

## Basic Concepts

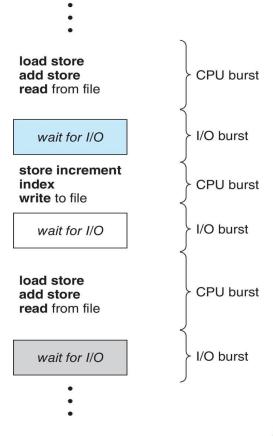


□ The objective of multiprogramming is to try to have a process running at all times → maximize CPU utilization 利用率

□ Process execution consists of cycles of CPU execution and I/O wait – referred as CPU burst and I/O burst (when not running on CPU)

□ Whenever CPU is idle, OS tries to select one of processes on the ready queue to execute unless the ready queue is empty, i.e., no process is in ready state

□ The selection of process is done by the CPU scheduler or also called process scheduler, short-term scheduler



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## Chapter 5: CPU Scheduling



- Basic Concepts
- Scheduling Criteria 调度标准
- Scheduling Algorithms
- Thread Scheduling 线程调度
- Multi-Processor Scheduling 多处理器调度
- Real-Time Scheduling 实时调度
- Algorithm Evaluation 算法评估

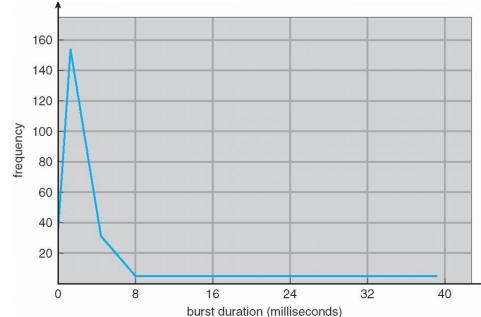
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## Histogram of CPU-burst Times

- 直方图
- The durations of CPU bursts have been measured extensively over the years. The frequency curve is similar to that shown below
  - There are many short CPU bursts and a small number of long CPU bursts (long-tail distribution). An I/O-bound program typically has many short CPU bursts, while a CPU-bound program might have a few long CPU bursts.
  - This distribution is important for designing a CPU-scheduling algorithm



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## Objectives

- Describe various CPU scheduling algorithms
- Evaluate CPU scheduling algorithms based on scheduling criteria
- Explain the issues related to multiprocessor and multicore scheduling
- Describe real-time scheduling algorithms
- Apply modeling and simulations to evaluate CPU scheduling algorithms

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## CPU Scheduler

- The CPU scheduler selects one process or thread from processes on ready queue, and allocates the CPU core to the selected process
  - Queue may be ordered in various ways, single or multiple queues
- CPU scheduling may take place in the following four conditions:
  1. Switches from running to waiting state, e.g., I/O request, or wait()
  2. Process terminates
  3. Switches from running to ready state, e.g., interrupt
  4. Switches from waiting to ready, e.g., completion of I/O or from new to ready, a new process arrives on the ready queue with a higher priority
- Scheduling under 1 and 2 is non-preemptive, in which a process gives up CPU voluntarily by itself
- Scheduling under 3 and 4 is preemptive 强占式的
  - Consider access to shared data (discussed in Chapter 6)
  - Consider preemption while in kernel mode
  - Consider interrupts occurring during crucial OS activities

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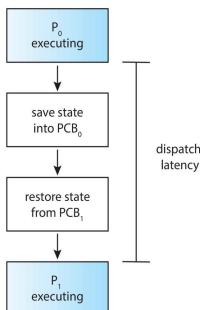


## Dispatcher 调度器



- Dispatcher module allocates the CPU to the process selected by CPU scheduler; this involves:

- switching context from one process to another
  - switching to user mode
  - jumping to the proper location in the user program to restart that program
- 调度延迟**
- Dispatch latency – the time it takes for the dispatcher to stop one process and start another running – an overhead
  - The number of context switches can be obtained by using `vmstat` on Linux, typically hundreds of context switches per second



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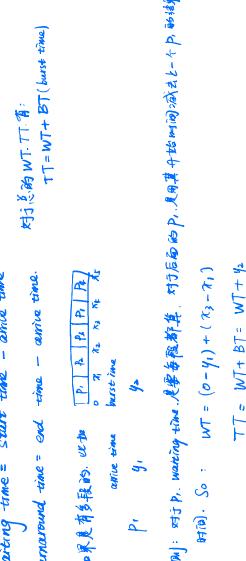


## Scheduling Criteria 调度标准

- CPU utilization** – fraction of the time that CPU is busy
- Throughput** – # of processes or jobs completed per time unit
  - Efficient use of the resources (CPU, memory, disk, etc.), favor short processes
- Waiting time** – amount of time a process waiting on the ready queue
- Turnaround time** – the amount of time to execute a particular process, measured by CPU burst time, I/O burst time and waiting time
  - With a single CPU burst, the turnaround time = waiting time + CPU burst time
- Response time** – the amount of time it takes from when a request is submitted until the first response is produced
  - Time to echo a keystroke in editor, or games
  - This is more relevant to interactive programs (typically using RR scheduling)
  - Considering single CPU burst, this is the time between the completion of first CPU time minus the time that this process joins the ready queue
- Fairness**
  - Resources such as CPU are utilized in some “fair” manner

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## Scheduling Criteria (Cont.)

- It is desirable to maximize CPU utilization and throughput and to minimize turnaround time, waiting time, and response time. But these can be conflicting set of criteria, there are different considerations in practice
- In most cases, we optimize an average measure, e.g., the average waiting time or average turn-around time. However, under special circumstances, we prefer to optimize the minimum or maximum values rather than the average
  - Considering all users, we may want to minimize the maximum response time
- For interactive systems (such as a desktop or laptop), it might be more important to minimize the variance in the response time than to minimize the average response time
  - A system with reasonable and predictable response time may be considered more desirable than a system that is faster on the average but is highly variable
- Different CPU-scheduling algorithms have different properties. we next describe several scheduling algorithms in the context of **only one CPU core** – the system is capable of only running one process or thread at a time

以下算法都是 only one CPU core

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## First-Come, First-Served (FCFS) Scheduling

先到先服务

Process	Burst Time
$P_1$	24
$P_2$	3
$P_3$	3

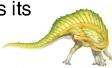
- Suppose that the processes arrive in the order:  $P_1, P_2, P_3$ . The Gantt Chart for the schedule is:



- Waiting time for  $P_1 = 0$ ;  $P_2 = 24$ ;  $P_3 = 27$
- Average waiting time:  $(0 + 24 + 27)/3 = 17$
- Average turn-around time:  $(24+27+30)/3 = 27$
- In earlier systems, FCFS means that one program is scheduled to run until completion including all I/O
- In multiprogramming systems, this usually means a process finishes its current CPU burst time

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## 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 shorter!)
  - Average turn-around time:  $(30+3+6)/3 = 13$
- 排队延时** Convoy effect – A short process stuck behind a long process, bad for short jobs, depending purely on the arrival order
- Consider one CPU-bound and many I/O-bound processes, FCFS results also in low I/O device utilization
  - Waiting in banks: depositing a check, stuck behind new account opening

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## Round Robin (RR) 轮转调度.

- The FCFS scheduling algorithm is **non-preemptive**. Once the CPU core allocated to a process, the process keeps the CPU until it releases CPU
- The FCFS is thus particularly troublesome for interactive systems, where it is important that each process get a share of the CPU at regular intervals.
- The **round-robin (RR)** scheduling algorithm is similar to FCFS scheduling, but preemption is added to enable system to switch between processes
- 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 **被抢占** and added to the **end of the ready queue** (exactly like FCFS).
- Given  $n$  processes, each process gets  $1/n$  of the CPU time in chunks of at most  $q$  time units at once – context switching time is ignored
  - No process waits more than  $(n-1)q$  time units.
- A **timer** interrupts every quantum to schedule next process, or the process **blocks** upon completing its current CPU burst time **when its CPU burst time or remaining CPU burst time < q**.

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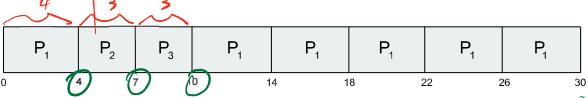


## Example of RR with Time Quantum = 4

Process	Burst Time
$P_1$	24
$P_2$	3
$P_3$	3

RR,  $q=4$ , 但  $P_2, P_3$  只用 3 就可以执行完。

- The Gantt chart is:

Waiting time for  $P_1=6, P_2=4, P_3=7$ 

- Average waiting time  $(6+4+7)/3 = 5.67$
- Average turn-around time:  $(30+7+10)/3 = 15.67$

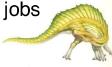
Response time for  $P_1=4, P_2=7, P_3=10$ , average = 7

- The average waiting time under RR policy can be long, but is inherently more "fair" (FIFO order), usually perform better for short jobs than FCFS, and offers better average response time – important for interactive jobs

看前面 ppt 中有关义。

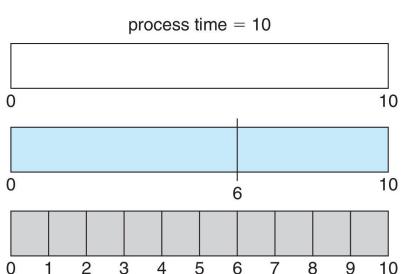
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## Time Quantum and Context Switch Time

- The performance of the RR algorithm depends heavily on the size of the **time quantum**
  - $q$  large  $\Rightarrow$  FCFS
  - $q$  small  $\Rightarrow$  interleaved, but  $q$  must be large with respect to context switch time (usually  $< 10$  usec), otherwise overhead is too high

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## Comparisons between FCFS and RR

Assuming zero-cost context-switching time, is RR **always better** than FCFS? **No!**

- An example: 10 jobs starting at the same time, each taking 100s of CPU time; RR scheduler quantum of 1s;

Job #	FIFO	RR
1	100	991
2	200	992
...	...	...
9	900	999
10	1000	1000

The average job turn-around time is much worse under RR!

- Bad when all jobs have the same length
- The average response time is much better

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轮转调度 (RR) 的优点  
1. 公平性：每个进程都能在固定时间间隔内获得CPU，适合需要快速响应的交互式任务。  
2. 短作业优先：短进程可以更快完成，减少了某些进程长时得不到执行的情况。

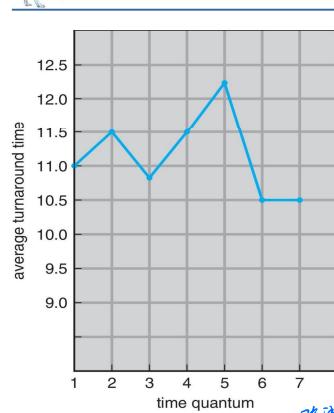
### 先来先服务 (FCFS) 的优点

- 简单性：实现简单，易于理解和支持。
- 短作业优先：进程按到达顺序执行，避免了某些进程长时间得不到执行的情况。

### 何时选择RR或FCFS

- RR更好：适合需要频繁交互的场景，例如操作系统的用户界面应用。
- FCFS更好：适合长作业的场景，特别是当进程的执行时间差异不大时。

## Turnaround Time Varies With The Time Quantum



- The average turnaround time does not necessarily improve when the quantum increases
- In general, the average turnaround time can be improved if most processes finish their current CPU bursts within a single quantum
- The time quantum **can not be too big**, in which RR degrades to an FCFS policy
- A rule of thumb:** 80% CPU bursts should be shorter than the time quantum  $q$

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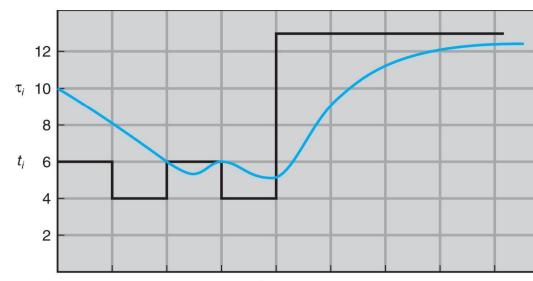


## Shortest-Job-First (SJF) Scheduling

- Noticing that in FCFS and RR, we do not need to know the next CPU burst time of each process during scheduling, and scheduling is done solely based on the arrival order to the ready queue
- What if we knew the future – the next CPU burst time of each process
- Associate with each process the length of its next CPU burst
  - To schedule the process with the shortest next CPU burst
- The Shortest Job First or SJF scheduling algorithm is optimal – it produces the minimum average waiting time for a given set of processes
- The difficulty is knowing the length of the next CPU request
  - The basic idea is to get the short jobs out of the system sooner
- Big effect on short jobs, relatively small effect on long jobs
  - This can be applied to an entire program, or the current CPU burst
  - Perhaps a more precise term should be the shortest-next-CPU-burst algorithm, but shortest job first or SJF is commonly used.



## Prediction of the Length of the Next CPU Burst



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

This shows an exponential average with  $\alpha = 1/2$  and  $\tau_0 = 10$ .



## Example of SJF

如果 SJF 也有 arrival time, 那么  
在已经 arrival 的多道任务  
short 的 job 未处理

Process	Burst Time
$P_1$	6
$P_2$	8
$P_3$	7
$P_4$	3

- SJF scheduling chart



- Average waiting time =  $(3 + 16 + 9 + 0) / 4 = 7$
- The “best” FCFS perform the same if arrival order happens to be the same
- Sketch Proof:** Moving a short process before a long one decreases the waiting time of the short process more than it increases the waiting time of the long process. Consequently, the average waiting time decreases



## 指数平均算法 Exponential Averaging Algorithm

- This is commonly used to estimate a future value based on historical data – the recent historical value(s) weight more than the past historical value(s)
  - $t_n$  = actual length of nth CPU burst
  - $\tau_{n+1}$  = predicted value for the next CPU burst
  - $\alpha$ ,  $0 \leq \alpha \leq 1$
  - Define:  $\tau_{n+1} = \alpha t_n + (1 - \alpha)\tau_n$

If we expand the formula, we get:

$$\begin{aligned}\tau_{n+1} &= \alpha t_n + (1 - \alpha)\tau_n \\ &= \alpha t_n + (1 - \alpha) \cdot (\alpha t_{n-1} + (1 - \alpha)\tau_{n-1}) \\ &= \alpha t_n + (1 - \alpha)\alpha t_{n-1} + (1 - \alpha)^2\tau_{n-1} \\ &= \alpha t_n + (1 - \alpha)\alpha t_{n-1} + (1 - \alpha)^2 \cdot (\alpha t_{n-2} + (1 - \alpha)\tau_{n-2}) \\ &= \alpha t_n + (1 - \alpha)\alpha t_{n-1} + (1 - \alpha)^2\alpha t_{n-2} + (1 - \alpha)^3\tau_{n-2} \\ &= \dots \\ &= \alpha t_n + (1 - \alpha)\alpha t_{n-1} + \dots + (1 - \alpha)^j\alpha t_{n-j} + \dots + (1 - \alpha)^{n+1}\tau_0\end{aligned}$$



## Determining Length of Next CPU Burst

- How to estimate the length based on the past behavior
  - Then pick the process with shortest predicted next CPU burst
- Can be done by using the lengths of previous CPU bursts and exponential averaging algorithm

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

- Commonly,  $\alpha$  set to  $1/2$  – the relative weight of recent and past history in the prediction
- Preemptive version called shortest-remaining-time-first (SRTF)

抢占式 版本

最短剩余时间优先



## Examples of Exponential Averaging

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

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

- All past values (i.e., the length of the CPU bursts) matter, since they ( $t_n, t_{n-1}, t_{n-2}, \dots$ ) are included in the formula

But recent values matter more. The past value effect is diminished exponentially fast, with each time multiple by a fraction  $(1 - \alpha)$ .

- For example, if  $\alpha = 0.5$ , the effect after 9 rounds,  $(1 - \alpha)^{9+1} = 1/1024$ , which can be ignored.





## Example of Shortest-Remaining-Time-First

- The SJF algorithm can be either **preemptive** or **nonpreemptive**. The choice arises when a new process arrives at the ready queue while another process is still executing

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:** If a new process arrives during the execution of another process and its burst time is shorter than the current process, the current process will be suspended, and the new process will be executed.
- Average waiting time =  $[(10-1)+(1-1)+(17-2)+5-3]/4 = 26/4 = 6.5$
- Now scheduling needs to be invoked when there is an arrival to the ready queue (scheduling condition 4)

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## Example of 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



$$(0+1+6+16+18)/5 = 8.2$$

- Average waiting time = 8.2 msec

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## Comparison of SJF/SRTF and FCFS

- SJF/SRTF are the best we can do towards minimizing the average waiting time, or minimizing the average turnaround time
  - Provably optimal (SJF among non-preemptive, SRTF among preemptive)
  - SRTF is always at least as good as SJF
- SJF/SRTF performs the same as FCFS if all processes have the same CPU burst times
- SJF/SRTF can possibly lead to starvation for long process if there is always shorter process joining the ready queue
  - "fairness" can not be enforced

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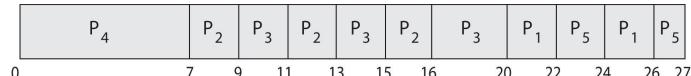


## Priority Scheduling w/ Round-Robin

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

- Gantt Chart with 2 ms time quantum



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## Priority Scheduling

- A priority number (e.g., integer) is associated with each process
- The CPU is allocated to the process with the highest priority (smallest integer = highest priority), it can be
  - Preemptive (upon new arrival of a higher priority process)
  - Nonpreemptive
- Equal-priority processes are scheduled in FCFS order
- SJF is a special case of the general priority-scheduling algorithm, 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
  - 随着时间的推移，进程的优先级会增加

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多级队列

## Multilevel Queue

- Multilevel queue scheduling can still be a priority scheduling combined with round-robin
- A priority is assigned statically to each process, and a process remains in the same queue for the duration of its runtime



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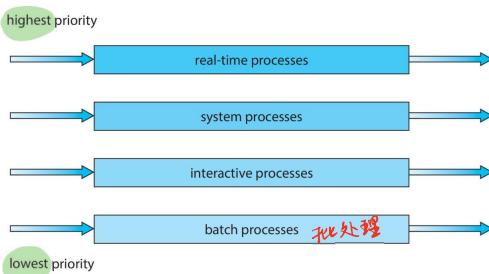
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## Multilevel Queue (Cont.)

Partition processes into different queues based on process type

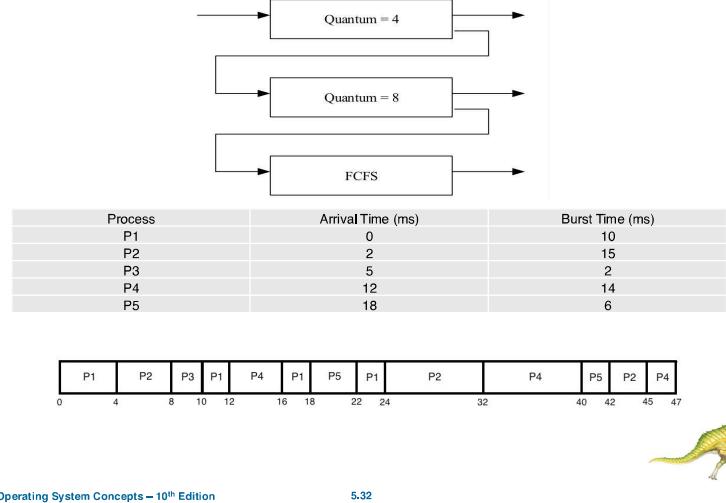
- Each queue can have its own scheduling algorithm based on the needs
- The scheduling among the queues, is commonly implemented as **fixed-priority preemptive scheduling** or each queue gets certain amount of CPU time – time-slice (for instance 60%, 20%, 10%, 10%)



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## MLFQ Example



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## Multilevel Feedback Queue (MLFQ) 多级反馈队列

- A process can move between the various queues; aging can be implemented this way. This provides the flexibility

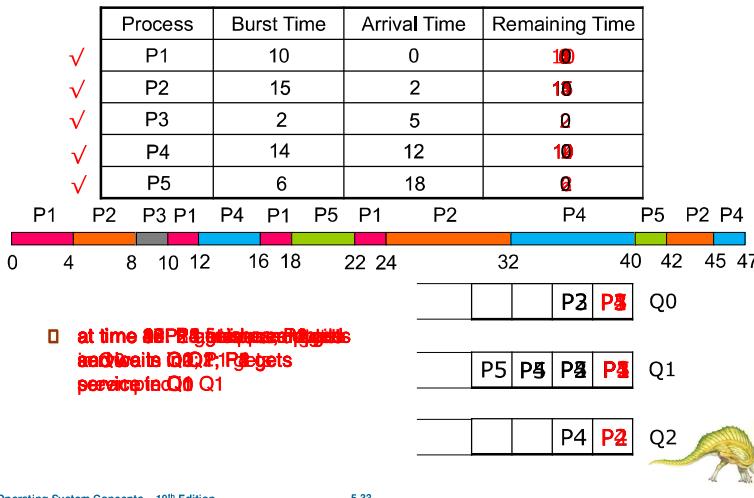
MLFQ scheduler defined by the following parameters:

- The number of queues
- scheduling algorithms for each queue
- method used to determine when to upgrade a process 升级
- method used to determine when to demote a process 降级
- method used to determine which queue a process will enter when that process needs service 服务

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## MLFQ Scheduling: Example



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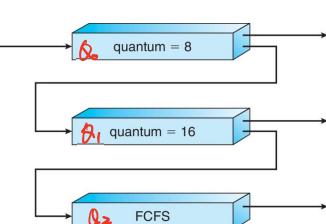
## Example of Multilevel Feedback Queue

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, also preempts jobs from  $Q_1$  or  $Q_2$  if currently running on CPU
  - When it gains CPU, job receives 8 ms
  - If it does not finish in 8 milliseconds, job is moved to the queue  $Q_1$



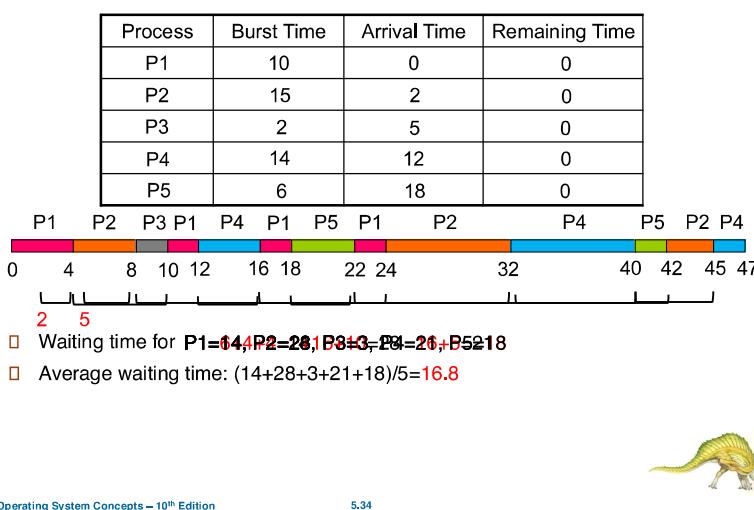
This approximates SRTF:

- CPU bound jobs drop like a rock
- Short-running I/O bound jobs stay near top

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## MLFQ Scheduling: Example



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## Multilevel Feedback Queue (MLFQ) 优先级队列

- MLFQ is commonly used in many systems such as BSD Unix, Solaris, Window NT and subsequent Window operating systems
- MLFQ has several 独特 优势 advantages:
  - It does not need prior knowledge of the next CPU burst time
  - It handles interactive jobs well by delivering better performance in term of 响应时间 response time than RR
  - It produces similar performance as that of SJF or SRTF
  - It is also "fair" by making progress on CPU-bound jobs
- The possible starvation problem can be handled by reshuffling the jobs to different queues periodically
  - E.g., after some period, move all jobs to the top queue

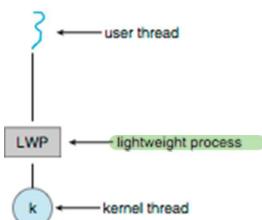
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## Thread Scheduling 线程调度

- On modern OS, kernel-level threads are the ones being scheduled, user-level threads are managed by a thread library instead
- The OS uses an intermediate data structure between user threads and kernel threads, a **lightweight process (LWP)**
  - Appears as a **virtual processor** on which user threads are scheduled to "run"
  - Each LWP attached to kernel thread (one-to-one)



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## Thread Scheduling

- Under **many-to-one** and **many-to-many** models, thread library "schedules" user-level threads to run on LWP. This is known as **process-contention scope (PCS)** – determine which user thread is mapped to which kernel thread
- Since scheduling competition takes place among the threads belonging to the same process, typically done via **priority** set by programmers
  - Thread library usually can not adjust the priority
  - PCS will typically preempt the thread currently running in favour of a higher-priority user-level thread
- Kernel thread scheduled onto available CPU is **system-contention scope (SCS)** – competition among all threads in the system – **CPU scheduling**
- Systems using one-to-one mapping model, such as Windows, Linux, and Solaris, schedule threads using only SCS

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## Multiple-Processor Scheduling

- CPU scheduling far more complex with multiple CPUs – **load sharing**
- Traditionally, the term **multiprocessor** referred to systems that provide multiple physical processors, where each physical processor chip contains one single-core CPU
- The definition of multiprocessor has evolved significantly, and in modern computing systems, **multiprocessor** now applies to multicore CPUs, multithreaded cores, NUMA systems, and heterogeneous multiprocessing
- There are generally two types of multiprocessing systems, **asymmetric multiprocessing** and **symmetric multiprocessing**
  - Asymmetric multiprocessing** – only one processor can access kernel data structures, alleviating the need for data sharing. The other processors execute only user codes
    - All scheduling decisions, I/O processing, and other system activities handled by a single processor — the master server
    - The master server can become a potential bottleneck

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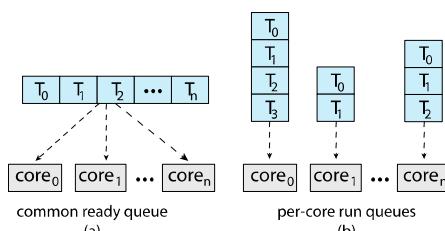
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对称多处理

## Symmetric multiprocessing (SMP)

- Symmetric multiprocessing (SMP)**: Each processor is self-scheduling, with one common ready queue, or each having its own private ready queue
  - Scheduling proceeds by having the scheduler of each processor examines the ready queue and select a thread to run
  - To ensure two separate processors do not choose to schedule the same thread with a common ready queue - possible race condition (discuss in Chapter 6)
  - All modern OS support SMP, including Window, Linux, Mac OS X, as well as mobile systems including Android and iOS



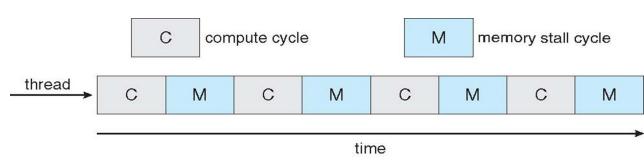
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## Multicore Processors 多核处理器

- Recent trend to place multiple processor cores on same physical chip
- 内存停滯** Faster and consumes less power, but complicate the scheduling design
- Memory stall**: when a processor accesses memory or cache, it spends a significant amount of time waiting for data to become available, primarily because modern processors operate at much faster speeds than memory, esp. when there is a cache miss
- Multiple **hardware threads** per core - each hardware thread has its own state, program counter (PC), register set appearing as a logical CPU to run a software thread. This is known as **chip multithreading (CMT)**



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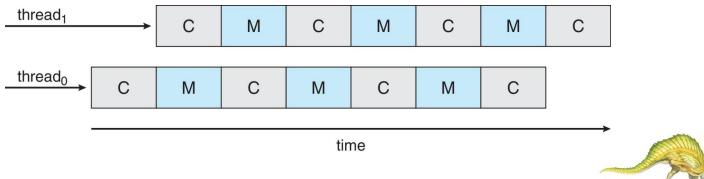




## 多线程多核系统 Multithreaded Multicore System

The scheduling can take advantage of **memory stall** to make progress on another hardware thread while memory retrieve happens for one hardware thread

- If one thread stalls while waiting for memory, the core can switch to another thread. This becomes a **dual-thread processor core**, or resembles two logical processors
- A **dual-threaded, dual-core system** presents **four** logical processors to the operating system
- UltraSPARC T3 CPU has 16 cores per chip and 8 hardware threads per core, from operating system perspective, this appear to be 128 logical processors



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## Multithreaded Multicore Scheduling 总结

- A **user-level thread** is schedule to a LWP – a **kernel-level thread**
  - Under many-to-one and many-to-many models, thread library schedules user-level threads known as process-contention scope (PCS), typically based on the **priority** set by programmers
- A **kernel thread** now referred as a **software thread** is scheduled onto a logical CPU – a **hardware thread**
  - CPU or process scheduling – operating system
- A **hardware thread** is scheduled to run on a CPU core
  - Each CPU core decides the scheduling, typically using RR

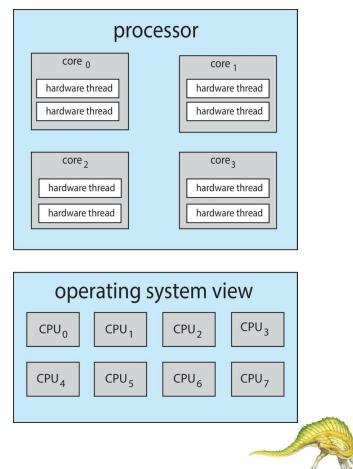
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## Multithreaded Multicore System

- From OS perspective, 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, i.e., a **kernel thread**
- **芯片多线程 (CMT)** assigns each core multiple hardware threads. (Intel refers to this as **超线程 hyperthreading**)
- On a quad-core system with 2 hardware threads per core, the operating system sees 8 logical processors.



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## Processor Affinity 处理器亲和力

- Processor affinity – process has an **affinity** for a processor on which it runs
- When a thread has been running on one processor, the cache content of that processor stores the memory accesses by that thread. We refer to this as a thread having **affinity** for a processor (i.e., “processor affinity”)
- There is a **high cost of invalidating and repopulating caches**, most SMP systems try to avoid migration of processes from one processor to another
- Essentially, **per-processor ready queues** provide processor affinity for free!
- **Soft affinity** – the OS attempts to keep a process running on the same processor (not guaranteeing that), and it is possible for a process to migrate between processors during **load balancing**
- **Hard affinity** – allow a process to specify a subset of processors it may run
- Many systems provide both soft and hard affinity
  - For example, Linux implements soft affinity, but it also provides the system call **sched\_setaffinity()**, which supports hard affinity by allowing a thread to specify the set of CPUs on which it is eligible to run

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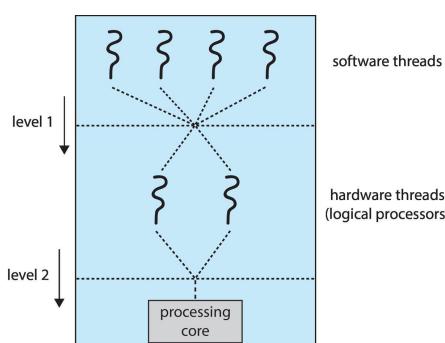
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## Multithreaded Multicore System

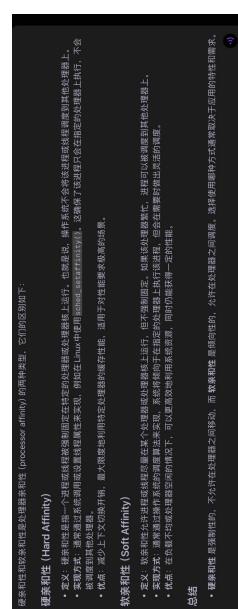
- Two levels of scheduling:

  1. The operating system deciding which **software thread** (kernel thread) to run on a logical CPU – CPU scheduling that we cover in this Chapter
  2. How each core decides which **hardware thread** to run on the physical core – could use RR scheduling (UltraSPARC T3)



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## 负载均衡 Multiple-Processor Scheduling – Load Balancing

均的

- Load balancing attempts to keep workload evenly distributed
  - On systems where each processor has its own private ready queue of eligible threads to execute
- There are two general approaches to load balancing
  - Push migration** – a specific task periodically checks the load on each processor, and if it finds an imbalance, pushes task(s) from overloaded CPU to idle or less-busy CPUs
  - Pull migration** – idle processors pulls waiting task(s) from a busy processor
  - Push and pull migration are not mutually exclusive and in fact often both implemented in parallel on load-balancing systems. For instance, Linux CFS implements both techniques
- Load balancing often counteracts the benefits of **processor affinity** – natural tension between load balancing and minimizing memory access times
  - Thus, scheduling algorithms for modern multicore NUMA systems have become quite complex

GPT-4o

负载均衡和处理器亲和性之间存在一种天然的紧张关系。负载均衡的目的是将工作均匀地分配到所有处理器上，以提高整体系统性能。然而，处理器亲和性则让任务尽可能在同一个处理器上运行，以减少内存访问时间和缓存失效的情况。当系统尝试负载均衡时，任务可能会被转移到其他处理器上，这会破坏处理器亲和性，从而增加内存访问时间。因此，在负载均衡和最小化内存访问时间之间需要找到一个平衡点。

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天然

抵消

吸引力

推拉

迁移

平衡

复杂

挑战

困难

复杂

困难



速率单调

## Rate-monotonic vs. EDF Scheduling

- The rate-monotonic scheduling algorithm schedules periodic tasks using a static priority policy with preemption
- The rate-monotonic scheduling is considered to be optimal in that if a set of processes cannot be scheduled by this algorithm, it cannot be scheduled by any other algorithm that assigns static priorities.
- Unlike rate-monotonic algorithm, EDF scheduling does not require that processes be periodic, nor must a process require a constant amount of CPU time per burst. The only requirement is that a process announce its deadline to the scheduler when it becomes runnable
- EDF scheduling is theoretically optimal - it can schedule processes such that each process can meet its deadline requirements and CPU utilization will be 100 percent
  - In practice, however, it is impossible to achieve this level of CPU utilization due to the cost of context switching between processes and interrupt handling



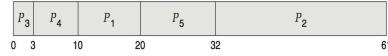
## Deterministic Evaluation

- For each algorithm, calculate the average waiting time
- Simple and fast, but requires exact numbers for input, applies only to those inputs

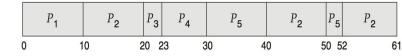
- FCFS is 28ms:



- Non-preemptive SJF is 13ms:



- RR (quantum 10) is 23ms:



## Algorithm Evaluation 算法评估

- Selecting CPU-scheduling algorithm in practice can be difficult – as there are many scheduling algorithms, each with its own set of parameters
- The first problem is defining the criteria to be used in selecting an algorithm - often defined in terms of CPU utilization, response time, or throughput
- Determine criteria – the criteria may include several measures with their relative importance, such as
  - Maximizing CPU utilization under the constraint that the maximum response time is 300 milliseconds
  - Maximizing throughput such that turnaround time is (on average) linearly proportional to total execution time



## Queueing Analysis

- Though the actual numbers (e.g., process arrival time, CPU or I/O bursts) vary from time (system) to time (system), the distributions of CPU and I/O bursts, and process arrival-time can be possibly measured and then approximated or simply estimated
- The computer system can be described as a network of servers, and each server has a queue of waiting processes.
  - The CPU is a server with its ready queue, I/O system with its device queues
  - Commonly use the exponential distribution, and described by mean
- Knowing arrival rates and service rates, we can compute the utilization, average queue length, average wait time, and so on.
- This area of study is called queueing-network analysis
- Queueing analysis can be useful in comparing scheduling algorithms, but the classes of algorithms and distributions that can be handled are very limited. Often the assumptions for the mathematical models to be tractable are unrealistic in practice



## Deterministic Modeling 确定性建模

- Deterministic modeling takes a particular predetermined workload and defines the performance of each algorithm for that workload
- Deterministic modeling is simple and fast. It gives us exact numbers, to compare algorithms. However, it requires exact numbers for input, and its answers apply only to those cases
- How processes run vary from time to time, so there is no static set of processes (or times) to use for deterministic modeling
- Consider 5 processes arriving at time 0:

Process	Burst Time
P <sub>1</sub>	10
P <sub>2</sub>	29
P <sub>3</sub>	3
P <sub>4</sub>	7
P <sub>5</sub>	12



## Queueing Models

- Mathematical approach for handling stochastic workloads
- $n$  = average queue length
- $W$  = average waiting time in queue
- $\lambda$  = average arrival rate into queue
- Little's Formula – in steady state (there are mathematical assumptions for this to hold, e.g., arrival rate must be smaller than service rate), processes leaving queue must equal processes arriving, thus:
 
$$n = \lambda \times W$$
  - Valid for any scheduling algorithm and arrival distribution
- For example, if on average 7 processes arrive per second, and normally 14 processes in queue, then average wait time per process = 2 seconds

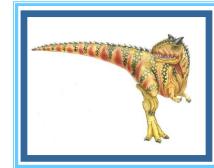
$$14 = W \cdot 7 \Rightarrow W = 2$$



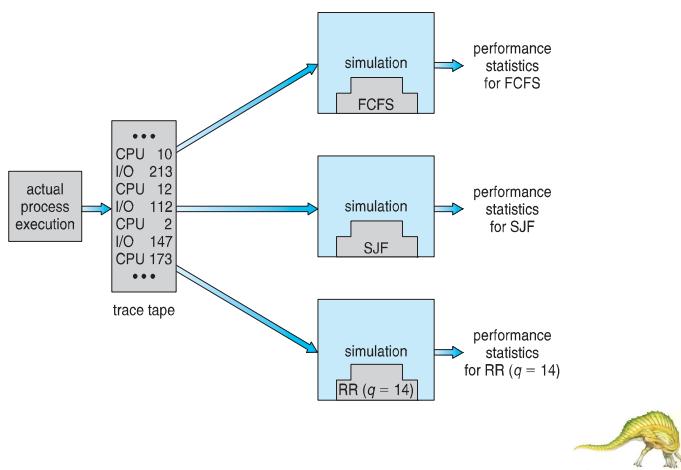
## Simulations 模拟

- Queueing models is restricted to a few known distributions
- Running simulations involves programming a model of the computer system – which is more accurate
- As the clock value is increased, the simulator modifies the system state to reflect the activities of the devices, the processes, and the scheduler.
- As the simulation executes, statistics that indicate algorithm performance are gathered and printed.
- The data to drive the simulation can be generated in several ways
  - Random number generator according to probability distributions - distributions can be defined mathematically (uniform, exponential, Poisson) or empirically
  - Trace files to monitor the real system and record the sequence of actual events

## End of Chapter 5



## Evaluation of CPU Schedulers by Simulation



## Implementation 执行

- Even simulations have limited accuracy
- Build a system which allows actual algorithms to run with real data set – more flexible and general.
- Implementing a new scheduler and test in real systems has difficulties:
  - This incurs high cost (coding the new scheduler), and high risk (e.g., potentially introducing new bugs)
  - Environments also changes constantly
- Most flexible scheduling algorithms are those that can be altered by the system managers so that they can be tuned for a specific application
  - A system supporting graphical applications or web (file) service, for instance, may have different scheduling needs
  - Many UNIX systems allow the system manager to fine-tune the scheduling parameters for a particular system configuration
- APIs can be used to modify priority of a process or thread – improving performance of specific application, not overall application performance
  - The Java, POSIX, and Windows APIs provide such functions

