

# CPU Scheduling



CPU scheduling is the basis of multiprogrammed operating systems. By switching the CPU among processes, the operating system can make the computer more productive. In this chapter, we introduce basic CPU-scheduling concepts and present several CPU-scheduling algorithms. We also consider the problem of selecting an algorithm for a particular system.

In Chapter 4, we introduced threads to the process model. On operating systems that support them, it is kernel-level threads—not processes—that are in fact being scheduled by the operating system. However, the terms **process scheduling** and **thread scheduling** are often used interchangeably. In this chapter, we use *process scheduling* when discussing general scheduling concepts and *thread scheduling* to refer to thread-specific ideas.

## Bibliographical Notes

Feedback queues were originally implemented on the CTSS system described in [Corbato et al. (1962)]. This feedback queue scheduling system was analyzed by [Schrage (1967)]. The preemptive priority scheduling algorithm of Exercise 6.23 was suggested by [Kleinrock (1975)]. The scheduling algorithms for hard real-time systems, such as rate monotonic scheduling and earliest-deadline-first scheduling, are presented in [Liu and Layland (1973)].

[Anderson et al. (1989)], [Lewis and Berg (1998)], and [Philbin et al. (1996)] discuss thread scheduling. Multicore scheduling is examined in [McNairy and Bhatia (2005)] and [Kongetira et al. (2005)].

[Fisher (1981)], [Hall et al. (1996)], and [Lowney et al. (1993)] describe scheduling techniques that take into account information regarding process execution times from previous runs.

Fair-share schedulers are covered by [Henry (1984)], [Woodside (1986)], and [Kay and Lauder (1988)].

Scheduling policies used in the UNIX V operating system are described by [Bach (1987)]; those for UNIX FreeBSD 5.2 are presented by [McKusick and Neville-Neil (2005)]; and those for the Mach operating system are discussed by [Black (1990)]. [Love (2010)] and [Mauerer (2008)] cover scheduling in Linux. [Faggioli et al. (2009)] discusses adding an EDF scheduler to the Linux

kernel. Details of the ULE scheduler can be found in [Roberson (2003)]. Solaris scheduling is described by [Mauro and McDougall (2007)]. [Rusinovich and Solomon (2009)] discusses scheduling in Windows internals. [Butenhof (1997)] and [Lewis and Berg (1998)] describe scheduling in Pthreads systems. [Siddha et al. (2007)] discuss scheduling challenges on multicore systems.

## Bibliography

- [Anderson et al. (1989)] T. E. Anderson, E. D. Lazowska, and H. M. Levy, “The Performance Implications of Thread Management Alternatives for Shared-Memory Multiprocessors”, *IEEE Transactions on Computers*, Volume 38, Number 12 (1989), pages 1631–1644.
- [Bach (1987)] M. J. Bach, *The Design of the UNIX Operating System*, Prentice Hall (1987).
- [Black (1990)] D. L. Black, “Scheduling Support for Concurrency and Parallelism in the Mach Operating System”, *IEEE Computer*, Volume 23, Number 5 (1990), pages 35–43.
- [Butenhof (1997)] D. Butenhof, *Programming with POSIX Threads*, Addison-Wesley (1997).
- [Corbato et al. (1962)] F. J. Corbato, M. Merwin-Daggett, and R. C. Daley, “An Experimental Time-Sharing System”, *Proceedings of the AFIPS Fall Joint Computer Conference* (1962), pages 335–344.
- [Faggioli et al. (2009)] D. Faggioli, F. Checconi, M. Trimarchi, and C. Scordino, “An EDF scheduling class for the Linux kernel”, *Proceedings of the 11th Real-Time Linux Workshop* (2009).
- [Fisher (1981)] J. A. Fisher, “Trace Scheduling: A Technique for Global Microcode Compaction”, *IEEE Transactions on Computers*, Volume 30, Number 7 (1981), pages 478–490.
- [Hall et al. (1996)] L. Hall, D. Shmoys, and J. Wein, “Scheduling To Minimize Average Completion Time: Off-line and On-line Algorithms”, *SODA: ACM-SIAM Symposium on Discrete Algorithms* (1996).
- [Henry (1984)] G. Henry, “The Fair Share Scheduler”, *AT&T Bell Laboratories Technical Journal* (1984).
- [Kay and Lauder (1988)] J. Kay and P. Lauder, “A Fair Share Scheduler”, *Communications of the ACM*, Volume 31, Number 1 (1988), pages 44–55.
- [Kleinrock (1975)] L. Kleinrock, *Queueing Systems, Volume II: Computer Applications*, Wiley-Interscience (1975).
- [Kongetira et al. (2005)] P. Kongetira, K. Aingaran, and K. Olukotun, “Niagara: A 32-Way Multithreaded SPARC Processor”, *IEEE Micro Magazine*, Volume 25, Number 2 (2005), pages 21–29.
- [Lewis and Berg (1998)] B. Lewis and D. Berg, *Multithreaded Programming with Pthreads*, Sun Microsystems Press (1998).

- [Liu and Layland (1973)] C. L. Liu and J. W. Layland, “Scheduling Algorithms for Multiprogramming in a Hard Real-Time Environment”, *Communications of the ACM*, Volume 20, Number 1 (1973), pages 46–61.
- [Love (2010)] R. Love, *Linux Kernel Development, Third Edition*, Developer’s Library (2010).
- [Lowney et al. (1993)] P. G. Lowney, S. M. Freudenberger, T. J. Karzes, W. D. Lichtenstein, R. P. Nix, J. S. O’Donnell, and J. C. Ruttenberg, “The Multiflow Trace Scheduling Compiler”, *Journal of Supercomputing*, Volume 7, Number 1-2 (1993), pages 51–142.
- [Mauerer (2008)] W. Mauerer, *Professional Linux Kernel Architecture*, Wiley Publishing (2008).
- [Mauro and McDougall (2007)] J. Mauro and R. McDougall, *Solaris Internals: Core Kernel Architecture*, Prentice Hall (2007).
- [McKusick and Neville-Neil (2005)] M. K. McKusick and G. V. Neville-Neil, *The Design and Implementation of the FreeBSD UNIX Operating System*, Addison Wesley (2005).
- [McNairy and Bhatia (2005)] C. McNairy and R. Bhatia, “Montecito: A Dual-Core, Dual-Threaded Itanium Processor”, *IEEE Micro Magazine*, Volume 25, Number 2 (2005), pages 10–20.
- [Philbin et al. (1996)] J. Philbin, J. Edler, O. J. Anshus, C. C. Douglas, and K. Li, “Thread Scheduling for Cache Locality”, *Architectural Support for Programming Languages and Operating Systems* (1996), pages 60–71.
- [Roberson (2003)] J. Roberson, “ULE: A Modern Scheduler For FreeBSD”, *Proceedings of the USENIX BSDCon Conference* (2003), pages 17–28.
- [Russinovich and Solomon (2009)] M. E. Russinovich and D. A. Solomon, *Windows Internals: Including Windows Server 2008 and Windows Vista, Fifth Edition, Fifth Edition*, Microsoft Press (2009).
- [Schrage (1967)] L. E. Schrage, “The Queue M/G/I with Feedback to Lower Priority Queues”, *Management Science*, Volume 13, (1967), pages 466–474.
- [Siddha et al. (2007)] S. Siddha, V. Pallipadi, and A. Mallick, “Process Scheduling Challenges in the Era of Multi-Core Processors”, *Intel Technology Journal*, Volume 11, (2007).
- [Woodside (1986)] C. Woodside, “Controllability of Computer Performance Tradeoffs Obtained Using Controlled-Share Queue Schedulers”, *IEEE Transactions on Software Engineering*, Volume SE-12, Number 10 (1986), pages 1041–1048.

