CS 422/522 Design & Implementation of Operating Systems

# Lecture 11: CPU Scheduling

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## CPU scheduler

- Selects from among the processes in memory that are ready to execute, and allocates the CPU to one of them.
- CPU scheduling decisions may take place when a process:
  1. switches from running to waiting state.
  2. switches from running to ready state.
  3. switches from waiting to ready.
  4. terminates.
- Scheduling under 1 and 4 is *nonpreemptive.*
- All other scheduling is *preemptive.*

## Main points

- Scheduling policy: what to do next, when there are multiple threads ready to run
  - Or multiple packets to send, or web requests to serve, or …
- Definitions
  - response time, throughput, predictability
- Uniprocessor policies
  - FIFO, round robin, optimal
  - multilevel feedback as approximation of optimal
- Multiprocessor policies
  - Affinity scheduling, gang scheduling
- Queueing theory
  - Can you predict/improve a system's response time?

## Example

- You manage a web site, that suddenly becomes wildly popular. Do you?
  - Buy more hardware?
  - Implement a different scheduling policy?
  - Turn away some users? Which ones?
- How much worse will performance get if the web site becomes even more popular?

## Definitions

- Task/Job
  - User request: e.g., mouse click, web request, shell command, …
- Latency/response time
  - How long does a task take to complete?
- Throughput
  - How many tasks can be done per unit of time?
- Overhead
  - How much extra work is done by the scheduler?
- Fairness
  - How equal is the performance received by different users?
- Predictability
  - How consistent is the performance over time?

## More definitions

- Workload
  - Set of tasks for system to perform
- Preemptive scheduler
  - If we can take resources away from a running task
- Work-conserving
  - Resource is used whenever there is a task to run
  - For non-preemptive schedulers, work-conserving is not always better
- Scheduling algorithm
  - takes a workload as input
  - decides which tasks to do first
  - Performance metric (throughput, latency) as output
  - Only preemptive, work-conserving schedulers to be considered

## Scheduling policy goals

- ***minimize response time*** : elapsed time to do an operation (or job)
  - Response time is what the user sees: elapsed time to
    - echo a keystroke in editor
    - compile a program
    - run a large scientific problem
- ***maximize throughput*** : operations (jobs) per second
  - two parts to maximizing throughput
    - minimize overhead (for example, context switching)
    - efficient use of system resources (not only CPU, but disk, memory, etc.)
- ***fair*** : share CPU among users in some equitable way

## First In First Out (FIFO)

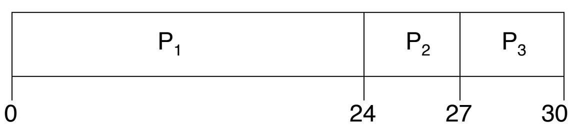
- Schedule tasks in the order they arrive
  - Continue running them until they complete or give up the processor
- Example: memcached
  - Facebook cache of friend lists, …
- On what workloads is FIFO particularly bad?

## FIFO scheduling

- Example:

| Process | Burst Time |
|---|---|
| $P_1$ | 24 |
| $P_2$ | 3 |
| $P_3$ | 3 |

- Suppose that the processes arrive in the order: $P_1$ , $P_2$ , $P_3$
  The Gantt Chart for the schedule is:



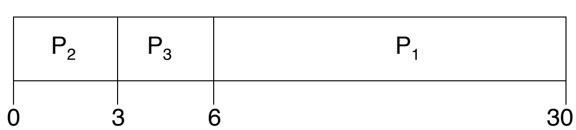

- Waiting time for $P_1$ = 0; $P_2$ = 24; $P_3$ = 27
- Average waiting time: (0 + 24 + 27)/3 = 17

## FIFO scheduling (cont' d)

Suppose that the processes arrive in the order

$P_2$ , $P_3$ , $P_1$ .

- The Gantt chart for the schedule is:




  - Waiting time for $P_1$ = 6; $P_2$ = 0; $P_3$ = 3
  - Average waiting time: (6 + 0 + 3)/3 = 3
  - Much better than previous case.

- FIFO Pros: simple; Cons: short jobs get stuck behind long jobs

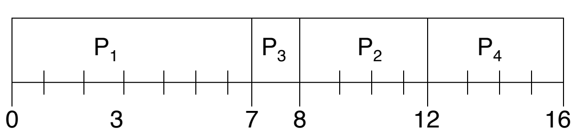
## Shortest-Job-First (SJF) scheduling

- Associate with each process the length of its next CPU burst. Use these lengths to schedule the process with the shortest time.
- Two schemes:
  - nonpreemptive – once given CPU it cannot be preempted until completes its CPU burst.
  - preemptive – if a new process arrives with CPU burst length less than remaining time of current executing process, preempt. A.k.a. Shortest-Remaining-Time-First (SRTF).
- SJF is optimal but unfair
  - pros: gives minimum average response time
  - cons: long-running jobs may starve if too many short jobs;
  - difficult to implement (how do you know how long it will take)

## Example of non-preemptive SJF

| Process | Arrival Time | Burst Time |
|---|---|---|
| $P_1$ | 0.0 | 7 |
| $P_2$ | 2.0 | 4 |
| $P_3$ | 4.0 | 1 |
| $P_4$ | 5.0 | 4 |

- SJF (non-preemptive)

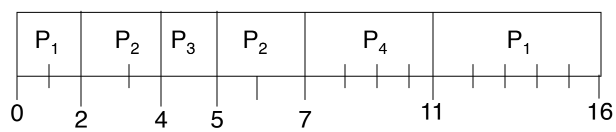



- Average waiting time = (0 + 6 + 3 + 7)/4 = 4

# Example of preemptive SJF

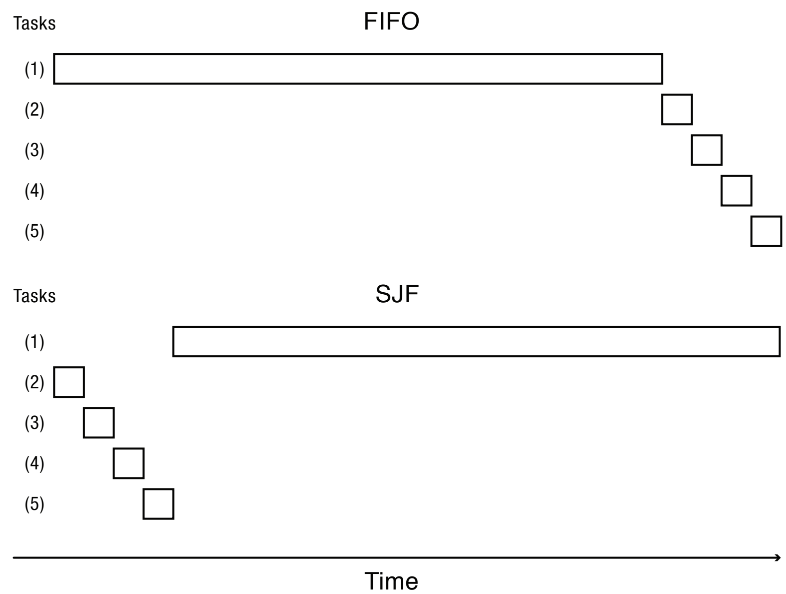
| Process | Arrival Time | Burst Time |
|---|---|---|
| $P_1$ | 0.0 | 7 |
| $P_2$ | 2.0 | 4 |
| $P_3$ | 4.0 | 1 |
| $P_4$ | 5.0 | 4 |

- SJF (preemptive)




- Average waiting time = (9 + 1 + 0 +2)/4 = 3

# FIFO vs. SJF



## Starvation and sample bias

- Suppose you want to compare two scheduling algorithms
  - Create some infinite sequence of arriving tasks
  - Start measuring
  - Stop at some point
  - Compute average response time as the average for completed tasks between start and stop
- Is this valid or invalid?

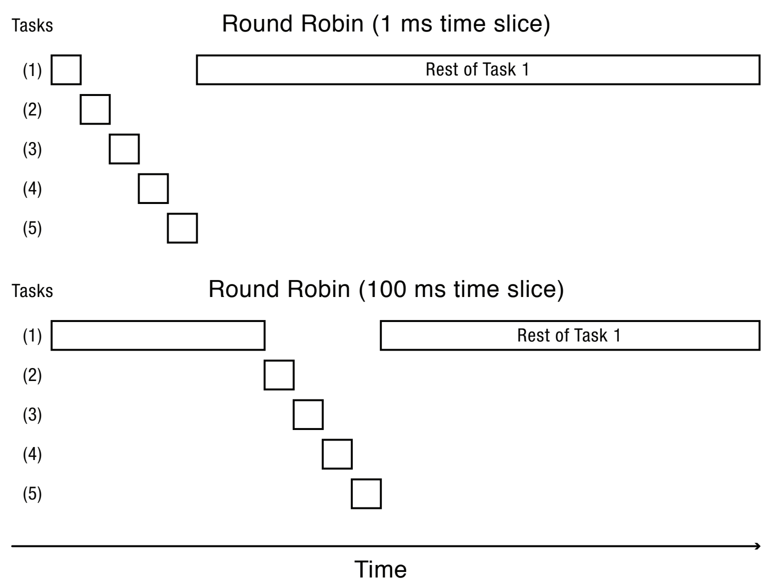
## Sample bias solutions

- Measure for long enough that
  - # of completed tasks >> # of uncompleted tasks
  - For both systems!
- Start and stop system in idle periods
  - Idle period: no work to do
  - If algorithms are work-conserving, both will complete the same tasks

## Round Robin (RR)

- Each process gets a small unit of CPU time (*time quantum*). After time slice, it is moved to the end of the ready queue.
  Time Quantum = 10 - 100 milliseconds on most OS
- $n$ processes in the ready queue; time quantum is $q$
  - each process gets $1/n$ of the CPU time in $q$ time units at once.
  - no process waits more than $(n-1)q$ time units.
  - each job gets equal shot at the CPU
- Performance
  - $q$ large $\Rightarrow$ FIFO
  - $q$ too small $\Rightarrow$ throughput suffers. Spend all your time context switching, not getting any real work done

## Round Robin



## Example: RR with time quantum = 20

| Process | Burst Time |
|---|---|
| $P_1$ | 53 |
| $P_2$ | 17 |
| $P_3$ | 68 |
| $P_4$ | 24 |

- The Gantt chart is:

| $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_1$ | $P_3$ | $P_4$ | $P_1$ | $P_3$ | $P_3$ |
|---|---|---|---|---|---|---|---|---|---|

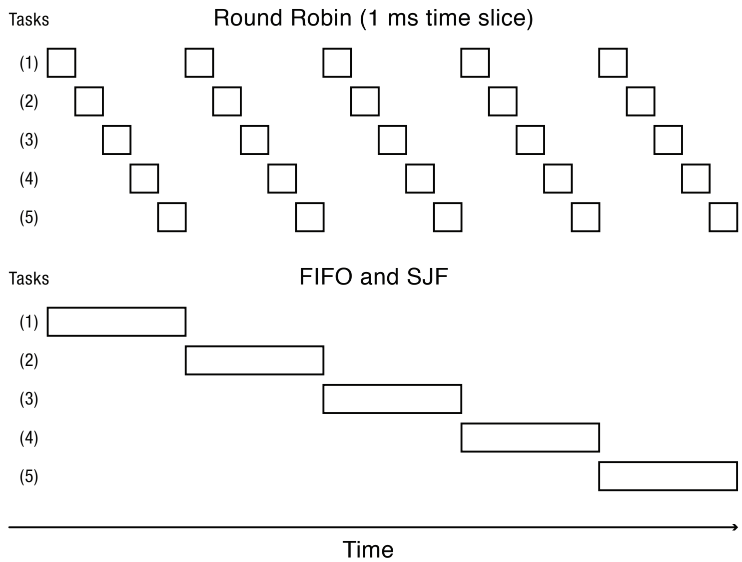
0 20 37 57 77 97 117 121 134 154 162

- Typically, higher average turnaround than SJF, but better *response*.

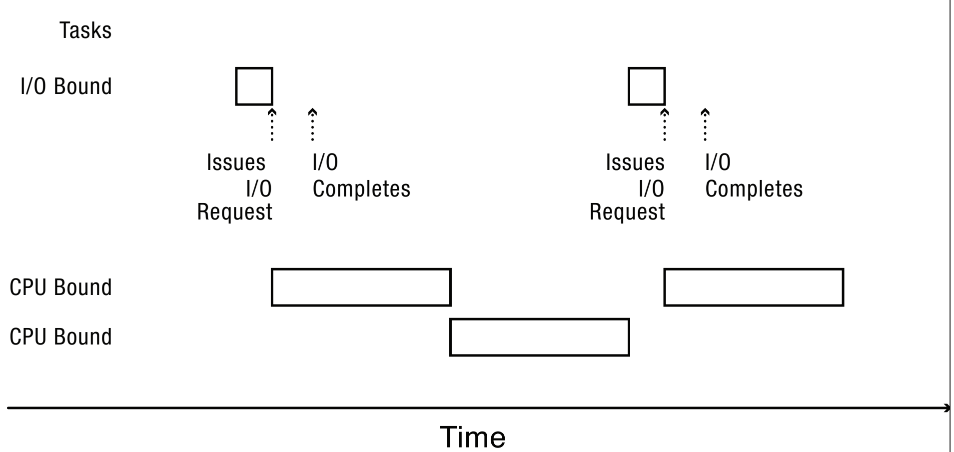
## RR vs. FIFO

- Assuming zero-cost time slice, is RR always better than FIFO?
  - 10 jobs, each take 100 secs, RR time slice 1 sec
  - what would be the average response time under RR and FIFO ?
- RR
  - job1: 991s, job2: 992s, ... , job10: 1000s
- FIFO
  - job 1: 100s, job2: 200s, ... , job10: 1000s
- Comparisons
  - RR is much worse for jobs about the same length
  - RR is better for short jobs

## RR vs. FIFO (cont'd)




## Mixed workload



## Max-Min Fairness

- How do we balance a mixture of repeating tasks:
  - Some I/O bound, need only a little CPU
  - Some compute bound, can use as much CPU as they are assigned
- One approach: maximize the minimum allocation given to a task
  - If any task needs less than an equal share, schedule the smallest of these first
  - Split the remaining time using max-min
  - If all remaining tasks need at least equal share, split evenly
- Approximation: every time the scheduler needs to make a choice, it chooses the task for the process with the least accumulated time on the processor

## Multi-level Feedback Queue (MFQ)

- Goals:
  - Responsiveness
  - Low overhead
  - Starvation freedom
  - Some tasks are high/low priority
  - Fairness (among equal priority tasks)
- Not perfect at any of them!
  - Used in Linux (and probably Windows, MacOS)

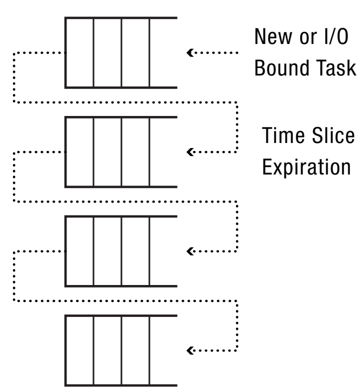
# MFQ

- Set of Round Robin queues
  - Each queue has a separate priority
- High priority queues have short time slices
  - Low priority queues have long time slices
- Scheduler picks first thread in highest priority queue
- Tasks start in highest priority queue
  - If time slice expires, task drops one level

# MFQ

| Priority | Time Slice (ms) |
|---|---|
| 1 | 10 |
| 2 | 20 |
| 3 | 40 |
| 4 | 80 |

Round Robin Queues



## Uniprocessor summary (1)

- FIFO is simple and minimizes overhead.
- If tasks are variable in size, then FIFO can have very poor average response time.
- If tasks are equal in size, FIFO is optimal in terms of average response time.
- Considering only the processor, SJF is optimal in terms of average response time.
- SJF is pessimal in terms of variance in response time.

## Uniprocessor summary (2)

- If tasks are variable in size, Round Robin approximates SJF.
- If tasks are equal in size, Round Robin will have very poor average response time.
- Tasks that intermix processor and I/O benefit from SJF and can do poorly under Round Robin.

## Uniprocessor summary (3)

- Max-Min fairness can improve response time for I/O-bound tasks.
- Round Robin and Max-Min fairness both avoid starvation.
- By manipulating the assignment of tasks to priority queues, an MFQ scheduler can achieve a balance between responsiveness, low overhead, and fairness.

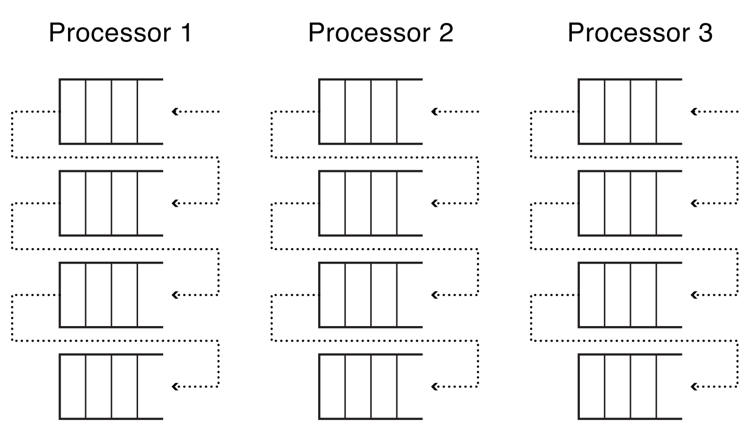
## Multiprocessor scheduling

- What would happen if we used MFQ on a multiprocessor?
  - Contention for scheduler spinlock
  - Cache slowdown due to ready list data structure pinging from one CPU to another
  - Limited cache reuse: thread's data from last time it ran is often still in its old cache

## Per-processor affinity scheduling

- Each processor has its own ready list
  - Protected by a per-processor spinlock
- Put threads back on the ready list where it had most recently run
  - Ex: when I/O completes, or on Condition->signal
- Idle processors can steal work from other processors

## Per-processor Multi-level Feedback with affinity scheduling



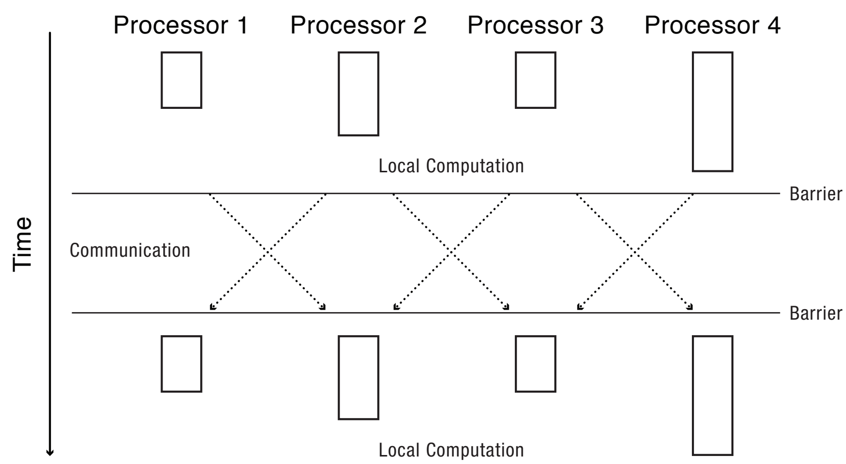
## Scheduling parallel programs

- What happens if one thread gets time-sliced while other threads from the same program are still running?
  - Assuming program uses locks and condition variables, it will still be correct
  - What about performance?

## Bulk synchronous parallelism

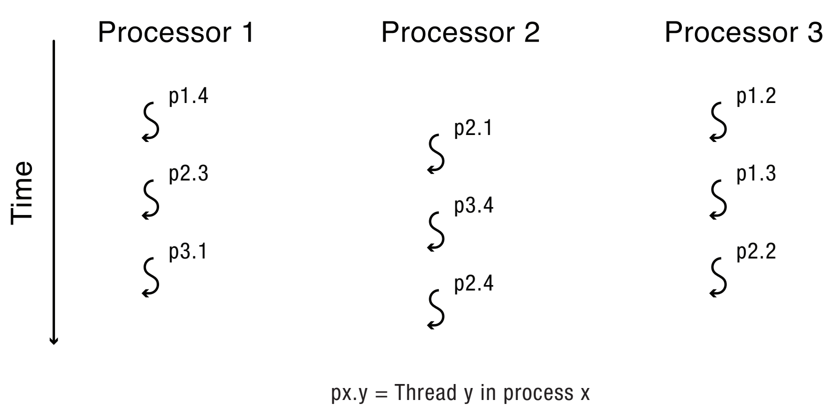
- Loop at each processor:
  - Compute on local data (in parallel)
  - Barrier
  - Send (selected) data to other processors (in parallel)
  - Barrier
- Examples:
  - MapReduce
  - Fluid flow over a wing
  - Most parallel algorithms can be recast in BSP
    - Sacrificing a small constant factor in performance

## Tail latency

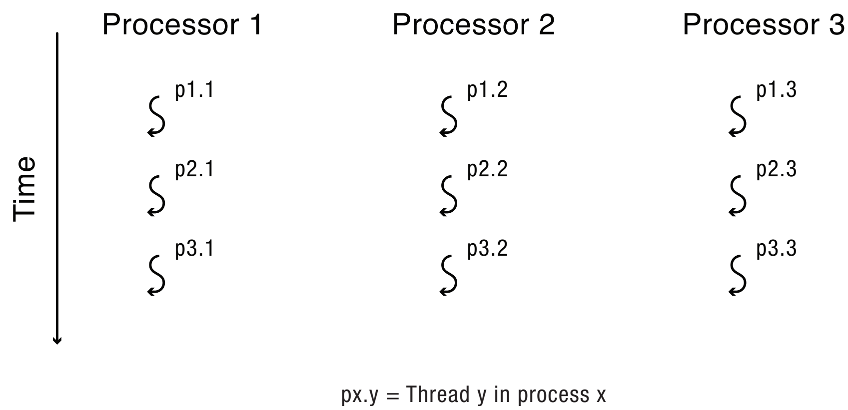



## Scheduling parallel programs

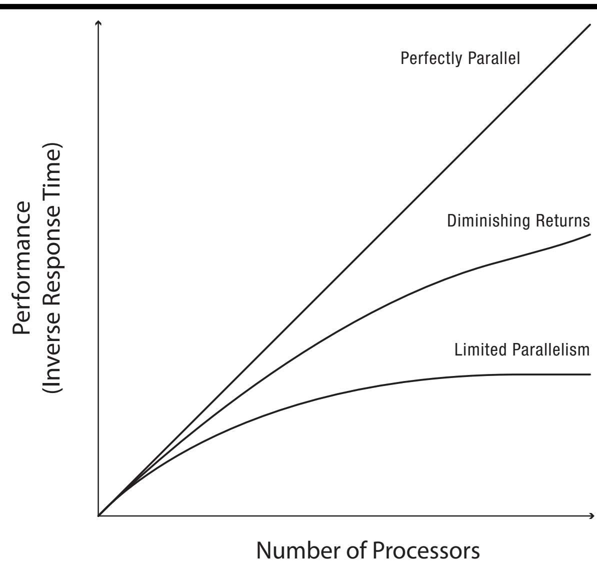
Oblivious: each processor time-slices its ready list independently of the other processors



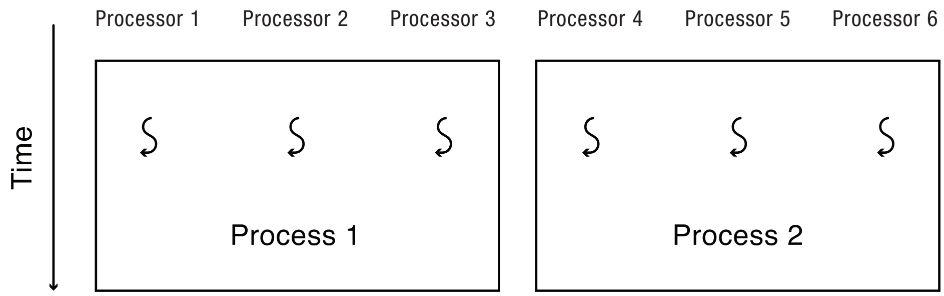
## Gang scheduling




## Parallel program speedup



## Space sharing

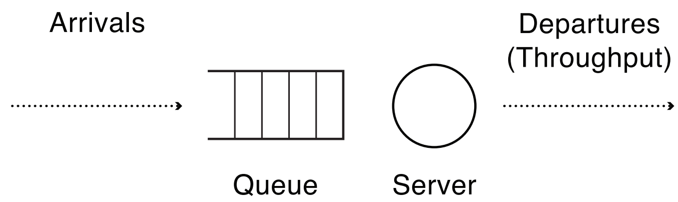



Scheduler activations: kernel tells each application its # of processors with upcalls every time the assignment changes

## Queueing theory

- Can we predict what will happen to user performance:
  - If a service becomes more popular?
  - If we buy more hardware?
  - If we change the implementation to provide more features?

## Queueing model




Assumption: average performance in a stable system, where the arrival rate (ƛ) matches the departure rate (μ)

## Definitions

- Queueing delay (W): wait time
  - Number of tasks queued (Q)
- Service time (S): time to service the request
- Response time (R) = queueing delay + service time
- Utilization (U): fraction of time the server is busy
  - Service time * arrival rate (ƛ)
- Throughput (X): rate of task completions
  - If no overload, throughput = arrival rate

## Little's law

$$N = X * R$$

N: number of tasks in the system

Applies to *any* stable system – where arrivals match departures.

## Question

Suppose a system has throughput (X) = 100 tasks/s, average response time (R) = 50 ms/task

- How many tasks are in the system on average?
- If the server takes 5 ms/task, what is its utilization?
- What is the average wait time?
- What is the average number of queued tasks?

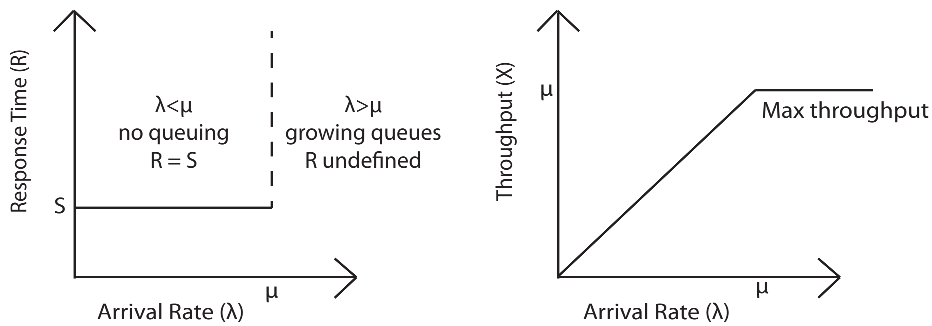
## Question

- From example:
  X = 100 task/sec
  R = 50 ms/task
  S = 5 ms/task
  W = 45 ms/task
  Q = 4.5 tasks
- Why is W = 45 ms and not 4.5 * 5 = 22.5 ms?
  - Hint: what if S = 10ms? S = 1ms?

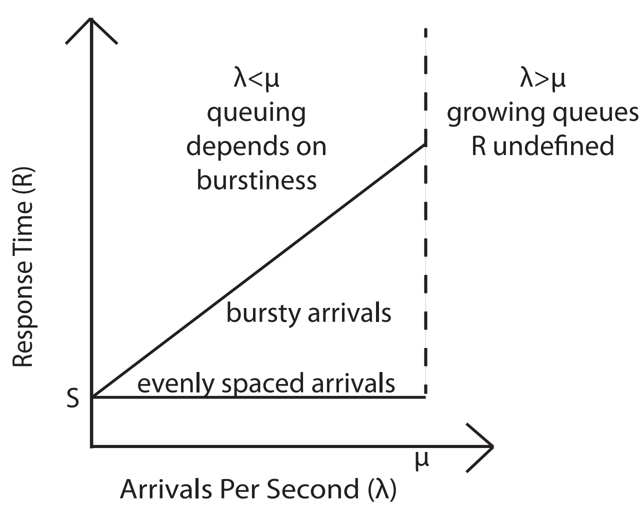
## Queueing

- What is the best case scenario for minimizing queueing delay?
  - Keeping arrival rate, service time constant
- What is the worst case scenario?

## Best case: evenly spaced arrivals



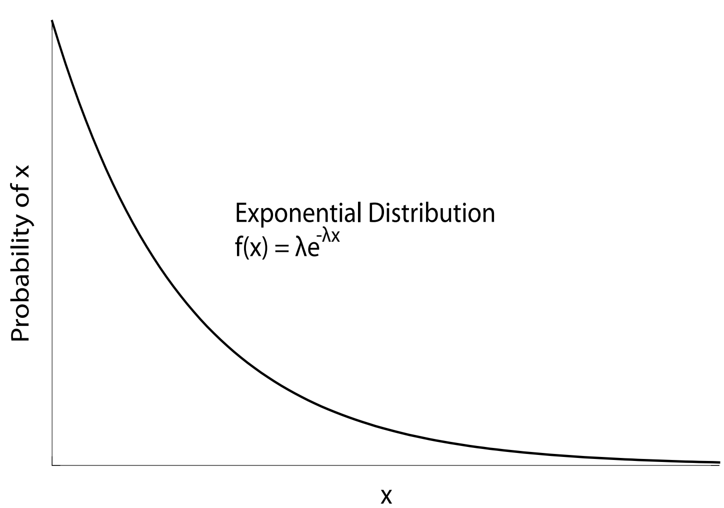

## Response time: best vs. worst case



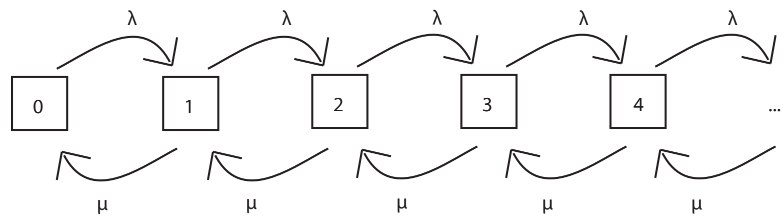
# Queueing: average case?

- What is average?
  - Gaussian: Arrivals are spread out, around a mean value
  - Exponential: arrivals are memoryless
  - Heavy-tailed: arrivals are bursty
- Can have randomness in both arrivals and service times

# Exponential distribution

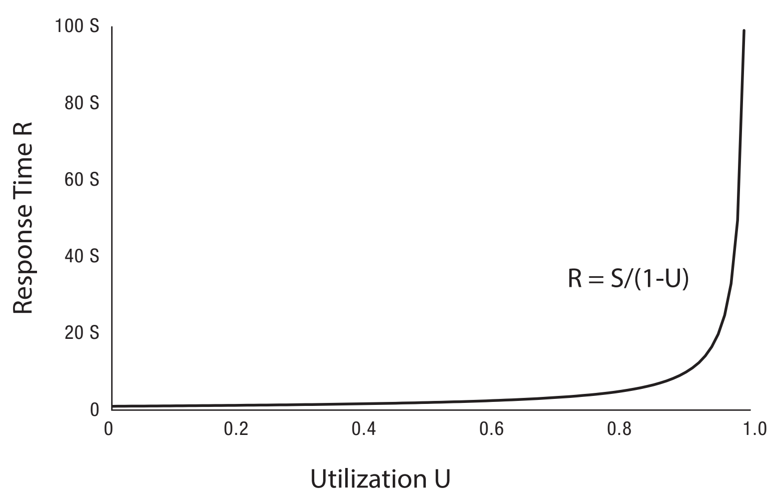


# Exponential distribution




Permits closed form solution to state probabilities, as function of arrival rate and service rate

# Response time vs. utilization



## Question

- Exponential arrivals: R = S/(1-U)
- If system is 20% utilized, and load increases by 5%, how much does response time increase?
- If system is 90% utilized, and load increases by 5%, how much does response time increase?

## Variance in response time

- Exponential arrivals
  - Variance in R = S/(1-U)^2
- What if less bursty than exponential?
- What if more bursty than exponential?

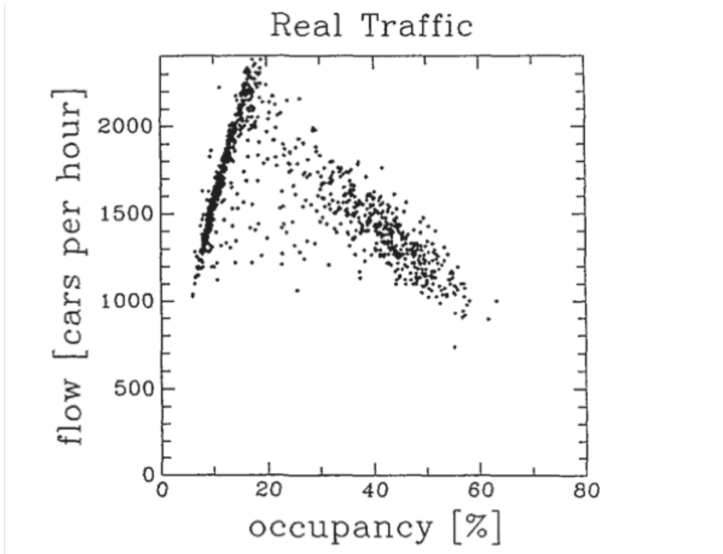
## What if multiple resources?

- Response time =
  Sum over all i
    Service time for resource i /
      (1 – Utilization of resource i)
- Implication
  - If you fix one bottleneck, the next highest utilized resource will limit performance

## Overload management

- What if arrivals occur faster than service can handle them
  - If do nothing, response time will become infinite
- Turn users away?
  - Which ones? Average response time is best if turn away users that have the highest service demand
  - Example: Highway congestion
- Degrade service?
  - Compute result with fewer resources
  - Example: CNN static front page on 9/11

## Highway congestion (measured)




## Why do metro buses cluster?

- Suppose two Metro buses start 15 minutes apart
  - Why might they arrive at the same time?