15-410

"...What goes around comes around..."

Disks
March 14, 2011

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Contributions from

- **Eno Thereska, Rahul Iyer**
- **15-213**
- **"How Stuff Works" web site**

Overview

Anatomy of a Hard Drive

Common Disk Scheduling Algorithms

A brief mention of SSD's

Anatomy of a Hard Drive

On the outside, a hard drive looks like this

Taken from “How Hard Disks Work”
http://computer.howstuffworks.com/hard-disk2.htm

Anatomy of a Hard Drive

If we take the cover off, we see that there actually is a "hard disk" inside

Taken from "How Hard Disks Work"
http://computer.howstuffworks.com/hard-disk2.htm

Anatomy of a Hard Drive

A hard drive usually contains multiple disks, called *platters*

These spin at thousands of RPM (5400, 7200, etc)

Taken from "How Hard Disks Work"
http://computer.howstuffworks.com/hard-disk2.htm

Anatomy of a Hard Drive

Information is written to and read from the platters by the *read/write heads* on the end of the *disk arm*

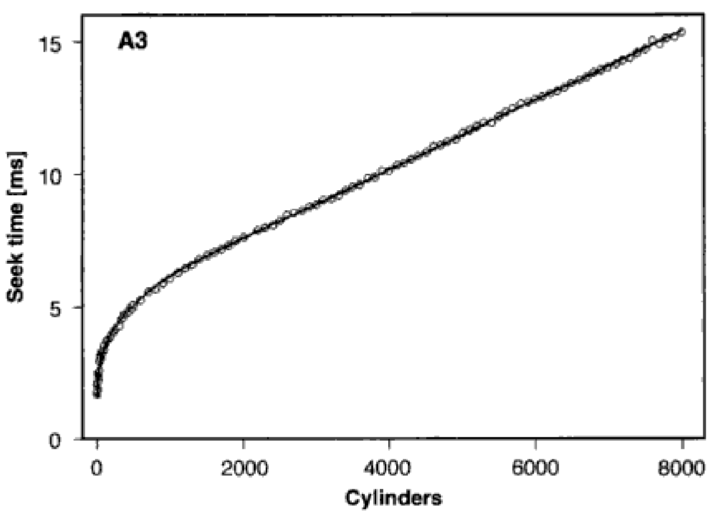
Taken from "How Hard Disks Work"
http://computer.howstuffworks.com/hard-disk2.htm

Anatomy of a Hard Drive

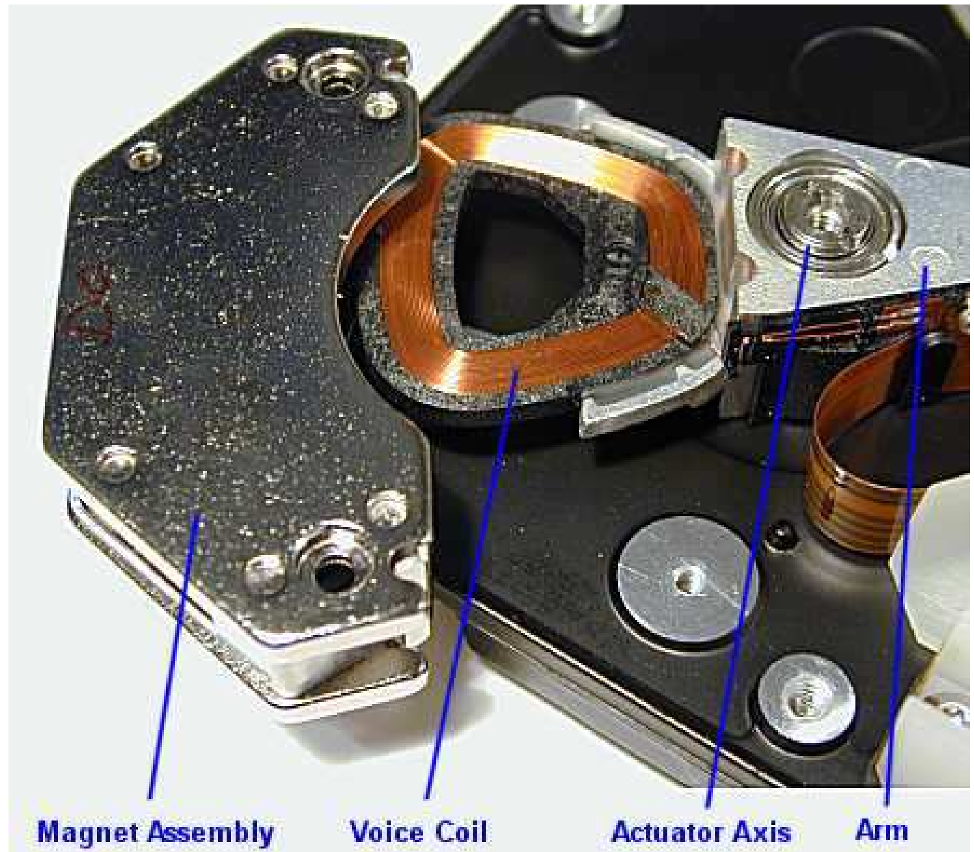
The arm is moved by a voice coil actuator

Slow, as computers go

- **Acceleration time**
- **Travel time**



Oklobdzija, Comp. Eng. Handbook, 2002



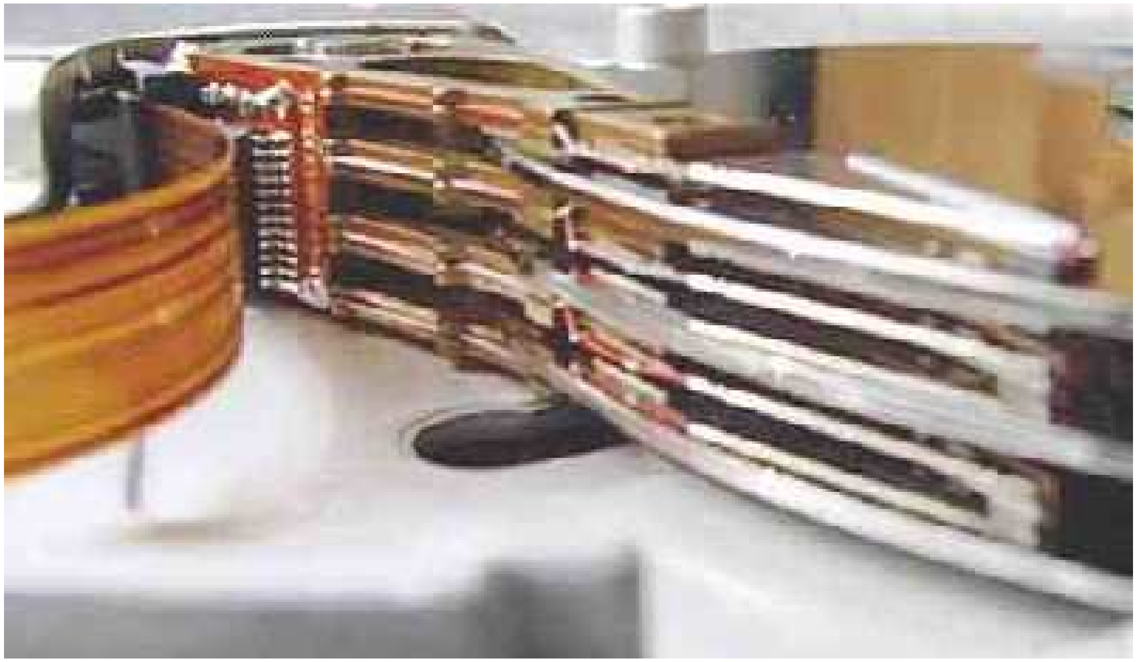
Taken from “Hard Disk Drives”
http://www.pcguide.com/ref/hdd

Anatomy of a Hard Drive

Both sides of each platter store information

Each side of a platter is called a *surface*

Each surface has its own read/write head



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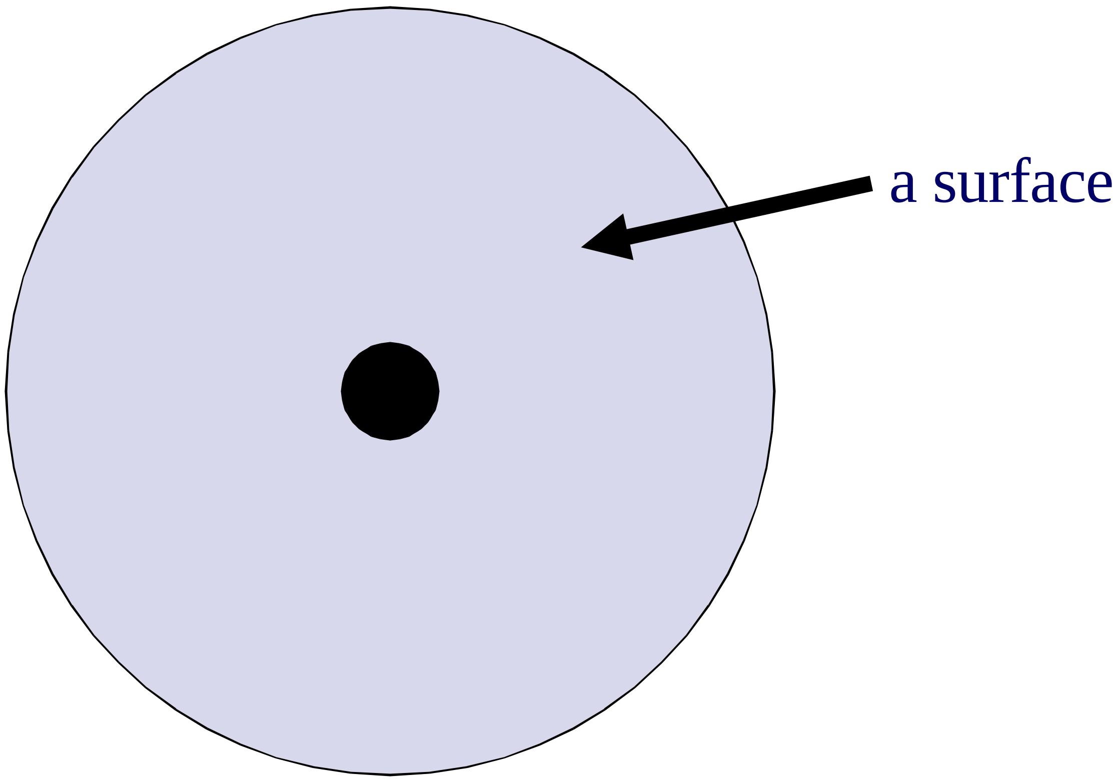
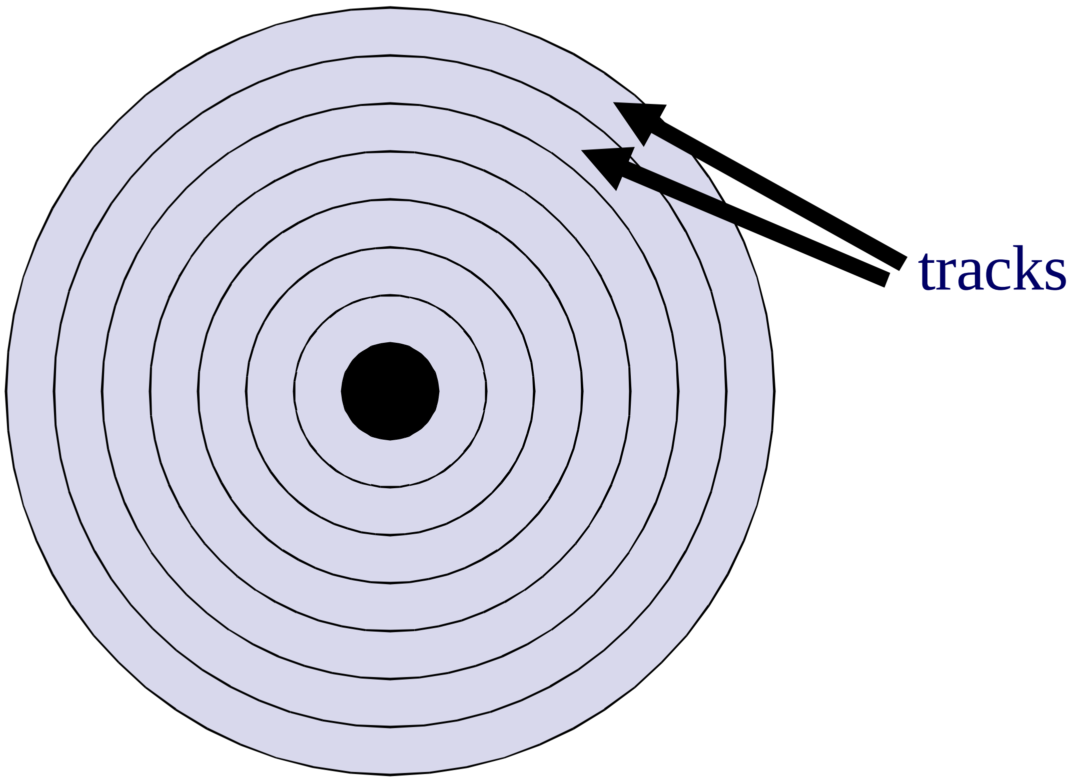
Anatomy of a Hard Drive

How are the surfaces organized?



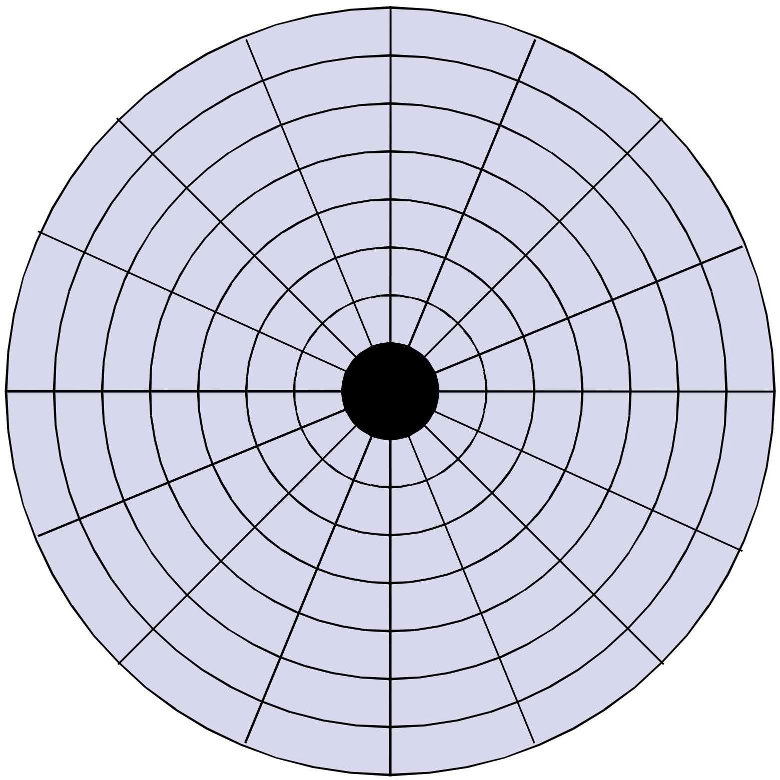
Anatomy of a Hard Drive

Each surface is divided by concentric circles, creating *tracks*



Anatomy of a Hard Drive

These tracks are further divided into *sectors*



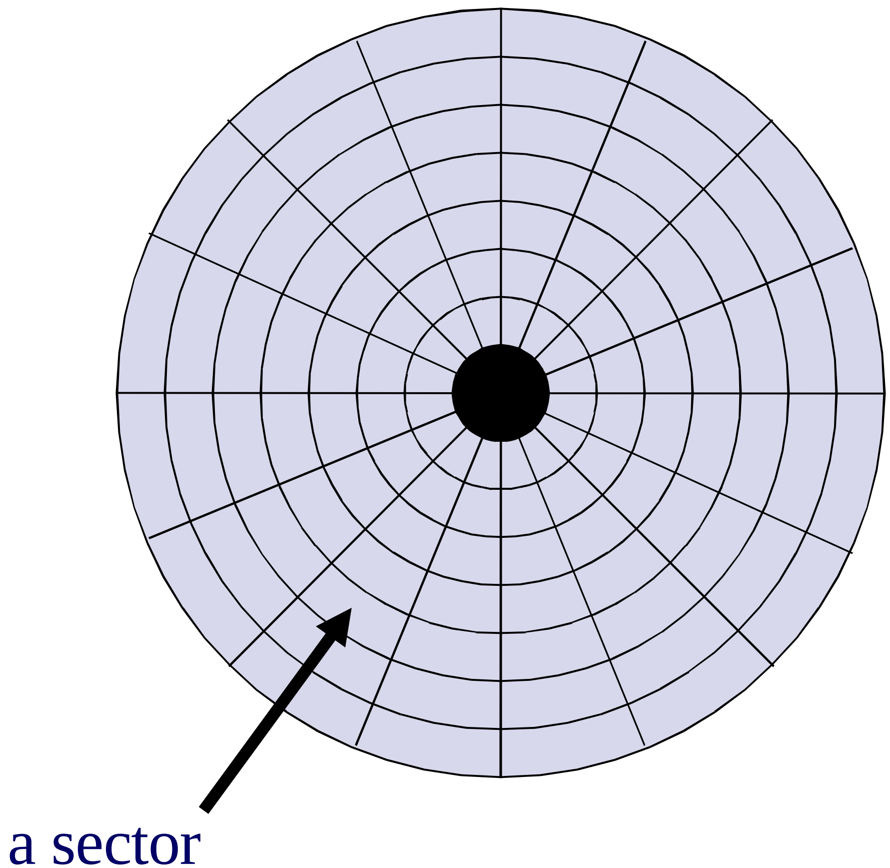
Anatomy of a Hard Drive

These tracks are further divided into *sectors*

A sector is the smallest unit of data transfer to or from the disk

- **512 bytes – traditional disks**
- **2048 bytes – CD-ROMs**
- **4096 bytes – 2010 disks**
  - **(pretend to be 512!)**

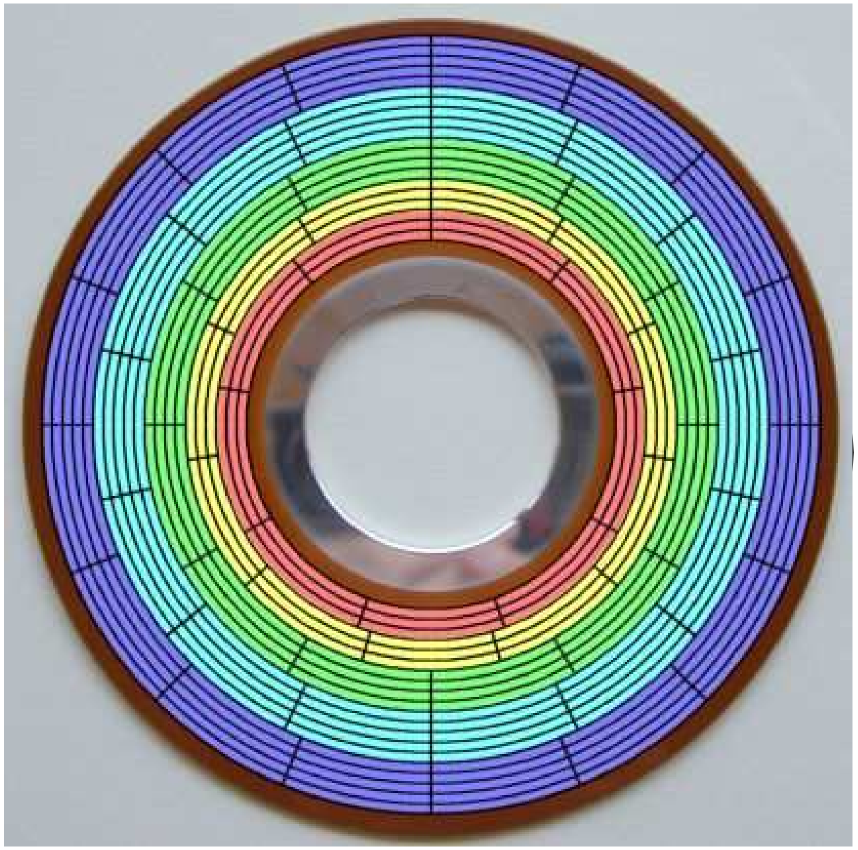
Gee, those outer sectors look bigger...?



Anatomy of a Hard Drive, Really

Modern hard drives use *zoned bit recording*

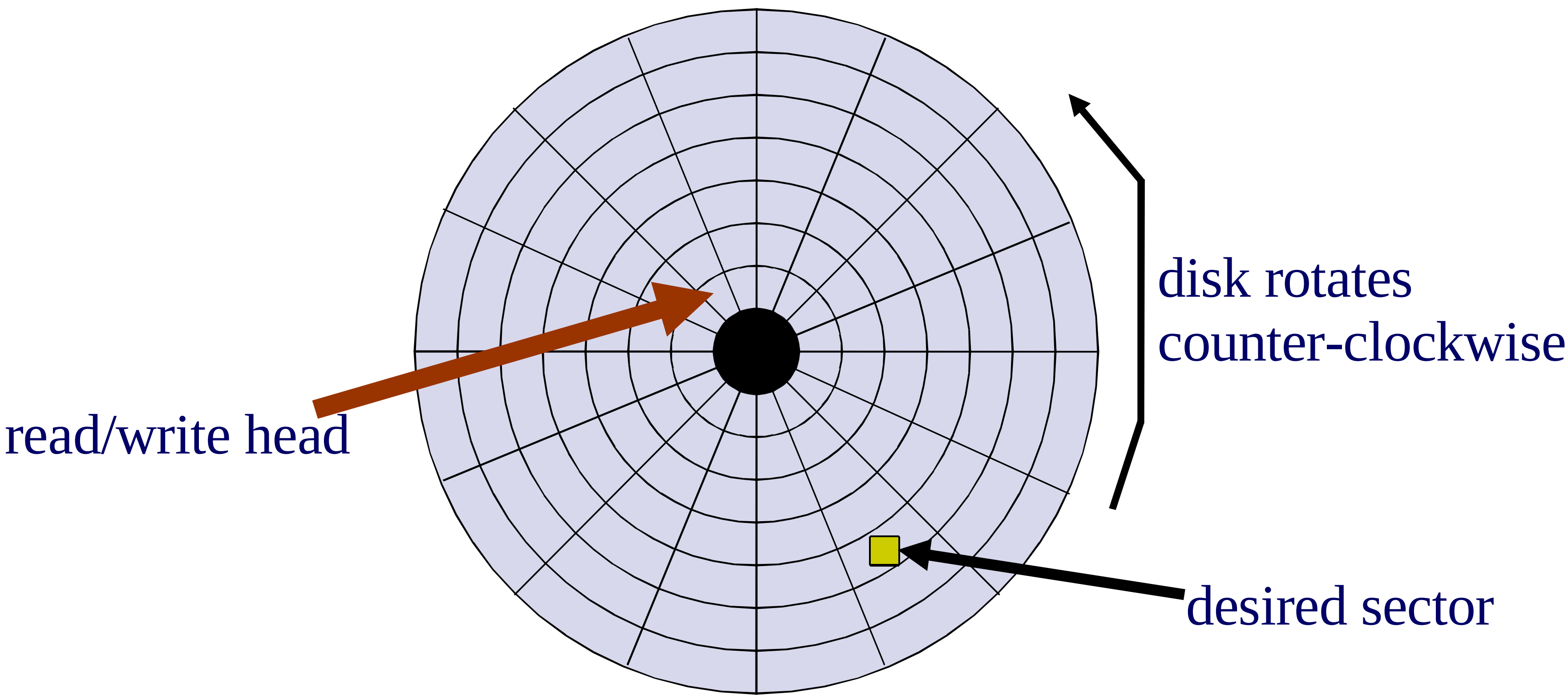
- **Disk has tables to map track# to #sectors**
- **Sectors are all roughly the same linear length**
- **Some old low-level code still thinks of "C/H/S addressing", but that's not what actually happens (for more than a decade!)**
  - **"sector address" names a sector like "page" names a frame**



Taken from "Reference Guide – Hard Disk Drives"
http://www.storagereview.com/map/lm.cgi/zone

Anatomy of a Hard Drive

Let's read in a sector from the disk



Anatomy of a Hard Drive

We need to do two things to transfer a sector

1. Move the read/write head to the appropriate track ("seek time")

2. Wait until the desired sector spins around ("rotational delay"/"rotational latency")

Observe

- **Average seeks are 2 – 10 msec**
- **Rotation of 5400/7200/10K/15K rpm means rotational delay of 11/8/6/4 msec**
- **Rotation dominates short seeks, matches average seeks**

Anatomy of a Hard Drive

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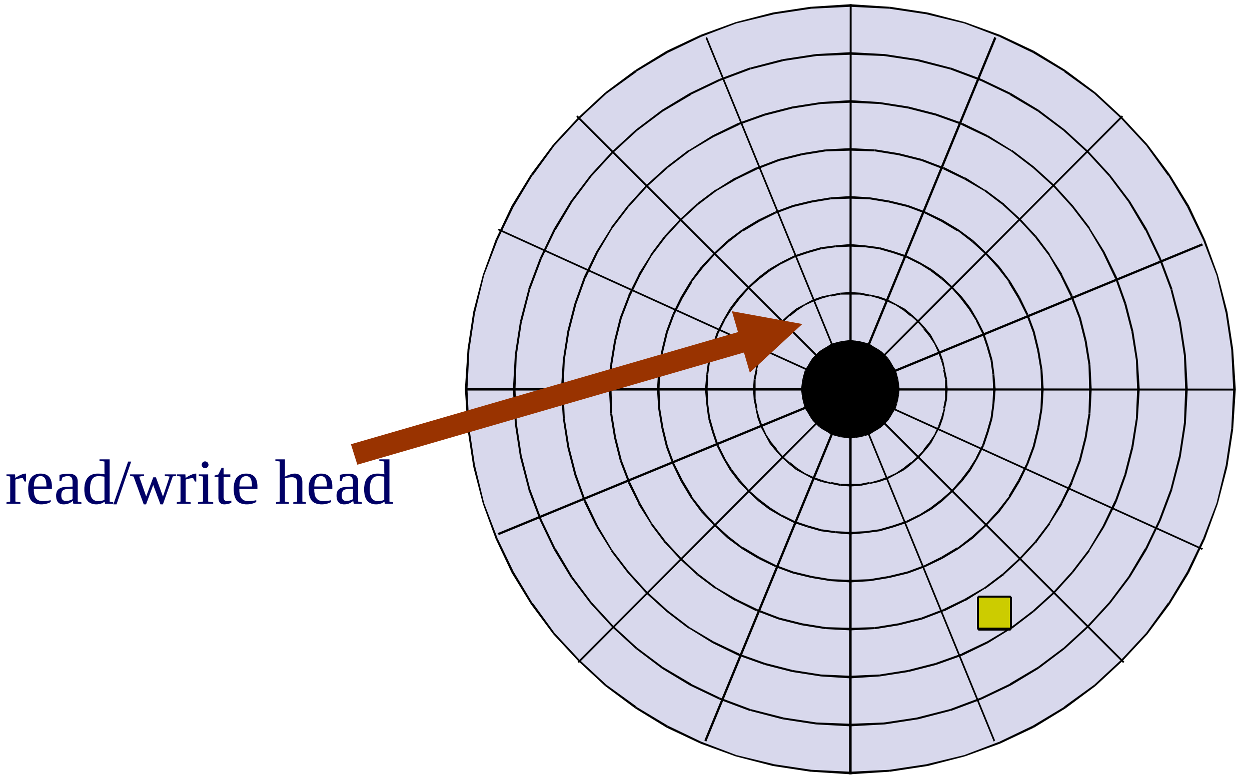

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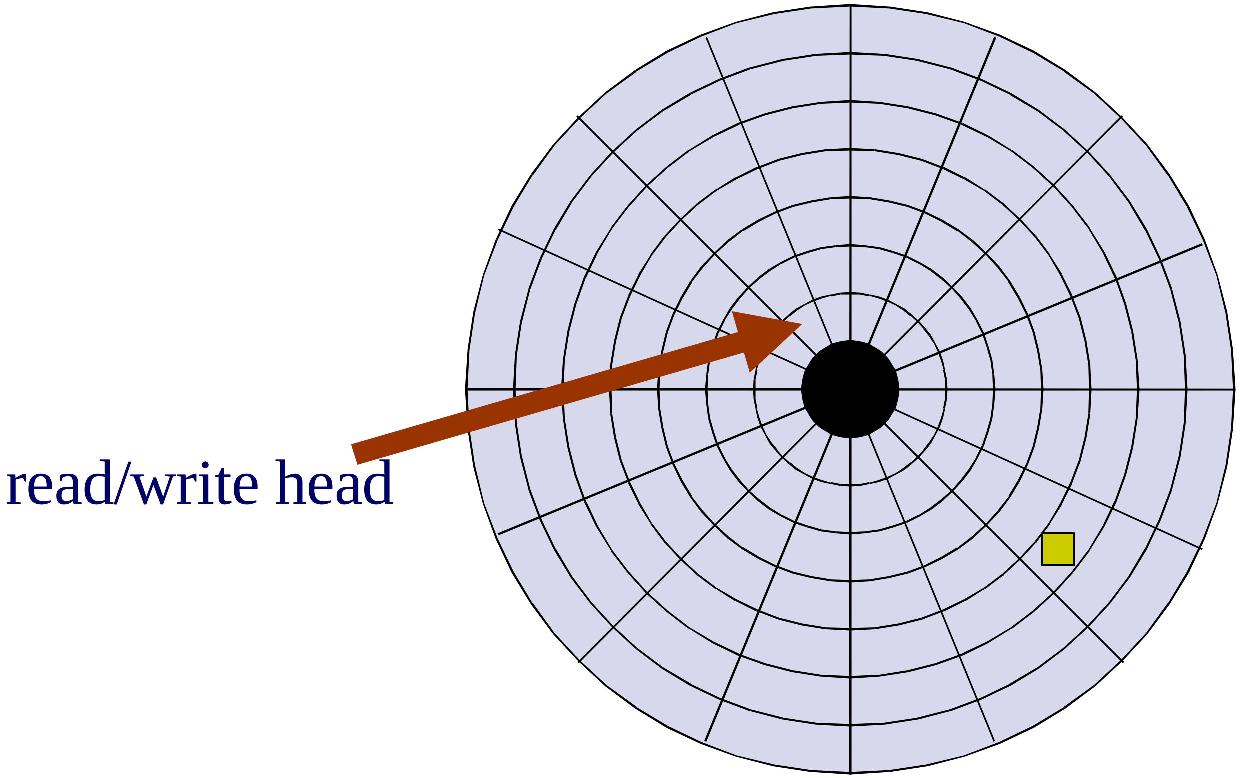

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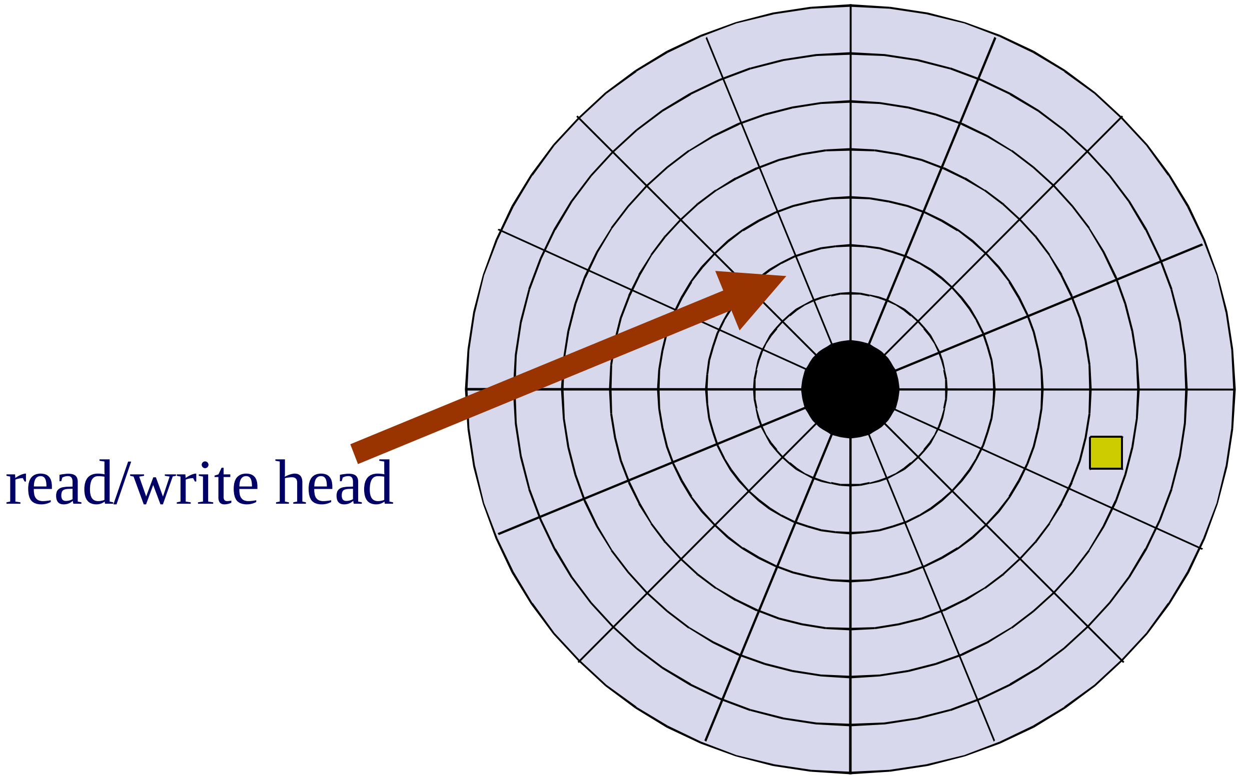

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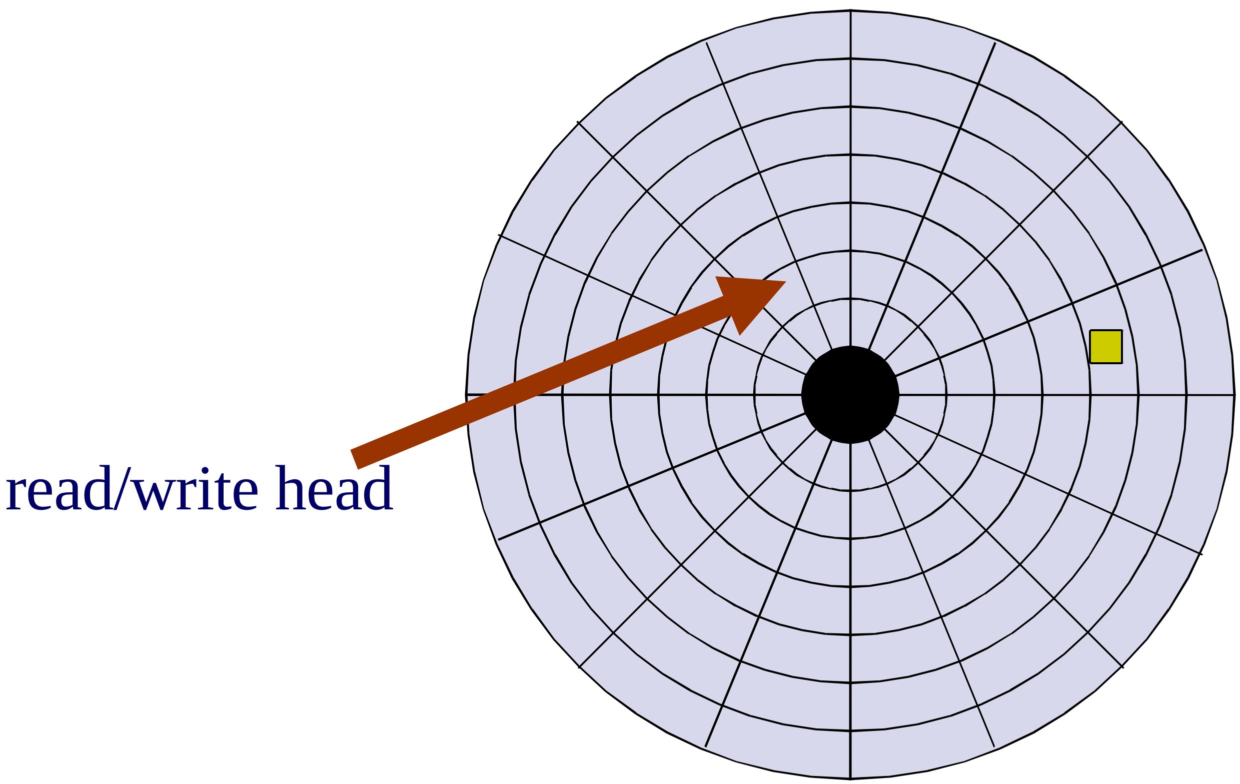

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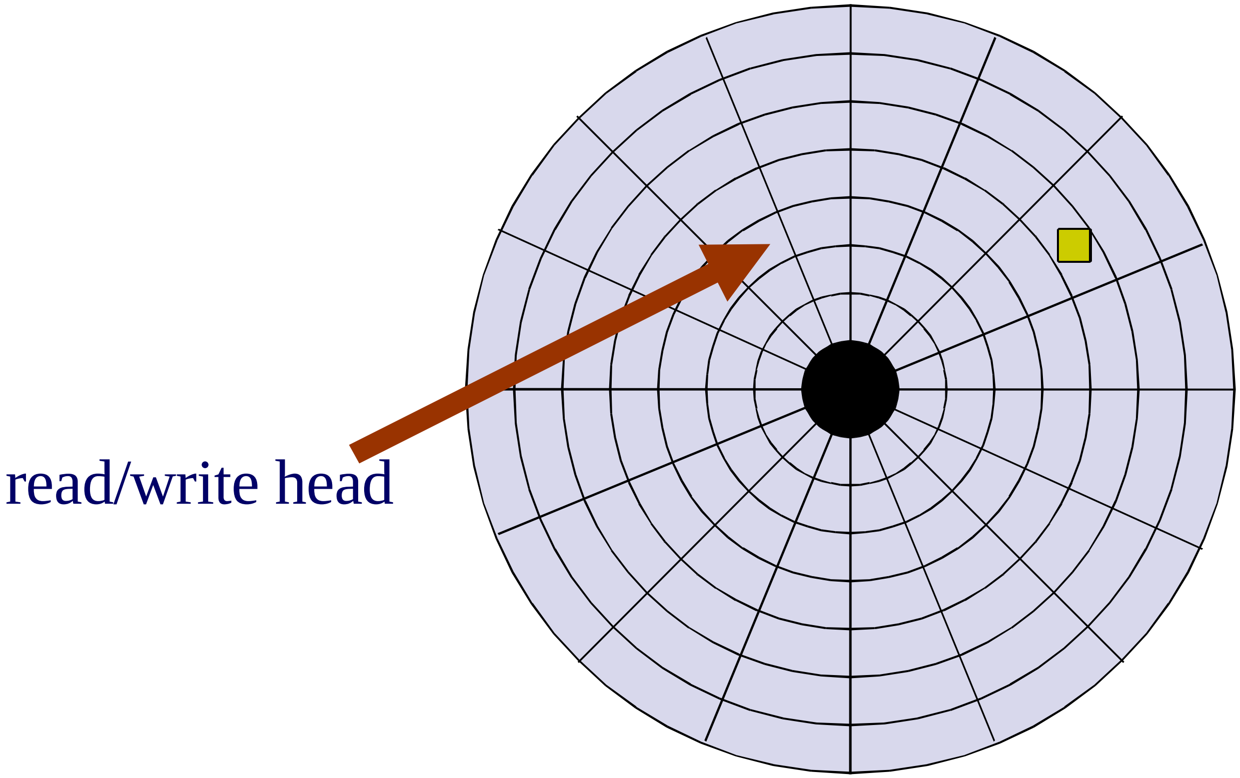

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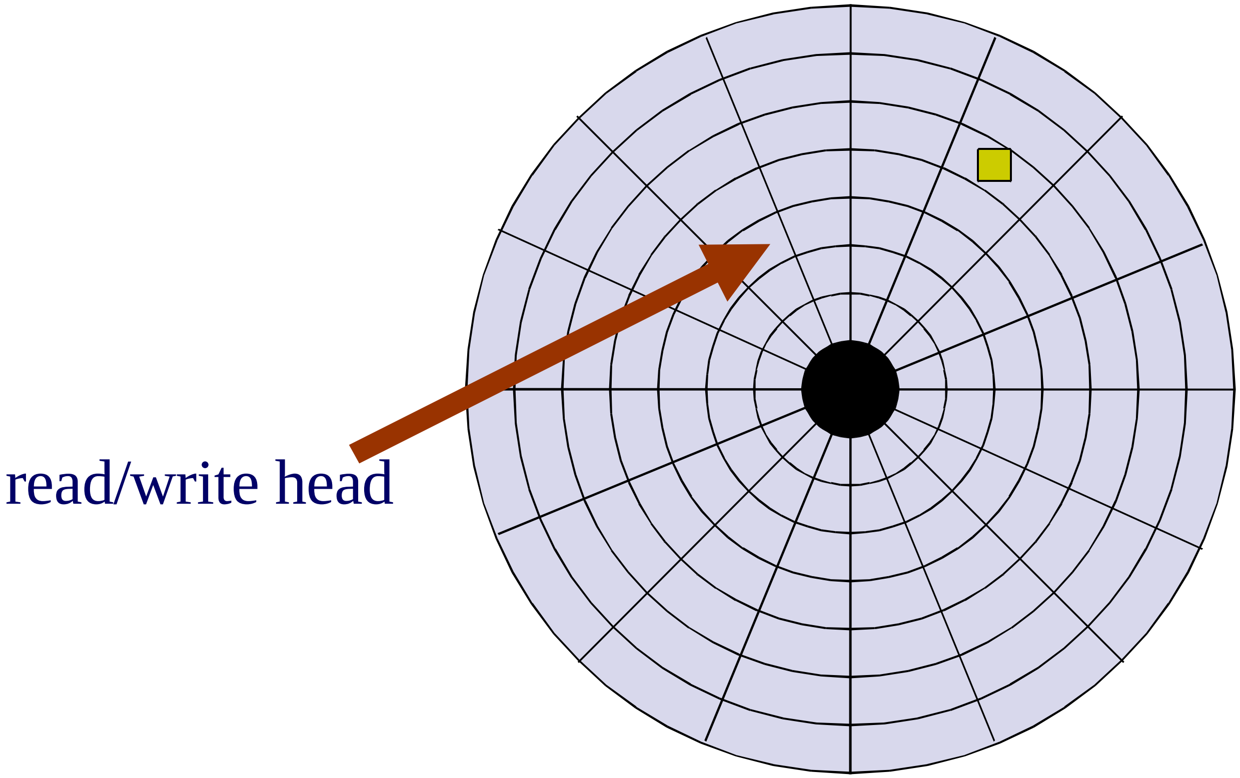

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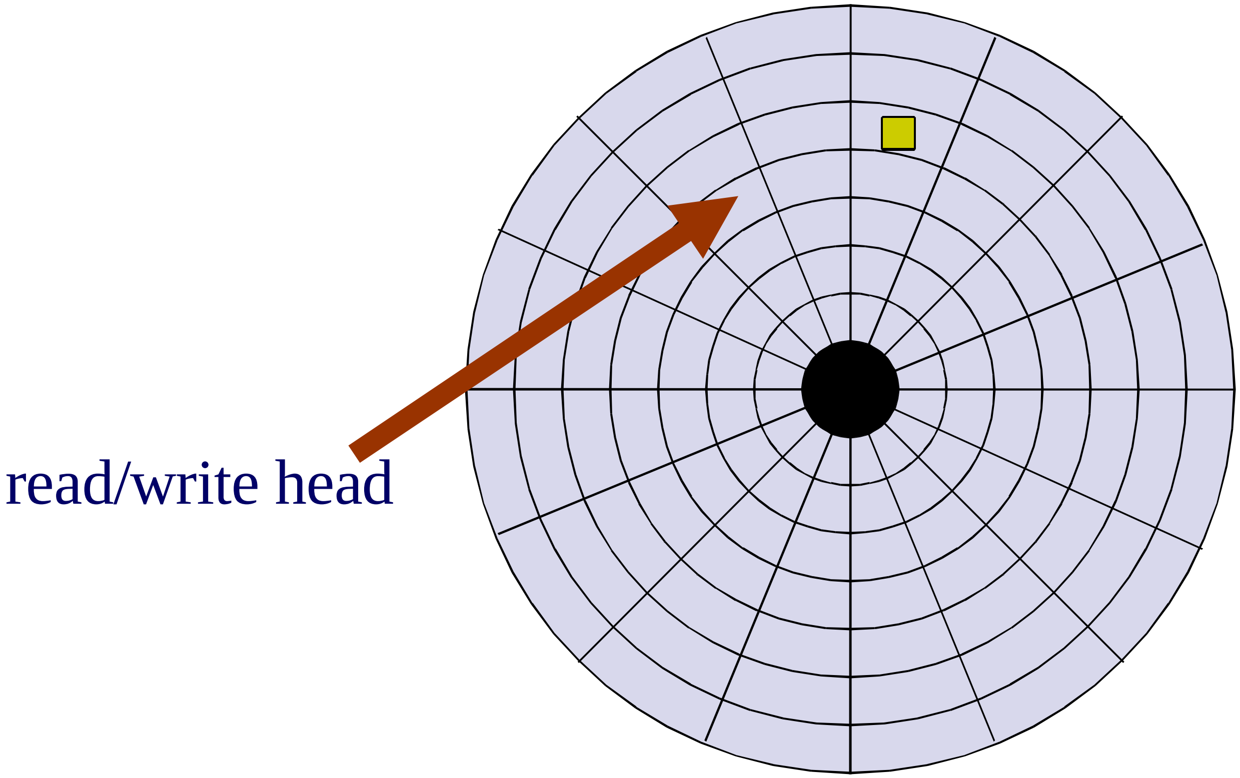

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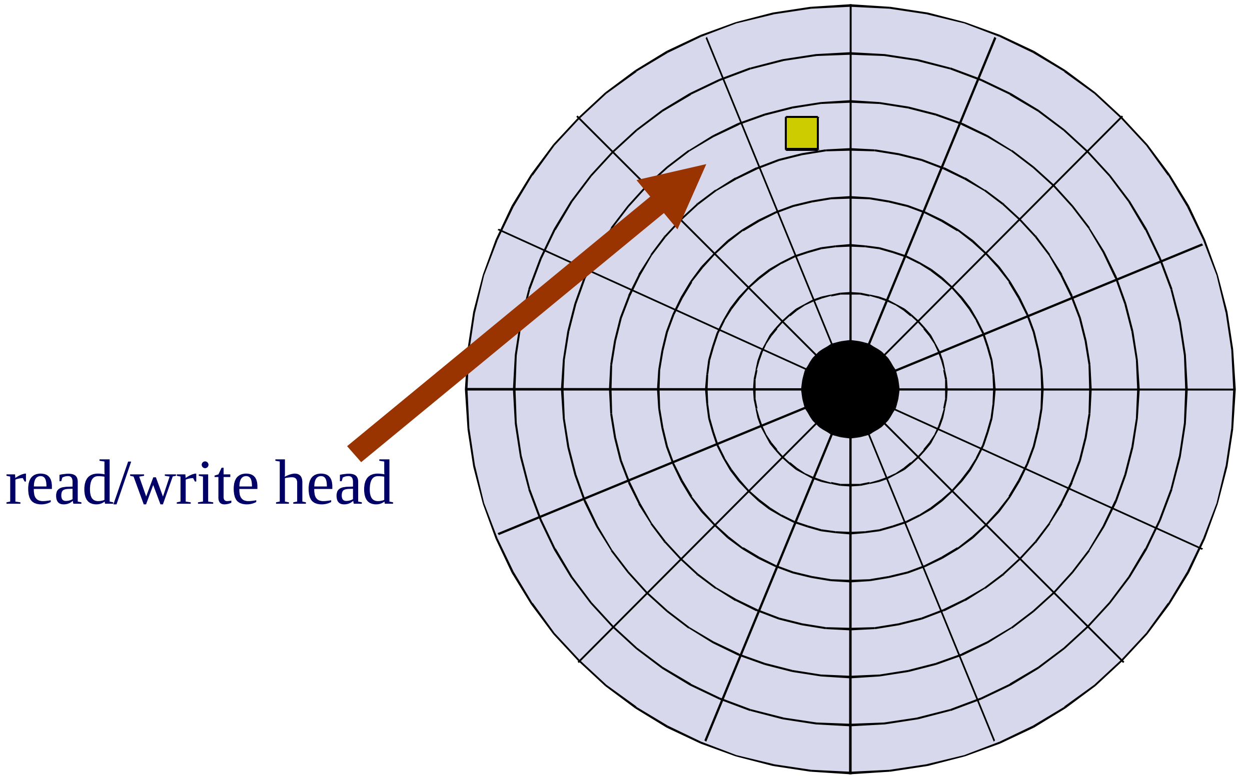

Anatomy of a Hard Drive

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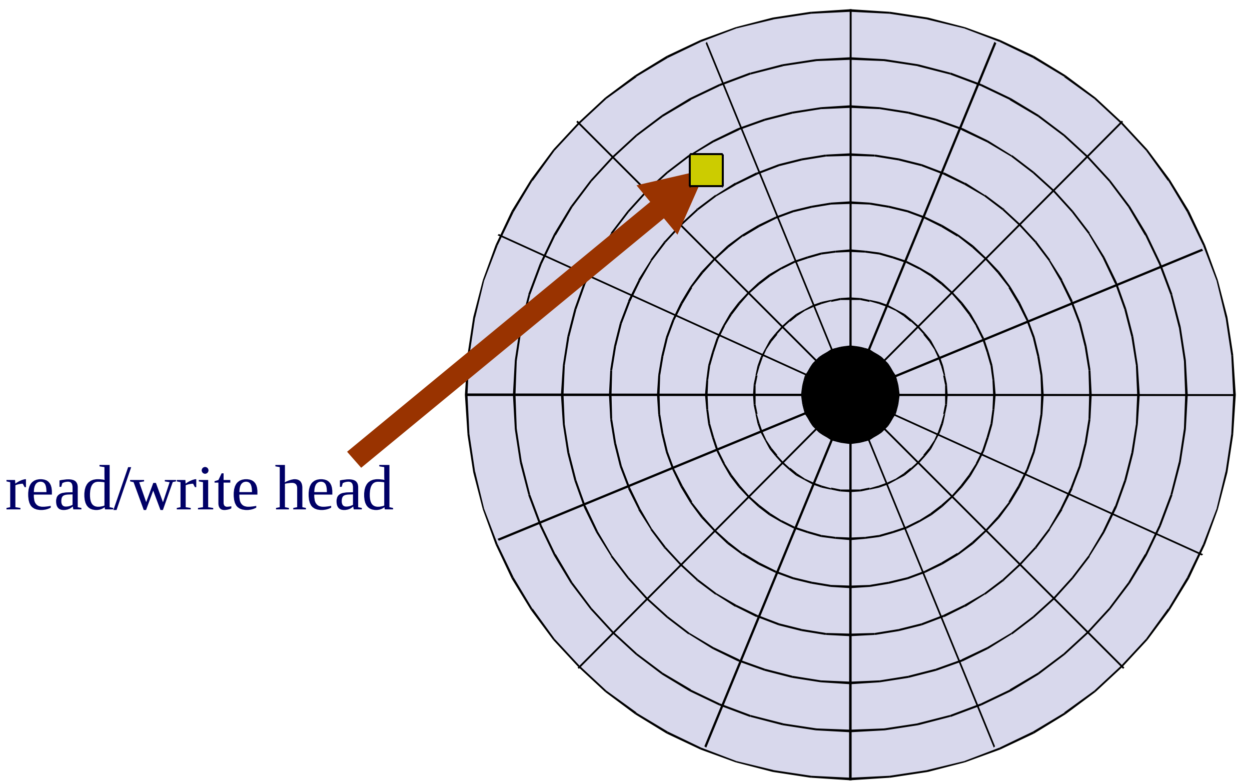
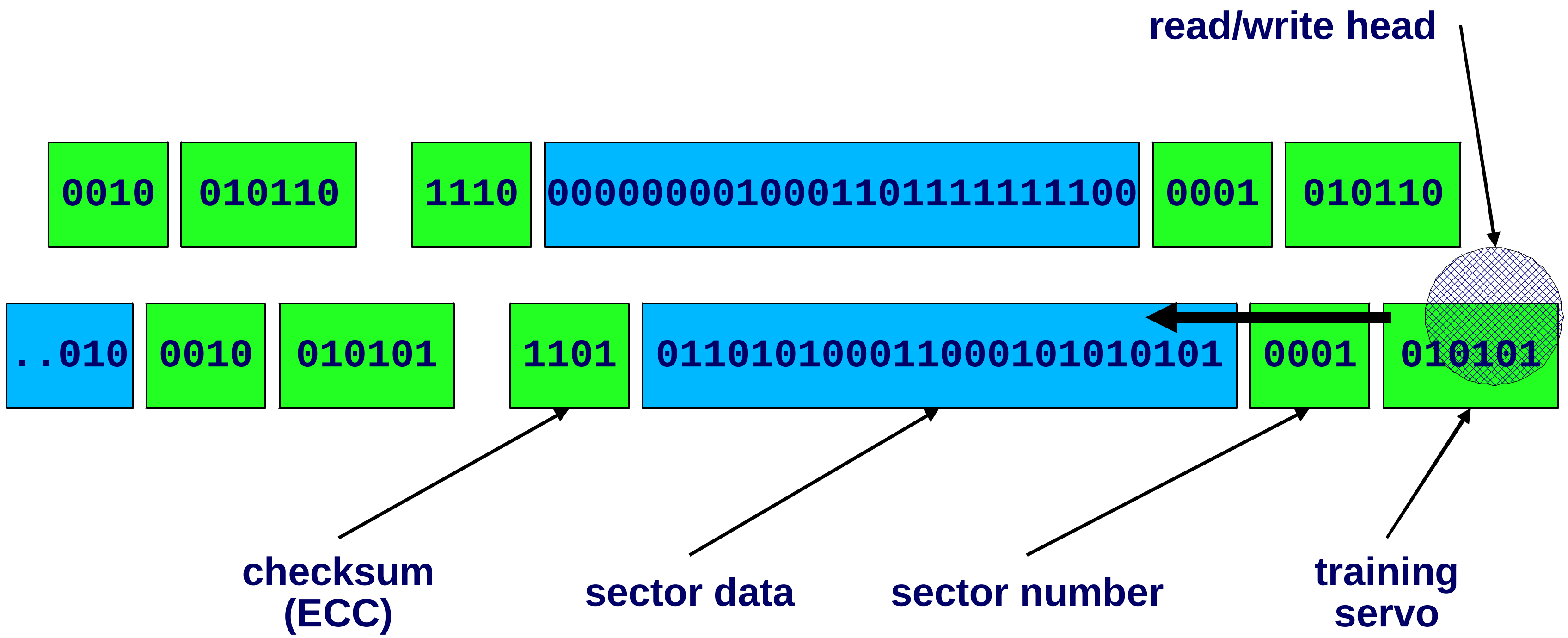


Anatomy of a "Sector"

Finding a sector involves real work

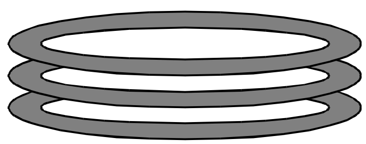
- Locate correct track; scan sector headers for number



After sector is read, compare data to checksum

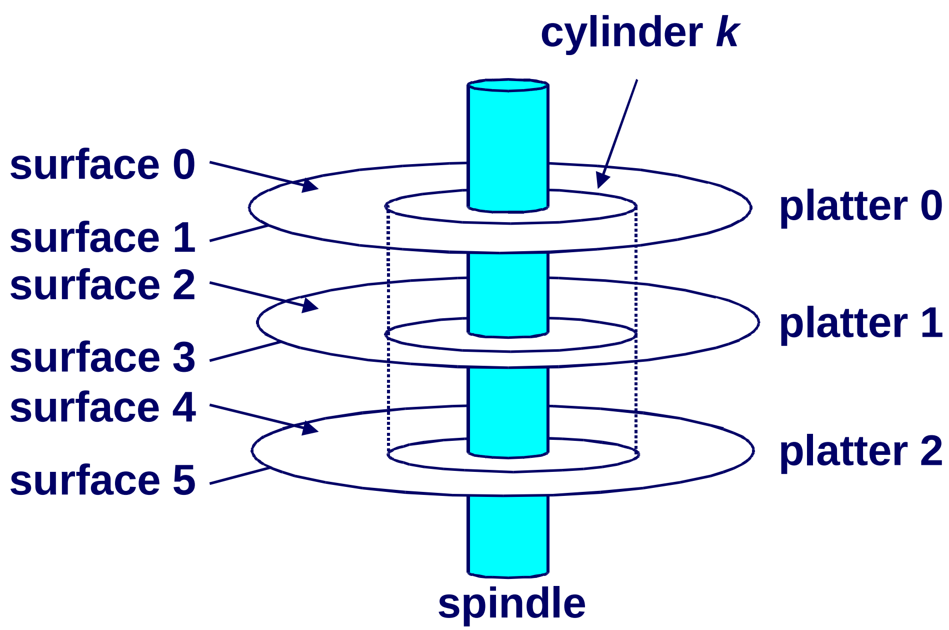
Disk Cylinder

Matching tracks across surfaces are collectively called a *cylinder*



Disk Cylinder

Matching tracks form a cylinder.



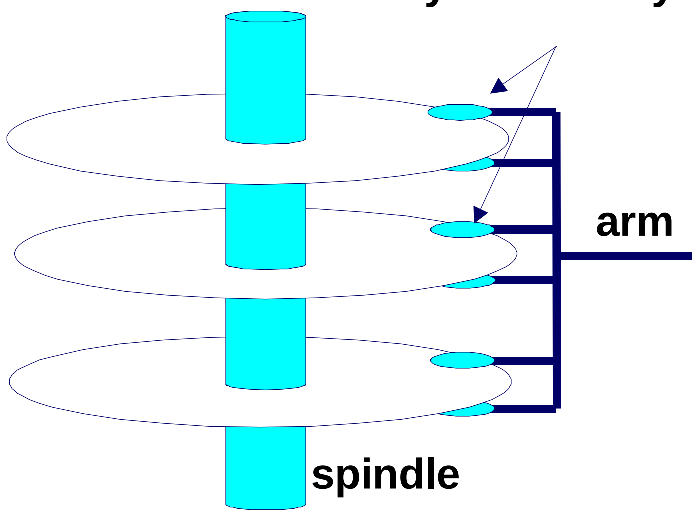
Access Within A Cylinder is Faster

Heads share one single arm

- All heads always on same cylinder
- Active head is aligned, others are “close”

Switching heads is “cheap”

- Deactivate head I, activate J
- Read a few sector headers to fine-tune arm position for J's track



Optimal transfer rate?

1. Transfer all sectors on a track
2. Transfer all tracks on a cylinder
3. ***Then*** move the arm

Access Time

On average, we will have to move the read/write head over one third of the tracks

- The time to do this is the "average seek time"
  - 5400 rpm: ~10 ms
  - 7200 rpm: ~8.5 ms

We will also must wait half a rotation, on average

- The time to do this is "average rotational delay"
  - 5400 rpm: ~5.5 ms
  - 7200 rpm: ~4 ms

These numbers don't exactly add

- While arm moves sideways, disk spins below it

Access Time

Other factors influence overall disk access time

- Settle time, the time to stabilize the read/write head after a seek
- Command overhead, the time for the disk to process a command and start doing something

Minor compared to seek time and rotational delay

Access Time

Total random access time is ~7 to 20 milliseconds

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  - **That's slower than DSL!!!**

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What can we, as O.S. programmers, do about this?

- **Read more per seek (multi-sector transfers)**
- **Don't seek so randomly ("disk scheduling")**

Disk Scheduling Algorithms

The goal of a disk scheduling algorithm is to be nice to the disk

We can help the disk by giving it requests that are located close to each other

- This minimizes seek time, and possibly rotational latency

There exist a variety of ways to do this

Addressing Disks

What the OS knows about the disk

- Interface type (SATA/SCSI), unit number, number of sectors

What happened to sectors, tracks, etc?

- Old disks were addressed by cylinder/head/sector (CHS)
- Modern disks are addressed by abstract sector number
  - LBA = logical block addressing

Who uses sector numbers?

- File systems assign logical blocks to files

Terminology

- To disk people, “block” and “sector” are the same
- To file system people, a “block” is some number of sectors

Disk Addresses vs. Scheduling

Goal of OS disk-scheduling algorithm

- Maintain queue of requests
- When disk finishes one request, give it the "best" request
    - E.g., whichever one is closest in terms of disk geometry

Goal of disk's logical addressing

- Hide messy details of which sectors are located where
    - Disk change fast – more than once a year
    - OSs change slowly – up to 5 years for Windows

A good approximation

- Older OS's tried to understand disk layout
- Modern OS's just assume nearby sector numbers are close

Scheduling Algorithms

“Don't try this at home”

- FCFS
- SSTF

Arguably less wrong

- SCAN, C-SCAN

Plausible

- LOOK, C-LOOK

Useful, but hard

- SPTF

First Come First Served (FCFS)

Send requests to disk as they are generated by the OS

Trivial to implement – FIFO queue in device driver

Fair

- **What could be more fair?**

“Unacceptably high mean response time”

- **File “abc” in sectors 1, 2, 3, ...**
- **File “def” in sectors 16384, 16385, 16386, ...**
- **Sequential reads: 1, 16384, 2, 16385, 3, 16386, …**
    - **(disk shakes so much it “walks” across the room)**

Shortest Seek Time First (SSTF)

Maintain "queue" of disk requests

Serve the request nearest to the disk arm

- **Estimate nearness by subtracting block numbers**

Great!

- **Excellent throughput (most seeks are short)**
- **Very good average response time**

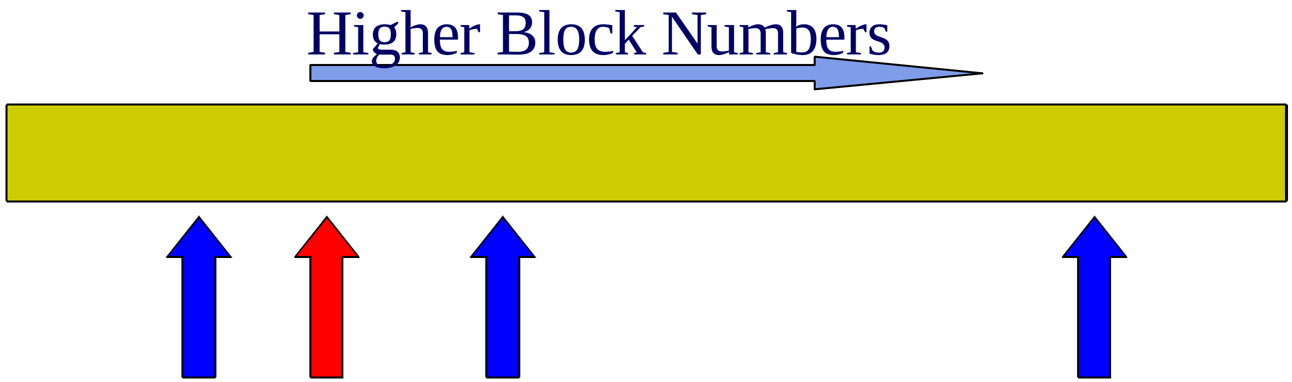
Intolerable response time *variance*, however

Why?

SSTF

Blue are requests

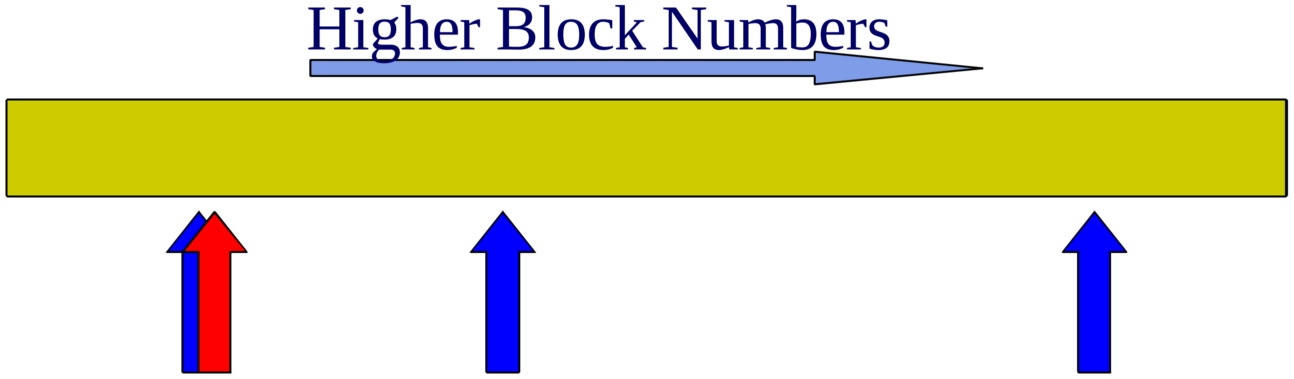
Yellow is disk



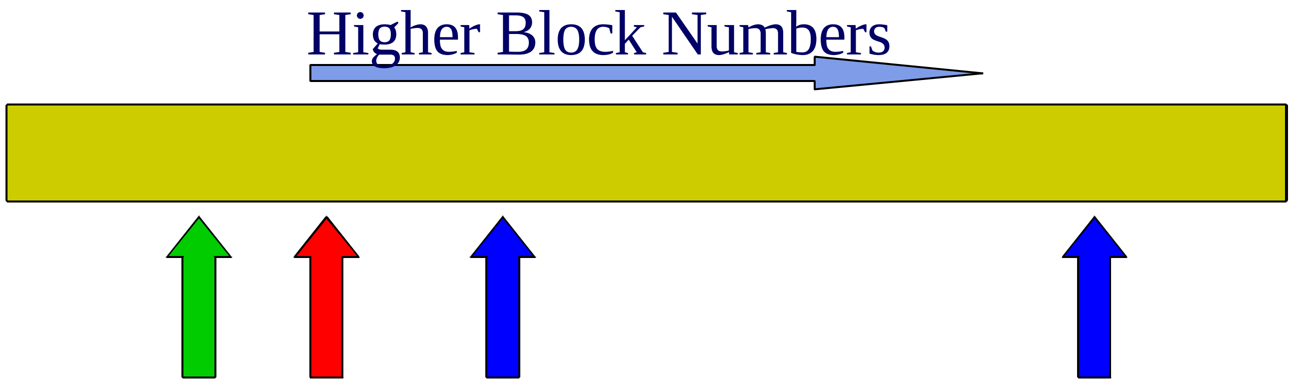
Red is disk head

Green is completed requests

SSTF

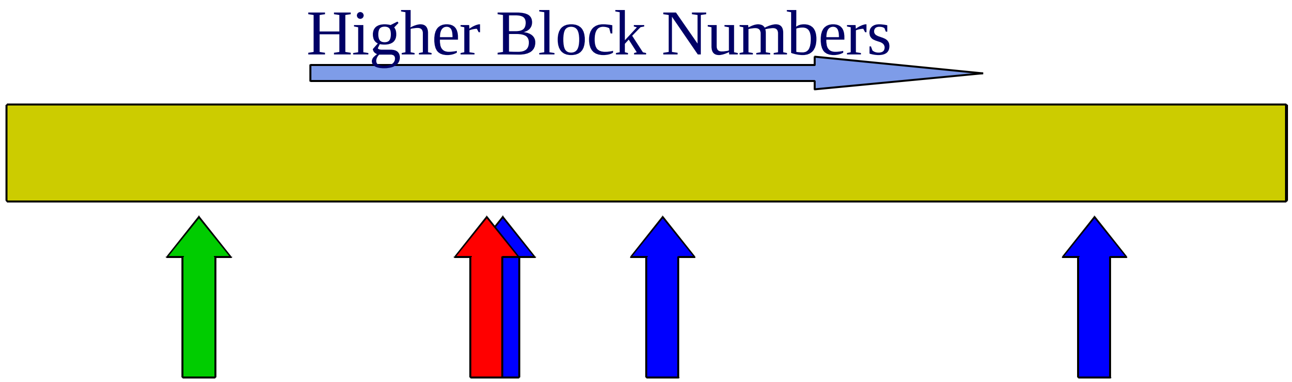


SSTF



SSTF

New Requests arrive…



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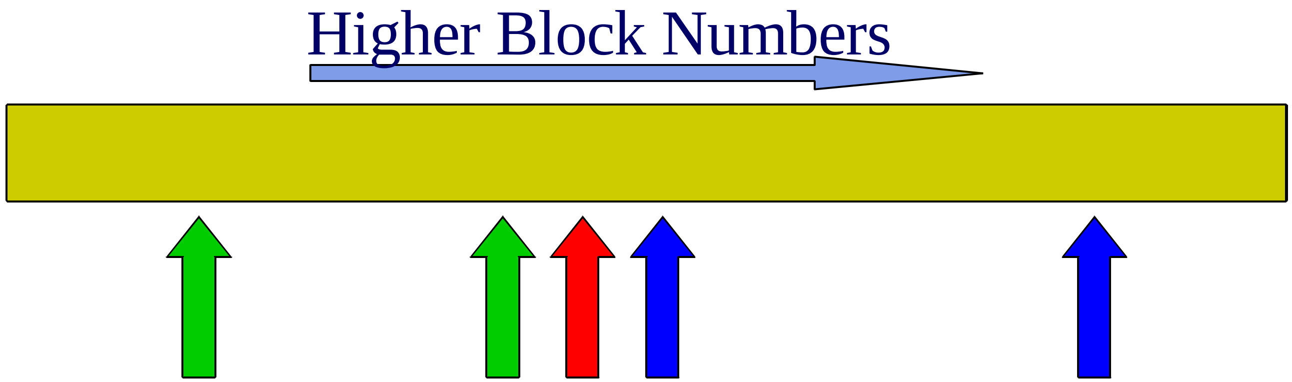

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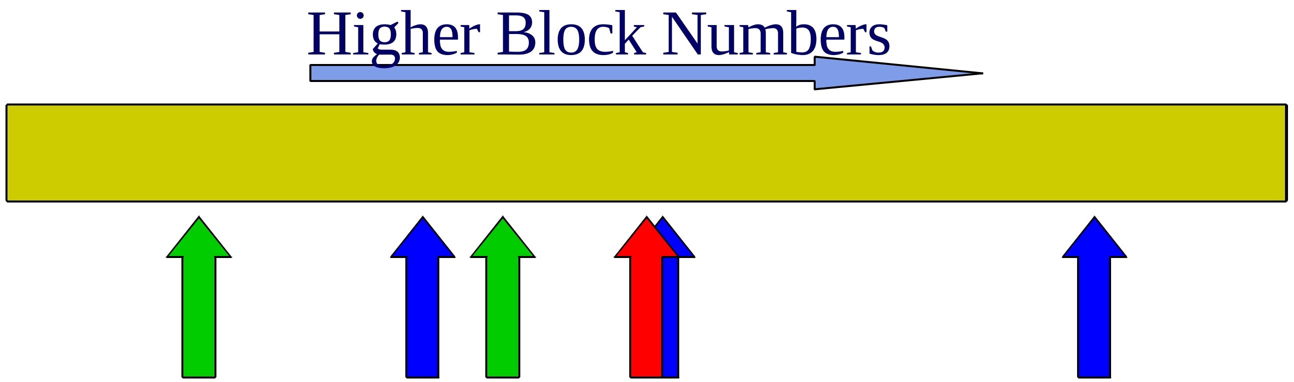
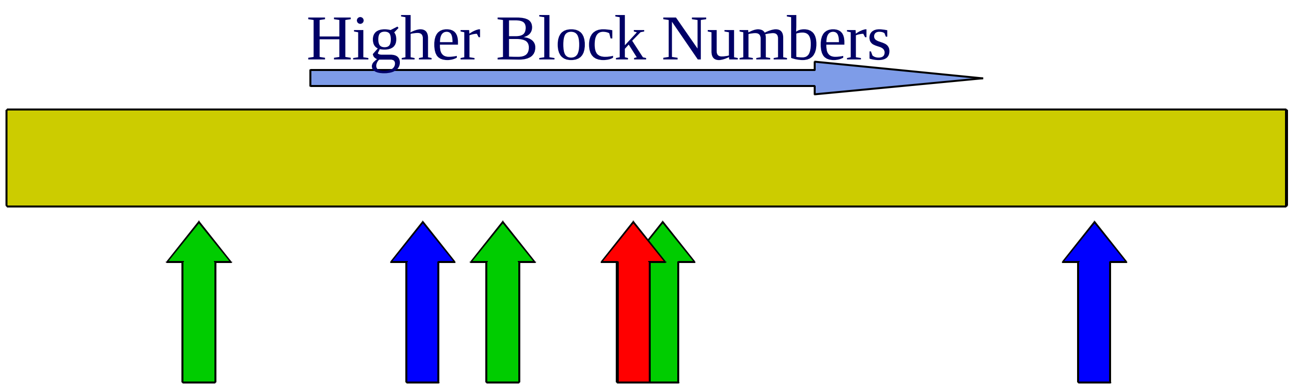
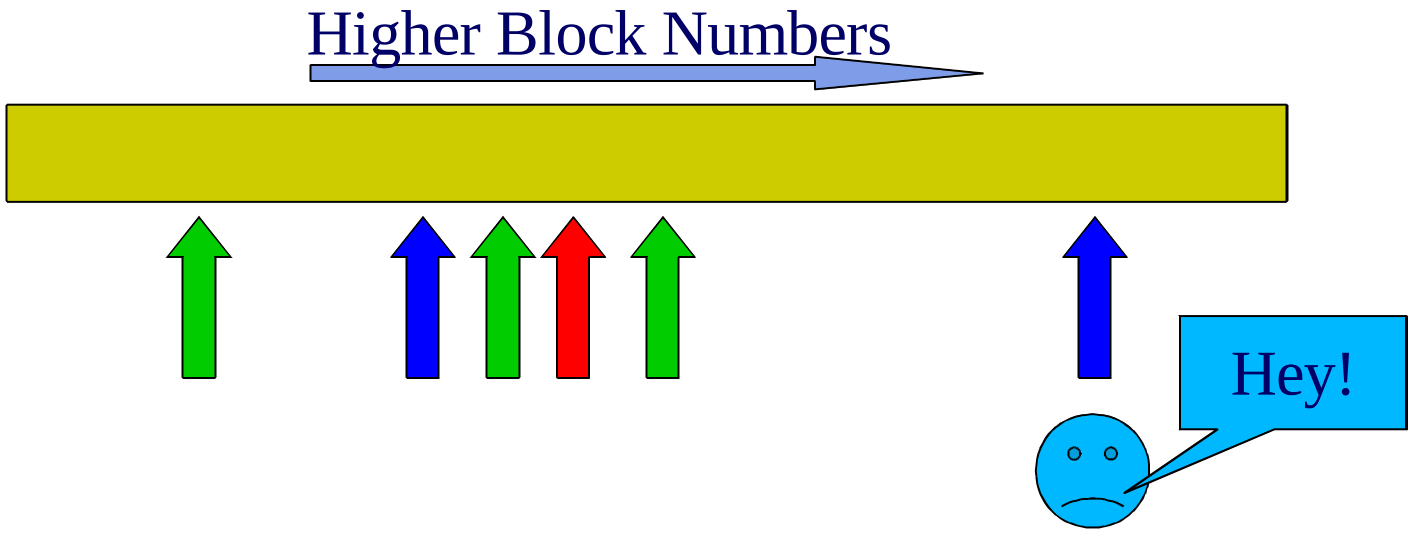


SSTF

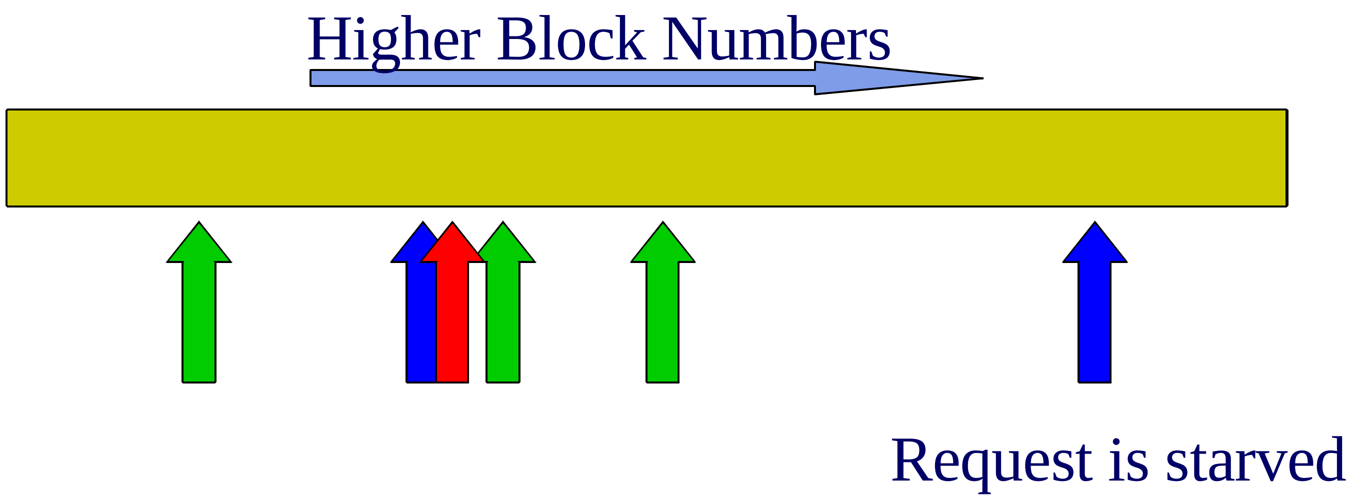


SSTF



SSTF

Starves requests that are “far away” from the head



What Went Wrong?

FCFS - “fair, but slow”

- Ignores position of disk arm, so it's slow

SSTF – good throughput, very unfair

- Pays too much attention to requests near disk arm
- Ignores necessity of eventually scanning entire disk

What Went Wrong?

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SSTF – good throughput, very unfair

- Pays too much attention to requests near disk arm
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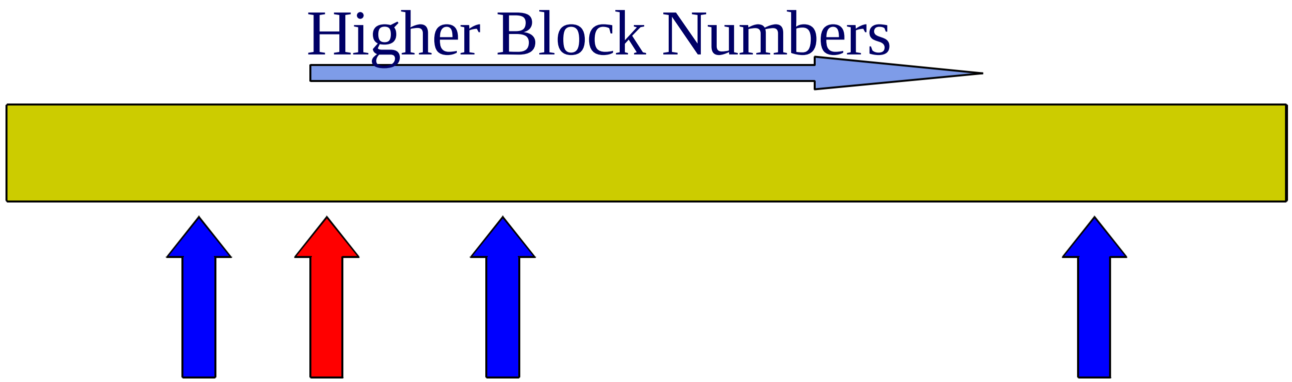
"Scan entire disk" - now that's an idea!

- Start disk arm moving in one direction
- Serve requests as the arm moves past them
  - No matter when they were queued
- When arm bangs into stop, reverse direction

SCAN

Blue are requests

Yellow is disk



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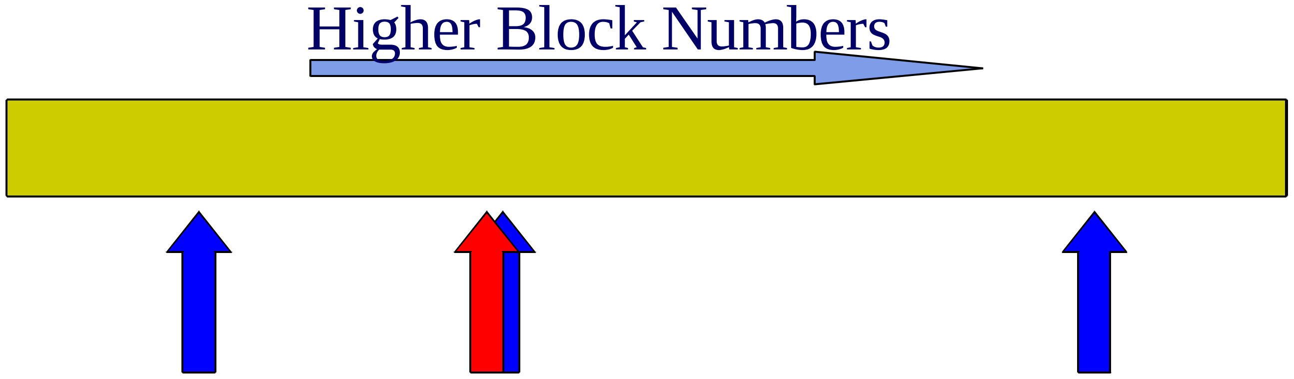

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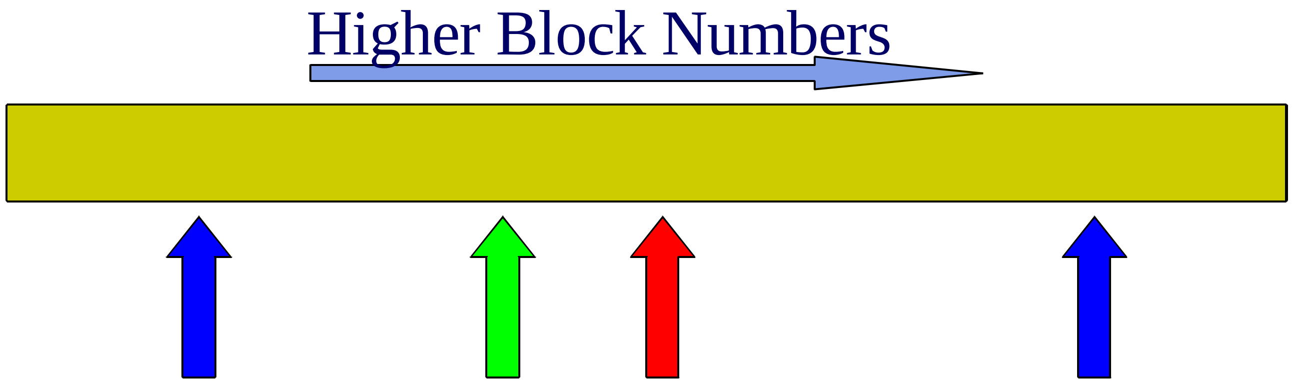

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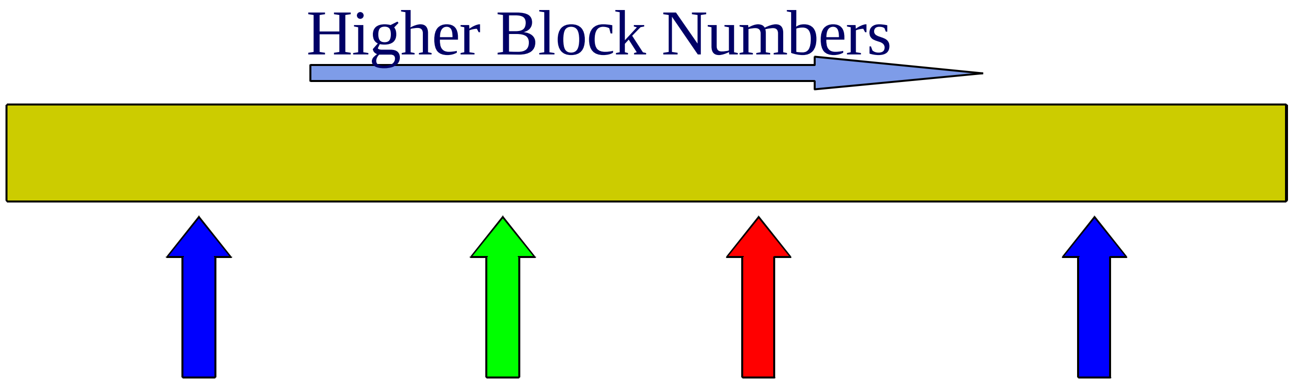

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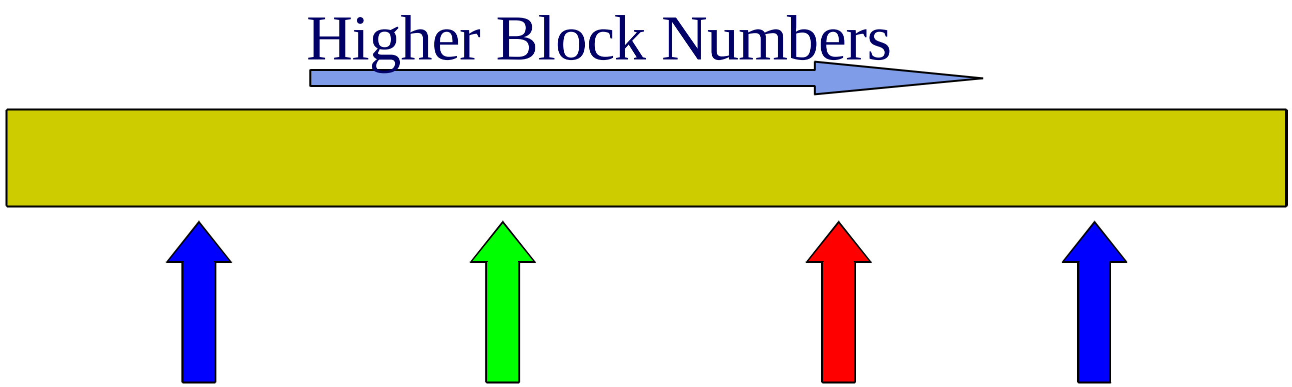

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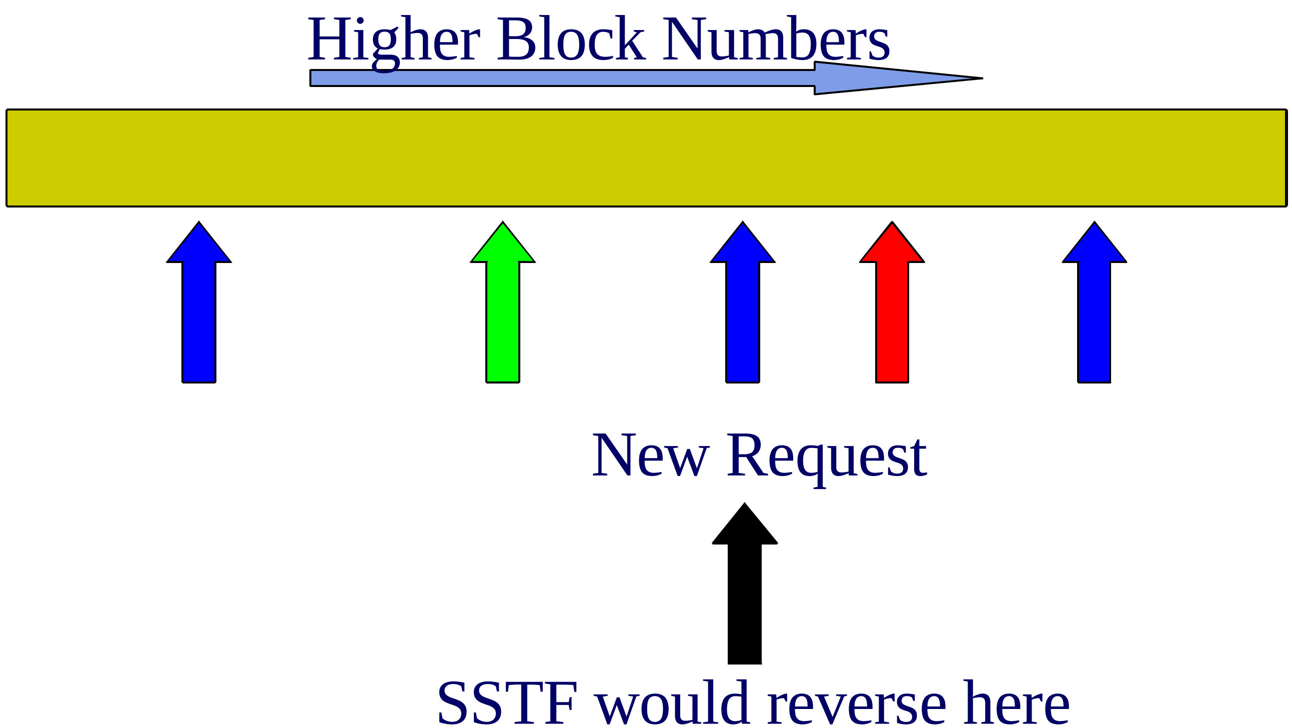

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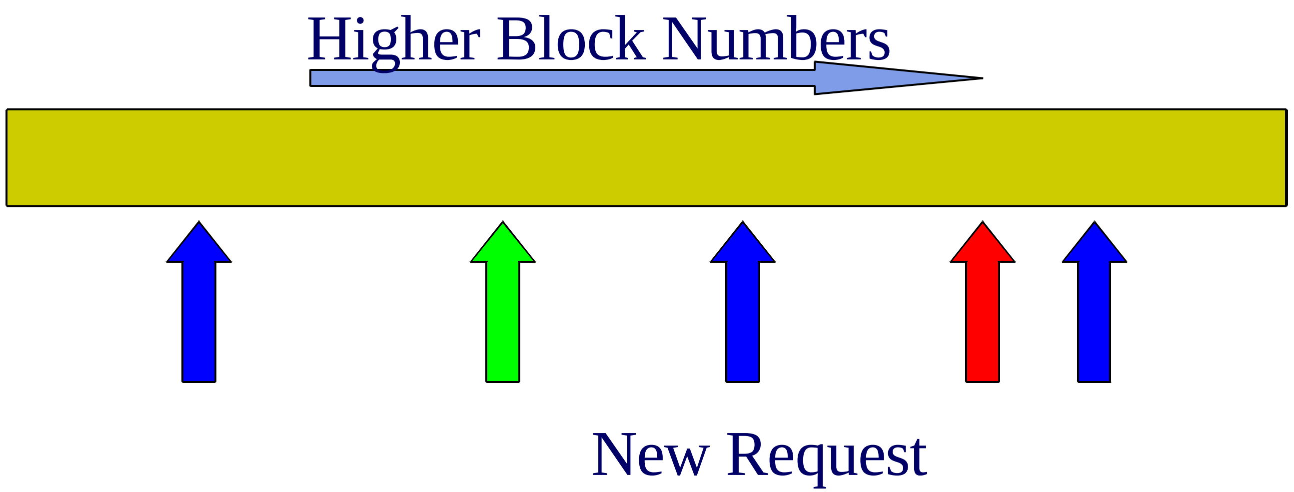

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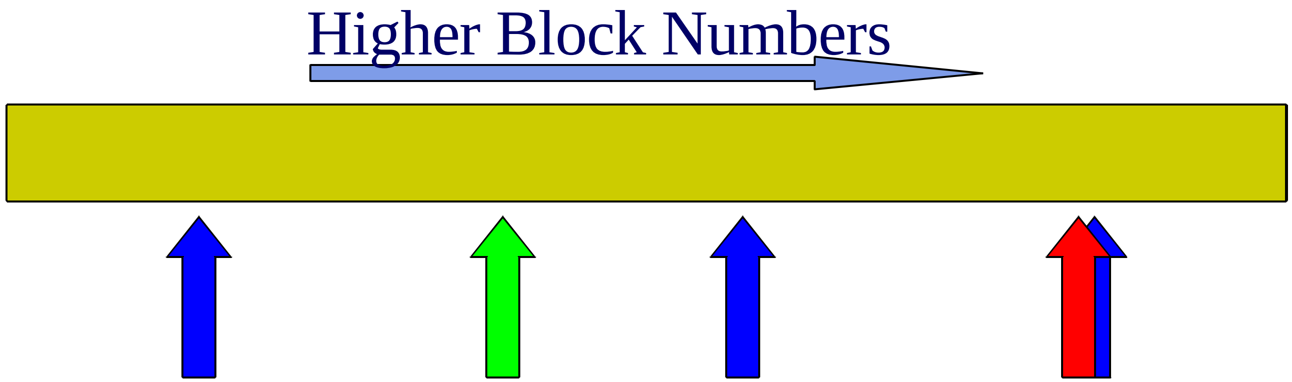
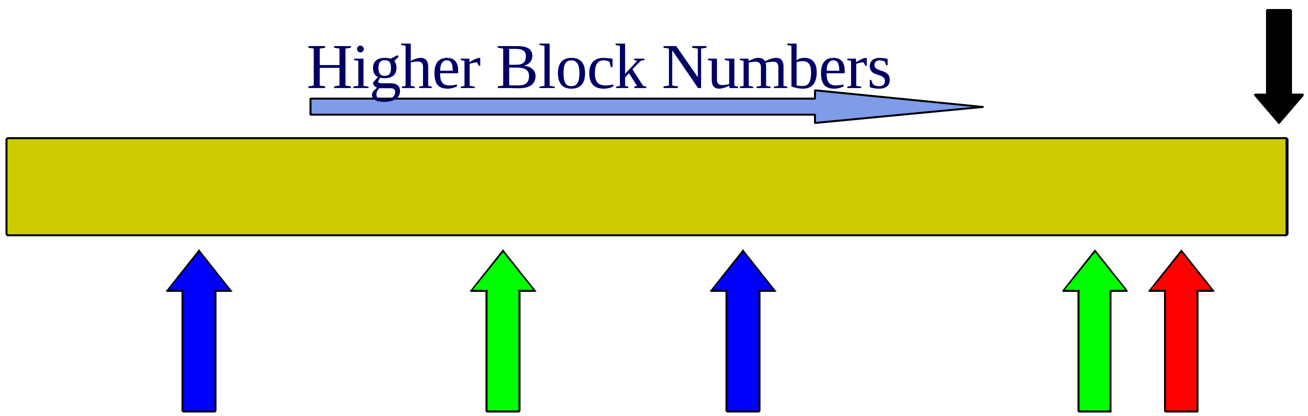


SCAN

In SCAN, we continue to the end of the disk



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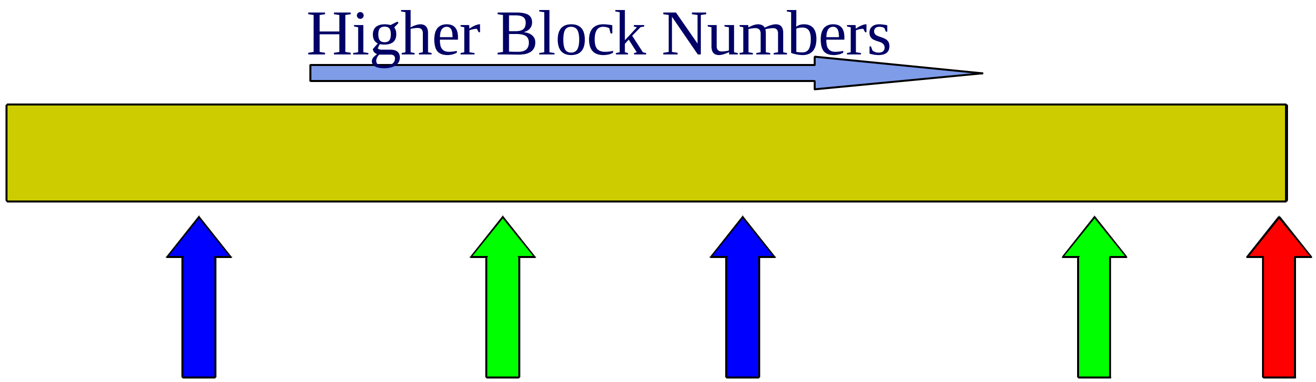

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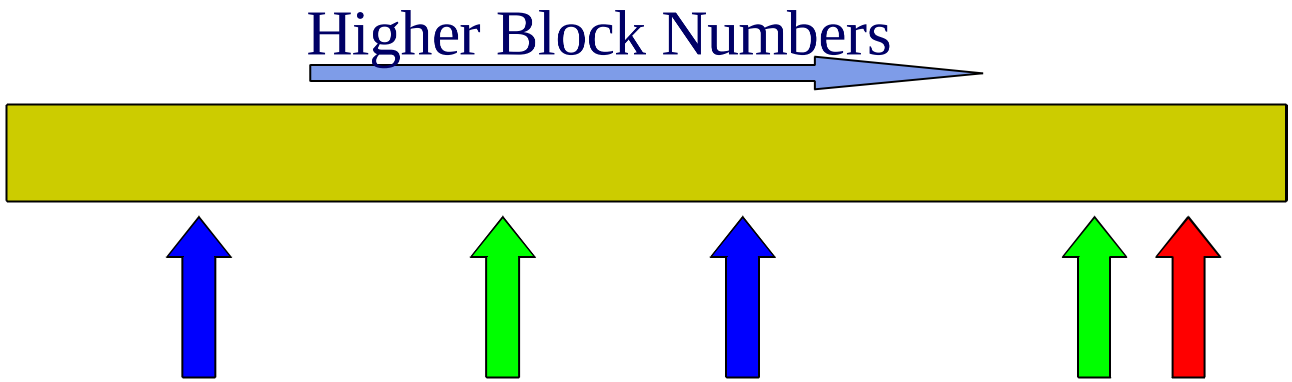

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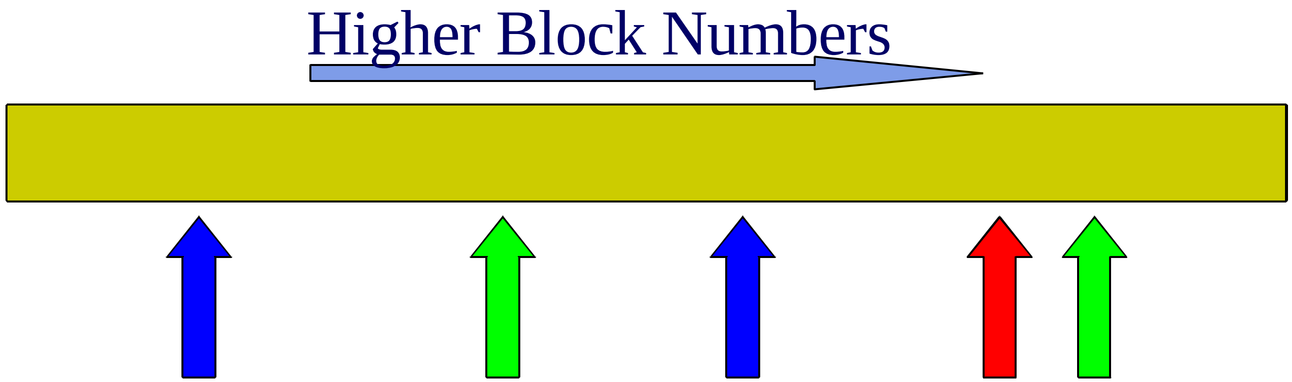

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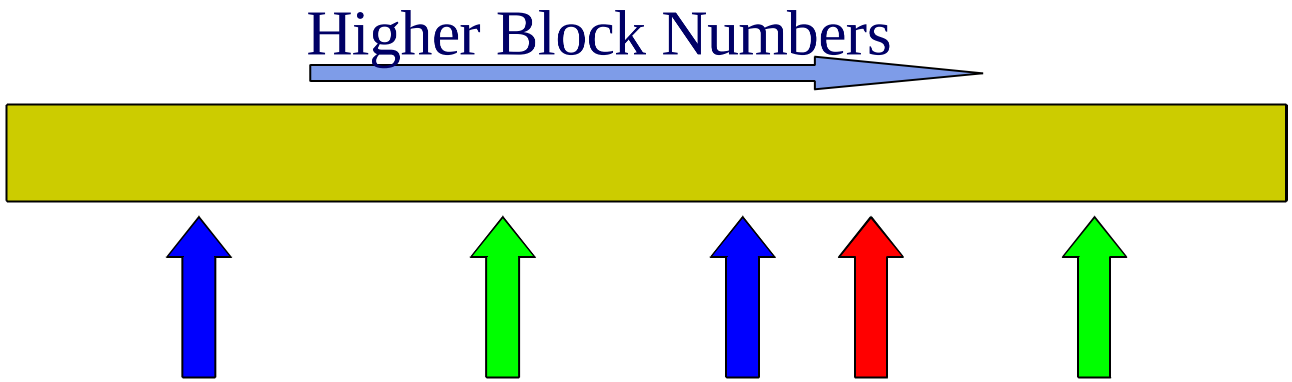

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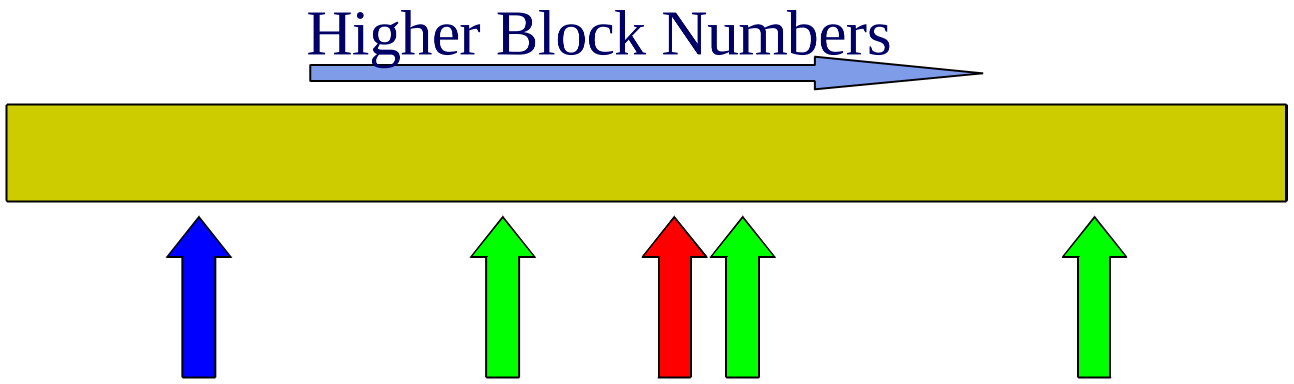

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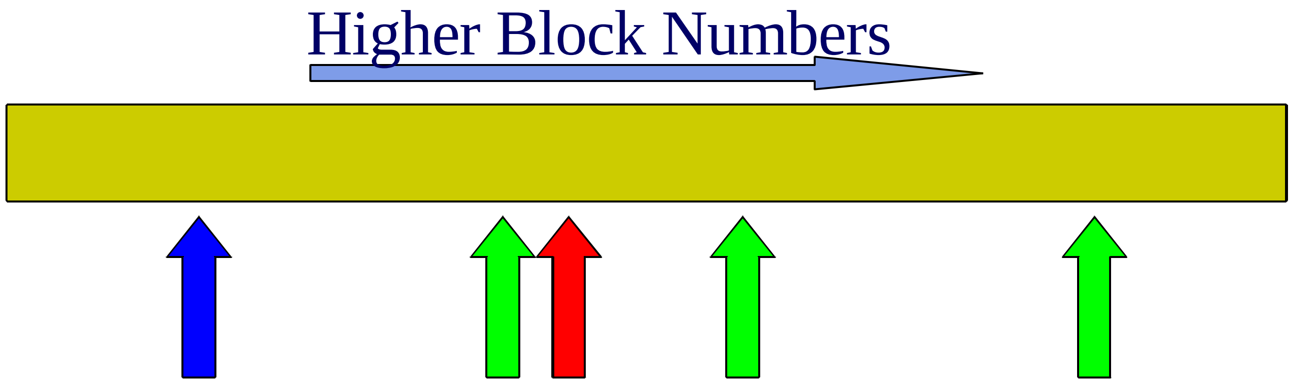

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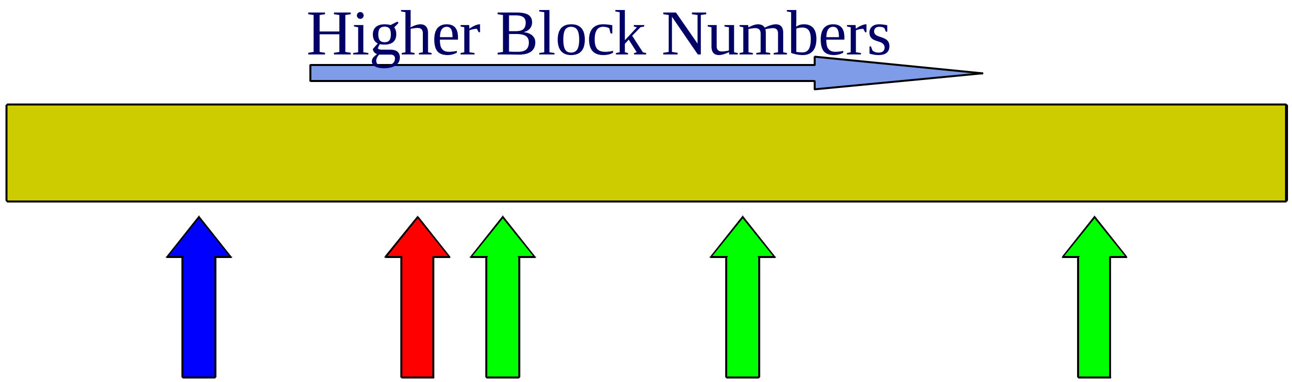

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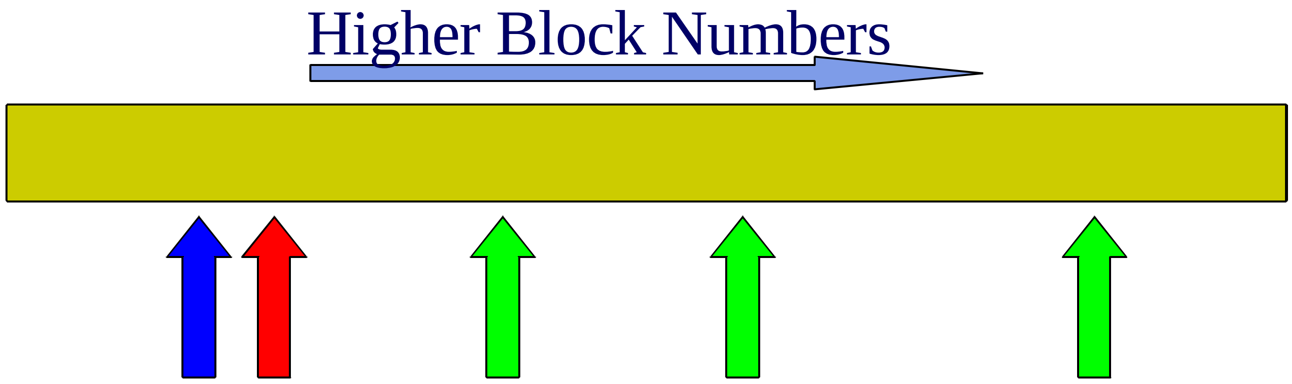

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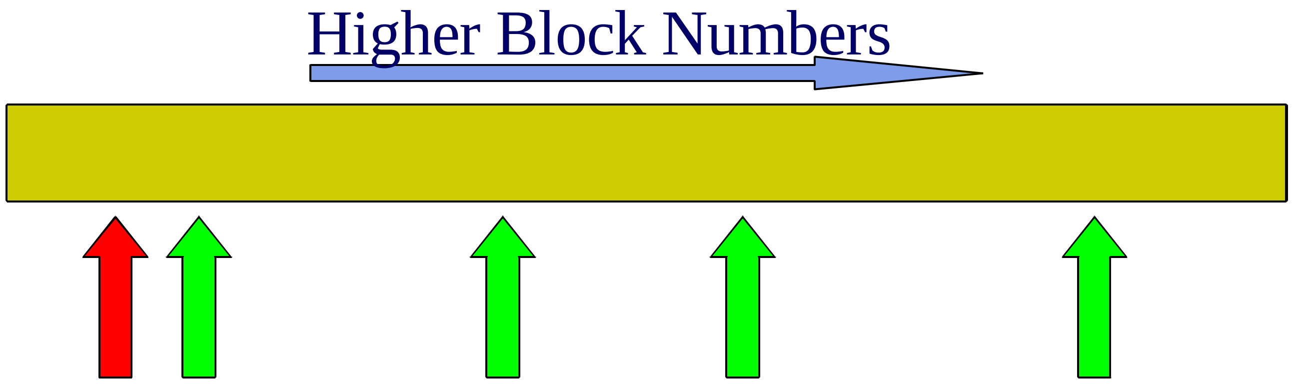

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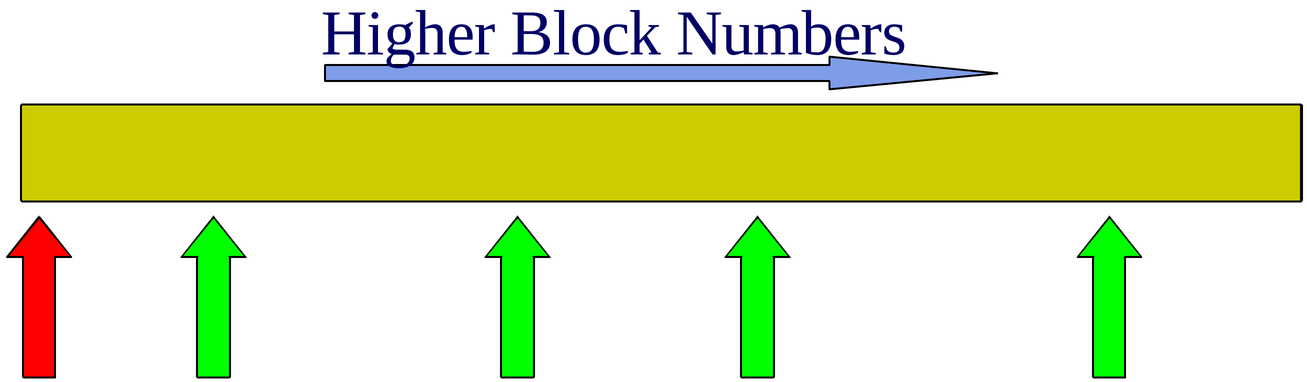


Evaluating SCAN

Mean response time

- **Worse than SSTF, better than FCFS**
- **You should be able to say why**

Response time *variance*

- **Better than SSTF**

Do we need to go all the way to the end of the disk?

The LOOK Optimization

Just like SCAN – sweep back and forth through cylinders

Don't wait for the "thud" to reverse the scan

- **Reverse when there are no requests "ahead" of the arm**

Improves mean response time, variance

Both SCAN and LOOK are unfair – why?

C-SCAN - “Circular SCAN”

Send requests in ascending cylinder order

When the last cylinder is reached, seek all the way back to the first cylinder

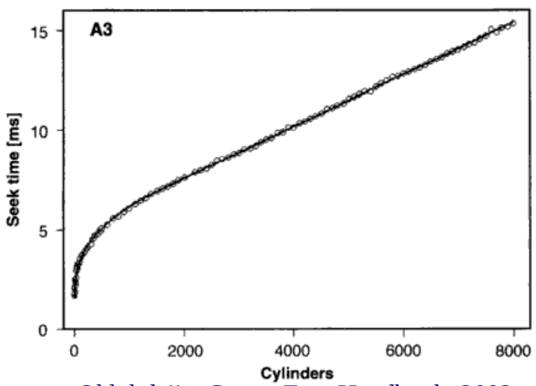
Long seek is amortized across all accesses

- **Key implementation detail**
  - **Seek time is a *non-linear* function of seek distance**
  - **One big seek is faster than N smaller seeks**

Variance is improved

Fair

Still missing something though…



Oklobdzija, Comp. Eng. Handbook, 2002

C-LOOK

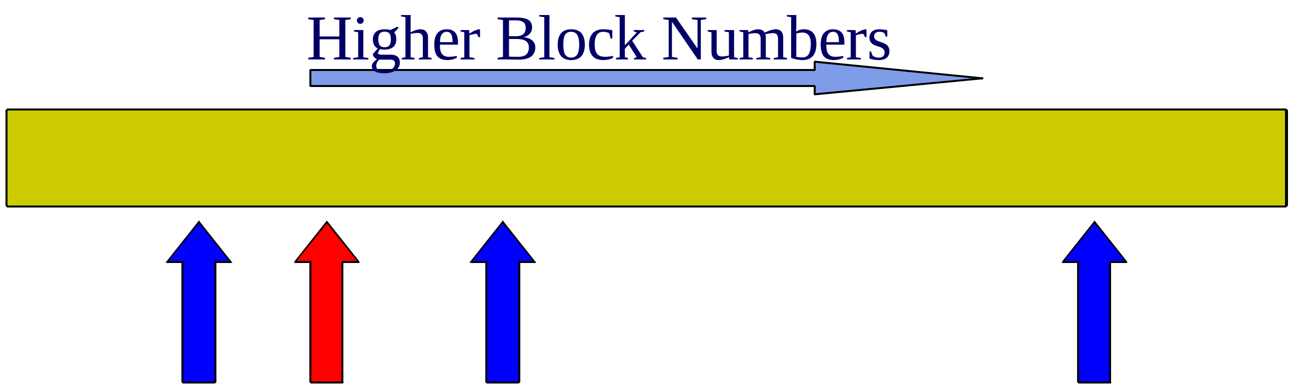
CSCAN + LOOK

Scan in one direction, as in CSCAN

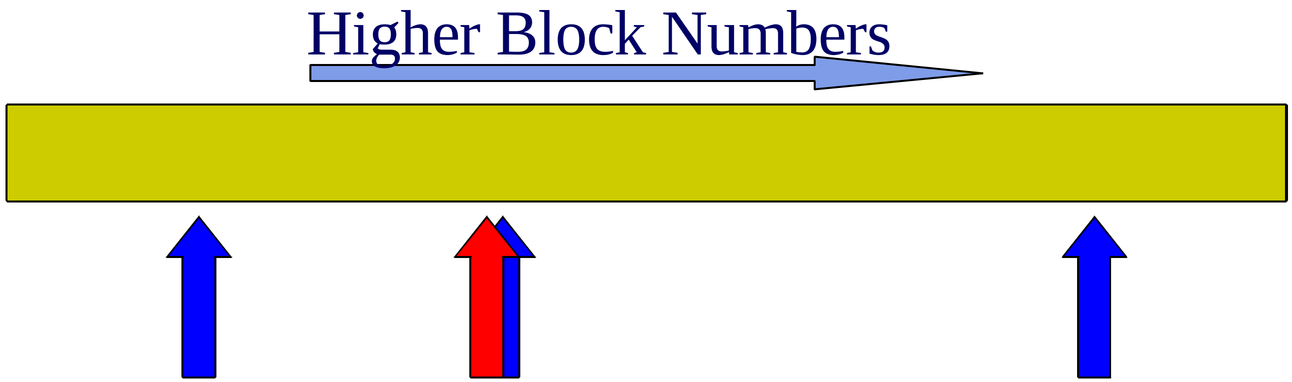
If there are no more requests in current direction go back to furthest request

Very popular

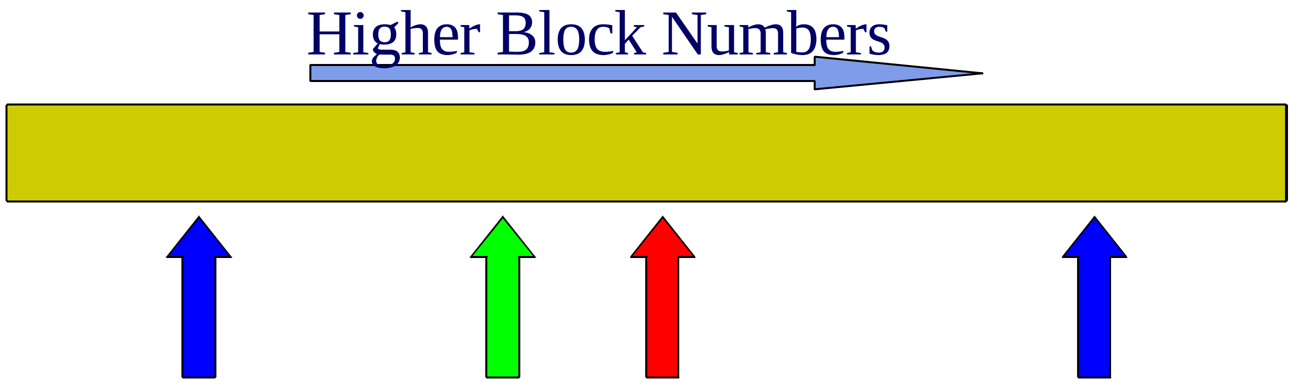
C-LOOK



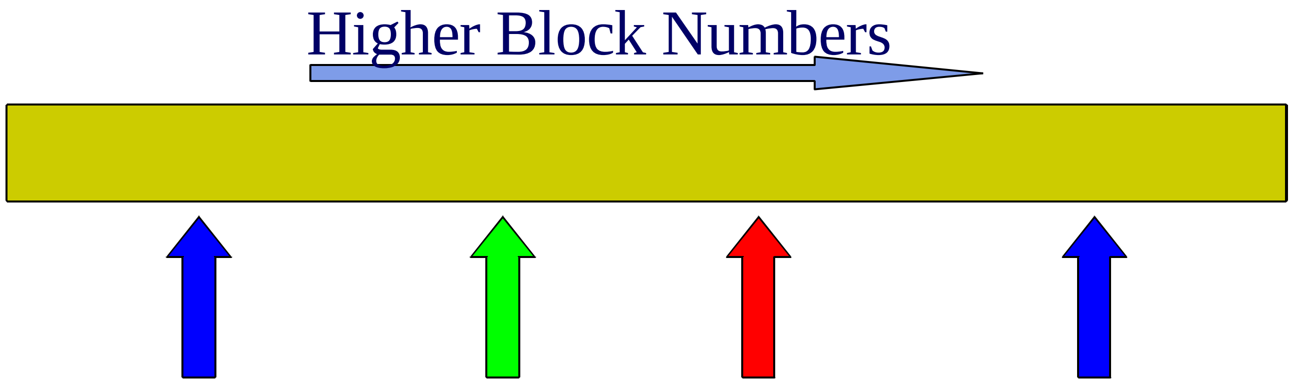
C-LOOK



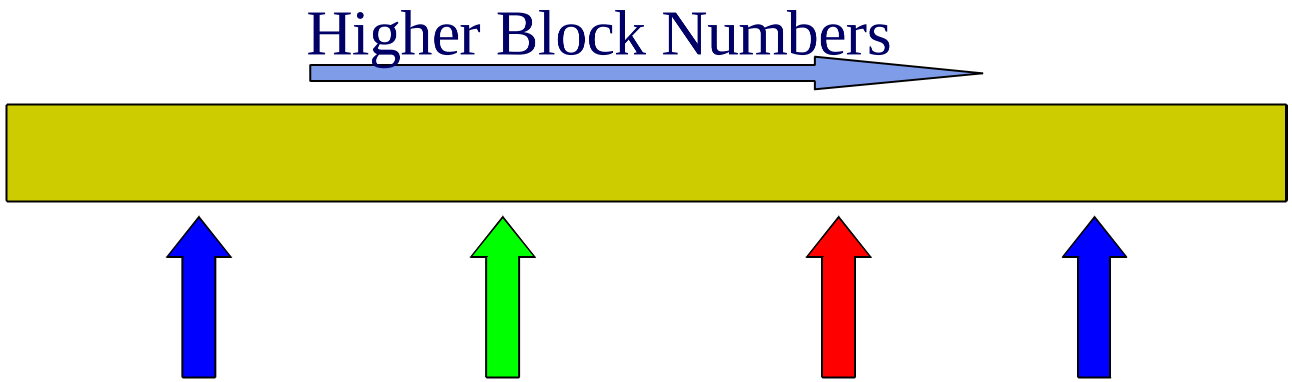
C-LOOK



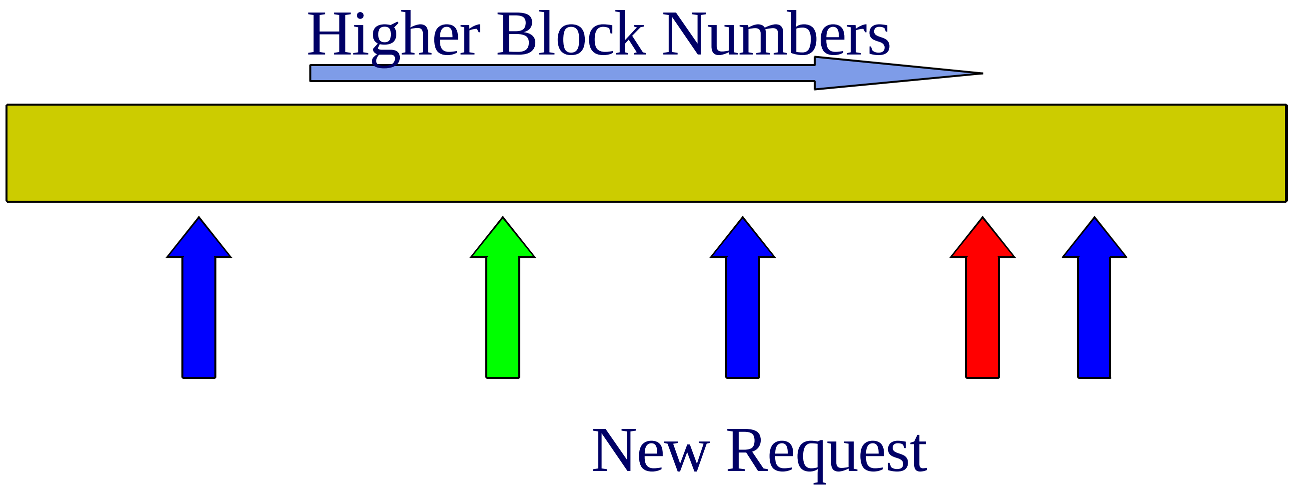
C-LOOK



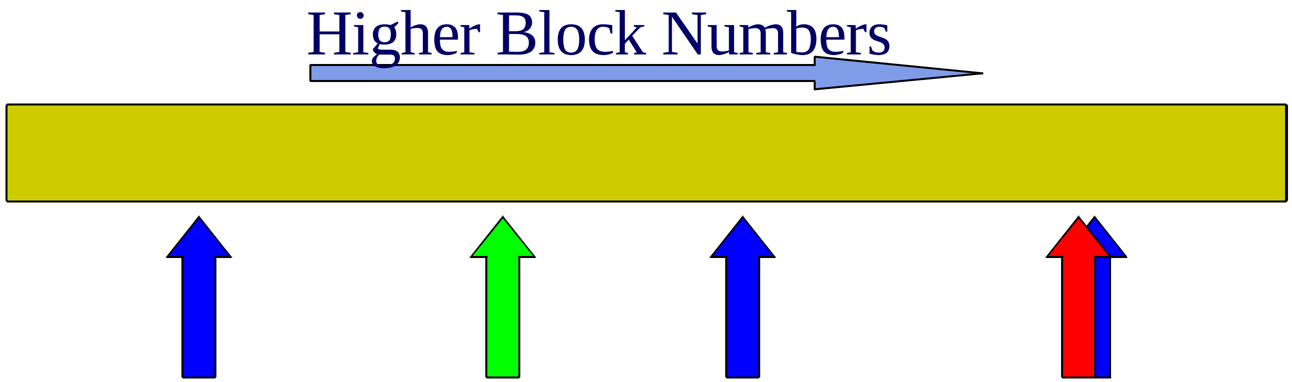
C-LOOK



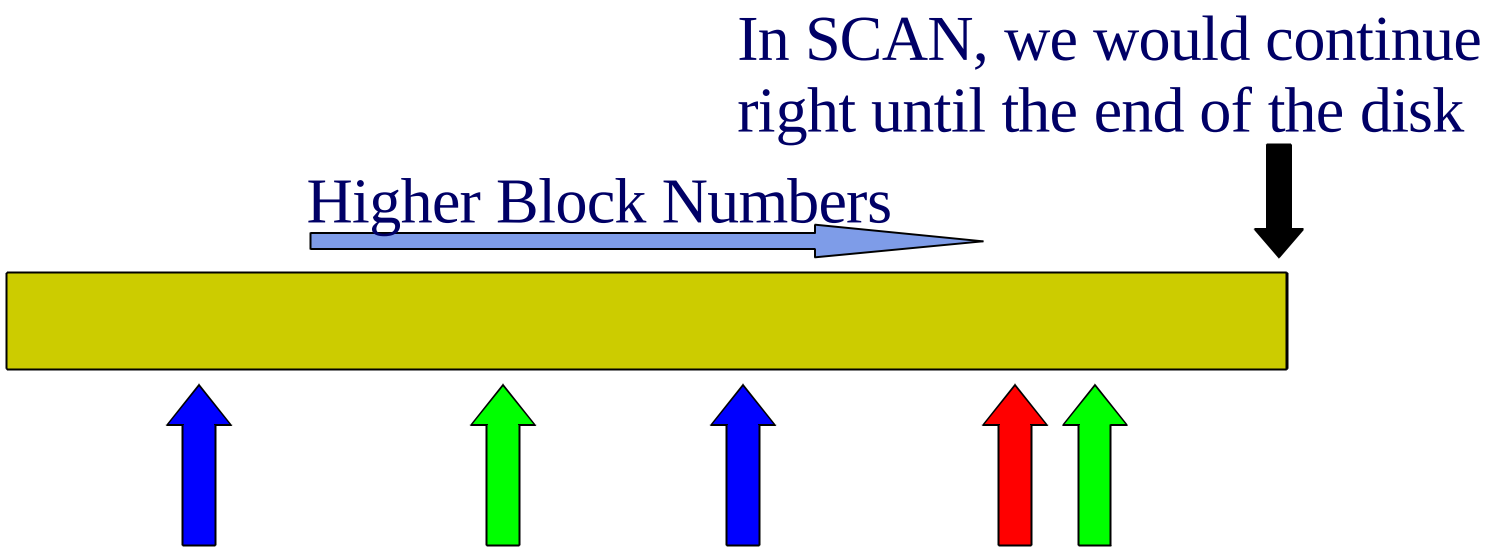
C-LOOK



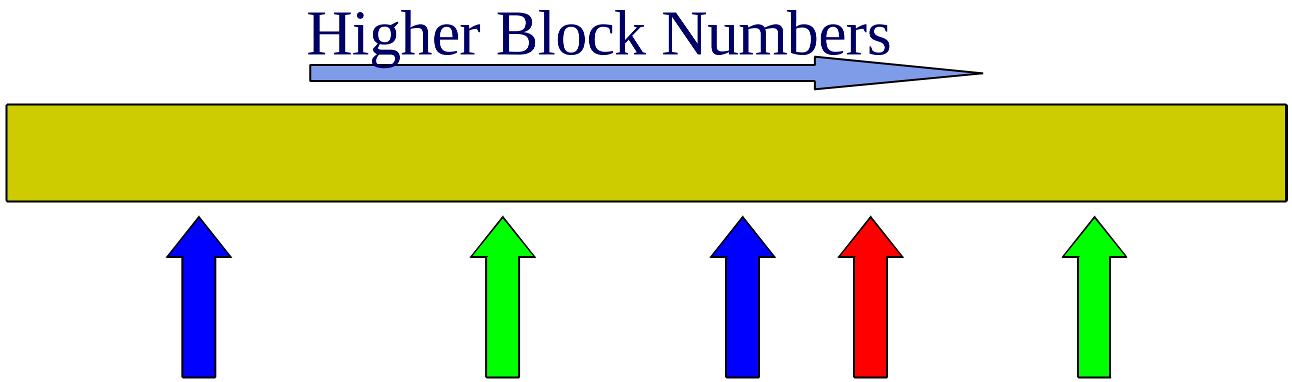
C-LOOK



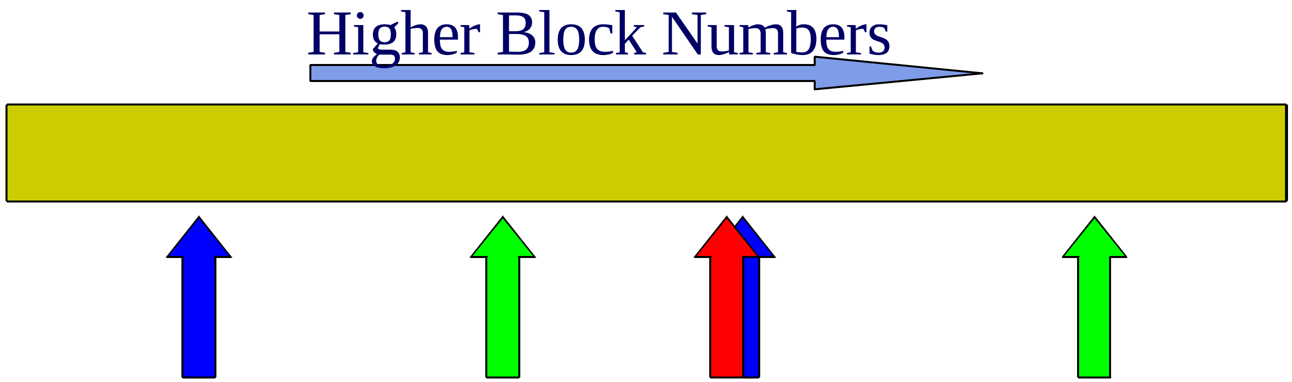
C-LOOK


In SCAN, we would continue right until the end of the disk
Higher Block Numbers

C-LOOK

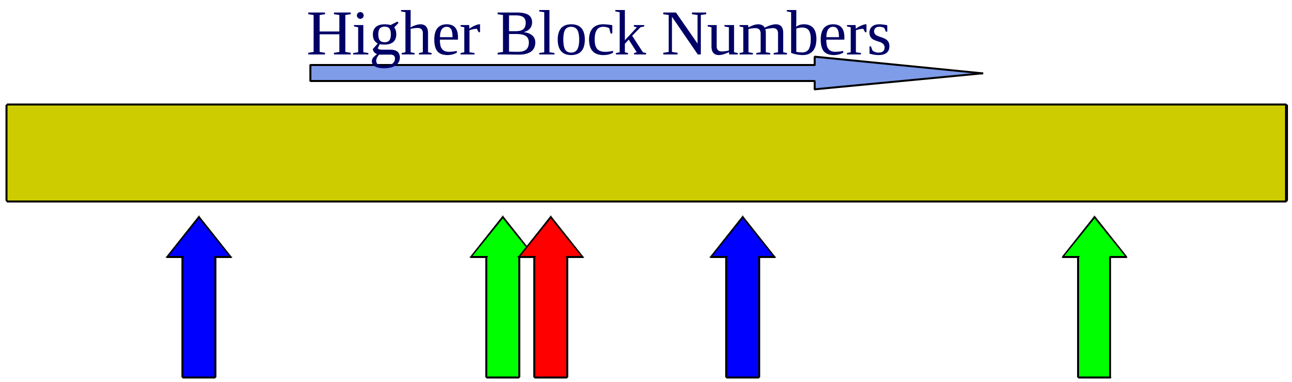


C-LOOK

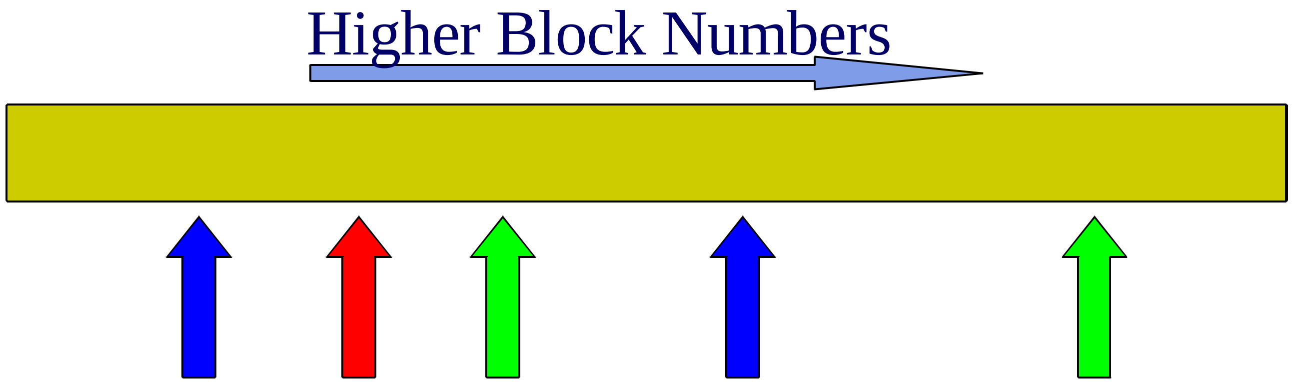


In LOOK, we would have read this request
(unfair extra service—so we'll skip it)

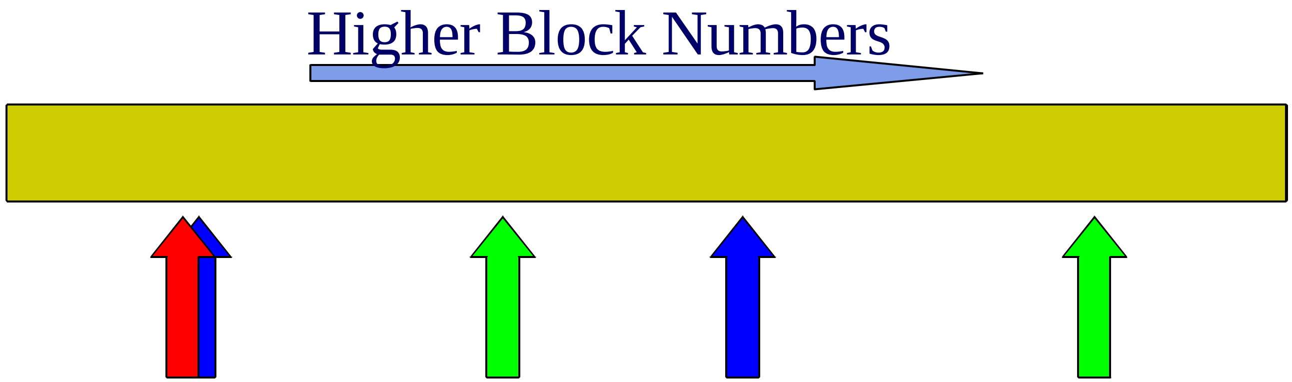
C-LOOK



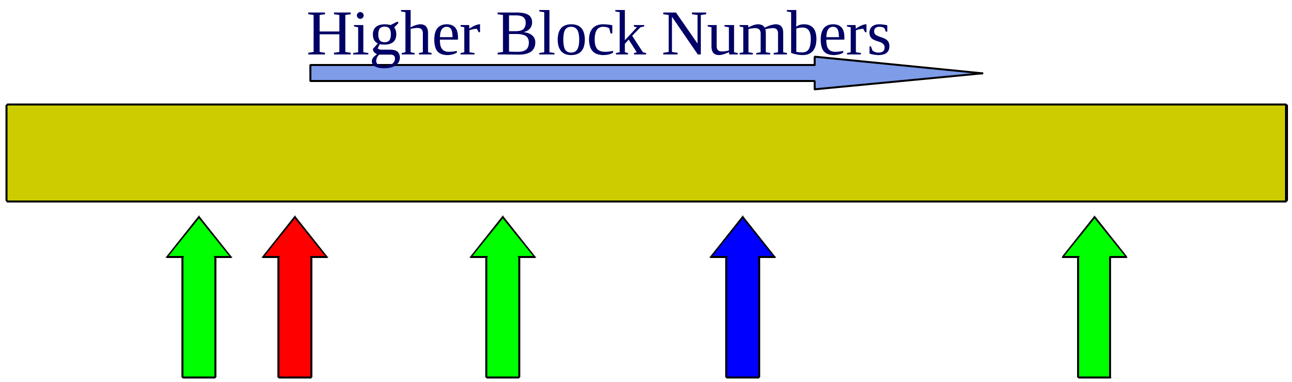
C-LOOK



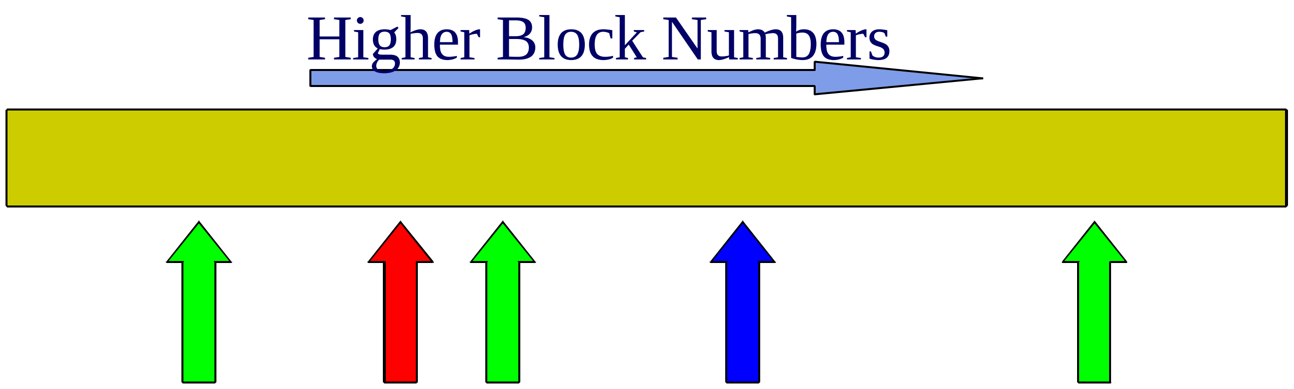
C-LOOK



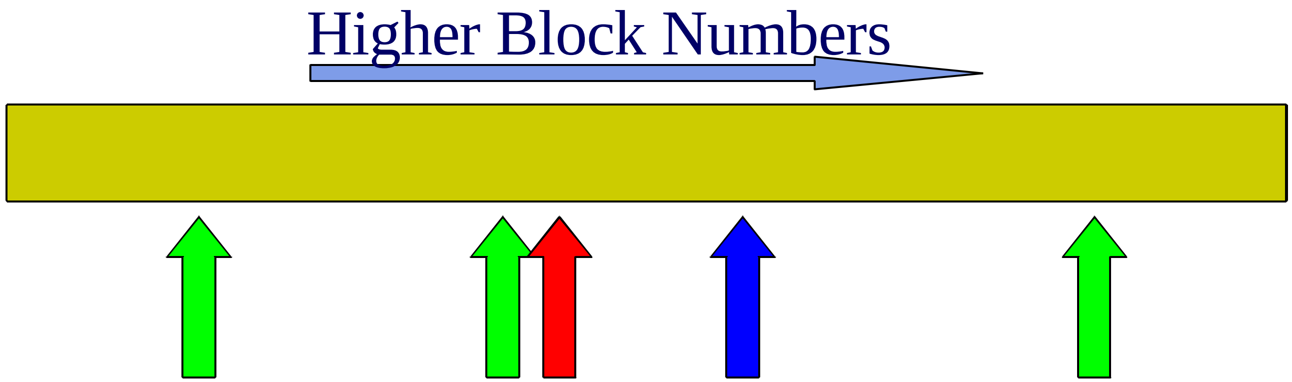
C-LOOK



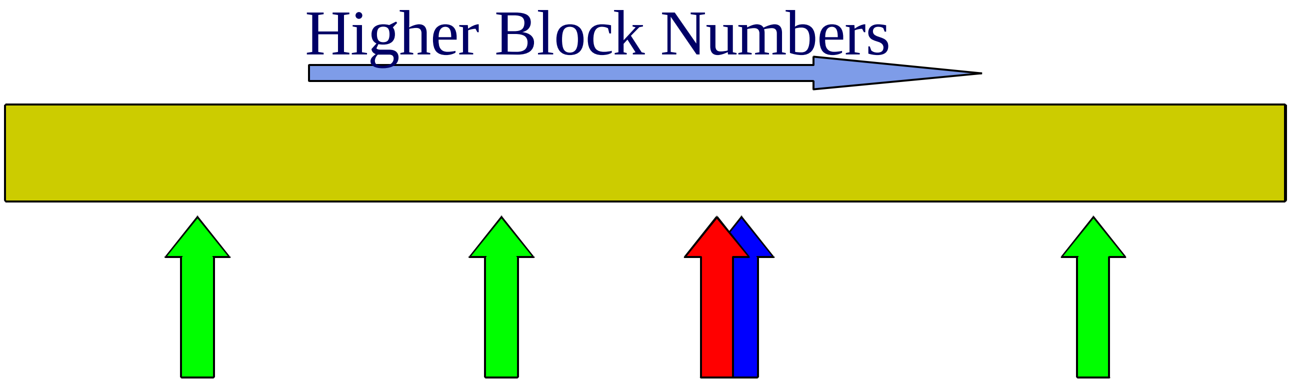
C-LOOK



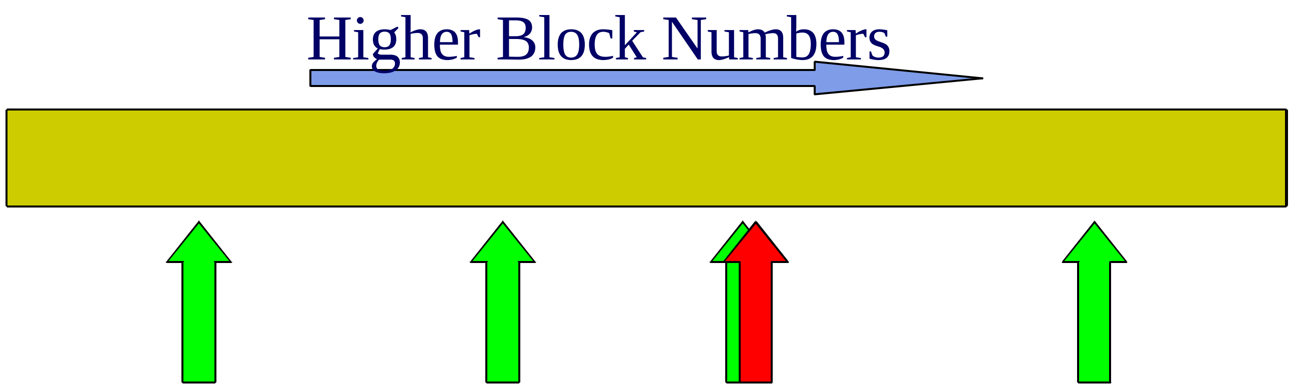
C-LOOK



C-LOOK



C-LOOK



Algorithm Classification

SCAN vs. LOOK

- LOOK doesn't visit far edges of disk unless there are requests

LOOK vs. C-LOOK

- C for “circular” - don't double-serve middle sectors

We are now excellent disk-arm schedulers

- Done, right?

Shortest ***Positioning*** Time First

Key observation

- **Seek time takes a while, C-LOOK is a reasonable response**
- **But rotational delay is comparable!**
  - **More: short seeks are *faster* than whole-disk rotations**
- **What matters is *positioning* time, not seek time**

SPTF is like SSTF

- **Serve “temporally nearest” sector next**

Challenge

- **Driver can't estimate positions from sector numbers**
- **Must know layout, plus rotation position of disk in real time!**

Performs better than SSTF, but still starves requests

Weighted Shortest Positioning Time First (WSPTF)

SPTF plus fairness

Requests are “aged” to prevent starvation

- **Compute “temporal distance” to each pending request**
- **Subtract off “age factor” - old requests are artificially close**
- **Result: sometimes serve old request, not closest request**

Various aging policies possible, many work fine

Excellent performance

As SPTF, hard for OS to know disk status in real time

- **On-disk schedulers can manage this, though...**
  - **Modern disks (SATA, SCSI) accept a *request queue***
  - **Sector complete ⇒ give OS both data and sector number**

Scheduling Concept Summary

LOOK vs SCAN

- SCAN goes to the very end of the disk
- LOOK goes only as far as the farthest request

2-way vs circular

- 2-way reverses directions at the extremes, unfair
- Circular starts back at the "starting" position

Modern disks queue internally, using positioning time

- Head of request queue managed by disk – two-level scheduler

Fairness

- "High-throughput" algorithms can starve requests
- "Complete fairness" is slow
- Balance somehow... "aging" is one option

Command Queueing In Action

Disks serve read requests out of order

- OS queues: “read 37”, “read 83”, “read 2”
  - Disk returns 37, 2, 83
    - Great! That's why we buy smart disks and queue multiple requests
- OS queues: “read 37”, “read 38”, “read 39”
  - Disk does one seek, reads 37-40, plus also 40-72 while it's in the neighborhood
  - Sends sectors as they become available

Disks serve *write* requests out of order, too

- OS queues “write 23”, “write 24”, “write 1000”, “read 4-8”, ...
  - Disk writes 24, 23 (!!), gives you 4, 5, 6, 7, 8, writes 1000
    - What if power fails before last write?
    - What if power fails between first two writes?

Command Queueing In Action

How can OS ensure data-structure integrity?

- **Special commands**
  - **“Flush all pending writes”**
    - **Think “my disk is 'modern'”, think “disk barrier”**
    - **Can even queue a flush to apply to all before now**
    - **Can apply these “barrier” flushes to subsets of requests**
      - Rarely used by operating system
  - **“Disable write cache”**
    - **Think “please don't be quite so modern”**

Solid-State Disks (SSD)

SSD vs. disk

- ☺ SSD's Implement write-sector, read-sector, “park heads”, etc.
- ☺ Read operations are extremely fast (100X faster), no “seek time” or “rotational delay” (every sector is “nearby”)
- ? Write operations “vary widely” (maybe 100X faster, maybe not faster at all)
- ☺ SSD's use less power than actual disks (~1/5?)
- ☺ SSD's are shock-resistant
- ☹ Writing to an SSD wears it out much faster than a disk
- ☹ SSD's are ***expensive*** (20X or more)

Solid-State Disks (SSD)

SSD pretends to be a disk

- Identify, read/write, “park heads”, SMART, ...

It's a big lie

- “Write amplification”
  - Flash must be erased in big blocks (256KB)
  - So storing 512B could blow up by 512X!
- Wear leveling
  - When a block is written 10K/100K times, it breaks
  - File systems tend to write “favorite blocks” over and over...
- “Flash translation layer” (computer) maps LBA to arbitrary flash locations
  - This is a tough, complicated, messy job
  - Approaches and algorithms still in flux

Solid-State Disks (SSD)

Opportunity & threat

- "TRIM" command speeds up writes!
  - "Dear FTL, logically zero-fill these blocks"
- "Securely erase disk" is impossible

The future?

- Lots more SSD's
- Lots more disks too
- Hybrid systems to take advantage of best features of both

Conclusions

Disks are mechanical (voice coil == speakers)

Disks are slow, best if accesses are big & sequential

Disks are complicated (there's a computer inside)

FCFS is a very bad idea

- C-LOOK is ok in practice
- Disks probably do something like SPTF internally

Flexible queuing is good for performance

- Data-structure integrity and performance pull opposite ways

SSD's are "hot"

- (cool)

Further Reading

Terabyte Territory

Brian Hayes

American Scientist, May/June 2002

http://www.americanscientist.org/issues/pub/terabyte-territory

A Conversation with Jim Gray

Dave Patterson

ACM Queue, June 2003

http://queue.acm.org/detail.cfm?id=864078

Reliably Erasing Data from Flash-based Solid State Drives

Wei et al., UCSD

FAST '11

http://www.usenix.org/events/fast11/tech/full_papers/Wei.pdf