CS162
Operating Systems and Systems Programming
Lecture 17

Performance
Storage Devices, Queueing Theory

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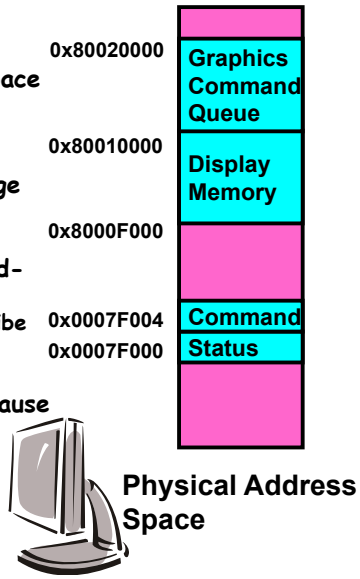
Recall: Memory-Mapped Display Controller

- Memory-Mapped:
  - Hardware maps control registers and display memory into physical address space
    - » Addresses set by hardware jumpers or programming at boot time
  - Simply writing to display memory (also called the "frame buffer") changes image on screen
    - » Addr: 0x8000F000—0x8000FFFF
  - Writing graphics description to command-queue area
    - » Say enter a set of triangles that describe some scene
    - » Addr: 0x80010000—0x8001FFFF
  - Writing to the command register may cause on-board graphics hardware to do something
    - » Say render the above scene
    - » Addr: 0x0007F004
- Can protect with address translation



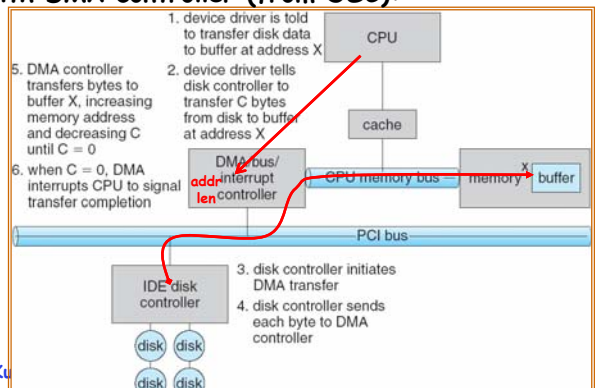
Goals for Today

- Finish discussion of device interfaces
- Discussion of performance
- Disks and SSDs
  - Hardware performance parameters
  - Queuing Theory

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne. Many slides generated from my lecture notes by Kubiatowicz.

Transferring Data To/From Controller

- Programmed I/O:
  - Each byte transferred via processor in/out or load/store
  - Pro: Simple hardware, easy to program
  - Con: Consumes processor cycles proportional to data size
- Direct Memory Access:
  - Give controller access to memory bus
  - Ask it to transfer data blocks to/from memory directly
- Sample interaction with DMA controller (from OSC):



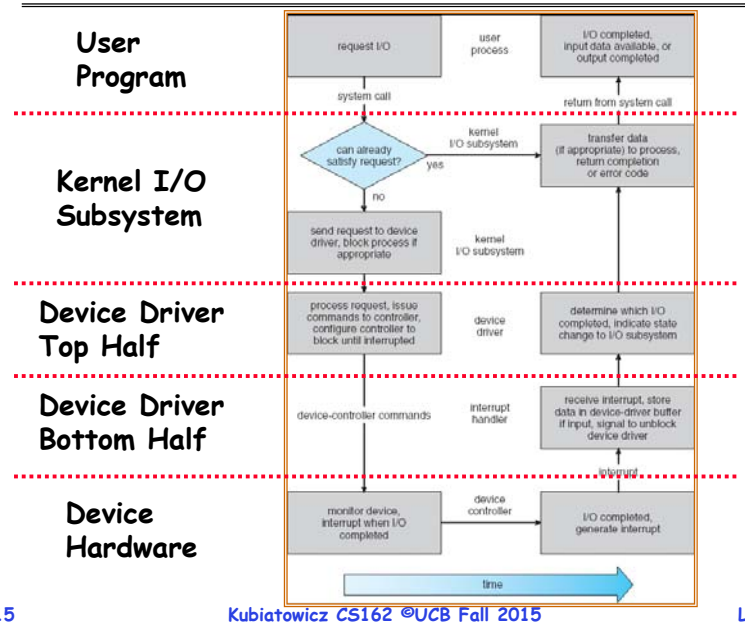
I/O Device Notifying the OS

- The OS needs to know when:
  - The I/O device has completed an operation
  - The I/O operation has encountered an error
- I/O Interrupt:
  - Device generates an interrupt whenever it needs service
  - Pro: handles unpredictable events well
  - Con: interrupts relatively high overhead
- Polling:
  - OS periodically checks a device-specific status register
    - » I/O device puts completion information in status register
  - Pro: low overhead
  - Con: may waste many cycles on polling if infrequent or unpredictable I/O operations
- Actual devices combine both polling and interrupts
  - For instance – High-bandwidth network adapter:
    - » Interrupt for first incoming packet
    - » Poll for following packets until hardware queues are empty

Device Drivers

- Device Driver: Device-specific code in the kernel that interacts directly with the device hardware
  - Supports a standard, internal interface
  - Same kernel I/O system can interact easily with different device drivers
  - Special device-specific configuration supported with the `ioctl()` system call
- Device Drivers typically divided into two pieces:
  - Top half: accessed in call path from system calls
    - » implements a set of standard, cross-device calls like `open()`, `close()`, `read()`, `write()`, `ioctl()`, `strategy()`
    - » This is the kernel's interface to the device driver
    - » Top half will *start* I/O to device, may put thread to sleep until finished
  - Bottom half: run as interrupt routine
    - » Gets input or transfers next block of output
    - » May wake sleeping threads if I/O now complete
- Linux: Swaps definition of "Top" and "Bottom"!

Life Cycle of An I/O Request

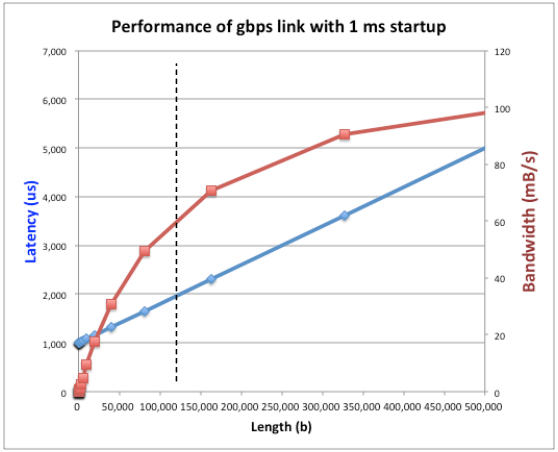


Basic Performance Concepts

- *Response Time* or *Latency*: Time to perform an operation (s)
- *Bandwidth* or *Throughput*: Rate at which operations are performed (op/s)
  - Files: MB/s, Networks: Mb/s, Arithmetic: GFLOP/s
- *Start up* or "Overhead": time to initiate an operation
- Most I/O operations are roughly linear
  - Latency (n) = Ovhd + n/Bandwidth
- Note on units and measurements:
  - "B" means "byte" while "b" means bit
  - Sizes usually given in bytes, bandwidths often in bits/s
  - Bandwidths in powers of 10 (Mb/s = 10^6 bits/s)
  - Sizes in powers of 2 (MB = 2^{20} bytes, technically MiB)

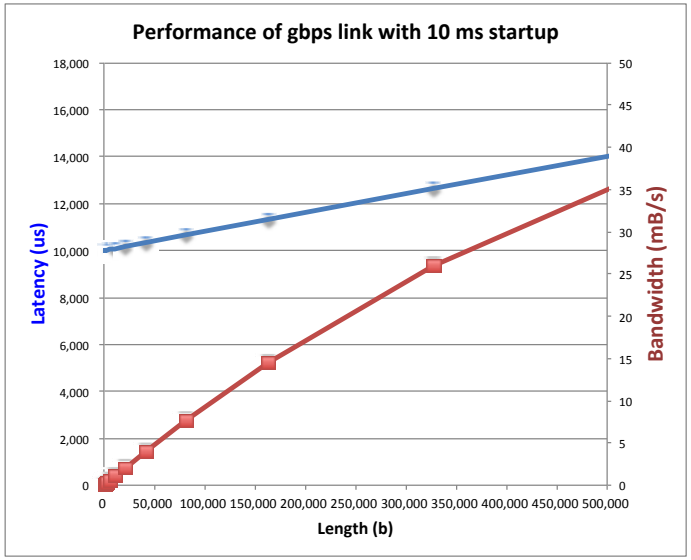
Example (fast network)

- Consider a gpbs link (125 MB/s)
  - With a startup cost S = 1 ms



- Theorem: half-power point occurs at n=S*B:
  - When transfer time = startup T(S*B) = S + S*B/B

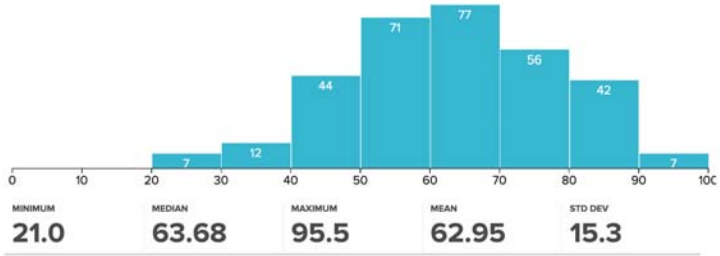
Example: at 10 ms startup (like Disk)



What determines peak BW for I/O ?

- Bus Speed
  - PCI-X: 1064 MB/s = 133 MHz x 64 bit (per lane)
  - ULTRA WIDE SCSI: 40 MB/s
  - Serial Attached SCSI & Serial ATA & IEEE 1394 (firewire) : 1.6 Gb/s full duplex (200 MB/s)
  - USB 1.5 – 12 Mb/s
  - USB 3.0 – 5 Gb/s
- Device Transfer Bandwidth
  - Rotational speed of disk
  - Write / Read rate of NAND flash
  - Signaling rate of network link
- Whatever is the bottleneck in the path

Administrivia



- Midterm I: Grading finished
  - Mean: 62.95, Std: 15.3
- Regrades on Midterm I:
  - You have 1 week to request a regrade
  - Be sure: If we receive a request, we may regrade whole exam (could lose points)
- Do your own work on Homeworks and Projects!
  - We have seen some incidences of cheating and will be calling people in. JUST SAY NO!

Recall: CS 162 Collaboration Policy

Explaining a concept to someone in another group

Discussing algorithms/testing strategies with other groups

Helping debug someone else's code (in another group)

Searching online for generic algorithms (e.g., hash table)

Sharing code or test cases with another group

Copying OR reading another group's code or test cases

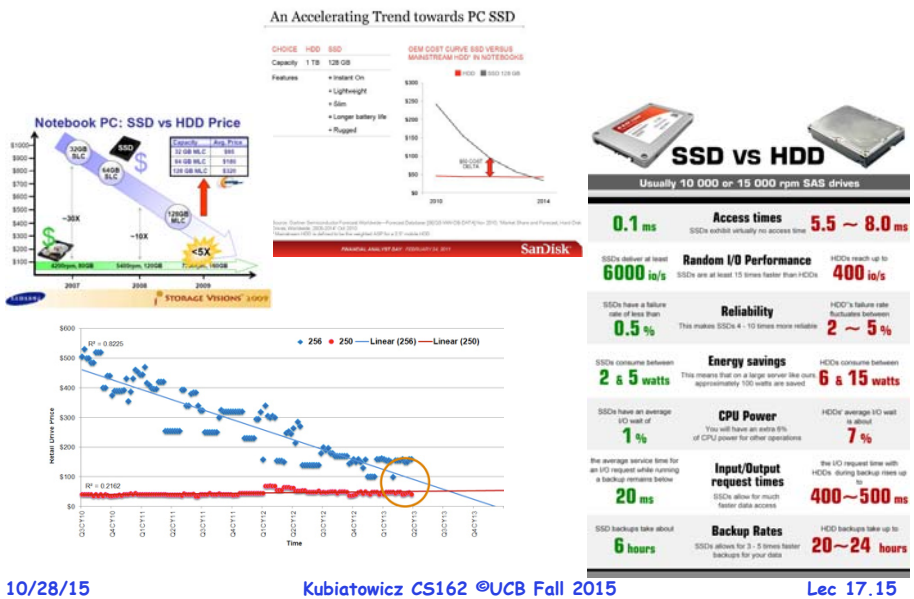
Copying OR reading online code or test cases from from prior years

We compare all project submissions against prior year submissions and online solutions and will take actions (described on the course overview page) against offenders

Storage Devices

- Magnetic disks
  - Storage that rarely becomes corrupted
  - Large capacity at low cost
  - Block level random access (except for SMR – later!)
  - Slow performance for random access
  - Better performance for streaming access
- Flash memory
  - Storage that rarely becomes corrupted
  - Capacity at intermediate cost (50x disk ???)
  - Block level random access
  - Good performance for reads; worse for random writes
  - Erasure requirement in large blocks
  - Wear patterns

Are we in an inflection point?



Hard Disk Drives (HDDs)

Western Digital Drive
http://www.storagereview.com/guide/

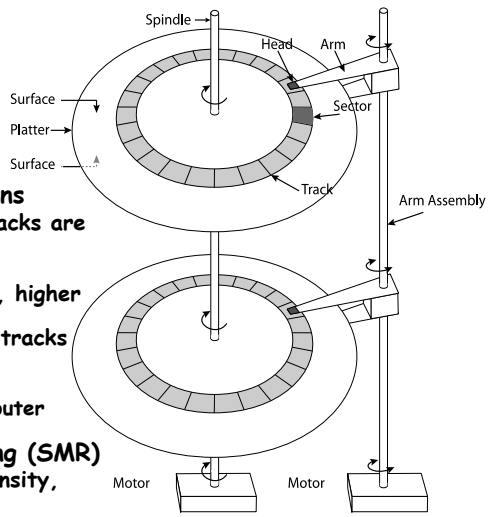
Read/Write Head Side View

IBM/Hitachi Microdrive

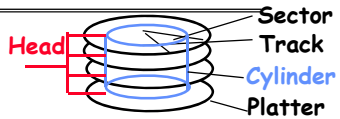
IBM Personal Computer/AT (1986)
30 MB hard disk - $500
30-40ms seek time
0.7-1 MB/s (est.)

The Amazing Magnetic Disk

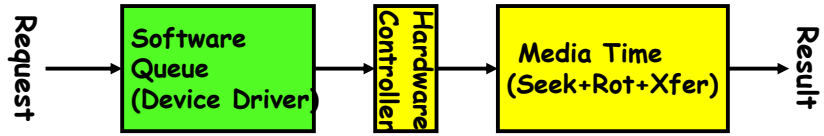
- Unit of Transfer: Sector
  - Ring of sectors form a track
  - Stack of tracks form a cylinder
  - Heads position on cylinders
- Disk Tracks ~ 1μm (micron) wide
  - Wavelength of light is ~ 0.5μm
  - Resolution of human eye: 50μm
  - 100K on a typical 2.5" disk
- Separated by unused guard regions
  - Reduces likelihood neighboring tracks are corrupted during writes
  - Track length varies across disk
  - Outside: More sectors per track, higher bandwidth
  - Disk is organized into regions of tracks with same # of sectors/track
  - Only outer half of radius is used
    - » Most of the disk area in the outer regions of the disk
- New: Shingled Magnetic Recording (SMR)
  - Overlapping tracks ⇒ greater density, restrictions on writing
  - Seagate (8TB), Hitachi (10TB)



Magnetic Disk Characteristic



- Cylinder: all the tracks under the head at a given point on all surfaces
- Read/write: three-stage process:
  - Seek time: position the head/arm over the proper track (into proper cylinder)
  - 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
- Disk Latency = Queuing Time + Controller time + Seek Time + Rotation Time + Xfer Time



- Highest Bandwidth:
  - Transfer large group of blocks sequentially from one track

Typical Numbers for Magnetic Disk

Parameter	Info / Range
Space/Density	Space: 8TB (Seagate), 10TB (Hitachi) in 3½ inch form factor! (Introduced in Fall of 2014) Areal Density: ≥ 1Terabit/square inch! (SMR, Helium, …)
Average seek time	Typically 5-10 milliseconds. Depending on reference locality, actual cost may be 25-33% of this number.
Average rotational latency	Most laptop/desktop disks rotate at 3600-7200 RPM (16-8 ms/rotation). Server disks up to 15,000 RPM. Average latency is halfway around disk yielding corresponding times of 8-4 milliseconds
Controller time	Depends on controller hardware
Transfer time	Typically 50 to 100 MB/s. Depends on: • Transfer size (usually a sector): 512B – 1KB per sector • Rotation speed: 3600 RPM to 15000 RPM • Recording density: bits per inch on a track • Diameter: ranges from 1 in to 5.25 in
Cost	Drops by a factor of two every 1.5 years (or even faster). $0.03-0.07/GB in 2013

Disk Performance Example

- Assumptions:
  - Ignoring queuing and controller times for now
  - Avg seek time of 5ms,
  - 7200RPM ⇒ Time for rotation: 60000(ms/M)/7200(rev/M) ~= 8ms/rev
  - Transfer rate of 40MByte/s, sector size of 1 Kbyte ⇒ 1024 bytes/4×10^7 (bytes/s) = 256 × 10^{-7} sec ≅ .026 ms
- Read sector from random place on disk:
  - Seek (5ms) + Rot. Delay (4ms) + Transfer (0.026ms)
  - *Approx* 9ms to fetch/put data: 100 KByte/sec
- Read sector from random place in same cylinder:
  - Rot. Delay (4ms) + Transfer (0.026ms)
  - *Approx* 4ms to fetch/put data: 256 KByte/sec
- Read next sector on same track:
  - Transfer (0.026ms): 40 MByte/sec
- Key to using disk effectively (especially for file systems) is to *minimize seek and rotational delays*

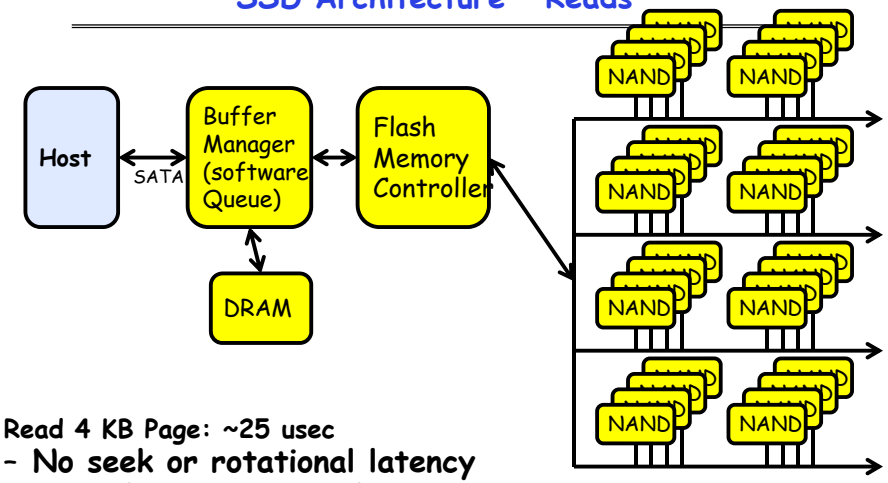
Intelligence in the controller

- Sectors contain sophisticated error correcting codes
  - Disk head magnet has a field wider than track
  - Hide corruptions due to neighboring track writes
- Sector sparing
  - Remap bad sectors transparently to spare sectors on the same surface
- Slip sparing
  - Remap all sectors (when there is a bad sector) to preserve sequential behavior
- Track skewing
  - Sector numbers offset from one track to the next, to allow for disk head movement for sequential ops
- …

Solid State Disks (SSDs)

- 1995 – Replace rotating magnetic media with non-volatile memory (battery backed DRAM)
- 2009 – Use NAND Multi-Level Cell (2 or 3-bit/cell) flash memory
  - Sector (4 KB page) addressable, but stores 4-64 "pages" per memory block
  - Trapped electrons distinguish between 1 and 0
- No moving parts (no rotate/seek motors)
  - Eliminates seek and rotational delay (0.1-0.2ms access time)
  - Very low power and lightweight
  - Limited "write cycles"
- Rapid advance in capacity and cost ever since

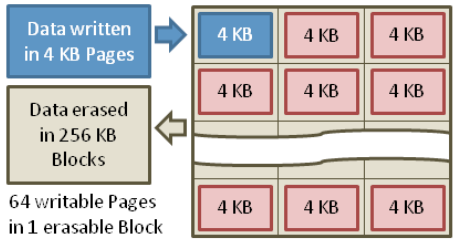
SSD Architecture – Reads



Read 4 KB Page: ~25 usec
- No seek or rotational latency
- Transfer time: transfer a 4KB page
  - » SATA: 300-600MB/s => ~4 x10^3 b / 400 x 10^6 bps => 10 us
- Latency = Queuing Time + Controller time + Xfer Time
- Highest Bandwidth: Sequential OR Random reads

SSD Architecture – Writes (I)

- Writing data is complex! (~200µs – 1.7ms)
  - Can only write empty pages in a block
  - Erasing a block takes ~1.5ms
  - Controller maintains pool of empty blocks by coalescing used pages (read, erase, write), also reserves some % of capacity
- Rule of thumb: writes 10x reads, erasure 10x writes



Typical NAND Flash Pages and Blocks

https://en.wikipedia.org/wiki/Solid-state_drive

Amusing calculation: is a full Kindle heavier than an empty one?

- Actually, "Yes", but not by much
- Flash works by trapping electrons:
  - So, erased state lower energy than written state
- Assuming that:
  - Kindle has 4GB flash
  - ½ of all bits in full Kindle are in high-energy state
  - High-energy state about 10^{-15} joules higher
  - Then: Full Kindle is 1 attogram (10^{-18}gram) heavier (Using $E = mc^2$)
- Of course, this is less than most sensitive scale (which can measure 10^{-9}grams)
- Of course, this weight difference overwhelmed by battery discharge, weight from getting warm, ….
- According to John Kubiatowicz, New York Times, Oct 24, 2011

Storage Performance & Price (jan 13)

	Bandwidth (Sequential R/W)	Cost/GB	Size
HDD[2]	50-100 MB/s	$0.03-0.07/GB	2-4 TB
SSD[1,2]	200-550 MB/s (SATA) 6 GB/s (read PCI) 4.4 GB/s (write PCI)	$0.87-1.13/GB	200GB-1TB
DRAM[2]	10-16 GB/s	$4-14*/GB *SK Hynix 9/4/13 fire	64GB-256GB

[1] http://www.fastestssd.com/featured/ssd-rankings-the-fastest-solid-state-drives/

[2] http://www.extremetech.com/computing/164677-storage-pricewatch-hard-drive-and-ssd-prices-drop-making-for-a-good-time-to-buy

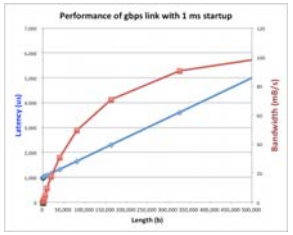
BW: SSD up to x10 than HDD, DRAM > x10 than SSD
Price: HDD x20 less than SSD, SSD x5 less than DRAM

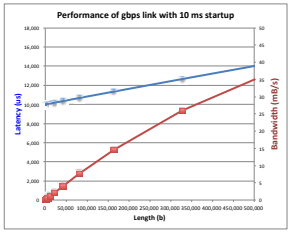
SSD Summary

- Pros (vs. hard disk drives):
  - Low latency, high throughput (eliminate seek/rotational delay)
  - No moving parts:
    - » Very light weight, low power, silent, very shock insensitive
  - Read at memory speeds (limited by controller and I/O bus)
- Cons
  - Small storage (0.1-0.5x disk), expensive (20x disk ???)
    - » Hybrid alternative: combine small SSD with large HDD
  - Asymmetric block write performance: read pg/erase/write pg
    - » Controller garbage collection (GC) algorithms have major effect on performance
  - Limited drive lifetime
    - » 1-10K writes/page for MLC NAND
    - » Avg failure rate is 6 years, life expectancy is 9–11 years
- These are changing rapidly

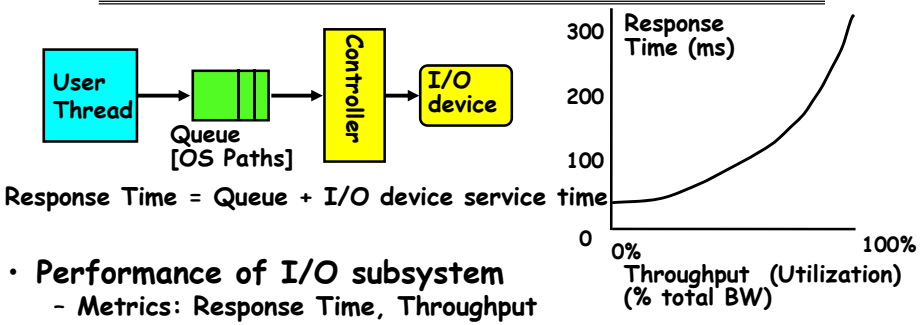
What goes into startup cost for I/O?

- Syscall overhead
- Operating system processing
- Controller Overhead
- Device Startup
  - Mechanical latency for a disk
  - Media Access + Speed of light + Routing for network
- Queuing (next topic)



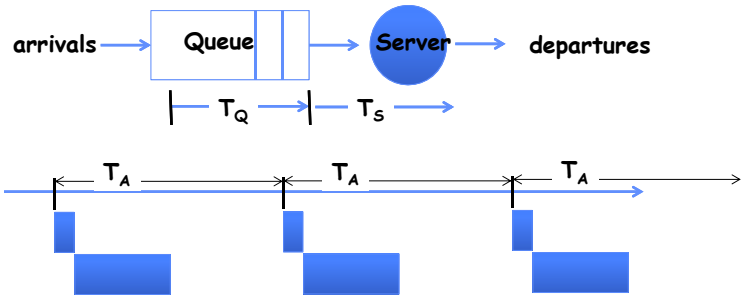


I/O Performance



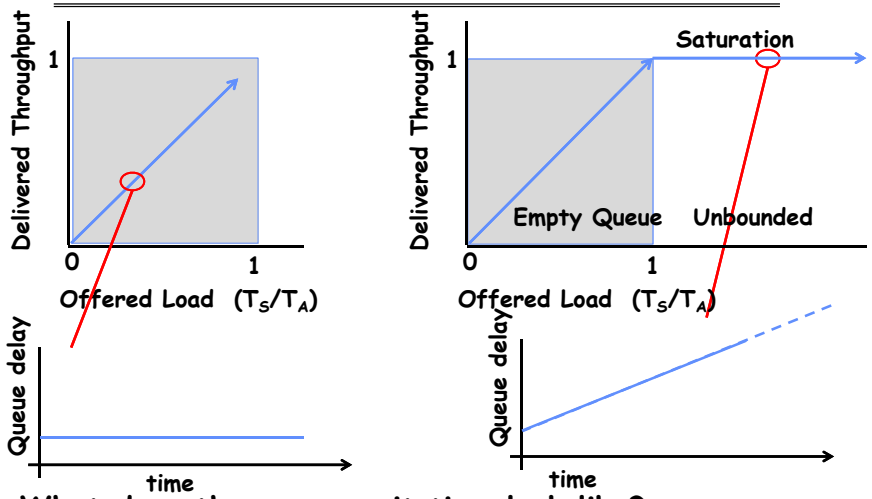
- Performance of I/O subsystem
  - Metrics: Response Time, Throughput
  - Effective BW per op = transfer size / response time
    - » EffBW(n) = n / (S + n/B) = B / (1 + SB/n)
  - Contributing factors to latency:
    - » Software paths (can be loosely modeled by a queue)
    - » Hardware controller
    - » I/O device service time
- Queuing behavior:
  - Can lead to big increases of latency as utilization increases
  - Solutions?

A Simple Deterministic World



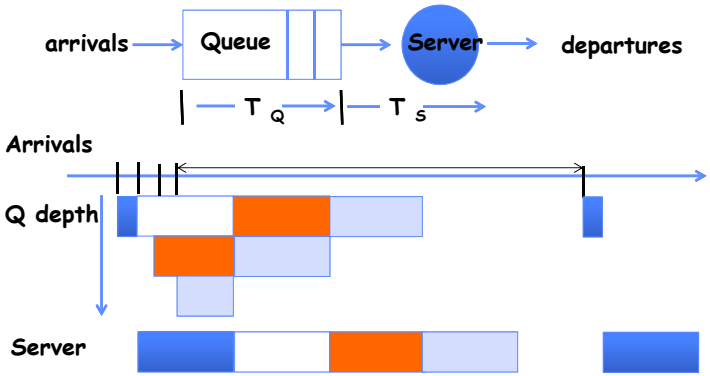
- Assume requests arrive at regular intervals, take a fixed time to process, with plenty of time between …
- Service rate ($\mu = 1/T_S$) - operations per sec
- Arrival rate: ($\lambda = 1/T_A$) - requests per second
- Utilization: $U = \lambda/\mu$, where $\lambda < \mu$
- Average rate is the complete story

A Ideal Linear World



- What does the queue wait time look like?
  - Grows unbounded at a rate ~ (T_s/T_A) till request rate subsides

A Bursty World

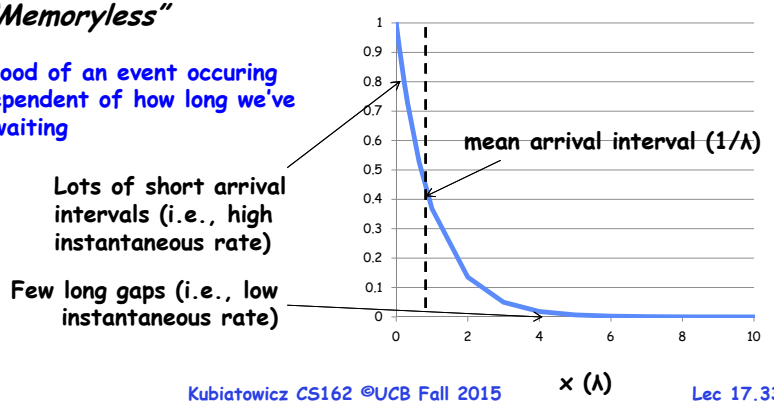


- Requests arrive in a burst, must queue up till served
- Same average arrival time, but almost all of the requests experience large queue delays
- Even though average utilization is low

So how do we model the burstiness of arrival?

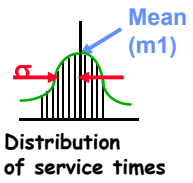
- Elegant mathematical framework if you start with *exponential distribution*
  - Probability density function of a continuous random variable with a mean of 1/λ
  - $f(x) = \lambda e^{-\lambda x}$
  - *"Memoryless"*

Likelihood of an event occuring is independent of how long we've been waiting

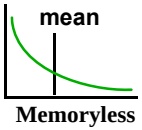


Background: General Use of random distributions

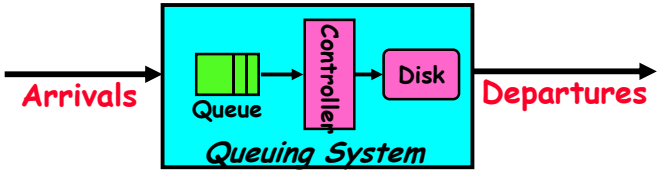
- Server spends variable time with customers
  - Mean (Average) m1 = $\Sigma p(T) \times T$
  - Variance $\sigma^2 = \Sigma p(T) \times (T-m1)^2 = \Sigma p(T) \times T^2 - m1^2$
  - Squared coefficient of variance: $C = \sigma^2/m1^2$
    Aggregate description of the distribution.



- Important values of C:
  - No variance or deterministic ⇒ C=0
  - "memoryless" or exponential ⇒ C=1
    - » Past tells nothing about future
    - » Many complex systems (or aggregates) well described as memoryless
  - Disk response times C ≈ 1.5 (majority seeks < avg)



Introduction to Queuing Theory



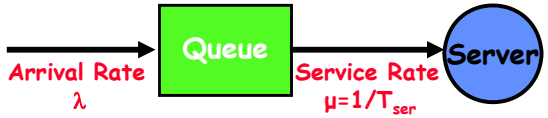
- What about queuing time??
  - Let's apply some queuing theory
  - Queuing Theory applies to long term, steady state behavior ⇒ Arrival rate = Departure rate
- Arrivals characterized by some probabilistic distribution
- Departures characterized by some probabilistic distribution

Little's Law

- In any *stable* system
  - Average arrival rate = Average departure rate
- the average number of tasks in the system (N) is equal to the throughput (B) times the response time (L)
- N (ops) = B (ops/s) x L (s)
- Regardless of structure, bursts of requests, variation in service
  - instantaneous variations, but it washes out in the average
  - Overall requests match departures

A Little Queuing Theory: Some Results

- Assumptions:
  - System in equilibrium; No limit to the queue
  - Time between successive arrivals is random and memoryless



- Parameters that describe our system:
  - λ: mean number of arriving customers/second
  - T_{ser}: mean time to service a customer ("m1")
  - C: squared coefficient of variance = $\sigma^2/m1^2$
  - μ: service rate = $1/T_{ser}$
  - u: server utilization ($0 \le u \le 1$): $u = \lambda/\mu = \lambda \times T_{ser}$
- Parameters we wish to compute:
  - T_q: Time spent in queue
  - L_q: Length of queue = $\lambda \times T_q$ (by Little's law)
- Results:
  - Memoryless service distribution (C = 1):
    - » Called M/M/1 queue: $T_q = T_{ser} \times u/(1 - u)$
  - General service distribution (no restrictions), 1 server:
    - » Called M/G/1 queue: $T_q = T_{ser} \times \frac{1}{2}(1+C) \times u/(1 - u)$)

A Little Queuing Theory: An Example

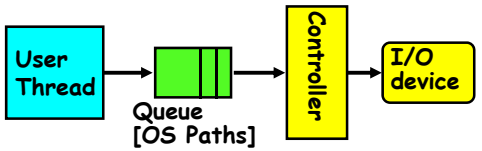
- Example Usage Statistics:
  - User requests 10 x 8KB disk I/Os per second
  - Requests & service exponentially distributed (C=1.0)
  - Avg. service = 20 ms (From controller+seek+rot+trans)
- Questions:
  - How utilized is the disk?
    - » Ans: server utilization, $u = \lambda T_{ser}$
  - What is the average time spent in the queue?
    - » Ans: T_q
  - What is the number of requests in the queue?
    - » Ans: L_q
  - What is the avg response time for disk request?
    - » Ans: $T_{sys} = T_q + T_{ser}$
- Computation:

λ (avg # arriving customers/s) = 10/s
T_{ser} (avg time to service customer) = 20 ms (0.02s)
u (server utilization) = $\lambda \times T_{ser}$ = 10/s x .02s = 0.2
T_q (avg time/customer in queue) = $T_{ser} \times u/(1 - u)$
= 20 x 0.2/(1-0.2) = 20 x 0.25 = 5 ms (0 .005s)
L_q (avg length of queue) = $\lambda \times T_q$=10/s x .005s = 0.05
T_{sys} (avg time/customer in system) =$T_q + T_{ser}$= 25 ms

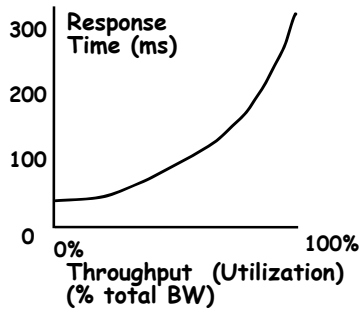
Queuing Theory Resources

- Handouts page contains Queueing Theory Resources:
  - Scanned pages from Patterson and Hennesey book that gives further discussion and simple proof for general eq.
  - A complete website full of resources
- Midterms with queueing theory questions:
  - Midterm IIs from previous years that I've taught
- Assume that Queueing theory is fair game for Midterm II and/or the final!

Optimize I/O Performance



Response Time =
Queue + I/O device service time



- Howto improve performance?
  - Make everything faster ☺
  - More Decoupled (Parallelism) systems
    - » multiple independent buses or controllers
  - Optimize the bottleneck to increase service rate
    - » Use the queue to optimize the service
  - Do other useful work while waiting
- Queues absorb bursts and smooth the flow
- Admissions control (finite queues)
  - Limits delays, but may introduce unfairness and livelock

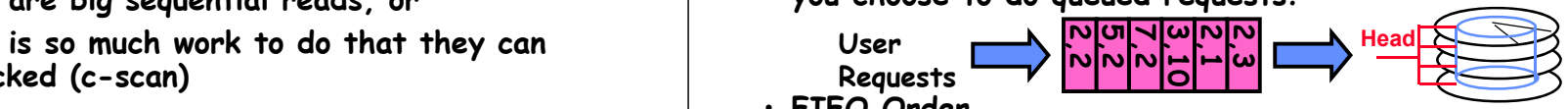
When is the disk performance highest

- When there are big sequential reads, or
- When there is so much work to do that they can be piggy backed (c-scan)

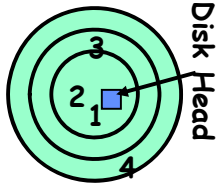
- OK, to be inefficient when things are mostly idle
- Bursts are both a threat and an opportunity
- <your idea for optimization goes here>
  - Waste space for speed?

Disk Scheduling

- Disk can do only one request at a time; What order do you choose to do queued requests?



- FIFO Order
  - Fair among requesters, but order of arrival may be to random spots on the disk ⇒ Very long seeks
- SSTF: Shortest seek time first
  - Pick the request that's closest on the disk
  - Although called SSTF, today must include rotational delay in calculation, since rotation can be as long as seek
  - Con: SSTF good at reducing seeks, but may lead to starvation

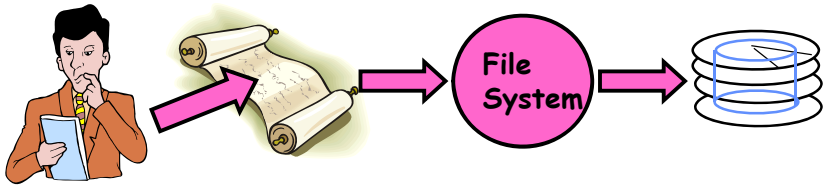


- SCAN: Implements an Elevator Algorithm: take the closest request in the direction of travel
  - No starvation, but retains flavor of SSTF
- C-SCAN: Circular-Scan: only goes in one direction
  - Skips any requests on the way back
  - Fairer than SCAN, not biased towards pages in middle

Building a File System

- File System: Layer of OS that transforms block interface of disks (or other block devices) into Files, Directories, etc.
- File System Components
  - Disk Management: collecting disk blocks into files
  - Naming: Interface to find files by name, not by blocks
  - Protection: Layers to keep data secure
  - Reliability/Durability: Keeping of files durable despite crashes, media failures, attacks, etc
- User vs. System View of a File
  - User's view:
    - » Durable Data Structures
  - System's view (system call interface):
    - » Collection of Bytes (UNIX)
    - » Doesn't matter to system what kind of data structures you want to store on disk!
  - System's view (inside OS):
    - » Collection of blocks (a block is a logical transfer unit, while a sector is the physical transfer unit)
    - » Block size ≥ sector size; in UNIX, block size is 4KB

Translating from User to System View



- What happens if user says: give me bytes 2—12?
  - Fetch block corresponding to those bytes
  - Return just the correct portion of the block
- What about: write bytes 2—12?
  - Fetch block
  - Modify portion
  - Write out Block
- Everything inside File System is in whole size blocks
  - For example, `getc()`, `putc()` ⇒ buffers something like 4096 bytes, even if interface is one byte at a time
- From now on, file is a collection of blocks

Disk Management Policies

- Basic entities on a disk:
  - File: user-visible group of blocks arranged sequentially in logical space
  - Directory: user-visible index mapping names to files (next lecture)
- Access disk as linear array of sectors. Two Options:
  - Identify sectors as vectors [cylinder, surface, sector]. Sort in cylinder-major order. Not used much anymore.
  - Logical Block Addressing (LBA). Every sector has integer address from zero up to max number of sectors.
  - Controller translates from address ⇒ physical position
    - » First case: OS/BIOS must deal with bad sectors
    - » Second case: hardware shields OS from structure of disk
- Need way to track free disk blocks
  - Link free blocks together ⇒ too slow today
  - Use bitmap to represent free space on disk
- Need way to structure files: File Header
  - Track which blocks belong at which offsets within the logical file structure
  - Optimize placement of files' disk blocks to match access and usage patterns

Summary

- Devices have complex protocols for interaction and performance characteristics
  - Response time (Latency) = Queue + Overhead + Transfer
    - » Effective BW = BW * T/(S+T)
  - HDD: controller + seek + rotation + transfer
  - SDD: controller + transfer (erasure & wear)
- Bursts & High Utilization introduce queuing delays
- Systems (e.g., file system) designed to optimize performance and reliability
  - Relative to performance characteristics of underlying device
- Disk Performance:
  - Queuing time + Controller + Seek + Rotational + Transfer
  - Rotational latency: on average ½ rotation
  - Transfer time: spec of disk depends on rotation speed and bit storage density
- Queuing Latency:
  - M/M/1 and M/G/1 queues: simplest to analyze
  - As utilization approaches 100%, latency → ∞

$$T_q = T_{ser} \times \tfrac{1}{2}(1+C) \times u/(1-u))$$