CE 440 Introduction to Operating System

Lecture 15: I/O & Disks
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Prof. Yigong Hu

BOSTON UNIVERSITY

Slides courtesy of Manuel Egele, Ryan Huang and Baris Kasikci

Overview

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

Virtualization	Concurrency	Persistence
Processes	Threads	I/O
Scheduling	Synchronization	Disks
Virtual Memory	Semaphores and Monitors	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



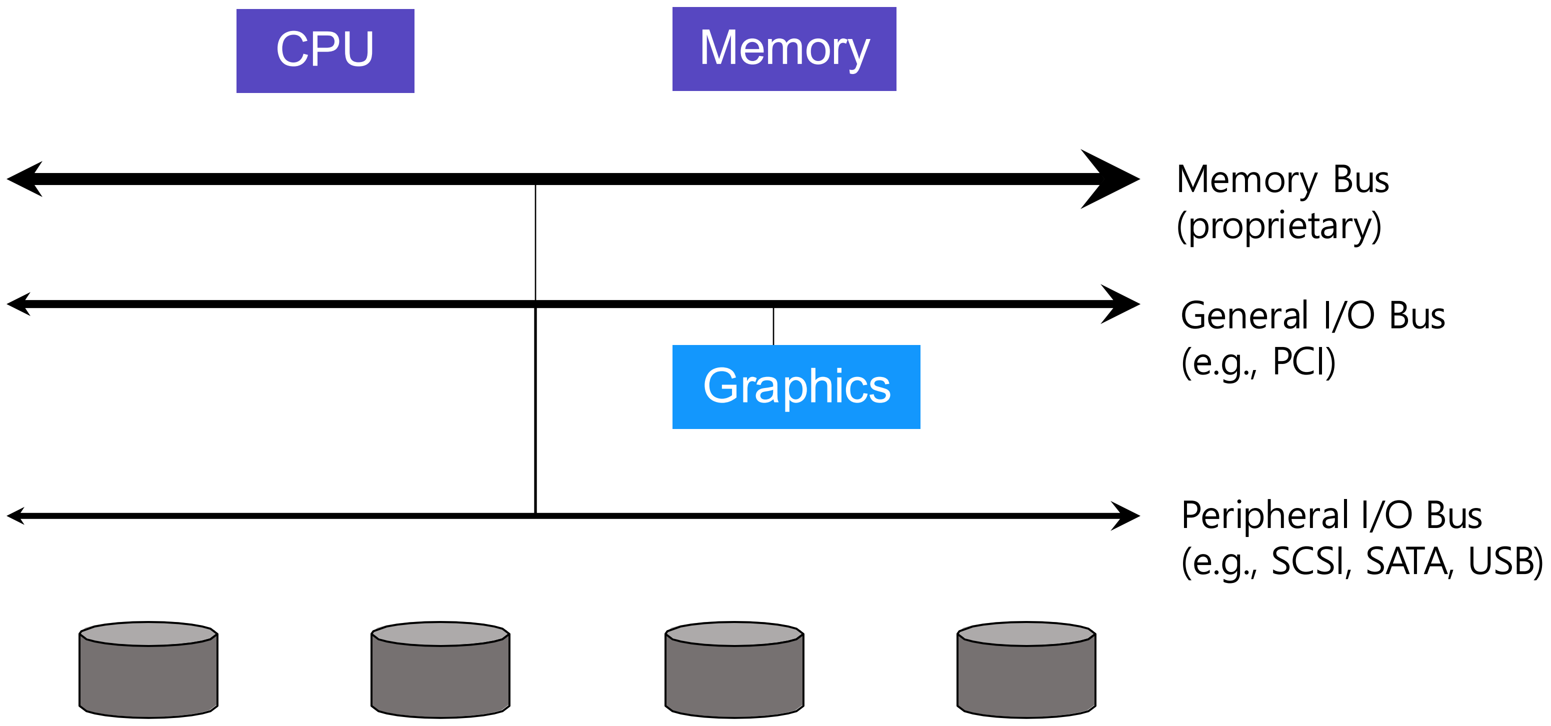



...

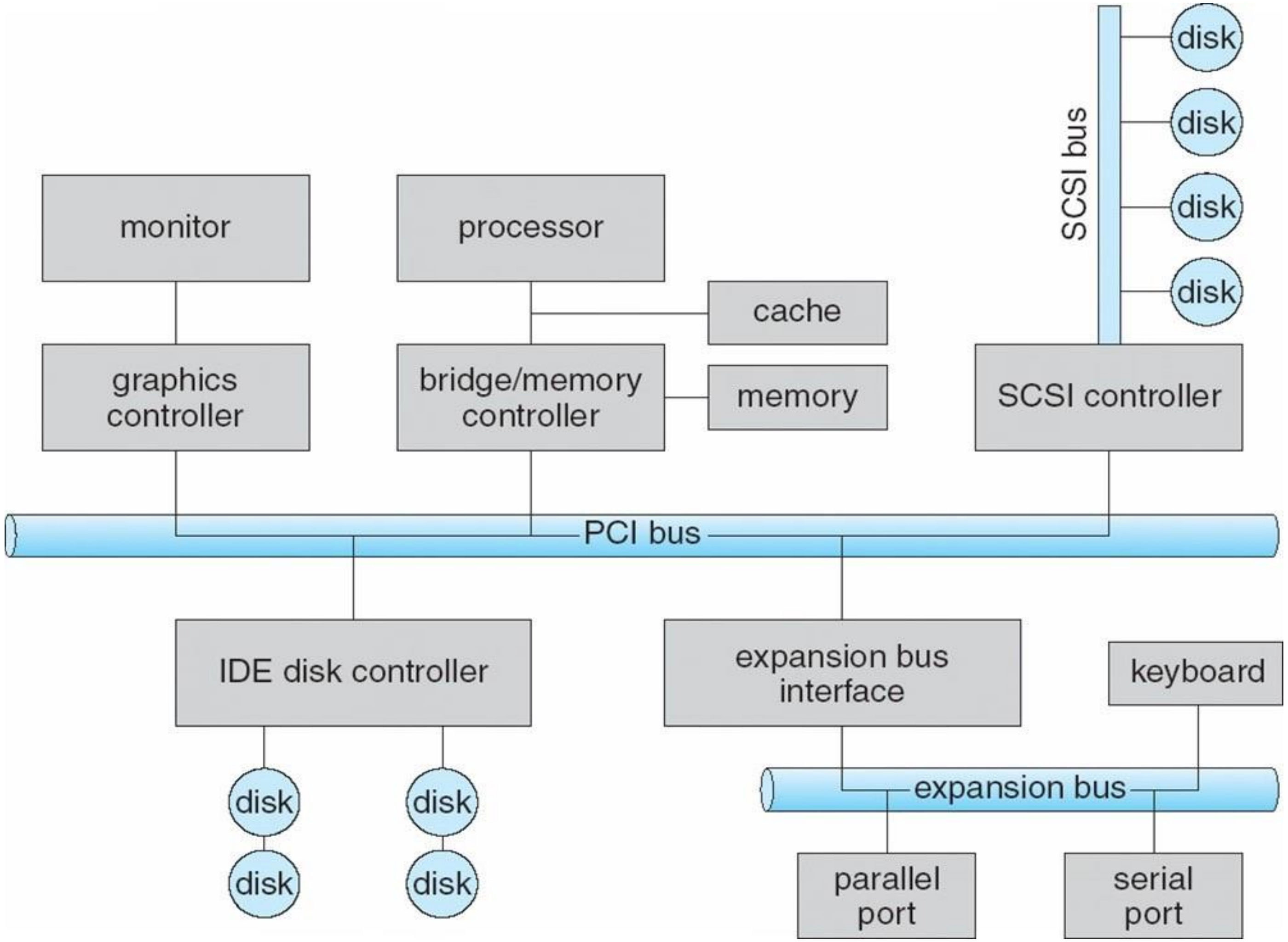
Issues to address:

- 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

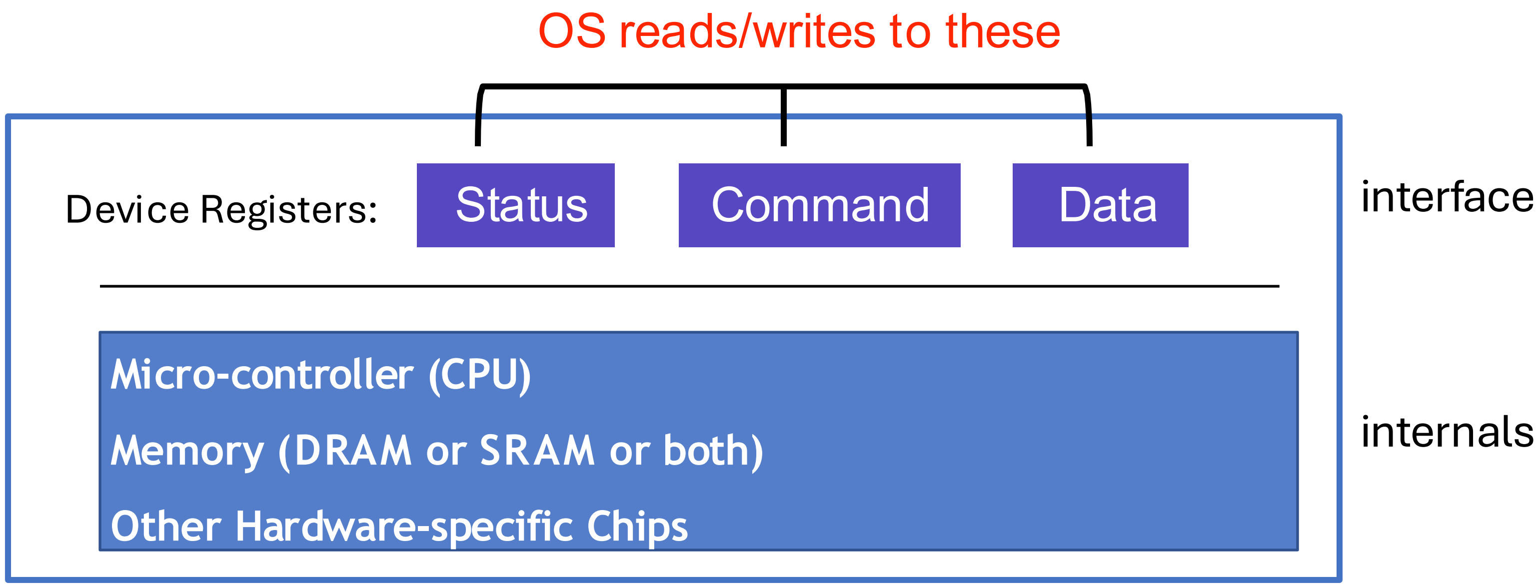


Structure of I/O Device



Device Interaction

How does the OS communicate with an I/O device?



Canonical I/O 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
```

Programming a device

One approach: I/O instructions

- `in` and `out` instructions on x86
- Devices usually have registers
  - places commands, addresses, and data there to read/write registers
- How to identify (address) a device?
  - With a port location (I/O address range)

Typical Device I/O Port Locations

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 instruction

```
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`

IDE Disk Driver

```c
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
}
```

```c
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

Another approach: Memory-mapped I/O

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

```
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

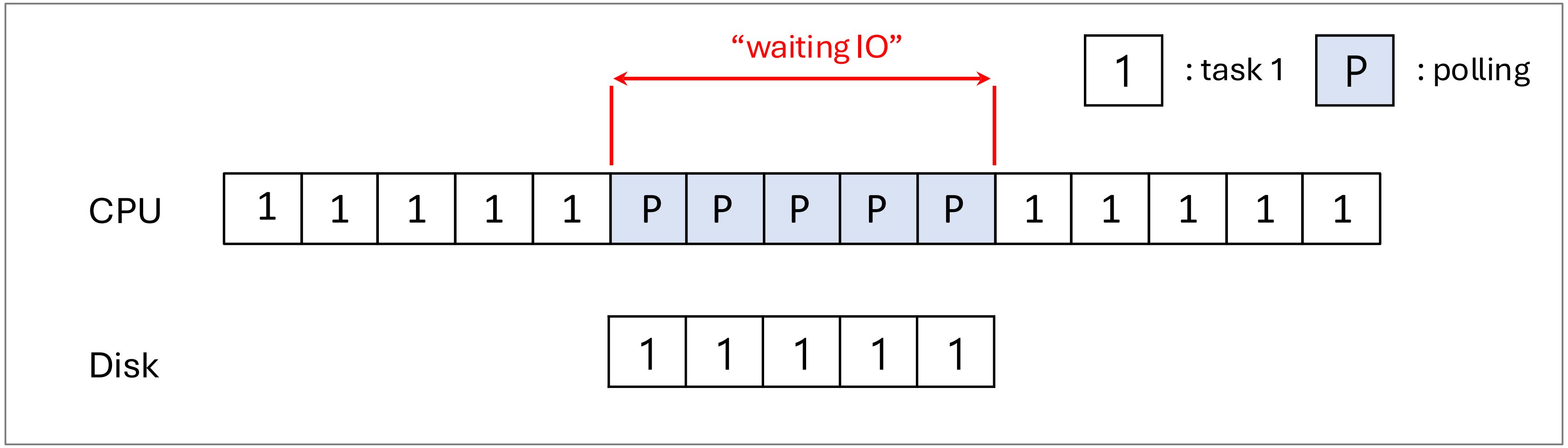


Diagram of CPU utilization by polling

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

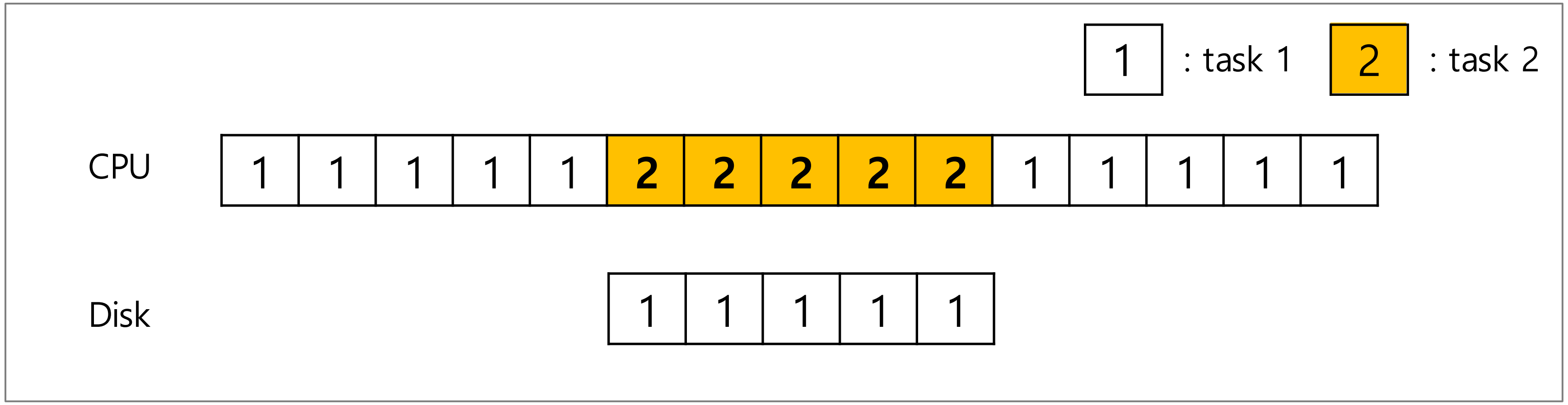


Diagram of CPU utilization by interrupt

Polling vs Interrupts

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

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

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

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

Adaptive switching between interrupts and polling

One More Problem: Data Copying

CPU wastes a lot of time in copying large *data* from memory to a device register one byte a time (termed *programmed I/O, PIO*)

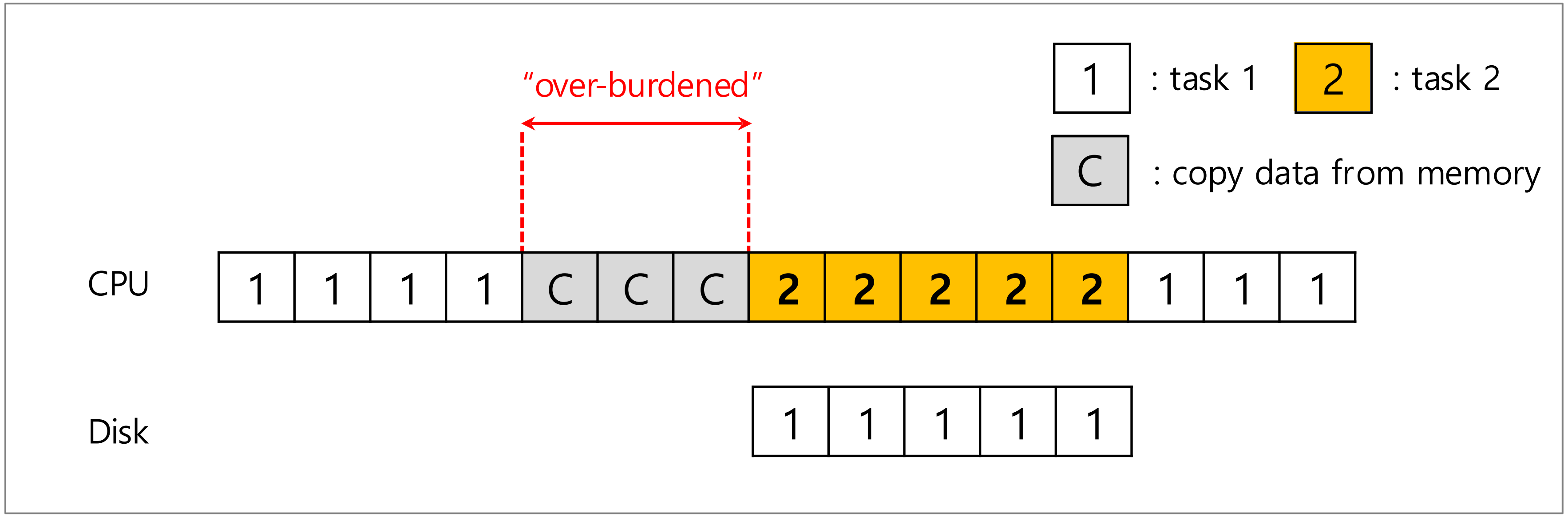
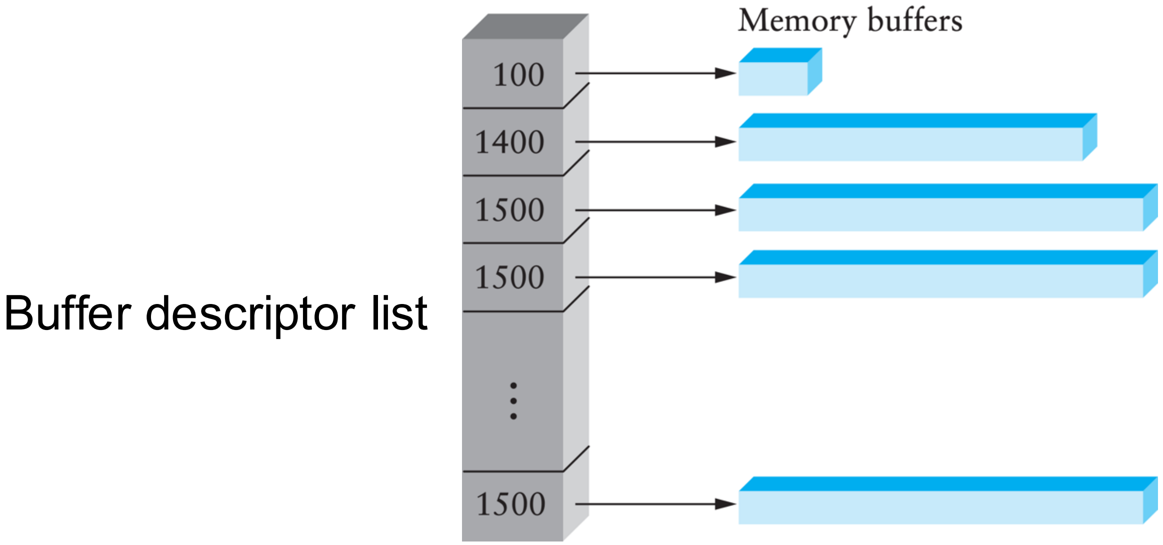


Diagram of CPU utilization

DMA (Direct Memory Access)



Idea: only use CPU to transfer control requests, not data

Include list of buffer locations in main memory

- Device reads list and accesses buffers through DMA

DMA (Direct Memory Access) Cont.

When completed, DMA raises an interrupt, I/O begins on Disk.

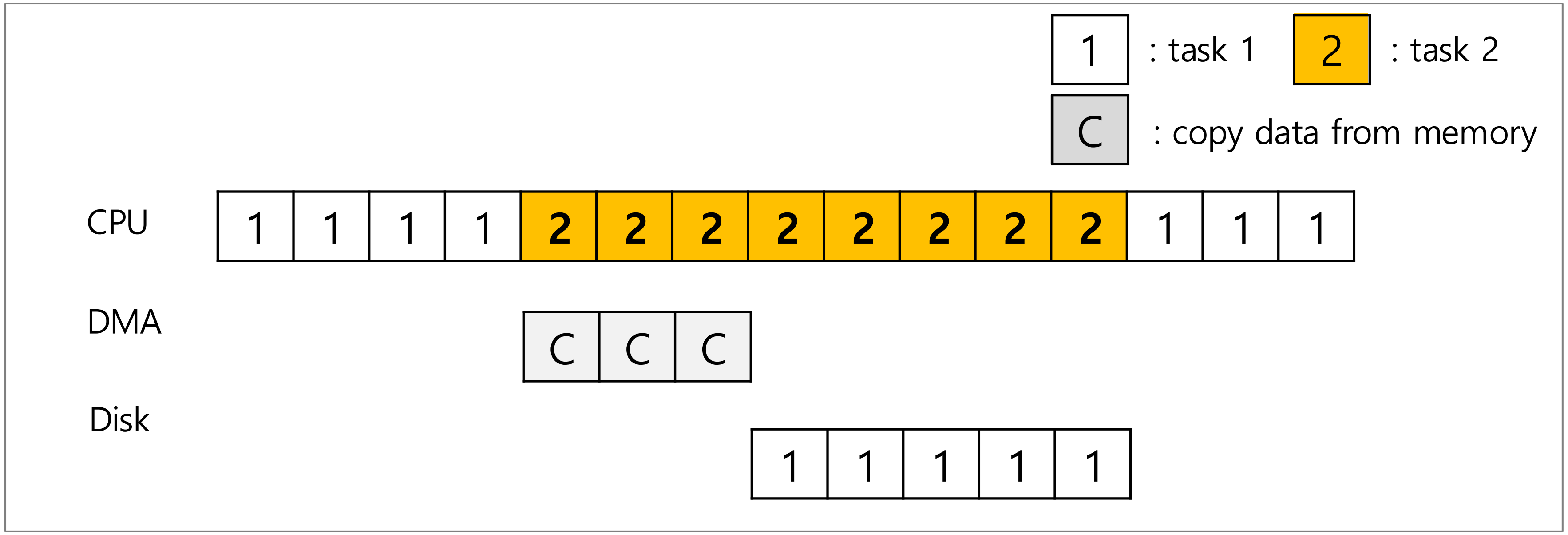


Diagram of CPU utilization by DMA

Direct Memory Access

Avoid programmed I/O for large data movement

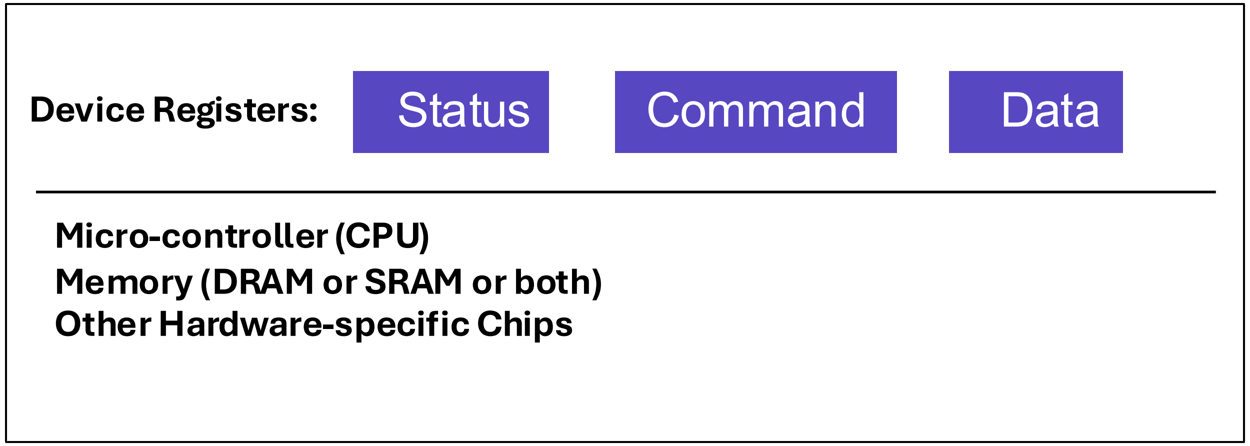
Requires DMA controller

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

Device Protocol Variants



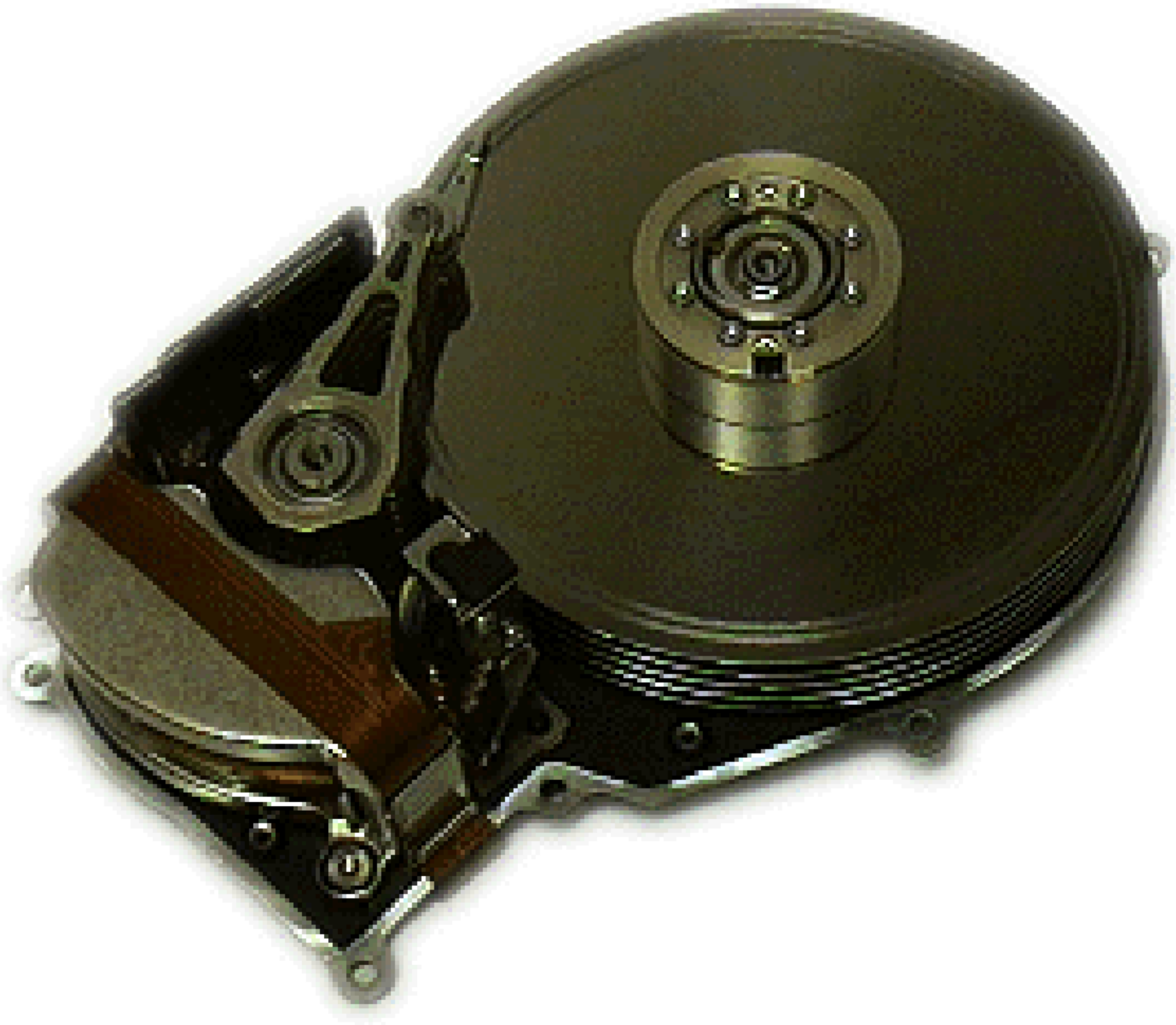
Canonical I/O Device

Status checks: ***polling*** **vs.** ***interrupts***

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

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

Hard Disk



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.

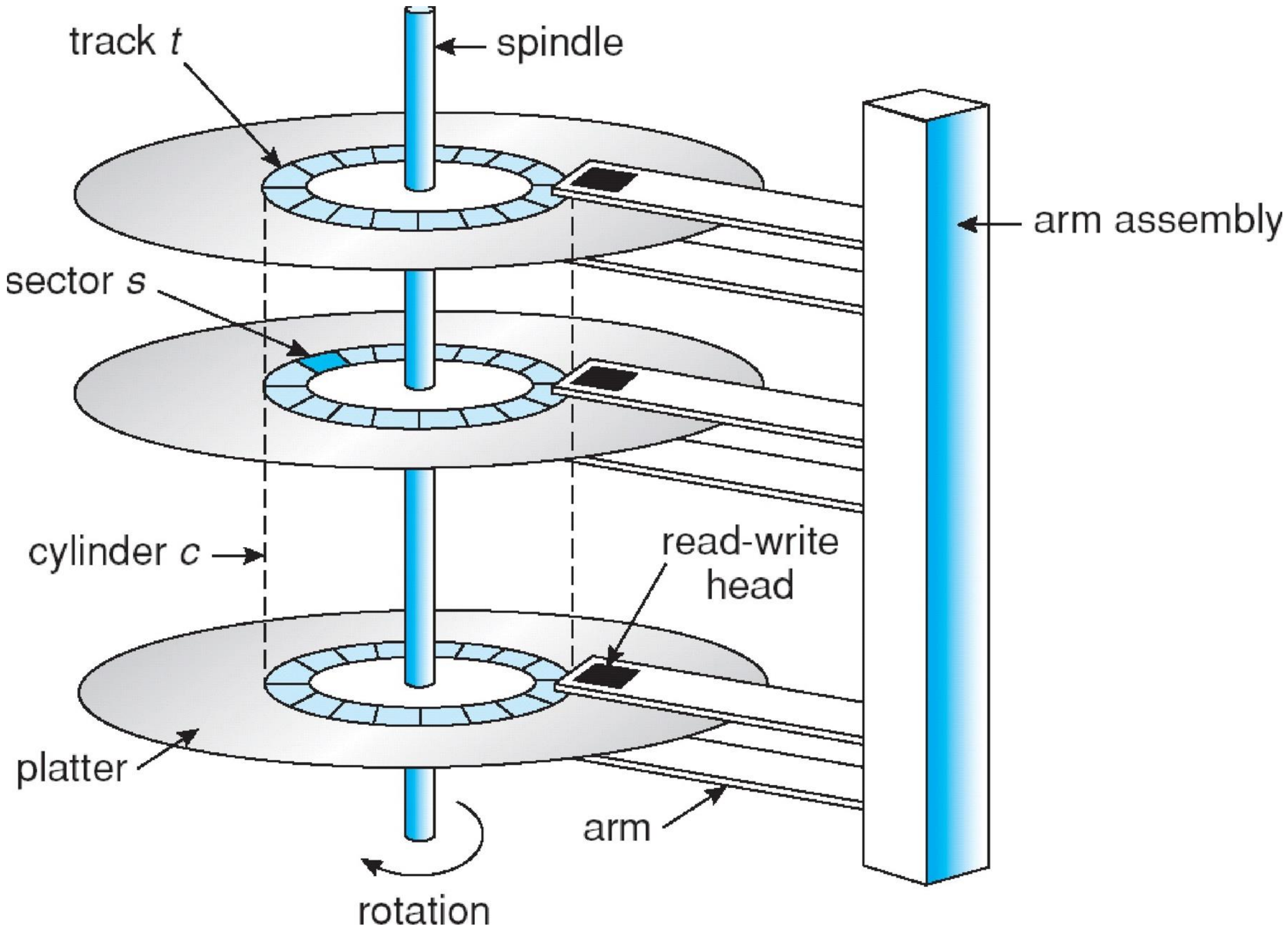
Track

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

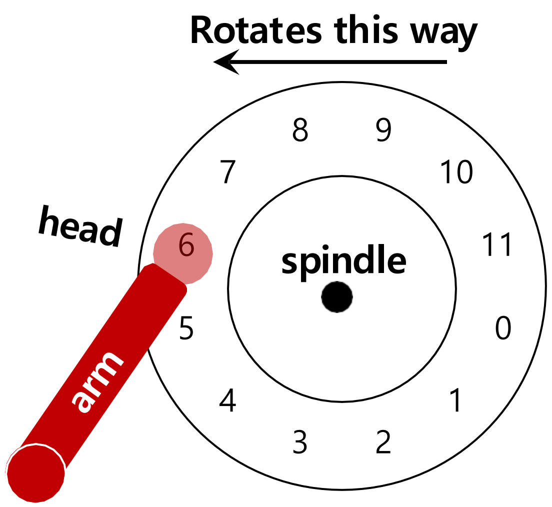
Cylinder

- 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

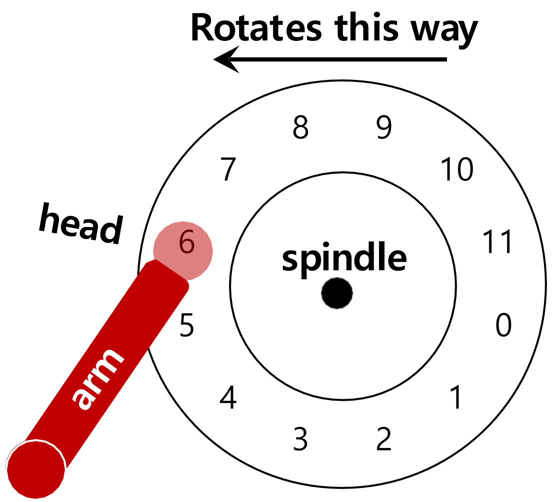


A Single Track Plus A Head

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



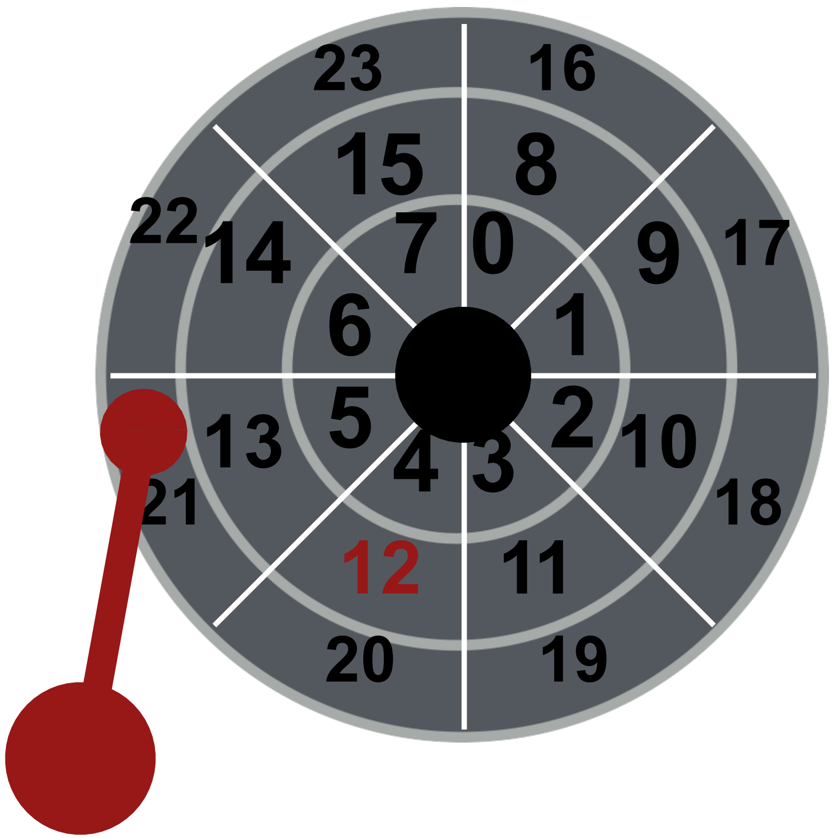
A Single Track Plus A Head

Rotational delay: Time for the desired sector to rotate

- 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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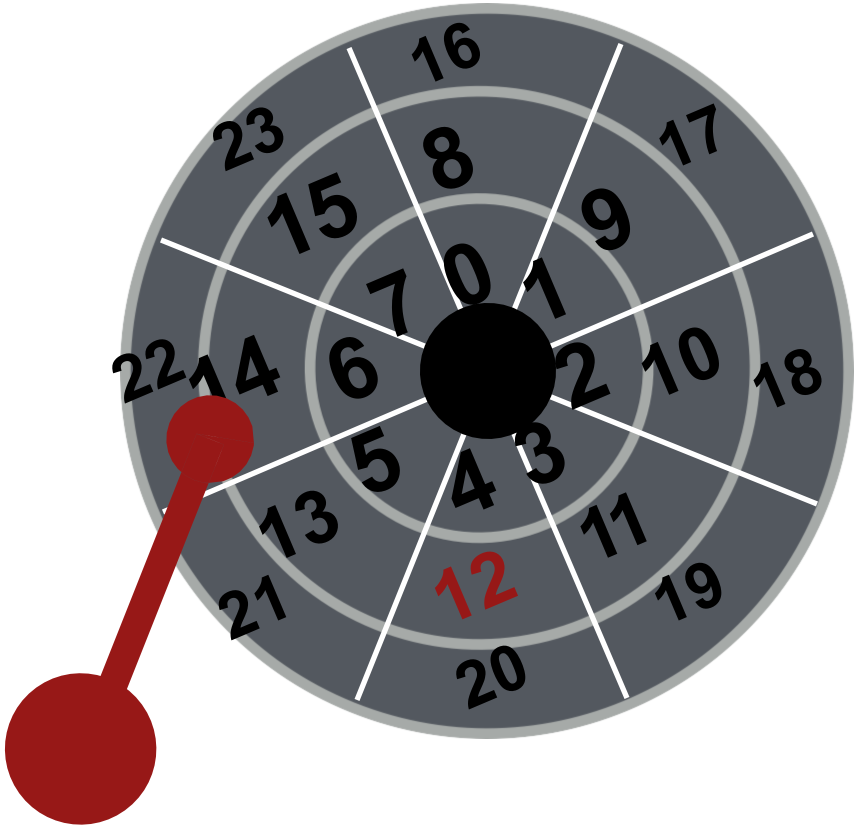

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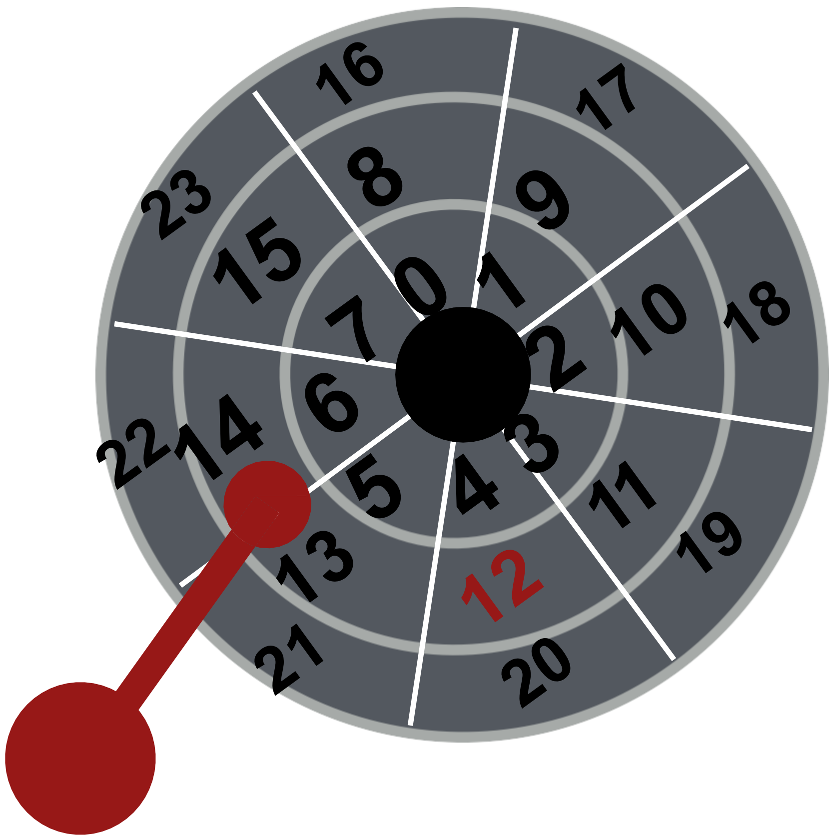
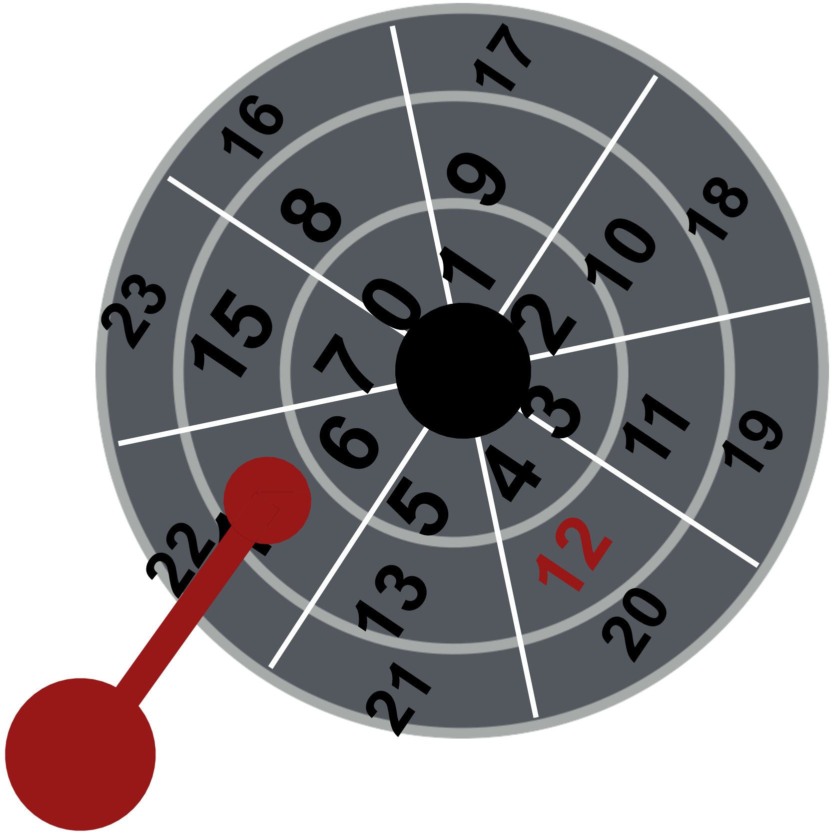


Multiple Tracks: Wait for Rotation

Let's Read 12!



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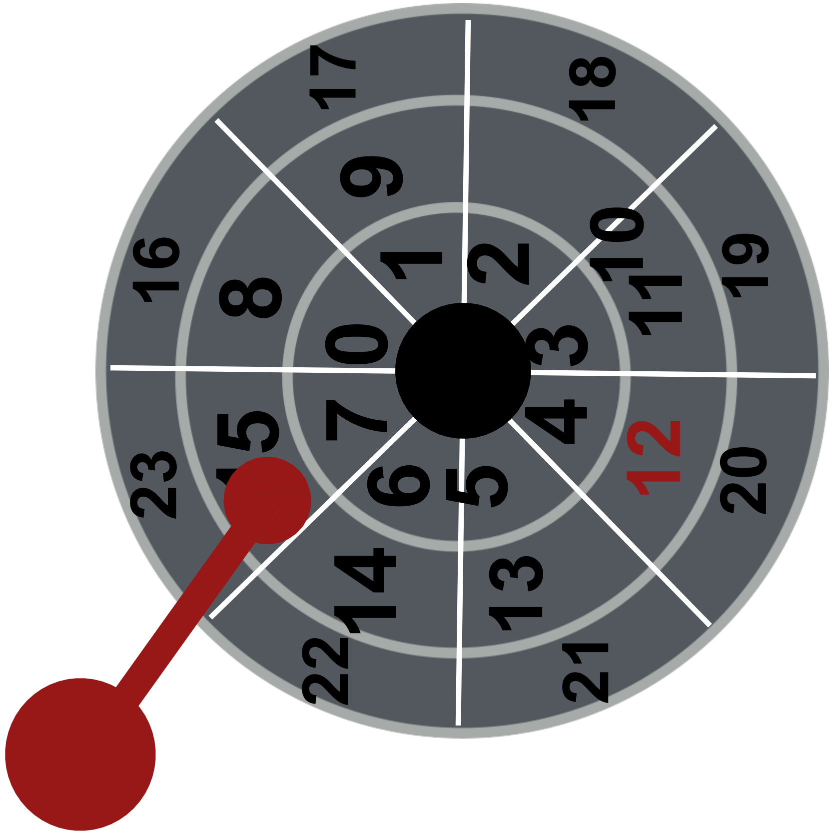

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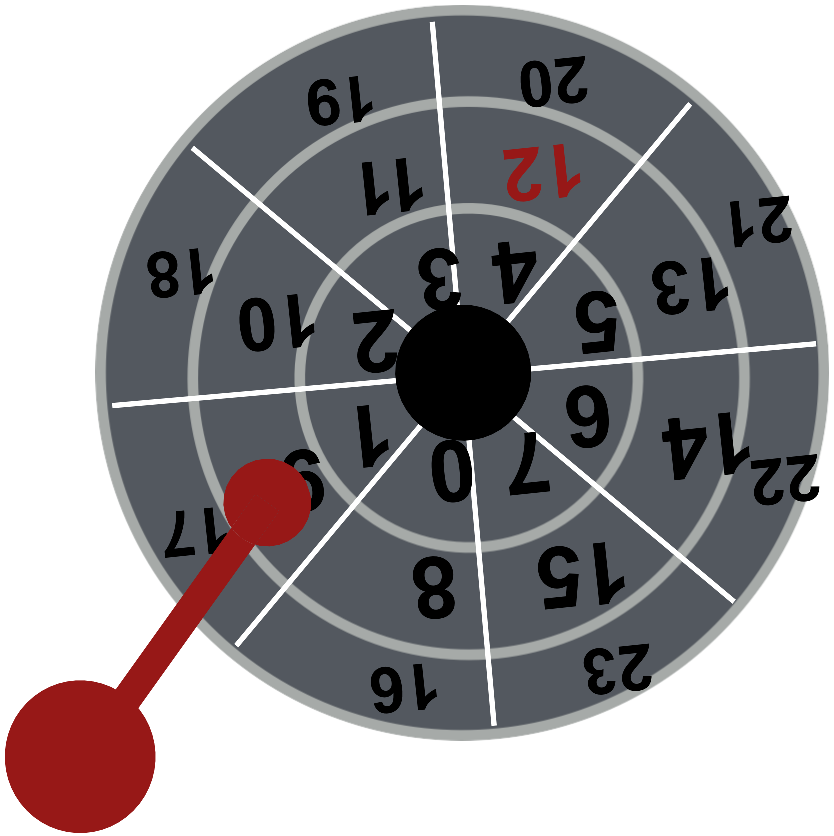

Multiple Tracks: Wait for Rotation

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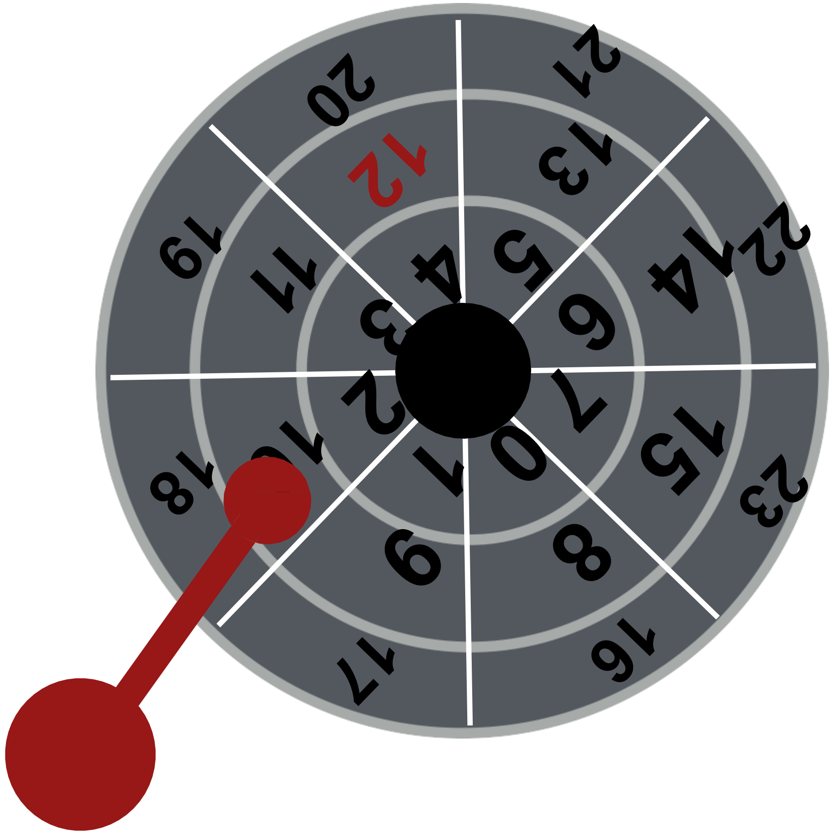
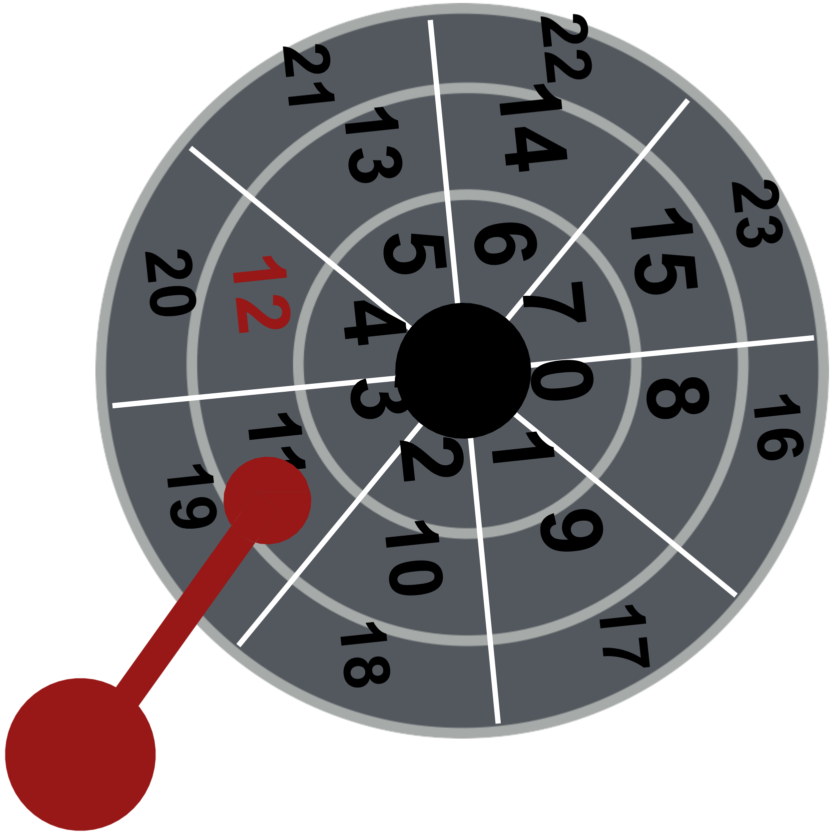


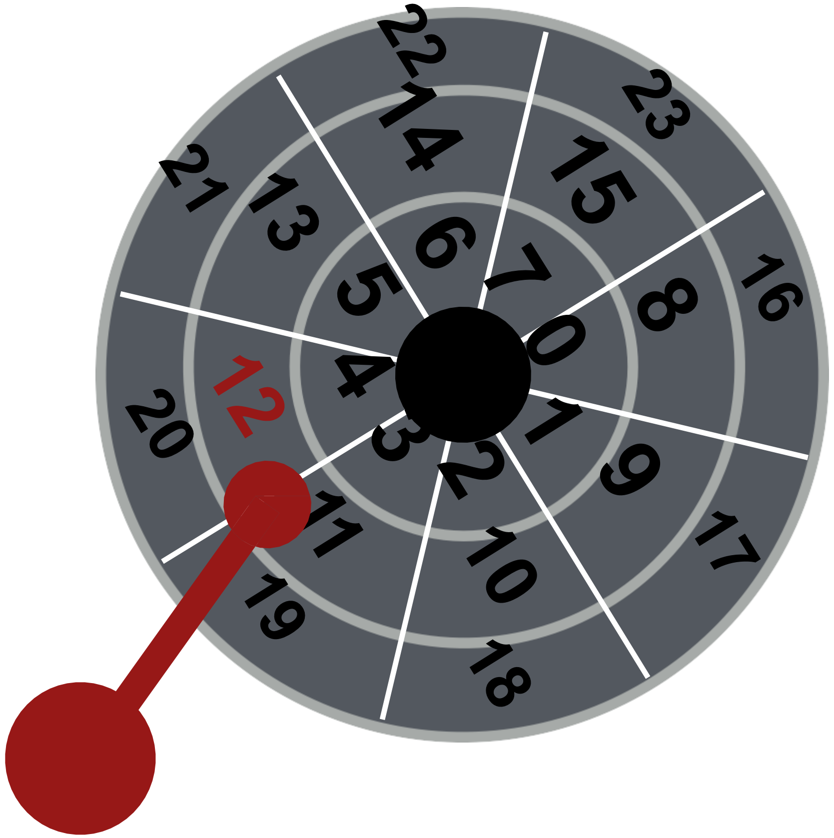
Multiple Tracks: Wait for Rotation

Let’s Read 12!



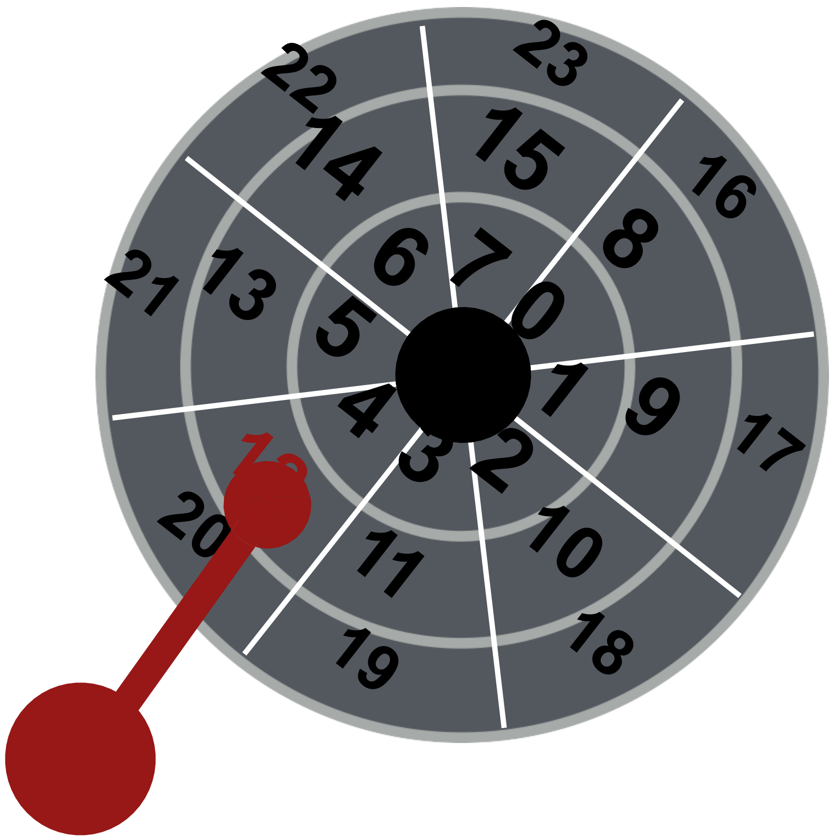
Multiple Tracks: Transfer Data

Let's Read 12!



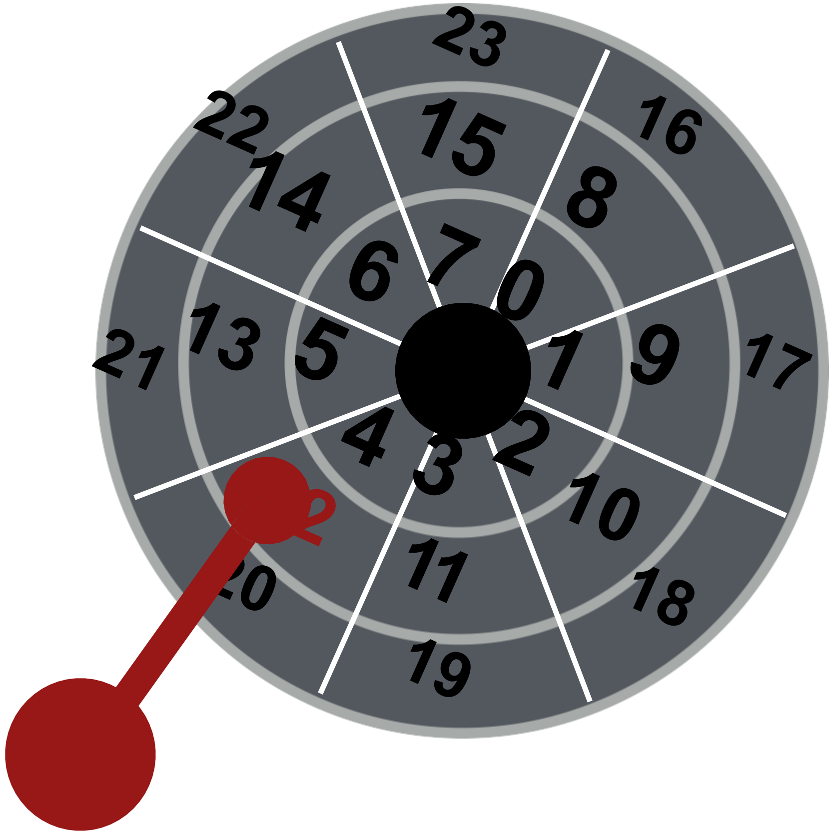
Multiple Tracks: Transfer Data

Let’s Read 12!

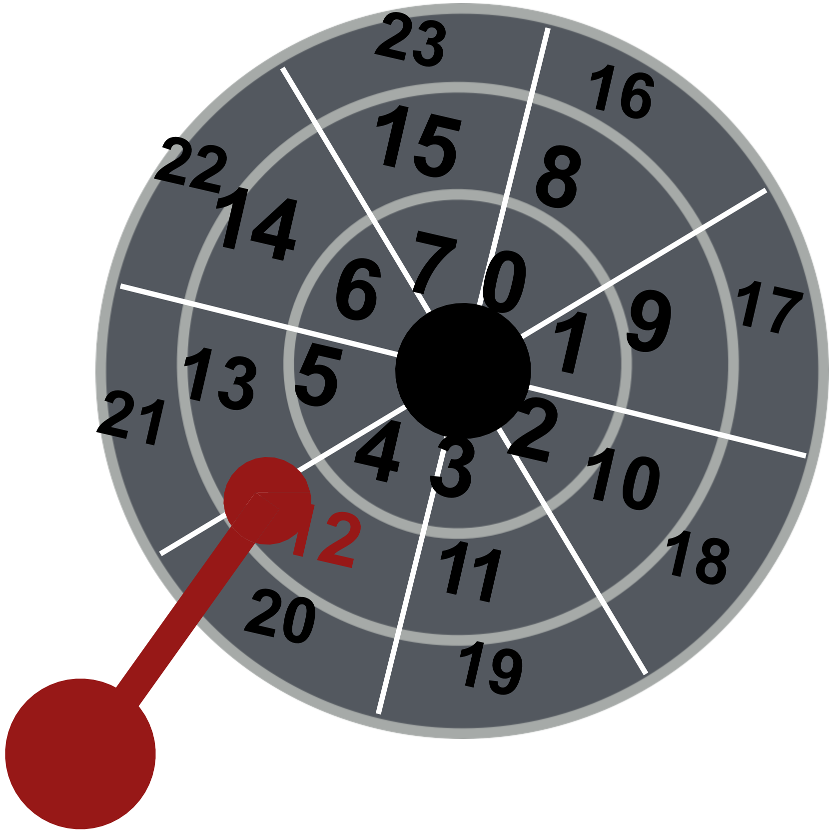


Multiple Tracks: Transfer Data

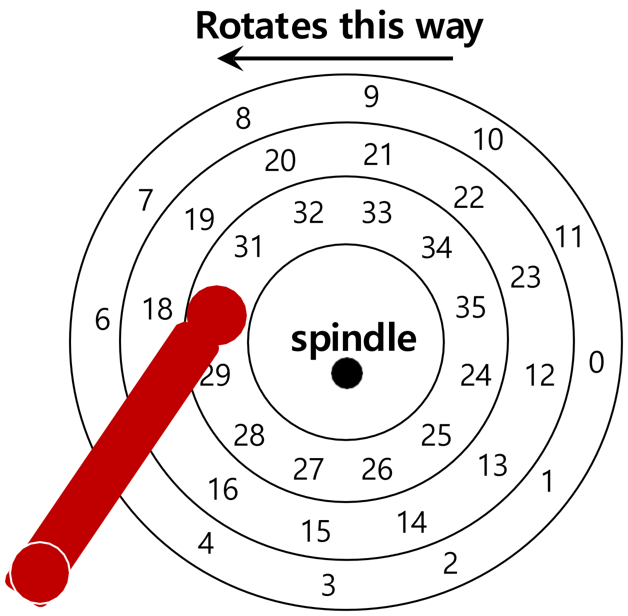
Let's Read 12!

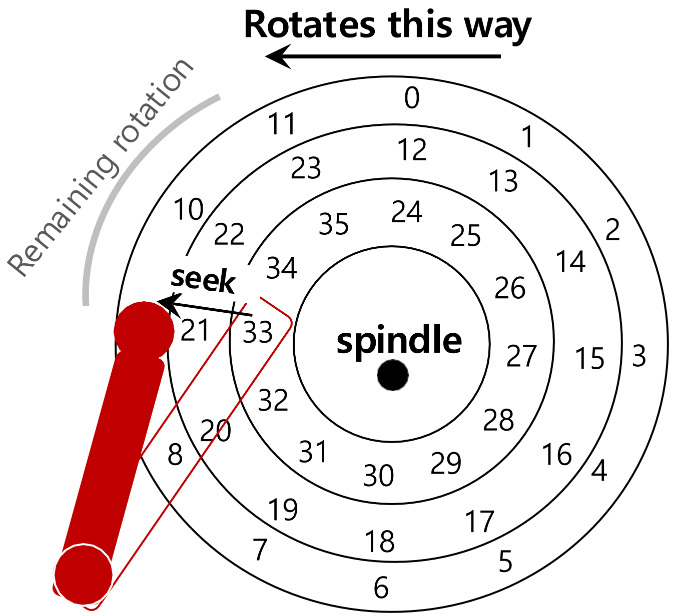


Yay!



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

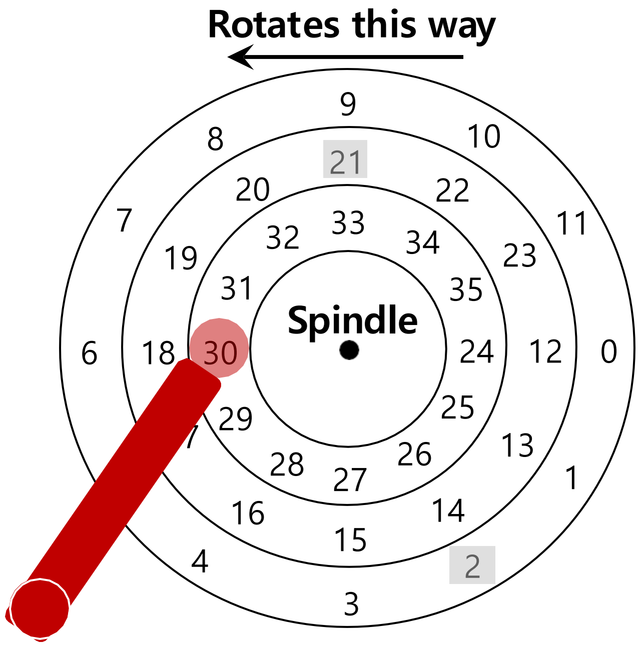
So...

- 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

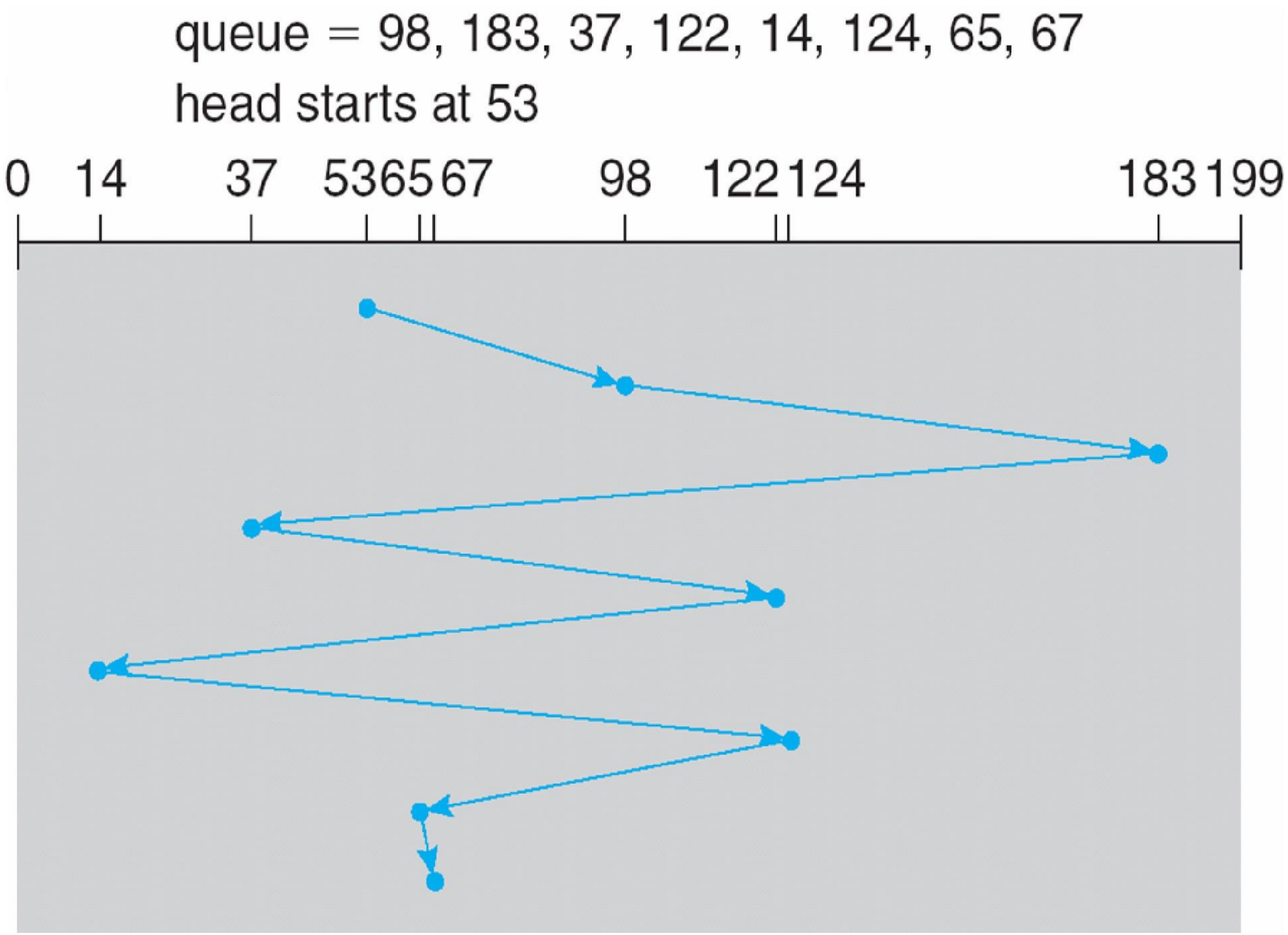
Advantages

- 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)

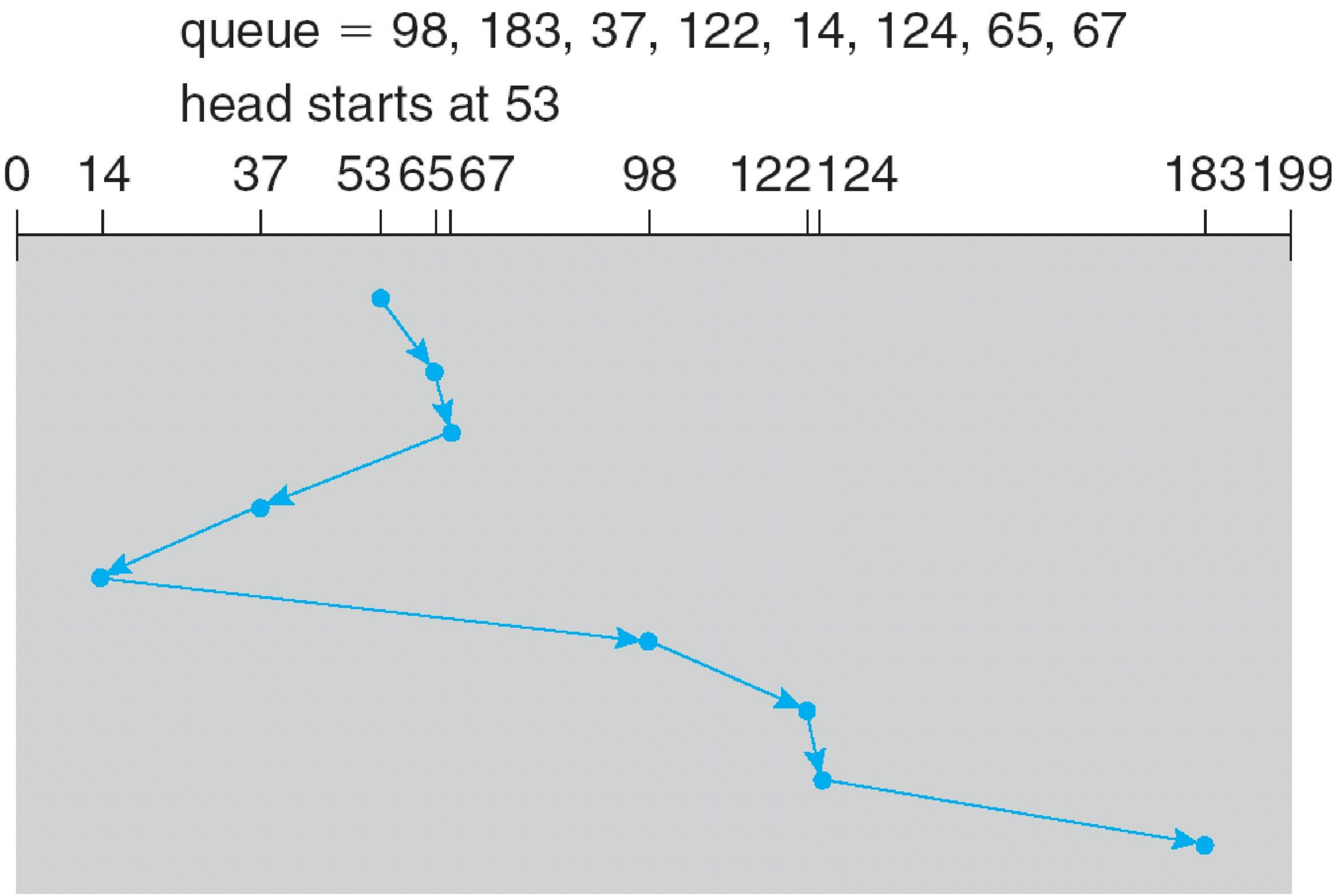
Advantages

- Exploits locality of disk requests
- Higher throughput

Disadvantages

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

SSTF Example



“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

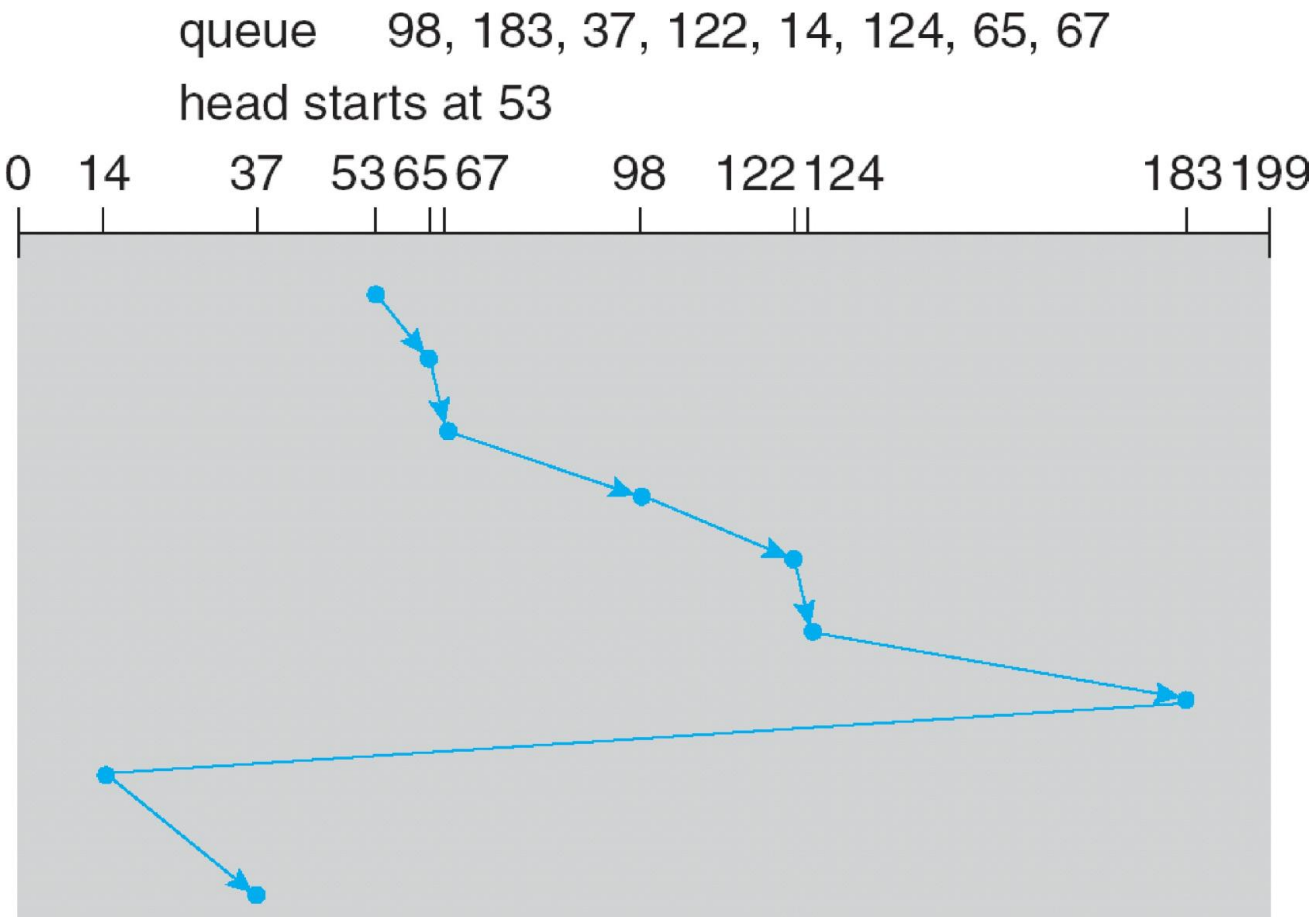
Disadvantages

- 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