CS162
Operating Systems and Systems Programming
Lecture 17

Performance
Storage Devices, Queueing Theory

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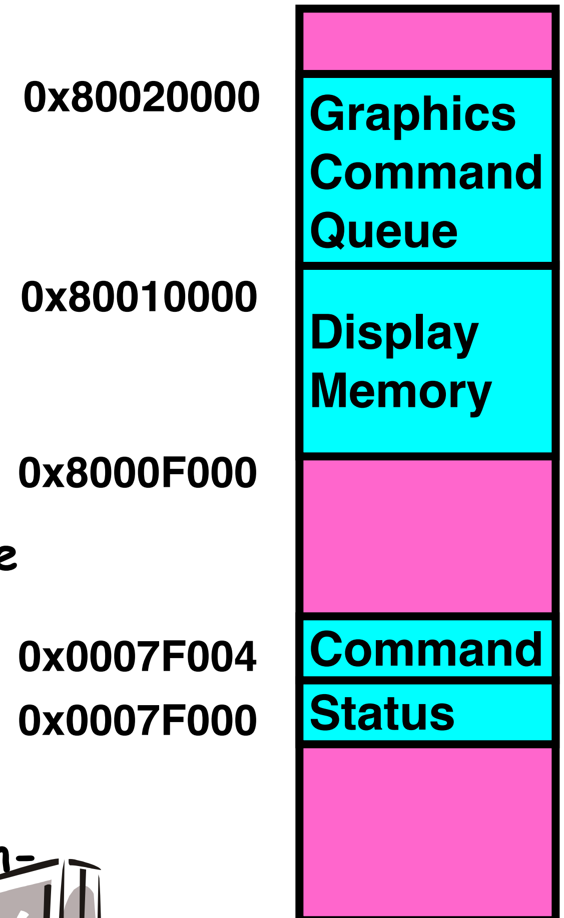
http://cs162.eecs.Berkeley.edu

Acknowledgments: Lecture slides are from the Operating Systems course taught by John Kubiatowicz at Berkeley, with few minor updates/changes. *When slides are obtained from other sources, a a reference will be noted on the bottom of that slide, in which case a full list of references is provided on the last slide.*

Recall: Memory-Mapped Display Controller

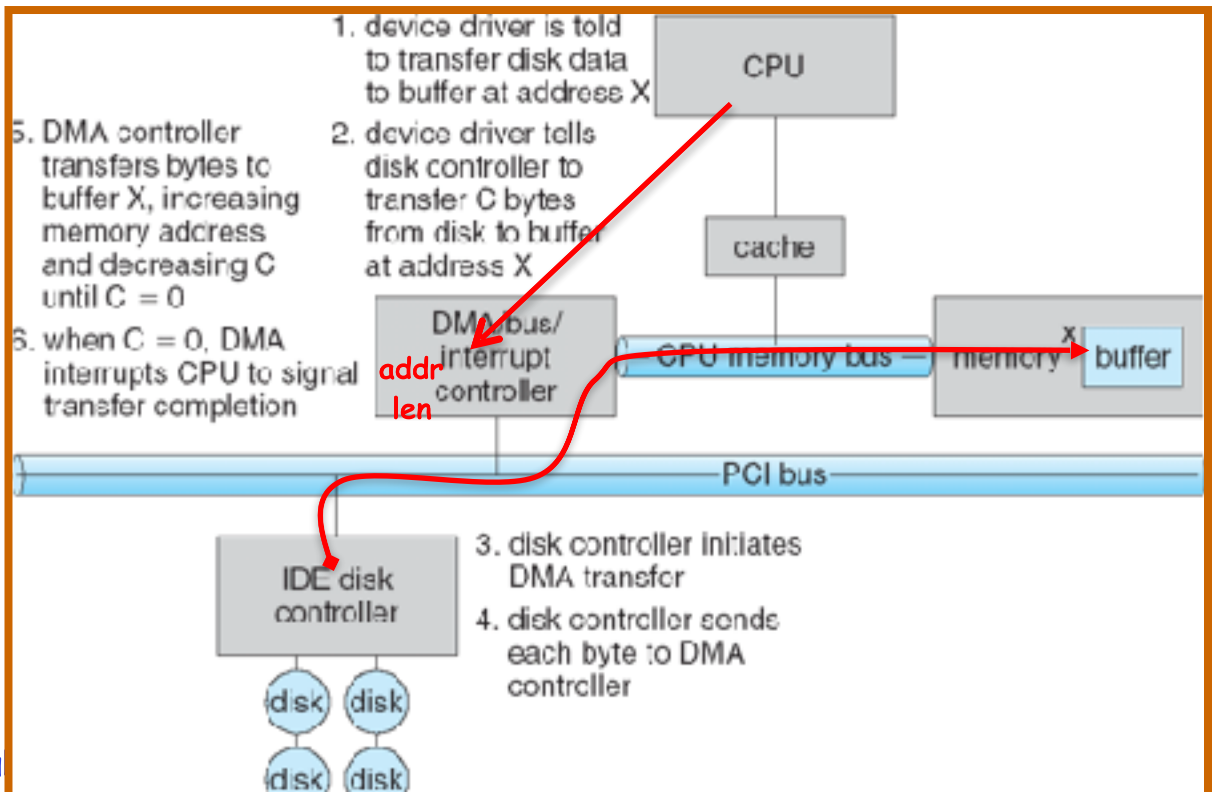
- Memory-Mapped:
  - Hardware maps control registers and display memory into physical address space
    - » Addresses set by hardware jumpers or programming at boot time
  - Simply writing to display memory (also called the "frame buffer") changes image on screen
    - » Addr: 0x8000F000—0x8000FFFF
  - 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



Physical Address Space

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):



Goals for Today

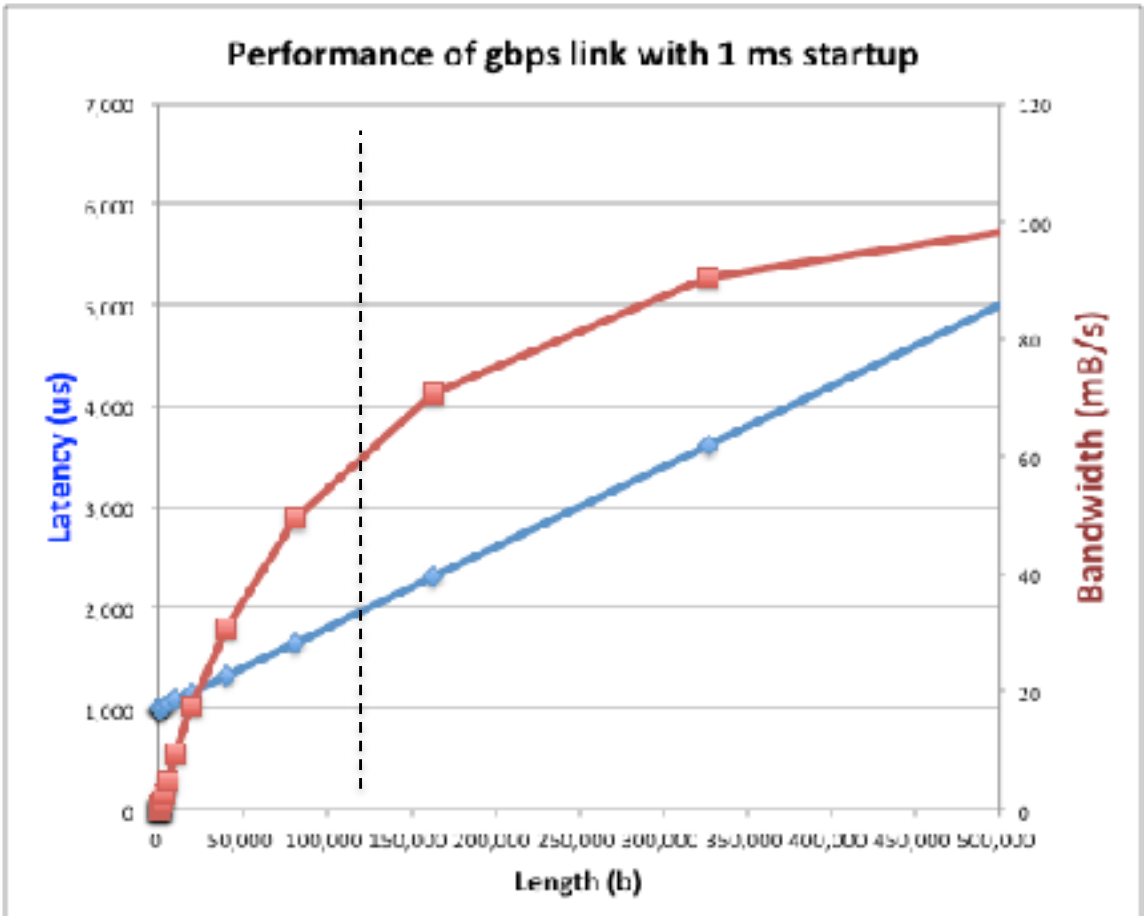
- Finish discussion of device interfaces
- Discussion of performance
- Disks and SSDs
  – Hardware performance parameters
  – Queuing Theory

Basic Performance Concepts

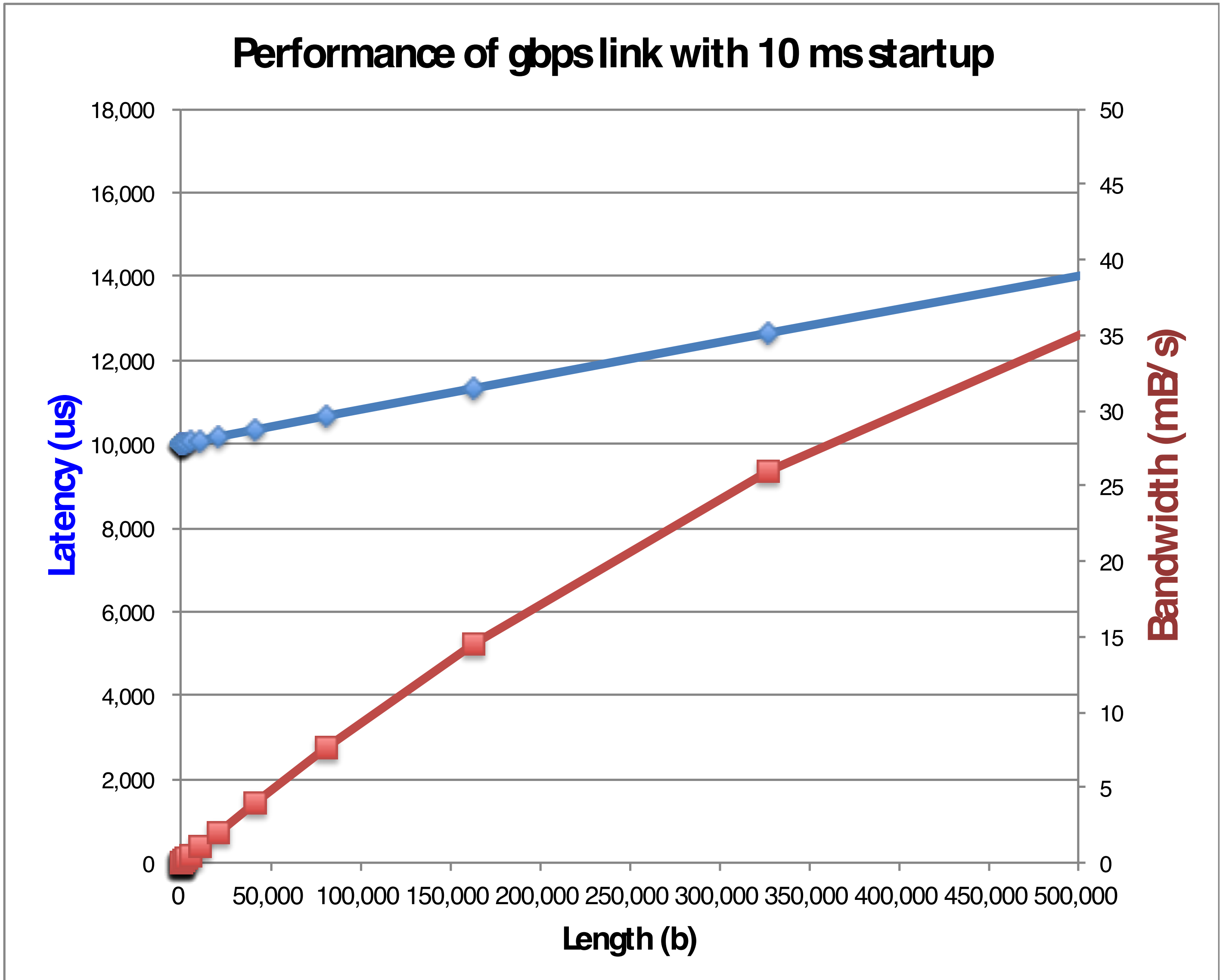
- **Response Time or Latency:** Time to perform an operation (s)
- **Bandwidth or Throughput:** Rate at which operations are performed (op/s)
  - Files: mB/s, Networks: mb/s, Arithmetic: GFLOP/s
- **Start up or "Overhead":** time to initiate an operation
- Most I/O operations are roughly linear
  - Latency (n) = Ovhd + n/Bandwidth

Example (fast network)

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



Example: at 10 ms startup (like Disk)



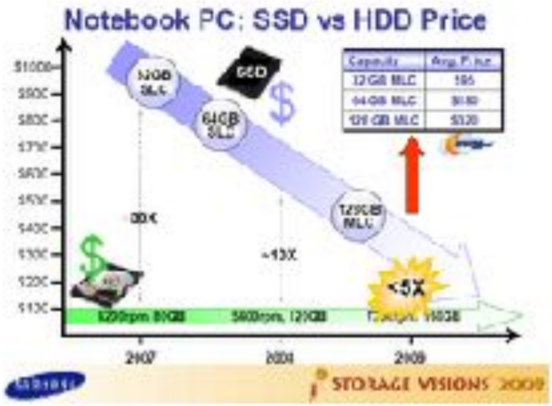
What determines peak BW for I/O ?

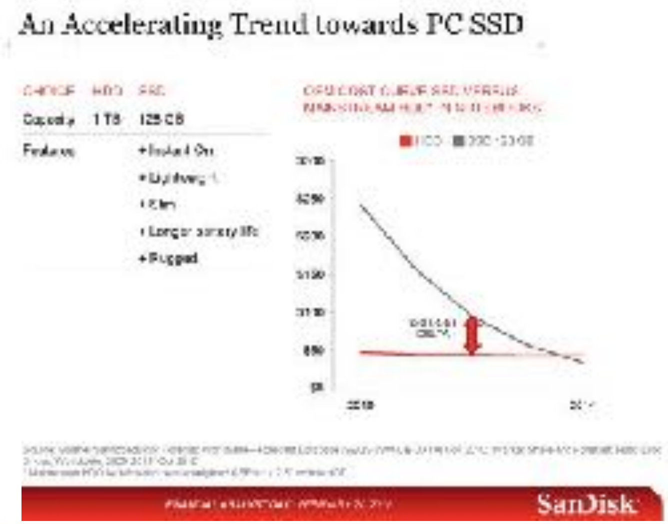
- Bus Speed
  - PCI-X: 1064 MB/s = 133 MHz x 64 bit (per lane)
  - ULTRA WIDE SCSI: 40 MB/s
  - Serial Attached SCSI & Serial ATA & IEEE 1394 (firewire) : 1.6 Gbps full duplex (200 MB/s)
  - USB 1.5 – 12 MB/s
- Device Transfer Bandwidth
  - Rotational speed of disk
  - Write / Read rate of NAND flash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

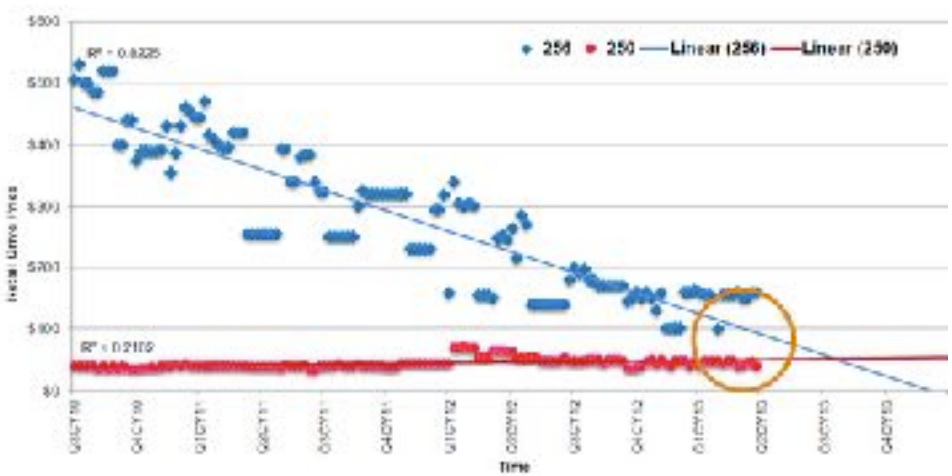
Storage Devices

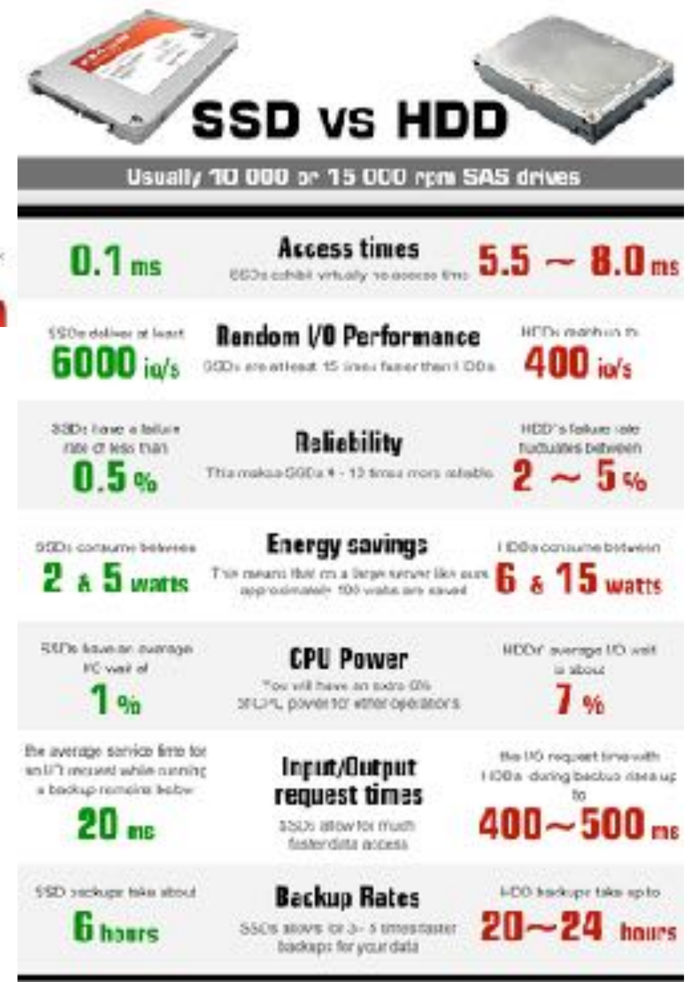
- Magnetic disks
  - Storage that rarely becomes corrupted
  - Large capacity at low cost
  - Block level random access (except for SMR – later!)
  - Slow performance for random access
  - Better performance for streaming access
- Flash memory
  - Storage that rarely becomes corrupted
  - Capacity at 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?

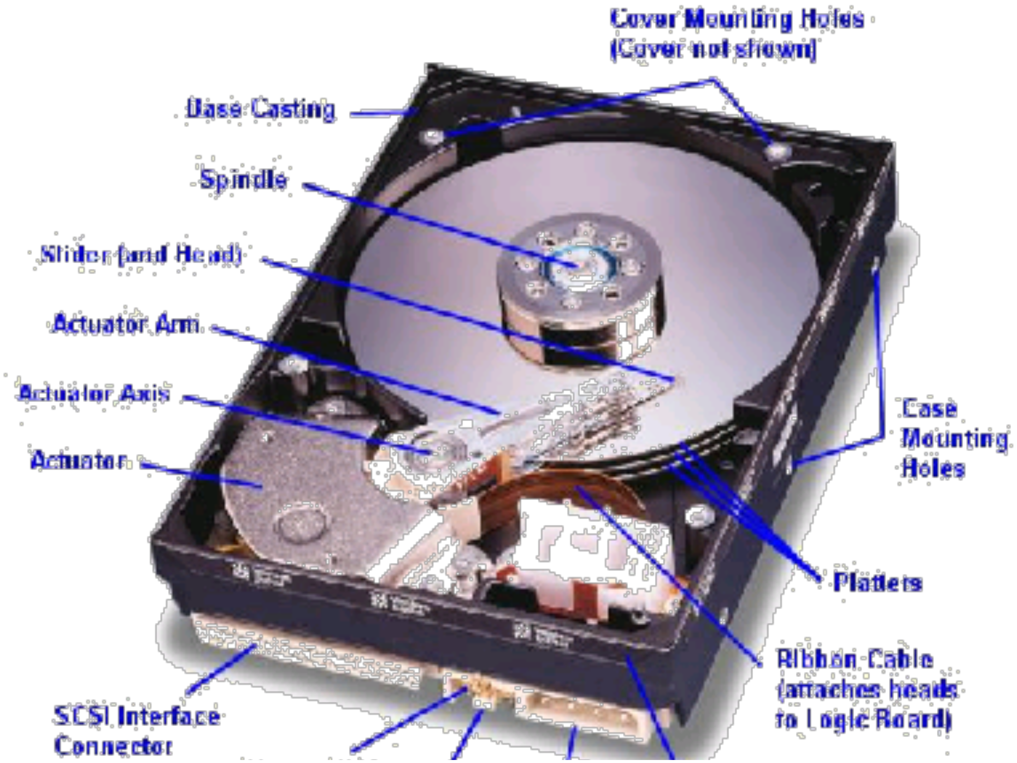




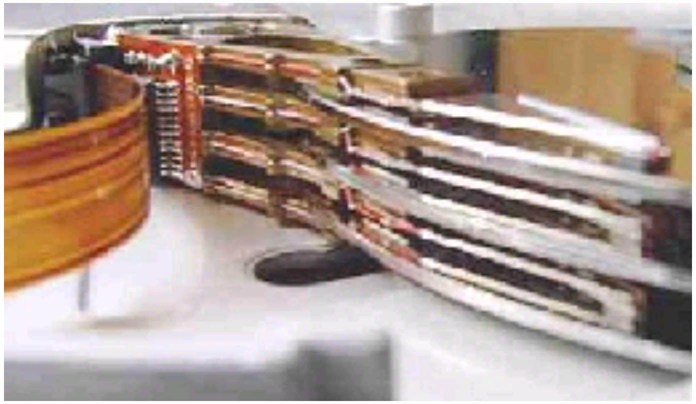




Hard Disk Drives (HDDs)



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



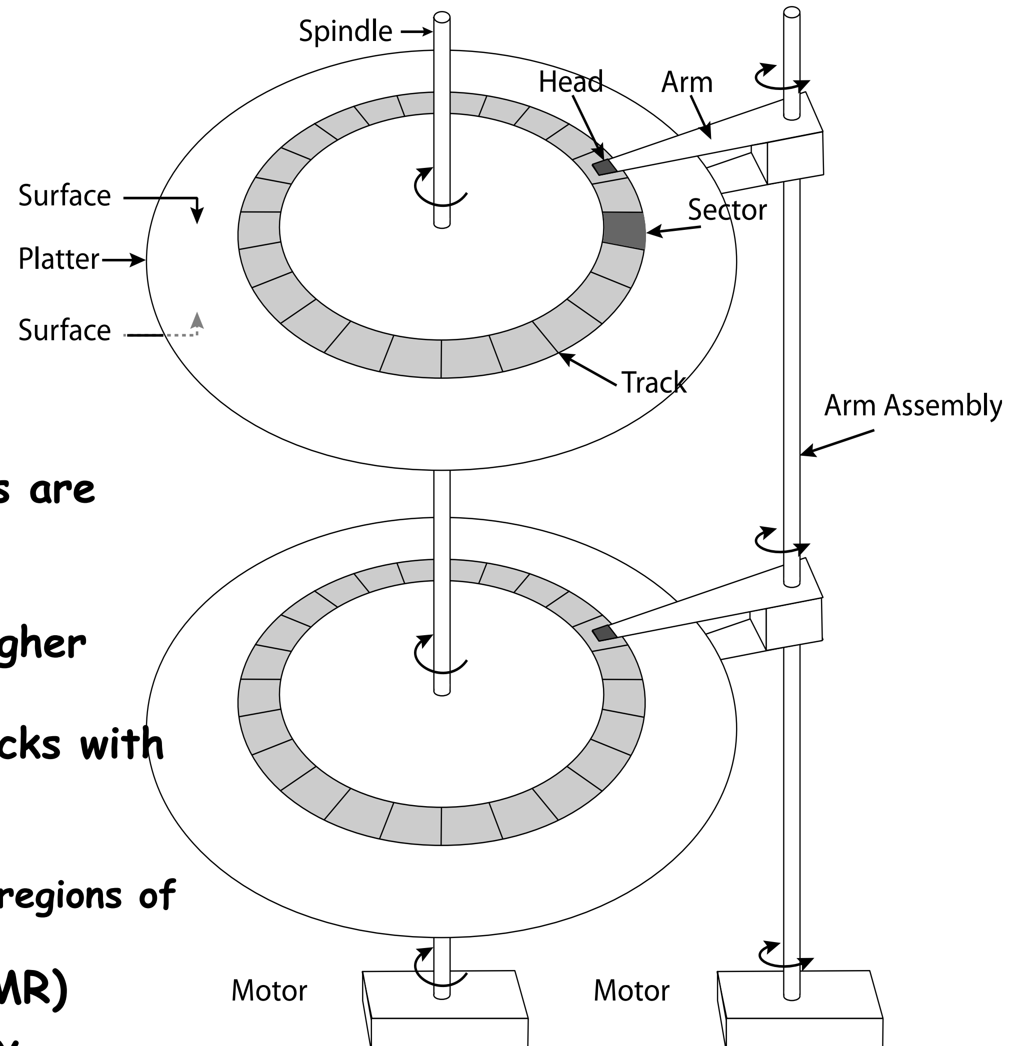
Read/Write Head Side View

IBM/Hitachi Microdrive

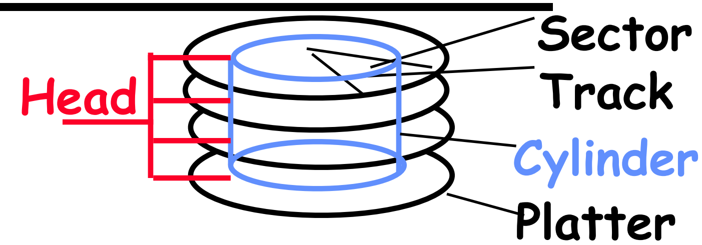
IBM Personal Computer/AT (1986)
- 30 MB hard disk - $500
- 30-40ms seek time
- 0.7-1 MB/s (est.)

The Amazing Magnetic Disk

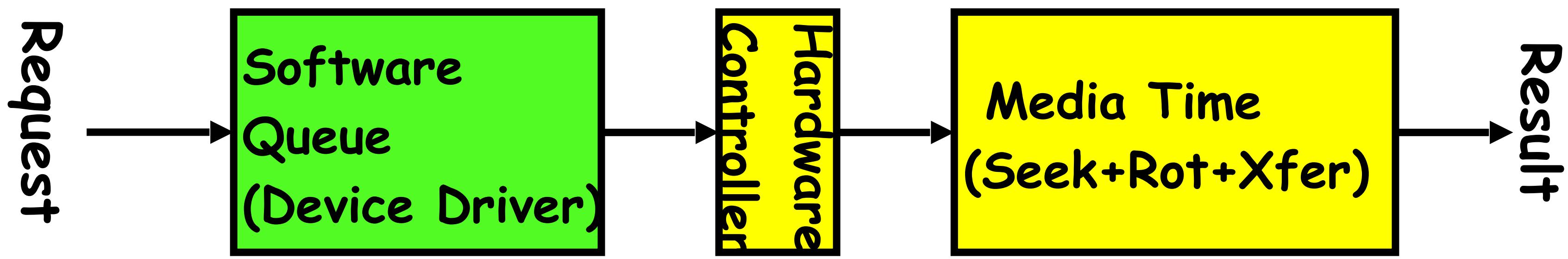
- Unit of Transfer: Sector
  - Ring of sectors form a track
  - Stack of tracks form a cylinder
  - Heads position on cylinders
- Disk Tracks ~ 1μm (micron) wide
  - Wavelength of light is ~ 0.5μm
  - Resolution of human eye: 50μm
  - 100K on a typical 2.5" disk
- Separated by unused guard regions
  - 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

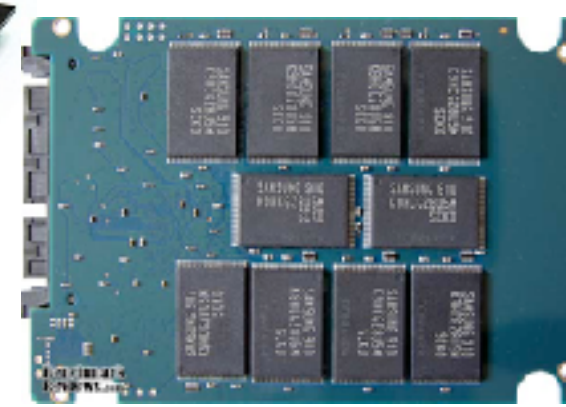
Disk Performance Example

- **Assumptions:**
  - Ignoring queuing and controller times for now
  - Avg seek time of 5ms,
  - 7200RPM ⇒ Time for rotation: 60000(ms/M)/7200(rev/M) ~= 8ms
  - Transfer rate of 4MByte/s, sector size of 1 Kbyte ⇒ 1024 bytes/4×10^6 (bytes/s) = 256 × 10^{-6} sec ≅ .26 ms
- **Read sector from random place on disk:**
  - Seek (5ms) + Rot. Delay (4ms) + Transfer (0.26ms)
  - Approx 10ms to fetch/put data: 100 KByte/sec
- **Read sector from random place in same cylinder:**
  - Rot. Delay (4ms) + Transfer (0.26ms)
  - Approx 5ms to fetch/put data: 200 KByte/sec
- **Read next sector on same track:**
  - Transfer (0.26ms): 4 MByte/sec
- **Key to using disk effectively (especially for file systems) is to minimize seek and rotational delays**

Intelligence in the controller

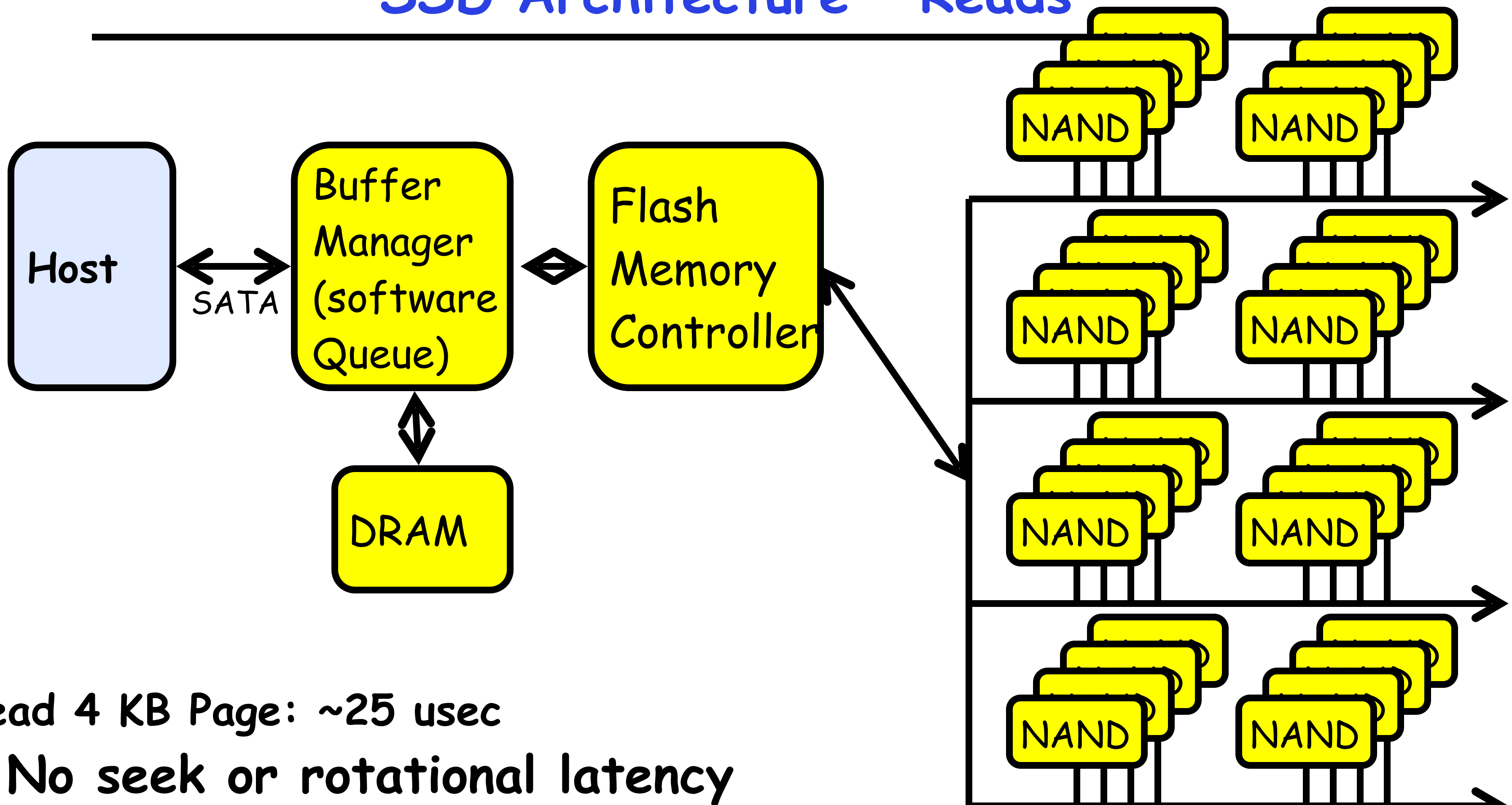
- Sectors contain sophisticated error correcting codes
  - Disk head magnet has a field wider than track
  - Hide corruptions due to neighboring track writes
- Sector sparing
  - Remap bad sectors transparently to spare sectors on the same surface
- Slip sparing
  - Remap all sectors (when there is a 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

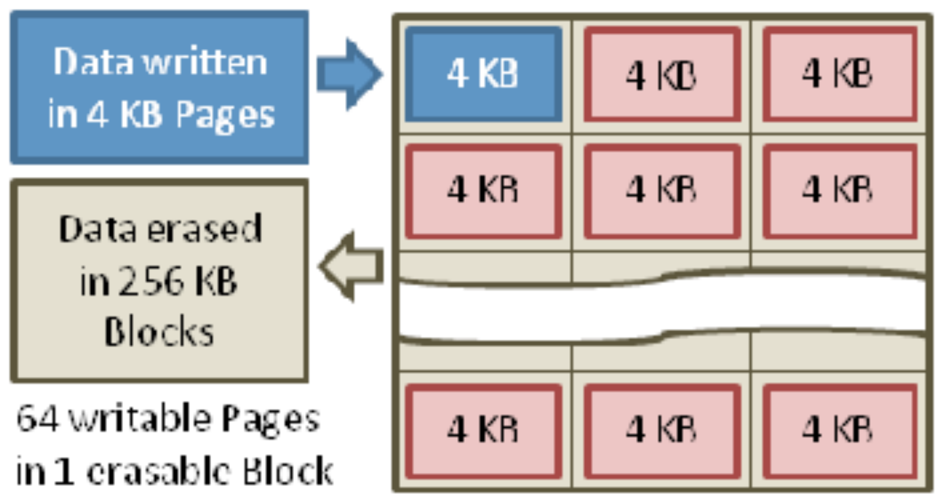


Read 4 KB Page: ~25 usec

- 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

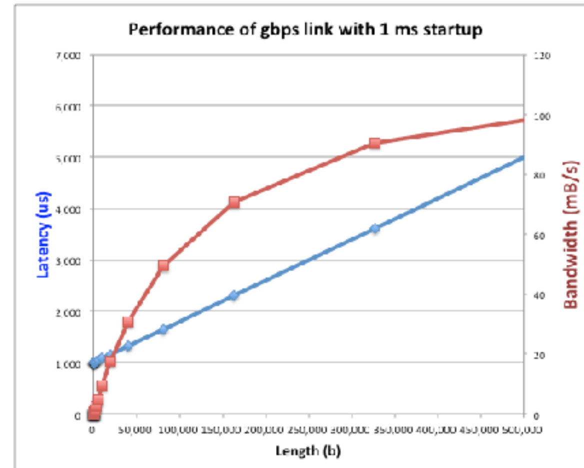
BW: SSD up to x10 than HDD, DRAM > x10 than SSD
Price: HDD x20 less than SSD, SSD x5 less than DRAM

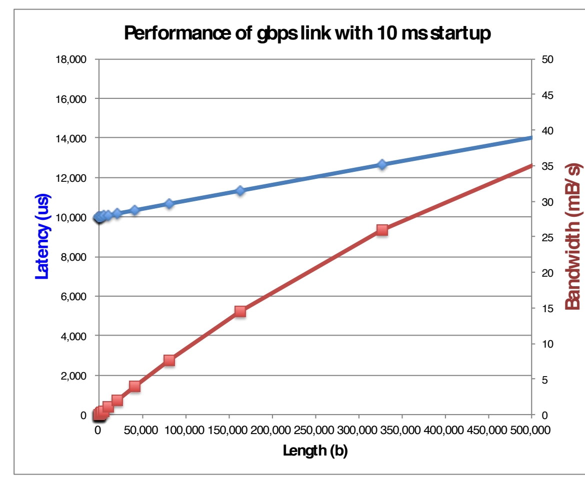
SSD Summary

- 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

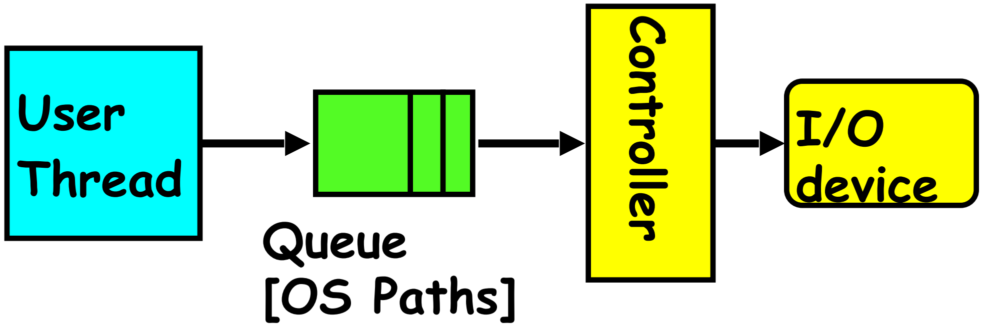
What goes into startup cost for I/O?

- 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)

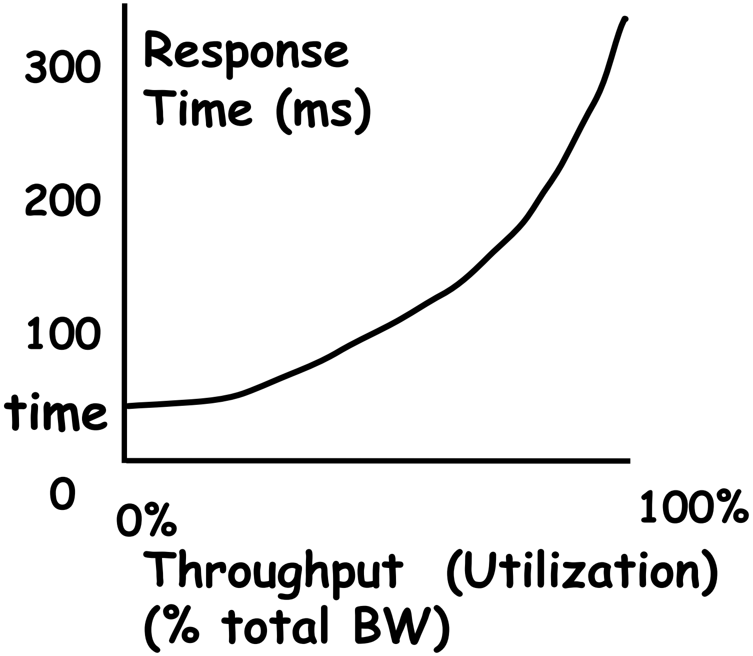




I/O Performance

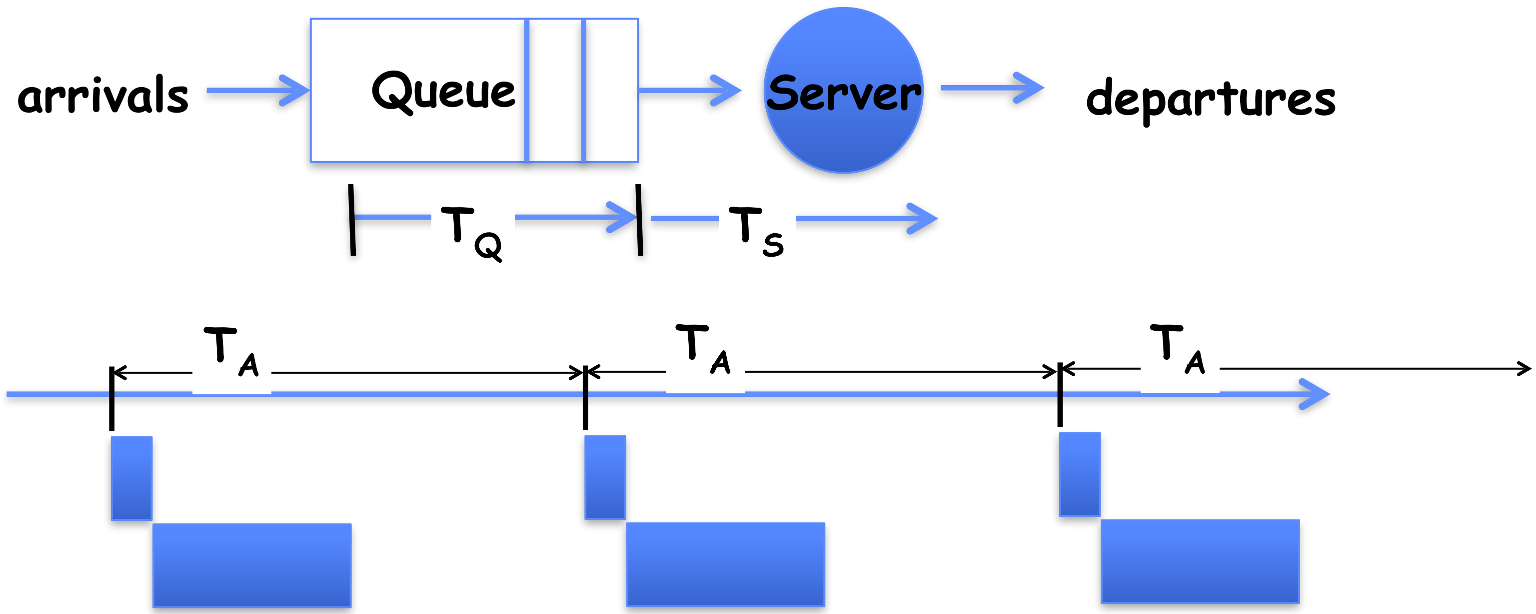


Response Time = Queue + I/O device service time



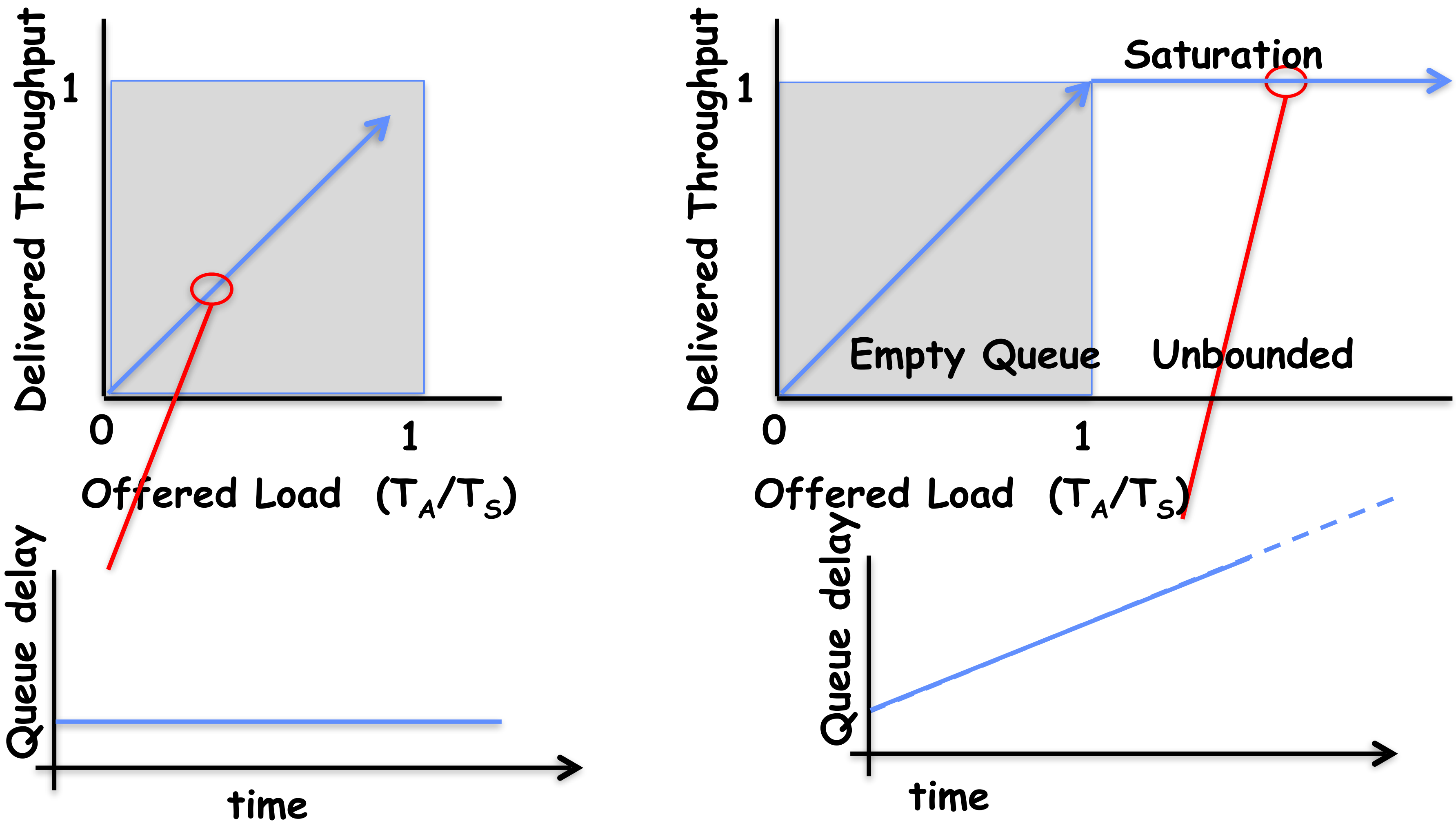
- Performance of I/O subsystem
  - Metrics: Response Time, Throughput
  - Effective BW per op = transfer size / response time
    - » $EffBW(n) = n / (S + n/B) = B / (1 + SB/n)$
  - Contributing factors to latency:
    - » Software paths (can be loosely modeled by a queue)
    - » Hardware controller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

A Simple Deterministic World



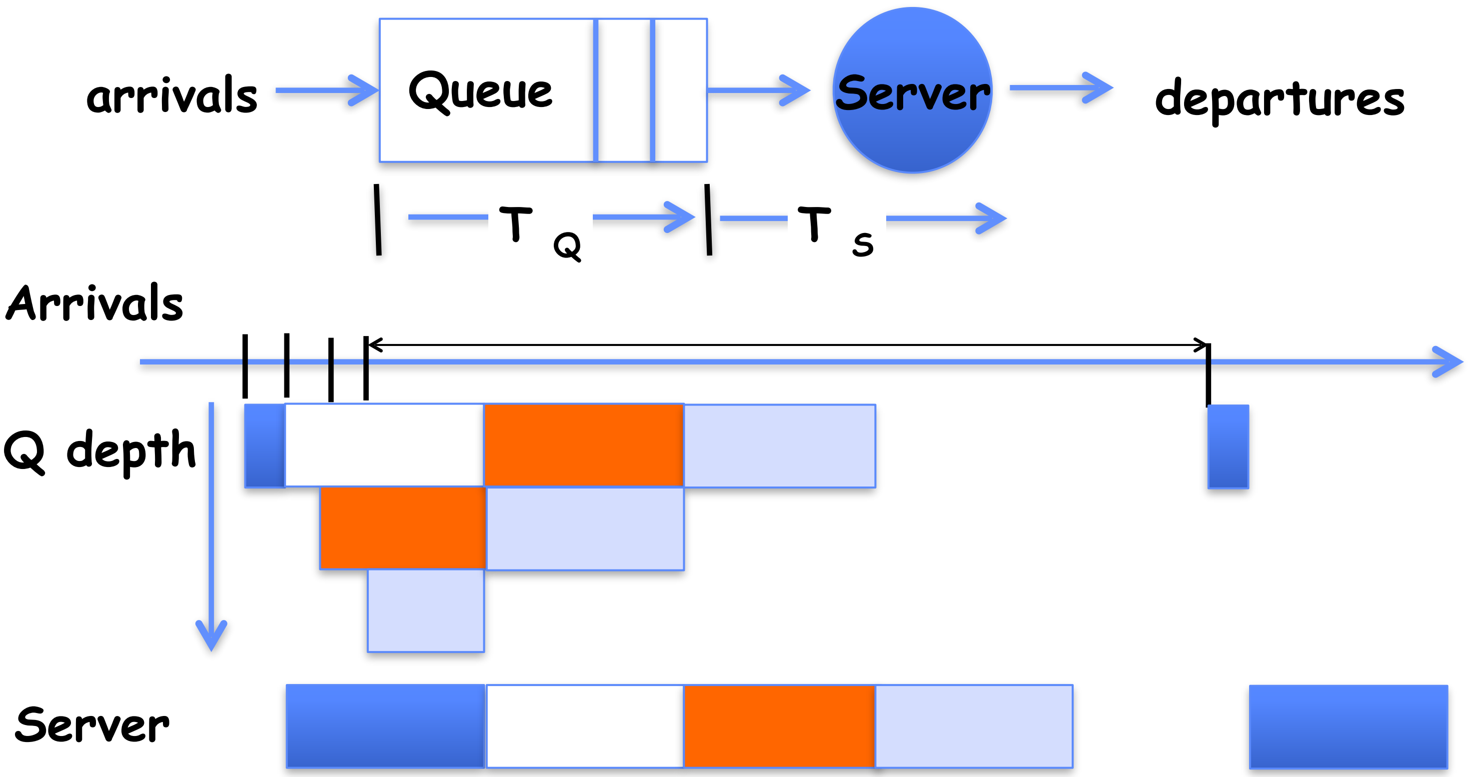
- Assume requests arrive at regular intervals, take a fixed time to process, with plenty of time between …
- Service rate ($\mu = 1/T_S$) - operations per sec
- Arrival rate: ($\lambda = 1/T_A$) - requests per second
- Utilization: $U = \lambda/\mu$, where $\lambda < \mu$

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

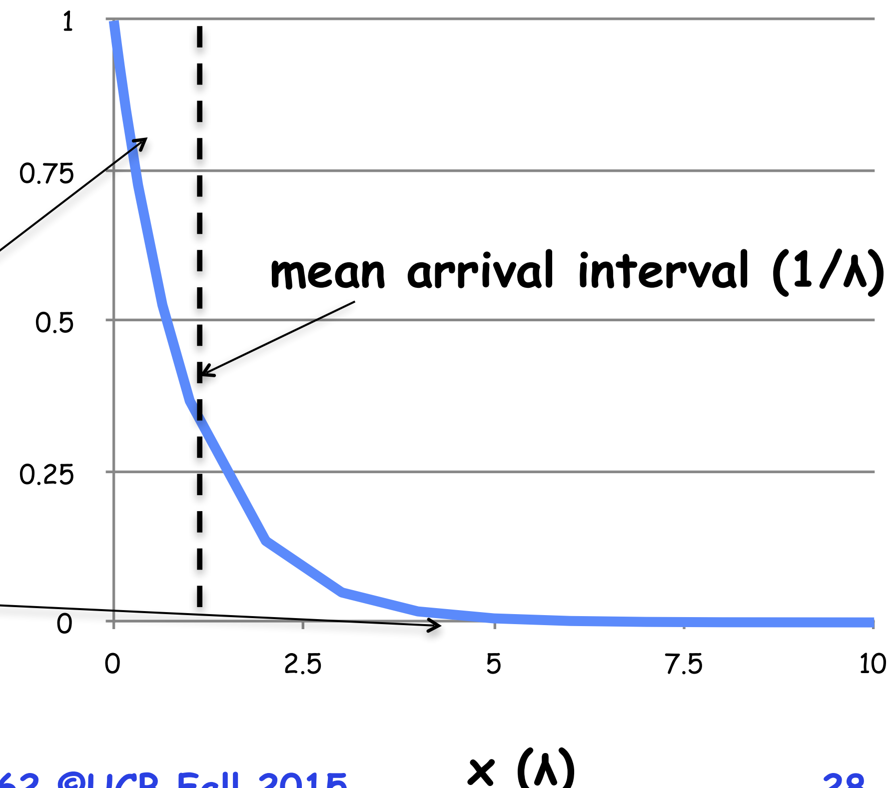
So how do we model the burstiness of arrival?

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

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

Lots of short arrival intervals (i.e., high instantaneous rate)

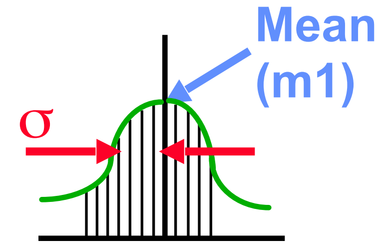
Few long gaps (i.e., low instantaneous rate)



Background: General Use of random distributions

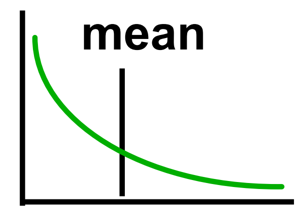
- Server spends variable time with customers
  - Mean (Average) m1 $= \Sigma p(T) \times T$
  - Variance $\sigma^2 = \Sigma p(T) \times (T-m1)^2 = \Sigma p(T) \times T^2 - m1^2$
  - Squared coefficient of variance: $C = \sigma^2/m1^2$

    Aggregate description of the distribution.



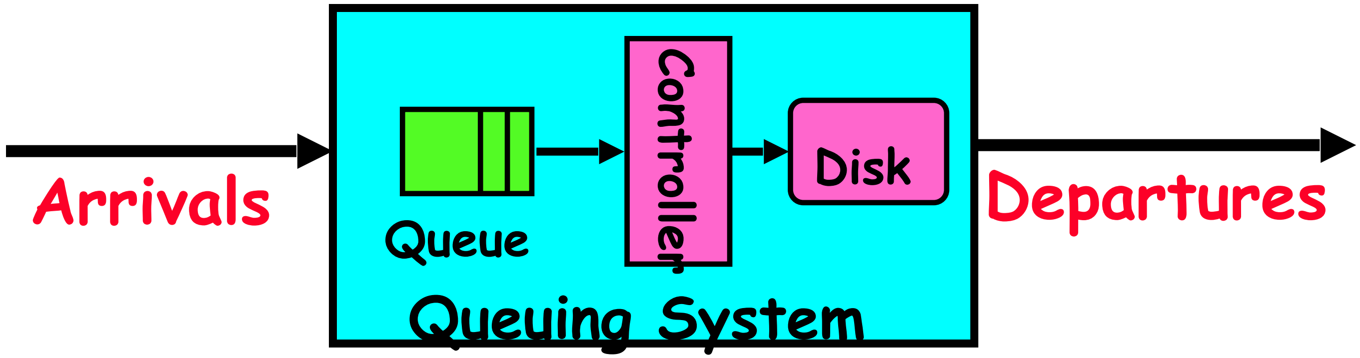
Distribution of service times

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



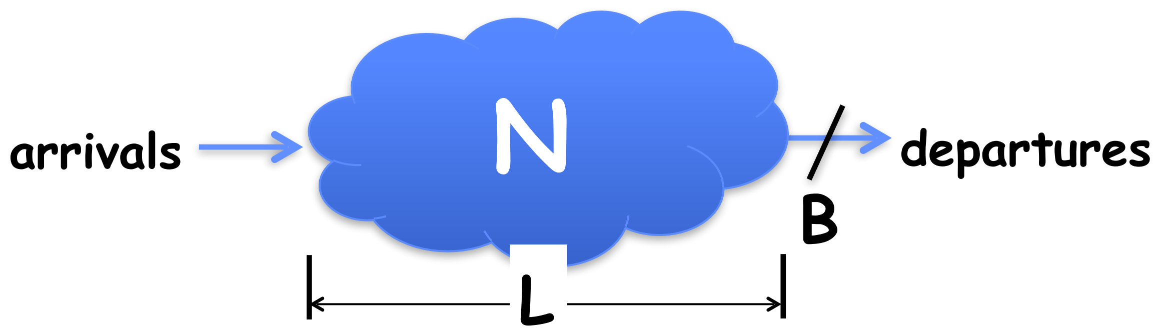
Memoryless

Introduction to Queuing Theory



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

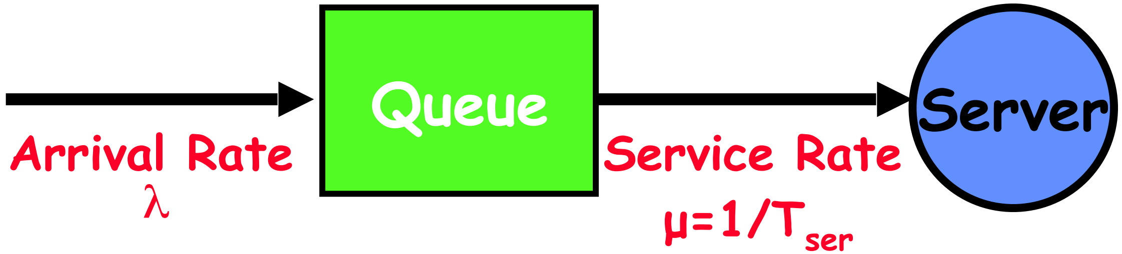
Little's Law



- 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

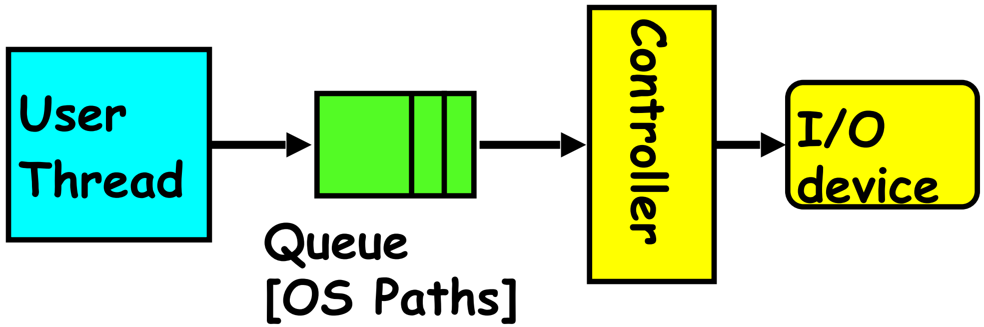
T_q (avg time/customer in queue) = $T_{ser} \times u/(1 - u)$

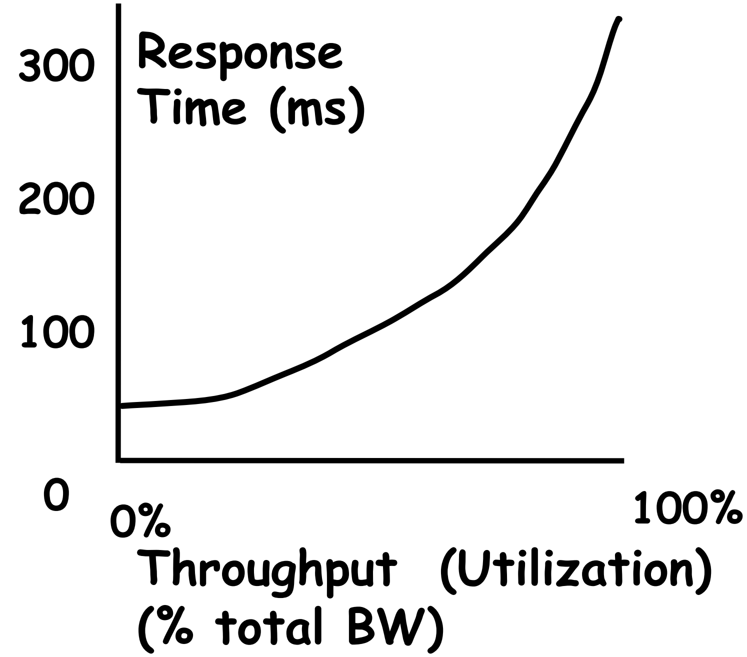
= 20 x 0.2/(1-0.2) = 20 x 0.25 = 5 ms (0 .005s)

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

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

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 $\rightarrow \infty$

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