EEL-4713
Computer Architecture
I/O Systems

Outline

° I/O Performance Measures

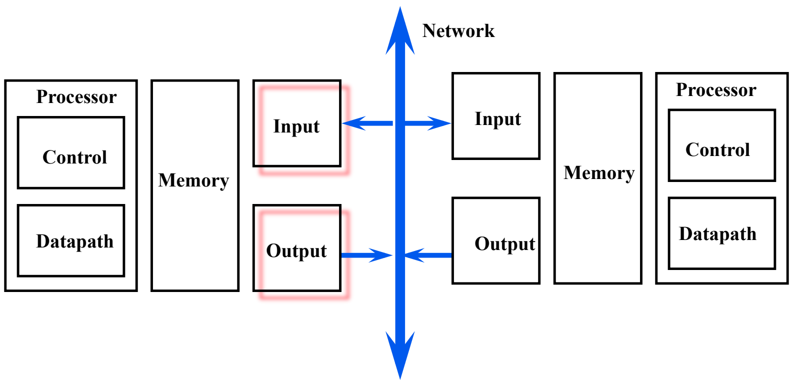
° Types and Characteristics of I/O Devices

° Magnetic Disks

° Summary

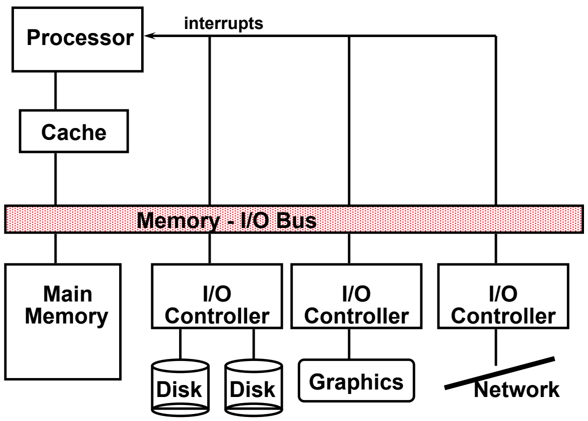
The Big Picture: Where are We Now?

° Today's Topic: I/O Systems



I/O System Design Issues

- Performance
- Expandability
- Resilience in the face of failure



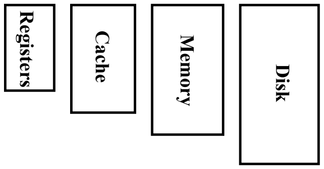
Types and Characteristics of I/O Devices

- Behavior: how does an I/O device behave?
  - Input: read only
  - Output: write only, cannot read
  - Storage: can be reread and usually rewritten
- Partner:
  - Either a human or a machine is at the other end of the I/O device
  - Either feeding data on input or reading data on output
- Data rate:
  - The peak rate at which data can be transferred:
    - Between the I/O device and the main memory
    - Or between the I/O device and the CPU

I/O Device Examples

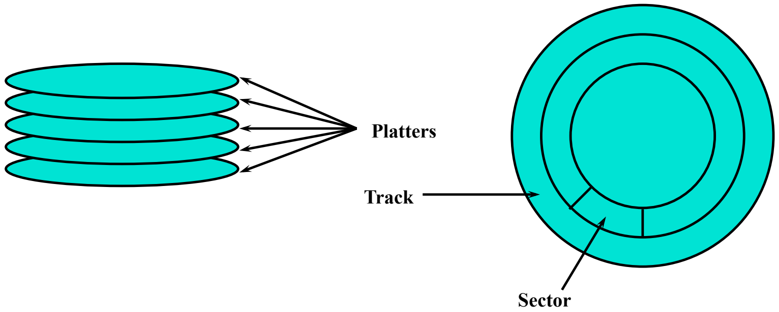
Device	Behavior	Partner	Data Rate (MBit/sec)
Keyboard	Input	Human	0.0001
Mouse	Input	Human	0.004
Graphics Display	Output	Human	800-8000
Network-LAN	Input or Output	Machine	100-1000
Wireless LAN	Input or Output	Machine	11-54
Optical Disk	Storage	Machine	80
Magnetic Disk	Storage	Machine	340-2560

Magnetic Disk



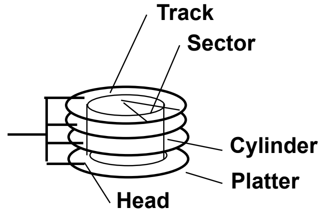
- Purpose:
  - Long term, nonvolatile storage
  - Large, inexpensive, and slow
  - Lowest level in the memory hierarchy
- Hard disks:
  - Rely on a rotating platter coated with a magnetic surface
  - Use a moveable read/write head to access the disk
  - Platters are rigid (metal or glass)
  - High density
  - High data access rate: disks spin fast, plus can incorporate more than one platter and r/w head

Organization of a Hard Magnetic Disk



- Typically, 10,000-50,000 tracks per surface
  - 100-500 sectors per track
- A sector is the smallest unit that can be read/written
  - 512Bytes – 4096Bytes
- Early days: all tracks had the same number of sectors
  - Zone bit recording: record more sectors on the outer tracks

Magnetic Disk Characteristic



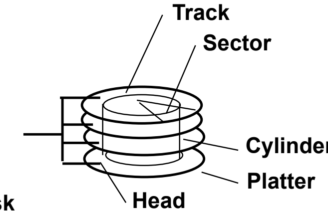
° Cylinder: all the tracks under the head at a given point on all surface

° Read/write data is a three-stage process:
- Seek time: position the arm over the proper track
- Rotational latency: wait for the desired sector to rotate under the read/write head
- Transfer time: transfer a block of bits (sector) under the read-write head

° Average seek time as reported by the industry:
- Typically in the range of 3 ms to 14 ms
- (Sum of the time for all possible seek) / (total # of possible seeks)

° Due to locality of disk reference, actual average seek time may:
- Only be 25% to 33% of the advertised number

Typical Numbers of a Magnetic Disk



° Rotational Latency:
- Most disks rotate at 5K-15K RPM
- Approximately 4-12ms per revolution
- An average latency to the desired information is halfway around the disk

° Transfer Time is a function of :
- Transfer size (usually a sector): 512B-4KB / sector
- Rotation speed (5K-15K RPM)
- Recording density: typical diameter ranges from 2 to 3.5 in
- Typical values: 30-80 MB per second
  - Caches near disk; higher bandwidth (320MB/s)

Future Disk Size and Performance

° Capacity growth (60%/yr) overshoots bandwidth growth (40%/yr)

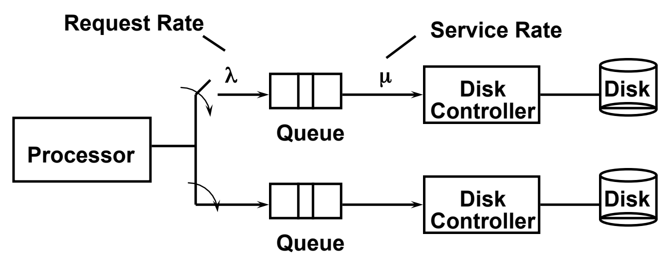
° Slow improvement in seek, rotation (8%/yr)

° Time to read whole disk

Year	Sequentially (bandwidth)		Randomly (latency) (1 sector/seek)	
1990	4 minutes		6 hours	
2000	12 minutes	3x	1 week(!)	24x
2006	56 minutes	4.6x	3 weeks (SCSI)	3x
2006	171 minutes	3x	7 weeks (SATA)	2.3x

° Disks are now like tapes, random access is slow!

Disk I/O Performance



° Disk Access Time = Seek time + Rotational Latency + Transfer time + Controller Time + Queueing Delay

° Estimating Queue Length:
- Will see later

*Magnetic Disk Examples

Characteristics	ST373453	ST3200822	ST94811A
Disk diameter (inches)	3.50	3.50	2.50
Formatted data capacity (GB)	73.4	200.0	40.0
MTTF (hours)	1.2 million	600,000	330,000
Number of heads	8	4	2
Rotation speed (RPM)	15,000	7,200	5,400
Transfer rate (MB/sec)	57-86	32-58	34
Power (oper/idle) (watts)	20/12	12/8	2.4/1.0
GB/watt	4	16	17
GB/cubic feet	3	9	10
Price, 2004 US$/GB	5	0.5	2.5

I/O System Performance

° **I/O System performance depends on many aspects of the system:**
- **The CPU**
- **The memory system:**
  - **Internal and external caches**
  - **Main Memory**
- **The underlying interconnection (buses)**
- **The I/O controller**
- **The I/O device**
- **The speed of the I/O software**
- **The efficiency of the software's use of the I/O devices**

° **Two common performance metrics:**
- **Throughput: I/O bandwidth**
- **Response time: Latency**

Bandwidth/latency example

° **Which has higher bandwidth?**

- **You are driving to Tallahassee to visit a friend. You carry two DVD-ROMs**
- **A 1Mbit/s cable modem link to your ISP and high-bandwidth, fiber-optic backbone connecting ISP to FSU**

Car + DVD bandwidth

° **Data:**
- **One DVD: 3250MBytes**
- **Two DVDs: 2*3250M*8 = 52Gbits**

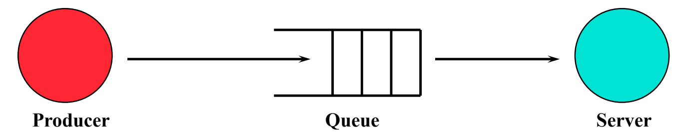
° **Time:**
- **140 miles**
- **70 mph**
- **2 hours**

° **Bandwidth:**
- **(52*10^9) / (2*60*60) = 7.2 Mbit/s**

Car vs. cable

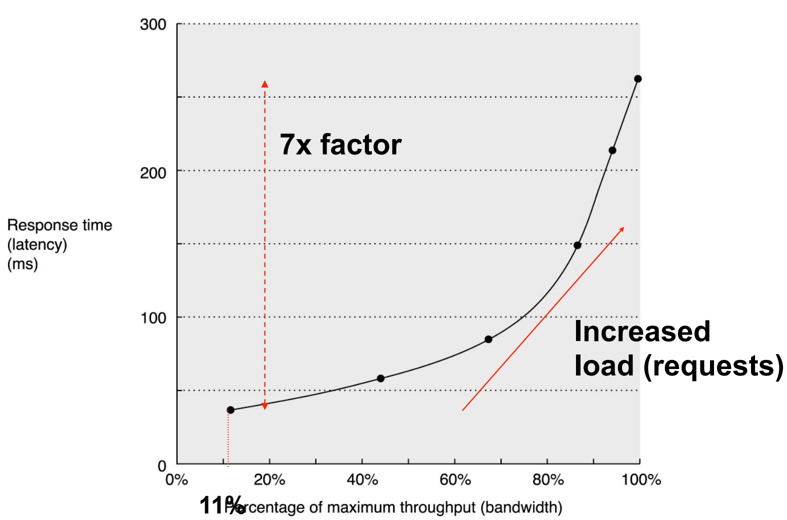
- Car has higher bandwidth!
- Latency?
  - How long before your friend will see first chapter of first DVD?
  - Hours vs. seconds
  - Cable modem has smaller latency

Producer-Server Model

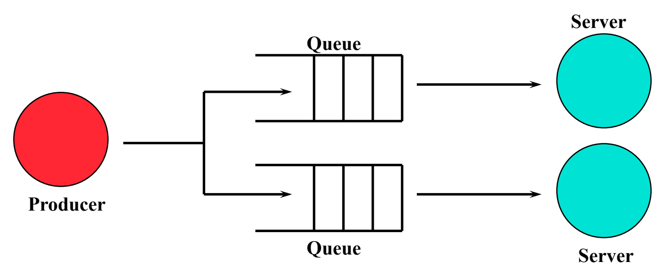


- Throughput:
  - The number of tasks completed by the server in a unit of time
  - In order to get the highest possible throughput:
    - The server should never be idle
    - The queue should never be empty
- Response time:
  - Begins when a task is placed in the queue
  - Ends when it is completed by the server
  - In order to minimize the response time:
    - The queue should be empty
    - The server is ready to take a task

Latency vs. throughput



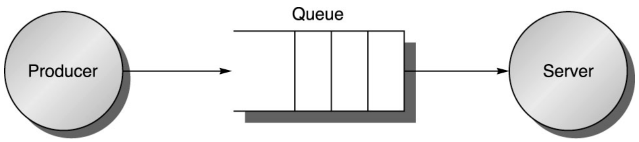
Throughput Enhancement



- In general throughput can be improved by:
  - Throwing more hardware at the problem
- Response time is much harder to reduce:
  - Ultimately it is limited by the speed of light

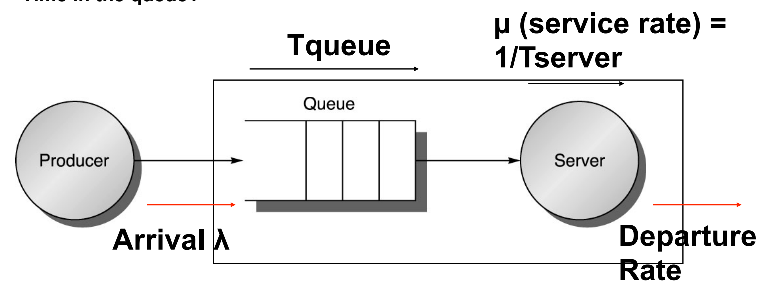
Example: disk I/O Performance

- I/O requests produced by an application, serviced by a disk
- Latency (response time)
  - Time elapsed between producing and consuming
- Bandwidth (throughput)
  - Rate of service (number of tasks completed per unit of time)



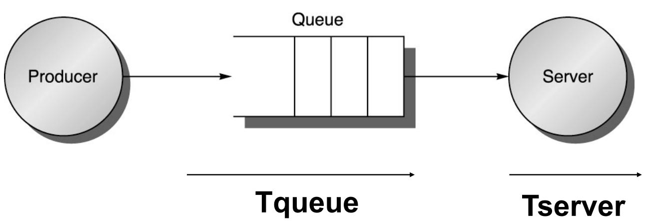
Queuing theory 101

- M/M/1 queues: exponentially distributed random request arrival times and a single server
  - For simplicity, assume the system is in equilibrium (Arrival Rate = Departure Rate)
  - Infinite queue, FIFO discipline
  - Arrivals are random in time, average requests/second (arrival rate) is λ
  - Average time for server to service a task: Tservice
  - Average service rate is μ = 1/Tserver (assuming a single server)
  - What is the average response time? Throughput? Length of the queue? Time in the queue?



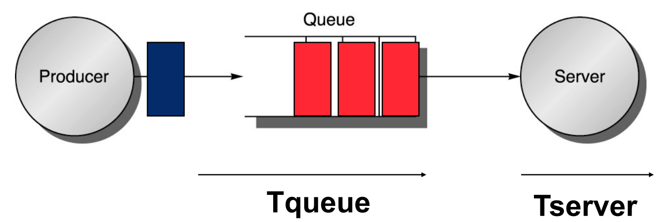
Latency

- Requests on queue will delay the servicing of another incoming request
  - Time(system) = Tqueue + Tserver
  - If goal is to minimize latency for a given server, attempt to keep queue empty
    - Reduce Tqueue or Tserver



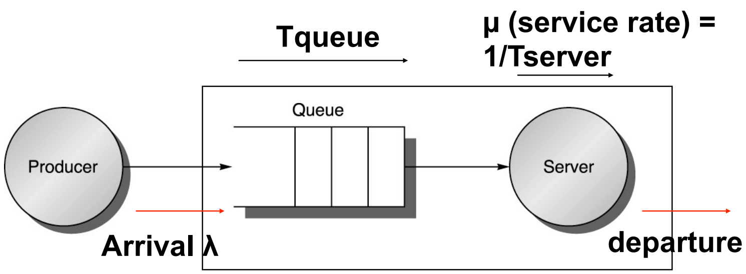
Throughput

- An empty queue will make the server idle
  - If goal is to maximize throughput, must maximize the utilization of the server
    - Always have requests on the queue



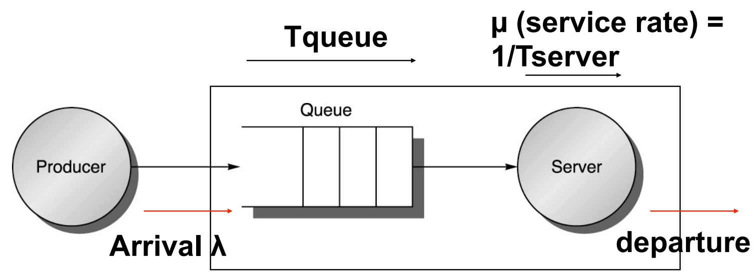
Queuing theory 101

- Length or number of tasks in each area
  - LengthServer = average number of tasks in service
  - LengthQueue = Average length of the queue = λ*Tqueue
  - LengthSystem = LengthServer + LengthQueue



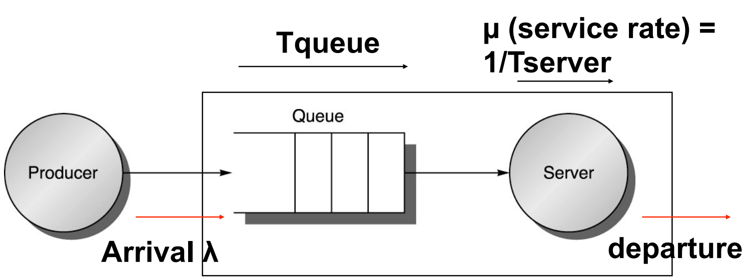
Queuing theory 101

- How busy is the server?
  - Server utilization must be between 0 and 1 for a system in equilibrium; AKA traffic intensity ρ
  - Server utilization ρ = mean number of tasks in service = λ (arrival rate) * Tserver
  - Example: What is disk utilization if get 50 I/O requests per second for disk and average disk service time is 10 ms (0.01 sec)?
    - Server utilization = 50/sec x 0.01 sec = 0.5
    - Or server is busy on average 50% of time



Time in Queue vs. Queue Latency

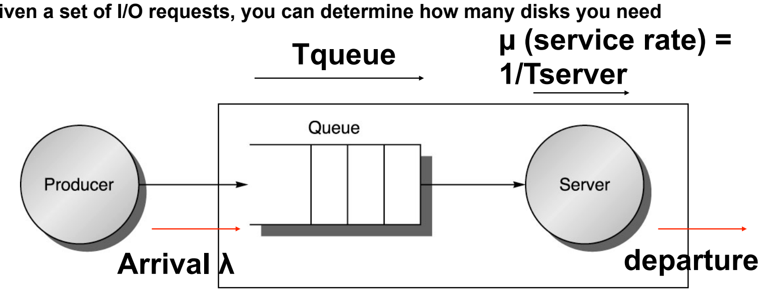
- FIFO queue
- Tqueue = LengthQueue * Tserver + "Mean time to complete service of task when a new task arrives if the server is busy (residual service time)"
- New task can arrive at any instance; how do we predict the residual service time
- To predict performance, need to know something about distribution of events….but that is outside the scope of this class so we move straight to …



Time in Queue

- All tasks in queue (QueueLength) ahead of new task must be completed before task can be serviced
  - Each task takes on average Tserver
  - Task at server takes average residual service time to complete
- Chance server is busy is *server utilization*
  ⇒ expected time for service is Server utilization × Average residual service time
- Tqueue = QueueLength x Tserver + Server utilization x Average residual service time
- Substituting definitions for QueueLength, Average residual service time, & rearranging:

  Tqueue = Tserve x Server utilization/(1-Server utilization)
- So, given a set of I/O requests, you can determine how many disks you need



M/M/1 Queuing Model

- System is in equilibrium
- Times between 2 successive requests arriving, "*interarrival times*", are exponentially distributed
- Number of sources of requests is unlimited "infinite population model"
- Server can start next job immediately
- Single queue, no limit to length of queue, and FIFO discipline, so all tasks in line must be completed
- There is one server
- Called M/M/1
  1. Exponentially random request arrival
  2. Exponentially random service time
  3. 1 server
  - *M* standing for Markov, mathematician who defined and analyzed the memoryless processes

Example 1

- 40 disk I/Os / sec, requests are exponentially distributed, and average service time is 20 ms

⇒ Arrival rate/sec = 40, $Time_{server}$ = 0.02 sec

1. On average, how utilized is the disk?
- Server utilization = Arrival rate × Tserver
  = 40 x 0.02 = 0.8 = 80%

2. What is the average time spent in the queue?
- Tqueue = Tserver
  x Server utilization/(1-Server utilization)

  = 20 ms x 0.8/(1-0.8) = 20 x 4 = 80 ms

3. What is the average response time for a disk request, including the queuing time and disk service time?
- Tsystem = Tqueue + Tserver = 80+20 ms = 100 ms

Example 2: How much better with 2X faster disk?

- Average service time is 10 ms

⇒ Arrival rate/sec = 40, $Time_{server}$ = 0.01 sec

1. On average, how utilized is the disk?
- Server utilization = Arrival rate × $Time_{server}$
  = 40 x 0.01 = 0.4 = 40%

2. What is the average time spent in the queue?
- Tqueue= Tserver
  x Server utilization/(1-Server utilization)

  = 10 ms x 0.4/(1-0.4) = 10 x 2/3 = 6.7 ms

3. What is the average response time for a disk request, including the queuing time and disk service time?
- Tsystem=Tqueue+ Tserver =6.7+10 ms = 16.7 ms
- 6X faster response time with 2X faster disk!

Value of Queueing Theory in practice

- Learn quickly do not try to utilize resource 100% but how far should back off?
- Allows designers to decide impact of faster hardware on utilization and hence on response time
- Works surprisingly well

I/O Benchmarks for Magnetic Disks

° Supercomputer application:
  - Large-scale scientific problems

° Transaction processing:
  - Examples: Airline reservations systems and banks

° File system:
  - Example: UNIX file system

Supercomputer I/O

° Supercomputer I/O is dominated by access to large files on magnetic disks

° The overriding supercomputer I/O measures is data throughput:
  - Bytes/second that can be transferred between disk and memory

Transaction Processing I/O

° Transaction processing:
  - Examples: airline reservations systems, bank ATMs
  - A lot of small changes to a large body of shared data

° Transaction processing requirements:
  - Throughput and response time are both important

° Transaction processing is chiefly concerned with I/O rate:
  - The number of disk accesses per second

° Each transaction in typical transaction processing system takes:
  - Between 2 and 10 disk I/Os
  - Between 5,000 and 20,000 CPU instructions per disk I/O

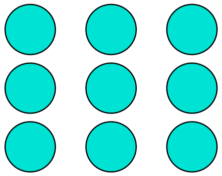
File System I/O

° Measurements of UNIX file systems in an engineering environment:
  - 80% of accesses are to files less than 10 KB
  - 90% of all file accesses are to data with sequential addresses on the disk
  - 67% of the accesses are reads
  - 27% of the accesses are writes
  - 6% of the accesses are read-write accesses

*Reliability and Availability

- Two terms that are often confused:
  - Reliability: Is anything broken?
  - Availability: Is the system still available to the user?
- Availability can be improved by adding hardware:
  - Example: adding ECC to memory
- Reliability can only be improved by:
  - Bettering environmental conditions
  - Building more reliable components
  - Building with fewer components
    - Improved availability may come at the cost of lower reliability

Disk Arrays



- An array organization of disk storage (RAID):
  - Arrays of small and inexpensive disks
  - Increase potential throughput by having many disk drives:
    - Data is spread over multiple disks
    - Multiple accesses are made to several disks
- Reliability is lower than a single disk:
  - But availability can be improved by adding redundant disks: Lost information can be reconstructed from redundant information

What is a failure?

- The user perception of a service does not match its specified behavior
- Decomposition: faults, errors and failure
  - Failures are caused by errors
  - Errors are caused by faults
  - But, the inverse is not necessarily true:
    - Faults cause “latent” errors that may never be activated
    - Errors may not cause failures

Example

- A DRAM transistor loses its charge between refresh cycles
  - A fault
- Its consequence is a latent error
  - It is not activated if no program loads this memory word
- If this memory word is loaded:
  - The load returns an erroneous word
  - Not a failure until manifested in the service
    - E.g. what if the faulty bit is masked with an AND operation in an application?

Reliability, availability and RAID

- Storage devices are slower than CPU, memory
  - Parallelism can also be exploited in this case for improving throughput/ bandwidth
    - Not the speed of a single request
- Motivations for disk arrays:
  - High storage capacity
  - Potential overlapping of multiple disk operations (seek, rotate, transfer) for high throughput
  - Best price/gigabyte on small/medium disks that are sold in high volume

Reliability issues

- But, computer systems are prone to failure
  - Hardware, software, operator
    - In particular, disks, moving parts
  - More components (array) - increased probability of system failure

Reliability/Availability

- Reliability: measure of continuous service until a failure
  - Mean time to failure (MTTF) is an average measurement of a typical component's reliability
- Availability: measure of continuous service with respect to the continuous and interrupted intervals
  - MTTF/(MTTF+MTTR)
    - MTTR: mean time to repair

System reliability

- If individual modules have exponentially distributed lifetimes:
  - FIT (Failures in Time or Failure rate) = 1/MTTF
- A system's failure distribution:
  - If independent, exponential distribution
    - System total = Product of reliability distributions of individual components
    - Resulting failure rate is the sum of each module's failure rate
- Example: 10 disks, each MTTF=5 years
  - FIT (disk) = 1/5 (1/year)
  - FIT (system) = 1/5 (1/year) * 10 disks = 2 (disks/year)
  - MTTF (system) = 1/2 year/disk

Example

- A disk has MTTF of 100 days, MTTR of 1 day
  - Availability = 100/101 = 99%
- If you have two disks storing different parts of your data
  - MTTF(1 disk) still 100 days
  - MTTF(2 disks) = 100/2 = 50 days
  - Availability = 50/51 = 98%
- What if the second disk "mirrors" the first and each one can take over on failure of the other?
  - MTTF(1 disk) still 100 days
  - Assuming failed disks are repaired at same MTTR, availability is a function of the probability that both disks fail within the same day
    - Each disk's availability is 99%, so only a 1% chance of failure for 1 and a 1%*1% = .01% chance of failure of both
    - MTTF both disks = 100 days * 100 days = 10,000 days
    - 10000/(10000+1) = 99.99%

Quantifying Availability

System Type	Unavailable (min/year)	Availability	Availability Class
Unmanaged	50,000	90.%	1
Managed	5,000	99.%	2
Well Managed	500	99.9%	3
Fault Tolerant	50	99.99%	4
High-Availability	5	99.999%	5
Very-High-Availability	.5	99.9999%	6
Ultra-Availability	.05	99.99999%	7

UnAvailability = MTTR/MTBF

can cut it in ½ by cutting MTTR *or* MTBF

From Jim Gray's "Talk at UC Berkeley on Fault Tolerance " 11/9/00

How Realistic is "5 Nines"?

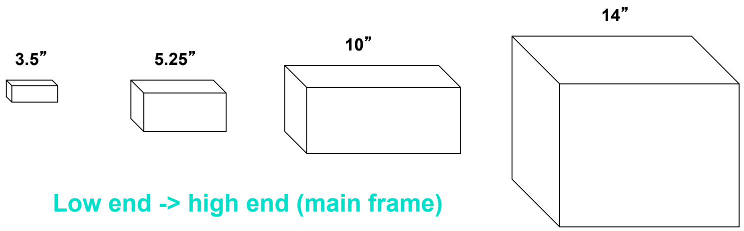
- HP claims HP-9000 server HW and HP-UX OS can deliver 99.999% availability guarantee "in certain pre-defined, pre-tested customer environments"
  - Application faults?
  - Operator faults?
  - Environmental faults?
- Collocation sites (lots of computers in 1 building on Internet) have
  - 1 network outage per year (~1 day)
  - 1 power failure per year (~1 day)
- Microsoft Network unavailable for a day due to problem in Domain Name Server: if only outage per year, 99.7% or 2 Nines
  - Needed 250 years of interruption free service to meet their target "nines"

MTTF Implications

- Disk arrays have shorter MTTFs
  - But are desirable for performance/capacity reasons
- Approach: use redundancy to improve availability in disk arrays
  - Redundant Array of Inexpensive Disks (RAID)

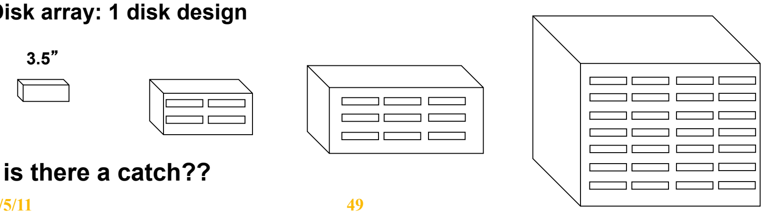
The case for RAID in the past:
Manufacturing Advantages of Disk Arrays (1987)

° Conventional: 4 disk designs (4 product teams):



Low end -> high end (main frame)

° Disk array: 1 disk design



But is there a catch??

The case for RAID in the past:
Arrays of Disks to Close the Performance Gap (1988 disks)

° Replace small number of large disks with a large number of small disks

	IBM 3380	Smaller disk	Smaller disk x50
Data Capacity	7.5 GBytes	320 MBytes	**16 GBytes**
Volume	**24 cu. ft.**	0.2 cu. ft.	**20 cu. ft**
Power	1.65 KW	10 W	**0.5 KW**
Data Rate	12 MB/s	2 MB/s	**100 MB/s**
I/O Rate	200 I/Os/s	40 I/Os/s	**2000 I/Os/s**
Cost	**$100k**	$2k	**$100k**

° Data arrays have potential for
- Large data and I/O rates
- High MB per cu. ft
- High MB per KW

PROBLEM: Array Reliability

- Reliability of N disks = Reliability of 1 Disk ÷ N
  - 50,000 Hours ÷ 70 disks = 700 hours
  - Disk system MTTF: Drops from 6 years to 1 month!
- Arrays (without redundancy) *too unreliable* to be useful!
- Originally concerned with performance, but reliability became an issue, so it was the end of disk arrays until…

Improving Reliability with Redundancy

° Add redundant drives to handle failures

Redundant
Array of
Inexpensive (Independent? - First disks weren’t cheap)
Disks

° Redundancy offers 2 advantages:
- Data not lost: Reconstruct data onto new disks
- Continuous operation in presence of failure

° Several RAID organizations
- Mirroring/Shadowing (Level 1 RAID)
- ECC (Level 2 RAID)
- Parity (Level 3 RAID)
- Rotated Parity (Level 5 RAID)
- Levels were used to distinguish between work at different institutions

Key: Reliability with redundancy

- Do not use all space available to store data
  - Also store information that can be used to prevent faults from becoming failures
- Technique used in other computing/ communications systems
  - Error-correction codes
  - E.g. the parity bit in a DRAM can be used to detect single-bit faults

MTTF and MTTR

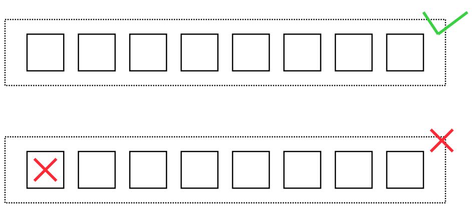
- Disks have MTTRs that are much shorter than MTTFs
  - Hours (MTTR) vs. years (MTTF)
  - Redundancy allows system to tolerate one or more faults while a defective device (e.g. a hot-swappable disk) is replaced

Notes

- Faults are not avoided by redundancy
  - Improvements in fault rates only achieved with better manufacturing/environmental conditions
- Redundancy is used to prevent errors from becoming failures
  - Reliability of a system vs. individual components
- Redundancy adds cost:
  - Need to purchase more storage capacity
  - Need to spend more power
  - Design complexity (Has a fault occurred? Who takes over? How to restore state once repaired?)
- But, redundancy can help improve performance
  - Mirrored disks – easy to split read requests

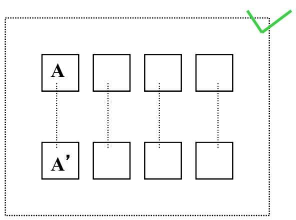
RAID redundancy

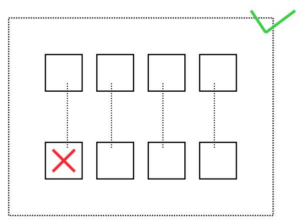
- Several “levels” of RAID can be implemented and configured in a given controller
  - Tradeoffs in controller complexity, fault tolerance and performance
- RAID0
  - No redundancy – plain disk array
    - Best performance, simplest, but a faulty disk activates an error if accessed



RAID 1

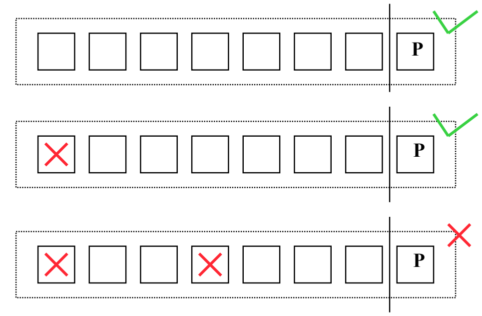
- Mirrored redundancy
  - Data written to disk A is always written to mirror disk A'
  - Uses 2N X-Byte disks to store N*X Bytes of information
  - Bandwidth sacrifice
  - 100% overhead!





RAID 3

- Bit-interleaved parity
  - Story striped parity across all disks on one parity disk
  - Ex: Xor all bits
- Rely on interface to know which disk failed
- Do not store entire copy of data in redundant disk
  - Rather, just enough information to recover data in case of a fault
  - One disk holds blocks containing the parity sum of blocks of other disks
    - N+1 X-Byte disks to store N*X Bytes
  - Can avoid failures from a *single* fault



Parity example

Data (disks 1-4)

1: 00000011

2: 00001111

3: 11000011

4: 11111111

Parity (disk 5):

5: 00110000

When reading data,
also calculate parity (xor)
if 0, OK;
if 1, fault

Parity example

Disk 3 fails

1: 00000011

2: 00001111

~~3: 11000011~~

4: 11111111

Parity (disk 5):

5: 00110000

How to recover 3's data
from 1, 2, 4, 5?

Parity example

Disk 3 fails

1: 00000011

2: 00001111

4: 11111111

5: 00110000 +

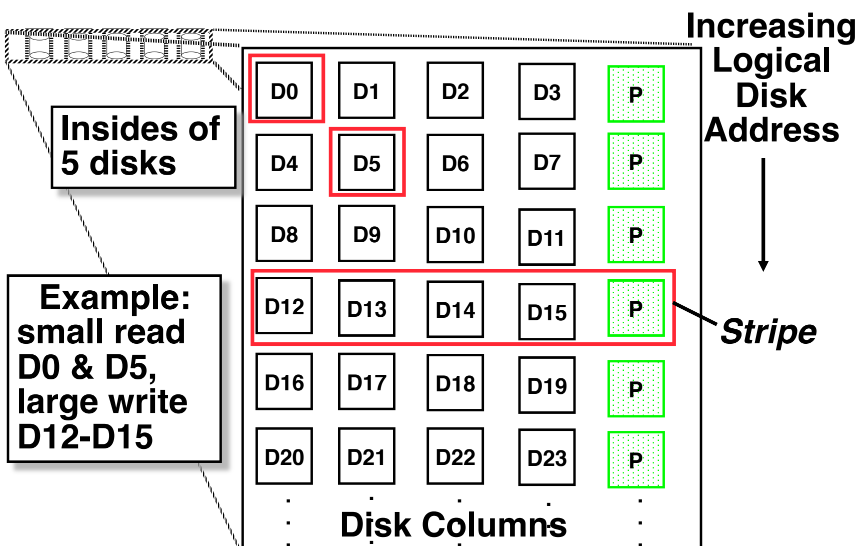
11000011

Bit-level sum modulo 2 (xor) of 1,2,4,5 recovers 3

Inspiration for RAID 4

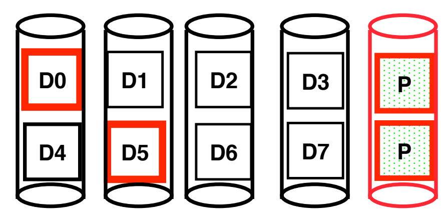
- RAID 3 relies on parity disk to discover errors on read – parity disk is a bottleneck
- But every sector (on each disk) has its own error detection field
- To catch errors on read, could just rely on error detection field on the disk
  - Allows independent reads to different disks simultaneously, parity disk is no longer a bottleneck on reads
  - Still need to update on writes
- Define:
  - Small read/write - read/write to one disk
    - Applications are dominated by these
  - Large read/write - read/write to more than one disk

Redundant Arrays of Inexpensive Disks RAID 4: High I/O Rate Parity

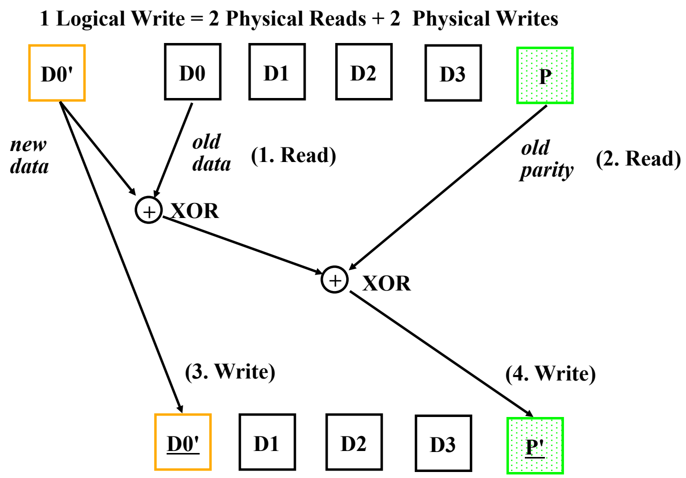


Inspiration for RAID 5

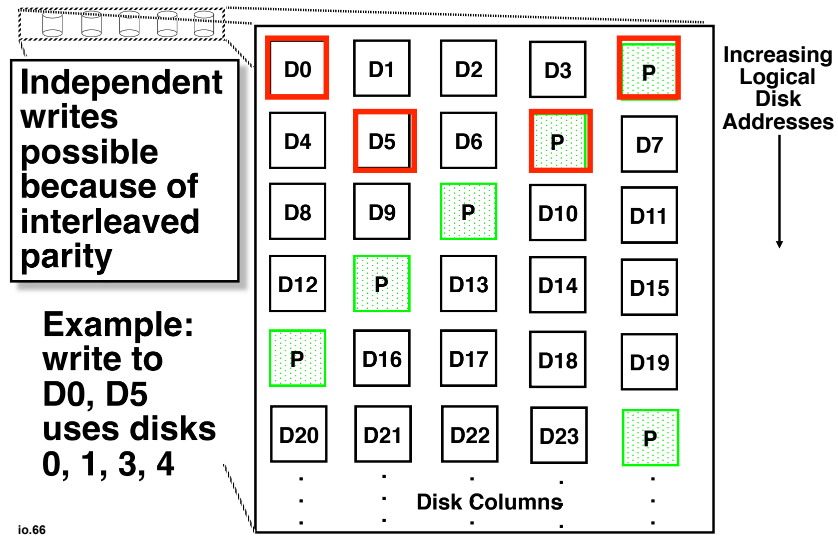
- RAID 4 works well for small reads
- Small writes:
  - Option 1: read other data disks, create new sum and write to Parity Disk (P)
  - Option 2: since P has old sum, compare old data to new data, add the difference to P
- Parity disk bottleneck: Write to D0, D5 both also write to P disk



Problems of Disk Arrays: Option 2 for Small Writes



Redundant Arrays of Inexpensive Disks RAID 5: High I/O Rate Interleaved Parity



RAID 6: Recovering from 2 failures

° **RAID 6 was always there but not so popular**
  - **Has recently become more popular. Why?**

° **Recover from more than 1 failure - Why?**
  - Operator might accidentally replaces the wrong disk during a failure
  - since disk bandwidth is growing more slowly than disk capacity, the MTTR a disk in a RAID system is increasing
    - Long time to copy data back to disk after replacement
    - increases the chances of a 2nd failure during repair since takes longer
  - reading much more data during reconstruction meant increasing the chance of an uncorrectable media failure, which would result in data loss
    - **Uncorrectable error - ECC doesn't catch. Insert another error**

RAID 6: Recovering from 2 failures

° Recovering from 2 failures
  - Network Appliance's (make NSF file servers primarily) *row-diagonal parity* or *RAID-DP*

° Like the standard RAID schemes, it uses redundant space based on parity calculation per stripe

° Since it is protecting against a double failure, it adds two check blocks per stripe of data.
  - 2 check disks - row and diagonal parity
  - 2 ways to calculate parity

° Row parity disk is just like in RAID 4
  - Even parity across the other n-2 data blocks in its stripe
  - So n-2 disks contain data and 2 do not for each parity stripe

° Each block of the diagonal parity disk contains the even parity of the blocks in the same diagonal
  - Each diagonal does not cover 1 disk, hence you only need n-1 diagonals to protect n disks

Example

- Assume disks 1 and 3 fail
- Can't recover using row parity because 2 data blocks are missing
- However, we can use diagonal parity 0 since it covers every disk except disk 1, thus we can recover some information on disk 3
- Recover in an iterative fashion, alternating between row and diagonal parity recovery