고려대학교
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KU-The Future

Operating Systems (10th Ed., by A. Silberschatz)

Chapter 5 CPU Scheduling

Process Management의 핵심 내용이다

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Contents

- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Thread Scheduling
- Multiple-Processor Scheduling
- Real-Time CPU Scheduling
- Operating System Examples
- Algorithm Evaluation

Objectives

- Describe various CPU scheduling algorithms.
- Assess CPU scheduling algorithms based on scheduling criteria.
- Explain the issues related to multiprocessor and multicore scheduling. 실시간성이 있는 것은 우선순위, 데드라인을 맞추는 일과 항상 밀접하게 연관되어 있음
- Describe various real-time scheduling algorithms.
- Describe the scheduling algorithms used in the Windows, Linux, and Solaris operating systems.
- Apply modeling and simulations to evaluate CPU scheduling algorithms.
- Design a program that implements several different CPU scheduling algorithms.

Basic Concepts

- The objective of multiprogramming is to have some process running at all times, to maximize CPU utilization CPU에게 idle이 많은 것은 절대 좋은 것이 아니다
- CPU–I/O Burst Cycle – Process execution consists of a cycle of CPU execution and I/O wait (Figure 5.1)
- CPU burst distribution – Figure 5.2
  - ✓ A large number of short CPU bursts and a small number of long CPU bursts
  - ✓ I/O-bound program has many short CPU bursts
  - ✓ CPU-bound program might have a few long CPU bursts

Alternating Sequence of CPU And I/O Bursts

CPU & I/O 작업이 번갈아 작동하는 것이 가장 일반적인 상황이다

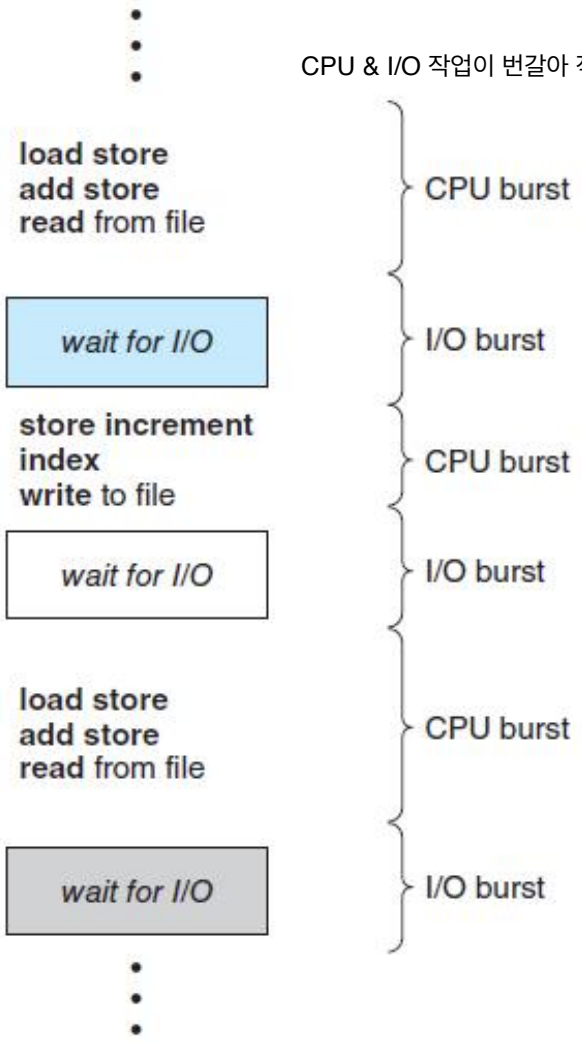


Figure 5.1 Alternating sequence of CPU and I/O bursts.

Histogram of CPU-burst Times

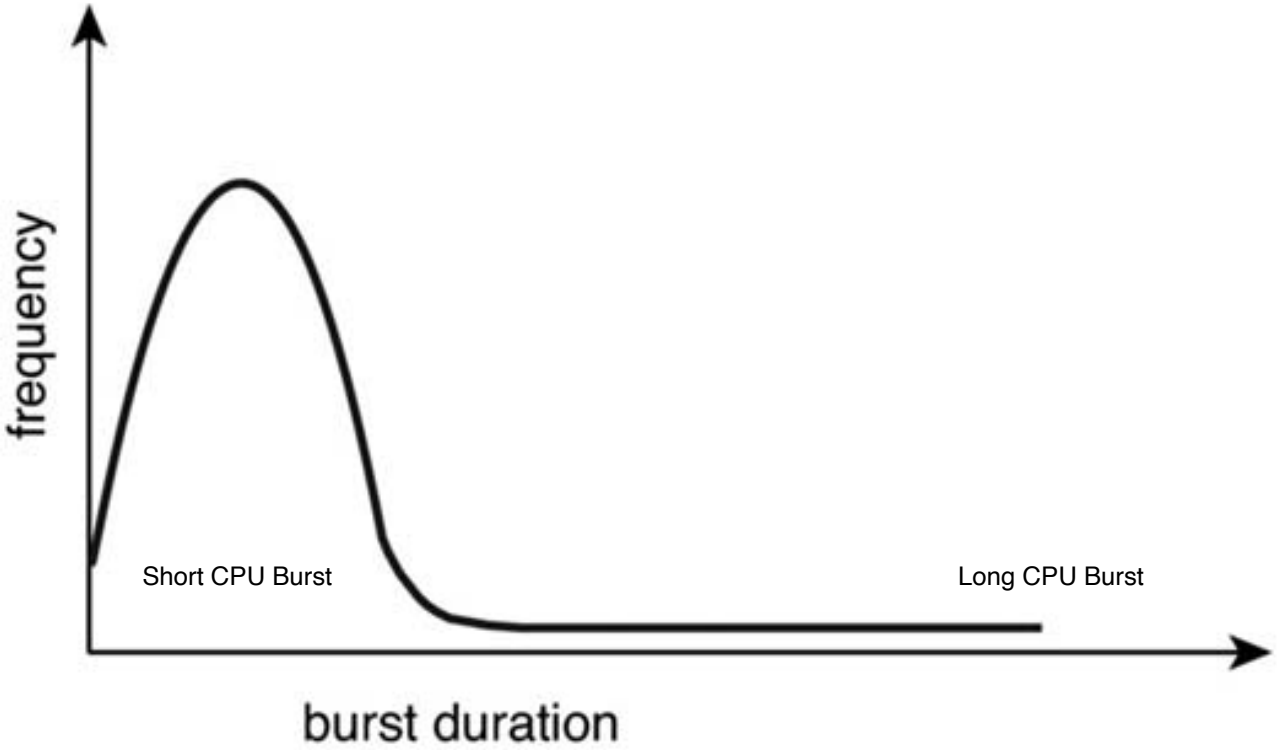


Figure 5.2 Histogram of CPU-burst durations.

CPU Scheduler

- Selects a process from the processes in memory that are ready to execute and allocates the CPU to that process
- CPU-scheduling decisions may take place when a process:
  - ✓ Switches from the running state to the waiting state
  - ✓ Switches from the running state to the ready state
  - ✓ Switches from the waiting state to the ready state
  - ✓ Terminates

Nonpreemptive :

- Scheduling under 1 and 4 is *nonpreemptive*
- All other scheduling is *preemptive*

Preemptive : 선점하다라는 뜻으로 Running -> Waiting / Waiting -> running으로 가던 현재 프로세스에 변화를 주는 것
비교 요소에서 우선순위가 있으면 현재 작업 중인 프로세스를 새로운 프로세스로 대체하는 것 (ready-queue에 변화가 있는 것)

Dispatcher

시스템 소프트웨어를 의미함

- Dispatcher module gives control of the CPU's core to the process selected by the CPU scheduler; This function involves:
  - ✓ Switching context
  - ✓ Switching to user mode 해당 수행하려는 address로 저장하게 된다
  - ✓ Jumping to the proper location in the user program to resume that program
- *Dispatch latency* – the time it takes for the dispatcher to stop one process and start another running

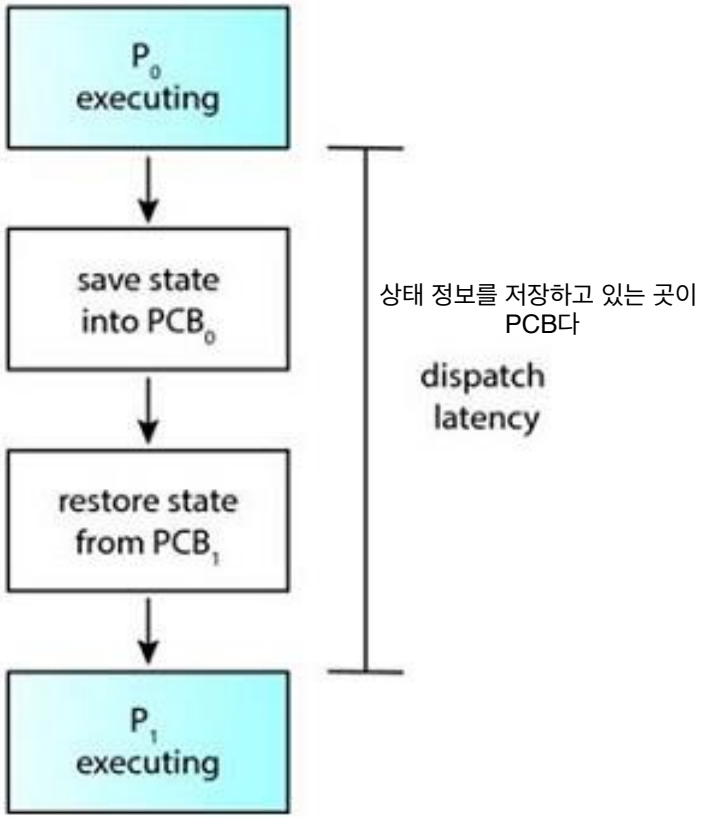


Figure 5.3 The role of the dispatcher.

Scheduling Criteria

스케줄링이 좋고 나쁨을 평가하는 기준

- CPU utilization – keep the CPU as busy as possible
- Throughput – the number of processes that are completed per time unit 끝낸 프로세스의 갯수가 많으면 많을 수록 일을 잘했다고 평가할 수도 있다
- Turnaround time – the interval from the time of submission of a process to the time of completion 주로 turnaround & waiting time을 기준으로 평가를 많이한다
- Waiting time – the sum of the periods spent waiting in the ready queue
- Response time – the time from the submission of a request until the first response is produced, **not** the time it takes to output the response
- To maximize CPU utilization and throughput
- To minimize turnaround time, waiting time, and response time

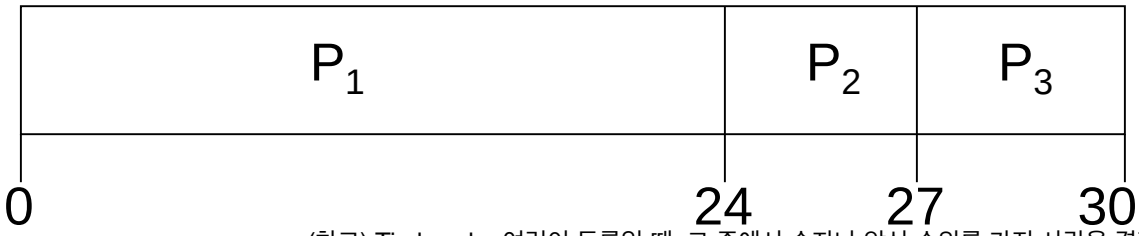
First-Come, First-Served (FCFS) Scheduling

ready-queue에 가장 먼저 들어온 프로세스가 먼저 처리되는 형태

- The process that requests the CPU first is allocated the CPU first.
- Is managed with a FIFO queue 다른 복잡한 알고리즘 쓸 필요 없이 queue를 쓰면 FIFO가 구현된다

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:



관련해서 정리된 글들이 매우 많다

(참고) Tie break : 여럿이 동률일 때, 그 중에서 승자나 앞선 순위를 가진 사람을 결정하는 방법
동시에 발생하면 어떻게 처리할까? Tie-Break를 해줄 수 있는 코드를 추가해야한다

- ✓ Waiting time for $P_1 = 0$; $P_2 = 24$; $P_3 = 27$
  - ❖ Average waiting time: $(0 + 24 + 27)/3 = 17$
- ✓ Turnaround time for $P_1 = 24$; $P_2 = 27$; $P_3 = 30$ Turnaround time은 완료된 시간을 측정하는 방법이다
  - ❖ Average turnaround time: $(24 + 27 + 30)/3 = 27$

FCFS Scheduling (Cont.)

- Suppose that the processes arrive in the order

  P_2 , P_3 , P_1 하나의 Assumption

  ✓ 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

  ✓ Turnaround time for $P_1 = 30; P_2 = 3; P_3 = 6$
  - ❖ Average turnaround time: (30 + 3 + 6)/3 = 13

  ✓ Much better than previous case

  ✓ **Convoy effect** : All the other processes wait for the one big process to get off the CPU. 하나의 큰 프로세스 때문에 나머지 프로세스들이 기다리게 되는 일이 발생한다

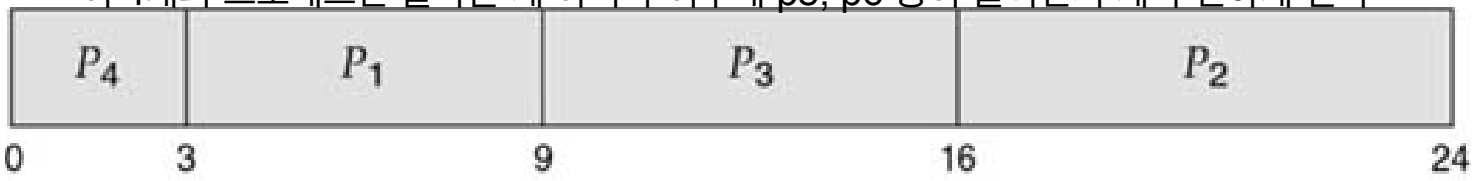
Shortest-Job-First (SJF) Scheduling

data structure는 뭘 쓸거냐 —> ready-queue에 적용할 알고리즘을 뭘 쓸거냐?

- Associate with each process the length of the process's next CPU burst.
  - ✓ It is assigned to the process that has the smallest next CPU burst
    - ⇒ shortest-next-CPU-burst algorithm

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3

이 4개의 프로세스만 끝나는 게 아니라 이후에 p5, p6 등이 들어면서 계속 변하게 된다



- Average waiting time: (3 + 16 + 9 + 0)/4 = 7

Average Turnaround Time : (9 + 24 + 16 + 3) / 4 = 13

Shortest-Job-First (SJF) Scheduling

- Two schemes: 2가지 방식 모두 구현 가능하다
  - ✓ nonpreemptive – allow the currently running process to finish its CPU burst 현재 running 중인 프로세스를 뺏지 않는다
  - ✓ preemptive – preempt the currently executing process
    - ❖ Shortest-Remaining-Time-First (SRTF)
- SJF is optimal – gives the minimum average waiting time for a given set of processes
- Difficulty : knowing the length of the next CPU request
  - ✓ We can use as the length the process time limit that a user specifies when he submits the job
  - ✓ We may be able to predict its value.

Determining Length of Next CPU Burst

13장의 Difficulty를 해결하기 위해 4가지 방식으로 결정가능하다

- The next CPU burst is predicted as an exponential average of the measured length of previous CPU bursts
  1. t_n : actual length of n^{th} CPU burst
  2. τ_{n+1} : predicted value for the next CPU burst 타우라고 읽는다
  3. $\alpha, 0 \leq \alpha \leq 1$
  4. Define : $\tau_{n+1} = \alpha\, t_n + (1-\alpha)\,\tau_n$

Examples of Exponential Averaging

- α =0 Tn값을 무시하는 경우다
  - ✓ $\tau_{n+1} = \tau_n$
  - ✓ Recent history has no effect
- α =1 타우 값을 무시하는 경우다
  - ✓ $\tau_{n+1} = t_n$
  - ✓ Only the most recent CPU burst matters
- α =1/2 타우와 Tb값을 반반씩 줘서 계산하겠다는 의미
  - ✓ Recent history and past history are equally weighted
- If we expand the formula for τ_{n+1} by substituting for τ_n, we get:

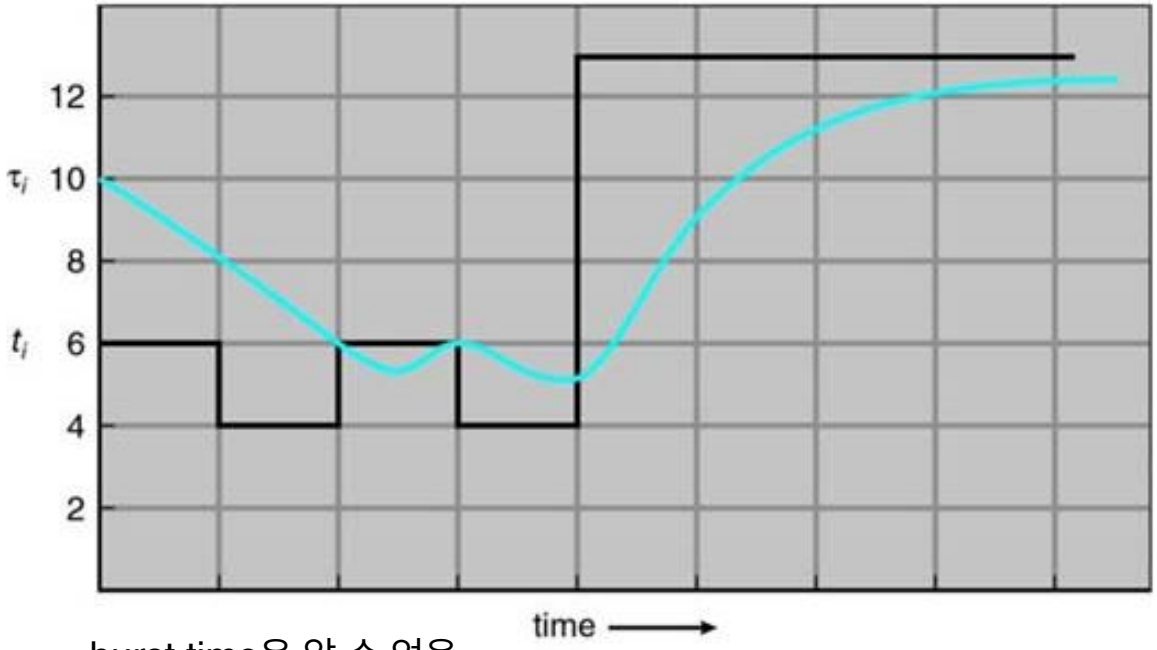
$$\tau_{n+1} = \alpha\, t_n + (1 - \alpha)\alpha\, t_{n-1} + \ldots$$
$$+ (1 - \alpha)^j \alpha\, t_{n-j} + \ldots$$
$$+ (1 - \alpha)^{n+1} \tau_0$$

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

  가장 최근에 사용한 값에 weight를 더 많이 주고, 이전에 사용한 값은 weight값이 작게 부여되서 계산된다

Prediction of the Length of the Next CPU Burst

- An exponential average with α = 1/2 and τ_0=10



burst time은 알 수 없음

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

Figure 5.4 Prediction of the length of the next CPU burst.

Example of Shortest-remaining-time-first

계산은 단순한데, 절차가 있으니 유의해야한다

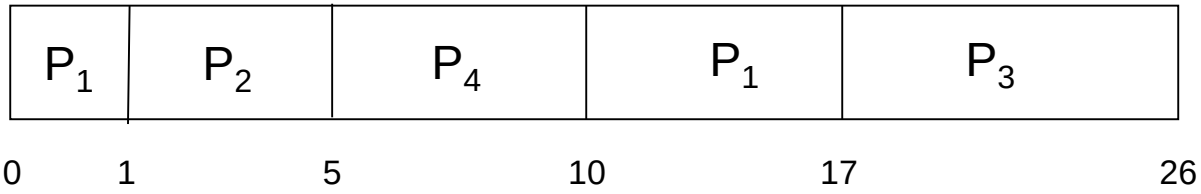
- Now we add the concepts of varying arrival times and preemption to the analysis CPU Burst time을 서로 비교해서 실행하게 되는 것이다

Process	*Arrival* Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

현재 p1만 들어왔기 때문에 바로 P1 실행

1. 처음엔 p1이 제일 먼저 도착했으므로 p1이 바로 실행
2. 그리고 1에 p2가 도착했는데, burst time을 비교하게 되므로 (8-1)과 4를 비교, p2가 더 작기에 p2가 실행됨
3. p2가 실행되는 와중에 P3, P4가 각각 도착 (2,3 시간에)
4. P3, P4가 각각 도착했을 때, P2의 burst time은 3, 2가 되어 있음 (4 -1, 3 -1)
5. p2 종료 후, p1 & p3 & p4 비교 -> p4의 burst time이 제일 짧아 바로 실행
6. 추가 프로세스 들어오는 것이 없기 때문에 이후에 p1, p3 비교 실행됨

- *Preemptive* SJF Gantt Chart



✓ Average waiting time = [(10-1)+(1-1)+(17-2)+5-3)]/4 = 26/4 = 6.5 ms

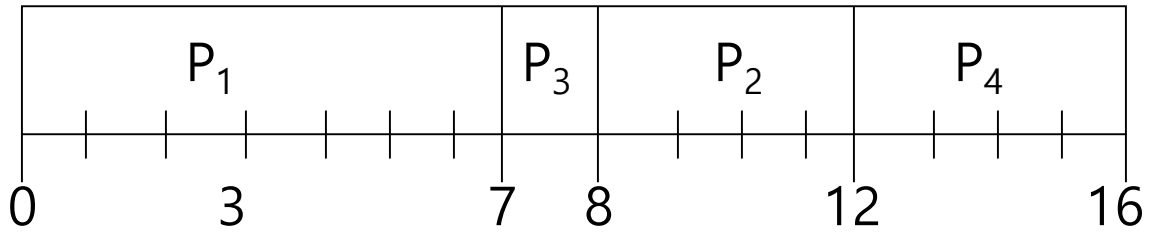
AWT의 경우, 도착한 시간을 빼줘야한다

Average Turnaround Time : [(17) + (5) + (26) + (10)] / 4 = 14.5? -> 교수님이 풀이 안해줌

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)



arrival time을 반드시 고려하고 코드를 작성해야한다

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

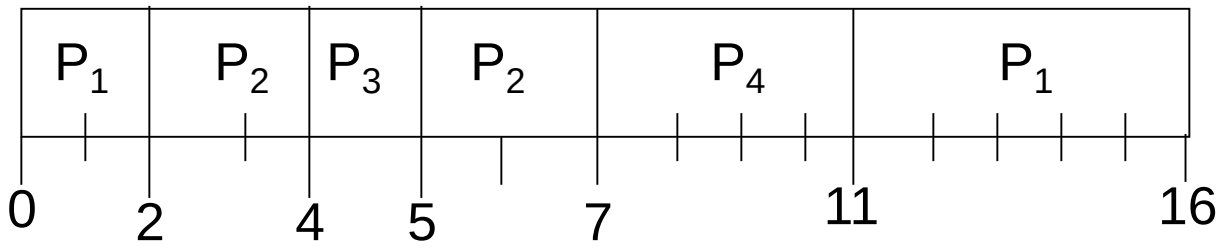
[(0) +(8-2)+(7-4) + (12-5)] / 4 = 4

ATT = (7 + 8 + 12 + 16) / 4 = 10.75

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)



{ [(0-0)+(11-2)] + [(5-4)+(2-2)] + (4-4) + (7-5) } / 4 = 3

p1은 2가 도착할 때까지 실행됨 (7-2)
p1(BT=5), p2(BT=4) 비교 후, p2 실행
이후 4에 p3 도착, p2(4-2)와 p3 비교 (1), p3 실행
p3는 p4 도착시 프로세스 종료, p2가 실행 (2)
그리고 마지막에 순서대로 p4, p1 실행

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

ATT = (16 + 7 + 5 + 11) / 4 = 9.75

Round Robin (RR)

Time Slice가 무조건 적용되어 있고,
timeout이 되면 interrupt가 발생하게 되어 있음

- It is similar to FCFS scheduling, but preemption is added to enable the system to switch between processes.
  Time Slice 또는 Time Quantum이라 함
- 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.
  q = 5이고, t = 4면 time slice가 끝나기 전에 terminate되는 작업도 있을 것임
  - ✓ Each process must wait no longer than (*n*-1)*q* time units until its next time quantum.
- Performance of the RR algorithm
  - ✓ If the time quantum is extremely large ⇒ FCFS
    주어진 프로세스 burst time보다
    time quantum이 너무 커서 FCFS랑 동일
  - ✓ If the time quantum is extremely small ⇒ a large number of context switches
    context switch = pure overhead

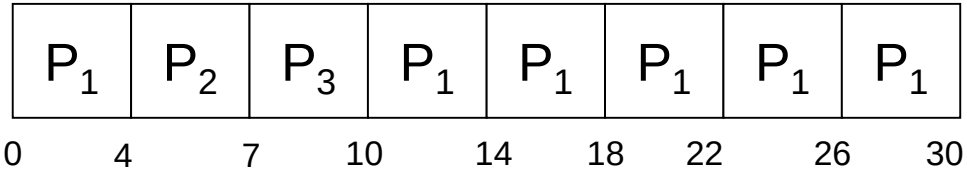
가장 적절한 time quantum을 찾는 것이 중요하다

Example of RR with Time Quantum = 4

Process	Burst Time
P_1	24
P_2	3
P_3	3

여기서는 arrival time은 없고,
time quantum이 맞춰지면
context switching이 자동 발생

- The Gantt chart is:



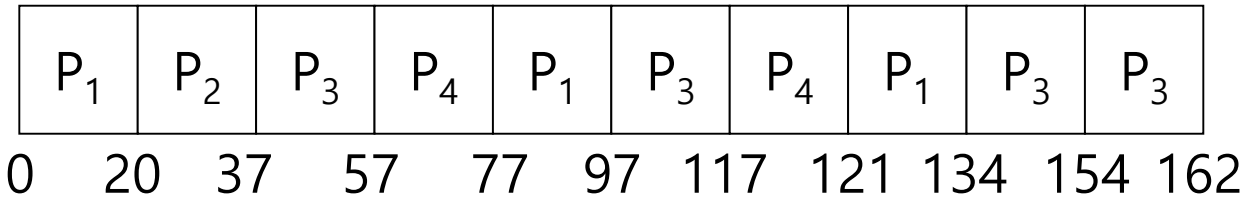
✓ Average waiting time = [(10-4) + 4 + 7]/3 = 17/3 = 5.66

✓ Average turnaround time = (30 + 7 + 10)/3 = 47/3 = 15.67

Example of RR with Time Quantum = 20

Process	Burst Time
P_1	53
P_2	17
P_3	68
P_4	24

- The Gantt chart is:

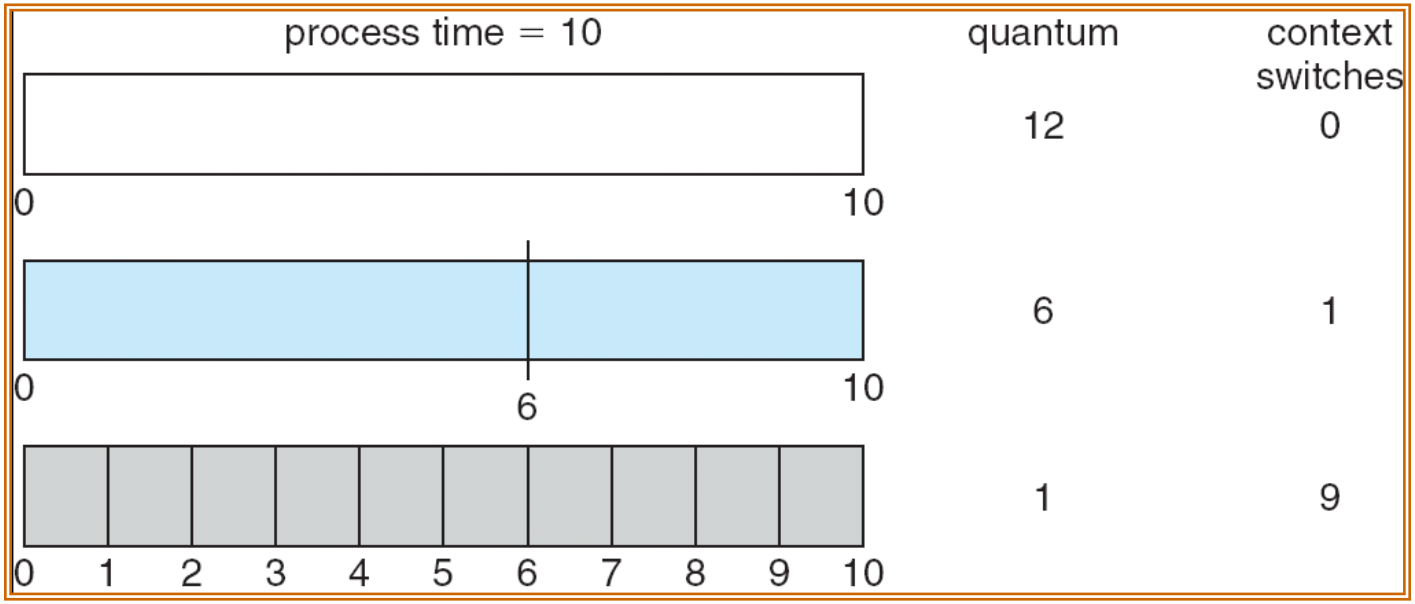


교수님이 풀이 안해준 파트

✓ Average waiting time ? [(0 + 57 + 24) + 20 + (37 + 40) + (57 + 40)] / 4 = 68.75

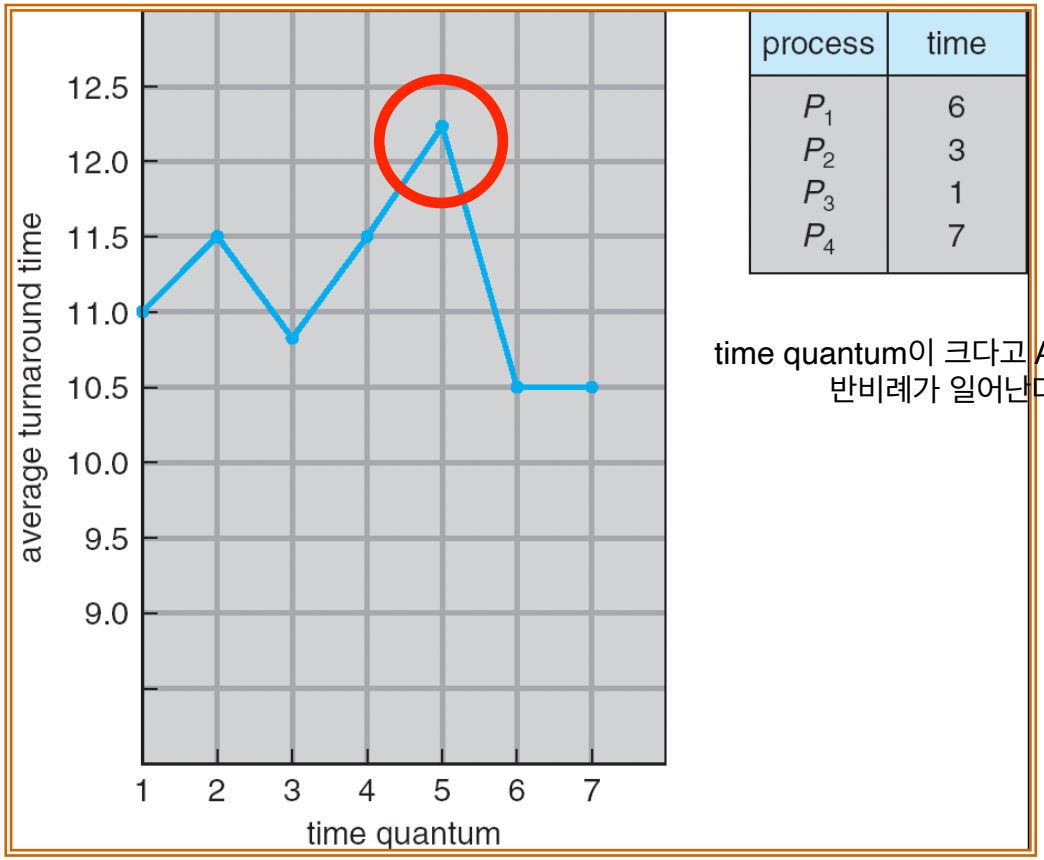
✓ Average turnaround time ? (134 + 37 + 162 + 121) / 4 = 113.75

Time Quantum and Context Switch Time



- We want the time quantum to be large with respect to the context-switch time, otherwise overhead is too high.

Turnaround Time Varies With The Time Quantum



process	time
P_1	6
P_2	3
P_3	1
P_4	7

time quantum이 크다고 ATT가 줄어드는 형태로
반비례가 일어난다고 볼 수 없다

- The average turnaround time can be improved if most processes finish their next CPU burst in a single time quantum.

Priority Scheduling

- A priority number (integer) is associated with each process
- The CPU is allocated to the process with the highest priority
  - ✓ Equal-priority processes are scheduled in FCFS order.
  - ✓ An SJF algorithm is simply a priority algorithm where the priority (p) is the inverse of the (predicted) next CPU burst. The larger the CPU burst, the lower the priority, and vice versa. 시스템에서 어떻게 설정하느냐에 따라 달라진다
- Priorities can be defined either internally or externally
  - ✓ Internally defined priorities – use some measurable quantity or quantities to compute the priority of a process
    - ❖ Time limits, memory requirements, the number of open files, the ratio of average I/O burst to average CPU burst
  - ✓ External priorities – set by criteria outside the operating system
    - ❖ Importance of the process, the type and amount of funds being paid for computer use, the department sponsoring the work, other political factors

Priority Scheduling

Process	Burst Time	Priority
P_1	10	3
P_2	1	1
P_3	2	4
P_4	1	5
P_5	5	2

✓ Average waiting time = (6 + 0 + 16 + 18 + 1)/5 = 41/5 = 8.2

ATT = (16 + 1 + 18 + 19 + 6) / 5 = 12

Priority Scheduling

- Preemptive or nonpreemptive
  - ✓ A preemptive priority scheduling algorithm will preempt the CPU if the priority of the newly arrived process is higher than the priority of the currently running process. 앞부분 실습 내용의 요약이다
- SJF is a priority scheduling where priority is the predicted next CPU burst time SJF 자체가 우선순위 스케줄링이다
- Problem – Starvation (indefinite blocking)
  - ✓ Can leave some low-priority processes waiting indefinitely
  - ✓ In a heavily loaded computer system, a steady stream of higher-priority processes can prevent a low-priority process from ever getting the CPU.
- Solution – Aging 상황을 개선하는 방법
  - ✓ A technique of gradually increasing the priority of the processes that wait in the system for a long time

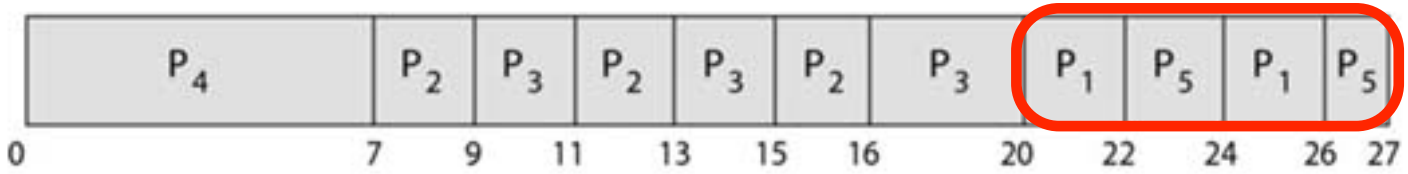
Priority Scheduling

Performance Evaluation을 측정하는 것은 매우 중요한 이슈다

Process	Burst Time	Priority
P_1	4	3
P_2	5	2
P_3	8	2
P_4	7	1
P_5	3	3

유선순위가 같은 것에 대해서 RR 방식을 적용해 Time Quantum을 지정해 교차로 실행하는 방식임
여기서는 Time Quantum = 2로 지정해 작업함

P1 과 P5의 우선순위도 같아서 quantum을 2로 두고 교차 작업



- ✓ Using priority scheduling with round-robin for processes with equal priority
- ✓ Average waiting time = [(20+2) + (7+2+2) + (9+2+1) + 0 + (22+2)]/5
  = (22+11+12+0+24)/5 = 69/5 = 13.8

Multilevel Queue Scheduling

- Depending on how the queues are managed, an $O(n)$ search may be necessary to determine the highest-priority process.
  - ✓ Is often easier to have separate queues for each distinct priority

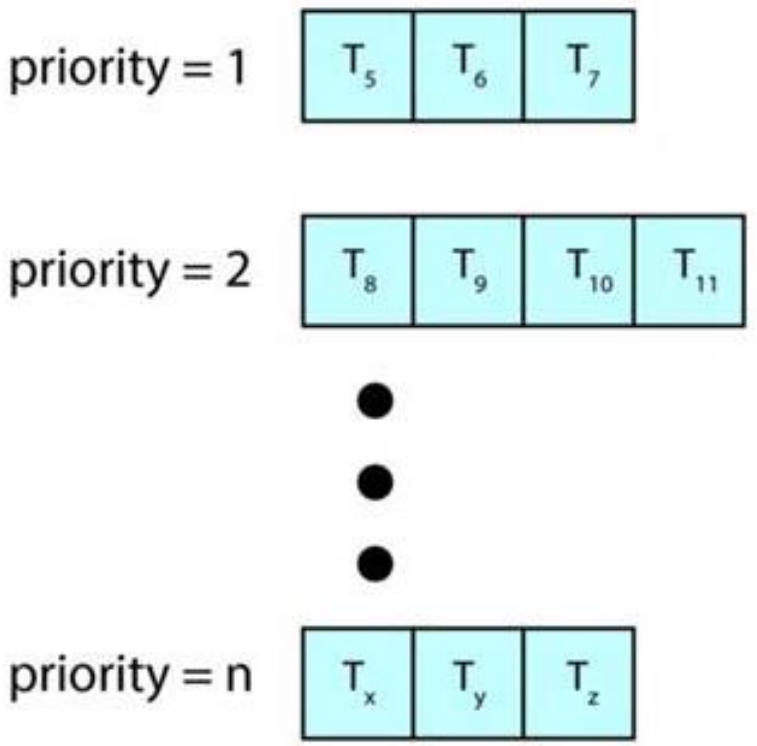


Figure 5.7 Separate queues for each priority.

Multilevel Queue Scheduling

멀티레벨에서도 우선순위가 높은 작업을 먼저 처리하게 될 것이다

- A multilevel queue scheduling algorithm can also be used to partition processes into several separate queues based on the process type.
  - ✓ foreground (interactive), background (batch)
- Each queue has its own scheduling algorithm
  - ✓ foreground – RR
  - ✓ background – FCFS
- There must be scheduling among the queues.
  - ✓ Each queue has absolute priority over lower-priority queues.
    - ❖ Serve all from foreground then from background
    - ❖ Possibility of starvation.
  - ✓ Time slice – each queue gets a certain portion of the CPU time, which it can schedule amongst its various processes
    - ❖ Foreground queue – 80% of the CPU time for RR
    - ❖ Background queue – 20% of the CPU time for FCFS

Multilevel Queue Scheduling

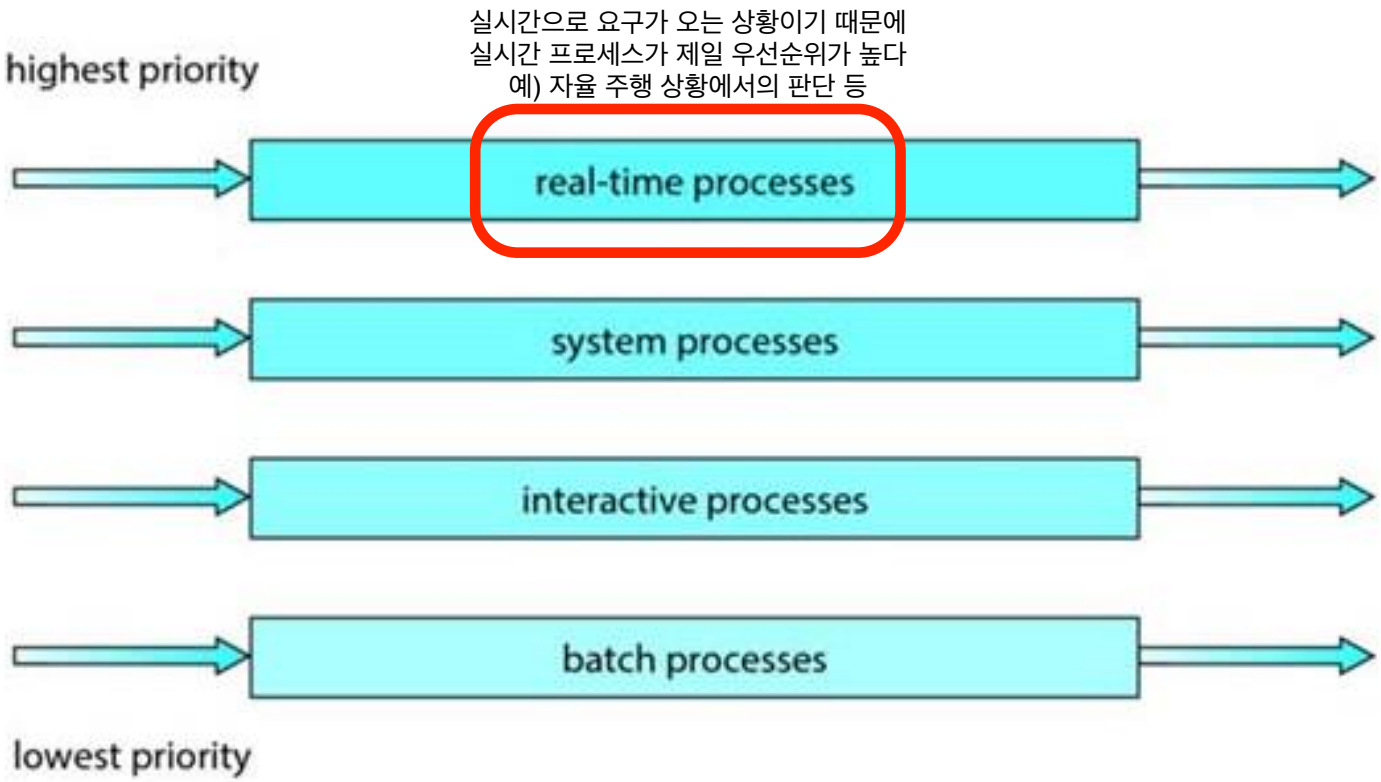


Figure 5.8 Multilevel queue scheduling.

Multilevel Feedback Queue Scheduling

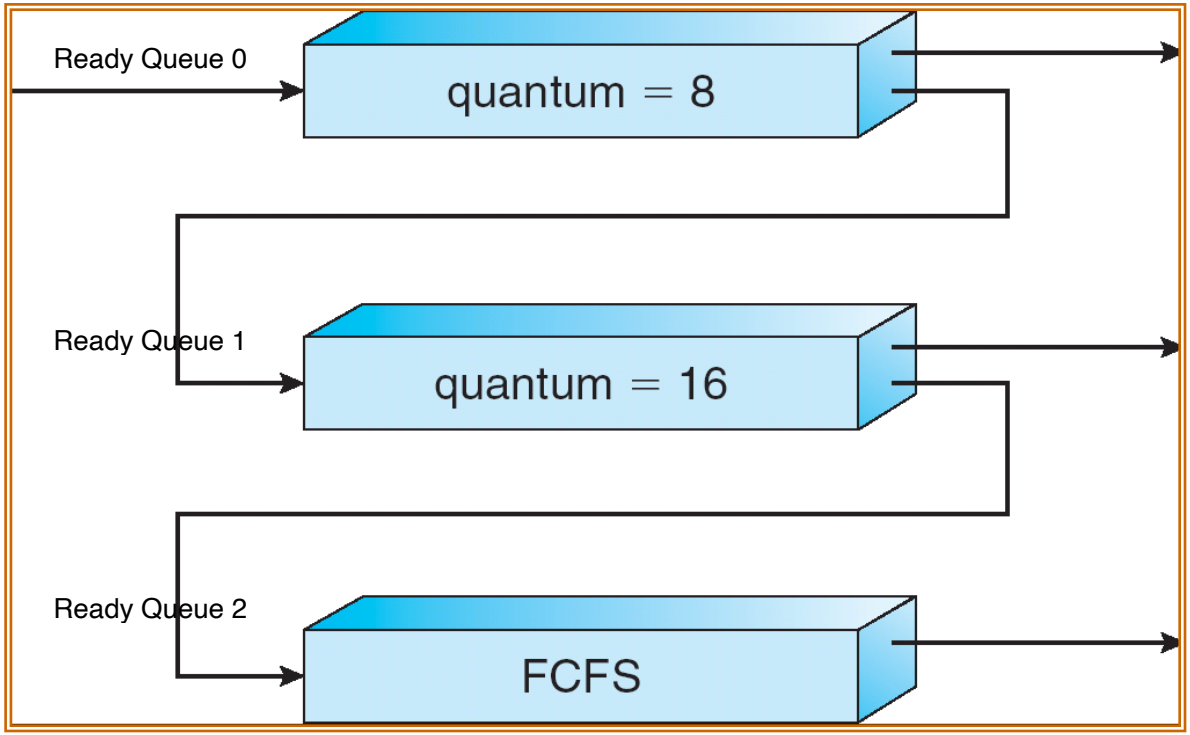
- When the multilevel queue scheduling algorithm is used, processes are permanently assigned to a queue when they enter the system.
- Allows a process to move between queues
  queue들 간의 이동이 불가능함
- This form of aging prevents starvation.
  - ✓ If a process uses too much CPU time, it will be moved to a lower-priority queue.
  - ✓ A process that waits too long in a lower-priority queue may be moved to a higher-priority queue

Example of Multilevel Feedback Queue

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

Multilevel Feedback Queue Scheduling

여기서 양방향으로 되어 있다고 이해하면 된다



Multilevel Feedback Queue Scheduling

- Multilevel-feedback-queue scheduler is defined by the following parameters: 이 부분들이 고민되고 설계가 되어야한다
  - ✓ The number of queues
  - ✓ The scheduling algorithm for each queue
  - ✓ The method used to determine when to upgrade a process
  - ✓ The method used to determine when to demote a process
  - ✓ The method used to determine which queue a process will enter when that process needs service

Multiple-Processor Scheduling

여기서는 코어가 여러개일때를 가정하는 것이다

- CPU scheduling more complex when multiple CPUs are available
- Homogeneous processors within a multiprocessor 동질적인 코어들의 collection이다.
- Asymmetric multiprocessing Master - Slave 노드 구조로 구성
  - ✓ Handled by a single processor – master server
  - ✓ Only one processor accesses the system data structures, reducing the need for data sharing
- Symmetric multiprocessing
  - ✓ Each processor is self-scheduling 각 프로세서마다 각자 알아서 구성
  - ✓ Common ready queue or its own private queue

코어마다 레디 큐를 따로 갖고 있다

Multiple-Processor Scheduling

- Common ready queue
  - ✓ possible race condition on the shared ready queue
  - ✓ use locking to protect the common ready queue from this race condition
- Its own private queue
  - ✓ workloads of varying sizes
  - ✓ balancing algorithms to equalize workloads among all processors

Private Ready Queue
스케줄링 정책에 따라 다르기 때문에
환경의 변화에 따라 기법이 어떻게 적용되는지 알고 있으면 됨

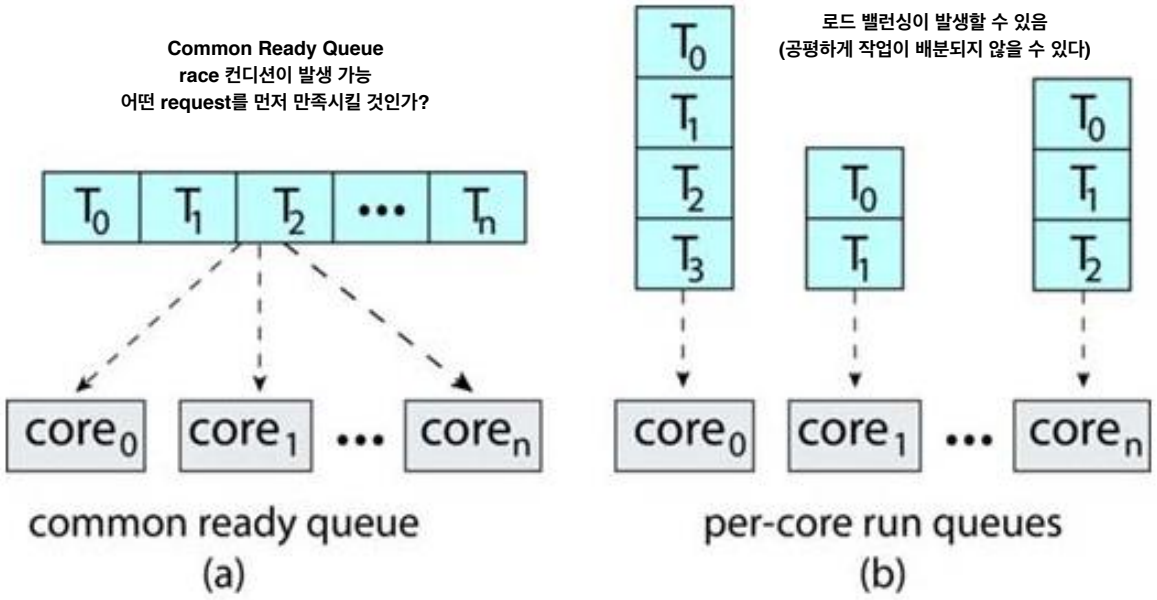


Figure 5.11 Organization of ready queues.

Multiple-Processor Scheduling

- Multicore processor – placing multiple computing cores on the same physical chip
  - ✓ Is faster and consume less power than systems in which each CPU has its own physical chip
- Memory stall – When a processor accesses memory, it spends a significant amount of time waiting for the data to become available.
  - ✓ The processor can spend up to 50 percent of its time waiting for data to become available from memory

코어를 바쁘게 만드는 것이 중요한데, 효율적이지 못한 상황을 지적하는 것이 memory stall

메모리 접근 전까지 대기하는 시간은 어쩔 수 없이 발생하지만,
이를 좀 더 활용할 수 있는 방법이 없겠느냐?
이 방법을 고민한 게 multi-thread process

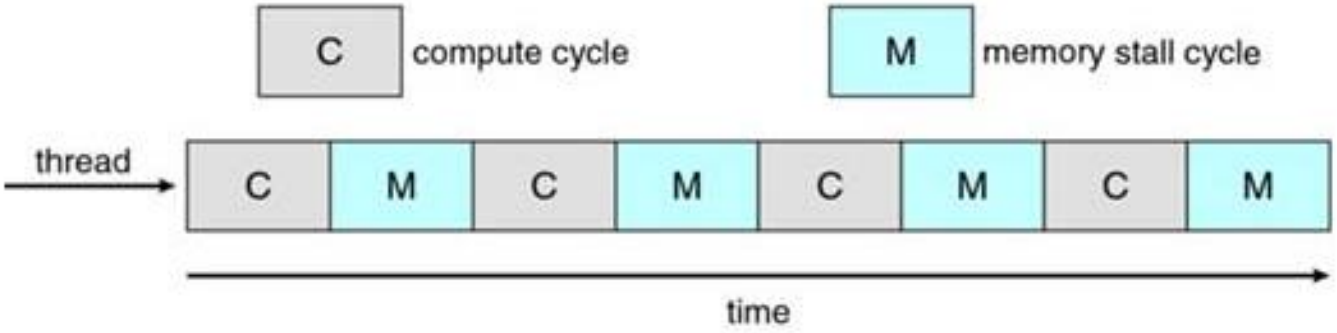


Figure 5.12 Memory stall.

Multiple-Processor Scheduling

- Multithreaded processing cores Memory Stall을 해결하기 위해 멀티스레드 프로세싱 코어가 적용됨
  - ✓ Two or more hardware threads are assigned to each core
  - ✓ Figure 5.13
    - ❖ Dual-threaded processing core on which the execution of thread 0 and the execution of thread 1 are interleaved

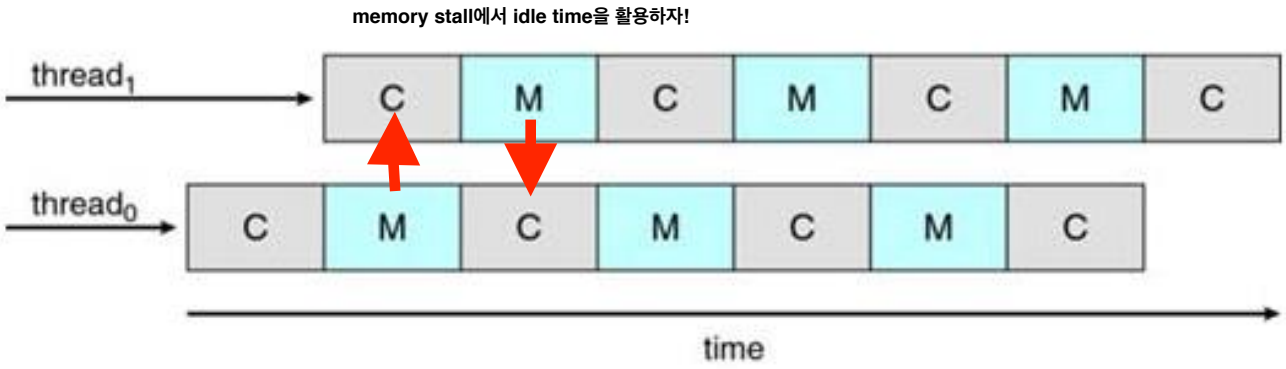


Figure 5.13 Multithreaded multicore system.

Multiple-Processor Scheduling

- Multithreaded processing cores
  - ✓ Figure 5.14
    - ❖ Each hardware thread maintains its architectural state, such as instruction pointer and register set, and thus appears as a logical CPU that is available to run a software thread.
    - ❖ Chip multithreading (CMT)
    - ❖ Four computing cores, with each core containing two hardware threads – eight logical CPUs

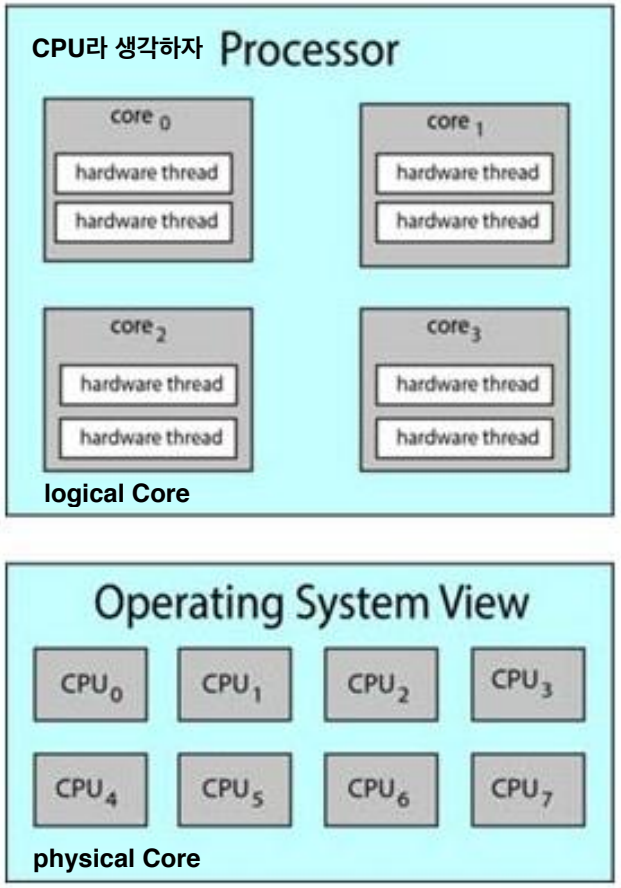


Figure 5.14 Chip multithreading.

여기선 OS가 CPU가 8개가 있다고 생각하는 것이다

Multiple-Processor Scheduling

- Intel processors use the term hyper-threading (also known as simultaneous multithreading or SMT)
- Two ways to multithread : 여기서 알고리즘을 소개하는 것은 아니다
  - ✓ Coarse-grained multithreading : a thread executes on a core until a long-latency event such as a memory stall
  - ✓ Fine-grained (or interleaved) multithreading : switches between threads at a much finer level of granularity – typically at the boundary of an instruction cycle occurs 굉장히 세세한 레벨까지 관리
- Figure 5.15
  - ✓ the resources of the physical core (such as caches and pipelines) must be shared among its hardware threads
  - ✓ a processing core can only execute one hardware thread at a time

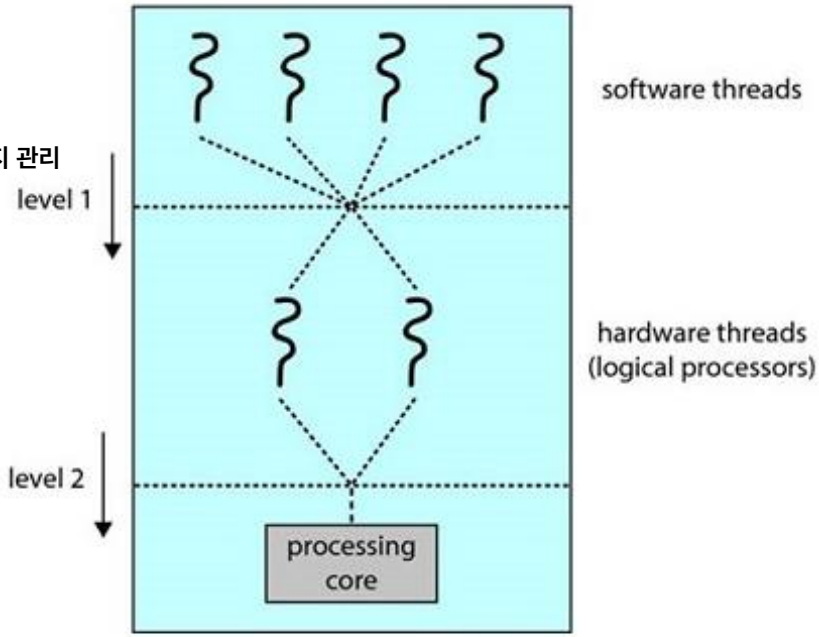


Figure 5.15 Two levels of scheduling.

Multiple-Processor Scheduling

- A, B, C are three threads. 12 cycles of those threads are as follows.

공백 부분이 memory stall

- Fine-grained multithreading 이론적인 측면에서 표현된 감이 있다

- Coarse-grained multithreading

✓ Wasting a clock cycle due to stalling

Multiple-Processor Scheduling

- Load balancing attempts to keep the workload evenly distributed across all processors in an SMP system
  - ✓ Each processor has its own private ready queue.
- Two approaches to load balancing 로드 밸런싱을 하는 2가지 방법
  - ✓ Push migration 많은 쪽에서 적은 쪽으로 옮겨주는 것
    - ❖ A specific task periodically checks the load on each processor
    - ❖ Distributes the load by moving (or pushing) threads from overloaded to idle or less-busy processors
  - ✓ Pull migration
    - ❖ When an idle processor pulls a waiting task from a busy processor

Multiple-Processor Scheduling

한쪽에서는 없었던 일로 (invalidate),
한쪽에서는 새로운 일로 생성 (repopulate)하게 되는 것

- What happens if the thread migrates to another processor
  - ✓ The contents of cache memory must be invalidated for the first processor, and the cache for the second processor must be repopulated
  - ✓ High cost of invalidating and repopulating caches **발생하는 일들이 여러가지로 복잡할 때, High Cost라는 표현을 쓴다.**
- Processor affinity **친밀도** 로드 밸런싱하는 것과 processor affinity는 서로 반대의 개념일 수 있음
  - ✓ Attempt to keep a thread running on the same processor
  - ✓ Soft affinity **좀 더 유연하게 적용됨**
    - ❖ When an operating system has a policy of attempting to keep a process running on the same processor – but not guaranteeing that it will do so
  - ✓ Hard affinity **옮기지 못하게 좀 더 strict함**
    - ❖ Allowing a process to specify a subset of processors on which it can run
  - ✓ Load balancing counteracts the benefits of processor affinity.

로드 밸런싱을 한다는 것이 옮기는 것인데,
이게 Processor Affinity의 이점을 줄이는 행위를 하는 것임

Multiple-Processor Scheduling

- Figure 5.16 – NUMA and CPU scheduling None Uniform Memory Access
  - ✓ An architecture featuring non-uniform memory access (NUMA) where there are two physical processor chips each with their own CPU and local memory
  - ✓ A CPU has faster access to its local memory than to memory local to another CPU

레디큐 작업을 옮기는 것 자체가 CPU간의 작업을 옮기는 것이다

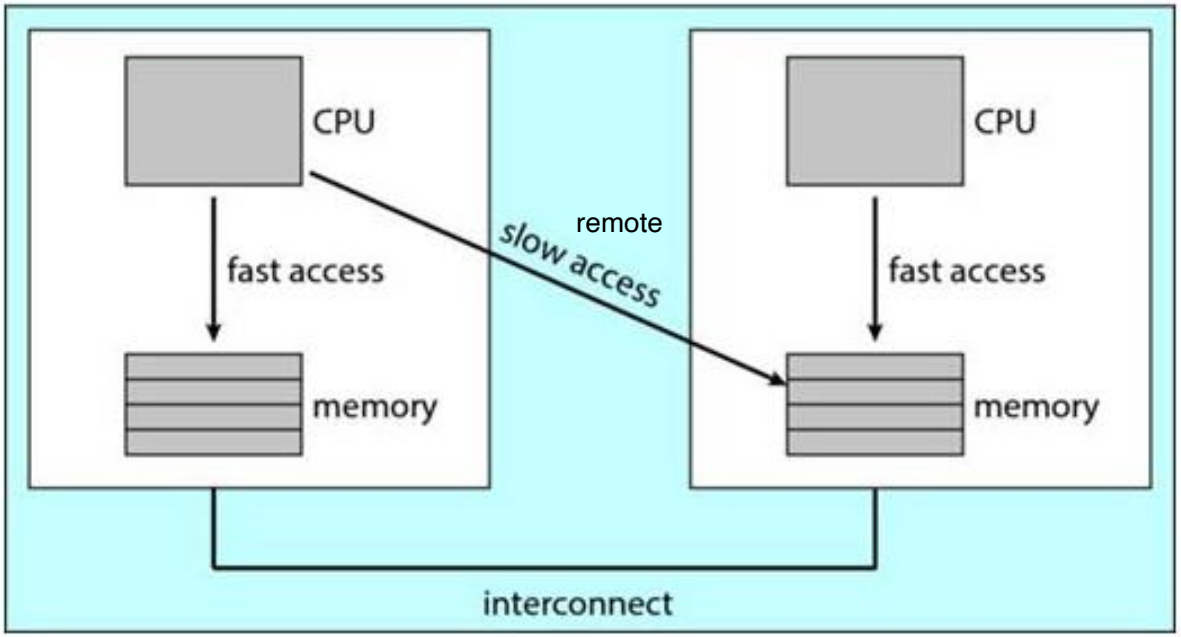


Figure 5.16 NUMA and CPU scheduling.

Real-Time CPU Scheduling

기존의 스케줄링을 작업하는 방식과 다르다

- CPU scheduling for real-time OS involves special issues.
  - ✓ **Soft real-time systems** – no guarantee as to when critical real-time process will be scheduled.
  - ✓ **Hard real-time systems** – a task must be serviced by its deadline.

  여기서는 deadline을 더 엄격하게 지켜야한다가 hard
- Event latency – the amount of time that elapses from when an event occurs to when it is serviced

급박하고, 데드라인 이내에 작업을 마무리 못하면 심각한 문제를 초래할 수 있음

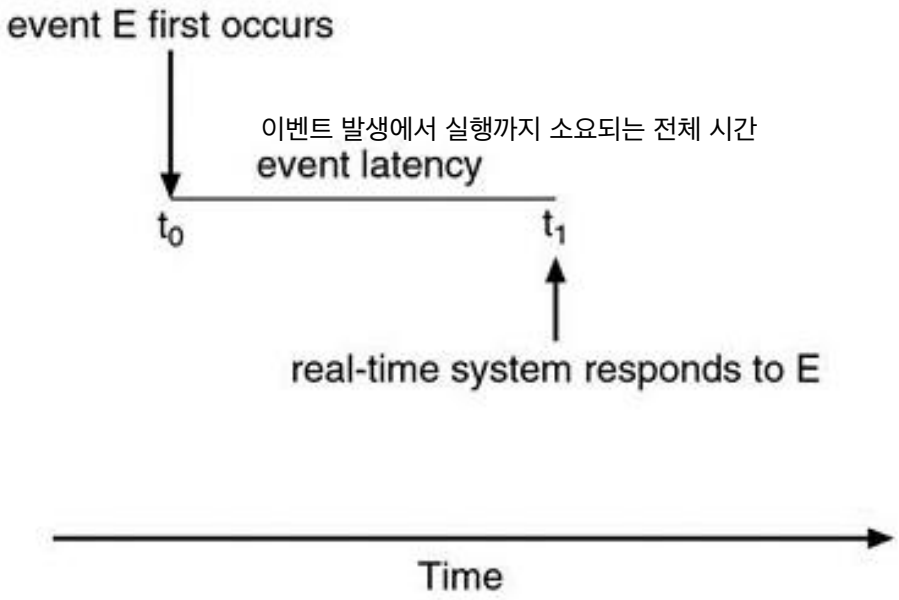


Figure 5.17 Event latency.

Real-Time CPU Scheduling

참고로 알아둘 것

- Two types of latencies affect performance
  - ✓ Interrupt latency – time from arrival of interrupt at the CPU to start of routine that services the interrupt 어떤 interrupt가 발생하고, 소요되는 시간
  - ✓ Dispatch latency – the amount of time required for the scheduling dispatcher to stop one process and start another

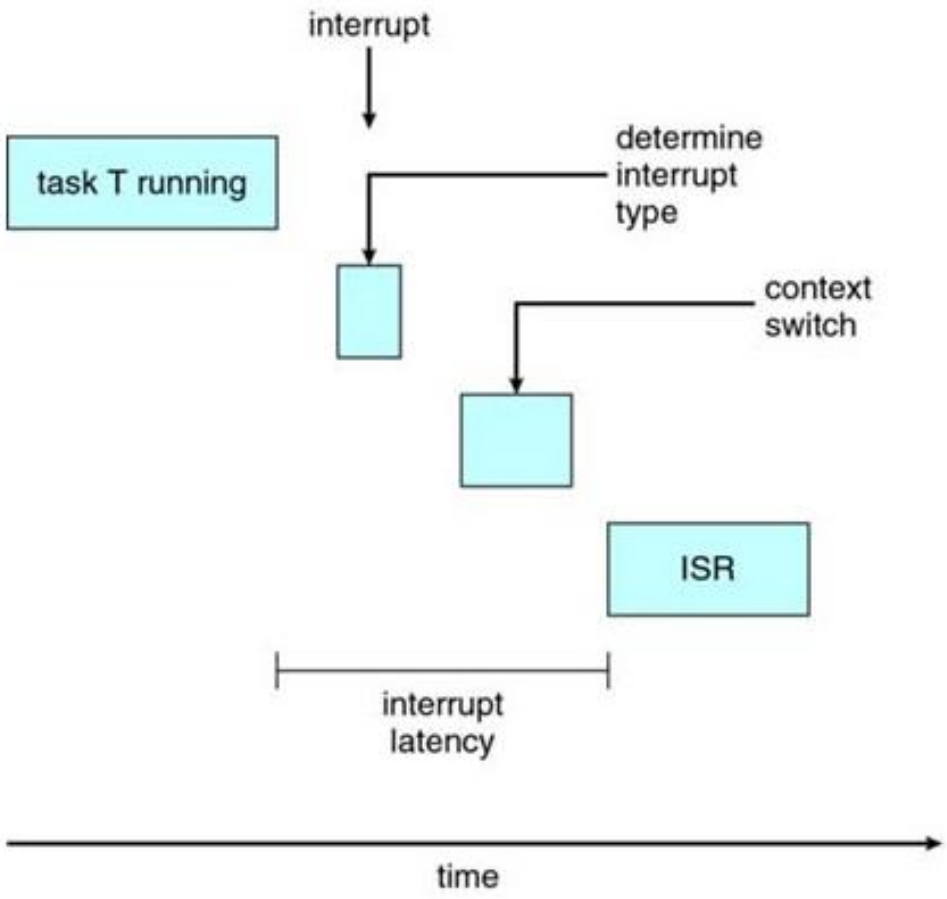


Figure 5.18 Interrupt latency.

Real-Time CPU Scheduling (Cont.)

- Conflict phase of dispatch latency:
  1. Preemption of any process running in the kernel
  2. Release by low-priority processes of resources needed by a high-priority process

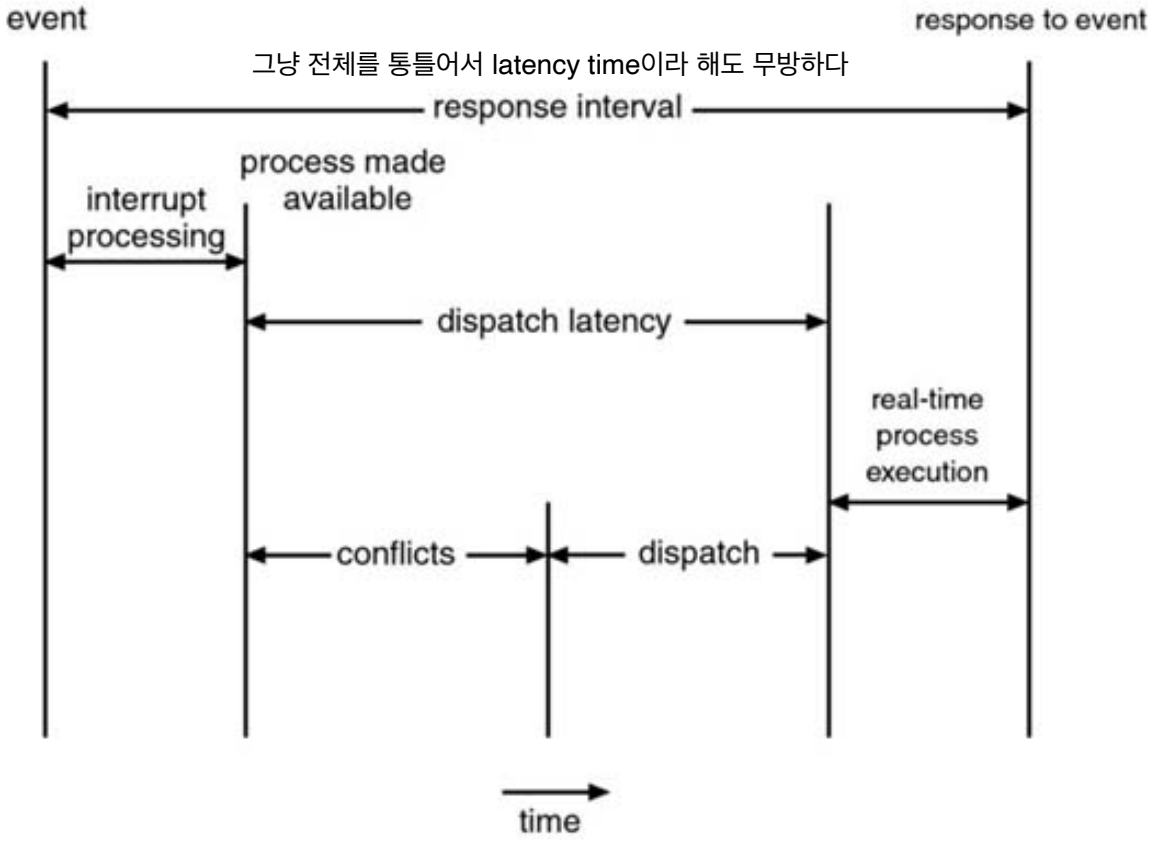


Figure 5.19 Dispatch latency.

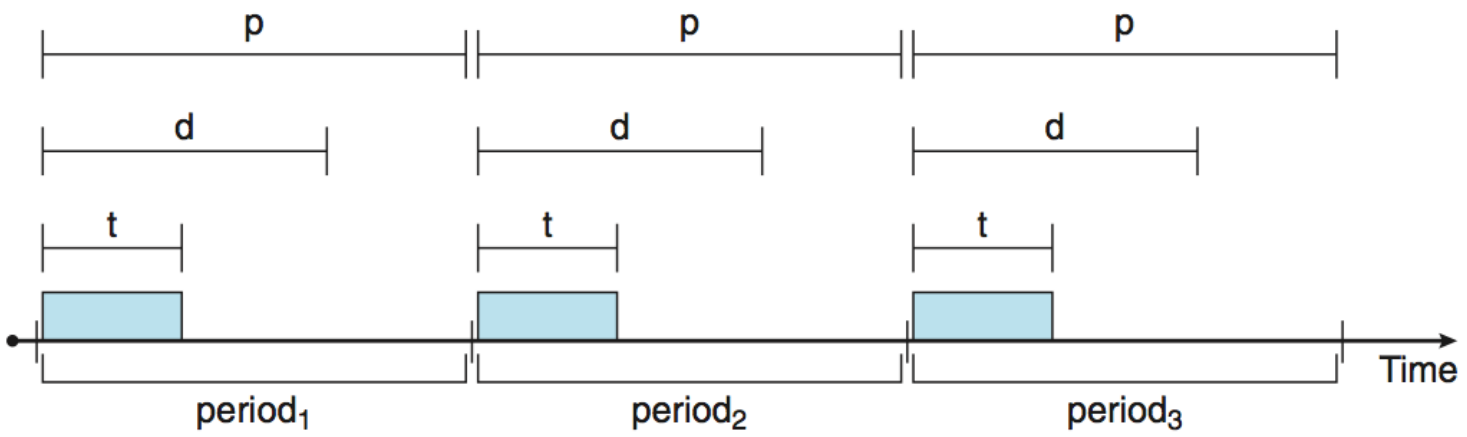
Priority-based Scheduling

- The scheduler for a real-time operating system must support a priority-based algorithm with preemption.
  - ✓ But only guarantees soft real-time functionality
- Hard real-time systems must guarantee that real-time tasks will be serviced in accord with their deadline requirements.
- Define certain characteristics of the processes that are to be scheduled: **periodic** ones require CPU at constant intervals
  - ✓ Once a periodic process has acquired the CPU, it has a fixed processing time *t*, a deadline *d* by which it must be serviced by the CPU, and a period *p*.
    - ❖ $0 \leq t \leq d \leq p$ 주기를 갖고 데드라인이 설정되어 작업이 실행된다
  - ✓ **Rate** of periodic task is $1/p$

Priority-based Scheduling

- Figure 5.20
  - ✓ The execution of a periodic process over time

p,d,t가 모두 같을 수도 있다.



Rate-Monotonic Scheduling

- The rate-monotonic scheduling algorithm schedules periodic tasks using a static priority policy with preemption.
- Each periodic task is assigned a priority inversely based on its period.
  - ✓ The shorter the period, the higher the priority 급박한 작업은 우선순위를 높게
  - ✓ The longer the period, the lower the priority
- The periods of two processes P_1 and P_2 are 50 and 100, that is p_1=50 and p_2=100. The processing times are t_1=20 for P_1 and t_2=35 for P_2. 대문자 P는 process, 소문자 p는 period
  - ✓ Whether it is possible to schedule these tasks so that each meets its deadlines.
  - ✓ If we measure the CPU utilization of a process P_i as the ratio of its burst to its period – t_i / p_i – the CPU utilization of P_1 is 20/50=0.40 and that of P_2 is 35/100=0.35, for a total CPU utilization of 75%. 두 개의 프로세스 합이 0.75라고 얘기하는 것이다
  - ✓ Therefore, it seems we can schedule these tasks in such a way that both meet their deadlines and still leave the CPU with available cycles.

Rate-Monotonic Scheduling

CPU 스케줄링의 첫번째 기법

- Suppose we assign P_2 a higher priority than P_1.

Rate-Monotonic의 설명과는
우선순위가 반대로 설정되어 있는 예시로 보고 풀이

- ✓ P_2 starts execution first and completes at time 35. At this point, P_1 starts; it completes its CPU burst at time 55.
- ✓ However, the first deadline for P_1 was at time 50, so the scheduler has caused P_1 to miss its deadline.

p1 : t = 20 / p = 50
p2 : t = 35 / p = 100
그런데 P2가 우선순위가 높다고 가정하고 진행
(51페이지 가정과 다르게 적용되어 있음!)

period = deadline

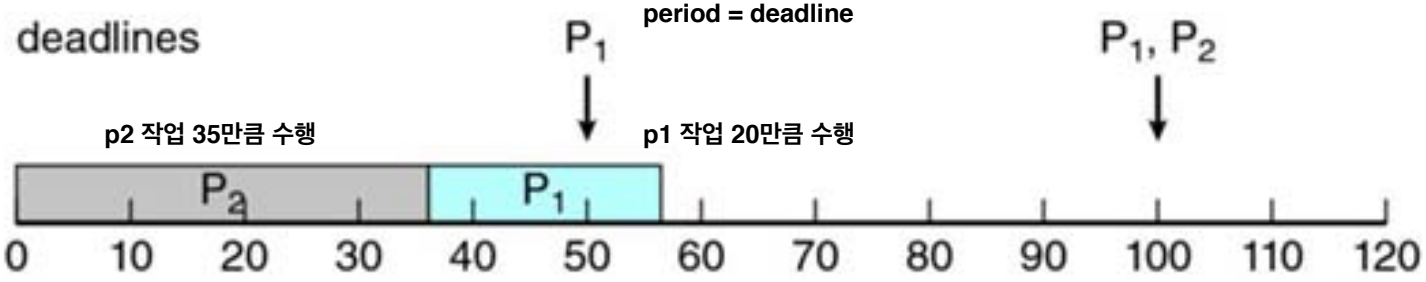


Figure 5.21 Scheduling of tasks when P_2 has a higher priority than P_1.

위의 예제 상황
p2가 먼저 실행되면서 p1의 마감기한 (p = 50)까지 작업이 마무리 안되면서 스케줄링이 잘못 설정되어 있음

Rate-Monotonic Scheduling

- Suppose we use rate-monotonic scheduling, in which we assign P_1 a higher priority than P_2 because the period of P_1 is shorter than that of P_2.
  - ✓ P_1 starts first and completes its CPU burst at time 20.
  - ✓ At time 50, P_2 is preempted by P_1, although it still has 5ms remaining in its CPU burst. P_2 completes its CPU burst at time 75

적절하게 2개의 프로세스가 스케줄링 된 사례

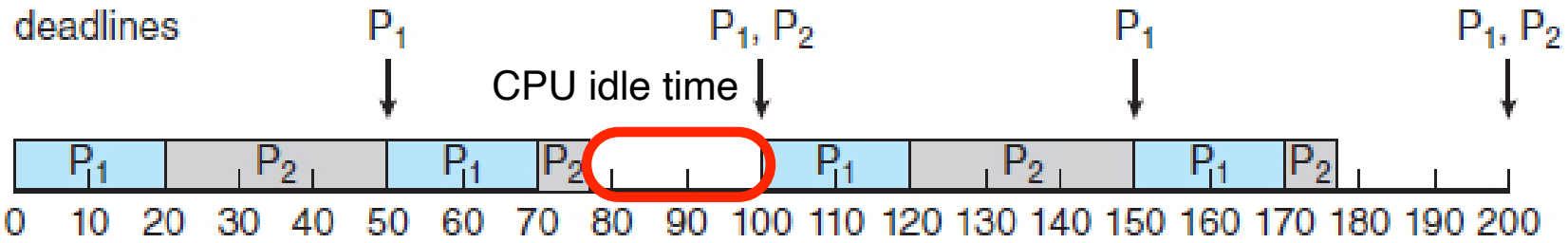


Figure 5.22 Rate-monotonic scheduling.

P1의 데드라인을 만나면 Context Switching이 발생하게 된다

P1은 여기서 50마다 데드라인을 만나 수행하고
p2는 100마다 데드라인을 만나 수행

Missing Deadlines with Rate-Monotonic Scheduling

- Assume that process P_1 has a period of p_1=50 and a CPU burst of t_1=25. For P_2, the corresponding values are p_2=80 and t_2=35.
  - ✓ Assign process P_1 a higher priority
  - ✓ P_1 runs until it completes its CPU burst at time 25. P_2 begins running and runs until time 50, when it is preempted by P_1.
  - ✓ P_2 finishes its burst at time 85, after the deadline for completion of its CPU burst at time 80.

deadline miss 발생
p2프로세스가 적절하게 수행되지 못했다

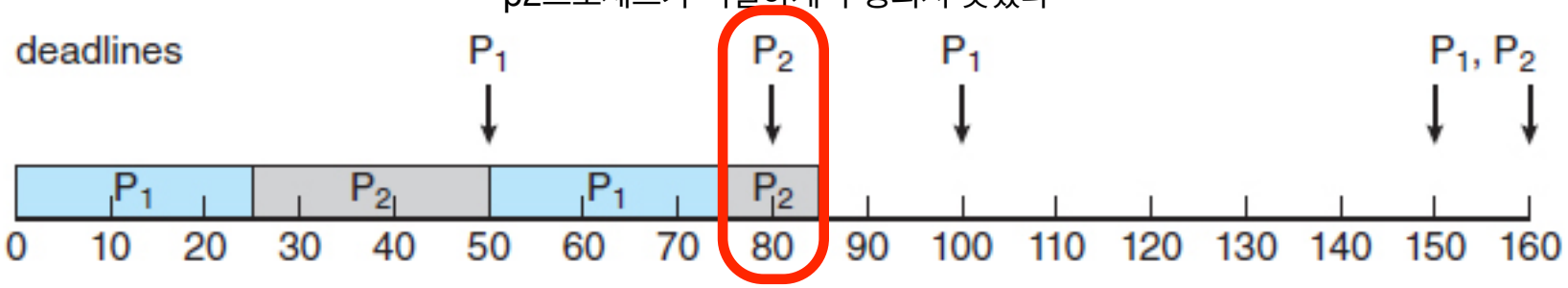


Figure 5.23 Missing deadlines with rate-monotonic scheduling.

원래 주어진 룰에 따라 스케줄링할 수 있고,
스케줄링이 될 때가 있고, 안될 때가 발생할 수 있음

이 이슈를 해결하기 위해 earliest deadline first(EDF) 기법이 뒤에 나온다

Rate-Monotonic Scheduling

그럭저럭 괜찮은 성능의 알고리즘이다

잠깐 설명하고 나가는 내용

- Rate-Monotonic scheduling has a limitation.
  - ✓ CPU utilization is bounded, and it is not always possible to maximize CPU resources fully. 이론적으로 제안한 간단한 수식

    cpu maximize를 하는 값은 한정되어 있다
  - ✓ The worst-case CPU utilization for scheduling N processes
    - ❖ $N(2^{1/N} - 1)$
    - ❖ With one process in the system, CPU utilization is 100 percent, but it falls to approximately 69 percent as the number of processes approaches infinity. 프로세스의 갯수가 기하급수적으로 커지면? 곤란하다
    - ❖ With two processes, CPU utilization is bounded at about 83 percent.

실제적으로 적용된다면, 굉장히 심각한 상황이 초래될 수 있다

Earliest Deadline First Scheduling (EDF)

- Priorities are assigned according to deadlines:

  the earlier the deadline, the higher the priority;

  the later the deadline, the lower the priority

- P_1 has values of p_1=50 and t_1=25 and P_2 has values of p_2=80 and t_2=35.
  - ✓ Process P_1 has the earliest deadline, so its initial priority is higher than that of process P_2.
  - ✓ Whereas rate-monotonic scheduling allows P_1 to preempt P_2 at the beginning of its next period at time 50, EDF scheduling allows process P_2 to continue running.

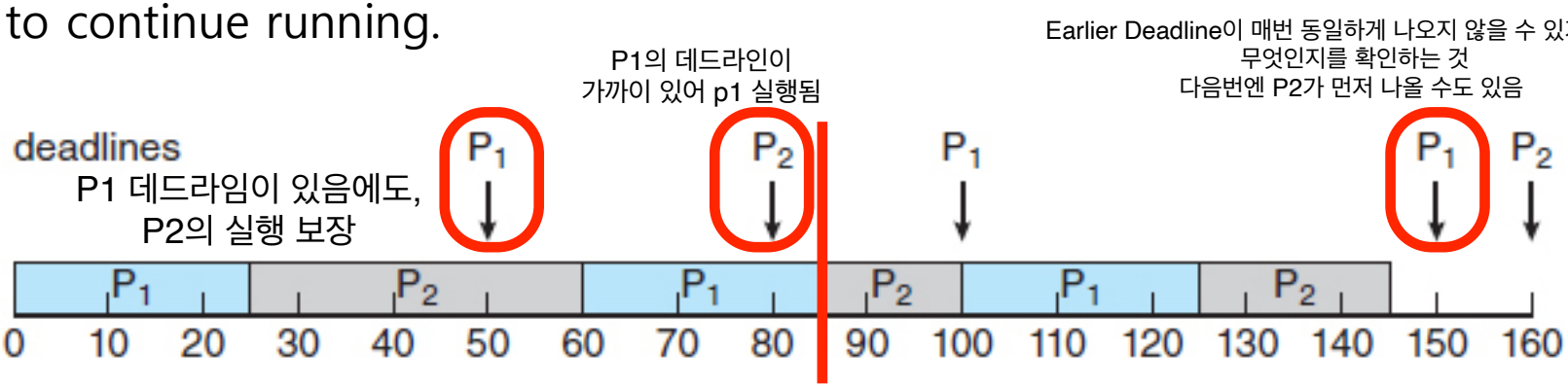


Figure 5.24 Earliest-deadline-first scheduling.

Operating System Examples – Linux

참고로 보면 좋다

- Linux scheduling 많은 경우에 RR과 Priority가 같이 쓰이는 경우가 많다
  - ✓ In release 2.6.23 of the kernel, **Completely Fair Scheduler** (**CFS**) became the default Linux scheduling algorithm.
  - ✓ To decide which task to run next, the scheduler selects the highest-priority task belonging to the highest-priority scheduling class.
  - ✓ Standard Linux kernels implement two scheduling classes: (1) a default scheduling class using the CFS scheduling algorithm and (2) a real-time scheduling class.
  - ✓ Rather than using strict rules that associate a relative priority value with the length of a time quantum, the CFS scheduler assigns a proportion of CPU processing time to each task.
  - ✓ This proportion is calculated based on the **nice value** assigned to each task. Nice values range from -20 to +19, where a numerically lower nice value indicates a higher relative priority.
  - ✓ CFS doesn't use discrete values of time slices and instead identifies a **targeted latency**, which is an interval of time during which every runnable task should run at least once.

Operating System Examples – Linux

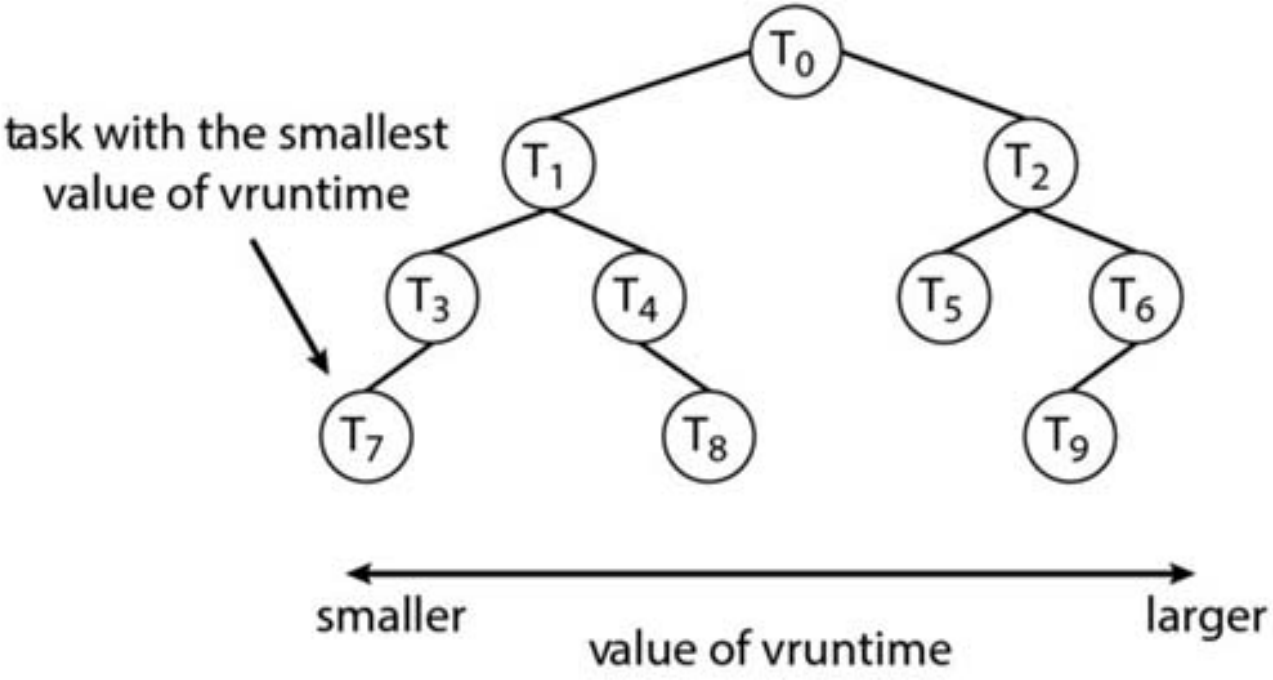
- Linux scheduling
  - ✓ The CFS scheduler doesn't directly assign priorities. Rather, it records how long each task has run by maintaining the **virtual run time** of each task using the per-task variable `vruntime`.
  - ✓ The virtual run time is associated with a decay factor based on the priority of a task: lower-priority tasks have higher rates of decay than higher-priority tasks.
  - ✓ For tasks at normal priority (nice values of 0), virtual run time is identical to actual physical run time.
    - ❖ If a task with default priority runs for 200ms, its `vruntime` will be 200ms. If a lower-priority task runs for 200ms, its `vruntime` will be higher than 200ms. Similarly, if a higher-priority task runs for 200ms, its `vruntime` will be less than 200ms.
  - ✓ To decide which task to run next, the scheduler simply selects the task that has the smallest `vruntime` value. In addition, a higher-priority task that becomes available to run can preempt a lower-priority task.

Operating System Examples – Linux

- CFS Performance
  - ✓ The Linux CFS scheduler provides an efficient algorithm for selecting which task to run next. Rather than using a standard queue data structure, each runnable task is placed in a **red-black tree** – a balanced binary search tree whose key is based on the value of `vruntime`.
  - ✓ When a task becomes runnable, it is added to the tree. If a task on the tree is not runnable ([Ex] if it is blocked while waiting for I/O), it is removed.
  - ✓ According to the properties of a binary search tree, the leftmost node has the smallest key value, which for the sake of the CFS scheduler means that it is the task with the highest priority.
  - ✓ Because the red-black tree is balanced, navigating it to discover the leftmost node will require O(log N) operations.

Operating System Examples – Linux

- CFS Performance
  - ✓ Tasks that have been given less processing time (smaller values of `vruntime`) are toward the left side of the tree, and tasks that have been given more processing time are on the right side.



Operating System Examples – Linux

- Linux scheduling
  - ✓ Linux uses two separate priority ranges: Real-time tasks are assigned static priorities within the range of 0 to 99, and normal tasks are assigned priorities from 100 to 139.
    - ❖ Lower values indicate higher priorities.

Figure 5.26 Scheduling priorities on a Linux system.

Operating System Examples – Windows

- Windows scheduling
  - ✓ A priority-based, preemptive scheduling algorithm
    - ❖ the following six priority classes to which a process can belong
    - ❖ The values for relative priorities
  - ✓ By default, the base priority is the value of the NORMAL relative priority for that class.

time-critical에서 숫자가 클 수록 우선순위가 높음

	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

Operating System Examples – Solaris

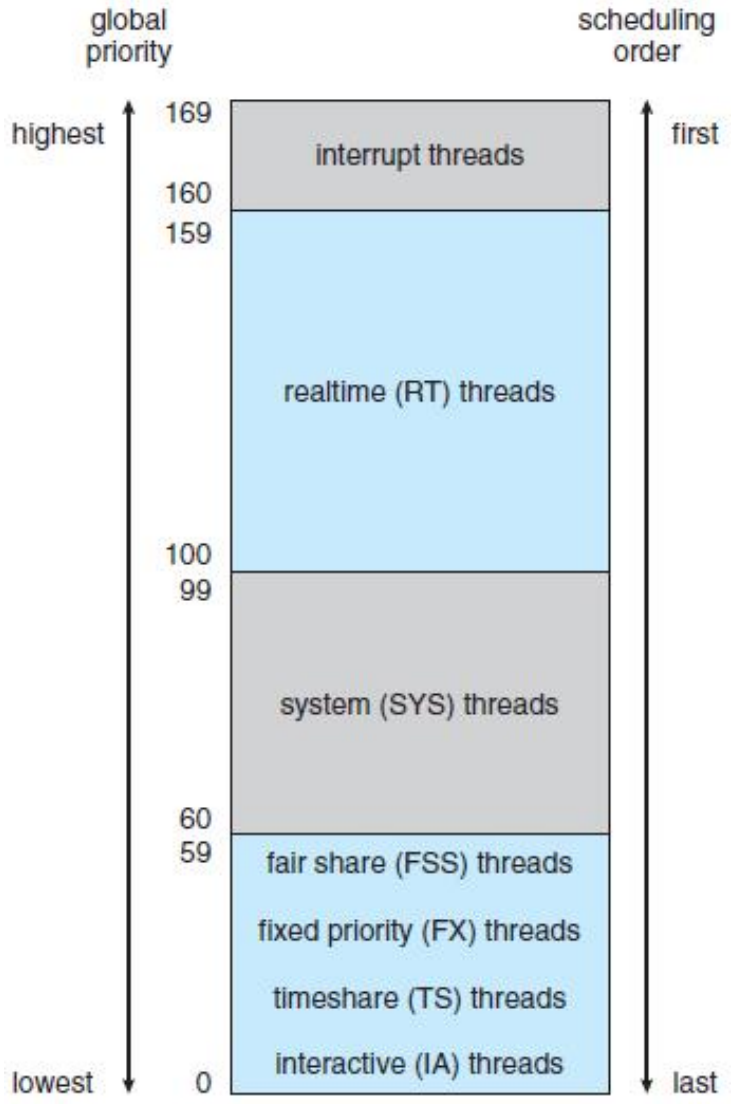
- The default scheduling class for a process is time sharing
- The inverse relationship between priorities and time quanta:
  - ✓ The lowest priority (0) has the highest time quantum (200ms)
  - ✓ The highest priority (59) has the lowest time quantum (20ms)
- Interactive processes have a higher priority
- CPU-bound processes have a lower priority

시스템에서 채용된 정책이라, 이게 왜 이렇게 설정되었는지는 얘기하기 어렵다

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

Operating System Examples – Solaris

- Each thread belongs to one of six classes.
- Threads in the real-time class are given the highest priority.
- the scheduler converts the class-specific priorities into global priorities and selects the thread with the highest global priority to run.
- The selected thread runs on the CPU until it (1) blocks, (2) uses its time slice, or (3) is preempted by a higher-priority thread.



Algorithm Evaluation

- Defining the criteria to be used in selecting an algorithm
  - ✓ Maximizing CPU utilization
  - ✓ Maximizing throughput

Average Waiting Time
Average Turnaround Time

- Deterministic modeling
  - ✓ One type of analytic evaluation
  - ✓ takes a particular predetermined workload and defines the performance of each algorithm for that workload
  - ✓ Example

Process	Burst Time
P_1	10
P_2	29
P_3	3
P_4	7
P_5	12

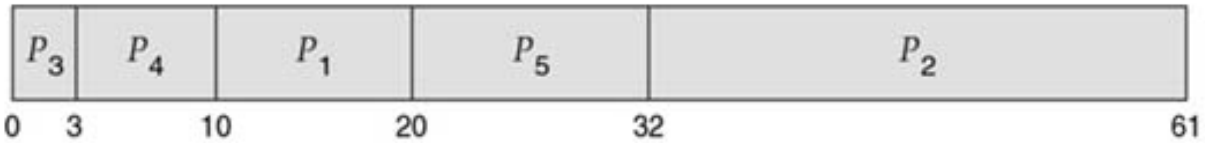
Algorithm Evaluation

여기선 Priority가 없기 때문에 단순히 계산하면 될 것 같다.

- FCFS algorithm

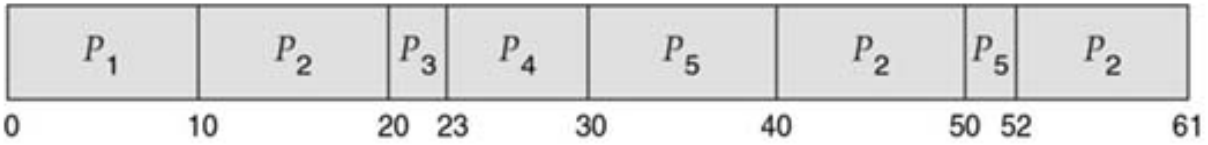
✓ Average waiting time = (0 + 10 + 39 + 42 + 49) / 5 = 28

- SJF algorithm



✓ Average waiting time = (10 + 32+ 0 + 3 + 20) / 5 = 13

- RR algorithm



✓ Average waiting time = (0 + 32 + 20 + 23 + 40) / 5 = 23

Algorithm Evaluation

- Queueing models
  - ✓ There is no static set of processes (or times) to use for deterministic modeling
    - ❖ What can be determined is the distribution of CPU and I/O bursts. These distributions can be measured and then approximated or estimated. ⇒ mathematical formula
  - ✓ Queueing-network analysis
    - ❖ Let n be the average queue length, let W be the average waiting time in the queue, and let λ be the average arrival rate for new processes in the queue
      - » **n = λ x W**
- Simulation
  - ✓ Involves programming a model of the computer system
- Implementation
  - ✓ The only completely accurate way

Evaluation of CPU schedulers by simulation