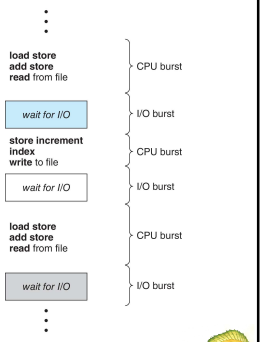
Chapter 4 : CPU Scheduling

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** followed by **I/O burst**
- CPU burst distribution is of main concern



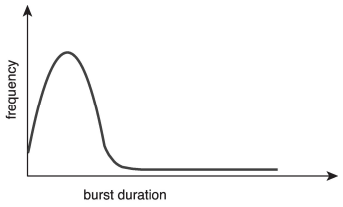
Chapter 4 : CPU Scheduling

- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Thread Scheduling
- Multi-Processor Scheduling
- Operating Systems Example
- Algorithm Evaluation

Histogram of CPU-burst Times

Large number of short bursts

Small number of longer bursts



Objectives

- Describe various CPU scheduling algorithms
- Assess CPU scheduling algorithms based on scheduling criteria
- Explain the issues related to multiprocessor and multicore scheduling
- Describe the scheduling algorithm used in the Windows operating system
- Apply modeling and simulations to evaluate CPU scheduling algorithms

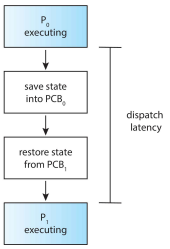
CPU Scheduler

- The **CPU scheduler** selects from among the processes in ready queue, and allocates a CPU core to one of them
  - Queue may be ordered in various ways
- 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
- Scheduling under 1 and 4 is **nonpreemptive**
- All other scheduling is **preemptive**
  - Consider access to shared data
  - Consider preemption while in kernel mode
  - Consider interrupts occurring during crucial OS activities

nonpreemptive: ไม่สามารถแทรกการทำงานกลางคัน
preemptive: แทรกการทำงานกลางคัน

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



Dispatcher: ตัวส่งข่าวสารไปยัง state อื่น , ตัวส่งต่อ

Scheduling Criteria

- **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
  (เวลาของโพรเซสที่ถูกประมวลผลนั้น ๆ จบการทำงาน)
- **Waiting time** – amount of time a process has been waiting in the ready queue (เวลาที่โพรเซสนั้น ๆ รอคอยที่ Ready queue ก่อนจะถูกประมวลผลกับ CPU)
- **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)

Scheduling Algorithm Optimization Criteria

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

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 mS
  P_1 P_2 P_3
- Average waiting time: (0 + 24 + 27)/3 = 17 mS
- Turnaround Time : P_1= 24 ; P_2= 27 ; P_3= 30 mS

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 mS
  P_1 P_2 P_3
- Average waiting time: (6 + 0 + 3)/3 = 3 mS
- Turnaround Time : P_1= 30 ; P_2= 3 ; P_3= 6 mS
- Much better than previous case
- **Convoy effect** - short process behind long process
  - Consider one CPU-bound and many I/O-bound processes

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 know as the Shortest-Remaining-Time-First (SRTF).
- 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

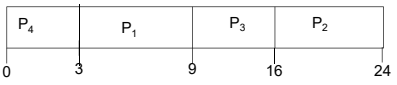
arrive : มาถึง

Example of SJF

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3

** ทุก Process มาถึงเวลาเดียวกัน

- SJF scheduling chart



P1 P2 P3 P4

- Average waiting time = (3 + 16 + 9 + 0) / 4 = 7 mS
- Turnaround Time : P_1= 9; P_2 = 24; P_3 =16; P_4= 3 ; mS

Practice: Shortest-remaining-time-first

- Now we add the concepts of varying arrival times and preemption to the analysis

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

- *Preemptive* SJF Gantt Chart

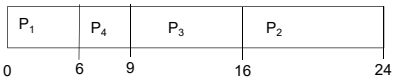
- Average waiting time = ????
- Turnaround time = ???

Example of nonpreemptive SJF

Process	Arrival Time	Burst Time
P_1	0.0	6
P_2	2.0	8
P_3	4.0	7
P_4	5.0	3

** Process มาถึงเวลาไม่เท่ากัน

- SJF scheduling chart : แบบ **nonpreemptive** ไม่สามารถแทรกการทำงานกลางคันได้



P1 P2 P3 P4

- Average waiting time =(0 + 14 + 5 + 1) / 4 = 20/4 = 5 mS

0-0 16-2 9-4 6-5

* คิด Arrival time ด้วย

- Turnaround Time = P_1= 6 , P_2= 22 , P_3= 12 , P_4= 4 mS

6-0 24-2 16-4 9-5

Round Robin (RR)

- Each process gets a small unit of CPU time (**time quantum** *q*), 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.
- Timer interrupts every quantum to schedule next process
- Performance
  - *q* large ⇒ FIFO
  - *q* small ⇒ *q* must be large with respect to context switch, otherwise overhead is too high

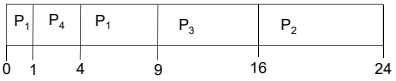
time quantum: ส่วนแบ่งเวลา

Example of preemptive SJF

Process	Arrival Time	Burst Time
P_1	0.0	6
P_2	2.0	8
P_3	4.0	7
P_4	1.0	3

** Process มาถึงเวลาไม่เท่ากัน

- SJF scheduling chart : แบบ **preemptive** แทรกการทำงานกลางคันได้



P1 P2 P3 P4

- Average waiting time = (3 + 14 + 5 + 0) / 4 = 22/4 = 5.5 mS

4-1 16-2 9-4 1-1

* คิด Arrival time ด้วย

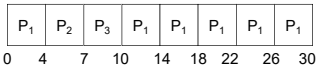
- Turnaround Time = ???

Example of RR with Time Quantum = 4

Process	Burst Time
P_1	24
P_2	3
P_3	3

* ทุก process มาถึงเวลาเดียวกัน

- The Gantt chart is:



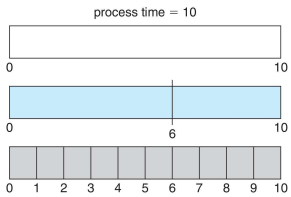
P1 P2 P3

- average waiting time: (6 + 4 + 7) /3 = 5.67 mS

26-4-4-4-4-4 4 7

- Turnaround time : P_1= 30 ; P_2 = 7 ; P_3= 10 ;
- Typically, higher average turnaround than SJF, but better *response*
- q should be large compared to context switch time
- q usually 10ms to 100ms, context switch < 10 usec

Time Quantum and Context Switch Time

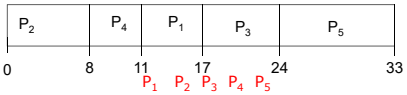


Example of Priority Scheduling

Process	Burst Time	Priority
P_1	6	3
P_2	8	1
P_3	7	4
P_4	3	2
P_5	9	5

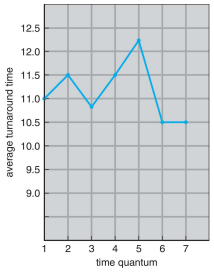
** ทุก Process มาถึงเวลาเดียวกัน

- priority scheduling chart



- Average waiting time = (11 + 0 + 17 + 8+ 24) / 5 = 12 mS
- Turnaround Time : P_1= 17; P_2 = 8; P_3 =24; P_4= 11; P_5= 33;

Turnaround Time Varies With The Time Quantum



process	time
P_1	6
P_2	3
P_3	1
P_4	7

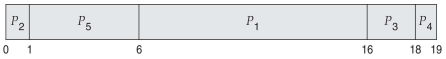
80% of CPU bursts should be shorter than q

Turnaround time depends on the size of quantum time

Practice: 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

- Priority scheduling Gantt Chart



- Average waiting time = ???
- Turnaround Time : ???

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 priority scheduling where priority is the inverse of predicted next CPU burst time
- Problem ≡ **Starvation** – low priority processes may never execute
- Solution ≡ **Aging** – as time progresses increase the priority of the process

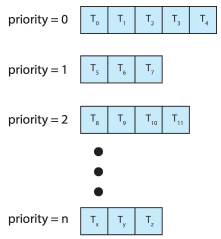
Practice: Priority Scheduling w/ Round-Robin

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

- Run the process with the highest priority. Processes with the same priority run round-robin
- จงเขียน Gantt Chart with 2 ms time quantum ???

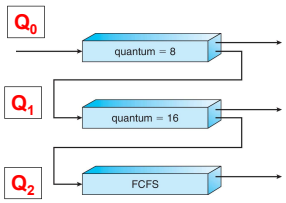
Multilevel Queue

- With priority scheduling, have separate queues for each priority.
- Schedule the process in the highest-priority queue!



Example of Multilevel Feedback Queue

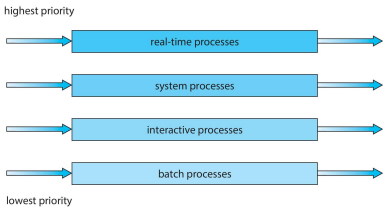
- Three queues:
  - Q_0 – RR with time quantum 8 milliseconds
  - Q_1 – RR time quantum 16 milliseconds
  - Q_2 – FCFS
- Scheduling
  - A new job enters queue Q_0 which is served FCFS
    - When it gains CPU, job receives 8 milliseconds
    - If it does not finish in 8 milliseconds, job is moved to queue 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



Queue อัดมาไม่สามารถถึงทำงานได้ หาก Queue ก่อนหน้าทำงานไม่เสร็จ หรือ อันไม่ empty หรือ อันไม่หมดช่วงเวลาที่กำหนดให้ (time quantum)

Multilevel Queue

- Prioritization based upon process type



Thread Scheduling

- Distinction between user-level and kernel-level threads
- When threads supported, threads scheduled, not processes
- 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
  - Typically done via priority set by programmer
- Kernel thread scheduled onto available CPU is **system-contention scope** (**SCS**) – competition among all threads in system

LWP: Light-Weight Process เป็นโพรเซสที่ทำงานอยู่ในส่วนของ user space ในกรณีที่มี LWP หลายตัวจะมีการใช้ทรัพยากรร่วมกันกับโพรเซสหลักด้วย

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

aging : เพิ่มลำดับขึ้น
demote: ลดลำดับลง

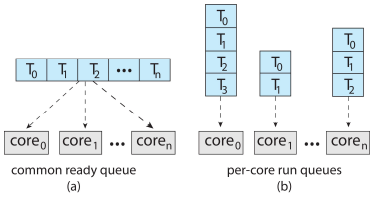
Multiple-Processor Scheduling

- CPU scheduling more complex when multiple CPUs are available
- Multiprocess may be any one of the following architectures:
  - Multicore CPUs
  - Multithreaded cores
  - NUMA systems
  - Heterogeneous multiprocessing

Homogeneous : แบบเดียวกัน เช่น cpu เป็น Intel เหมือนกัน
Heterogeneous : หลายแบบ เช่น cpu เป็น Intel, AMD, ultra spark

Multiple-Processor Scheduling

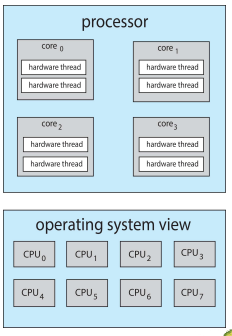
- Symmetric multiprocessing (SMP) is where each processor is self scheduling.
- All threads may be in a common ready queue (a)
- Each processor may have its own private queue of threads (b)



SMP: Symmetric Multiprocessing คือการทำงานที่แต่ละ Processor มีการจัดคาราง scheduling ของตัวเอง

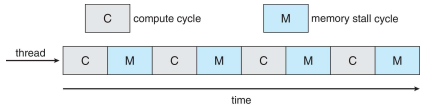
Multithreaded Multicore System

- **Chip-multithreading** (CMT) assigns each core multiple hardware threads. (Intel refers to this as **hyperthreading**.)
- On a quad-core system with 2 hardware threads per core, the operating system sees 8 logical processors.



Multicore Processors

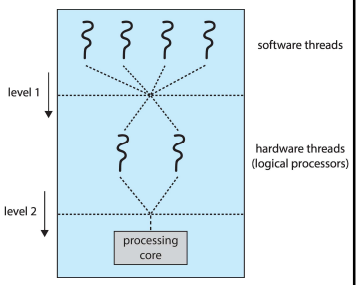
- Recent trend to place multiple processor cores on same physical chip
- Faster and consumes less power
- Multiple threads per core also growing
  - Takes advantage of memory stall to make progress on another thread while memory retrieve happens



Multithreaded Multicore System

- Two levels of scheduling:

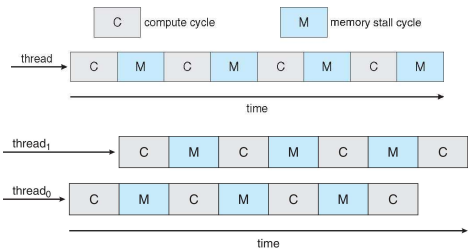
1. The operating system deciding which software thread to run on a logical CPU
2. How each core decides which hardware thread to run on the physical core.



Multithreaded Multicore System

Each core has > 1 hardware threads.

If one thread has a memory stall, switch to another thread!



memory stall cycle : ช่วงเวลาที่ cpu ต้องรอการนำข้อมูลที่ไม่ได้อยู่ในหน่วยความจำให้ถูกload มาไว้ในหน่วยความจำ

Multiple-Processor Scheduling – Load Balancing

- If SMP, need to keep all CPUs loaded for efficiency
- **Load balancing** attempts to keep workload evenly distributed
- **Push migration** – periodic task checks load on each processor, and if found pushes task from overloaded CPU to other CPUs
- **Pull migration** – idle processors pulls waiting task from busy processor

SMP: Symmetric Multiprocessing คือการทำงานที่แต่ละ Processor มีการจัดคาราง scheduling ของตัวเอง

Operating System Example

- Windows scheduling

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 Priority Classes

- Win32 API identifies several priority classes to which a process can belong
  - REALTIME_PRIORITY_CLASS, HIGH_PRIORITY_CLASS, ABOVE_NORMAL_PRIORITY_CLASS,NORMAL_PRIORITY_CLASS, BELOW_NORMAL_PRIORITY_CLASS, IDLE_PRIORITY_CLASS
  - All are variable except REALTIME
- A thread within a given priority class has a relative priority
  - TIME_CRITICAL, HIGHEST, ABOVE_NORMAL, NORMAL, BELOW_NORMAL, LOWEST, IDLE
- Priority class and relative priority combine to give numeric priority
- Base priority is NORMAL within the class
- If quantum expires, priority lowered, but never below base

Windows Priority Classes (Cont.)

- If wait occurs, priority boosted depending on what was waited for
- Foreground window given 3x priority boost
- Windows 7 added **user-mode scheduling** (**UMS**)
  - Applications create and manage threads independent of kernel
  - For large number of threads, much more efficient
  - UMS schedulers come from programming language libraries like C++ **Concurrent Runtime** (ConcRT) framework

Windows 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

Algorithm Evaluation

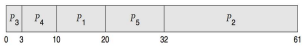
- How to select CPU-scheduling algorithm for an OS?
- Determine criteria, then evaluate algorithms
- **Deterministic modeling**
  - Type of **analytic evaluation**
  - Takes a particular predetermined workload and defines the performance of each algorithm for that workload
- Consider 5 processes arriving at time 0:

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

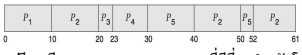
Deterministic Evaluation

- For each algorithm, calculate minimum average waiting time
- Simple and fast, but requires exact numbers for input, applies only to those inputs
  - FCS is 28ms:

  - Non-preemptive SFJ is 13ms:



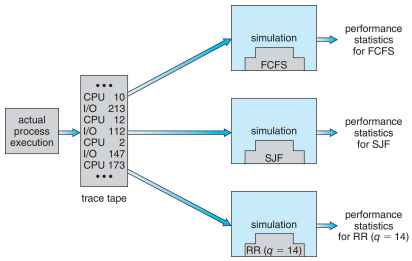
  - RR is 23ms:



การพิจารณาเปรียบเทียบ Scheduling Algorithm ที่ดีที่สุดสำหรับโพรเซสกลุ่มนี้ จะพิจารณาจากค่า average waiting time ของ Algorithm ที่มีค่าน้อยที่สุด

ดังนั้นในกรณีนี้ Algorithm Non-preemptive SJF ที่มีค่า 13 mS จึงดีที่สุด

Evaluation of CPU Schedulers by Simulation



Queueing Models

- Describes the arrival of processes, and CPU and I/O bursts probabilistically
  - Commonly exponential, and described by mean
  - Computes average throughput, utilization, waiting time, etc
- Computer system described as network of servers, each with queue of waiting processes
  - Knowing arrival rates and service rates
  - Computes utilization, average queue length, average wait time, etc

Implementation

- Even simulations have limited accuracy
- Just implement new scheduler and test in real systems
  - High cost, high risk
  - Environments vary
- Most flexible schedulers can be modified per-site or per-system
- Or APIs to modify priorities
- But again environments vary

Simulations

- Queueing models limited
- Simulations more accurate
  - Programmed model of computer system
  - Clock is a variable
  - Gather statistics indicating algorithm performance
  - Data to drive simulation gathered via
    - Random number generator according to probabilities
    - Distributions defined mathematically or empirically
    - Trace tapes record sequences of real events in real systems

End of Chapter 4