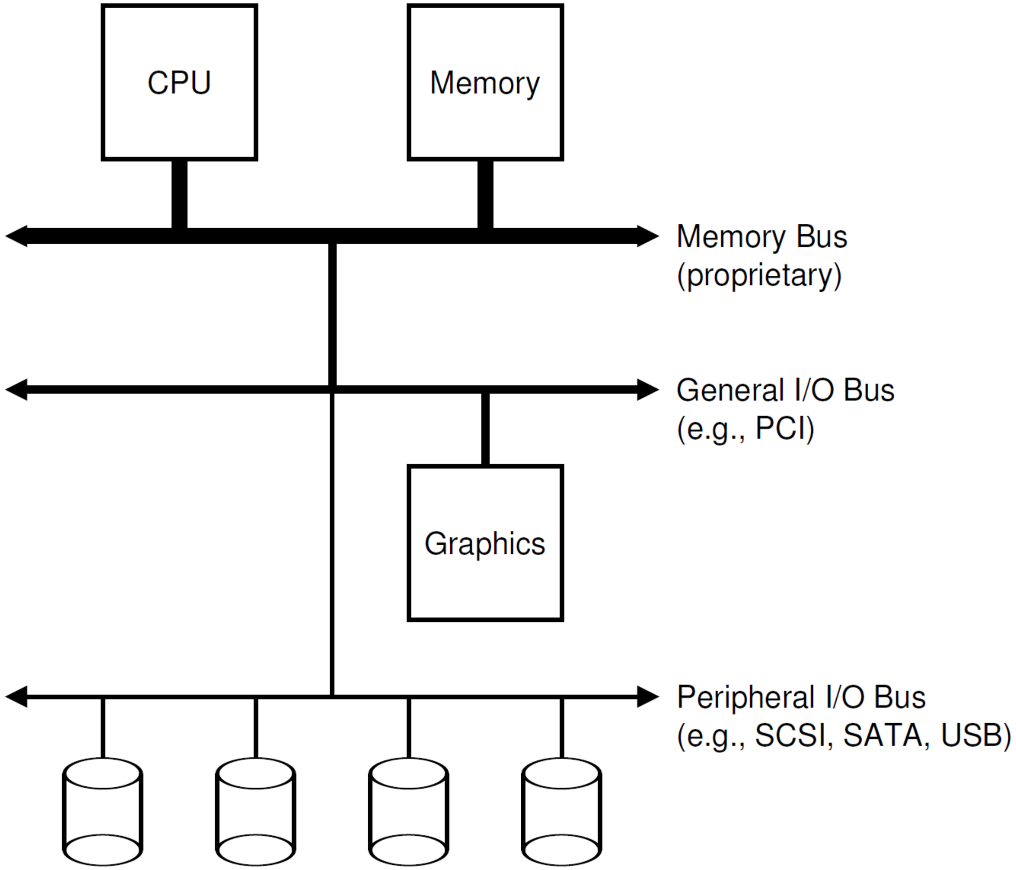
CS162
Operating Systems and Systems Programming
Lecture 18

Storage Devices, Performance, Queuing Theory

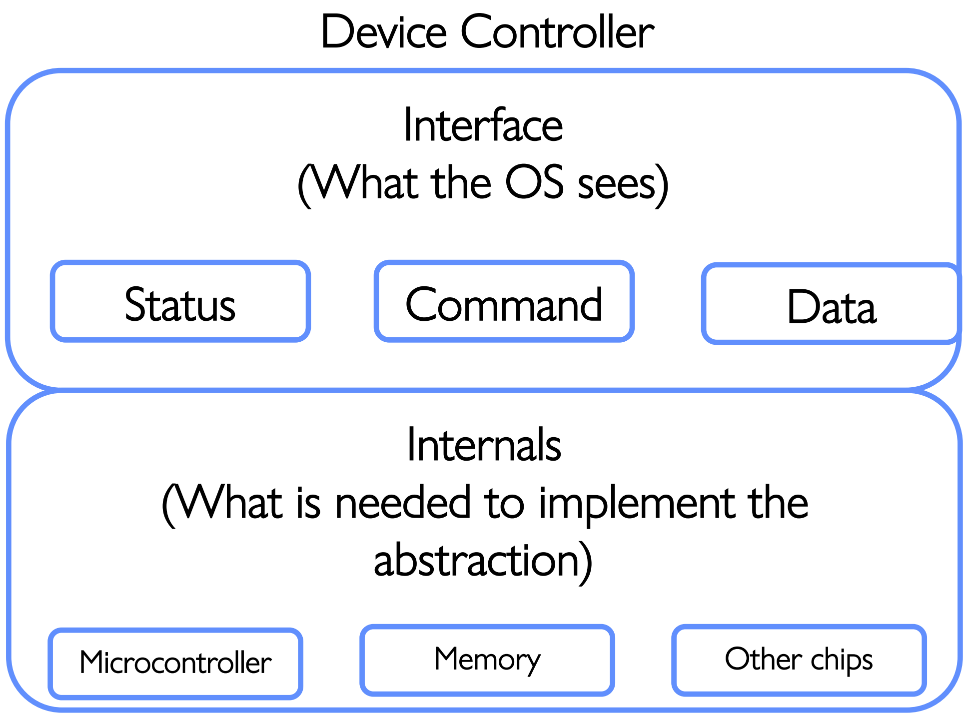
Recall : Simplified IO architecture



Follows a hierarchical structure because of cost: the faster the bus, the more expensive it is

Recall: How does the processor talk to devices?

- Remember, it's all about abstractions!



Hardware interface device presents to OS

Hardware interface device presents to OS

Recall: Device Drivers

- Device Driver: Device-specific code in the kernel that interacts directly with the device hardware
  - Supports a standard, internal interface
  - 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

- Your body is 90% water, the OS is 70% device-drivers

Recall: Life Cycle of An I/O Request

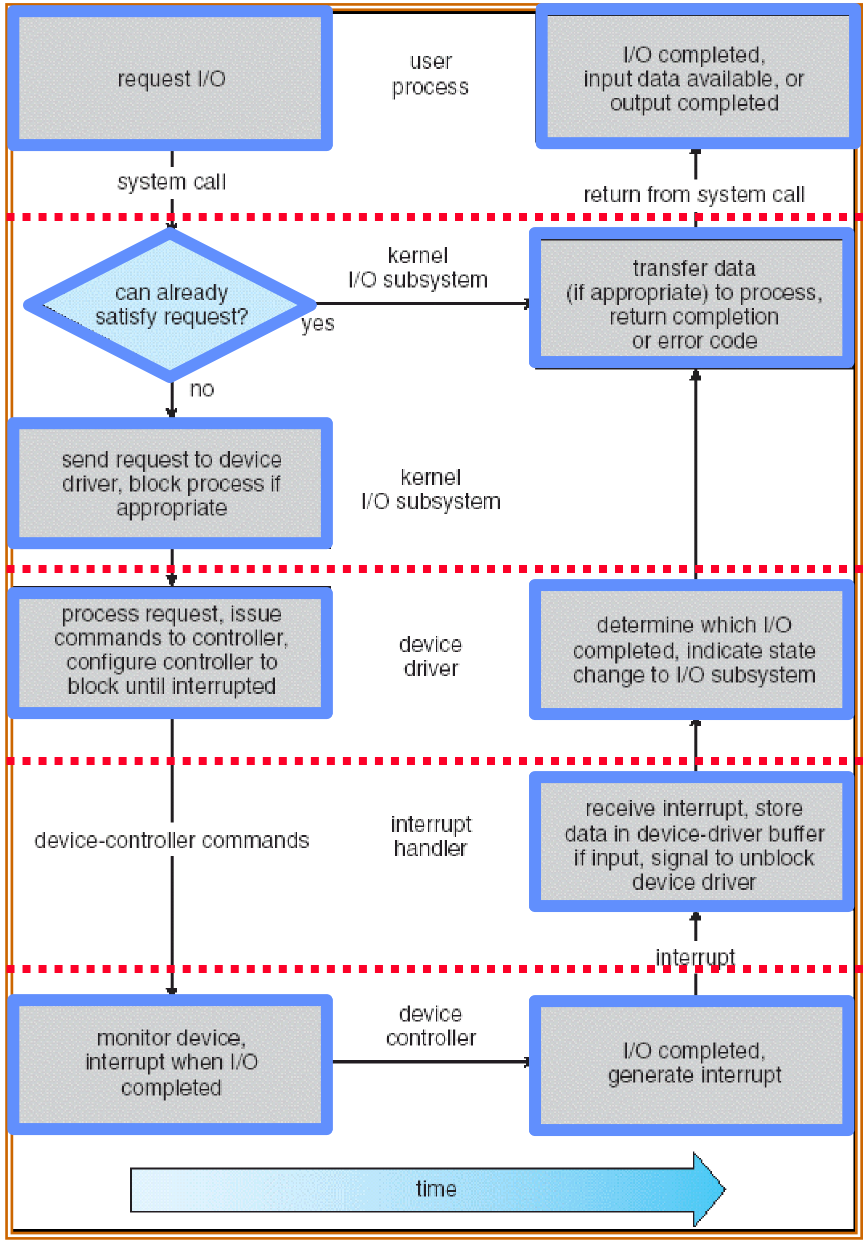
User Program

Kernel I/O Subsystem

Device Driver Top Half

Device Driver Bottom Half

Device Hardware



Ways of Measuring Performance: Times (s) and Rates (op/s)

- *Response Time or Latency* - time to complete a task
  – Measured in units of time (s, ms, us, …, hours, years)

- *Throughput* or *Bandwidth* – rate at which tasks are performed
  – Measured in units of things per unit time (ops/s, GFLOP/s)

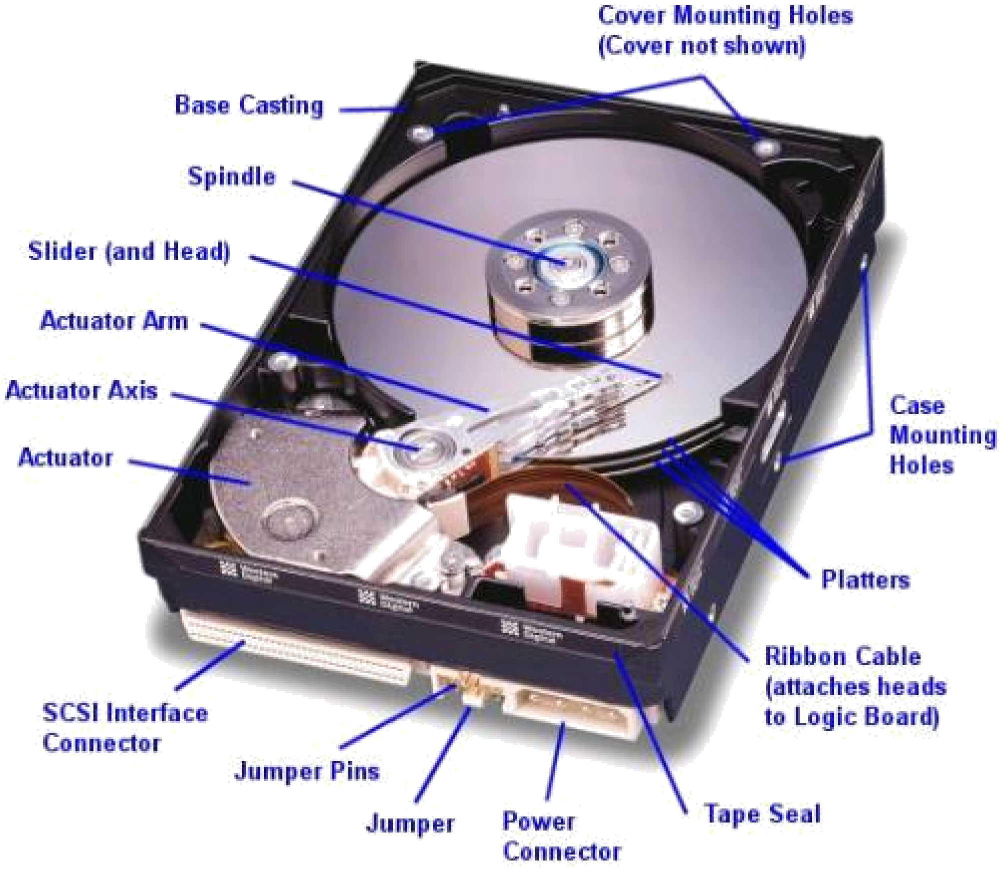
- *Start up or Overhead* – time to initiate an operation

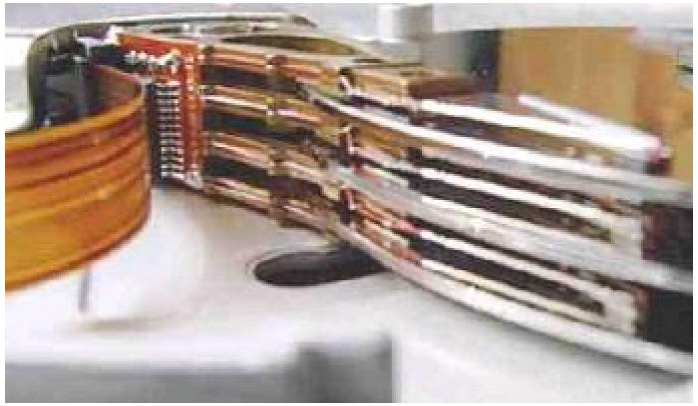
- Most I/O operations are roughly linear in *b* bytes
  – Latency(b) = Overhead + b/TransferCapacity

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 sequential access
- Flash memory
  - Storage that rarely becomes corrupted
  - Capacity at intermediate cost (5-20x disk)
  - Block level random access
  - Good performance for reads; worse for random writes
  - Wear patterns issue

Hard Disk Drives (HDDs)





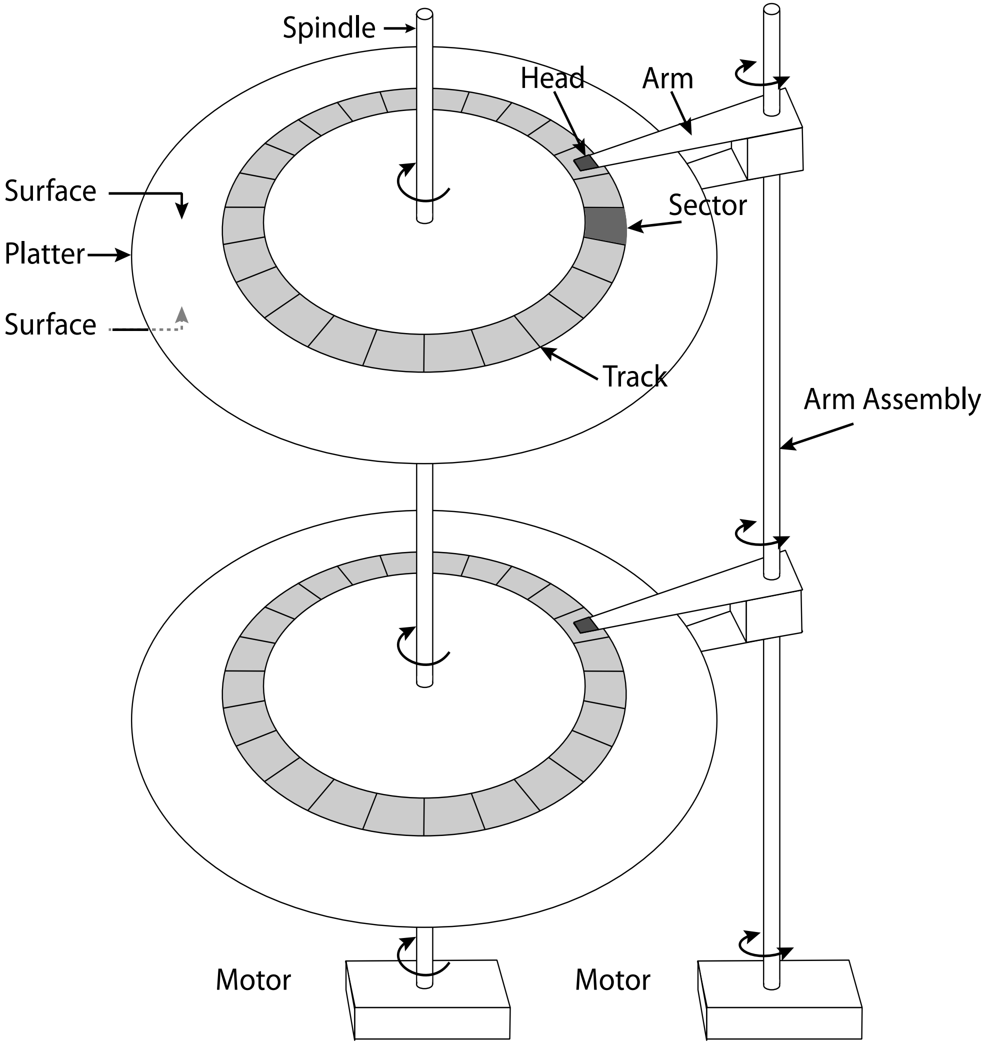
Read/Write Head Side View

IBM Personal Computer 1986

30MB Hard Disk for 500 dollars

The Amazing Magnetic Disk

- Store data magnetically on thin metallic film bonded to rotating disk of glass, ceramic, or aluminum



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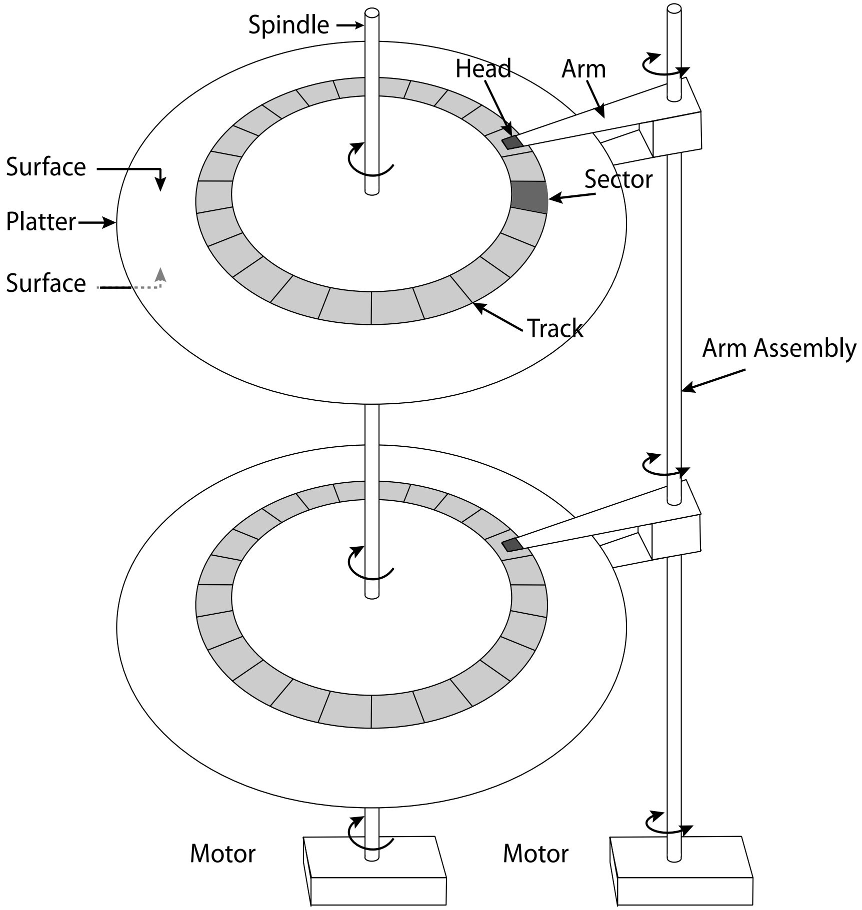


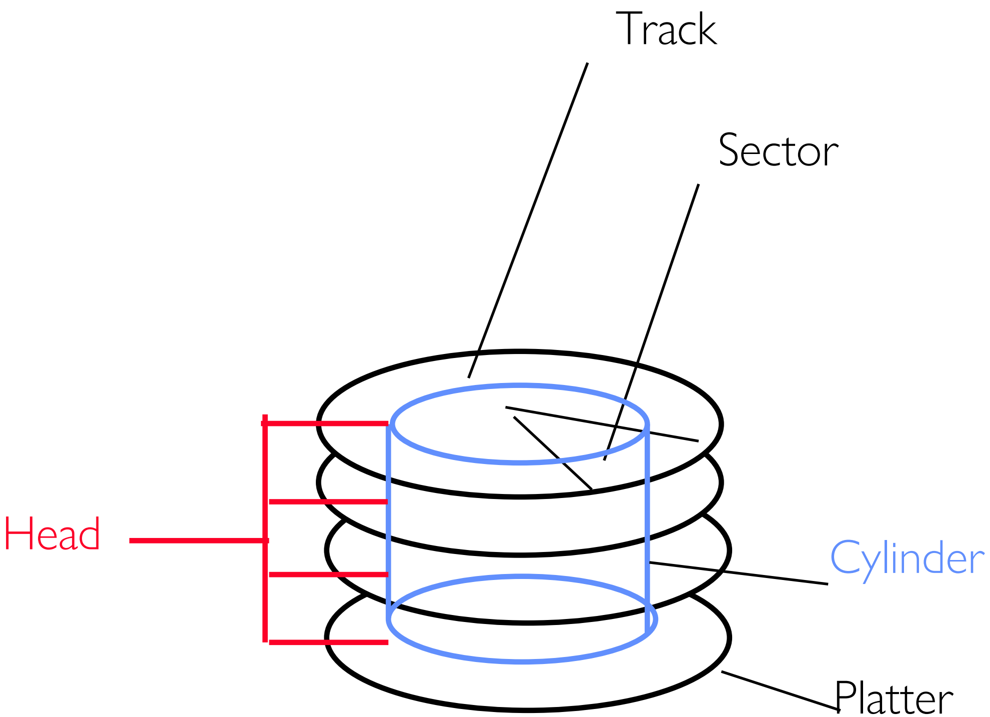
Track: concentric circle on surface

Sectors: slice of a track

- Smallest addressable unit
- Are units of transfers

Cylinder all the tracks under the head at a given point on all surfaces

The Amazing Magnetic Disk



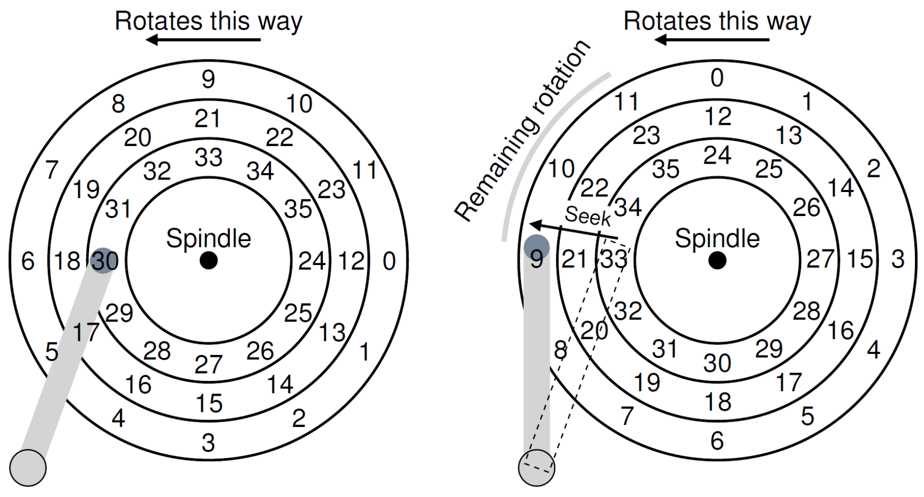
Track lengths vary across disk: outside tracks have more sectors per track, higher bandwidth

Disk is organized into regions of tracks with the same number of sector/tracks

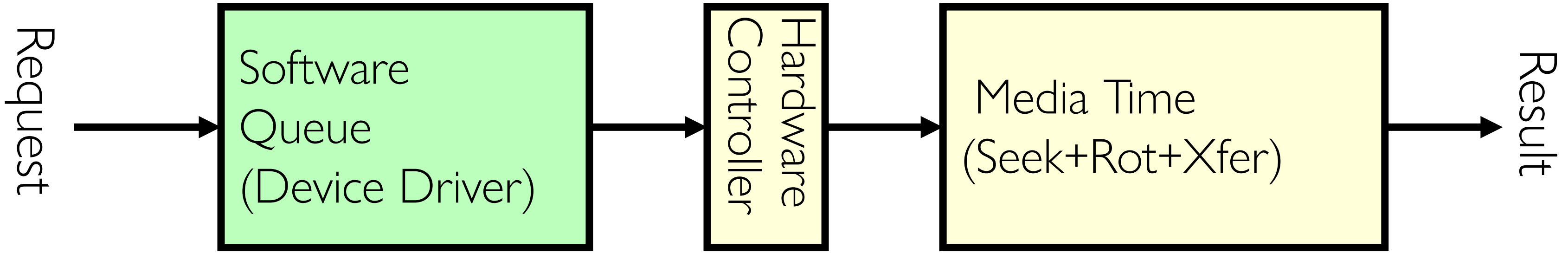
Usually, only outer half of radius is used

The Amazing Magnetic Disk

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



Request Time = Queueing Time + Controller Time + Seek + Rotational + Transfer



Typical Numbers for Magnetic Disk

Parameter	Info/Range
Space/Density	Space: 14TB (Seagate), 8 platters, in 3½ inch form factor! Areal Density: ≥ 1 Terabit/square inch! (PMR, Helium, …)
Average Seek Time	Typically 4-6 milliseconds
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 so 4-8 milliseconds
Controller Time	Depends on controller hardware
Transfer Time	Typically 50 to 250 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	Used to drop by a factor of two every 1.5 years (or faster), now slowing down

Disk Performance Example

- Key to using disk effectively (especially for file systems) is to minimize seek and rotational delays
- Assumptions:
  – Ignoring queuing and controller times for now
  – Avg seek time of 5ms,
  – 7200RPM ⇒ Time for rotation: 60000 (ms/min) / 7200(rev/min) ~= 8ms
  – Transfer rate of 50MByte/s, block size of 4Kbyte ⇒ 4096 bytes/50×10^6 (bytes/s) = 81.92×10^{-6} sec ≅ 0.082 ms for 1 sector

Disk Performance Example

- Read block from random place on disk (random reads):
  - Seek (5ms) + Rot. Delay (4ms) + Transfer (0.082ms) = 9.082ms
  - Approx 9ms to fetch/put data: 4096 bytes/9.082×10^{-3} s ≅ 451KB/s

- Read block from random place in same cylinder:
  - Rot. Delay (4ms) + Transfer (0.082ms) = 4.082ms
  - Approx 4ms to fetch/put data: 4096 bytes/4.082×10^{-3} s ≅ 1.03MB/s

- Read next block on same track (sequential reads):
  - Transfer (0.082ms): 4096 bytes/0.082×10^{-3} s ≅ 50MB/sec

Lots of Intelligence in the Controller

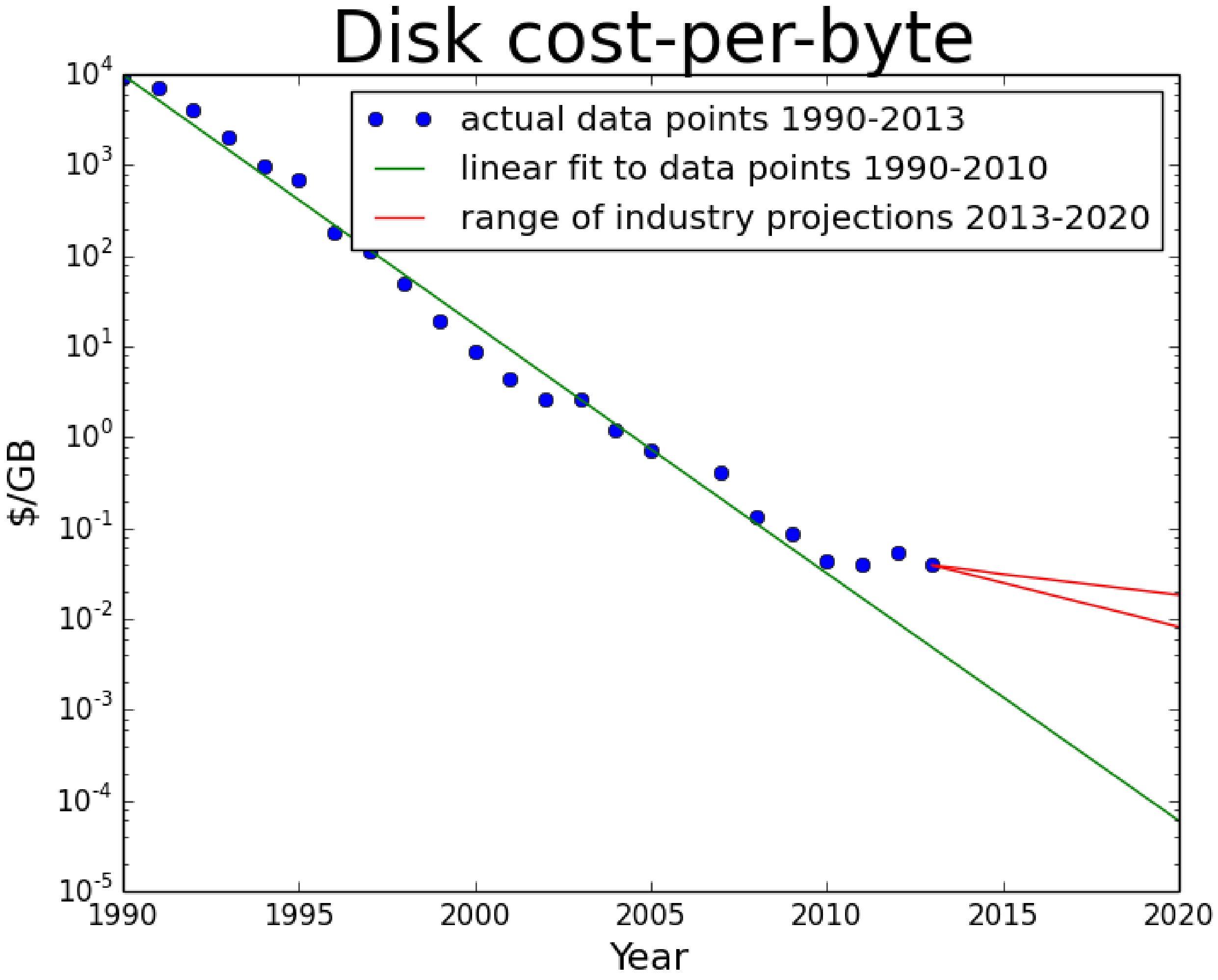
- Sectors contain sophisticated error correcting codes
  – Disk head magnet has a field wider than track
  – Hide corruptions due to neighboring track writes

- 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

Hard Drive Prices over Time



Example of Current HDDs

- Seagate Exos X18 (2020)
  - 18 TB hard disk
    - » 9 platters, 18 heads
    - » Helium filled: reduce friction and power
  - 4.16ms average seek time
  - 4096 byte physical sectors
  - 7200 RPMs
  - Dual 6 Gbps SATA /12Gbps SAS interface
    - » 270MB/s MAX transfer rate
    - » Cache size: 256MB
  - Price: $ 562 (~ $0.03/GB)

- IBM Personal Computer/AT (1986)
  - 30 MB hard disk
  - 30-40ms seek time
  - 0.7-1 MB/s (est.)
  - Price: $500 ($17K/GB, 340,000x more expensive !!)

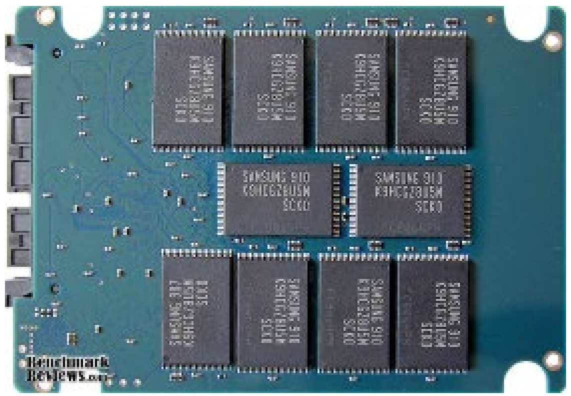
Solid State Drives

- 1995 – Replace rotating magnetic media with non-volatile memory (battery backed DRAM)

- 2009 – Use 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 advances in capacity and cost ever since!



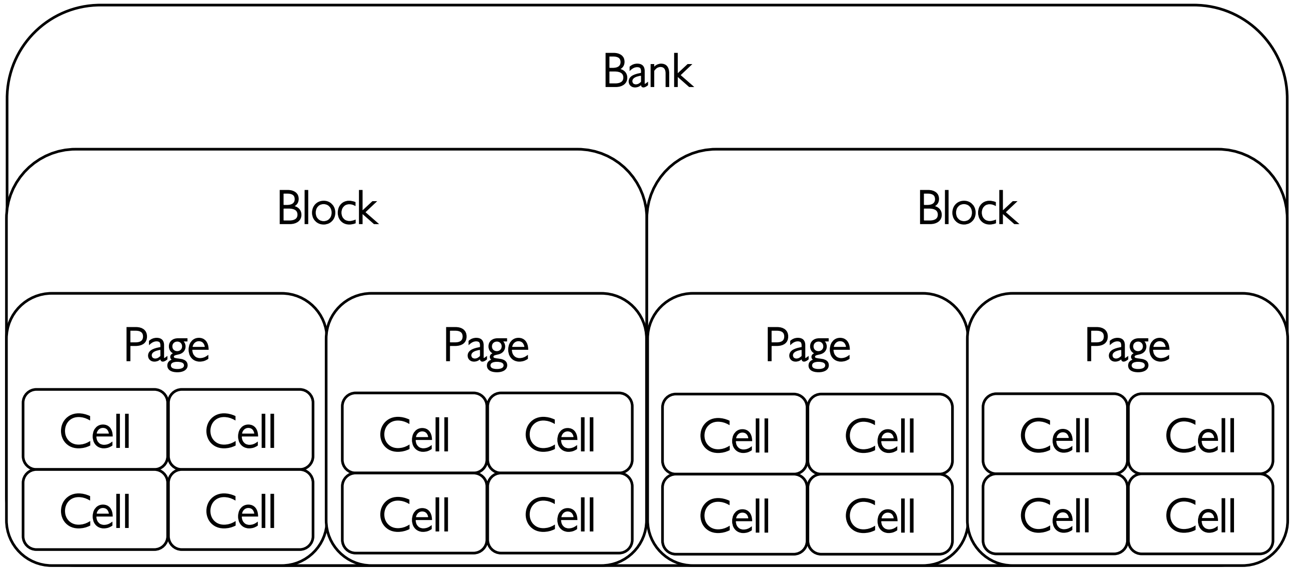
The Flash Cell

- Encode bit by trapping electrons into a cell

- Single-level cell (SLC)
  - Single bit is stored within a transistor
  - Faster, more lasting (50k to 100k writes before wear out)

- Multi-level cell (MLC)
  - Two/three bits are encoded into different levels of charge
  - Wear out much faster (1k to 10k writes)

Of banks, blocks, cells

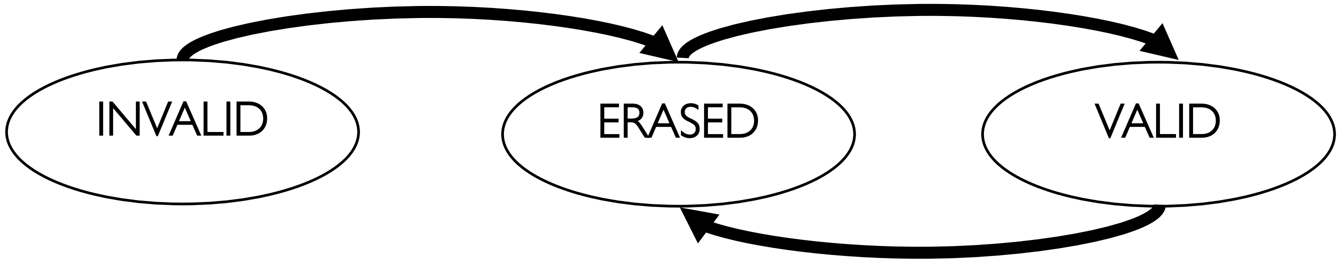


- Flash chips organized in **banks**
  - Banks can be accessed in parallel
- **Blocks**: 128 KB/256KB
  - (64 to 258 pages)
- **Pages**: Few KB
- **Cells:** 1 to 4 bits
- Distinction between blocks and pages important in operations!

Low-level flash operations

- How do you read?
  - Chip supports reading *pages*
  - 10s of microseconds, independently of the previous read page
- What about writing? More complicated!
  - Must first *erase the block*
    - » Erase quite expensive (milliseconds)
  - Once block has been erased, can then *program a page*
    - » Change 1s to 0s within a page.
    - » 100s of microseconds.
  - Blocks can only be erased a limited number of times!

Low-level flash operations



		`iiii`	*Initial: pages in block are invalid* (`i`)
Erase()	→	`EEEE`	*State of pages in block set to erased* (`E`)
Program(0)	→	`VEEE`	*Program page 0; state set to valid* (`V`)
Program(0)	→	**error**	*Cannot re-program page after programming*
Program(1)	→	`VVEE`	*Program page 1*
Erase()	→	`EEEE`	*Contents erased; all pages programmable*

Low-level flash operations

- Assume block of 4 pages. All valid. Want to write Page 0

Page 0	Page 1	Page 2	Page 3
00011000	11001110	00000001	00111111
VALID	VALID	VALID	VALID

Step 1: erase **full** block

Page 0	Page 1	Page 2	Page 3
11111111	11111111	11111111	11111111
ERASED	ERASED	ERASED	ERASED

Step 2: program page 0

Page 0	Page 1	Page 2	Page 3
00000011	11111111	11111111	11111111
VALID	ERASED	ERASED	ERASED

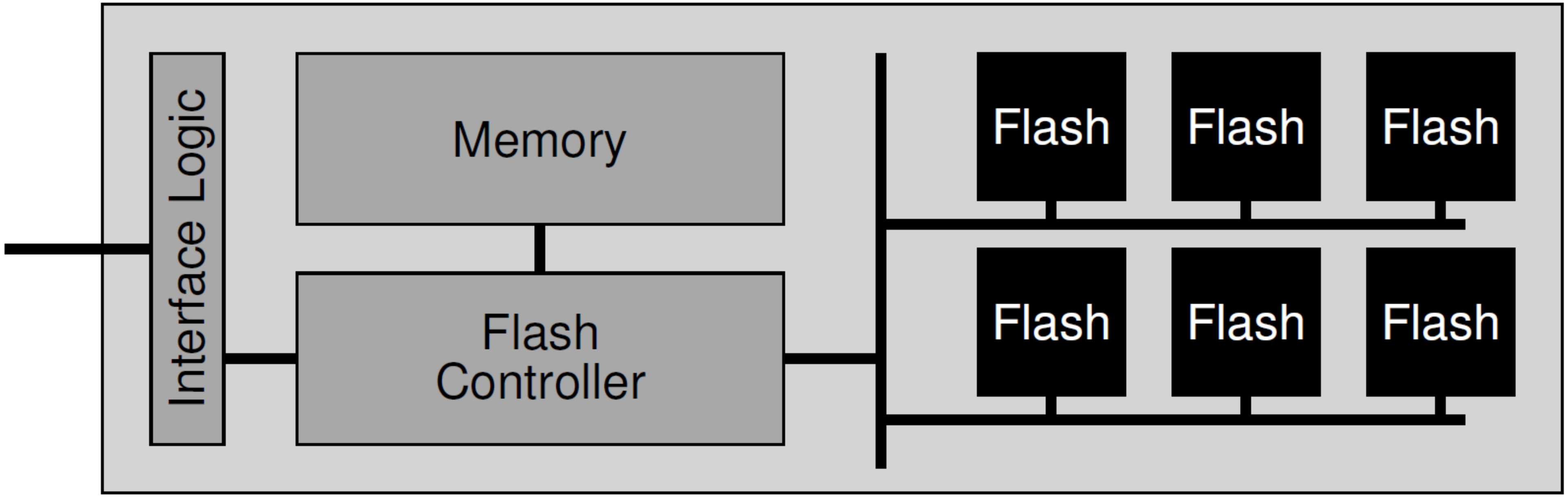
SSD Architecture

- Recall that SSDs uses low-level Flash operations to provide same interface as HDD
  - read and write chunk (4KB) at a time

- Reads are easy, but for writes, can only overwrite data one block (256KB) at a time!

- Why not just erase and rewrite new version of entire 256KB block?
  - Erasure is very slow (milliseconds)
  - Each block has a finite lifetime, can only be erased and rewritten about 10K times
  - Heavily used blocks likely to wear out quickly

SSD Architecture (Simplified)



Flash Translation Layer (FTL)

- Add a layer of indirection: the flash translation layer
  - Translates request for logical blocks (device interface) to low-level Flash blocks and pages
- Goal: performance and reliability
- Reduce **write amplification**
  - Ratio of the total write traffic in bytes issues by the flash chip by the FTL devided by the total write traffic issued by the OS to the device
- Avoid **wear out**
  - A single block should not be erased too often

FTL – Two Systems Principles

- FTL uses *indirection* and *copy-on-write*

- Maintains mapping tables in DRAM
  - Map virtual block numbers (which OS uses) to physical page numbers (which flash mem. controller uses)
  - Can now freely relocate data w/o OS knowing

- Copy on Write/ Log-structured FTL
  - Don't overwrite a page when OS updates its data
  - Instead, write new version in a free page
  - Update FTL mapping to point to new location

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FTL Example

Initial State

Mapping Table:			
Block 0		Block 1	
E	E	E	E

Write(a0)

Mapping Table a0->0,0			
Block 0		Block 1	
a0			
V	E	E	E

Write(a1)

Mapping Table: a0->0,0/a1->0,1			
Block 0		Block 1	
a0	a1		
V	V	E	E

Write(a1)

Mapping Table: a0->0,0/a1->1,0			
Block 0		Block 1	
a0	a1	a1	
V	V	V	E

Write(a1)

Mapping Table: a0->1,1/a1->1,0			
Block 0		Block 1	
a0	a1	a1	a0
V	V	V	V

Garbage Collect

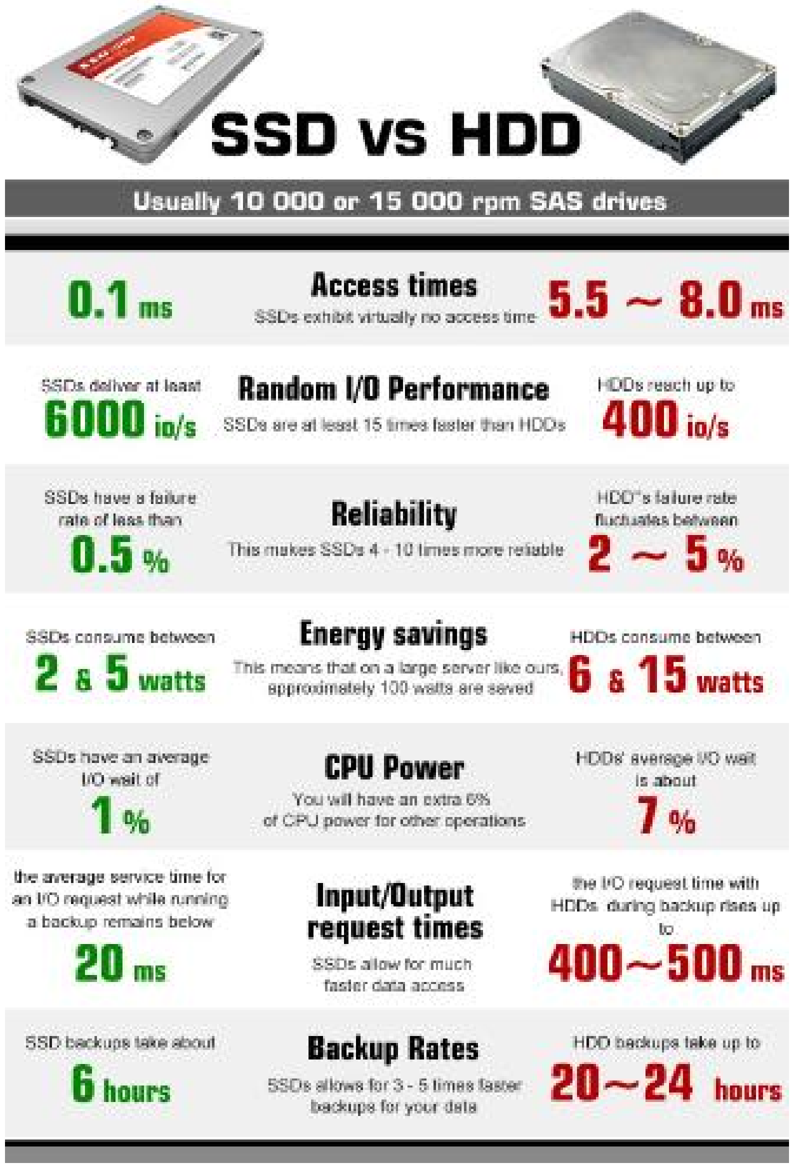
Mapping Table: a0->1,1/a1->1,0			
Block 0		Block 1	
		a1	a0
E	E	V	V

Some “Current” (large) 3.5in SSDs

- Seagate Exos SSD: 15.36TB (2017)
  - Seq reads 860MB/s
  - Seq writes 920MB/s
  - Price (Amazon): $5495 ($0.36/GB)

- Nimbus SSD: 100TB (2019)
  - Seq reads/writes: 500MB/s
  - Random Read Ops (IOPS): 100K
  - *Unlimited writes for 5 years!*
  - Price: ~ $40K? ($0.4/GB)
    - » However, 50TB drive costs $12500 ($0.25/GB)

HDD vs. SSD Comparison



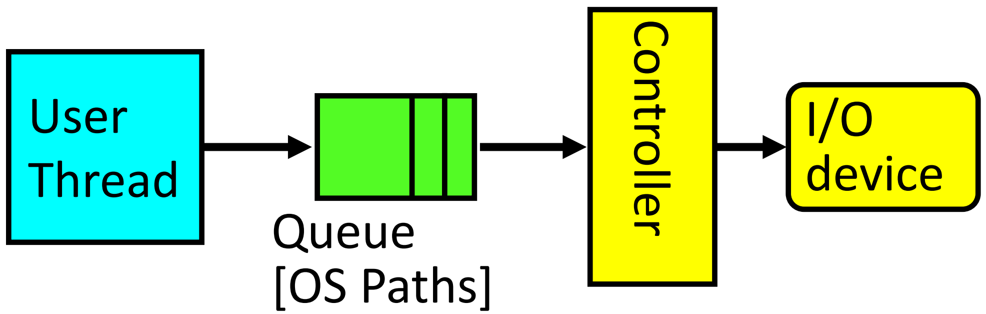
HDD	SDD
Require seek + rotation	No seeks
Not parallel (one head)	Parallel
Brittle (moving parts)	No moving parts
Random reads take 10s milliseconds	Random reads take 10s microseconds
Slow (Mechanical)	Wears out
Cheap/large storage	Expensive/smaller storage

Recall: Overall Performance for I/O Path

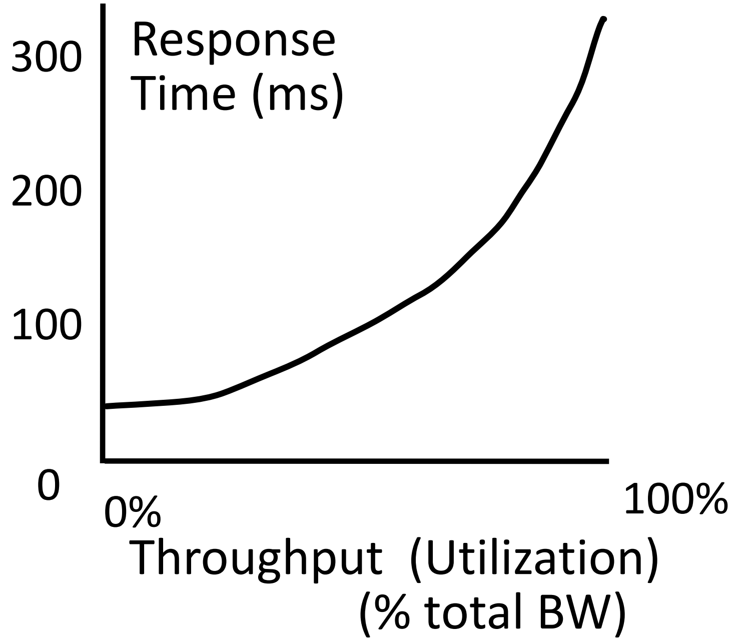
- Performance of I/O subsystem
  – Metrics: Response Time, Throughput

- Contributing factors to latency:
  » Software paths (can be loosely modeled by a queue)
  » Hardware controller
  » I/O device service time

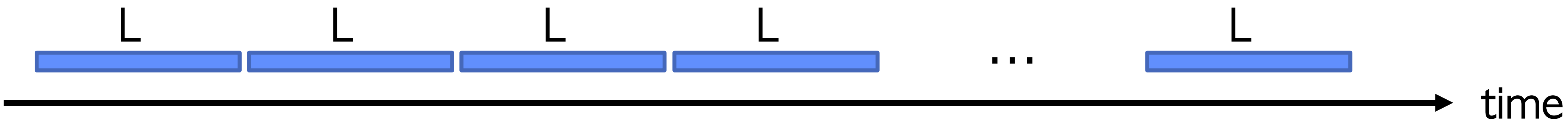
- Queuing behavior:
  – Can lead to big increases of latency as utilization increases
  – Solutions?



Response Time = Queue + I/O device service time

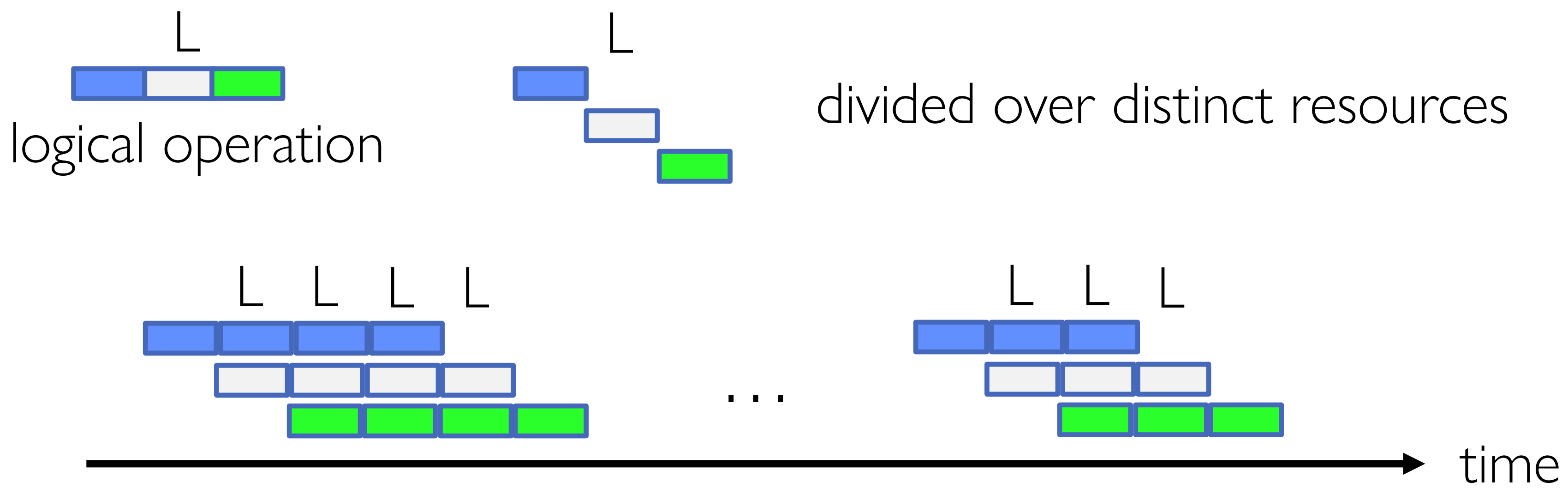


Sequential Server Performance



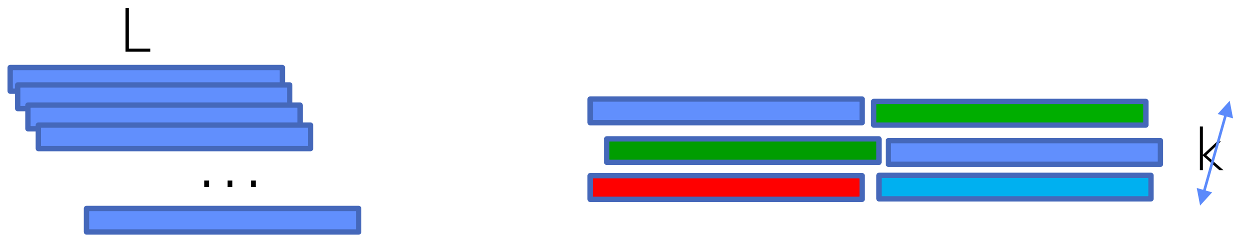
- Single sequential "server" that can complete a task in time L operates at rate $\leq \frac{1}{L}$ (on average, in steady state, …)
  - $L = 10$ ms $\rightarrow B = 100$ $^{op}/_{s}$

Single Pipelined Server



- Single pipelined server of k stages for tasks of length L (i.e., time $^{L}/_{k}$ per stage) delivers at rate $\leq {}^{k}/_{L}$.
  - $L = 10$ ms, $k = 4 \rightarrow B = 400$ $^{\text{op}}/_{\text{s}}$

Multiple Servers

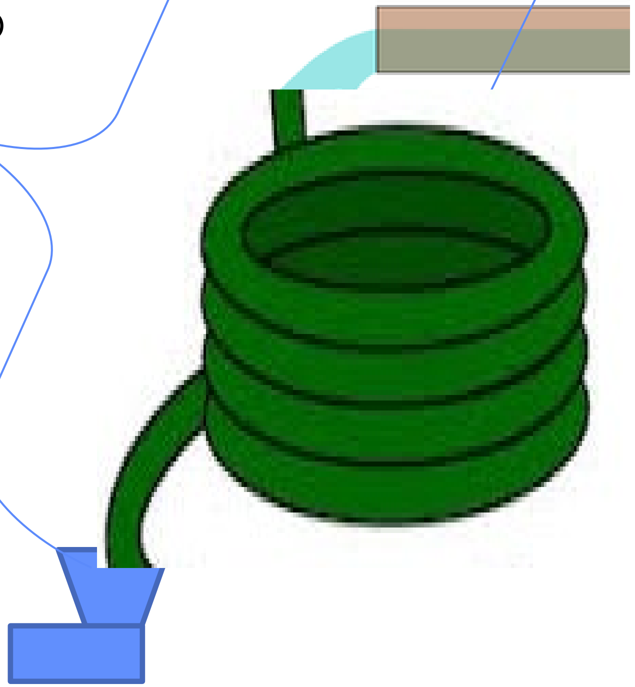


- k servers handling tasks of length L delivers at rate $\leq {}^{k}/_{L}$.
  - $L = 10$ ms, $k = 4 \rightarrow B = 400\ {}^{\text{op}}/_{\text{s}}$

A Simple Systems Performance Model

Latency (L): time per op
- How long does it take to flow through the system

Bandwidth (B): Rate, Op/s
e.g., flow: gal per min



If $B = 2$ $^{\text{ops}}/_{\text{s}}$ and $\mathbf{L} = \mathbf{3}$ s
How much water is "in the system?"

A Simple Systems Performance Model

Latency (L): time per op

- How long does it take to flow through the system

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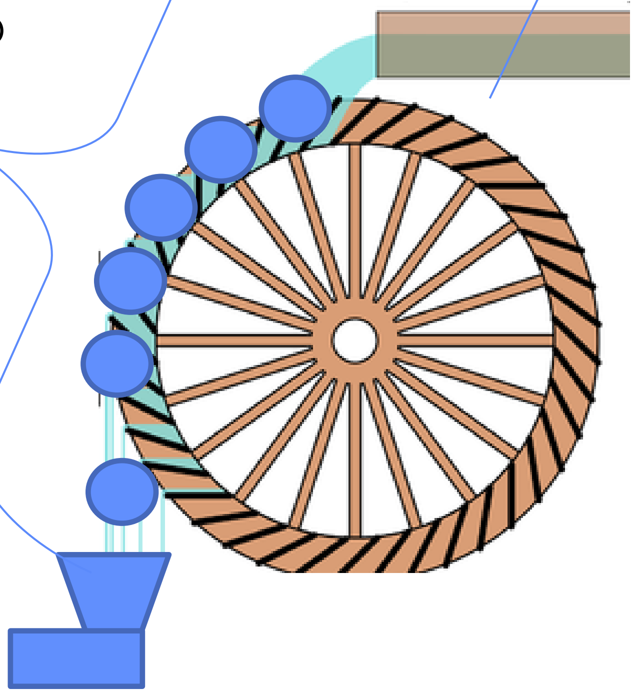
e.g., flow: gal per min



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A Simple Systems Performance Model

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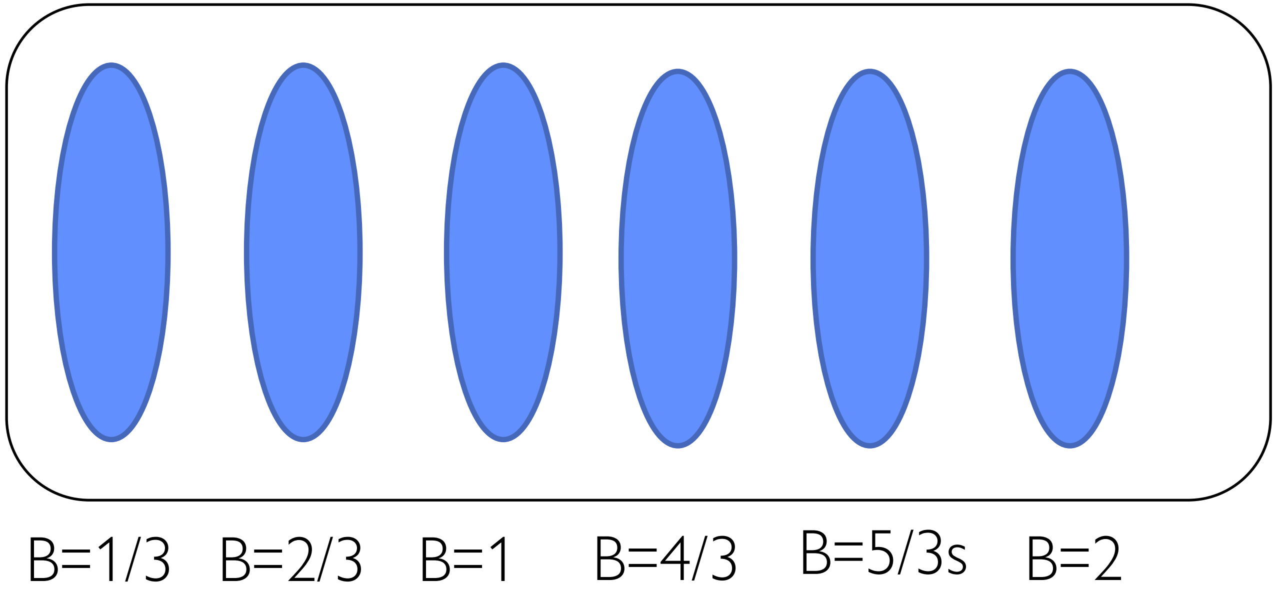
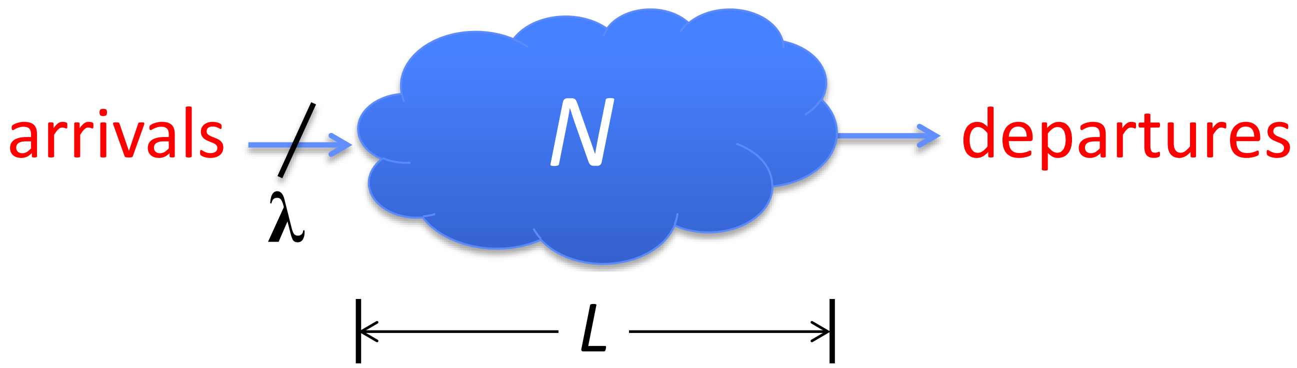
How many ops are "in the system?"

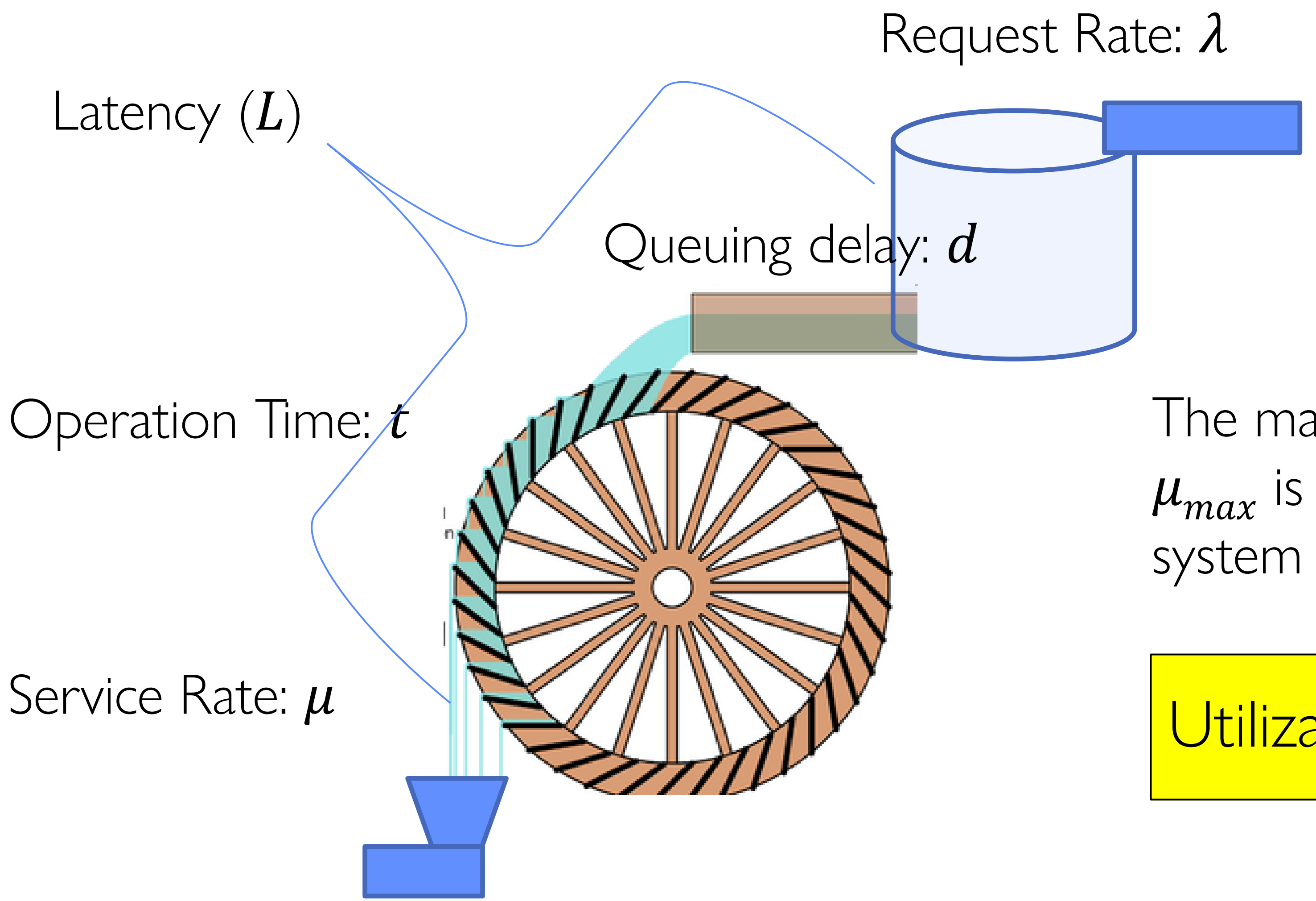


Little's Law ($B \Rightarrow \lambda$)



- In any stable system
  - Average arrival rate = Average departure rate
- The number of "things" in a system is equal to the bandwidth times the latency (on average)
  - *N (jobs) = λ (jobs/s) x L (s)*
  - Applies to any stable system
- Can be applied to an entire system:
  - Including the queues, the processing stages, parallelism, whatever
- Or to just one processing stage:
  - i.e., disk I/O subsystem, queue leading into a CPU or I/O stage, …

A Simple Systems Performance Model

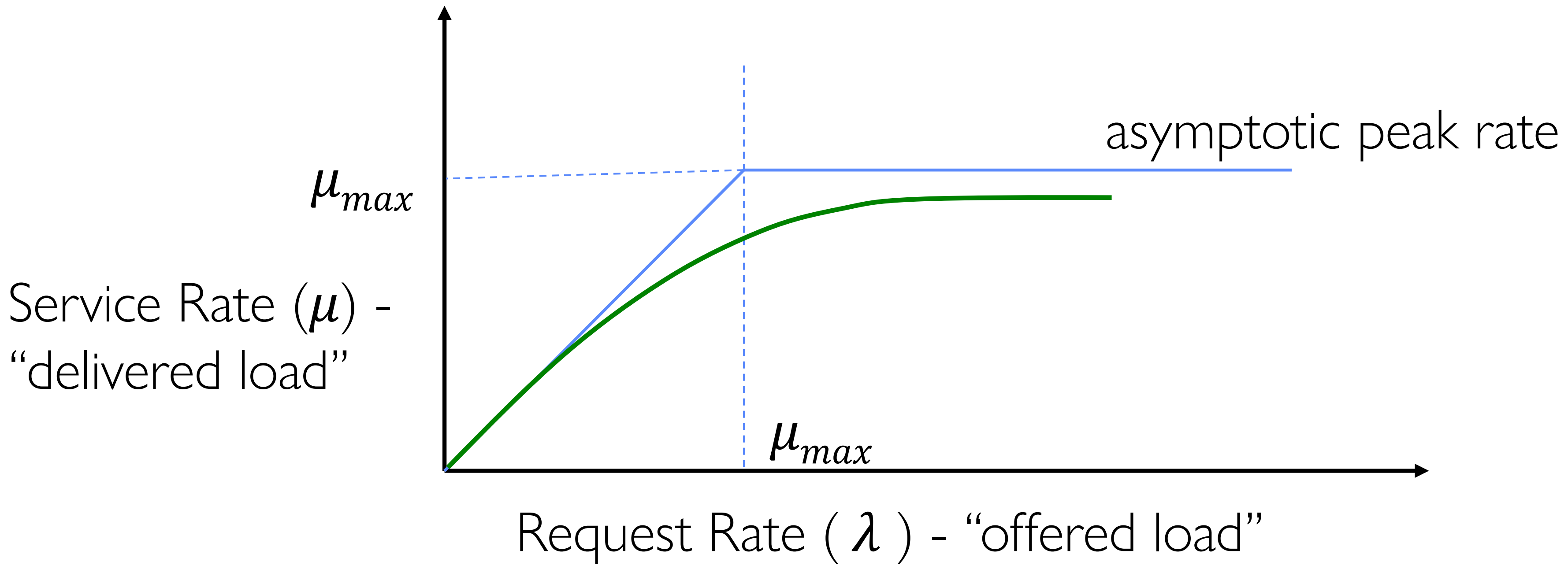


The maximum service rate μ_{max} is a property of the system – the "bottleneck"

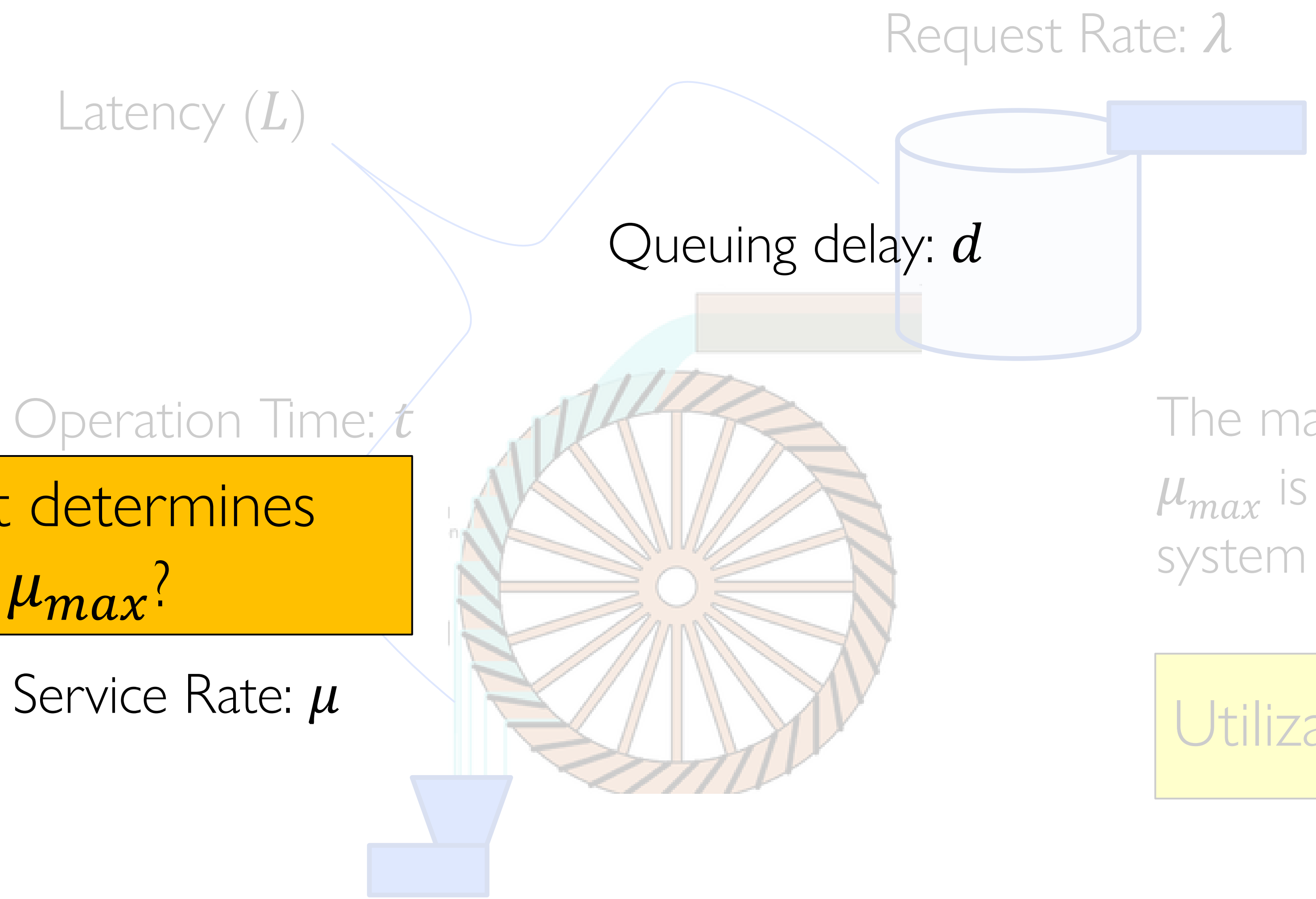
Utilization: $\rho = \frac{\lambda}{\mu_{max}}$

Ideal System Performance

How does μ (service rate) vary with λ (request rate)?



Two Related Questions



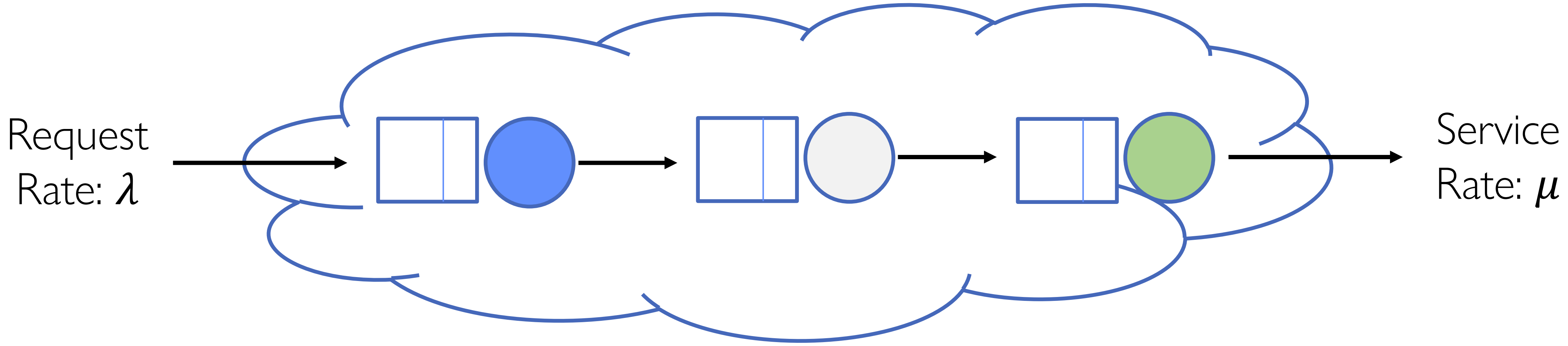
What about "internal" queues?

What determines μ_{max}?

The maximum service rate μ_{max} is a property of the system – the "bottleneck"

Utilization: $\rho = \frac{\lambda}{\mu_{max}}$

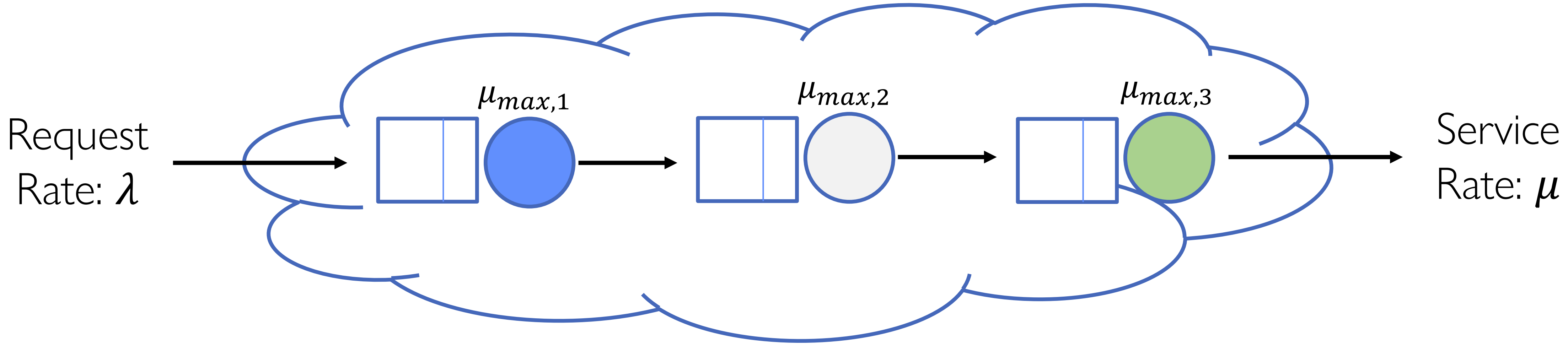
Bottleneck Analysis



Overall System: Series of Stages

Bottleneck Analysis

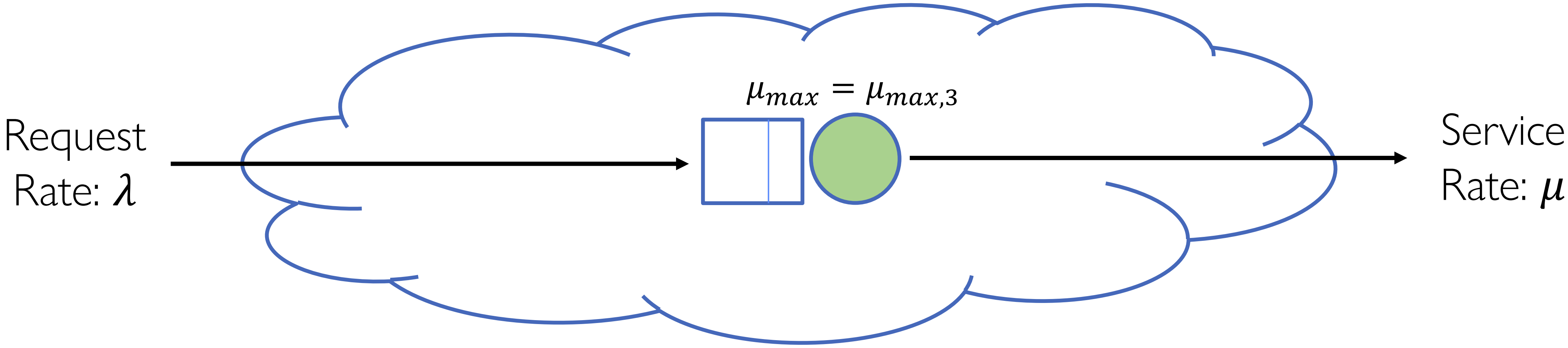
- Each stage has its own queue and maximum service rate
- Suppose the green stage is the bottleneck



Overall System: Series of Stages

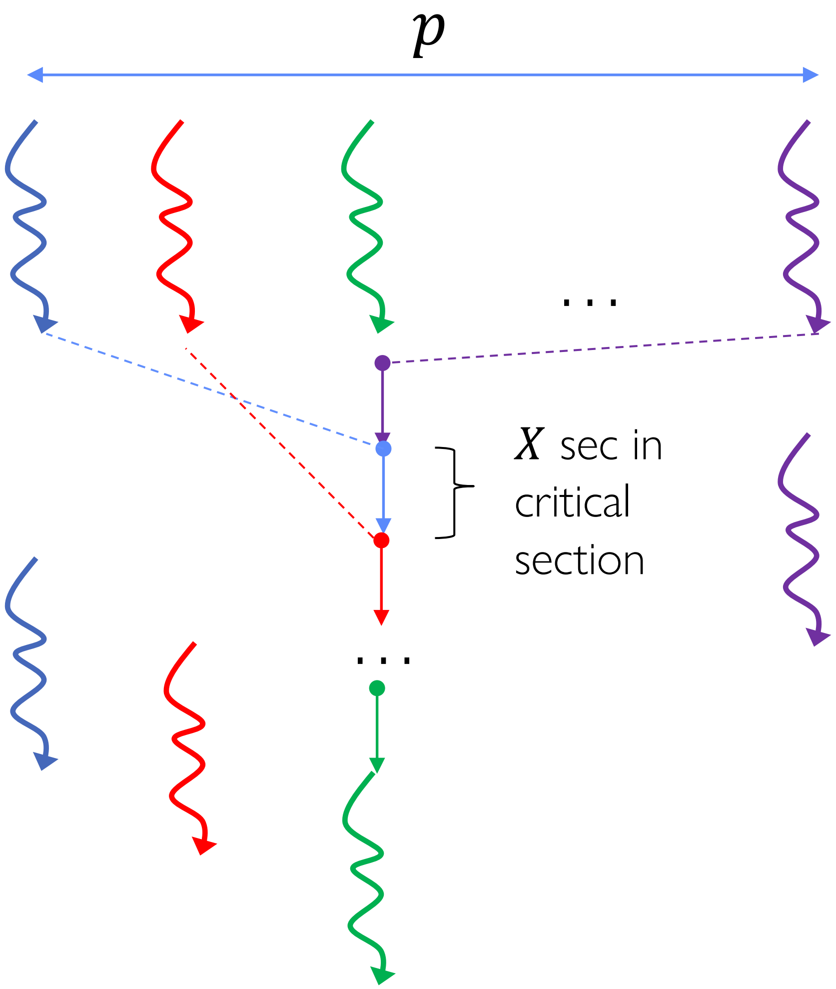
Bottleneck Analysis

- Each stage has its own queue and maximum service rate
- Suppose the green stage is the bottleneck
- The bottleneck stage dictates the maximum service rate μ_{max}



System Model: Bottleneck Stage

Example: Servicing a Highly Contended Lock

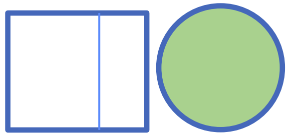


All try to grab lock

Time = $p \cdot X$ sec
Rate = $^1/_X$ ops/sec, regardless of # cores

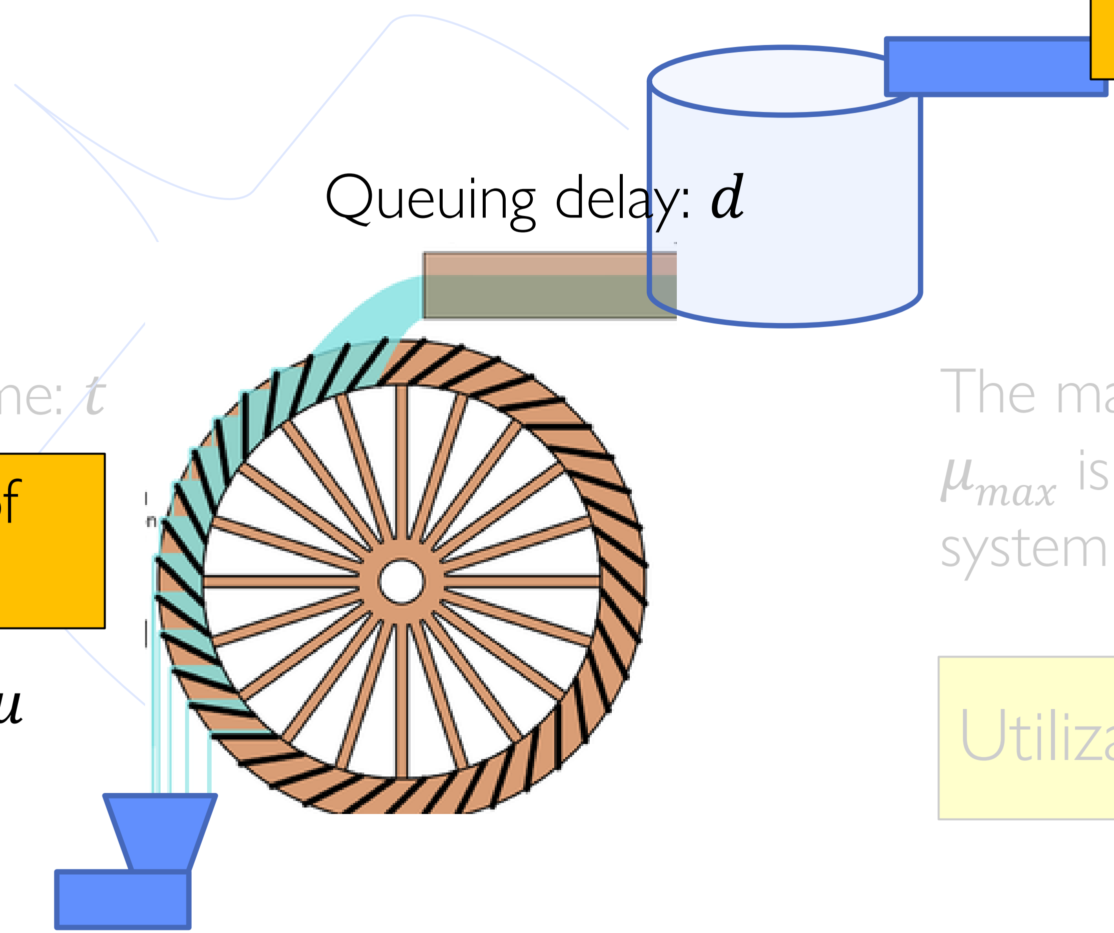
Queue of waiting threads

$\mu_{max} = {^1/_X}$



Critical section guarded by lock

Two Related Questions



Tank represents queue of bottleneck stage

μ_{max} is service rate of bottleneck stage

The maximum service rate μ_{max} is a property of the system – the "bottleneck"

Utilization: $\rho = \frac{\lambda}{\mu_{max}}$

Queuing

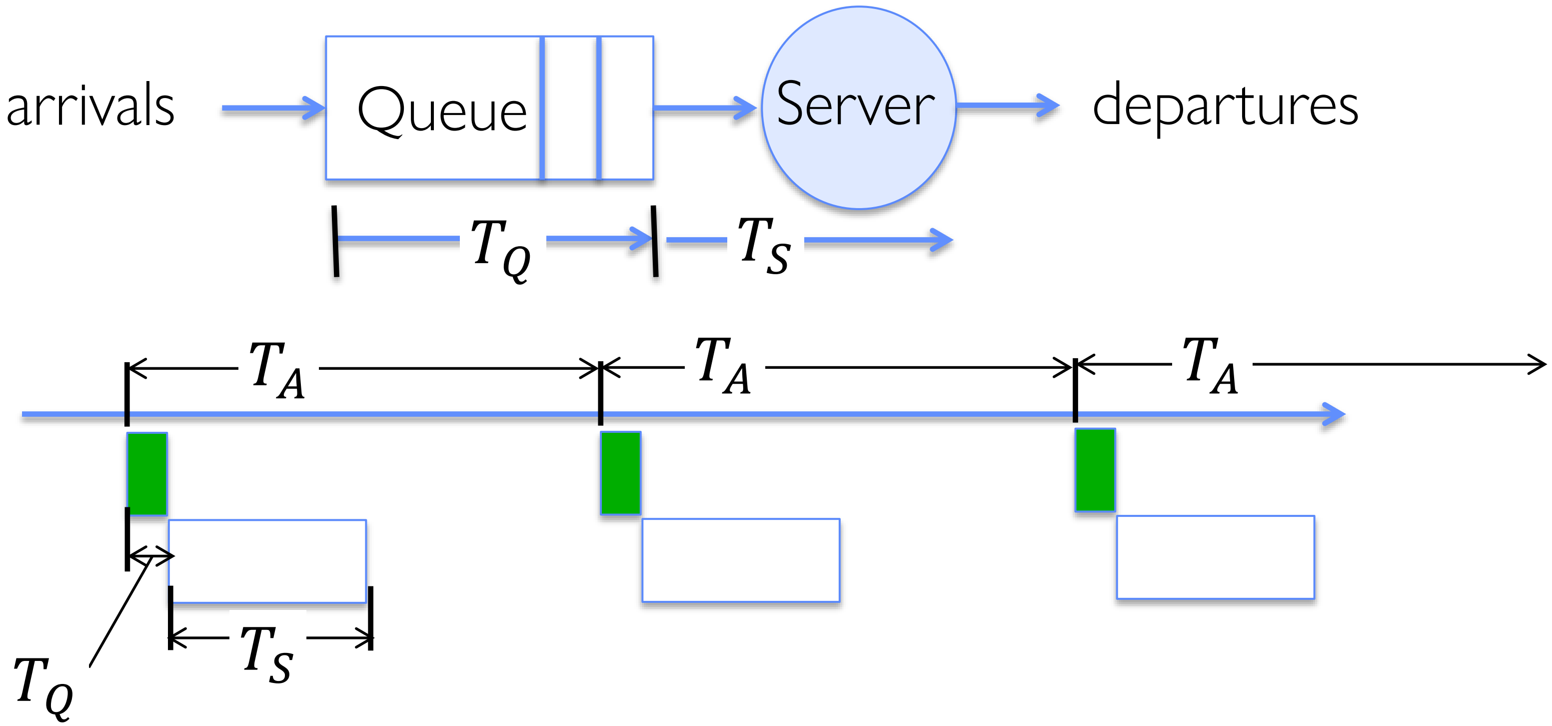
- What happens when request rate (λ) exceeds max service rate (μ_{max})?

- Short bursts can be absorbed by the queue
  - If on average $\lambda < \mu$, it will drain eventually

- Prolonged $\lambda > \mu \rightarrow$ queue will grow without bound

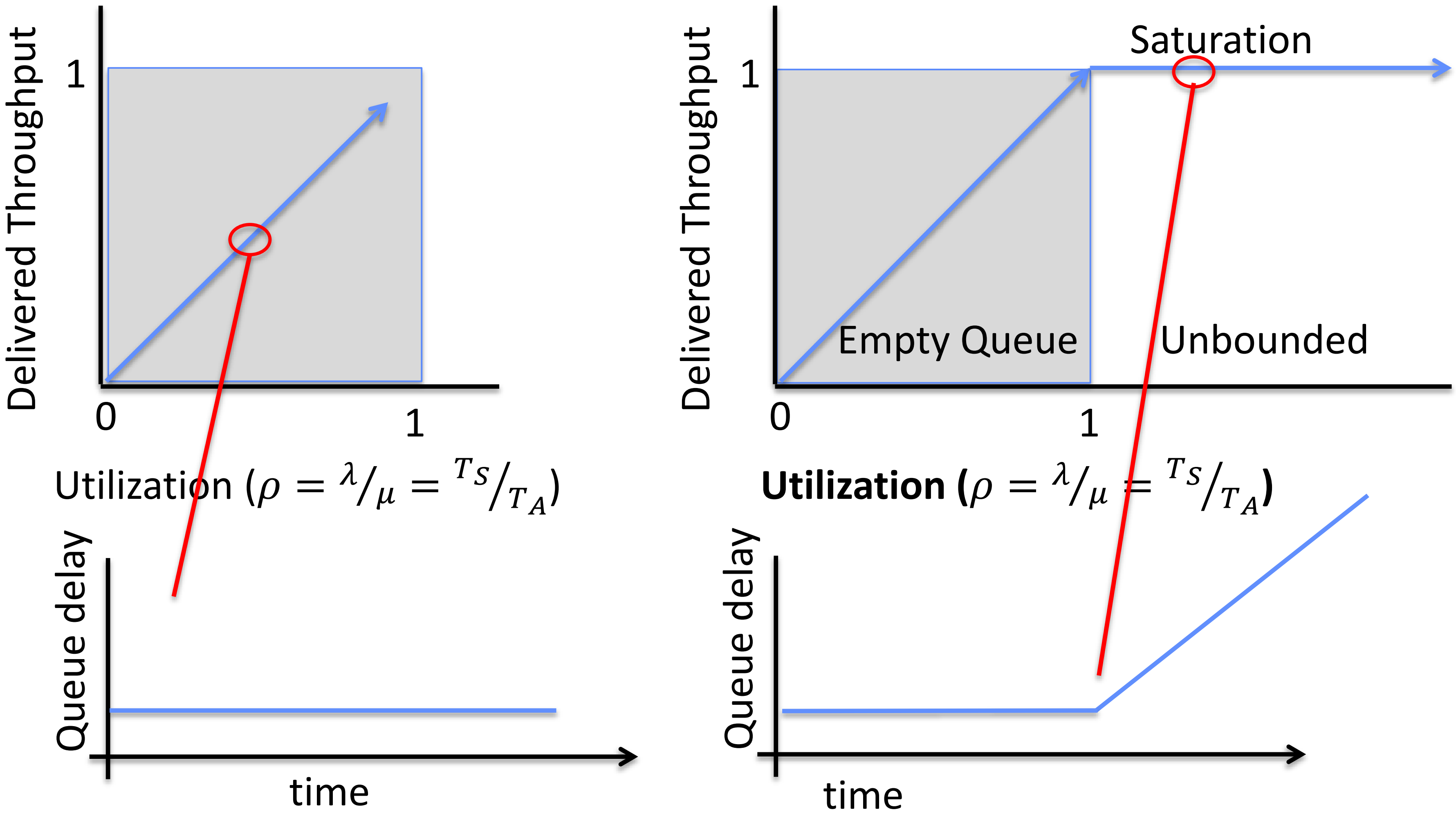
A Simple, Deterministic World

- T_A: time between arrivals
  - $\lambda = 1/T_A$
- T_S: service time
  - $\mu = k/T_S$
- T_Q: queuing time
- $L = T_Q + T_S$



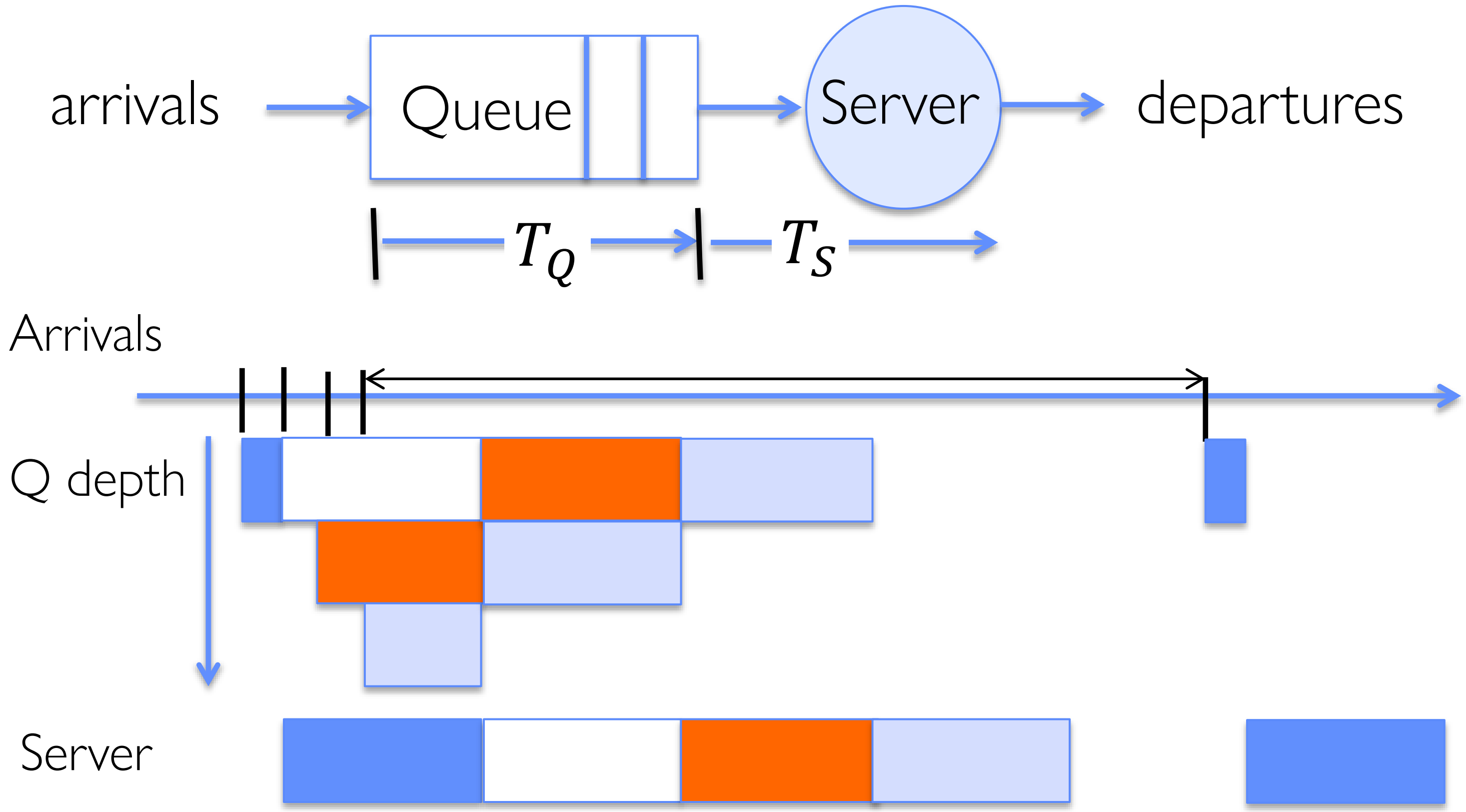
- Assume requests arrive at regular intervals, take a fixed time to process, with plenty of time between …

A Simple, Deterministic World



A Bursty World

- T_A: time between arrivals
  - Now, a random variable
- T_S: service time
  - $\mu = {}^{k}/_{T_S}$
- T_Q: queuing time
  - $L = T_Q + T_S$

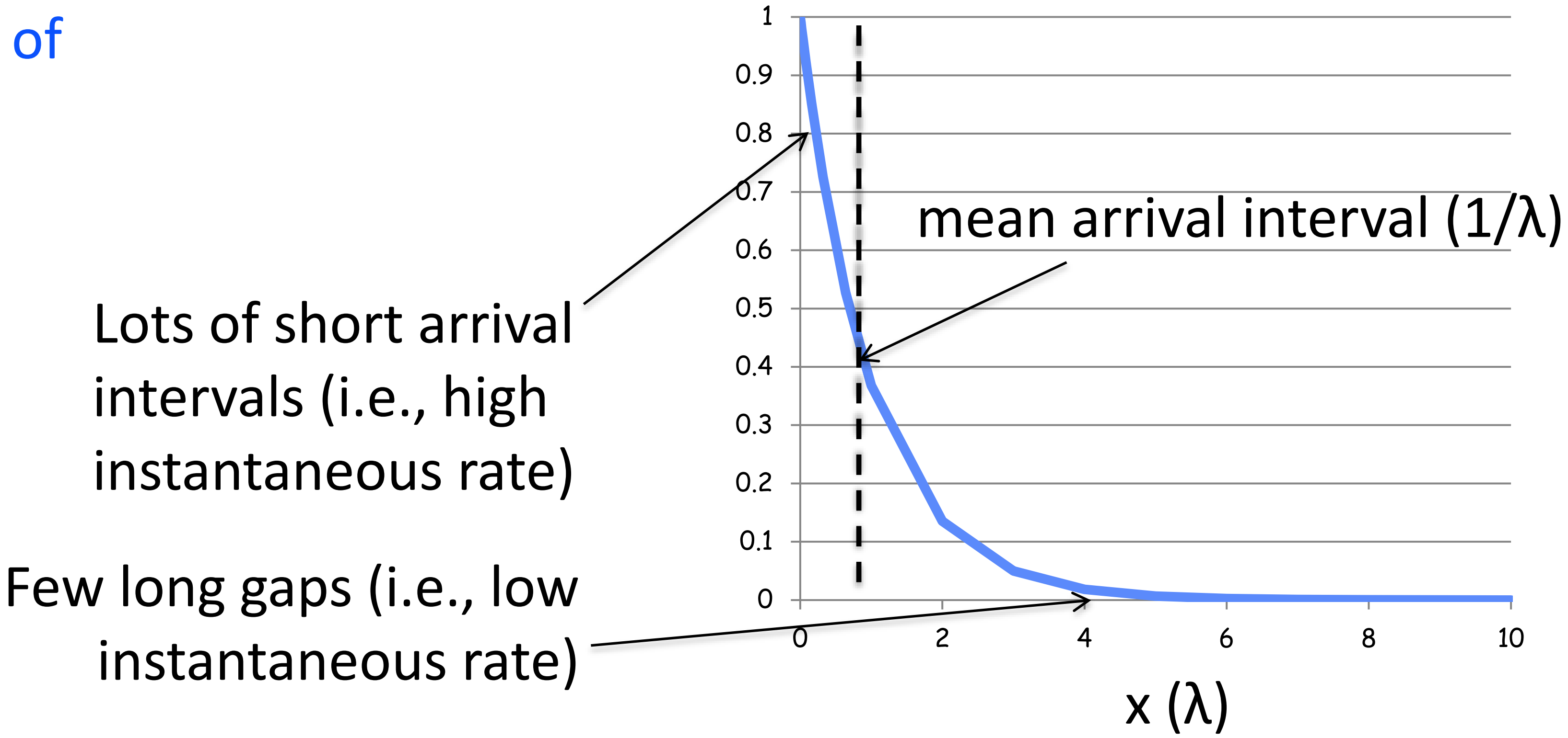


- Requests arrive in a burst, must queue up until served
- Same average arrival time, but almost all of the requests experience large queue delays (even though average utilization is low)

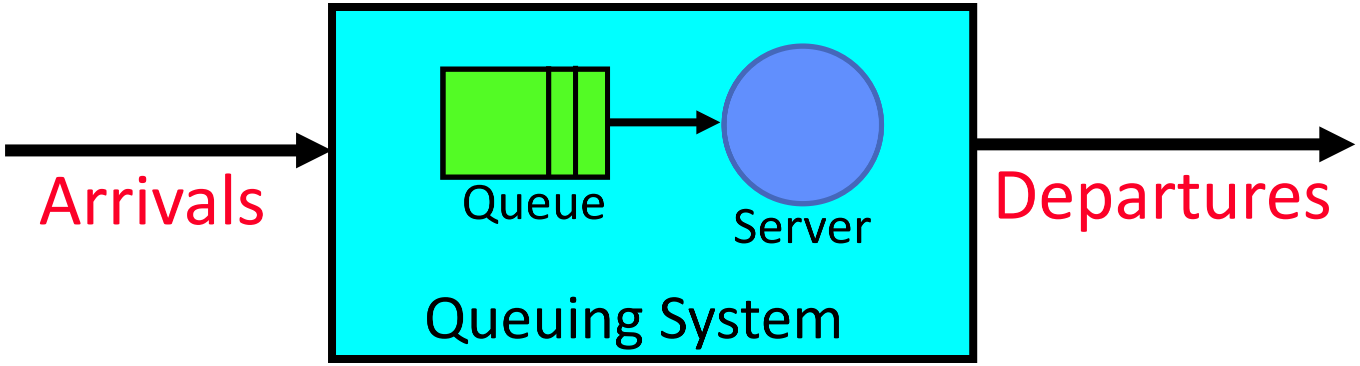
How to model burstiness of arrival?

- T_A, the time between arrivals, is now a random variable
  - Elegant mathematical framework if we model it as an *exponential distribution*
  - Probability distribution function of an exponential distribution with parameter λ is $f(x) = \lambda e^{-\lambda x}$

"Memoryless": Likelihood of an event occurring is independent of how long we've been waiting



Steady State Queuing Theory



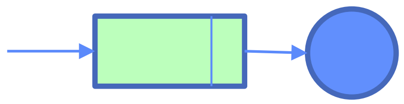
- Queuing Theory applies to long term, steady state behavior
  - Arrival rate = Departure rate

- Arrivals characterized by some probabilistic distribution

- Departures characterized by some probabilistic distribution

Little's Law Applied to a Queue

- When applied to a queue, we get:



$$L_Q = \lambda T_Q$$

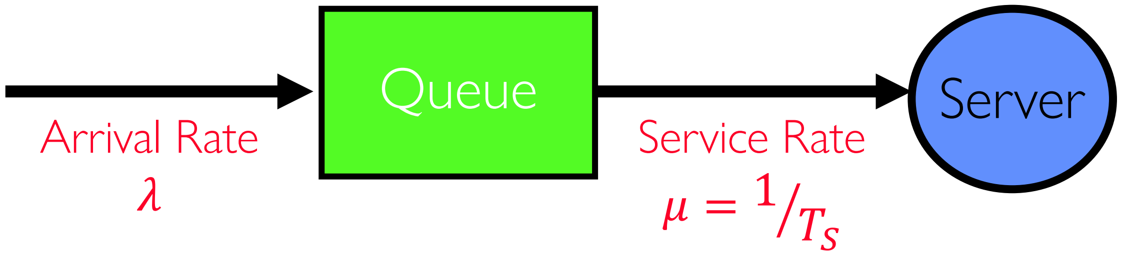
Average Arrival Rate

Average length of the queue

Average time "waiting"

Some Results from Queuing Theory

- Assumptions: system in equilibrium, no limit to the queue, time between successive arrivals is random and memoryless



- λ: arrival rate
- T_S: mean time to service a customer
- C: squared coefficient of variance $({}^{\sigma^2}/_{T_S^2})$
- μ: service rate $({}^{1}/_{T_S})$
- ρ: utilization $({}^{\lambda}/_{\mu})$

Some Results from Queuing Theory

- Memoryless service distribution ($C = 1$)—an "M/M/1 queue":

$$T_Q = \frac{\rho}{1-\rho} \cdot T_S$$

- General service distribution (no restrictions)—an "M/G/1 queue":

$$T_Q = \frac{1+C}{2} \cdot \frac{\rho}{1-\rho} \cdot T_S$$

- λ: arrival rate
- T_S: mean time to service a customer
- C: squared coefficient of variance (σ^2 / T_S^2)
- μ: service rate ($1 / T_S$)
- ρ: utilization (λ / μ)

Some Results from Queuing Theory (con't)

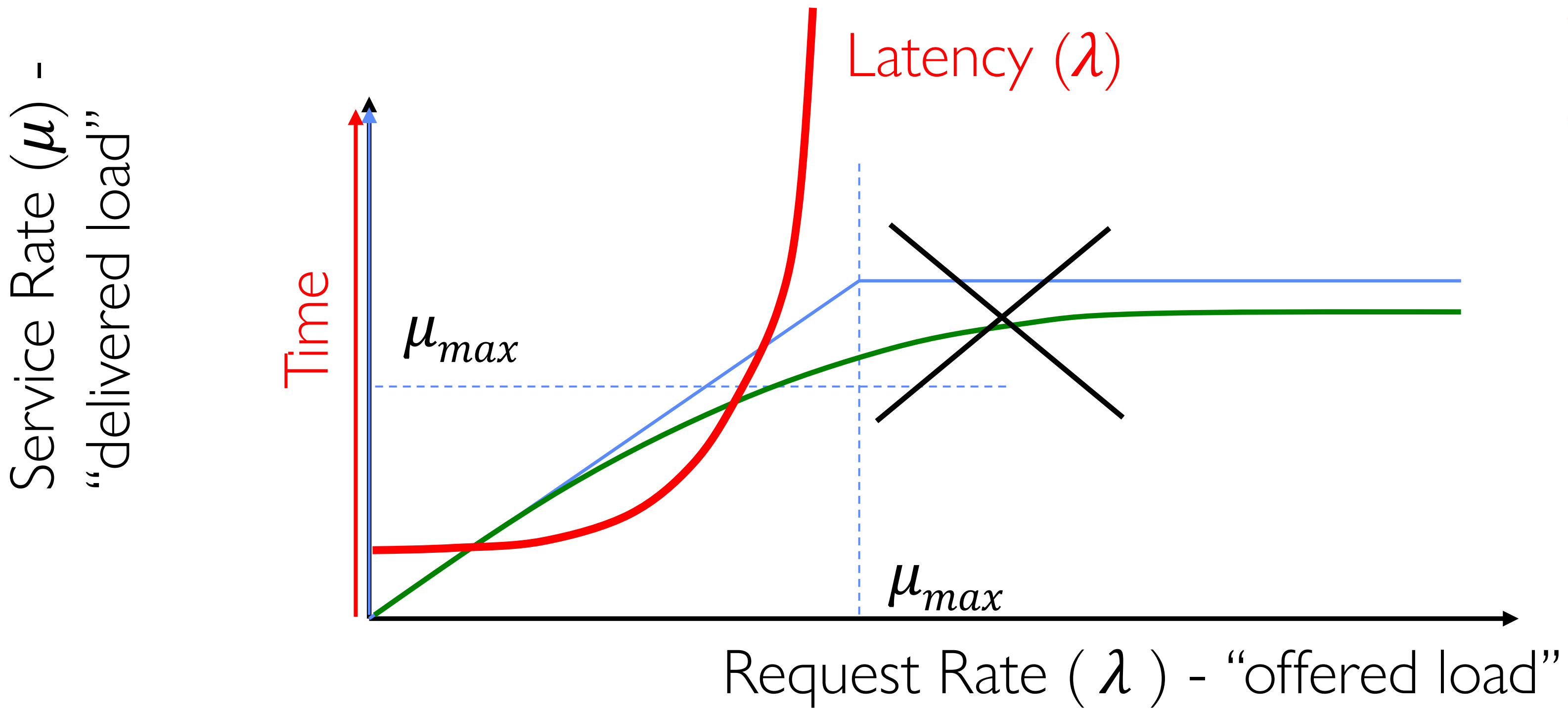
- $T_Q = \frac{\rho}{1-\rho} \cdot T_S$ (memoryless service distribution)

- $L_Q = \lambda T_Q$ (by Little's Law)

Utilization is $\rho = {}^{\lambda}/_{\mu_{max}} = \lambda T_S$, so

- $L_Q = \lambda T_Q = \frac{\rho}{T_S} \cdot T_Q = \frac{\rho^2}{1-\rho}$ (for a single server)

Ideal System Performance



- $T_Q \sim \frac{\rho}{1-\rho}$, $\rho = {}^{\lambda}/_{\mu_{max}}$
- Why does latency blow up as we approach 100% utilization?
  - Queue builds up on each burst
  - But very rarely (or never) gets a chance to drain

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, $\rho = \lambda T_{ser}$
  - 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)

ρ (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

Conclusion

- Two types of storage devices:
  – HDDs, which are organized as a set of platters split into tracks, which are being spinned by a motor. HDDs have suffer from rotational delay and high seek latency
  – SDDs are built on top of flash technology. Flash offers three operations: read, write, program
  – SDDs do not suffer from seek/rotation delay but suffer from wear out.

- Performance
  – Bottleneck & queueing delay
  – Model arrival/departure rate as probability distributions