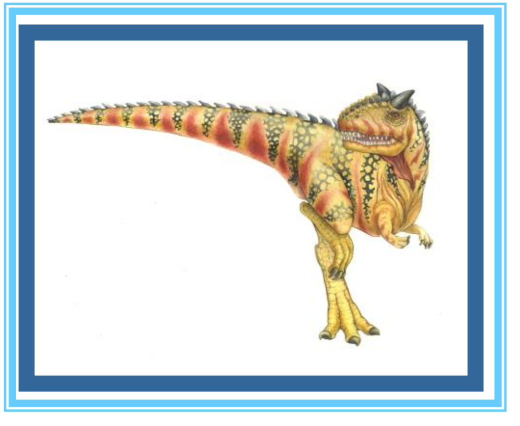
Chapter 5: Process Scheduling



Chapter 5: Process Scheduling

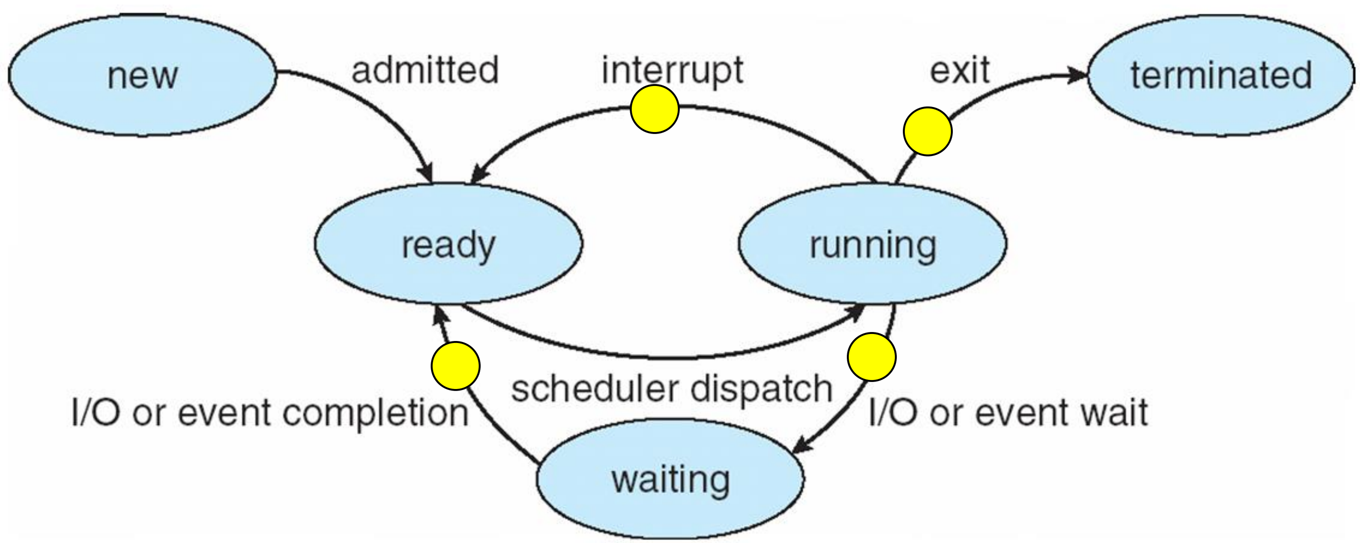
- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Thread Scheduling
- Multiple-Processor Scheduling
- Operating Systems Examples
- Algorithm Evaluation

Process Scheduling

- Have M jobs ready to run
- Have N≥1 CPUs
- Which job to assign to which CPU(s) at what time?

CPU Scheduler

- 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
- **nonpreemptive scheduler uses 1 and 4**
- **Preemptive scheduler kicks in for all four time points**



CPU Scheduler

LXR linux/fs/block_d ×

lxr.linux.no/linux+v3.6.3/fs/block_dev.c#L748

```c
        else
                return true;     /* is a partition of an un-held device */
}

/**
 * bd_prepare_to_claim - prepare to claim a block device
 * @bdev: block device of interest
 * @whole: the whole device containing @bdev, may equal @bdev
 * @holder: holder trying to claim @bdev
 *
 * Prepare to claim @bdev.  This function fails if @bdev is already
 * claimed by another holder and waits if another claiming is in
 * progress.  This function doesn't actually claim.  On successful
 * return, the caller has ownership of bd_claiming and bd_holder[s].
 *
 * CONTEXT:
 * spin_lock(&bdev_lock).  Might release bdev_lock, sleep and regrab
 * it multiple times.
 *
 * RETURNS:
 * 0 if @bdev can be claimed, -EBUSY otherwise.
 */
static int bd_prepare_to_claim(struct block_device *bdev,
                               struct block_device *whole, void *holder)
{
retry:
        /* if someone else claimed, fail */
        if (!bd_may_claim(bdev, whole, holder))
                return -EBUSY;

        /* if claiming is already in progress, wait for it to finish */
        if (whole->bd_claiming) {
                wait_queue_head_t *wq = bit_waitqueue(&whole->bd_claiming, 0);
                DEFINE_WAIT(wait);

                prepare_to_wait(wq, &wait, TASK_UNINTERRUPTIBLE);
                spin_unlock(&bdev_lock);
                schedule();
                finish_wait(wq, &wait);
                spin_lock(&bdev_lock);
                goto retry;
        }

        /* yay, all mine */
        return 0;
}
```

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

Context switch

lxr.linux.no/linux+v3.6.3/kernel/sched/core.c#L2046

```c
context_switch(struct rq *rq, struct task_struct *prev,
               struct task_struct *next)
{
        struct mm_struct *mm, *oldmm;

        prepare_task_switch(rq, prev, next);

        mm = next->mm;
        oldmm = prev->active_mm;
        /*
         * For paravirt, this is coupled with an exit in switch_to to
         * combine the page table reload and the switch backend into
         * one hypercall.
         */
        arch_start_context_switch(prev);

        if (!mm) {
                next->active_mm = oldmm;
                atomic_inc(&oldmm->mm_count);
                enter_lazy_tlb(oldmm, next);
        } else
                switch_mm(oldmm, mm, next);

        if (!prev->mm) {
                prev->active_mm = NULL;
                rq->prev_mm = oldmm;
        }
        /*
         * Since the runqueue lock will be released by the next
         * task (which is an invalid locking op but in the case
         * of the scheduler it's an obvious special-case), so we
         * do an early lockdep release here:
         */
#ifndef __ARCH_WANT_UNLOCKED_CTXSW
        spin_release(&rq->lock.dep_map, 1, _THIS_IP_);
#endif

        /* Here we just switch the register state and the stack. */
        switch_to(prev, next, prev);

        barrier();
        /*
         * this_rq must be evaluated again because prev may have moved
         * CPUs since it called schedule(), thus the 'rq' on its stack
         * frame will be invalid.
         */
        finish_task_switch(this_rq(), prev);
}
```

switching address space

switching register state and stack

Context switch

lxr.linux.no/linux+v3.6.3/arch/x86/include/asm/switch_to.h

```
/* frame pointer must be last for get_wchan */
#define SAVE_CONTEXT    "pushf ; pushq %%rbp ; movq %%rsi,%%rbp\n\t"
#define RESTORE_CONTEXT "movq %%rbp,%%rsi ; popq %%rbp ; popf\t"

#define __EXTRA_CLOBBER  \
        , "rcx", "rbx", "rdx", "r8", "r9", "r10", "r11", \
          "r12", "r13", "r14", "r15"

#ifdef CONFIG_CC_STACKPROTECTOR
#define __switch_canary                                               \
        "movq %P[task_canary](%%rsi),%%r8\n\t"                        \
        "movq %%r8,"__percpu_arg([gs_canary])"\n\t"
#define __switch_canary_oparam                                        \
        , [gs_canary] "=m" (irq_stack_union.stack_canary)
#define __switch_canary_iparam                                        \
        , [task_canary] "i" (offsetof(struct task_struct, stack_canary))
#else   /* CC_STACKPROTECTOR */
#define __switch_canary
#define __switch_canary_oparam
#define __switch_canary_iparam
#endif  /* CC_STACKPROTECTOR */

/* Save restore flags to clear handle leaking NT */
#define switch_to(prev, next, last) \
        asm volatile(SAVE_CONTEXT                                     \
             "movq %%rsp,%P[threadrsp](%[prev])\n\t" /* save RSP */   \
             "movq %P[threadrsp](%[next]),%%rsp\n\t" /* restore RSP */ \
             "call __switch_to\n\t"                                   \
             "movq "__percpu_arg([current_task])",%%rsi\n\t"          \
             __switch_canary                                          \
             "movq %P[thread_info](%%rsi),%%r8\n\t"                   \
             "movq %%rax,%%rdi\n\t"                                   \
             "testl  %[_tif_fork],%P[ti_flags](%%r8)\n\t"             \
             "jnz   ret_from_fork\n\t"                                \
             RESTORE_CONTEXT                                          \
             : "=a" (last)                                            \
               __switch_canary_oparam                                 \
             : [next] "S" (next), [prev] "D" (prev),                  \
               [threadrsp] "i" (offsetof(struct task_struct, thread.sp)), \
               [ti_flags] "i" (offsetof(struct thread_info, flags)),  \
               [_tif_fork] "i" (_TIF_FORK),                           \
               [thread_info] "i" (offsetof(struct task_struct, stack)), \
               [current_task] "m" (current_task)                      \
               __switch_canary_iparam                                 \
             : "memory", "cc" __EXTRA_CLOBBER)

#endif /* CONFIG_X86_32 */

#endif /* _ASM_X86_SWITCH_TO_H */
```

switching kernel stack happens in here

Context switch / switch kernel stack

lxr.linux.no/linux+v3.6.3/arch/x86/kernel/process_64.c#L269

```
 *
 * This could still be optimized:
 * - fold all the options into a flag word and test it with a single test.
 * - could test fs/gs bitsliced
 *
 * Kprobes not supported here. Set the probe on schedule instead.
 * Function graph tracer not supported too.
 */
__notrace_funcgraph struct task_struct *
__switch_to(struct task_struct *prev_p, struct task_struct *next_p)
{
        struct thread_struct *prev = &prev_p->thread;
        struct thread_struct *next = &next_p->thread;
        int cpu = smp_processor_id();
        struct tss_struct *tss = &per_cpu(init_tss, cpu);
        unsigned fsindex, gsindex;
        fpu_switch_t fpu;

        fpu = switch_fpu_prepare(prev_p, next_p, cpu);

        /*
         * Reload esp0, LDT and the page table pointer:
         */
        load_sp0(tss, next);

        /*
         * Switch DS and ES.
         * This won't pick up thread selector changes, but I guess that is ok.
         */
        savesegment(es, prev->es);
        if (unlikely(next->es | prev->es))
                loadsegment(es, next->es);

        savesegment(ds, prev->ds);
        if (unlikely(next->ds | prev->ds))
                loadsegment(ds, next->ds);


        /* We must save %fs and %gs before load_TLS() because
         * %fs and %gs may be cleared by load_TLS().
         *
         * (e.g. xen_load_tls())
         */
        savesegment(fs, fsindex);
        savesegment(gs, gsindex);

        load_TLS(next, cpu);
```

Switch kernel stack

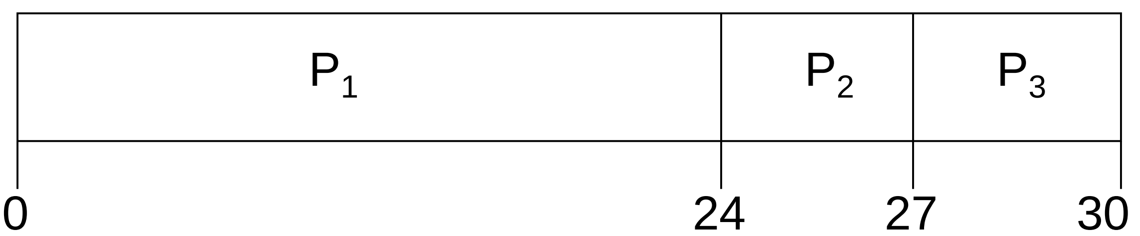
Scheduling Criteria

- **Throughput** – # of processes that complete their execution per time unit
  - Higher is better
- **Turnaround time** – amount of time to execute a particular process
  - Lower is better
- **Response time** – time from request to first response
  - E.g. mouse clicking on the menu bar to the showing of the menu
  - Lower is better
- Above criteria are affected by secondary criteria
  - **CPU utilization** – keep the CPU as busy as possible
  - **Waiting time** – amount of time a process has been waiting in the ready queue

First-Come, First-Served (FCFS) Scheduling

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:



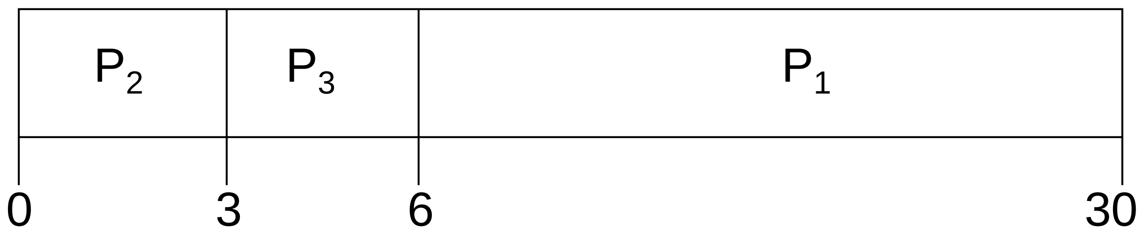
- Waiting time for P_1 = 0; P_2 = 24; P_3 = 27
- Average waiting time: (0 + 24 + 27)/3 = 17
- Throughput: 3 processes / 30 seconds = 0.1 processes / sec
- Turnaround Time: P_1: 24, P_2: 27, P_3: 30
  - Avg. TT: (24+27+30)/3 = 27

FCFS Scheduling (Cont)

Suppose that the processes arrive in the order

$$P_2 , P_3 , P_1$$

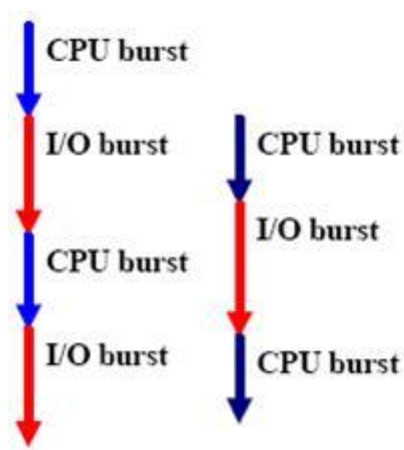
- The Gantt chart for the schedule is:

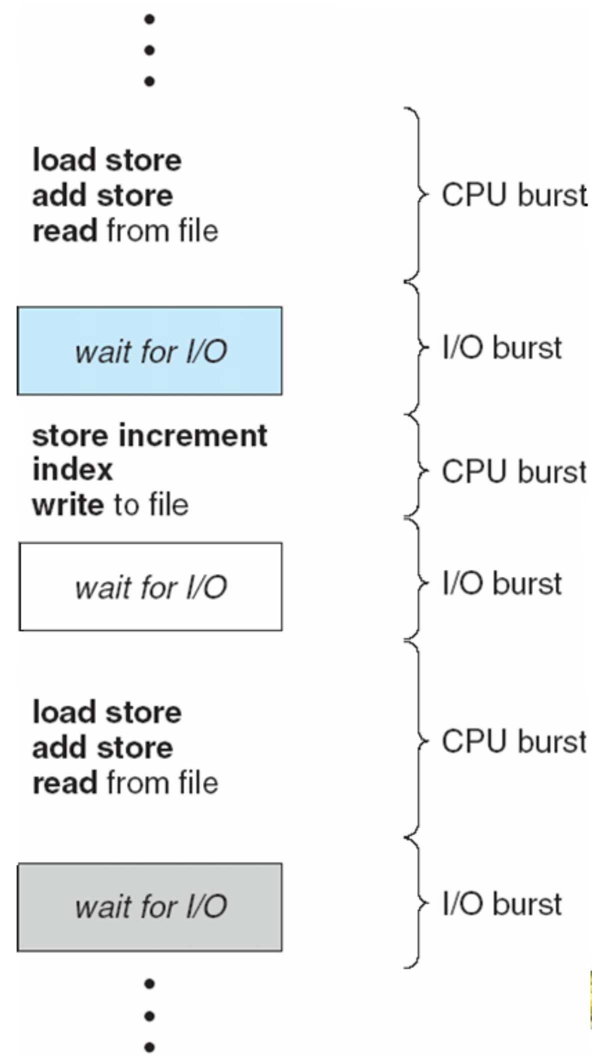


- Waiting time for $P_1 = 6$; $P_2 = 0$; $P_3 = 3$
- Average waiting time: (6 + 0 + 3)/3 = 3
- Throughput: 3 / 30 = 0.1 processes / sec
- Turnaround time: Time: P_1: 30, P_2: 3, P_3: 6
  - Avg. TT: (30+3+6)/3 = 13
- Much better than previous case
- Scheduling algorithm can reduce TT
  - Minimize waiting time to minimize TT
- What about throughput?

Alternating Sequence of CPU And I/O Bursts

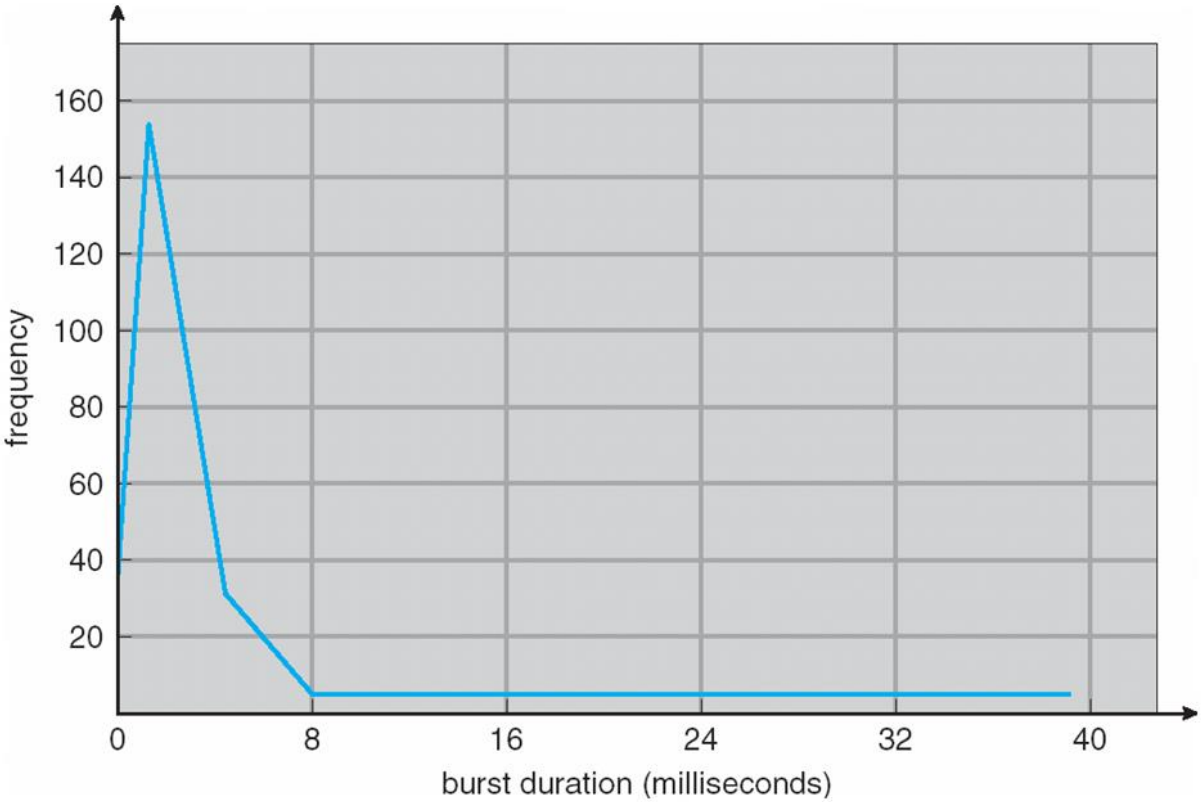
- CPU–I/O Burst Cycle – Process execution consists of a *cycle* of CPU execution, I/O wait, and event wait
- An I/O device can be considered as a special purpose CPU
- Goal: keep all CPUs and all I/O devices busy





Histogram of CPU-burst Times

Many short CPU bursts an few long bursts



What does this mean for FCFS?

FCFS Convoy effect

- CPU bound jobs will hold CPU until exit or I/O
  - I/O rare for CPU-bound thread
  - Long periods where no I/O requests issued, and CPU held
  - => poor I/O device utilization
- Example: one CPU-bound job, many I/O bound
  - CPU bound runs (I/O device idle)
  - CPU bound blocks
  - I/O bound job(s) run, quickly block on I/O
  - CPU bound runs again
  - I/O completes
  - CPU bound still runs while I/O device idle (continue?)

Shortest-Job-First (SJF) Scheduling

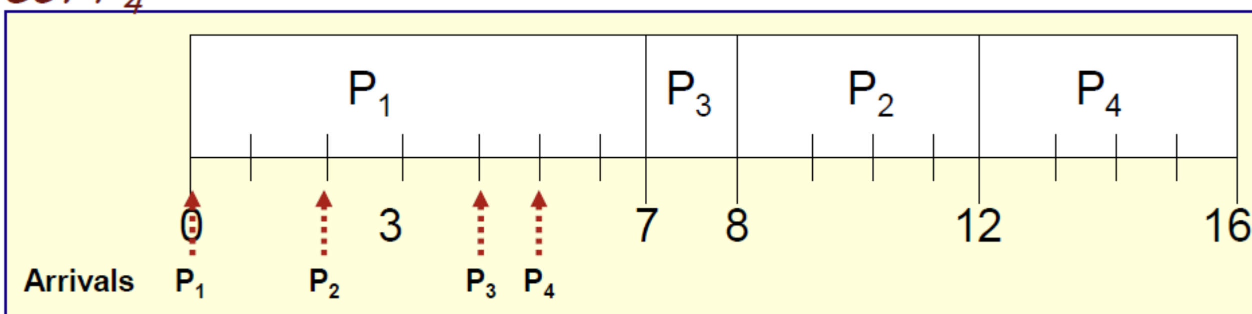
- Associate with each process the length of its next CPU burst. Use these lengths to schedule the process with the shortest time
- Process with shortest burst goes next
  - If tie then use FCFS to break tie
- SJF is optimal – gives minimum average waiting time for a given set of processes
  - The difficulty is knowing the length of the next CPU request
- Two schemes:
  - *Non-preemptive* – once CPU assigned, process not preempted until its CPU burst completes
  - *Preemptive* – if a process with CPU burst less than remaining time of current, preempt
    - Shortest-Remaining-Time-First (SRTF)

Example of Non-Preemptive SJF

- T = 0: RQ = {P_1}
  Select P_1
- T = 2: RQ = {P_2}
  No-Preemption
- T = 4: RQ = {P_3, P_2}
  No-Preemption
- T = 5: RQ = {P_3, P_2 , P_4}
  No-Preemption
- T = 7: RQ = {P_3, P_2 , P_4}
  P_1 completes, *Select P_3*
- T = 8: RQ = {P_2 , P_4}
  P_3 completes, *Select P_2*
- T = 12: RQ = {P_4}
  P_2 completes, *Select P_4*
- T = 16: RQ = {}
  P_4 completes

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

- Average Waiting Time:
  [0 + (8 – 2) + (7 – 4) + (12 – 5)]/4 =
  [6 + 3 + 7]/4 = 4

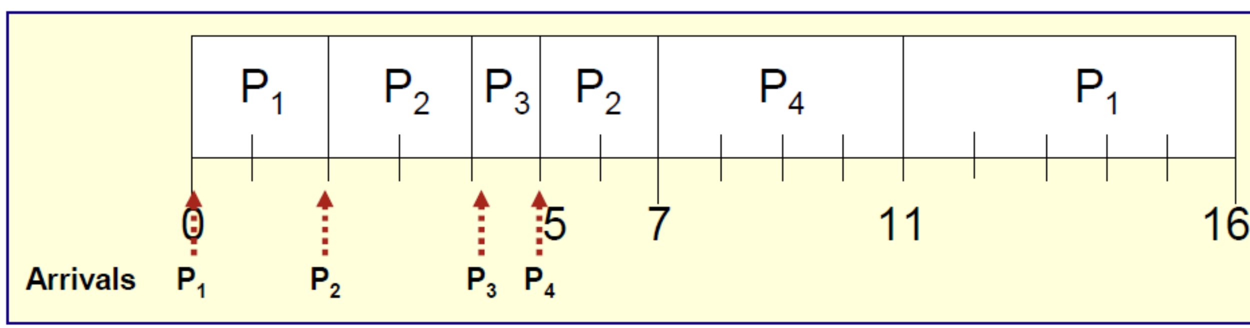


Example of Preemptive SJF

- T = 0: RQ = {P_1}
  Select P_1
- T = 2: RQ = {P_2}
  preempt P_1 , Select P_2
- T = 4: RQ = {P_3, P_1}
  preempt P_2 , Select P_3
- T = 5: RQ = {P_2, P_4 , P_1}
  P_3 completes, Select P_2
- T = 7: RQ = {P_4, P_1}
  P_2 completes, Select P_4
- T = 11: RQ = {P_1}
  P_4 completes, Select P_1
- T = 16: RQ = {}
  $P_2$1completes

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

- Average Waiting Time:
  [(11-2) + (5-4) + (0) + (7-5)]/4 =
  [9 + 1 + 0 + 2]/4 = 3

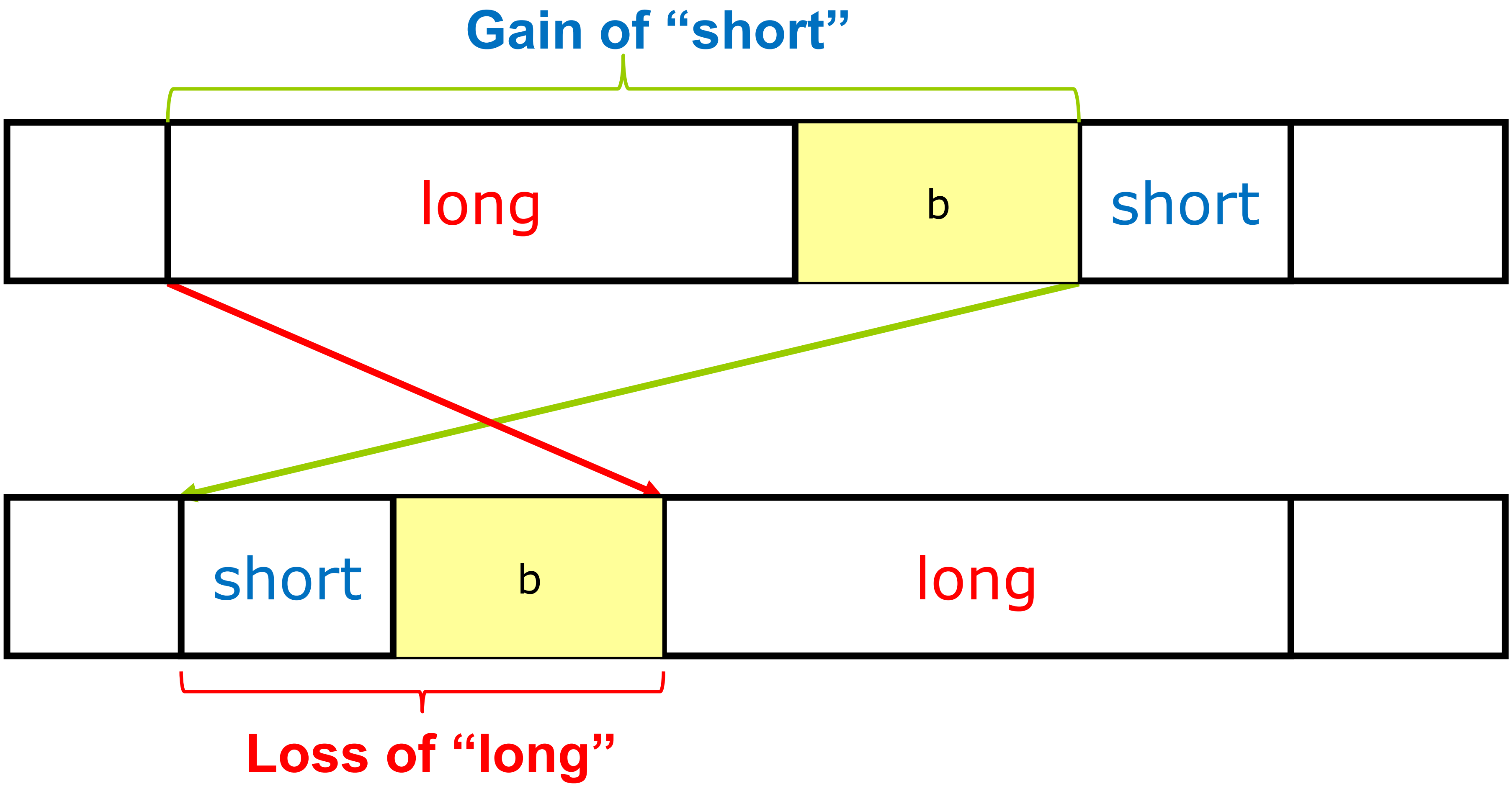


Determining Length of Next CPU Burst

- Can only estimate the length
- Can be done by using the length of previous CPU bursts, using exponential averaging

1. $t_n =$ actual length of n^{th} CPU burst
2. $\tau_{n+1} =$ predicted value for the next CPU burst
3. $\alpha, 0 \leq \alpha \leq 1$
4. Define : $\tau_{n+1} = \alpha\, t_n + (1-\alpha)\tau_n.$

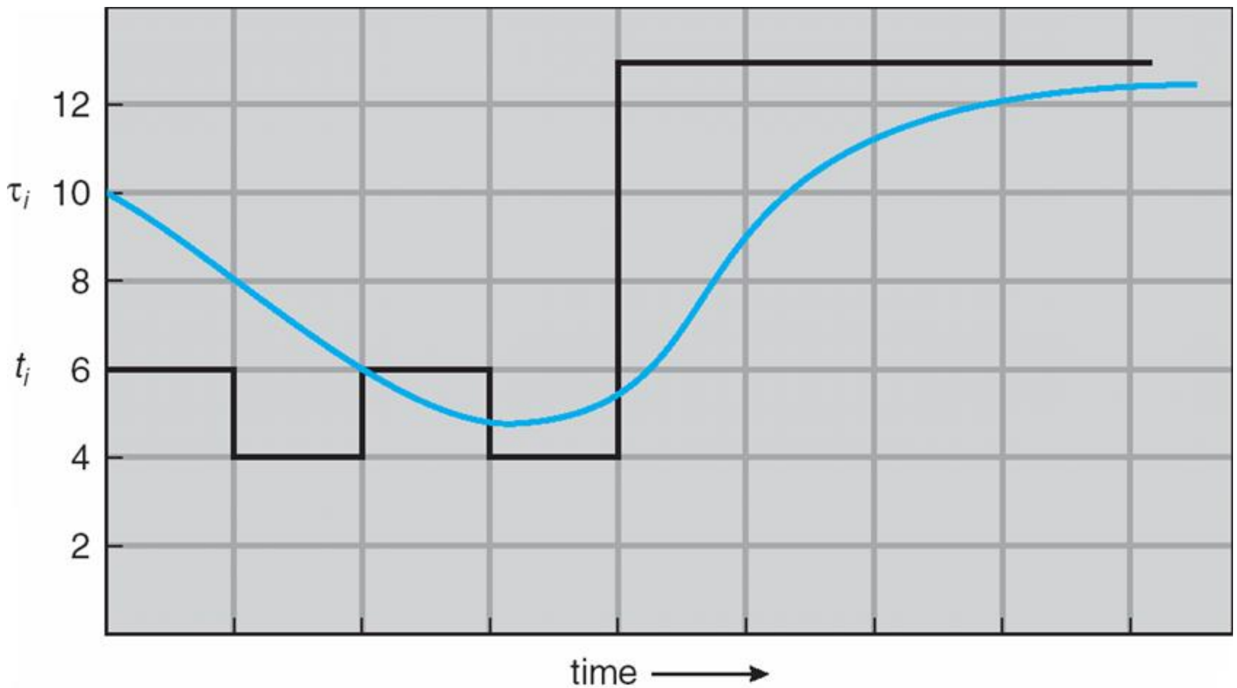
SJF Optimality



Proof that the SJF algorithm is optimal

Gain of short > Loss of long

Prediction of the Length of the Next CPU Burst



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

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

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

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

Priority Scheduling

- 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 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

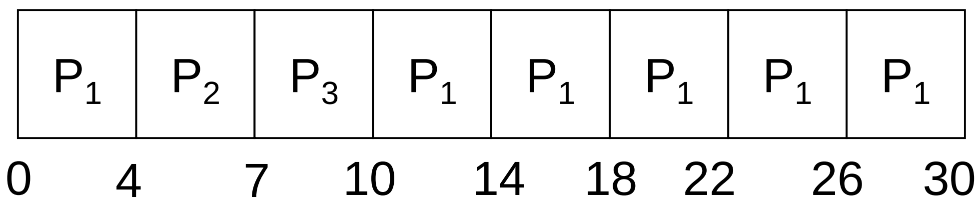
Round Robin (RR)

- Each process gets a small unit of CPU time (*time quantum*), usually 10-100 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 $\Rightarrow$ processor sharing (appears as dedicated processor with speed 1/n actual)
  - *q* must be large with respect to context switch, otherwise overhead is too high

Example of RR with Time Quantum = 4

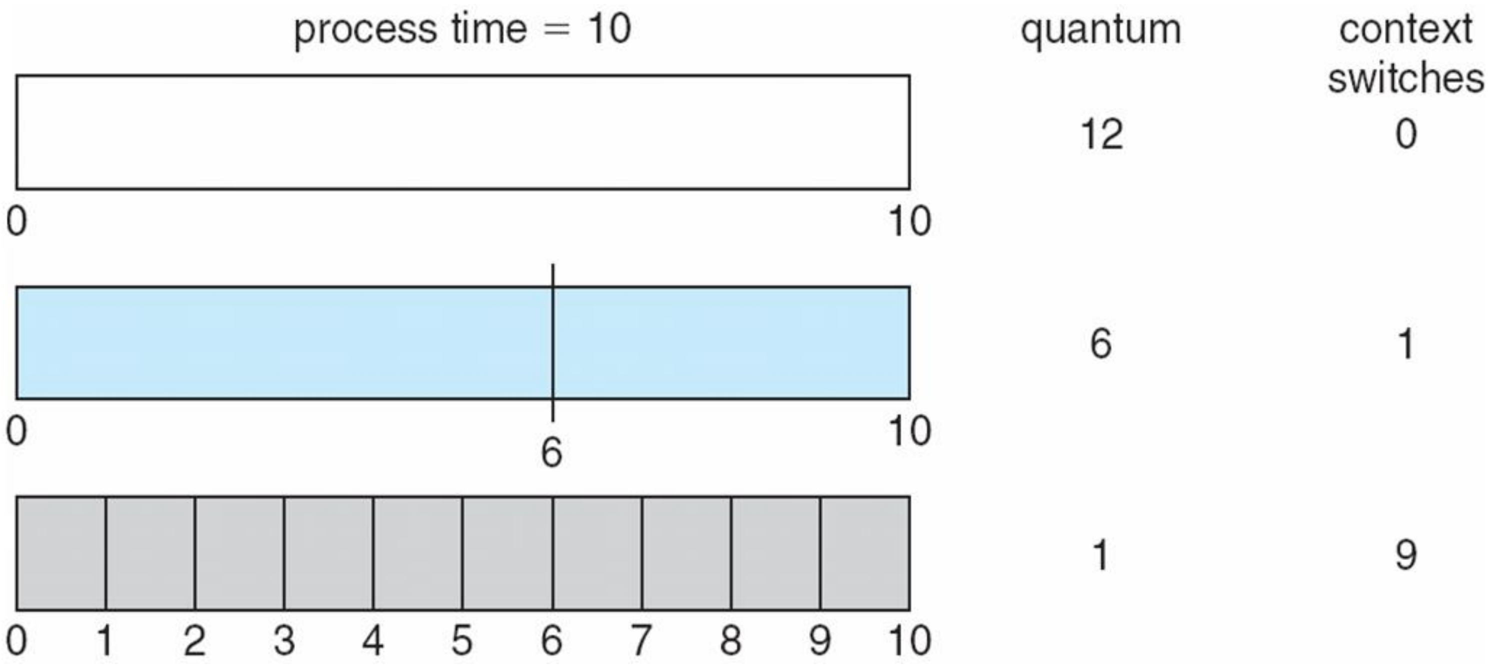
Process	Burst Time
P_1	24
P_2	3
P_3	3

- The Gantt chart is:

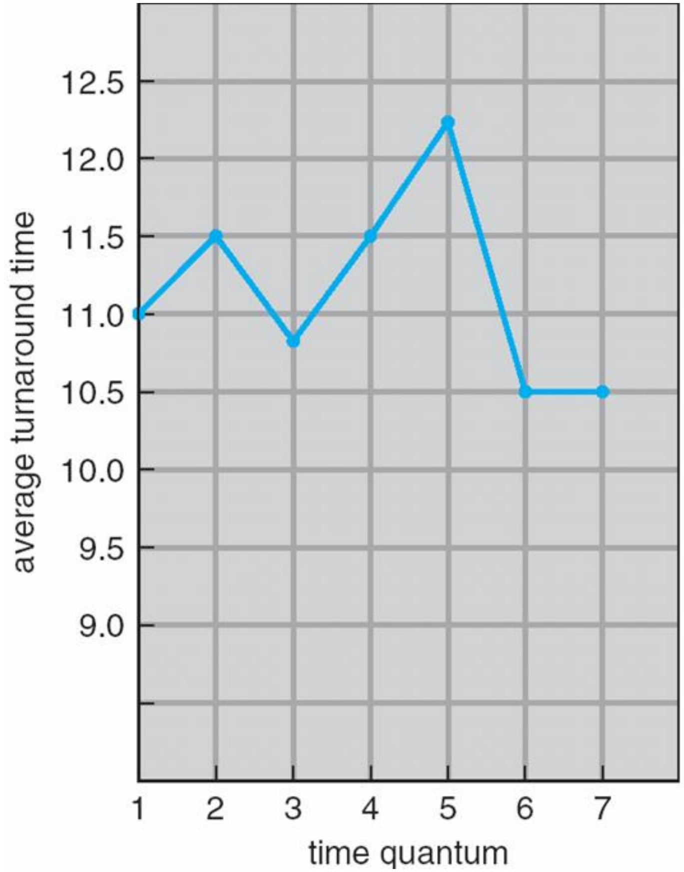


- Typically, higher average turnaround than SJF, but better *response*

Time Quantum and Context Switch Time



Turnaround Time Varies With The Time Quantum

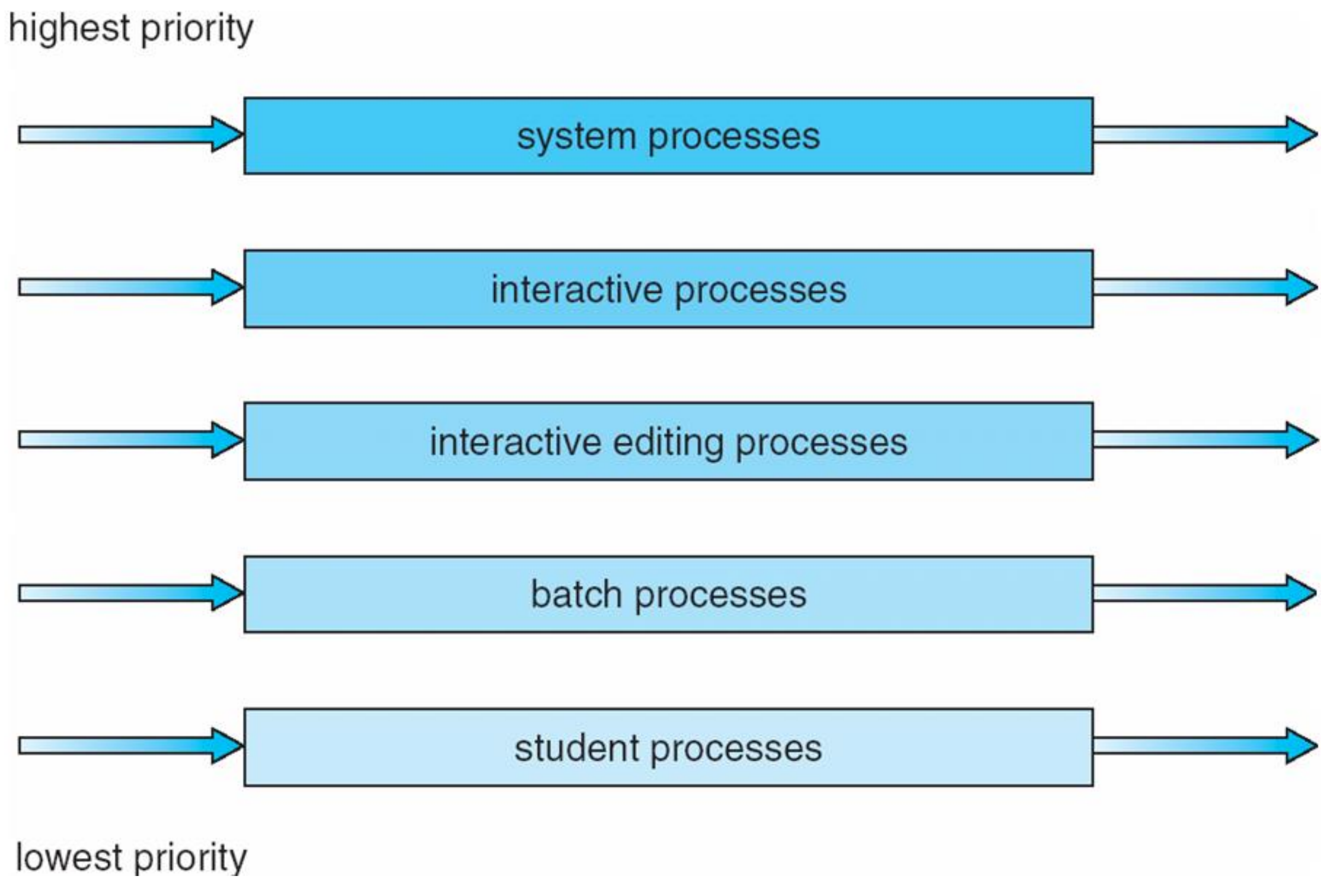


process	time
P_1	6
P_2	3
P_3	1
P_4	7

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; i.e., 80% to foreground in RR
  - 20% to background in FCFS

Multilevel Queue Scheduling



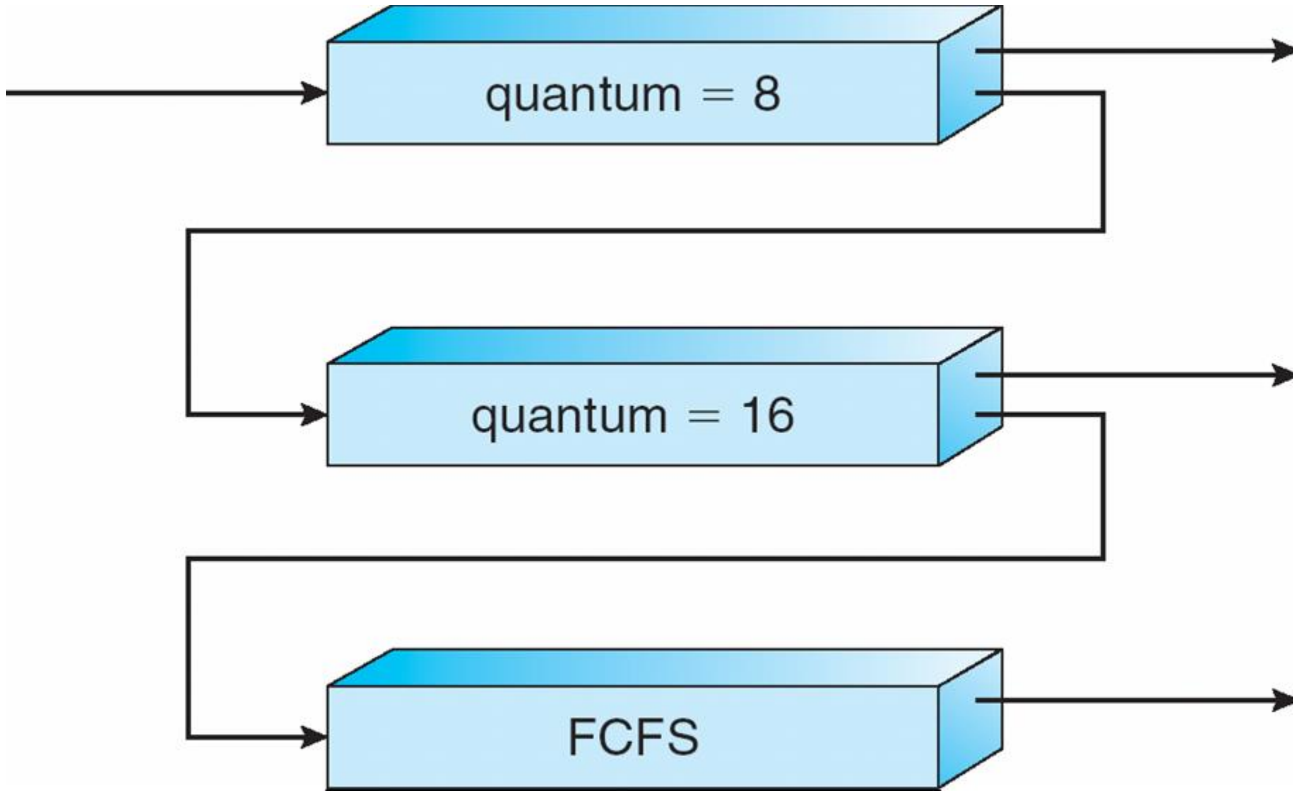
Multilevel Feedback Queue

- 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

Example of Multilevel Feedback Queue

- Three queues:
  - Q_0 – RR with time quantum 8 milliseconds
  - Q_1 – RR time quantum 16 milliseconds
  - Q_2 – FCFS
- Scheduling
  - A new job enters queue Q_0 which is served FCFS. 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 is again served FCFS and receives 16 additional milliseconds. If it still does not complete, it is preempted and moved to queue Q_2.

Multilevel Feedback Queues



Thread Scheduling

- Distinction between user-level and kernel-level threads
- Many-to-one and many-to-many models, thread library schedules user-level threads to run on LWP
  - Known as **process-contention scope (PCS)** since scheduling competition is within the process
- Kernel thread scheduled onto available CPU is **system-contention scope (SCS)** – competition among all threads in system

Pthread Scheduling

- API allows specifying either PCS or SCS during thread creation
  - PTHREAD SCOPE PROCESS schedules threads using PCS scheduling
  - PTHREAD SCOPE SYSTEM schedules threads using SCS scheduling.

Pthread Scheduling API

```
#include <pthread.h>
#include <stdio.h>
#define NUM THREADS 5
int main(int argc, char *argv[])
{
        int i;
       pthread t tid[NUM THREADS];
       pthread attr t attr;
       /* get the default attributes */
       pthread attr init(&attr);
       /* set the scheduling algorithm to PROCESS or SYSTEM */
       pthread attr setscope(&attr, PTHREAD SCOPE SYSTEM);
       /* set the scheduling policy - FIFO, RT, or OTHER */
       pthread attr setschedpolicy(&attr, SCHED OTHER);
       /* create the threads */
       for (i = 0; i < NUM THREADS; i++)
                pthread create(&tid[i],&attr,runner,NULL);
```

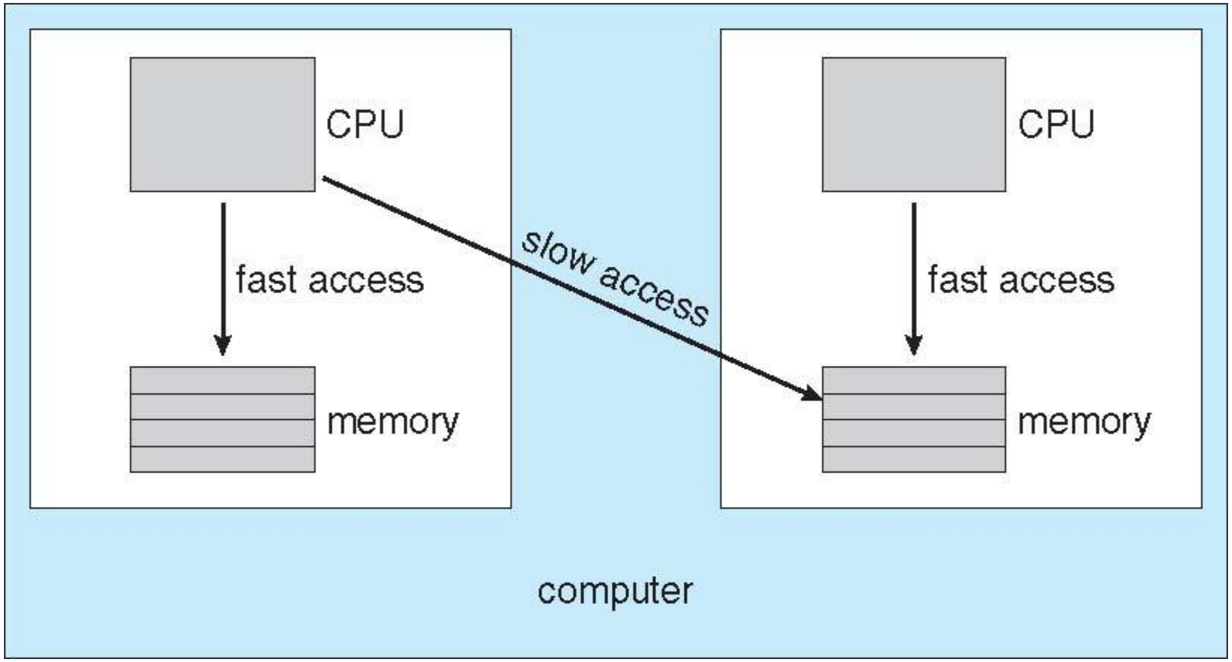
Pthread Scheduling API

```
        /* now join on each thread */
        for (i = 0; i < NUM THREADS; i++)
                pthread join(tid[i], NULL);
}
 /* Each thread will begin control in this function */
void *runner(void *param)
{
        printf("I am a thread\n");
        pthread exit(0);
}
```

Multiple-Processor Scheduling

- CPU scheduling more complex when multiple CPUs are available
- **Homogeneous processors** within a multiprocessor
- **Asymmetric multiprocessing** – only one processor accesses the system data structures, alleviating the need for data sharing
- **Symmetric multiprocessing (SMP)** – each processor is self-scheduling, all processes in common ready queue, or each has its own private queue of ready processes
- **Processor affinity** – process has affinity for processor on which it is currently running
  - **soft affinity**
  - **hard affinity**

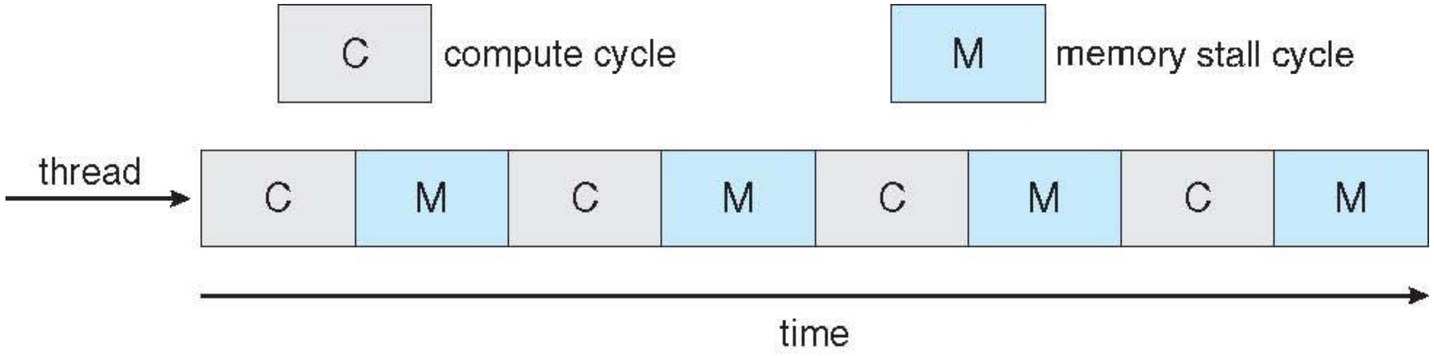
NUMA and CPU Scheduling



Multicore Processors

- Recent trend to place multiple processor cores on same physical chip
- Faster and consume less power
- Multiple threads per core also growing
  - Takes advantage of memory stall to make progress on another thread while memory retrieve happens

Multithreaded Multicore System



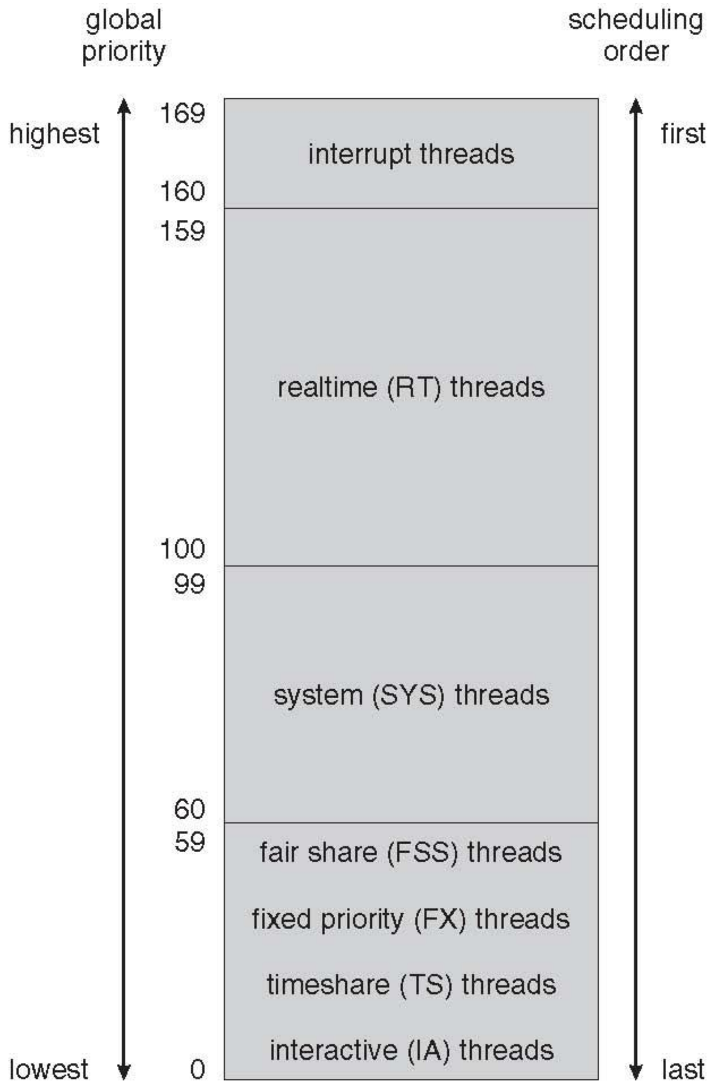
Operating System Examples

- Solaris scheduling
- Windows XP scheduling
- Linux scheduling

Solaris Dispatch Table

priority	time quantum	time quantum expired	return from sleep
0	200	0	50
5	200	0	50
10	160	0	51
15	160	5	51
20	120	10	52
25	120	15	52
30	80	20	53
35	80	25	54
40	40	30	55
45	40	35	56
50	40	40	58
55	40	45	58
59	20	49	59

Solaris Scheduling



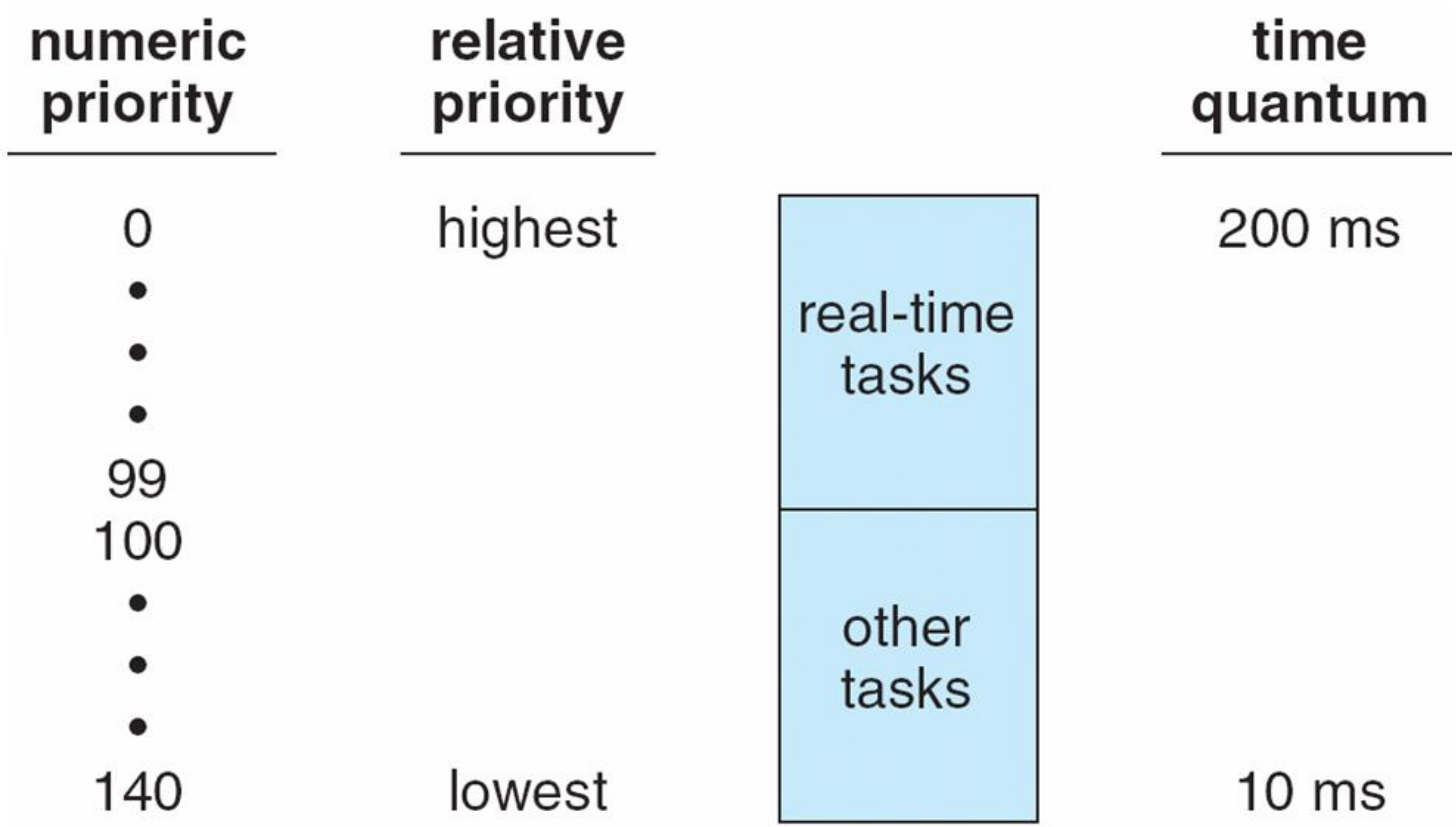
Windows XP Priorities

	real-time	high	above normal	normal	below normal	idle priority
time-critical	31	15	15	15	15	15
highest	26	15	12	10	8	6
above normal	25	14	11	9	7	5
normal	24	13	10	8	6	4
below normal	23	12	9	7	5	3
lowest	22	11	8	6	4	2
idle	16	1	1	1	1	1

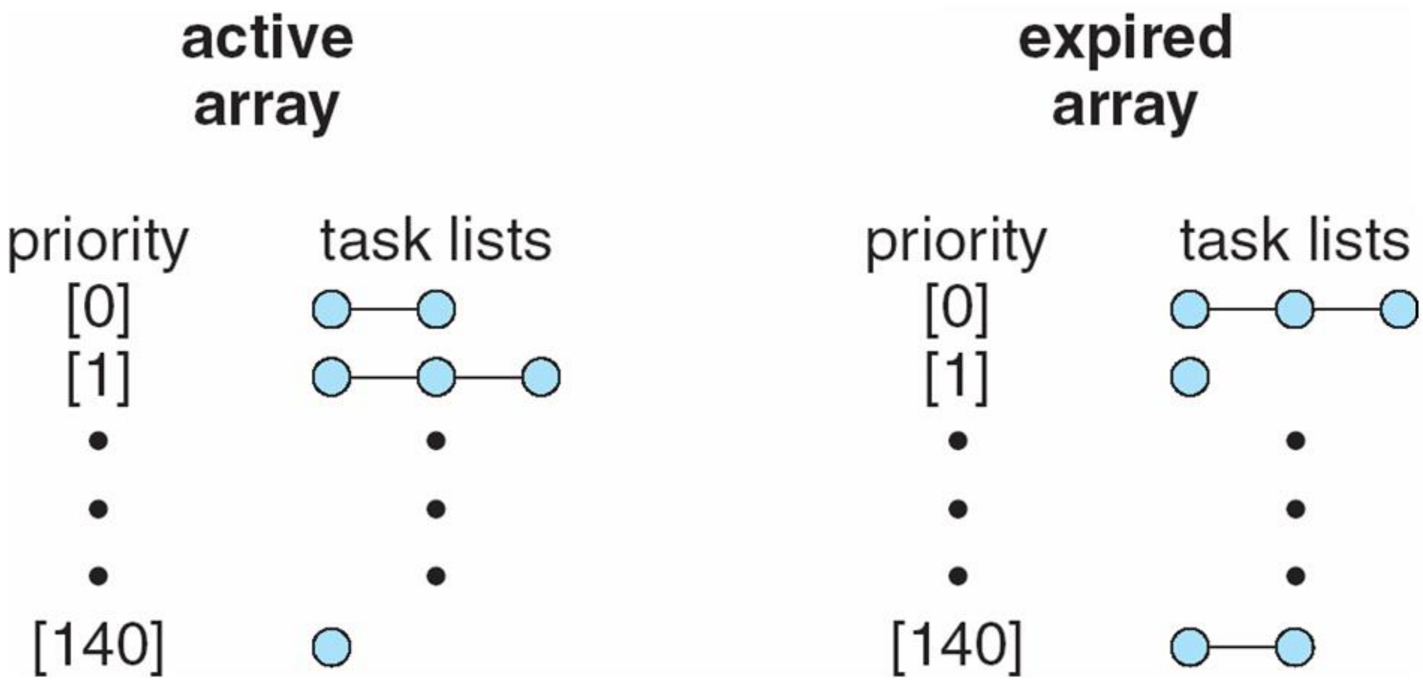
Linux Scheduling

- Constant order $O(1)$ scheduling time
- Two priority ranges: time-sharing and real-time
- **Real-time** range from 0 to 99 and **nice** value from 100 to 140
- (figure 5.15)

Priorities and Time-slice length



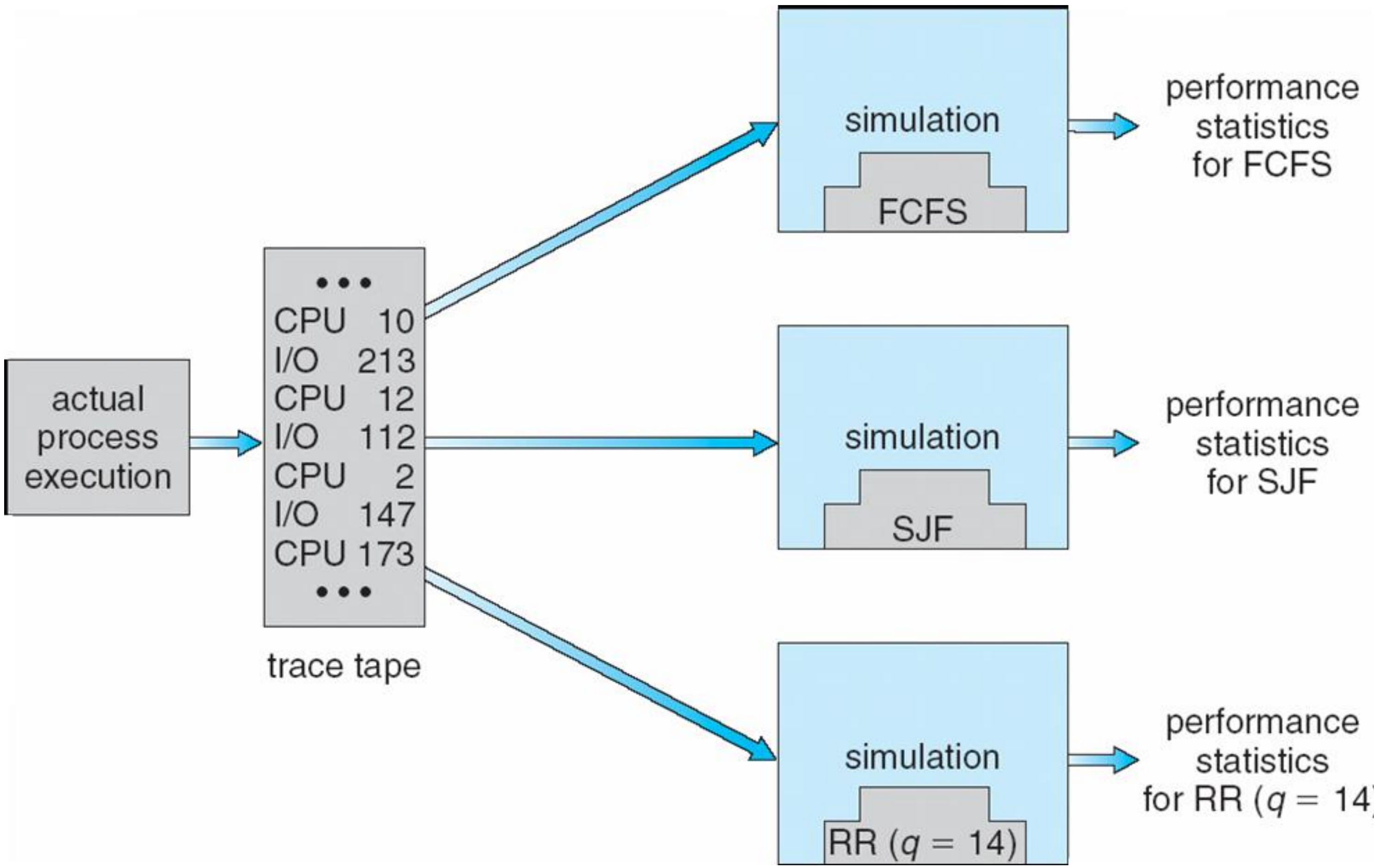
List of Tasks Indexed According to Priorities



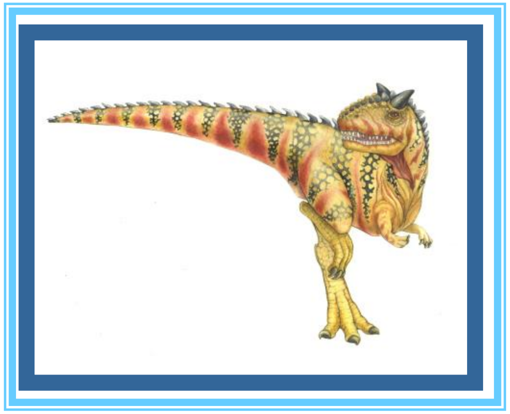
Algorithm Evaluation

- Deterministic modeling – takes a particular predetermined workload and defines the performance of each algorithm for that workload
- Queueing models
- Implementation

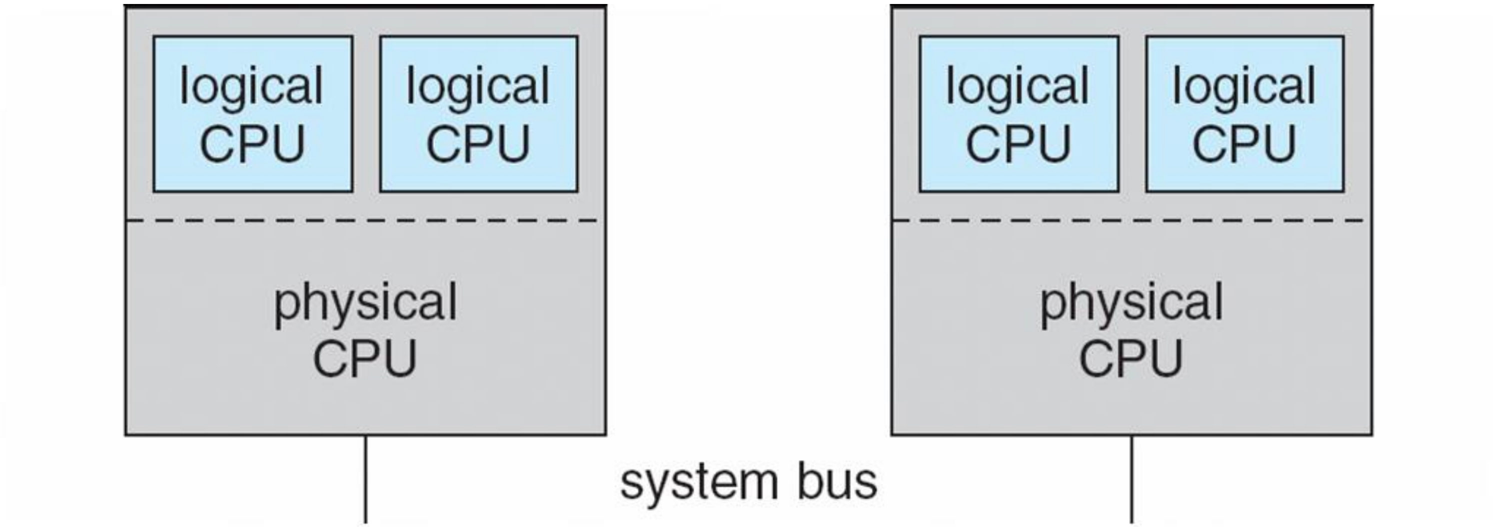
Evaluation of CPU schedulers by Simulation



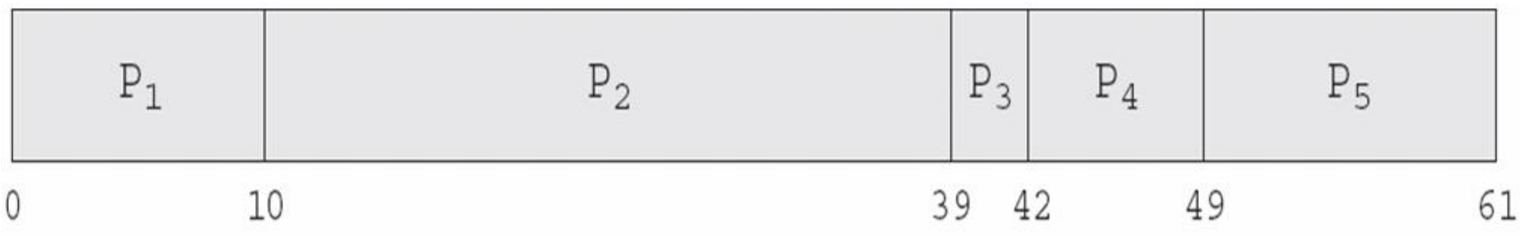
End of Chapter 5



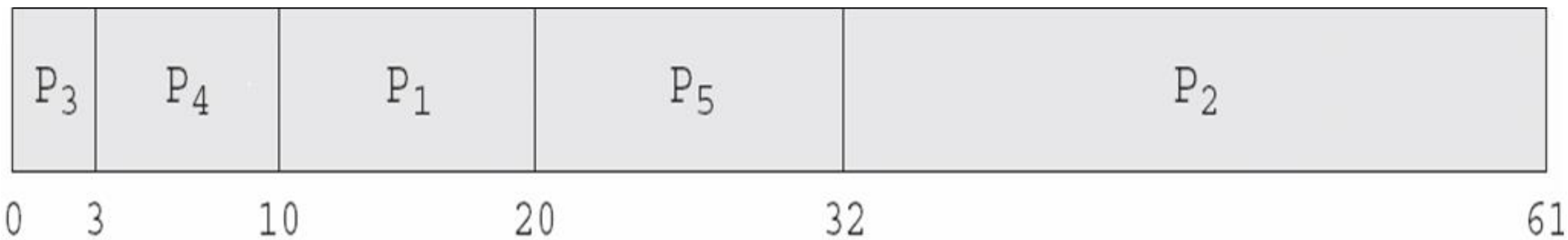
5.08


logical
CPU
logical
CPU
physical
CPU
logical
CPU
logical
CPU
physical
CPU
system bus

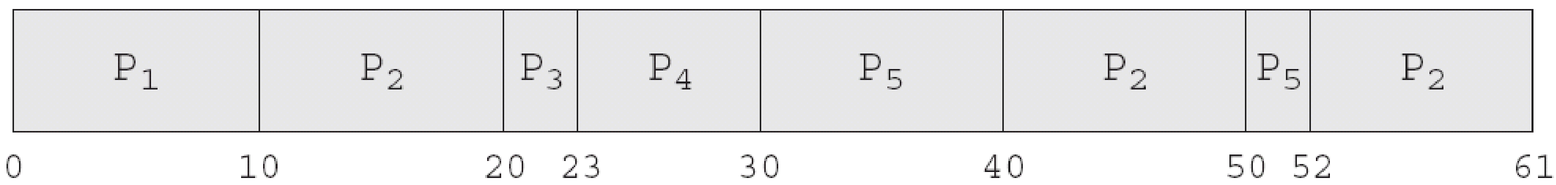
In-5.7



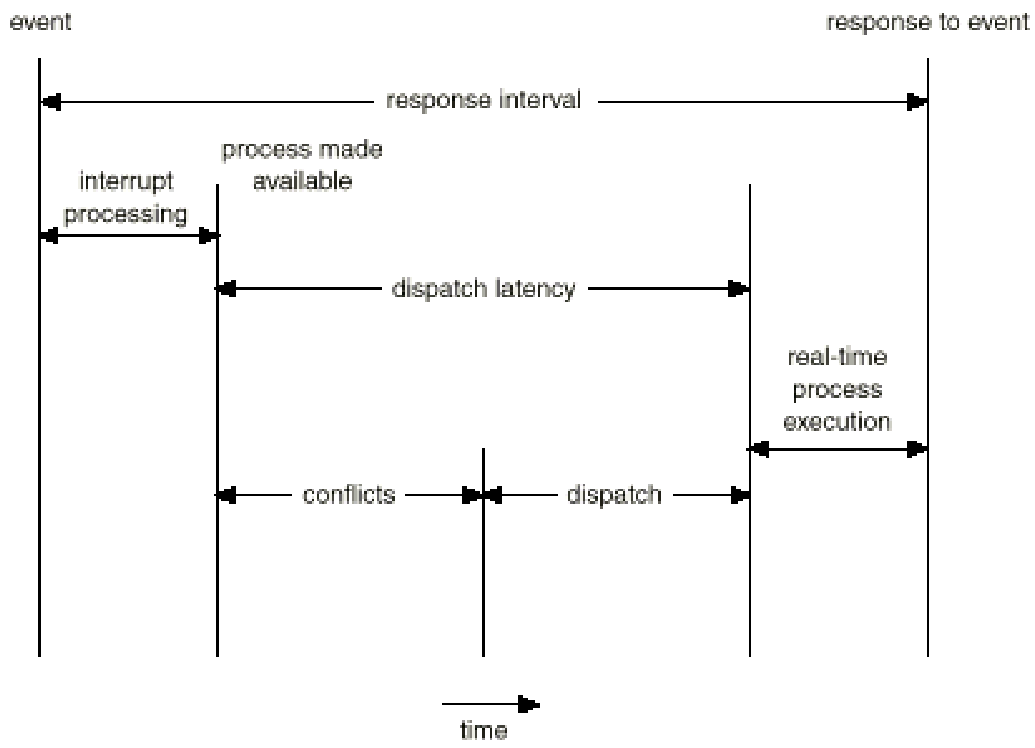
In-5.8



In-5.9



Dispatch Latency



Java Thread Scheduling

- JVM Uses a Preemptive, Priority-Based Scheduling Algorithm
- FIFO Queue is Used if There Are Multiple Threads With the Same Priority

Java Thread Scheduling (cont)

JVM Schedules a Thread to Run When:

1. The Currently Running Thread Exits the Runnable State
2. A Higher Priority Thread Enters the Runnable State

* Note – the JVM Does Not Specify Whether Threads are Time-Sliced or Not

Time-Slicing

Since the JVM Doesn't Ensure Time-Slicing, the yield() Method May Be Used:

```
while (true) {
        // perform CPU-intensive task
        . . .
        Thread.yield();
}
```

This Yields Control to Another Thread of Equal Priority

Thread Priorities

Priority	Comment
Thread.MIN_PRIORITY	Minimum Thread Priority
Thread.MAX_PRIORITY	Maximum Thread Priority
Thread.NORM_PRIORITY	Default Thread Priority

Priorities May Be Set Using setPriority() method:

```
setPriority(Thread.NORM_PRIORITY + 2);
```

Solaris 2 Scheduling