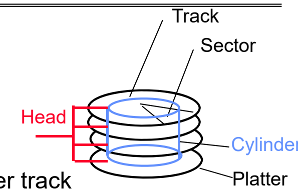
CS162
Operating Systems and Systems Programming
Lecture 21

Filesystems 1: Performance, Queueing Theory, Filesystem Design

April 9th, 2024

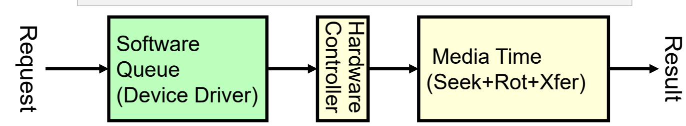
Prof. John Kubiatowicz
http://cs162.eecs.Berkeley.edu

Recall: Magnetic Disks

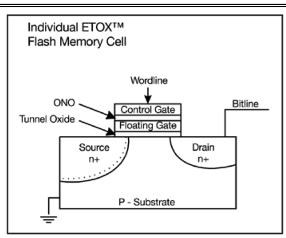


- Cylinders: all the tracks under the head at a given point on all surfaces
- Read/write data is a three-stage process:
  – Seek time: position the head/arm over the proper track
  – Rotational latency: wait for desired sector to rotate under r/w head
  – Transfer time: transfer a block of bits (sector)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

Disk Latency = Queueing Time + Controller time + Seek Time + Rotation Time + Xfer Time



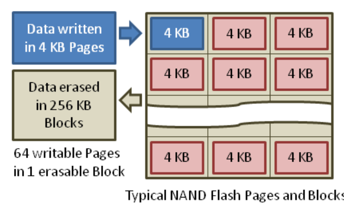
Recall: FLASH Memory

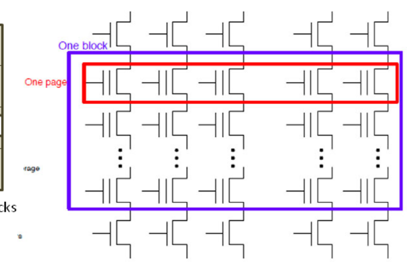


Samsung 2015: 512GB, NAND Flash

- Like a normal transistor but:
  – Has a floating gate that can hold charge
  – To write: raise or lower wordline high enough to cause charges to tunnel
  – To read: turn on wordline as if normal transistor
    » presence of charge changes threshold and thus measured current
- Two varieties:
  – NAND: denser, must be read and written in blocks
  – NOR: much less dense, fast to read and write
- V-NAND: 3D stacking (Samsung claims 1TB possible in 1 chip)

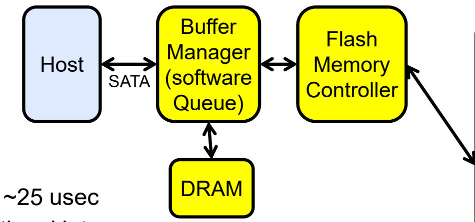
Flash Memory (Con't)

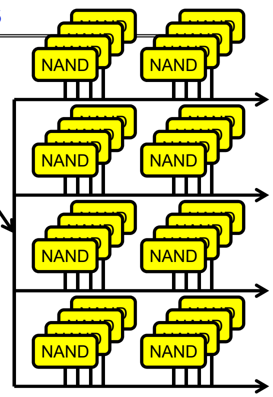




- Data read and written in page-sized chunks (e.g. 4K)
  – Cannot be addressed at byte level
  – Random access at block level for reads (no locality advantage)
  – Writing of new blocks handled in order (kinda like a log)
- Before writing, must be *erased* (256K block at a time)
  – Requires free-list management
  – CANNOT write over existing block (Copy-on-Write is normal case)

SSD Architecture – Reads



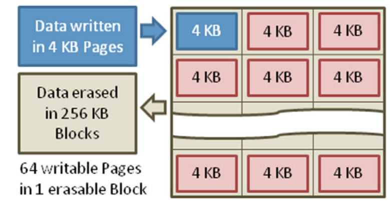


Read 4 KB Page: ~25 usec

- 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

- Writing data to NAND Flash is complex!
  - Can only write empty pages in a block (~ 200μs)
  - 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
- SSDs provide same interface as HDDs: read and write chunk (4KB) 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

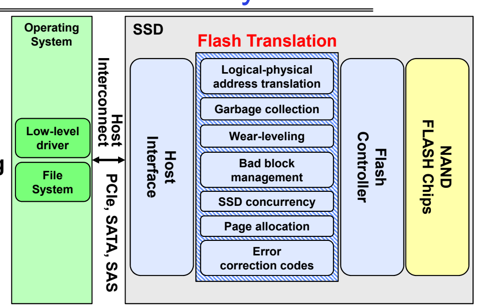


Typical NAND Flash Pages and Blocks

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

Managing Writes: Flash Translation Layer

- Maintain *Flash Translation Layer (FTL)* in SSD
  - Layer of Indirection between OS and FLASH
  - 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**
- FTL advantages/mechanism:
  - Copy on Write: No need to immediately erase entire 256K block when modifying 4K page
    - » Don't overwrite page when OS updates data
    - » Instead, write new version in a free page
    - » Update FTL mapping to point to new location
  - Wear Levelling: Try to wear out NAND evenly
    - » SSD controller can assign mappings to spread workload across pages
  - What to do with old versions of pages?
    - » *Garbage Collection* in background
    - » Erase blocks with old pages, add to free list



Some "Current" (large) 3.5in SSDs

- Seagate Exos SSD: 15.36TB (2017)
  - Dual 12Gb/s interface
  - Seq reads 860MB/s
  - Seq writes 920MB/s
  - Random Reads (IOPS): 102K
  - Random Writes (IOPS): 15K
  - Price (Amazon): $5495 ($0.36/GB)
- Nimbus SSD: 100TB (2019)
  - Dual port: 12Gb/s interface
  - 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)

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 can measure (it can measure 10^{-9} grams)
- Of course, this weight difference overwhelmed by battery discharge, weight from getting warm, ….
- Source: John Kubiatowicz (New York Times, Oct 24, 2011)

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 (3-20x disk)
    - » Hybrid alternative: combine small SSD with large HDD

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- Cons
  - ~~Small storage (0.1-0.5x disk), expensive (3-20x disk)~~ **No longer true!**
    - » 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!

Administrivia (4/9/2024)

- Midterm 3: Thursday April 25th
  - All topics up to an including lecture on the 23rd
  - 3 sheets of notes, double-sided
- Extra (fun!) lecture on Tuesday April 30th
  - Topics TBA
- Class attendance: No credit for people who use the same photo!
- Data4All@Berkeley: This Friday!
  - Friday 4/12, 12:00-1:00 in Soda 510
  - Undergraduate or Masters students interested in Systems broadly defined (DB, Arch, Sec, Networking, Systems, etc.) who identify as an URM in Computer Science
  - Come by for free lunch to meet fellow interested students
  - Talk to relevant faculty, discuss possible classes, research opportunities in systems, as well as the best pizza topping!

https://tinyurl.com/3r3cj3ya

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

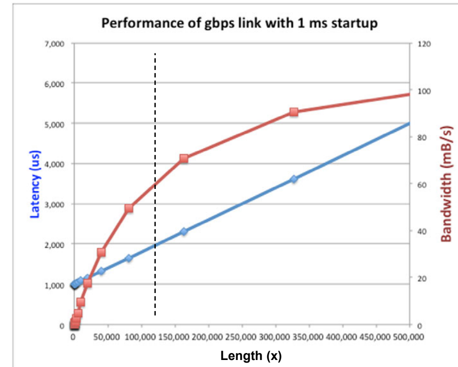
- ***Latency*** – time to complete a task
  - Measured in units of time (s, ms, us, …, hours, years)
- ***Response Time*** - time to initiate and operation and get its response
  - Able to issue one that *depends* on the result
  - Know that it is done (anti-dependence, resource usage)
- ***Throughput*** 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
- Performance???
  - Operation time (4 mins to run a mile…)
  - Rate (mph, mpg, …)

Example: Overhead in Fast Network

- Consider a $1\ \mathrm{Gb/s}$ link ($B_w = 125\ \mathrm{MB/s}$) with startup cost $S = 1\ \mathrm{ms}$
- Latency: $L(x) = S + \frac{x}{B_w}$
- Effective Bandwidth:

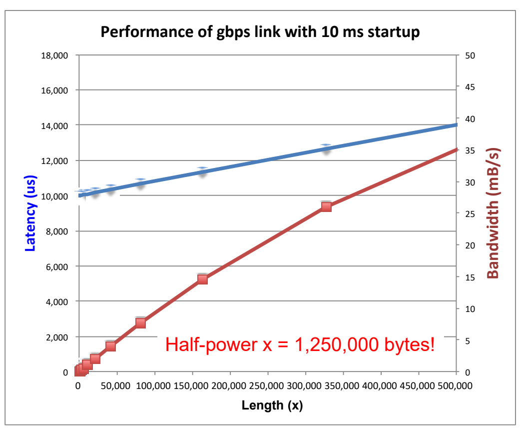
$$E(x) = \frac{x}{S + \frac{x}{B_w}} = \frac{B_w \cdot x}{B_w \cdot S + x} = \frac{B_w}{\frac{B_w \cdot S}{x} + 1}$$

- Half-power Bandwidth: $E(x) = \frac{B_w}{2}$
- For this example, half-power bandwidth occurs at x = $125\ \mathrm{KB}$



Example: 10 ms Startup Cost (e.g., Disk)

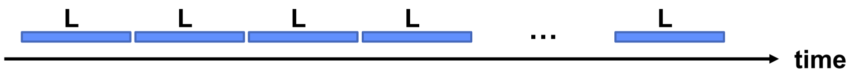
- Half-power bandwidth at $\mathrm{x} = 1.25\ \mathrm{MB}$
- Large startup cost can degrade effective bandwidth
- Amortize it by performing I/O in larger blocks



What Determines Peak BW for I/O?

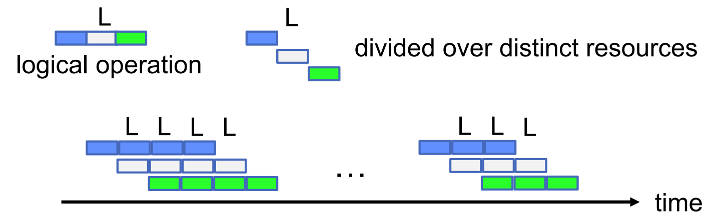
- Bus Speed
  - PCI-X: 1064 MB/s = 133 MHz x 64 bit (per lane)
  - ULTRA WIDE SCSI: 40 MB/s
  - Serial Attached SCSI & Serial ATA & IEEE 1394 (firewire): 1.6 Gb/s full duplex (200 MB/s)
  - USB 3.0 – 5 Gb/s
  - Thunderbolt 3 – 40 Gb/s
- Device Transfer Bandwidth
  - Rotational speed of disk
  - Write / Read rate of NAND flash
  - Signaling rate of network link
- Whatever is the bottleneck in the path…

Sequential Server Performance



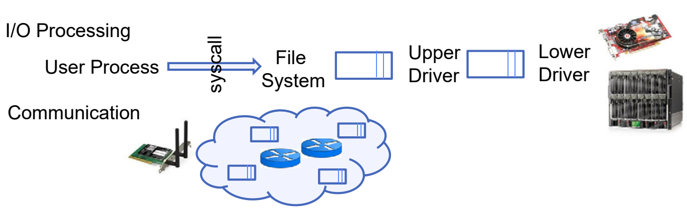
- Single sequential "server" that can deliver a task in time L operates at rate $\leq \frac{1}{L}$ (on average, in steady state, …)
  - $L = 10$ ms $\rightarrow B = 100$ $^{\text{op}}/_{\text{s}}$
  - $L = 2$ yr $\rightarrow B = 0.5$ $^{\text{op}}/_{\text{yr}}$
- Applies to a processor, a disk drive, a person, a TA, …

Single Pipelined Server



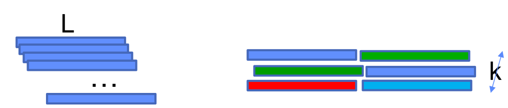
- Single pipelined server of k stages for tasks of length L (i.e., time $^{L}/_{k}$ per stage) delivers at rate $\leq {}^{k}/_{L}$.
  - $L = 10$ ms, $k = 4 \rightarrow B = 400$ $^{\text{op}}/_{\text{s}}$
  - $L = 2$ yr, $k = 2 \rightarrow B = 1$ $^{\text{op}}/_{\text{yr}}$

Example Systems "Pipelines"



- Anything with queues between operational process behaves roughly "pipeline like"
- Important difference is that "initiations" are decoupled from processing
  - May have to queue up a burst of operations
  - Not synchronous and deterministic like in 61C

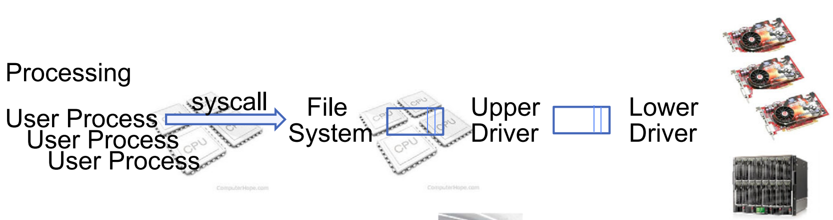
Multiple Servers



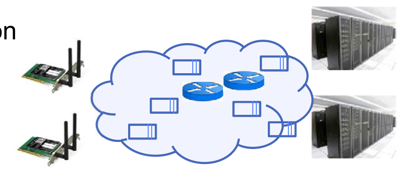
- k servers handling tasks of length L delivers at rate $\leq {}^{k}/_{L}$.
  - $L = 10$ ms, $k = 4 \rightarrow B = 400$ $^{\text{op}}/_{\text{s}}$
  - $L = 2$ yr, $k = 2 \rightarrow B = 1$ $^{\text{op}}/_{\text{yr}}$
- In 61C you saw multiple processors (cores)
  - Systems present lots of multiple parallel servers
  - Often with lots of queues

Example Systems “Parallelism”

I/O Processing

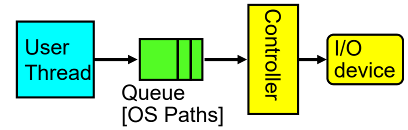


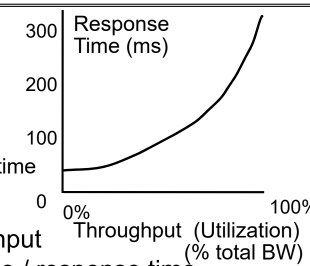
Communication



Parallel Computation, Databases, …

I/O Performance





Response Time = Queue + I/O device service time

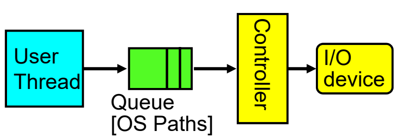
- Performance of I/O subsystem
  - Metrics: Response Time, Throughput
  - Effective BW per op = transfer size / response time
    - » EffBW(n) = n / (S + n/B) = B / (1 + SB/n)

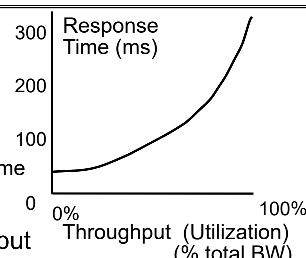
# of ops

Fixed overhead

time per op

I/O Performance





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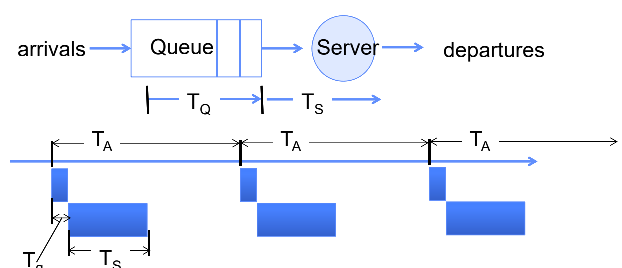
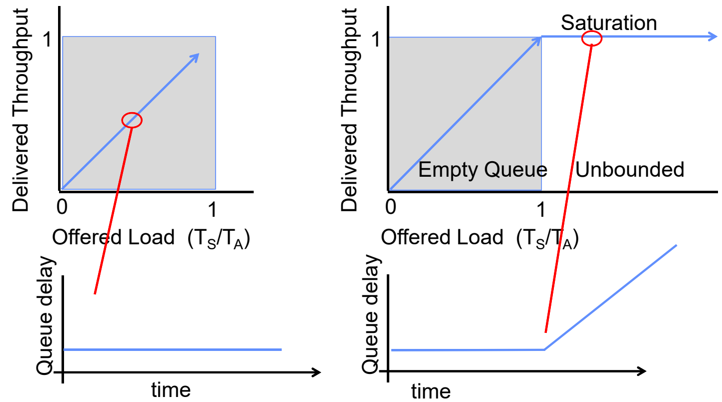
- Performance of I/O subsystem
  - Metrics: Response Time, Throughput
  - Effective BW per op = transfer size / response time
    - » EffBW(n) = n / (S + n/B) = B / (1 + SB/n)
  - Contributing factors to latency:
    - » Software paths (can be loosely modeled by a queue)
    - » Hardware controller
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

A Simple Deterministic World



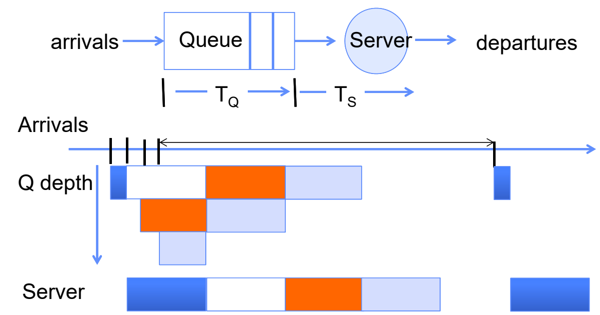
- Assume requests arrive at regular intervals, take a fixed time to process, with plenty of time between …
- Service rate ($\mu = 1/T_S$) - operations per second
- Arrival rate: ($\lambda = 1/T_A$) - requests per second
- Utilization: $U = \lambda/\mu$, where $\lambda < \mu$
- Average rate is the complete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

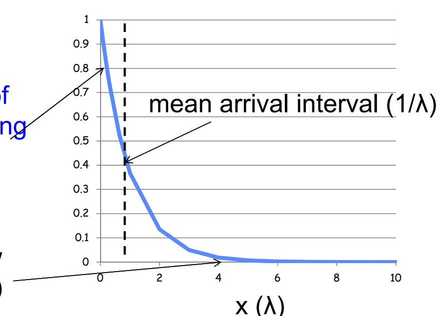
So how do we model the burstiness of arrival?

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

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

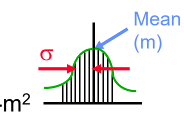
Lots of short arrival intervals (i.e., high instantaneous rate)

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



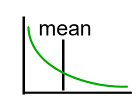
Background: General Use of Random Distributions

- Server spends variable time (T) with customers
  – Mean (Average) $m = \Sigma p(T) \times T$
  – Variance (stddev²) $\sigma^2 = \Sigma p(T) \times (T-m)^2 = \Sigma p(T) \times T^2 - m^2$
  – Squared coefficient of variance: $C = \sigma^2/m^2$
  Aggregate description of the distribution



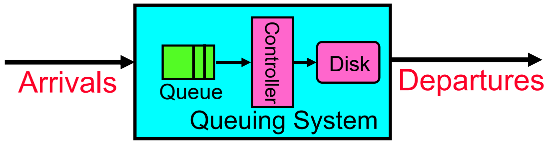
Distribution of service times

- Important values of C:
  – No variance or deterministic ⇒ $C=0$
  – "Memoryless" or exponential ⇒ $C=1$
    » Past tells nothing about future
    » Poisson process – *purely* or *completely* random process
    » Many complex systems (or aggregates) are well described as memoryless
  – Disk response times $C \approx 1.5$ (majority seeks < average)



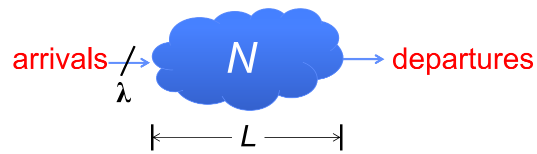
Memoryless

Introduction to Queuing Theory



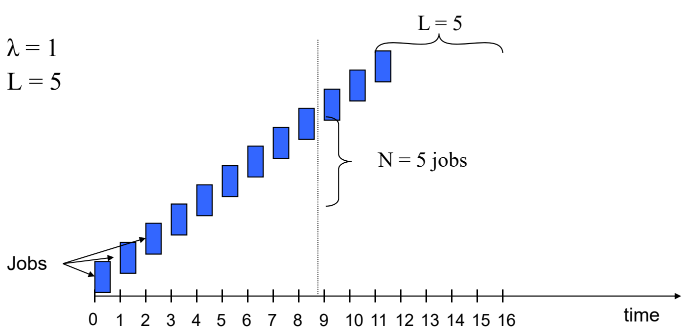
- What about queuing time??
  - Let's apply some queuing theory
  - Queuing Theory applies to long term, steady state behavior ⇒ Arrival rate = Departure rate
- Arrivals characterized by some probabilistic distribution
- Departures characterized by some probabilistic distribution

Little's Law



- In any *stable* system
  - Average arrival rate = Average departure rate
- The average number of jobs/tasks in the system (N) is equal to arrival time / throughput (λ) times the response time (L)
  - *N (jobs) = λ (jobs/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

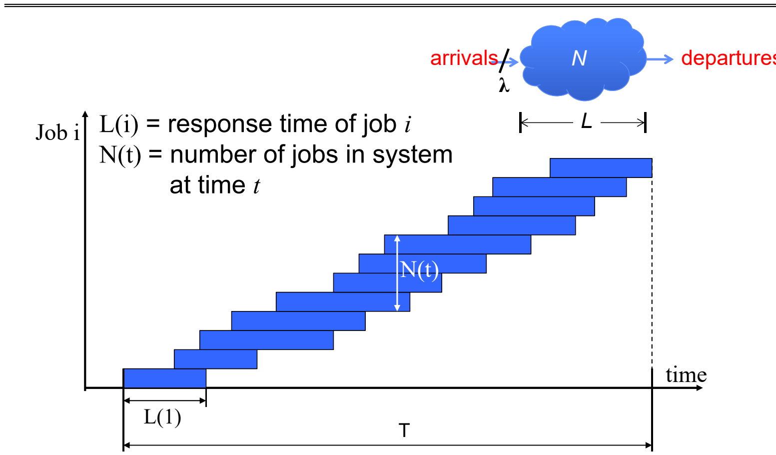
Example



A: $N = \lambda \times L$

- E.g., $N = \lambda \times L = 5$

Little's Theorem: Proof Sketch



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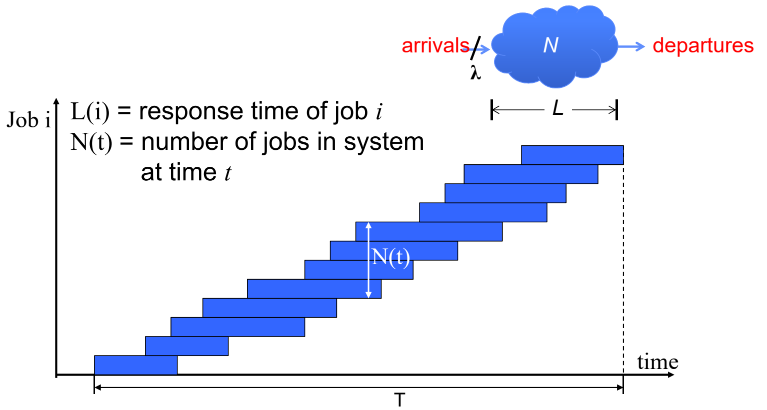
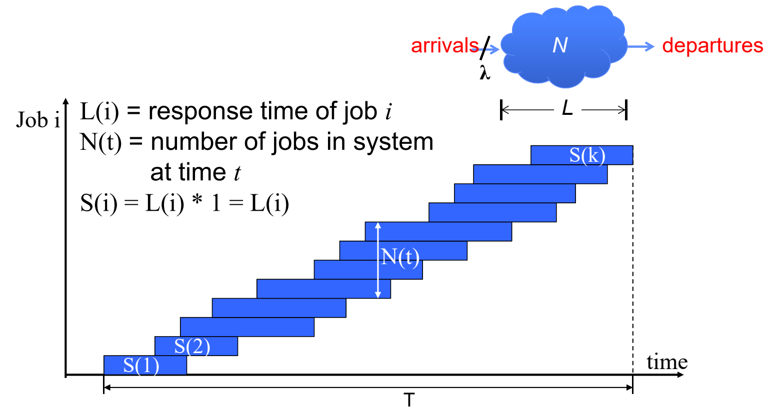


L(i) = response time of job *i*
N(t) = number of jobs in system at time *t*

- What is the system occupancy, i.e., average number of jobs in the system?

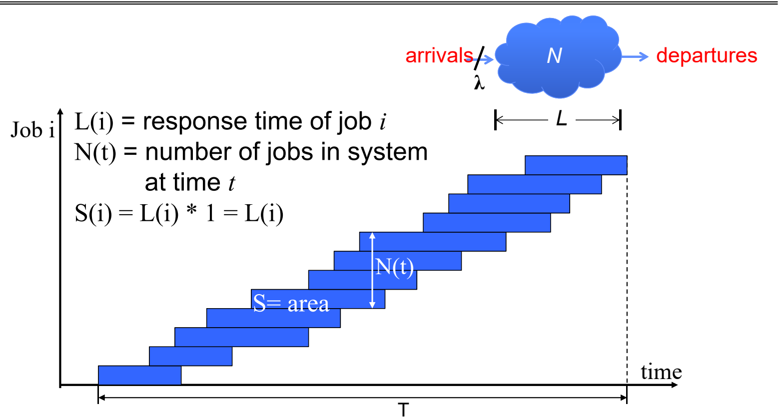
Little's Theorem: Proof Sketch



L(i) = response time of job *i*
N(t) = number of jobs in system at time *t*
S(i) = L(i) * 1 = L(i)

$S = S(1) + S(2) + \ldots + S(k) = L(1) + L(2) + \ldots + L(k)$

Little's Theorem: Proof Sketch



L(i) = response time of job *i*
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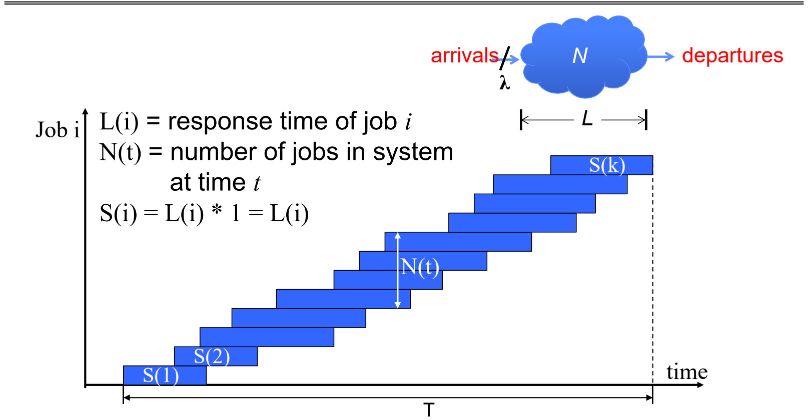
- Average occupancy (N_{avg}) = S/T

Little's Theorem: Proof Sketch



L(i) = response time of job *i*
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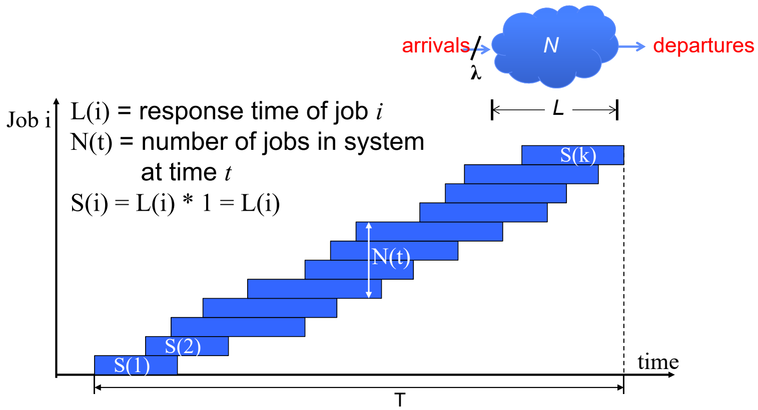
S(i) = L(i) * 1 = L(i)

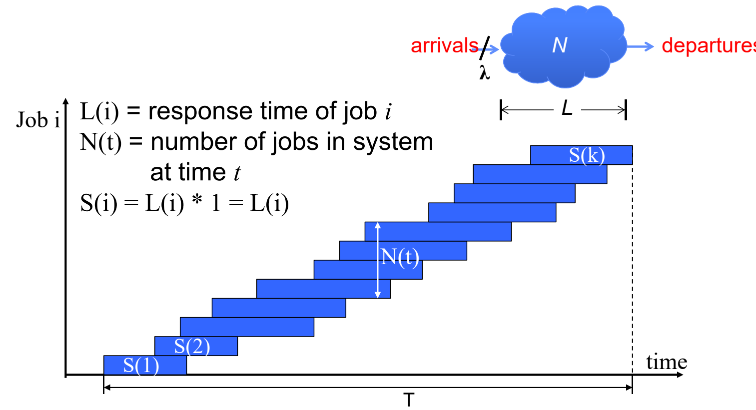
$N_{avg} = S/T = (L(1) + \ldots + L(k))/T$

Little's Theorem: Proof Sketch



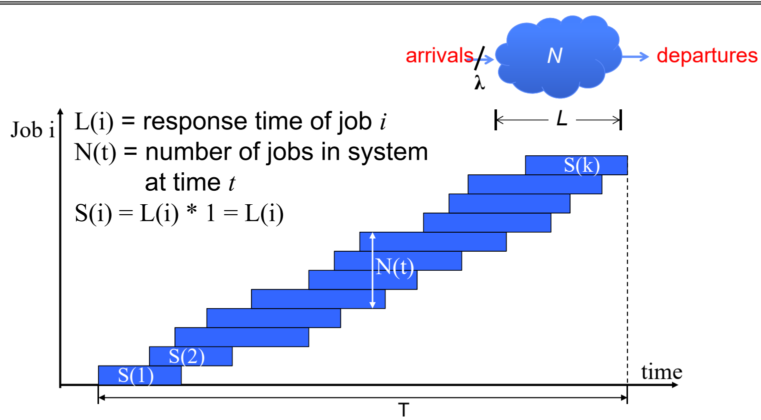
$N_{avg} = (L(1) + \ldots + L(k))/T = (N_{total}/T)*(L(1) + \ldots + L(k))/N_{total}$

Little's Theorem: Proof Sketch



$N_{avg} = (N_{total}/T)*(L(1) + \ldots + L(k))/N_{total} = \lambda_{avg} \times L_{avg}$

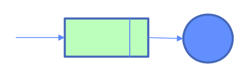
Little's Theorem: Proof Sketch



$N_{avg} = \lambda_{avg} \times L_{avg}$

Little's Law Applied to a Queue

- When Little's Law applied to a queue, we get:



$$L_Q = \lambda T_Q$$

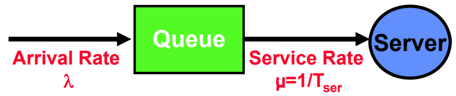
Average Arrival Rate

Average length of the queue

Average time "waiting" in queue

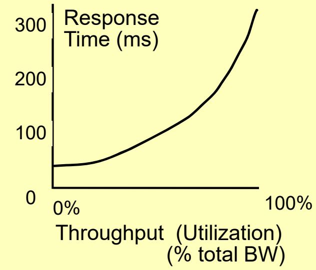
A Little Queuing Theory: Computing T_Q

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

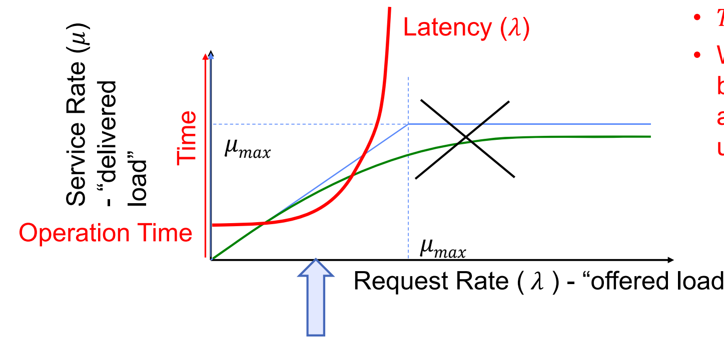


- Parameters that describe our system:
  - λ: mean number of arriving customers/seco
  - T_{ser}: mean time to service a customer ("m
  - C: squared coefficient of variance
  - μ: service rate = $1/T_{ser}$
  - u: server utilization (0≤u ...): u = λ/μ = λ × T_s
- Results:
  - Memoryless service distribution (C = 1): (an "M/M/1 queue"):
    - » $T_q = T_{ser} \times u/(1 - u)$
  - General service distribution ... server (an "M/G/1 queue"):
    - » $T_q = T_{ser} \times ½(1+C) \times u/(1 - u)$

Why does response/queueing delay grow unboundedly even though the utilization is < 1 ?



System Performance In presence of a Queue

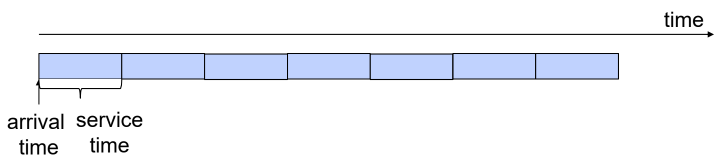


- $T_Q \sim \frac{u}{1-u}$, $u = \lambda/\mu_{max}$
- Why does latency blow up as we approach 100% utilization?
  - Queue builds up on each burst
  - But very rarely (or never) gets a chance to drain

"Half-Power Point" : load at which system delivers half of peak performance
- Design and provision systems to operate roughly in this regime
- Latency low and predictable, utilization good: ~50%

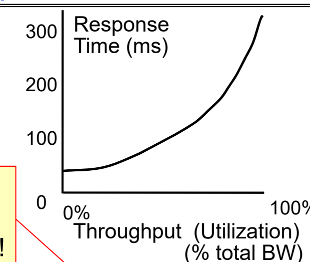
Why unbounded response time?

- Assume deterministic arrival process and service time
  - Possible to sustain utilization = 1 with bounded response time!

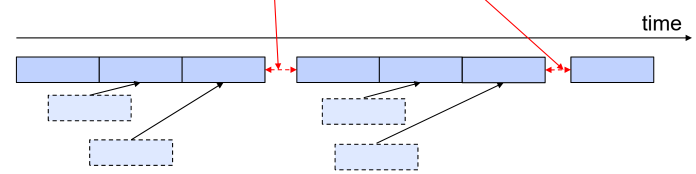


Why unbounded response time?

- Assume stochastic arrival process (and service time)
  - No longer possible to achieve utilization = 1



This wasted time can never be reclaimed! So cannot achieve u = 1!



A Little Queuing Theory: An Example

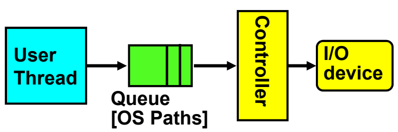
- Example Usage Statistics:
  - User requests 10 x 8KB disk I/Os per second
  - Requests & service exponentially distributed (C=1.0)
  - Avg. service = 20 ms (From controller+seek+rot+trans)
- Questions:
  - How utilized is the disk?
    - » Ans: server utilization, $u = \lambda T_{ser}$
  - What is 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

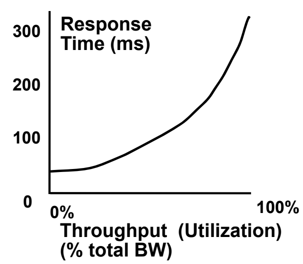
Queuing Theory Resources

- Resources page contains Queueing Theory Resources (under Readings):
  - Scanned pages from Patterson and Hennessy book that gives further discussion and simple proof for general equation: https://cs162.eecs.berkeley.edu/static/readings/patterson_queue.pdf
  - A complete website full of resources: http://web2.uwindsor.ca/math/hlynka/qonline.html
- Some previous midterms with queueing theory questions
- Assume that Queueing Theory is fair game for Midterm III!

Optimize I/O Performance

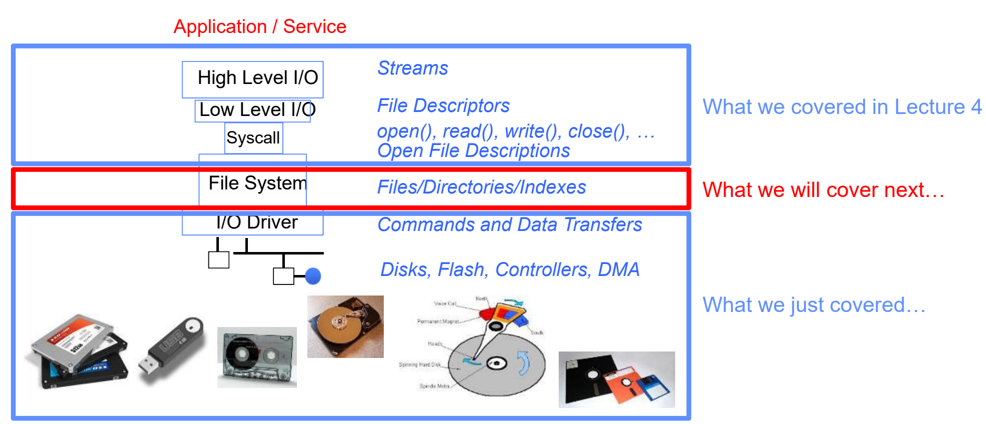


Response Time = Queue + I/O device service time

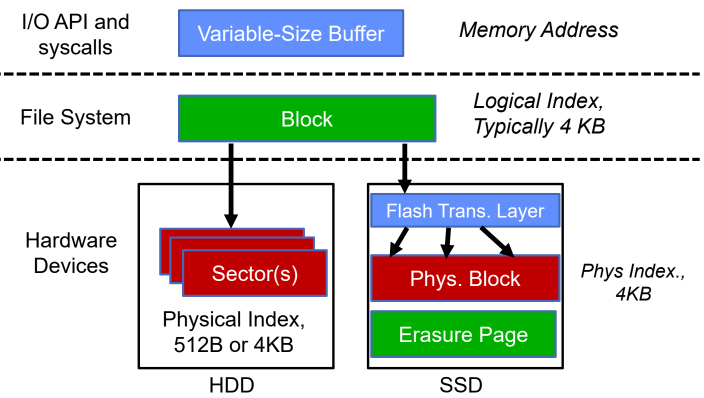


- How to improve performance?
  - Make everything faster ☺
  - More Decoupled (Parallelism) systems
    - » multiple independent buses or controllers
  - Optimize the bottleneck to increase service rate
    - » Use the queue to optimize the service
  - Do other useful work while waiting
- Queues absorb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

Recall: I/O and Storage Layers



From Storage to File Systems



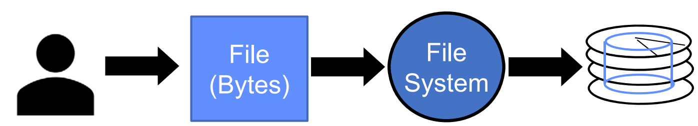
Building a File System

- File System: Layer of OS that transforms block interface of disks (or other block devices) into Files, Directories, etc.
- Classic OS situation: Take limited hardware interface (array of blocks) and provide a more convenient/useful interface with:
  - Naming: Find file by name, not block numbers
  - Organize file names with directories
  - Organization: Map files to blocks
  - Protection: Enforce access restrictions
  - Reliability: Keep files intact despite crashes, hardware failures, etc.

Recall: 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

Translation 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 writing bytes 2 – 12?
  - Fetch block, modify relevant portion, write out block
- Everything inside file system is in terms of whole-size blocks
  - Actual disk I/O happens in blocks
  - read/write smaller than block size needs to translate and buffer

Disk Management

- Basic entities on a disk:
  - File: user-visible group of blocks arranged sequentially in logical space
  - Directory: user-visible index mapping names to files
- The disk is accessed as linear array of sectors
- How to identify a sector?
  - Physical position
    - » Sectors is a vector [cylinder, surface, sector]
    - » Not used anymore
    - » OS/BIOS must deal with bad sectors
  - Logical Block Addressing (LBA)
    - » Every sector has integer address
    - » Controller translates from address ⇒ physical position
    - » Shields OS from structure of disk

What Does the File System Need?

- Track free disk blocks
  - Need to know where to put newly written data
- Track which blocks contain data for which files
  - Need to know where to read a file from
- Track files in a directory
  - Find list of file's blocks given its name
- Where do we maintain all of this?
  - Somewhere on disk

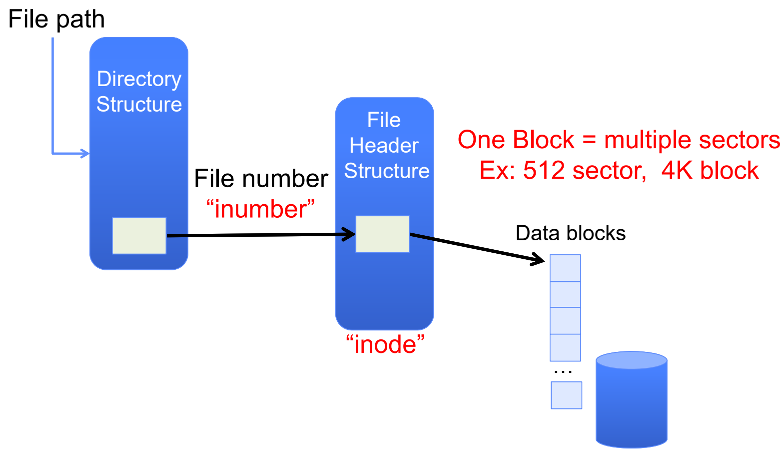
Data Structures on Disk

- Somewhat different from data structures in memory
- Access a block at a time
  - Can't efficiently read/write a single word
  - Have to read/write full block containing it
  - Ideally want sequential access patterns
- Durability
  - Ideally, file system is in meaningful state upon shutdown
  - This obviously isn't always the case…

Critical Factors in File System Design

- (Hard) Disks Performance !!!
  - Maximize sequential access, minimize seeks
- Open before Read/Write
  - Can perform protection checks and look up where the actual file resource are, in advance
- Size is determined as they are used !!!
  - Can write (or read zeros) to expand the file
  - Start small and grow, need to make room
- Organized into directories
  - What data structure (on disk) for that?
- Need to carefully allocate / free blocks
  - Such that access remains efficient

Components of a File System



Conclusion

- Devices have complex interaction and performance characteristics
  - Response time (Latency) = Queue + Overhead + Transfer
    - » Effective BW = BW * T/(S+T)
  - HDD: Queuing time + controller + seek + rotation + transfer
  - SSD: Queuing time + controller + transfer (erasure & wear)
- Bursts & High Utilization introduce queuing delays
- Queuing Latency:
  - M/M/1 and M/G/1 queues: simplest to analyze
  - As utilization approaches 100%, latency $\rightarrow \infty$

$$T_q = T_{ser} \times ½(1+C) \times u/(1 - u))$$

- File System:
  - Transforms blocks into Files and Directories
  - Optimize for access and usage patterns
  - Maximize sequential access, allow efficient random access