Karlsruhe Institute of Technology

Betriebssysteme

06. Dispatching and Scheduling

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KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT) – OPERATING SYSTEMS GROUP

4 Europaviertel - Waldstadt - Hauptfriedhof - Durlacher Tor - Marktplatz - Europaplatz - Mathystr. - Hbf Vorplatz - Tivoli →

Montag - Freitag																	
VERKEHRSHINWEIS			Ri	Ri													
Waldstadt Europäische Schule ab	0.04	0.34	1.04	1.34	—	—	4.43	—	5.03	—	5.23		19.03	19.23	19.44		23.44
- Osteroder Straße	0.05	0.35	1.05	1.35	—	—	4.44	—	5.04	—	5.24		19.04	19.24	19.45		23.45
- Elbinger Str. (Ost)	0.06	0.36	1.06	1.36	—	—	4.45	—	5.05	—	5.25		19.05	19.25	19.46		23.46
- Jägerhaus	0.07	0.37	1.07	1.37	—	—	4.46	—	5.06	—	5.26		19.06	19.26	19.47		23.47
- Zentrum BUS	0.08	0.38	1.08	1.38	—	—	4.47	—	5.07	—	5.27		19.07	19.27	19.48		23.48
- Glogauer Straße	0.09	0.39	1.09	1.39	—	—	4.48	—	5.08	—	5.28		19.08	19.28	19.49		23.49
- Im Eichbäumle	0.10	0.40	1.10	1.40	—	—	4.49	—	5.09	—	5.29		19.09	19.29	19.50		23.50
Hagsfeld Fächerbad BUS	0.11	0.41	1.11	1.41	—	—	4.50	—	5.10	—	5.30		19.10	19.30	19.51		23.51
Rintheim Sinsheimer Straße	0.12	0.42	1.12	1.42	—	—	4.51	—	5.11	—	5.31		19.11	19.31	19.52		23.52
Karlsruhe Hirtenweg/Techn.park	0.13	0.43	1.13	1.43	—	—	4.52	—	5.12	—	5.32		19.12	19.32	19.53		23.53
- Hauptfriedhof	0.15	0.45	1.15	1.45	—	—	4.54	5.04	5.14	5.24	5.34		19.14	19.34	19.55		23.55
- Karl-Wilhelm-Platz	0.16	0.46	—	—	—	—	4.55	5.05	5.15	5.25	5.35		19.15	19.35	19.56		23.56
- Durlacher Tor / KIT-Campus Süd	0.18	0.48	—	—	—	—	4.58	5.08	5.18	5.28	5.38	alle 10 Min.	19.18	19.38	19.58	alle 20 Min.	23.58
- Kronenplatz (Kaiserstr.)	0.20	0.50	—	—	—	—	5.00	5.10	5.20	5.30	5.40		19.20	19.40	20.00		0.00
- Marktplatz (Kaiserstr.)	0.21	0.51	—	—	—	—	5.01	5.11	5.21	5.31	5.41		19.21	19.41	20.01		0.01
- Herrenstraße	0.23	0.53	—	—	—	—	5.03	5.13	5.23	5.33	5.43		19.23	19.43	20.03		0.03
- Europapl./PostGalerie (Kaiser)	0.25	0.55	—	—	—	—	5.05	5.15	5.25	5.35	5.45		19.25	19.45	20.05		0.05
- Europapl./PostGalerie (Karl)	0.26	0.56	—	—	4.36	4.56	5.06	5.16	5.26	5.36	5.46		19.26	19.46	20.06		0.06
- Karlstor	0.28	0.58	—	—	4.38	4.58	5.08	5.18	5.28	5.38	5.48		19.28	19.48	20.08		0.08
- Mathystraße	0.29	0.59	—	—	4.39	4.59	5.09	5.19	5.29	5.39	5.49		19.29	19.49	20.09		0.09

In Lecture 4 we learned about Processes

- A process is a running instance of a program
  - Program : Recipe is like Process : Cooking

- Processes are a resource container for the OS
  - Processes simplify the programming model greatly
  - Each process has its own view of the machine: It has its own CPU, address space, open files, . . .

- Processes allow for a better resource utilization
  - Modern OSes run multiple processes “simultaneously”
  - The OS implements multiprogramming by rapidly switching processes
  - E.g., run firefox and xmms at the “same” time
  - When a process waits for I/O (blocking) the OS switches to another process that is ready for computation on the CPU
  - E.g., make -j n with n larger than the number of CPU cores

In Lecture 5 we learned about PCBs and TCBs

- The OS maintains a process table with information about each process.
- Each process is associated with a table entry: Process Control Block
- Each thread is associated with a Thread Control Block
- Let us assume for now, that every process has only one thread and that PCB and TCB are consolidated in the PCB
  - Process ID
  - Process state
  - CPU scheduling information
  - CPU registers (e.g., instruction/stack pointer)
  - Credentials (UID, GID, ...)
  - Memory-management information
  - I/O status information

Today: Scheduling Problem

- Have **K** jobs ready to run
  - Jobs can be processes or threads
- Have **N** CPUs with: $K > N \geq 1$ CPUs

- Scheduling Problem
  - Which jobs should the kernel assign to which CPUs?
  - When should it make the decision?

Dispatching

Which jobs should be assigned to which CPU(s)?

We generally differentiate between dispatcher and scheduler

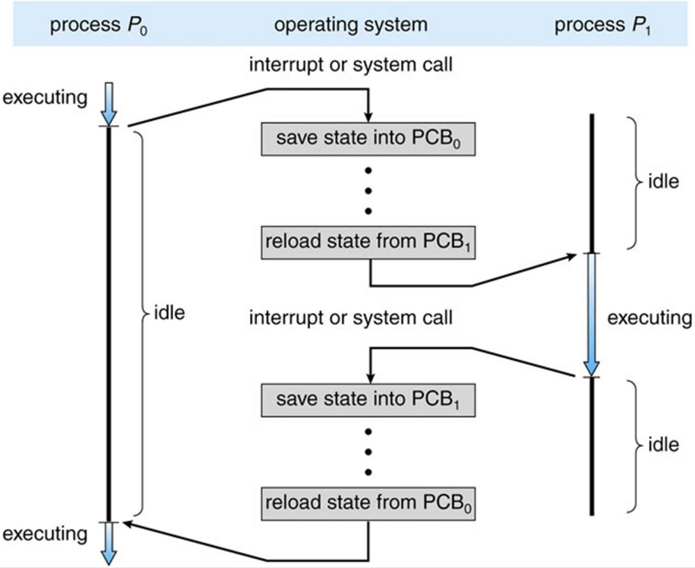
- The dispatcher performs the actual process switch
  - Mechanism
  - Saving/restoring process context
  - Switching to user mode

- The CPU scheduler selects the next process to run
  - Policy

Voluntary Yielding vs. Preemption

- The kernel is responsible for performing the CPU switch
- The kernel does not always run and cannot dispatch a different process unless it is invoked!
  - The kernel can switch at any system call
  - Using cooperative multitasking, the currently running process performs a yield system call to ask the kernel to switch to another process
- The kernel often wants to preempt the currently running process to schedule a different process
  - Preemptive scheduling requires the kernel to be invoked in certain time intervals
  - In general, the kernel uses the timer interrupt as a trigger to make scheduling decisions after every time-slice

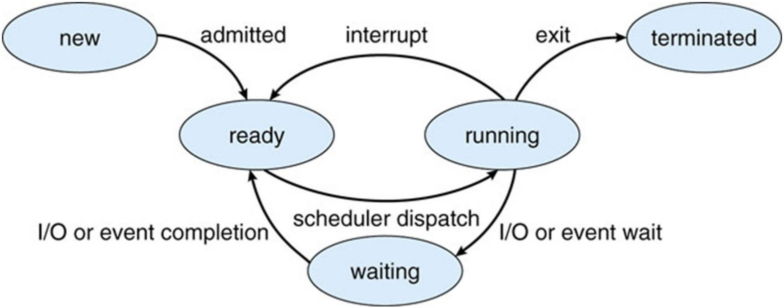
CPU Switch From Process to Process



Scheduling

Process State

- From the OS perspective, a process can be in different states:
  - new: The process has been created but was never run
  - running: Instructions are currently being executed
  - waiting: The process is waiting for some event to occur
  - ready: The process is waiting to be assigned a processor
  - terminated: The process has finished execution (zombie state)



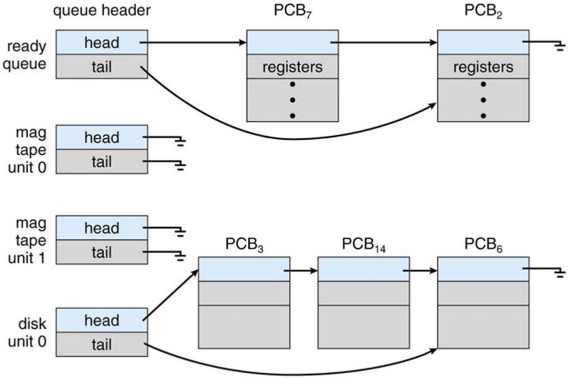
Different Schedulers

- Short-term scheduler (or CPU scheduler)
  - Selects which process should be executed next and allocates CPU
  - Short-term scheduler is invoked very frequently (milliseconds)
    → must be fast
- Long-term scheduler (or job scheduler)
  - Selects which processes should be brought into the ready queue
  - Long-term scheduler is invoked very infrequently (seconds, minutes)
    → can be slow
  - The long-term scheduler controls the degree of multiprogramming
- We focus on the CPU scheduler in this lecture

Process Scheduling Queues

- Job queue: Set of all processes in the system
- Ready queue: Processes in main memory, states: ready and waiting
- Device queues: Processes waiting for an I/O device

Processes migrate among the various queues



Scheduling Policies

Categories of Scheduling Policies

Different scheduling policies are needed in different environments

- Batch Scheduling
  - Still widespread in business: payroll, inventory, accounting, . . .
  - No users waiting for a quick response
  - Non-preemptive algorithms acceptable → less switches → less overhead
- Interactive Scheduling
  - Need to optimize for response time
  - Preemption essential to keep processes from hogging CPU
- Real-Time Scheduling
  - Guarantee completion of jobs within time constraints
  - Need to be able to plan when which process runs and how long
  - Preemption is not always needed

Scheduling Goals Vary for Different Categories

- All Systems
  - Fairness give each process a fair share of CPU
  - Balance keep all parts of the system busy
- Batch Scheduling
  - Throughput # of processes that complete per time unit
  - Turnaround Time time from submission to completion of a job
  - CPU Utilization keep the CPU as busy as possible
- Interactive Scheduling
  - Waiting time time each process waits in ready queue
  - Response Time time from request to first response
    - For a job: e.g., key press to echo
    - For a scheduler: submission of a job to the first time it is dispatched
- Real-Time Scheduling
  - Meeting Deadlines finish jobs in time
  - Predictability minimize jitter

First-Come, First-Served (FCFS) Scheduling

- FCFS: Schedule the processes in the order of arrival
- Suppose that 3 processes arrive in the order: P_1, P_2, P_3 (at time 0)

Process	Burst Time
P_1	24
P_2	3
P_3	3

- The Gantt Chart for the schedule is:

- Turnaround times: $P_1 = 24$, $P_2 = 27$, $P_3 = 30$
- Average turnaround time: $\frac{24+27+30}{3} = 27$ ➞ Can we do better?

First-Come, First-Served (FCFS) Scheduling

- Suppose that the 3 processes arrived in the order: P_2, P_3, P_1 (at time 0)

Process	Burst Time
P_1	24
P_2	3
P_3	3

- Turnaround times: $P_1 = 30$; $P_2 = 3$; $P_3 = 6$
- Average turnaround time: $\frac{30+3+6}{3} = 13$
  → Much better than the previous 27

Good scheduling can reduce turnaround time

Shortest-Job-First (SJF) Scheduling

- FCFS is prone to Convoy effect
  - One long job arrived first
  - All short ("fast") jobs now have to wait for the first job to finish

  ➞ Idea: Run shortest jobs first (SJF)

- SJF has optimal average turnaround (and waiting, and response) times
  - Assume sorted jobs by SJF: make formula for average turnaround time
  - Switch any two jobs j, k, where $j<k$ ➞ longer job now earlier
  - Contradiction: Average turnaround time larger (subtract times)

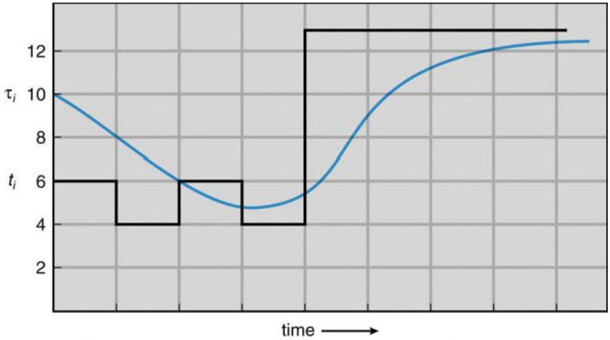
- Challenge: Cannot know job lengths in advance

- Solution: Predict length of next CPU burst for each process

  ➞ Schedule the process with the shortest burst next
  - Now suboptimal turnaround time possible
    (e.g., longest job has shortest bursts)
  - Still optimizes waiting and response times

SJF: Estimating the Length of Next CPU Burst

- Length of previous CPU bursts → exponential averaging
  - $t_n =$ actual length of n^{th} CPU burst
  - $\tau_{n+1} =$ predicted value for the next CPU burst
  - Define: $\tau_{n+1} = \alpha t_n + (1 - \alpha)\tau_n$, with $0 \leq \alpha \leq 1$
- Example:
  $\alpha = 0.5$

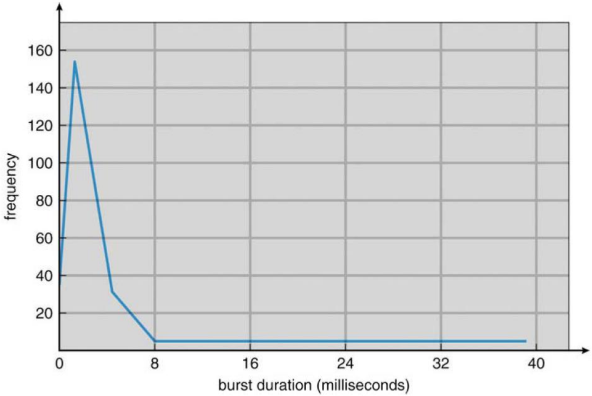


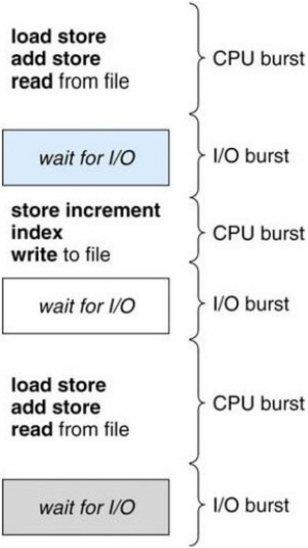
CPU burst (t_i)		6	4	6	4	13	13	13	...
"guess" (τ_i)	10	8	6	6	5	9	11	12	...

CPU vs. I/O Burst Cycles

- Why do CPU bursts exist?
  - CPU burst then I/O wait

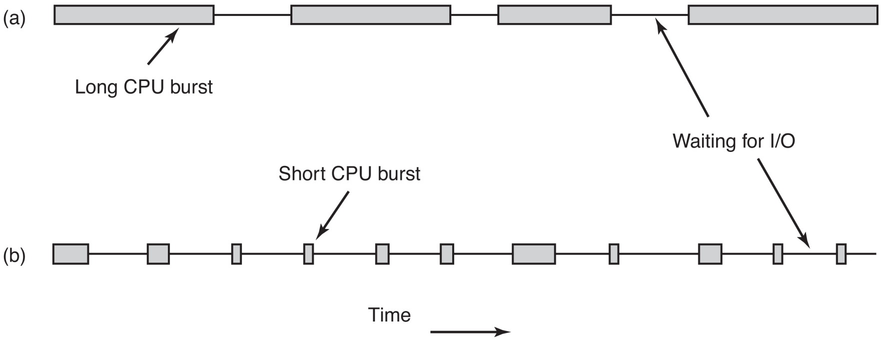
Histogram of CPU burst times





Process Behavior: Boundedness

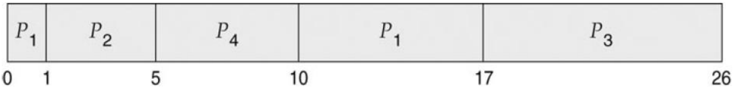
- Processes can be characterized as:
  - (a) CPU-bound process Spends more time doing computations
    → few very long CPU bursts
  - (b) I/O-bound process Spends more time doing I/O than computations
    → many short CPU bursts



Preemptive Shortest-Job-First (PSJF) Scheduling

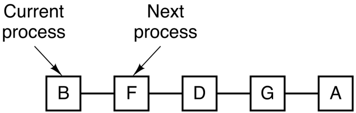
- SJF optimizes waiting time and response time
  (and offline also turnaround time)
- But what about throughput?
  - CPU bound jobs hold CPU until exit or I/O → poor I/O device utilization
- Idea: SJF, but preempt periodically to make a new scheduling decision
  - At each time slice schedule job with shortest remaining time next
  - Alternatively: Schedule job whose next CPU burst is the shortest

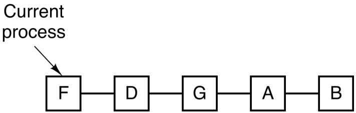
Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5



Round Robin (RR) Scheduling

- Batch schedulers suffer from starvation and do not provide fairness
- Idea: Each process runs for a small unit of CPU time
  - Time quantum/time slice length usually 10-100 milliseconds
  - Preempt processes that have not blocked by the end of the time slice
  - Append current thread to end of run queue, run next thread





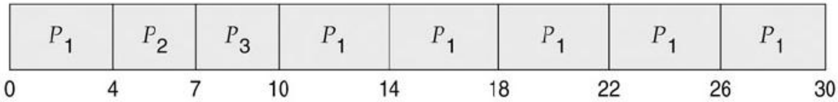
- Time slice length needs to balance interactivity and overhead
  - Need time to dispatch new process (overhead)
  - If time slice is much larger than dispatch time
    → dispatch overhead is small compared to run-time of process
  - If the time slice length is in the area of the dispatch time
    → waste 50% of CPU time for switching between processes

Round Robin (RR) Scheduling

- Example:
  Time slice length = 4 time units

Process	Burst Time
P_1	24
P_2	3
P_3	3

- Gantt chart:



- Typically, higher average turnaround than SJF, but better response time
- Good average waiting time if job lengths vary

Virtual Round Robin (RR) Scheduling

- RR is unfair for I/O-bound jobs
  - I/O-bound jobs block before they use up their time quantum
  - CPU-bound jobs use up their entire quantum

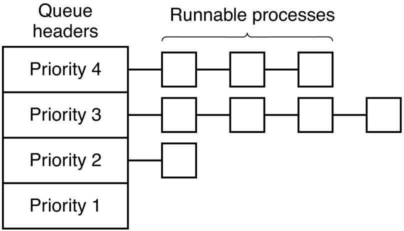
  → with same number of slices, CPU-bound jobs get more CPU time

- Idea: Virtual Round Robin
  - Put jobs that didn't use up their quantum into an additional queue
  - Store the share of the time-slice that they have not used up with the job
  - Give jobs in the additional queue priority over jobs in other queue until they have used up their quantum
  - Afterwards put them back in normal queue

(Strict) Priority Scheduling

- Not all jobs are equally important
  → Different priorities

- Priority Scheduling: Associate priority number with each process
  - Allocate CPU RR to processes with the highest priority
  - Can be preemptive or non-preemptive
  - Usually: smallest integer ≡ highest priority



- SJF ≡ Priority scheduling where priority is the predicted next burst time

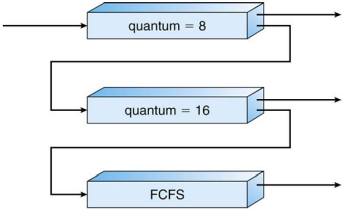
- Strict priority scheduling: processes with low priorities never execute if there is always a process runnable with a higher priority (starvation)
  - Possible Solution: Weaken strictness through aging
    → As time progresses increase the priority of the processes that have not run

Multi-Level Feedback Queue (MLFB) Scheduling

- Context switching can be expensive
  - Can we get a good trade-off between interactivity and overhead?
- Goals:
  - Give higher priority to I/O-bound jobs
    (they usually don't use up their quantum but deserve a fair CPU share)
  - Give low priority to CPU-bound jobs, but run them for longer at a time
    (rather run the job every "round" for twice the time)
- Idea: Different queues with different priorities and time slices lengths
  - Schedule queues with (static) priority scheduling
  - Double time slice length in each next-lower priority
  - Promote processes into a higher priority queue when
    they don't use up their quantum repeatedly
  - Demote processes that repeatedly use up their quantum

Multi-Level Feedback Queue (MLFB) Scheduling

- Example with three queues:



- Q_0: RR time slice length 8 ms
- Q_1: RR time slice length 16 ms
- Q_2: FCFS

- Example Scheduling:
  - A new job enters queue Q_0 which is scheduled using RR
  - When the job is dispatched, it receives 8 milliseconds
  - If it does not finish in 8 milliseconds, job is moved to queue Q_1
  - In Q_1 the job is run for additional 16 milliseconds
  - If it still does not complete, it is preempted and moved to queue Q_2

Priority Donation

- Problem: Process B may wait for result of process A
  - A has a lower priority than B

  → B has effectively lower priority now

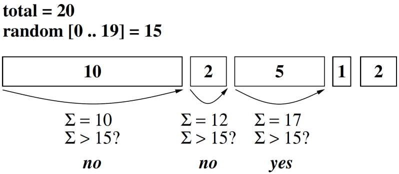
- Solution: Priority donation (a.k.a. priority inheritance)
  - Give A priority of B as long as B waits for A
  - What if C, D and E also wait for B?
  - Should we donate priorities transitively?

  → A only gets highest priority of B, C, D, E

- Shouldn't A's priority increase even more if many processes wait for it?

Lottery Scheduling

- Issue number of lottery tickets to processes
  - More tickets for processes with higher priority
  - Tickets not associated with concrete numbers
- Amount of tickets controls average proportion of CPU for each process
- ∃ a list of all runnable processes
  - A schedule operation draws a random number N and traverses the list to find the winner of the timeslice (≡ process with the N'th ticket)



- Processes may transfer tickets to other processes if they wait for them
  - Ticket donation "stronger" than priority donation.

Real-Time Scheduling

- Not relevant for this lecture
- If you are interested, a good starting point is:
  - Jane W.S. Liu, “Real-Time Systems”, Prentice Hall, 2000

Summary

- Processes have phases of computation and of waiting for I/O
  - Appropriate switching between processes increases the utilization of computing systems

- Based on goals, the scheduler decides what appropriate means
  - Long-term scheduler: degree of multiprogramming
  - Short-term scheduler: which process to run next

- Dispatching can only happen when the OS is invoked
  - Cooperative scheduling: The currently running thread yields (syscall)
  - Preemptive scheduling: OS is called periodically (e.g., timer interrupt) to switch threads

Further Reading

- Tanenbaum/Bos, “Modern Operating Systems”, 4th Edition: Pages 149–167
- Silberschatz, Galvin, Gagne, “Operating System Concepts”, 8th Edition: Pages 183–223
- Waldspurger/Weihl, “Lottery Scheduling: Flexible Proportional-Share Resource Management”