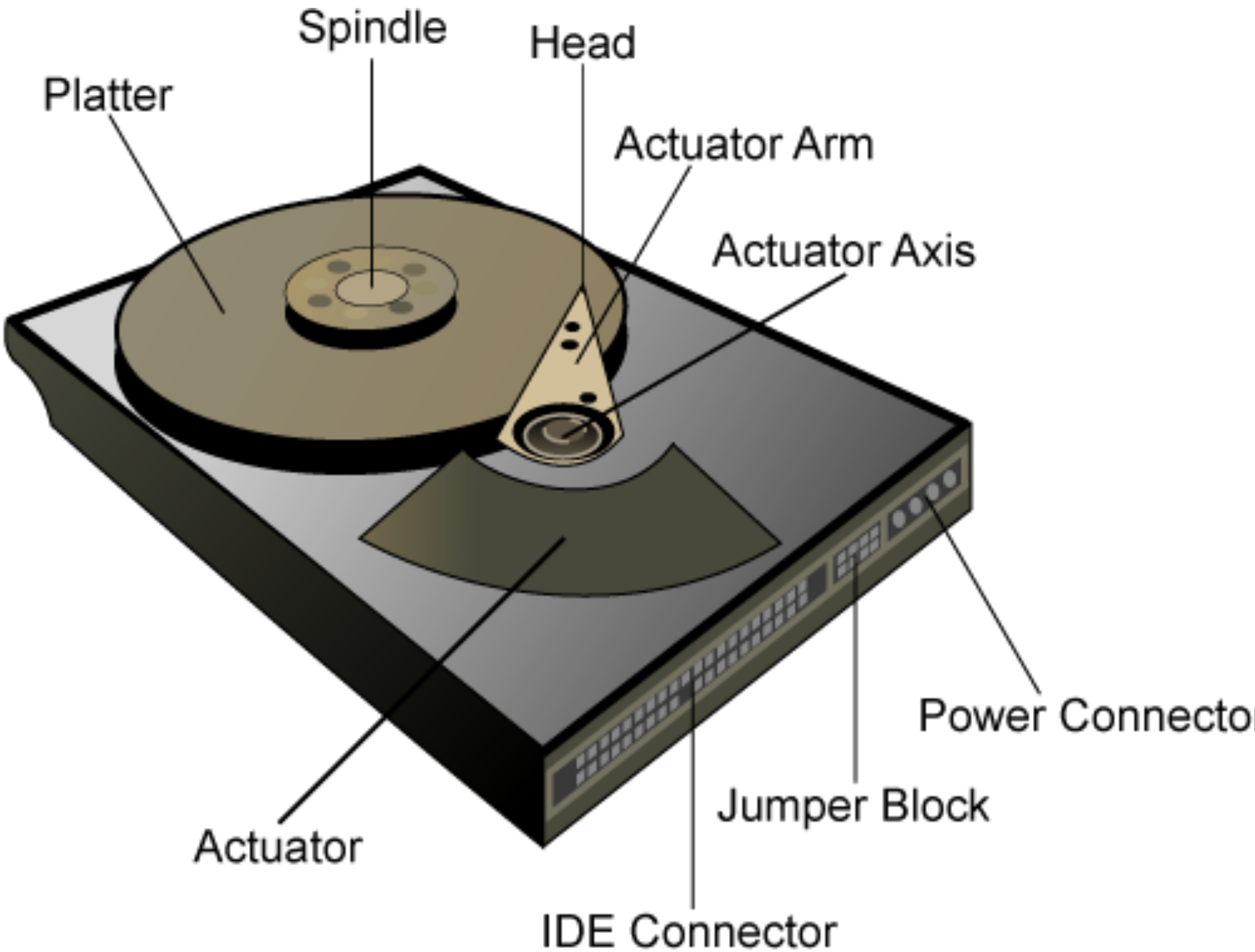
CS 5600
Computer Systems

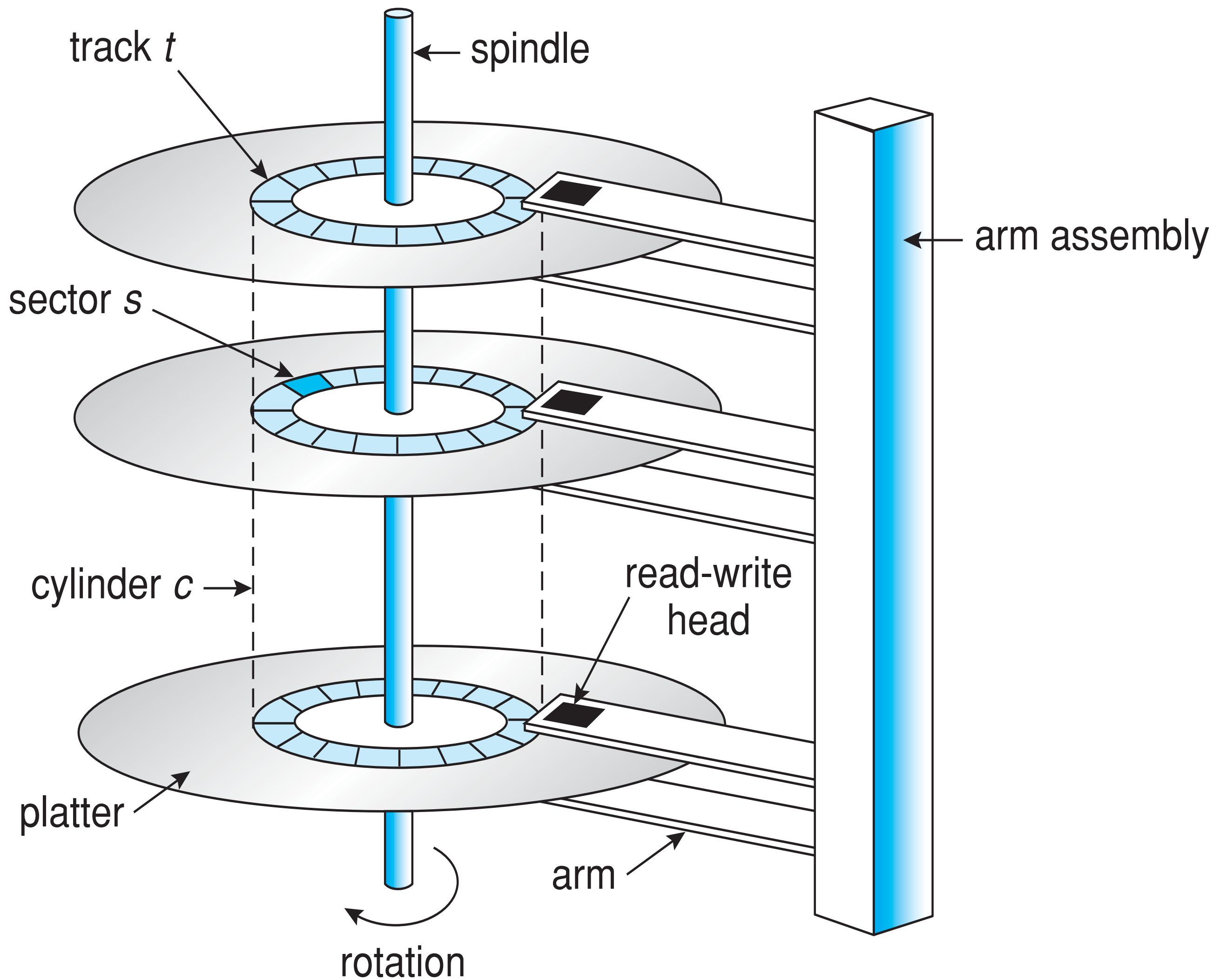
Lecture 8: Storage Devices

- Hard Drives
- RAID
- SSD

Hard Drive Hardware



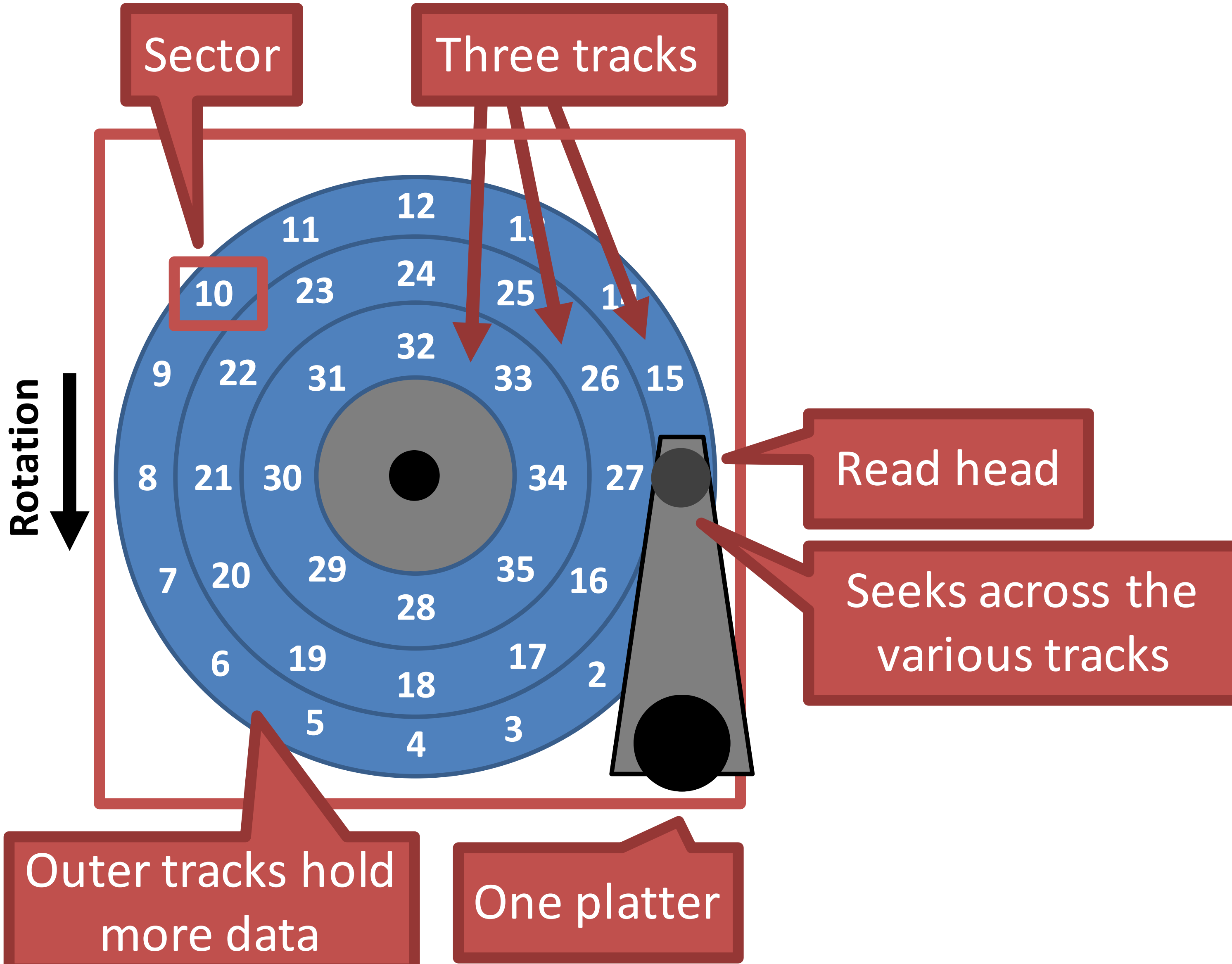
A Multi-Platter Disk



Addressing and Geometry

- Externally, hard drives expose a large number of sectors (blocks)
  - Typically 512 or 4096 bytes
  - Individual sector writes are atomic
  - Multiple sectors writes may be interrupted (torn write)
- Drive geometry
  - Sectors arranged into tracks
  - A cylinder is a particular track on multiple platters
  - Tracks arranged in concentric circles on platters
  - A disk may have multiple, double-sided platters
- Drive motor spins the platters at a constant rate
  - Measured in revolutions per minute (RPM)

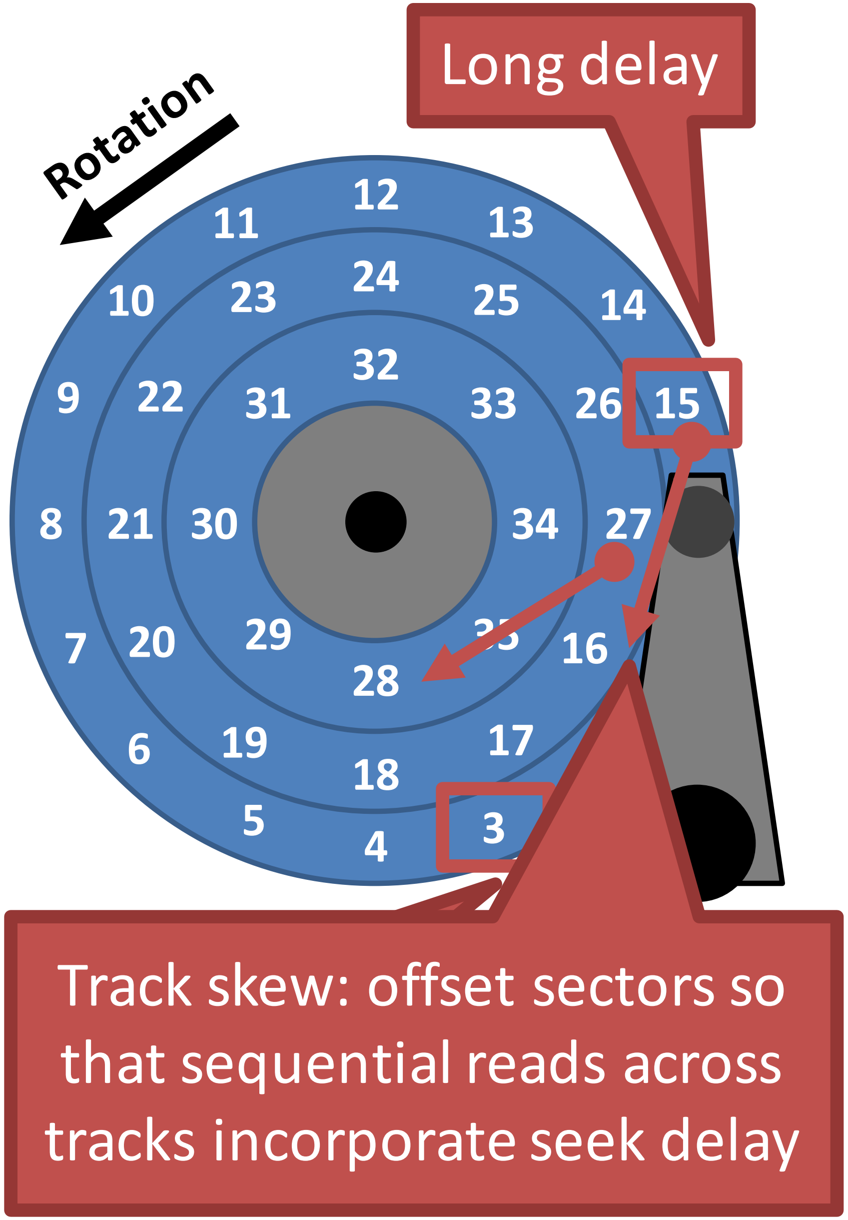
Geometry Example



Common Disk Interfaces

- ST-506 → ATA → IDE → SATA
  - Ancient standard
  - Commands (read/write) and addresses in cylinder/head/sector format placed in device registers
  - Recent versions support Logical Block Addresses (LBA)
- SCSI (Small Computer Systems Interface)
  - Packet based, like TCP/IP
  - Device translates LBA to internal format (e.g. c/h/s)
  - Transport independent
    - USB drives, CD/DVD/Bluray, Firewire
    - iSCSI is SCSI over TCP/IP and Ethernet

Types of Delay With Disks



<u>Three types of delay</u>

1. Rotational Delay
   - Time to rotate the desired sector to the read head
   - Related to RPM
2. Seek delay
   - Time to move the read head to a different track
3. Transfer time
   - Time to read or write bytes

How To Calculate Transfer Time

Seagate

	Cheetah 15K.5	Barracuda
Capacity	300 GB	1 TB
RPM	15000	7200
Avg. Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

Transfer time

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

Sequential vs. Random Access

Rate of I/O

$$R_{I/O} = \text{transfer\_size} / T_{I/O}$$

Access Type	Transfer Size		Cheetah 15K.5	Barracuda
Random	4096 B	$T_{I/O}$	6 ms	13.2 ms
		$R_{I/O}$	0.66 MB/s	0.31 MB/s

Random I/O results in very poor disk performance!

Caching

- Many disks incorporate caches (track buffer)
  - Small amount of RAM (8, 16, or 32 MB)
- Read caching
  - Reduces read delays due to seeking and rotation
- Write caching
  - Write back cache: drive reports that writes are complete after they have been cached
    - Possibly dangerous feature. Why?
  - Write through cache: drive reports that writes are complete after they have been written to disk
- Today, some disks include flash memory for persistent caching (hybrid drives)

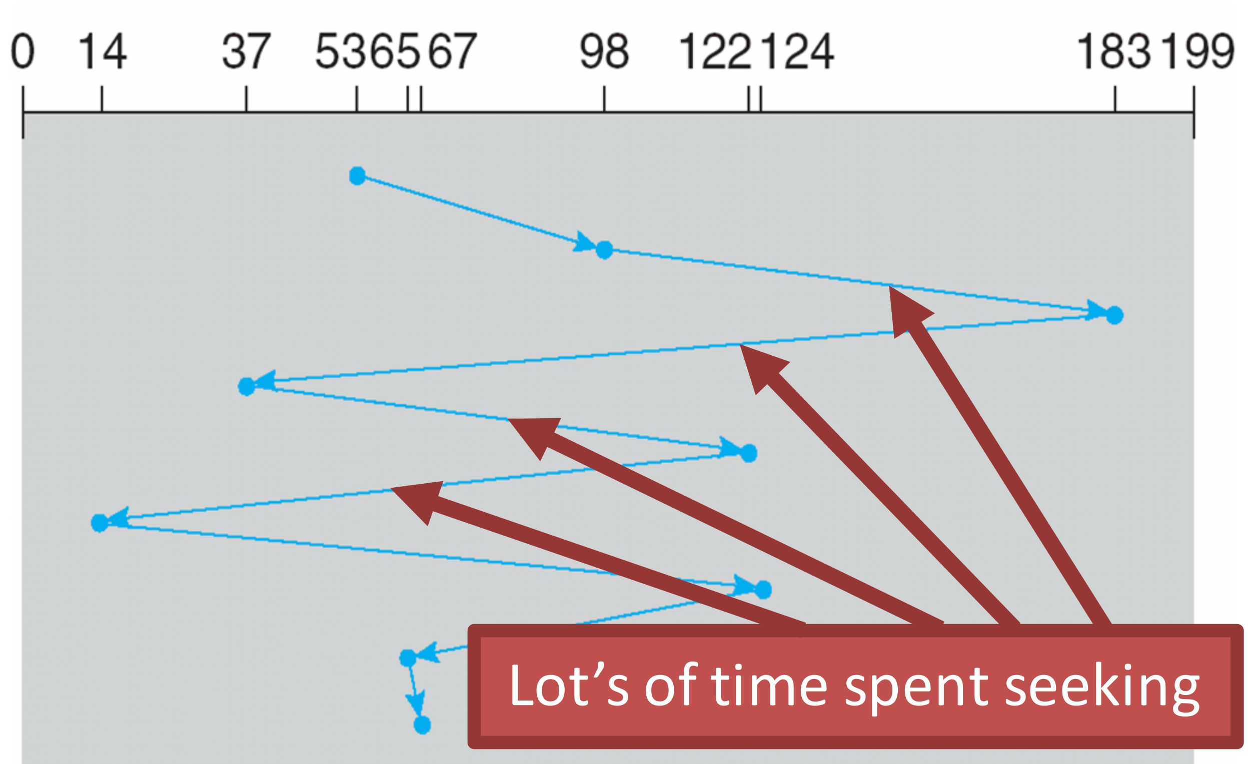
Disk Scheduling

- Caching helps improve disk performance
- But it can’t make up for poor random access times
- Key idea: if there are a queue of requests to the disk, they can be reordered to improve performance
  - First come, first serve (FCFC)
  - Shortest seek time first (SSTF)
  - SCAN, otherwise know as the elevator algorithm
  - C-SCAN, C-LOOK, etc.

FCFS Scheduling

- Most basic scheduler, serve requests in order

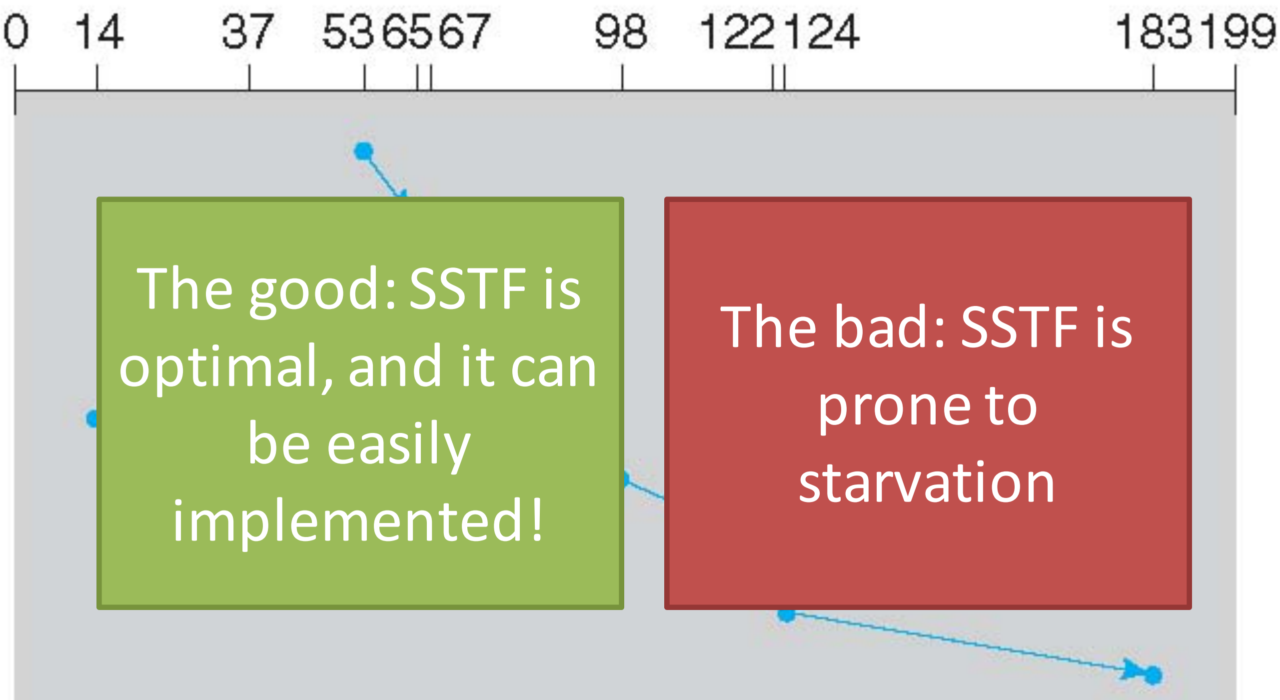
- Head starts at block 53
- Queue: 98, 183, 37, 122, 14, 124, 65, 67



- Total movement: 640 cylinders

SSTF Scheduling

- Idea: minimize seek time by always selecting the block with the shortest seek time
- Head starts at block 53
- Queue: 98, 183, 37, 122, 14, 124, 65, 67



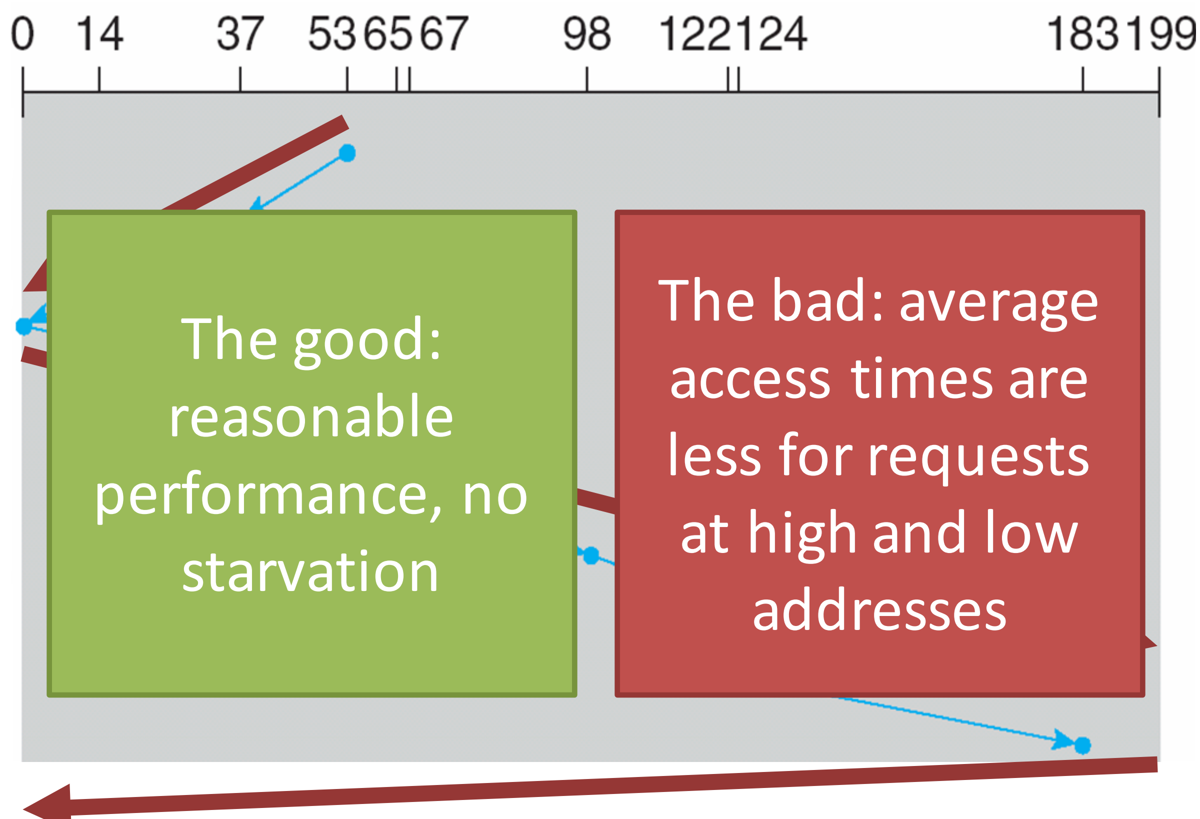
The good: SSTF is optimal, and it can be easily implemented!

The bad: SSTF is prone to starvation

- Total movement: 236 cylinders

SCAN Example

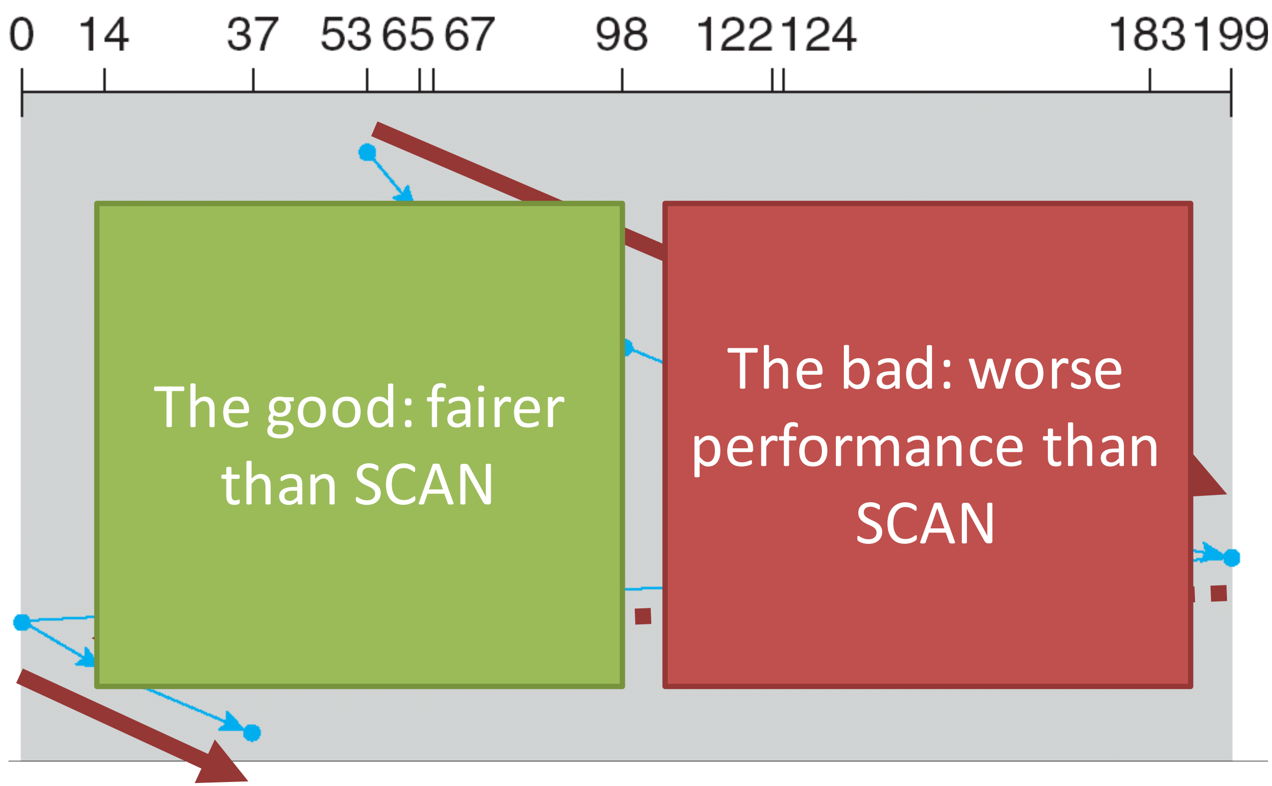
- Head sweeps across the disk servicing requests in order
- Head starts at block 53
- Queue: 98, 183, 37, 122, 14, 124, 65, 67



- Total movement: 236 cylinders

C-SCAN Example

- Like SCAN, but only service requests in one direction
- Head starts at block 53
- Queue: 98, 183, 37, 122, 14, 124, 65, 67



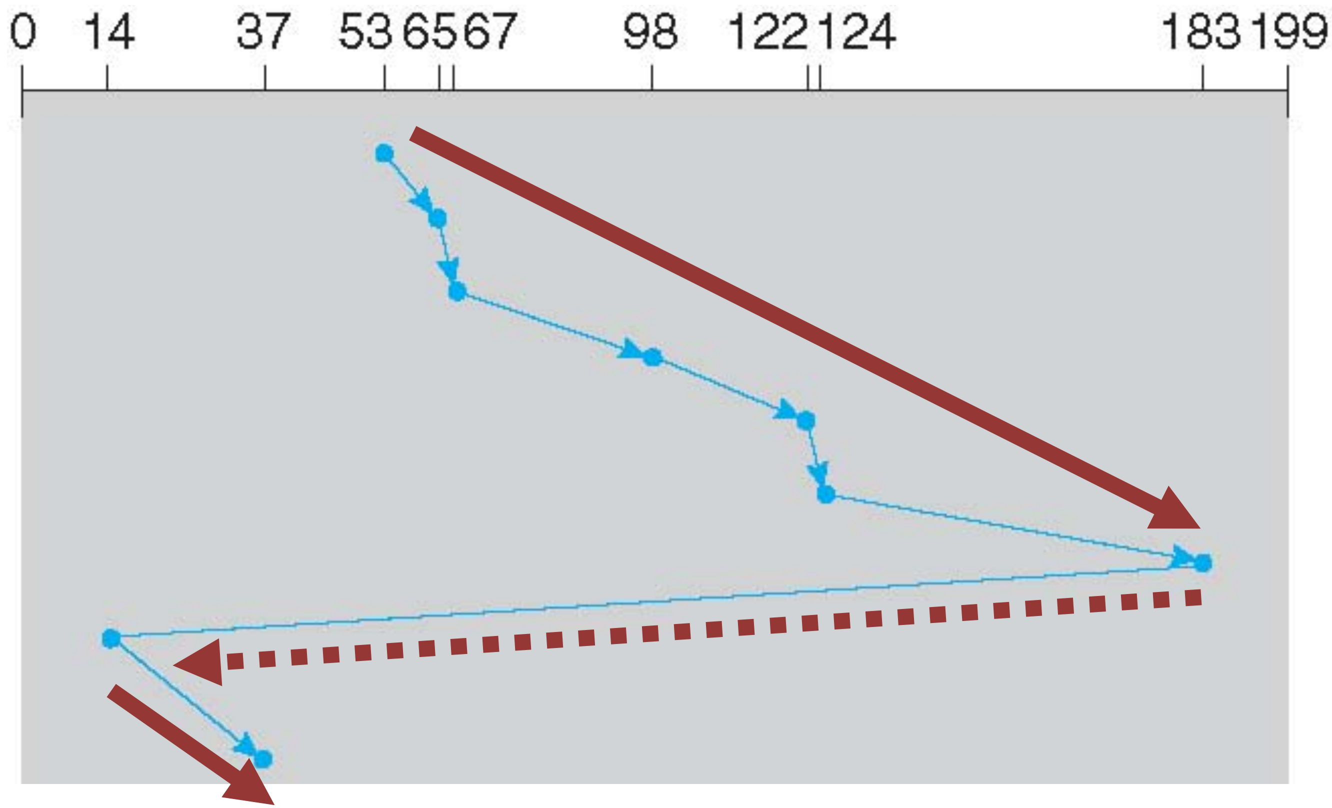
- Total movement: 382 cylinders

C-LOOK Example

- Peek at the upcoming addresses in the queue
  - Addresses in your direction, service them
  - No address left in your direction, change direction

- Head starts at block 53

- Queue: 98, 183, 37, 122, 14, 124, 65, 67



- Total movement: 322 cylinders

Implementing Disk Scheduling

- We have talked about several scheduling problems that take place in the kernel
  - Process scheduling
  - Page swapping
- Where should disk scheduling be implemented?
  - OS scheduling
    - OS can implement SSTF or LOOK by ordering the queue by LBA
    - However, the OS cannot account for rotation delay
  - On-disk scheduling
    - Disk knows the exact position of the head and platters
    - Can implement more advanced schedulers (SPTF)
    - But, requires specialized hardware and drivers

Command Queuing

- Feature where a disk stores a queue of pending read/write requests
  - Called Native Command Queuing (NCQ) in SATA
- Disk may reorder items in the queue to improve performance
  - E.g. batch operations to close sectors/tracks
- Supported by SCSI and modern SATA drives
- Tagged command queuing: allows the host to place constraints on command re-ordering

- Hard Drives
- RAID
- SSD

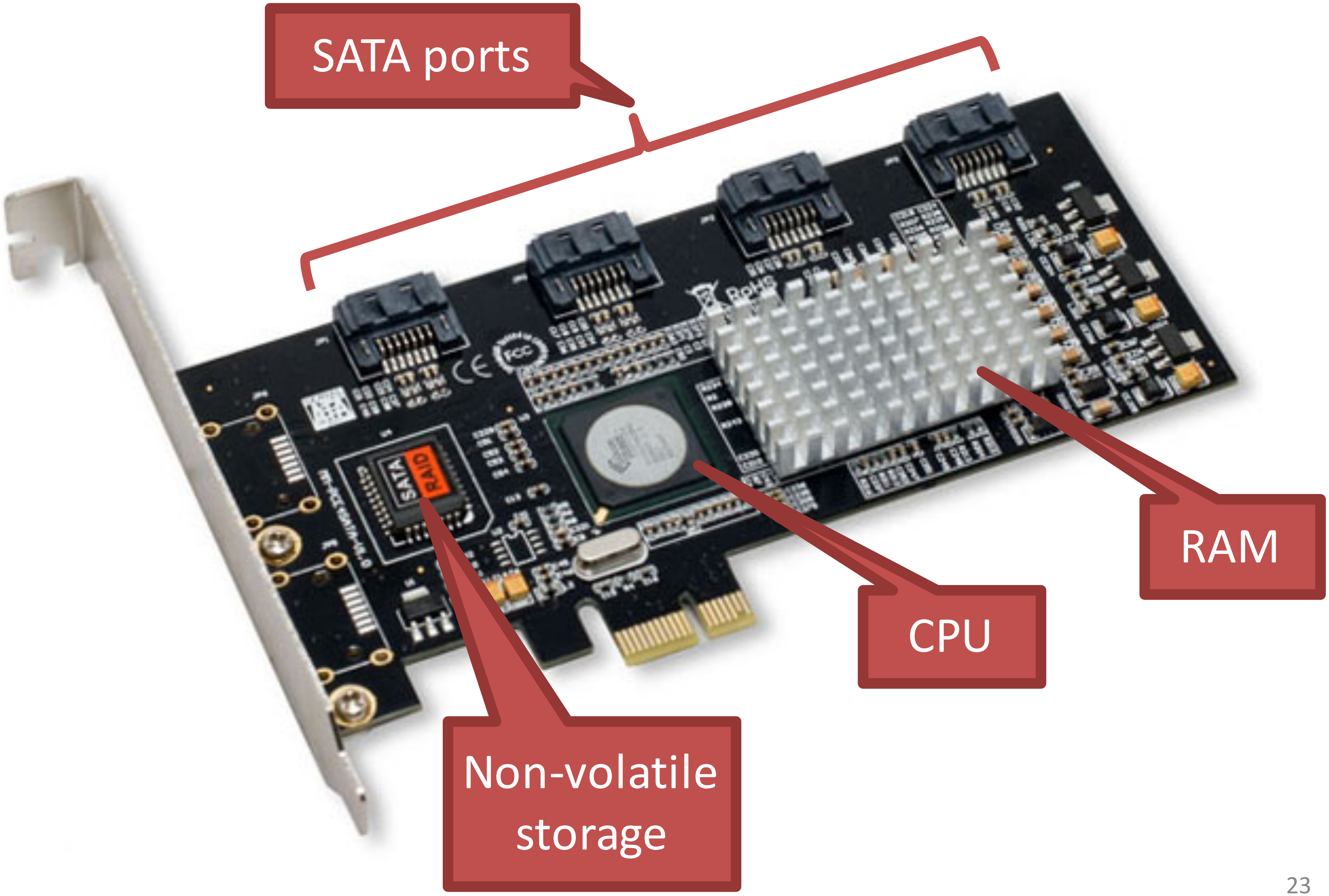
Beyond Single Disks

- Hard drives are great devices
  - Relatively fast, persistent storage
- Shortcomings:
  - How to cope with disk failure?
    - Mechanical parts break over time
    - Sectors may become silently corrupted
  - Capacity is limited
    - Managing files across multiple physical devices is cumbersome
    - Can we make 10x 1 TB drives look like a 10 TB drive?

Redundant Array of Inexpensive Disks

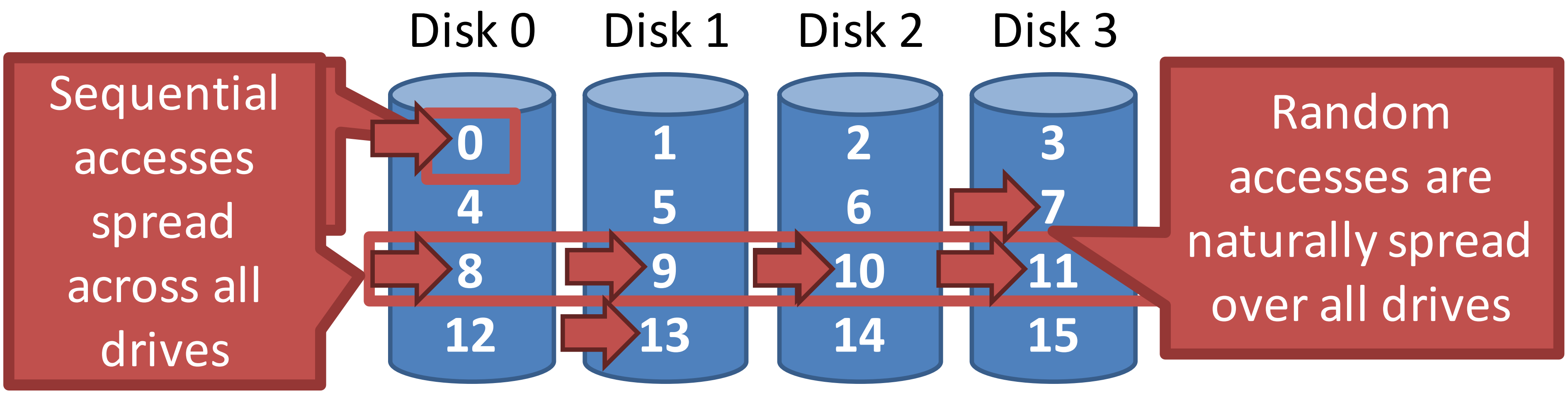
- RAID: use multiple disks to create the illusion of a large, faster, more reliable disk
- Externally, RAID looks like a single disk
  - i.e. RAID is transparent
  - Data blocks are read/written as usual
  - No need for software to explicitly manage multiple disks or perform error checking/recovery
- Internally, RAID is a complex computer system
  - Disks managed by a dedicated CPU + software
  - RAM and non-volatile memory
  - Many different configuration options (RAID levels)

Example RAID Controller



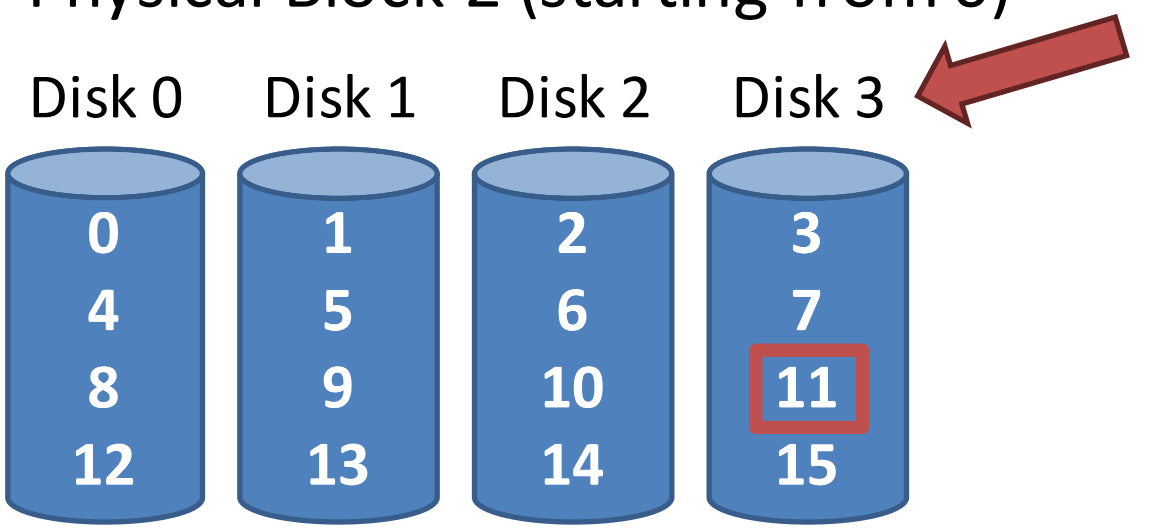
RAID 0: Striping

- Key idea: present an array of disks as a single large disk
- Maximize parallelism by striping data cross all *N* disks

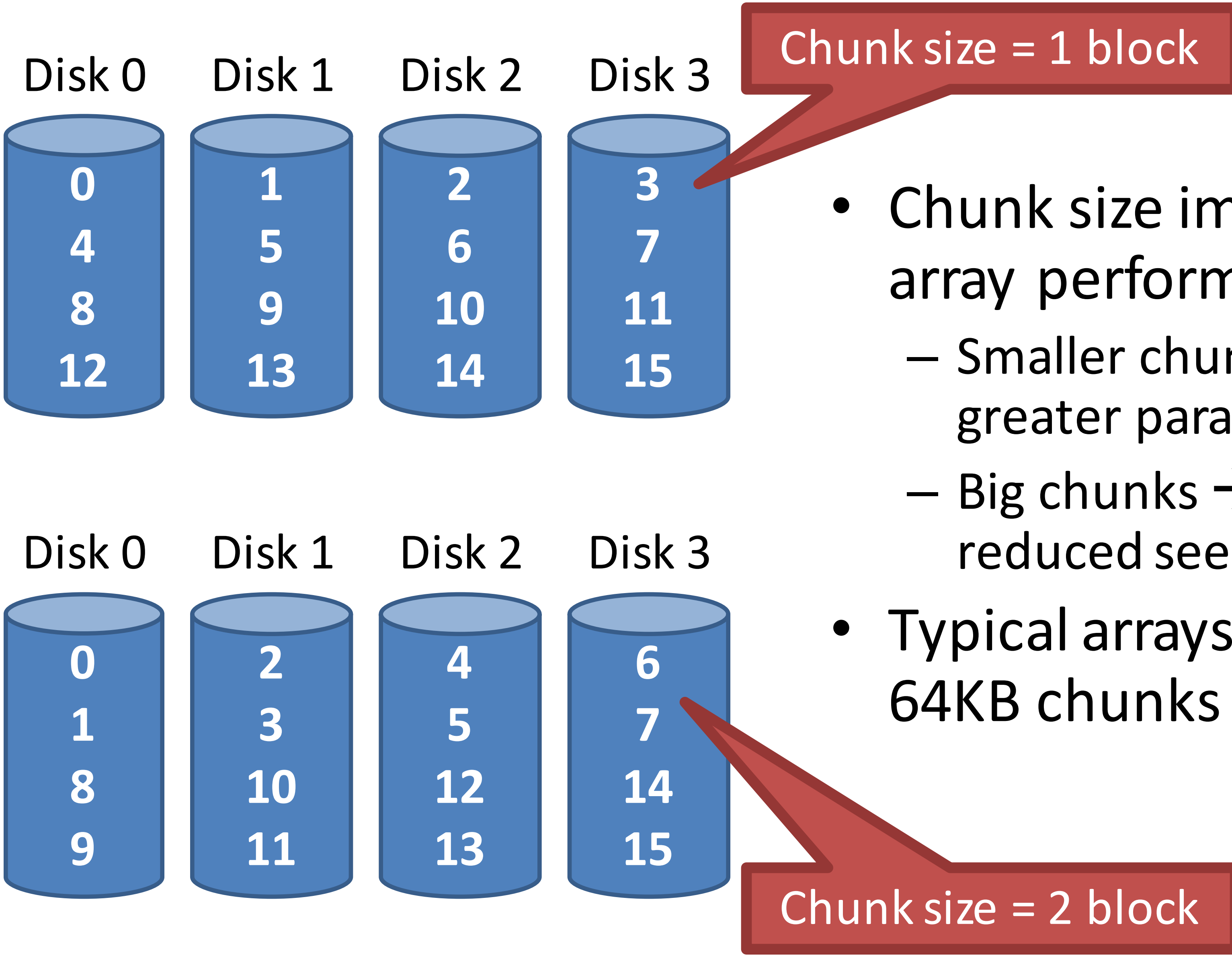


Addressing Blocks

- How do you access specific data blocks?
  - Disk = logical_block_number % number_of_disks
  - Offset = logical_block_number / number_of_disks
- Example: read block 11
  - 11 % 4 = Disk 3
  - 11 / 4 = Physical Block 2 (starting from 0)



Chunk Sizing



- Chunk size impacts array performance
  - Smaller chunks → greater parallelism
  - Big chunks → reduced seek times
- Typical arrays use 64KB chunks

Measuring RAID Performance (1)

- As usual, we focus on sequential and random workloads
- Assume disks in the array have **sequential** access time *S*
  - 10 MB transfer
  - *S = transfer_size / time_to_access*
  - 10 MB / (7 ms + 3 ms + 10 MB / 50 MB/s) = 47.62 MB/s

Average seek time	7 ms
Average rotational delay	3 ms
Transfer rate	50 MB/s

Measuring RAID Performance (2)

- As usual, we focus on sequential and random workloads
- Assume disks in the array have **random** access time *R*
  - 10 KB transfer
  - *R = transfer_size / time_to_access*
  - 10 KB / (7 ms + 3 ms + 10 KB / 50 MB/s) = 0.98 MB/s

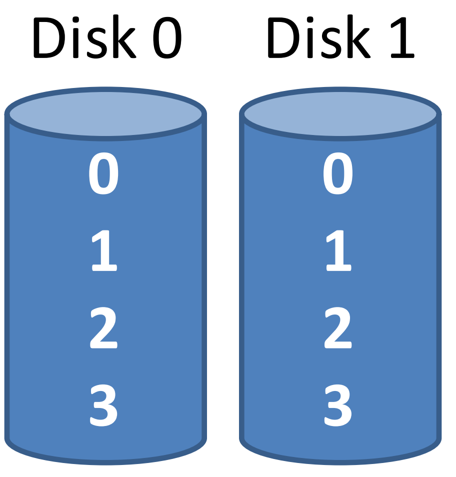
Average seek time	7 ms
Average rotational delay	3 ms
Transfer rate	50 MB/s

Analysis of RAID 0

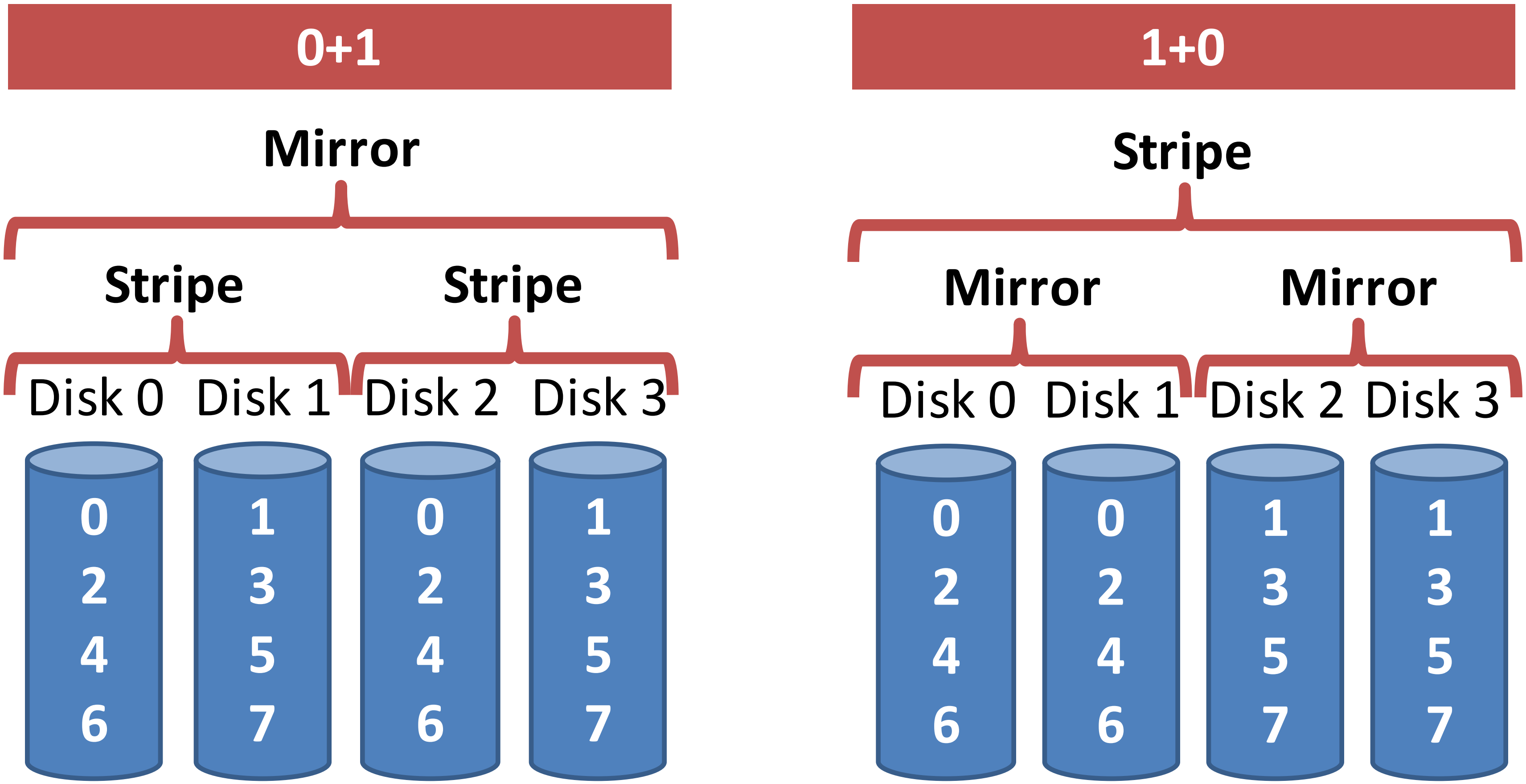
- Capacity: *N*
  - All space on all drives can be filled with data
- Reliability: 0
  - If any drive fails, data is permanently lost
- Sequential read and write: $N * S$
  - Full parallelization across drives
- Random read and write: $N * R$
  - Full parallelization across all drives

RAID 1: Mirroring

- RAID 0 offers high performance, but zero error recovery
- Key idea: make two copies of all data



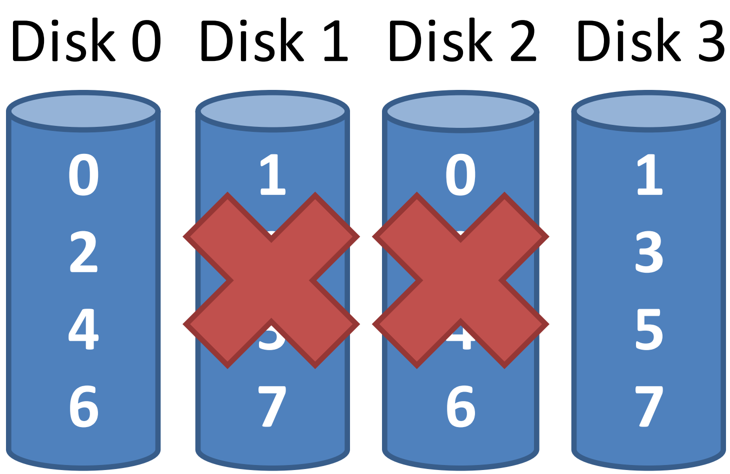
RAID 0+1 and 1+0 Examples



- Combines striping and mirroring
- Superseded by RAID 4, 5, and 6

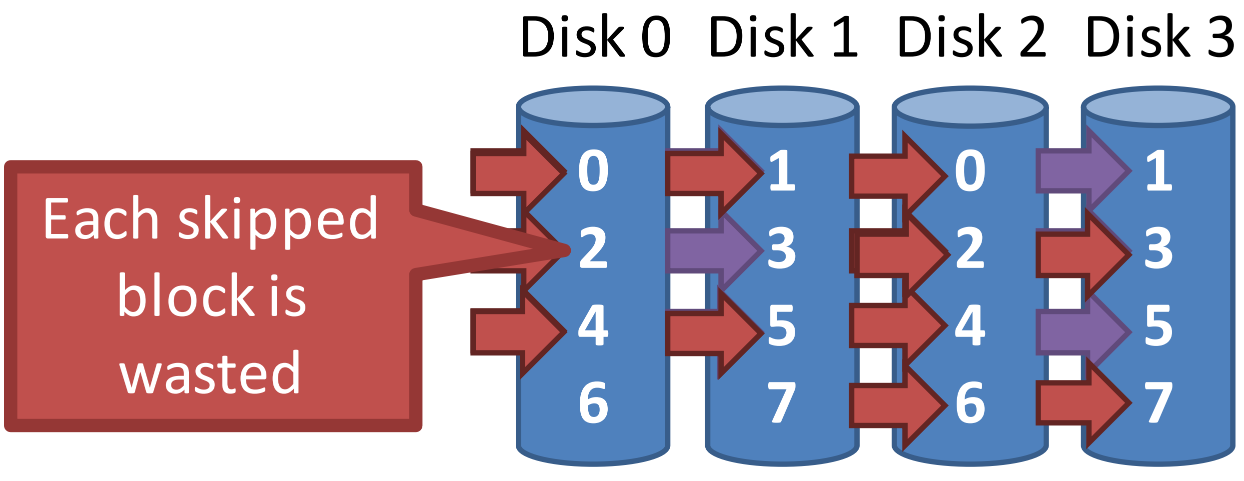
Analysis of RAID 1 (1)

- Capacity: *N / 2*
  - Two copies of all data, thus half capacity
- Reliability: 1 drive can fail, sometime more
  - If you are lucky, *N / 2* drives can fail without data loss



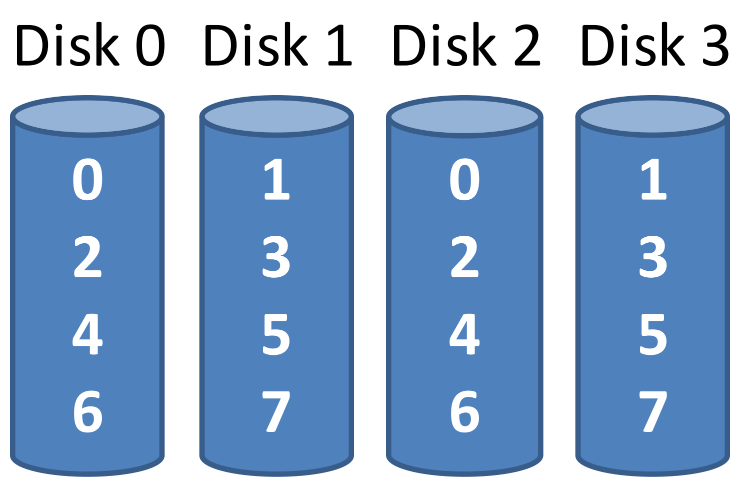
Analysis of RAID 1 (2)

- Sequential write: *(N / 2) * S*
  - Two copies of all data, thus half throughput
- Sequential read: *(N / 2) * S*
  - Half of the read blocks are wasted, thus halving throughput



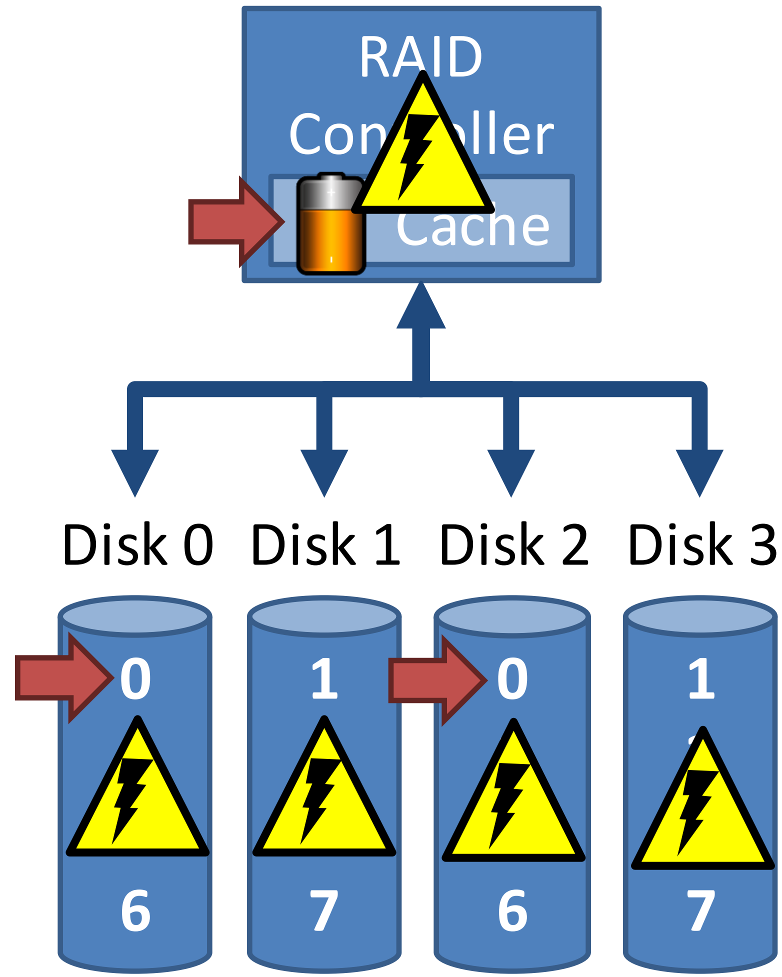
Analysis of RAID 1 (3)

- Random read: *N * R*
  - Best case scenario for RAID 1
  - Reads can parallelize across all disks
- Random write: *(N / 2) * R*
  - Two copies of all data, thus half throughput



The Consistent Update Problem

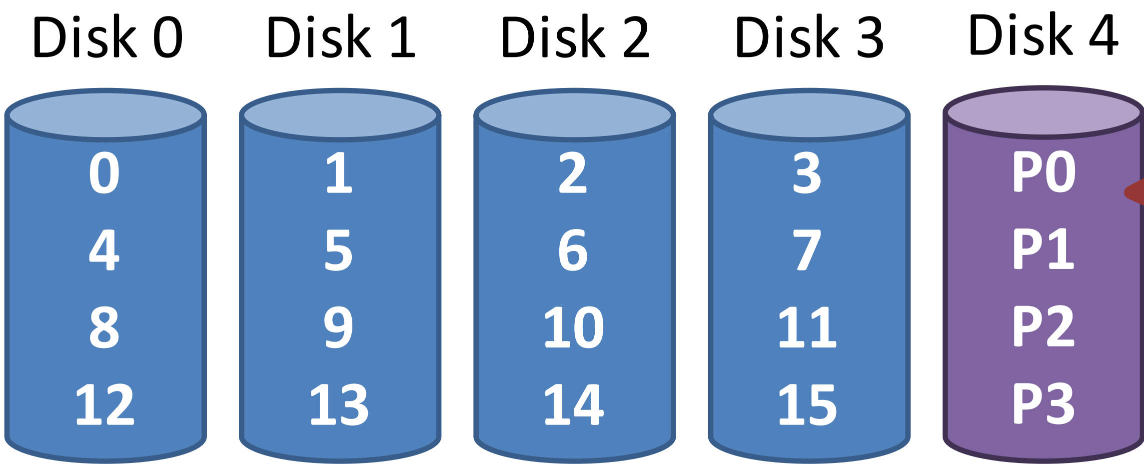
- Mirrored writes should be atomic
  - All copies are written, or none are written
- However, this is difficult to guarantee
  - Example: power failure
- Many RAID controllers include a write-ahead log
  - Battery backed, non-volatile storage of pending writes



Decreasing the Cost of Reliability

- RAID 1 offers highly reliable data storage
- But, it uses *N / 2* of the array capacity
- Can we achieve the same level of reliability without wasting so much capacity?
  - Yes!
  - Use information coding techniques to build light-weight error recovery mechanisms

RAID 4: Parity Drive



Disk *N* only stores parity information for the other *N-1* disks

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	0	1	1	0 ^ 0 ^ 1 ^ 1 = 0
0	1	0	0	0 ^ 1 ^ 0 ^ 0 = 1
1	1	1	1	1 ^ 1 ^ 1 ^ 1 = 0
0	1	1	1	0 ^ 1 ^ 1 ^ 1 = 1

Parity calculated using XOR

Updating Parity on Write

- How is parity updated when blocks are written?

1. Additive parity

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	0	0	1	0 ^ 0 ^ 0 ^ 1 = 1

Read other blocks

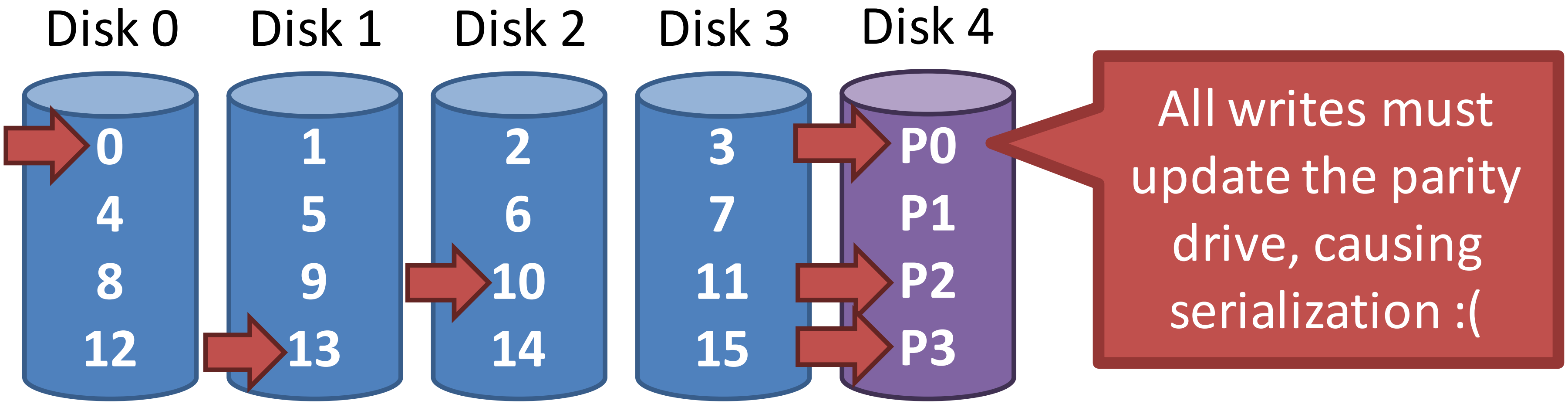
Update parity block

2. Subtractive parity

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	0	1 0	1	0 ^ 0 ^ 1 ^ 1 1

$P_{new} = C_{old} \wedge C_{new} \wedge P_{old}$

Random Writes and RAID 4

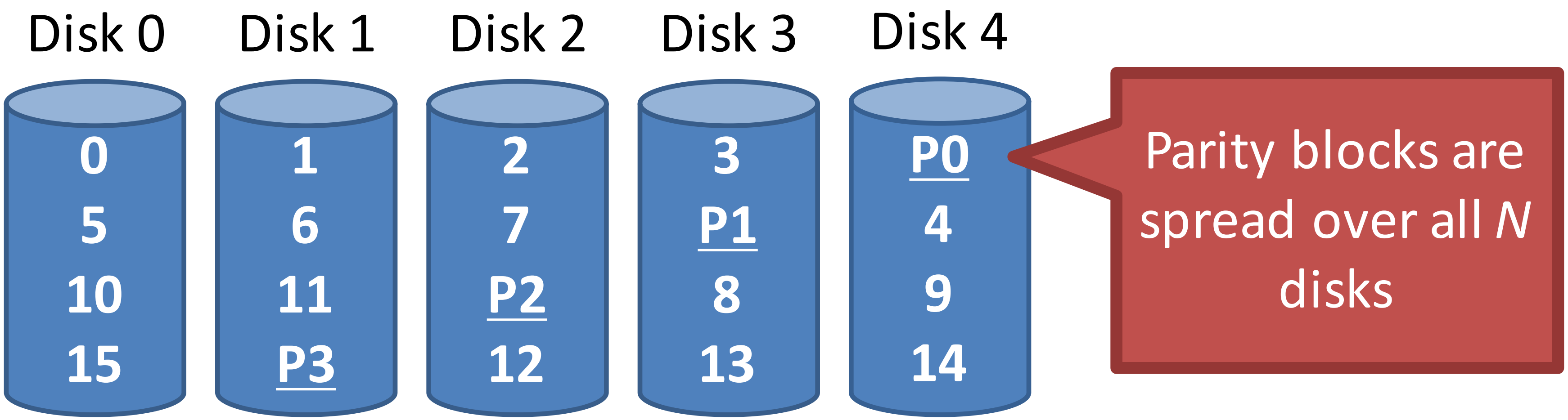


- Random writes in RAID 4
  1. Read the target block and the parity block
  2. Use subtraction to calculate the new parity block
  3. Write the target block and the parity block
- RAID 4 has terrible write performance
  - Bottlenecked by the parity drive

Analysis of RAID 4

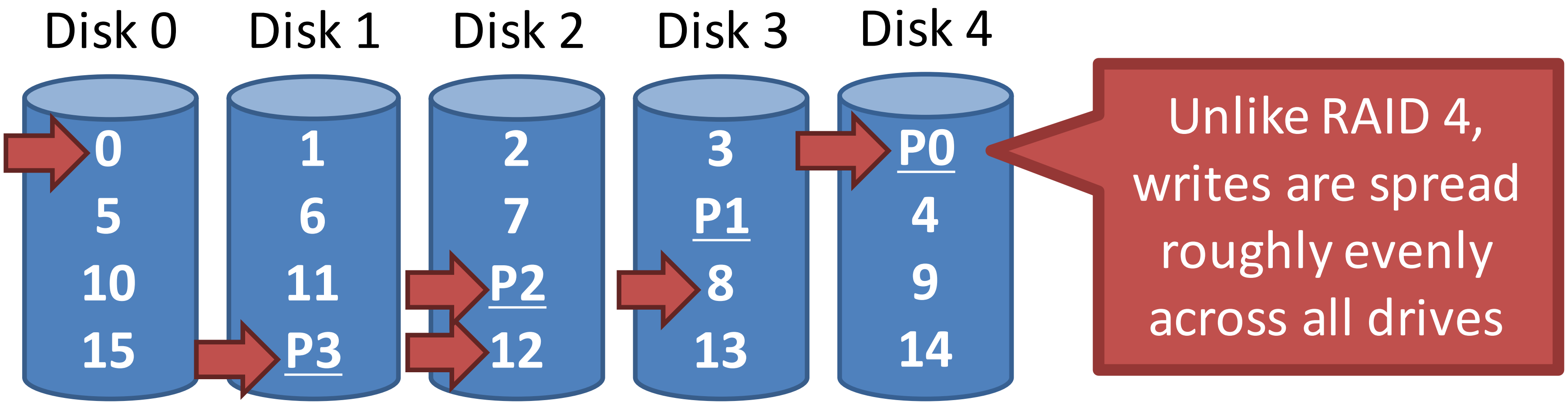
- Capacity: *N – 1*
  - Space on the parity drive is lost
- Reliability: 1 drive can fail
- Sequential Read and write: *(N – 1) * S*
  - Parallelization across all non-parity blocks
- Random Read: *(N – 1) * R*
  - Reads parallelize over all but the parity drive
- Random Write: *R / 2*
  - Writes serialize due to the parity drive
  - Each write requires 1 read and 1 write of the parity drive, thus *R / 2*

RAID 5: Rotating Parity



Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	0	1	1	0 ^ 0 ^ 1 ^ 1 = 0
1	0	0	0 ^ 1 ^ 0 ^ 0 = 1	0
1	1	1 ^ 1 ^ 1 ^ 1 = 0	1	1
1	0 ^ 1 ^ 1 ^ 1 = 1	0	1	1

Random Writes and RAID 5



- Random writes in RAID 5
  1. Read the target block and the parity block
  2. Use subtraction to calculate the new parity block
  3. Write the target block and the parity block
- Thus, 4 total operations (2 reads, 2 writes)
  - Distributed across all drives

Analysis of Raid 5

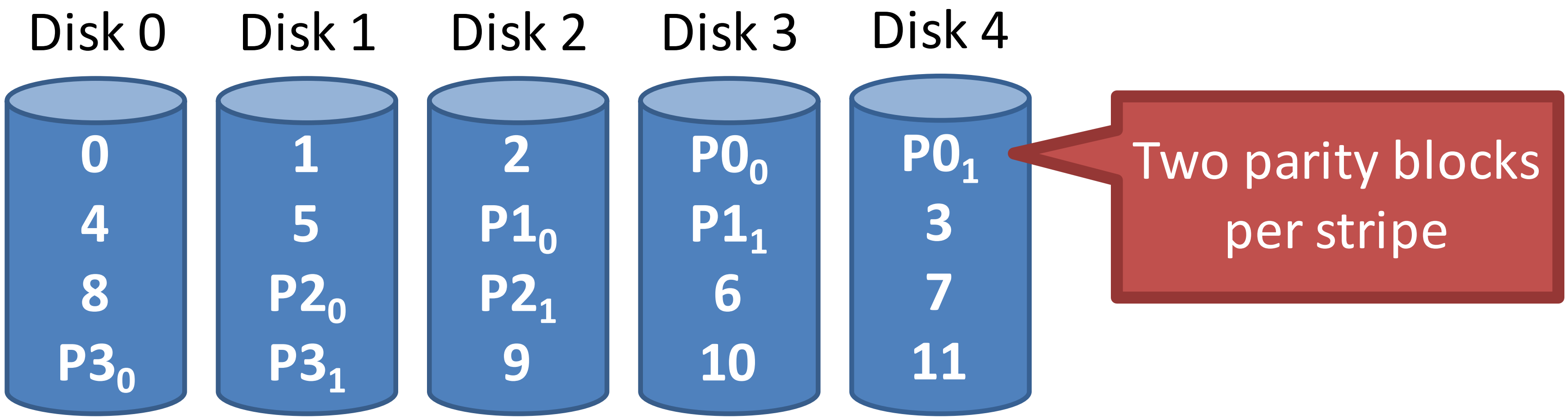
- Capacity: $N - 1$ [same as RAID 4]
- Reliability: 1 drive can fail [same as RAID 4]
- Sequential Read and write: $(N - 1) * S$ [same]
  - Parallelization across all non-parity blocks
- Random Read: $N * R$ [vs. $(N - 1) * R$]
  - Unlike RAID 4, reads parallelize over all drives
- Random Write: $N / 4 * R$ [vs. $R / 2$ for RAID 4]
  - Unlike RAID 4, writes parallelize over all drives
  - Each write requires 2 reads and 2 write, hence $N / 4$

Comparison of RAID Levels

- *N* – number of drives
- *S* – sequential access speed
- *R* – random access speed
- *D* – latency to access a single disk

		RAID 0	RAID 1	RAID 4	RAID 5
	Capacity	***N***	*N / 2*	*N – 1*	*N – 1*
	Reliability	*0*	***1* (maybe *N / 2*)**	*1*	*1*
Throughput	Sequential Read	***N * S***	*(N / 2) * S*	*(N – 1) * S*	*(N – 1) * S*
Throughput	Sequential Write	***N * S***	*(N / 2) * S*	*(N – 1) * S*	*(N – 1) * S*
Throughput	Random Read	***N * R***	***N * R***	*(N – 1) * R*	***N * R***
Throughput	Random Write	***N * R***	*(N / 2) * R*	*R / 2*	*(N / 4) * R*
Latency	Read	***D***	***D***	***D***	***D***
Latency	Write	***D***	***D***	*2 * D*	*2 * D*

RAID 6



- Any two drives can fail
- *N – 2* usable capacity
- No overhead on read, significant overhead on write
- Typically implemented using Reed-Solomon codes

Choosing a RAID Level

- Best performance and most capacity?
  – RAID 0
- Greatest error recovery?
  – RAID 1 (1+0 or 0+1) or RAID 6
- Balance between space, performance, and recoverability?
  – RAID 5

Other Considerations

- Many RAID systems include a hot spare
  - An idle, unused disk installed in the system
  - If a drive fails, the array is immediately rebuilt using the hot spare
- RAID can be implemented in hardware or software
  - Hardware is faster and more reliable…
  - But, migrating a hardware RAID array to a different hardware controller almost never works
  - Software arrays are simpler to migrate and cheaper, but have worse performance and weaker reliability
    - Due to the consistent update problem

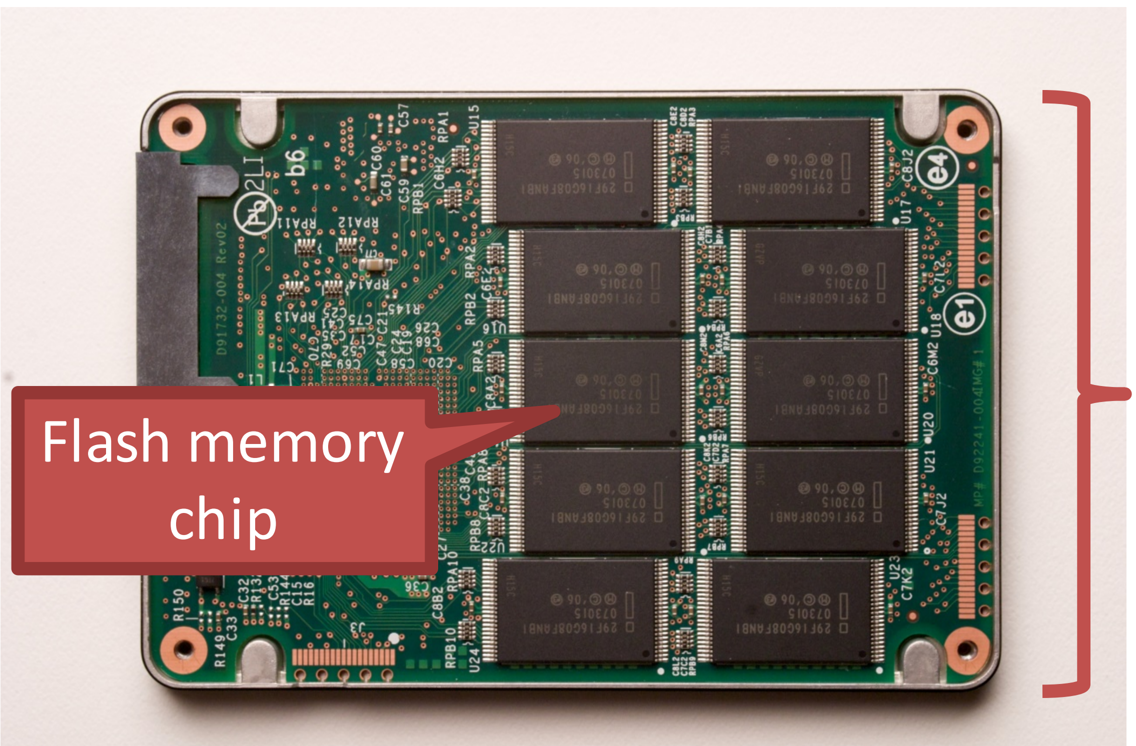
- Hard Drives
- RAID
- SSD

Beyond Spinning Disks

- Hard drives have been around since 1956
  - The cheapest way to store large amounts of data
  - Sizes are still increasing rapidly
- However, hard drives are typically the slowest component in most computers
  - CPU and RAM operate at GHz
  - PCI-X and Ethernet are GB/s
- Hard drives are not suitable for mobile devices
  - Fragile mechanical components can break
  - The disk motor is extremely power hungry

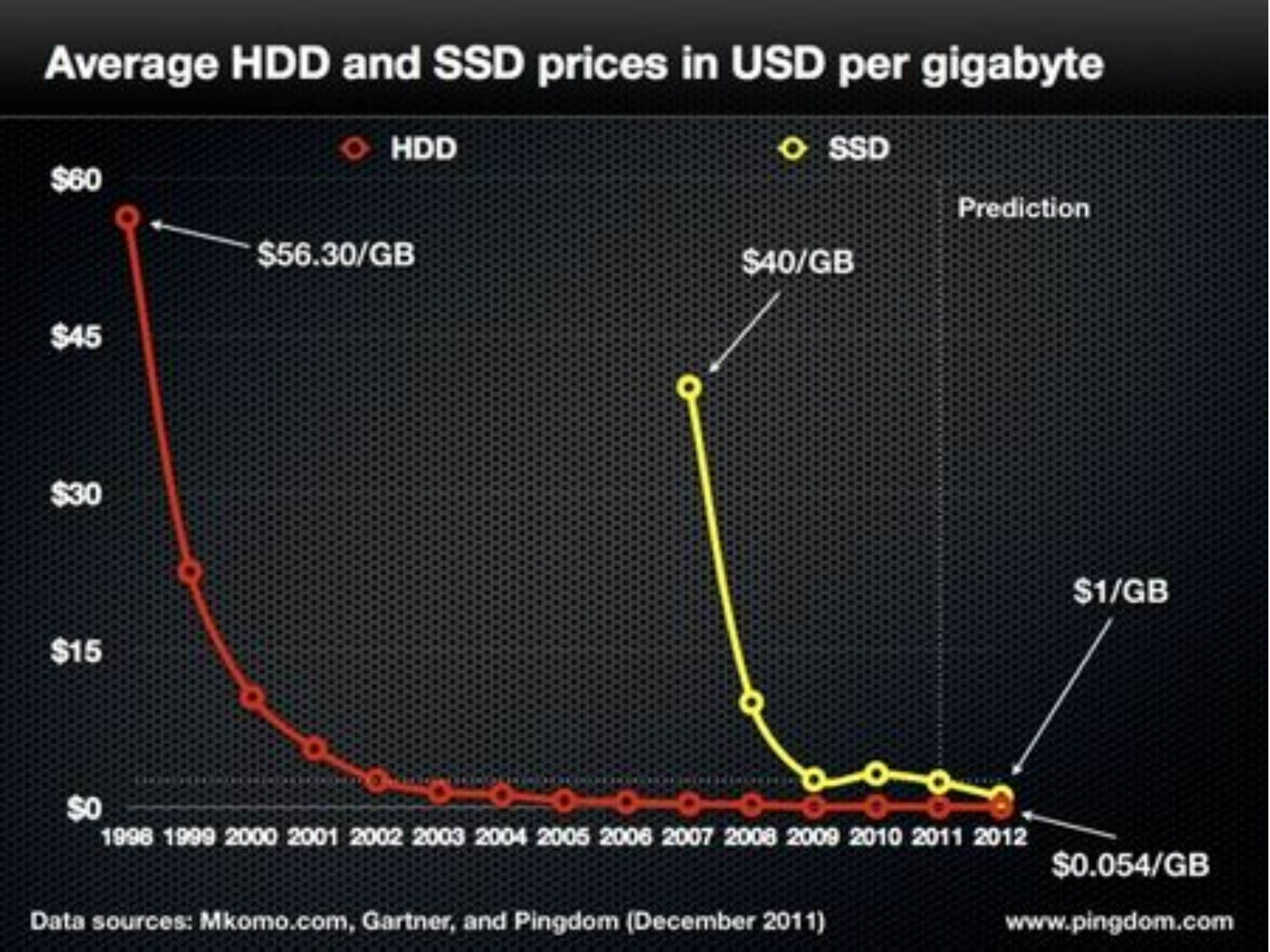
Solid State Drives

- NAND flash memory-based drives
  - High voltage is able to change the configuration of a floating-gate transistor
  - State of the transistor interpreted as binary data



Advantages of SSDs

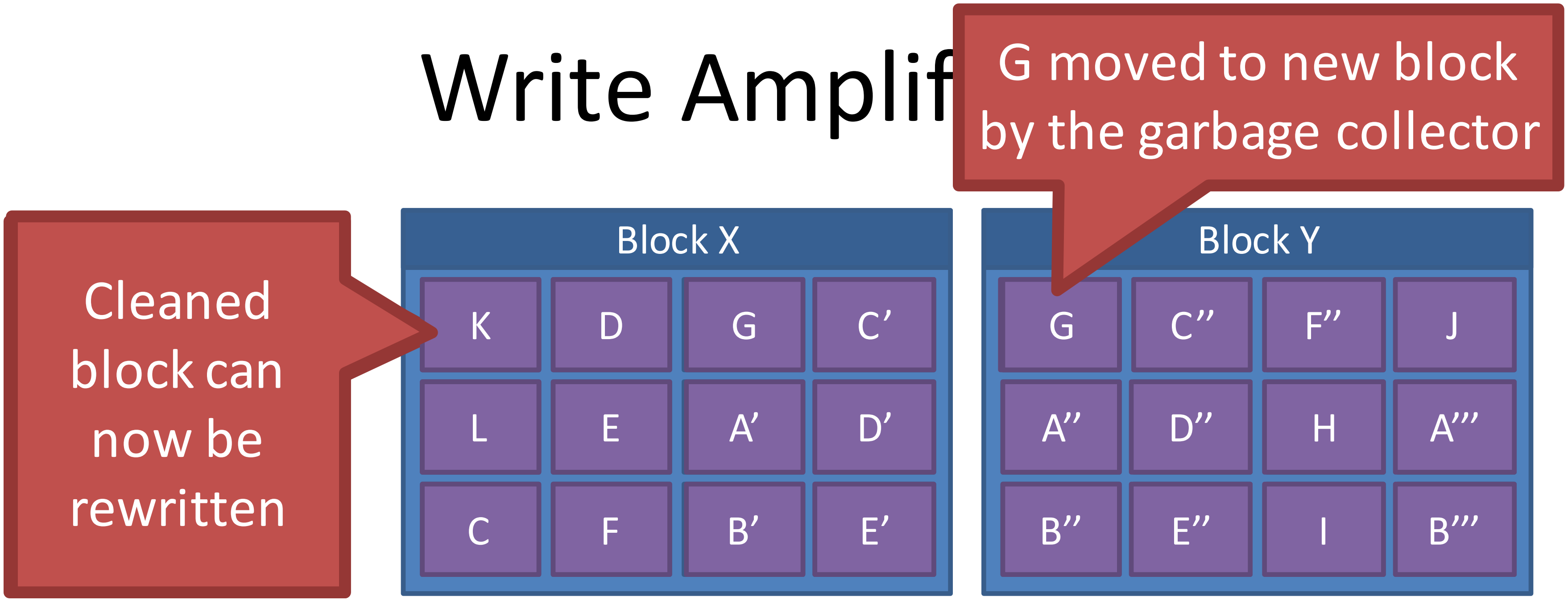
- More resilient against physical damage
  - No sensitive read head or moving parts
  - Immune to changes in temperature
- Greatly reduced power consumption
  - No mechanical, moving parts
- Much faster than hard drives
  - >500 MB/s vs ~200 MB/s for hard drives
  - No penalty for random access
    - Each flash cell can be addressed directly
    - No need to rotate or seek
  - Extremely high throughput
    - Although each flash chip is slow, they are RAIDed


Average HDD and SSD prices in USD per gigabyte
HDD
SSD
$60
$45
$30
$15
$0
Prediction
$56.30/GB
$40/GB
$1/GB
$0.054/GB
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
Data sources: Mkomo.com, Gartner, and Pingdom (December 2011)
www.pingdom.com

Challenges with Flash

- Flash memory is written in pages, but erased in blocks
  - Pages: 4 – 16 KB, Blocks: 128 – 256 KB
  - Thus, flash memory can become fragmented
  - Leads to the write amplification problem
- Flash memory can only be written a fixed number of times
  - Typically 3000 – 5000 cycles for MLC
  - SSDs use wear leveling to evenly distribute writes across all flash cells

Write Amplif



- Once all pages have been written, valid pages must be consolidated to free up space
- Write amplification: a write triggers garbage collection/compaction
  - One or more blocks must be read, erased, and rewritten before the write can proceed

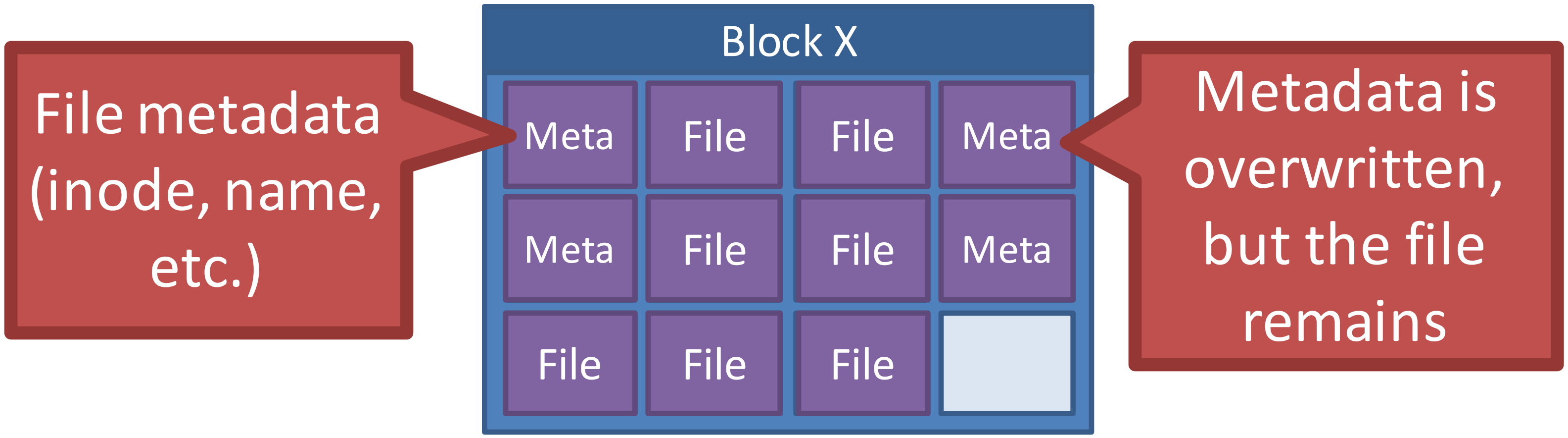
Garbage Collection

- Garbage collection (GC) is vital for the performance of SSDs
- Older SSDs had fast writes up until all pages were written once
  - Even if the drive has lots of “free space,” each write is amplified, thus reducing performance
- Many SSDs over-provision to help the GC
  - 240 GB SSDs actually have 256 GB of memory
- Modern SSDs implement background GC
  - However, this doesn’t always work correctly

The Ambiguity of Delete

- Goal: the SSD wants to perform background GC
  - But this assumes the SSD knows which pages are invalid
- Problem: most file systems don't actually delete data
  - On Linux, the "delete" function is unlink()
  - Removes the file meta-data, but not the file itself

Delete Example

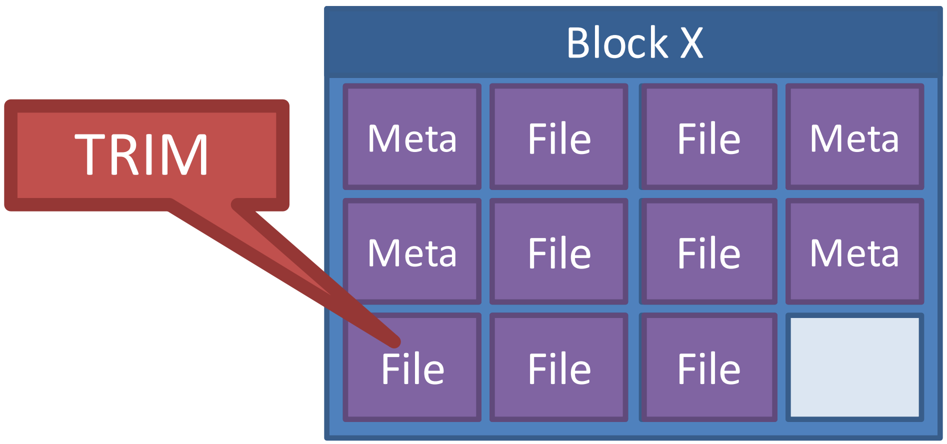


1. File is written to SSD
2. File is deleted
3. The GC executes
   - 9 pages look valid to the SSD
   - The OS knows only 2 pages are valid

- Lack of explicit delete means the GC wastes effort copying useless pages
- Hard drives are not GCed, so this was never a problem

TRIM

- New SATA command TRIM (SCSI – UNMAP)
  – Allows the OS to tell the SSD that specific LBAs are invalid, may be GCed

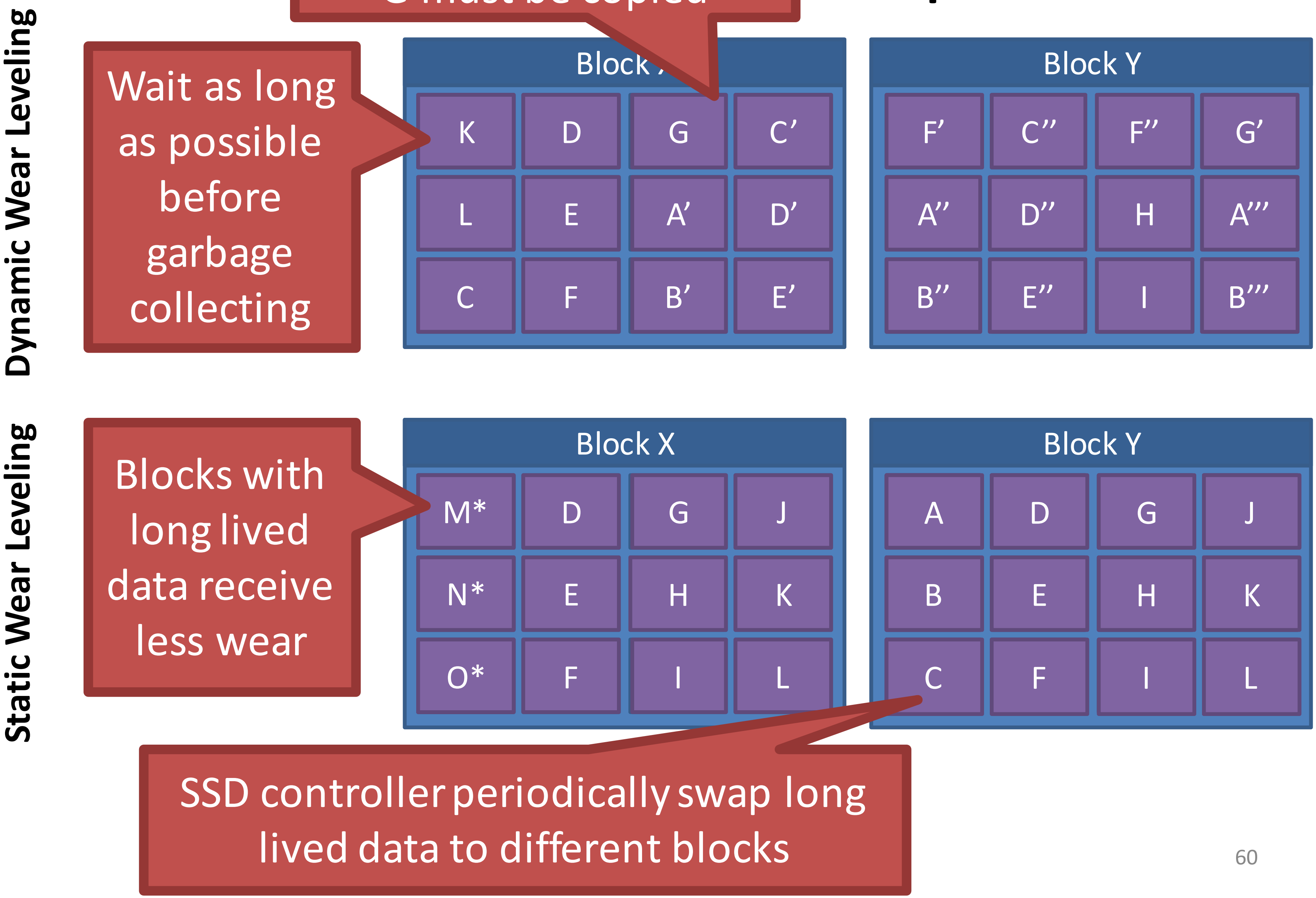


- OS support for TRIM
  – Win 7, OSX Snow Leopard, Linux 2.6.33, Android 4.3
- Must be supported by the SSD firmware

Wear Leveling

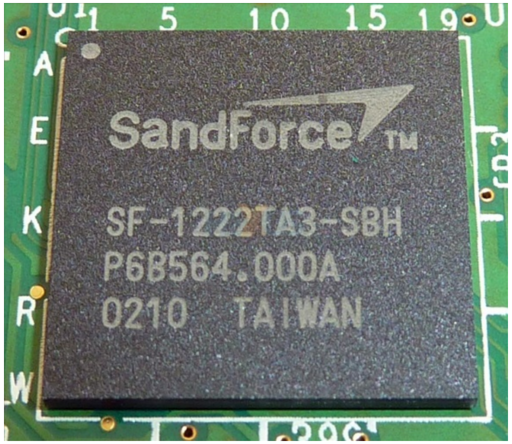
- Recall: each flash cell wears out after several thousand writes
- SSDs use wear leveling to spread writes across all cells
  - Typical consumer SSDs should last ~5 years

W xamples



If the GC runs now, page G must be copied
Dynamic Wear Leveling
Wait as long as possible before garbage collecting
Block X
K D G C’
L E A’ D’
C F B’ E’
Block Y
F’ C’’ F’’ G’
A’’ D’’ H A’’’
B’’ E’’ I B’’’
Static Wear Leveling
Blocks with long lived data receive less wear
Block X
M* D G J
N* E H K
O* F I L
Block Y
A D G J
B E H K
C F I L
SSD controller periodically swap long lived data to different blocks

SSD Controllers



- SSDs are extremely complicated internally
- All operations handled by the SSD controller
  - Maps LBAs to physical pages
  - Keeps track of free pages, controls the GC
  - May implement background GC
  - Performs wear leveling via data rotation
- Controller performance is crucial for overall SSD performance

Flavors of NAND Flash Memory

Multi-Level Cell (MLC)

- Multiple bits per flash cell
  - For two-level: 00, 01, 10, 11
  - 2, 3, and 4-bit MLC is available
- Higher capacity and cheaper than SLC flash
- Lower throughput due to the need for error correction
- 3000 – 5000 write cycels
- Consumes more power

Consumer-grade drives

Single-Level Cell (SLC)

- One bit per flash cell
  - 0 or 1
- Lower capacity and more expensive than MLC flash
- Higher throughput than MLC
- 10000 – 100000 write cycles

Expensive, enterprise drives