Scheduling

Today

- Introduction to scheduling
- Classical algorithms
- Thread scheduling
- Evaluating scheduling
- OS example

Next Time

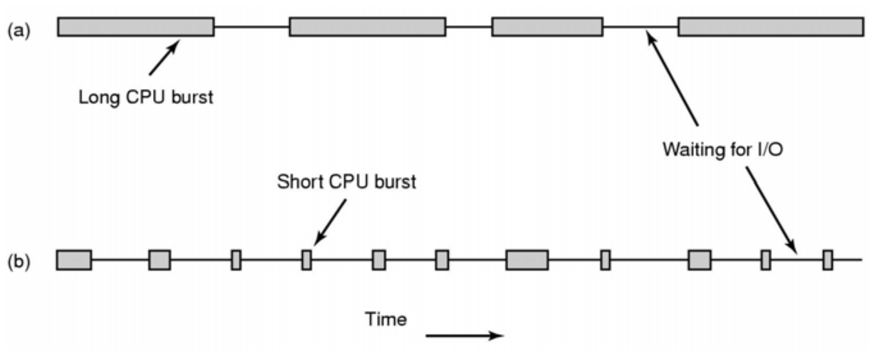
- Process interaction & communication

Scheduling

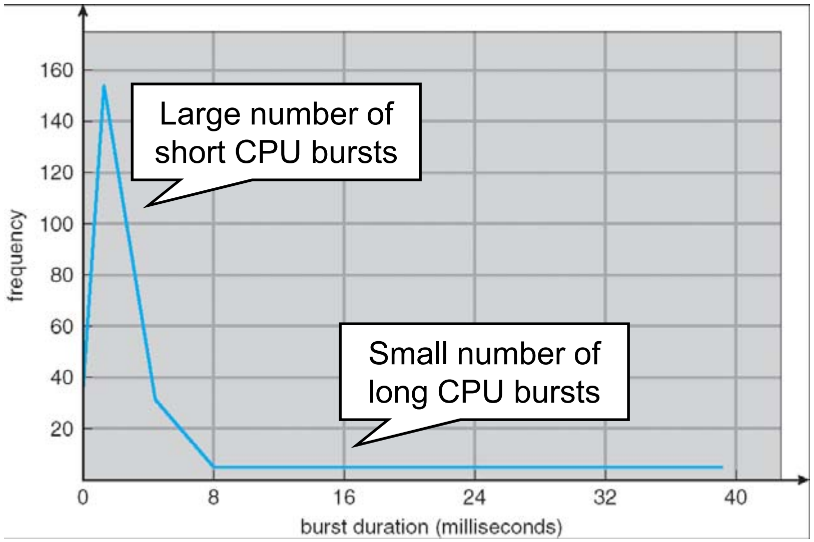
- Problem
  - Several ready processes & fewer CPUs than processes
- A choice has to be made
  - By the *scheduler,* using a *scheduling algorithm*
- Scheduling through time
  - Early batch systems – Just run the next job in the tape
  - Early timesharing systems – Scarce CPU time so scheduling is critical
  - Personal computers – Commonly one active process so scheduling is easy; with fast & per-user CPU so scheduling is not critical
  - Networked workstations and servers – All back again, multiple competing processes ready & expensive CS, scheduling is critical

Process behavior

- Bursts of CPU usage alternate with periods of I/O wait
  - CPU-bound process
  - I/O bound process
- As CPU gets faster – more I/O bound processes

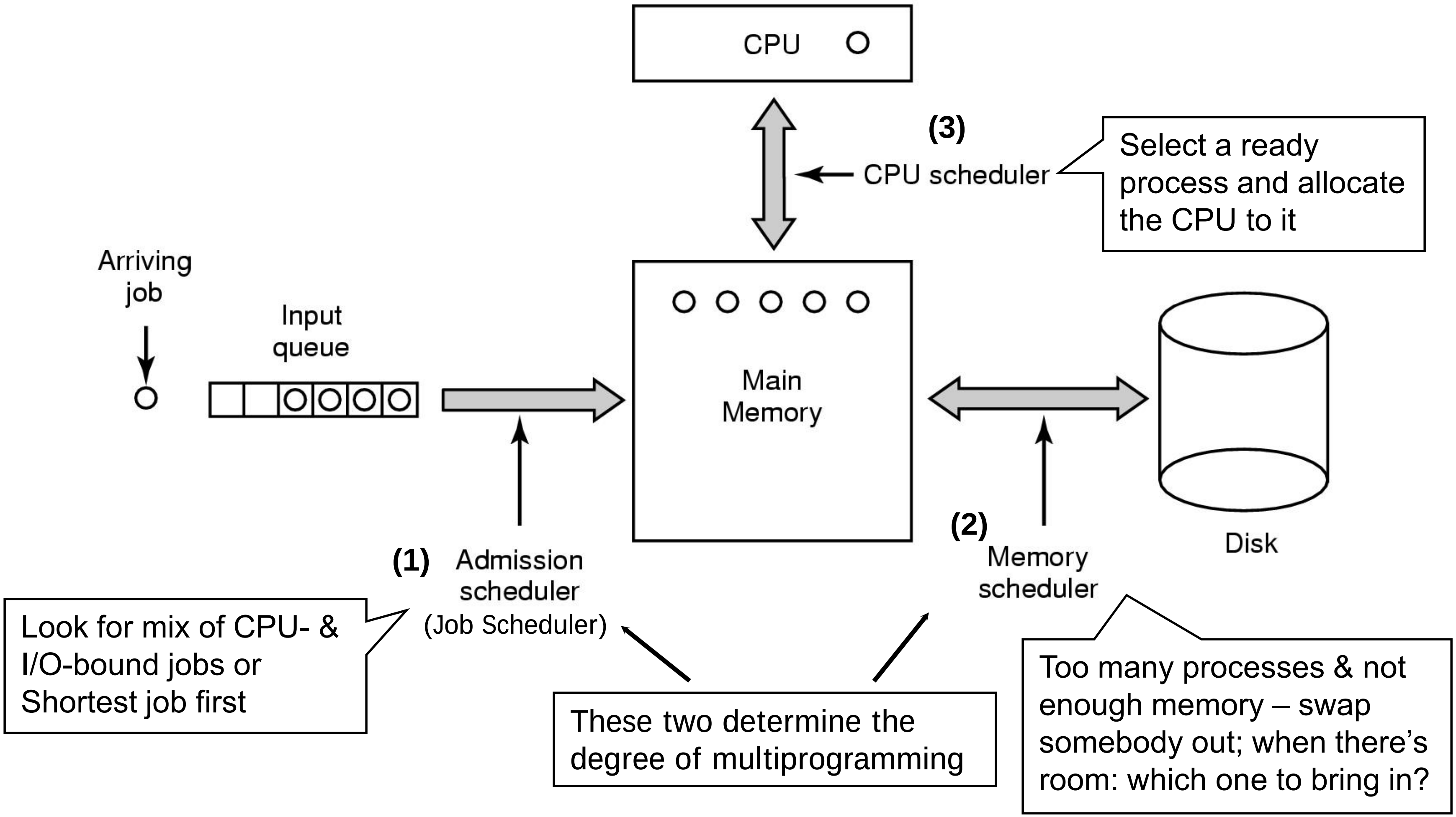


Histogram of CPU-burst times



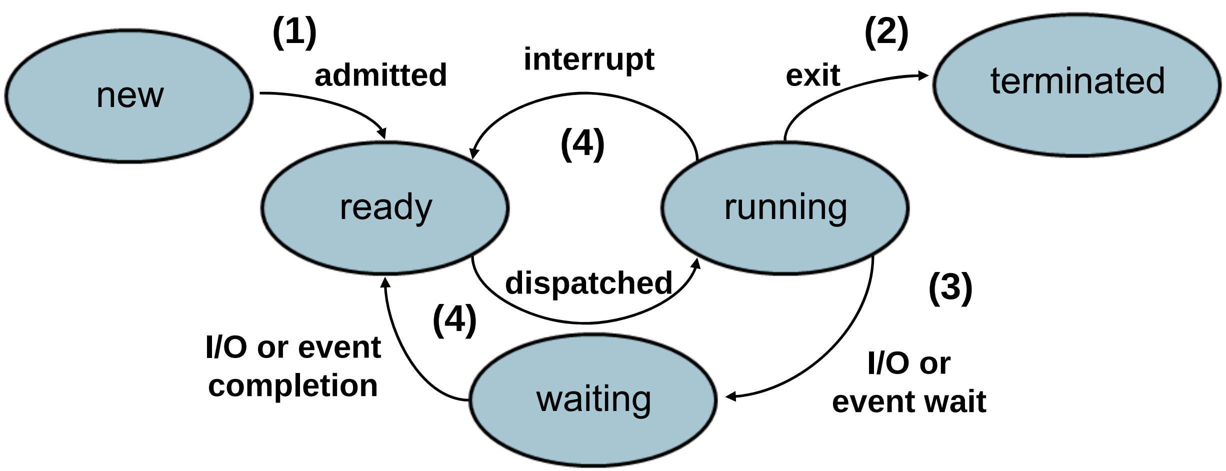
Multilevel scheduling

- Batch systems allow scheduling at 3 levels



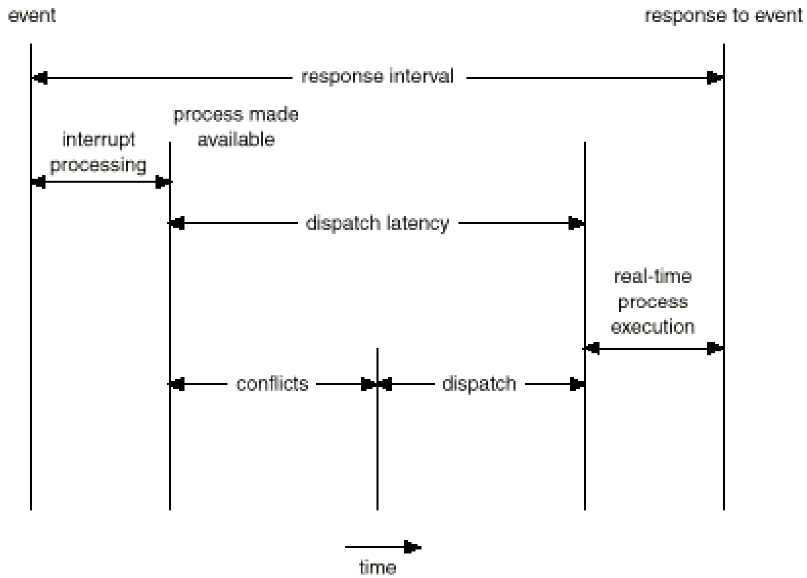
When to schedule?

1. At process creation
2. When a process exits
3. When a process blocks on I/O, a semaphore, …
4. When an I/O interrupts occurs
5. At fixed periods of time
   - Preemptive and non-preemptive schedulers
     - No-preemptive: once the CPU has been allocated, it is not release until the process terminates or switches to waiting
   - Need a HW clock interrupting



Dispatcher

- Dispatcher module gives control of CPU to process selected by short-term scheduler
  - switching context
  - switching to user mode
  - jumping to proper location in user program to restart it
- Dispatch latency – time it takes for dispatcher to stop one process and start another running



Environments and goals

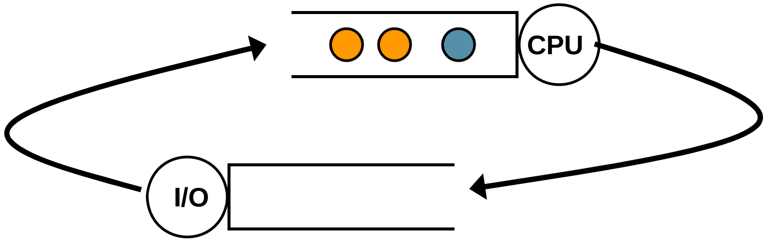
- Different scheduling algorithms for different application areas
- Worth distinguishing
  - Batch
  - Interactive
  - Real-time
- All systems
  - Fairness – comparable processes getting comparable service
  - Policy enforcement – seeing that stated policy is carried out
  - Balance – keeping all parts of the system busy (mix pool of processes)

Environments and goals

- Batch systems
  - Throughput – max. jobs per hour
  - Turnaround time – min. time bet/ submission & termination
    - Waiting time – sum of periods spent waiting in ready queue
  - CPU utilization – keep the CPU busy all time
- Interactive systems
  - Response time – respond to requests quickly (time to start responding)
  - Proportionality – meet users' expectations
- Real-time system
  - Meeting deadlines – avoid losing data
  - Predictability – avoid quality degradation in multimedia systems
- Average, maximum, minimum or variance?

First-Come First-Served scheduling

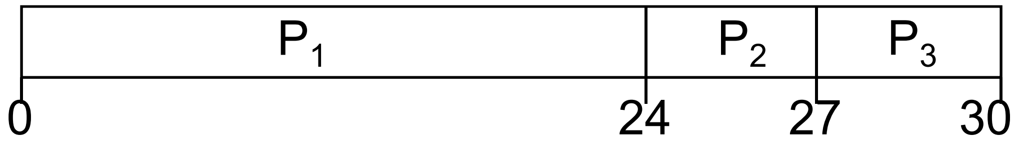
- First-Come First-Served
  - Simplest, easy to implement, non-preemptive
  - Problem:
    - 1 CPU-bound process (burst of 1 sec.)
    - Many I/O-bound ones (needing to read 1000 records to complete)
    - Each I/O-bound process reads one block per sec!



FCFS scheduling

Order of arrival: P1 , P2 , P3

Gantt Chart for schedule

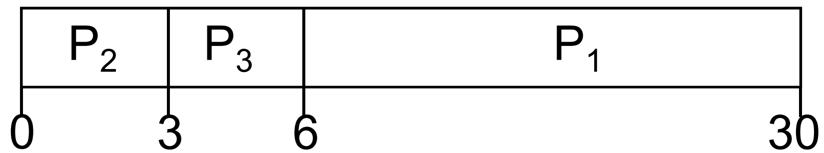


Process	Burst Time
P1	24
P2	3
P3	3

Waiting times: P1 = 0; P2 = 24; P3 = 27
Average waiting time: (0 + 24 + 27)/3 = 17

Order of arrival: P_2 , P_3 , P_1

Gantt chart for schedule is



Waiting times: *P1* = 6*; P2* = 0*; P3* = 3
Average waiting time: (6 + 0 + 3)/3 = 3

Preempetive or not?

Shortest Job/Remaining Time First sched.

- Shortest-Job First
  - Assumption – total time needed (or length of next CPU burst) is known
  - Provably optimal

    First job finishes at time a

    Second job at time a + b

    …

    Mean turnaround time

    (4a + 3 b + 2c + d)/4

    ↑

    Biggest contributor

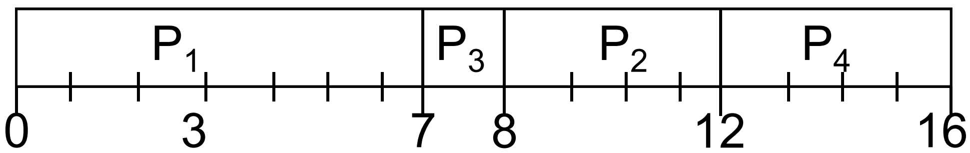
Job #	Finish time
1	a
2	b
3	c
4	d

Preempetive or not?

- A preemptive variation – Shortest Remaining Time (or SRPT)

SJF and SRT

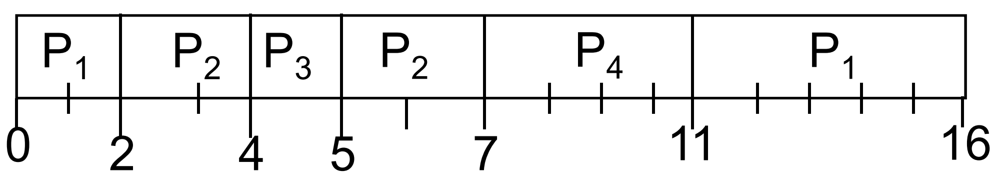
- SJF Non-preemptive



avg. waiting time = (0 + 6 + 3 + 7)/4 = 4

Process	Arrival	Burst Time
P1	0.0	7
P2	2.0	4
P3	4.0	1
P4	5.0	4

- SRT Preemptive



avg. waiting time = (9 + 1 + 0 +2)/4 = 3

Determining length of next CPU burst

- Can only *estimate* length
- Can be done using length of previous CPU bursts and exponential averaging

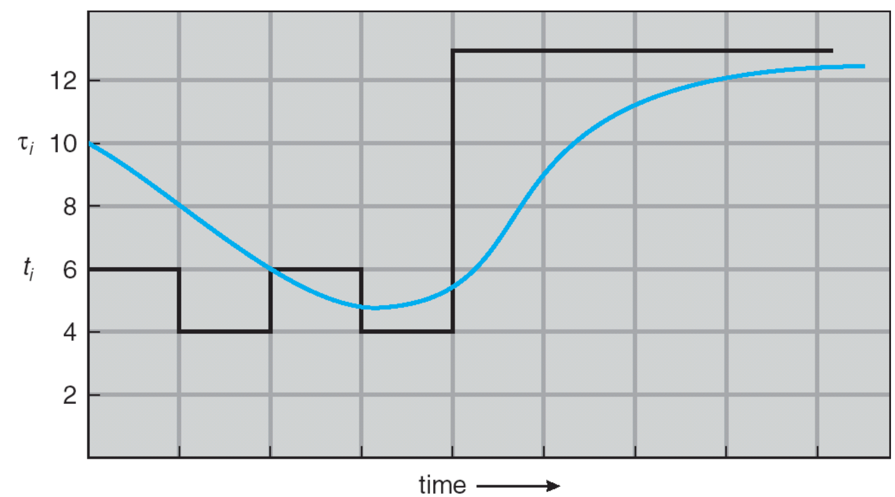
- t_n = actual lenght of n^{th} CPU burst
- τ_{n+1} = predicted value for the next CPU burst
- $\alpha, 0 \le \alpha \le 1$
- Define:

Weight of history

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

Most recent information

Past history



CPU burst (t_i)	6	4	6	4	13	13	13	…
"guess" (τ_i)	10	8	6	6	5	9	11	12	…

Examples of Exponential Averaging

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

- $\alpha = 0$
  - $\tau_{n+1} = \tau_n$
  - Recent history does not count
- $\alpha = 1$
  - $\tau_{n+1} = t_n$
  - Only the actual last CPU burst counts
- If we expand the formula, we get:

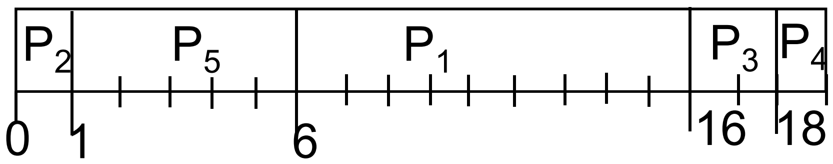
$$\tau_{n+1} = \alpha\, t_n + (1 - \alpha)\alpha\, t_{n-1} + \ldots + (1 - \alpha)^j \alpha\, t_{n-j} + \ldots + (1 - \alpha)^{n+1} \tau_0$$

- Since both α and $(1 - \alpha)$ are less than or equal to 1, each successive term has less weight than its predecessor

Priority scheduling

- SJF is a special case of priority-based scheduling
  - Priority = reverse of predicted next CPU burst
- Pick process with highest priority (lowest number)
- Problem
  - Starvation – low priority processes may never execute
- Solution:
  - Aging → increases priority (Unix's nice)
  - Assigned maximum quantum

Process	Burst time	Priority
P1	10	3
P2	1	1
P3	2	4
P4	1	5
P5	5	2

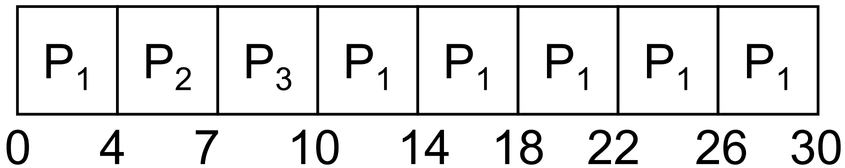


avg. waiting time = (6 + 0 + 16 +18 + 1)/5 = 8.2

Round-robin scheduling

- Simple, fair, easy to implement, & widely-used
- Each process gets a fix *quantum* or *time slice*
- When quantum expires, if running preempt CPU
- With *n* processes & quantum *q*, each one gets 1/*n* of the CPU time, no-one waits more than (*n*-1) *q*

$q = 4$



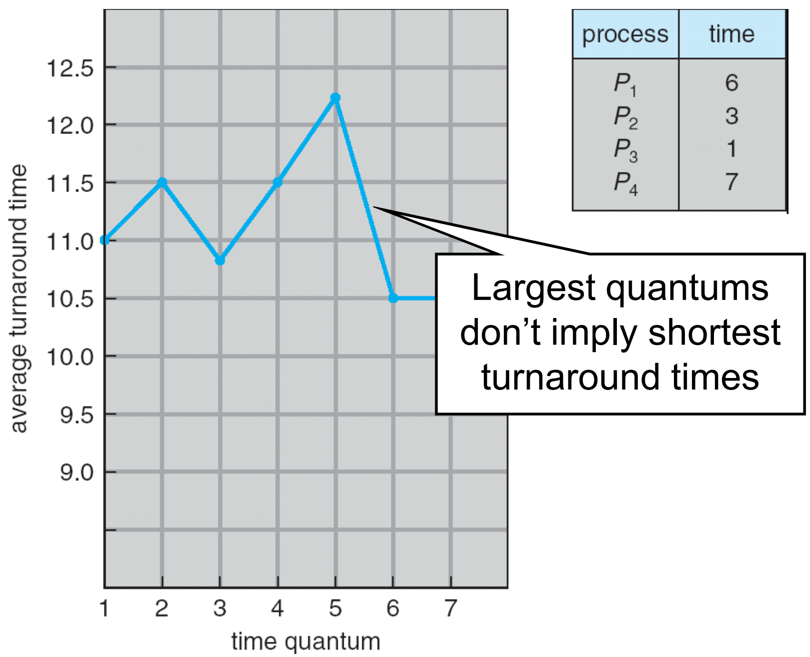
avg. waiting time = (6 + 4 +7)/3 = 5.66

Process	Burst Time
P1	24
P2	3
P3	3

Preempetive or not?

Quantum & Turnaround time

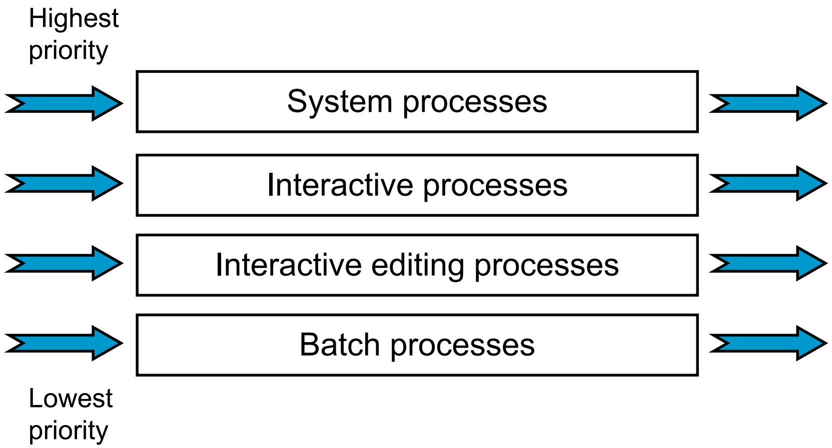
- Length of quantum
  - Too short – low CPU efficiency (*why?*)
  - Too long – low response time
    (*really long, what do you get?)*
  - Commonly ~ 50-100 msec.



process	time
P_1	6
P_2	3
P_3	1
P_4	7

Combining algorithms

- In practice, any real system uses some hybrid approach, with elements of each algorithm
- Multilevel queue
  - Ready queue partitioned into separate queues
  - Each queue has its own scheduling algorithm
  - Scheduling must be done between the queues
    - Fixed priority scheduling; (i.e., foreground first); starvation?
    - Time slice – each queue gets a certain amount of CPU time which it can schedule amongst its processes



Multiple (feedback) queues

- Multiple queues & allow processes to move between queues
- Example CTSS – Idea: separate processes based on CPU bursts
  - 7094 had only space for 1 process in memory (switch = swap)
  - Goals: low context switching cost & good response time
  - Priority classes: class *i* gets 2^i quantas *(i: 0 …)*
  - Scheduler executes first all processes in queue 0; if empty, all in queue 1, …
  - If process uses all its quanta → move to next lower queue (leave I/O-bound & interact. processes in high-priority queue)
  - What about process with long start but interactive after that?

Carriage-return hit → promote process to top class ☺

Some other algorithms

- Guaranteed scheduling - e.g. proportional to # processes
  - Priority = amount used / amount promised
  - Lower ratio → higher priority
- Lottery scheduling – simple & predictable
  - Each process gets lottery tickets for resources (CPU time)
  - Scheduling – lottery, i.e. randomly pick a ticket
  - Priority – more tickets means higher chance
  - Processes may exchange tickets
- Fair-Share scheduling –
  - Schedule aware of ownership
  - Owners get a % of CPU, processes are picked to enforce it

Real-time scheduling

- Different categories
  - *Hard RT* – no on time ~ not at all
  - *Soft RT* – important to meet guarantees but not critical
- Scheduling can be static or dynamic
- Schedulable real-time system
  - *m* periodic events
  - event *i* occurs within period P_i and requires C_i seconds

Then the load can only be handled if

$$\sum_{i=1}^{m} \frac{C_i}{P_i} \leq 1$$

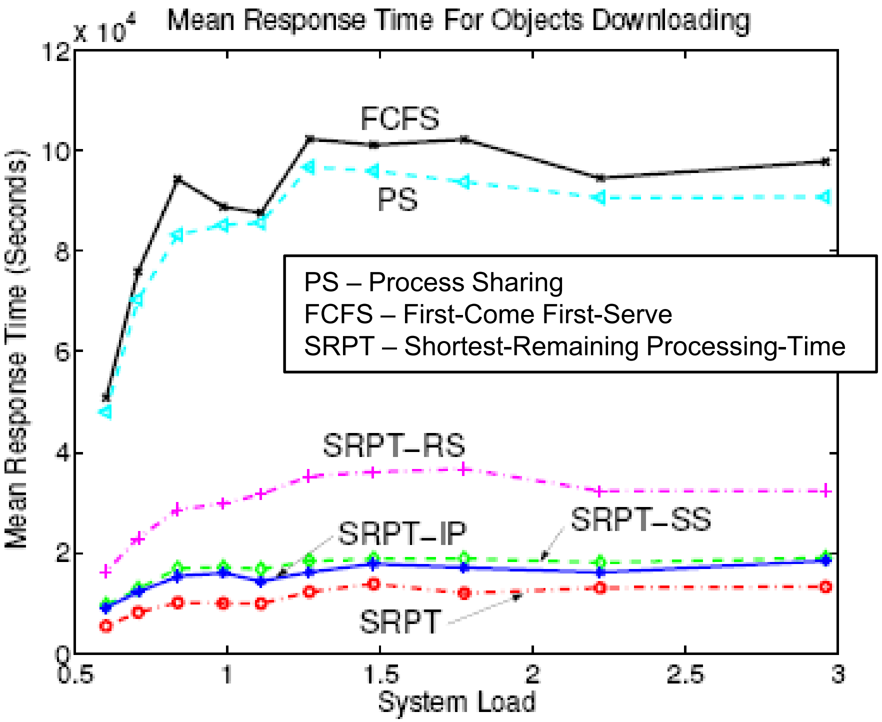
P1: C = 50 msec, P = 100msec (.5)
P2: C = 30 msec, P = 200msec (.15)
P3: C = 100 msec, P = 500msec (.2)
P4: C = 200 msec, P= 1000msec (.2)

Multiple-processor scheduling

- Scheduling more complex w/ multiple CPUs (assuming homogeneous processors)
- Asymmetric/symmetric (SMP) multiprocessing
  - Supported by most OSs (common or independent ready queues)
- Processor affinity – benefits of past history in a processor
- Load balancing – keep workload evenly distributed
  - Push migration – specific task periodically checks load in processors & pushes processes for balance
  - Pull migration – idle processor pulls processes from busy one
- Symmetric multithreading (hyperthreading or SMT)
  - Multiple logical processors on a physical one
  - Each w/ own architecture state, supported by hardware
  - Shouldn't require OS to know about it (but could benefit from)

Scheduling the server-side of P2P systems

- The response time experienced by users of P2P data sharing services is dominated by the downloading process.
  - >80% of all download requests in Kazaa are rejected due to capacity saturation at server peers
  - >50% of all requests for large objects (>100MB) take more than one day & ~20% take over one week to complete
- Most implementations use FCFS or PS
- *Apply SRPT!* Work by Qiao et al. @ Nortwestern



Mean response time of object download as a function of system load.

Thread scheduling

- Now add threads – user or kernel level?
- User-level (process-contention scope)
  - Context switch is cheaper
  - You can have an application-specific scheduler at user level
  - Kernel doesn’t know of your threads
- Kernel-level (system-contention scope)
  - Any scheduling of threads is possible (since the kernel knows of all)
  - Switching threads inside same process is cheaper than switching processes

Pthread scheduling API

```
#include <pthread.h>
#include <stdio.h>
#define NUM THREADS 5

/* Each thread begin control in this function */
void *runner(void *param)
{
  printf("I am a thread\n");
  pthread exit(0);
}

int main(int argc, char *argv[])
{
  int i;
  pthread_t tid[NUM THREADS]; pthread_attr_t attr;

  pthread_attr_init(&attr); /* get the default attributes */
  pthread_attr_setscope(&attr, PTHREAD_SCOPE_SYSTEM); /* set the sched algo */
  pthread_attr_setschedpolicy(&attr, SCHED_OTHER); /* set the sched policy */

  for (i = 0; i < NUM_THREADS; i++) /* create the threads */
     pthread_create(&tid[i],&attr,runner,NULL);

  for (i = 0; i < NUM_THREADS; i++) /* now join on each thread */
     pthread_join(tid[i], NULL);
}
```

Policy vs. mechanism

- Separate what is done from how it is done
  - Think of parent process with multiple children
  - Parent process may knows relative importance of children (if, for example, each one has a different task)
- None of the algorithms presented take the parent process input for scheduling
- Scheduling algorithm parameterized
  - Mechanism in the kernel
- Parameters filled in by user processes
  - Policy set by user process
  - Parent controls scheduling w/o doing it

Algorithm evaluation

- First problem: criteria to be used in selection
  - E.g. Maximize CPU utilization, but w/ max. response time of 1 sec.
- Evaluation forms
  - Analytic evaluation - deterministic modeling:
    - Given workload & algorithm → number or formula
    - Simple & fast, but workload specific
  - Queueing models
    - Computer system described as a network of servers
    - Load characterized by distributions
    - Applicable to limited number of algorithms – complicated maths & questionable assumptions
  - Simulations
    - Distribution-driven or trace-based
  - Implementation
    - Highly accurate & equally expensive

Next time

- Process synchronization
  - Race condition & critical regions
  - Software and hardware solutions
  - Review of classical synchronization problems
  - …
- *What really happened in Mars?*

  http://research.microsoft.com/~mbj/Mars_Pathfinder/Mars_Pathfinder.html

OS examples – Linux

- Preemptive, priority-based scheduling
  - Two separate priority ranges (real-time [0,99] & nice [100,140]) mapping to a global priority scheme
- Two algorithms: time-sharing and real-time
- Time-sharing
  - Prioritized credit-based – process w/ most credits is scheduled next
  - Credit subtracted when timer interrupt occurs
  - When credit = 0, another process chosen
  - When all processes have credit = 0, re-crediting occurs
    - Based on factors including priority and history
- (Soft) Real-time
  - Static priority for RT tasks
  - Two classes
    - FCFS (2+ task w/ = priority RR) and RR (FCFS w/ quantum)
    - Highest priority process always runs first

OS examples – Linux (Ingo Molnar's O(1))

- Perfect SMP scalability & improved SMP affinity
- O(1) scheduling – constant-time, regardless of # of running processes
  - One runqueue per processor
  - Two priority arrays per
    - Active – tasks w/ remaining quantum
    - Expired – tasks w/ …
  - Each priority array includes 1 queue of runnable processes per priority level
  - Recalculation of task's dynamic priority done when task has exhausted its time quantum & moved to expired
  - When active is empty – swap