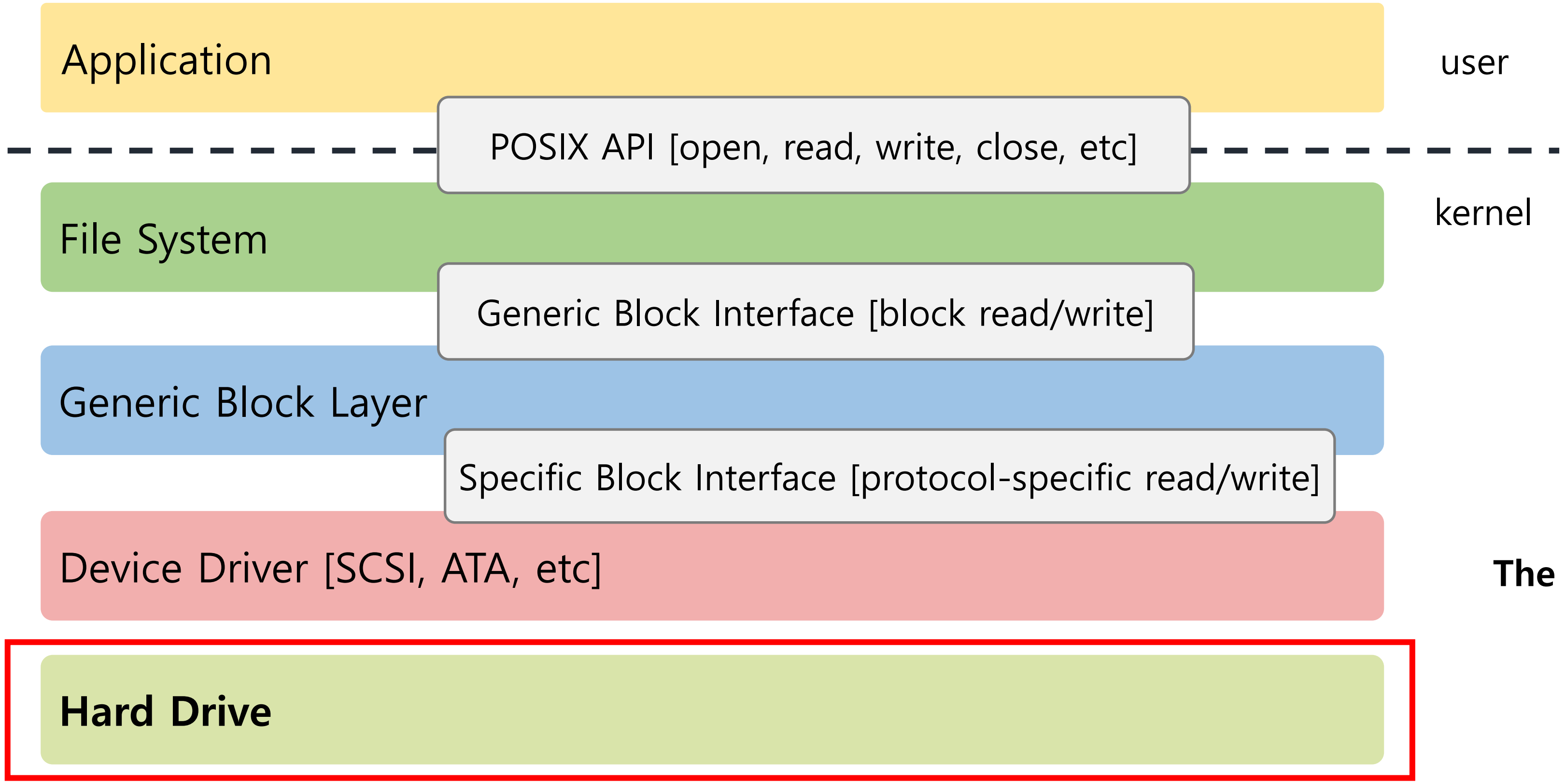
Solution: Abstraction!

- Build a common interface
- Write device driver for each device
- Drivers are 70% of Linux source code

File System Abstraction

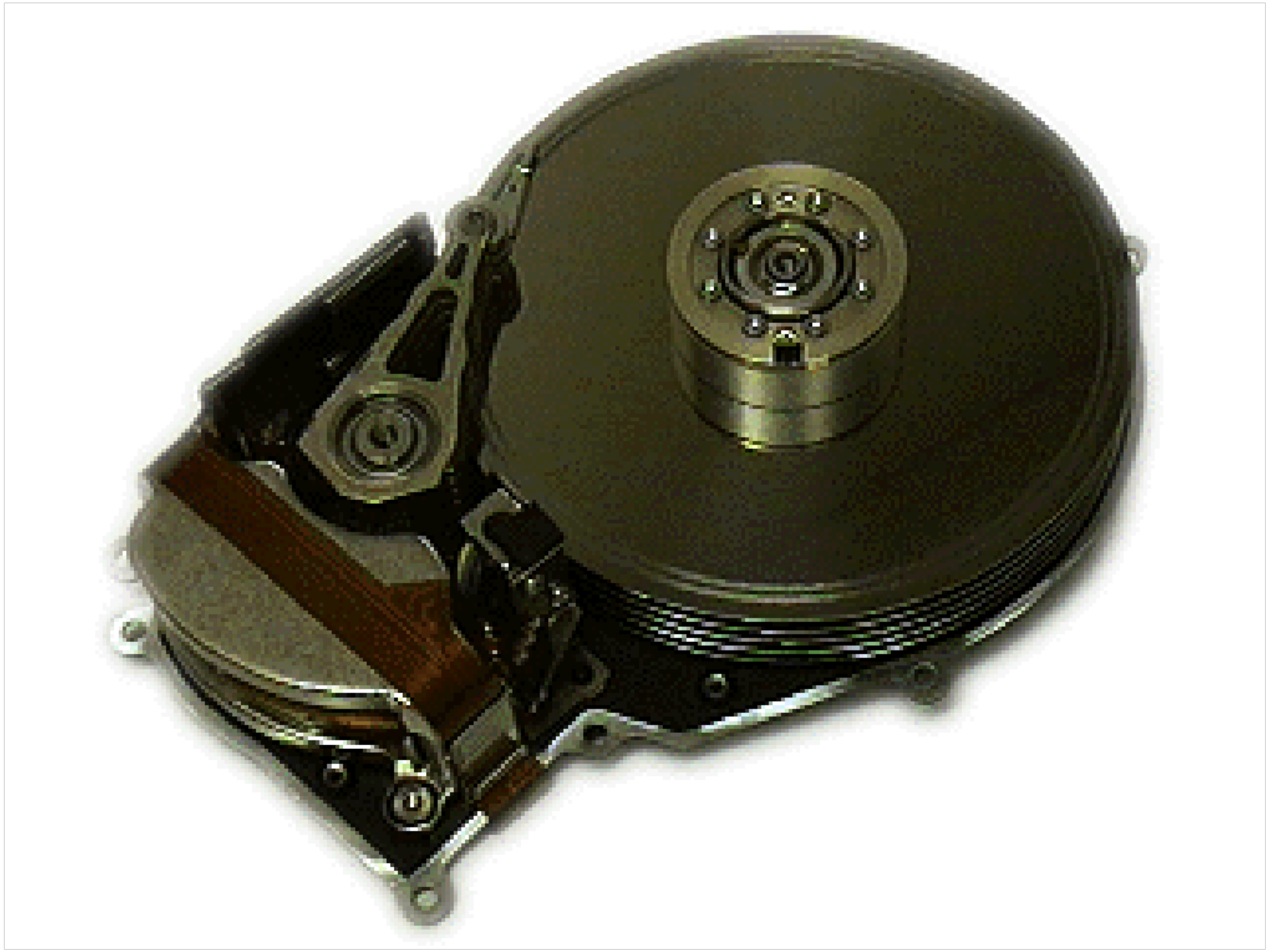
File system specifics of which disk class it is using.

- Ex) It issues **block read** and **write** request to the generic block layer.

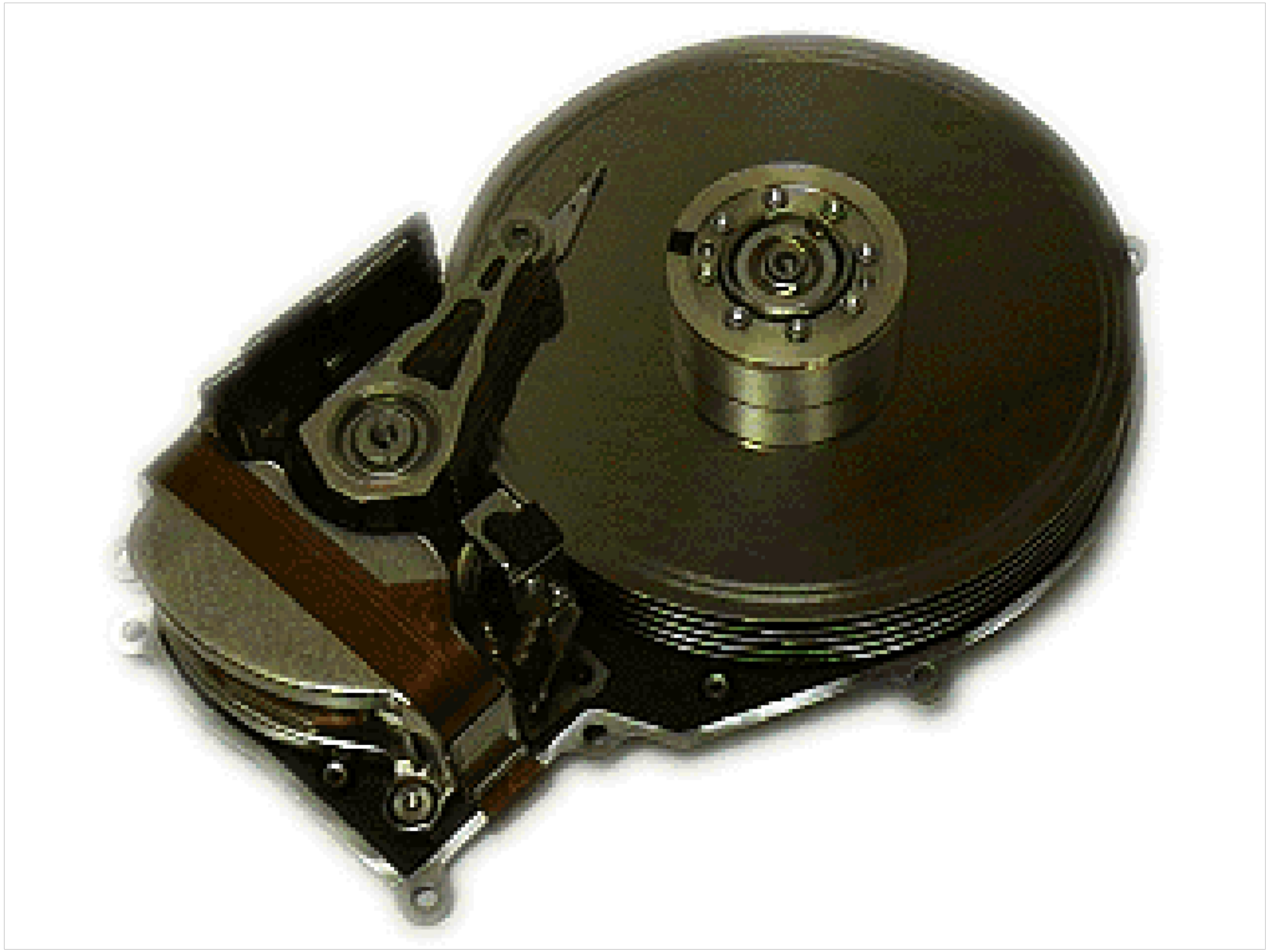


The File System Stack

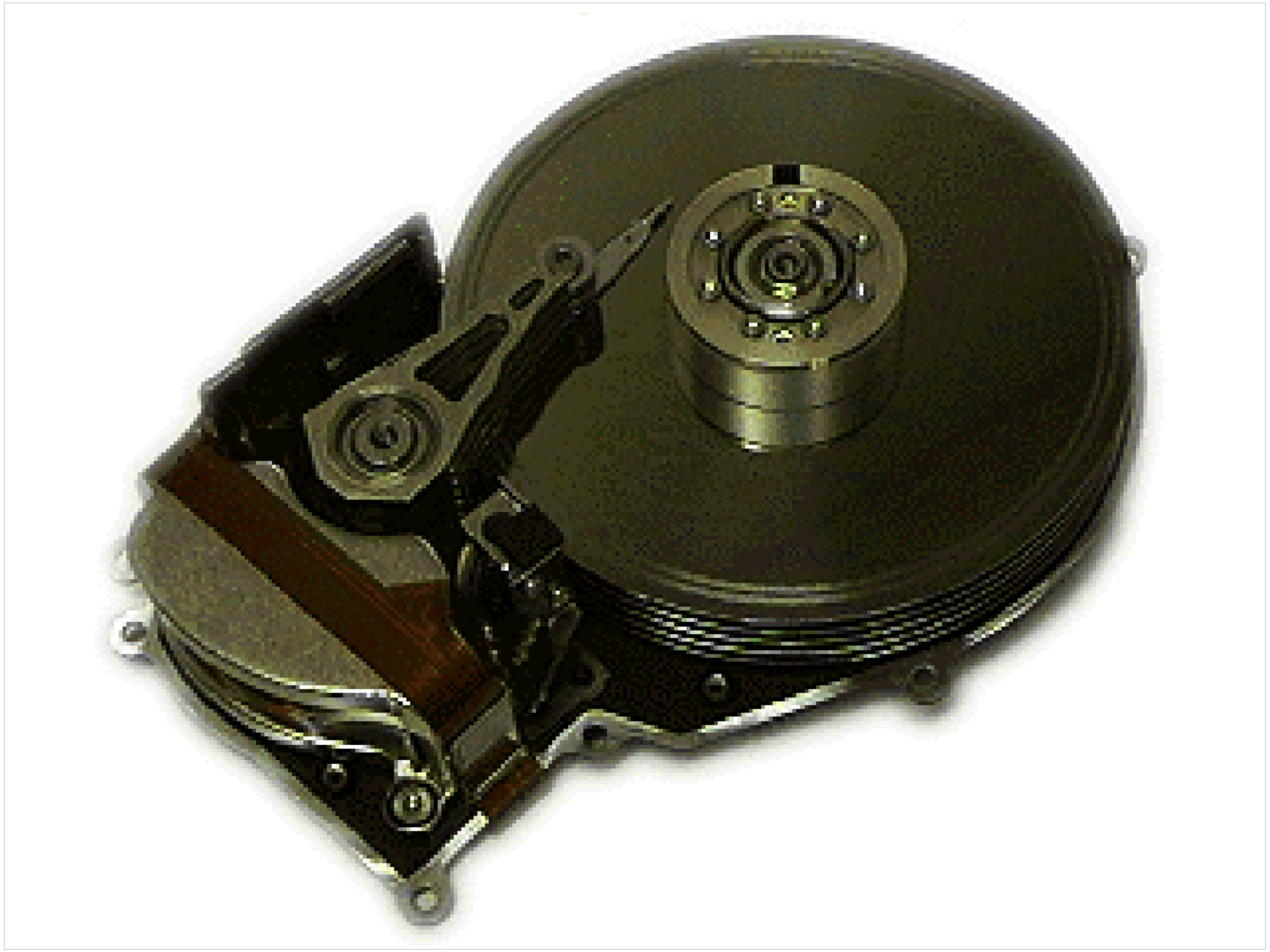
Hard Disks



Hard Disks



Hard Disks



Basic Interface

Disk interface presents linear array of sectors

- Historically 512 Bytes
- Written atomically (even if there is a power failure)
- 4 KiB in “advanced format” disks
    - Torn write: If an untimely power loss occurs, only a portion of a larger write may complete

Disk maps logical sector #s to physical sectors

OS doesn’t know logical to physical sector mapping

Basic Geometry

Platter (Aluminum coated with a thin magnetic layer)

- A circular hard surface
- Data is stored persistently by inducing magnetic changes to it.
- Each platter has 2 sides, each of which is called a **surface**.

Basic Geometry (Cont.)

Spindle

- Spindle is connected to a motor that spins the platters around.
- The rate of rotations is measured in **RPM** (Rotations Per Minute).
  - Typical modern values : 7,200 RPM to 15,000 RPM.

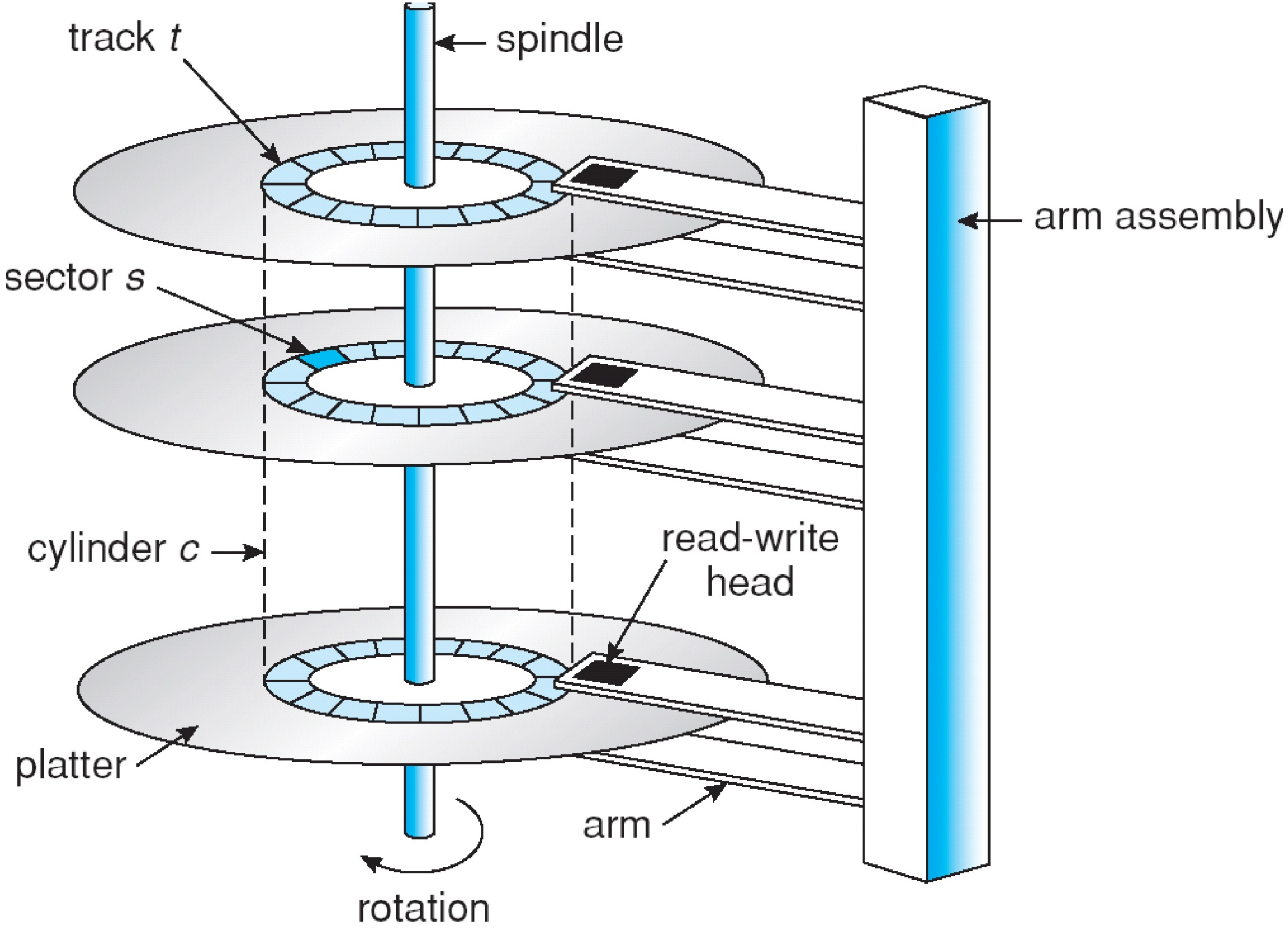
Track

- Concentric circles of sectors
- Data is encoded on each surface in a track.
- A single surface contains many thousands and thousands of tracks.

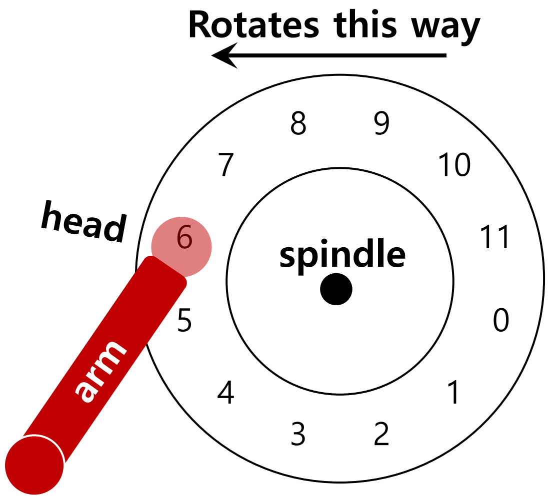
Cylinder

- A stack of tracks of fixed radius
- Heads record and sense data along cylinders
- Generally only one head active at a time

Cylinders, Tracks, & Sectors



A Simple Disk Drive

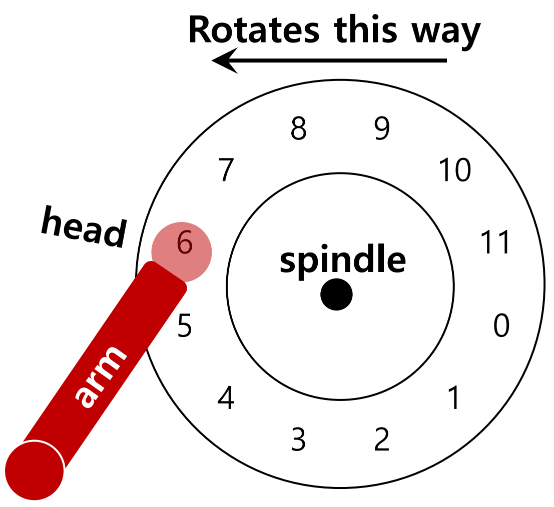


A Single Track Plus A Head

Disk head (One head per surface of the drive)

- The process of *reading* and *writing* is accomplished by the **disk head**.
- Attached to a single disk arm, which moves across the surface.

Single-track Latency: The Rotational Delay



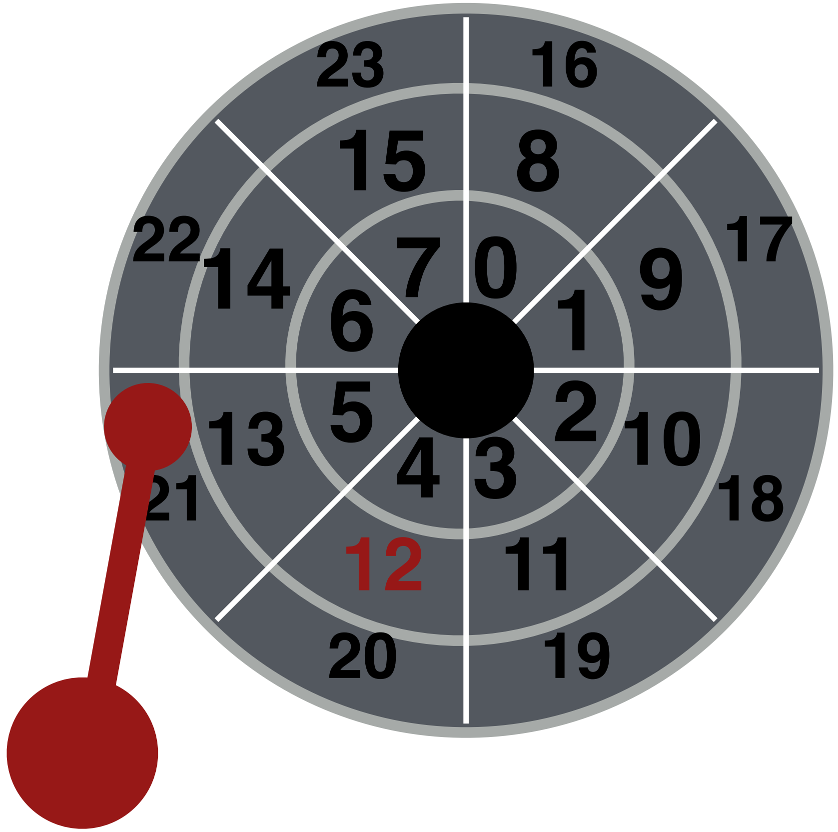
A Single Track Plus A Head

Rotational delay: Time for the desired sector to rotate

- Ex) Full rotational delay is `R` and we start at `sector 6`
  - Read sector 0: Rotational delay = $\frac{R}{2}$
  - Read sector 5: Rotational delay = `R-1` (worst case.)

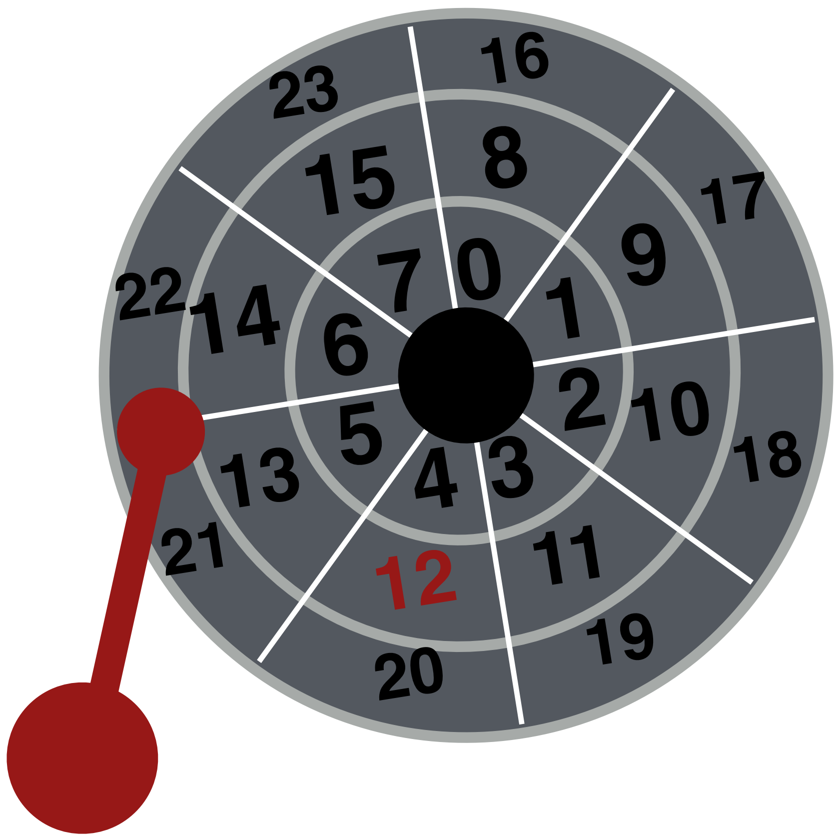
Multiple Tracks

Let's Read 12!



Multiple Tracks: Seek To Right Track

Let's Read 12!



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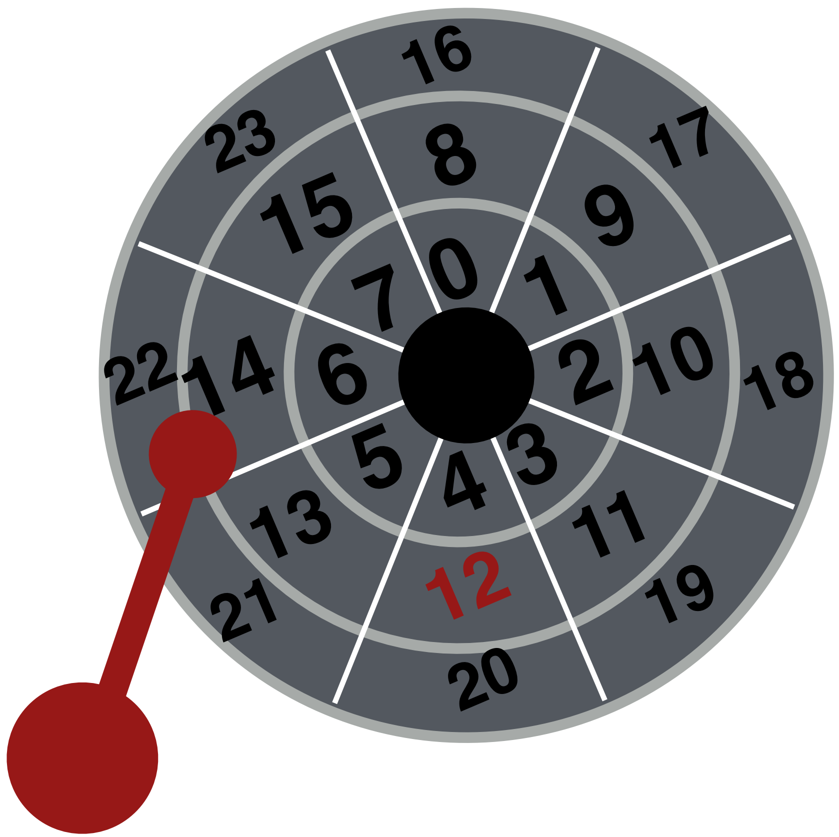

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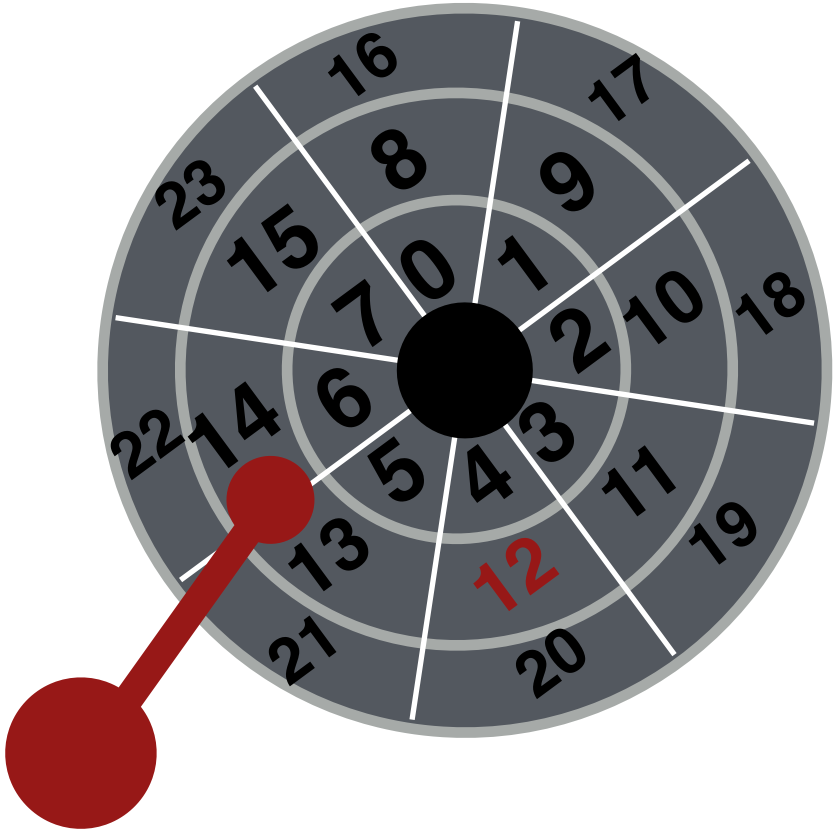
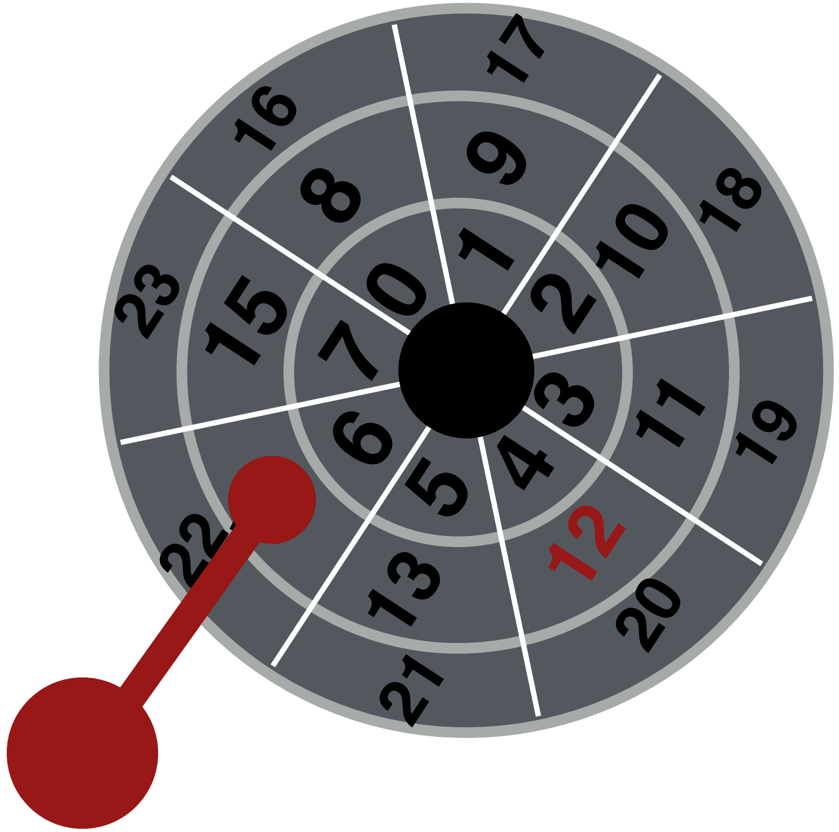


Multiple Tracks: Wait for Rotation

Let's Read 12!



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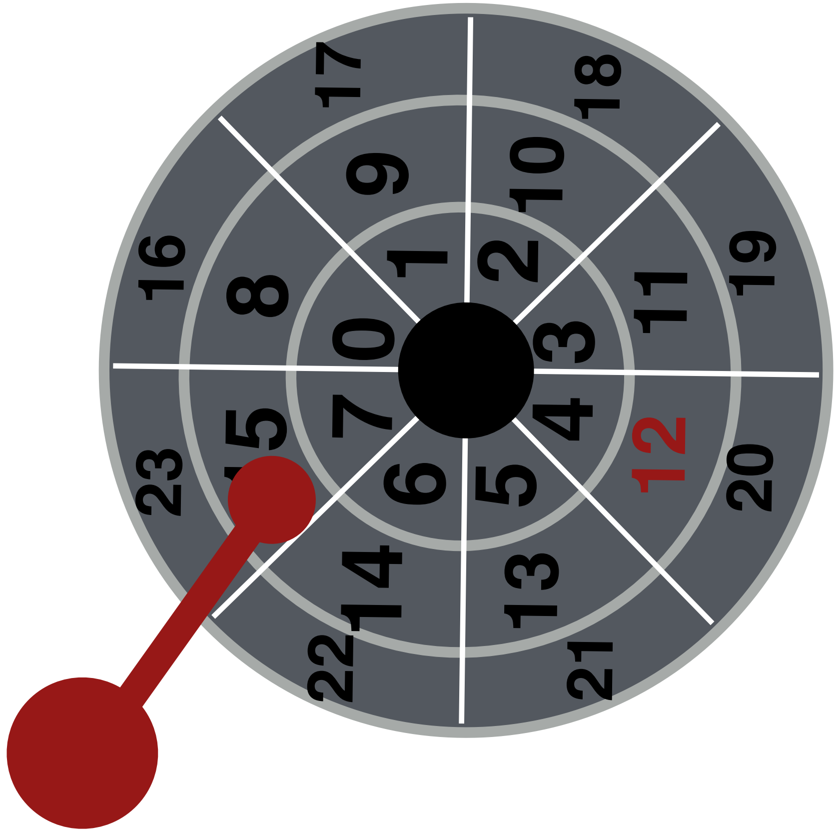

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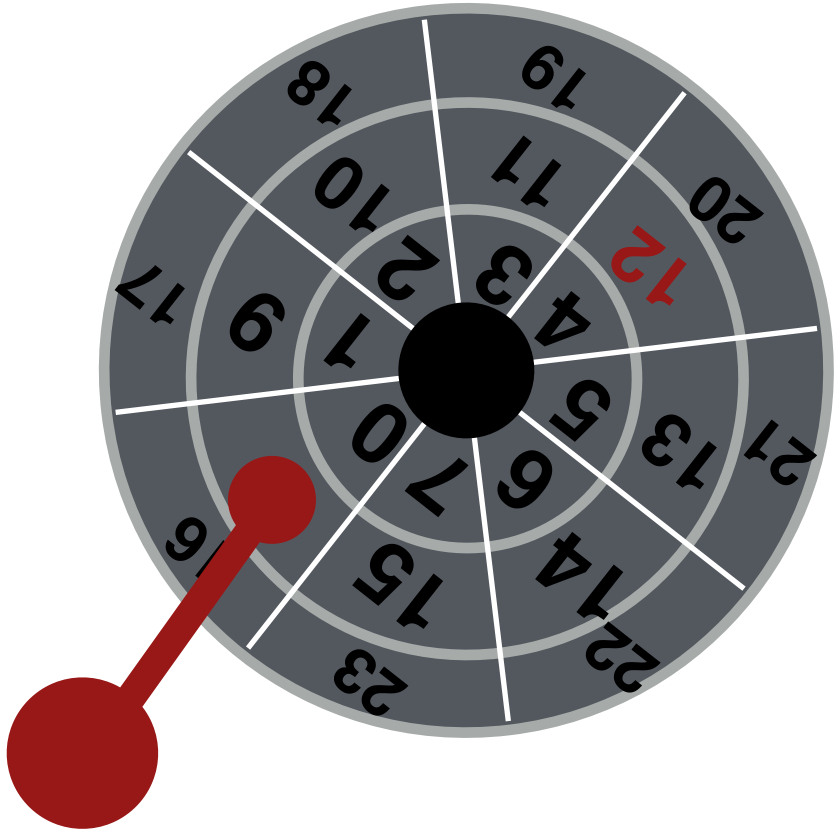

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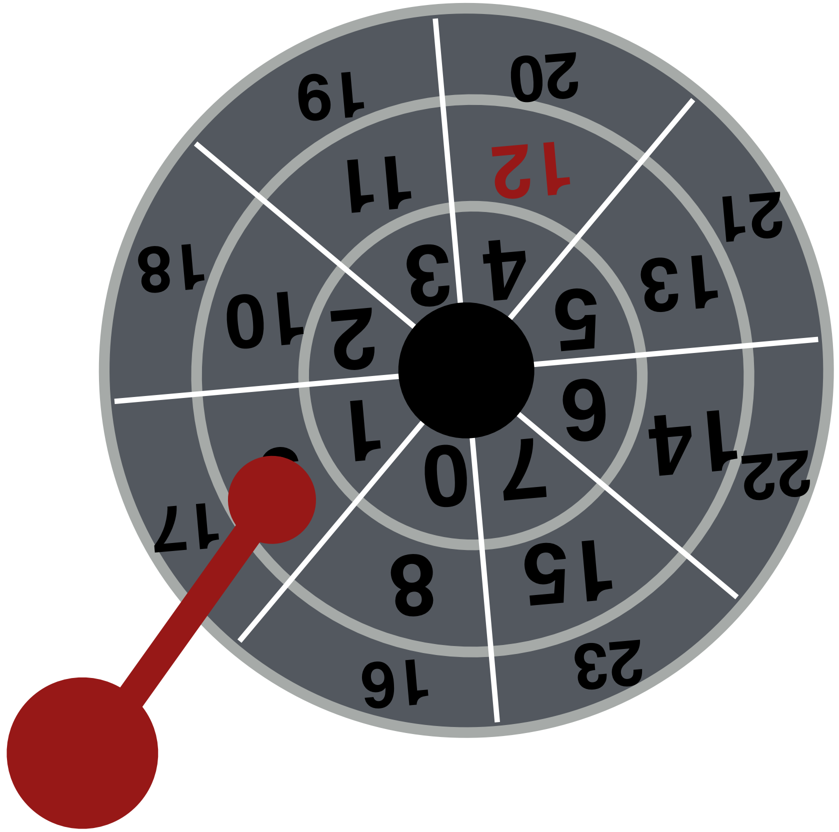

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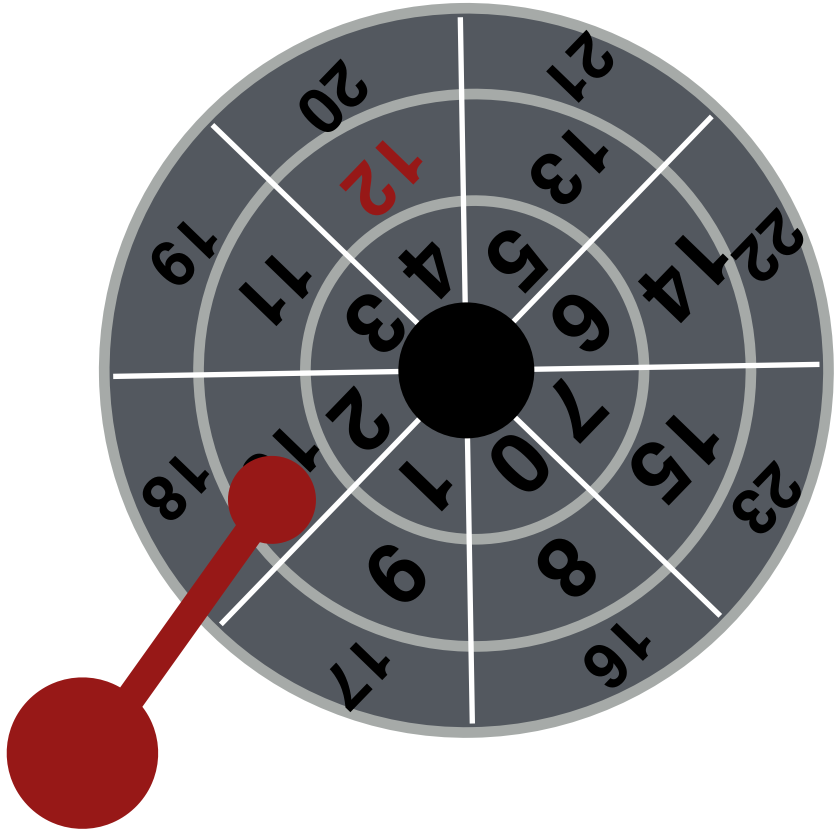
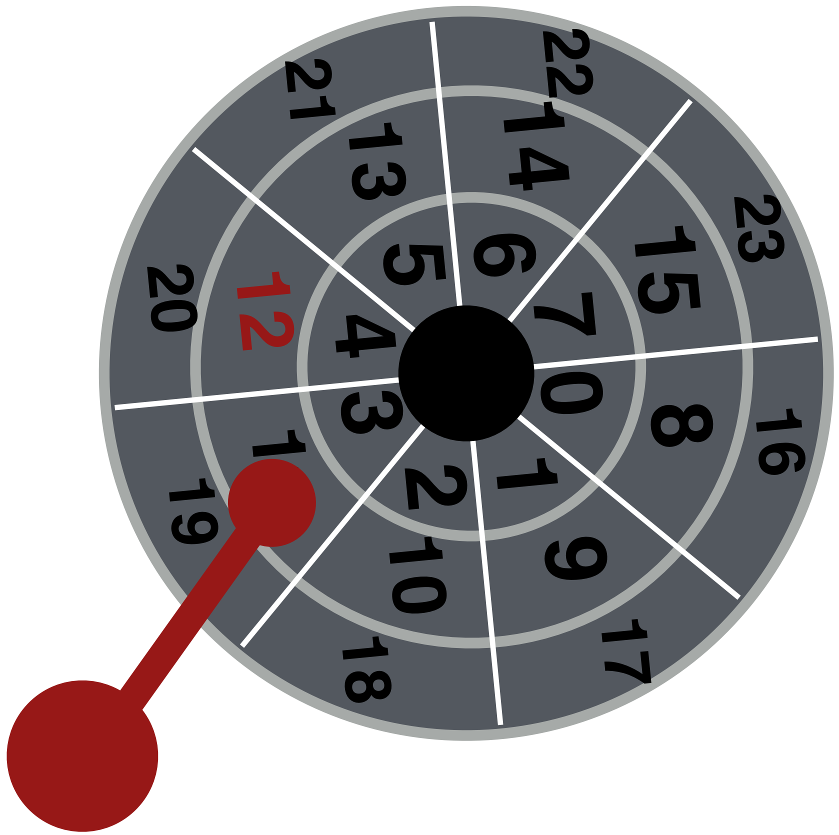


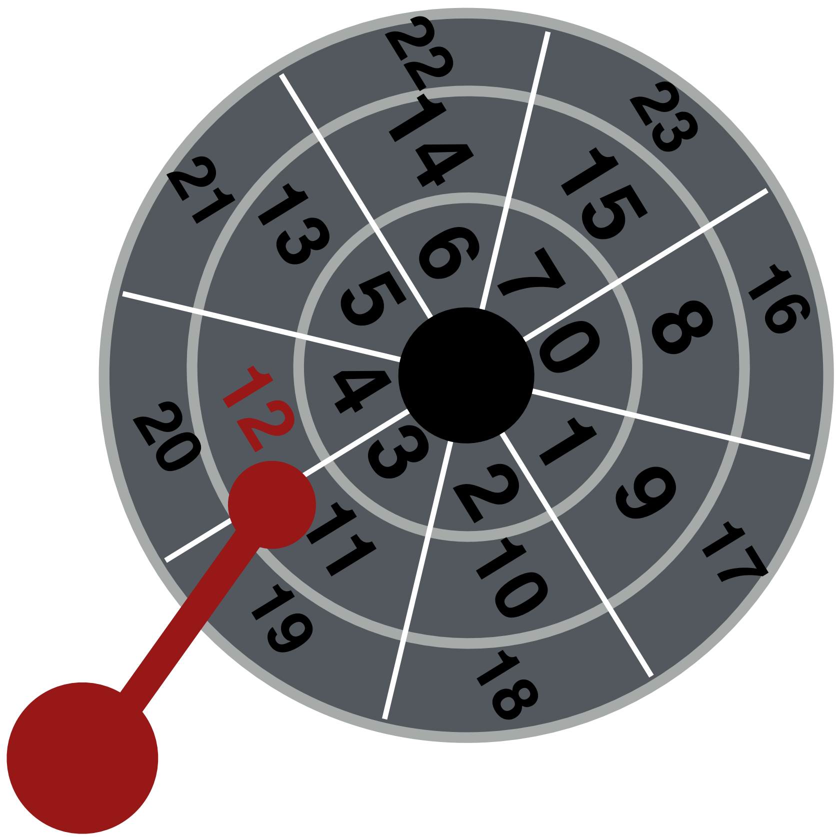
Multiple Tracks: Wait for Rotation

Let's Read 12!



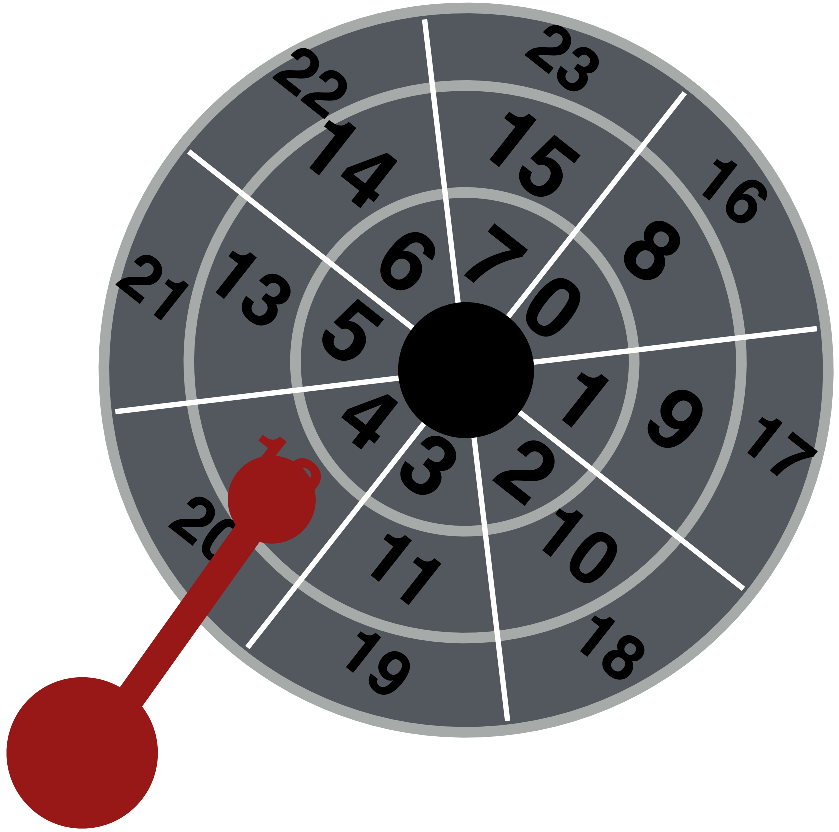
Multiple Tracks: Transfer Data

Let's Read 12!



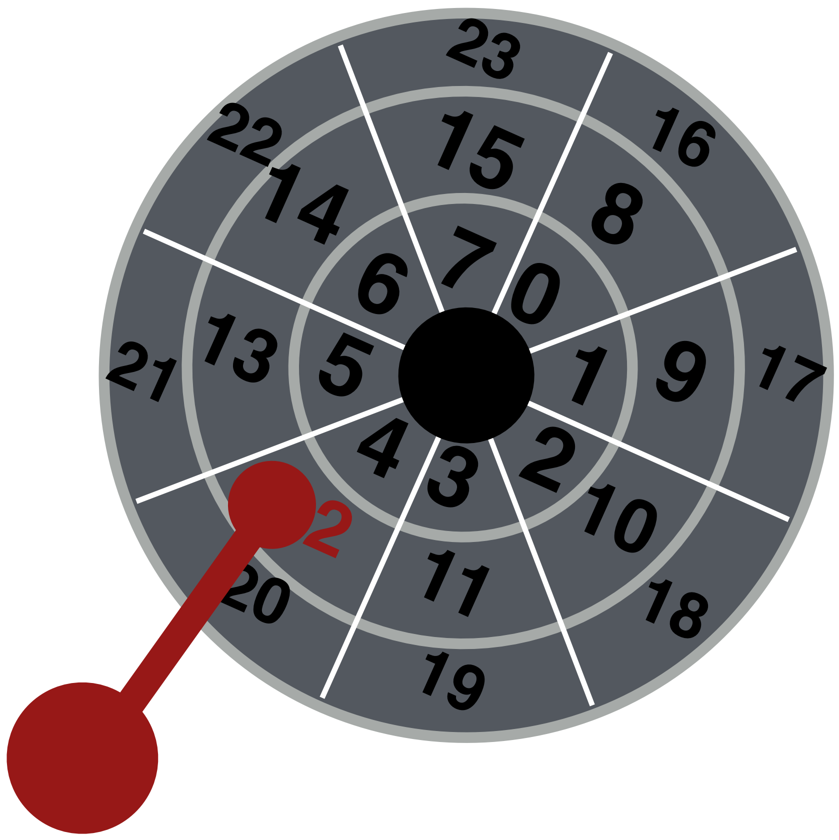
Multiple Tracks: Transfer Data

Let's Read 12!

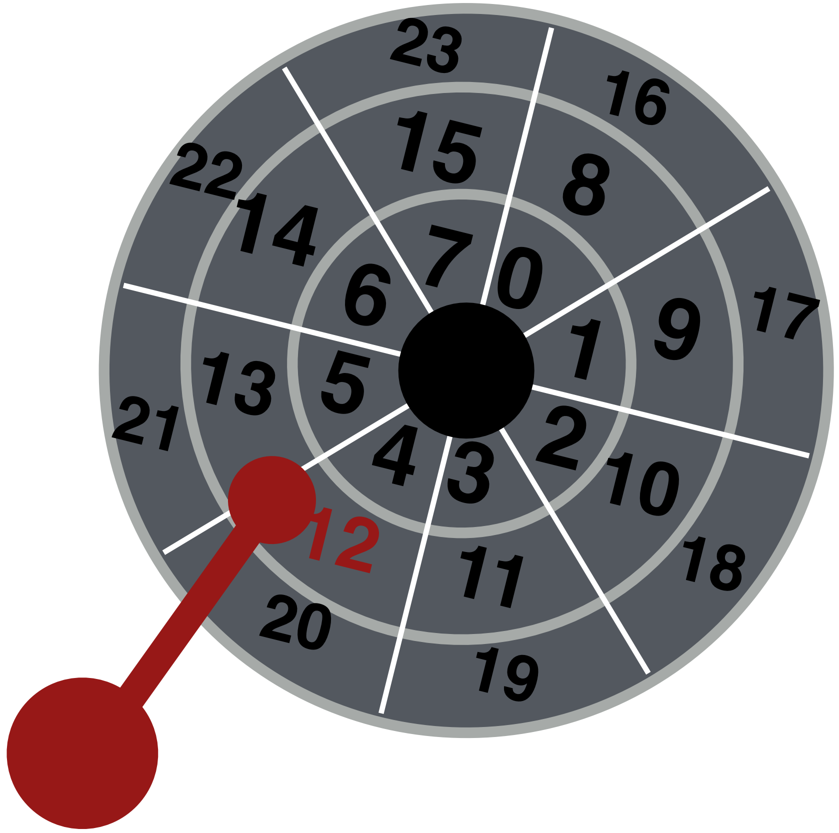


Multiple Tracks: Transfer Data

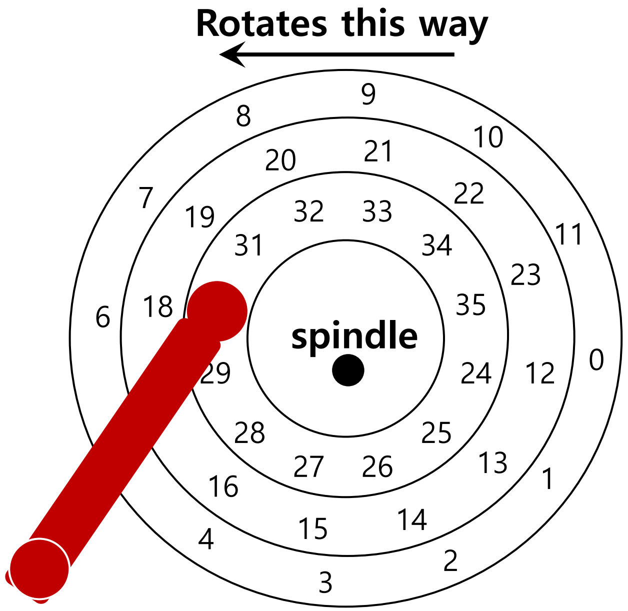
Let's Read 12!

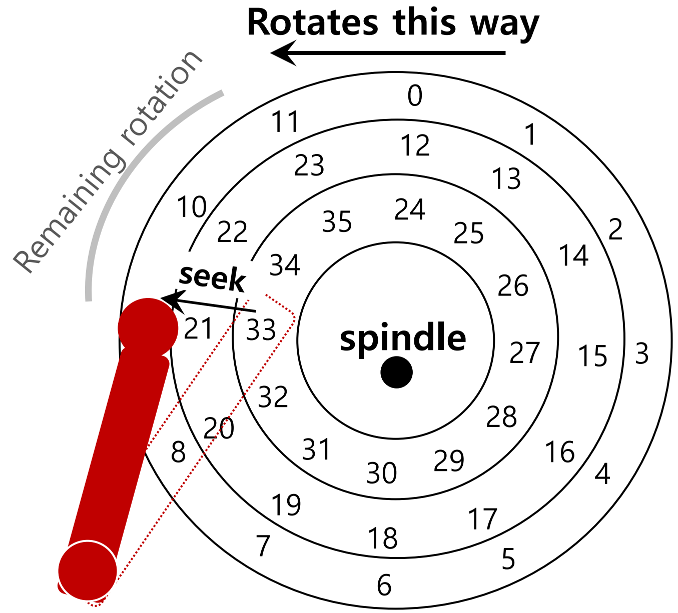


Yay!



Multiple Tracks: Seek Time





Seek: Move the disk arm to the correct track

- **Seek time**: Time to move head to the track contain the desired sector.
- One of the most costly disk operations.

Seek, Rotate, Transfer

Acceleration → Coasting → Deceleration → Settling

- **Acceleration**: The disk arm gets moving.
- **Coasting**: The arm is moving at full speed.
- **Deceleration**: The arm slows down.
- **Settling**: The head is *carefully positioned* over the correct track.

Seeks often take several milliseconds!

- settling alone can take 0.5 to 2ms.
- entire seek often takes 4 - 10 ms.

Seek, Rotate, Transfer

Depends on rotations per minute (RPM)

- 7200 RPM is common, 15000 RPM is high-end.

With 7200 RPM, how long to rotate around?

- 1 / 7200 RPM = 1 minute / 7200 rotations = 1 second / 120 rotations = 8.3 ms / rotation

Average rotation?

- 8.3 ms / 2 = 4.15 ms

Seek, Rotate, Transfer

The final phase of I/O

- Data is either *read from* or *written* to the surface.

Pretty fast — depends on RPM and sector density

100+ MB/s is typical for maximum transfer rate

How long to transfer 512-bytes?

- 512 bytes * (1s / 100 MB) = 5 μs

Workload

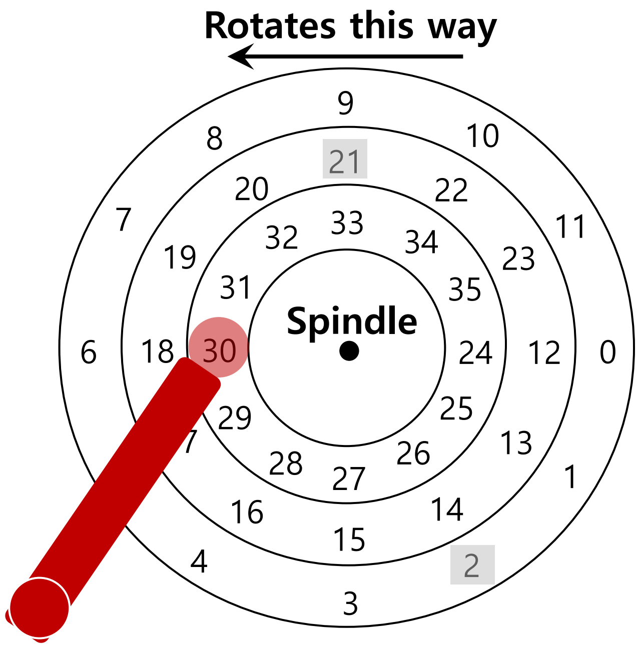
So…

- seeks are slow
- rotations are slow
- transfers are fast

What kind of workload is fastest for disks?

- **Sequential**: access sectors in order (transfer dominated)
- **Random**: access sectors arbitrarily (seek+rotation dominated)

Disk Scheduling



Disk Scheduler decides which I/O request to schedule next

Disk Scheduling: FCFS

"First Come First Served"

- Process disk requests in the order they are received

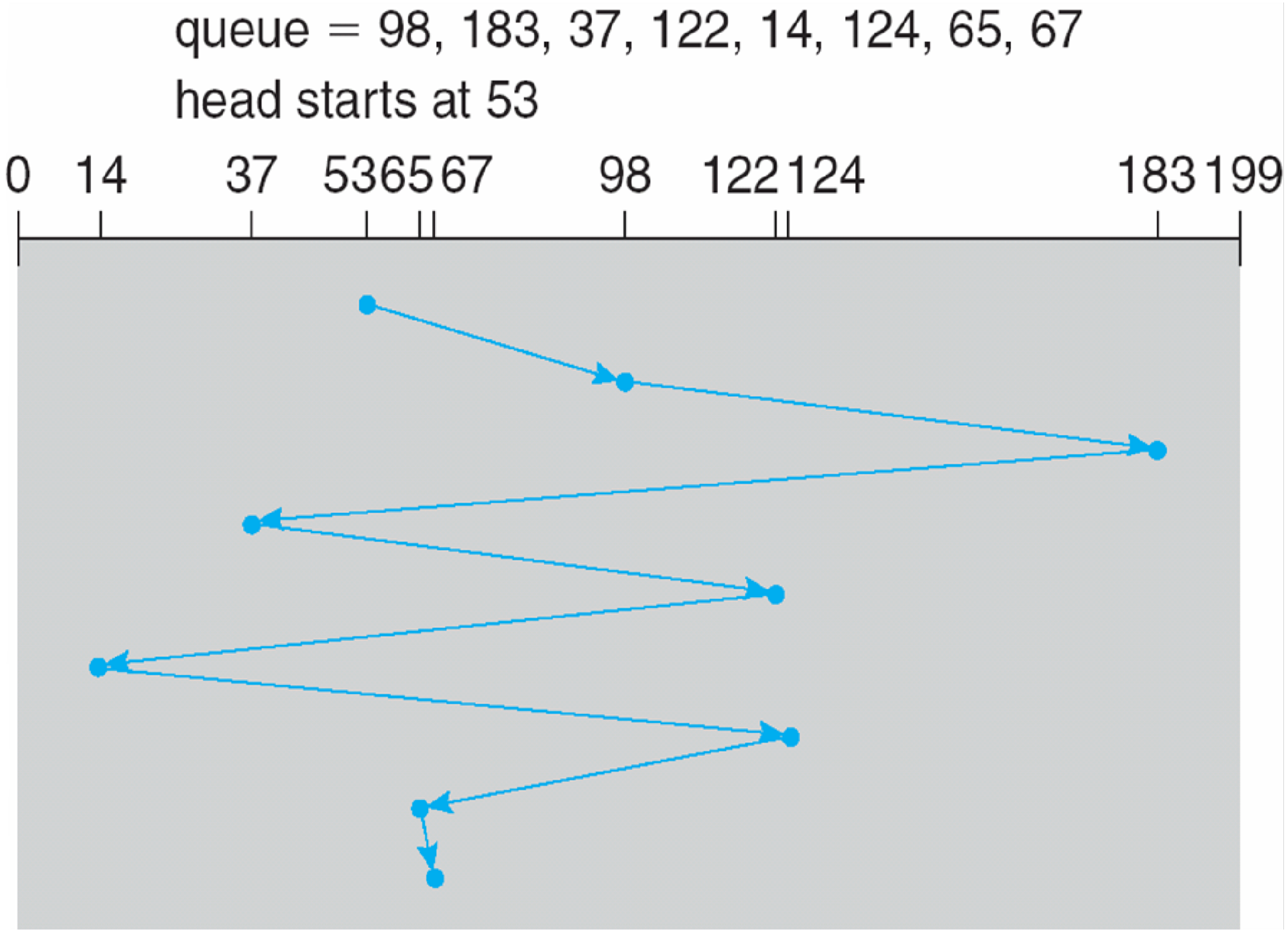
Advantages

- Easy to implement
- Good fairness

Disadvantages

- Cannot exploit request locality
- Increases average latency, decreasing throughput

FCFS Example



SSTF (Shortest Seek Time First)

Order the queue of I/O request by track

Pick requests on the nearest track to complete first

- Also called shortest positioning time first (SPTF)

Advantages

- Exploits locality of disk requests
- Higher throughput

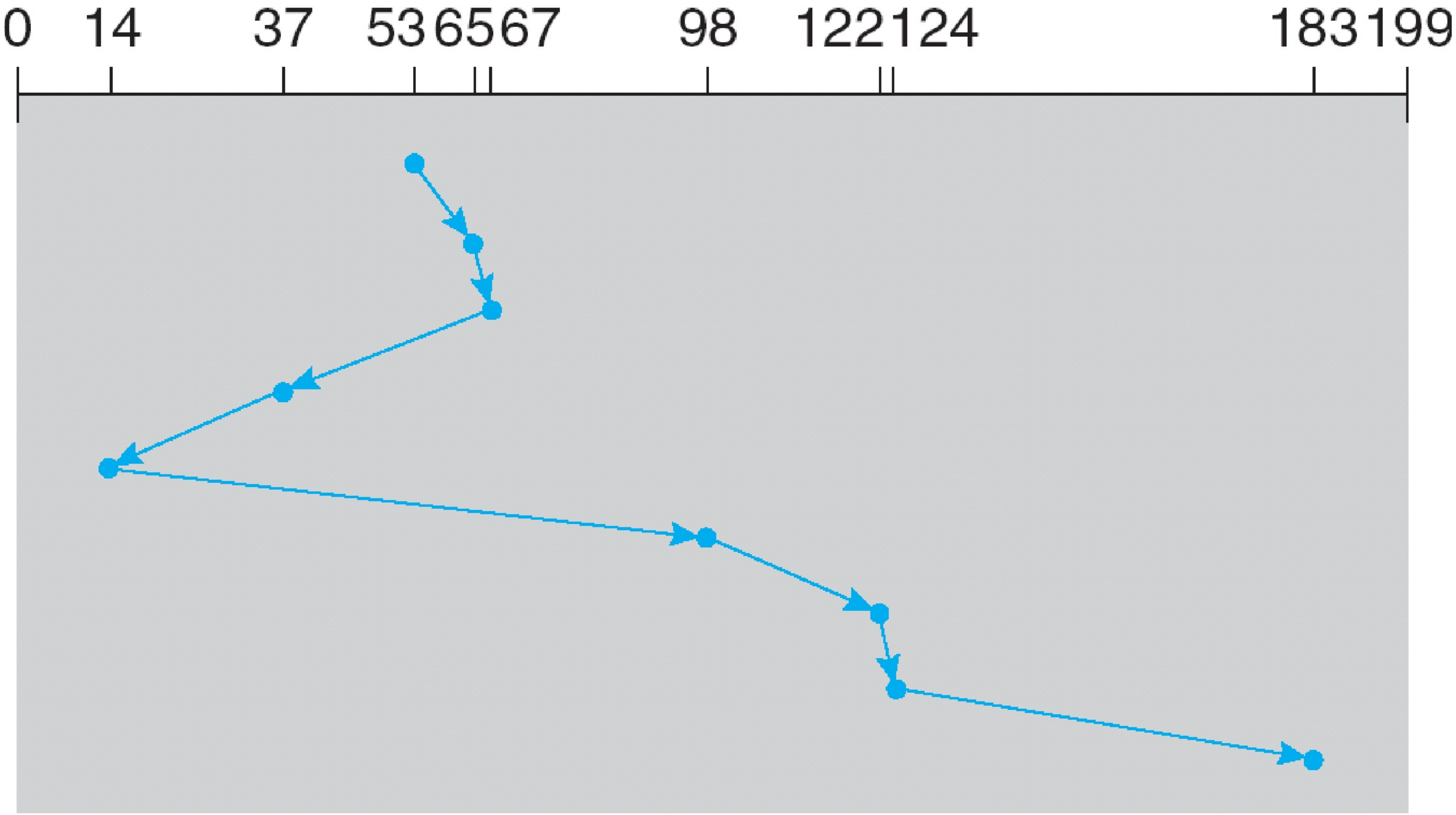
Disadvantages

- Starvation
- Don't always know what request will be fastest

SSTF Example

queue = 98, 183, 37, 122, 14, 124, 65, 67

head starts at 53



“Elevator” Scheduling (SCAN)

Sweep across disk, servicing all requests passed

- Like SSTF, but next seek must be in same direction
- Switch directions only if no further requests

Advantages

- Takes advantage of locality
- Bounded waiting

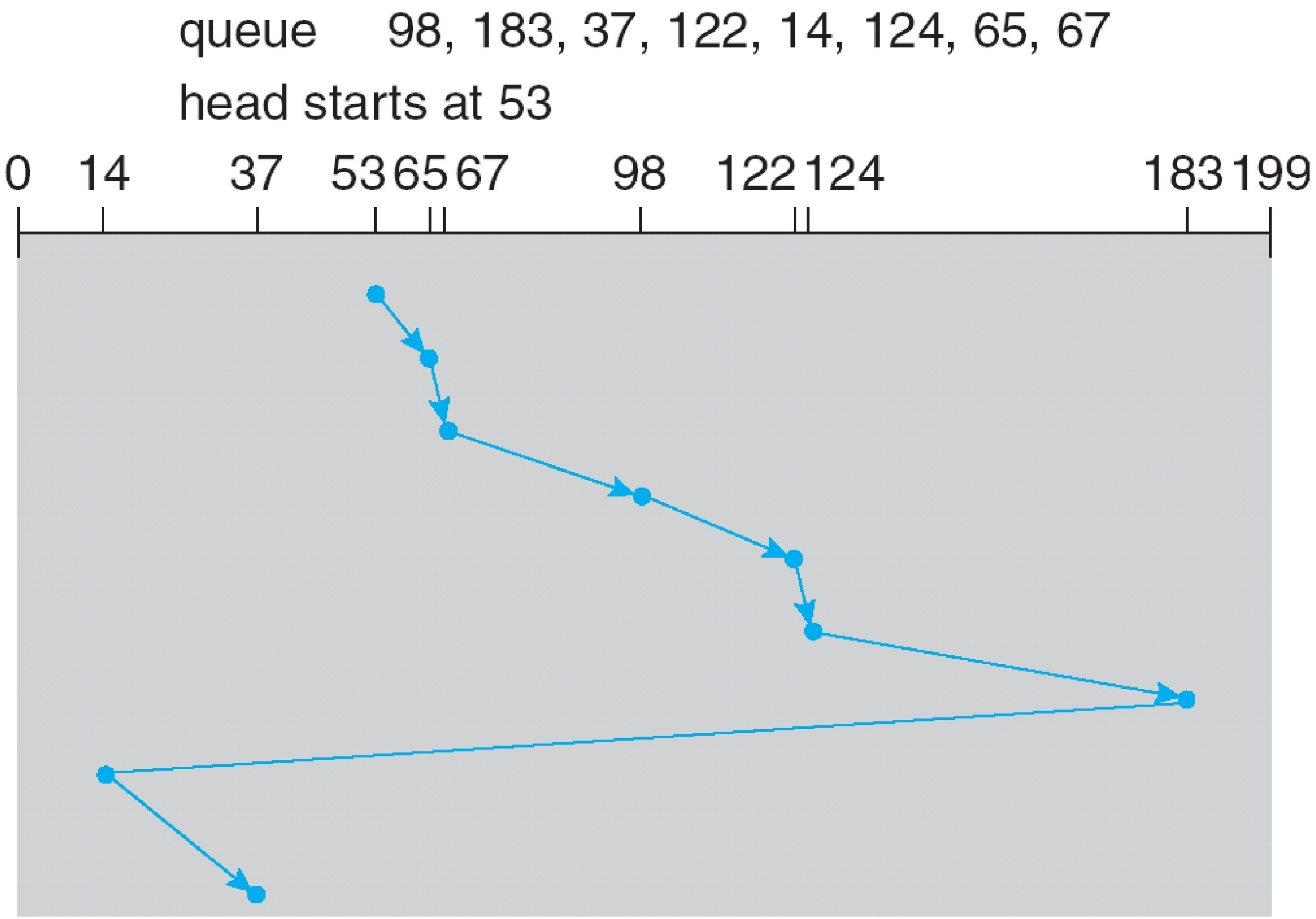
Disadvantages

- Cylinders in the middle get better service
- Might miss locality SSTF could exploit

CSCAN: Only sweep in one direction

- **Very commonly used algorithm in Unix**

CSCAN example



Flash Memory

Today, people increasingly using flash memory

Completely solid state (no moving parts)

- Remembers data by storing charge
- Lower power consumption and heat
- No mechanical seek times to worry about

Limited # overwrites possible

- Blocks wear out after 10,000 (MLC) – 100,000 (SLC) erases
- Requires flash translation layer (FTL) to provide wear leveling, so repeated writes to logical block don't wear out physical block
- FTL can seriously impact performance

Limited durability

- Charge wears out over time
- Turn off device for a year, you can potentially lose data!

Next Time…

Read Chapter 39, 40