CS162
Operating Systems and Systems Programming
Lecture 17

Performance
Storage Devices, Queueing Theory

October 25, 2017

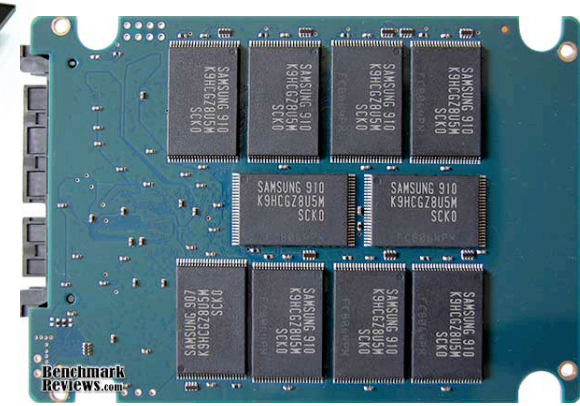
Prof. Ion Stoica

http://cs162.eecs.Berkeley.edu

Review: Basic Performance Concepts

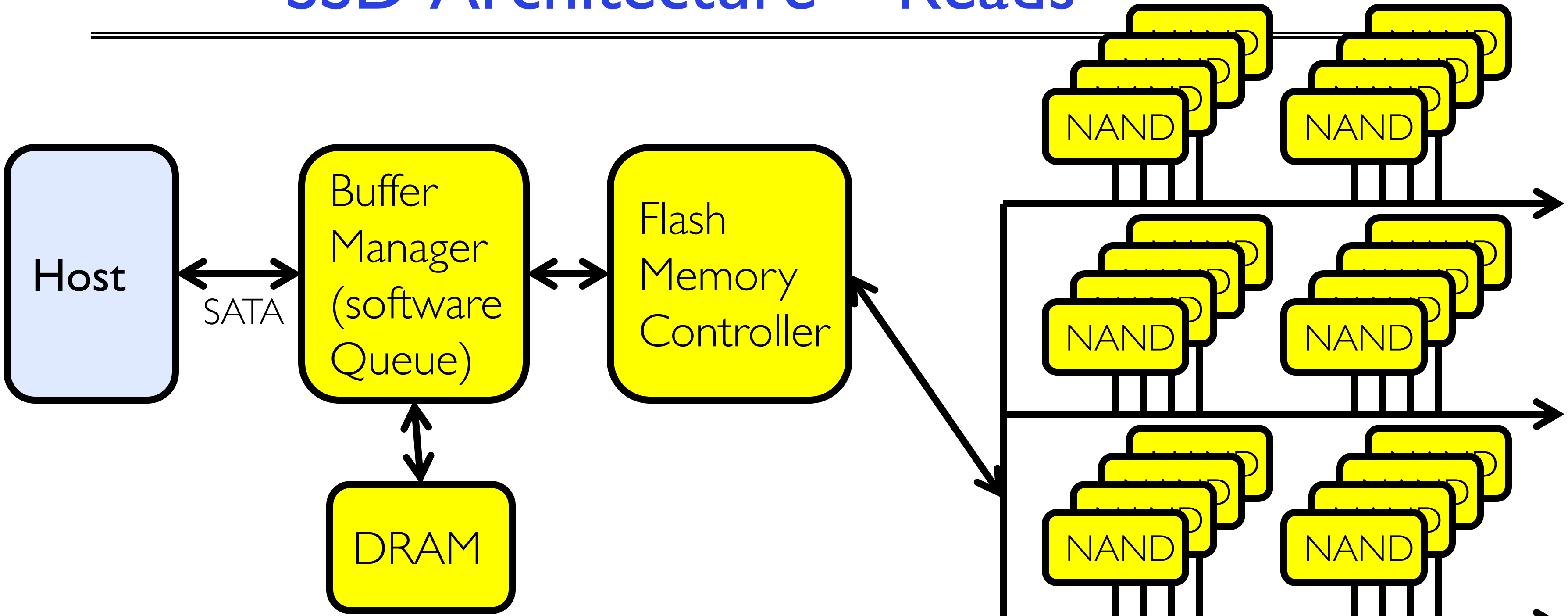
- *Response Time or Latency*: Time to perform an operation
- *Bandwidth or Throughput*: Rate at which operations are performed (op/s)
  – Files: NB/s, Networks: Mb/s, Arithmetic: GFLOP/s
- *Start up* or "Overhead": time to initiate an operation
- Most I/O operations are roughly linear in *n* bytes
 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

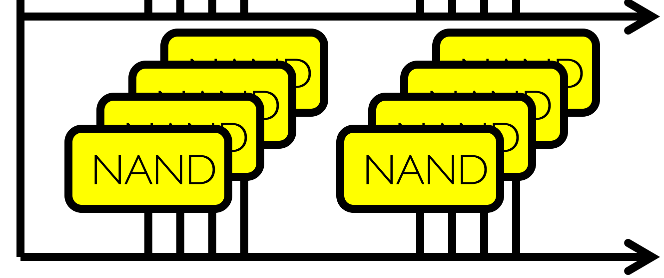
Solid State Disks (SSDs)



- 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 advances 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

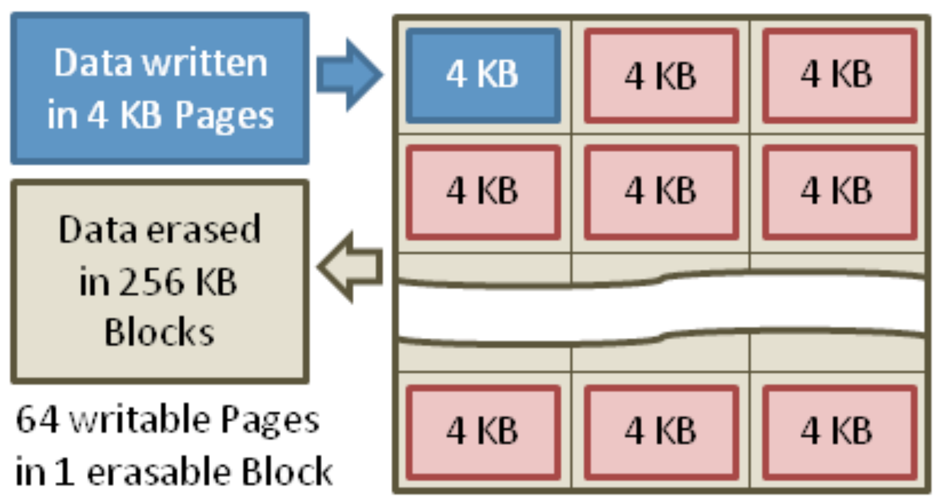
  » SATA: 300-600MB/s => ~4 x10^3 b / 400 x 10^6 bps => 10 us

– Latency = Queuing Time + Controller time + Xfer Time

– Highest Bandwidth: Sequential OR Random reads

SSD Architecture – Writes

- 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 can measure (it 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)

SSD Summary

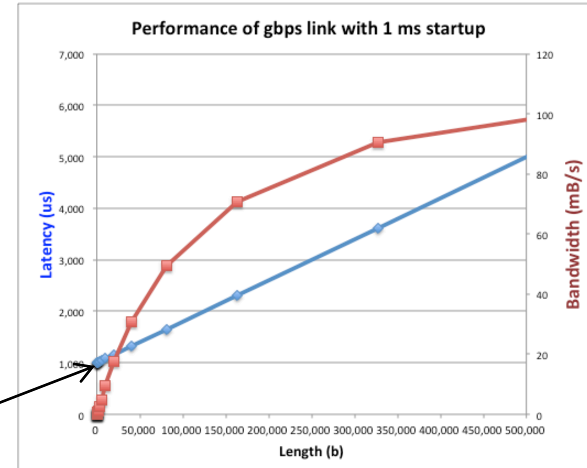
- Pros (vs. hard disk drives):
  - Low latency, high throughput (eliminate seek/rotational delay)
  - No moving parts:
    - » Very light weight, low power, silent, very shock insensitive
  - Read at memory speeds (limited by controller and I/O bus)
- Cons
  - ~~Small storage (0.1-0.5x disk)~~, expensive (3-20x disk)
    - » Hybrid alternative: combine small SSD with large HDD
  - 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!

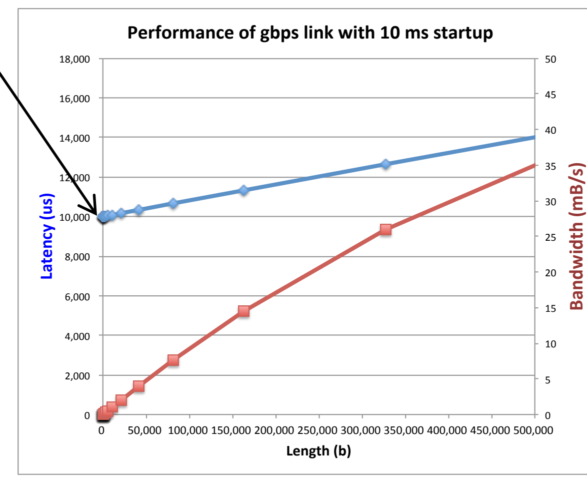
No longer true!

What Goes into Startup Cost for I/O?

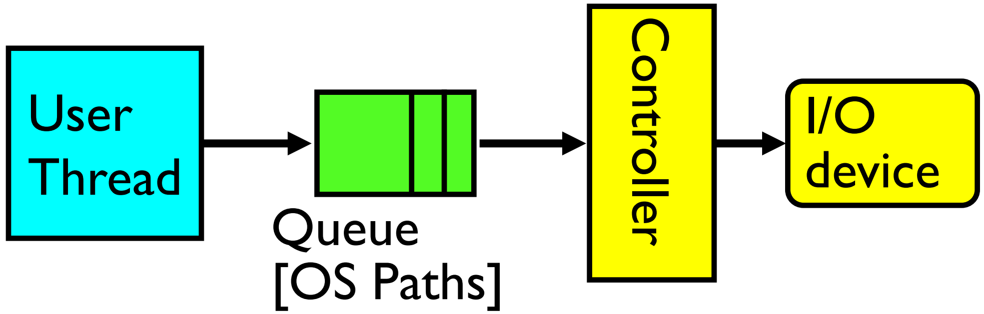
- Syscall overhead
- Operating system processing
- Controller Overhead
- Device Startup
  - Mechanical latency for a disk
  - Media Access + Speed of light + Routing for network
- Queuing (next topic)

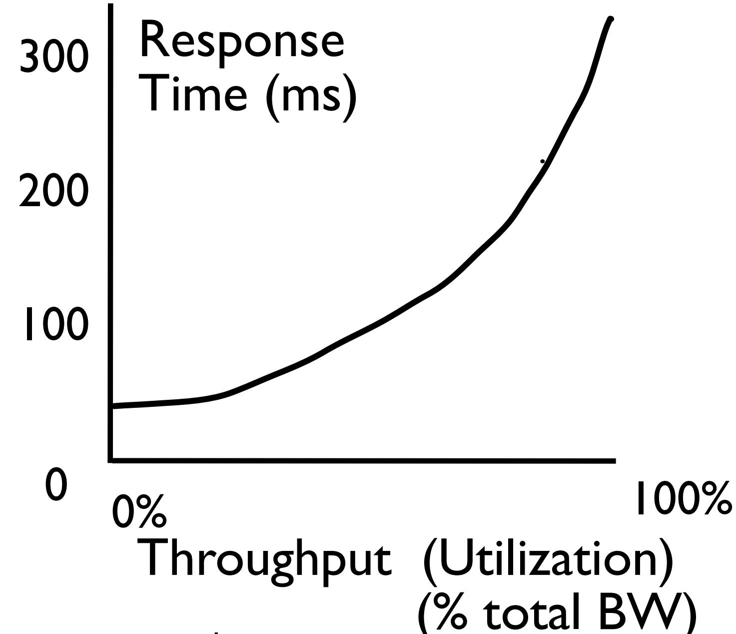
Startup cost (fixed overhead)





I/O Performance





Response Time = Queue + I/O device service time

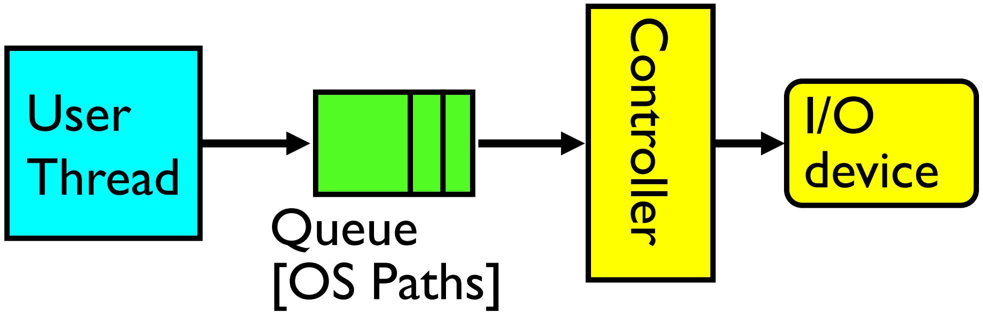
- Performance of I/O subsystem
  - Metrics: Response Time, Throughput
  - Effective BW per op = transfer size / response time
    - » $\text{EffBW}(n) = n / (S + n/B) = B / (1 + SB/n)$

# of ops

Fixed overhead

time per op

I/O Performance



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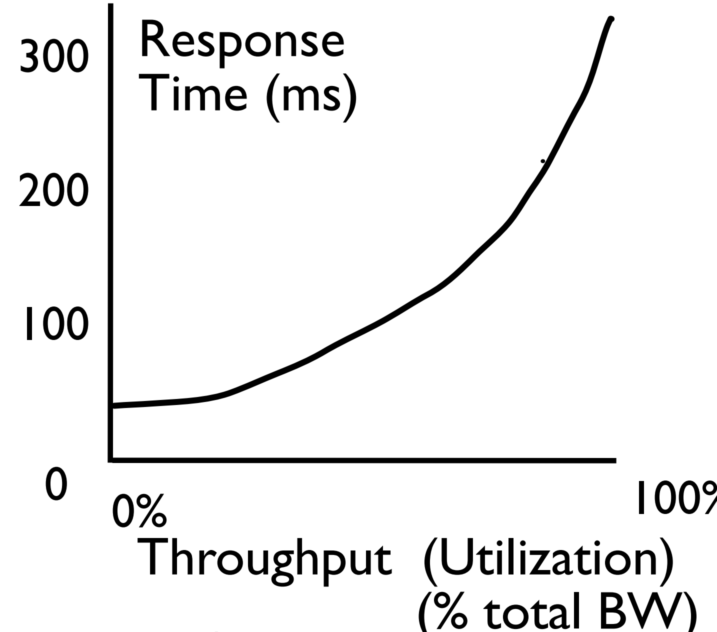
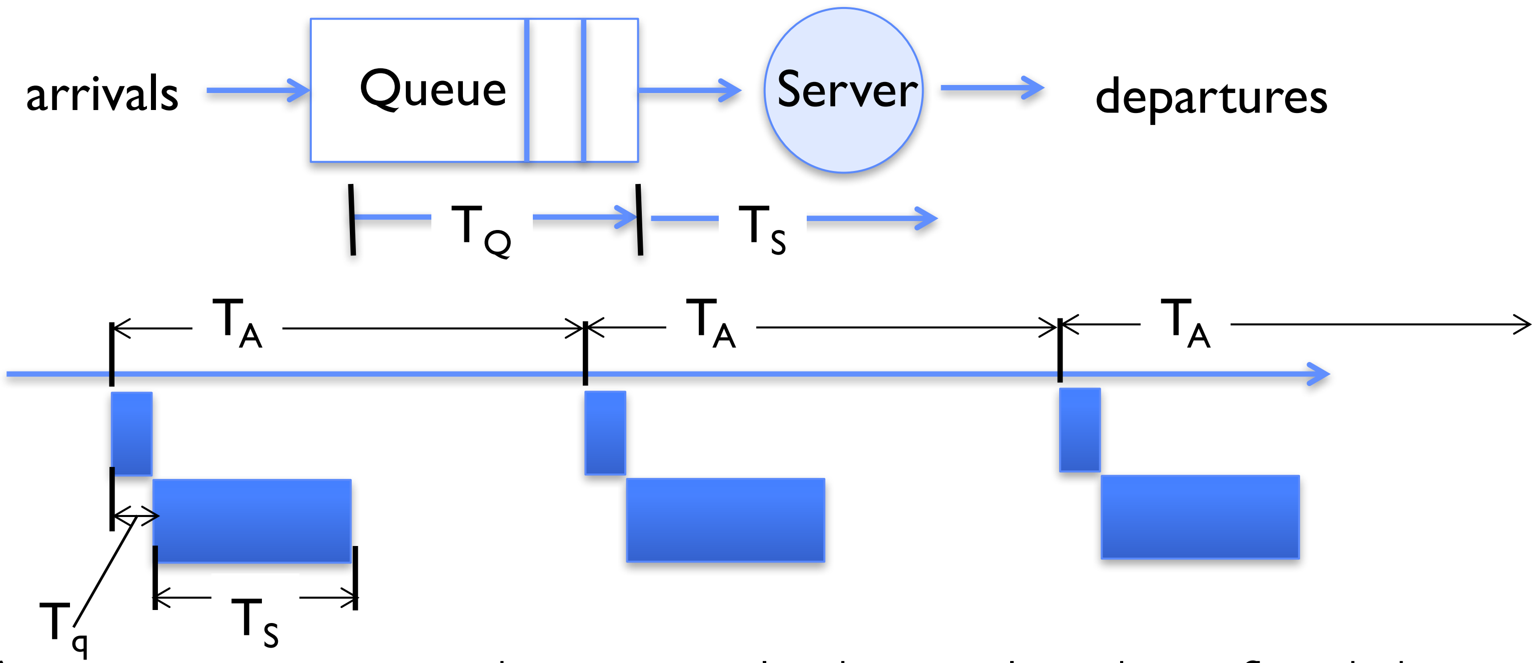


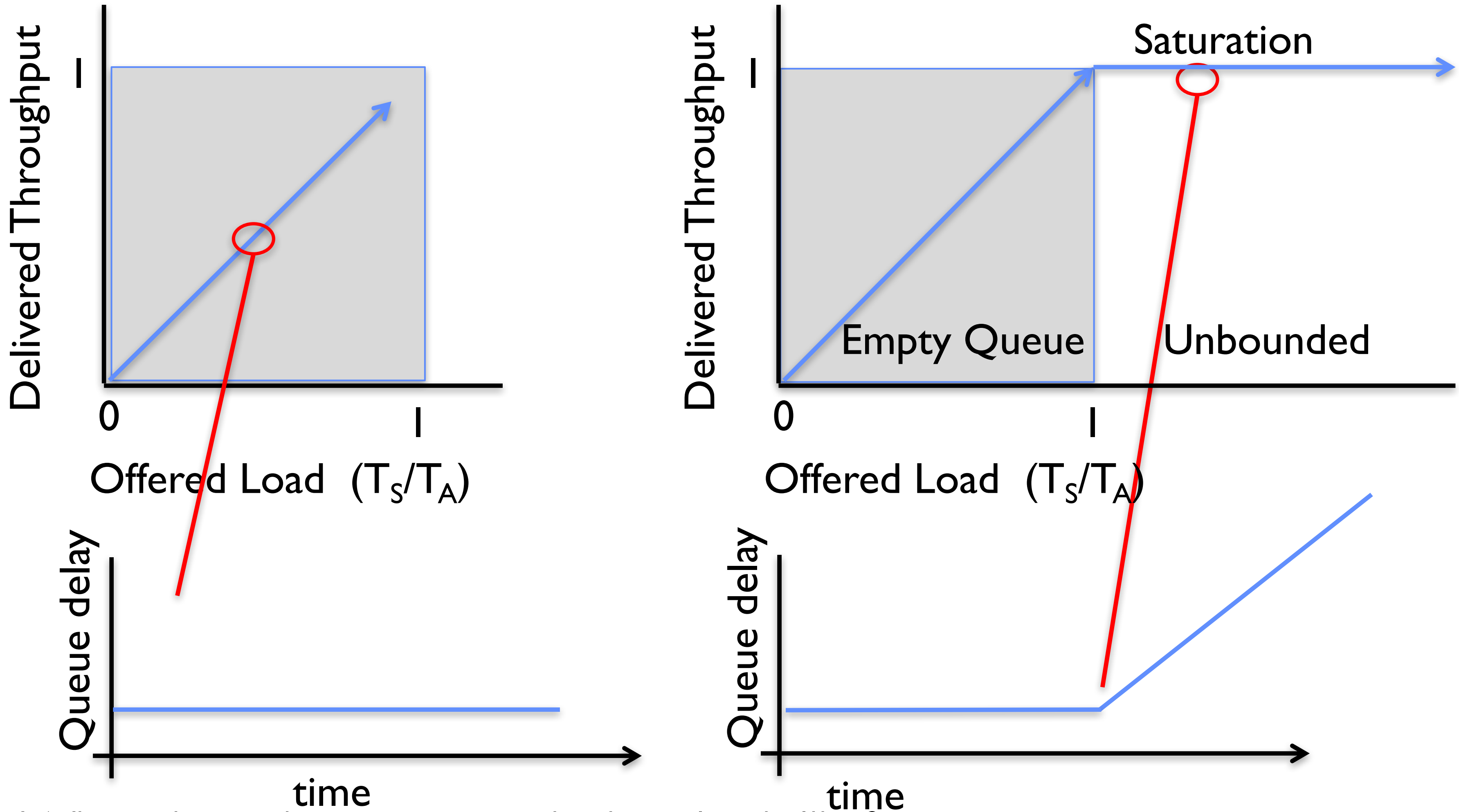
- Performance of I/O subsystem
  - Metrics: Response Time, Throughput
  - Effective BW per op = transfer size / response time
    - » EffBW(n) = n / (S + n/B) = B / (1 + SB/n)
  - Contributing factors to latency:
    - » Software paths (can be loosely modeled by a queue)
    - » Hardware controller
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

A Simple Deterministic World



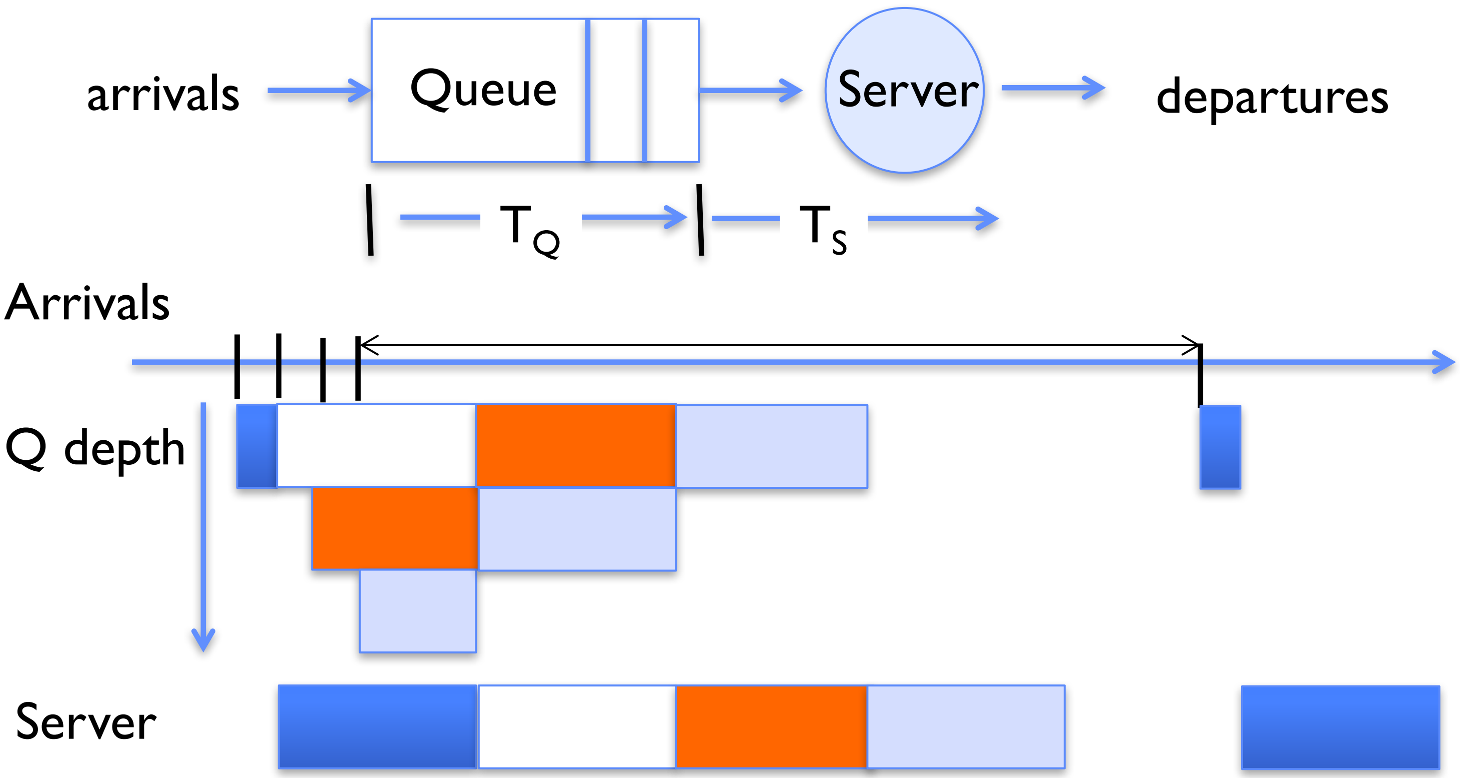
- Assume requests arrive at regular intervals, take a fixed time to process, with plenty of time between …
- Service rate ($\mu = 1/T_S$) - operations per sec
- Arrival rate: ($\lambda = 1/T_A$) - requests per second
- Utilization: $U = \lambda/\mu$, where $\lambda < \mu$
- Average rate is the complete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

A Ideal Linear World



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

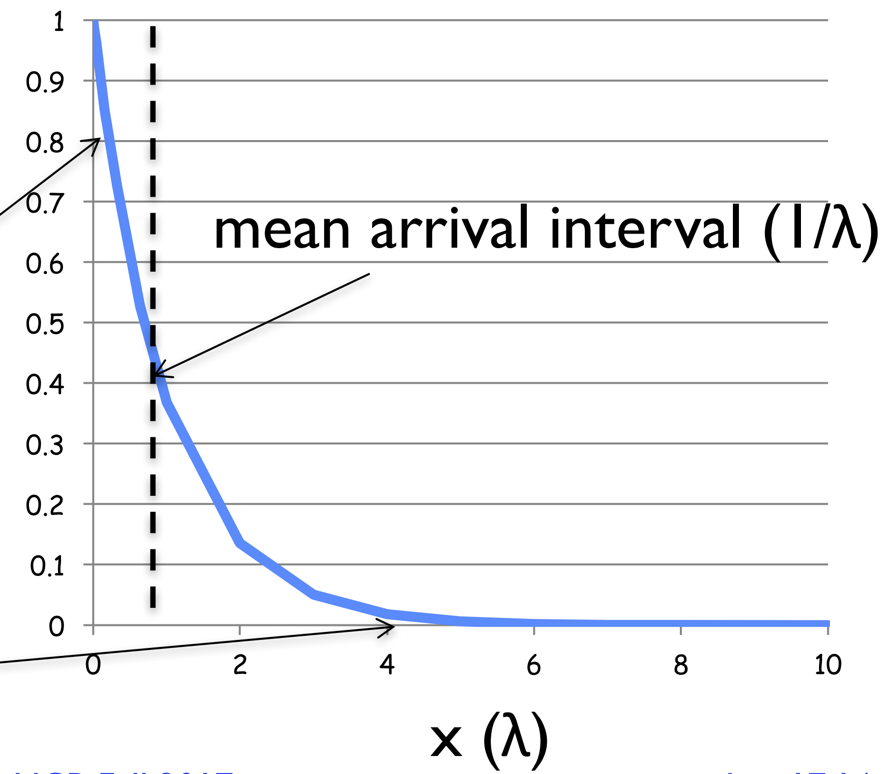
A Bursty World



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

So how do we model the burstiness of arrival?

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



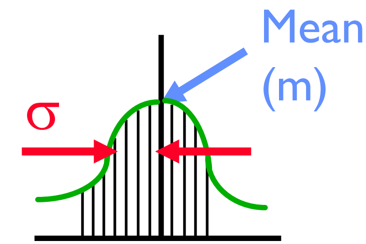
Likelihood of an event occurring is independent of how long we've been waiting

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

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

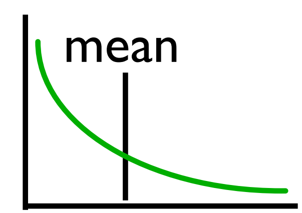
Background: General Use of Random Distributions

- 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



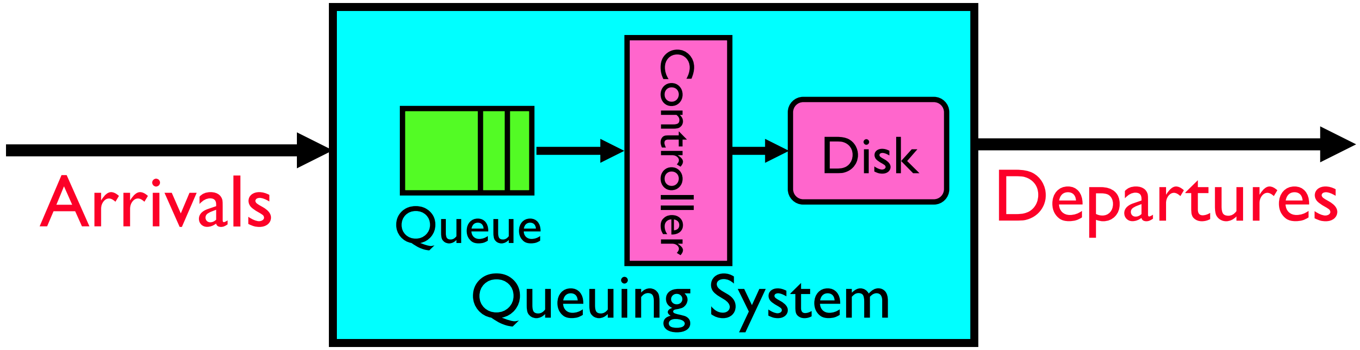
Distribution of service times

- 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)



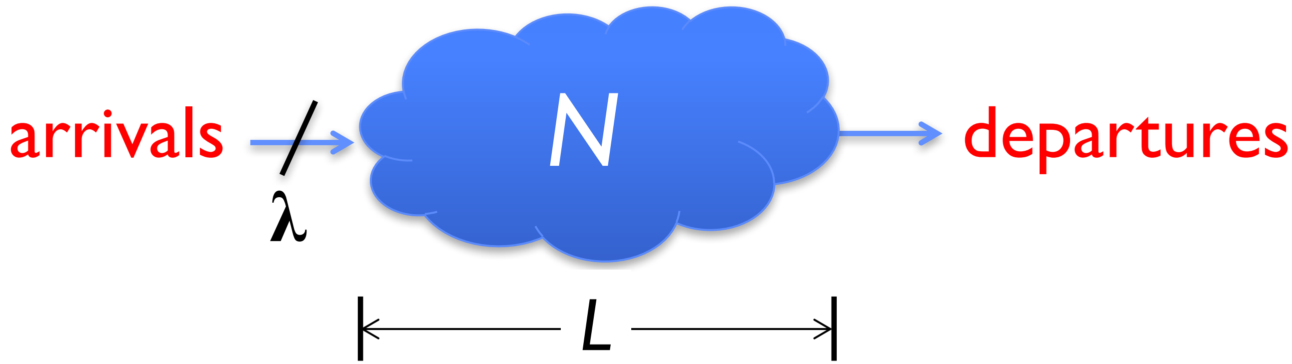
Memoryless

Introduction to Queuing Theory



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

Little's Law

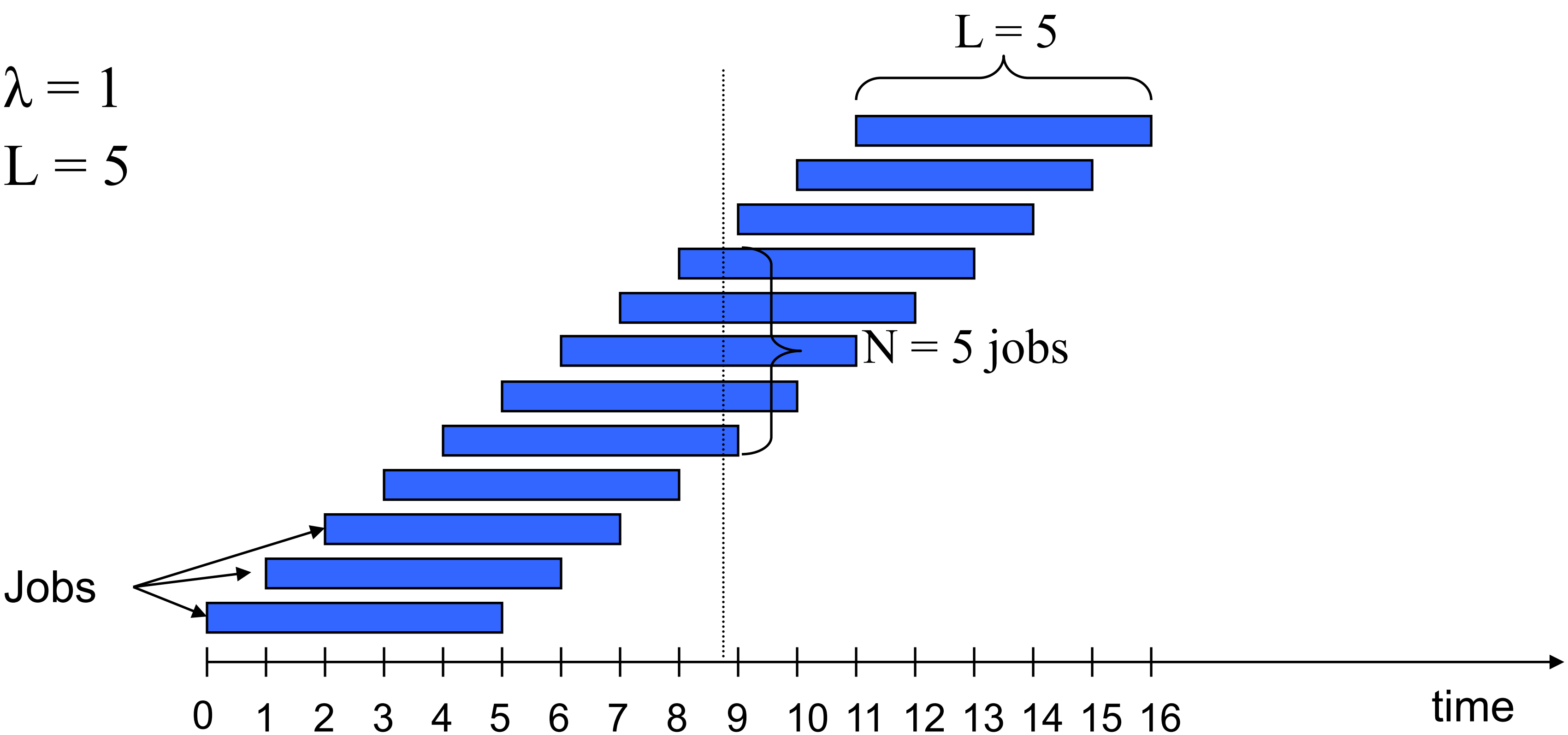


- In any *stable* system
  - Average arrival rate = Average departure rate
- The average number of jobs/tasks in the system (*N*) is equal to arrival time / throughput (λ) times the response time (*L*)
  - *N (jobs) = λ (jobs/s) x L (s)*
- Regardless of structure, bursts of requests, variation in service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

Example

$\lambda = 1$

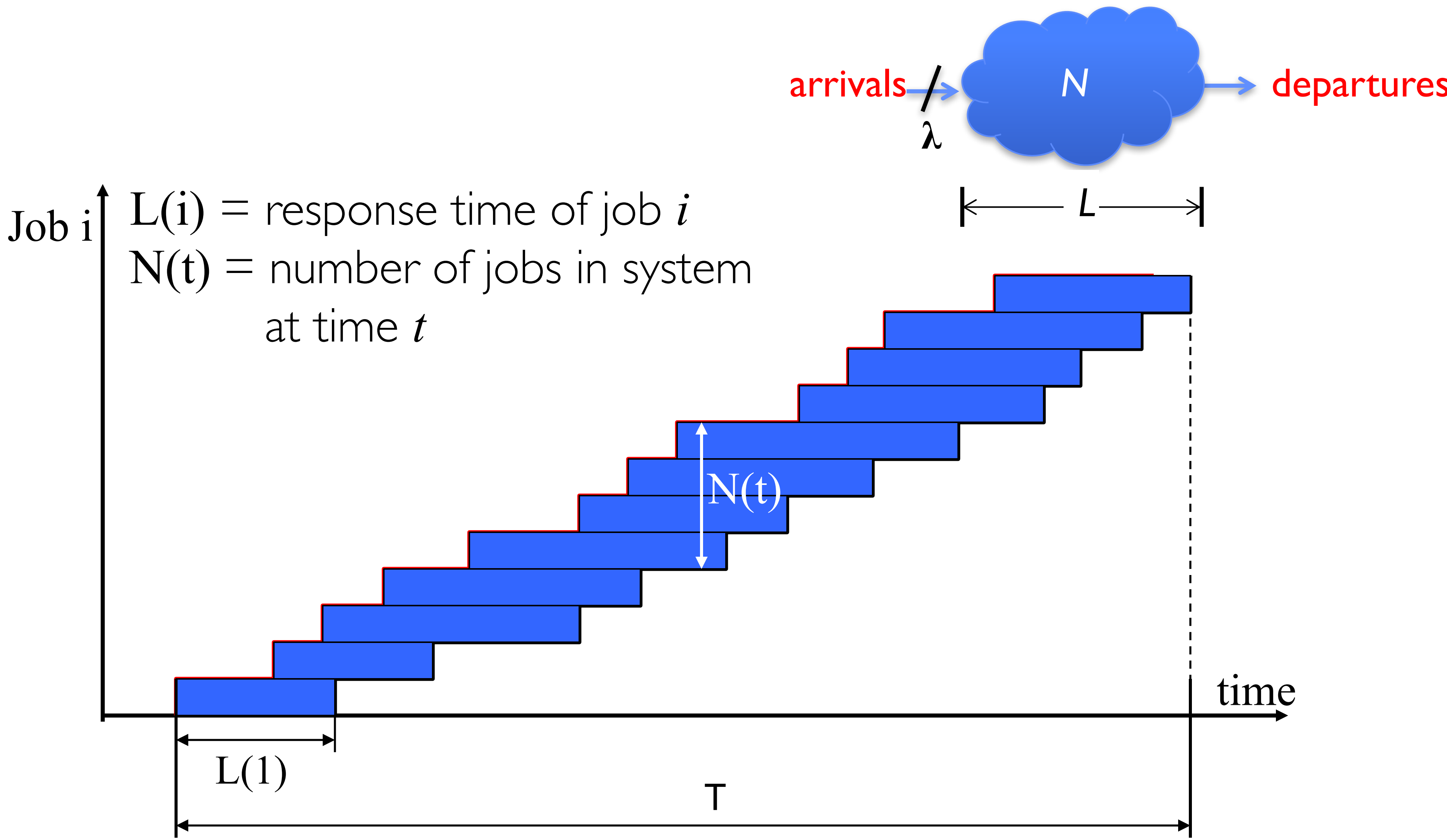
$L = 5$



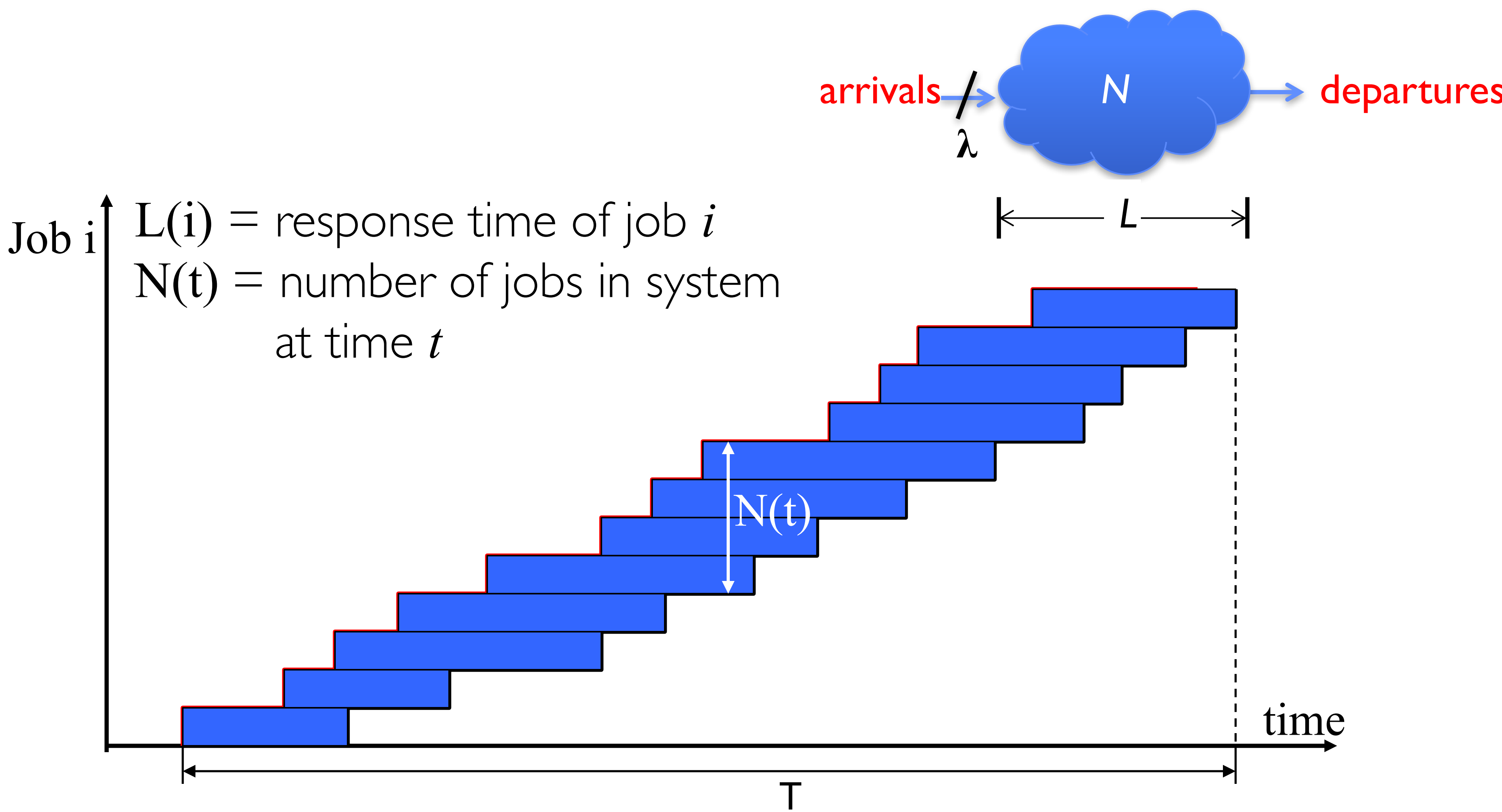
A: $N = \lambda \times L$

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

Little's Theorem: Proof Sketch

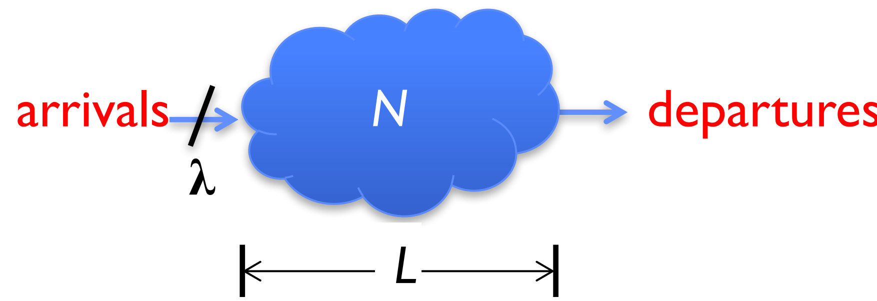


Little's Theorem: Proof Sketch



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

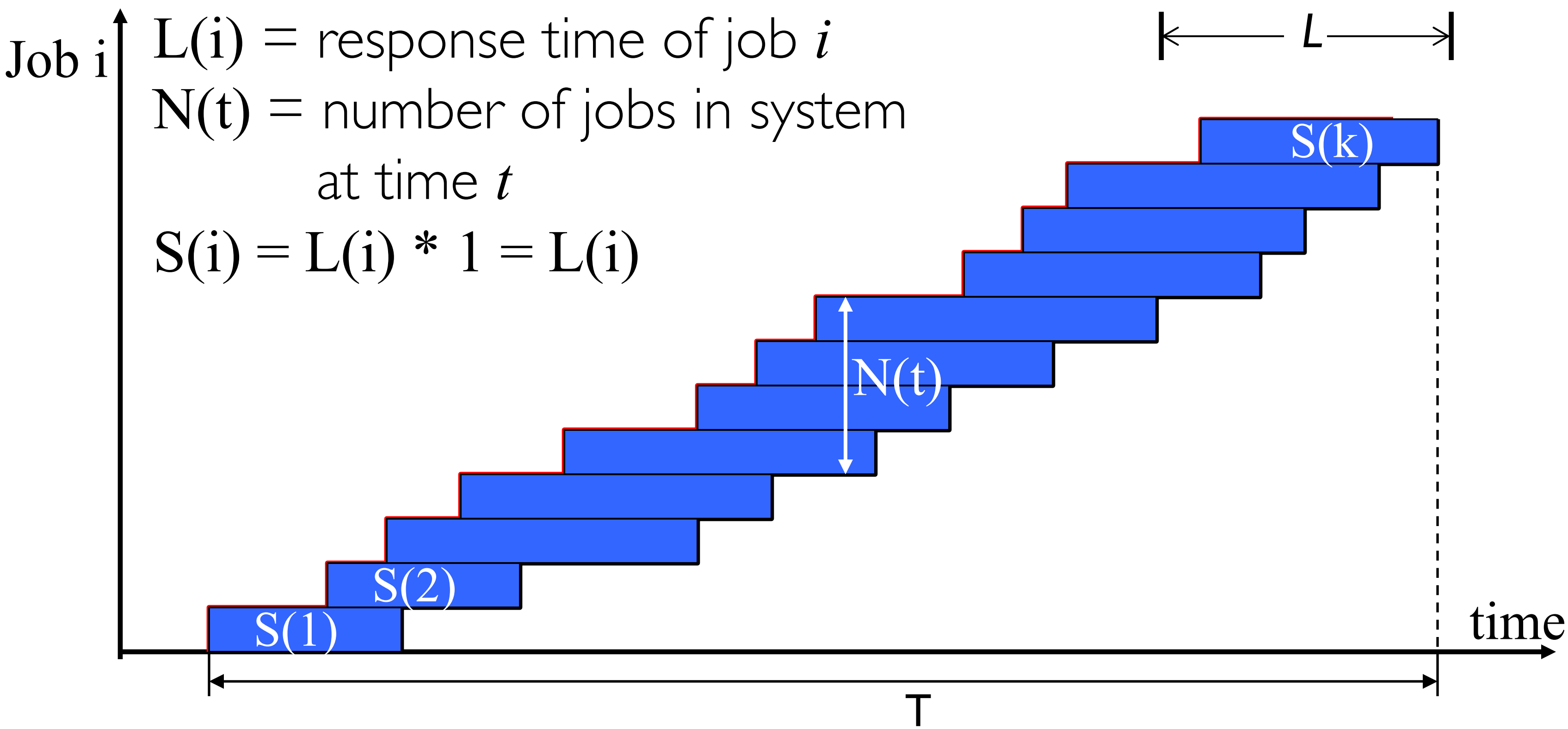
Little's Theorem: Proof Sketch



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

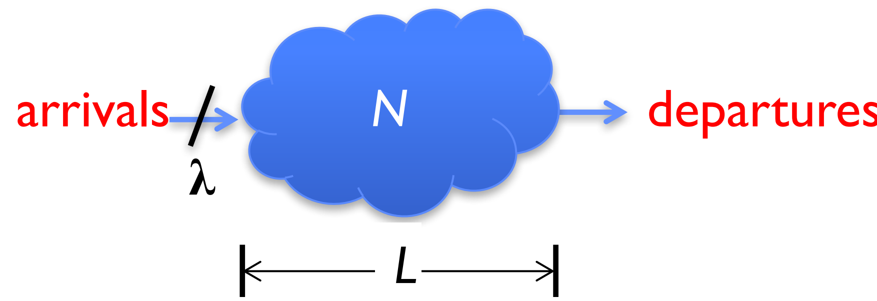
$N(t)$ = number of jobs in system at time t

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



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

Little's Theorem: Proof Sketch



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

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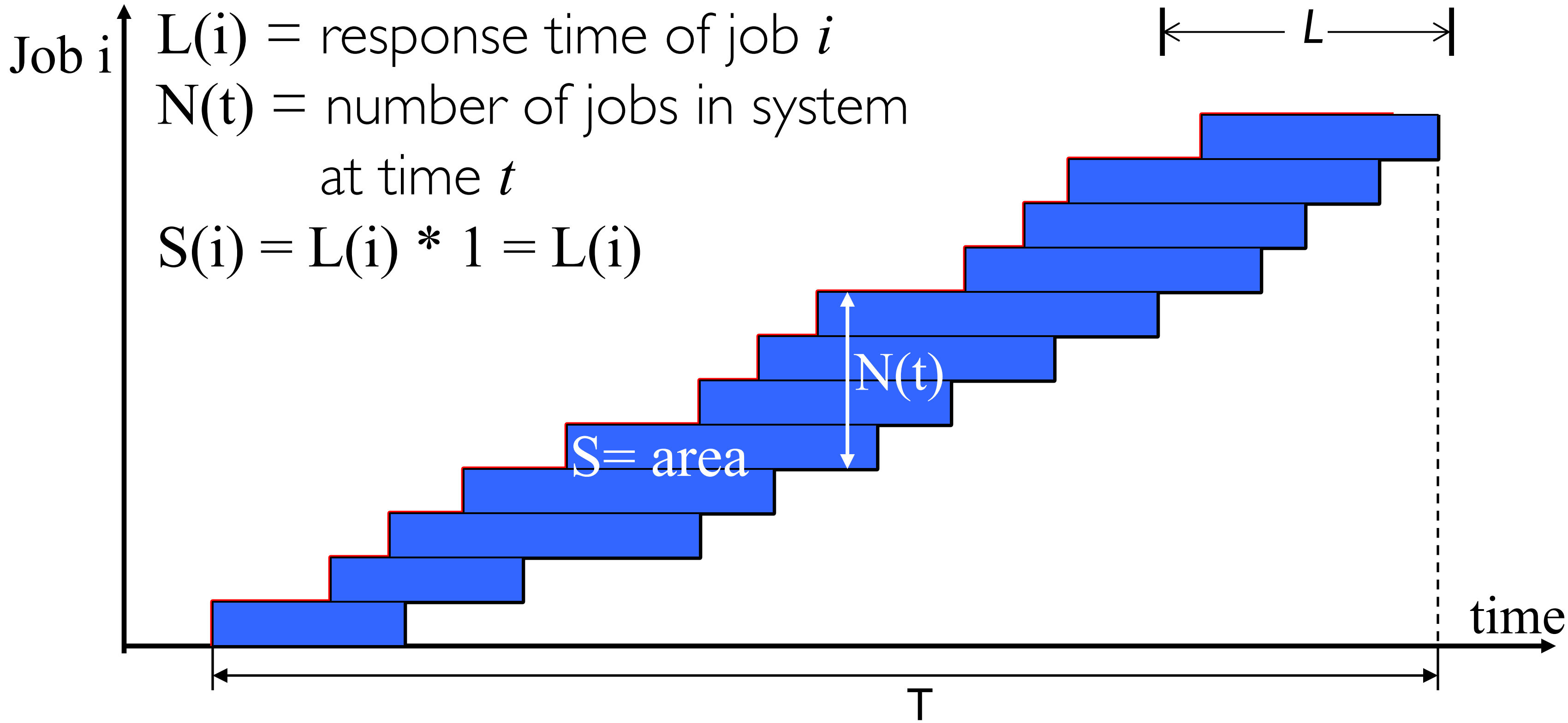
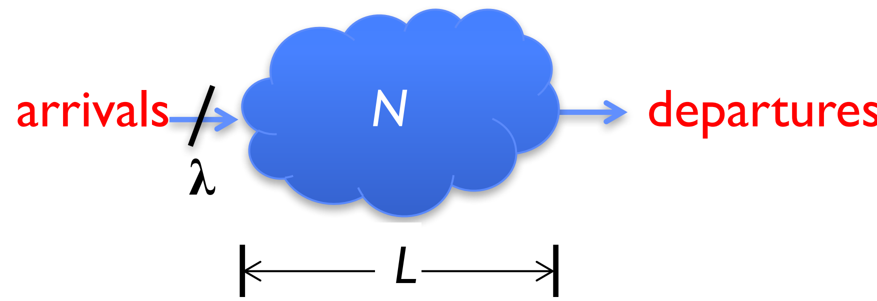


Average occupancy (N_{avg}) = S/T

Little's Theorem: Proof Sketch



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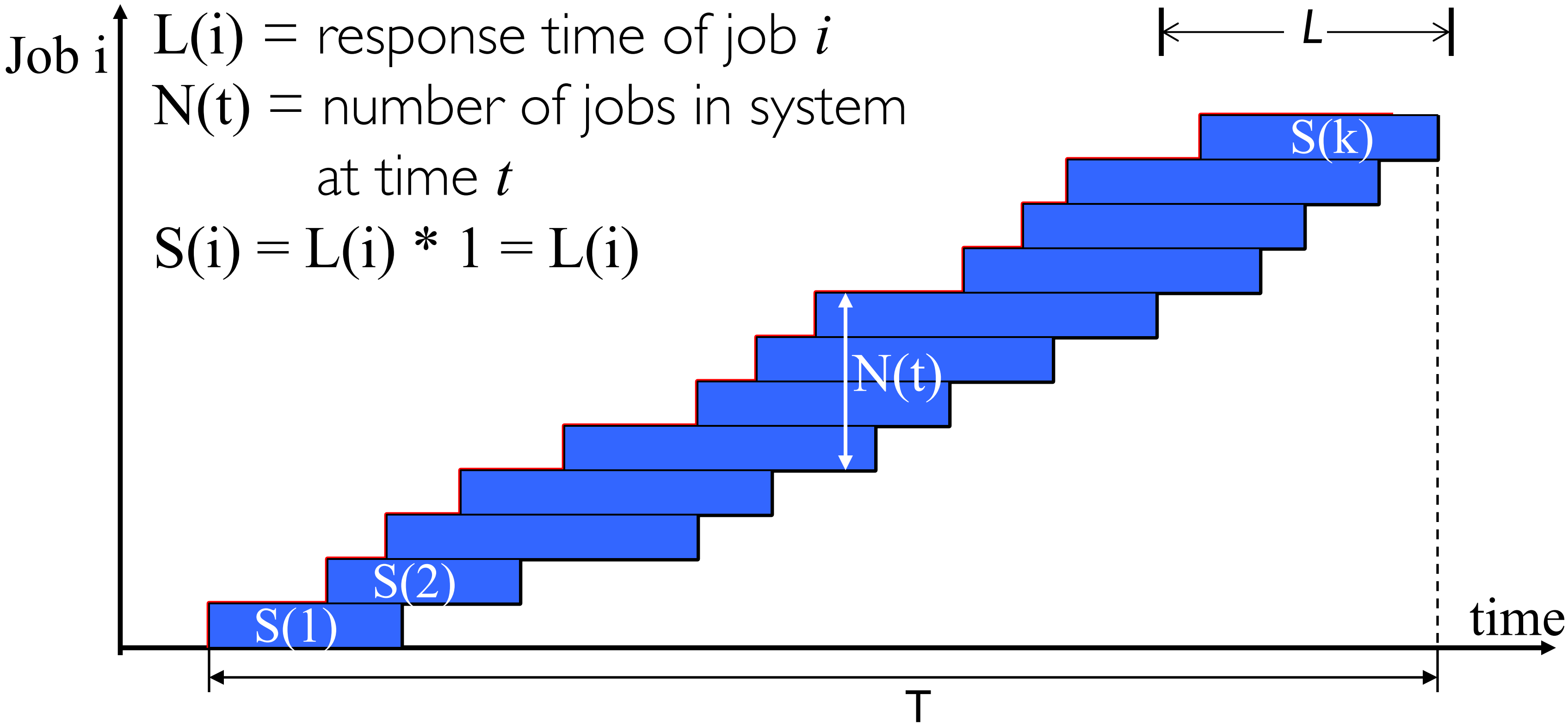
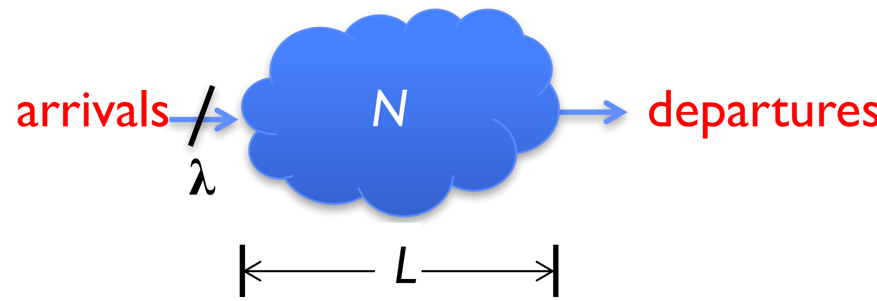


$$\text{Navg} = S/T = (L(1) + \ldots + L(k))/T$$

Little's Theorem: Proof Sketch



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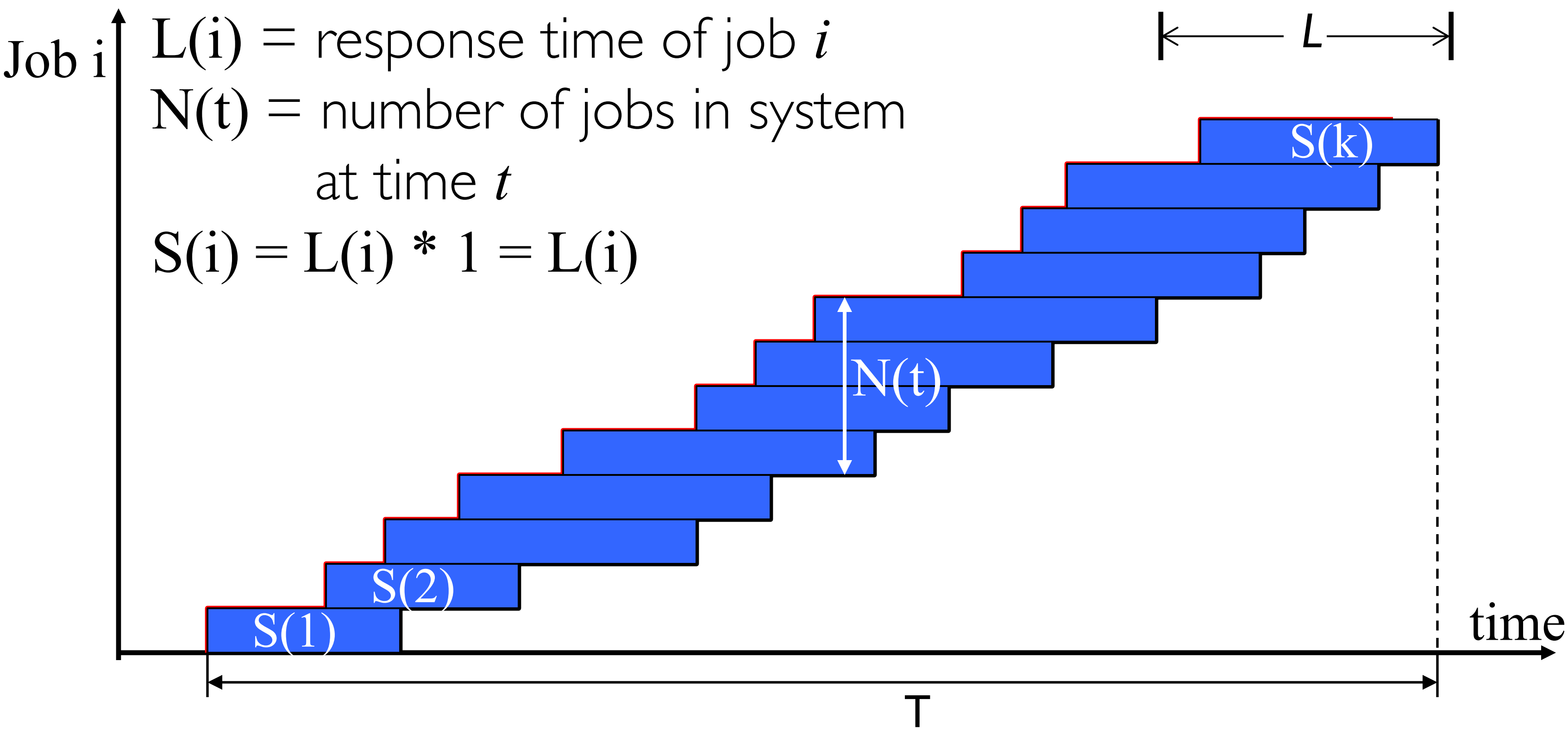
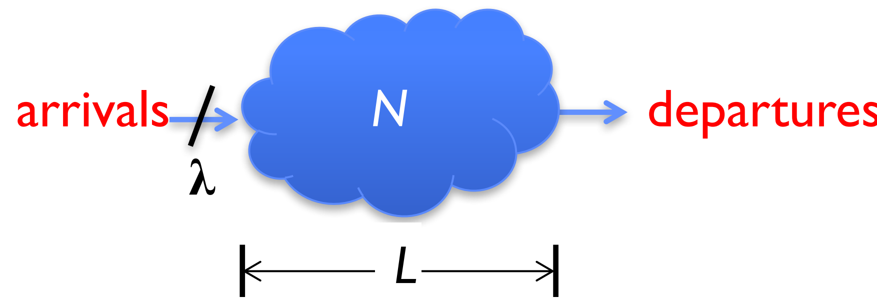


$$N_{avg} = (L(1) + \ldots + L(k))/T = (N_{total}/T)*(L(1) + \ldots + L(k))/N_{total}$$

Little's Theorem: Proof Sketch



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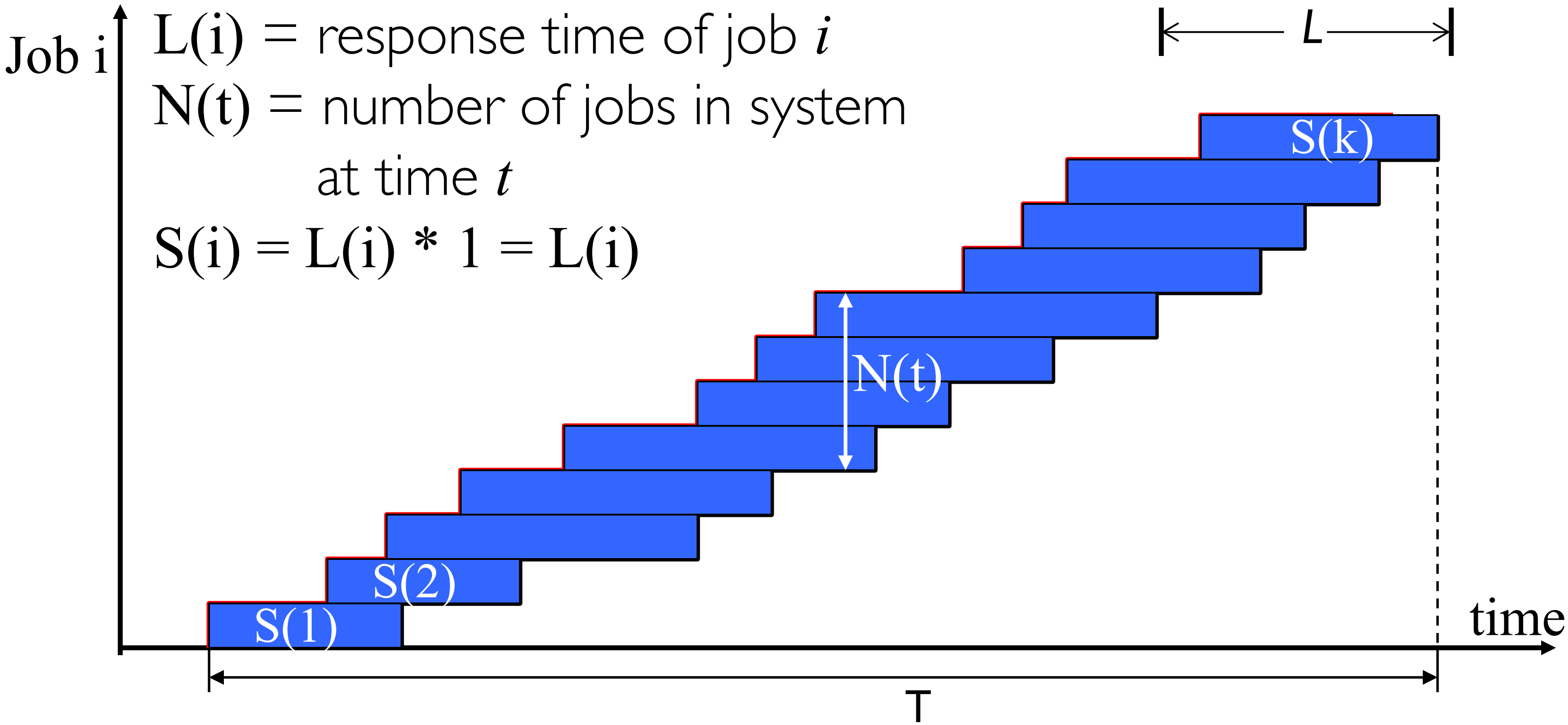
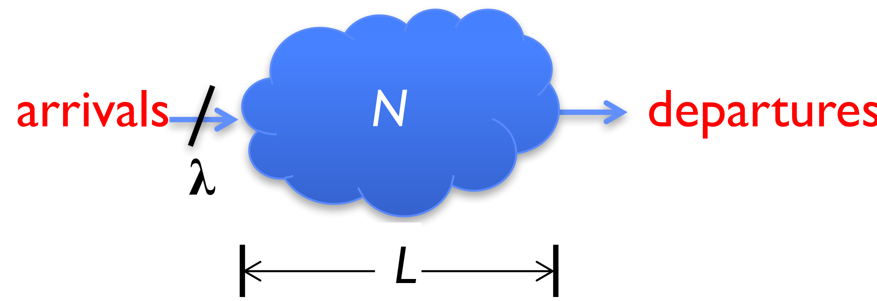


$$N_{avg} = (N_{total}/T)*(L(1) + \ldots + L(k))/N_{total} = \lambda_{avg} \times L_{avg}$$

Little's Theorem: Proof Sketch



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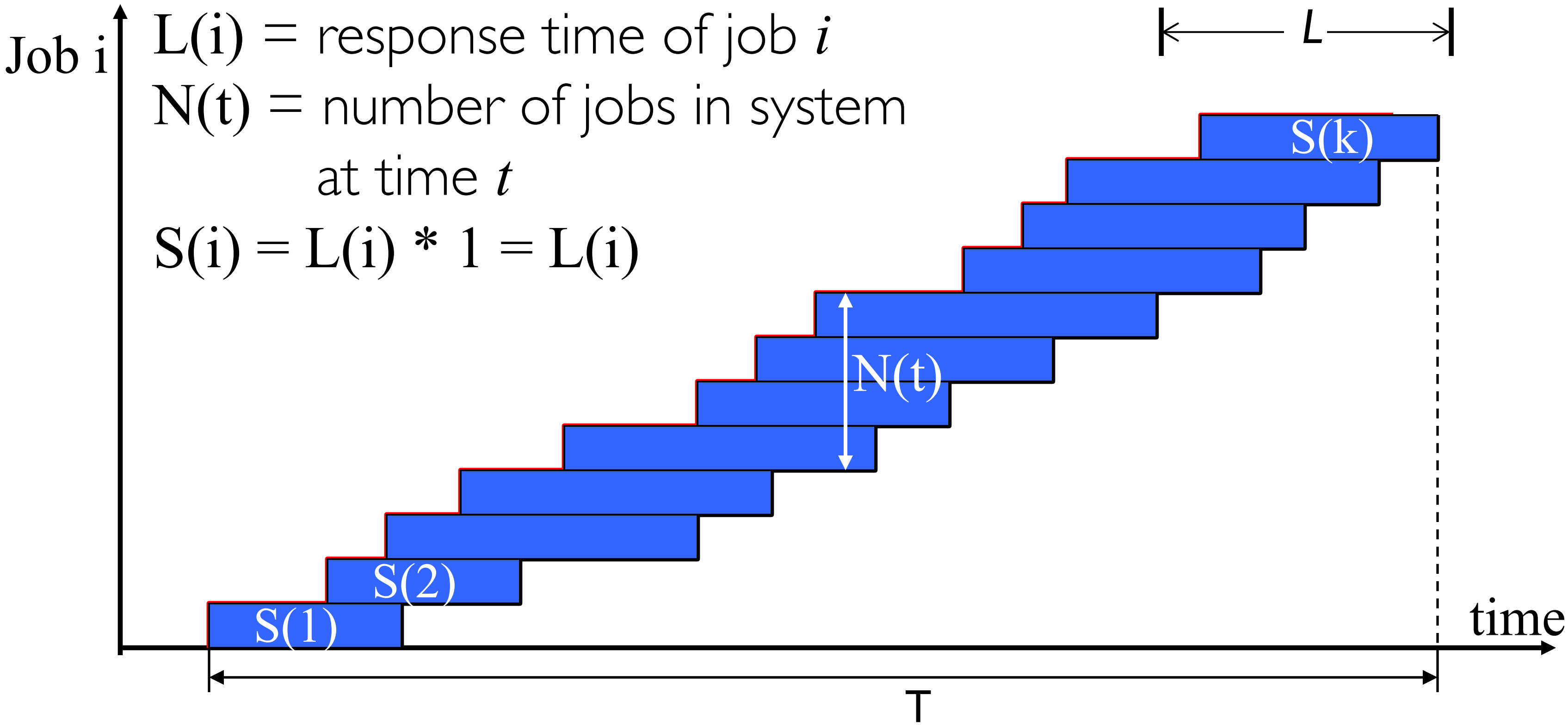

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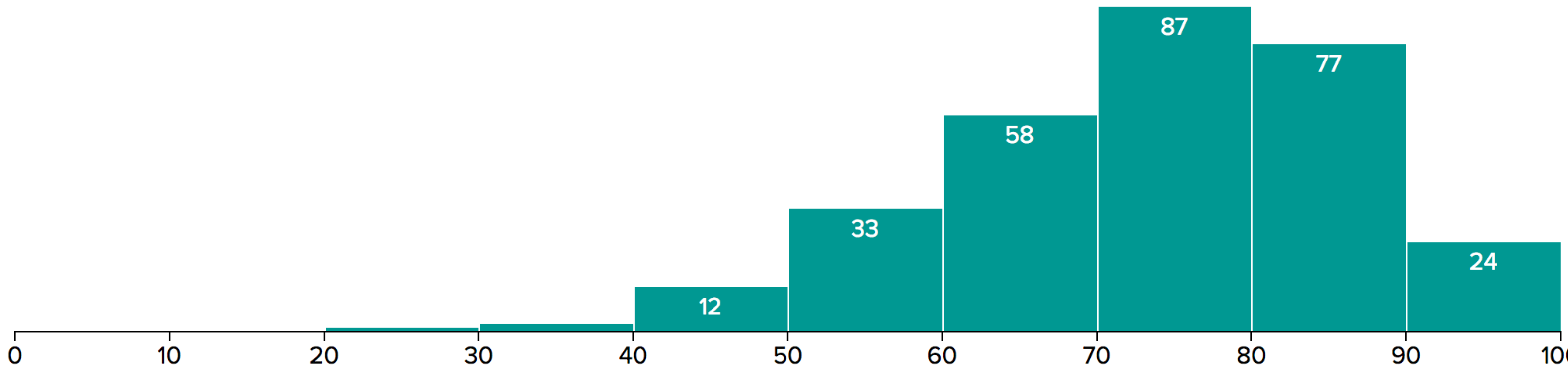
Administrivia



MINIMUM	MEDIAN	MAXIMUM	MEAN	STD DEV
28.0	73.75	97.0	72.91	12.78

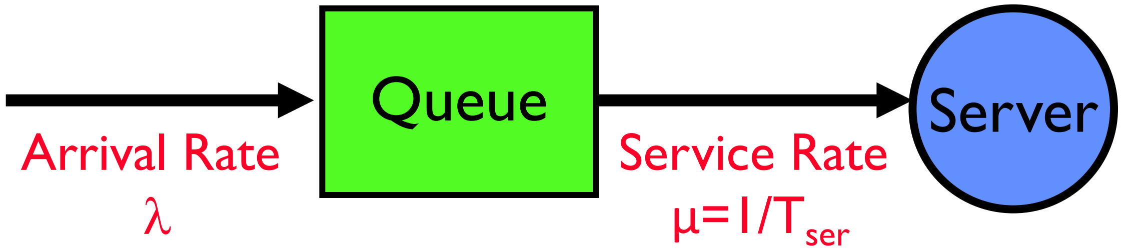
- Regrade request deadline Tue 10/31 at midnight
  - *Please only submit regrade requests for grading errors!*

- Ion out again on Monday (attending SOSP), 10/29
  - Lecture will be given by Anthony Joseph

BREAK

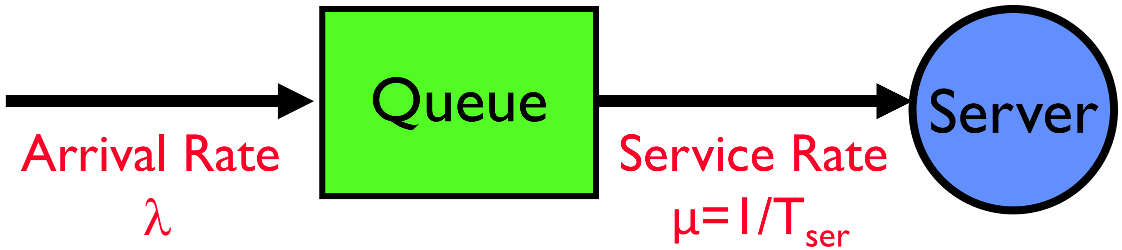
A Little Queuing Theory: Some Results (1/2)

- 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 ("m")
  - C: squared coefficient of variance $= \sigma^2/m^2$
  - 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)

A Little Queuing Theory: Some Results (2/2)



- Parameters that describe our system:
  - λ: mean number of arriving customers/second $\lambda = 1/T_A$
  - T_{ser}: mean time to service a customer ("m")
  - C: squared coefficient of variance $= \sigma^2/m^2$
  - 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** (**M**: Poisson arrival process, **1** server):
  - **M**emoryless service time distribution (C = 1): Called an **M/M/1** queue
    - » $T_q = T_{ser} \times \boxed{u/(1-u)}$
  - **G**eneral service time distribution (no restrictions): Called an **M/G/1** queue
    - » $T_q = T_{ser} \times \frac{1}{2}(1+C) \times \boxed{u/(1-u)})$

A Little Queuing Theory: An Example (1/2)

- 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 + rotation + transfer)
- Questions:
  - How utilized is the disk (server utilization)? Ans:, $u = \lambda T_{ser}$
  - 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: $T_{sys} = T_q + T_{ser}$

A Little Queuing Theory: An Example (2/2)

- Questions:
  - How utilized is the disk (server utilization)? Ans:, $u = \lambda T_{ser}$
  - 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 × .02s = 0.2

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

L_q (avg length of queue) = $\lambda \times T_q$=10/s × .005s = 0.05s

T_{sys} (avg time/customer in system) =$T_q + T_{ser}$= 25 ms

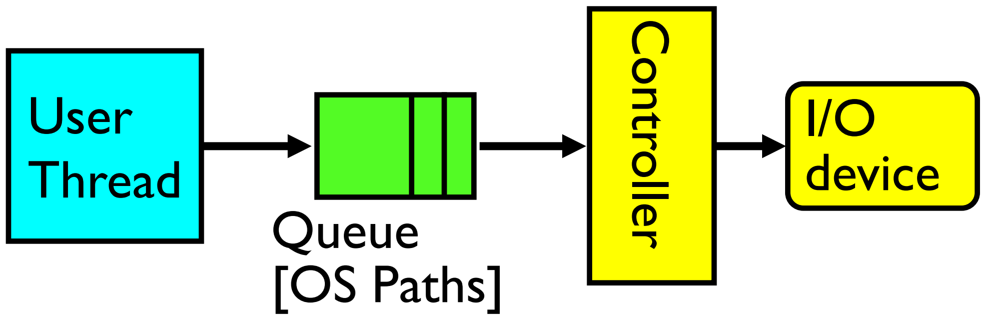
Queuing Theory Resources

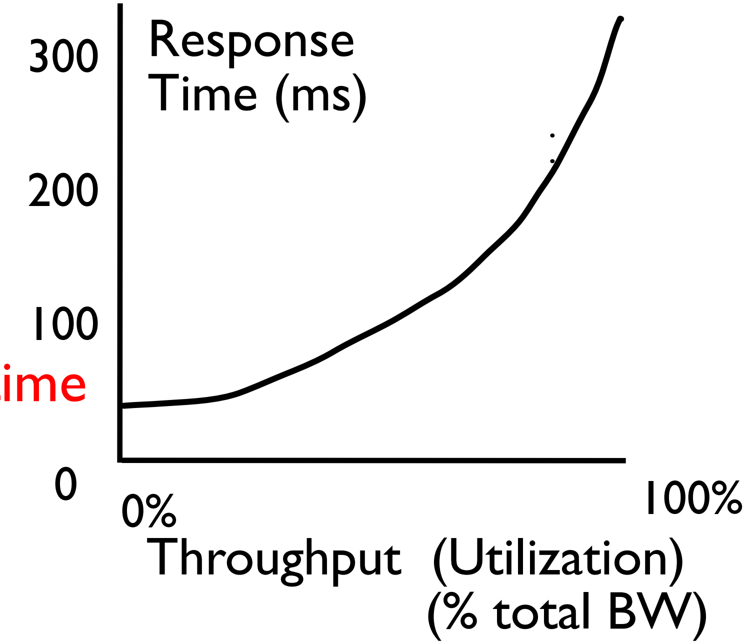
- Resources page contains Queueing Theory Resources (under Readings):
  - Scanned pages from Patterson and Hennessy book that gives further discussion and simple proof for general equation: https://cs162.eecs.berkeley.edu/static/readings/patterson_queue.pdf
  - A complete website full of resources: http://web2.uwindsor.ca/math/hlynka/qonline.html

- 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
  - Do other useful work while waiting
    - » Multiple independent buses or controllers
  - Optimize the bottleneck to increase service rate
    - » Use the queue to optimize the service
- Queues absorb bursts and smooth the flow
- Add admission control (finite queues)
  - Limits delays, but may introduce unfairness and livelock

When is Disk Performance Highest?

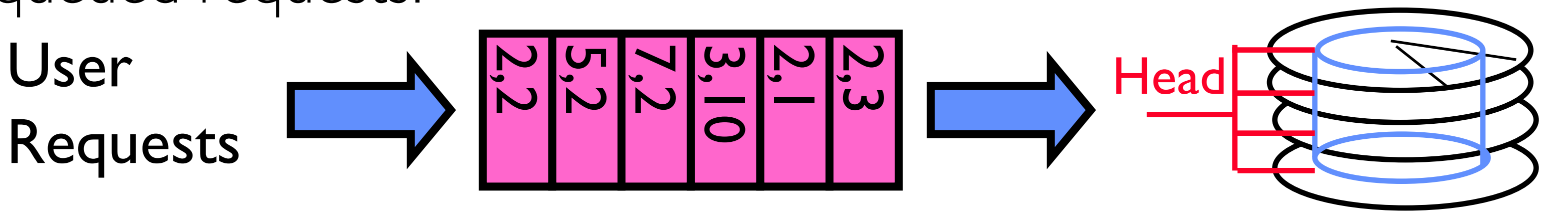
- When there are big sequential reads, or
- When there is so much work to do that they can be piggy backed (reordering queues—one moment)

- 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?

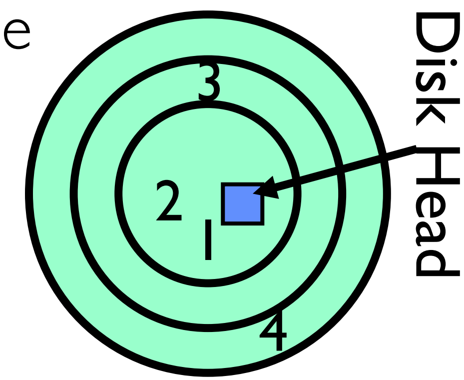
- Other techniques:
  - Reduce overhead through user level drivers
  - Reduce the impact of I/O delays by doing other useful work in the meantime

Disk Scheduling (1/2)

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

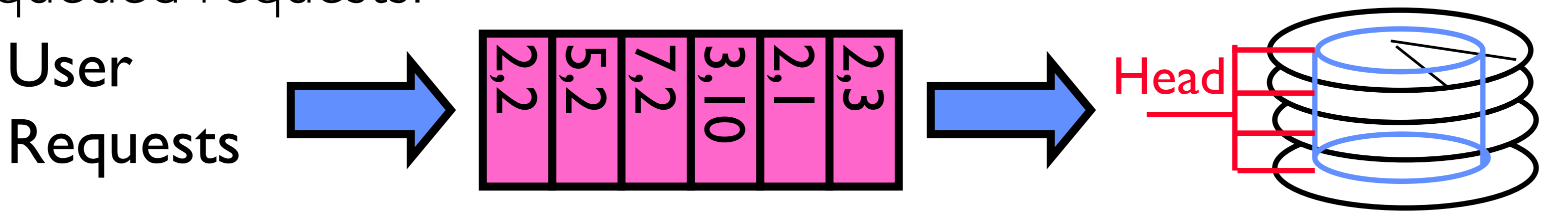


- FIFO Order
  – Fair among requesters, but order of arrival may be to random spots on the disk ⇒ Very long seeks
- SSTF: Shortest seek time first
  – Pick the request that's closest on the disk
  – Although called SSTF, today must include rotational delay in calculation, since rotation can be as long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

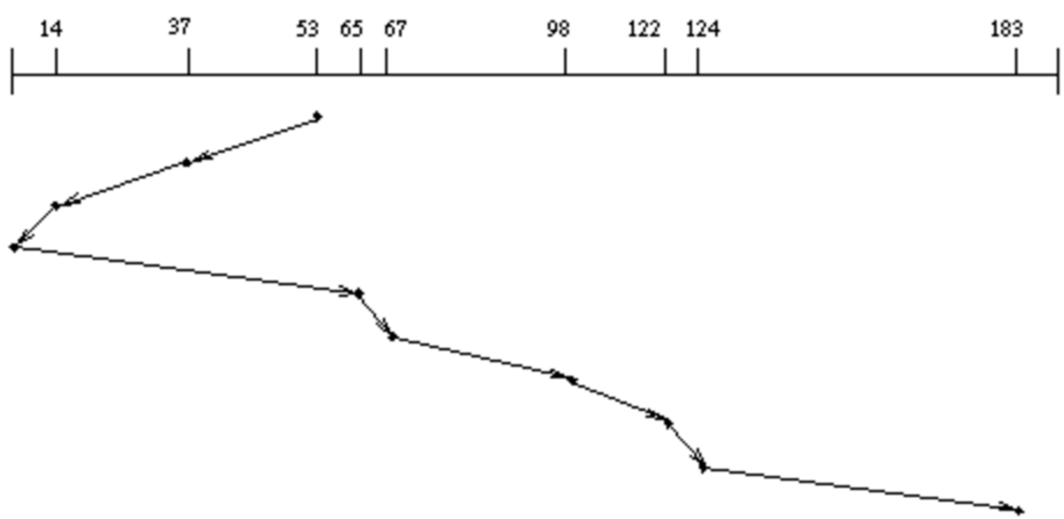


Disk Scheduling (2/2)

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



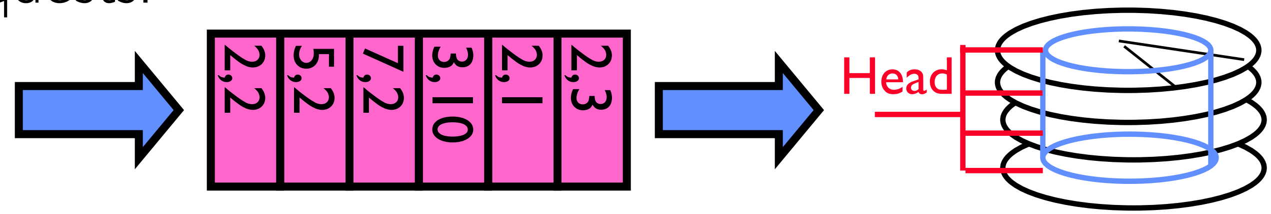
- SCAN: Implements an Elevator Algorithm: take the closest request in the direction of travel
  - No starvation, but retains flavor of SSTF



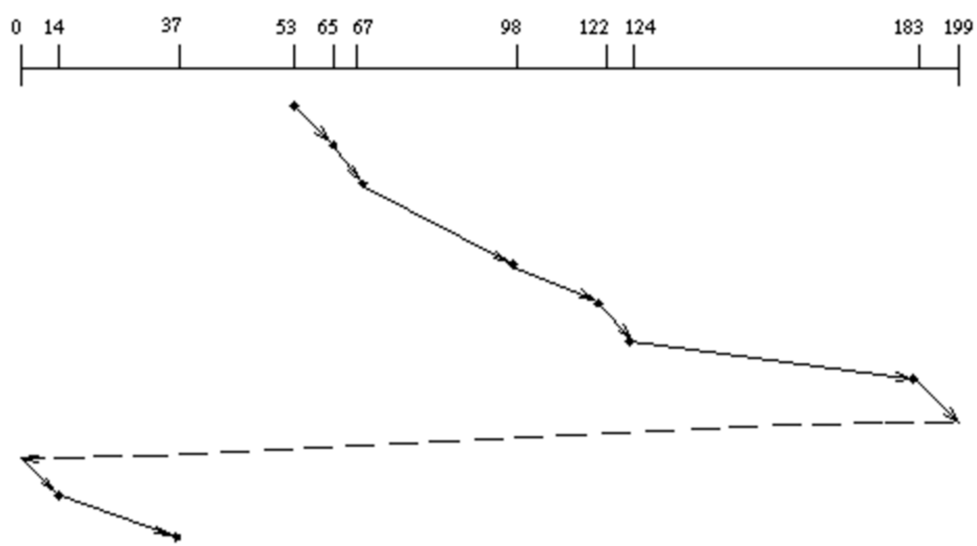
Disk Scheduling (2/2)

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

User 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



Summary

- 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 $\rightarrow \infty$

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