Disks

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Storage Technology

[Source: http://www-03.ibm.com/ibm/history/exhibits/storage/storage_photo.html]

Filesystems & Disks

Contents

- Non-volatile storage
- Solid State Disks
- Disks
  - Mechanics, properties, and performance
- Disk scheduling
- Additional Material:
  - Data placement
  - Prefetching and buffering
  - Memory caching
  - Disk errors
  - Multiple disks (RAID)

Storage Properties

- Volatile and non-volatile

- ROM

- Access (sequential, random)

- Mechanical issues

- “Wear out”

Storage Hierarchy

- L1 cache
- L2 cache
- RAM
- ROM
- EPROM & flash memory (SSD)
- Hard disks

- (CD & DVD)

- … and what about Floppy disks?

Storage Metrics

- Maximum/sustained read bandwidth
- Maximum/sustained write bandwidth
- Read latency
- Write latency

Interfaces

- Parallel ATA or simply ATA
- Parallel Small Computer Interface (SCSI)
- Fiber Channel (FC)
- Serial ATA 1.0 (SATA)
- Serial ATA II (SATA II)
- Serial Attached SCSI (SAS)

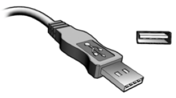
Interfaces

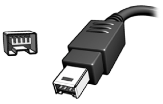
	ATA	SCSI	Fiber Channel	SATA	SATA II[1]	Serial Attached SCSI[1]
PERFORMANCE						
Technology Introduction[2]	2000	2002	2001	2002	2003	2004
Maximum Bus Speed[3]	100MB/s shared/channel	320MB/s shared/channel	4.0Gb/s (400MB/s) dedicated or shared[4]	1.5Gb/s (150MB/s) dedicated per device	3.0Gb/s (300MB/s) dedicated per device	3.0Gb/s (300MB/s) dedicated per device
Topology	Shared bus master/slave	Shared bus	Arbitrated loop/ switched fabric[5]	Point-to-point	Point-to-point	Point-to-point
Number of Devices Per Channel	2	15	127 per arbitrated loop	1 (expandable to 128)	1 (expandable to 128)	1 (expandable to 128)
Command Queuing	No	Yes	Yes	Yes	Yes	Yes

[Source: http://www.intel.com/technology/serialata/pdf/np2108.pdf]

Interfaces

- USB
  - USB 1.0/1.1: max 12 Mb/s
  - USB 2.0: max 480 Mb/s, sustained 10 – 30 MB/
  - USB 3.0: max 4.8 Gb/s, sustained 100 – 300 M
- FireWire
  - FireWire 400: max 400 Mb/s
  - FireWire 800: max 800 Mb/s
- eSATA: max 6 Gb/s


Standard USB 2.0 or 3.0


FireWire 400 (IEEE 1394a) 4-pin


FireWire 400 (IEEE 1394a) 6-pin

[from: http://www.wdc.com/en/library/2579-001151.pdf]

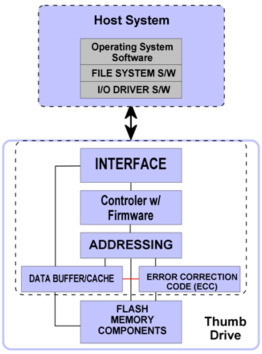
Solid State Drives (SSD)

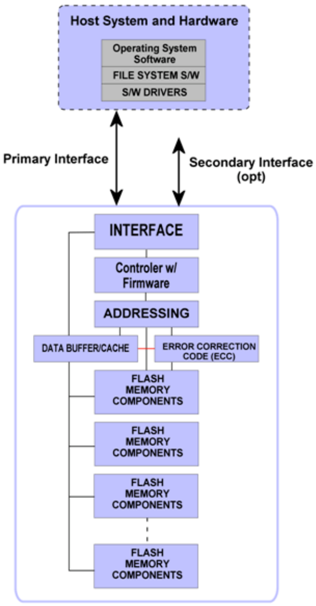
- From the “outside” the look like hard disks
  - Interface
  - Physical formats
- Inside very different to disks:
  - NAND Flash
  - Transistor arrays implemented by floating gate MOSFET
  - Every cell that is written to retains its charge until it is intentionally released through a “flash” of current
  - Erasing NAND flash needs to be done in 64, 128, or 256 KB

SSD

- 2 technologies
  - Single Level Cell (SLC)
  - Multi-Level Cell (MLC)
- Wear and tear
  - Toshiba 128GB: write capacity 80 Terabytes
  - Wear leveling: spread out the data
  - Do not defragment a SSD!!
- TRIM: for delete
  - OSes that are not aware of SSD -> flagged as not in use
  - TRIM -> push delete to the SSD controller (e.g. in Windows 7)

SSD Architecture


Host System
Operating System Software
FILE SYSTEM S/W
I/O DRIVER S/W
INTERFACE
Controler w/ Firmware
ADDRESSING
DATA BUFFER/CACHE
ERROR CORRECTION CODE (ECC)
FLASH MEMORY COMPONENTS
Thumb Drive


Host System and Hardware
Operating System Software
FILE SYSTEM S/W
S/W DRIVERS
Primary Interface
Secondary Interface (opt)
INTERFACE
Controler w/ Firmware
ADDRESSING
DATA BUFFER/CACHE
ERROR CORRECTION CODE (ECC)
FLASH MEMORY COMPONENTS
FLASH MEMORY COMPONENTS
FLASH MEMORY COMPONENTS
FLASH MEMORY COMPONENTS

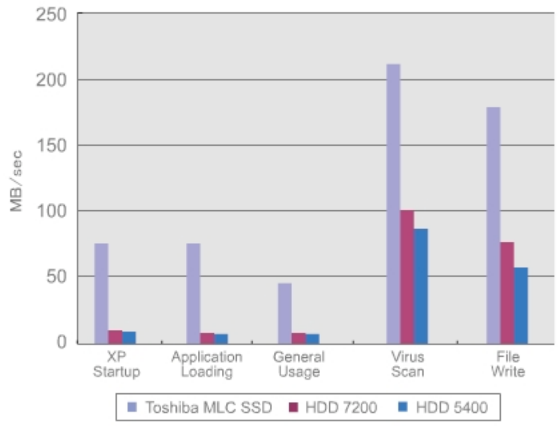
[Source: http://www.storagereview.com/ssd_architecture]

SSD vs. HDD

- SSD:
  Faster
  Quieter
  More reliable
  Less power

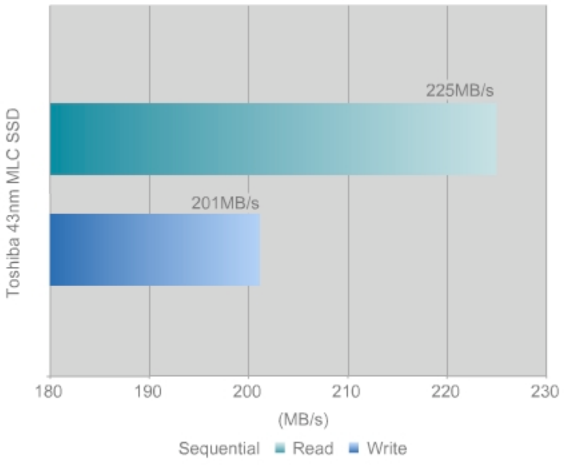
- HDD:
  Cheaper

SSD Performance


Benchmark by PCMark05

[Source: http://ssd.toshiba.com/benchmark-scores.html]

SSD Performance


H2BenchW 3.13
Repetitive Sequential Transfer Rates (Maximum)

[Source: http://ssd.toshiba.com/benchmark-scores.html]

Disks

- Disks ...
  - are used to have a **persistent system**
  - are orders of magnitude *slower* than main memory
  - are *cheaper*
  - have *more capacity*

- Two resources of importance
  - storage space
  - I/O bandwidth

- Because...
  - ...there is a *large* speed mismatch (ms vs. ns) compared to main memory (this gap will increase according to Moore's law),
  - ...disk I/O is often the main performance bottleneck
  - ...we need to minimize the number of accesses,
  - ...
  - ...we must look closer on how to manage disks

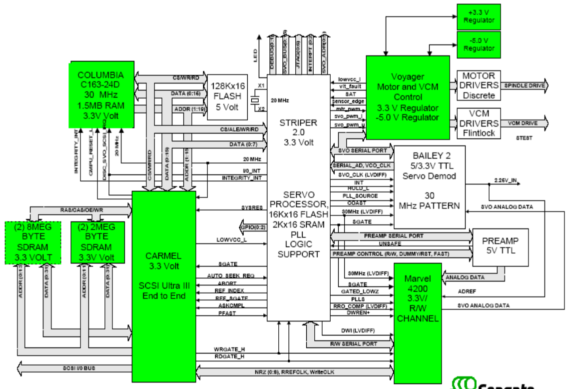
Hard Disk Drive (HDD) Components

- Electromechanical
  - Rotating disks
  - Arm assembly
- Electronics
  - Disk controller
  - Cache
  - Interface controller

Drive Electronics

- Common blocks found:
  - Host Interface
  - Buffer Controller
  - Disk Sequencer
  - ECC
  - Servo Control
  - CPU
  - Buffer Memory
  - CPU Memory
  - Data Channel

Cheetah Architecture



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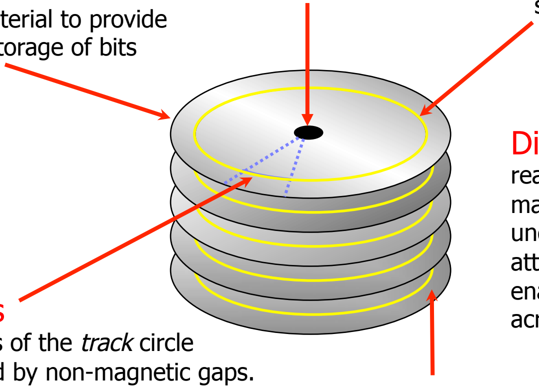
Seagate Technology Copyright 2002

Mechanics of Disks



Platters
circular platters covered with magnetic material to provide nonvolatile storage of bits

Spindle
of which the platters rotate around

Tracks
concentric circles on a single platter

Disk heads
read or alter the magnetism (bits) passing under it. The heads are attached to an arm enabling it to move across the platter surface

Sectors
segments of the *track* circle separated by non-magnetic gaps. The gaps are often used to identify beginning of a sector

Cylinders
corresponding tracks on the different platters are said to form a cylinder

Disk Specifications

- Disk technology develops “fast”
- Seagate disks from 2002:

	Barracuda 180	*Cheetah 36*	*Cheetah X15*
Capacity (GB)	181.6	36.4	36.7
Spindle speed (RPM)	7200	10.000	15.000
#cylinders (and tracks)	24.247	9.772	18.479
average seek time (ms)	7.4	5.7	3.6
min (track-to-track) seek (ms)	0.8	0.6	0.3
max (full stroke) seek (ms)	16	12	7
average latency (ms)	4.17	3	2
internal transfer rate (Mbps)	282 – 508	520 – 682	522 – 709
disk buffer cache	16 MB	4 MB	8 MB

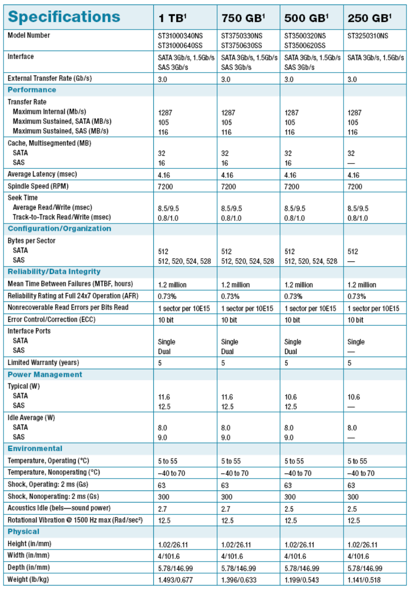
Note 1:
disk manufacturers usually denote GB as 10^9 whereas computer quantities often are powers of 2, i.e., GB is 2^{30}

Note 2:
there is a difference between internal and formatted transfer rate. ***Internal*** is only between platter. ***Formatted*** is after the signals interfere with the electronics (cabling loss, interference, retransmissions, checksums, etc.)

Note 3:
there is usually a trade off between speed and capacity

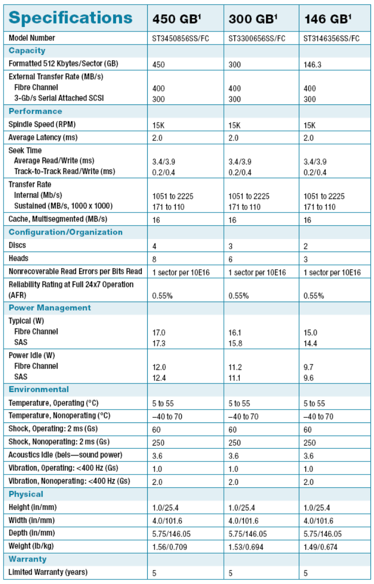
Disk Specification

Seagate Barracuda ES.2



Specifications	1 TB[1]	750 GB[1]	500 GB[1]	250 GB[1]
Model Number	ST31000340NS ST31000640SS	ST3750330NS ST3750630SS	ST3500320NS ST3500620SS	ST3250310NS
Interface	SATA 3Gb/s, 1.5Gb/s SAS 3Gb/s	SATA 3Gb/s, 1.5Gb/s SAS 3Gb/s	SATA 3Gb/s, 1.5Gb/s SAS 3Gb/s	SATA 3Gb/s, 1.5Gb/s
External Transfer Rate (Gb/s)	3.0	3.0	3.0	3.0
Performance				
Transfer Rate				
Maximum Internal (Mb/s)	1287	1287	1287	1287
Maximum Sustained, SATA (MB/s)	105	105	105	105
Maximum Sustained, SAS (MB/s)	116	116	116	116
Cache, Multisegmented (MB)				
SATA	32	32	32	32
SAS	16	16	16	—
Average Latency (msec)	4.16	4.16	4.16	4.16
Spindle Speed (RPM)	7200	7200	7200	7200
Seek Time				
Average Read/Write (msec)	8.5/9.5	8.5/9.5	8.5/9.5	8.5/9.5
Track-to-Track Read/Write (msec)	0.8/1.0	0.8/1.0	0.8/1.0	0.8/1.0
Configuration/Organization				
Bytes per Sector				
SATA	512	512	512	512
SAS	512, 520, 524, 528	512, 520, 524, 528	512, 520, 524, 528	—
Reliability/Data Integrity				
Mean Time Between Failures (MTBF, hours)	1.2 million	1.2 million	1.2 million	1.2 million
Reliability Rating at Full 24x7 Operation (AFR)	0.73%	0.73%	0.73%	0.73%
Nonrecoverable Read Errors per Bits Read	1 sector per 10E15	1 sector per 10E15	1 sector per 10E15	1 sector per 10E15
Error Control/Correction (ECC)	10 bit	10 bit	10 bit	10 bit
Interface Ports				
SATA	Single	Single	Single	Single
SAS	Dual	Dual	Dual	—
Limited Warranty (years)	5	5	5	5
Power Management				
Typical (W)				
SATA	11.6	11.6	10.6	10.6
SAS	12.5	12.5	12.5	—
Idle Average (W)				
SATA	8.0	8.0	8.0	8.0
SAS	9.0	9.0	9.0	—
Environmental				
Temperature, Operating (°C)	5 to 55	5 to 55	5 to 55	5 to 55
Temperature, Nonoperating (°C)	–40 to 70	–40 to 70	–40 to 70	–40 to 70
Shock, Operating: 2 ms (Gs)	63	63	63	63
Shock, Nonoperating: 2 ms (Gs)	300	300	300	300
Acoustics Idle (bels—sound power)	2.7	2.7	2.5	2.5
Rotational Vibration @ 1500 Hz max (Rad/sec^2)	12.5	12.5	12.5	12.5
Physical				
Height (in/mm)	1.02/26.11	1.02/26.11	1.02/26.11	1.02/26.11
Width (in/mm)	4/101.6	4/101.6	4/101.6	4/101.6
Depth (in/mm)	5.78/146.99	5.78/146.99	5.78/146.99	5.78/146.99
Weight (lb/kg)	1.493/0.677	1.396/0.633	1.199/0.543	1.141/0.518

Seagte Cheetah 15K.6

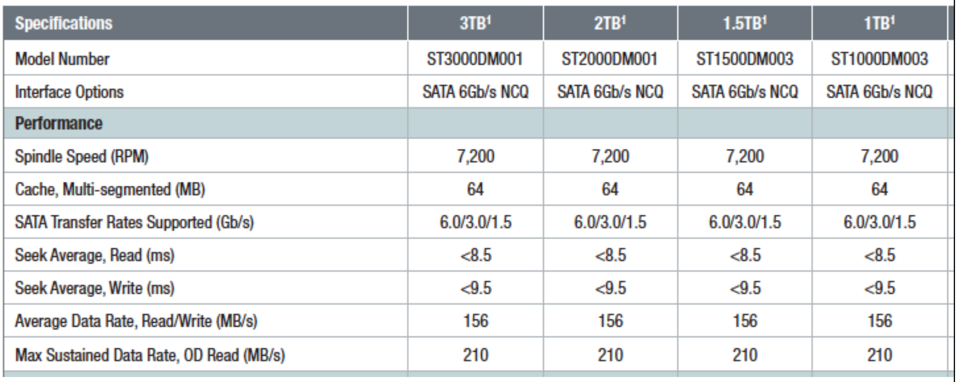


Specifications	450 GB[1]	300 GB[1]	146 GB[1]
Model Number	ST3450856SS/FC	ST3300656SS/FC	ST3146356SS/FC
Capacity			
Formatted 512 Kbytes/Sector (GB)	450	300	146.3
External Transfer Rate (MB/s)			
Fibre Channel	400	400	400
3-Gb/s Serial Attached SCSI	300	300	300
Performance			
Spindle Speed (RPM)	15K	15K	15K
Average Latency (ms)	2.0	2.0	2.0
Seek Time			
Average Read/Write (ms)	3.4/3.9	3.4/3.9	3.4/3.9
Track-to-Track Read/Write (ms)	0.2/0.4	0.2/0.4	0.2/0.4
Transfer Rate			
Internal (Mb/s)	1051 to 2225	1051 to 2225	1051 to 2225
Sustained (MB/s, 1000 x 1000)	171 to 110	171 to 110	171 to 110
Cache, Multisegmented (MB/s)	16	16	16
Configuration/Organization			
Discs	4	3	2
Heads	8	6	3
Nonrecoverable Read Errors per Bits Read	1 sector per 10E16	1 sector per 10E16	1 sector per 10E16
Reliability Rating at Full 24x7 Operation (AFR)	0.55%	0.55%	0.55%
Power Management			
Typical (W)			
Fibre Channel	17.0	16.1	15.0
SAS	17.3	15.8	14.4
Power Idle (W)			
Fibre Channel	12.0	11.2	9.7
SAS	12.4	11.1	9.6
Environmental			
Temperature, Operating (°C)	5 to 55	5 to 55	5 to 55
Temperature, Nonoperating (°C)	–40 to 70	–40 to 70	–40 to 70
Shock, Operating: 2 ms (Gs)	60	60	60
Shock, Nonoperating: 2 ms (Gs)	250	250	250
Acoustics Idle (bels—sound power)	3.6	3.6	3.6
Vibration, Operating: <400 Hz (Gs)	1.0	1.0	1.0
Vibration, Nonoperating: <400 Hz (Gs)	2.0	2.0	2.0
Physical			
Height (in/mm)	1.0/25.4	1.0/25.4	1.0/25.4
Width (in/mm)	4.0/101.6	4.0/101.6	4.0/101.6
Depth (in/mm)	5.75/146.05	5.75/146.05	5.75/146.05
Weight (lb/kg)	1.56/0.709	1.53/0.694	1.49/0.674
Warranty			
Limited Warranty (years)	5	5	5

Specifications from www.seagate.com on 4. 11. 2008

Disk Specification

Seagate Barracuda 7200.14



Specifications	3TB[1]	2TB[1]	1.5TB[1]	1TB[1]
Model Number	ST3000DM001	ST2000DM001	ST1500DM003	ST1000DM003
Interface Options	SATA 6Gb/s NCQ	SATA 6Gb/s NCQ	SATA 6Gb/s NCQ	SATA 6Gb/s NCQ
Performance				
Spindle Speed (RPM)	7,200	7,200	7,200	7,200
Cache, Multi-segmented (MB)	64	64	64	64
SATA Transfer Rates Supported (Gb/s)	6.0/3.0/1.5	6.0/3.0/1.5	6.0/3.0/1.5	6.0/3.0/1.5
Seek Average, Read (ms)	<8.5	<8.5	<8.5	<8.5
Seek Average, Write (ms)	<9.5	<9.5	<9.5	<9.5
Average Data Rate, Read/Write (MB/s)	156	156	156	156
Max Sustained Data Rate, OD Read (MB/s)	210	210	210	210

Specifications from www.seagate.com on 15. 10. 2012

Disk Capacity

- The size (storage space) of the disk is dependent on

  the number of platters
  whether the platters use one or both sides
  number of tracks per surface
  (average) number of sectors per track
  number of bytes per sector

- Example (Cheetah X15):

  4 platters using both sides: 8 surfaces
  18497 tracks per surface
  617 sectors per track (average)
  512 bytes per sector
  Total capacity = 8 x 18497 x 617 x 512 $\approx 4.6 \times 10^{10}$ = 42.8 GB
  Formatted capacity = 36.7 GB

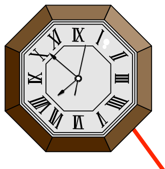
Note:
there is a difference between formatted and total capacity. Some of the capacity is used for storing checksums, spare tracks, gaps, etc.

Disk Access Time

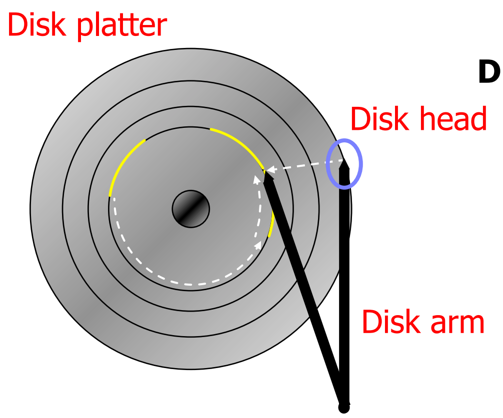
- How do we retrieve data from disk?
  - position head over the cylinder (track) on which the block (consisting of one or more sectors) are located
  - read or write the data block as the sectors move under the head when the platters rotate
- The time between the moment issuing a disk request and the time the block is resident in memory is called *disk latency* or *disk access time*

Disk Access Time

I want block X



block x in memory



Disk access time =

Seek time

\+ Rotational delay

\+ Transfer time

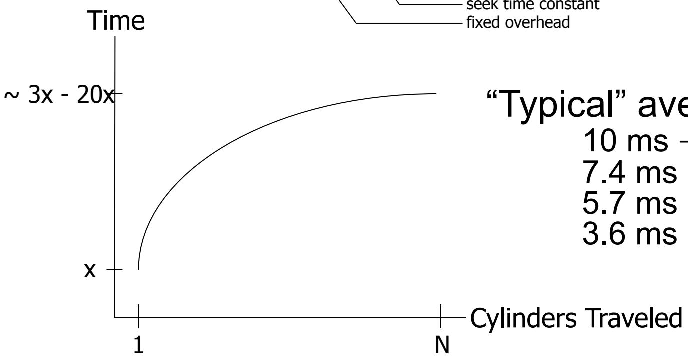
\+ Other delays

Disk Access Time: Seek Time

- Seek time is the time to position the head
  - the heads require a minimum amount of time to start and stop moving the head
  - some time is used for actually moving the head – roughly proportional to the number of cylinders traveled

Time to move head: $\alpha + \beta\sqrt{n}$

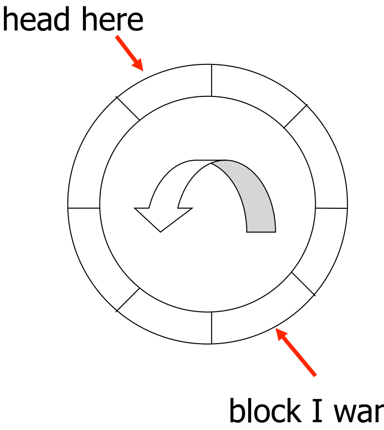
number of tracks
seek time constant
fixed overhead



“Typical” average:
10 ms → 40 ms
7.4 ms (Barracuda 180)
5.7 ms (Cheetah 36)
3.6 ms (Cheetah X15)

Disk Access Time: Rotational Delay

- Time for the disk platters to rotate so the first of the required sectors are under the disk head



Average delay is 1/2 revolution

“Typical” average:

8.33 ms	(3.600 RPM)
5.56 ms	(5.400 RPM)
4.17 ms	(7.200 RPM)
3.00 ms	(10.000 RPM)
2.00 ms	(15.000 RPM)

Disk Access Time: Transfer Time

- Time for data to be read by the disk head, i.e., time it takes the sectors of the requested block to rotate under the head
- Transfer rate = $\frac{\text{amount of data per track}}{\text{time per rotation}}$
- Transfer time = amount of data to read / transfer rate
- Example – *Barracuda 180:*
  406 KB per track x 7.200 RPM ≈ 47.58 MB/s
- Example – *Cheetah X15:*
  316 KB per track x 15.000 RPM ≈ 77.15 MB/s

Note:
one might achieve these transfer rates reading continuously on disk, but time must be added for seeks, etc.

- Transfer time is dependent on data density and rotation speed
- If we have to change track, time must also be added for moving the head

Disk Access Time: Other Delays

- There are several other factors which might introduce additional delays:
  - CPU time to issue and process I/O
  - contention for controller
  - contention for bus
  - contention for memory
  - verifying block correctness with checksums (retransmissions)
  - **waiting in scheduling queue**
  - ...
- Typical values: “0”
  (maybe except from waiting in the queue)

Disk Throughput

- How much data can we retrieve per second?
- Throughput = $\frac{\text{data size}}{\text{transfer time (including all)}}$
- Example:

for each operation we have
- average seek
- transfer time
- average rotational delay
- no gaps, etc.

Cheetah X15 (max 77.15 MB/s)
4 KB blocks → 0.71 MB/s
64 KB blocks → 11.42 MB/s

Barracuda 180 (max 47.58 MB/s)
4 KB blocks → 0.35 MB/s
64 KB blocks → 5.53 MB/s

Block Size

- The block size may have large effects on performance
- Example:

assume random block placement on disk and sequential file access

doubling block size will halve the number of disk accesses

- each access take some more time to transfer the data, but the total transfer time is the same (i.e., more data per request)
- halve the seek times
- halve rotational delays are omitted

e.g., when increasing block size from 2 KB to 4 KB (no gaps,...)
for *Cheetah X15* typically an average of:

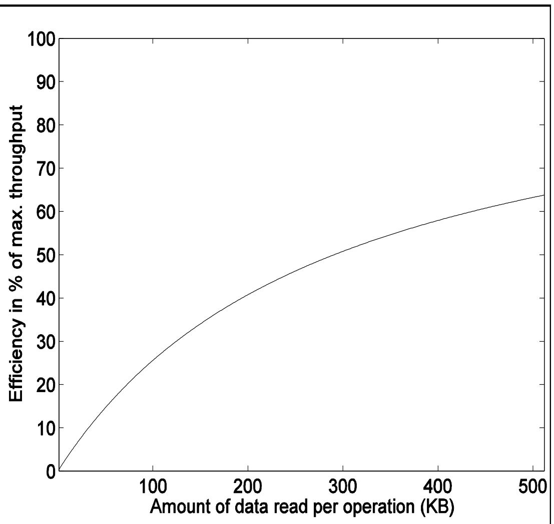
3.6 ms is *saved* for seek time
2 ms is *saved* in rotational delays
0.026 ms is *added* per transfer time

} saving a total of 5.6 ms when reading 4 KB (49,8 %)

increasing from 2 KB to 64 KB saves ~96,4 % when reading 64 KB

Block Size

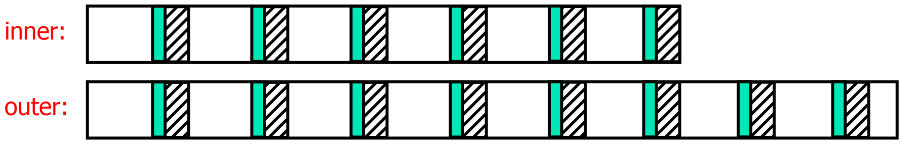
- Thus, increasing block size can increase performance by reducing seek times and rotational delays
- However, a large block size is not always best
  - blocks spanning several tracks still introduce latencies
  - small data elements may occupy only a fraction of the block



- Which block size to use therefore depends on data size and data reference patterns
- The trend, however, is to use large block sizes as new technologies appear with increased performance – at least in high data rate systems

Disk Access Time: Complicating Issues

- There are several complicating factors:
  - the “other delays” described earlier like consumed CPU time, resource contention, etc.
  - unknown data placement on modern disks
  - zoned disks, i.e., outer tracks are longer and therefore usually have more sectors than inner - transfer rates are higher on outer tracks
  - gaps between each sector
  - checksums are also stored with each the sectors
    - read for each track and used to validate the track
    - usually calculated using Reed-Solomon interleaved with CRC
    - for older drives the checksum is 16 bytes
  - (SCSI disks sector sizes may be changed by user!!??)



Writing and Modifying Blocks

- A write operation is analogous to read operations
  - must add time for block allocation
  - a complication occurs if the write operation has to be *verified* – must wait another rotation and then read the block to see if it is the block we wanted to write
  - Total write time ≈ read time + time for one rotation

- Cannot modify a block directly:
  - read block into main memory
  - modify the block
  - write new content back to disk
  - (verify the write operation)
  - Total modify time ≈ read time + time to modify + write time

Disk Controllers

- To manage the different parts of the disk, we use a *disk controller*, which is a small processor capable of:
  - controlling the actuator moving the head to the desired track
  - selecting which platter and surface to use
  - knowing when right sector is under the head
  - transferring data between main memory and disk

- New controllers acts like small computers themselves
  - both disk and controller now has an own buffer reducing disk access time
  - data on damaged disk blocks/sectors are just moved to spare room at the disk – the system above (OS) does not know this, i.e., a block may lie elsewhere than the OS thinks

Efficient Secondary Storage Usage

- Must take into account the use of secondary storage
  - there are large access time gaps, i.e., a disk access will probably dominate the total execution time
  - there may be huge performance improvements if we reduce the number of disk accesses
  - a “slow” algorithm with few disk accesses will probably outperform a “fast” algorithm with many disk accesses

- **Several ways to optimize .....**
  - block size
  - disk scheduling
  - multiple disks
  - prefetching
  - file management / data placement
  - memory caching / replacement algorithms
  - …

Disk Scheduling

- **Seek time is a dominant factor of total disk I/O time**

- Let operating system or disk controller choose which request to serve next depending on the head’s current position and requested block’s position on disk (disk scheduling)

Is (or should) disk scheduling be preemptive or non-preemptive?

- General goals
  - short response time
  - high overall throughput
  - fairness (equal probability for all blocks to be accessed in the same time)

- Tradeoff: seek and rotational delay vs. maximum response time

Disk Scheduling

- Several traditional algorithms

  First-Come-First-Serve (FCFS)

  Shortest Seek Time First (SSTF)

  SCAN (and variations)

  Look (and variations)

  …

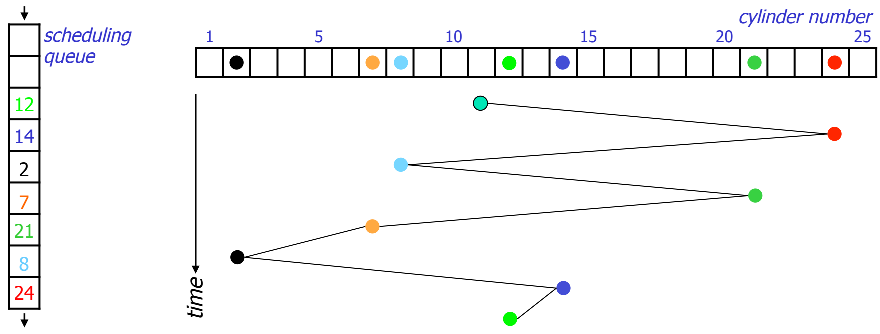
First–Come–First–Serve (FCFS)

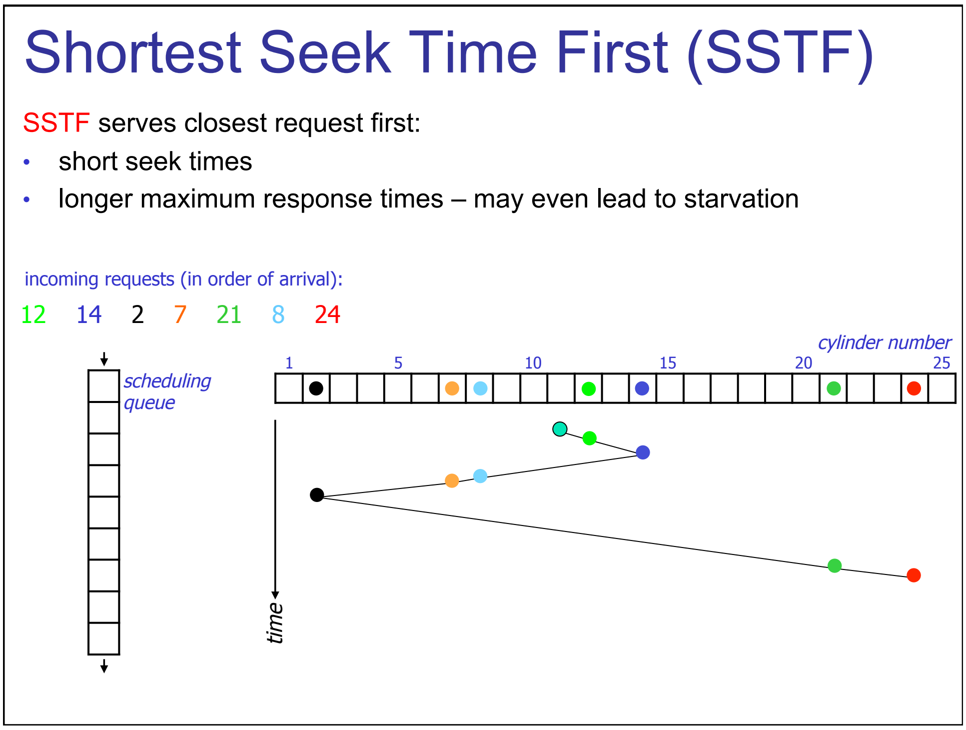
FCFS serves the first arriving request first:

- Long seeks
- "Short" average response time

incoming requests (in order of arrival):

12 14 2 7 21 8 24





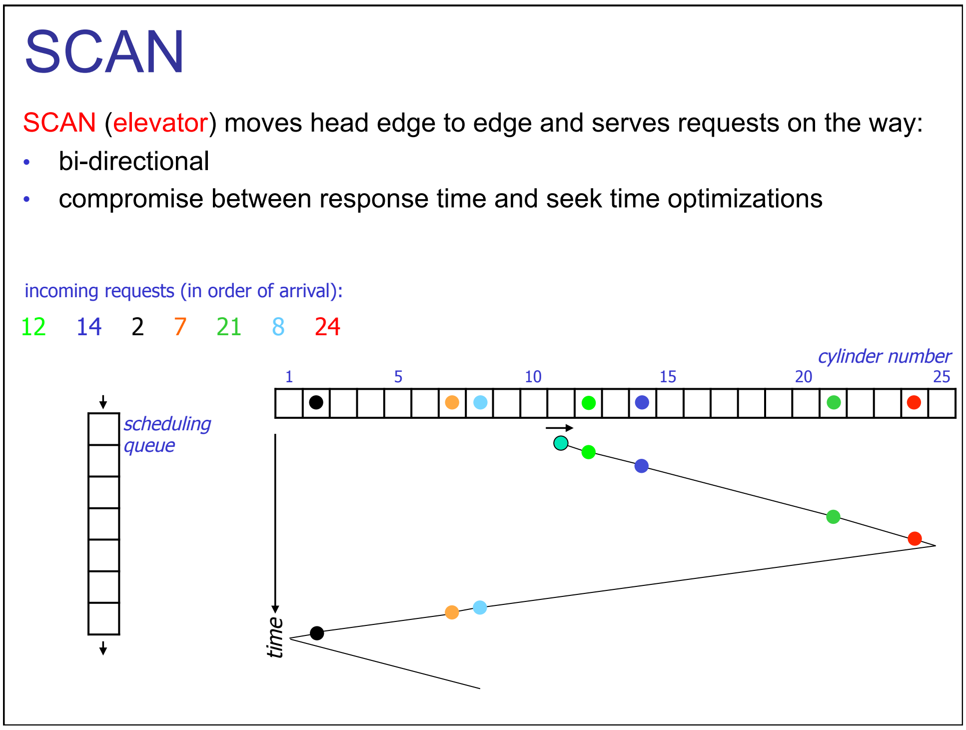
Shortest Seek Time First (SSTF)

SSTF serves closest request first:

- short seek times
- longer maximum response times – may even lead to starvation

incoming requests (in order of arrival):

12 14 2 7 21 8 24



SCAN

SCAN (elevator) moves head edge to edge and serves requests on the way:

- bi-directional
- compromise between response time and seek time optimizations

incoming requests (in order of arrival):

12 14 2 7 21 8 24

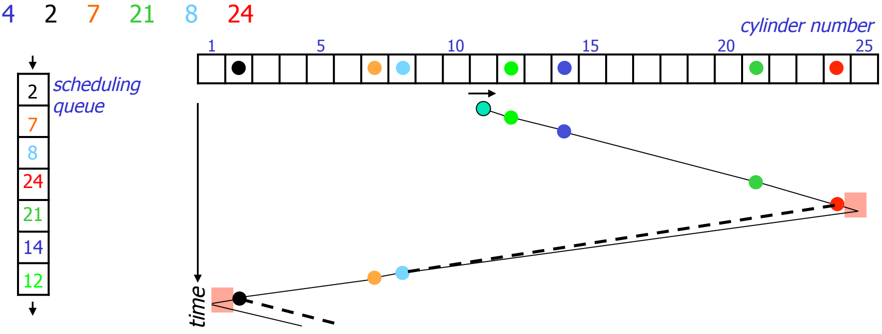
LOOK

LOOK is a variation of SCAN:

- same schedule as SCAN
- does not run to the edges
- stops and returns at outer- and innermost request
- increased efficiency
- SCAN vs. LOOK example:

incoming requests (in order of arrival):

12 14 2 7 21 8 24



Data Placement on Disk

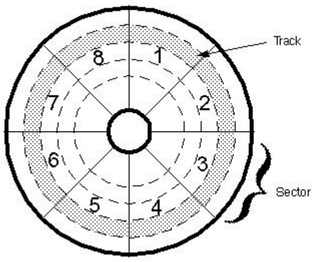
- Disk blocks can be assigned to files many ways, and several schemes are designed for

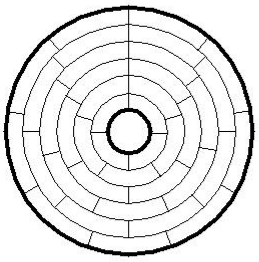
optimized latency

increased throughput

access pattern dependent

Disk Layout





- Constant angular velocity (CAV) disks
  - equal amount of data in each track
(and thus constant transfer time)
  - constant rotation speed

- Zoned CAV disks
  - zones are ranges of tracks
  - typical few zones
  - the different zones have
    - different amount of data
    - different bandwidth
    - i.e., better on outer tracks

Disk Layout

- Cheetah X15.3 is a zoned CAV disk:

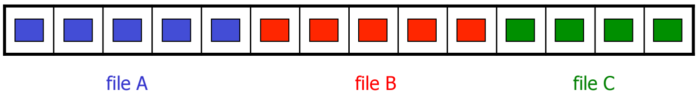
Zone	Cylinders per Zone	Sectors per Track	Spare Cylinders	Zone Transfer Rate Mb/s	Sectors per Zone	Efficiency	Formatted Capacity (Mbytes)
0	**3544**	**672**	7	**890,98**	19014912	77,2%	**9735,635**
1	3382	652	7	878,43	17604000	76,0%	9013,248
3	3079	624	6	835,76	15340416	76,5%	7854,293
4	2939	595	6	801,88	13961080	76,0%	7148,073
5	2805	576	6	755,29	12897792	78,1%	6603,669
6	2676	537	5	728,47	11474616	75,5%	5875,003
7	2554	512	5	687,05	10440704	76,3%	5345,641
8	2437	480	5	649,41	9338880	75,7%	4781,506
9	2325	466	5	632,47	8648960	75,5%	4428,268
10	**2342**	**438**	5	**596,07**	8188848	75,3%	**4192,690**

✓ Always place often used data on outermost tracks (zone 0) …!?

↳ **NO**, arm movement is often more important than transfer time

Data Placement on Disk

- Contiguous placement stores disk blocks contiguously on disk



minimal disk arm movement reading the whole file (no intra-file seeks)

possible advantage

  head must not move between read operations - no seeks or rotational delays

  can approach theoretical transfer rate

  often WRONG: read other files as well

real advantage

  do not have to pre-determine block (read operation) size
  (whatever amount to read, at most track-to-track seeks are performed)

no inter-operation gain if we have unpredictable disk accesses

---

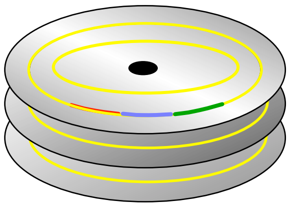
Data Placement on Disk

- To avoid seek time (and possibly rotational delay), we can *store data likely to be accessed together* on

adjacent sectors
(similar to using larger blocks)

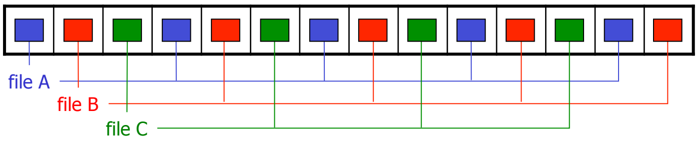
if the track is full, use another track
on the same cylinder
(only use another head)

if the cylinder is full, use
next (adjacent) cylinder
(track-to-track seek)



Data Placement on Disk

- Interleaved placement tries to store blocks from a file with a fixed number of other blocks in-between each block



minimal disk arm movement reading the files A, B and C
(starting at the same time)

fine for predictable workloads reading multiple files

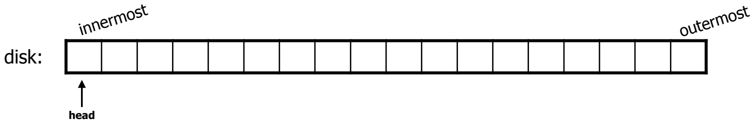
no gain if we have unpredictable disk accesses

- Non-interleaved (or even random) placement can be used for highly unpredictable workloads

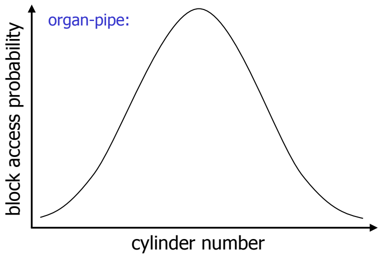
---

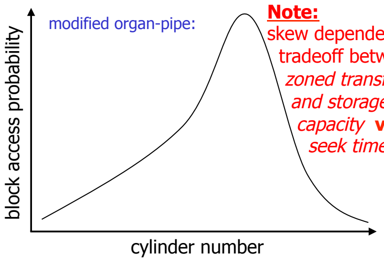
Data Placement on Disk

- Organ-pipe placement consider the usual disk head position
  place most popular data where head is most often



center of the disk is closest to the head using CAV disks
but, a bit outward for *zoned* CAV disks (modified organ-pipe)





Note:
skew dependent on tradeoff between *zoned transfer time and storage capacity* **vs.** *seek time*

Concluding Questions

- What are the main differences between HDD and SDD?
- What are the main parameter of HDD performance?
- What is the goal of disk scheduling?
- Would disk scheduling for SDD be useful?
- Why should we not defragment SDDs?

Additional Material

- Prefetching & Buffering
- RAID systems

Prefetching

- If we can predict the access pattern, one might speed up performance using prefetching
  - a video playout is often linear → easy to predict access pattern

  - eases disk scheduling
  - read larger amounts of data per request
  - data in memory when requested – reducing page faults

- One simple (and efficient) way of doing prefetching is read-ahead:
  - read more than the requested block into memory
  - serve next read requests from buffer cache

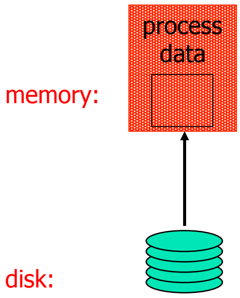
- Another way of doing prefetching is double (multiple) buffering:
  - read data into first buffer
  - process data in *first* buffer and at the same time read data into *second* buffer
  - process data in *second* buffer and at the same time read data into *first* buffer
  - etc.

Multiple Buffering

- Example:
  have a file with block sequence B1, B2, ...
  our program processes data sequentially, i.e., B1, B2, ...

single buffer solution:

- read B1 → buffer
- process data in buffer
- read B2 → buffer
- process data in Buffer
- ...



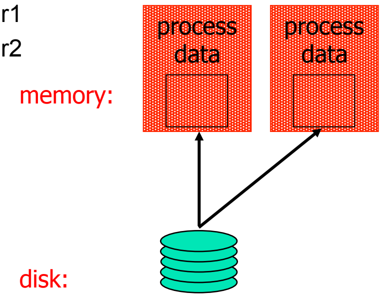
if P = time to process a block
R = time to read in 1 block
n = # blocks

single buffer time = n (P+R)

Multiple Buffering

double buffer solution:

read B1 → buffer1
process data in buffer1, read B2 → buffer2
process data in buffer2, read B3 → buffer1
process data in buffer1, read B4 → buffer2
...

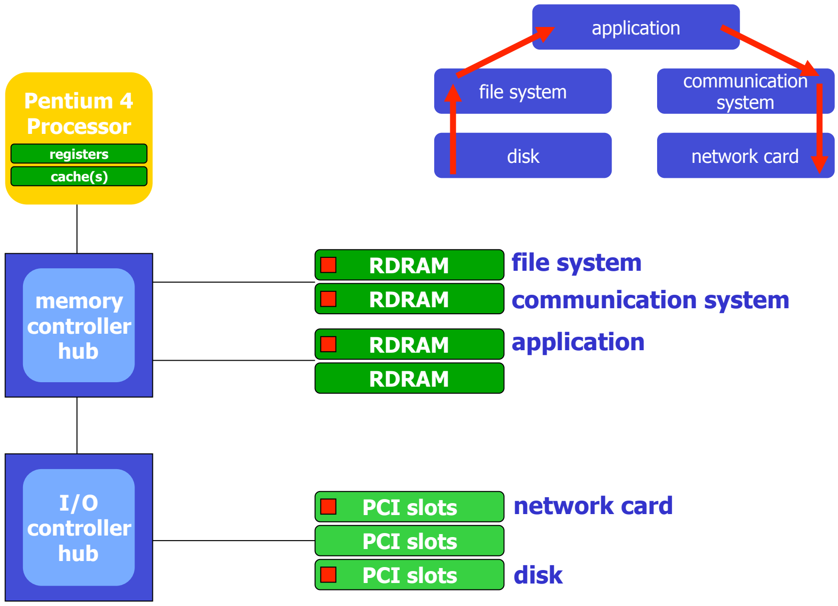


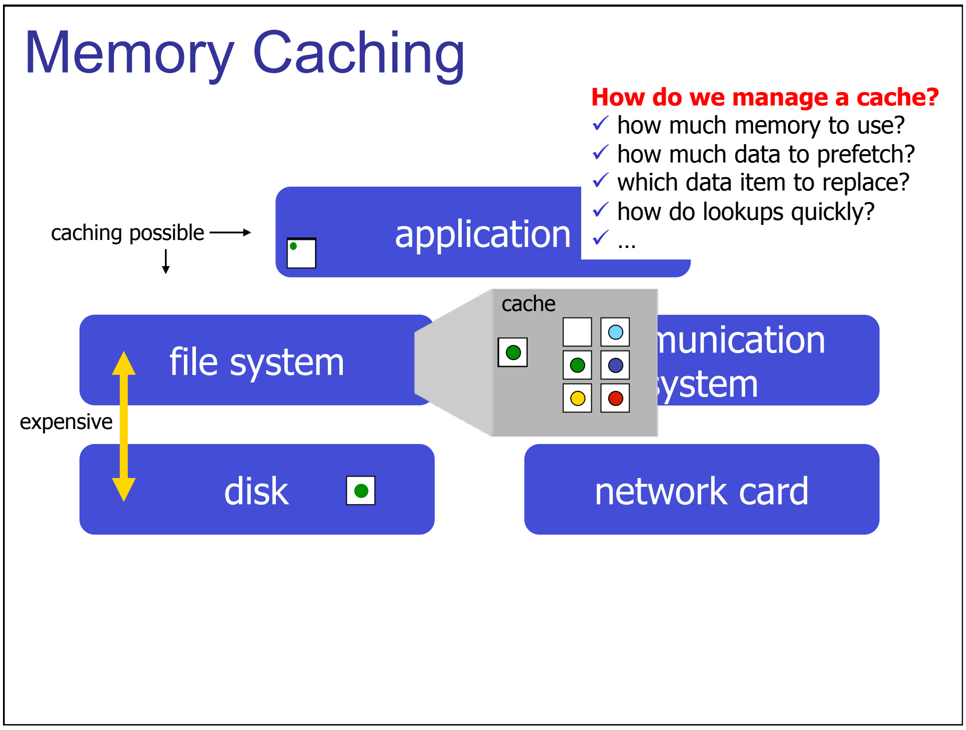
if P = time to process a block
R = time to read in 1 block
n = # blocks

if $P \geq R$
double buffer time = $R + nP$

if $P < R$, we can try to add buffers (*n* - buffering)

Data Path (Intel Hub Architecture)

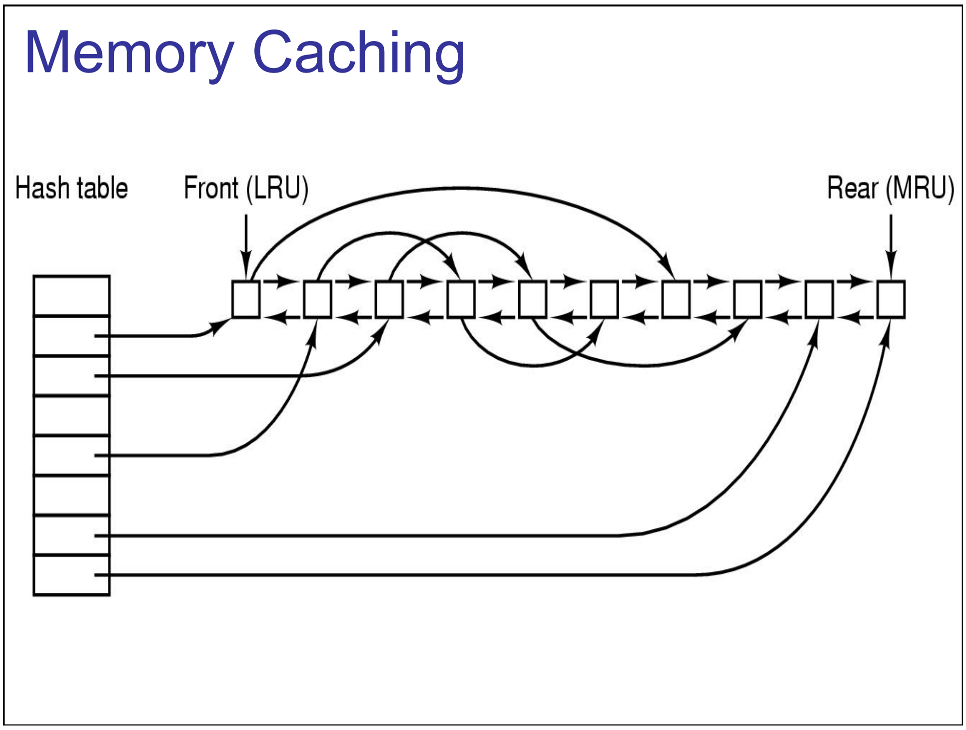




Memory Caching

How do we manage a cache?

- ✓ how much memory to use?
- ✓ how much data to prefetch?
- ✓ which data item to replace?
- ✓ how do lookups quickly?
- ✓ …



Memory Caching

Disk Errors

- Disk errors are rare:

	Barracuda 180	*Cheetah 36*	*Cheetah X15*
mean time to failure (MTTF)	1.2 x 10^6	1.2 x 10^6	1.2 x 10^6
recoverable errors	10 per 10^{12}	10 per 10^{12}	10 per 10^{12}
unrecoverable errors	1 per 10^{15}	1 per 10^{15}	1 per 10^{15}
seek errors	10 per 10^8	10 per 10^8	10 per 10^8

MTTF:
MTTF is the time in hours between each time the disk crashes

Unrecoverable:
how often do we get permanent errors on a sector – data moved to spare tracks

Recoverable:
how often do we read wrong values – corrected when re-reading

Seek:
how often do we move the arm wrong (over wrong cylinder) – make another

Disk Errors

- Even though rare, a disk can fail in several ways

intermittent failure –
temporarily errors corrected by re-reading the block, e.g., dust on the platter making a bit value wrong

media decay/write errors –
permanent errors where the bits are corrupted, e.g., disk head touches the platter and damages the magnetic surface

disk crashes –
the entire disk becomes permanent unreadable

Checksums

- Disk sectors are stored with some redundant bits, called *checksums*

- Used to validate a read or written sector:
  read sector and stored checksum
  compute checksum on read sector
  compare read and computed checksum

- If the validation fails (read and computed checksum differ), the read operation is repeated until
  the read operation succeed → return correct content
  the limit of retries is reached → return error “bad disk block”

- Many ways to compute checksums,
  but (usually) they only detect errors

Disk Failure Models

- Our Seagate disks have a MTTF of ~130 years
  (at this time ~50 % of the disks are damaged), but

  many disks fail during the first months (production errors)

  if no production errors, disks will probably work many years

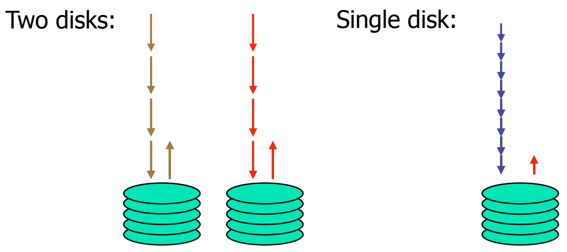
  old disks have again a larger probability of failure due to accumulated effects of dust, etc.

Crash Recovery

- The most serious type of errors are disk crashes, e.g.,
  - head have touched platter and is damaged
  - platters are out of position
  - ...
- Usually, no way to restore data unless we have a backup on another medium, e.g., tape, mirrored disk, etc.
- A number of schemes have been developed to reduce the probability of data loss during permanent disk errors
  - usually using an extended parity check
  - most known are the Redundant Array of Independent Disks (RAID) strategies

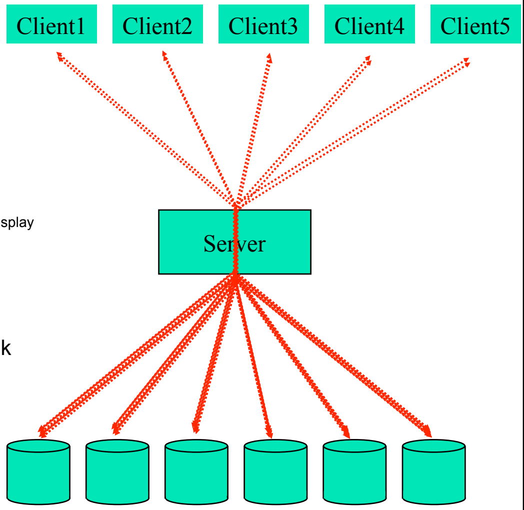
Multiple Disks

- Disk controllers and busses manage several devices
- One *can* improve total system performance by replacing one large disk with many small accessed in parallel
- Several independent heads can read simultaneously (if the other parts of the system can manage the speed)



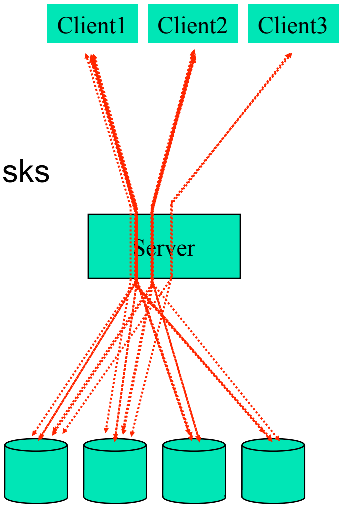
Striping

- Another reason to use multiple disks is when one disk cannot deliver requested data rate
- In such a scenario, one might use several disks for striping:
  - bandwidth disk: B_{disk}
  - required bandwidth: $B_{display}$
  - $B_{display} > B_{disk}$
  - read from *n* disks in parallel: $n\ B_{disk} > B_{display}$
  - clients are serviced in *rounds*
- Advantages
  - high data rates
  - higher transfer rate compared to one disk
- Drawbacks
  - can't serve multiple clients in parallel
  - positioning time increases
    (i.e., reduced efficiency)



Interleaving (Compound Striping)

- Full striping usually not necessary today:
  - faster disks
  - better compression algorithms
- Interleaving lets each client may be serviced by only a set of the available disks
  - make groups
  - "stripe" data in a way such that
    a consecutive request arrive at
    next group (here each disk is a group)



Redundant Array of Inexpensive Disks (RAID)

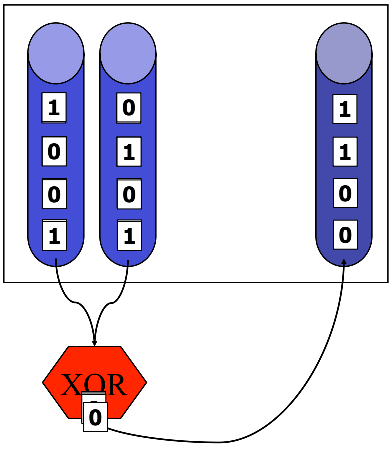
- The various RAID levels define different disk organizations to achieve higher performance and more reliability
  - RAID 0 - striped disk array without fault tolerance (non-redundant)

  - RAID 1 - mirroring
  - RAID 2 - memory-style error correcting code (Hamming Code ECC)
  - RAID 3 - bit-interleaved parity
  - RAID 4 - block-interleaved parity
  - RAID 5 - block-interleaved distributed-parity
  - RAID 6 - independent data disks with two independent distributed parity schemes

  - RAID 7
  - RAID 10
  - RAID 53
  - RAID 1+0

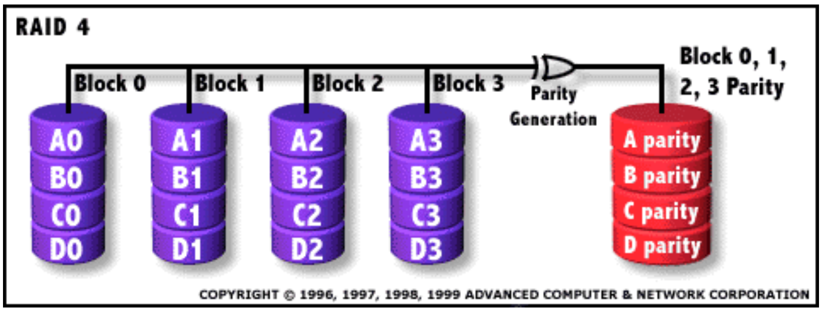
RAID

- Main idea
  - Store the XORs of the content of a block to the spare disk
  - Upon any failure, one can recover the entire block from the spare disk (or any disk) using XORs
- Pros
  - Reliability
  - High bandwidth
- Cons
  - The controller is complex



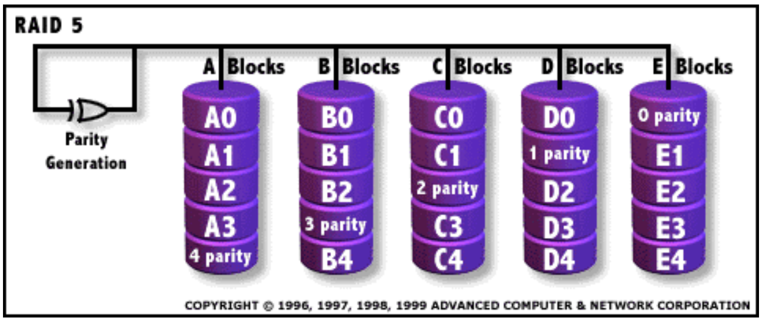
RAID 4

- RAID 4: independent data disks with shared parity disk
- Each entire block is written onto one data disk. Parity for same rank blocks is generated on writes, recorded on the parity disk and checked on reads.



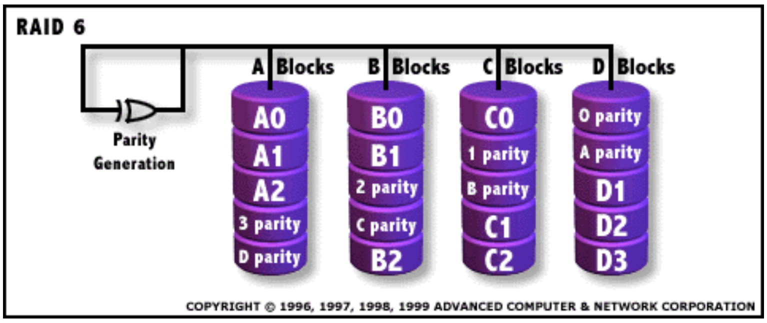
RAID 5

- RAID 5: independent data disks with distributed parity disk (read, write, and recovery operations are analogous to RAID 4, but parity is distributed)
- Each entire data block is written on a data disk; parity for blocks in the same rank is generated on writes, recorded in a distributed location and checked on reads.



RAID 6

- RAID 6: independent data disks with two independent distributed parity schemes
- RAID 6 is essentially an extension of RAID level 5 which allows for additional fault tolerance by using a second independent distributed parity scheme
- Data is striped on a block level across a set of drives, just like in RAID 5, and a second set of parity is calculated and written across all the drives



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RAID 6

- In general, we can add several redundancy disks to be able do deal with several simultaneous disk crashes
- Many different strategies based on different EECs, e.g.,:

  Read-Solomon Code (or derivates):
    - corrects n simultaneous disk crashes using n parity disks
    - a bit more expensive parity calculations compared to XOR

  Hamming Code:
    - corrects 2 disk failures using $2^K – 1$ disks where k disks are parity disks and $2^K – k – 1$
    - the parity disks are calculated using the data disks determined by the hamming code, i.e., a k x $(2^K – 1)$ matrix of 0’s and 1’s representing the $2^K – 1$ numbers written binary except 0

RAID 6

- Example:
  using a Hamming code matrix, 7 disks, 3 parity disks

	disk number			
parity	*7*	0	0	1
	6	0	1	0
	5	1	0	0
data	*4*	0	1	1
	3	1	0	1
	2	1	1	0
	1	1	1	1

Note 1:
the rows represent binary numbers 1 - 7

Note 2:
the rows for the parity disks have single 1's

Note 3:
the rows for the data disks have two or more 1's

Note 4:
the idea of each column now is that the parity disk having a 1 in this column is generated using the data disks having one in this column:

- parity disk 5 is generated using disk 1, 2, 3
- parity disk 6 is generated using disk 1, 2, 4
- parity disk 7 is generated using disk 1, 3, 4

Note 5:
the parity blocks are generated using modulo-2 sum from the data blocks

---

RAID 6

- Example (cont.):

  calculating parity using the hamming matrix to find the corresponding data disks to each parity disk

Hamming code matrix

parity	*7*	0	0	1
	6	0	1	0
	5	1	0	0
data	*4*	0	1	1
	3	1	0	1
	2	1	1	0
	1	1	1	1

disk block values

parity	*7*	
	6	
	5	
data	*4*	01000010
	3	00111000
	2	10101010
	1	11110000

Note 1: parity disk 5 is generated using disk 1, 2, 3
11110000 ⊕ 10101010 ⊕ 00111000 = 01100010

Note 2: parity disk 6 is generated using disk 1, 2, 4
11110000 ⊕ 10101010 ⊕ 01000010 = 00011011

Note 3: parity disk 7 is generated using disk 1, 3, 4
11110000 ⊕ 00111000 ⊕ 01000010 = 10001001

RAID 6

- Read operations is performed from any data disk as a normal read operation
- Write operations are performed as shown on previous slide (similar RAID 5), but
  - now there are several parity disks
  - each parity disk does not use all data disks
- Update operations are performed as for RAID 4 or RAID 5:
  - perform XOR of old and new version of the block, and simply add the sum (again using XOR) to the parity block

---

RAID 6

- Example update:
  - update data disk 2 to 00001111
  - parity disks 5 and 6 is using data disk 2

disk block values

parity	*7*	10001001
	6	10111110
	5	11000111
data	*4*	01000010
	3	00111000
	2	00001111
	1	11110000

Note 1:
old value is 10101010.
Difference is 10101010 ⊕ 00001111 = 10100101

Note 2:
insert new value in data disk 2: 00001111

Note 3:
update parity disk 5, take difference between old and new block, and perform XOR with parity:
10100101 ⊕ 01100010 = 11000111

Note 4:
insert new value in parity disk 5: 11000111

Note 5:
parity disk 6 is similarly updated

RAID 6

- Recovery operations is performed using XOR and the parity disks

  one disk failure is easy – just apply one set of parity and recover

  two disk failures a bit more tricky
    - note that all parity disk computations are different
    - we will always find one configuration where only one disk has failed
    - use this configuration to recover the failed disk
    - now there is only one failed disk, and any configuration can be used

---

RAID 6

- Example recovery:

  disk 2 and 5 have failed

Hamming code matrix

parity	7	0	0	1
	6	0	1	0
	5	1	0	0
data	4	0	1	1
	3	1	0	1
	2	1	1	0
	1	1	1	1

disk block values

7	10001001
6	00011011
5	???
4	01000010
3	00111000
2	???
1	11110000

Note 1:
there is always a column in the hamming code matrix where only one of the failed disks have a 1- value

Note 2:
column 2 use data disk 2, and no other disks have crashed, i.e., use disk 1, 4, and 6 to recover disk 2

Note 3:
restoring disk 2:
11110000 ⊕ 01000010 ⊕ 00011011 = 10101001

Note 4:
restoring disk 5 can now be done using column 1

Challenges Managing Multiple Disks

- How large should a stripe group and stripe unit be?
- Can one avoid hot sets of disks (load imbalance)?
- What and when to replicate?
- Heterogeneous disks?

Summary

- The main bottleneck is disk I/O performance due to disk mechanics: seek time and rotational delays
- Much work has been performed to optimize disks performance
  Many algorithms trying to minimize seek overhead
  (most existing systems uses a SCAN derivate)
  use large block sizes or read many continuous blocks
  prefetch data from disk to memory
  striping might not be necessary on new disks (at least not on all disks)
  memory caching can save disk I/Os
- World today more complicated
  (both different access patterns and unknown disk characteristics)
  → new disks are "smart", we cannot fully control the device