Chapter 5: CPU Scheduling

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Chapter 5: Process Scheduling

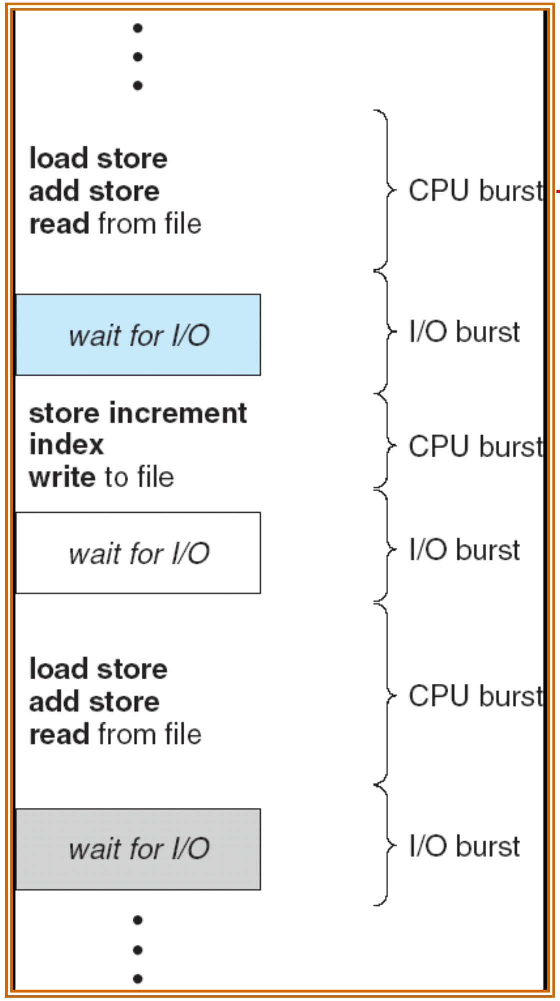
- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Multiple-Processor Scheduling
- Thread Scheduling
- Operating Systems Examples
- Algorithm Evaluation

BASIC CONCEPTS

Basic Concepts

- Maximum CPU utilization obtained with multiprogramming
- CPU–I/O Burst Cycle – Process execution consists of a cycle of CPU execution and I/O wait
- CPU burst distribution

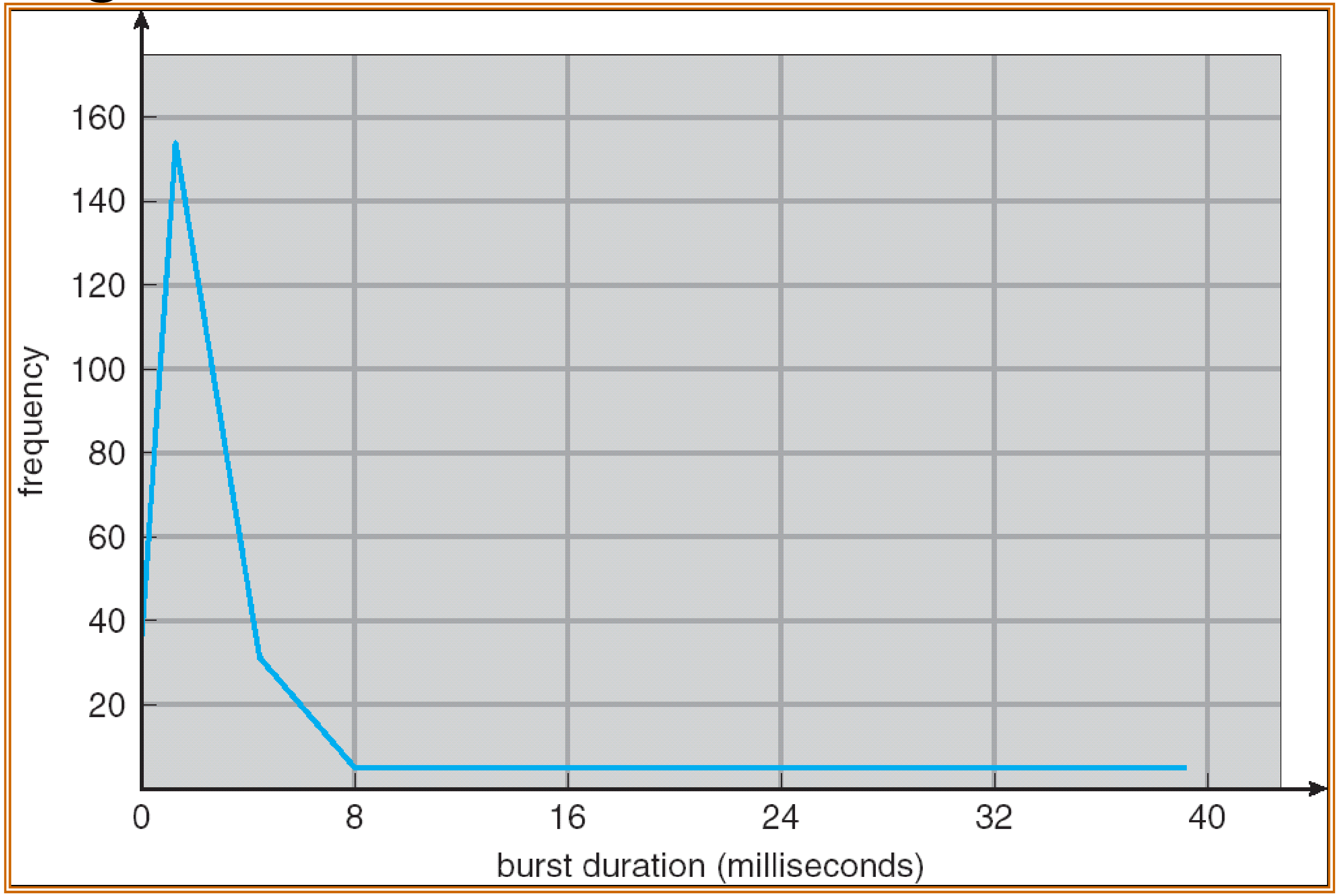
Alternating Sequence of CPU And I/O Bursts



一段連續CPU使用時間

Histogram of CPU-burst Times

CPU time slot 一般是 10ms



The majority of CPU bursts are short

通常是跟user互動的程式，等使用者input data or Internet

CPU Scheduler

short-term：在 ready queue中抓出一個process
進入 running state

- 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 (←?) 通常是有高優先權的process回來ready了
  4. Terminates
- Scheduling under only 1 and 4 is non-preemptive or cooperative
- All other scheduling is preemptive

一旦拿到CPU，就跑到process自願把CPU讓出來為止

Cooperative scheduling

一但有process陷入 infinite loop就完蛋了

- Easy to implement and requires no extra hardware (e.g., the timer)
- A process may voluntarily gives up the CPU
  - Call Sleep(0) or yield()
  - A blocking call also causes a context switch
- An ill-behaved process can take over the entire system
- Example
  - Windows 3.1
  - Old versions of Mac OS
  - Sensor-node OS (e.g., TinyOS)

Scheduler Preemptivity

- Preemptive scheduling
  - Higher responsiveness
  - Higher overheads
  - Must deal with race conditions process不知道其他p什麼時候會衝進來改東西
- Cooperative scheduling
  - Easy to implement
  - Poor responsiveness
  - Ill-behaved processes will take over the system

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

the context-switch overhead

SCHEDULING CRITERIA

Scheduling Criteria

work-conserving：
只要ready queue不為空，CPU就不閒置

- (+)CPU utilization – keep the CPU as busy as possible
- (+) Throughput – # of processes that complete their execution per time unit
- (-)Turnaround time – amount of time to execute a particular process 總執行時間
- (-) Waiting time – amount of time a process has been waiting in the ready queue
- (-) Response time – amount of time it takes from when a request was submitted until the first response is produced, not output (for time-sharing environment) 這邊沒正式定義

衝突，
公平會
降低效率

Good average performance vs. Predictable worst-case performance

Optimization Criteria

- Max CPU utilization
- Max throughput
- Min turnaround time
- Min waiting time
- Min response time

- There are conflicts among the objectives
  - E.g., throughput vs. response

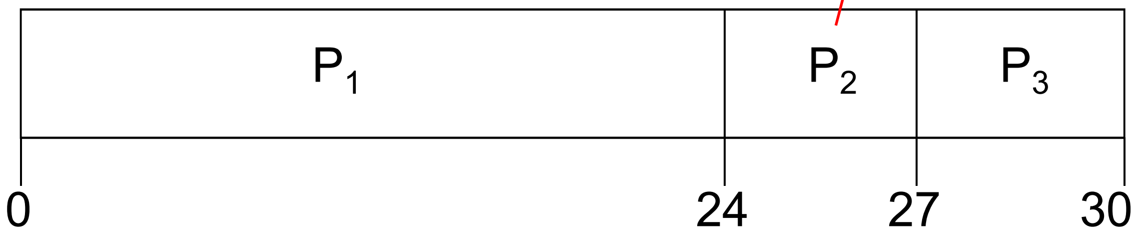
SCHEDULING ALGORITHMS

First-Come, First-Served (FCFS) Scheduling

Process	Burst Time
P_1	24
P_2	3
P_3	3

通常短的是I/O bound
等太久會讓I/O utilization 變很差

- 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 大的工作墊高了waiting time

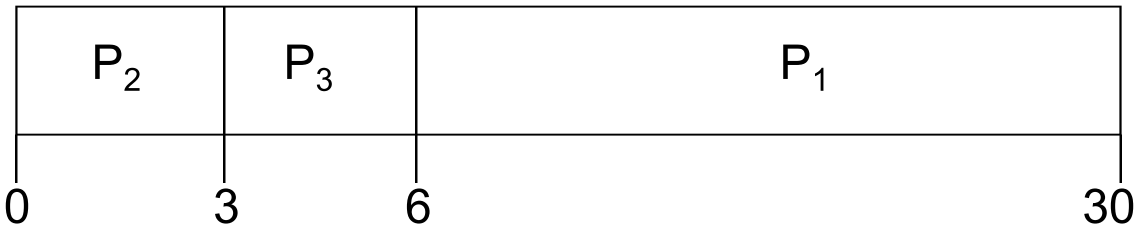
If a short job arrives late…

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: $(6 + 0 + 3)/3 = 3$
- Much better than previous case

- *Convoy effect* short process behind long process
  - Non-preemptible.
  - Harmful to I/O-bound processes and result in poor I/O utilization!! (why?)

優點：等待時間固定，進來時前面有多少人就等多久
缺點：I/O utilization 不好

- Which one(s) of the following could be the performance issue of FCFS?
  - Lengthy response
  - Poor I/O utilization
  - ~~Low CPU utilization~~

Shortest-Job-First (SJF) Scheduling

- Associate with each process the length of its next CPU burst. Use these lengths to schedule the process with the shortest time
- Two schemes:
  - nonpreemptive – once 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 known as the Shortest-Remaining-Time-First (SRTF) 是檢查還要多少時間，而不是一開始要多少時間
- SJF is optimal – gives minimum average waiting time for a given set of processes

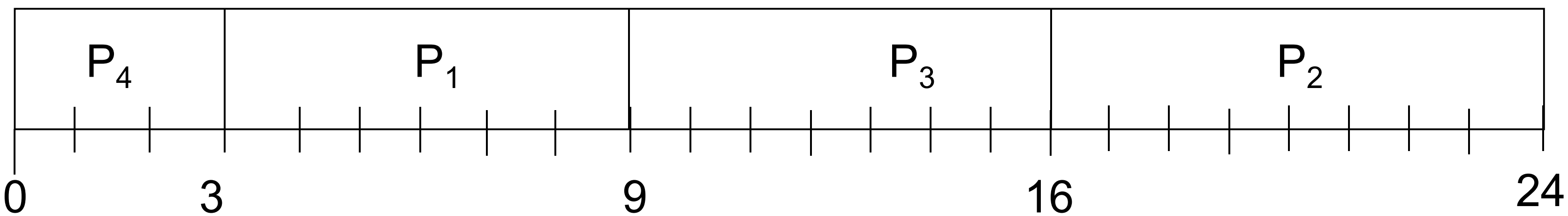
假設共有n個processes
x ≠ y ≠ z ≠ …

等待時間為Px + (Px+Py) + (Px+Py+Pz) + …
= (n-1)Px + (n-2)Py + (n-3)Pz + …

SJF: All ready at time 0

Process	Arrival Time	Burst Time
P1	0.0	6
P2	0.0	8
P3	0.0	7
P4	0.0	3

SJF (non-preemptive)



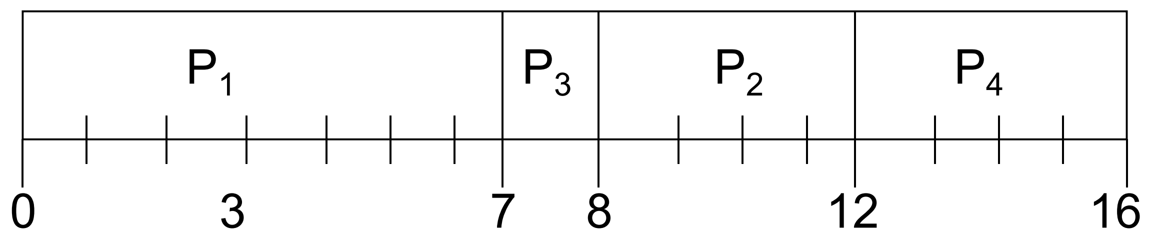
- Average waiting time = (0 + 3 + 9 + 16)/4 = 7 一定是最短的
- Compared to FCFS? (0+6+14+21)/4=10.25

一旦開始跑就跑到完

Non-Preemptive SJF with arbitrary arrival times

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

- SJF (non-preemptive)

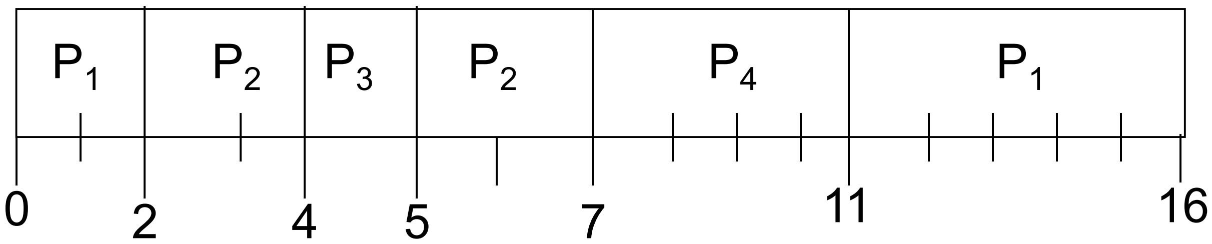


- Average waiting time = (0 + 6 + 3 + 7)/4 = 4

Preemptive SJF with arbitrary arrival times

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

- SJF (preemptive)



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

但如果有一個很長的的work，可能它要等非常久
→waiting time的變化很大

- Which one(s) is the characteristic of SJF?
  - Short waiting time
  - ~~Small waiting time variation~~

Fairness vs. Efficiency

- SJF is not a fair scheduling algorithm
  - Processes have long CPU bursts may starve
  - In FCFS, a process’s waiting time is bounded

- Long jobs may be indefinitely delayed if short jobs keep arriving
  - starvation

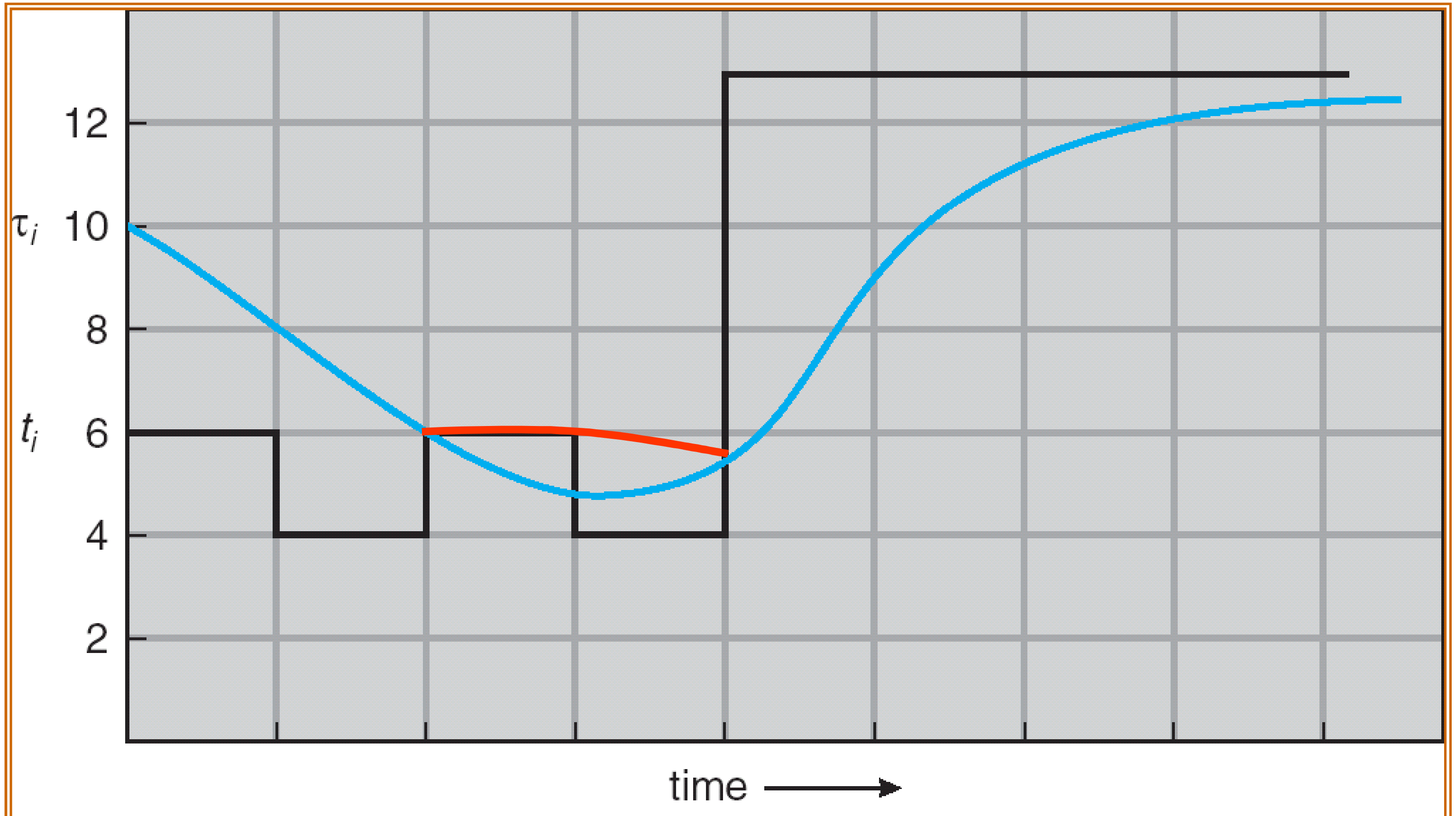
Determining Length of Next CPU Burst

- It is nearly impossible to know the actual job execution time in advance
- The exponential moving average method
  - Can only estimate the length
  - Can be done by using the length of previous CPU bursts

1. $t_n =$ actual lenght 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 :

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

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	…

Alpha=0.5

Examples of Exponential Moving Average

- $\alpha = 0$
  - $\tau_{n+1} = \tau_n$
  - 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:

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

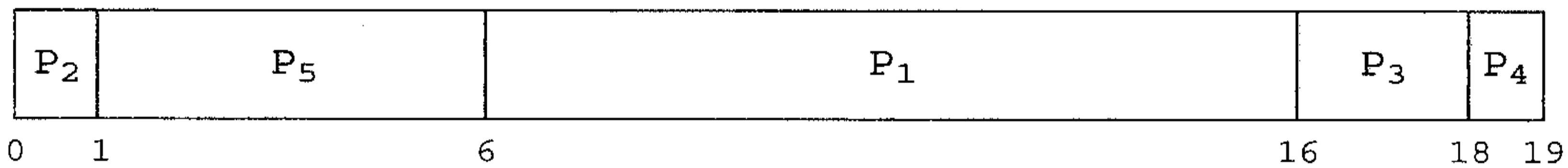
- Since both α and $(1 - \alpha)$ are less than or equal to 1, each successive term has less weight than its predecessor

Priority Scheduling

- 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
  - nonpreemptive
- 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 隨等待時間priority會增加

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

Using priority scheduling, we would schedule these processes according to the following Gantt chart:



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 $\Rightarrow$ q must be large with respect to context switch, otherwise overhead is too high

Example of RR with Time Quantum = 20

Process	Burst Time
P_1	53
P_2	17
P_3	68
P_4	24

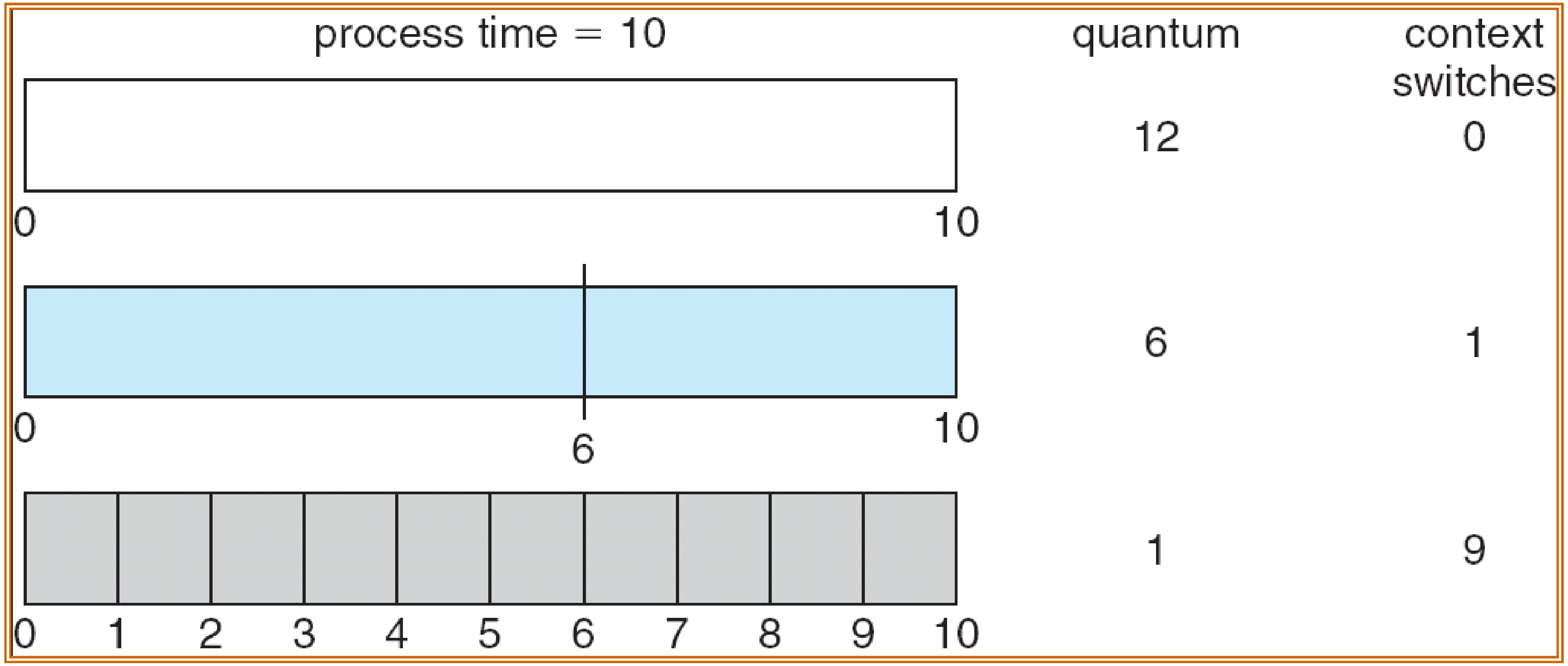
- The Gantt chart is:

P_1	P_2	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_3

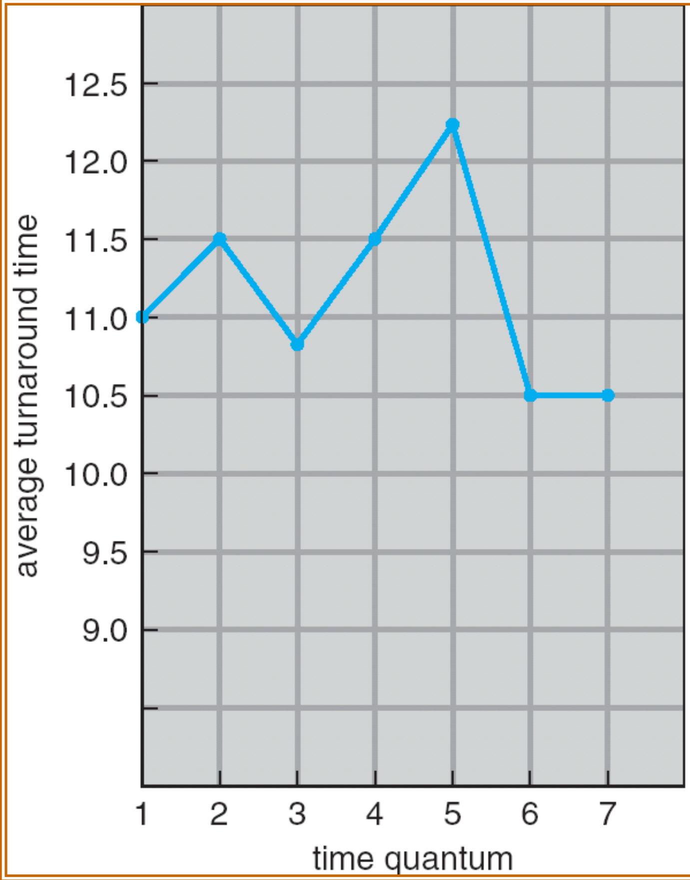
0 20 37 57 77 97 117 121 134 154 162

- Processes with RR have longer turnaround time than with SJF, but better response
  - With RR and if Q is very small, two bursts having the same length cam complete at the same time

Time Quantum and Context Switch Time



Turnaround Time Varies With The Time Quantum



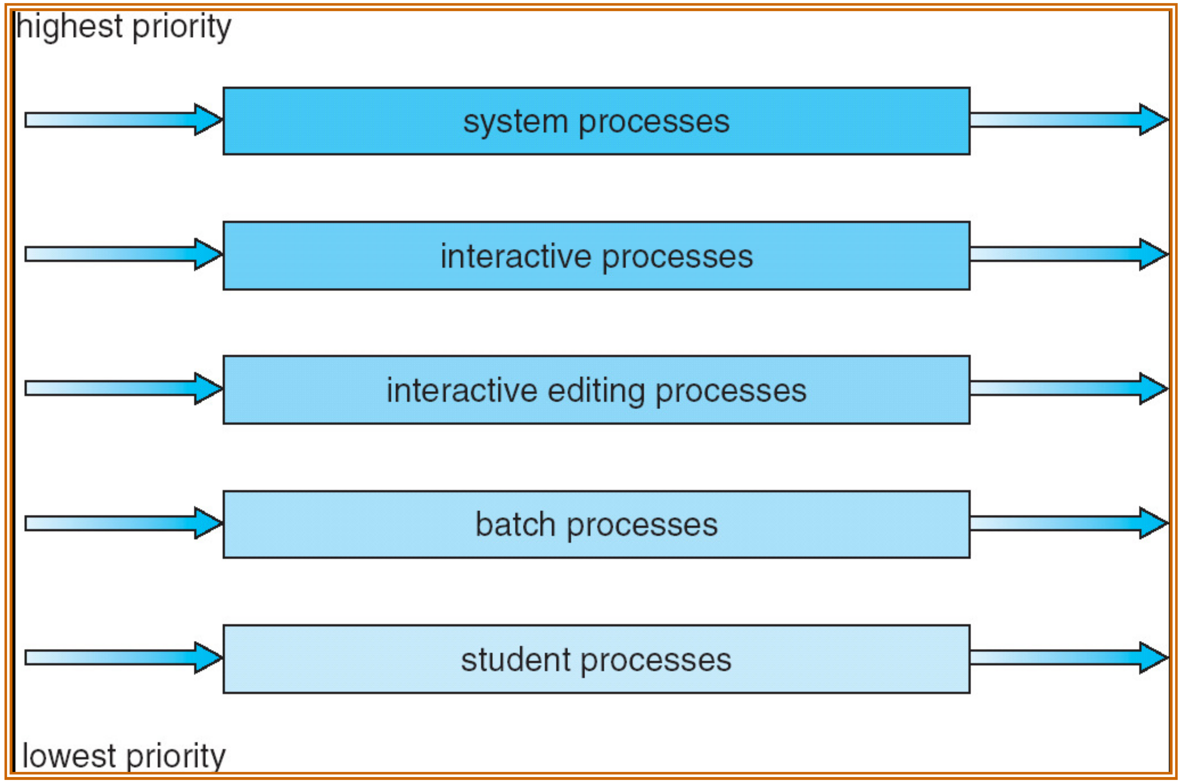
process	time
P_1	6
P_2	3
P_3	1
P_4	7

Better *interactive* response ←Time quantum→ better turnaround time

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



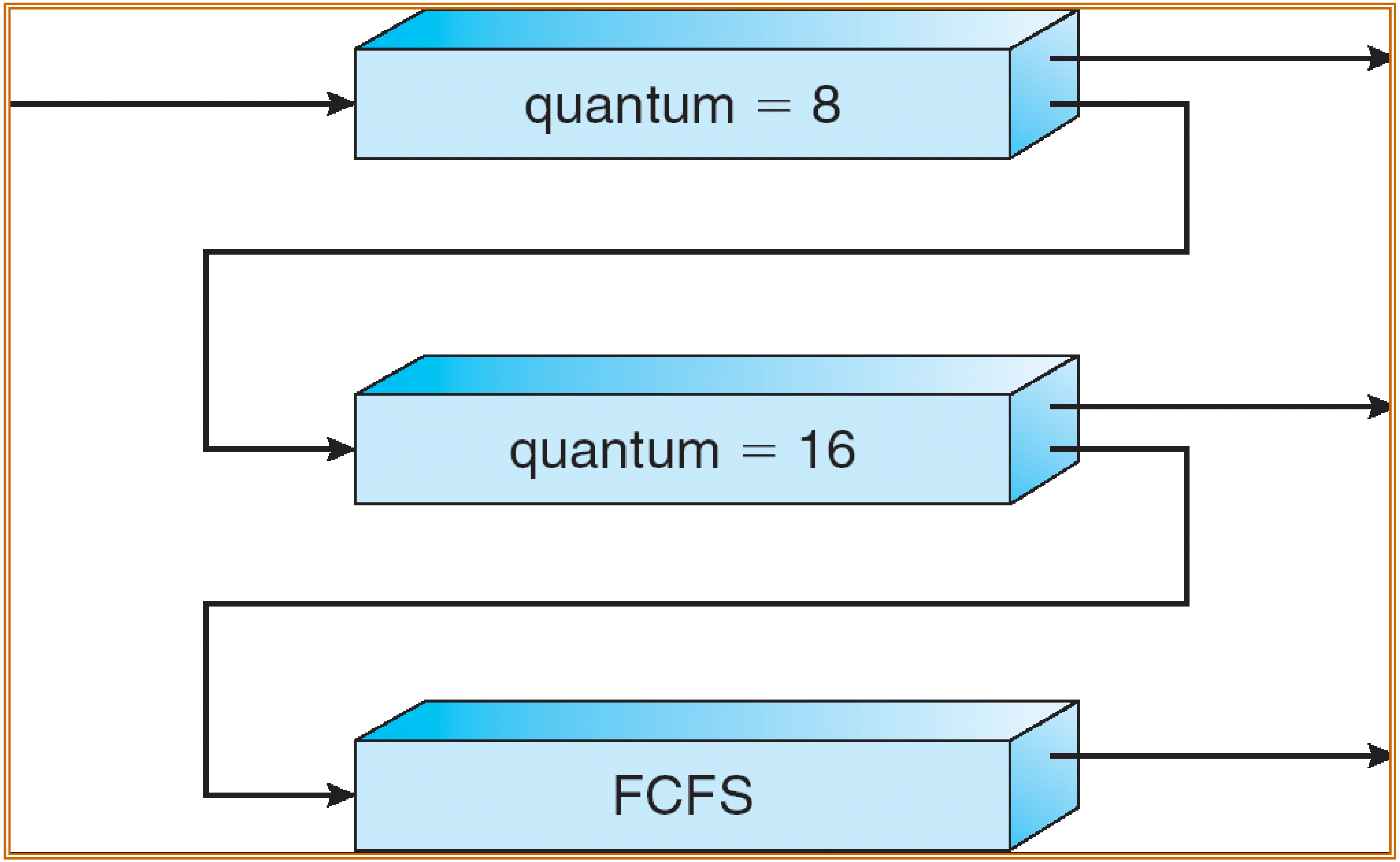
Multilevel Feedback Queue

- 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:
  - Q0 – RR with time quantum 8 milliseconds
  - Q1 – RR time quantum 16 milliseconds
  - Q2 – FCFS
- Scheduling
  - A new job enters queue Q0 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 Q1.
  - At Q1 job is again served FCFS and receives 16 additional milliseconds. If it still does not complete (?), it is preempted and moved to queue Q2.

Multilevel Feedback Queues



We should add a promotion policy

Example of Multilevel Feedback Queue

- Real designs employ a promotion policy
  - See the Solaris priority table

- Why do we prefer I/O-bound processes (short bursts)?
  - To improve I/O utilization (vs the convoy effect of FCFS)
  - To favor interactive processes
- Why CPU-bound processes (long bursts) are given to larger time quantum?
  - To improve throughput and turnaround

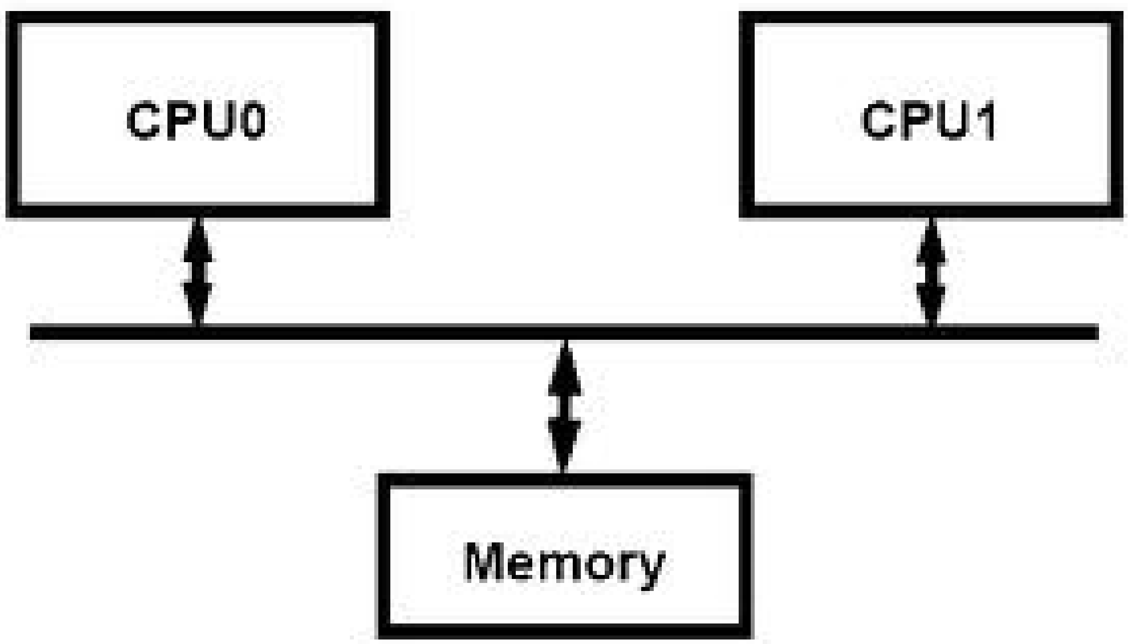
MULTIPLE PROCESSOR SCHEDULING

Multiple-Processor Scheduling

- CPU scheduling more complex when multiple CPUs are available
- Symmetric multiprocessing (SMP) – each processor is self-scheduling, all processes in common ready queue, or each has its own private queue of ready processes
- Asymmetric multiprocessing – only one processor accesses the system data structures, alleviating the need for data sharing
  - NUMA (Non-uniform memory access)

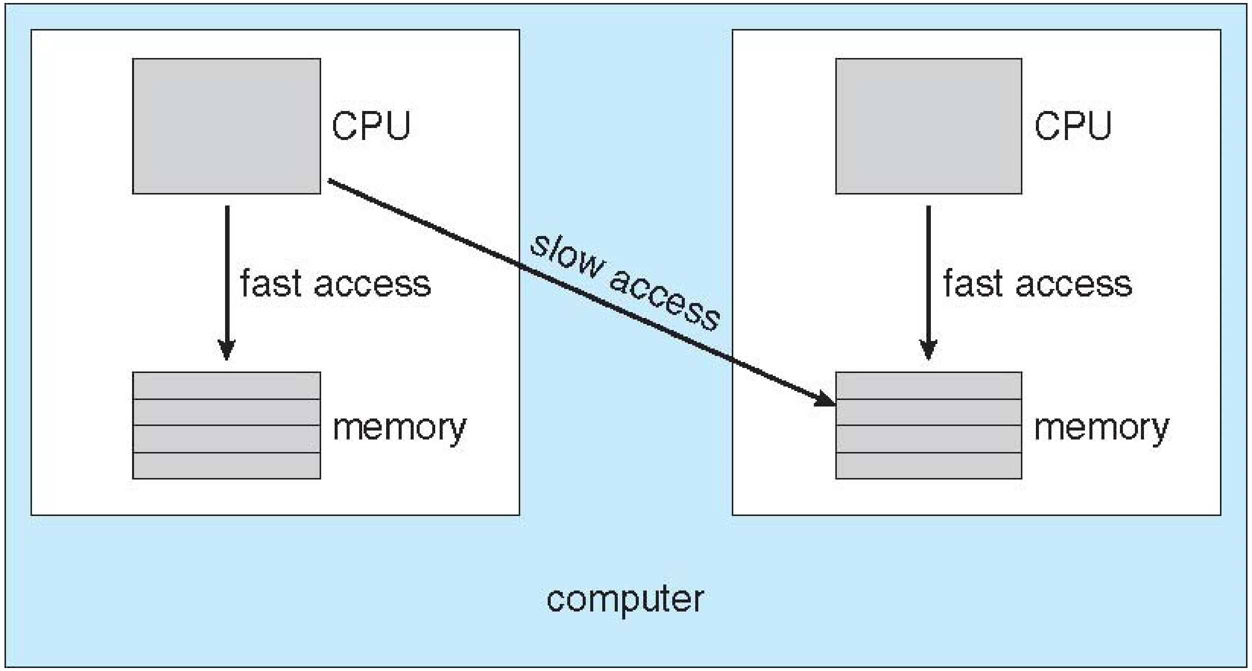
Symmetric multiprocessing (SMP)

- Many CPUs share the same main memory
- Contend for memory cycles via the common bus
- Good performance with a small # of processors



Non-Uniform Memory Access (NUMA)

- Memory access time depends on the location of memory
- More scalable than SMP



Multiple-Processor Scheduling

偏好

- Processor affinity 盡量保持在原本的Processor上工作，避免切換需要的overhead
  - The cost of process migration: cache population, housekeeping data transfer
  - Sometimes it's better to stick processes with processors
  - Soft affinity, hard affinity

- Load balancing 重點是如何平均分配工作
  - Push migration – push a process away from a heavily loaded processor to an idle processor
  - Pull migration – pull a waiting process from a heavily loaded processor into an idle processor
  - Linux – runs push migration every 200ms and runs pull migration whenever a processor queue is empty

- The two goals conflict with each other!

將process在CPU中移動(process migration)會造成效能損失、pipe失效等
→還是要做，但頻率不能高

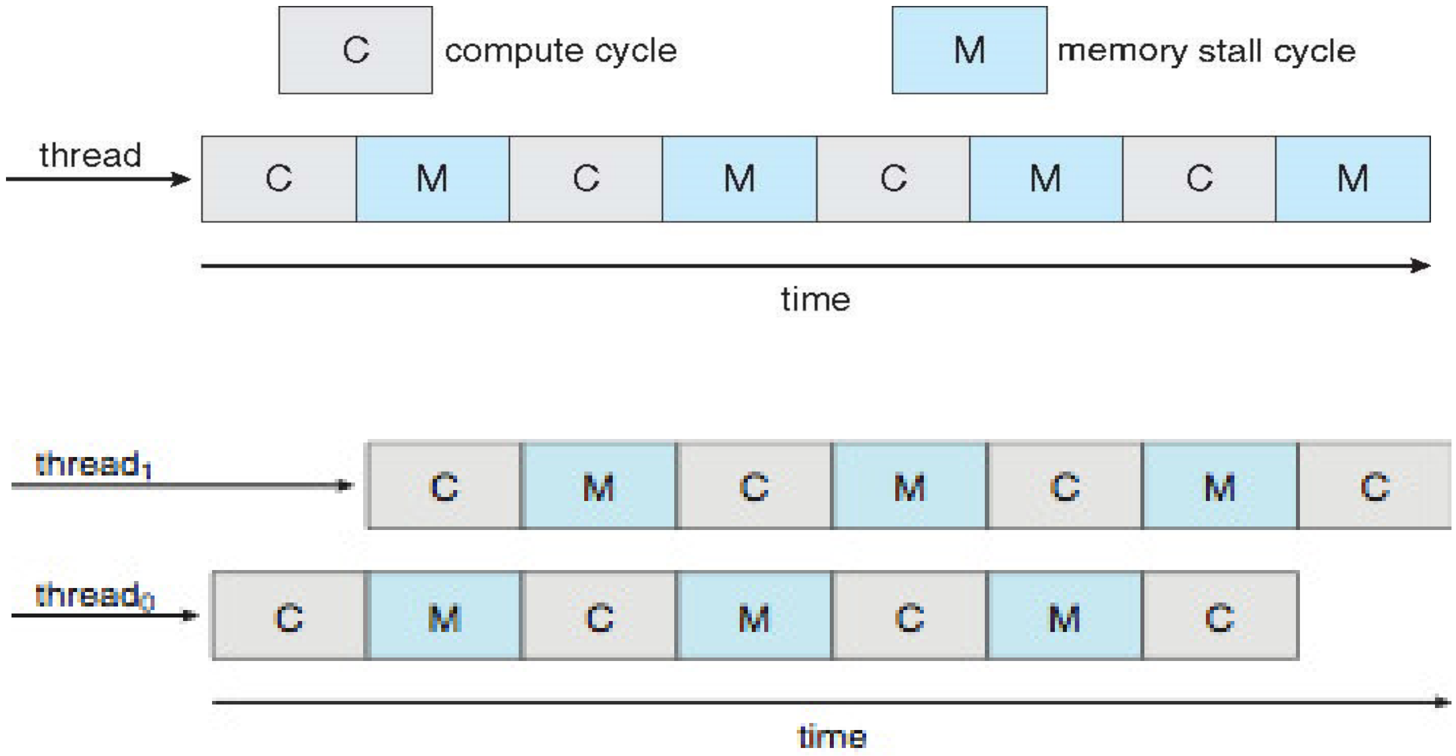
Multicore and Multithreading Processors

- Multiple processor cores on the same physical chip
  - Faster communication
  - More power efficient
  - Better cache sharing

跟前面的thread不一樣

- Multiple (hardware) threads per core also growing
  - Takes advantage of memory stall to make progress on another thread while memory retrieve happens
  - A thread here is hardware-oriented, different from “threads” in Chapter 4
  - A thread corresponds to a logical processor, emulated by an independent set of registers

Improving CPU and Memory Cycle Utilizations



Higher utilizations of both CPU and memory

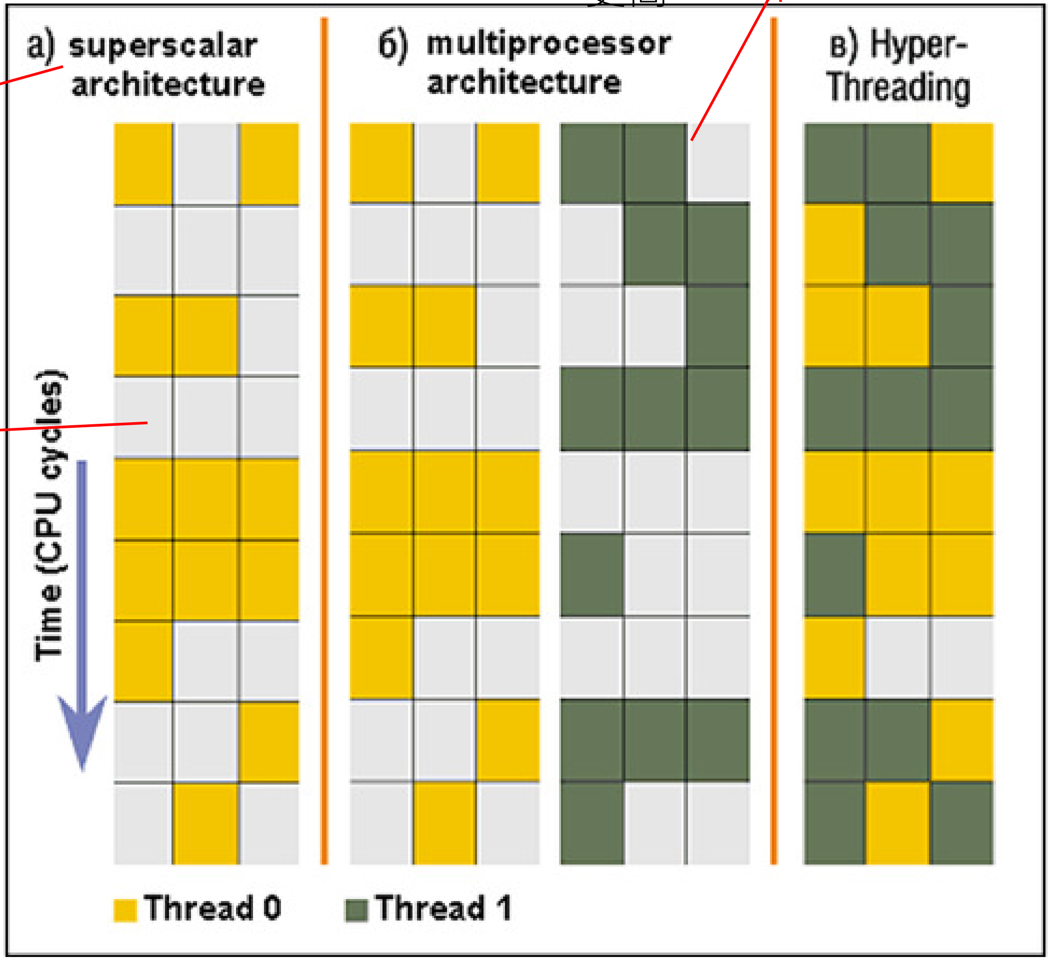
多thread→CPU核心裡面有多組register，讓**compute cycle** 和 **memory stall cycle**交互配合執行

Better Utilization of Processing Units in Superscalar Processors

用另一組register載入另一串獨立的，來讓ALU效率更高

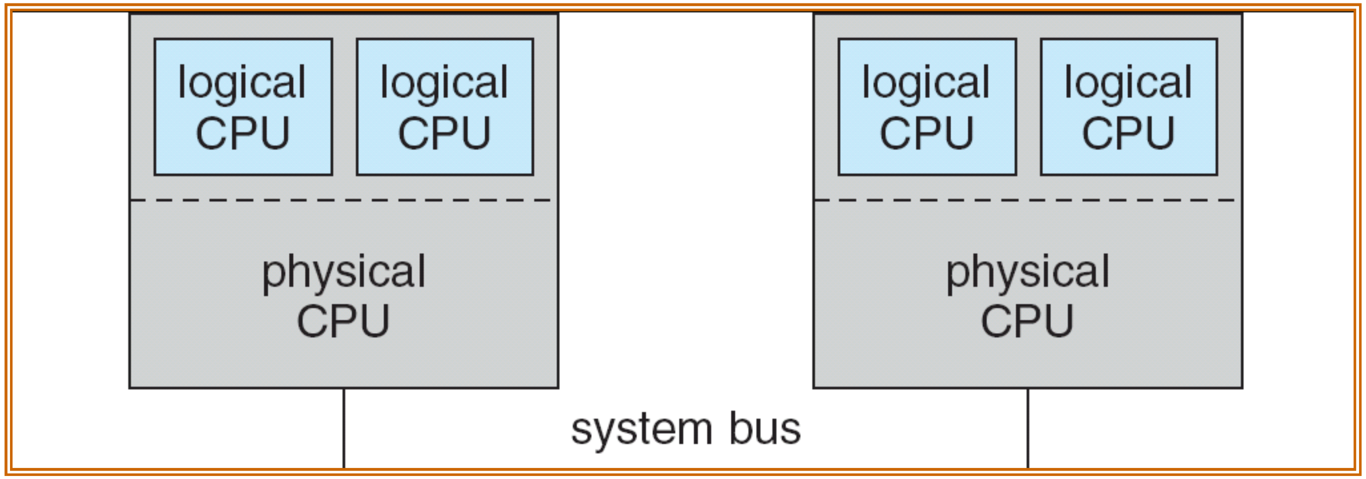
多ALU處理單元

因為hasser造成多ALU單元無法發揮全部效能



http://www.quora.com/Multithreading/How-would-you-explain-multithreading-to-a-first-year-computer-science-student

Multithreaded Multoprocessor Systems



Assume: 2 PP, each has 2 LP.

[1 1][1 1] is better than [2 0][2 0]
[1 0][1 0] is better than [1 1][0 0]

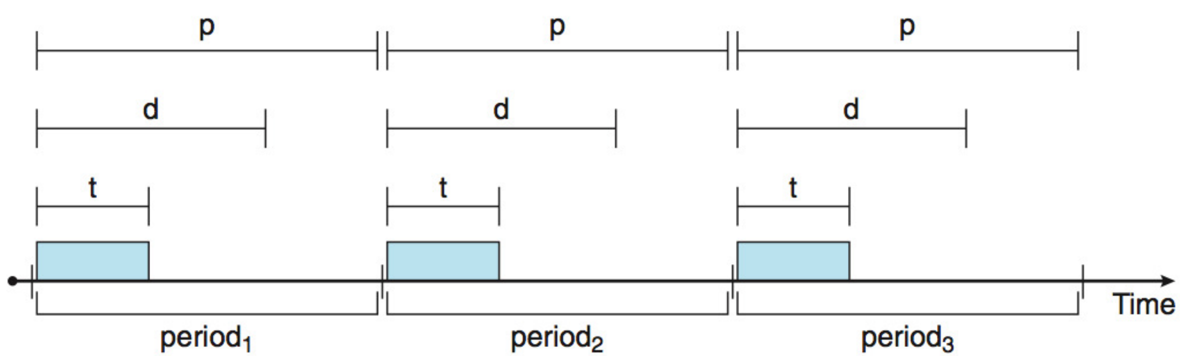
Firstly, evenly distribute process among physical CPUs
In each physical CPU, evenly distribute processes among logical CPUs

Real-Time Scheduling

Real-Time CPU Scheduling

- IEEE definition of real time systems:
  反映要及時
  - “A real-time system is a system whose correctness includes its response time as well as its functional correctness.”
    算出來是對的
- Soft real-time systems – no guarantee as to when critical real-time process will be scheduled
- Hard real-time systems – task must be serviced by its deadline
  一定要即時反應，不然會來不及而造成嚴重後果

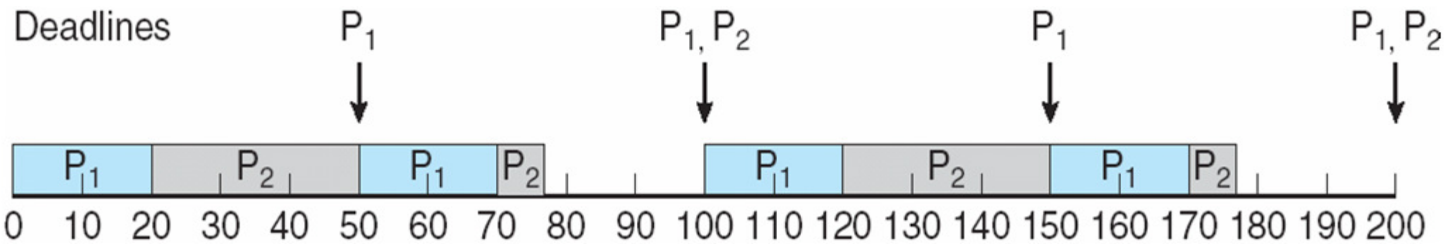
Priority-based Scheduling

- For real-time scheduling, scheduler must support preemptive, priority-based scheduling
  - But only guarantees soft real-time
- For hard real-time must also provide ability to meet deadlines
- Processes have new characteristics: periodic ones require CPU at constant intervals
  - Has processing time t, deadline d, period p
  - $0 \leq t \leq d \leq p$
  - Rate of periodic task is $1/p$
  - 

週期倒數

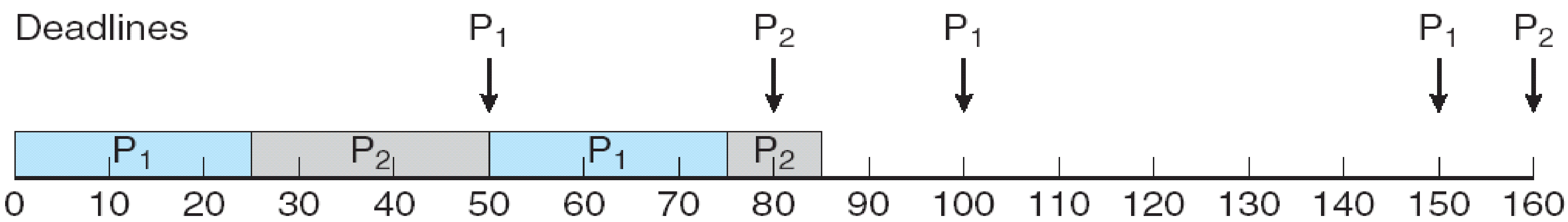
Rate Montonic Scheduling

- A priority is assigned based on the inverse of its period
- Shorter periods = higher priority;
- Longer periods = lower priority
- P1 is assigned a higher priority than P2.



Computation: c1=20, c2=35
Periods: P1=50, P2=100

Missed Deadlines with Rate Monotonic Scheduling



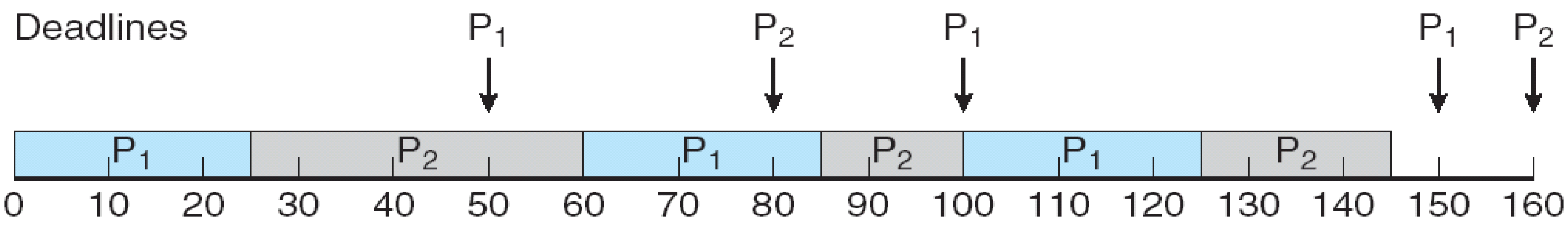
Computation: c1=25, c2=35
Periods: P1=50, P2=80

做deadline最近的那個

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

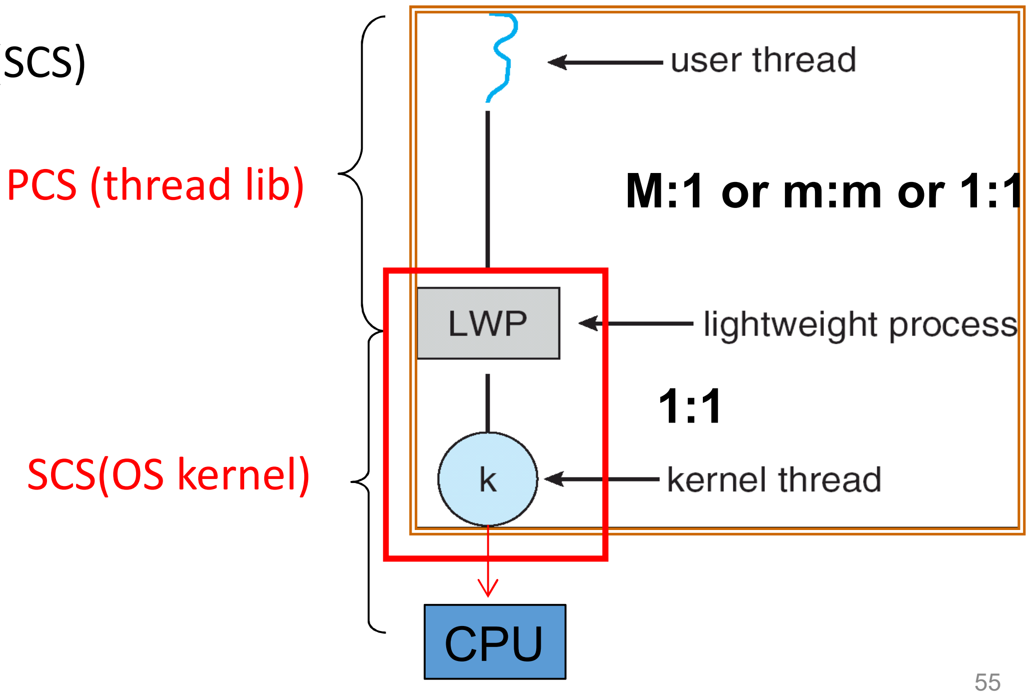


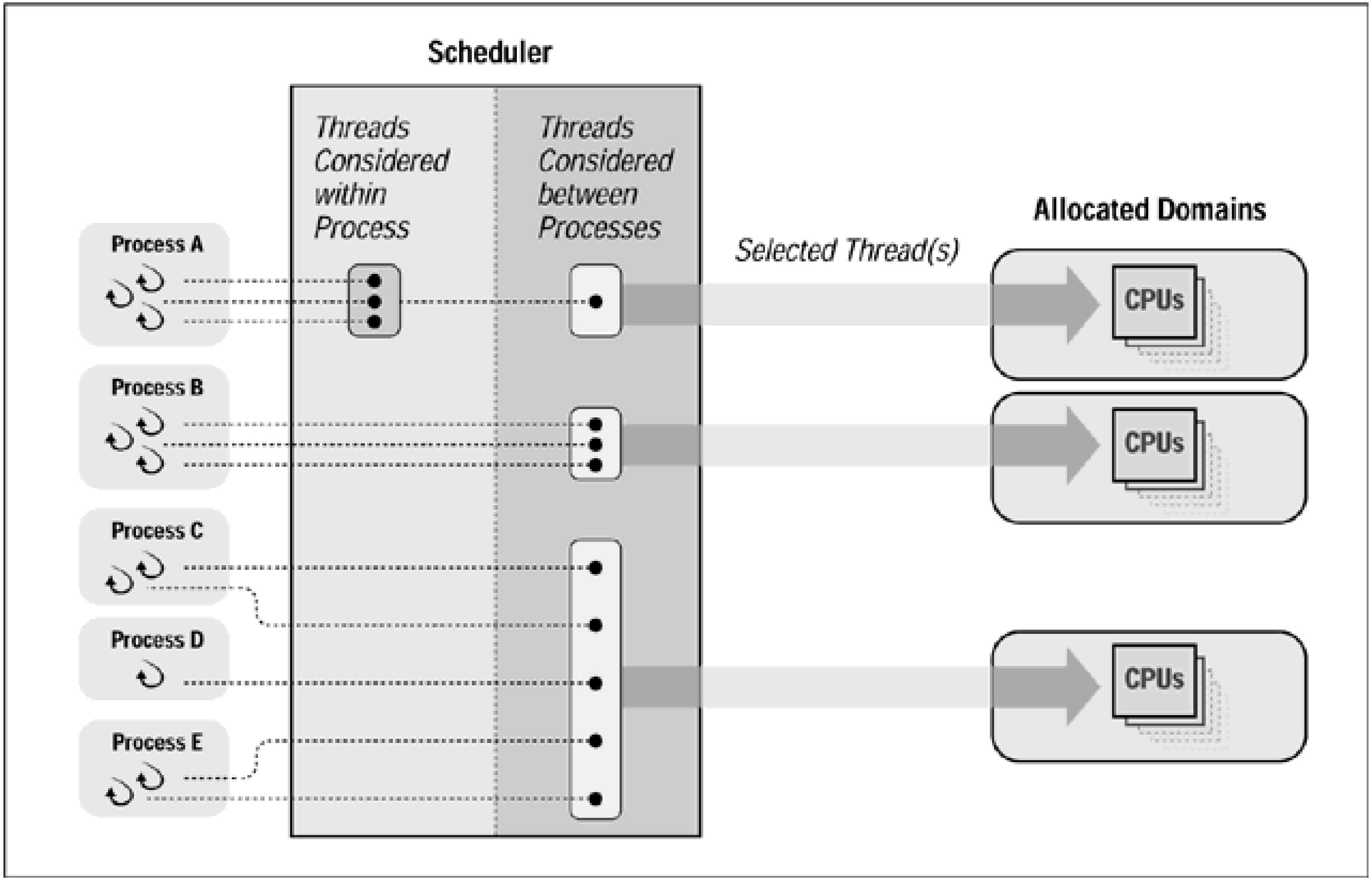
Computation: c1=25, c2=35
Periods: P1=50, P2=80

THREAD SCHEDULING

Thread Scheduling

- Local Scheduling – How the threads library decides which thread to put onto an available LWP
  - Process contention scope (PCS)
- Global Scheduling – How the kernel decides which kernel thread to run next
  - System contention scope (SCS)





http://maxim.int.ru/bookshelf/PthreadsProgram/htm/r_37.html

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, RR, 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);
   /* 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);
}
```

PTHREAD_SCOPE_SYSTEM
PTHREAD_SCOPE_PROCESS

SCHED_FIFO
SCHED_RR
SCHED_OTHER

OPERATING-SYSTEM EXAMPLES

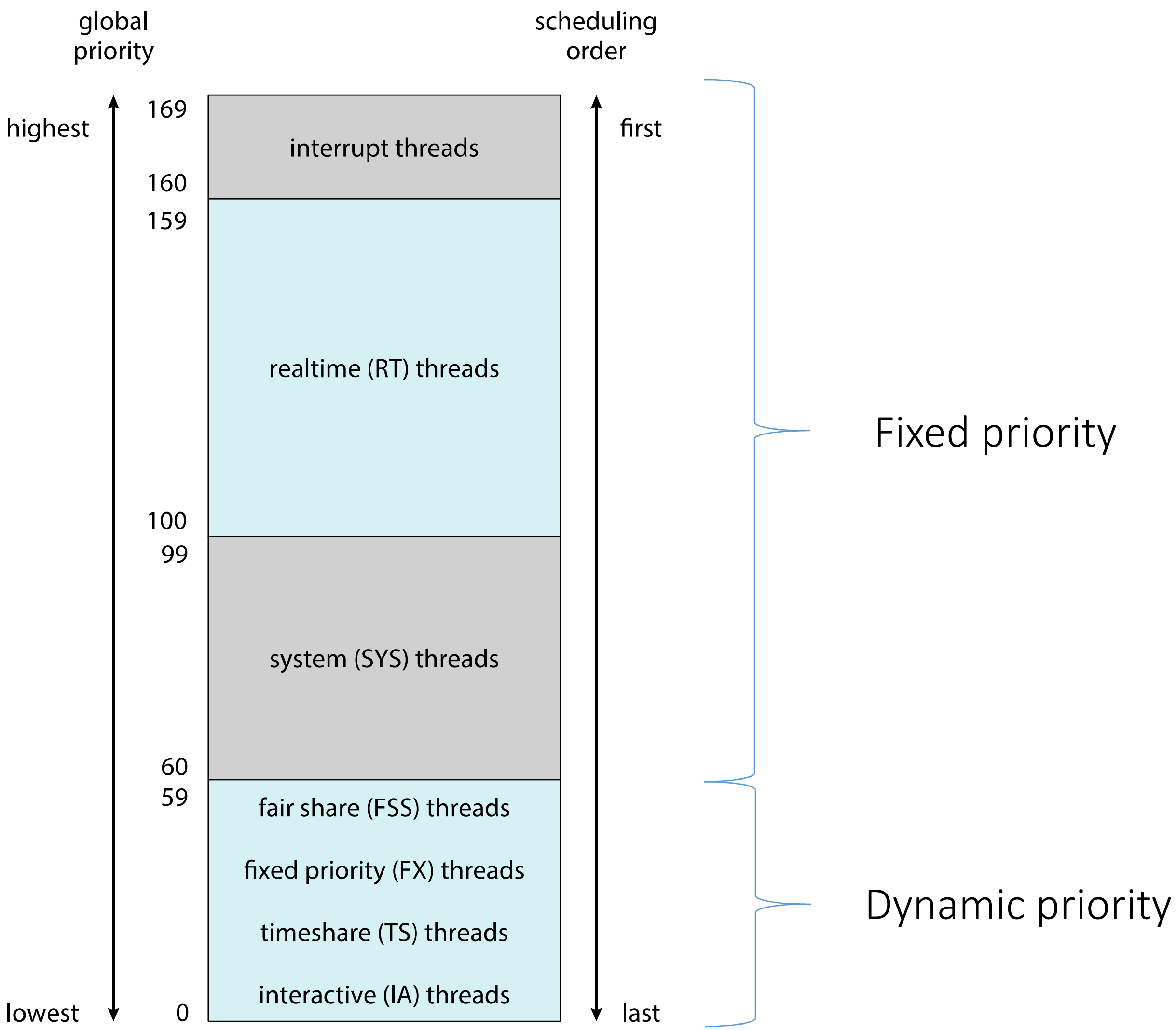
Operating System Examples

- Solaris scheduling
- Windows XP scheduling
- Linux scheduling

Solaris

- Priority-based scheduling
  - RR on threads of the same priority
- Six classes available
  - Time sharing (default) (TS)
  - Interactive (IA)
  - Real time (RT)
  - System (SYS)
  - Fair Share (FSS)
  - Fixed priority (FP)
- Given thread can be in one class at a time
- Each class has its own scheduling algorithm
- Time sharing is multi-level feedback queue
  - Loadable table configurable by sysadmin

Solaris 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

- Priority + → time quantum –
- Processes run out their time quantum are demoted
- Processes return from I/O operations are promoted

High

Windows Scheduling

- Windows uses priority-based preemptive scheduling
- Highest-priority thread runs next
- **Dispatcher** is scheduler
- Thread runs until (1) blocks, (2) uses time slice, (3) preempted by higher-priority thread
- Real-time threads can preempt non-real-time
- 32-level priority scheme
- **Variable class** is 1-15, **real-time class** is 16-31
- Priority 0 is memory-management thread
- Queue for each priority
- If no run-able thread, runs **idle thread**

Windows Priorities

Six priority classes

Fixed priority

Variable priority

	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

Relative priority with respect to a priority class

Priorities in each individual variable-priority classes are adjusted as they are in the feedback scheduling

Linux Scheduling in Version 2.6.23 +

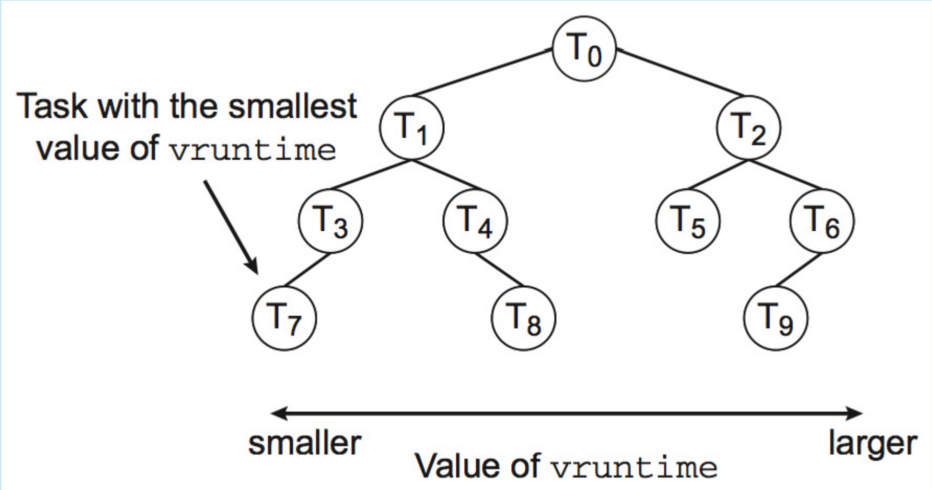
Round Robin平均分配，這個演算法能調配process得到的CPU時間

vruntime越慢得到的CPU越多

- Completely Fair Scheduler (CFS)
- Virtual runtime (vruntime)
  - Increases as a process executes on the CPU
  - The process of the smallest vruntime is selected for running
  - CFS favor IO-bound processes over CPU-bound processes
    - IO-bound processes increase their vruntime slower than CPU-bound processes
- Nice value
  - -20~+19 (high priority ~ low priority)
  - The increasing rate of vruntime
    - E.g., with -20, after a process runs 200ms, its vruntime increases less than 200ms
    - with +19, after a process runs 200ms, its vruntime increases larger than 200ms
  - Processes with small nice values increase their vruntime slower, and thus, receive larger portions of CPU time

CFS Performance

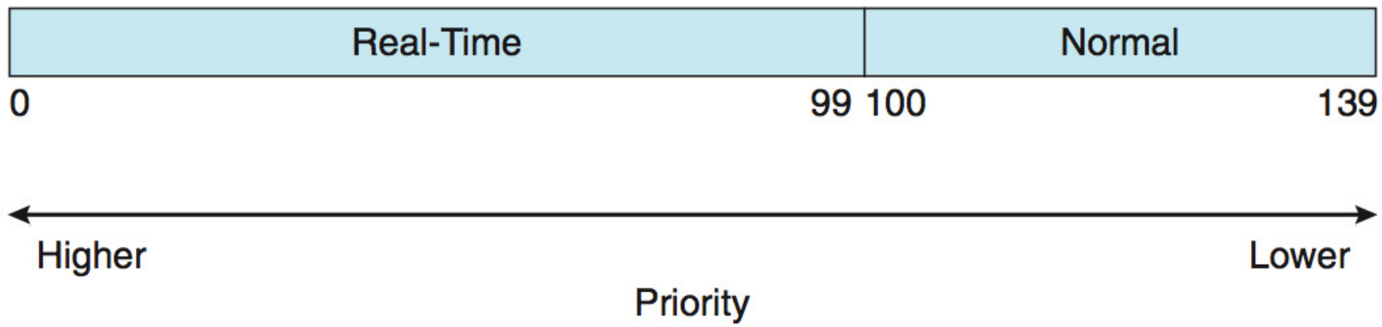
The Linux CFS scheduler provides an efficient algorithm for selecting which task to run next. Each runnable task is placed in a red-black tree—a balanced binary search tree whose key is based on the value of `vruntime`. This tree is shown below:



When a task becomes runnable, it is added to the tree. If a task on the tree is not runnable (for example, if it is blocked while waiting for I/O), it is removed. Generally speaking, 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. 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 $O(lg N)$ operations (where N is the number of nodes in the tree). However, for efficiency reasons, the Linux scheduler caches this value in the variable `rb_leftmost`, and thus determining which task to run next requires only retrieving the cached value.

Linux Scheduling (Cont.)

- Real-time processes in POSIX.1b
  - Real-time tasks have static priorities
  - Real-time plus normal map into global priority scheme
- Normal processes
  - Nice value of -20 maps to global priority 100
  - Nice value of +19 maps to priority 139



End of Chapter 5