ANNOUNCEMENTS

2nd Exam: Congratulations on finishing!

- More than half-way through course material

P3: Due tomorrow at 9:00 pm

- Only turn in code in one project partner's handin directory

P4: Threads (Part a and b) available near end of week

- Can choose or be matched with new partner

Read as we go along!

- Chapter 36 + 37

UNIVERSITY of WISCONSIN-MADISON
Computer Sciences Department

CS 537
Introduction to Operating Systems

Andrea C. Arpaci-Dusseau
Remzi H. Arpaci-Dusseau

PERSISTENCE: I/O DEVICES

Questions answered in this lecture:

How does the OS **interact** with I/O devices (check status, send data+control)?

What is a **device driver**?

What are the components of a **hard disk drive**?

How can you calculate **sequential** and **random throughput** of a disk?

What algorithms are used to **schedule I/O** requests?

MOTIVATION

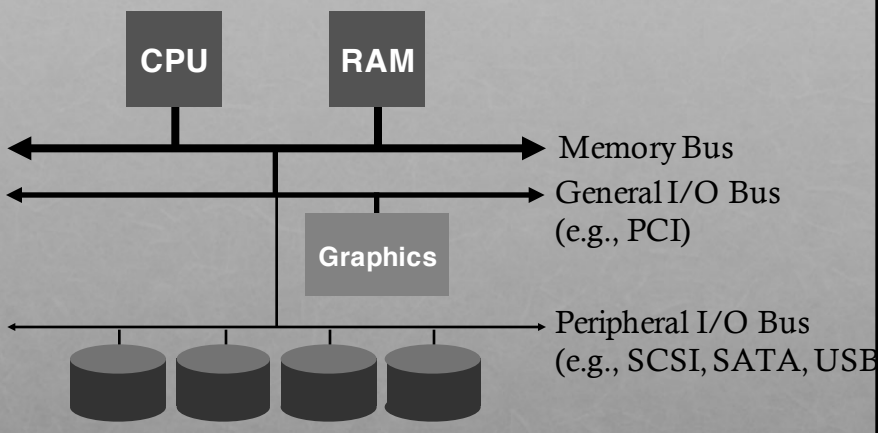
What good is a computer without any I/O devices?

- keyboard, display, disks

We want:

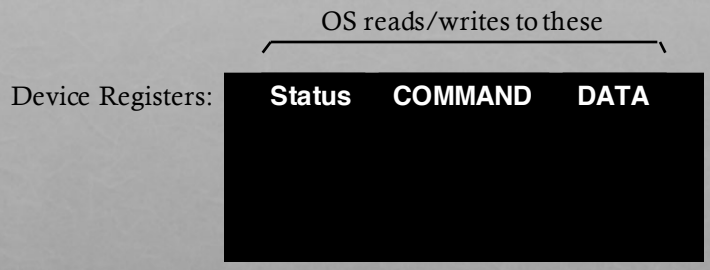
- **H/W** that will let us plug in different devices
- **OS** that can interact with different combinations

HARDWARE SUPPORT FOR I/O



Why use hierarchical buses?

CANONICAL DEVICE



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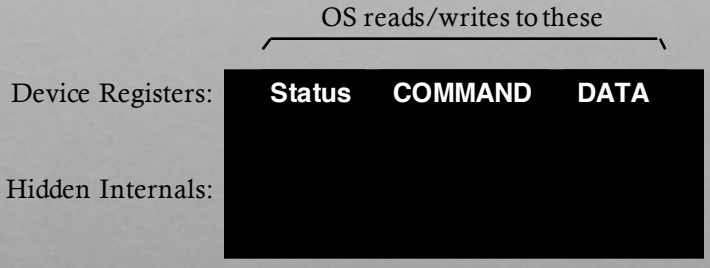

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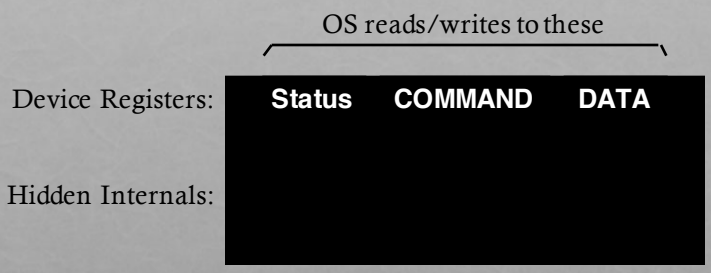

EXAMPLE WRITE PROTOCOL


```
while (STATUS == BUSY)
  ; // spin
Write data to DATA register
Write command to COMMAND register
while (STATUS == BUSY)
  ; // spin
```

CPU:

Disk:

```
while (STATUS == BUSY)              // 1
  ;
Write data to DATA register         // 2
Write command to COMMAND register   // 3
while (STATUS == BUSY)              // 4
  ;
```

CPU: **A**

Disk: **C**

```
while (STATUS == BUSY)              // 1
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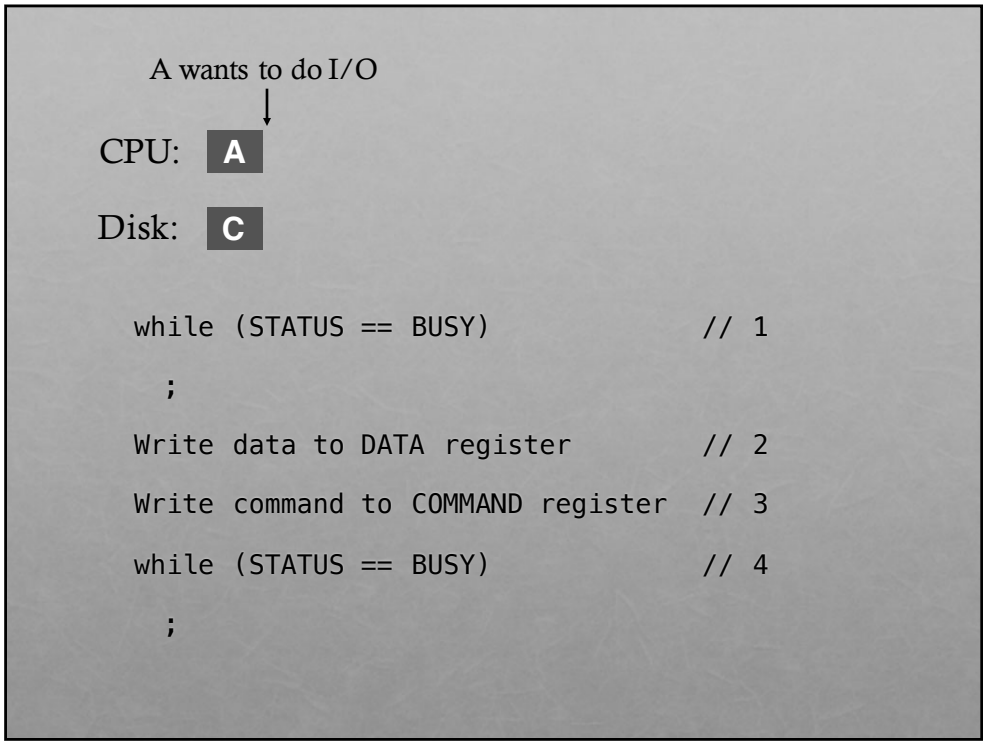


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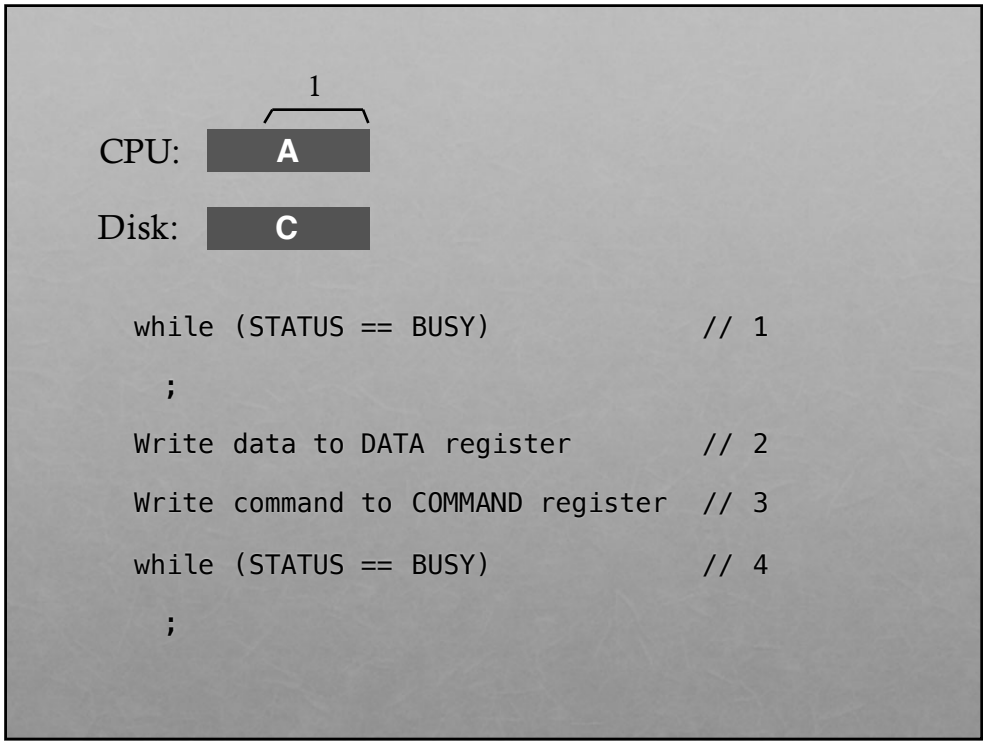


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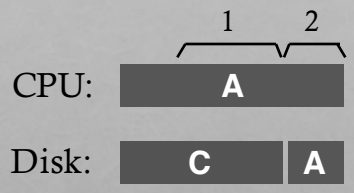


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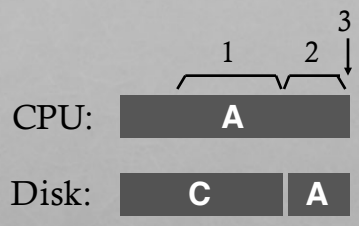


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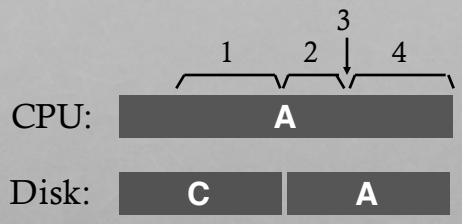


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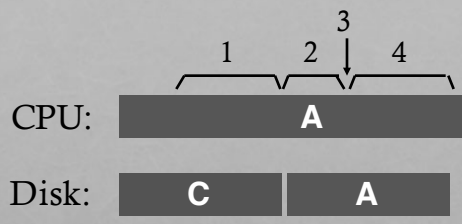


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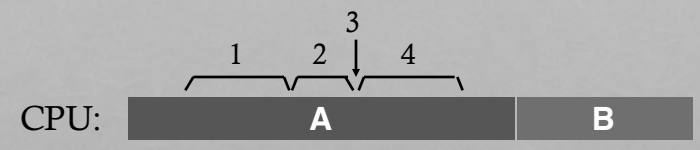


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how to avoid spinning? interrupts!

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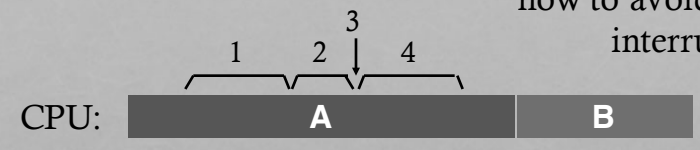


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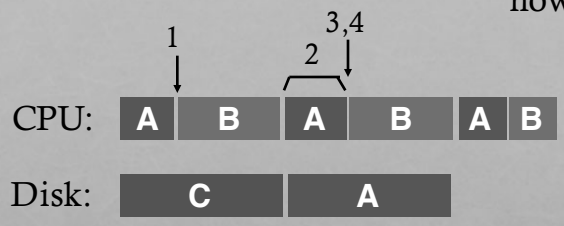
how to avoid spinning?
interrupts!

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INTERRUPTS VS. POLLING

Are interrupts ever worse than polling?

Fast device: Better to spin than take interrupt overhead

- Device time unknown? Hybrid approach (spin then use interrupts)

Flood of interrupts arrive

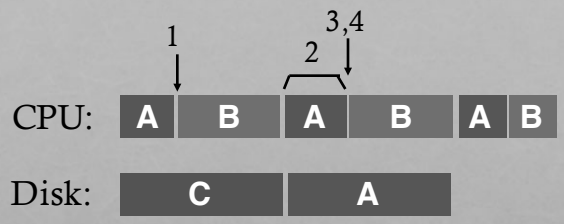
- Can lead to livelock (always handling interrupts)
- Better to ignore interrupts while make some progress handling them

Other improvement

- Interrupt coalescing (batch together several interrupts)

PROTOCOL VARIANTS

- **Status checks**: polling *vs.* interrupts
- **Data**: PIO *vs.* DMA
- **Control**: special instructions *vs.* memory-mapped I/O

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```

what else can we optimize? data transfer!

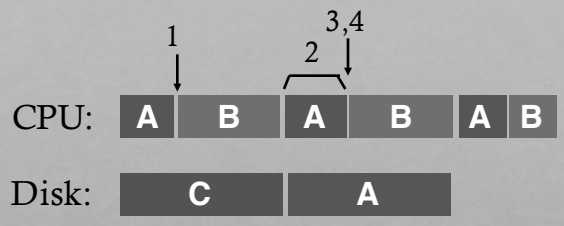
PROGRAMMED I/O VS. DIRECT MEMORY ACCESS

PIO (Programmed I/O):

- CPU directly tells device what the data is

DMA (Direct Memory Access):

- CPU leaves data in memory
- Device reads data directly from memory

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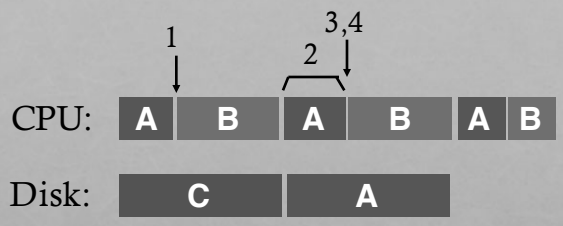


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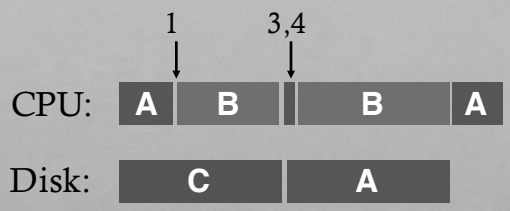


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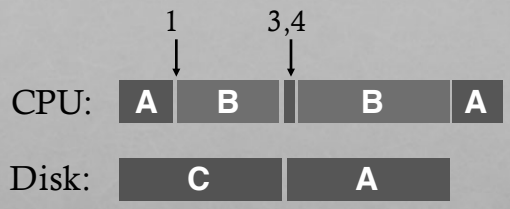
PROTOCOL VARIANTS

Status checks: polling *vs.* interrupts

Data: PIO *vs.* DMA

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

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```

how does OS read and write registers?

SPECIAL INSTRUCTIONS VS. MEM-MAPPED I/O

Special instructions
- each device has a port
- in/out instructions (x86) communicate with device

Memory-Mapped I/O
- H/W maps registers into address space
- loads/stores sent to device

Doesn't matter much (both are used)

PROTOCOL VARIANTS

Status checks: polling *vs.* interrupts

Data: PIO *vs.* DMA

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

VARIETY IS A CHALLENGE

Problem:

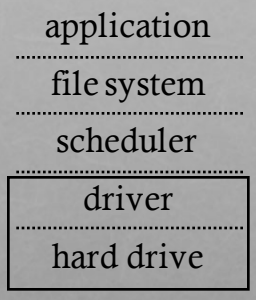
- many, many devices
- each has its own protocol

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

Write device driver for each device

Drivers are **70%** of Linux source code

STORAGE STACK



build common interface on top of all HDDs

HARD DISKS

BASIC INTERFACE

Disk has a sector-addressable address space
- Appears as an array of sectors

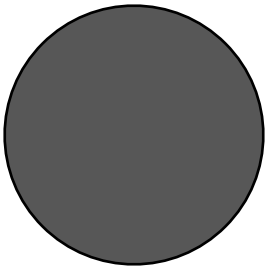
Sectors are typically 512 bytes or 4096 bytes.

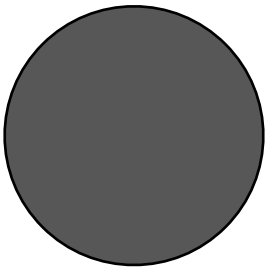
Main operations: reads + writes to sectors

Mechanical (slow) nature makes management "interesting"

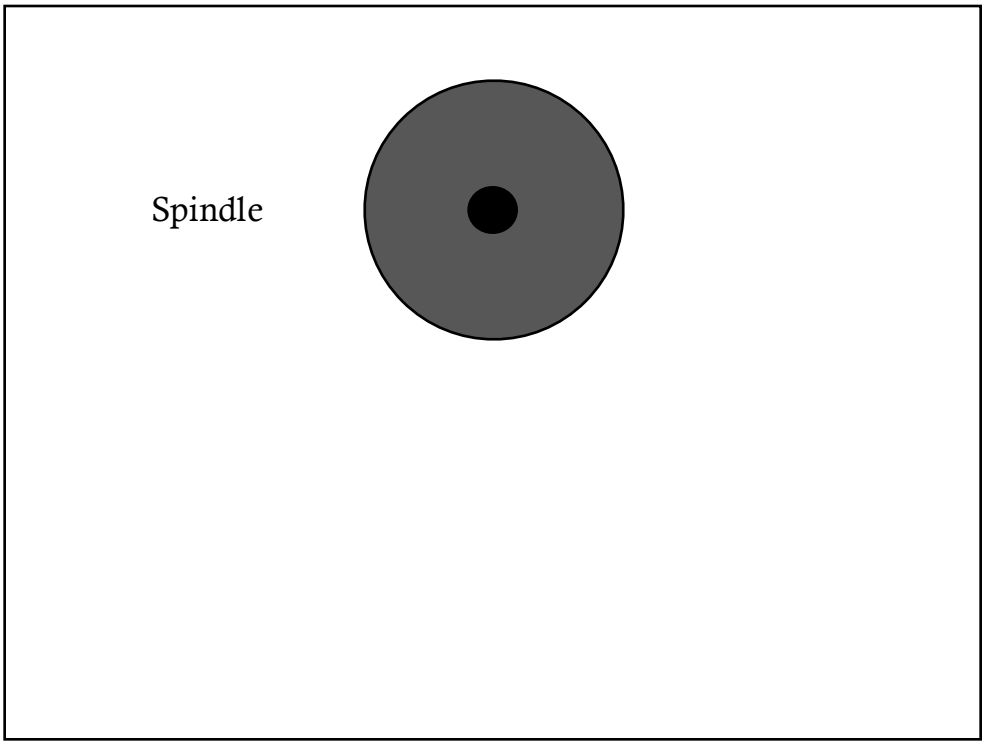
Disk Internals

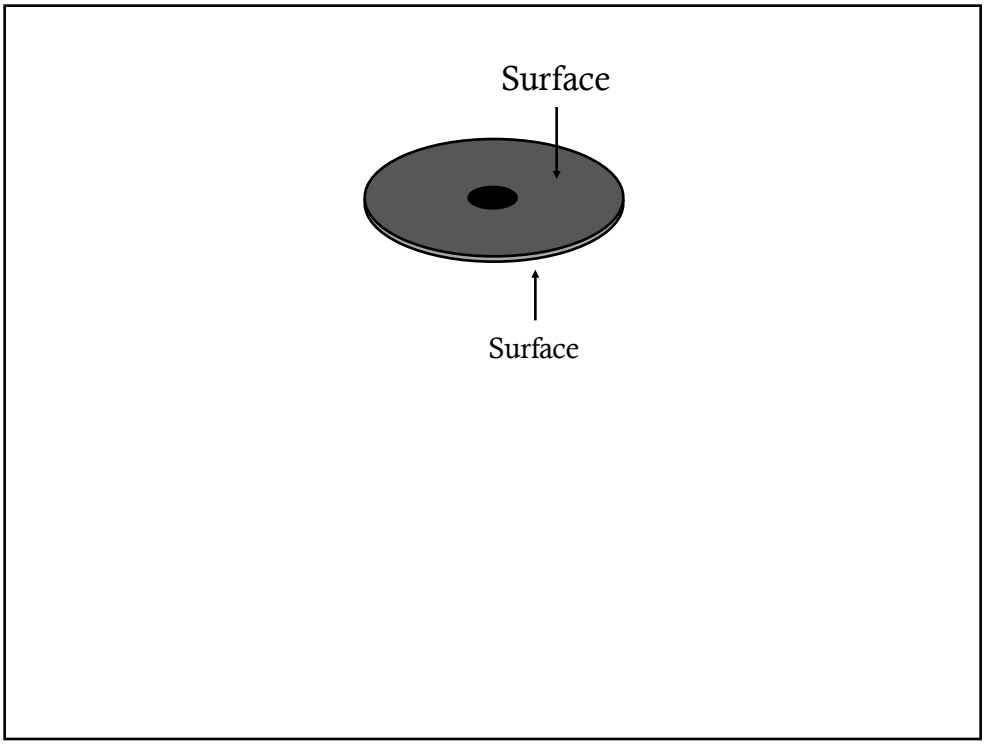
Platter

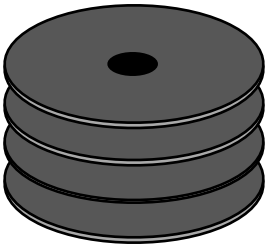




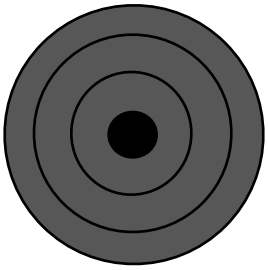
Platter is covered with a magnetic film.


Spindle

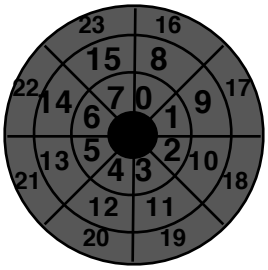

Surface
Surface



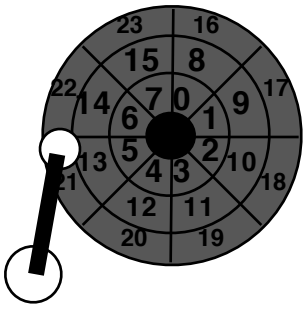
Many platters may be bound to the spindle.



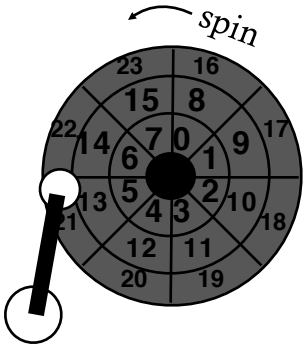
Each surface is divided into rings called tracks.
A stack of tracks (across platters) is called a cylinder.



The tracks are divided into numbered sectors.

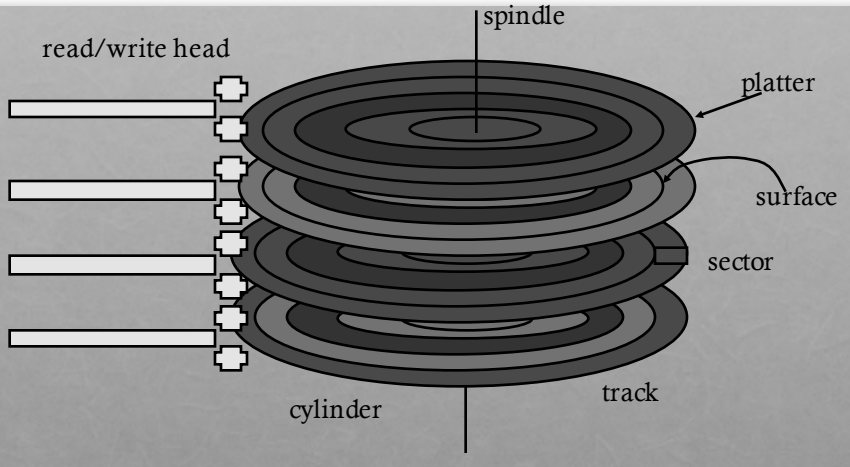


Heads on a moving arm can read from each surface.



Spindle/platters rapidly spin.

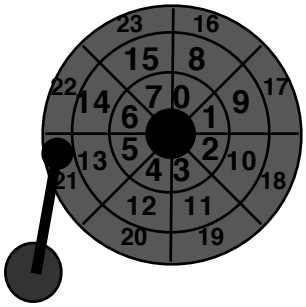
DISK TERMINOLOGY



HARD DRIVE DEMO

- http://youtu.be/9eMWG3fwiEU?t=30s
- https://www.youtube.com/watch?v=L0nbo1VOF4M

LET'S READ 12!



POSITIONING

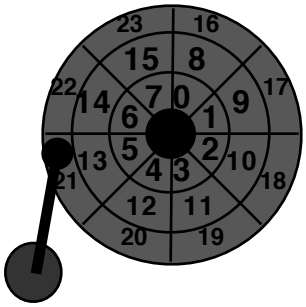
Drive servo system keeps head on track

- How does the disk head know where it is?
- Platters not perfectly aligned, tracks not perfectly concentric (runout) -- difficult to stay on track
- More difficult as density of disk increase
  - More bits per inch (BPI), more tracks per inch (TPI)

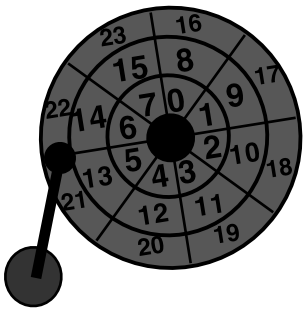
Use servo burst:

- Record placement information every few (3-5) sectors
- When head cross servo burst, figure out location and adjust as needed

LET'S READ 12!



SEEK TO RIGHT TRACK.



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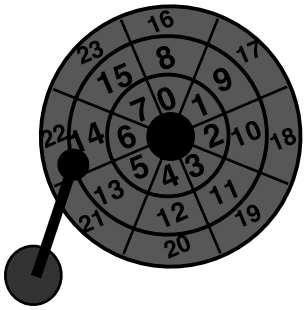

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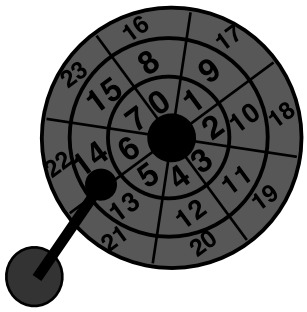
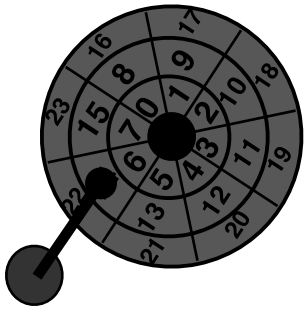


WAIT FOR ROTATION.



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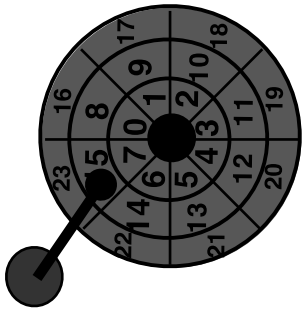

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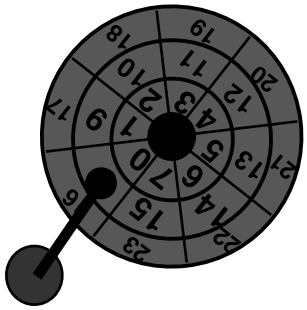

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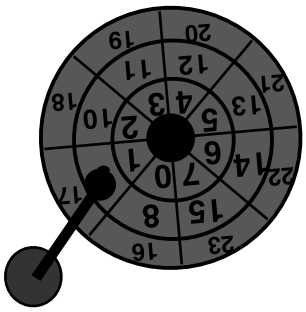
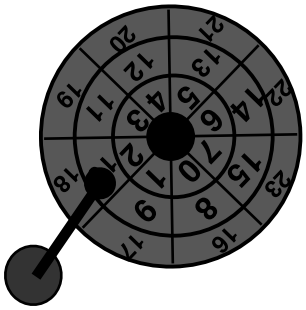
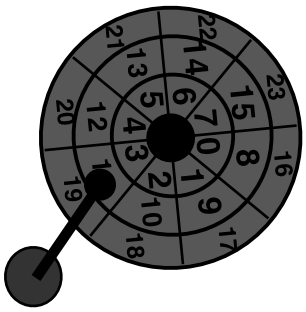


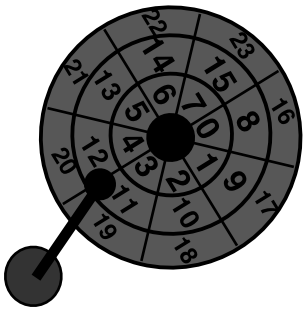
WAIT FOR ROTATION.



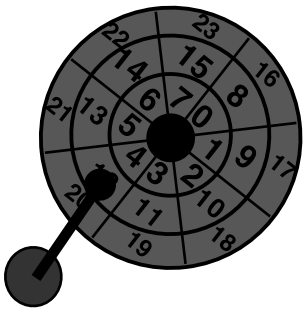
WAIT FOR ROTATION.



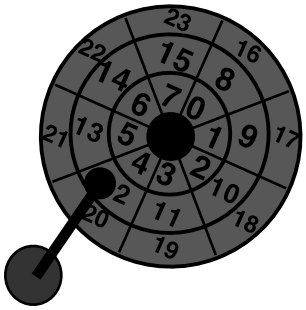
TRANSFER DATA.



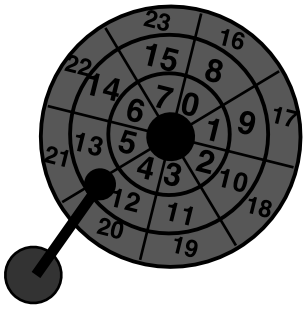
TRANSFER DATA.



TRANSFER DATA.



YAY!



TIME TO READ/WRITE

Three components:

Time = seek + rotation + transfer time

SEEK, ROTATE, TRANSFER

Seek cost: Function of cylinder distance

- Not purely linear cost

Must accelerate, coast, decelerate, settle

Settling alone can take 0.5 - 2 ms

Entire seeks often takes several milliseconds

- 4 - 10 ms

Approximate average seek distance = 1/3 max seek distance

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

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 us

WORKLOAD PERFORMANCE

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 SPEC

	Cheetah	Barracuda
Capacity	300 GB	1 TB
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s
Platters	4	4
Cache	16 MB	32 MB

Sequential workload: what is throughput for each?

Cheeta: 125 MB/s.
Barracuda: 105 MB/s.

DISK SPEC

	Cheetah	Barracuda
Capacity	300 GB	1 TB
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Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s
Platters	4	4
Cache	16 MB	32 MB

Random workload: what is throughput for each?
(what else do you need to know?)

What is size of each random read?
Assume 16-KB reads

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average random 16-KB read take w/ Cheetah?

Seek + rotation + transfer

Seek = 4 ms

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average random 16-KB read take w/ Cheetah?
Average rotation in ms?

$$\text{avg rotation} = \frac{1}{2} \times \frac{1\ \text{min}}{15000} \times \frac{60\ \text{sec}}{1\ \text{min}} \times \frac{1000\ \text{ms}}{1\ \text{sec}} = 2\ \text{ms}$$

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average random 16-KB read take w/ Cheetah?

Transfer of 16 KB?

$$\text{transfer} = \frac{1\ \text{sec}}{125\ \text{MB}} \times 16\ \text{KB} \times \frac{1{,}000{,}000\ \text{us}}{1\ \text{sec}} = 125\ \text{us}$$

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average random 16-KB read take w/ Cheetah?

Cheetah time = 4ms + 2ms + 125us = 6.1ms

Throughput?

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average random 16-KB read take w/ Cheetah?

Cheetah time = 4ms + 2ms + 125us = 6.1ms

$$\text{throughput} = \frac{16\,\text{KB}}{6.1\text{ms}} \times \frac{1\,\text{MB}}{1024\,\text{KB}} \times \frac{100\,\text{ms}}{1\,\text{sec}} = 2.5\,\text{MB/s}$$

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average random 16-KB read take w/ Barracuda?

Time = seek + rotation + transfer

Seek = 9ms

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average random 16-KB read take w/ Barracuda?

$$\text{avg rotation} = \frac{1}{2} \times \frac{1\text{ min}}{7200} \times \frac{60\text{ sec}}{1\text{ min}} \times \frac{1000\text{ ms}}{1\text{ sec}} = 4.1\text{ ms}$$

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average random 16-KB read take w/ Barracuda?

$$\text{transfer} = \frac{1\text{ sec}}{105\text{ MB}} \times 16\text{ KB} \times \frac{1{,}000{,}000\text{ us}}{1\text{ sec}} = 149\text{ us}$$

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average random 16-KB read take w/ Barracuda?

Barracuda time = 9ms + 4.1ms + 149us = 13.2ms

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average random 16-KB read take w/ Barracuda?

Barracuda time = 9ms + 4.1ms + 149us = 13.2ms

$$\text{throughput} = \frac{16\,\text{KB}}{13.2\text{ms}} \times \frac{1\,\text{MB}}{1024\,\text{KB}} \times \frac{1000\,\text{ms}}{1\,\text{sec}} = 1.2\,\text{MB/s}$$

	Cheetah	Barracuda
Capacity	300 GB	1 TB
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s
Platters	4	4
Cache	16 MB	32 MB

	Cheetah	Barracuda
Sequential	125 MB/s	105 MB/s
Random	2.5 MB/s	1.2 MB/s

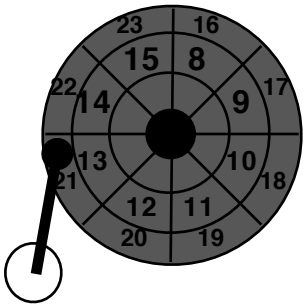
OTHER IMPROVEMENTS

Track Skew

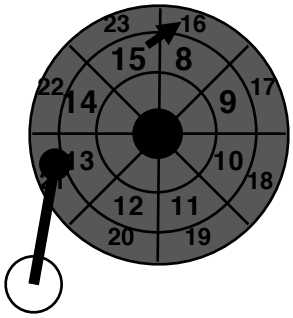
Zones

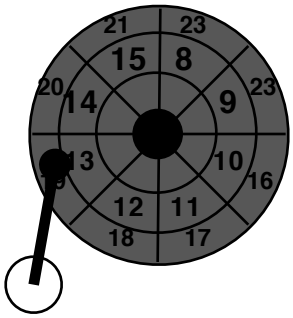
Cache

Imagine sequential reading,
how should sectors numbers be laid out on disk?

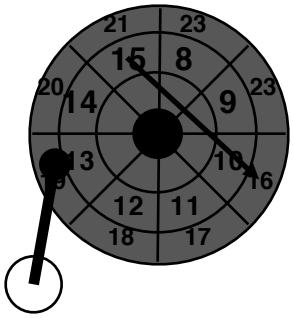


When reading 16 after 15, the head won't settle
quick enough, so we need to do a rotation.





enough time to settle now

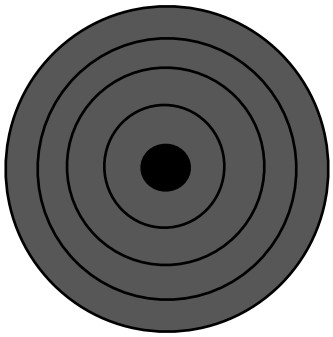


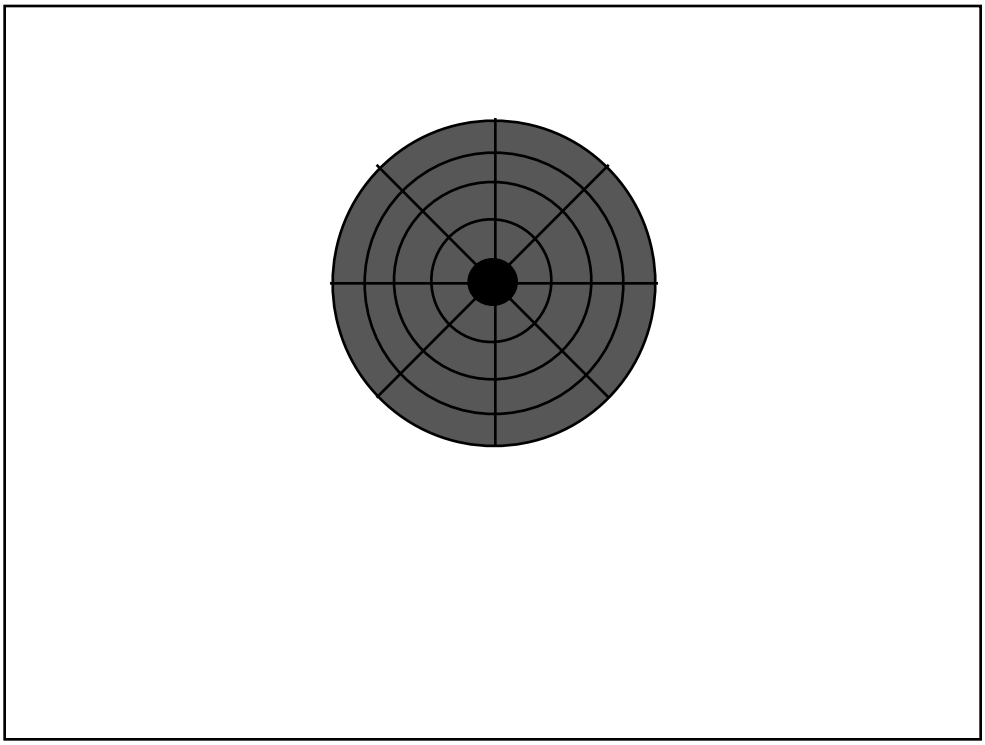
OTHER IMPROVEMENTS

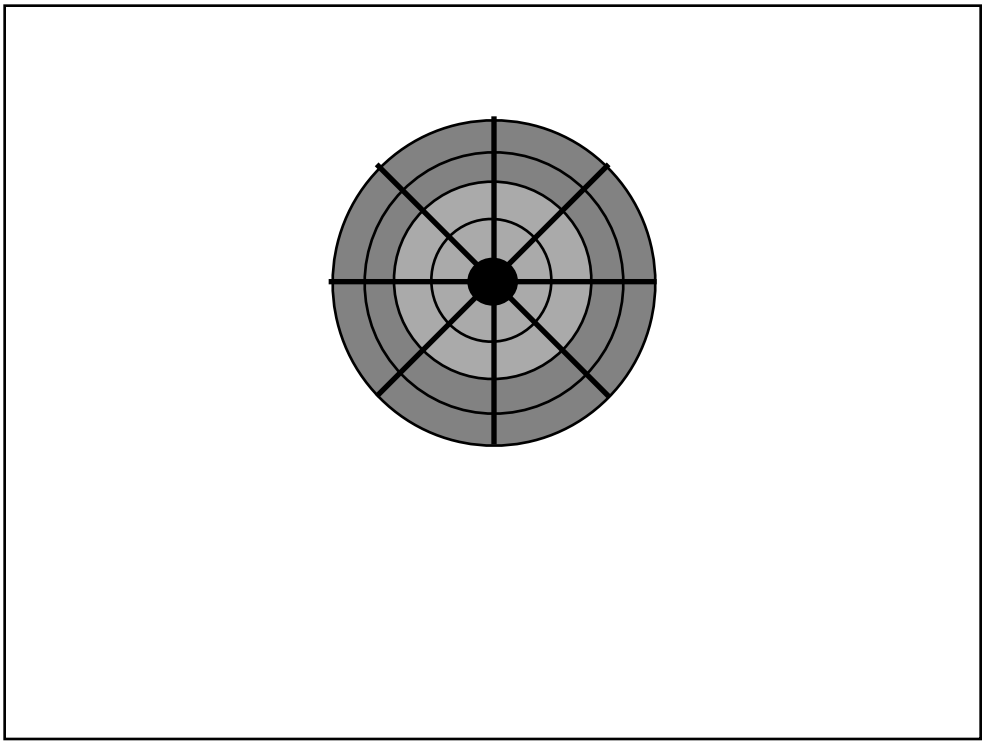
Track Skew

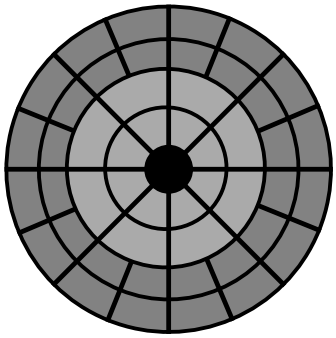
Zones

Cache









ZBR (Zoned bit recording): More sectors on outer tracks

OTHER IMPROVEMENTS

Track Skew

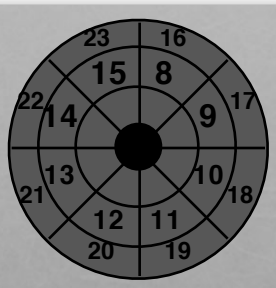
Zones

Cache

DRIVE CACHE

Drives may cache both reads and writes.

- OS caches data too



What advantage does caching in **drive** have for reads?

What advantage does caching in **drive** have for writes?

BUFFERING

Disks contain internal memory (2MB-16MB) used as cache

Read-ahead: "Track buffer"

- Read contents of entire track into memory during rotational delay

Write caching with volatile memory

- Immediate reporting: Claim written to disk when not
- Data could be lost on power failure

Tagged command queueing

- Have multiple outstanding requests to the disk
- Disk can reorder (schedule) requests for better performance

I/O SCHEDULERS

I/O SCHEDULERS

Given a stream of I/O requests, in what order should they be served?

Much different than CPU scheduling

Position of disk head relative to request position matters more than length of job

FCFS (FIRST-COME-FIRST-SERVE)

Assume seek+rotate = 10 ms for random request

How long (roughly) does the below workload take?

- Requests are given in sector numbers

300001, 700001, 300002, 700002, 300003, 700003

~60ms

FCFS (FIRST-COME-FIRST-SERVE)

Assume seek+rotate = 10 ms for random request

How long (roughly) does the below workload take?

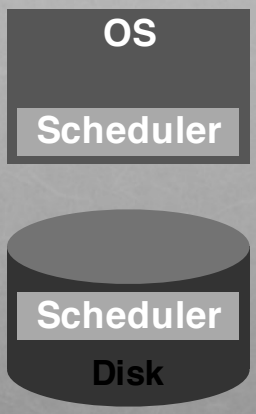
- Requests are given in sector numbers

~60ms

300001, 700001, 300002, 700002, 300003, 700003

300001, 300002, 300003, 700001, 700002, 700003 ~20ms

SCHEDULERS



Where should the scheduler go?

SPTF (SHORTEST POSITIONING TIME FIRST)

Strategy: always choose request that requires least positioning time (time for seeking and rotating)

- Greedy algorithm (just looks for best NEXT decision)

How to implement in **disk**?

How to implement in **OS**?

Use Shortest Seek Time First (SSTF) instead

Disadvantages?

Easy for far away requests to **starve**

SCAN

Elevator Algorithm:

- Sweep back and forth, from one end of disk other, serving requests as pass that cylinder
- Sorts by cylinder number; ignores rotation delays

Pros/Cons?

Better: C-SCAN (circular scan)

- Only sweep in one direction

WHAT HAPPENS?

Assume 2 processes each calling read() with C-SCAN

```
void reader(int fd) {
      char buf[1024];
      int rv;
      while((rv = read(buf)) != 0) {
            assert(rv);
            // takes short time, e.g., 1ms
            process(buf, rv);
      }
}
```

WORK CONSERVATION

Work conserving schedulers always try to do work if there's work to be done

Sometimes, it's better to wait instead if system **anticipates** another request will arrive

Such **non-work-conserving schedulers** are called **anticipatory** schedulers

CFQ (LINUX DEFAULT)

Completely Fair Queueing

- Queue for each process
- Weighted round-robin between queues, with slice time proportional to priority
- Yield slice only if idle for a given time (anticipation)

Optimize order within queue

I/O DEVICE SUMMARY

Overlap I/O and CPU whenever possible!

- use interrupts, DMA

Storage devices provide common block interface

On a disk: Never do random I/O unless you must!

- e.g., Quicksort is a terrible algorithm on disk

Spend time to schedule on slow, stateful devices