CPU Scheduling

Operating Systems

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What and Why?

What is processor scheduling?

Why?

At first to share an expensive resource – multiprogramming

Now to perform concurrent tasks because processor is so powerful

Future looks like past + now

Computing utility – large data/processing centers use multiprogramming to maximize resource utilization

Systems still powerful enough for each user to run multiple concurrent tasks

Assumptions

Pool of jobs contending for the CPU

Jobs are independent and compete for resources (this assumption is not true for all systems/scenarios)

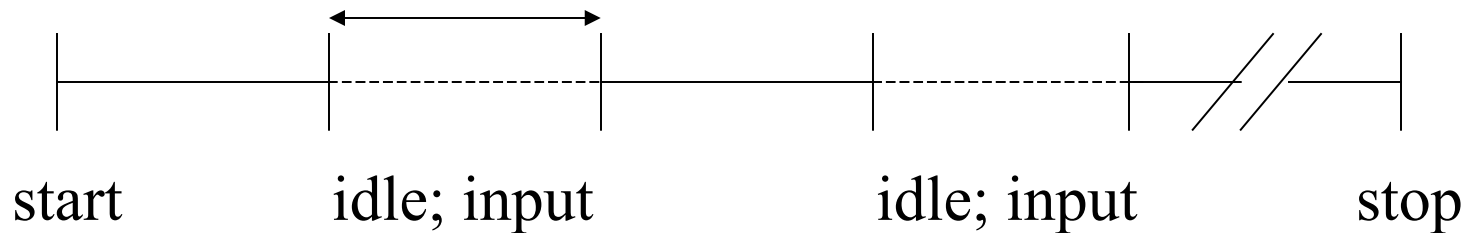Scheduler mediates between jobs to optimize some performance criterion

In this lecture, we will talk about processes and threads interchangeably. We will assume a single-threaded CPU.

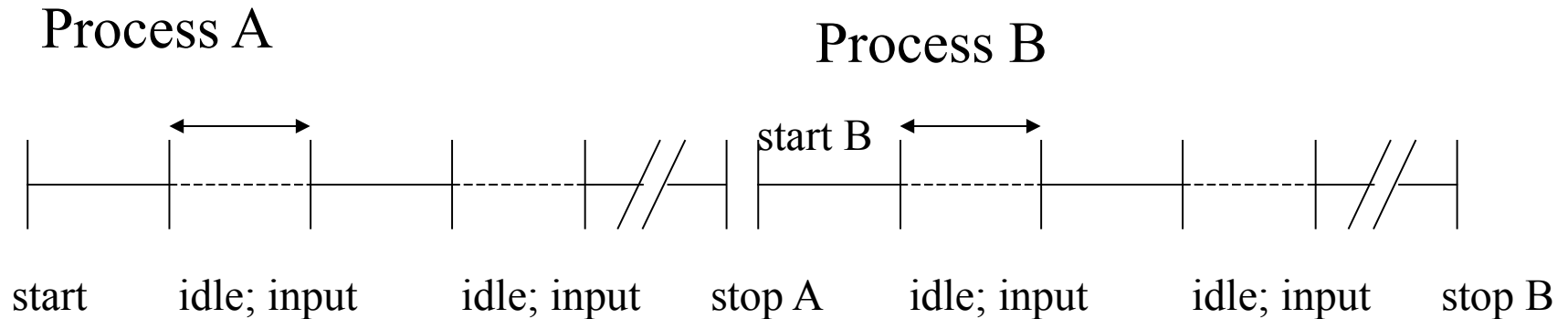# Multiprogramming Example

Process A

1 sec

start   idle; input   idle; input   stop

Process B

start   idle; input   idle; input   stop
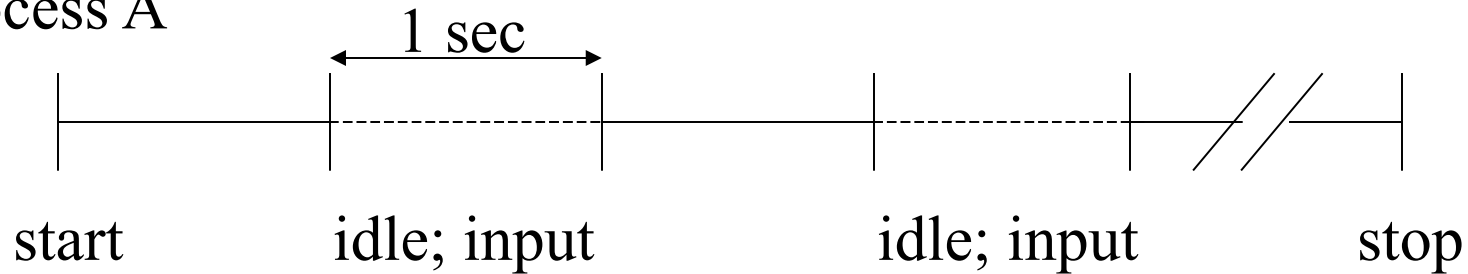
Time = 10 seconds

Multiprogramming Example (cont)

Process A

Process B

start   idle; input   idle; input   stop A   idle; input   idle; input   stop B
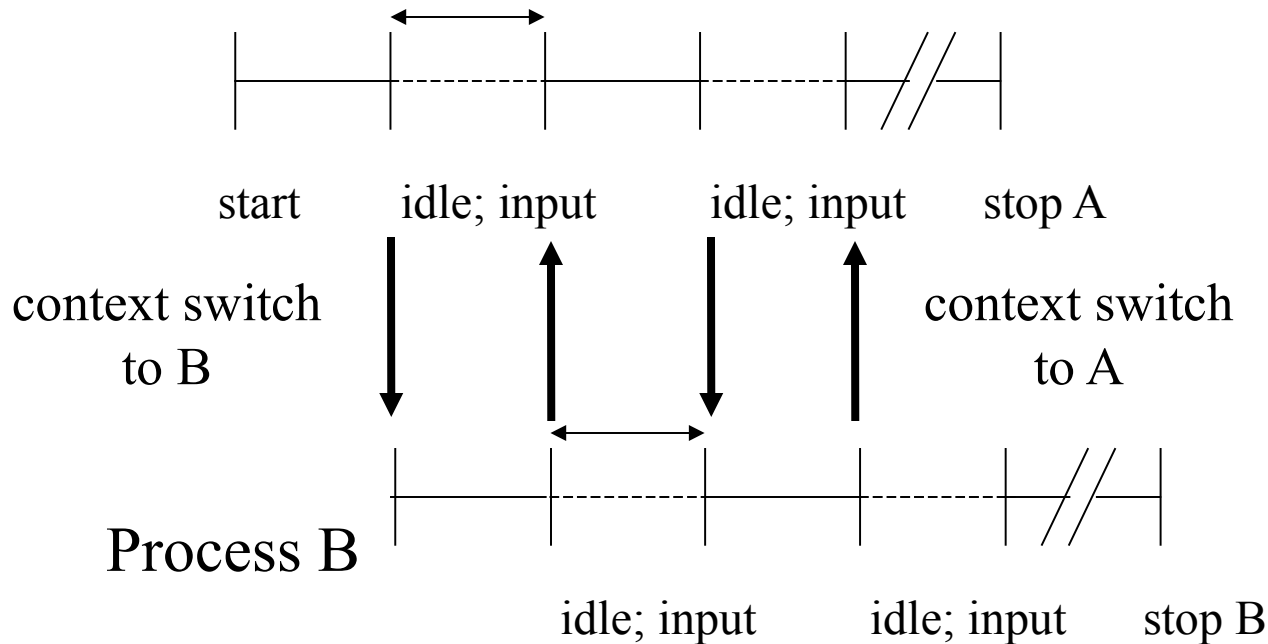
Total Time = 20 seconds

Throughput = 2 jobs in 20 seconds = 0.1 jobs/second

Avg. Waiting Time = (0+10)/2 = 5 seconds

Multiprogramming Example (cont)

Process A

start   idle; input   idle; input   stop A

context switch
to B

context switch
to A

Process B

idle; input   idle; input   stop B

Throughput = 2 jobs in 11 seconds = 0.18 jobs/second

Avg. Waiting Time = (0+1)/2 = 0.5 seconds

What Do We Optimize?

System-oriented metrics:

Processor utilization: percentage of time the processor is busy

Throughput: number of processes completed per unit of time

User-oriented metrics:

Turnaround time: interval of time between submission and termination (including any waiting time). Appropriate for batch jobs

Response time: for interactive jobs, time from the submission of a request until the response begins to be received

Deadlines: when process completion deadlines are specified, the percentage of deadlines met must be promoted

Design Space

Two dimensions

Selection function
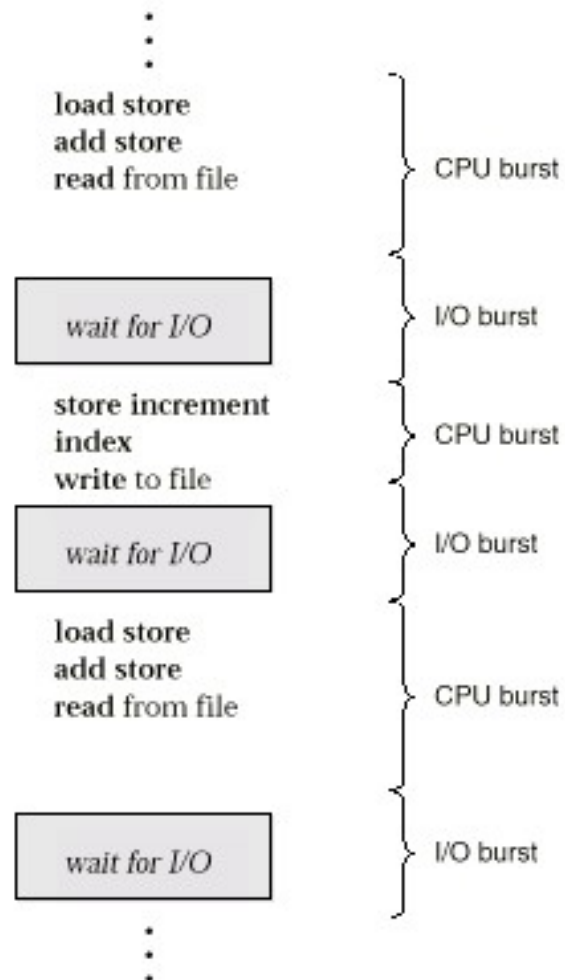
Which of the ready jobs should be run next?

Preemption

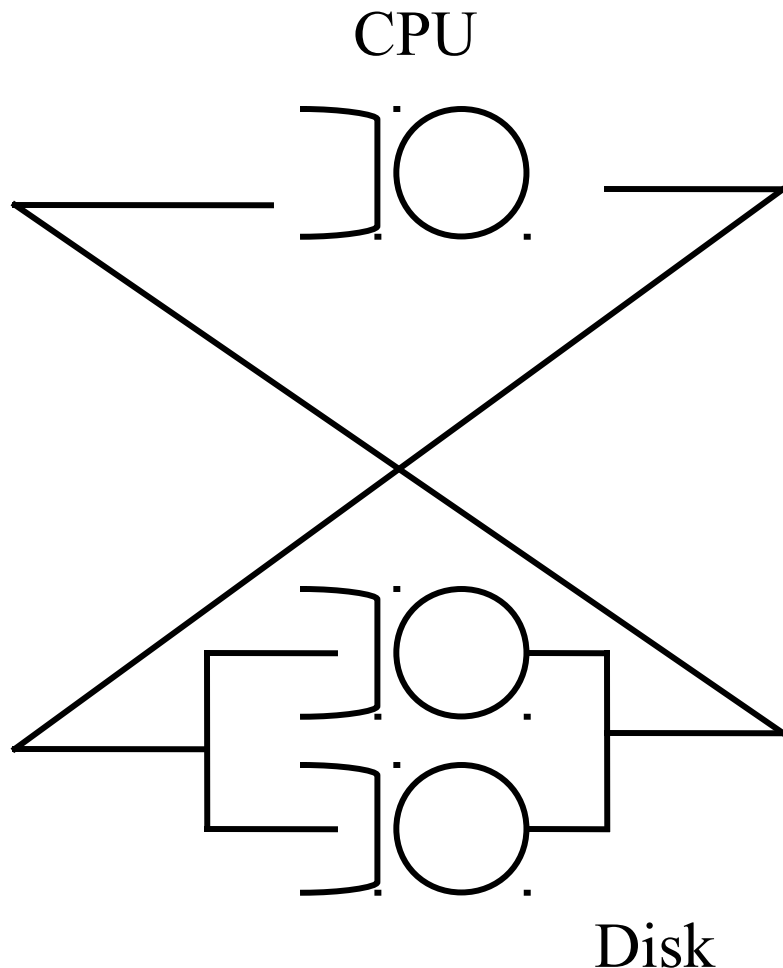Preemptive: currently running job may be interrupted and moved to Ready state

Non-preemptive: once a process is in Running state, it continues to execute until it terminates or blocks

Job Behavior

load store
add store
read from file — CPU burst

wait for I/O — I/O burst

store increment
index
write to file — CPU burst

wait for I/O — I/O burst

load store
add store
read from file — CPU burst

wait for I/O — I/O burst

Job Behavior

CPU

Disk

I/O-bound jobs

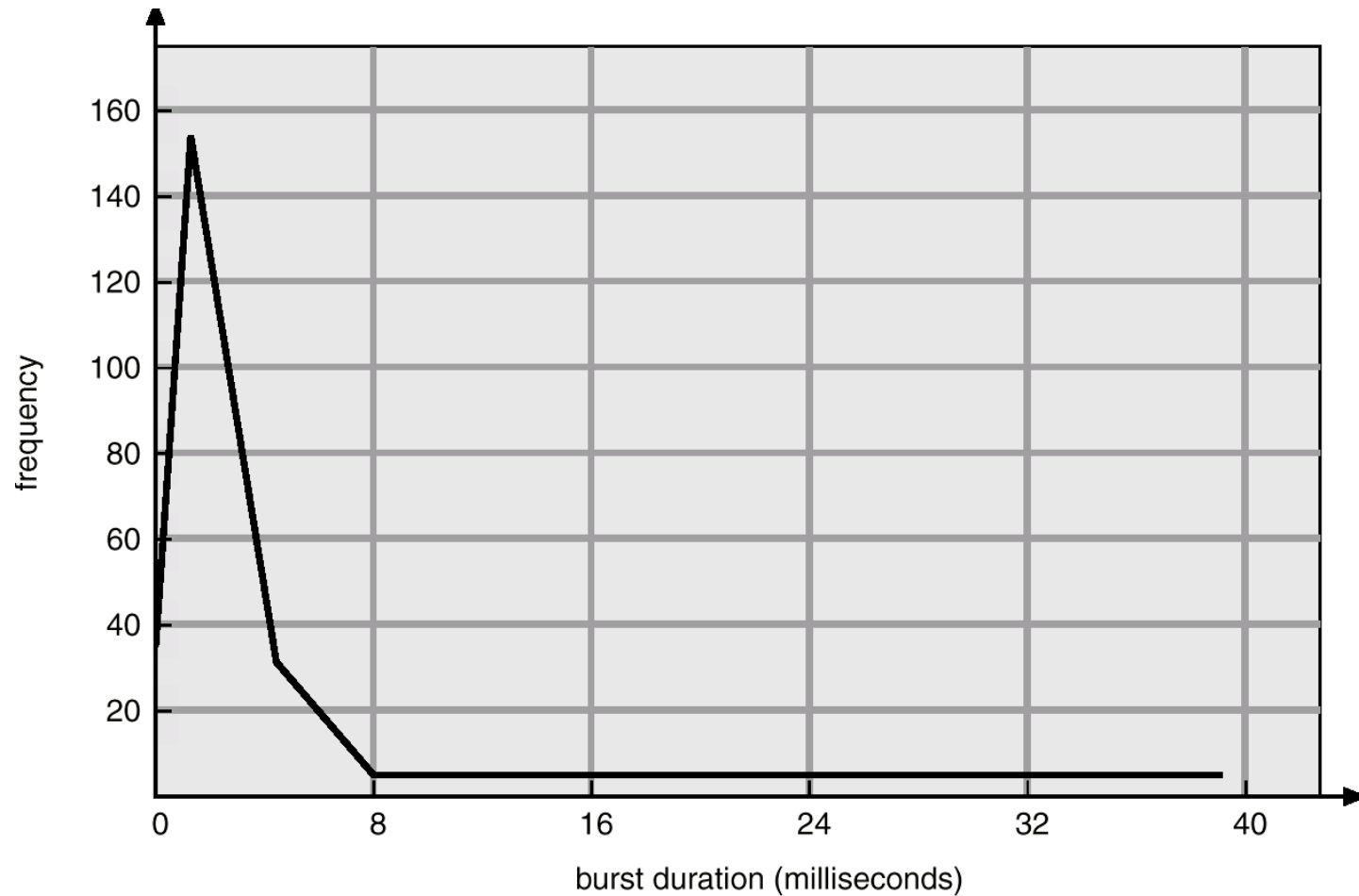> Jobs that perform lots of I/O
>
> Tend to have short CPU bursts

CPU-bound jobs

> Jobs that perform very little I/O
>
> Tend to have very long CPU bursts

Histogram of CPU-burst Times

(Short-Term) 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.

Dispatcher

Dispatcher module gives control of the CPU to the process selected by the short-term scheduler; this involves:

  switching context

  switching to user mode

  jumping to the proper location in the user program to restart that program

Dispatch latency – time it takes for the dispatcher to stop one process and start another running.
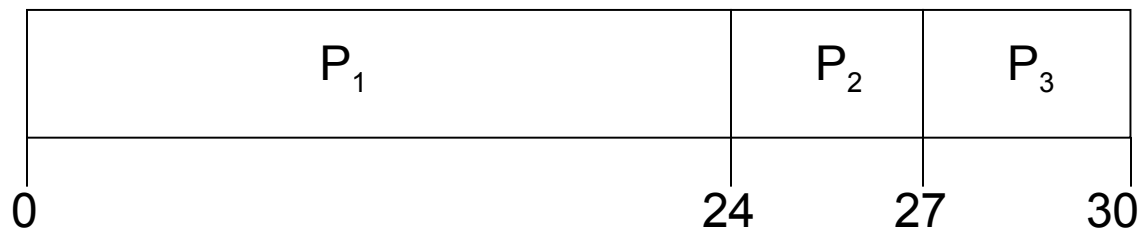
First-Come, First-Served (FCFS) Scheduling

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:

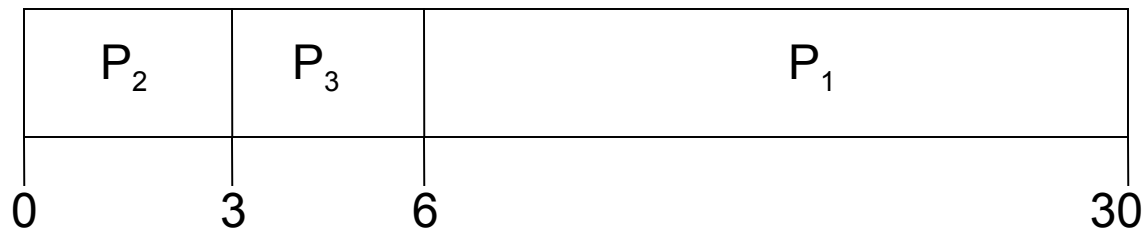| P_1				P_2	P_3
0			24	27	30

Waiting time for $P_1 = 0$; $P_2 = 24$; $P_3 = 27$

Average waiting time: $(0 + 24 + 27)/3 = 17$

Suppose that the processes arrive in the order

P_2 , P_3 , P_1 .

The Gantt chart for the schedule is:

P$_2$	P$_3$	P$_1$

0   3   6   30

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.

Convoy effect short process behind long process

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:

Non-preemptive – once CPU given to the process 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. This scheme is know as the Shortest-Remaining-Time-First (SRTF).
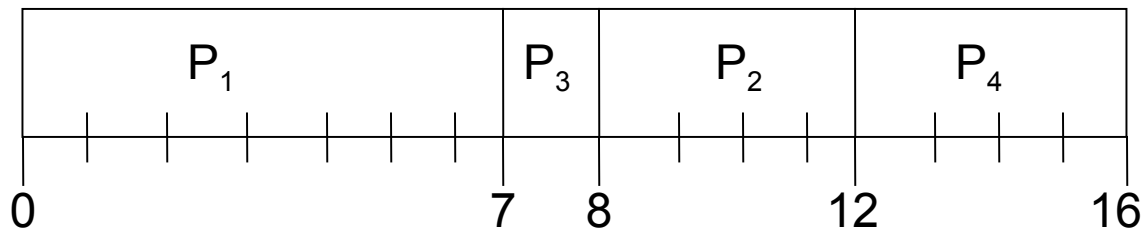
SJF is optimal – gives minimum average waiting time for a given set of processes.

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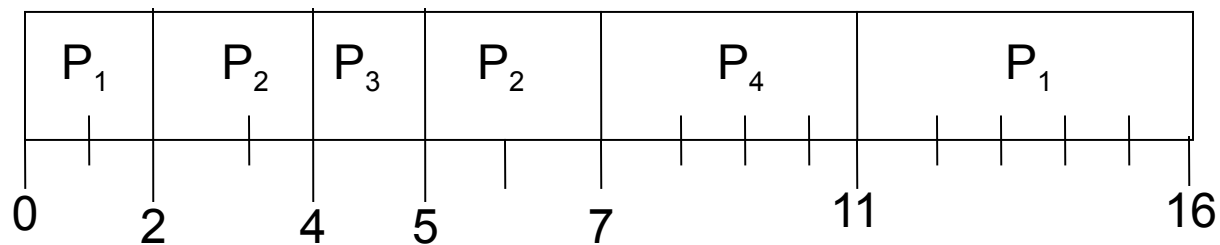
Average waiting time = $(9 + 1 + 0 + 2)/4 = 3$

Determining Length of Next CPU Burst

Can only estimate the length.

Can be done by using the length of previous CPU bursts, using exponential averaging.

1. t_n = actual lenght of nth CPU burst
2. τ_{n+1} = predicted value for the next CPU burst
3. α, $0 \leq \alpha \leq 1$
4. Define:

$$\tau_{n+1} = \alpha\, t_n + (1 - \alpha)\, \tau_n.$$

Examples of Exponential Averaging

$\alpha = 0$

$\tau_{n+1} = \tau_n$

Recent history does not count.

$\alpha = 1$

$\tau_{n+1} = t_n$

Only the actual last CPU burst counts.

Round Robin (RR)

Each process gets a small unit of CPU time (*time quantum*), usually 1-50 milliseconds. After this time has elapsed, the process is preempted and added to the end of the ready queue.

If there are n processes in the ready queue and the time quantum is q, then each process gets $1/n$ of the CPU time in chunks of at most q time units at once. No process waits more than $(n-1)q$ time units.
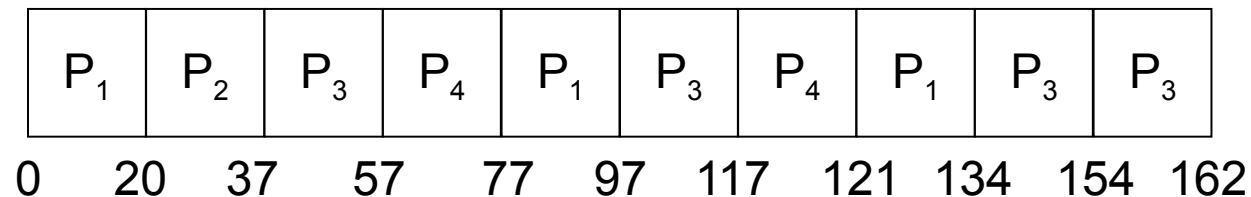
Performance

q large $\Rightarrow$ FIFO

q small $\Rightarrow$ q must be large with respect to context switch, otherwise overhead is too high.
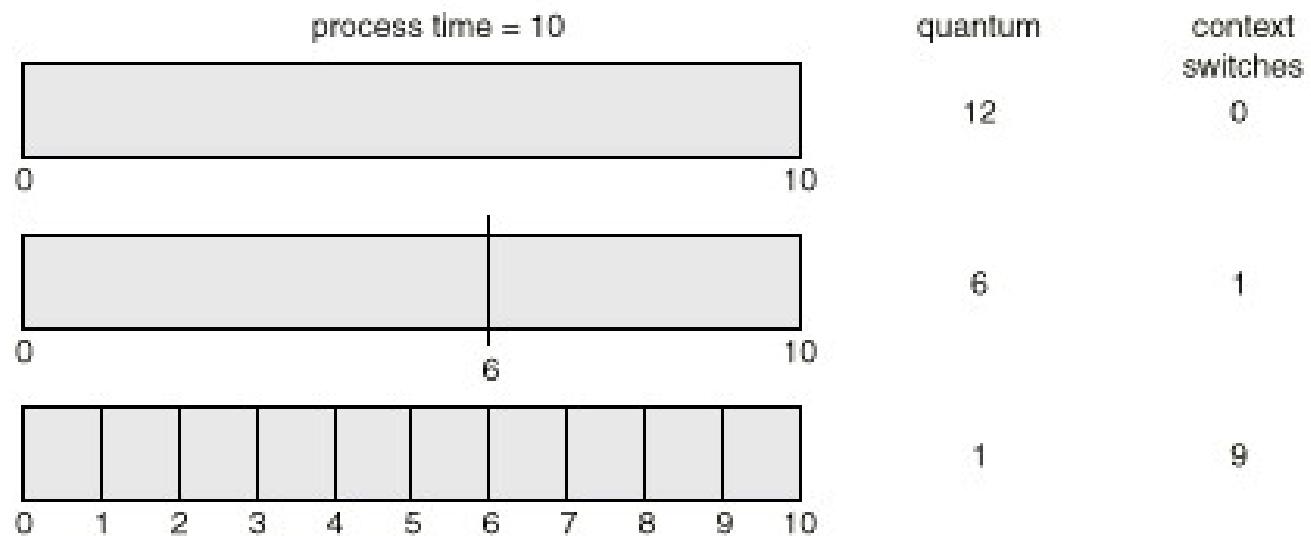
Example: RR with Time Quantum = 20

Process	Burst Time
P_1	53
P_2	17
P_3	68
P_4	24

The Gantt chart is:

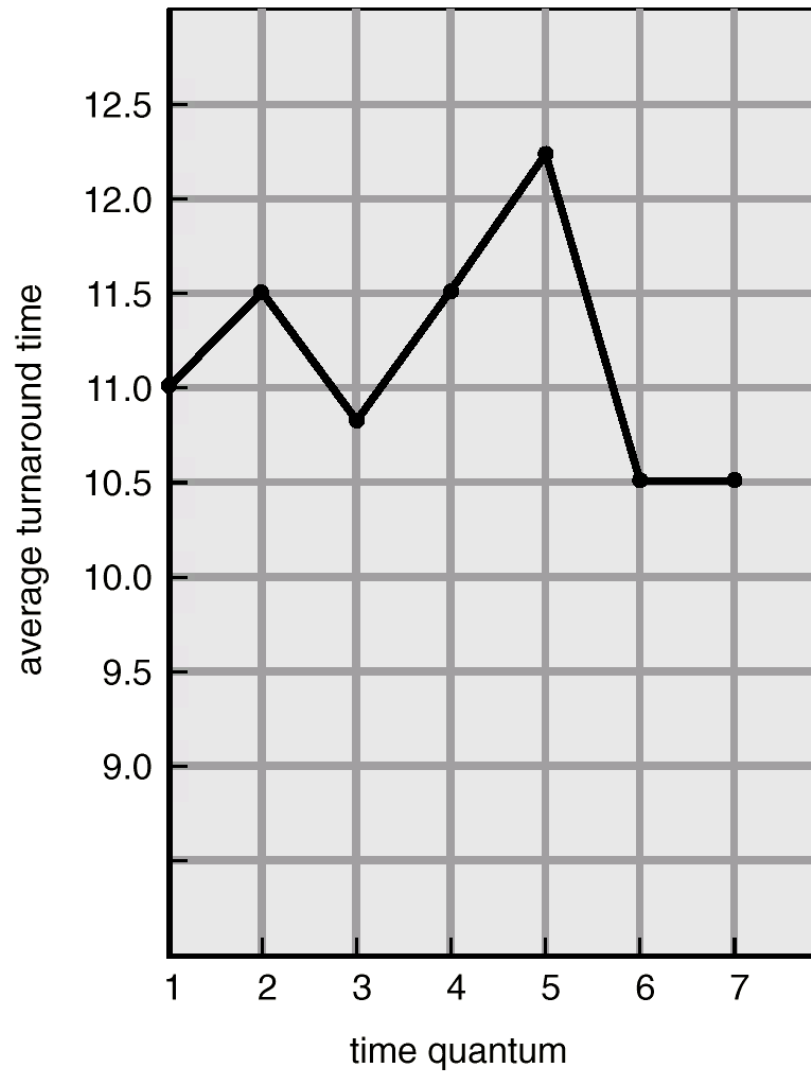| P_1	P_2	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_3

0   20   37   57   77   97   117   121   134   154   162

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

How a Smaller Time Quantum Increases Context Switches

process time = 10

quantum	context switches
12	0
6	1
1	9

Turnaround Time Varies With Time Quantum

process	time
P_1	6
P_2	3
P_3	1
P_4	7

Priority Scheduling

A priority number (integer) is associated with each process

The CPU is allocated to the process with the highest priority (smallest integer ≡ highest priority).

    Preemptive

    Non-preemptive

SJF is a priority scheduling policy where priority is the predicted next CPU burst time.

Problem ≡ Starvation – low priority processes may never execute.

Solution ≡ Aging – as time progresses increase the priority of the process.

Multilevel Queue

Ready queue is partitioned into separate queues:
foreground (interactive)
background (batch)

Each queue has its own scheduling algorithm,
foreground – RR
background – FCFS

Scheduling must be done between the queues.

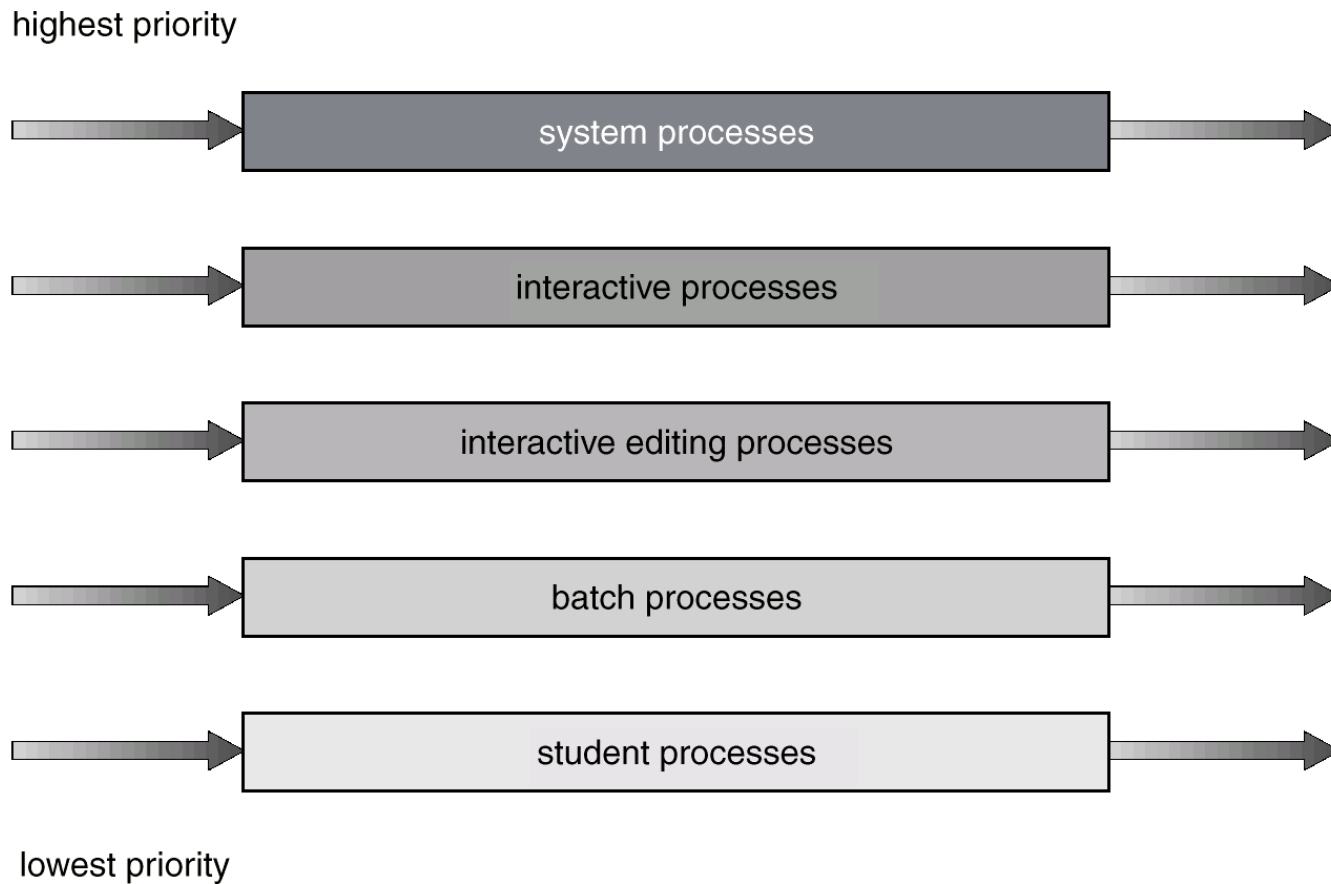Fixed priority scheduling; i.e., serve all from foreground then from background. Possibility of starvation.

Time slice – each queue gets a certain amount of CPU time which it can schedule amongst its processes; e.g.,
80% to foreground in RR

20% to background in FCFS

Multilevel Queue Scheduling

highest priority

```
→ [ system processes ] →

→ [ interactive processes ] →

→ [ interactive editing processes ] →

→ [ batch processes ] →

→ [ student processes ] →
```

lowest priority

Multilevel Feedback Queue

A process can move between the various queues; aging can be implemented this way.

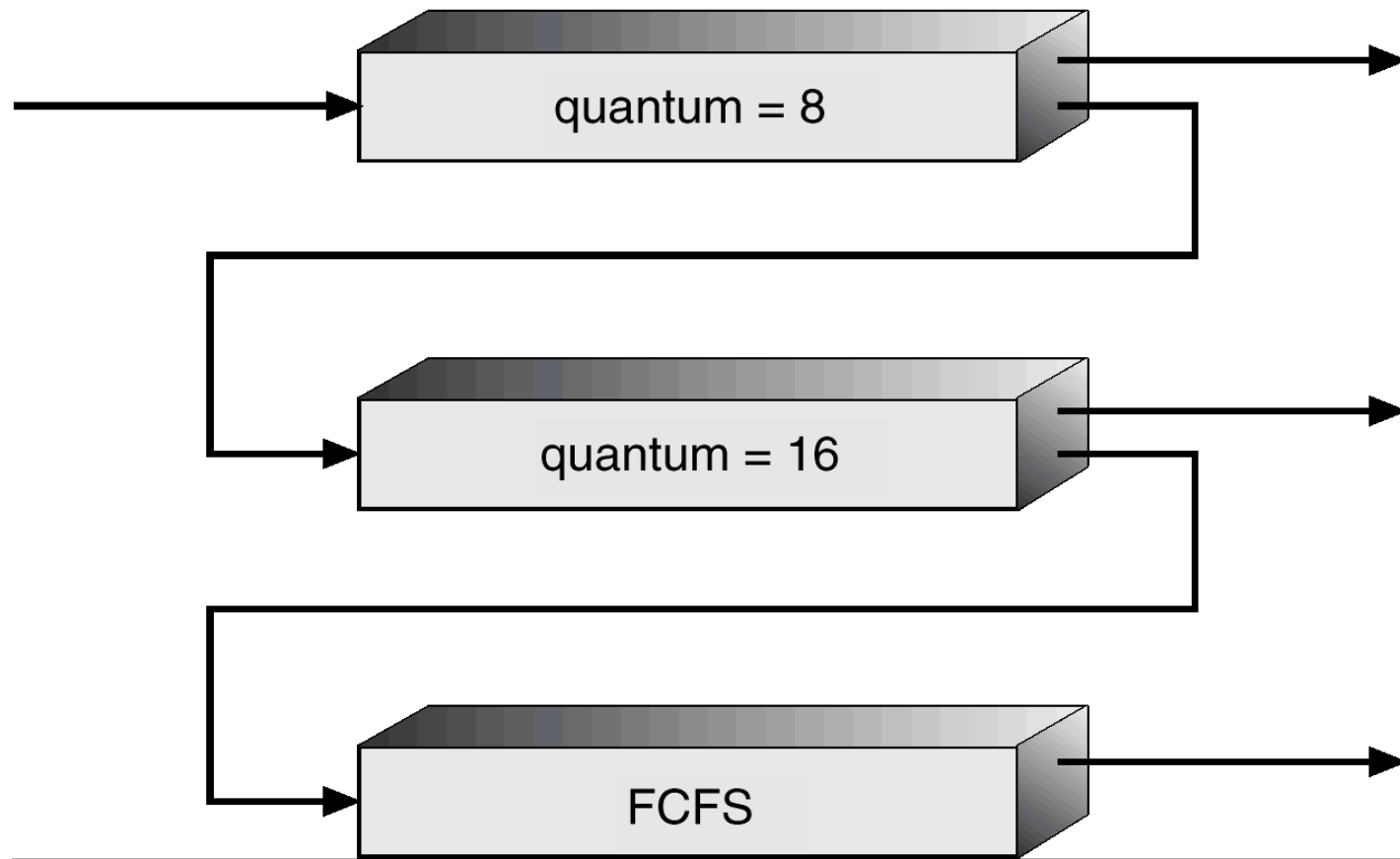Multilevel-feedback-queue scheduler defined by the following parameters:

number of queues

scheduling algorithms for each queue

method used to determine when to upgrade a process

method used to determine when to demote a process

method used to determine which queue a process will enter when that process needs service

Multilevel Feedback Queues

Example of Multilevel Feedback Queue

Three queues:

Q_0 – time quantum 8 milliseconds

Q_1 – time quantum 16 milliseconds

Q_2 – FCFS

Scheduling

A new job enters queue Q_0. When it gains CPU, job receives 8 milliseconds. If it does not finish in 8 milliseconds, job is moved to queue Q_1.

At Q_1 job receives 16 additional milliseconds. If it still does not complete, it is preempted and moved to queue Q_2.

After that, job is scheduled according to FCFS.

Traditional UNIX Scheduling

Multilevel feedback queues

128 priorities possible (0-127; 0 most important)

1 Round Robin queue per priority

At every scheduling event, the scheduler picks the highest priority non-empty queue and runs jobs in round-robin (note: high priority means low Q #)

Scheduling events:

Clock interrupt

Process gives up CPU, e.g. to do I/O

I/O completion

Process termination

Traditional UNIX Scheduling

All processes assigned a baseline priority based on the type and current execution status:

    swapper 0

    waiting for disk   20

    waiting for lock   35

    user-mode execution   50

At scheduling events, all process priorities are adjusted based on the amount of CPU used, the current load, and how long the process has been waiting.

Most processes are not running/ready, so lots of computing shortcuts are used when computing new priorities.

UNIX Priority Calculation

Every 4 clock ticks a process priority is updated:

$$P = BASELINE + \left[\frac{utilization}{4}\right] + 2\,NiceFactor$$

The utilization is incremented by 1 every clock tick during which process is running.

The NiceFactor allows some control of job priority. It can be set from –20 to 20.

Jobs using a lot of CPU increase the priority value. Interactive jobs not using much CPU will return to the baseline.

UNIX Priority Calculation

Very long running CPU-bound jobs will get "stuck" at the lowest priority, i.e. they will run infrequently.

Decay function used to weight utilization to recent CPU usage.

A process's utilization at time *t* is decayed every second:

$$u_t = \left[\frac{2load}{(2load + 1)} \right] * u_{(t-1)} + NiceFactor$$

The system-wide load is the average number of runnable jobs during last 1 second

UNIX Priority Decay

Assume 1 job on CPU. Load will thus be 1. Assume NiceFactor is 0.

Compute utilization at time N:

+1 second:
$$U_1 = \frac{2}{3} U_0$$

Utilization in the previous second

+2 seconds:
$$U_2 = \frac{2}{3}\left[U_1 + \frac{2}{3} U_0 \right] = \frac{2}{3} U_1 + \left(\frac{2}{3}\right)^2 U_0$$

+N seconds:
$$U_n = \frac{2}{3} U_{n-1} + \left(\frac{2}{3}\right)^2 U_{n-2} \ldots$$

UNIX Priority Reset

When a process transitions from "blocked" to "ready" state, its priority is set as follows:

$$u_t = \left[\frac{2load}{(2load + 1)} \right]^{tblocked} * \ u_{(t-1)}$$

where tblocked is the amount of time blocked.

Scheduling Algorithms

FIFO/FCFS is simple but leads to poor average turnaround times. Short processes are delayed by long processes that arrive before them

SJN and SRT alleviate the problem with FIFO, but require information on the length (service time) of each process. This information is not always available (though it can sometimes be approximated based on past history or user input)

RR eliminates achieves good response times, but favors CPU-bound jobs, which have longer CPU bursts

Feedback is a way of achieving good response times without information on process length, but is more complex than RR

Multiprocessor Scheduling

Several different policies:

Load sharing – an idle processor takes the first process out of the ready queue and runs it. Is this a good idea? How can it be made better?

Gang scheduling – all processes/threads of each application are scheduled together. Why is this good? Any difficulties?

Hardware partitions – applications get different parts of the machine. Any problems here?

Summary: Multiprocessor Scheduling

Load sharing: poor locality; poor synchronization behavior; simple; good processor utilization. Affinity or per processor queues can improve locality.

Gang scheduling: central control; fragmentation – unnecessary processor idle times (e.g., two applications with P/2+1 threads); good synchronization behavior; if careful, good locality
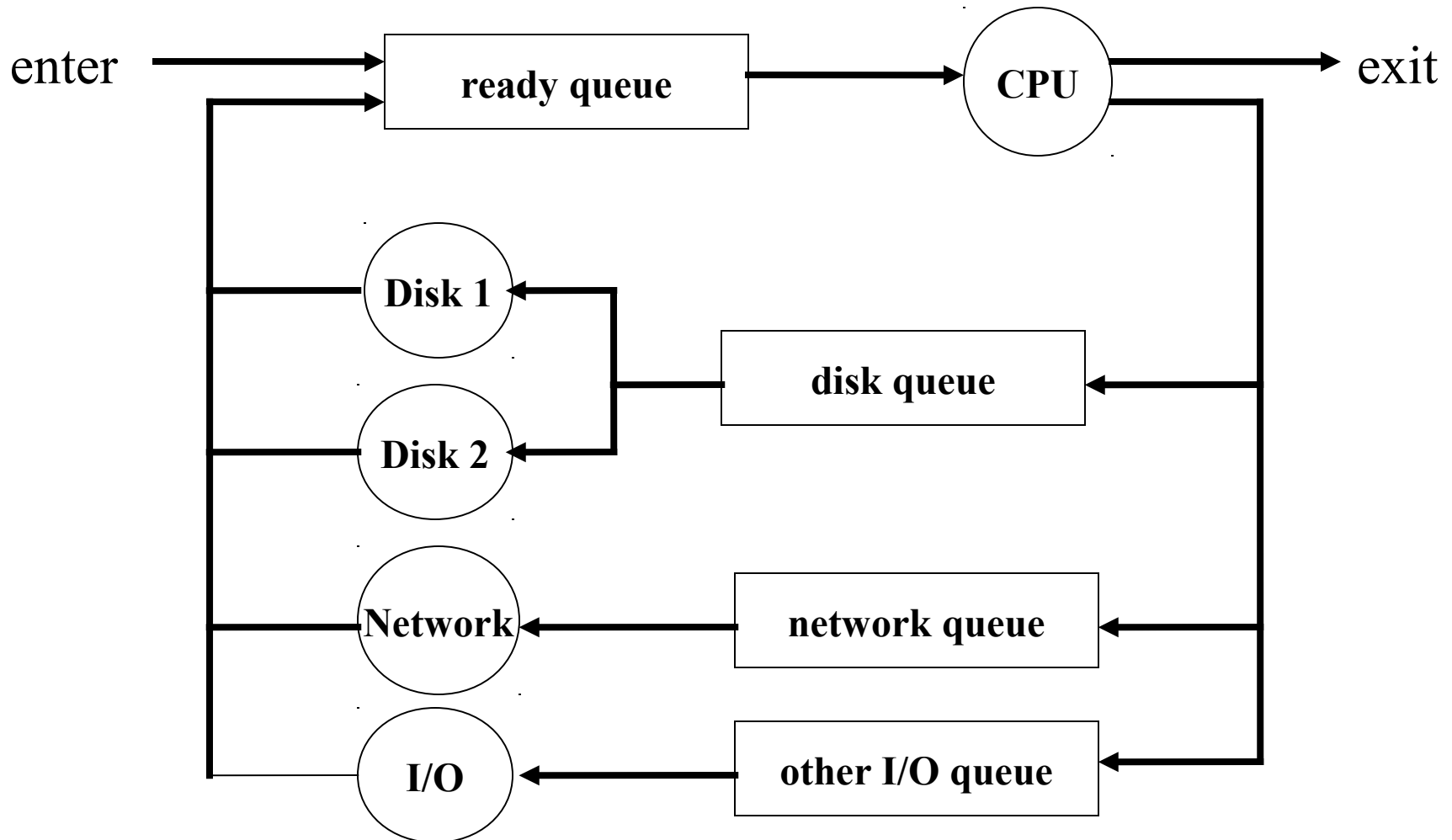
Hardware partitions: poor utilization for I/O-intensive applications; fragmentation – unnecessary processor idle times when partitions left are small; excellent locality and synchronization behavior

Backup Slides

Network Queuing Diagrams

enter → **ready queue** → **CPU** → exit

Disk 1

disk queue

Disk 2

Network

network queue

I/O

other I/O queue

Network Queuing Models

Circles are servers (resources), rectangles are queues

Jobs arrive and leave the system

Queuing theory lets us predict: avg length of queues, # jobs vs. service time

Little's law:

Mean # jobs in system = arrival rate x mean response time

Mean # jobs in queue = arrival rate x mean waiting time

jobs in system = # jobs in queue + # jobs being serviced

Response time = waiting + service

Waiting time = time between arrival and service

Stability condition:

Mean arrival rate < # servers x mean service rate per server

Example of Queuing Problem

A monitor on a disk server showed that the average time to satisfy an I/O request was 100 milliseconds. The I/O rate is 200 requests per second. What was the mean number of requests at the disk server?

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$$= 200 \text{ requests/sec x } 0.1 \text{ sec}$$

$$= 20$$

Assuming a single disk, how fast must it be for stability?

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Assuming a single disk, how fast must it be for stability? Service time must be lower than 0.005 secs.