Disks

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Overview

- Disks
  - mechanics and properties
- Disk scheduling
  - traditional
  - real-time
  - stream oriented
- Data placement
- Multiple disks
- Prefetching
- Memory caching

Disks

Disks

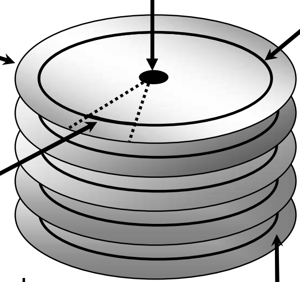
- Disks ...
  - are used to have a **persistent system**
  - are orders of magnitude *slower* than main memory
  - are *cheaper*
  - have *more capacity*

- 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

Mechanics of Disks



Disk Specifications

- Disk technology develops "fast"
- Some existing (Seagate) disks today (2002):

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

	Barracuda 180	*Cheetah 36*	*Cheetah X15*	**X15.3**
Capacity (GB)	181.6	36.4	36.7	73.4
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	0.2
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	609 – 891
disk buffer cache	16 MB	4 MB	8 MB	

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 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 x 10^{10} = 42.8 GB
  - Formatted capacity = 36.7 GB

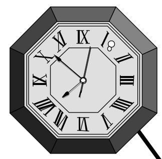
Note:
there is a difference between formatted and total capacity. Some of the capacity is used for storing checksums, spare tracks, gaps, etc.

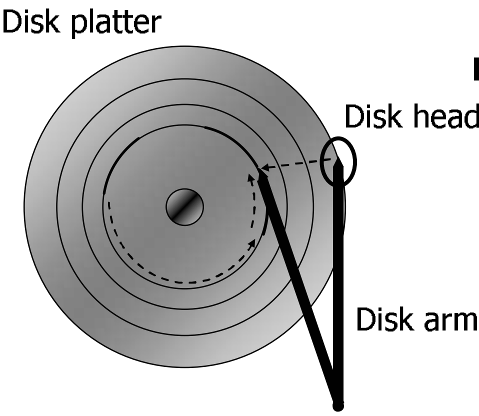
Disk Access Time

- 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

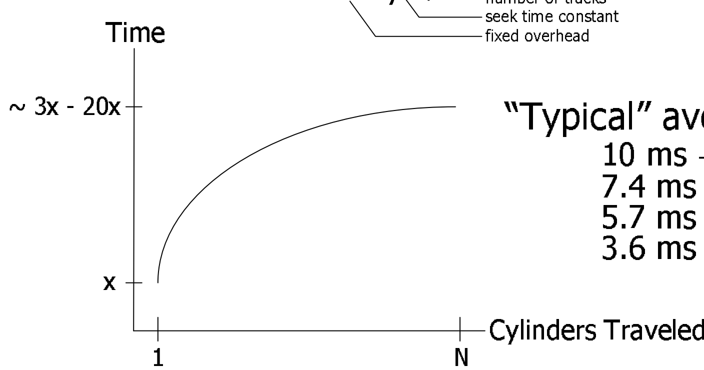
\+ Rotational delay

\+ 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: $\alpha + \beta\sqrt{n}$ (n: number of tracks; β: seek time constant; α: fixed overhead)

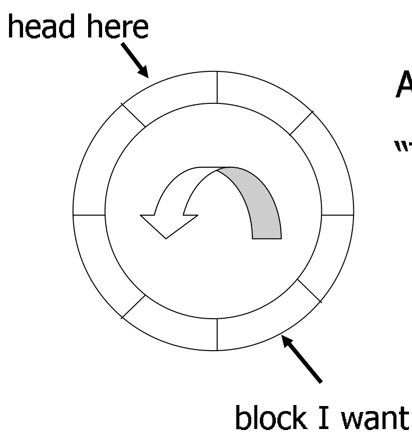


"Typical" average:

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
  - average rotational delay
  - transfer time
  - 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

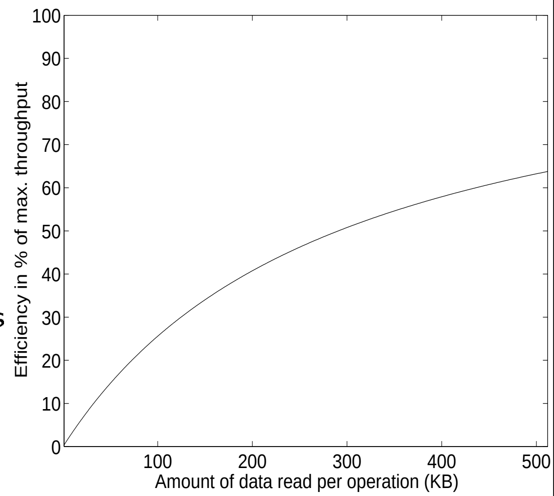
Block Size

- 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

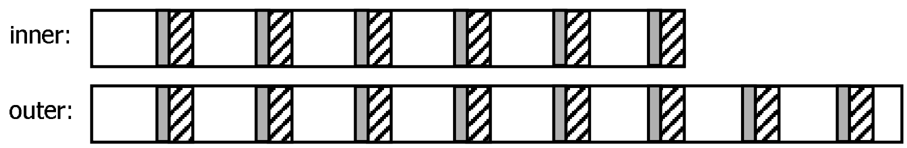
- Thus, increasing block size can increase performance by reducing seek times and rotational delays
- However, a large block size is not always best
  - ❑ blocks spanning several tracks still introduce latencies
  - ❑ small data elements may occupy only a fraction of the block



- 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: Some 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

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)
- Note that disk scheduling ≠ CPU scheduling
  - a mechanical device – hard to determine (accurate) access times
  - disk accesses cannot be preempted – runs until it finishes
  - disk I/O often the main performance bottleneck
- 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)
  - …

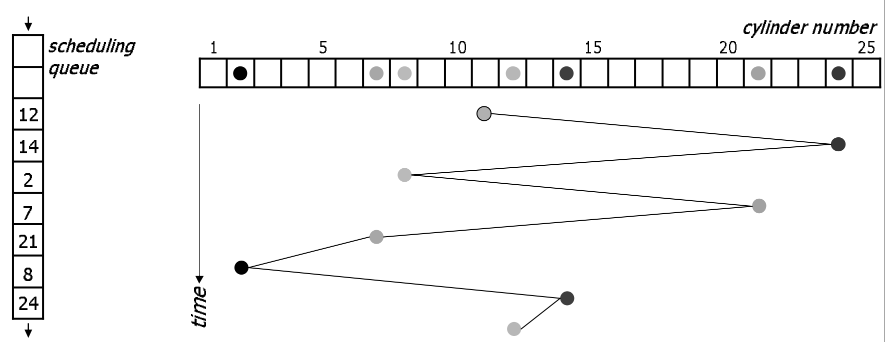
First–Come–First–Serve (FCFS)

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



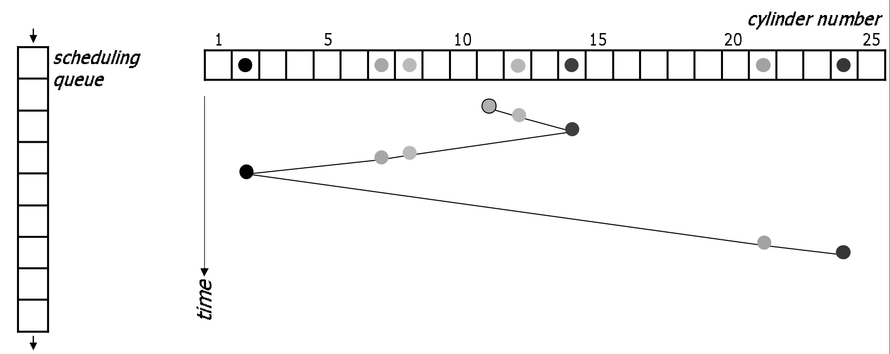
Shortest Seek Time First (SSTF)

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



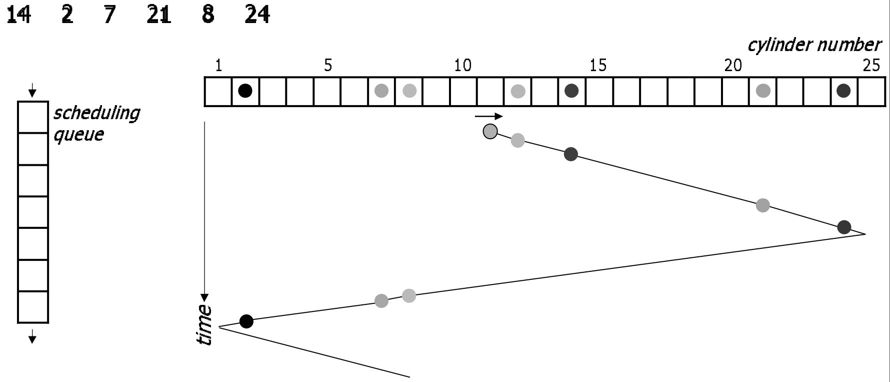
SCAN

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



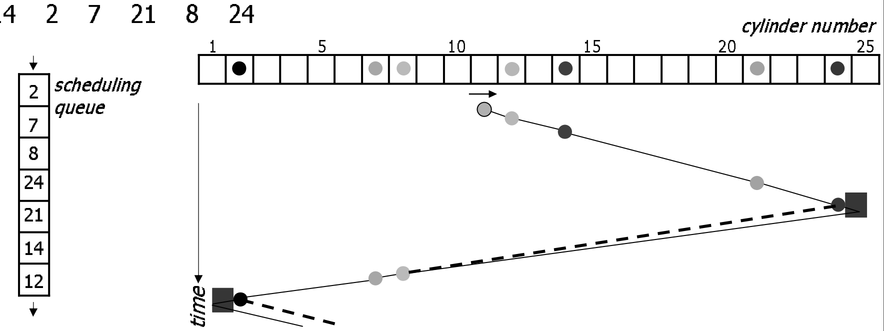
LOOK

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

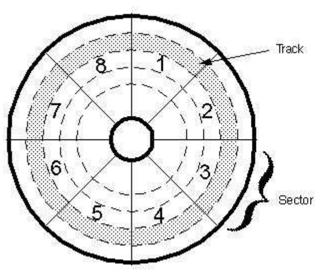


Data Placement on Disk

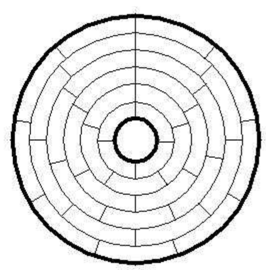
Data Placement on Disk

- 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., more better on outer tracks

Disk Layout

- Cheetah X15.3 is a zoned CAV disk:

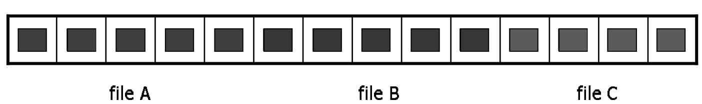
Zone	Cylinders per Zone	Sectors per Track	Spare Cylinders	Zone Transfer Rate Mb/s	Sectors per Zone	Efficiency	Formatted Capacity (Mbytes)
0	**3544**	**672**	7	**890,98**	19014912	77,2%	**9735,635**
1	3382	652	7	878,43	17604000	76,0%	9013,248
3	3079	624	6	835,76	15340416	76,5%	7854,293
4	2939	595	6	801,88	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

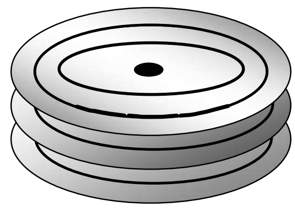
- Contiguous placement stores disk blocks contiguously on disk



- 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

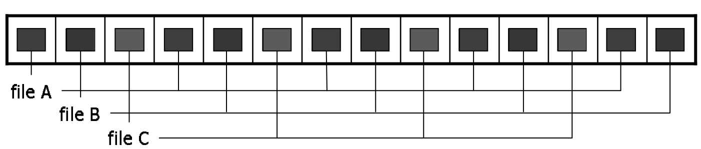
Data Placement on Disk

- 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

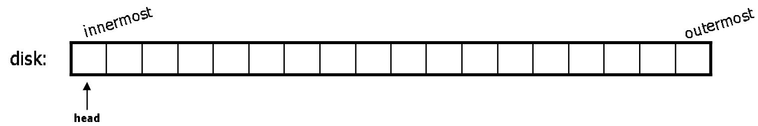
- Interleaved placement tries to store blocks from a file with a fixed number of other blocks in-between each block



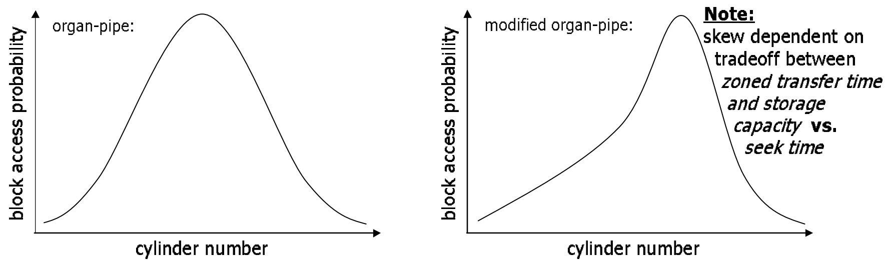
  - minimal disk arm movement reading the files A, B and C
    (starting at the same time)
  - fine for predictable workloads reading multiple files
  - no gain if we have unpredictable disk accesses
- Non-interleaved (or even random) placement can be used for highly unpredictable workloads

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)



Prefetching and Buffering

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

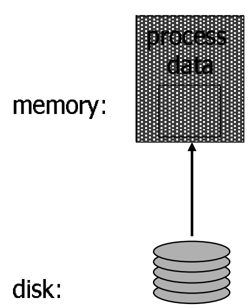
- One simple (and efficient) way of doing prefetching is read-ahead:
  - ❑ read more than the requested block into memory
  - ❑ serve next read requests from buffer cache

- 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

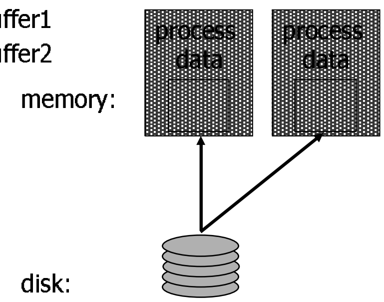
- Example:
  have a file with block sequence B1, B2, ...
  our program processes data sequentially, i.e., B1, B2, ...
  - ❑ single buffer solution:
    - read B1 → buffer
    - process data in buffer
    - read B2 → buffer
    - process data in Buffer
    - ...
    - if P = time to process a block
      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
  - ...



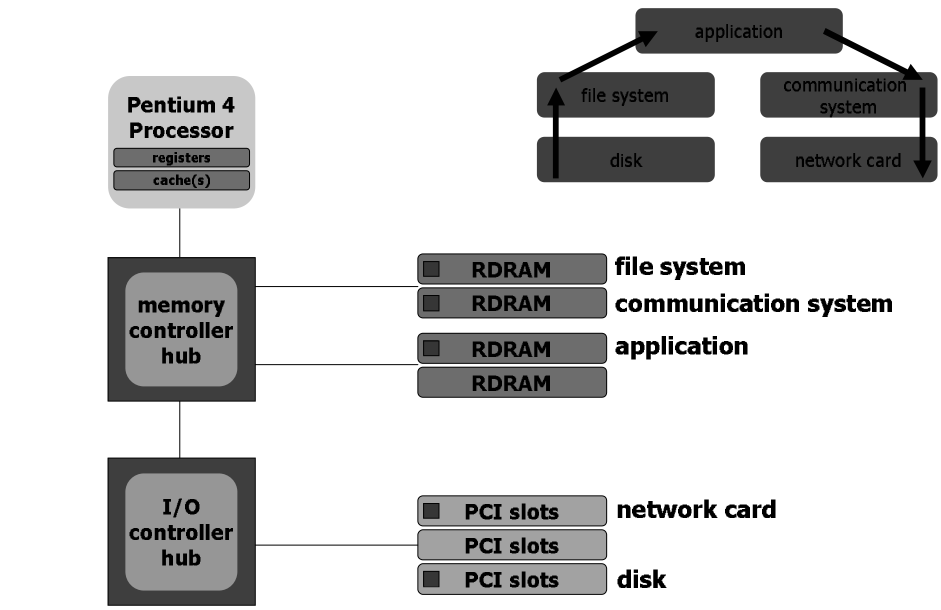
  - if P = time to process a block
    R = time to read in 1 block
    n = # blocks

    if P ≥ R
    double buffer time = R + nP

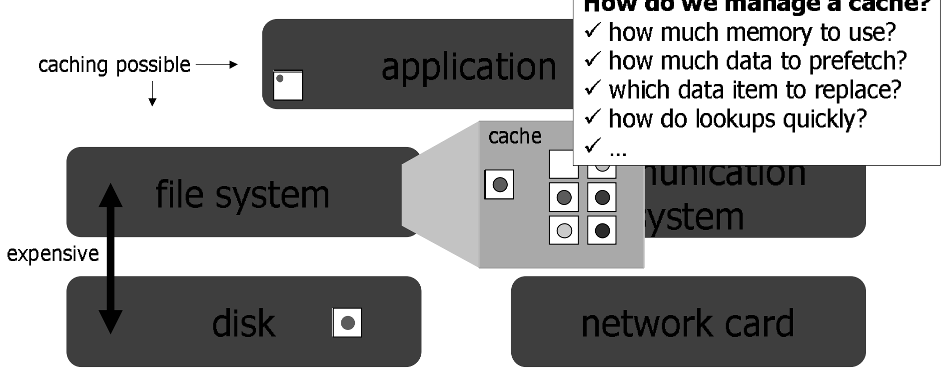
- if P < R, we can try to add buffers (*n* - buffering)

Memory Caching

Data Path (Intel Hub Architecture)

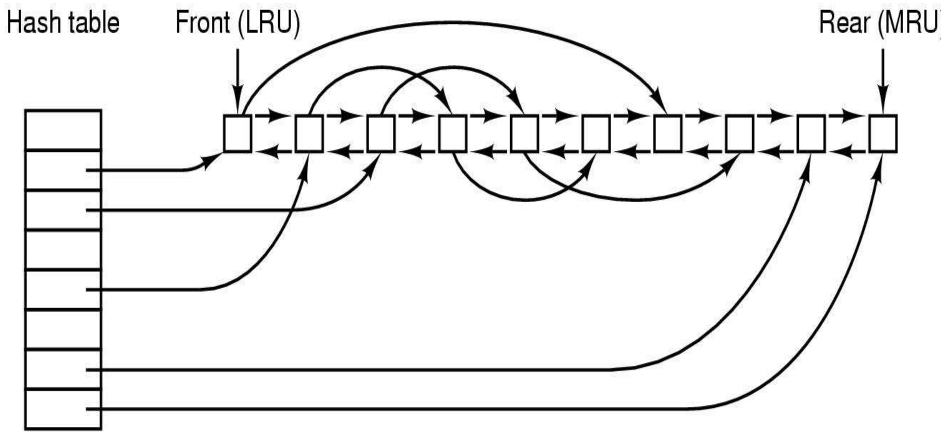


Memory Caching



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



Summary from yesterday....

- Disk access
  - seeks
  - rotational delays
  - transfer time
  - other delays
- Ways to optimize
  - scheduling
  - placement
  - block size
  - prefetching/caching
  - ...

Disk Errors

Disk Errors

- Disk errors are rare:

	Barracuda 180	*Cheetah 36*	*Cheetah X15*
mean time to failure (MTTF)	1.2×10^6	1.2×10^6	1.2×10^6
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.

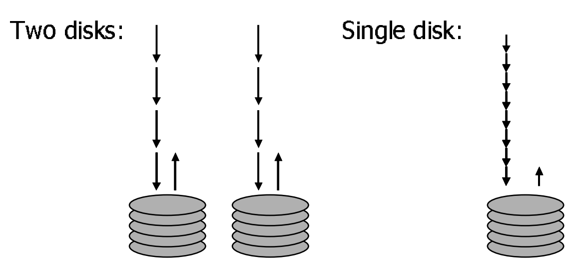
Crash Recovery

- 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

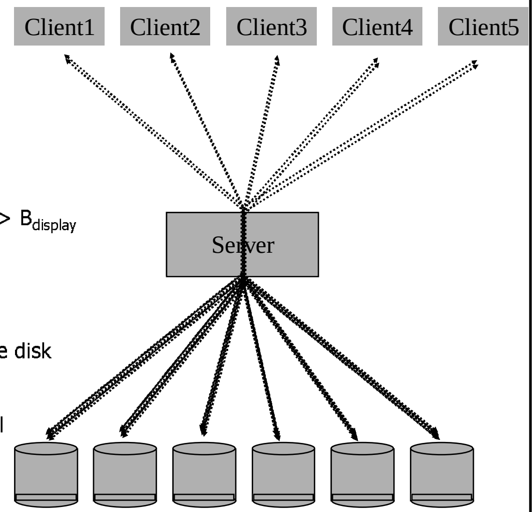
Multiple Disks

- 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)



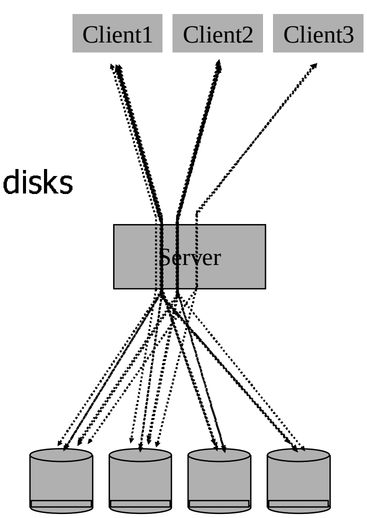
Striping

- 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)

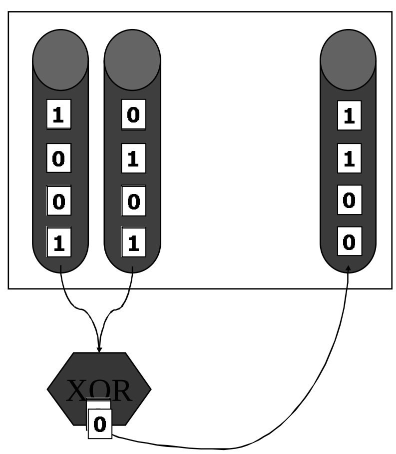


Redundant Array of Inexpensive Disks (RAID)

- 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

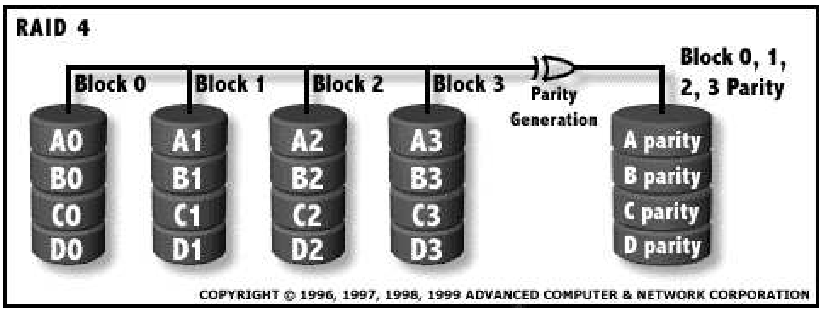
RAID

- 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



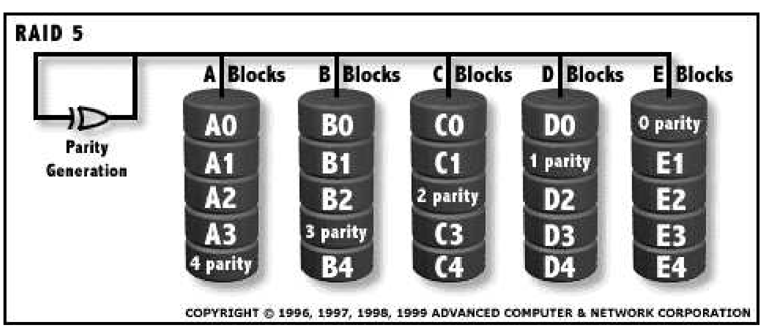
RAID 4

- 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.



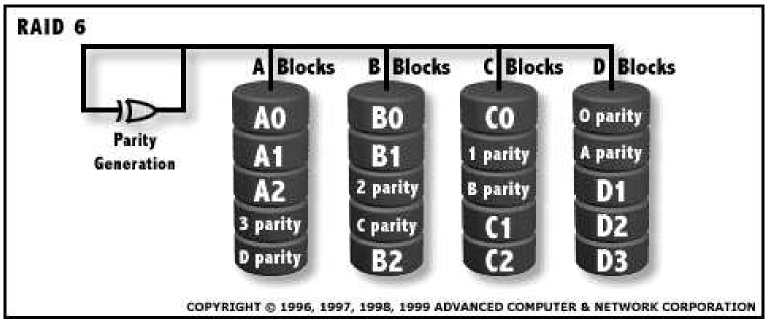
RAID 5

- 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



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

disk block values

parity	7	
parity	6	
parity	5	
data	4	01000010
data	3	00111000
data	2	10101010
data	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

7	10001001
6	10111110
5	11000111
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 (7, 6, 5: parity; 4, 3, 2, 1: data)

7	0	0	1
6	0	1	0
5	1	0	0
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:
$11110000 \oplus 01000010 \oplus 00011011 = 10101001$

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

Some 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?

The End:
Summary

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