Lecture 14: I/O and Disks

601.418/618 Operating Systems

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Agenda

- I/O devices
- Device interaction
  - Programmed I/O
  - Interrupts
  - DMA
- Hard disks and SSDs

Acknowledgments: These slides are shamelessly adapted from Prof. Ryan Huang's Fall 2022 slides, which in turn are based on Prof. David Mazières's OS lecture notes.

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

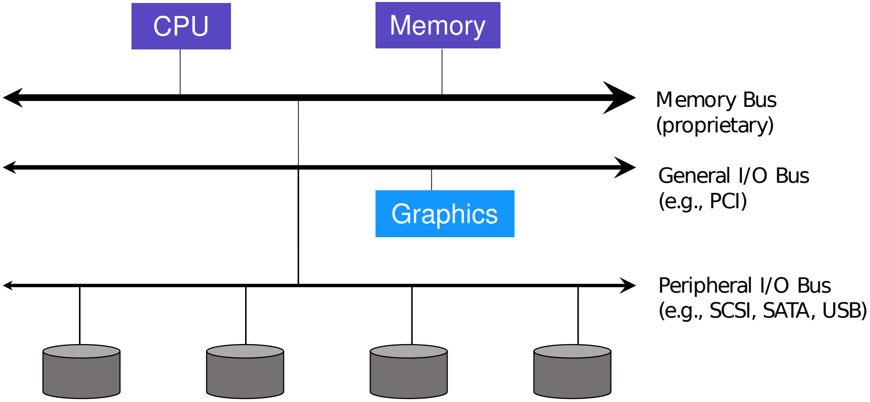
I/O Devices

...

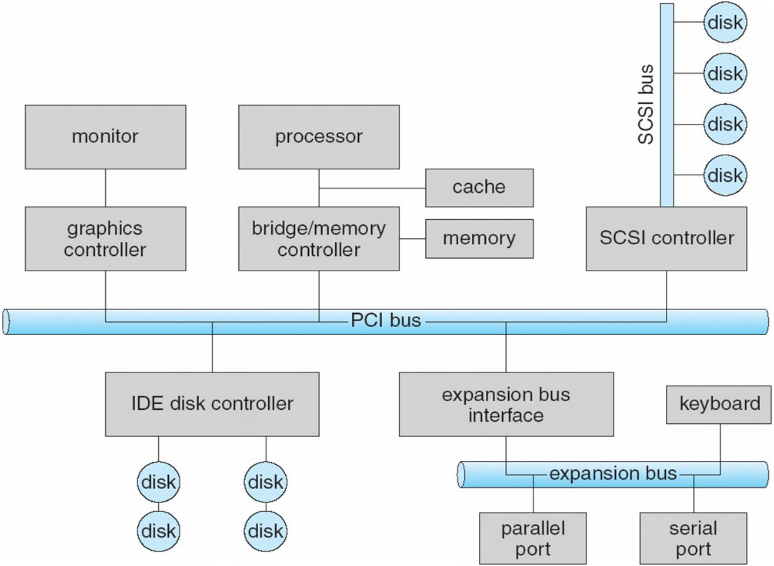
Issues to address:

- 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

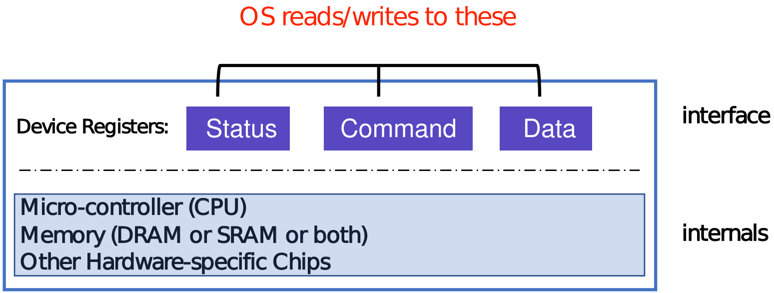


Structure of Input/Output (I/O) Device



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 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");
}
```

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.

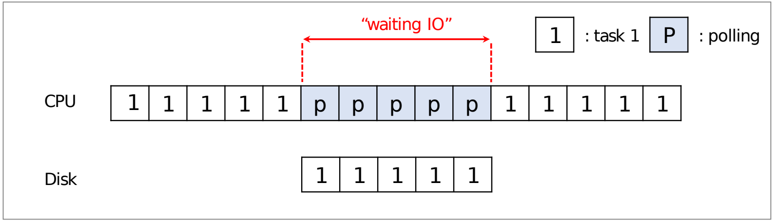


Diagram of CPU utilization by polling

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

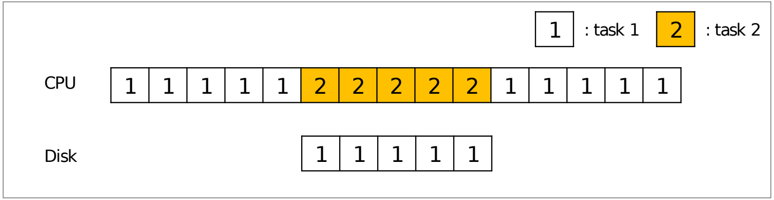


Diagram of CPU utilization by interrupt

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)

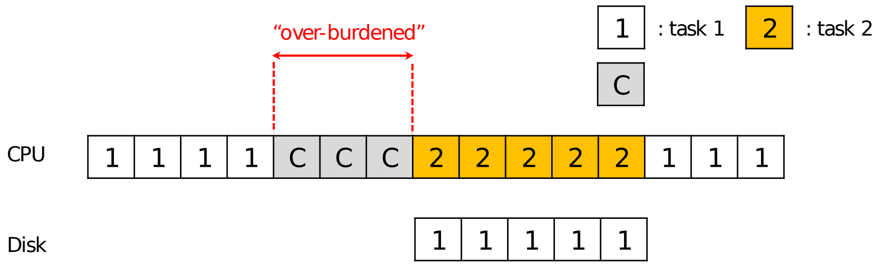
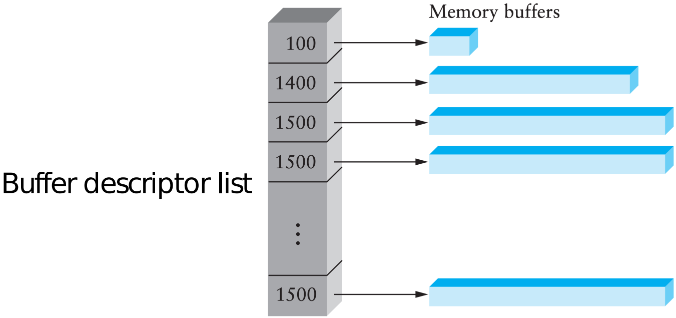


Diagram of CPU utilization

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.

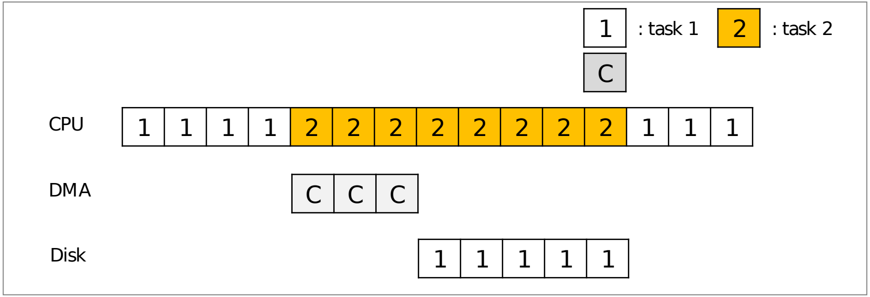


Diagram of CPU utilization by DMA

Direct Memory Access

Avoid programmed I/O for large data movement

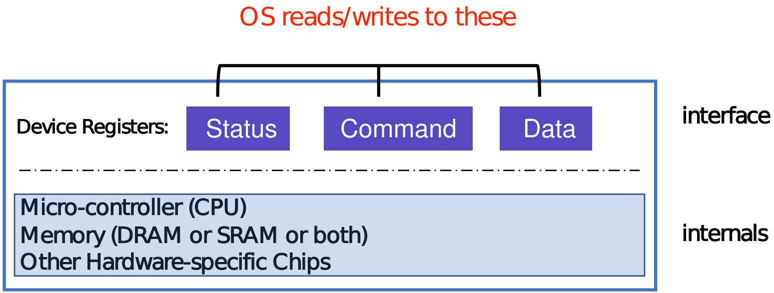
Requires DMA controller

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



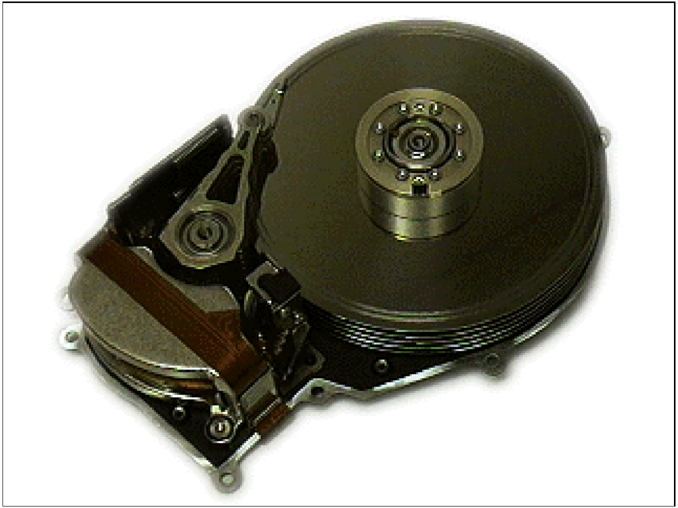
Canonical I/O Device

Status checks: *polling* vs. *interrupts*

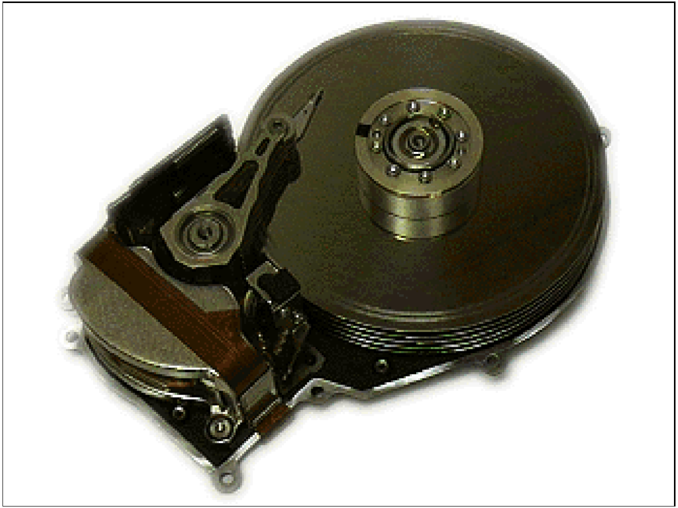
Command: *special instructions* vs. *memory-mapped I/O*

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

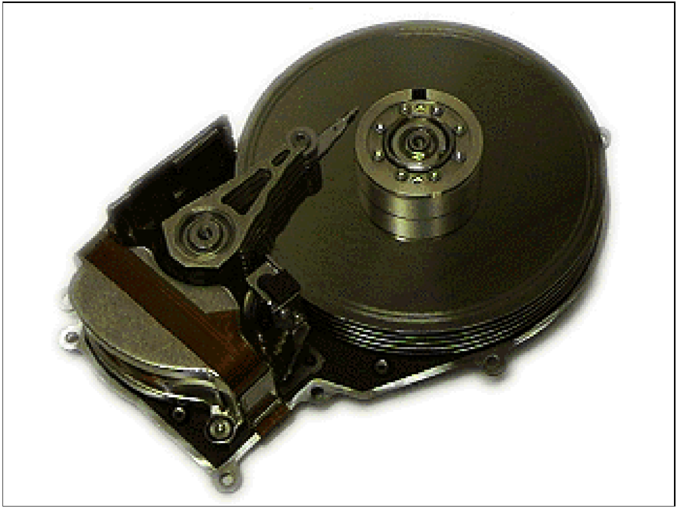
Hard Disks



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.

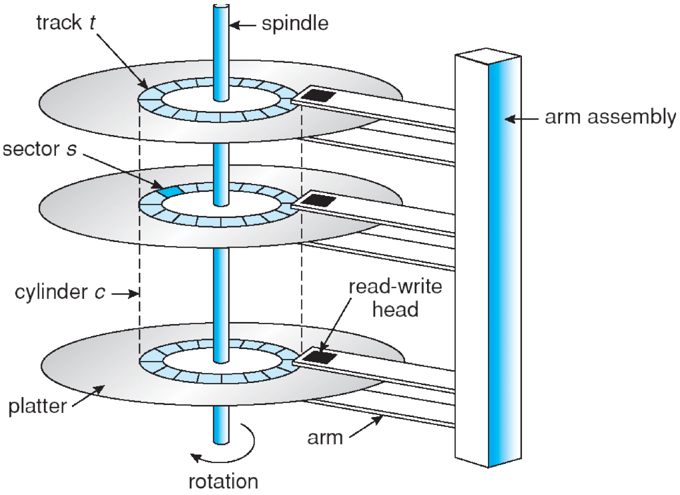
Track

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

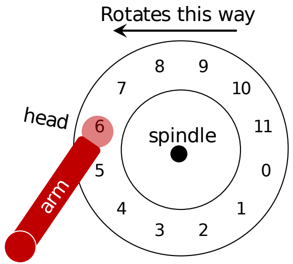
Cylinder

- 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

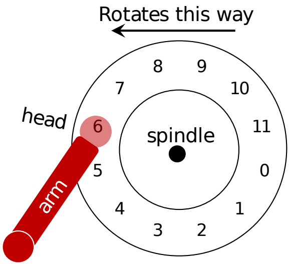


A Single Track Plus A Head

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



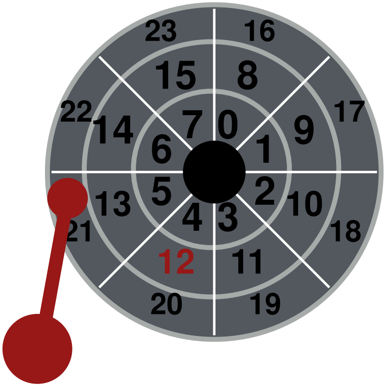
A Single Track Plus A Head

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 $= R/2$
  - Read sector 5: Rotational delay $= R - 1$ (worst case.)

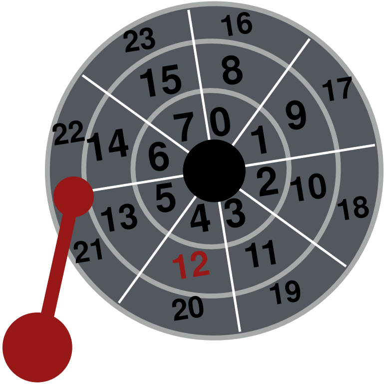
Multiple Tracks

Let's Read 12!



Multiple Tracks: Seek to Right Track

Let's Read 12!



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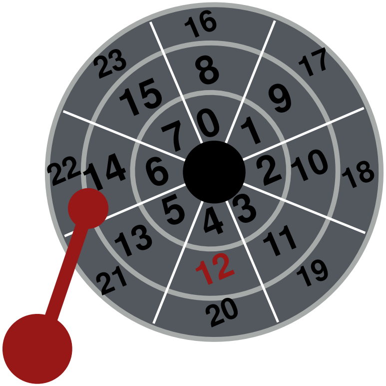

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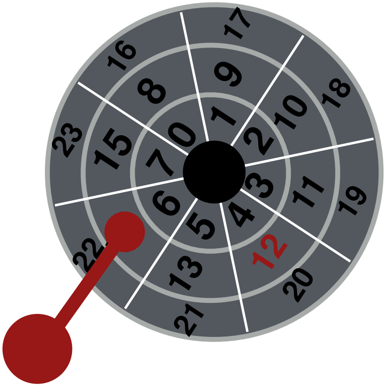
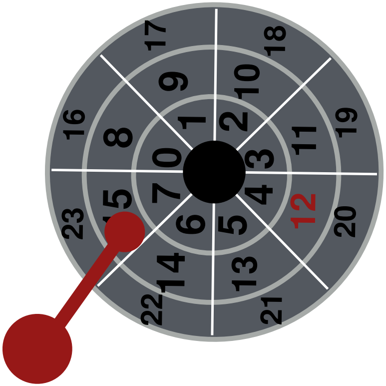


Multiple Tracks: Wait for Rotation

Let's Read 12!



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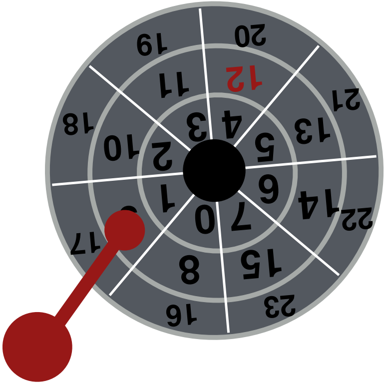

Multiple Tracks: Wait for Rotation

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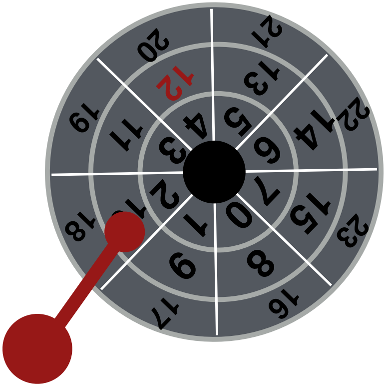
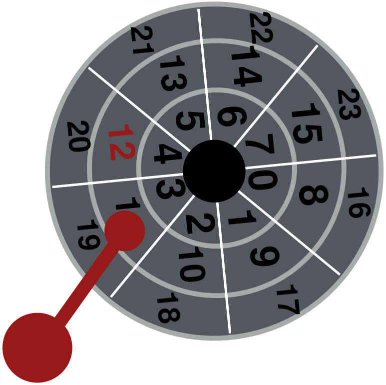


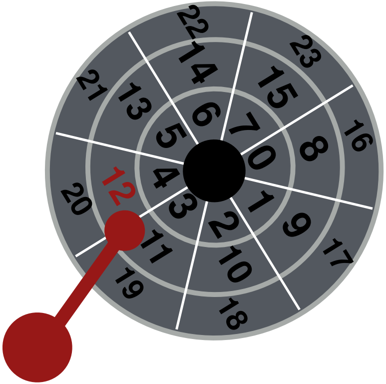
Multiple Tracks: Wait for Rotation

Let's Read 12!



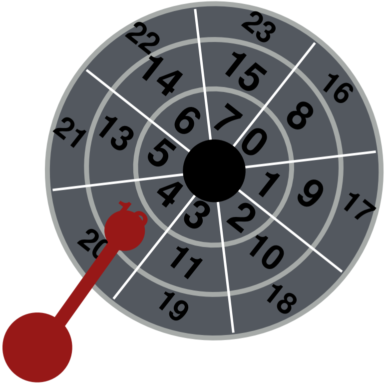
Multiple Tracks: Transfer Data

Let's Read 12!



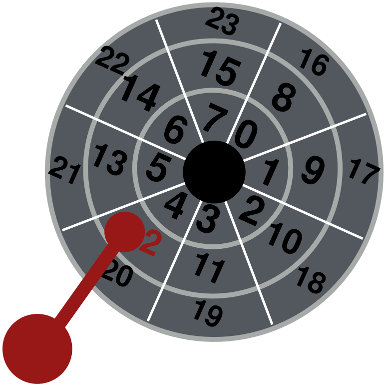
Multiple Tracks: Transfer Data

Let's Read 12!

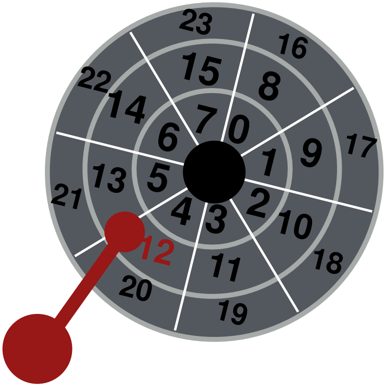


Multiple Tracks: Transfer Data

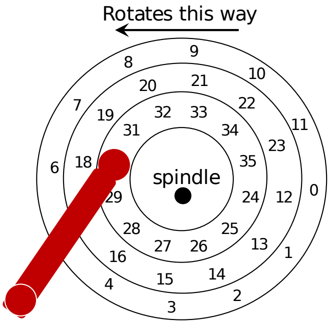
Let's Read 12!

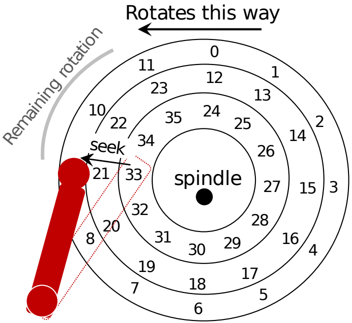


Yay!



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 $\rightarrow$ Coasting $\rightarrow$ Deceleration $\rightarrow$ 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 to 10 ms.

On a 1 GHz CPU (slow by modern standards), 1 ms is 1,000,000 clock cycles!

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 delay?

- 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?

- $512 \text{ bytes} \times (1 \text{ s}/100 \text{ MB}) = 5\ \mu\text{s} = 5 \times 10^{-6} \text{ s}$

Workload

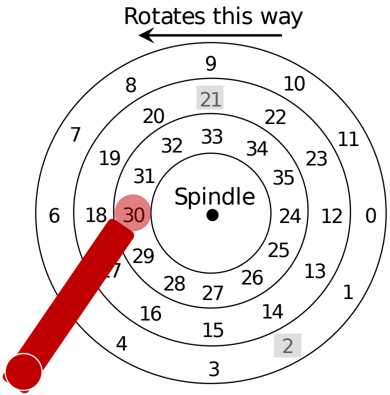
So. . .

- 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

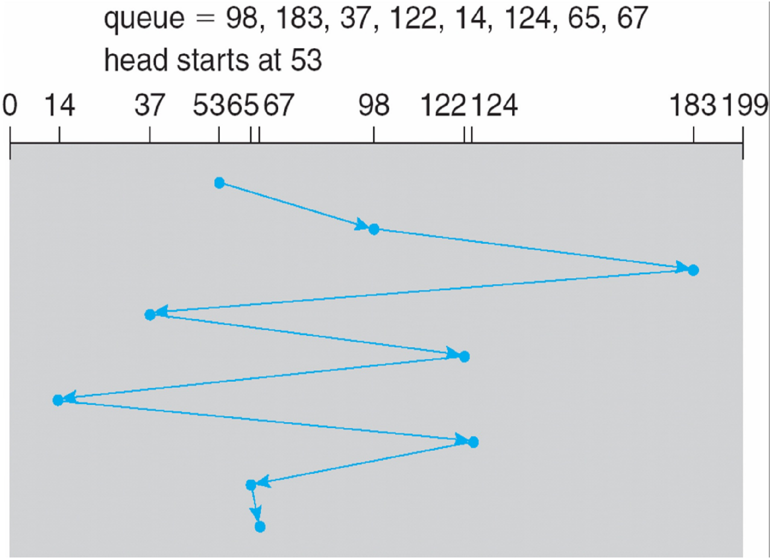
Advantages

- 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)

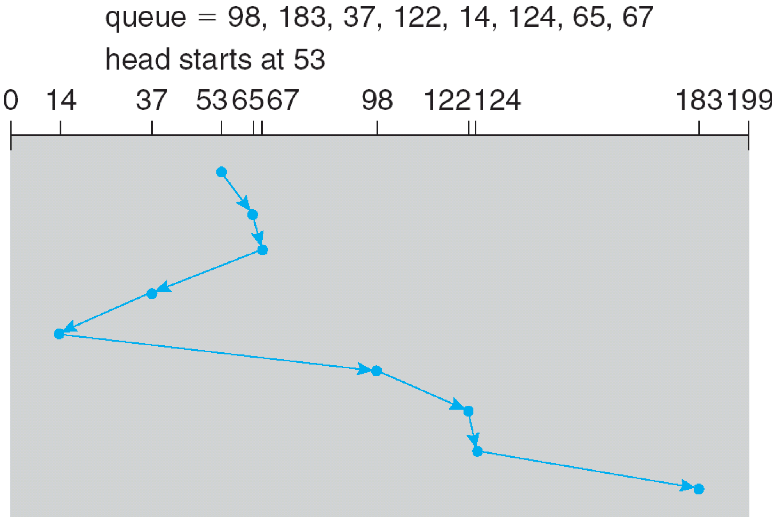
Advantages

- 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

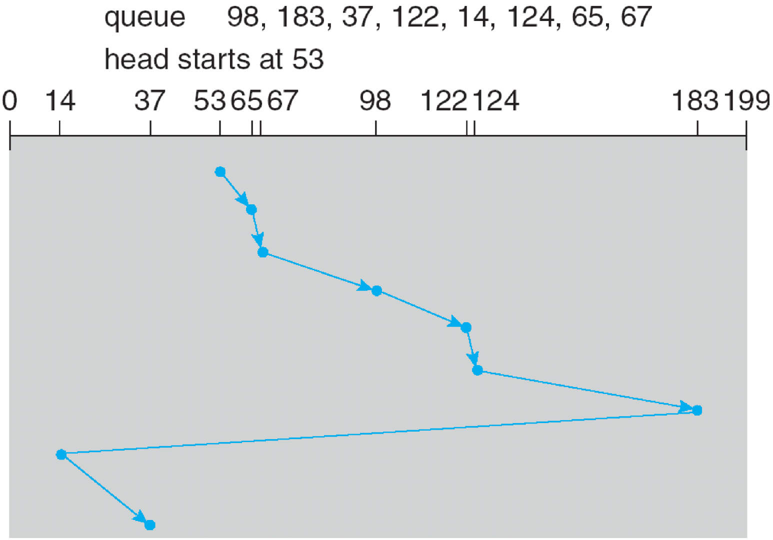
Disadvantages

- 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

Filesystems!