0117401: Operating System
计算机原理与设计
Chapter 5: CPU scheduling

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温馨提示：

为了您和他人的工作学习，

请在课堂上关机或静音。

不要在课堂上接打电话。

Chapter Objectives

- To introduce CPU scheduling.
- To describe various CPU-scheduling algorithms.
- To discuss evaluation crieria for selecting a CPU-scheduling algorithm for a particular system.

提纲——CPU scheduling

Outline

1. Basic Concepts
   - CPU-I/O Burst Cycle
   - CPU Scheduler
   - Preemptive Scheduling
   - Dispatcher

- Scheduling is a fundamental OS function.
  - Almost all computer resources are scheduled before use.
  - CPU scheduling is the basis of multiprogrammed OSes.

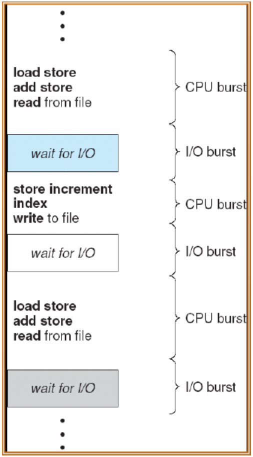
Objective of multiprogramming

- Maximum CPU utilization

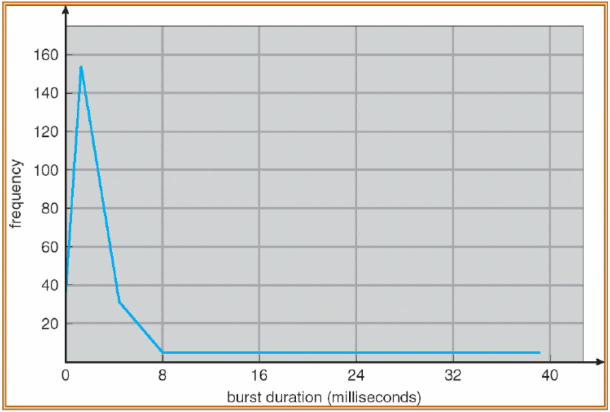
Outline

Basic Concepts: CPU-I/O Burst Cycle

- A property of process :
  CPU-I/O Burst Cycle
  - Process execution consists of a cycle of CPU execution and I/O wait
    - Alternating Sequence of CPU And I/O Bursts
    - Begin and end with a CPU burst
    - Process execution
      = n (CPU execution + I/O wait)
      + CPU execution



CPU burst distribution



Histogram of CPU-burst Times

Outline

- CPU scheduler (Short-term Scheduler)
  selects a process from the processes in memory that are ready to execute and allocates the CPU to the process
- Ready Queue could be:
  - a FIFO Queue?
  - a priority queue?
  - a tree?
  - an unordered linked list?

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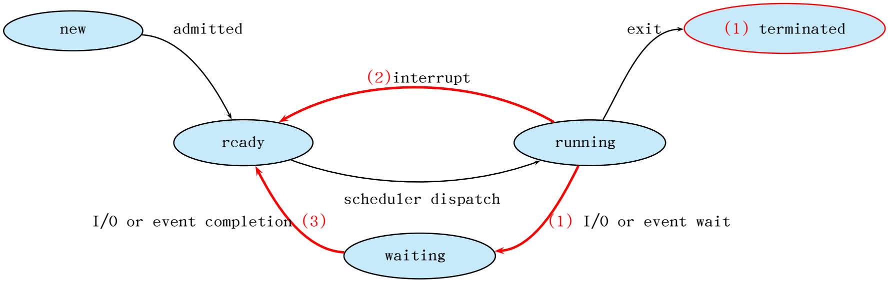
Preemptive Scheduling I

- 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

For 1 & 4, must schedule;
For 2 & 3, schedule? VS. not schedule?



Preemptive Scheduling II

- The scheduling scheme:
  - nonpreemptive(非抢占式): only 1 & 4
    - Windows 3.x
    - before Mac OS X
  - otherwise preemptive(抢占式)
    - Windows 95 & ...
    - Mac OS X
    - usually needs a hardware timer, synchronization overhead

Preemptive Scheduling III

Two processes sharing data

- If one process is preempted while it is updating the data.
- data is in an inconsistent(不一致) state

COST for preemption

1. needs special HW, for example, a timer.
2. synchronization overhead with shared data.

Preemption of the OS kernel

- What happens if the process is preempted in the middle of some activities that changes important kernel data?

- preemptive kernel VS. nonpreemptive kernel?
- Interrupt affected code VS normal kernel code?

- new mechnisms are needed, such as
  - disable interrupt
  - some synchronization mechnisms

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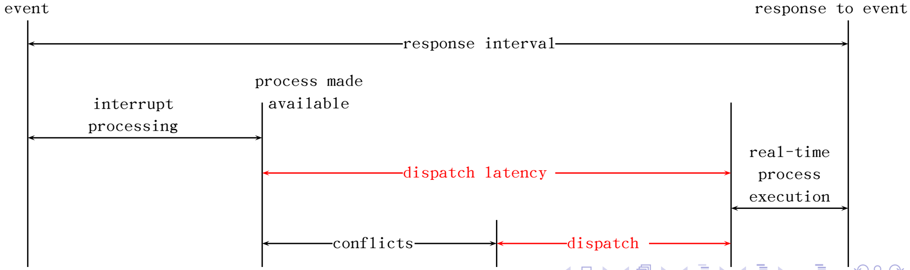
Dispatcher

- Dispatcher module gives control of the CPU to the process selected by the short-term scheduler; this involves:
  1. switching context
  2. switching to user mode
  3. 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
  - SHOULD be as fast as possible



Outline

2 Scheduling Criteria

- Scheduling Criteria

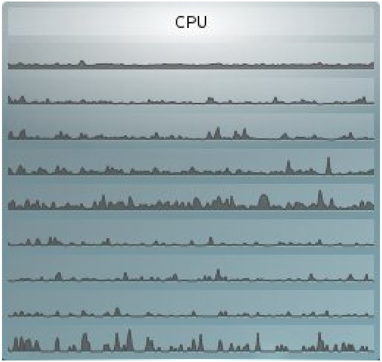
Outline

2 Scheduling Criteria

- Scheduling Criteria

Scheduling Criteria I

- CPU utilization （CPU 利用率） — keep the CPU as busy as possible
  - conceptually: $0\% \sim 100\%$; in a real system: $40\% \sim 90\%$



4核8线程编译Linux内核时的CPU利用率情况（0~7，总）

Scheduling Criteria II

- Throughput （吞吐率） — # of processes that complete their execution per time unit
  - different from one process set to another process set
  - for long processes: may be 1 process per hour
  - for short transactions: may be 10 processes per second
- Turnaround time (周转时间)— amount of time to execute a particular process
  - from the time of submission of a process to the time of completion
    = the periods spent waiting to get into memory, waiting in the ready queue, executing on the CPU, and doing I/O.
- Waiting time — amount of time a process has been waiting in the ready queue

Scheduling Criteria III

- 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

Optimization Criteria

- Maximize?
  - CPU utilization
  - throughput
- Minimize?
  - turnaround time
  - waiting time
  - response time
- Average?
- Stability?

different from system to system.

Outline

3. Scheduling Algorithms
   - FCFS Scheduling
   - SJF Scheduling
   - Priority Scheduling
   - Round Robin(时间片轮转) Scheduling
   - Multilevel Queue（多级队列） Scheduling
   - Multilevel Feedback Queue（多级反馈队列） Scheduling

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FCFS Scheduling

- First-Come, First-Served(先来先服务)
  - nonpreemptive(非抢占)
- Implementation:
  - Normal Queue: FIFO Queue
  - ordered by request time
  - linked list
  - Insert: linked to the tail of the queue
  - scheduling: removed from the head of the queue

Example of FCFS Scheduling

- Suppose that the processes arrive in the order:

  P1 , P2 , P3

Process	BurstTime(ms)
P1	24
P2	3
P3	3

- The Gantt Chart(甘特图) for the schedule is:

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

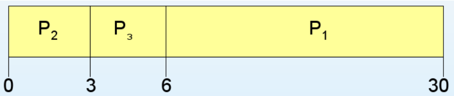
Example of FCFS Scheduling II

- Suppose that the processes arrive in the order

  P2 , P3 , P1

Process	BurstTime(ms)
P1	24
P2	3
P3	3

- The Gantt chart(甘特图) for the schedule is:



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

MUCH BETTER THAN PREVIOUS CASE!

Convoy effect（护航效应；护卫效应）

- example situation:
  - one CPU-bound process
  - many I/O-bound processes
- Convoy effect（护航效应；护卫效应）：
  - all the other processes wait for the one big process to get off the CPU
  - ≡short process behind long process

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SJF Scheduling

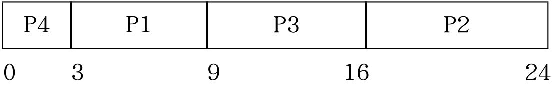
- Shortest-Job-First(短作业优先)
  Shortest-Next-CPU-Burst algorithm
  - Associate with each process the length of its next CPU burst.
  - Use these lengths to schedule the process with the shortest time.

SJF Scheduling

- SJF scheduling example

Process	BurstTime(ms)
P1	6
P2	8
P3	7
P4	3

- The Gantt chart for the schedule is:



1. Waiting time for P1 = 3; P2 = 16; P3 = 9; P4 = 0
2. Average waiting time: (3 + 16 + 9 + 0)/4 = 7

- If FCFS, average waiting time would be: (0 + 6 + 14 + 21)/4=10.25

SJF Scheduling

SJF is optimal(最优的)
— gives minimum average waiting time(平均等待时间最小) for a given set of processes

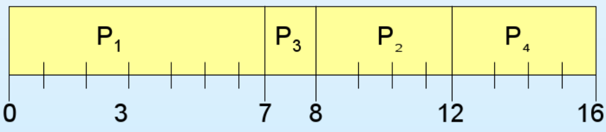
SJF scheduling schemes

- Two schemes:
  1. nonpreemptive
     — once CPU given to the process it cannot be preempted until completes its CPU burst
  2. 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)

1. Example of Non-Preemptive SJF

Process	ArrivalTime	BurstTime(ms)
P1	0.0	7
P2	2.0	4
P3	4.0	1
P4	5.0	4

- The Gantt chart for SJF (non-preemptive)

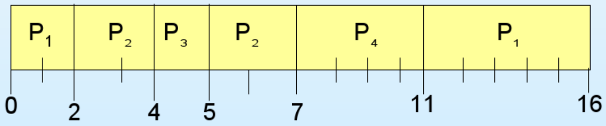


- Average waiting time = (0 + 6 + 3 + 7)/4 = 4

2. Example of Preemptive SJF

Process	ArrivalTime	BurstTime(ms)
P1	0.0	7
P2	2.0	4
P3	4.0	1
P4	5.0	4

- The Gantt chart for SJF (preemptive)



- Average waiting time = ((11 - 2) + (5 - 4) + 0 +(7 - 5))/4 = 3

Determining Length of Next CPU Burst

- For job scheduling:

  depend on user?

- For CPU scheduling:

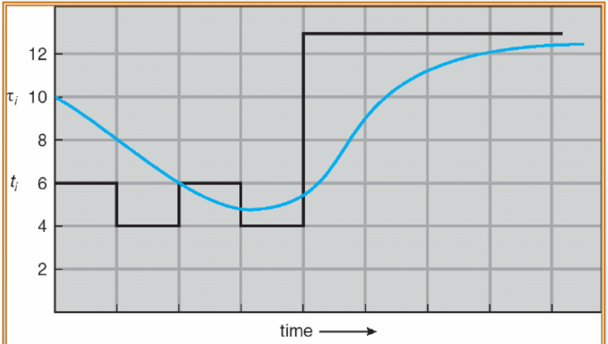
  can only estimate the length

- Example: by using the length of previous CPU bursts, using exponential averaging(指数平均)
  1. t_n =actual length of n^{th} CPU burst
  2. τ_{n+1}= predicted value for the next CPU burst
  3. α, $0 \leq \alpha \leq 1$
  4. Define: $\tau_{n+1} = \alpha t_n + (1-\alpha)\tau_n$
- If we expand the formula, we get:

$$\tau_{n+1} = \alpha\tau_n + (1-\alpha)\,\alpha\tau_{n-1} + \cdots + (1-\alpha)^j\,\alpha\tau_{n-j} + \cdots + (1-\alpha)^{n+1}\,\tau_0$$

Since $0 \leq \alpha,\ 1-\alpha \leq 1$, each successive term has less weight than its predecessor

- Prediction of the Length of the Next CPU Burst
  - Example: $\alpha = 1/2;\ \tau_0 = 10$



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

Determining Length of Next CPU Burst

- Examples of Exponential Averaging
  - if $\alpha = 0$
    - $\tau_{n+1} = \alpha t_n + (1-\alpha)\tau_n = \mathbf{0} \cdot t_n + \tau_n = \tau_n$
    - Recent history does not count
  - if $\alpha = 1$
    - $\tau_{n+1} = \alpha t_n + (1-\alpha)\tau_n = t_n + \mathbf{0} \cdot \tau_n = t_n$
    - Only the actual last CPU burst counts

Outline

Priority(优先级) Scheduling

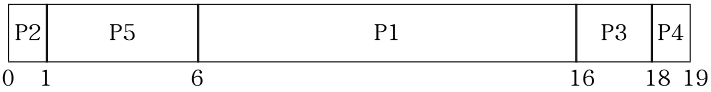
- A priority number(优先数) is associated with each process
  - priority number(优先数) VS. priority(优先级)
  - usually an integer, &
    usually, smallest integer ≡ highest priority
- The CPU is allocated to the process with the highest priority
  - Preemptive VS. Nonpreemptive
- SJF is a special case of general priority scheduling where priority is the predicted next CPU burst time

Priority(优先级) Scheduling

- Example

Process	BurstTime(ms)	Priority
P1	10	3
P2	1	1
P3	2	4
P4	1	5
P5	5	2

- The Gantt chart for the schedule is:



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

Priority(优先级) Scheduling

- The determination of priority
  - internally, for example:
    - time limits, memory requirement, the number of open files, ...
  - externally, for example:
    - the importance, the type and amount of funds, the department, ...
- Priority Scheduling problem - Starvation (indefinite blocking):
  low priority processes may never execute
  - Solution - Aging:
    as time progresses increase the priority of the process
    - Example:
      priorities: 127(low)~0(high)
      the priority of a waiting process is increased by 1 every 15 minutes
      How long from127 to 0?

Outline

3 Scheduling Algorithms

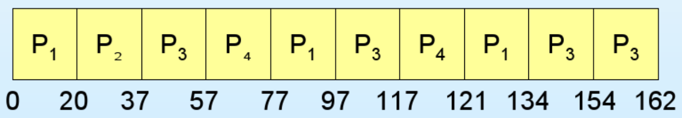
Round Robin（时间片轮转，RR）Scheduling

- Time quantum, time slice(时间片)
  - a small unit of CPU time
  - usually 10-100 ms
- Implementation
  - Ready queue: a FIFO circular queue
  - Each process gets 1 time quantum
  - Insert: to the tail of the queue
  - Scheduling: pick the first process; set timer; and dispatch
  - two situation:
    - CPU burst $\leq$1 time quantum
    - CPU burst > 1 time quantum. After this time has elapsed, the process is preempted(被抢占) and added to the end of the ready queue.

- Example of RR with Time Quantum = 20

Process	BurstTime
P1	53
P2	17
P3	68
P4	24

  - The Gantt chart is:



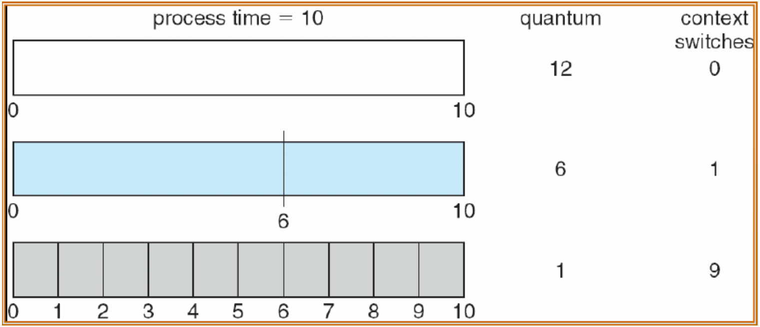
- Typically, higher average turnaround than SJF, but better response

Round Robin（时间片轮转，RR）Scheduling

- Performance
  - 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.
    - Example: 5 processes, time quantum=20ms
  - The performance of RR dependes heavily on the size of the time quantum.
    - if q is too large? ⇒FIFO
    - if q is too small? ⇒q must be large with respect to context switch, otherwise overhead is too high

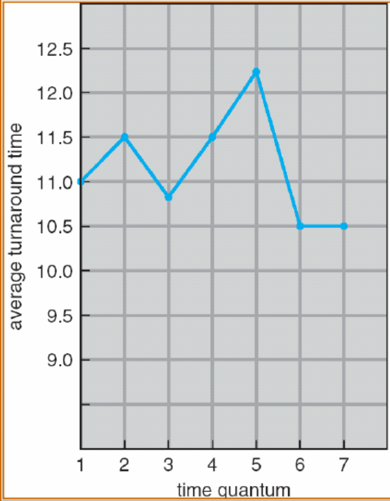
Time Quantum and Context Switch Time

- The effect of context switching on the performance of RR scheduling



- typically the context-switch time is a small fraction of the time quantum
  - usually: time quantum: 10 ~100ms & context switch time: 10μs

Turnaround Time Varies With The Time Quantum



process	time
P_1	6
P_2	3
P_3	1
P_4	7

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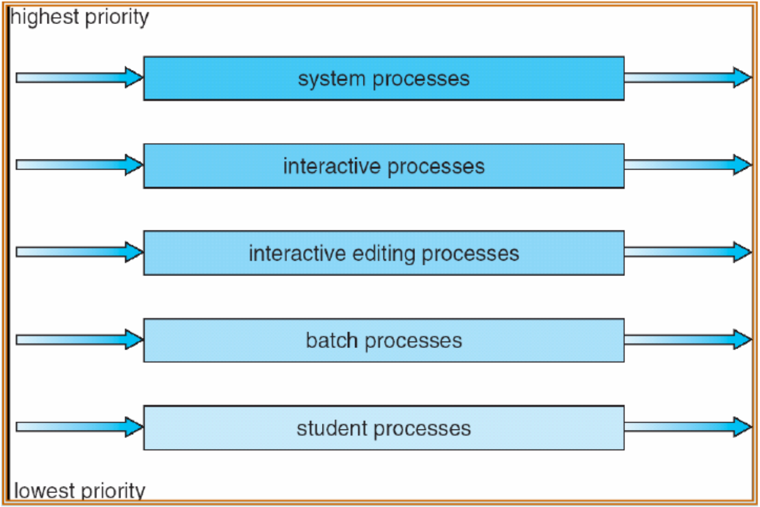
Multilevel Queue（多级队列） Scheduling I

- Ready queue is partitioned into separate queues. Each queue has its own scheduling algorithm
  - foreground (interactive) — RR
  - background (batch) — FCFS
- Scheduling must be done between the queues
  - Fixed priority scheduling;
    - Example: 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

example


highest priority
system processes
interactive processes
interactive editing processes
batch processes
student processes
lowest priority

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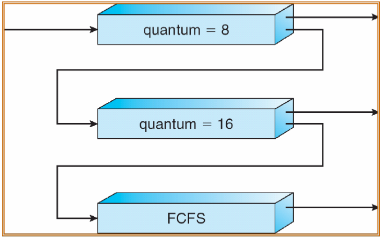
Multilevel-Feedback-Queue(多级反馈队列) Scheduling

- A process can move between the various queues; aging can be implemented this way
- Multilevel-feedback-queue(多级反馈队列) 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 8ms
  - Q_1 — RR time quantum 16ms
  - Q_2 — FCFS



- Scheduling
  - A new job enters Q_0 which is served FCFS.
    When it gains CPU, job receives 8ms.
    If it does not finish in 8ms, job is moved to Q_1.
  - At Q_1 job is again served FCFS and receives additional 16ms.
    If it still does not complete, it is preempted and moved to Q_2.

Outline

Multiple-Processor Scheduling

- One single processor $\rightarrow$ multiple CPUS
  - CPU scheduling more complex
  - Load sharing
- To be simple, suppose
  - the processors are identical — homogeneous — in terms of their functionality
  - so, any processor can execute any process in the queue

Multiple-Processor Scheduling

- Approches to Multiple-Processor Scheduling
  - Asymmetric multiprocessing — only one processor accesses the system data structures, alleviating the need for data sharing
  - Symmetric multiprocessing √
    - one common ready queue, or
    - one private ready queue for each processor

Multiple-Processor Scheduling

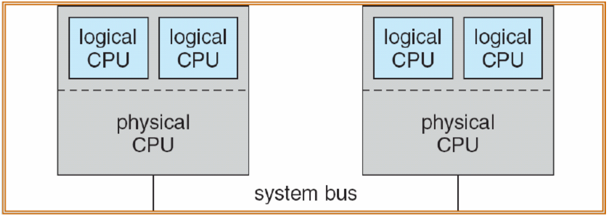
- Processor Affinity
  - Migration of processes from one processor to another processor COSTs much.
    - For example: cache
    - most SMP systems try to avoid such migration
  - Processor affinity(亲和性):
    a process has an affinity for the processor on which it is currently running.
  - SOFT affinity VS. HARD affinity.

Multiple-Processor Scheduling

- Load Balancing
  - Load balanceing attempts to keep the workload evenly
    - for SMP system with one private ready queue for each processor
  - two general approaches
    - push migration(迁移)
    - pull migration

    often works together in load balancing systems
  - load balancing VS. processor affinity

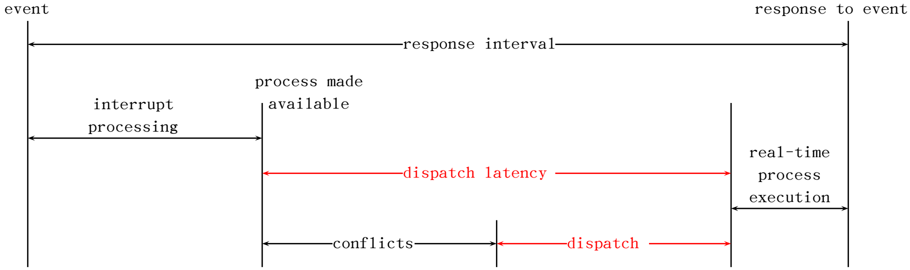
- Symmetric Multithreading
  - INTEL: hyperthreading technology (HT)
  - logical processors VS. physical processors
    - each logical processor has its own architecture state, including general-purpose registers and machine-state registers, and interrupts
    - share: cache memory and bueses
  - ? from the viewpoint of OS ?



Outline

Real-Time Scheduling

- Hard real-time systems — required to complete a critical task within a guaranteed amount of time
- Soft real-time computing — requires that critical processes receive priority over less fortunate ones
- OS
  1. priority scheduling
  2. short dispatch latency
- approaches for short dispatch latency
  1. preemption
     1. preemption point (抢占点) in system calls with long period
     2. preemptible kernel
  2. priority inversion
     1. priority-inheritance protocol
     2. priority-ceiling protocol



conflicts=preemption + resource releasing by processes with lower priority

6 OS examples
- Linux Scheduling
- uC/os-II scheduling

OS examples

- READING
  - Solaris (thread)
  - Windows (thread)
  - Linux (process)$\surd$
  - $\mu C/OS - II$$\surd$

Outline

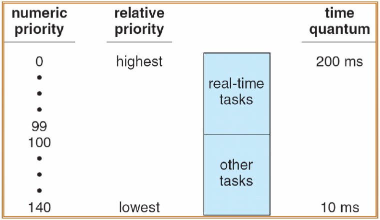
6 OS examples
- Linux Scheduling
- uC/os-II scheduling

Linux Scheduling

- Linux is a general-purpose OS
  - Processes: time-sharing/real-time
  - Linux scheduler is both time-sharing-based and priority-based
    - With the changing of version, time-sharing technique changes too
- Scheduling policy:
  是一组规则，它们决定什么时候以怎样的方式选择一个新进程运行。
  Linux 2.6.26中
  - SCHED_NORMAL
  - SCHED_FIFO (for real-time process)
  - SCHED_RR (for real-time process)
  - SCHED_BATCH
  - SCHED_IDLE

Priorities

- The Linux scheduler: preemptive, priority-based
  - two seperate priority ranges: lower value ≡ higher priority
    real-time range: 0~99
    a nice value rang: 100~140
- higher-priority ⇒ longer time quanta
  (Unlike Solaris and Windows XP)

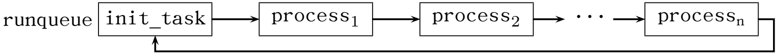


The Relationship Between Priorities and Time-slice length List of Tasks

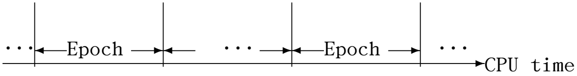
Priorities

- The Linux scheduler: preemptive, priority-based
  - two seperate priority ranges: lower value ≡ higher priority
    real-time range: 0~99
    a nice value rang: 100~140
- higher-priority ⇒ longer time quanta
  (Unlike Solaris and Windows XP)
- Dynamic priorities:
  scheduler may change the priority of a process
  - 较长时间未分配到CPU的进程，通常 ↑
  - 已经在CPU上运行了较长时间的进程，通常 ↓

- Linux 2.4 scheduler
  - need to traverse the runqueue, O(n)

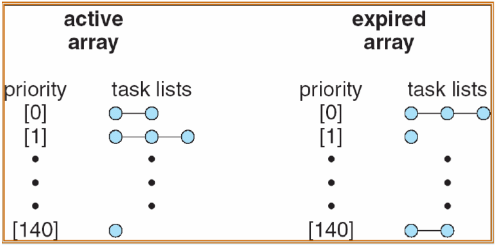


  - Epoch，default time slice (基本时间片)，dynamic priorities



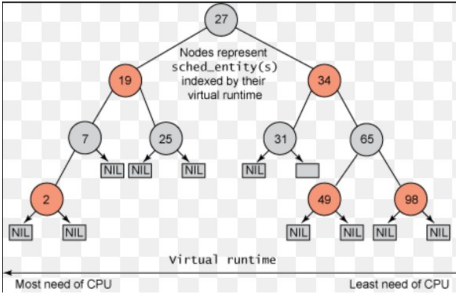
Linux scheduling algorithms

- Linux 2.6.17 scheduler (<2.6.23)
  - O(1)
  - Double priority-based arrays (双队列): active & expire



List of tasks indexed according to priorities

- Linux 2.6.26 scheduler ($\geq$2.6.23)
  - O(1)
  - non-real-time: Complete-Fair-Scheduling(CFS, 完全公平调度), vruntime, red-black tree (红黑树)
  - real-time: priority arrays



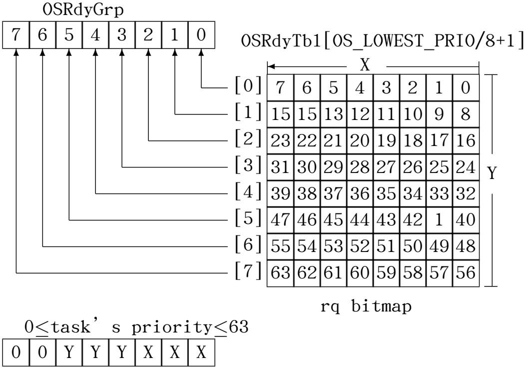
Outline

6 OS examples

- Linux Scheduling
- uC/os-II scheduling

uC/os-II scheduling

- Priority-based scheduler
  - MAX Tasks: 64
  - priority number: 0~63



Outline

Algorithm Evaluation

- How do we select a CPU scheduling algorithm for a particular system?
  - firstly, which criteria? What is the relative importance of these measures
  - then, evaluate the algorithms
    1. Deterministic Modeling(确定性建模)
    2. Queueing Models(排队模型)
    3. Simulations(模拟)
    4. Implementation

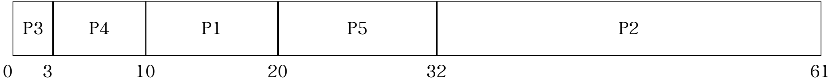
- Analytic evaluation(分析评估法): One major class of evaluation methods
  - uses the given algorithm and the system workload to produce a formula or number that evaluates the performance of the algorithm for that workload.
- Deterministic modeling(确定性建模) — takes a particular predetermined workload and defines the performance of each algorithm for that workload
- Example - Consider FCFS, SJF, and RR (quantum=10ms)

Process	BurstTime
P1	10
P2	29
P3	3
P4	7
P5	12

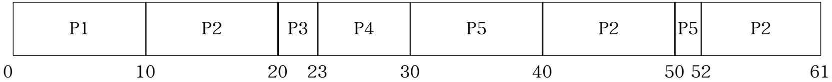
1. Deterministic Modeling(确定性建模) II

1. FCFS: average waiting time =(0+10+39+42+49)/5=28

2. SJF: average waiting time =(10+32+0+3+20)/5=13



3. RR: average waiting time =(0+(10+20+2)+20+23+(30+10))/5=23



- advantages and disadvantages
  - 确定性 vs. 适用性和实用性

2. Queueing Models(排队模型)

- Usually, two distributions can be measured and then approximated or simply estimated
  - the distribution of CPU and I/O bursts
  - the arrival-time distribution
- Queueing-network analysis(排队网络分析)
  - Computer System: a network of servers, each server has a queue of waiting processes
    - CPU: ready queue;
    - I/O: device queues (≡waiting queue)
  - Given arriving rates and service rates ⇒utilization, average queue length, average wait time, ...

- Example:
  1. n: the average queue length
  2. W: the average waiting time
  3. λ: the average arrival rate

  for a steady waits (Little formula, Little公式):

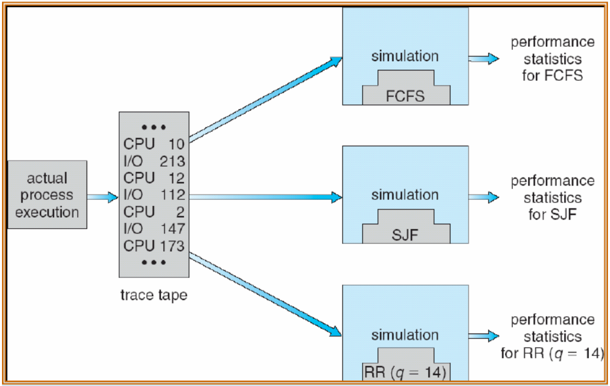
$$n = \lambda \times W$$

  - Little formula is particularly useful because it is valid for any scheduling algorithm and arrival distribution.
  - If we know two of the three variables, we can use Little formula to compute the other one.

3. Simulations(模拟) I

- Running simulations involves programming a model of the computer system.
  - Software data structures represent the major components
    - a clock
    - the system state is modified to reflect the activities of the devices, the processes and the scheduler.
  - finally, the statictics are gathered
- How to generate the data to drive the simulation?
  - distribution-driven simulation
    - ramdon-number generator, according to probability distributions, to generate processes, CPU burst times, arrivals, departures, ...
    - the distributions can be defined mathematically(uniform, exponential, Poisson) or empirically
    - may be inaccurate

- trace tapes(跟踪磁带)



eveluation of CPU schedulers by simulation

4. Implementation

- This approach put the actual algorithm in the real system for evaluation under real operating conditions
- the main difficulty: high cost

Outline

8 小结和作业

小结

1. Basic Concepts
   - CPU-I/O Burst Cycle
   - CPU Scheduler
   - Preemptive Scheduling
   - Dispatcher
2. Scheduling Criteria
   - Scheduling Criteria
3. Scheduling Algorithms
   - FCFS Scheduling
   - SJF Scheduling
   - Priority Scheduling
   - Round Robin(时间片轮转) Scheduling
   - Multilevel Queue（多级队列） Scheduling
   - Multilevel Feedback Queue（多级反馈队列） Scheduling
4. Multiple-Processor Scheduling
5. Real-Time Scheduling
6. OS examples
   - Linux Scheduling
   - uC/os-II scheduling
7. Algorithm Evaluation
8. 小结和作业

作业和上机

- 参见课程主页

谢谢！