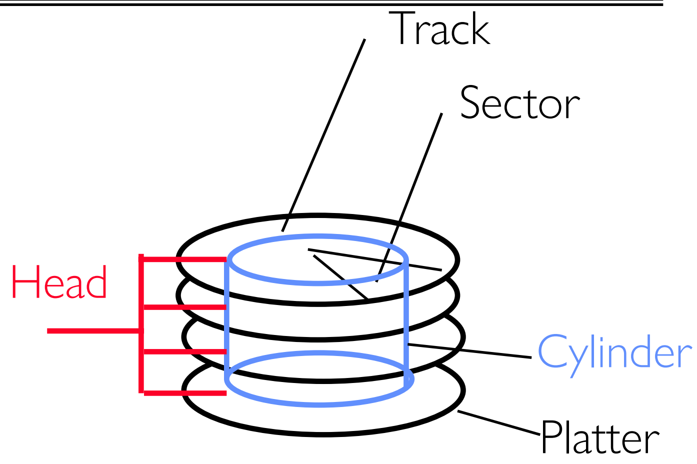
CSC 112: Computer Operating Systems
Lecture 19

Filesystems 1: Performance (Con’t), Queueing Theory, Filesystem Design

Department of Computer Science,
Hofstra University

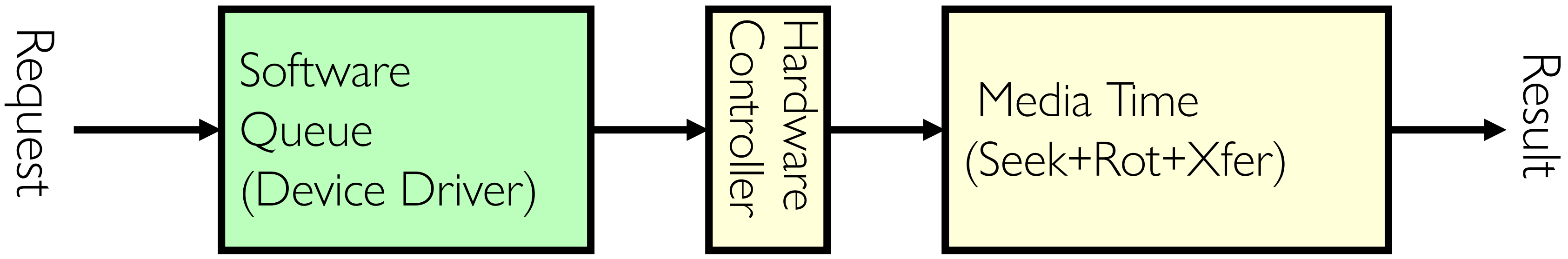
Acknowledgement: Lecture slides based on UC Berkeley CS 162: Operating Systems and System Programming

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

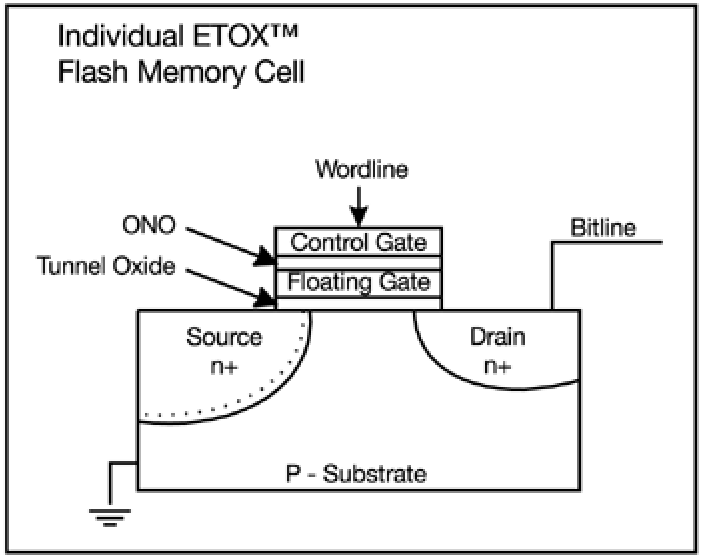
Disk Latency = Queueing Time + Controller time +
Seek Time + Rotation Time + Xfer Time



Recall: Typical Numbers for Magnetic Disk

Parameter	Info/Range
Space/Density	Space: 18TB (Seagate), 9 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

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)

Recall: 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)
    - » 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!

No longer true!

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

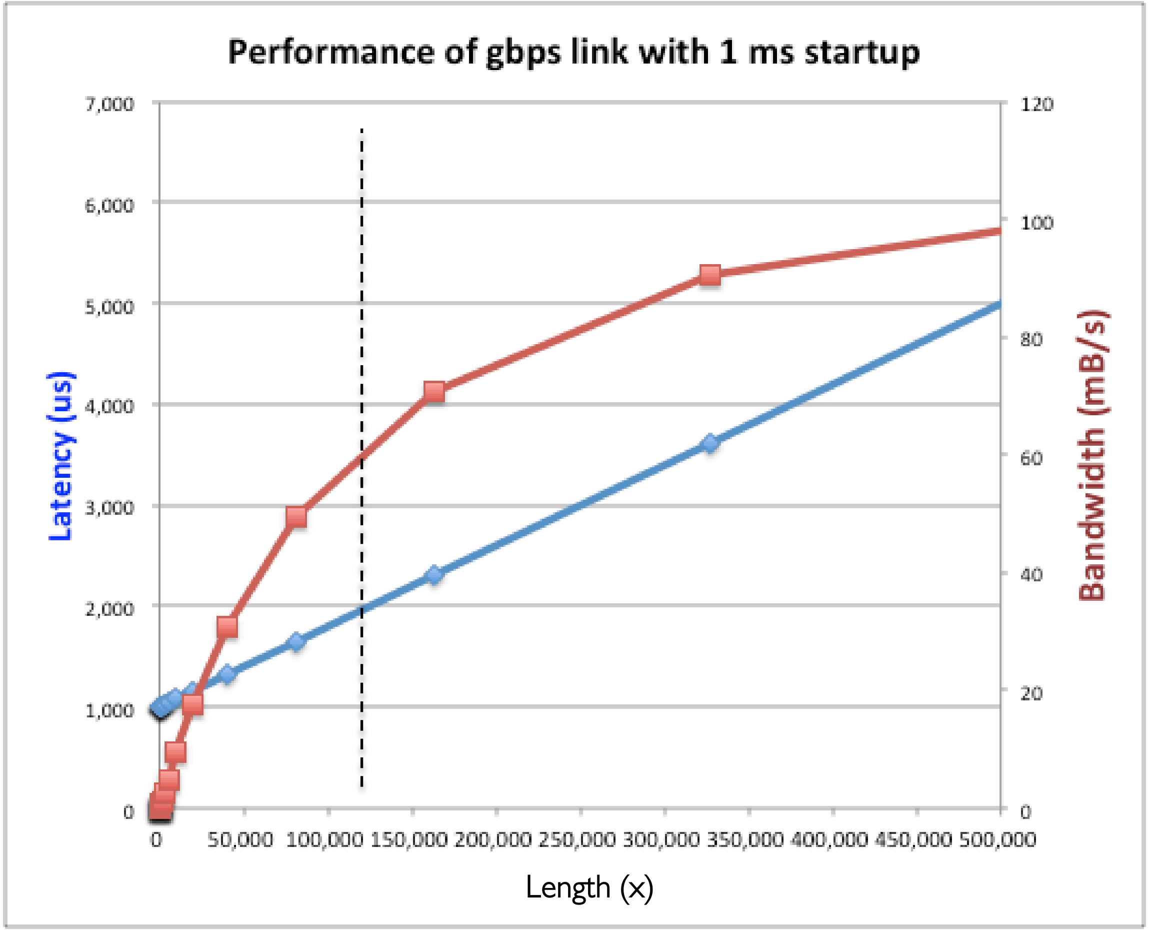
- *Latency* – time to complete a task
  – Measured in units of time (s, ms, us, …, hours, years)
- *Response Time* - time to initiate and operation and get its response
  – Able to issue one that *depends* on the result
  – Know that it is done (anti-dependence, resource usage)
- *Throughput* or *Bandwidth* – 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:

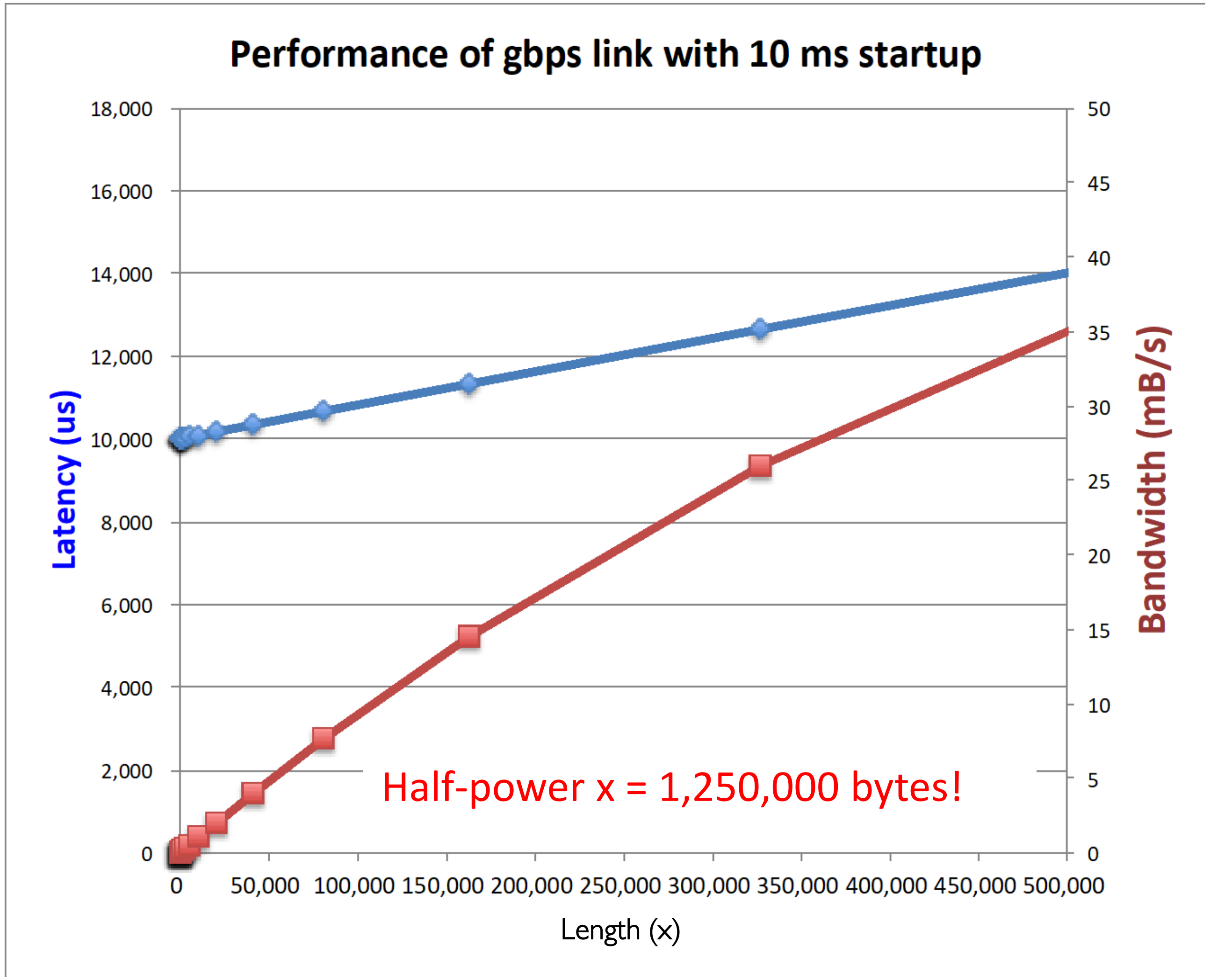
$$E(x) = \frac{x}{S + \frac{x}{B_w}} = \frac{B_w \cdot x}{B_w \cdot S + x} = \frac{B_w}{\frac{B_w \cdot S}{x} + 1}$$

- Half-power Bandwidth: $E(x) = \frac{B_x}{2}$
- 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



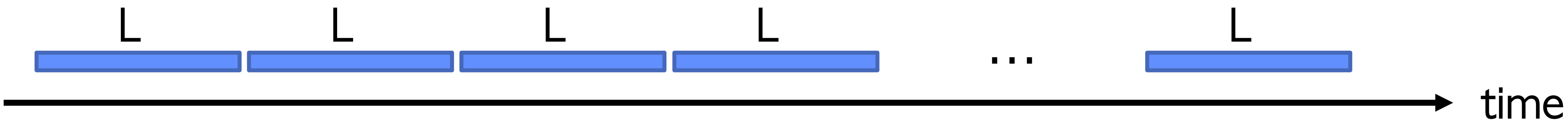
What Determines Peak BW for I/O?

- 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…

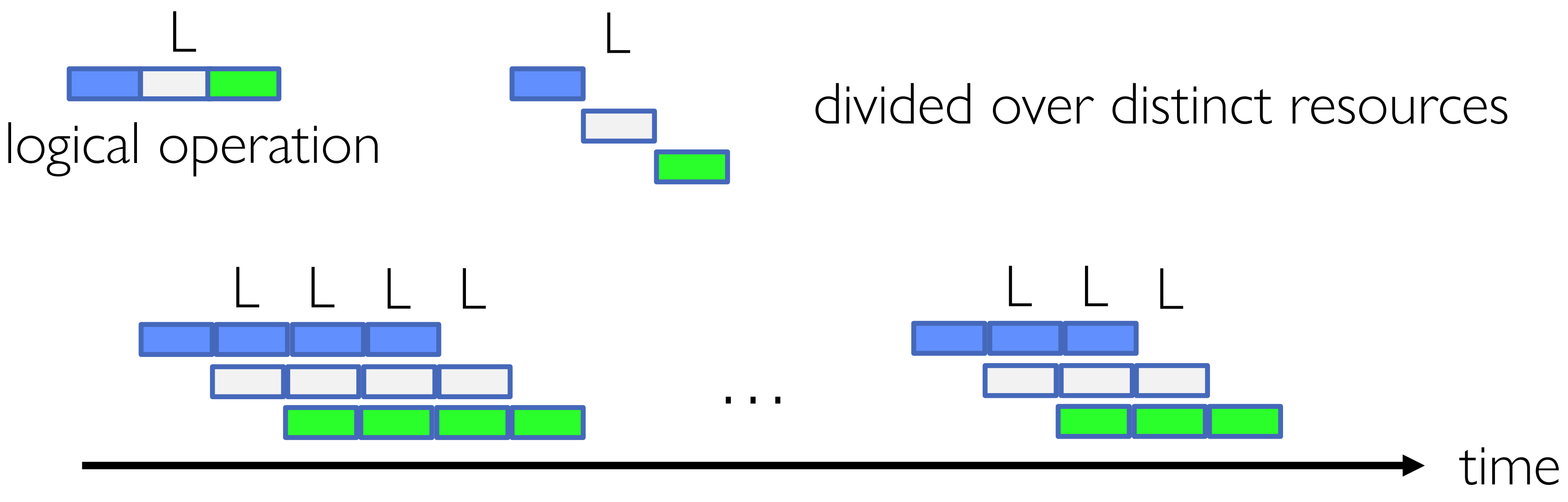
Sequential Server Performance



- 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 $\rightarrow B = 100$ $^{\mathrm{op}}/_{\mathrm{s}}$
  - $L = 2$ yr $\rightarrow B = 0.5$ $^{\mathrm{op}}/_{\mathrm{yr}}$

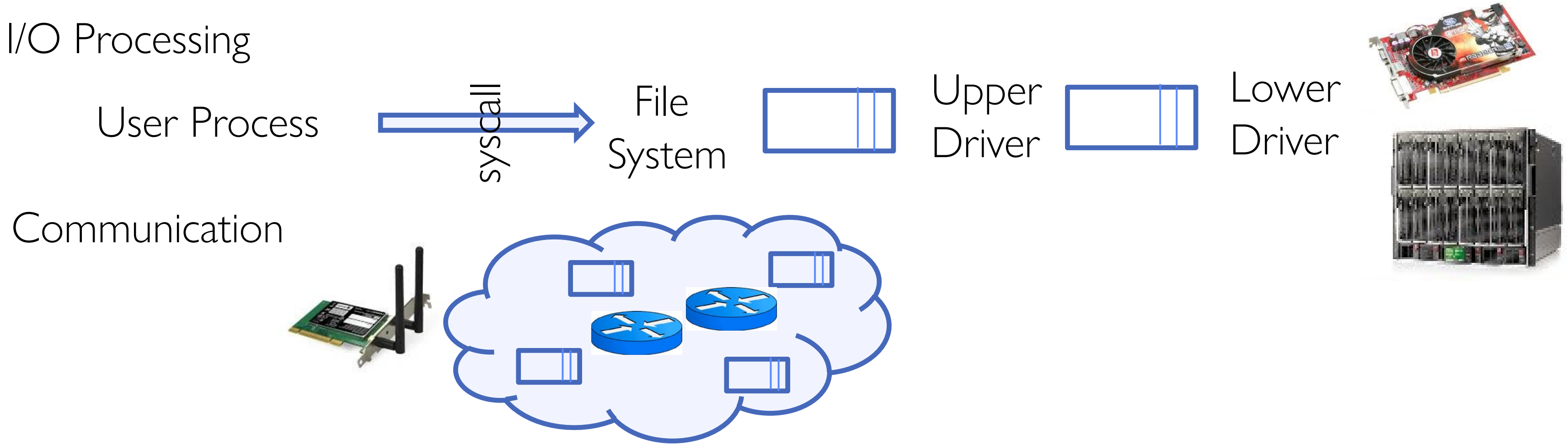
- Applies to a processor, a disk drive, a person, a TA, …

Single Pipelined Server



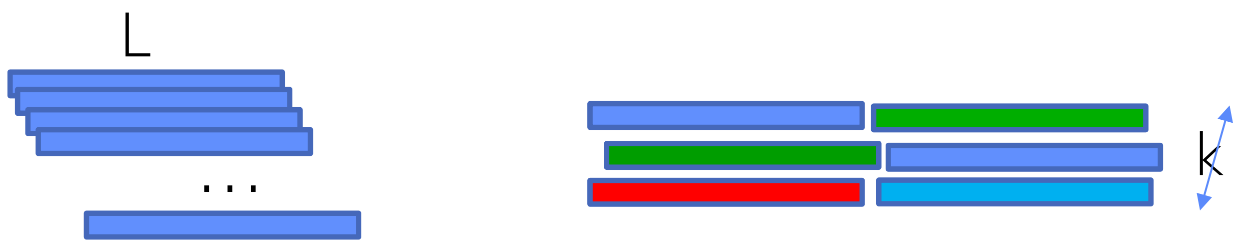
- Single pipelined server of k stages for tasks of length L (i.e., time $^{L}/_{k}$ per stage) delivers at rate $\leq {}^{k}/_{L}$.
  - $L = 10$ ms, $k = 4 \rightarrow B = 400$ $^{\text{op}}/_{\text{s}}$
  - $L = 2$ yr, $k = 2 \rightarrow B = 1$ $^{\text{op}}/_{\text{yr}}$

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

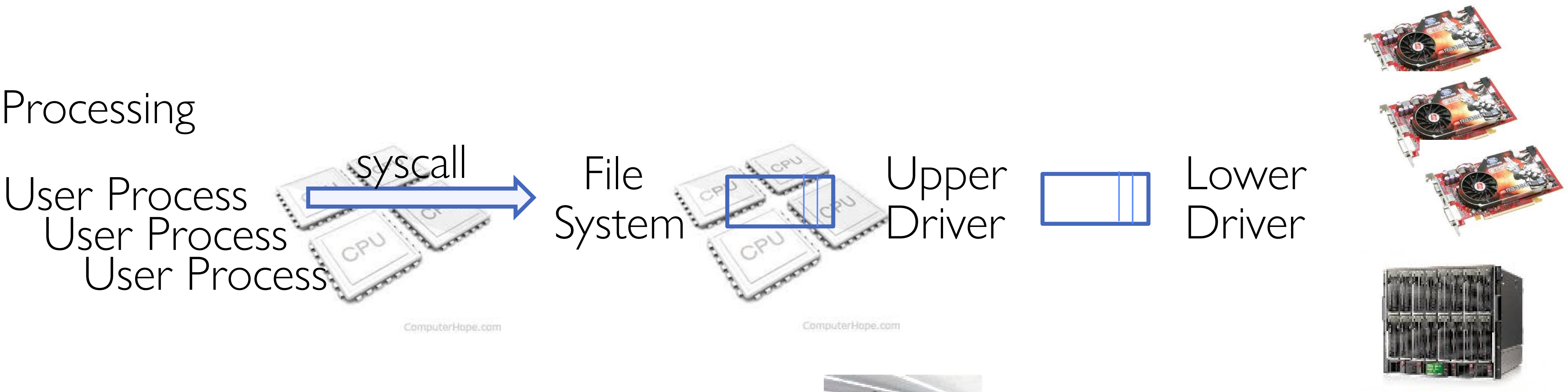
Multiple Servers



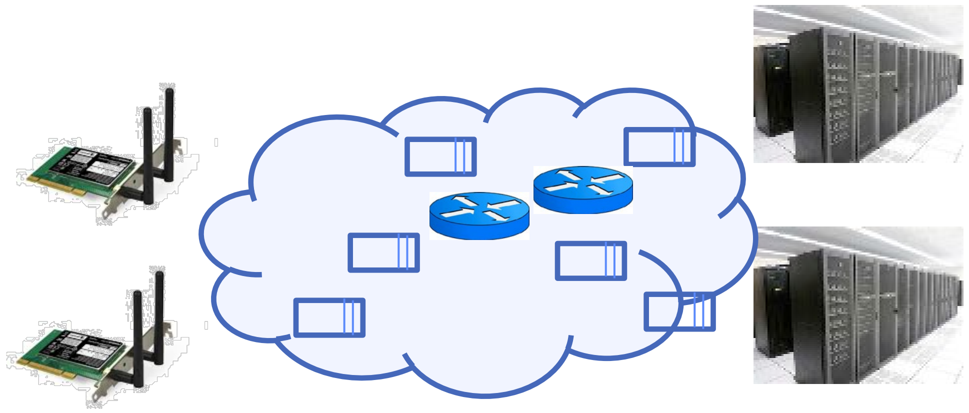
- k servers handling tasks of length L delivers at rate $\leq {}^{k}/_{L}$.
  - $L = 10$ ms, $k = 4 \rightarrow B = 400\ {}^{\text{op}}/_{\text{s}}$
  - $L = 2$ yr, $k = 2 \rightarrow B = 1\ {}^{\text{op}}/_{\text{yr}}$
- In 61C you saw multiple processors (cores)
  - Systems present lots of multiple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

Example Systems “Parallelism”

I/O Processing

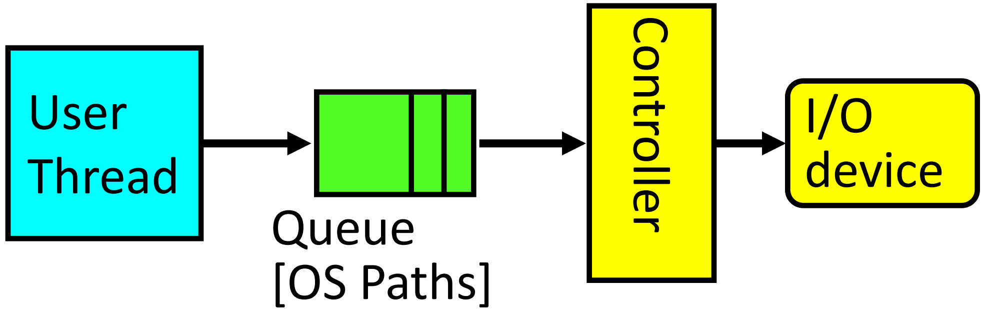


Communication

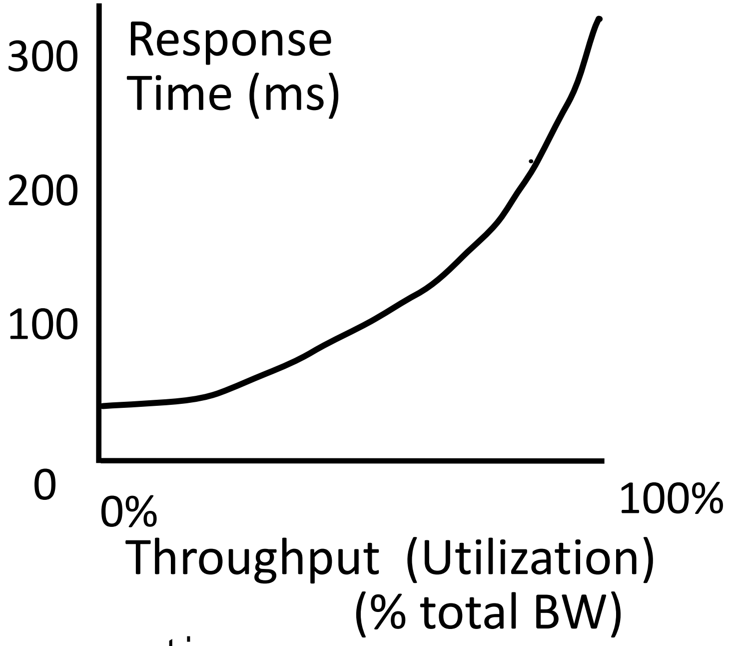


Parallel Computation, Databases, …

I/O Performance



Response Time = Queue + I/O device service time



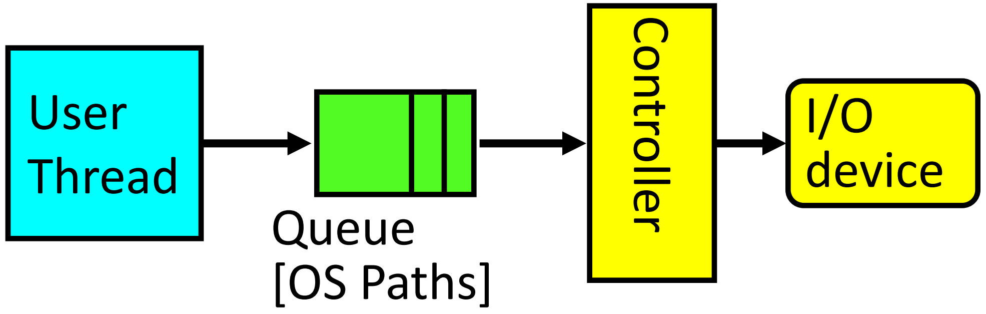
- Performance of I/O subsystem
  - Metrics: Response Time, Throughput
  - Effective BW per op = transfer size / response time
    - » EffBW(n) = n / (S + n/B) = B / (1 + SB/n)

# of ops

Fixed overhead

time per op

I/O Performance



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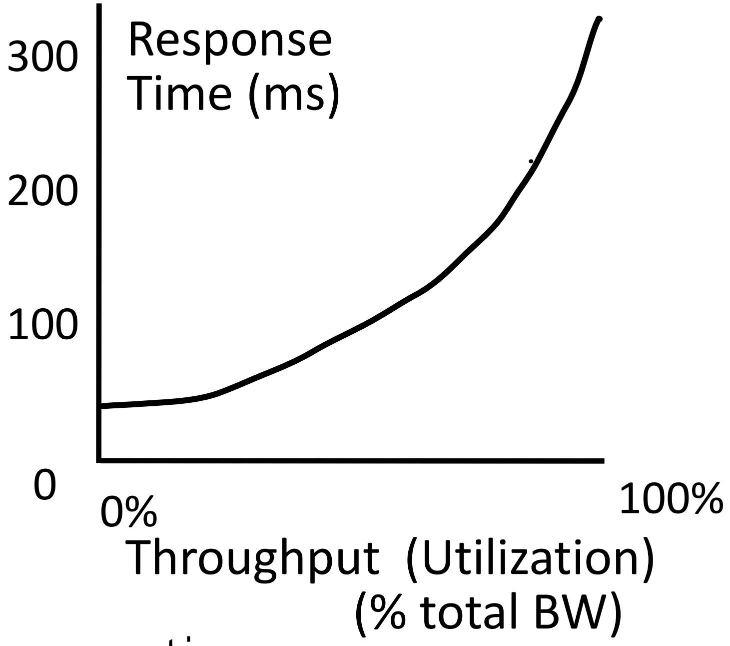

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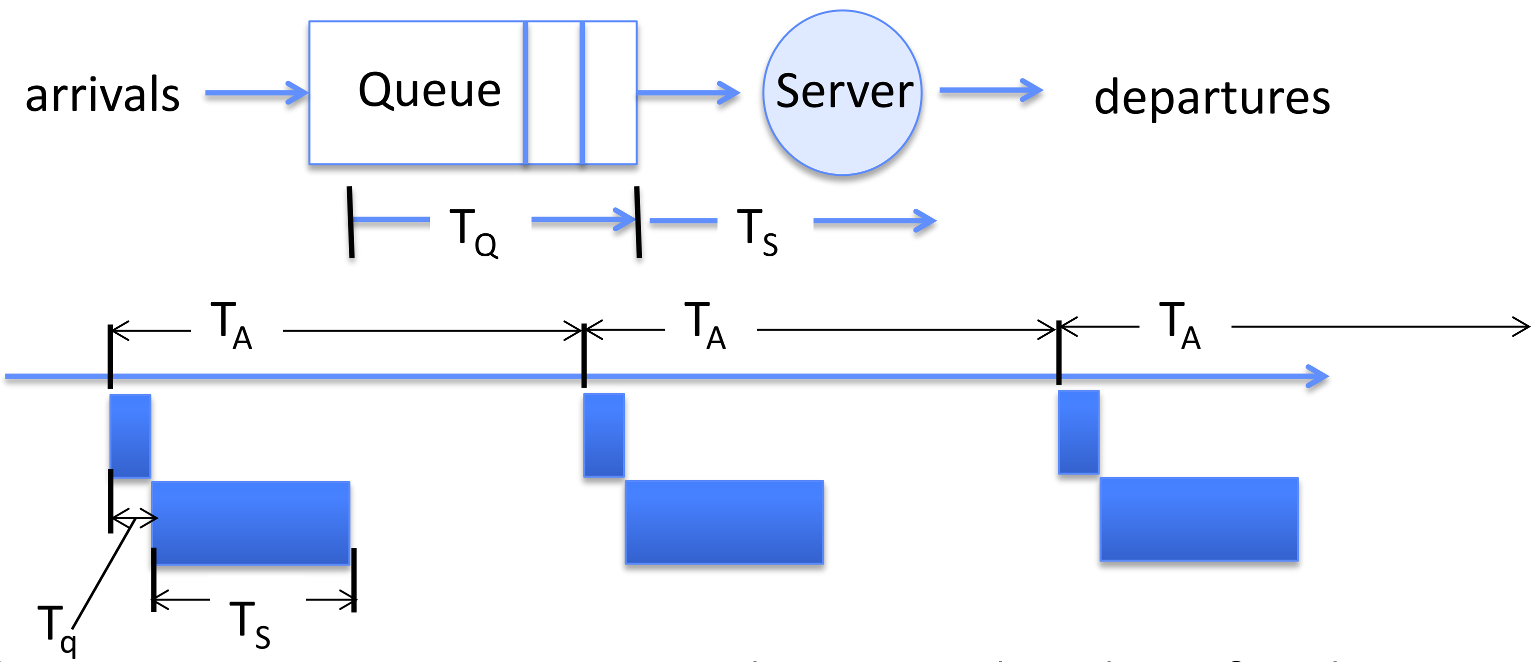
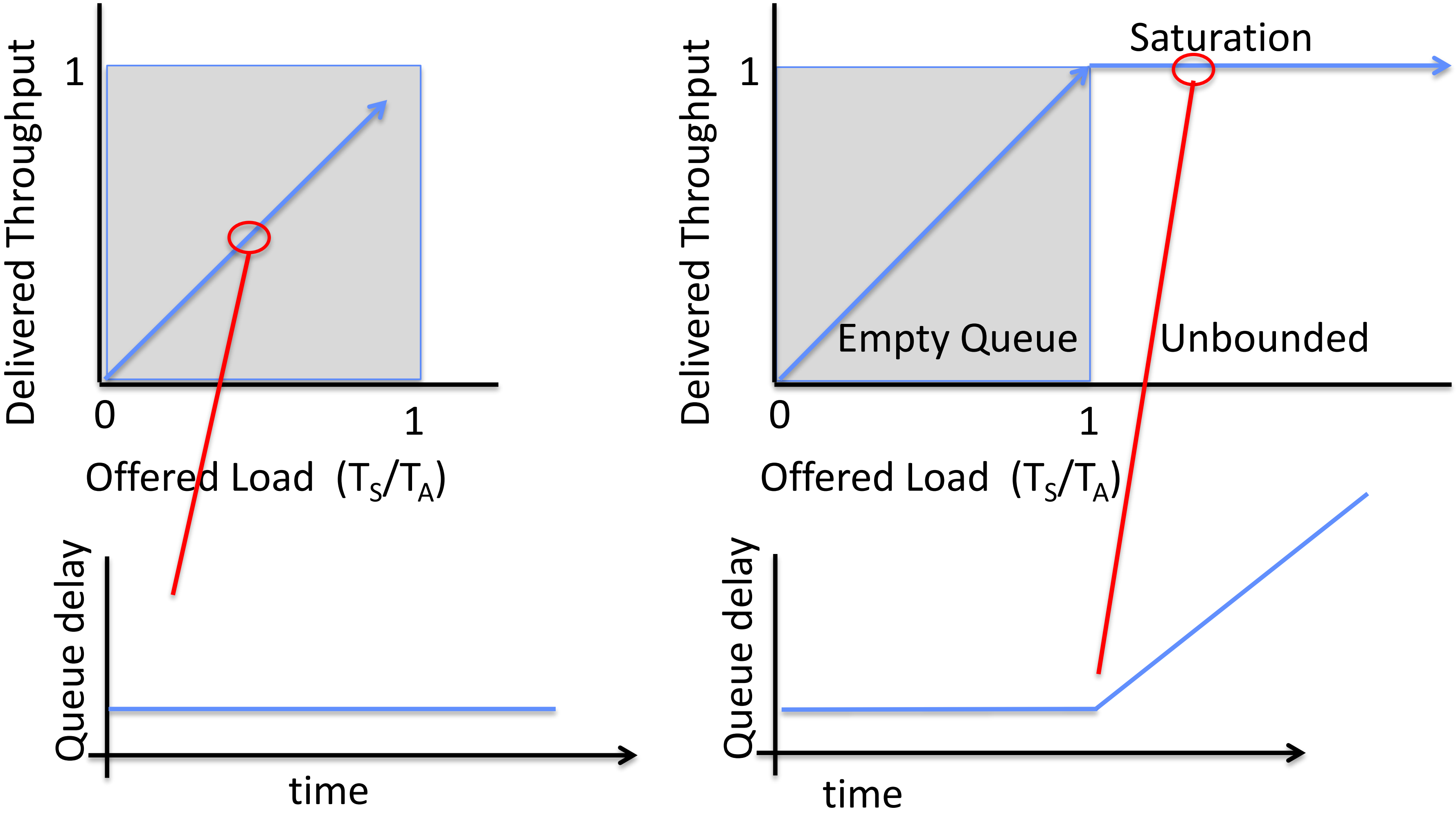
  - Metrics: Response Time, Throughput
  - Effective BW per op = transfer size / response time
    - » EffBW(n) = n / (S + n/B) = B / (1 + SB/n)
  - Contributing factors to latency:
    - » Software paths (can be loosely modeled by a queue)
    - » Hardware controller
    - » I/O device service time
-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

A Simple Deterministic World



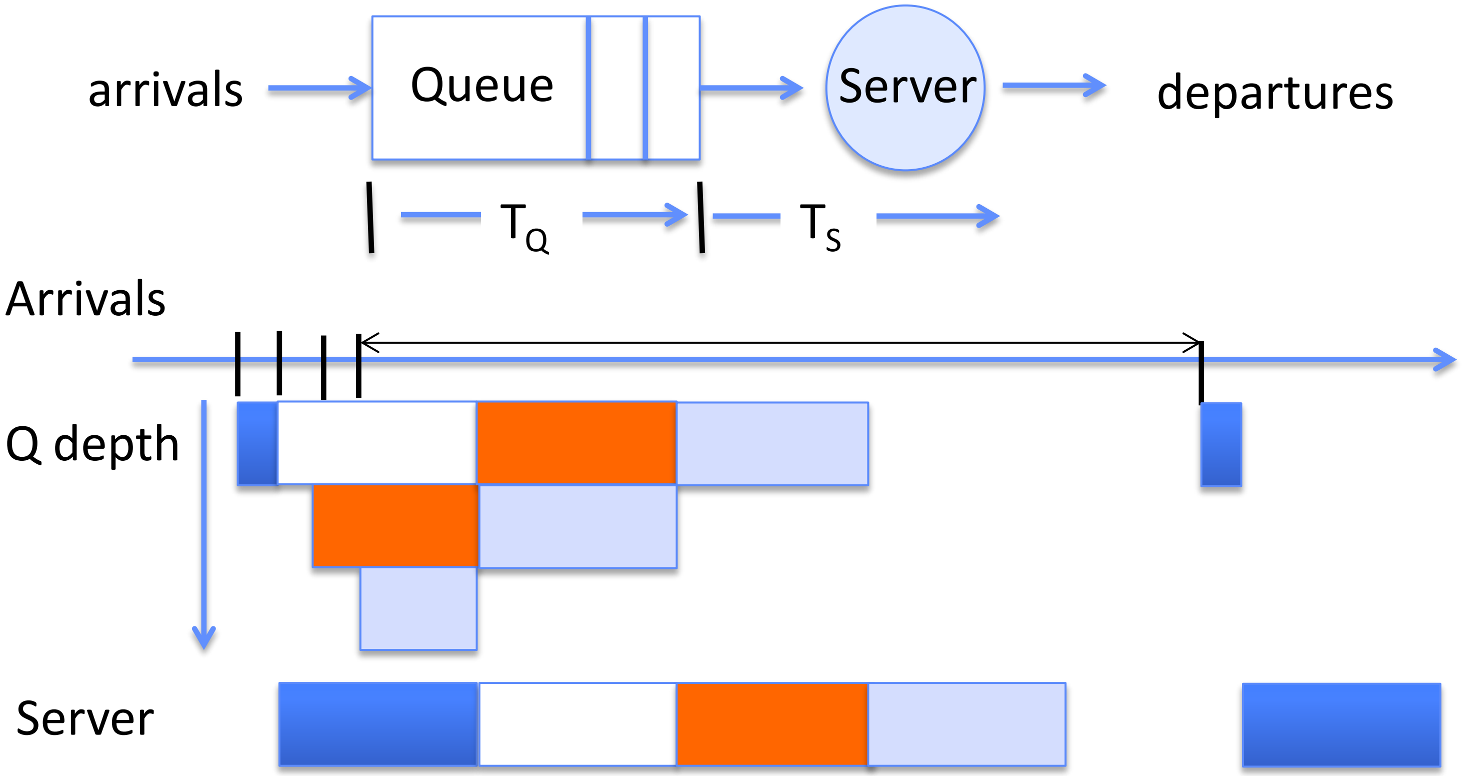
- Assume requests arrive at regular intervals, take a fixed time to process, with plenty of time between …
- Service rate ($\mu = 1/T_S$) - operations per second
- Arrival rate: ($\lambda = 1/T_A$) - requests per second
- Utilization: $U = \lambda/\mu$, where $\lambda < \mu$
- Average rate is the complete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

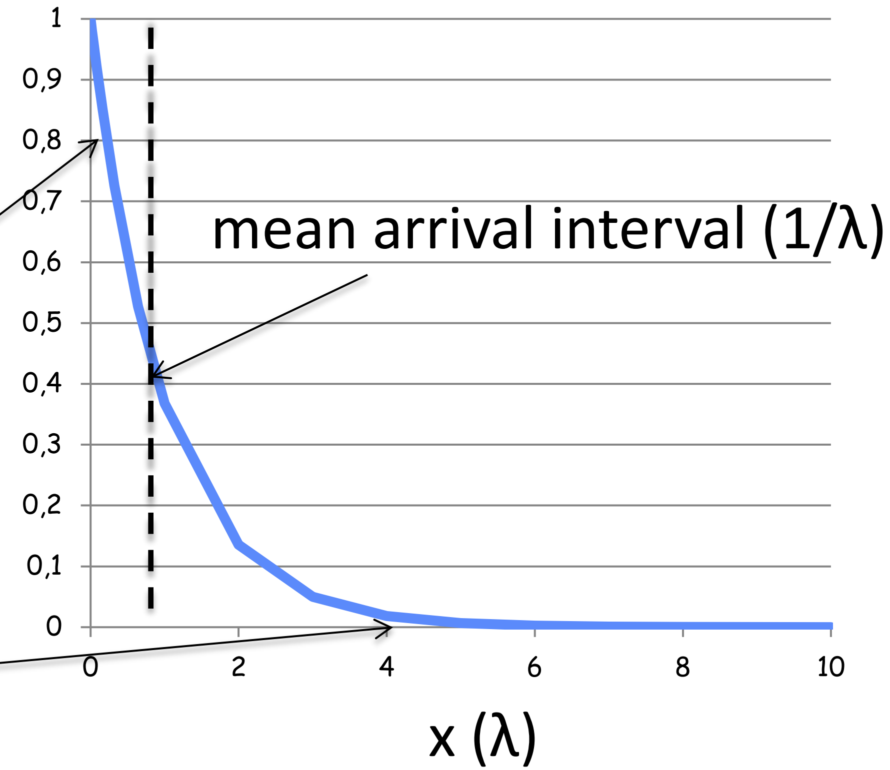
So how do we model the burstiness of arrival?

- 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

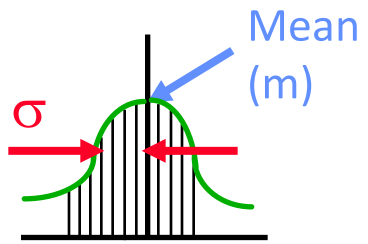
Lots of short arrival intervals (i.e., high instantaneous rate)

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



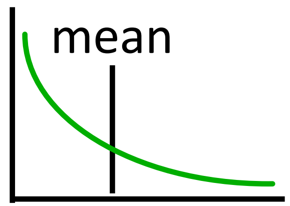
Background:
General Use of Random Distributions

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



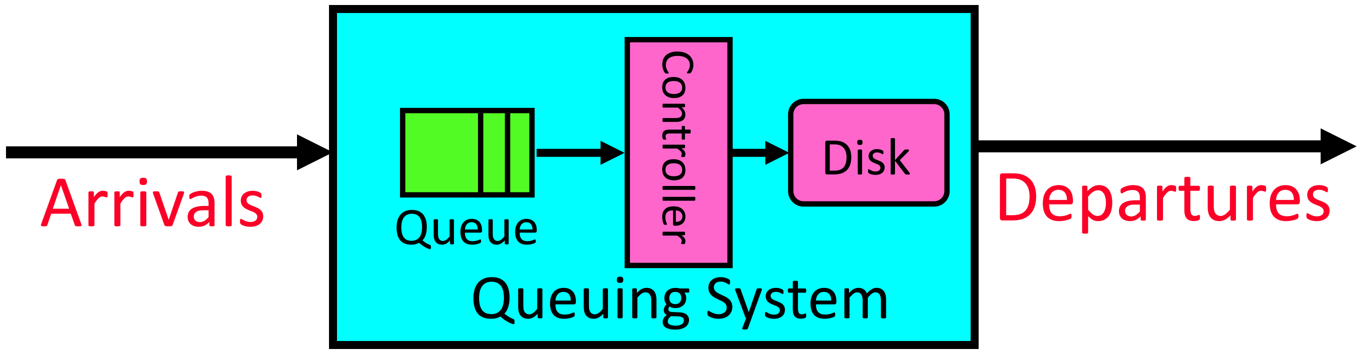
Distribution
of service times

- Important values of C:
  - No variance or deterministic $\Rightarrow$ C=0
  - "Memoryless" or exponential $\Rightarrow$ 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)



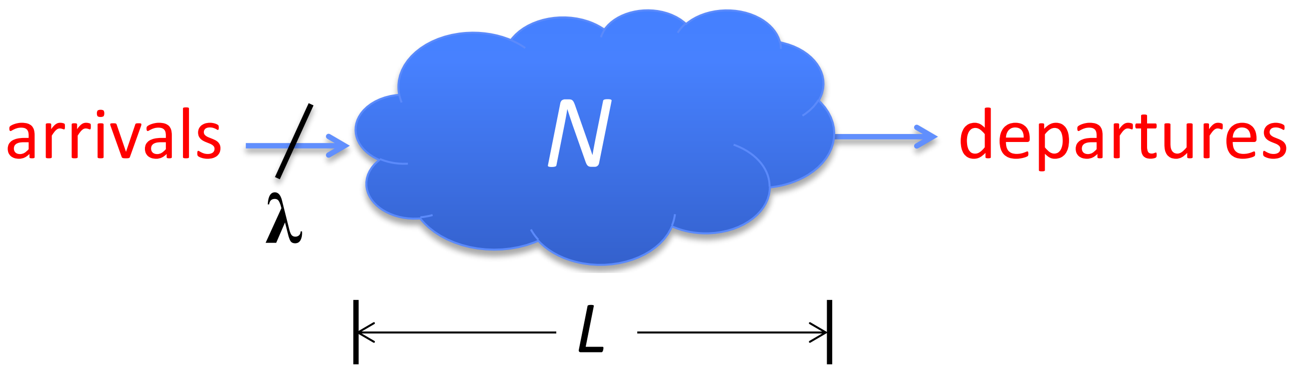
Memoryless

Introduction to Queuing Theory



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

Little's Law

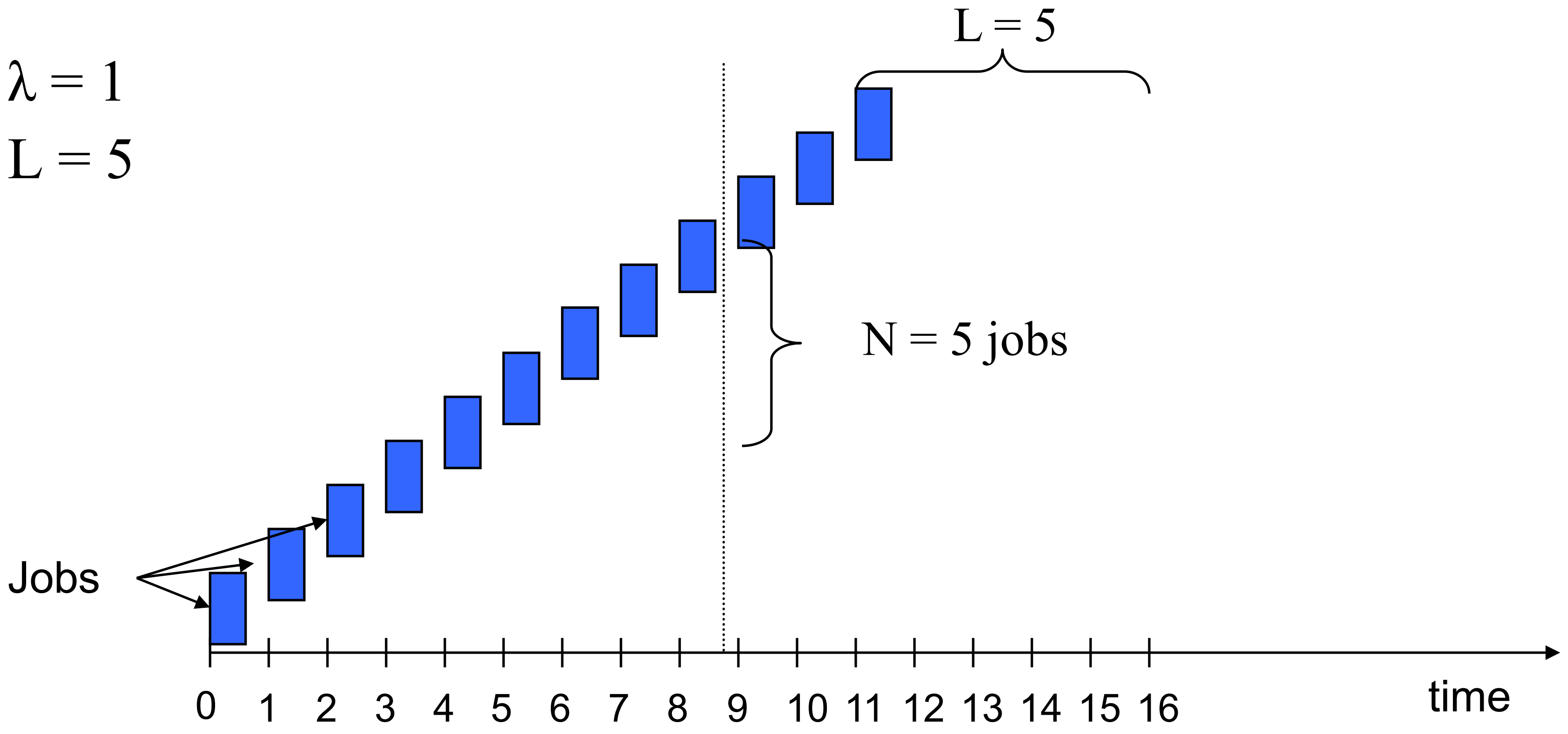


- In any *stable* system
  - Average arrival rate = Average departure rate
- The average number of jobs/tasks in the system (*N*) is equal to arrival time / throughput (λ) times the response time (*L*)
  - *N (jobs) = λ (jobs/s) x L (s)*
- Regardless of structure, bursts of requests, variation in service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

Example

$\lambda = 1$

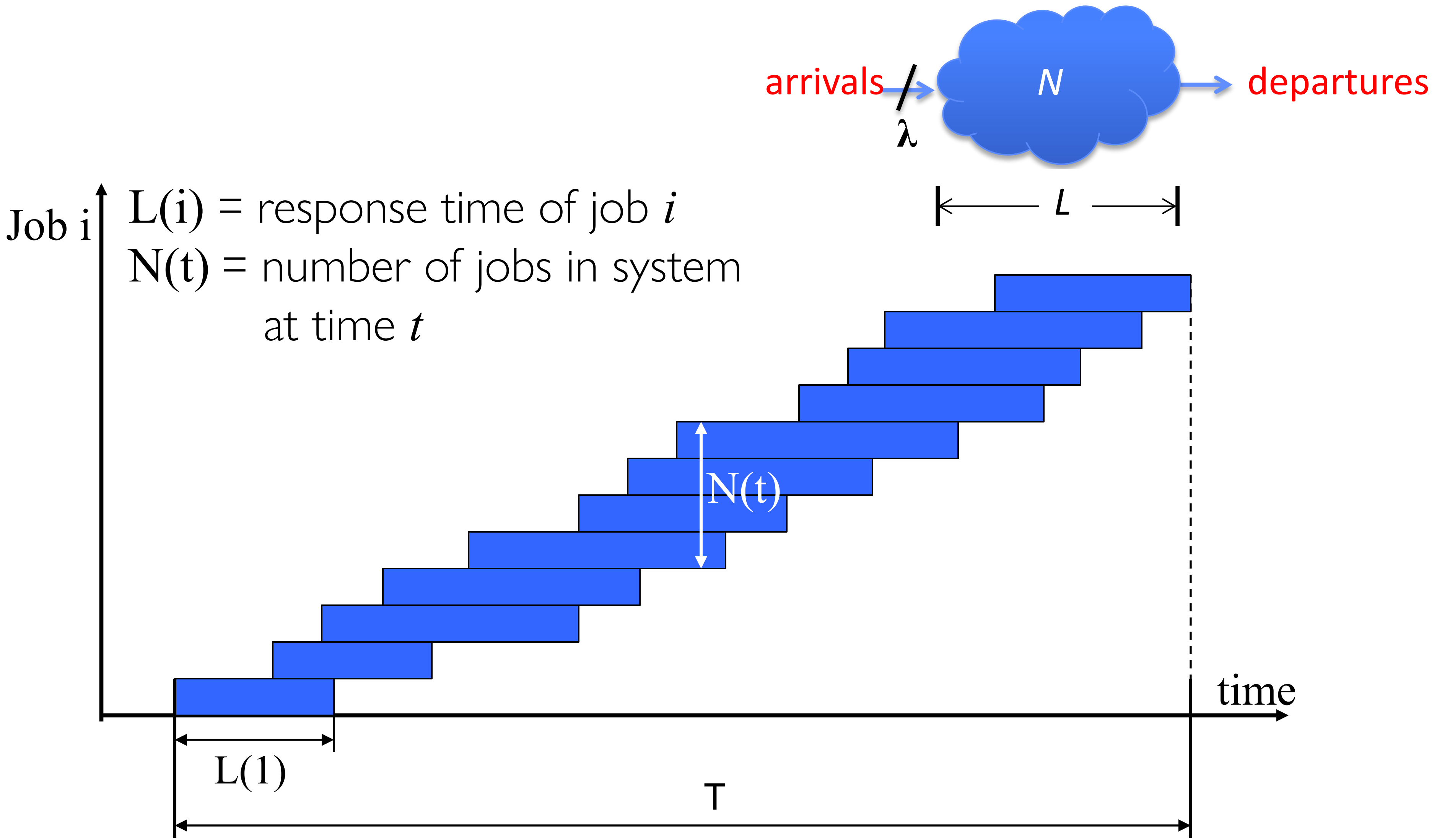
$L = 5$



A: $N = \lambda \times L$

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

Little’s Theorem: Proof Sketch



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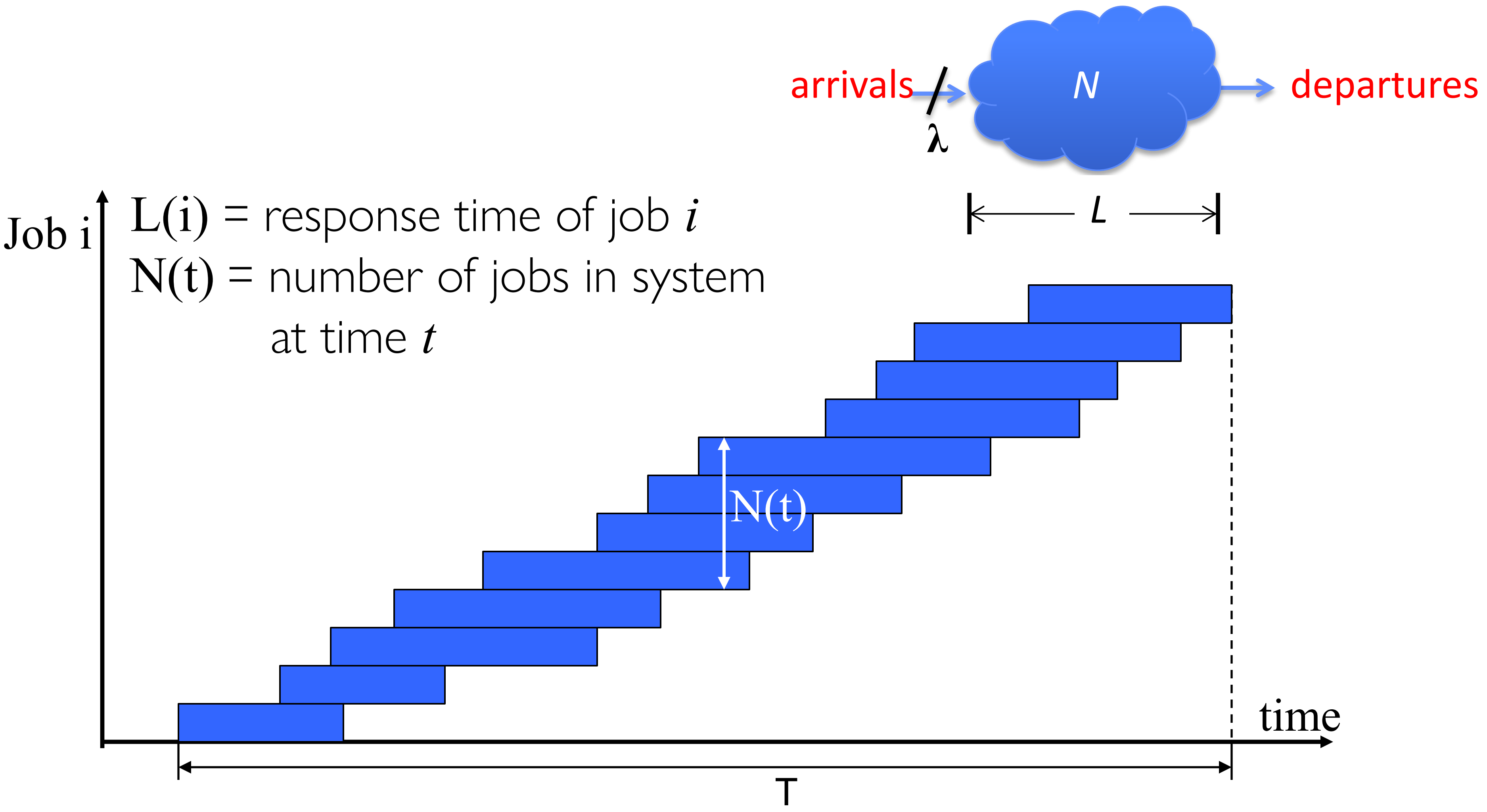
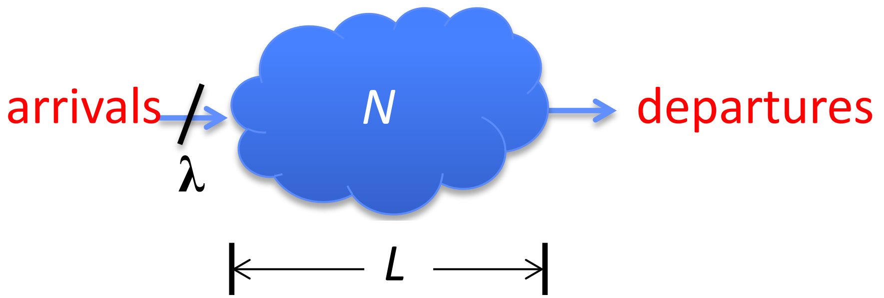


What is the system occupancy, i.e., average number of jobs in the system?

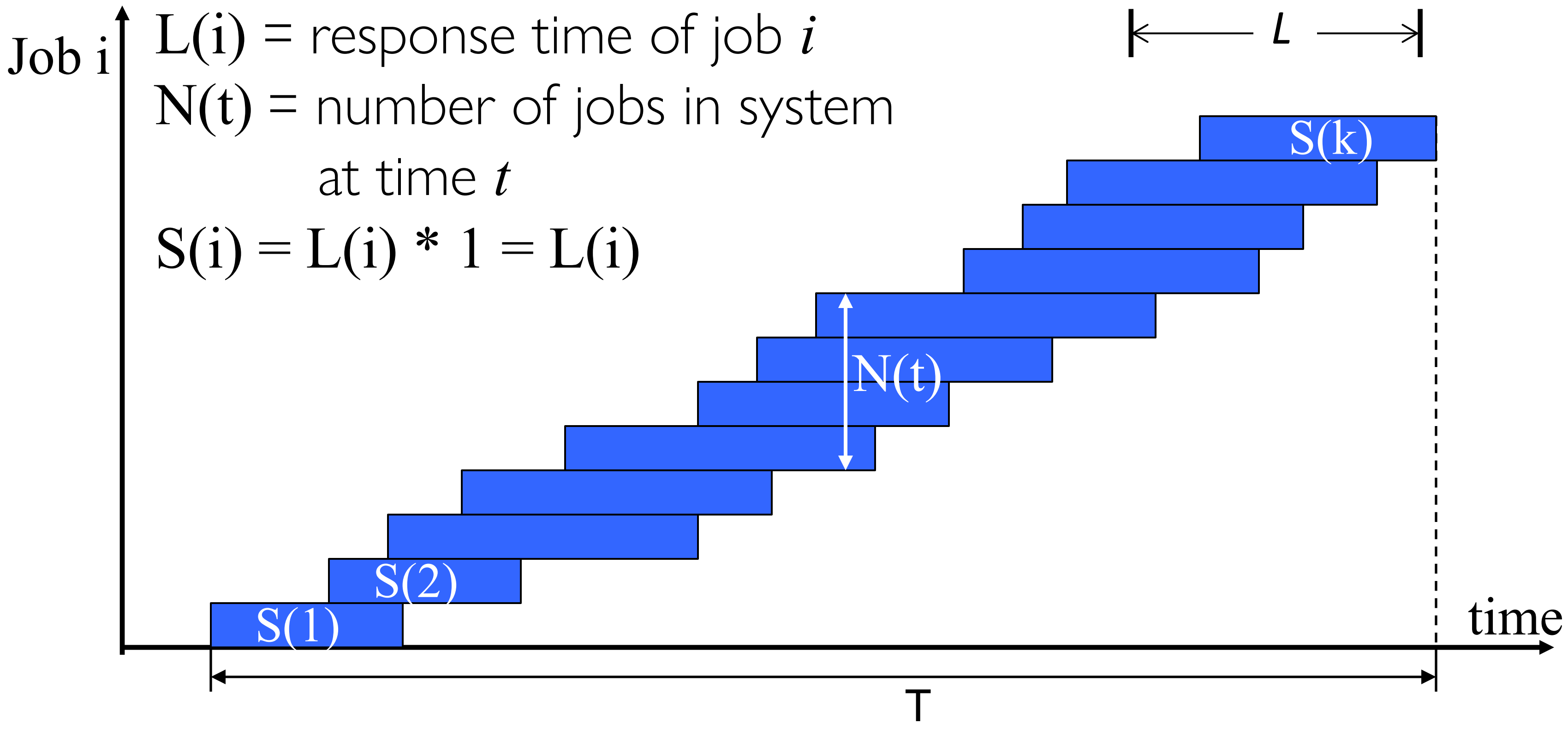
Little's Theorem: Proof Sketch



L(i) = response time of job i

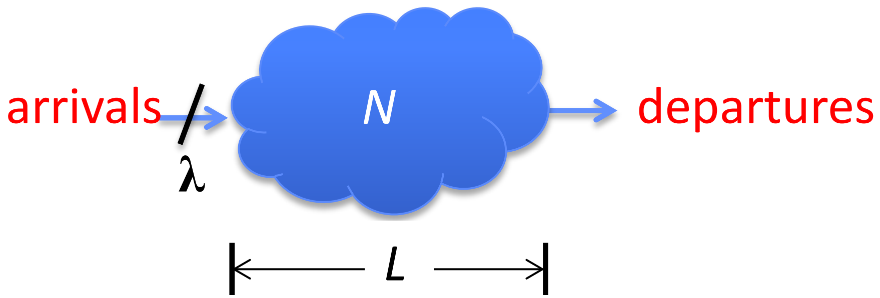
N(t) = number of jobs in system at time t

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



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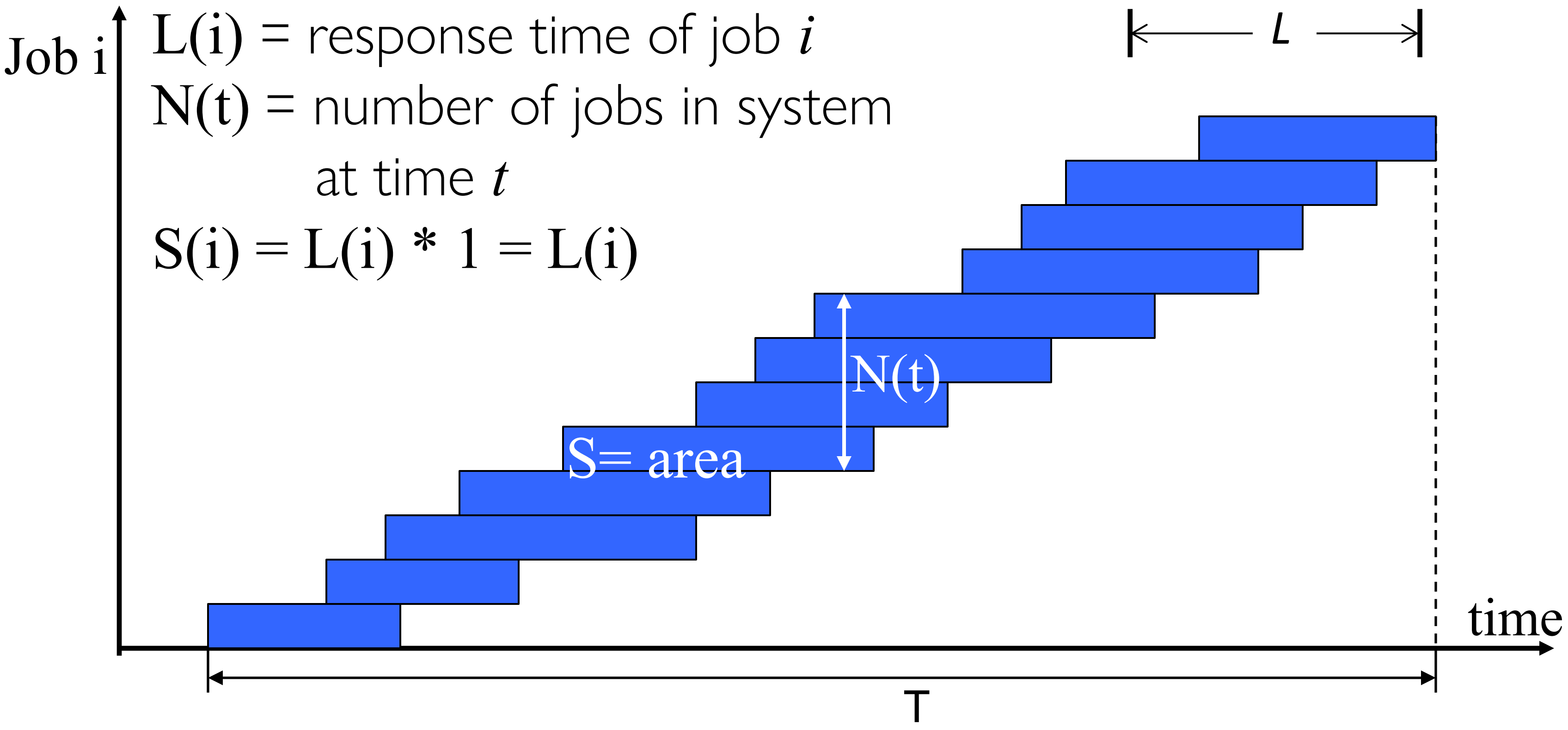
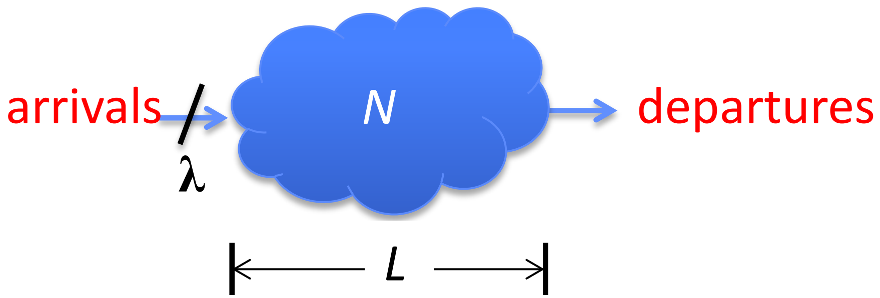


Average occupancy (N_{avg}) = S/T

Little's Theorem: Proof Sketch



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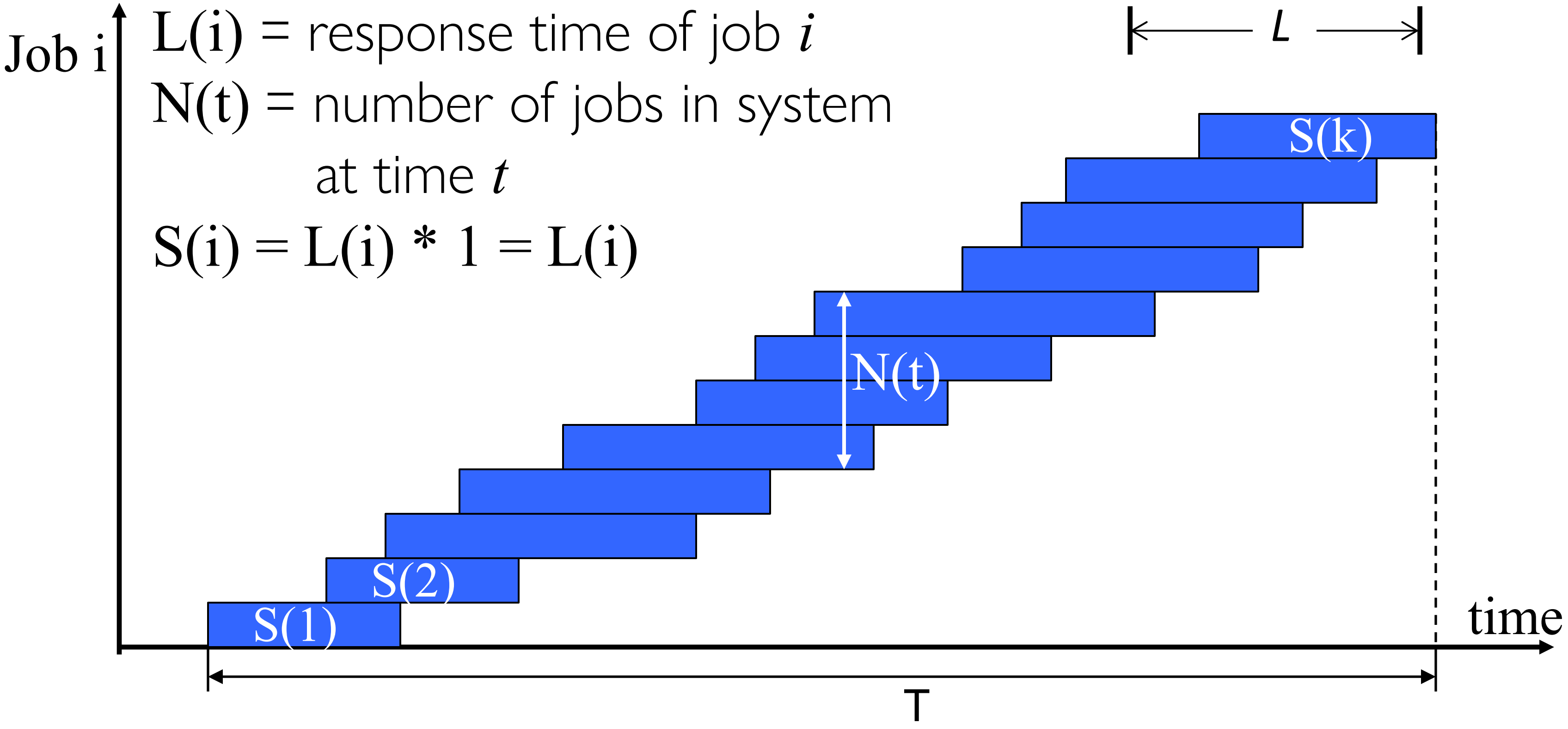
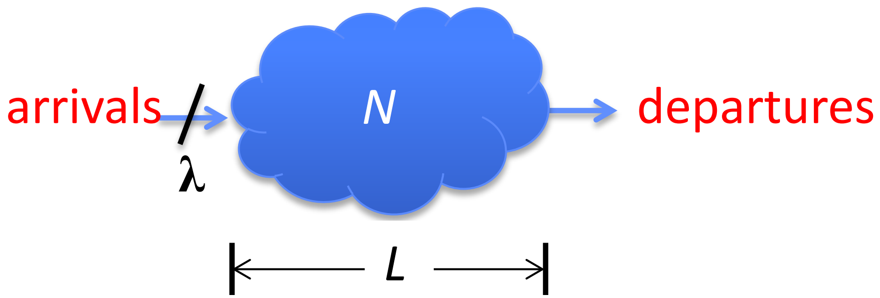


$$N_{avg} = S/T = (L(1) + \ldots + L(k))/T$$

Little’s Theorem: Proof Sketch



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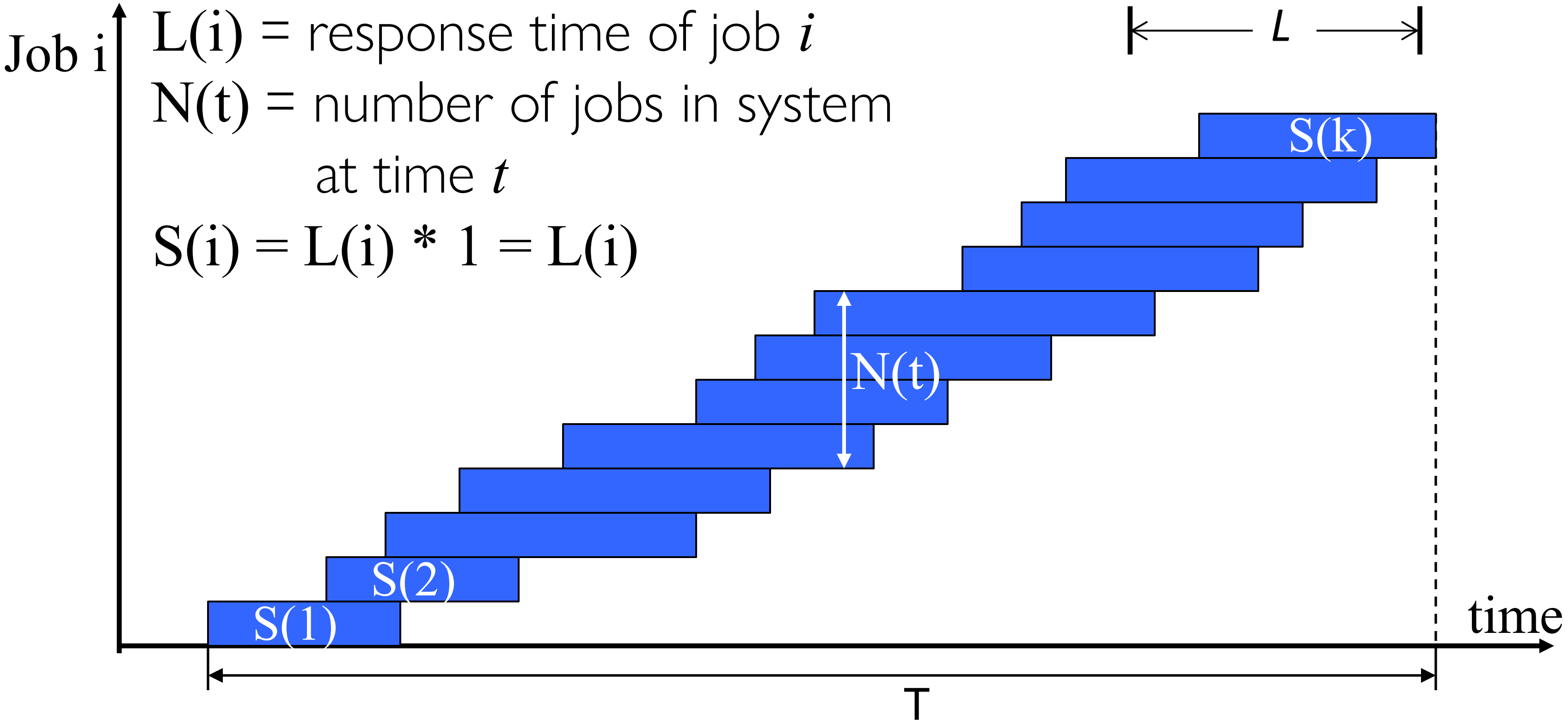
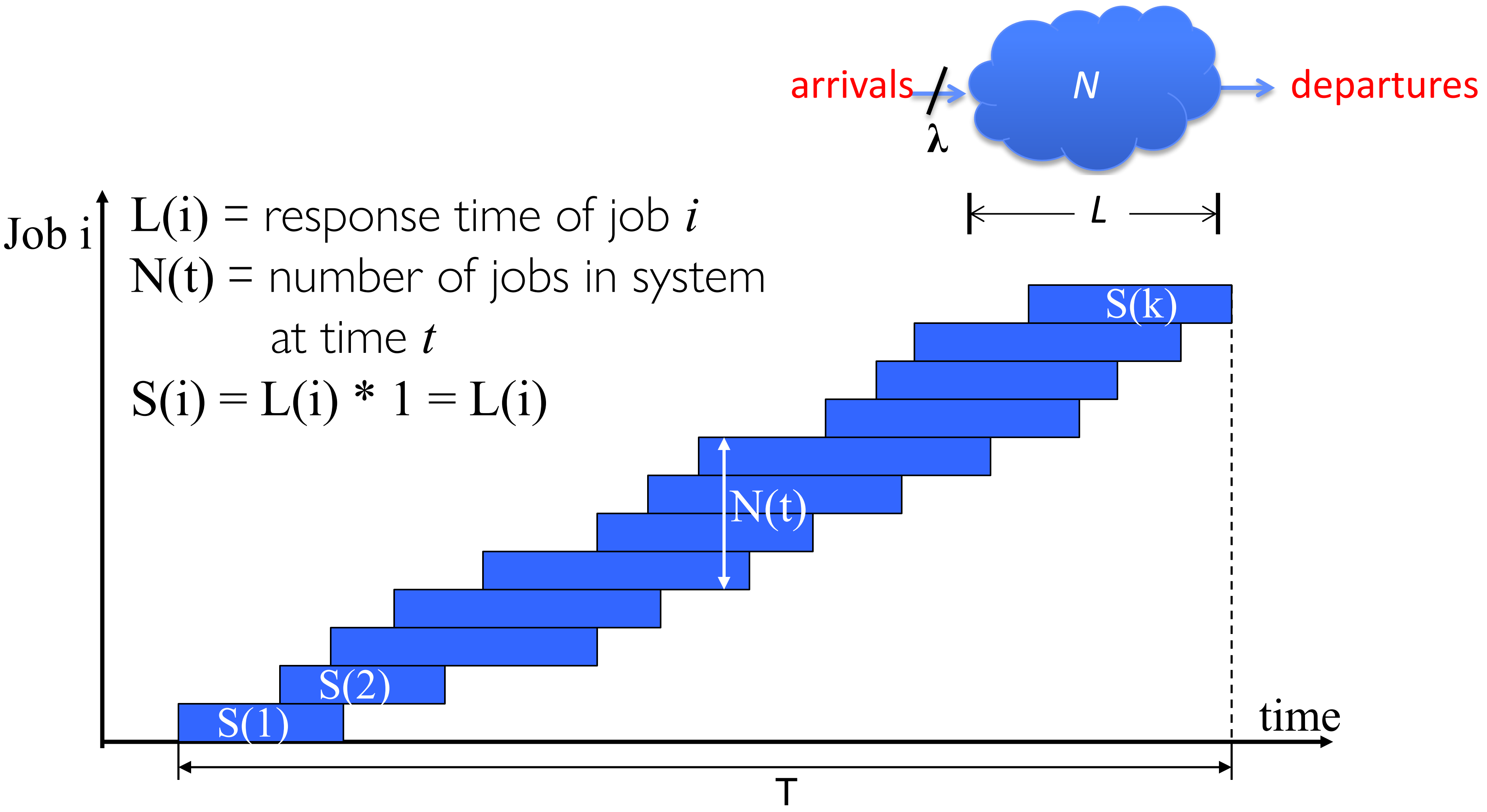


$$N_{avg} = (L(1) + \ldots + L(k))/T = (N_{total}/T)*(L(1) + \ldots + L(k))/N_{total}$$

Little's Theorem: Proof Sketch



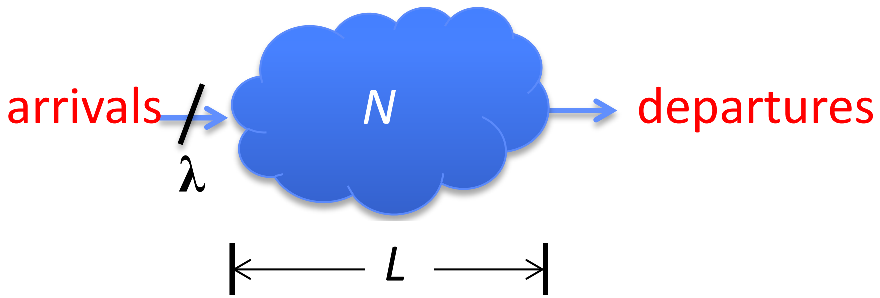
L(i) = response time of job *i*

N(t) = number of jobs in system at time *t*

S(i) = L(i) * 1 = L(i)

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

Little's Theorem: Proof Sketch



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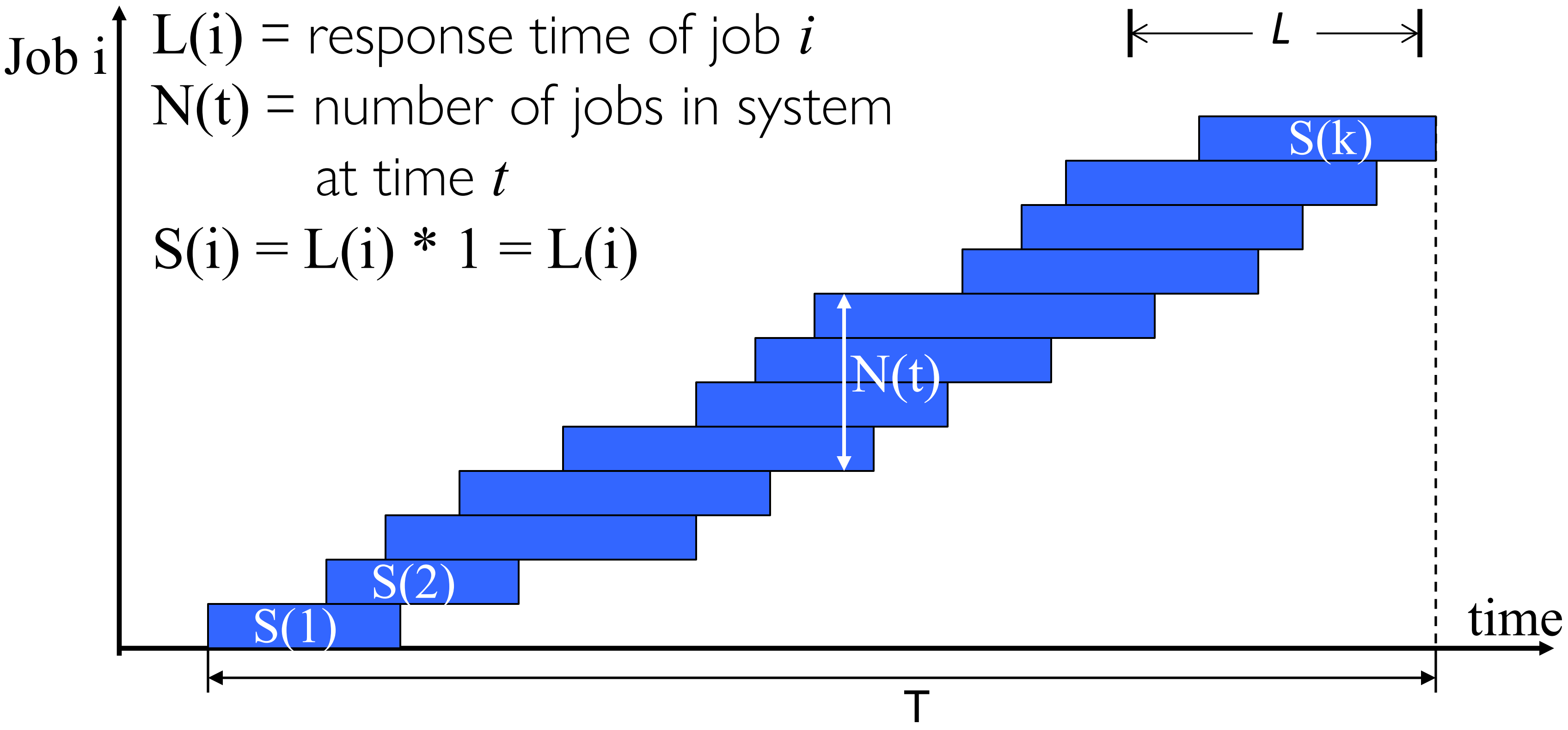
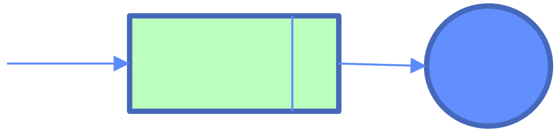


$$N_{avg} = \lambda_{avg} \times L_{avg}$$

Little's Law Applied to a Queue

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



Average Arrival Rate

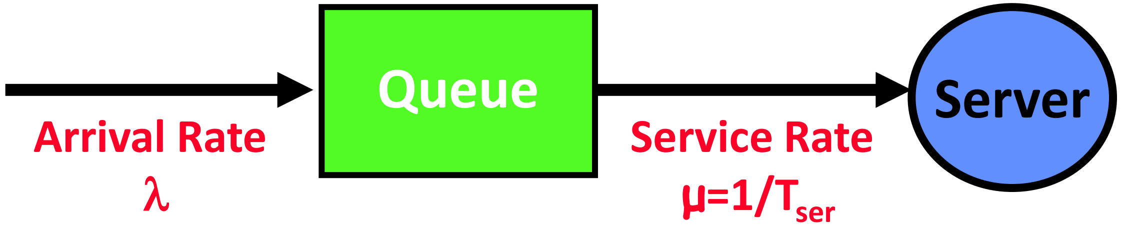
$$L_Q = \lambda T_Q$$

Average length of the queue

Average time "waiting" in queue

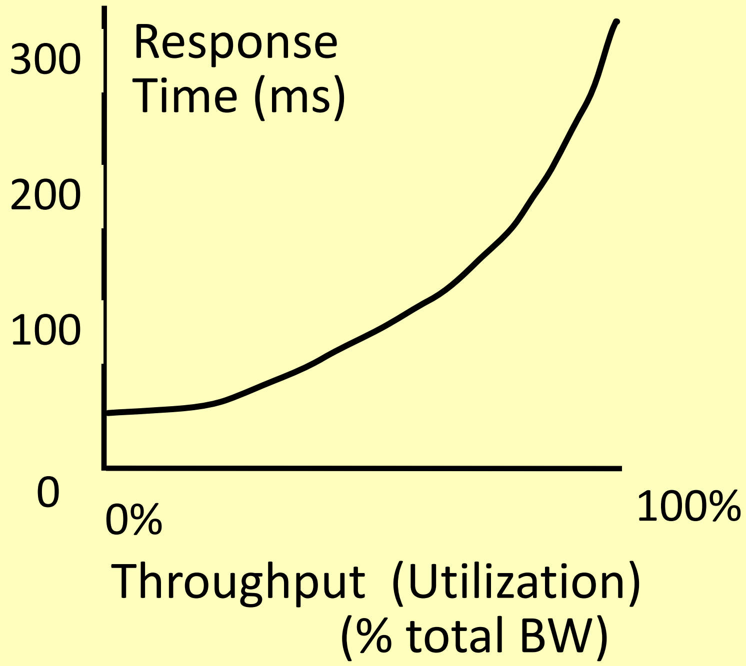
A Little Queuing Theory: Computing T_Q

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

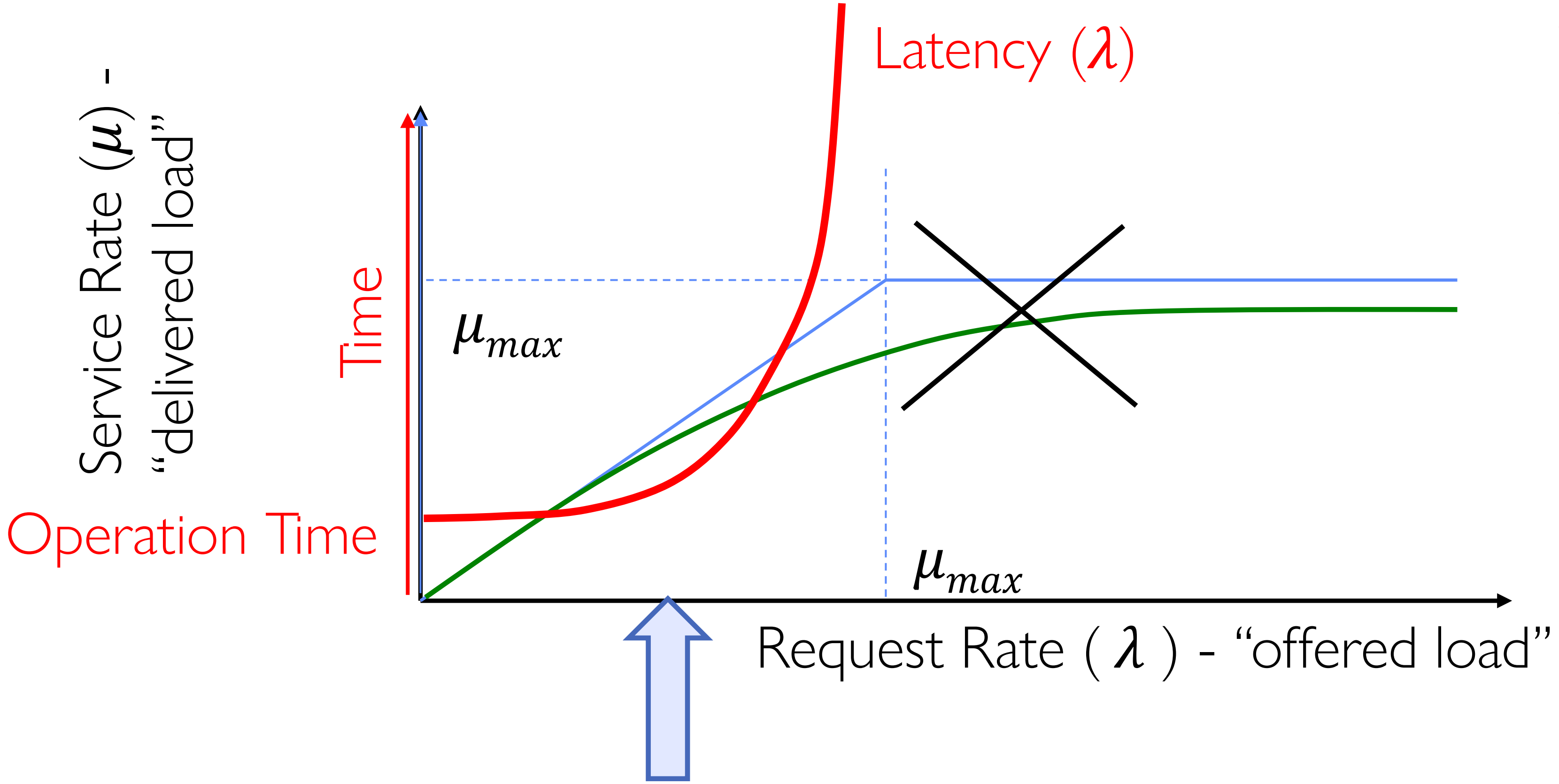


- Parameters that describe our system:
  - λ: mean number of arriving customers/second
  - T_{ser}: mean time to service a customer ("m1")
  - C: squared coefficient of variance = $\sigma^2/$
  - μ: service rate = $1/T_{ser}$
  - u: server utilization ($0 \le u \le 1$): $u = \lambda/\mu = \lambda \times T_{ser}$
- Results:
  - Memoryless service distribution (C = 1) (an "M/M/1 queue"):
    - » $T_q = T_{ser} \times \boxed{u/(1 - u)}$
  - General service distribution, 1 server (an "M/G/1 queue"):
    - » $T_q = T_{ser} \times \frac{1}{2}(1+C) \times \boxed{u/(1 - u)}$

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



System Performance In presence of a Queue



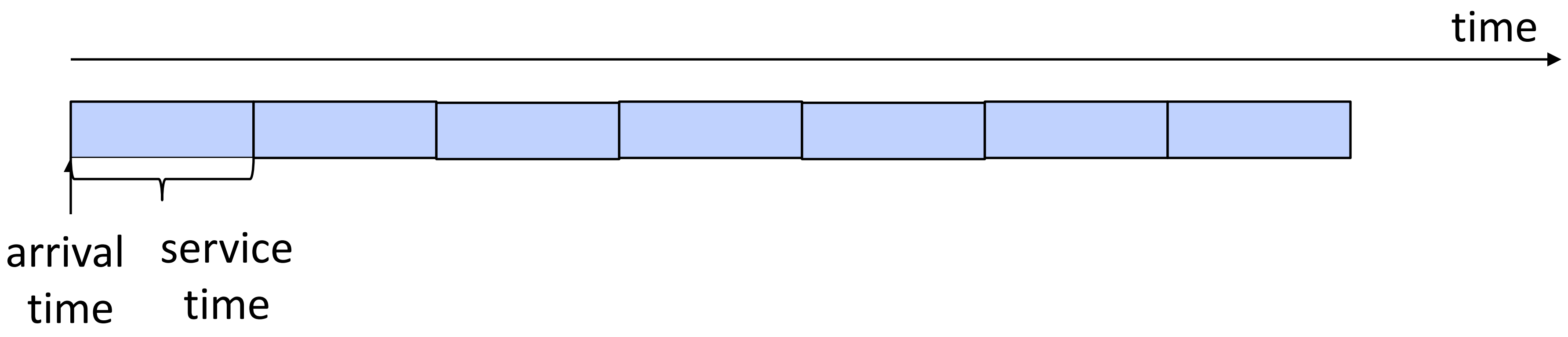
- $T_Q \sim \frac{u}{1-u}$, $\mathrm{u} = \lambda / \mu_{max}$
- Why does latency blow up as we approach 100% utilization?
  - Queue builds up on each burst
  - But very rarely (or never) gets a chance to drain

"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%

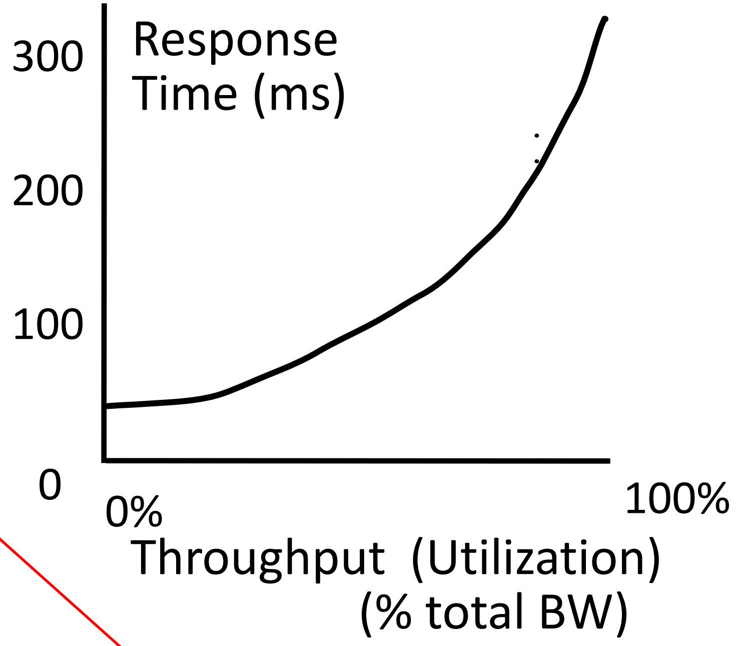
Why unbounded response time?

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

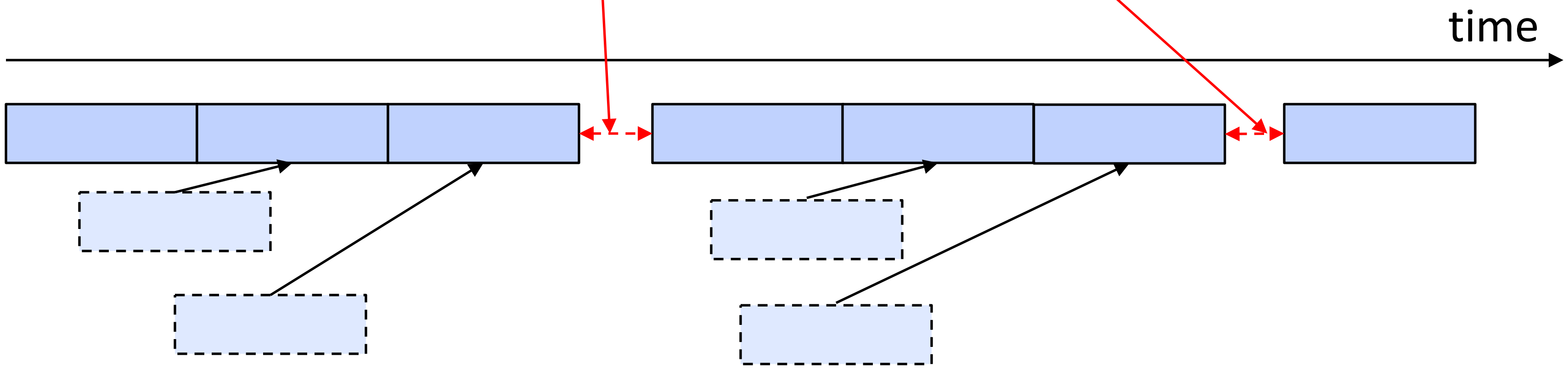


Why unbounded response time?

- 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)

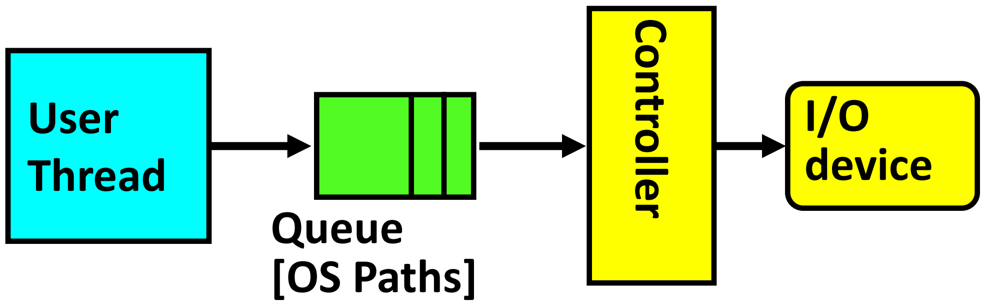
u (server utilization) = $\lambda \times T_{ser}$ = 10/s x .02s = 0.2

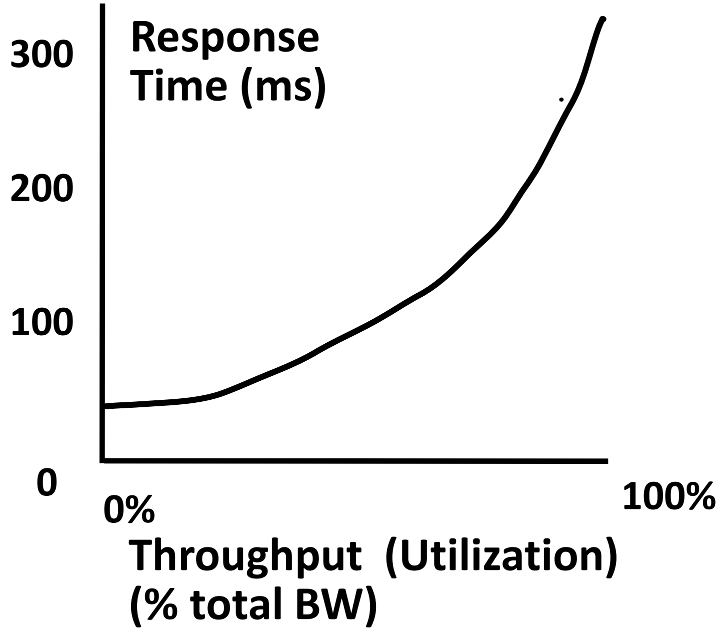
T_q (avg time/customer in queue) = $T_{ser} \times u/(1 - u)$
= 20 x 0.2/(1-0.2) = 20 x 0.25 = 5 ms (0 .005s)

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

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

When is Disk Performance Highest?

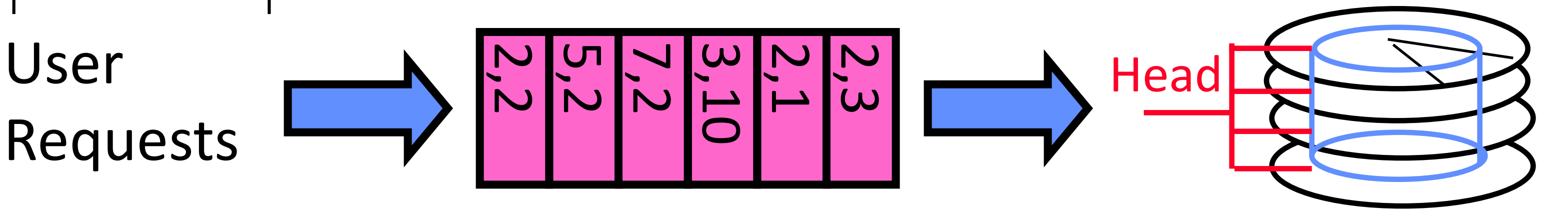
- When there are big sequential reads, or
- When there is so much work to do that they can be piggy backed (reordering queues—one moment)

- 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?

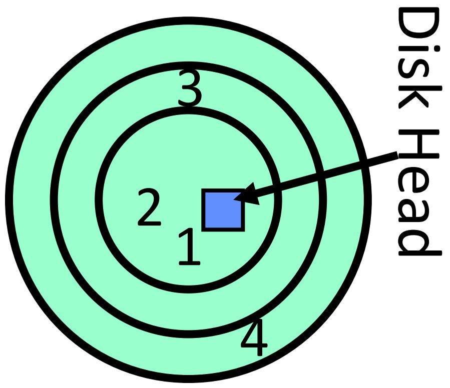
- Other techniques:
  – Reduce overhead through user level drivers
  – Reduce the impact of I/O delays by doing other useful work in the meantime

Disk Scheduling (1/3)

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



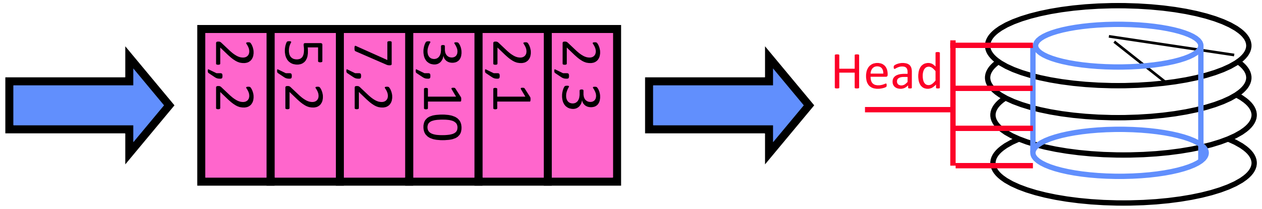
- FIFO Order
  - Fair among requesters, but order of arrival may be to random spots on the disk ⇒ Very long seeks
- SSTF: Shortest seek time first
  - Pick the request that's closest on the disk
  - Although called SSTF, today must include rotational delay in calculation, since rotation can be as long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



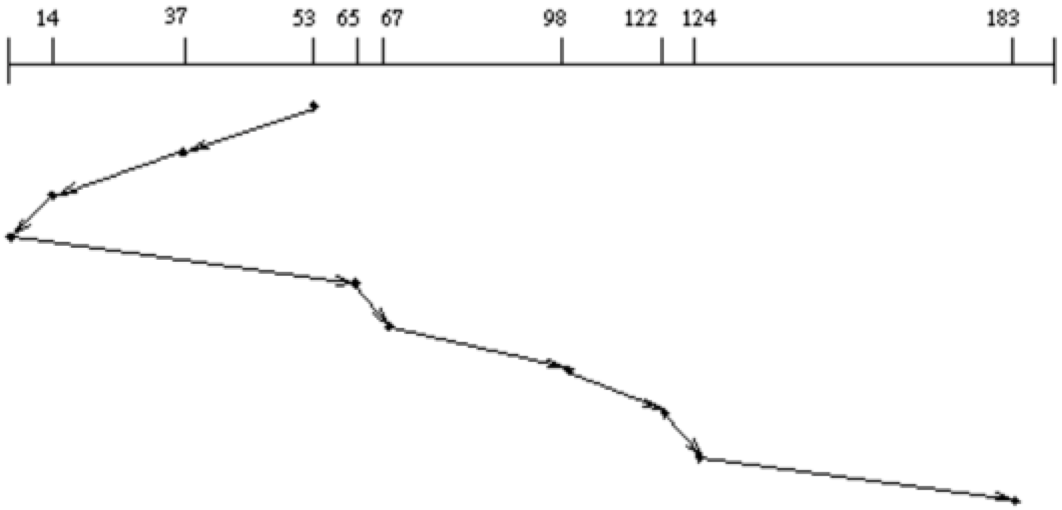
Disk Scheduling (2/3)

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

User Requests

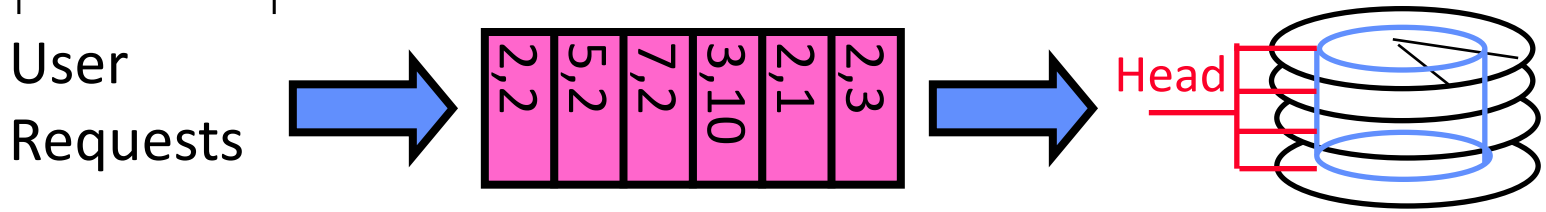


- SCAN: Implements an Elevator Algorithm: take the closest request in the direction of travel
  – No starvation, but retains flavor of SSTF

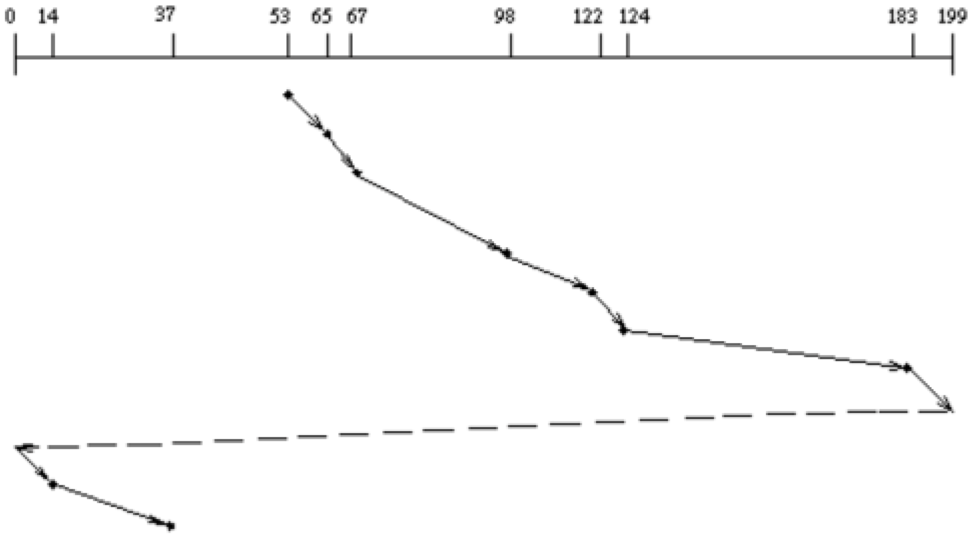


Disk Scheduling (3/3)

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



- 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



Recall: How do we Hide I/O Latency?

- Blocking Interface: “Wait”
  - When request data (e.g., read() system call), put process to sleep until data is ready
  - When write data (e.g., write() system call), put process to sleep until device is ready for data
- Non-blocking Interface: “Don’t Wait”
  - Returns quickly from read or write request with count of bytes successfully transferred to kernel
  - Read may return nothing, write may write nothing
- Asynchronous Interface: “Tell Me Later”
  - When requesting data, take pointer to user’s buffer, return immediately; later kernel fills buffer and notifies user
  - When sending data, take pointer to user’s buffer, return immediately; later kernel takes data and notifies user

Recall: I/O and Storage Layers

Application / Service

High Level I/O — *Streams*

Low Level I/O — *File Descriptors*

Syscall — *open(), read(), write(), close(), …*

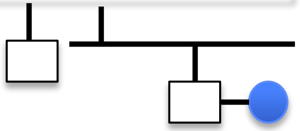
Open File Descriptions

What we covered in Lecture 4

File System — *Files/Directories/Indexes*

What we will cover next…

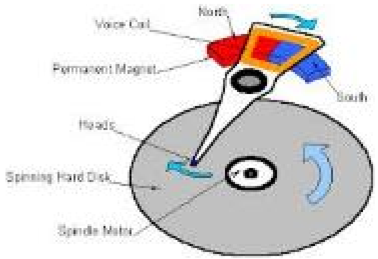
I/O Driver — *Commands and Data Transfers*



Disks, Flash, Controllers, DMA

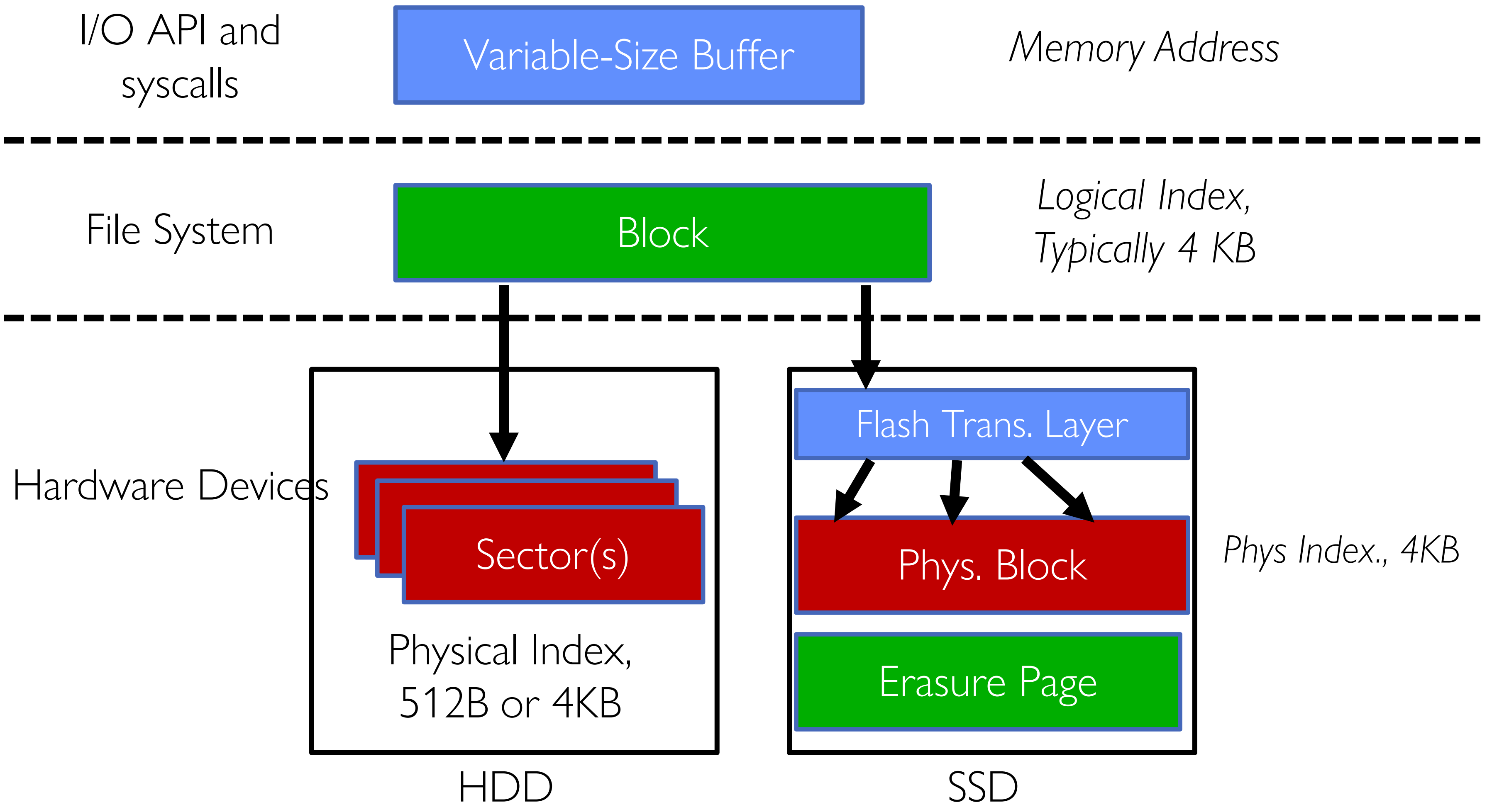






What we just covered…

From Storage to File Systems



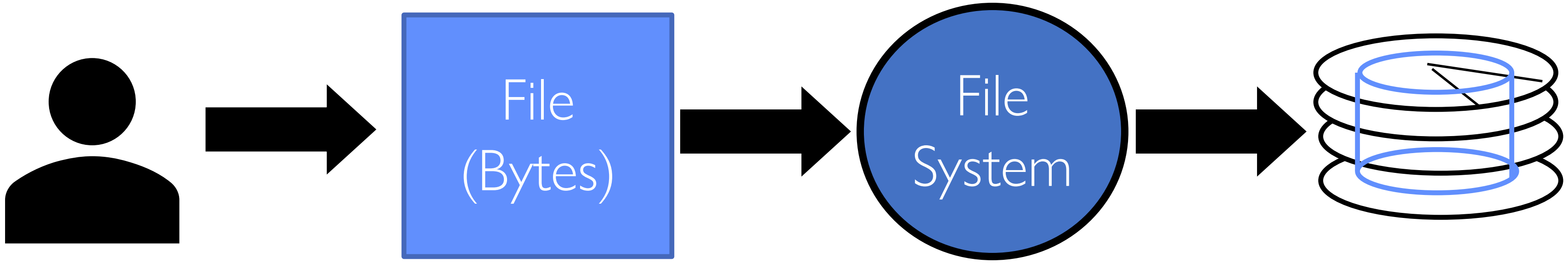
Building a File System

- **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 $\geq$ 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

Conclusion

- 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
- 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
  - SDD: Queuing time + controller + transfer (erasure & wear)
- Systems (e.g., file system) designed to optimize performance and reliability
  - Relative to performance characteristics of underlying device
- Bursts & High Utilization introduce queuing delays
- Queuing Latency:
  - M/M/1 and M/G/1 queues: simplest to analyze
  - As utilization approaches 100%, latency $\rightarrow \infty$

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