TCSS 422: OPERATING SYSTEMS

Beyond Physical Memory, I/O Devices, Hard Disk Drives,

Wes J. Lloyd
School of Engineering and Technology
University of Washington - Tacoma

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OBJECTIVES – 3/12

- Questions from 3/10
- Assignment 2 - March 12 TODAY AOE
- Assignment 3 (as a Tutorial) - March 20 AOE
- Memory Segmentation Activity + answers (available in Canvas)
- Quiz 4 – Page Tables - Due March 12 TODAY AOE
- Final exam - Thurs March 19 @ 3:40pm JOY 215 w/ HEAT!
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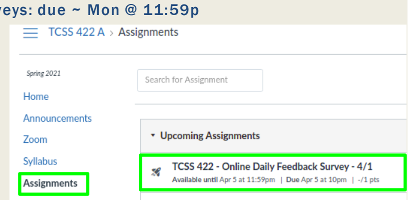
ONLINE DAILY FEEDBACK SURVEY

- Daily Feedback Quiz in Canvas – Available After Each Class
- Extra credit available for completing surveys ***ON TIME***
- Tuesday surveys: due by ~ Wed @ 11:59p
- Thursday surveys: due ~ Mon @ 11:59p



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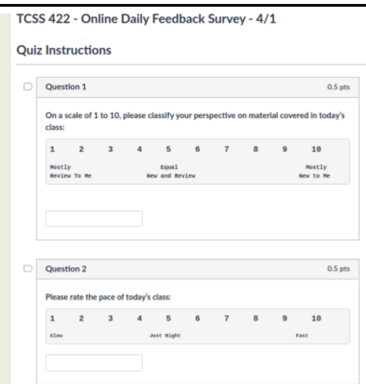

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (33 of 46 respondents (7 online) – 71.7%):
- 1-mostly review, 5-equal new/review, 10-mostly new
- Average – 6.45 (↑ - previous 4.73)

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- Average – 5.36 (↑ - previous 4.93)

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FEEDBACK FROM 3/10

- ***Why does every address translation have to go through the TLB?***
- Primarily to accelerate memory access. Without the TLB the OS would need to perform a costly 5-level page table look-up in memory for every instruction, memory access, etc. which is too slow.
- x86_64 machines with 64-bit Linux, have an addressable memory space of 128 PB which is addressable with 57-bits
- There are 2^{57} / 2^{12} pages, which is 2^{35} pages.
- 35-VPN bits are conveniently divided by 9 for 5-level page tables !!
  - Page Global Directory (PGD) = bits 56 to 48 (9 bits)
  - Page Level 4 Directory (P4D) = bits 47 to 39 (9 bits)
  - Page Upper Directory (PUD) = bits 38 to 30 (9 bits)
  - Page Middle Directory (PMD) = bits 29 to 21 (9 bits)
  - Page Table Entry (PTE) = bits 20 to 12 (9 bits)
  - Page Offset = final 12 bits of the 57-bit address

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TLB CACHING QUESTION

- Consider a computer that indexes memory using 4 KB pages
- The sizeof(int) in 64-bit Linux is 4 bytes
- Consider an array of 10,000 4-byte integers (40,000 bytes)

```
int big_array[10000];
```

- Assume static allocation on stack pages
- Assuming big_array[0] is allocated on the start of a 4K memory page, and array allocation is contiguous, how many TLB hits and misses will occur with the following code ?

```
for (int i=0;i<10000;i++)
     big_array[i]=0;
```

- Array 40,000 byte array storage spans 10 memory pages
- 10 misses, 9,990 hits
- 999 hits to 1 miss ratio = 99.9% cache hit rate

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FEEDBACK - 2

- ***Are there more efficient structures in development to replace 5-level paging schemes in Linux?***
- Huge Pages (2MB/1GB) and Transparent Huge Pages (THP) – an existing feature of Linux currently, Linux can merge 4KB pages into 2MB or 1GB pages to reduce the number of levels for address translation and also to increase TLB hits
  - Huge pages preconfigured and static at boot time (for libraries, etc)
  - Transparent huge pages (2MB) - kernel will allocate 2MB pages on demand as needed but defragmentation can introduce latency
- Huge pages help databases, VMs, HPC applications, but not required for typical use
- Enabled? `cat /sys/kernel/mm/transparent_hugepage/enabled`
- In Use? `cat /proc/meminfo | grep AnonHugePages`

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FEEDBACK - 3

- Neural Page Table Indexing – Researchers have proposed using neural networks to learn and predict page table indexes to speed up the translation process, aimed at alleviating performance for deeply nested page tables

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TUTORIAL - ASSIGNMENT 3: INTRODUCTION TO LINUX KERNEL MODULES

- Assignment 3 provides an introduction to kernel programming by demonstrating how to create a Linux Kernel Module as a tutorial
- Kernel modules are commonly used to write device drivers and can access protected operating system data structures
  - For example: Linux `task_struct` process data structure

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FINAL EXAM – THURS MARCH 19 @ 3:40PM JOY 215

- Thursday March 19 from 3:40 to 5:40 pm
  - Final (100 points), similar number of questions as the midterm
  - 2-hours, Joy 215 has heating !!
- What to Review for the Final Exam:
  - ***Final Exam Review Session* – Tuesday March 17 @ 6pm on Zoom**
  - Focus on new content – 70% since the midterm, 30% before
  - Complete Memory Segmentation Activity (ungraded)
  - Complete Canvas Quiz 4
  - Review In-Class Quiz 2 (from March 5)
- Format:
  - Individual work
  - 3 pages of notes (any sized paper), double sided
  - Basic calculators allowed
  - NO smartphones, laptop, book, Internet, group work

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TUTORIAL 3 - FILE SYSTEMS

- **(Optional, Extra Credit)**
- Due Saturday March 21 AOE time
- In Extra Credit Category
- Earn up to 2% extra credit added to overall course credit
- Topics:
  - Exploring the File API (Chapter 39)
  - File System Symbolic Links in Linux
  - File System types: ext2, ext4
  - Testing Performance Impact of File System Journaling w/ Sysbench
  - iNodes, iNode density on a file system

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CATCH UP FROM LECTURE 17

- Switch to Lecture 15 Slides
- Slides L15.86 to L15.90
  (Chapter 20 – Paging – Smaller Tables)
- Switch to Lecture 17 Slides
- Slides 17.20 to 17.50
  (Chapters 21/22 – Beyond Physical Memory)

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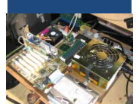
WE WILL RETURN AT 5:07PM



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CHAPTER 36: I/O DEVICES

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OBJECTIVES

- Chapter 36
  - I/O: Polling vs Interrupts
  - Programmed I/O (PIO)
    - Port-mapped I/O (PMIO)
    - Memory-mapped I/O (MMIO)
  - Direct memory Access (DMA)

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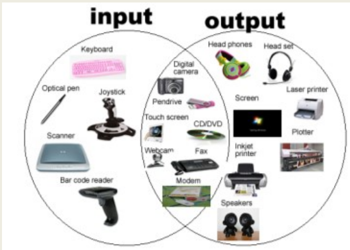
I/O DEVICES

- Modern computer systems interact with a variety of devices



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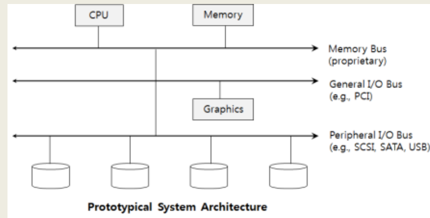
COMPUTER SYSTEM ARCHITECTURE



VERY FAST: CPU is attached to main memory via a Memory bus.
FAST: High speed devices (e.g. video) are connected via a General I/O bus.
SLOWER: Disks are connected via a Peripheral I/O bus.

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I/O BUSES

- Buses
  - Buses closer to the CPU are faster
  - Can support fewer devices
  - Further buses are slower, but support more devices
- Physics and costs dictate "levels"
  - Memory bus
  - General I/O bus
  - Peripheral I/O bus
- Tradeoff space: speed vs. locality

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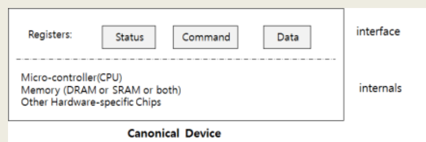
CANONICAL DEVICE

- Consider an arbitrary canonical ***"standard/generic"*** device



- Two primary components
  - Interface (registers for communication)
  - Internals: Local CPU, memory, specific chips, firmware (embedded software)

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CANONICAL DEVICE: HARDWARE INTERFACE

- Status register
  - Maintains current device status
- Command register
  - Where commands for interaction are sent
- Data register
  - Used to send and receive data to the device

General concept:
The OS interacts and controls device behavior by reading and writing the device registers.

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OS DEVICE INTERACTION

- Common example of device interaction

```
while ( STATUS == BUSY)                      ⇐ Poll- Is device available?
    ; //wait until device is not busy
write data to data register                  ⇐ Command parameterization
write command to command register            ⇐ Send command
    Doing so starts the device and executes the command
while ( STATUS == BUSY)                      ⇐ Poll – Is device done?
    ; //wait until device is done with your request
```


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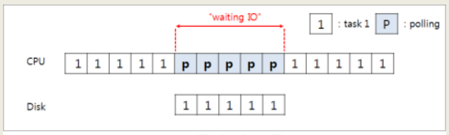
POLLING

- OS checks if device is *READY* by repeatedly checking the STATUS register
  - Simple approach
  - CPU cycles are wasted without doing meaningful work
  - Ok if only a few cycles, for rapid devices that are often READY
  - BUT polling, as with "spin locks" we understand is inefficient



CPU utilization by polling

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INTERRUPTS VS POLLING

- For longer waits, put process waiting on I/O to sleep
- Context switch (C/S) to another process
- When I/O completes, fire an interrupt to initiate C/S back
  - Advantage: better multi-tasking and CPU utilization
  - Avoids: unproductive CPU cycles (polling)

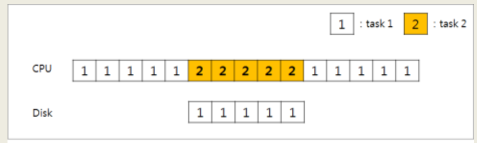

Diagram of CPU utilization by interrupt

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INTERRUPTS VS POLLING - 2

What is the tradeoff space ?

- Interrupts are not always the best solution
  - How long does the device I/O require?
  - What is the cost of context switching?

If device I/O is fast → polling is better.
When I/O time < 1 CPU time slice (e.g. 10 ms)

If device I/O is slow → interrupts are better.
When I/O time > 1 CPU time slice

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INTERRUPTS VS POLLING - 3

- Alternative: two-phase hybrid approach
  - Initially poll, then sleep and use interrupts
- Issue: livelock problem
  - Common with network I/O
  - Many arriving packets generate ***many many*** interrupts
  - Overloads the CPU!
  - No time to execute code, just interrupt handlers !
- Livelock optimization
  - Coalesce multiple arriving packets (for different processes) into fewer interrupts
  - Must consider number of interrupts a device could generate

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DEVICE I/O

- To interact with a device we must send/receive DATA
- There are two general approaches:
  - Programmed I/O (PIO):
    - Port mapped I/O (PMIO)
    - Memory mapped I/O (MMIO)
  - Direct memory access (DMA)

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Transfer Modes

Mode	#	Maximum transfer rate (MB/s)	cycle time
PIO	0	3.3	600 ns
	1	5.2	383 ns
	2	8.3	240 ns
	3	11.1	180 ns
	4	16.7	120 ns
Single-word DMA	0	2.1	960 ns
	1	4.2	480 ns
	2	8.3	240 ns
Multi-word DMA	0	4.2	480 ns
	1	13.3	150 ns
	2	16.7	120 ns
	3[34]	20	100 ns
	4[34]	25	80 ns
Ultra DMA	0	16.7	240 ns ÷ 2
	1	25.0	160 ns ÷ 2
	2 (Ultra ATA/33)	33.3	120 ns ÷ 2
	3	44.4	90 ns ÷ 2
	4 (Ultra ATA/66)	66.7	60 ns ÷ 2
	5 (Ultra ATA/100)	100	40 ns ÷ 2
	6 (Ultra ATA/133)	133	30 ns ÷ 2
	7 (Ultra ATA/167)[35]	167	24 ns ÷ 2

From https://en.wikipedia.org/wiki/Parallel_ATA

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PROGRAMMED I/O (PIO)

- I/O performed on the CPU
- CPU time is consumed performing I/O
- CPU supports data movement (input/output)
- PIO is slow: CPU is occupied with meaningless work

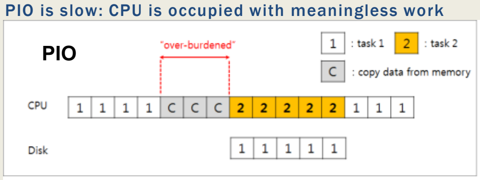

Diagram of CPU utilization

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PIO DEVICES

- Legacy serial ports
- Legacy parallel ports
- PS/2 keyboard and mouse
- Legacy MIDI, joysticks
- Old network interfaces

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PROGRAMMED I/O DEVICE (PIO) INTERACTION

- Two primary PIO methods
  - Port mapped I/O (PMIO)
  - Memory mapped I/O (MMIO)

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PORT MAPPED I/O (PMIO)

- Device specific CPU I/O Instructions
- Follows a CISC model:
  specific CPU instructions used for device I/O
- x86-x86-64: `in` and `out` instructions
- `outb`, `outw`, `outl`
- 1, 2, 4 byte copy from EAX → device's I/O port

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MEMORY MAPPED I/O (MMIO)

- Device's memory is mapped to standard memory addresses
- MMIO is common with RISC CPUs:
  Special CPU instructions for PIO eliminated
- Old days: 16-bit CPUs didn't have a lot of spare memory space
- Today's CPUs have LARGE address spaces:
  32-bit (4GB addr space) & 64-bit (128 TB addr space)
- Device I/O uses regular CPU instructions usually used to read/write memory to access device
- Device is mapped to unique memory address **reserved** for I/O
  - Address must not be available for normal memory operations.
  - Generally very high addresses (out of range of type addresses)
- Device monitors CPU address bus and respond to instructions on their addresses

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DIRECT MEMORY ACCESS (DMA)

- Copy data in memory by ***offloading*** to "DMA controller"
- Many devices (including CPUs) integrate DMA controllers
- CPU gives DMA: memory address, size, and copy instruction
- DMA performs I/O independent of the CPU
- DMA controller generates CPU interrupt when I/O completes

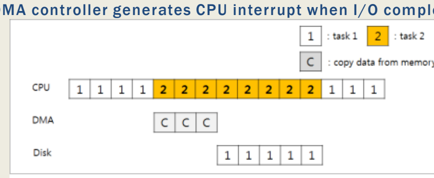

Diagram of CPU utilization by DMA

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DIRECTORY MEMORY ACCESS – 2

- Many devices use DMA
  - HDD/SSD controllers (ISA/PCI)
  - Graphics cards
  - Network cards
  - Sound cards
  - Intra-chip memory transfer for multi-core processors
- DMA allows computation and data transfer time to proceed in parallel

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DEVICE INTERACTION

- The OS must interact with a variety of devices
- Example: Consider a file system that works across a variety of types of disks:
  - SCSI, IDE, USB flash drive, DVD, etc.
- File system should be general purpose, where device specific I/O implementation details are abstracted
- **Device drivers** use abstraction to provide general interfaces for vendor specific hardware
- In Linux: block devices

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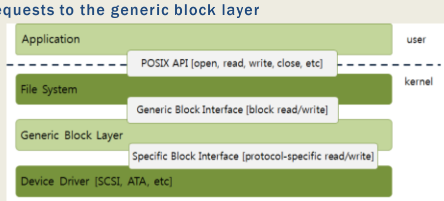
FILE SYSTEM ABSTRACTION

- Layers of I/O abstraction in Linux
- C functions (open, read, write) issue **block read** and **write** requests to the generic block layer



The File System Stack

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FILE SYSTEM ABSTRACTION ISSUES

- **Too much abstraction**
- Many devices provide special capabilities
- Example: SCSI Error handling
- SCSI devices provide extra details which are lost to the OS
- **Buggy device drivers**
- 70% of OS code is in device drivers
- Device drivers are required for every device plugged in
- Drivers are often 3rd party, which is not quality controlled at the same level as the OS (Linux, Windows, MacOS, etc.)

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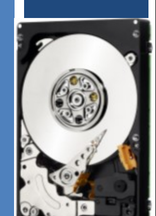
CH. 37: HARD DISK DRIVES



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OBJECTIVES

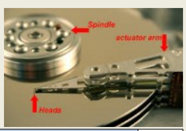
- Chapter 37
  - HDD Internals
  - Seek time
  - Rotational latency
  - Transfer speed
  - Capacity
  - Scheduling algorithms

HARD DISK DRIVE (HDD)

- Primary means of data storage (persistence) for decades
  - Remains inexpensive for high capacity storage
  - 2020: 16 TB HDD - $400, ~15.3 TB SSD - $4,380
- Consists of a large number of data **sectors**
- Sector size is 512-bytes
- An n sector HDD can be is addressed as an array of 0..n-1 sectors

HDD INTERFACE

- Writing disk sectors is atomic (512 bytes)
- Sector writes are completely successful, or fail
- Many file systems will read/write 4KB at a time
  - Linux ext3/4 default filesystem blocksize – 4096
- Same as typical memory page size



BLOCK SIZE IN LINUX EXT4

- `mkefs.ext4 -i <bytes-per-inode>`
- Formats disk w/ ext4 filesys with specified byte-to-inode ratio
- Today's disks are so large, some use cases with many small files can run out of inodes before running out of disk space
- Each inode record tracks a file on the disk
- Larger bytes-per-inode ratio results in fewer inodes
  - Default is around ~4096
- Value shouldn't be smaller than blocksize of filesystem
- Note: It is not possible to expand the number of inodes after the filesystem is created, - be careful deciding the value
- Check inode stats: `tune2fs -l /dev/sda1` *(← disk dev name)*

EXAMPLE: USDA SOIL EROSION MODEL WEB SERVICE (RUSLE2)

- Host ~2,000,000 small XML files totaling 9.5 GB on a ~20GB filesystem on a cloud-based Virtual Machine
- With default inode ratio (4096 block size), only ~488,000 files will fit
- Drive less than half full, but files will not fit !
- HDDs support a minimum block size of 512 bytes
- OS filesystems such as ext3/ext4 can support "finer grained" management at the expense of a larger catalog size
  - Small inode ratio- inodes will considerable % of disk space

EXAMPLE: USDA SOIL EROSION MODEL WEB SERVICE (RUSLE2) - 2

- Free space in bytes (df)

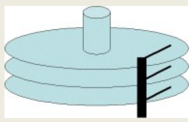
Device	total size	bytes-used	bytes-free	usage	
/dev/vda2	13315844	9556412	3049188	76%	/mnt

- Free inodes (df –i) @ 512 bytes / node

Device	total inodes	used	free	usage	
/dev/vda2	3552528	1999823	1552705	57%	/mnt

HDD INTERFACE - 2

- Torn write
  - When OS uses larger block size than HDD
  - Block writes not **atomic** - they SPAN multiple HDD sectors
  - Upon power failure only a portion of the OS block is written – *can lead to data corruption…*
- HDD access
  - Sequential reads of sectors is fastest
  - Random sector reads are slow
  - Disk head continuously must jump to different tracks



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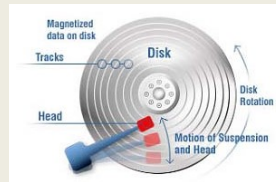
HDD PLATTER

- Made from aluminum coated with thin magnetic layer
- HDD records on both sides of each platter
- Data is stored by inducing magnetic changes



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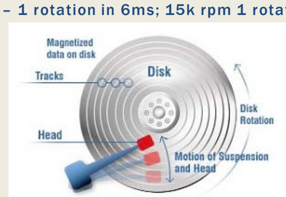
HDD SPINDLE

- Connected to motor which spins the disk
- Speed measures in RPM (rotations per minute)
- Typical: 7200-15000 rpm
- 10000 rpm – 1 rotation in 6ms; 15k rpm 1 rotation in 4ms



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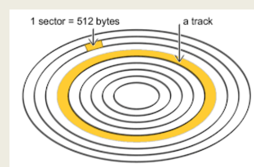
HDD TRACK

- Concentric circle of sectors
- Single side of platter contains 290 K tracks (2008)
- Zones: groups of tracks with same # of sectors

Outer tracks have More sectors



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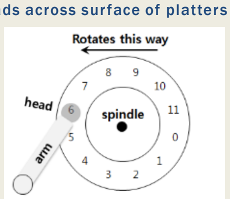
EXAMPLE: SIMPLE DISK DRIVE

- Single track disk
- Head: one per surface of drive
- Arm: moves heads across surface of platters



A Single Track Plus A Head

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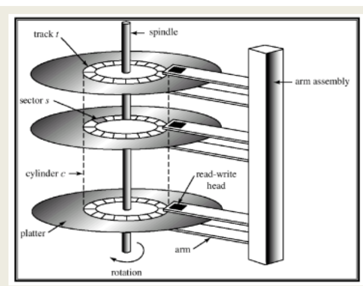
HARD DISK STRUCTURE



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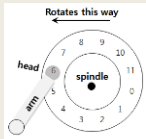
SINGLE-TRACK LATENCY: THE ROTATIONAL DELAY

- **Rotational latency** ($T_{rotation}$): time to rotate to desired sector
- Average $T_{rotation}$ is ~ about half the time of a full rotation
- How to calculate $T_{rotation}$ from rpm
  1. Calculate time for 1 rotation based on rpm
     > Convert rpm to rps
  2. Divide by two (*average rotational latency*)
- 7200rpm = 8.33ms per rotation /2= ~4.166ms
- 10000rpm = 6ms per rotation /2= ~3ms
- 15000rpm = 4ms per rotation /2= ~2ms



A Single Track Plus A Head

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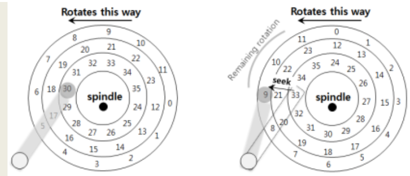
SEEK TIME



Three Tracks Plus A Head (Right: With Seek)
(e.g., read to sector 11)

- **Seek time** (T_{seek}): time to move disk arm to proper track
- Most time consuming HDD operation

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FOUR PHASES OF SEEK

- Acceleration → coasting → deceleration →settling
- **Acceleration**: the arm gets moving
- **Coasting**: arm moving at full speed
- **Deceleration**: arm slow down
- **Settling**: Head is carefully positioned over track
  - Settling time is often high, from .5 to 2ms

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HDD I/O

- Data transfer
  - Final phase of I/O: time to read or write to disk surface
- Complete I/O cycle:
  1. Seek (accelerate, coast, decelerate, settle)
  2. Wait on rotational latency (*until track aligns*)
  3. Data transfer

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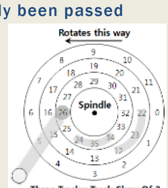
TRACK SKEW

- Sectors are offset across tracks to allow time for head to reposition for sequential reads
- Without track skew, when head is repositioned sector would have already been passed



Three Tracks: Track Skew Of 2

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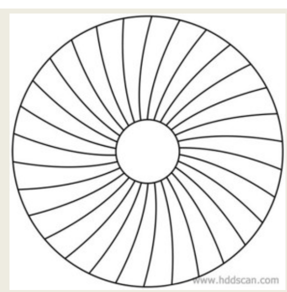
TRACK SKEW - 2



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HDD CACHE

- Buffer to support caching reads and writes
- Improves drive response time
- Up to 256 MB, slowly have been growing
- Two styles
  - Writeback cache
    - Report write complete immediately when data is transferred to HDD cache
    - Dangerous if power is lost
  - Writethrough cache
    - Reports write complete only when write is physically completed on disk

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TRANSFER SPEED

- Can calculate I/O transfer speed with:
- I/O Time: $T_{I/O} = T_{seek} + T_{rotation} + T_{transfer}$
- $T_{transfer}$ = $DATA_{size}$ x $Rate_{I/O}$
- Rate of I/O: $R_{I/O} = \frac{Size_{Transfer}}{T_{I/O}}$

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EXAMPLE: I/O SPEED

- Compare two disks:
1. Random workload: 4KB (random read on HDD)
2. Sequential workload: 100MB (contiguous sectors)
   > Calculate $T_{rotation}$ from rpm (rpm→rps, time for 1 rotation / 2)

	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

Disk Drive Specs: SCSI Versus SATA

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EXAMPLE: I/O SPEED

1. Random workload: 4KB (random read on HDD)
2. Sequential workload: 100MB (contiguous sectors)

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

$$T_{transfer} = Data_{size} \, x \, Rate_{I/O}$$

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

		Cheetah 15K.5	Barracuda
T_{seek}		4 ms	9 ms
$T_{rotation}$		2 ms	4.2 ms
4 KB Random	$T_{transfer}$	30 microsecs	38 microsecs
	$T_{I/O}$	6 ms	13.2 ms
	$R_{I/O}$	0.66 MB/s	0.31 MB/s
100 MB Sequential	$T_{transfer}$	800 ms	950 ms
	$T_{I/O}$	806 ms	963.2 ms
	$R_{I/O}$	125 MB/s	105 MB/s

Disk Drive Performance: SCSI Versus SATA

There is a huge gap in drive throughput between random and sequential workloads

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MODERN HDD SPECS

- See sample HDD configurations here:
  - Up to 20 TB
- https://www.westerndigital.com/products/data-center-drives#hard-disk-hdd

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DISK SCHEDULING

- Disk scheduler: determine how to order I/O requests
- Multiple levels - OS and HW
- OS: provides ordering
- HW: further optimizes using intricate details of physical HDD implementation and state

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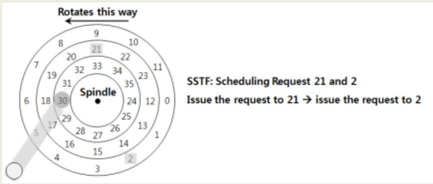
SSTF – SHORTEST SEEK TIME FIRST

- Disk scheduling – which I/O request to schedule next
- Shortest Seek Time First (SSTF)
- Order queue of I/O requests by nearest track



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SSTF ISSUES

- Problem 1: HDD abstraction
- Drive geometry not available to OS. Nearest-block-first is a comparable alternate algorithm.
- Problem 2: Starvation
- Steady stream of requests for local tracks may prevent arm from traversing to other side of platter

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DISK SCHEDULING ALGORITHMS

- **SCAN (SWEEP)**
- Perform single repeated passes back and forth across disk
- Issue: if request arrives for a recently visited track it will not be revisited until a full cycle completes
- **F-SCAN**
- Freeze incoming requests by adding to queue during scan
- Cache arriving requests until later
- Delays help avoid starvation by postponing servicing nearby newly arriving requests vs. requests at edge of sweep
- Provides better fairness
- **Elevator (C-SCAN)** – circular scan
- Sweep only one direction (e.g. outer to inner) and repeat
- SCAN favors middle tracks vs. outer tracks with 2-way sweep

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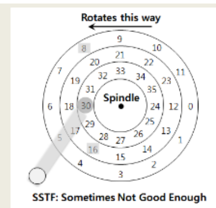
SHORTEST TIME POSITIONING FIRST

- Determine next sector to read?
  - Where: $T_{seek} = T_{rotation}$
- On which track?
- On which sector?



On modern drives, both seek and rotation are roughly equivalent:
Thus, SPTF (Shortest Positioning Time First) is useful.

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OPTIMIZATION: I/O MERGING

- Group temporary adjacent requests
- Reduce overhead
- Read (memory blocks): 33 8 34
- How long we should wait for I/O ?
- When do we know we have waited too long?

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QUESTIONS

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