Threads

References:

1. Abraham Silberschatz, Greg Gagne, and Peter Baer Galvin, "Operating System Concepts, Ninth Edition ", Chapter 4

Overview

- A ***thread*** is a basic unit of CPU utilization, consisting of a program counter, a stack, and a set of registers, (and a thread ID.)
- Traditional (heavyweight) processes have a single thread of control - There is one program counter, and one sequence of instructions that can be carried out at any given time.
- As shown in Figure 4.1, multi-threaded applications have multiple threads within a single process, each having their own program counter, stack and set of registers, but sharing common code, data, and certain structures such as open files.

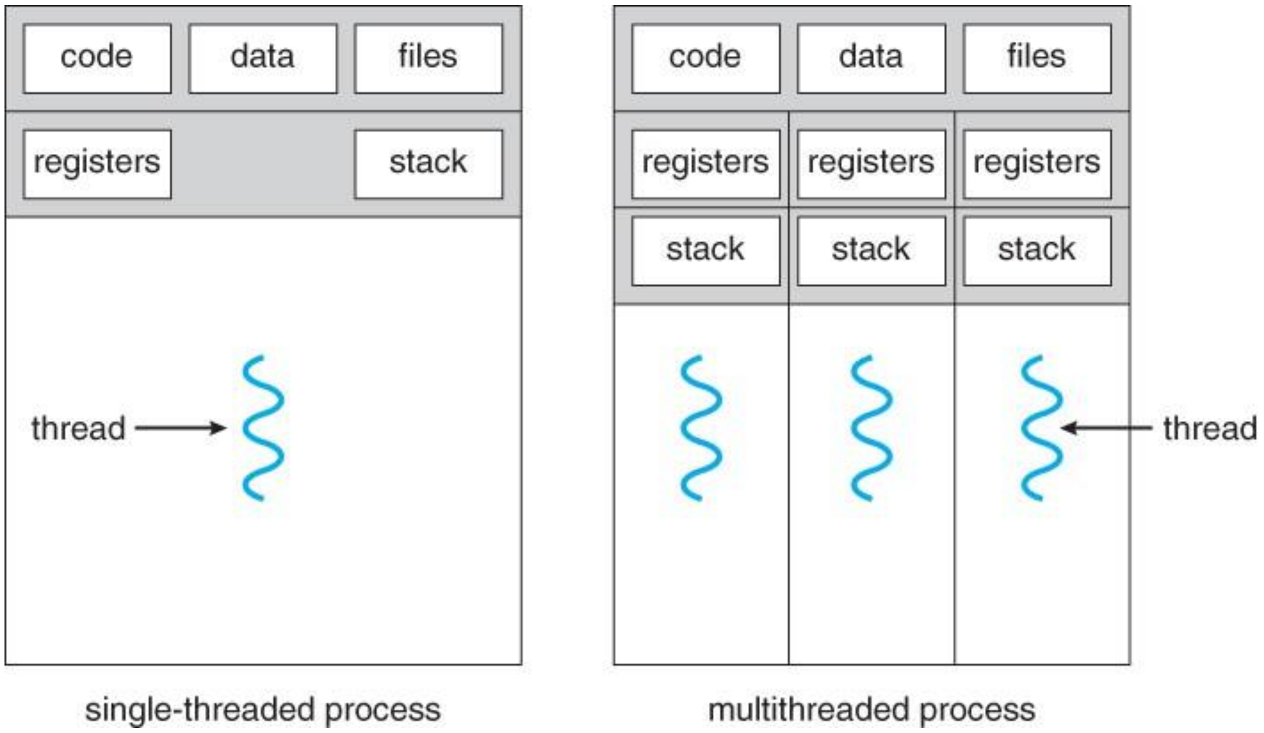
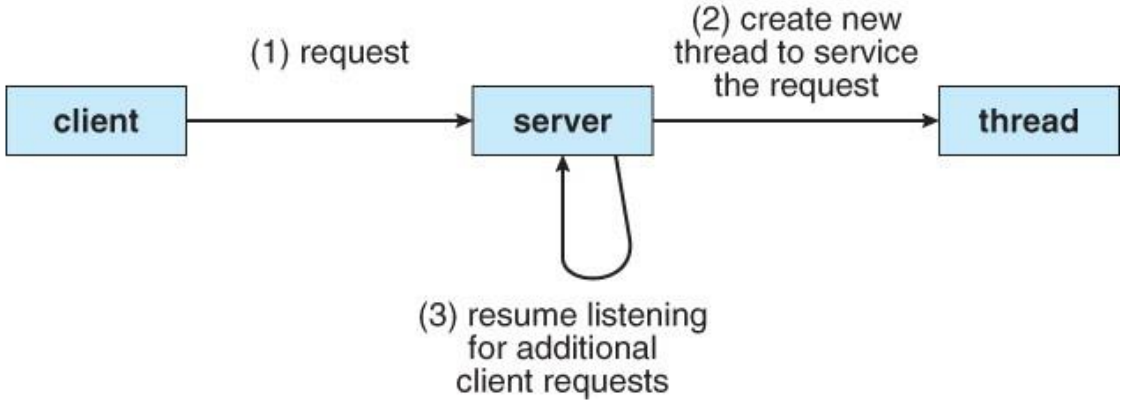


Figure 4.1 - Single-threaded and multithreaded processes

Motivation

- Threads are very useful in modern programming whenever a process has multiple tasks to perform independently of the others.
- This is particularly true when one of the tasks may block, and it is desired to allow the other tasks to proceed without blocking.
- For example in a word processor, a background thread may check spelling and grammar while a foreground thread processes user input (keystrokes), while yet a third thread loads images from the hard drive, and a fourth does periodic automatic backups of the file being edited.
- Another example is a web server - Multiple threads allow for multiple requests to be satisfied simultaneously, without having to service requests sequentially or to fork off separate processes for every incoming request. (The latter is how this sort of thing was done before the concept of threads was developed. A daemon would listen at a port, fork off a child for every incoming request to be processed, and then go back to listening to the port.)


(1) request
(2) create new thread to service the request
client
server
thread
(3) resume listening for additional client requests
Figure 4.2 - Multithreaded server architecture

Benefits

- There are four major categories of benefits to multi-threading:
    1. Responsiveness - One thread may provide rapid response while other threads are blocked or slowed down doing intensive calculations.
    2. Resource sharing - By default threads share common code, data, and other resources, which allows multiple tasks to be performed simultaneously in a single address space.
    3. Economy - Creating and managing threads (and context switches between them) is much faster than performing the same tasks for processes.
    4. Scalability, i.e. Utilization of multiprocessor architectures - A single threaded process can only run on one CPU, no matter how many may be available, whereas the execution of a multi-threaded application may be split amongst available processors. (Note that single threaded processes can still benefit from multi-processor architectures when there are multiple processes contending for the CPU, i.e. when the load average is above some certain threshold.)

Multicore Programming

- A recent trend in computer architecture is to produce chips with multiple ***cores***, or CPUs on a single chip.
- A multi-threaded application running on a traditional single-core chip would have to interleave the threads, as shown in Figure 4.3. On a multi-core chip, however, the threads could be spread across the available cores, allowing true parallel processing, as shown in Figure 4.4.

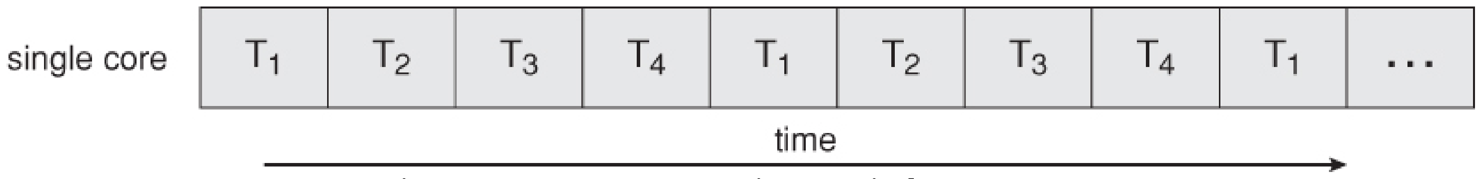


Figure 4.3 - Concurrent execution on a single-core system.

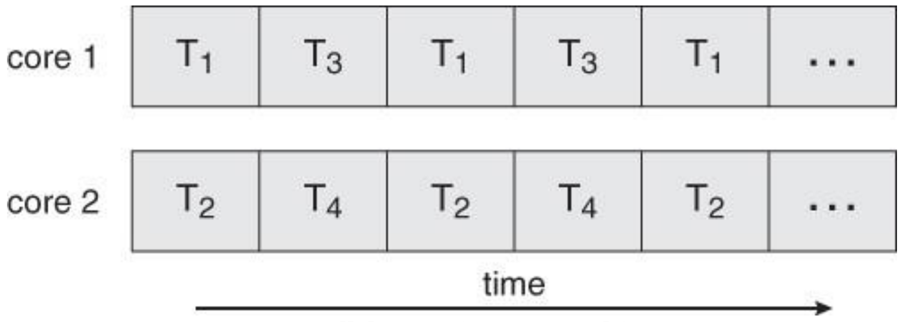


Figure 4.4 - Parallel execution on a multicore system

- For operating systems, multi-core chips require new scheduling algorithms to make better use of the multiple cores available.
- As multi-threading becomes more pervasive and more important (thousands instead of tens of threads), CPUs have been developed to support more simultaneous threads per core in hardware.

Programming Challenges (New section, same content ?)

- For application programmers, there are five areas where multi-core chips present new challenges:
  1. **Identifying tasks -** Examining applications to find activities that can be performed concurrently.
  2. **Balance -** Finding tasks to run concurrently that provide equal value. I.e. don't waste a thread on trivial tasks.
  3. **Data splitting -** To prevent the threads from interfering with one another.
  4. **Data dependency -** If one task is dependent upon the results of another, then the tasks need to be synchronized to assure access in the proper order.
  5. **Testing and debugging -** Inherently more difficult in parallel processing situations, as the race conditions become much more complex and difficult to identify.

Types of Parallelism (new)

In theory there are two different ways to parallelize the workload:

1. **Data parallelism** divides the data up amongst multiple cores (threads), and performs the same task on each subset of the data. For example dividing a large image up into pieces and performing the same digital image processing on each piece on different cores.
2. **Task parallelism** divides the different tasks to be performed among the different cores and performs them simultaneously.

In practice no program is ever divided up solely by one or the other of these, but instead by some sort of hybrid combination.

Multithreading Models

- There are two types of threads to be managed in a modern system: User threads and kernel threads.
- User threads are supported above the kernel, without kernel support. These are the threads that application programmers would put into their programs.
- Kernel threads are supported within the kernel of the OS itself. All modern OSes support kernel level threads, allowing the kernel to perform multiple simultaneous tasks and/or to service multiple kernel system calls simultaneously.
- In a specific implementation, the user threads must be mapped to kernel threads, using one of the following strategies.

Many-To-One Model

- In the many-to-one model, many user-level threads are all mapped onto a single kernel thread.
- Thread management is handled by the thread library in user space, which is very efficient.
- However, if a blocking system call is made, then the entire process blocks, even if the other user threads would otherwise be able to continue.
- Because a single kernel thread can operate only on a single CPU, the many-to-one model does not allow individual processes to be split across multiple CPUs.
- Green threads for Solaris and GNU Portable Threads implement the many-to-one model in the past, but few systems continue to do so today.

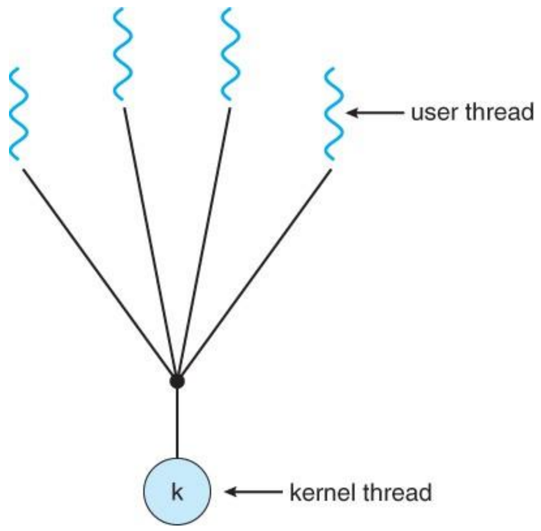


Figure 4.5 - Many-to-one model

One-To-One Model

- The one-to-one model creates a separate kernel thread to handle each user thread.
- One-to-one model overcomes the problems listed above involving blocking system calls and the splitting of processes across multiple CPUs.
- However the overhead of managing the one-to-one model is more significant, involving more overhead and slowing down the system.
- Most implementations of this model place a limit on how many threads can be created.
- Linux and Windows from 95 to XP implement the one-to-one model for threads.

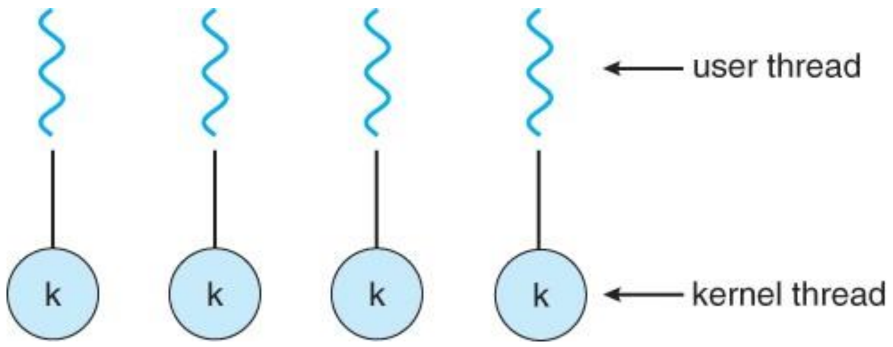


Figure 4.6 - One-to-one model

Many-To-Many Model

- The many-to-many model multiplexes any number of user threads onto an equal or smaller number of kernel threads, combining the best features of the one-to-one and many-to-one models.
- Users have no restrictions on the number of threads created.
- Blocking kernel system calls do not block the entire process.
- Processes can be split across multiple processors.
- Individual processes may be allocated variable numbers of kernel threads, depending on the number of CPUs present and other factors.

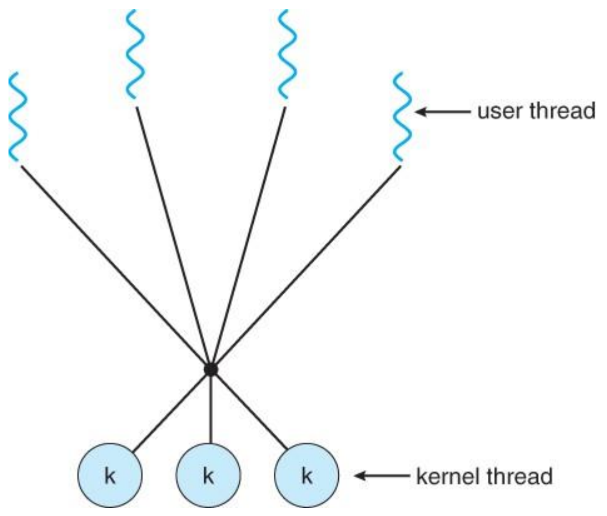


Figure 4.7 - Many-to-many model

- One popular variation of the many-to-many model is the two-tier model, which allows either many-to-many or one-to-one operation.
- IRIX, HP-UX, and Tru64 UNIX use the two-tier model, as did Solaris prior to Solaris 9.

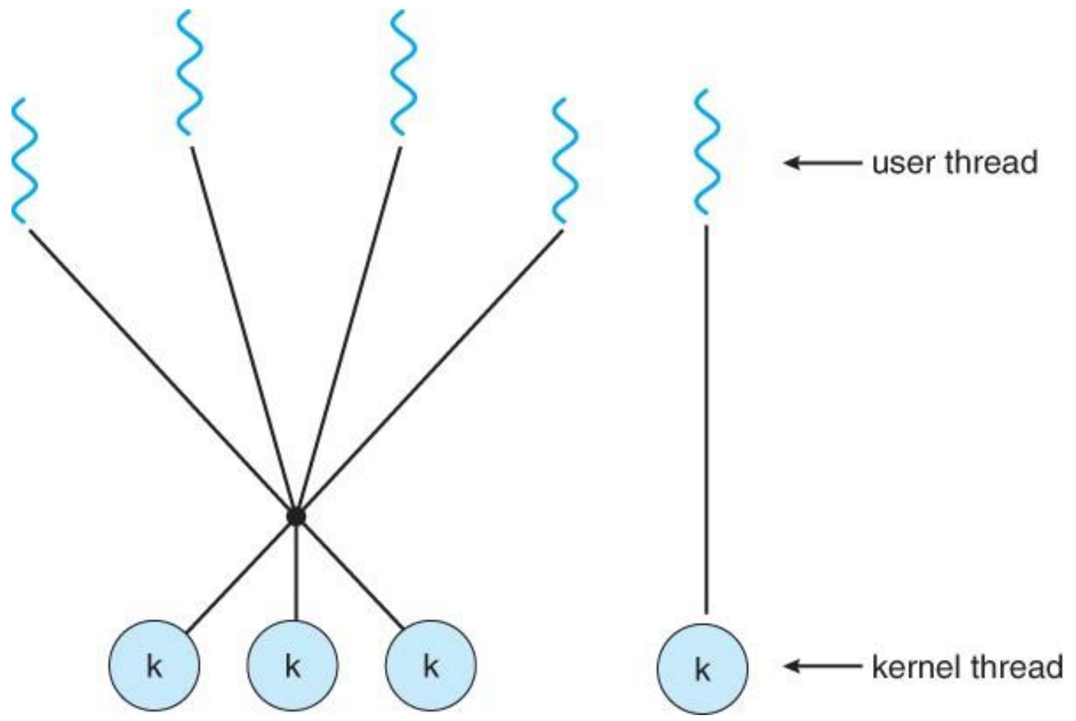


Figure 4.8 - Two-level model

Thread Libraries

- Thread libraries provide programmers with an API for creating and managing threads.
- Thread libraries may be implemented either in user space or in kernel space. The former involves API functions implemented solely within user space, with no kernel support. The latter involves system calls, and requires a kernel with thread library support.
- There are three main thread libraries in use today:
    1. POSIX Pthreads - may be provided as either a user or kernel library, as an extension to the POSIX standard.

    2. Win32 threads - provided as a kernel-level library on Windows systems.
    3. Java threads - Since Java generally runs on a Java Virtual Machine, the implementation of threads is based upon whatever OS and hardware the JVM is running on, i.e. either Pthreads or Win32 threads depending on the system.
- The following sections will demonstrate the use of threads in all three systems for calculating the sum of integers from 0 to N in a separate thread, and storing the result in a variable "sum".

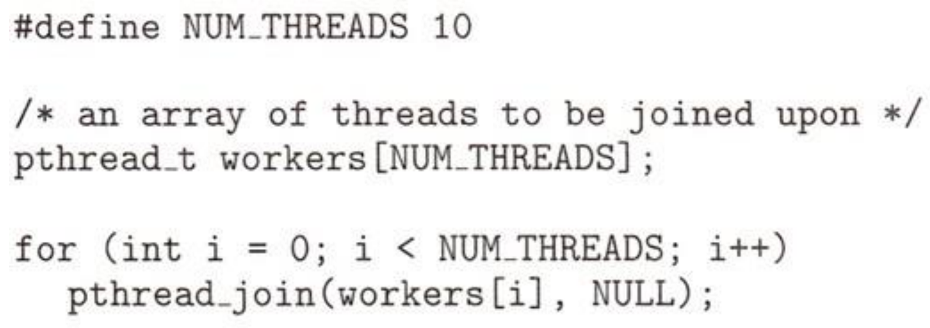
Pthreads

- The POSIX standard (IEEE 1003.1c) defines the *specification* for pThreads, not the *implementation*.
- pThreads are available on Solaris, Linux, Mac OSX, Tru64, and via public domain shareware for Windows.
- Global variables are shared amongst all threads.
- One thread can wait for the others to rejoin before continuing.
- pThreads begin execution in a specified function, in this example the runner( ) function:

```
#include <pthread.h>
#include <stdio.h>

int sum; /* this data is shared by the thread(s) */
void *runner(void *param); /* the thread */

int main(int argc, char *argv[])
{
  pthread_t tid; /* the thread identifier */
  pthread_attr_t attr; /* set of thread attributes */

  if (argc != 2) {
    fprintf(stderr,"usage: a.out <integer value>\n");
    return -1;
  }
  if (atoi(argv[1]) < 0) {
    fprintf(stderr,"%d must be >= 0\n",atoi(argv[1]));
    return -1;
  }

  /* get the default attributes */
  pthread_attr_init(&attr);
  /* create the thread */
  pthread_create(&tid,&attr,runner,argv[1]);
  /* wait for the thread to exit */
  pthread_join(tid,NULL);

  printf("sum = %d\n",sum);
}

/* The thread will begin control in this function */
void *runner(void *param)
{
  int i, upper = atoi(param);
  sum = 0;

  for (i = 1; i <= upper; i++)
    sum += i;

  pthread_exit(0);
}
```

Figure 4.6 Multithreaded C program using the Pthreads API.

Figure 4.9



```
#define NUM_THREADS 10

/* an array of threads to be joined upon */
pthread_t workers[NUM_THREADS];

for (int i = 0; i < NUM_THREADS; i++)
   pthread_join(workers[i], NULL);
```

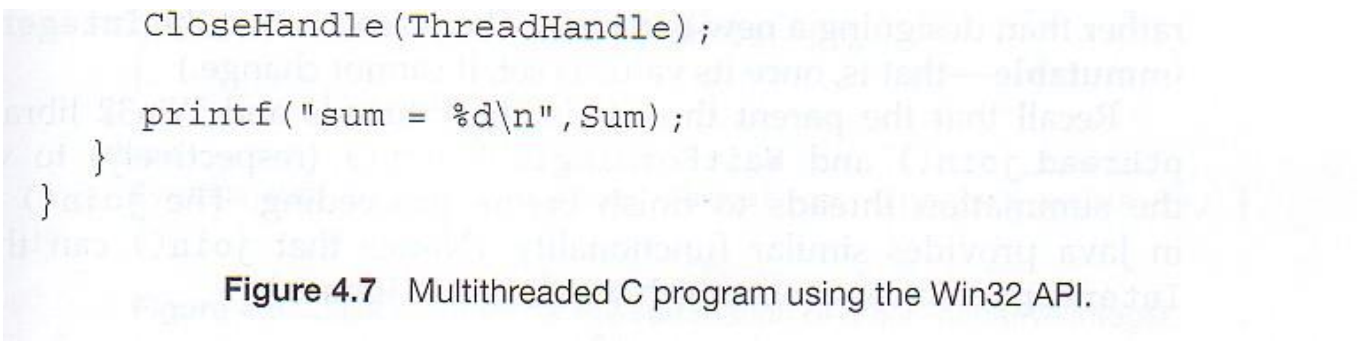
Figure 4.10 Pthread code for joining ten threads.

New

Windows Threads

- Similar to pThreads. Examine the code example to see the differences, which are mostly syntactic & nomenclature:

```
#include <windows.h>
#include <stdio.h>
DWORD Sum; /* data is shared by the thread(s) */
/* the thread runs in this separate function */

DWORD WINAPI Summation(LPVOID Param)
{
   DWORD Upper = *(DWORD*)Param;
   for (DWORD i = 0; i <= Upper; i++)
     Sum += i;
   return 0;
}

int main(int argc, char *argv[])
{
   DWORD ThreadId;
   HANDLE ThreadHandle;
   int Param;
   /* perform some basic error checking */
   if (argc != 2) {
     fprintf(stderr,"An integer parameter is required\n");
     return -1;
   }
   Param = atoi(argv[1]);
   if (Param < 0) {
     fprintf(stderr,"An integer >= 0 is required\n");
     return -1;
   }

   // create the thread
   ThreadHandle = CreateThread(
     NULL, // default security attributes
     0, // default stack size
     Summation, // thread function
       &Param, // parameter to thread function
     0, // default creation flags
     &ThreadId); // returns the thread identifier

   if (ThreadHandle != NULL) {
     // now wait for the thread to finish
     WaitForSingleObject(ThreadHandle,INFINITE);

     // close the thread handle
```



```
    CloseHandle(ThreadHandle);

    printf("sum = %d\n",Sum);
  }
}
```

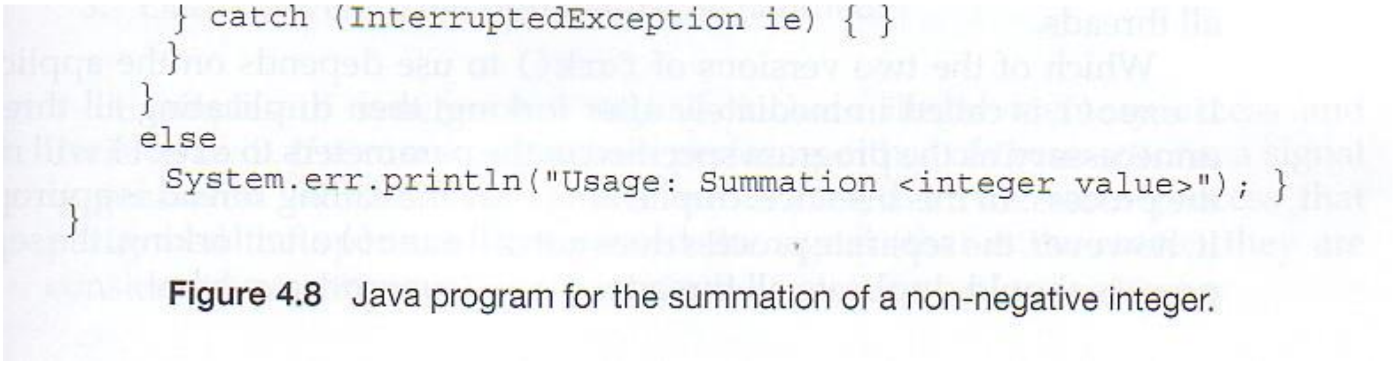
Figure 4.7 Multithreaded C program using the Win32 API.

Figure 4.11

Java Threads

- ALL Java programs use Threads - even "common" single-threaded ones.
- The creation of new Threads requires Objects that implement the Runnable Interface, which means they contain a method "public void run( )" . Any descendant of the Thread class will naturally contain such a method. (In practice the run( ) method must be overridden / provided for the thread to have any practical functionality.)
- Creating a Thread Object does not start the thread running - To do that the program must call the Thread's "start( )" method. Start( ) allocates and initializes memory for the Thread, and then calls the run( ) method. (Programmers do not call run( ) directly.)
- Because Java does not support global variables, Threads must be passed a reference to a shared Object in order to share data, in this example the "Sum" Object.
- Note that the JVM runs on top of a native OS, and that the JVM specification does not specify what model to use for mapping Java threads to kernel threads. This decision is JVM implementation dependant, and may be one-to-one, many-to-many, or many to one.. (On a UNIX system the JVM normally uses PThreads and on a Windows system it normally uses windows threads.)

```
class Sum
{
   private int sum;

   public int getSum() {
     return sum;
   }

   public void setSum(int sum) {
     this.sum = sum;
   }
}

class Summation implements Runnable
{
   private int upper;
   private Sum sumValue;

   public Summation(int upper, Sum sumValue) {
     this.upper = upper;
     this.sumValue = sumValue;
   }

   public void run() {
     int sum = 0;
     for (int i = 0; i <= upper; i++)
        sum += i;
     sumValue.setSum(sum);
   }
}

public class Driver
{
   public static void main(String[] args) {
     if (args.length > 0) {
       if (Integer.parseInt(args[0]) < 0)
        System.err.println(args[0] + " must be >= 0.");
       else {
        // create the object to be shared
        Sum sumObject = new Sum();
        int upper = Integer.parseInt(args[0]);
        Thread thrd = new Thread(new Summation(upper, sumObject));
        thrd.start();
        try {
           thrd.join();
           System.out.println
                   ("The sum of "+upper+" is "+sumObject.getSum());
```



```
      } catch (InterruptedException ie) { }
     }
    }
    else
     System.err.println("Usage: Summation <integer value>"); }
  }
```

Figure 4.8 Java program for the summation of a non-negative integer.

Figure 4.12

Implicit Threading (Optional)

Shifts the burden of addressing the programming challenges outlined in section 4.2.1 above from the application programmer to the compiler and run-time libraries.

Thread Pools

- Creating new threads every time one is needed and then deleting it when it is done can be inefficient, and can also lead to a very large (unlimited) number of threads being created.
- An alternative solution is to create a number of threads when the process first starts, and put those threads into a ***thread pool***.
  - Threads are allocated from the pool as needed, and returned to the pool when no longer needed.
  - When no threads are available in the pool, the process may have to wait until one becomes available.
- The (maximum) number of threads available in a thread pool may be determined by adjustable parameters, possibly dynamically in response to changing system loads.
- Win32 provides thread pools through the "PoolFunction" function. Java also provides support for thread pools through the java.util.concurrent package, and Apple supports thread pools under the Grand Central Dispatch architecture..

OpenMP

- OpenMP is a set of compiler directives available for C, C++, or FORTRAN programs that instruct the compiler to automatically generate parallel code where appropriate.
- For example, the directive:

  ```
  #pragma omp parallel
   {
         /* some parallel code here */
   }
  ```

  would cause the compiler to create as many threads as the machine has cores available, (e.g. 4 on a quad-core machine), and to run the parallel block of code, (known as a **parallel region**) on each of the threads.

- Another sample directive is "**`#pragma omp parallel for`**", which causes the for loop immediately following it to be parallelized, dividing the iterations up amongst the available cores.

Grand Central Dispatch, GCD

- GCD is an extension to C and C++ available on Apple's OSX and iOS operating systems to support parallelism.
- Similar to OpenMP, users of GCD define **blocks** of code to be executed either serially or in parallel by placing a carat just before an opening curly brace, i.e. **`^{ printf( "I am a block.\n" ); }`**
- GCD schedules blocks by placing them on one of several **dispatch queues**.
  - Blocks placed on a serial queue are removed one by one. The next block cannot be removed for scheduling until the previous block has completed.

    - There are three concurrent queues, corresponding roughly to low, medium, or high priority. Blocks are also removed from these queues one by one, but several may be removed and dispatched without waiting for others to finish first, depending on the availability of threads.
- Internally GCD manages a pool of POSIX threads which may fluctuate in size depending on load conditions.

Other Approaches

There are several other approaches available, including Microsoft's Threading Building Blocks (TBB) and other products, and Java's util.concurrent package.

Threading Issues

The fork( ) and exec( ) System Calls

- Q: If one thread forks, is the entire process copied, or is the new process single-threaded?
- A: System dependant.
- A: If the new process execs right away, there is no need to copy all the other threads. If it doesn't, then the entire process should be copied.
- A: Many versions of UNIX provide multiple versions of the fork call for this purpose.

Signal Handling

- Q: When a multi-threaded process receives a signal, to what thread should that signal be delivered?
- A: There are four major options:
    1. Deliver the signal to the thread to which the signal applies.
    2. Deliver the signal to every thread in the process.
    3. Deliver the signal to certain threads in the process.
    4. Assign a specific thread to receive all signals in a process.
- The best choice may depend on which specific signal is involved.
- UNIX allows individual threads to indicate which signals they are accepting and which they are ignoring. However the signal can only be delivered to one thread, which is generally the first thread that is accepting that particular signal.
- UNIX provides two separate system calls, **`kill( pid, signal )`** and **`pthread_kill( tid, signal )`**, for delivering signals to processes or specific threads respectively.
- Windows does not support signals, but they can be emulated using Asynchronous Procedure Calls (APCs). APCs are delivered to specific threads, not processes.

Thread Cancellation

- Threads that are no longer needed may be cancelled by another thread in one of two ways:
    1. **Asynchronous Cancellation** cancels the thread immediately.
    2. **Deferred Cancellation** sets a flag indicating the thread should cancel itself when it is convenient. It is then up to the cancelled thread to check this flag periodically and exit nicely when it sees the flag set.
- (Shared) resource allocation and inter-thread data transfers can be problematic with asynchronous cancellation.

Thread-Local Storage (was 4.4.5 Thread-Specific Data)

- Most data is shared among threads, and this is one of the major benefits of using threads in the first place.
- However sometimes threads need thread-specific data also.
- Most major thread libraries (pThreads, Win32, Java) provide support for thread-specific data, known as **thread-local storage** or **TLS.** Note that this is more like static data than local variables,because it does not cease to exist when the function ends.

Scheduler Activations

- Many implementations of threads provide a virtual processor as an interface between the user thread and the kernel thread, particularly for the many-to-many or two-tier models.
- This virtual processor is known as a "Lightweight Process", LWP.
    - There is a one-to-one correspondence between LWPs and kernel threads.
    - The number of kernel threads available, (and hence the number of LWPs) may change dynamically.
    - The application (user level thread library) maps user threads onto available LWPs.
    - kernel threads are scheduled onto the real processor(s) by the OS.
    - The kernel communicates to the user-level thread library when certain events occur (such as a thread about to block) via an ***upcall***, which is handled in the thread library by an ***upcall handler***. The upcall also provides a new LWP for the upcall handler to run on, which it can then use to reschedule the user thread that is about to become blocked. The OS will also issue upcalls when a thread becomes unblocked, so the thread library can make appropriate adjustments.
- If the kernel thread blocks, then the LWP blocks, which blocks the user thread.
- Ideally there should be at least as many LWPs available as there could be concurrently blocked kernel threads. Otherwise if all LWPs are blocked, then user threads will have to wait for one to become available.

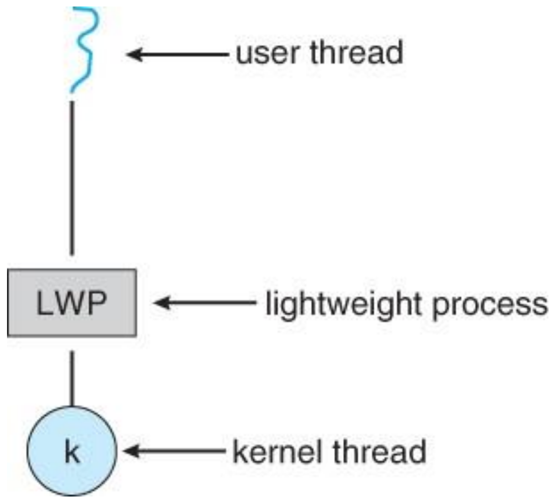


Figure 4.13 - Lightweight process (LWP)

Operating-System Examples (Optional)

Windows XP Threads

- The Win32 API thread library supports the one-to-one thread model
- Win32 also provides the ***fiber*** library, which supports the many-to-many model.
- Win32 thread components include:
    - Thread ID
    - Registers
    - A user stack used in user mode, and a kernel stack used in kernel mode.
    - A private storage area used by various run-time libraries and dynamic link libraries (DLLs).
- The key data structures for Windows threads are the ETHREAD (executive thread block), KTHREAD (kernel thread block), and the TEB (thread environment block). The ETHREAD and KTHREAD structures exist entirely within kernel space, and hence are only accessible by the kernel, whereas the TEB lies within user space, as illustrated in Figure 4.10:

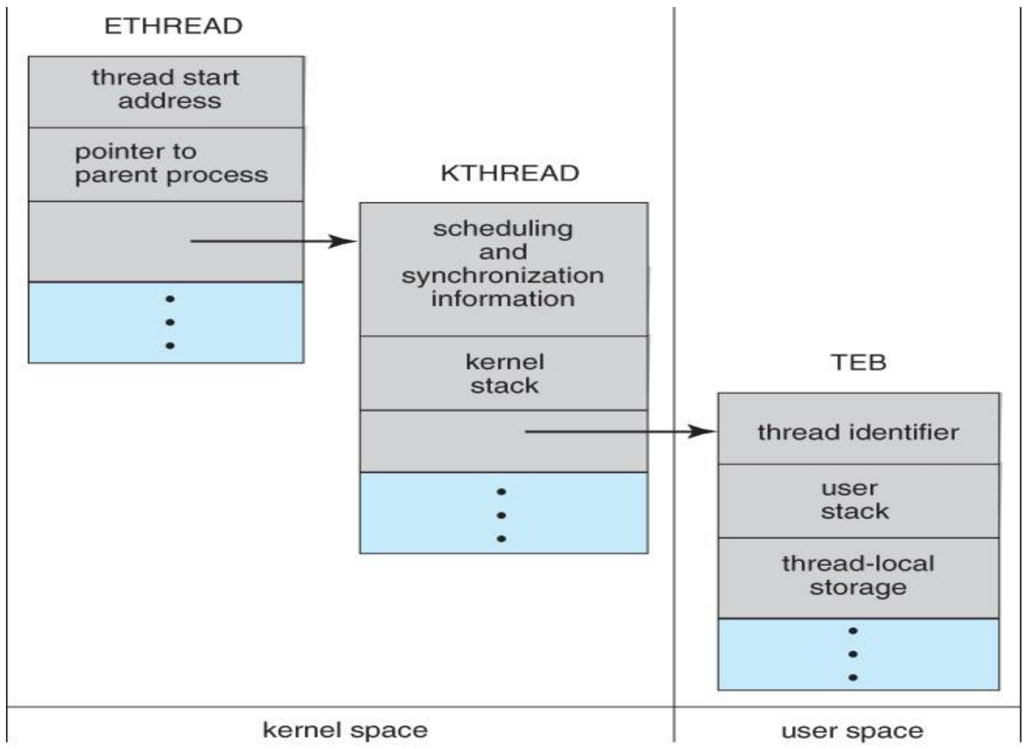


Figure 4.14 - Data structures of a Windows thread

Linux Threads

- Linux does not distinguish between processes and threads - It uses the more generic term "tasks".
- The traditional fork( ) system call completely duplicates a process (task), as described earlier.
- An alternative system call, clone( ) allows for varying degrees of sharing between the parent and child tasks, controlled by flags such as those shown in the following table:

flag	Meaning
CLONE_FS	File-system information is shared
CLONE_VM	The same memory space is shared
CLONE_SIGHAND	Signal handlers are shared
CLONE_FILES	The set of open files is shared

- Calling clone( )with no flags set is equivalent to fork( ). Calling clone( ) with CLONE_FS, CLONE_VM, CLONE_SIGHAND, and CLONE_FILES is equivalent to creating a thread, as all of these data structures will be shared.
- Linux implements this using a structure **`task_struct`**, which essentially provides a level of indirection to task resources. When the flags are not set, then the resources pointed to by the structure are copied, but if the flags are set, then only the pointers to the resources are copied, and hence the resources are shared. (Think of a deep copy versus a shallow copy in OO programming.)
- **(Removed from 9th edition)** Several distributions of Linux now support the NPTL (Native POXIS Thread Library)
  - POSIX compliant.
  - Support for SMP (symmetric multiprocessing), NUMA (non-uniform memory access), and multicore processors.
  - Support for hundreds to thousands of threads.

CPU Scheduling

Basic Concepts

- Almost all programs have some alternating cycle of CPU number crunching and waiting for I/O of some kind. (Even a simple fetch from memory takes a long time relative to CPU speeds.)
- In a simple system running a single process, the time spent waiting for I/O is wasted, and those CPU cycles are lost forever.
- A scheduling system allows one process to use the CPU while another is waiting for I/O, thereby making full use of otherwise lost CPU cycles.
- The challenge is to make the overall system as "efficient" and "fair" as possible, subject to varying and often dynamic conditions, and where "efficient" and "fair" are somewhat subjective terms, often subject to shifting priority policies.

CPU-I/O Burst Cycle

- Almost all processes alternate between two states in a continuing ***cycle***, as shown in Figure 6.1 below ***:***
  - A CPU burst of performing calculations, and
  - An I/O burst, waiting for data transfer in or out of the system.

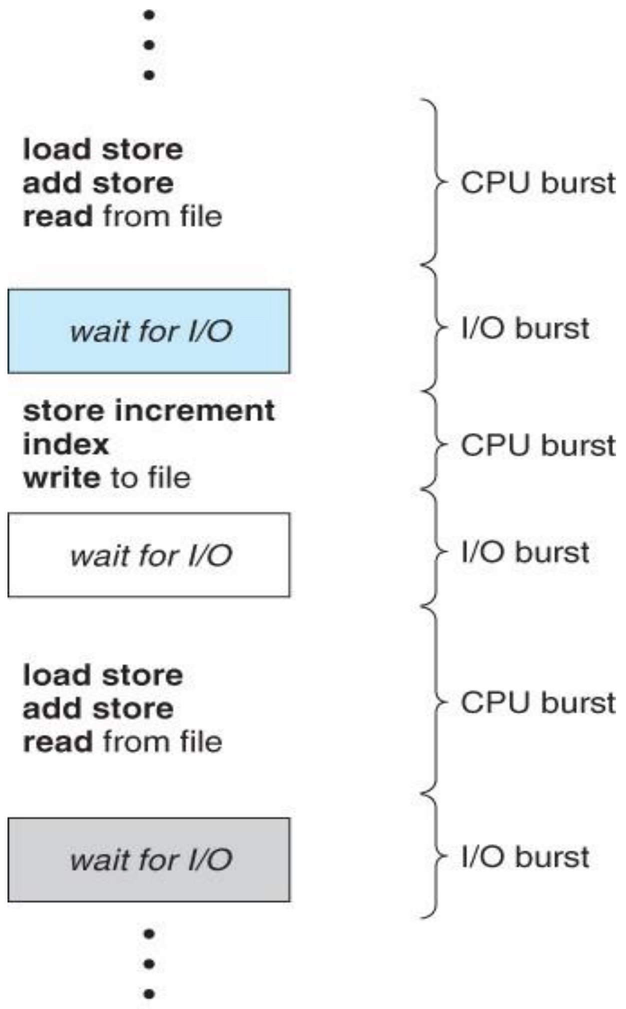


Figure 6.1 - Alternating sequence of CPU and I/O bursts.

- CPU bursts vary from process to process, and from program to program, but an extensive study shows frequency patterns similar to that shown in Figure 6.2:

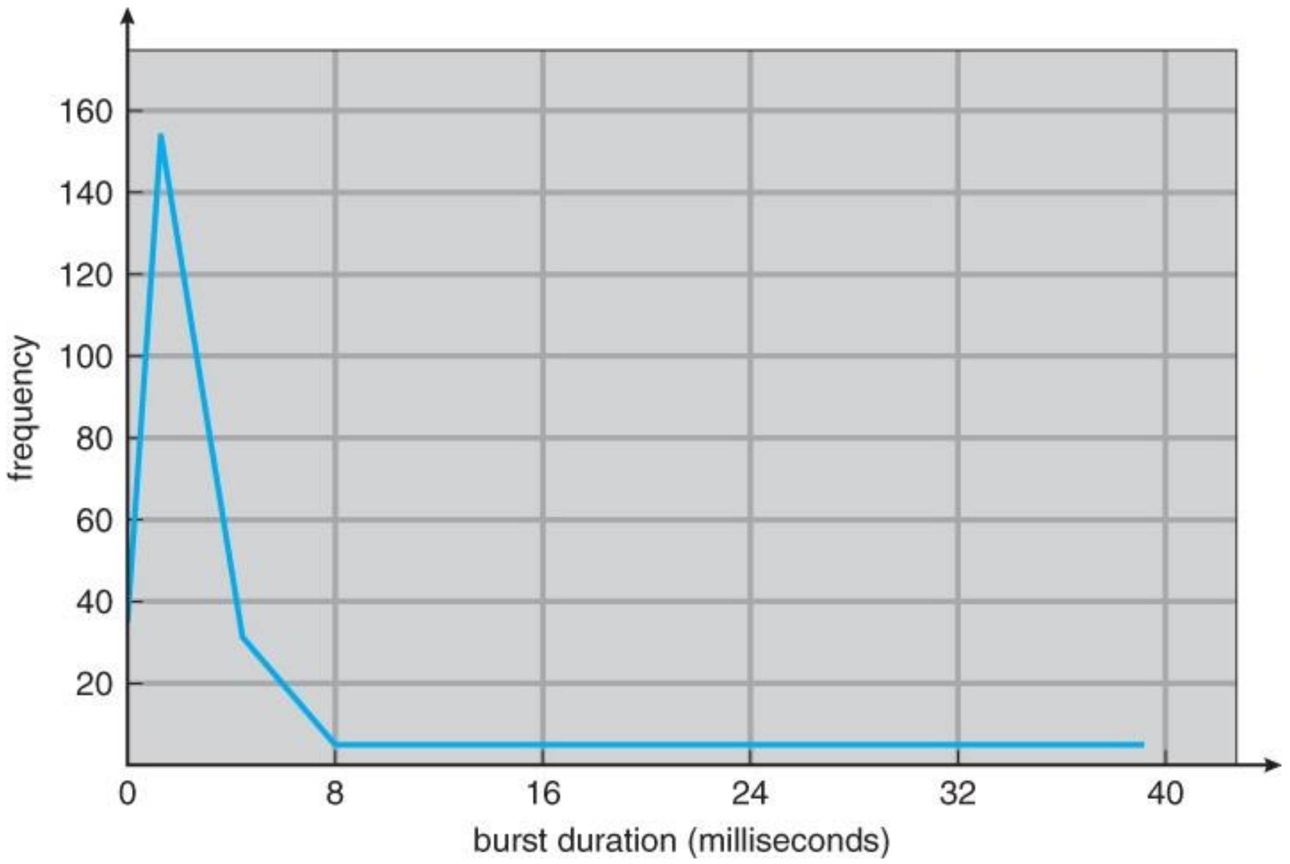


Figure 6.2 - Histogram of CPU-burst durations.

CPU Scheduler

- Whenever the CPU becomes idle, it is the job of the CPU Scheduler (a.k.a. the short-term scheduler) to select another process from the ready queue to run next.
- The storage structure for the ready queue and the algorithm used to select the next process are not necessarily a FIFO queue. There are several alternatives to choose from, as well as numerous adjustable parameters for each algorithm, which is the basic subject of this entire chapter.

Preemptive Scheduling

- CPU scheduling decisions take place under one of four conditions:
    1. When a process switches from the running state to the waiting state, such as for an I/O request or invocation of the wait( ) system call.
    2. When a process switches from the running state to the ready state, for example in response to an interrupt.
    3. When a process switches from the waiting state to the ready state, say at completion of I/O or a return from wait( ).
    4. When a process terminates.
- For conditions 1 and 4 there is no choice - A new process must be selected.
- For conditions 2 and 3 there is a choice - To either continue running the current process, or select a different one.
- If scheduling takes place only under conditions 1 and 4, the system is said to be ***non-preemptive***, or ***cooperative***. Under these conditions, once a process starts running it keeps running, until it either voluntarily blocks or until it finishes. Otherwise the system is said to be ***preemptive.***
- Windows used non-preemptive scheduling up to Windows 3.x, and started using pre-emptive scheduling with Win95. Macs used non-preemptive prior to OSX, and pre-emptive since then. Note that pre-emptive scheduling is only possible on hardware that supports a timer interrupt.
- Note that pre-emptive scheduling can cause problems when two processes share data, because one process may get interrupted in the middle of updating shared data structures. Chapter 5 examined this issue in greater detail.

- Preemption can also be a problem if the kernel is busy implementing a system call (e.g. updating critical kernel data structures) when the preemption occurs. Most modern UNIXes deal with this problem by making the process wait until the system call has either completed or blocked before allowing the preemption Unfortunately this solution is problematic for real-time systems, as real-time response can no longer be guaranteed.
- Some critical sections of code protect themselves from con currency problems by disabling interrupts before entering the critical section and re-enabling interrupts on exiting the section. Needless to say, this should only be done in rare situations, and only on very short pieces of code that will finish quickly, (usually just a few machine instructions.)

6.1.4 Dispatcher

- The **dispatcher** is the module that gives control of the CPU to the process selected by the scheduler. This function involves:
  - Switching context.
  - Switching to user mode.
  - Jumping to the proper location in the newly loaded program.
- The dispatcher needs to be as fast as possible, as it is run on every context switch. The time consumed by the dispatcher is known as **dispatch latency.**

Scheduling Criteria

- There are several different criteria to consider when trying to select the "best" scheduling algorithm for a particular situation and environment, including:
  - **CPU utilization -** Ideally the CPU would be busy 100% of the time, so as to waste 0 CPU cycles. On a real system CPU usage should range from 40% (lightly loaded) to 90% (heavily loaded.)
  - **Throughput -** Number of processes completed per unit time. May range from 10 / second to 1 / hour depending on the specific processes.
  - **Turnaround time -** Time required for a particular process to complete, from submission time to completion. (Wall clock time.)
  - **Waiting time -** How much time processes spend in the ready queue waiting their turn to get on the CPU.
    - (**Load average -** The average number of processes sitting in the ready queue waiting their turn to get into the CPU. Reported in 1-minute, 5-minute, and 15-minute averages by "uptime" and "who".)
  - **Response time -** The time taken in an interactive program from the issuance of a command to the ***commence*** of a response to that command.
- In general one wants to optimize the average value of a criteria (Maximize CPU utilization and throughput, and minimize all the others.) However some times one wants to do something different, such as to minimize the maximum response time.
- Sometimes it is most desirable to minimize the ***variance*** of a criteria than the actual value. I.e. users are more accepting of a consistent predictable system than an inconsistent one, even if it is a little bit slower.

Scheduling Algorithms

The following subsections will explain several common scheduling strategies, looking at only a single CPU burst each for a small number of processes. Obviously real systems have to deal with a lot more simultaneous processes executing their CPU-I/O burst cycles.

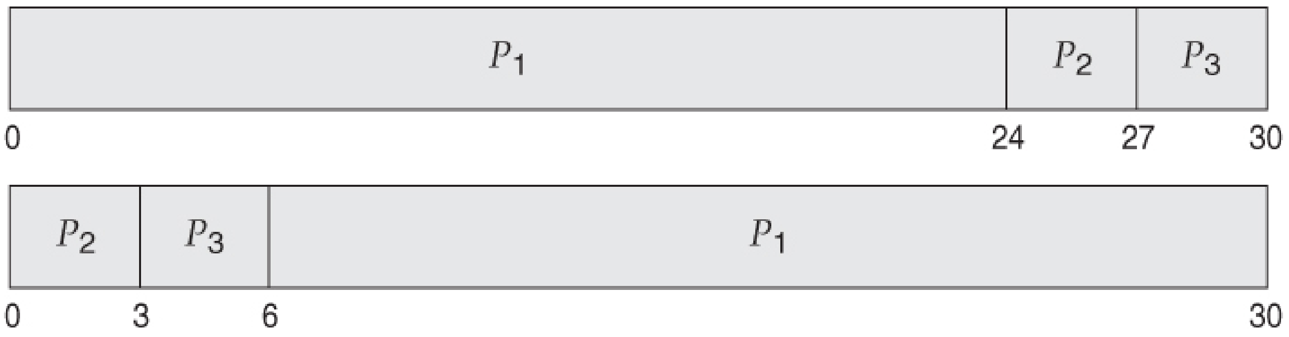
First-Come First-Serve Scheduling, FCFS

- FCFS is very simple - Just a FIFO queue, like customers waiting in line at the bank or the post office or at a copying machine.
- Unfortunately, however, FCFS can yield some very long average wait times, particularly if the first process to get there takes a long time. For example, consider the following three processes:

Process	Burst Time
P1	24
P2	3

P3	3

- In the first Gantt chart below, process P1 arrives first. The average waiting time for the three processes is (0 + 24 + 27) / 3 = 17.0 ms.
- In the second Gantt chart below, the same three processes have an average wait time of (0 + 3 + 6) / 3 = 3.0 ms. The total run time for the three bursts is the same, but in the second case two of the three finish much quicker, and the other process is only delayed by a short amount.

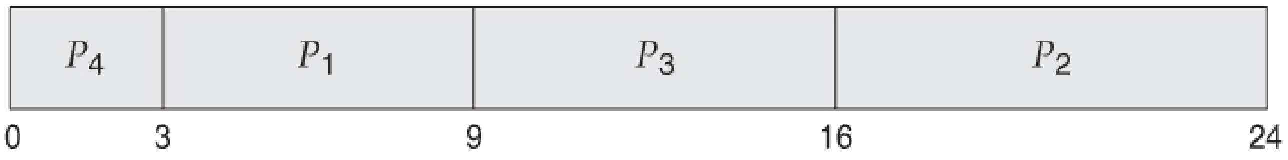


- FCFS can also block the system in a busy dynamic system in another way, known as the ***convoy effect***. When one CPU intensive process blocks the CPU, a number of I/O intensive processes can get backed up behind it, leaving the I/O devices idle. When the CPU hog finally relinquishes the CPU, then the I/O processes pass through the CPU quickly, leaving the CPU idle while everyone queues up for I/O, and then the cycle repeats itself when the CPU intensive process gets back to the ready queue.

Shortest-Job-First Scheduling, SJF

- The idea behind the SJF algorithm is to pick the quickest fastest little job that needs to be done, get it out of the way first, and then pick the next smallest fastest job to do next.
- (Technically this algorithm picks a process based on the next shortest **CPU burst**, not the overall process time.)
- For example, the Gantt chart below is based upon the following CPU burst times, (and the assumption that all jobs arrive at the same time.)

Process	Burst Time
P1	6
P2	8
P3	7
P4	3

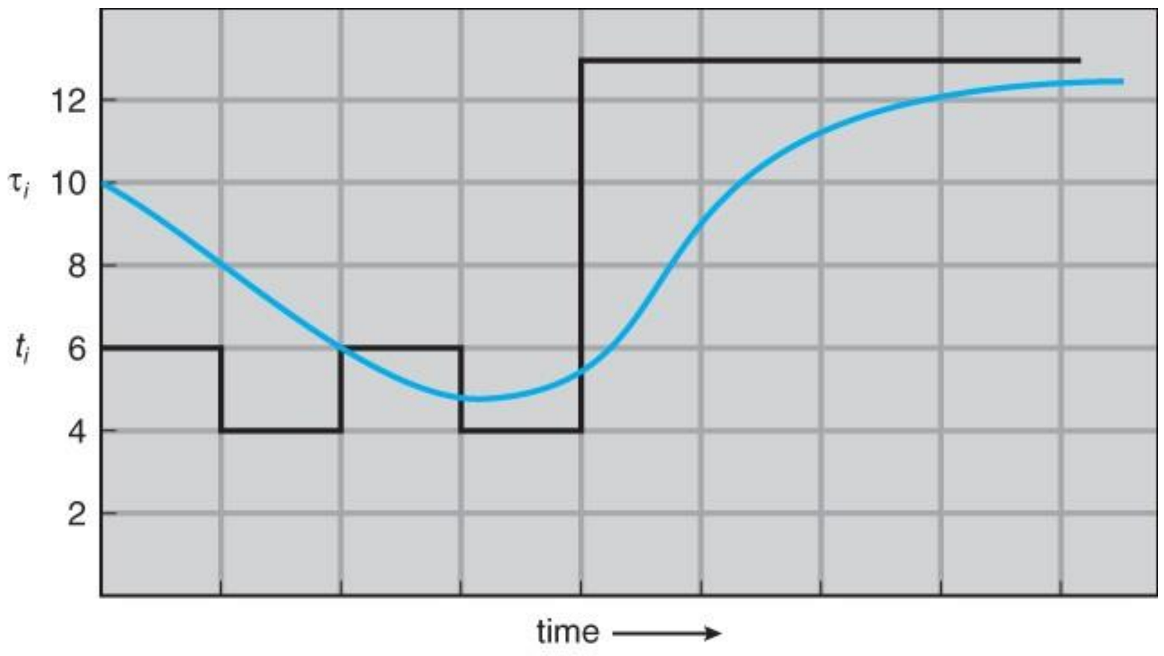


- In the case above the average wait time is (0 + 3 + 9 + 16) / 4 = 7.0 ms, (as opposed to 10.25 ms for FCFS for the same processes.)
- SJF can be proven to be the fastest scheduling algorithm, but it suffers from one important problem: How do you know how long the next CPU burst is going to be?
  - For long-term batch jobs this can be done based upon the limits that users set for their jobs when they submit them, which encourages them to set low limits, but risks their having to re-submit the job if they set the limit too low. However that does not work for short-term CPU scheduling on an interactive system.
  - Another option would be to statistically measure the run time characteristics of jobs, particularly if the same tasks are run repeatedly and predictably. But once again that really isn't a viable option for short term CPU scheduling in the real world.

    - A more practical approach is to ***predict*** the length of the next burst, based on some historical measurement of recent burst times for this process. One simple, fast, and relatively accurate method is the ***exponential average***, which can be defined as follows. (The book uses tau and t for their variables, but those are hard to distinguish from one another and don't work well in HTML.)

      estimate[i + 1] = alpha * burst[i] + (1.0 - alpha) * estimate[i]

    - In this scheme the previous estimate contains the history of all previous times, and alpha serves as a weighting factor for the relative importance of recent data versus past history. If alpha is 1.0, then past history is ignored, and we assume the next burst will be the same length as the last burst. If alpha is 0.0, then all measured burst times are ignored, and we just assume a constant burst time. Most commonly alpha is set at 0.5, as illustrated in Figure 5.3:

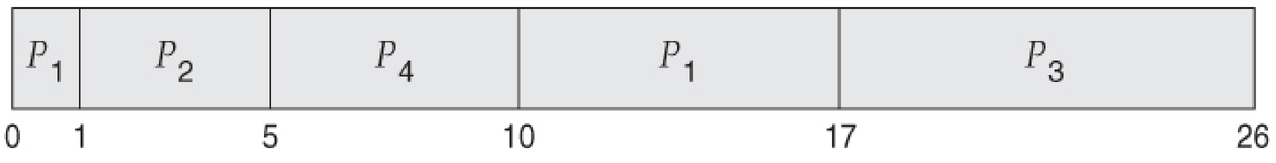


CPU burst (t_i)		6	4	6	4	13	13	13	...
"guess" (τ_i)	10	8	6	6	5	9	11	12	...

Figure 6.3 - Prediction of the length of the next CPU burst.

- SJF can be either preemptive or non-preemptive. Preemption occurs when a new process arrives in the ready queue that has a predicted burst time shorter than the time remaining in the process whose burst is currently on the CPU. Preemptive SJF is sometimes referred to as ***shortest remaining time first scheduling.***
- For example, the following Gantt chart is based upon the following data:

Process	Arrival Time	Burst Time
P1	0	8
P2	1	4
P3	2	9
p4	3	5

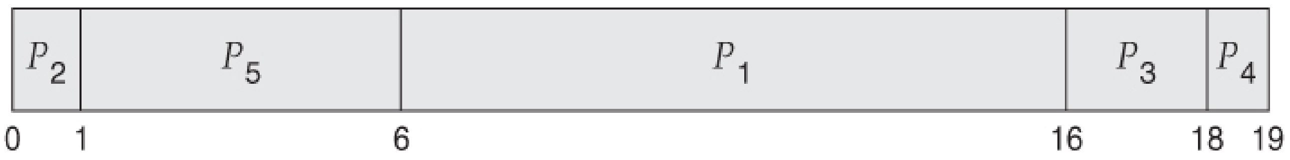


- The average wait time in this case is ((5 - 3) + (10 - 1) + (17 - 2)) / 4 = 26 / 4 = 6.5 ms. (As opposed to 7.75 ms for non-preemptive SJF or 8.75 for FCFS.)

Priority Scheduling

- Priority scheduling is a more general case of SJF, in which each job is assigned a priority and the job with the highest priority gets scheduled first. (SJF uses the inverse of the next expected burst time as its priority - The smaller the expected burst, the higher the priority.)
- Note that in practice, priorities are implemented using integers within a fixed range, but there is no agreed-upon convention as to whether "high" priorities use large numbers or small numbers. This book uses low number for high priorities, with 0 being the highest possible priority.
- For example, the following Gantt chart is based upon these process burst times and priorities, and yields an average waiting time of 8.2 ms:

Process	Burst Time	Priority
P1	10	3
P2	1	1
P3	2	4
P4	1	5
P5	5	2

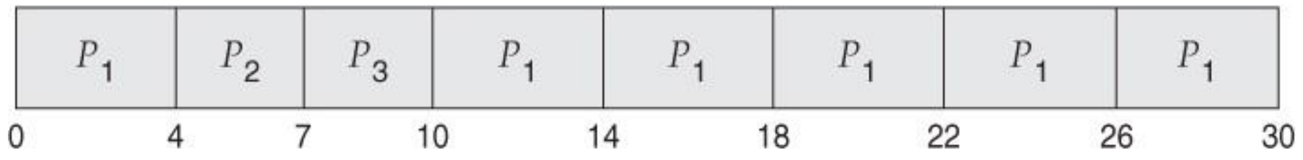


- Priorities can be assigned either internally or externally. Internal priorities are assigned by the OS using criteria such as average burst time, ratio of CPU to I/O activity, system resource use, and other factors available to the kernel. External priorities are assigned by users, based on the importance of the job, fees paid, politics, etc.
- Priority scheduling can be either preemptive or non-preemptive.
- Priority scheduling can suffer from a major problem known as ***indefinite blocking***, or ***starvation***, in which a low-priority task can wait forever because there are always some other jobs around that have higher priority.
    - If this problem is allowed to occur, then processes will either run eventually when the system load lightens (at say 2:00 a.m.), or will eventually get lost when the system is shut down or crashes. (There are rumors of jobs that have been stuck for years.)
    - One common solution to this problem is ***aging***, in which priorities of jobs increase the longer they wait. Under this scheme a low-priority job will eventually get its priority raised high enough that it gets run.

Round Robin Scheduling

- Round robin scheduling is similar to FCFS scheduling, except that CPU bursts are assigned with limits called ***time quantum***.
- When a process is given the CPU, a timer is set for whatever value has been set for a time quantum.
    - If the process finishes its burst before the time quantum timer expires, then it is swapped out of the CPU just like the normal FCFS algorithm.
    - If the timer goes off first, then the process is swapped out of the CPU and moved to the back end of the ready queue.
- The ready queue is maintained as a circular queue, so when all processes have had a turn, then the scheduler gives the first process another turn, and so on.
- RR scheduling can give the effect of all processors sharing the CPU equally, although the average wait time can be longer than with other scheduling algorithms. In the following example the average wait time is 5.66 ms.

Process	Burst Time
P1	24
P2	3
P3	3



- The performance of RR is sensitive to the time quantum selected. If the quantum is large enough, then RR reduces to the FCFS algorithm; If it is very small, then each process gets 1/nth of the processor time and share the CPU equally.
- **BUT**, a real system invokes overhead for every context switch, and the smaller the time quantum the more context switches there are. (See Figure 6.4 below.) Most modern systems use time quantum between 10 and 100 milliseconds, and context switch times on the order of 10 microseconds, so the overhead is small relative to the time quantum.

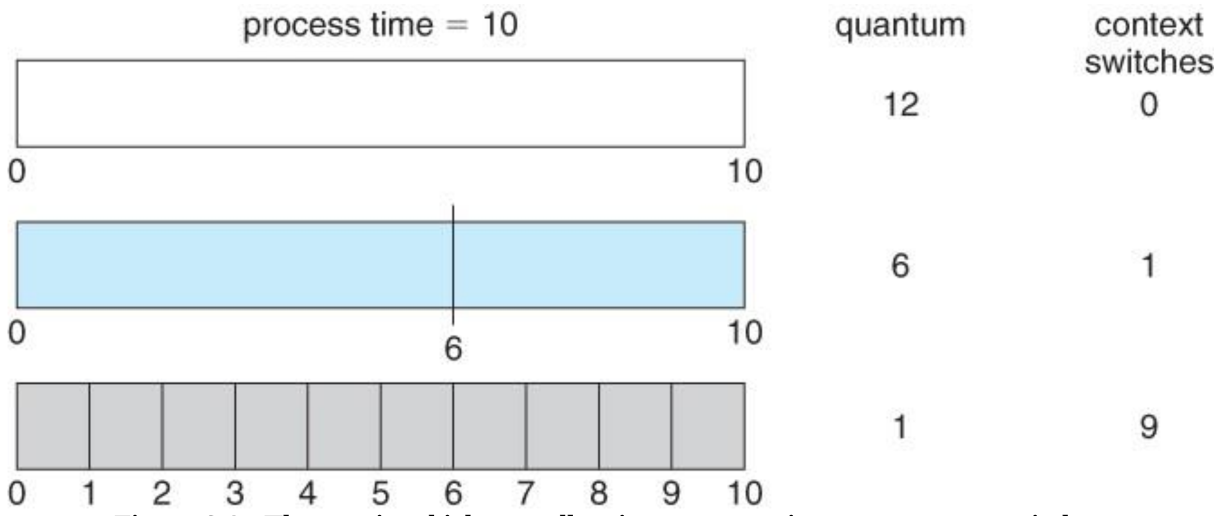
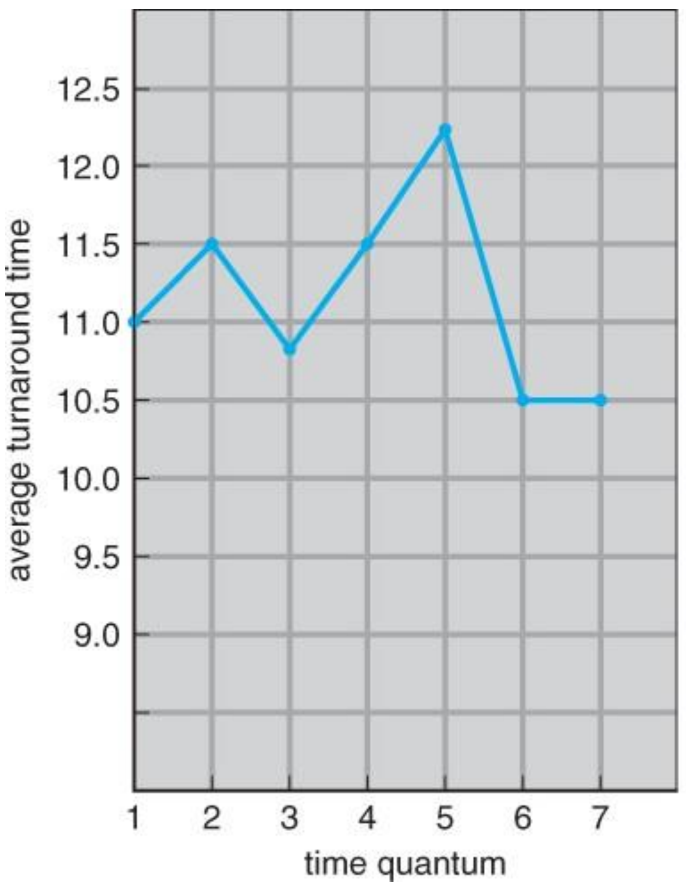


Figure 6.4 - The way in which a smaller time quantum increases context switches.

- Turn around time also varies with quantum time, in a non-apparent manner. Consider, for example the processes shown in Figure 6.5:



process	time
P_1	6
P_2	3
P_3	1
P_4	7

Figure 6.5 - The way in which turnaround time varies with the time quantum.

- In general, turnaround time is minimized if most processes finish their next cpu burst within one time quantum. For example, with three processes of 10 ms bursts each, the average turnaround time for 1 ms quantum is 29, and for 10 ms quantum it reduces to 20. However, if it is made too large, then RR just degenerates to FCFS. A rule of thumb is that 80% of CPU bursts should be smaller than the time quantum.

Multilevel Queue Scheduling

- When processes can be readily categorized, then multiple separate queues can be established, each implementing whatever scheduling algorithm is most appropriate for that type of job, and/or with different parametric adjustments.
- Scheduling must also be done between queues, that is scheduling one queue to get time relative to other queues. Two common options are strict priority (no job in a lower priority queue runs until all higher priority queues are empty) and round-robin (each queue gets a time slice in turn, possibly of different sizes.)
- Note that under this algorithm jobs cannot switch from queue to queue - Once they are assigned a queue, that is their queue until they finish.

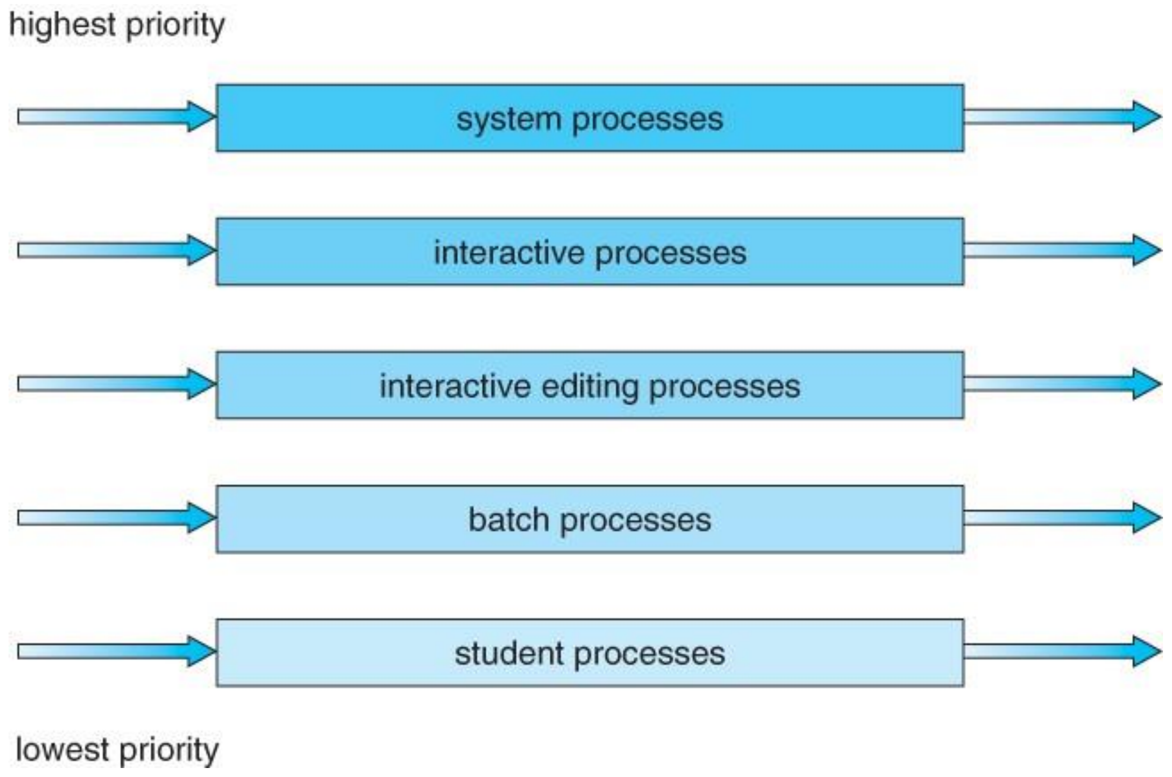


Figure 6.6 - Multilevel queue scheduling

Multilevel Feedback-Queue Scheduling

- Multilevel feedback queue scheduling is similar to the ordinary multilevel queue scheduling described above, except jobs may be moved from one queue to another for a variety of reasons:
  - If the characteristics of a job change between CPU-intensive and I/O intensive, then it may be appropriate to switch a job from one queue to another.
  - Aging can also be incorporated, so that a job that has waited for a long time can get bumped up into a higher priority queue for a while.
- Multilevel feedback queue scheduling is the most flexible, because it can be tuned for any situation. But it is also the most complex to implement because of all the adjustable parameters. Some of the parameters which define one of these systems include:
  - The number of queues.
  - The scheduling algorithm for each queue.
  - The methods used to upgrade or demote processes from one queue to another. (Which may be different.)
  - The method used to determine which queue a process enters initially.

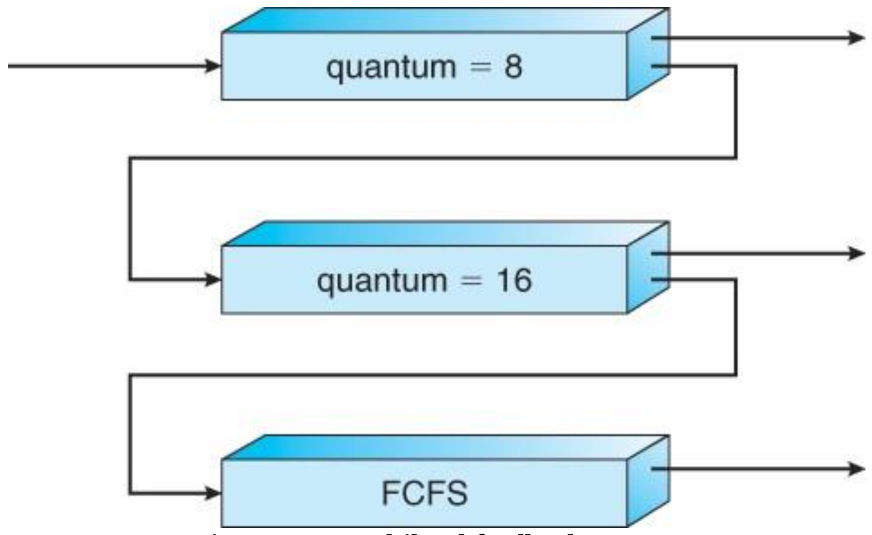


Figure 6.7 - Multilevel feedback queues.

Thread Scheduling

- The process scheduler schedules only the kernel threads.
- User threads are mapped to kernel threads by the thread library - The OS (and in particular the scheduler) is unaware of them.

Contention Scope

- ***Contention scope*** refers to the scope in which threads compete for the use of physical CPUs.
- On systems implementing many-to-one and many-to-many threads, ***Process Contention Scope, PCS,*** occurs, because competition occurs between threads that are part of the same process. (This is the management / scheduling of multiple user threads on a single kernel thread, and is managed by the thread library.)
- ***System Contention Scope, SCS,*** involves the system scheduler scheduling kernel threads to run on one or more CPUs. Systems implementing one-to-one threads (XP, Solaris 9, Linux), use only SCS.
- PCS scheduling is typically done with priority, where the programmer can set and/or change the priority of threads created by his or her programs. Even time slicing is not guaranteed among threads of equal priority.

Pthread Scheduling

- The Pthread library provides for specifying scope contention:
  - PTHREAD_SCOPE_PROCESS schedules threads using PCS, by scheduling user threads onto available LWPs using the many-to-many model.
  - PTHREAD_SCOPE_SYSTEM schedules threads using SCS, by binding user threads to particular LWPs, effectively implementing a one-to-one model.
- getscope and setscope methods provide for determining and setting the scope contention respectively:

```
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS 5

int main(int argc, char *argv[])
{
  int i, scope;
  pthread_t tid[NUM_THREADS];
  pthread_attr_t attr;

  /* get the default attributes */
  pthread_attr_init(&attr);

  /* first inquire on the current scope */
  if (pthread_attr_getscope(&attr, &scope) != 0)
    fprintf(stderr, "Unable to get scheduling scope\n");
  else {
    if (scope == PTHREAD_SCOPE_PROCESS)
     printf("PTHREAD_SCOPE_PROCESS");
    else if (scope == PTHREAD_SCOPE_SYSTEM)
     printf("PTHREAD_SCOPE_SYSTEM");
    else
     fprintf(stderr, "Illegal scope value.\n");
   }

  /* set the scheduling algorithm to PCS or SCS */
  pthread_attr_setscope(&attr, PTHREAD_SCOPE_SYSTEM);

  /* create the threads */
  for (i = 0; i < NUM_THREADS; i++)
     pthread_create(&tid[i],&attr,runner,NULL);

  /* now join on each thread */
  for (i = 0; i < NUM_THREADS; i++)
     pthread_join(tid[i], NULL);
}

/* Each thread will begin control in this function */
void *runner(void *param)
{
  /* do some work ... */

  pthread_exit(0);
}
```

Figure 6.8 - Pthread scheduling API.

Multiple-Processor Scheduling

- When multiple processors are available, then the scheduling gets more complicated, because now there is more than one CPU which must be kept busy and in effective use at all times.
- ***Load sharing*** revolves around balancing the load between multiple processors.
- Multi-processor systems may be **heterogeneous,** (different kinds of CPUs), or **homogenous,** (all the same kind of CPU). Even in the latter case there may be special scheduling constraints, such as devices which are connected via a private bus to only one of the CPUs. This book will restrict its discussion to homogenous systems.

Approaches to Multiple-Processor Scheduling

- One approach to multi-processor scheduling is ***asymmetric multiprocessing,*** in which one processor is the master, controlling all activities and running all kernel code, while the other runs only user code. This approach is relatively simple, as there is no need to share critical system data.
- Another approach is ***symmetric multiprocessing, SMP,*** where each processor schedules its own jobs, either from a common ready queue or from separate ready queues for each processor.
- Virtually all modern OSes support SMP, including XP, Win 2000, Solaris, Linux, and Mac OSX.

Processor Affinity

- Processors contain cache memory, which speeds up repeated accesses to the same memory locations.
- If a process were to switch from one processor to another each time it got a time slice, the data in the cache (for that process) would have to be invalidated and re-loaded from main memory, thereby obviating the benefit of the cache.
- Therefore SMP systems attempt to keep processes on the same processor, via ***processor affinity. Soft affinity*** occurs when the system attempts to keep processes on the same processor but makes no guarantees. Linux and some other OSes support ***hard affinity,*** in which a process specifies that it is not to be moved between processors.
- Main memory architecture can also affect process affinity, if particular CPUs have faster access to memory on the same chip or board than to other memory loaded elsewhere. (Non-Uniform Memory Access, NUMA.) As shown below, if a process has an affinity for a particular CPU, then it should preferentially be assigned memory storage in "local" fast access areas.

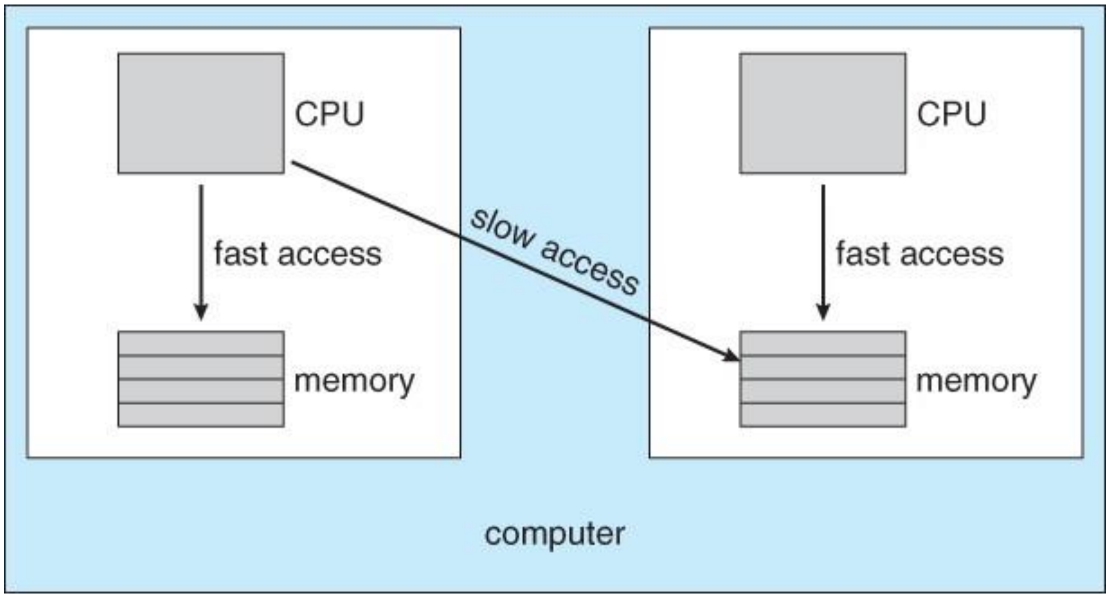


Figure 6.9 - NUMA and CPU scheduling.

Load Balancing

- Obviously an important goal in a multiprocessor system is to balance the load between processors, so that one processor won't be sitting idle while another is overloaded.
- Systems using a common ready queue are naturally self-balancing, and do not need any special handling. Most systems, however, maintain separate ready queues for each processor.
- Balancing can be achieved through either ***push migration*** or ***pull migration:***
    - ***Push migration*** involves a separate process that runs periodically, (e.g. every 200 milliseconds), and moves processes from heavily loaded processors onto less loaded ones.
    - ***Pull migration*** involves idle processors taking processes from the ready queues of other processors.
    - Push and pull migration are not mutually exclusive.
- Note that moving processes from processor to processor to achieve load balancing works against the principle of processor affinity, and if not carefully managed, the savings gained by balancing the system can be lost in rebuilding caches. One option is to only allow migration when imbalance surpasses a given threshold.

Multicore Processors

- Traditional SMP required multiple CPU chips to run multiple kernel threads concurrently.
- Recent trends are to put multiple CPUs (cores) onto a single chip, which appear to the system as multiple processors.
- Compute cycles can be blocked by the time needed to access memory, whenever the needed data is not already present in the cache. (Cache misses.) In Figure 5.10, as much as half of the CPU cycles are lost to memory stall.

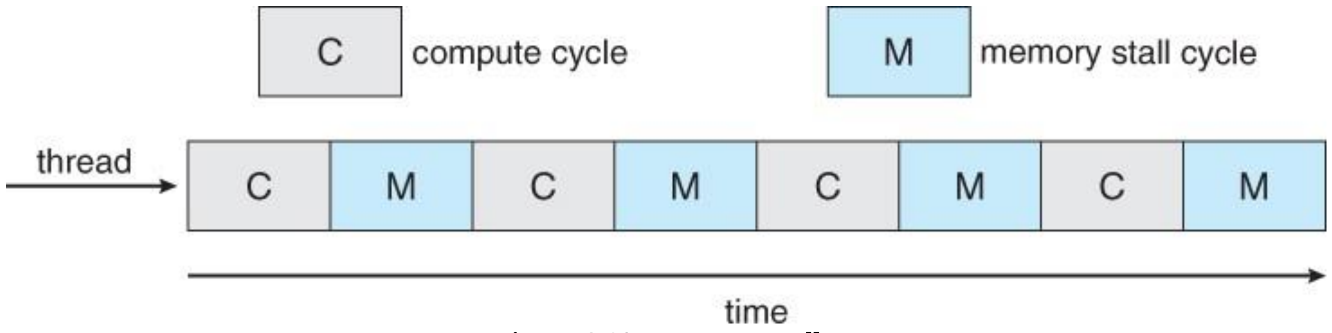


Figure 6.10 - Memory stall.

- By assigning multiple kernel threads to a single processor, memory stall can be avoided (or reduced) by running one thread on the processor while the other thread waits for memory.

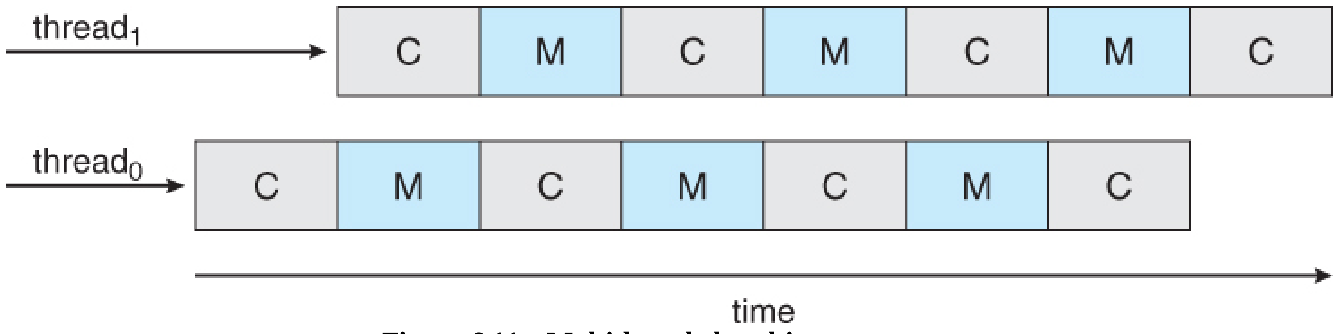


Figure 6.11 - Multithreaded multicore system.

- A dual-threaded dual-core system has four logical processors available to the operating system. The UltraSPARC T1 CPU has 8 cores per chip and 4 hardware threads per core, for a total of 32 logical processors per chip.
- There are two ways to multi-thread a processor:
    1. ***Coarse-grained*** multithreading switches between threads only when one thread blocks, say on a memory read. Context switching is similar to process switching, with considerable overhead.
    2. ***Fine-grained*** multithreading occurs on smaller regular intervals, say on the boundary of instruction cycles. However the architecture is designed to support thread switching, so the overhead is relatively minor.
- Note that for a multi-threaded multi-core system, there are **two** levels of scheduling, **at the kernel level:**

    - The OS schedules which kernel thread(s) to assign to which logical processors, and when to make context switches using algorithms as described above.
    - On a lower level, the hardware schedules logical processors on each physical core using some other algorithm.
        - The UltraSPARC T1 uses a simple round-robin method to schedule the 4 logical processors (kernel threads) on each physical core.
        - The Intel Itanium is a dual-core chip which uses a 7-level priority scheme (urgency) to determine which thread to schedule when one of 5 different events occurs.

/* Old 5.5.5 Virtualization and Scheduling (Optional, Omitted from 9th edition)

- Virtualization adds another layer of complexity and scheduling.
- Typically there is one host operating system operating on "real" processor(s) and a number of guest operating systems operating on virtual processors.
- The Host OS creates some number of virtual processors and presents them to the guest OSes as if they were real processors.
- The guest OSes don't realize their processors are virtual, and make scheduling decisions on the assumption of real processors.
- As a result, interactive and especially real-time performance can be severely compromised on guest systems. The time-of-day clock will also frequently be off.

***/**

Real-Time CPU Scheduling

Real-time systems are those in which the time at which tasks complete is crucial to their performance

- ***Soft real-time systems*** have degraded performance if their timing needs cannot be met. Example: streaming video.
- ***Hard real-time systems*** have total failure if their timing needs cannot be met. Examples: Assembly line robotics, automobile air-bag deployment.

Minimizing Latency

- ***Event Latency*** is the time between the occurrence of a triggering event and the (completion of) the system's response to the event:

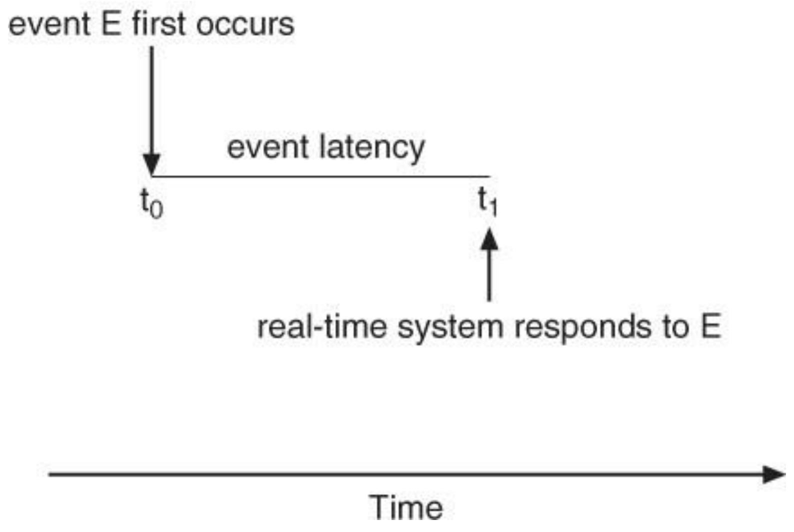


Figure 6.12 - Event latency.

- In addition to the time it takes to actually process the event, there are two additional steps that must occur before the event handler (Interrupt Service Routine, ISR), can even start:
    - Interrupt processing determines which interrupt(s) have occurred, and which interrupt handler routine to run. In the event of simultaneous interrupts, a priority scheme is needed to determine

which ISR has the highest priority and gets to go next.
- Context switching involves removing a running process from the CPU, saving its state, and loading up the ISR so that it can run.

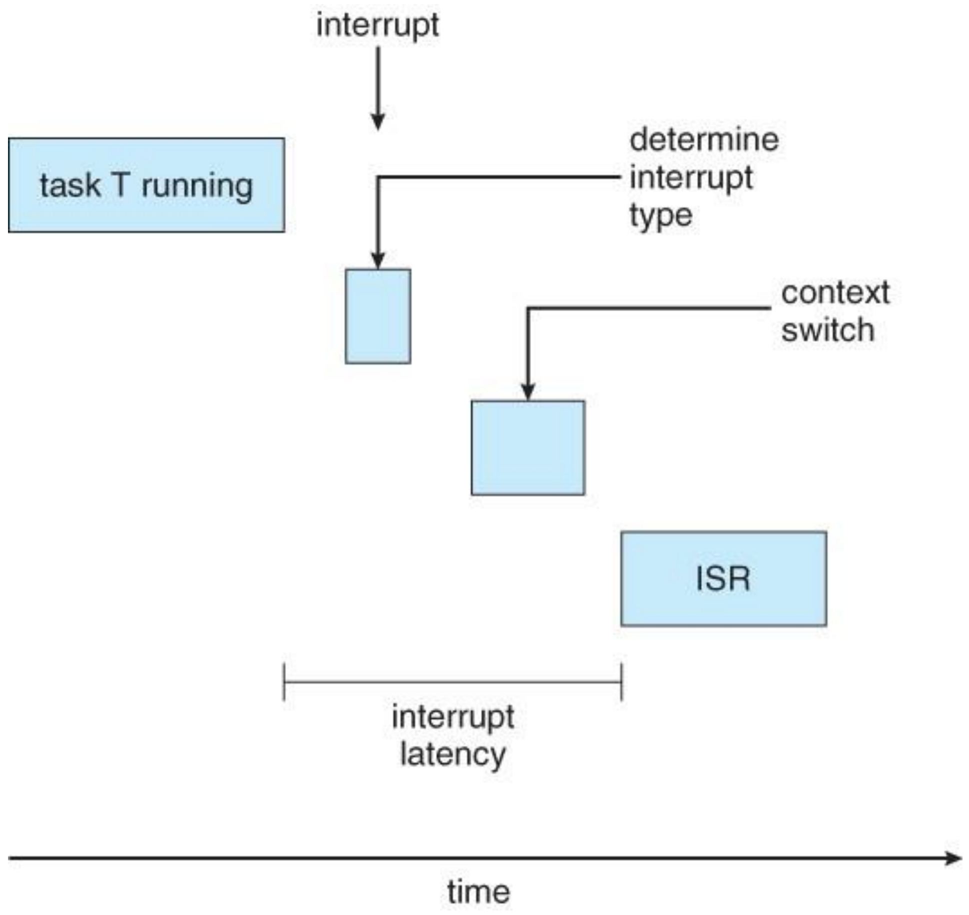


Figure 6.13 - Interrupt latency.

- The total dispatch latency (context switching) consists of two parts:
  - Removing the currently running process from the CPU, and freeing up any resources that are needed by the ISR. This step can be speeded up a lot by the use of pre-emptive kernels.
  - Loading the ISR up onto the CPU, (dispatching)

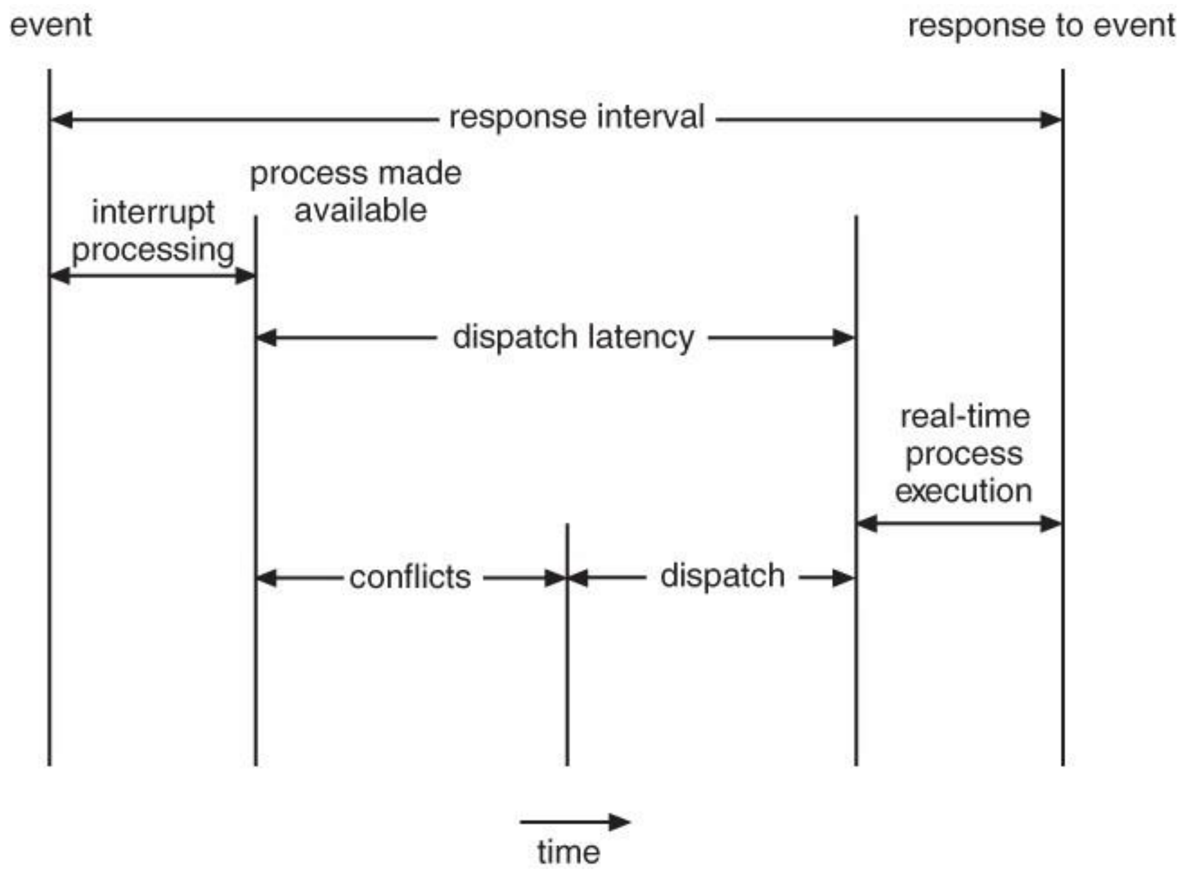


Figure 6.14 - Dispatch latency.

Priority-Based Scheduling

- Real-time systems require pre-emptive priority-based scheduling systems.
- Soft real-time systems do the best they can, but make no guarantees. They are generally discussed elsewhere.
- Hard real-time systems, described here, must be able to provide firm guarantees that a tasks scheduling needs can be met.
    - One technique is to use a ***admission-control*** algorithm, in which each task must specify its needs at the time it attempts to launch, and the system will only launch the task if it can guarantee that its needs can be met.
- Hard real-time systems are often characterized by tasks that must run at regular periodic intervals, each having a period p, a constant time required to execute, (CPU burst), t, and a deadline after the beginning of each period by which the task must be completed, d.
- In all cases, t <= d <= p

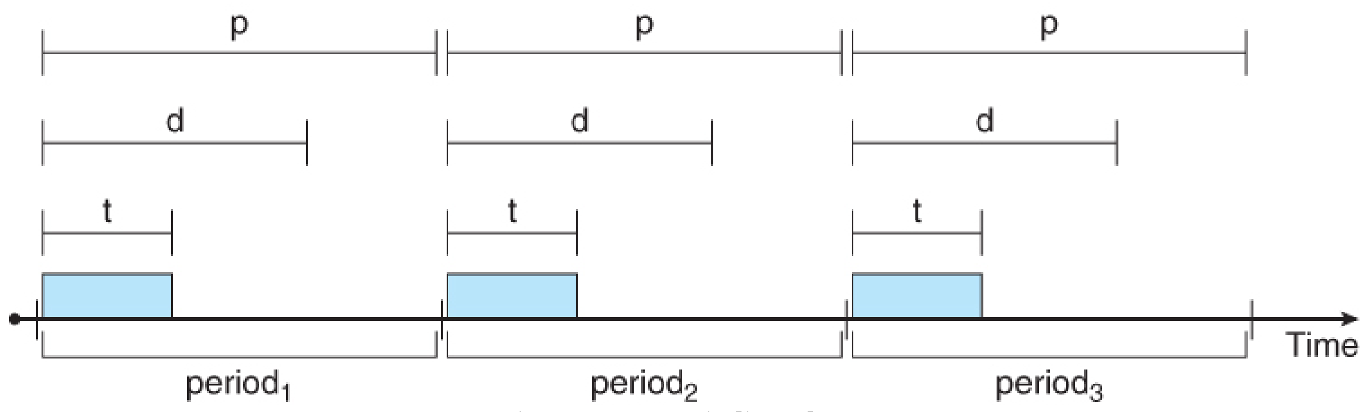


Figure 6.15 - Periodic task.

Rate-Monotonic Scheduling

- The rate-monotonic scheduling algorithm uses pre-emptive scheduling with static priorities.
- Priorities are assigned inversely to the period of each task, giving higher (better) priority to tasks with shorter periods.
- Let's consider an example, first showing what can happen if the task with the longer period is given higher priority:
    - Suppose that process P1 has a period of 50, an execution time of 20, and a deadline that matches its period (50).
    - Similarly suppose that process P2 has period 100, execution time of 35, and deadline of 100.
    - The total CPU utilization time is 20 / 50 = 0.4 for P1, and 25 / 100 = 0.35 for P2, or 0.75 (75%) overall.
    - However if P2 is allowed to go first, then P1 cannot complete before its deadline:

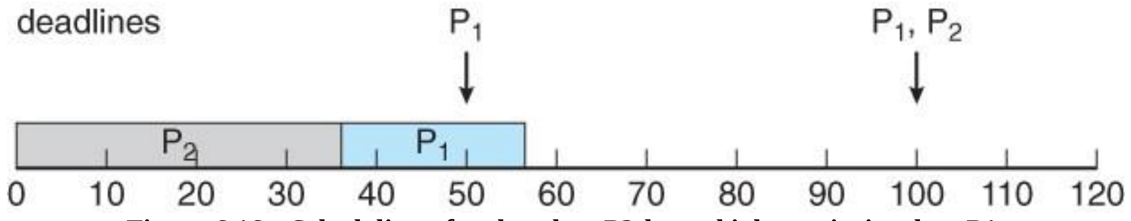


Figure 6.16 - Scheduling of tasks when P2 has a higher priority than P1.

- Now on the other hand, if P1 is given higher priority, it gets to go first, and P2 starts after P1 completes its burst.
- At time 50 when the next period for P1 starts, P2 has only completed 30 of its 35 needed time units, but it gets pre-empted by P1.
- At time 70, P1 completes its task for its second period, and the P2 is allowed to complete its last 5 time units.
- Overall both processes complete at time 75, and the cpu is then idle for 25 time units, before the process repeats.

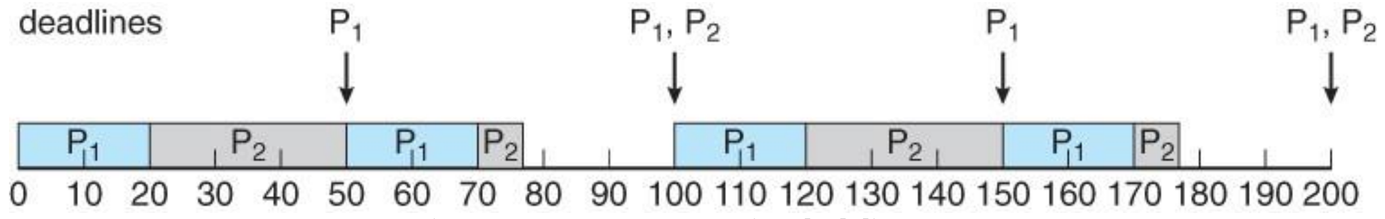


Figure 6.17 - Rate-monotonic scheduling.

- Rate-monotonic scheduling is considered optimal among algorithms that use static priorities, because any set of processes that cannot be scheduled with this algorithm cannot be scheduled with any other static-priority scheduling algorithm either.
- There are, however, some sets of processes that cannot be scheduled with static priorities.
    - For example, supposing that P1 =50, T1 = 25, P2 = 80, T2 = 35, and the deadlines match the periods.
    - Overall CPU usage is 25/50 = 0.5 for P1, 35 / 80 =0.44 for P2, or 0.94 (94%) overall, indicating it should be possible to schedule the processes.
    - With rate-monotonic scheduling, P1 goes first, and completes its first burst at time 25.
    - P2 goes next, and completes 25 out of its 35 time units before it gets pre-empted by P1 at time 50.
    - P1 completes its second burst at 75, and then P2 completes its last 10 time units at time 85, missing its deadline of 80 by 5 time units. :-(

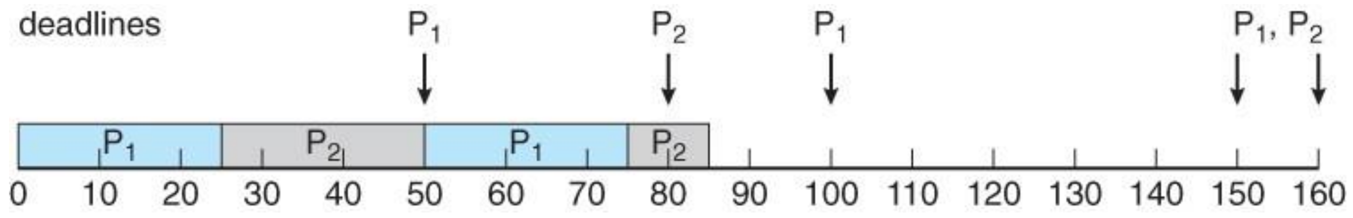


Figure 6.18 - Missing deadlines with rate-monotonic scheduling.

- The worst-case CPU utilization for scheduling N processes under this algorithm is N * (2^(1/N) - 1), which is 100% for a single process, but drops to 75% for two processes and to 69% as N approaches infinity. Note that in our example above 94% is higher than 75%.

Earliest-Deadline-First Scheduling

- Earliest Deadline First (EDF) scheduling varies priorities dynamically, giving the highest priority to the process with the earliest deadline.
- Figure 6.19 shows our previous example repeated under EDF scheduling:
  - At time 0 P1 has the earliest deadline, highest priority, and goes first., followed by P2 at time 25 when P1 completes its first burst.
  - At time 50 process P1 begins its second period, but since P2 has a deadline of 80 and the deadline for P1 is not until 100, P2 is allowed to stay on the CPU and complete its burst, which it does at time 60.
  - P1 then starts its second burst, which it completes at time 85. P2 started its second period at time 80, but since P1 had an earlier deadline, P2 did not pre-empt P1.
  - P2 starts its second burst at time 85, and continues until time 100, at which time P1 starts its third period.
  - At this point P1 has a deadline of 150 and P2 has a deadline of 160, so P1 preempts P2.
  - P1 completes its third burst at time 125, at which time P2 starts, completing its third burst at time 145.
  - The CPU sits idle for 5 time units, until P1 starts its next period at 150 and P2 at 160.
  - **Question:** Which process will get to run at time 160, and why?
    - **Answer:** Process P2, because P1 now has a deadline of 200 and P2's new deadline is 240.

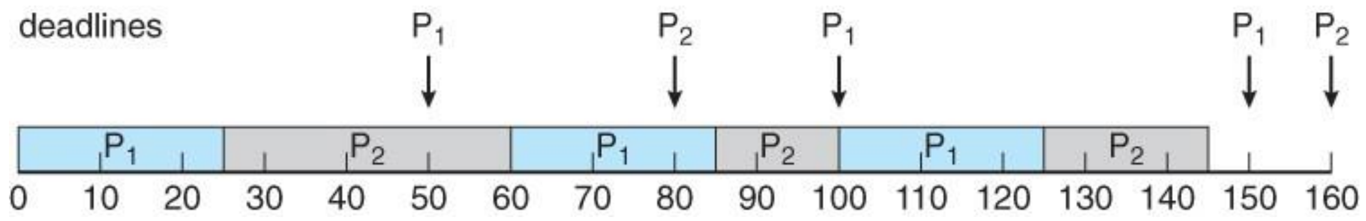


Figure 6.19 - Earliest-deadline-first scheduling.

Proportional Share Scheduling

- Proportional share scheduling works by dividing the total amount of time available up into an equal number of shares, and then each process must request a certain share of the total when it tries to start.
- Say for example that the total shares, T, = 100, and then a particular process asks for N = 30 shares when it launches. It will then be guaranteed 30 / 100 or 30% of the available time.
- Proportional share scheduling works with an admission-control policy, not starting any task if it cannot guarantee the shares that the task says that it needs.

POSIX Real-Time Scheduling

- POSIX defines two scheduling classes for real time threads, SCHED_FIFO and SCHED_RR, depending on how threads ***of equal priority*** share time.
- SCHED_FIFO schedules tasks in a first-in-first-out order, with no time slicing among threads of equal priority.
- SCHED_RR performs round-robin time slicing among threads of equal priority.
- POSIX provides methods for getting and setting the thread scheduling policy, as shown below:

```
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS 5

int main(int argc, char *argv[])
{
  int i, policy;
  pthread_t tid[NUM_THREADS];
  pthread_attr_t attr;

  /* get the default attributes */
  pthread_attr_init(&attr);

  /* get the current scheduling policy */
  if (pthread_attr_getschedpolicy(&attr, &policy) != 0)
    fprintf(stderr, "Unable to get policy.\n");
  else {
    if (policy == SCHED_OTHER)
     printf("SCHED_OTHER\n");
    else if (policy == SCHED_RR)
     printf("SCHED_RR\n");
    else if (policy == SCHED_FIFO)
     printf("SCHED_FIFO\n");
  }

  /* set the scheduling policy - FIFO, RR, or OTHER */
  if (pthread_attr_setschedpolicy(&attr, SCHED_FIFO) != 0)
    fprintf(stderr, "Unable to set policy.\n");

  /* create the threads */
  for (i = 0; i < NUM_THREADS; i++)
     pthread_create(&tid[i],&attr,runner,NULL);

  /* now join on each thread */
  for (i = 0; i < NUM_THREADS; i++)
    pthread_join(tid[i], NULL);
}

/* Each thread will begin control in this function */
void *runner(void *param)
{
  /* do some work ... */
```

```
    pthread_exit(0);
}
```

Figure 6.20 - POSIX real-time scheduling API.

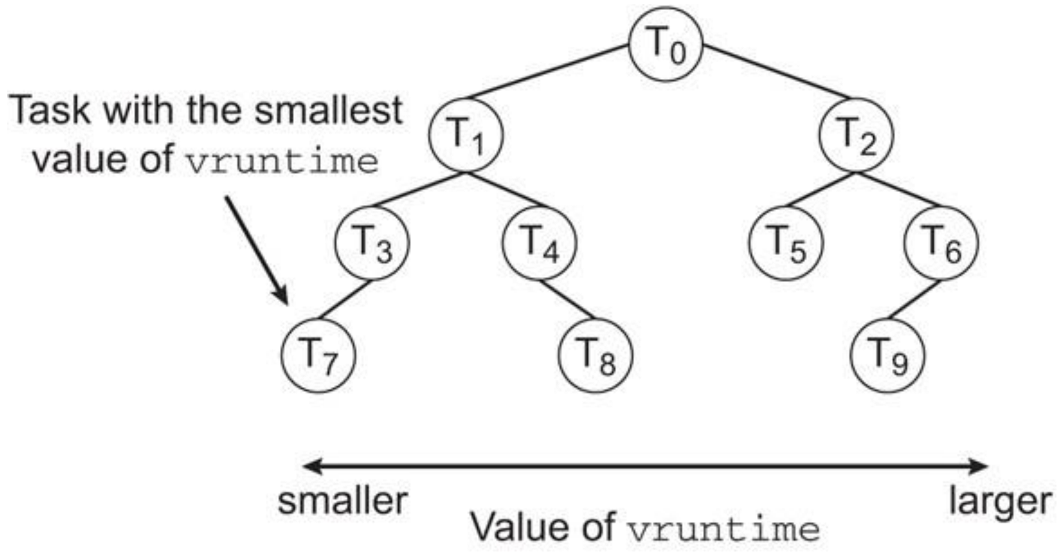
Operating System Examples (Optional)

Example: Linux Scheduling (was 5.6.3)

- Prior to version 2.5, Linux used a traditional UNIX scheduling algorithm.
- Version 2.6 used an algorithm known as O(1), that ran in constant time regardless of the number of tasks, and provided better support for SMP systems. However it yielded poor interactive performance.
- Starting in 2.6.23, the ***Completely Fair Scheduler, CFS,*** became the standard Linux scheduling system. See sidebar below

CFS (Completely Fair Scheduler) Performance

The Linux CFS scheduler provides an efficient algorithm for selecting which task to run next. Each runnable task is placed in a red-black tree—a balanced binary search tree whose key is based on the value of `vruntime`. This tree is shown below:



When a task becomes runnable, it is added to the tree. If a task on the tree is not runnable (for example, if it is blocked while waiting for I/O), it is removed. Generally speaking, tasks that have been given less processing time (smaller values of `vruntime`) are toward the left side of the tree, and tasks that have been given more processing time are on the right side. According to the properties of a binary search tree, the leftmost node has the smallest key value, which for the sake of the CFS scheduler means that it is the task with the highest priority . Because the red-black tree is balanced, navigating it to discover the leftmost node will require ***O(lgN)*** operations (where ***N*** is the number of nodes in the tree). However, for efficiency reasons, the Linux scheduler caches this value in the variable `rb_leftmost`, and thus determining which task to run next requires only retrieving the cached value.

New sidebar in ninth edition

- The Linux scheduler is a preemptive priority-based algorithm with two priority ranges - ***Real time*** from 0 to 99 and a ***nice*** range from 100 to 140.
- Unlike Solaris or XP, Linux assigns longer time quantums to higher priority tasks.

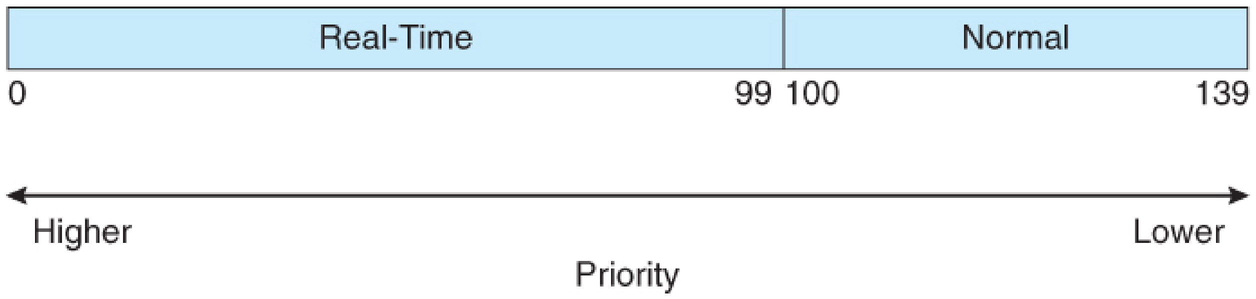


Figure 6.21 - Scheduling priorities on a Linux system.

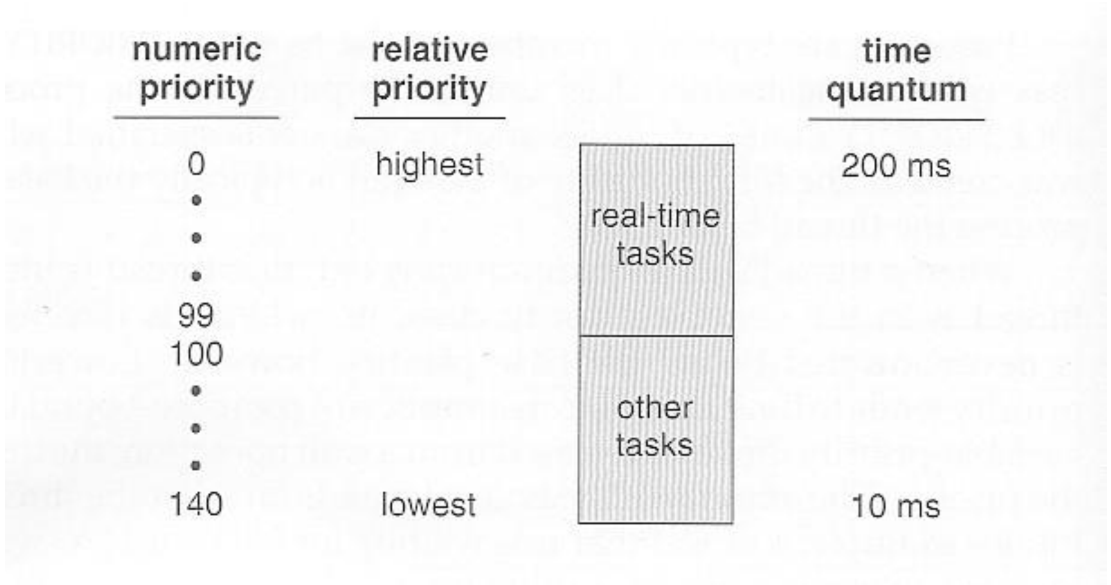


Figure 5.13 The relationship between priorities and time-slice length.

Replaced by Figure 6.21 in the ninth edition. Was Figure 5.15 in eighth edition

/* The Following material was omitted from the ninth edition:

- A runnable task is considered eligible for execution as long as it has not consumed all the time available in it's time slice. Those tasks are stored in an ***active array***, indexed according to priority.
- When a process consumes its time slice, it is moved to an ***expired array.*** The tasks priority may be re-assigned as part of the transferal.
- When the active array becomes empty, the two arrays are swapped.
- These arrays are stored in ***runqueue*** structures. On multiprocessor machines, each processor has its own scheduler with its own runqueue.

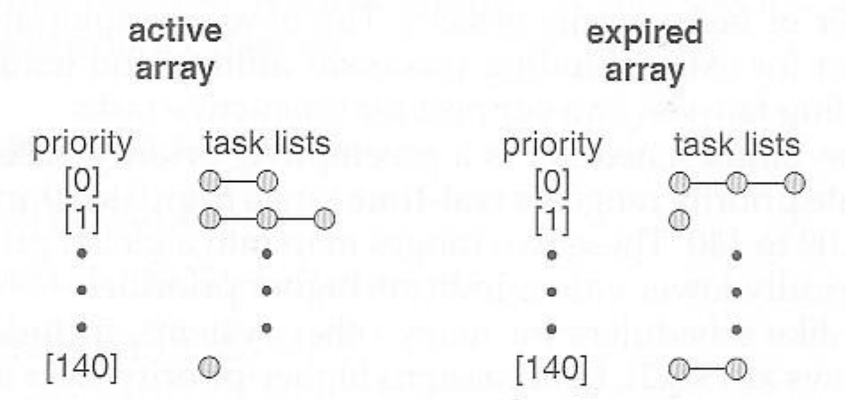


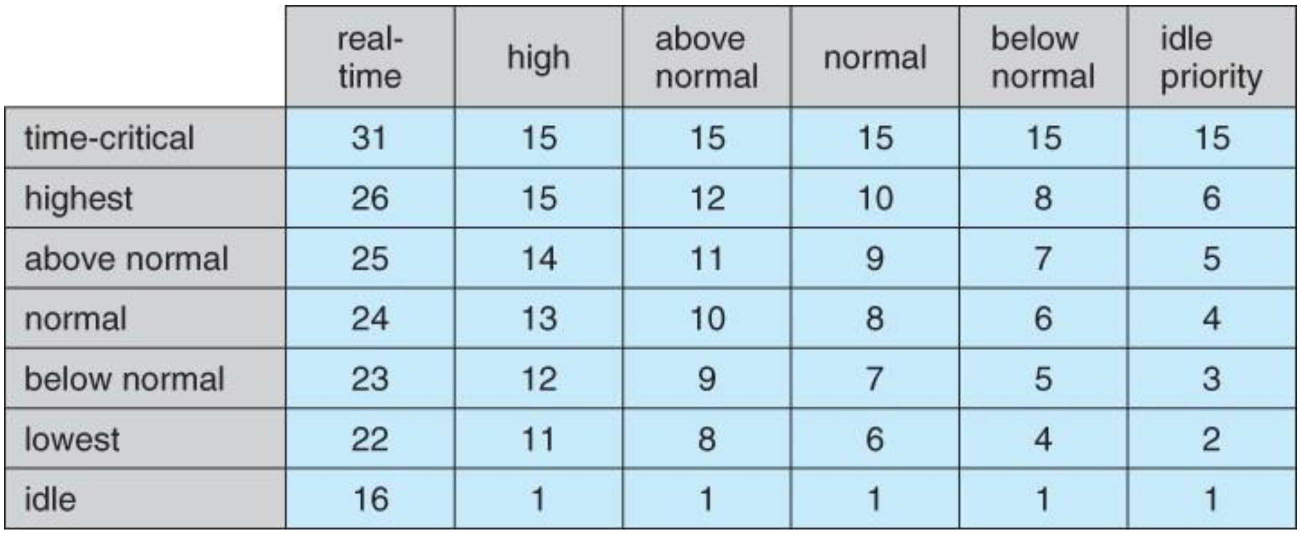
Figure 5.14 List of tasks indexed according to priority.

Omitted from ninth edition. Figure 5.16 in eighth edition.

*/

Example: Windows XP Scheduling (was 5.6.2)

- Windows XP uses a priority-based preemptive scheduling algorithm.
- The dispatcher uses a 32-level priority scheme to determine the order of thread execution, divided into two classes - ***variable class*** from 1 to 15 and ***real-time class*** from 16 to 31, (plus a thread at priority 0 managing memory.)
- There is also a special ***idle*** thread that is scheduled when no other threads are ready.
- Win XP identifies 7 priority classes (rows on the table below), and 6 relative priorities within each class (columns.)
- Processes are also each given a **base priority** within their priority class. When variable class processes consume their entire time quanta, then their priority gets lowered, but not below their base priority.
- Processes in the foreground (active window) have their scheduling quanta multiplied by 3, to give better response to interactive processes in the foreground.



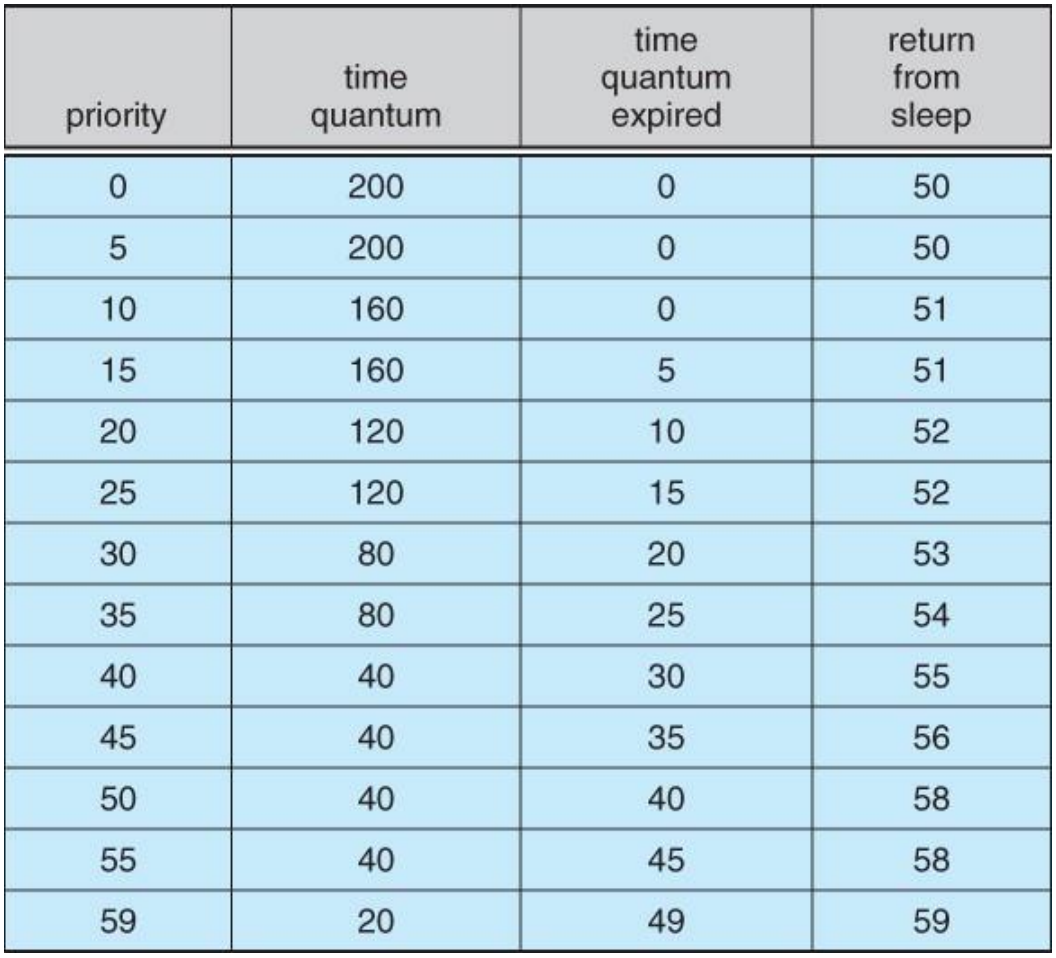
	real-time	high	above normal	normal	below normal	idle priority
time-critical	31	15	15	15	15	15
highest	26	15	12	10	8	6
above normal	25	14	11	9	7	5
normal	24	13	10	8	6	4
below normal	23	12	9	7	5	3
lowest	22	11	8	6	4	2
idle	16	1	1	1	1	1

Figure 6.22 - Windows thread priorities.

6.7.1 Example: Solaris Scheduling

- Priority-based kernel thread scheduling.
- Four classes (real-time, system, interactive, and time-sharing), and multiple queues / algorithms within each class.
- Default is time-sharing.

- Process priorities and time slices are adjusted dynamically in a multilevel-feedback priority queue system.
- Time slices are inversely proportional to priority - Higher priority jobs get smaller time slices.
- Interactive jobs have higher priority than CPU-Bound ones.
- See the table below for some of the 60 priority levels and how they shift. "Time quantum expired" and "return from sleep" indicate the new priority when those events occur. (Larger numbers are a higher, i.e. better priority.)



priority	time quantum	time quantum expired	return from sleep
0	200	0	50
5	200	0	50
10	160	0	51
15	160	5	51
20	120	10	52
25	120	15	52
30	80	20	53
35	80	25	54
40	40	30	55
45	40	35	56
50	40	40	58
55	40	45	58
59	20	49	59

Figure 6.23 - Solaris dispatch table for time-sharing and interactive threads.

- Solaris 9 introduced two new scheduling classes: Fixed priority and fair share.
  - Fixed priority is similar to time sharing, but not adjusted dynamically.
  - Fair share uses shares of CPU time rather than priorities to schedule jobs. A certain share of the available CPU time is allocated to a project, which is a set of processes.
- System class is reserved for kernel use. (User programs running in kernel mode are NOT considered in the system scheduling class.)

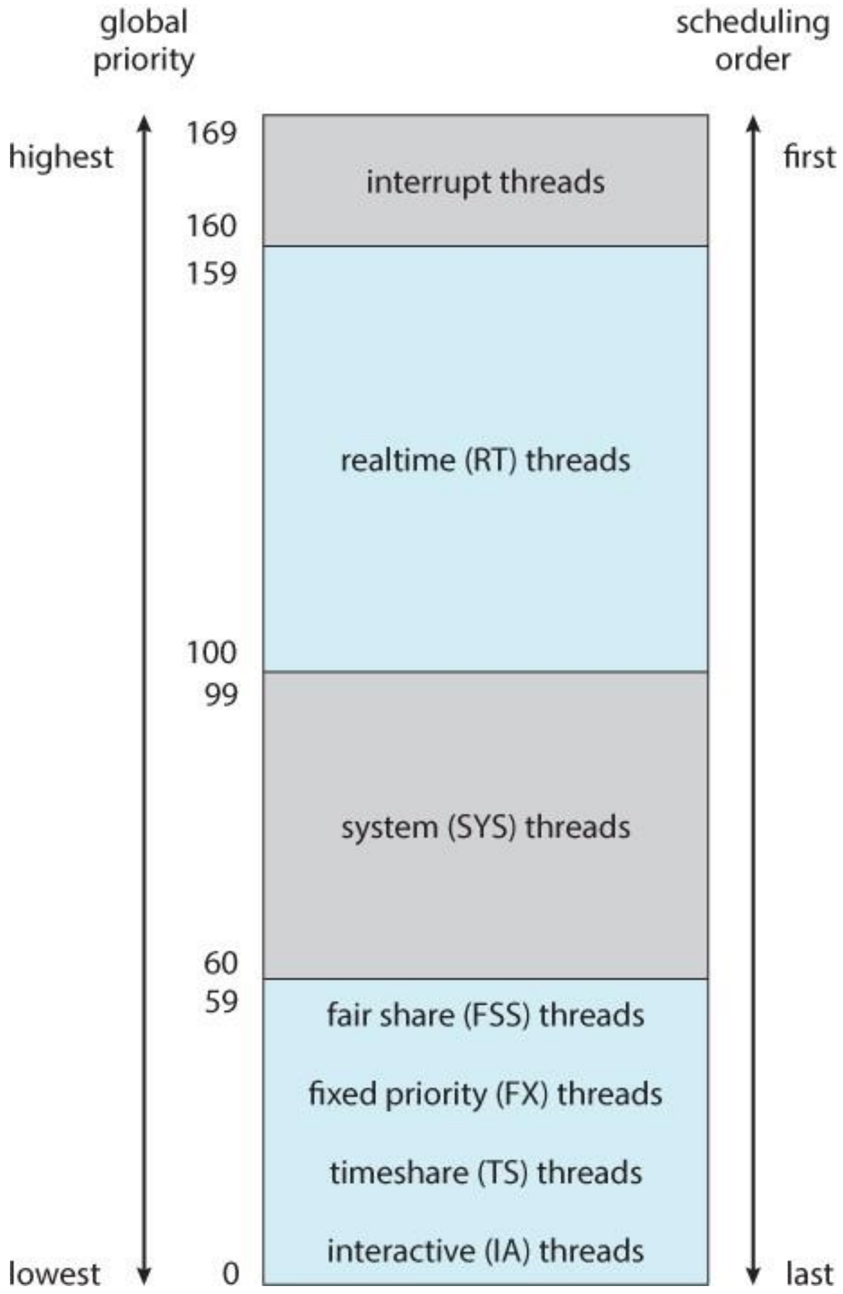


Figure 6.24 - Solaris scheduling.

Algorithm Evaluation

- The first step in determining which algorithm (and what parameter settings within that algorithm) is optimal for a particular operating environment is to determine what criteria are to be used, what goals are to be targeted, and what constraints if any must be applied. For example, one might want to "maximize CPU utilization, subject to a maximum response time of 1 second".
- Once criteria have been established, then different algorithms can be analyzed and a "best choice" determined. The following sections outline some different methods for determining the "best choice".

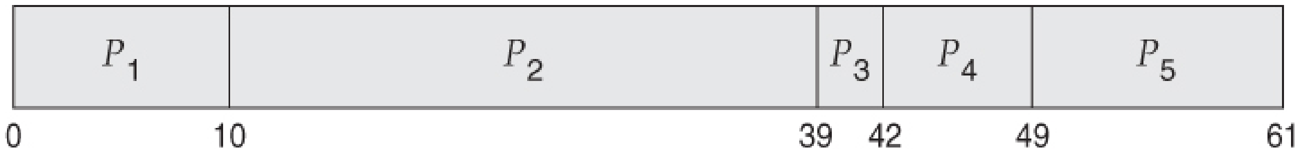
Deterministic Modeling

- If a specific workload is known, then the exact values for major criteria can be fairly easily calculated, and the "best" determined. For example, consider the following workload (with all processes arriving at time 0), and the resulting schedules determined by three different algorithms:

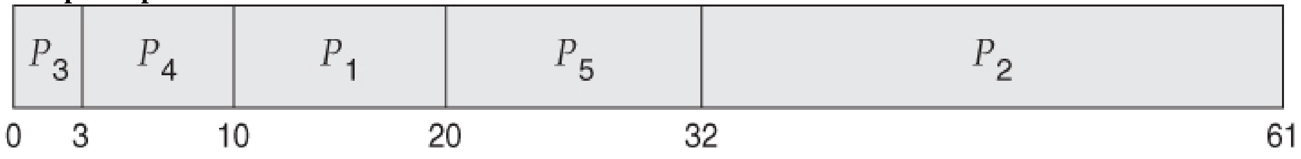
Process	Burst Time
P1	10

P2	29
P3	3
P4	7
P5	12

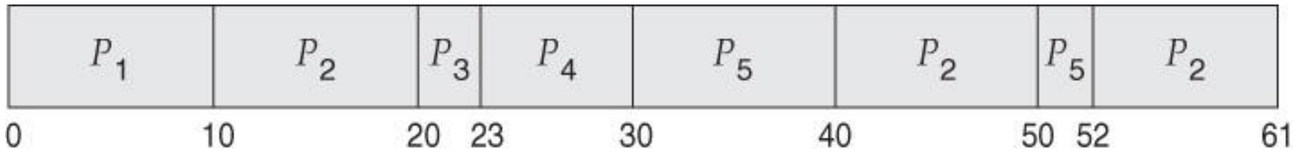
FCFS:



Non-preemptive SJF:



Round Robin:



- The average waiting times for FCFS, SJF, and RR are 28ms, 13ms, and 23ms respectively.
- Deterministic modeling is fast and easy, but it requires specific known input, and the results only apply for that particular set of input. However by examining multiple similar cases, certain trends can be observed. (Like the fact that for processes arriving at the same time, SJF will always yield the shortest average wait time.)

Queuing Models

- Specific process data is often not available, particularly for future times. However a study of historical performance can often produce statistical descriptions of certain important parameters, such as the rate at which new processes arrive, the ratio of CPU bursts to I/O times, the distribution of CPU burst times and I/O burst times, etc.
- Armed with those probability distributions and some mathematical formulas, it is possible to calculate certain performance characteristics of individual waiting queues. For example, **Little's Formula** says that for an average queue length of N, with an average waiting time in the queue of W, and an average arrival of new jobs in the queue of Lambda, then these three terms can be related by:

$$N = Lambda * W$$

- Queuing models treat the computer as a network of interconnected queues, each of which is described by its probability distribution statistics and formulas such as Little's formula. Unfortunately real systems and modern scheduling algorithms are so complex as to make the mathematics intractable in many cases with real systems.

Simulations

- Another approach is to run computer simulations of the different proposed algorithms (and adjustment parameters) under different load conditions, and to analyze the results to determine the "best" choice of operation for a particular load pattern.

- Operating conditions for simulations are often randomly generated using distribution functions similar to those described above.
- A better alternative when possible is to generate ***trace tapes***, by monitoring and logging the performance of a real system under typical expected work loads. These are better because they provide a more accurate picture of system loads, and also because they allow multiple simulations to be run with the identical process load, and not just statistically equivalent loads. A compromise is to randomly determine system loads and then save the results into a file, so that all simulations can be run against identical randomly determined system loads.
- Although trace tapes provide more accurate input information, they can be difficult and expensive to collect and store, and their use increases the complexity of the simulations significantly. There is also some question as to whether the future performance of the new system will really match the past performance of the old system. (If the system runs faster, users may take fewer coffee breaks, and submit more processes per hour than under the old system. Conversely if the turnaround time for jobs is longer, intelligent users may think more carefully about the jobs they submit rather than randomly submitting jobs and hoping that one of them works out.)

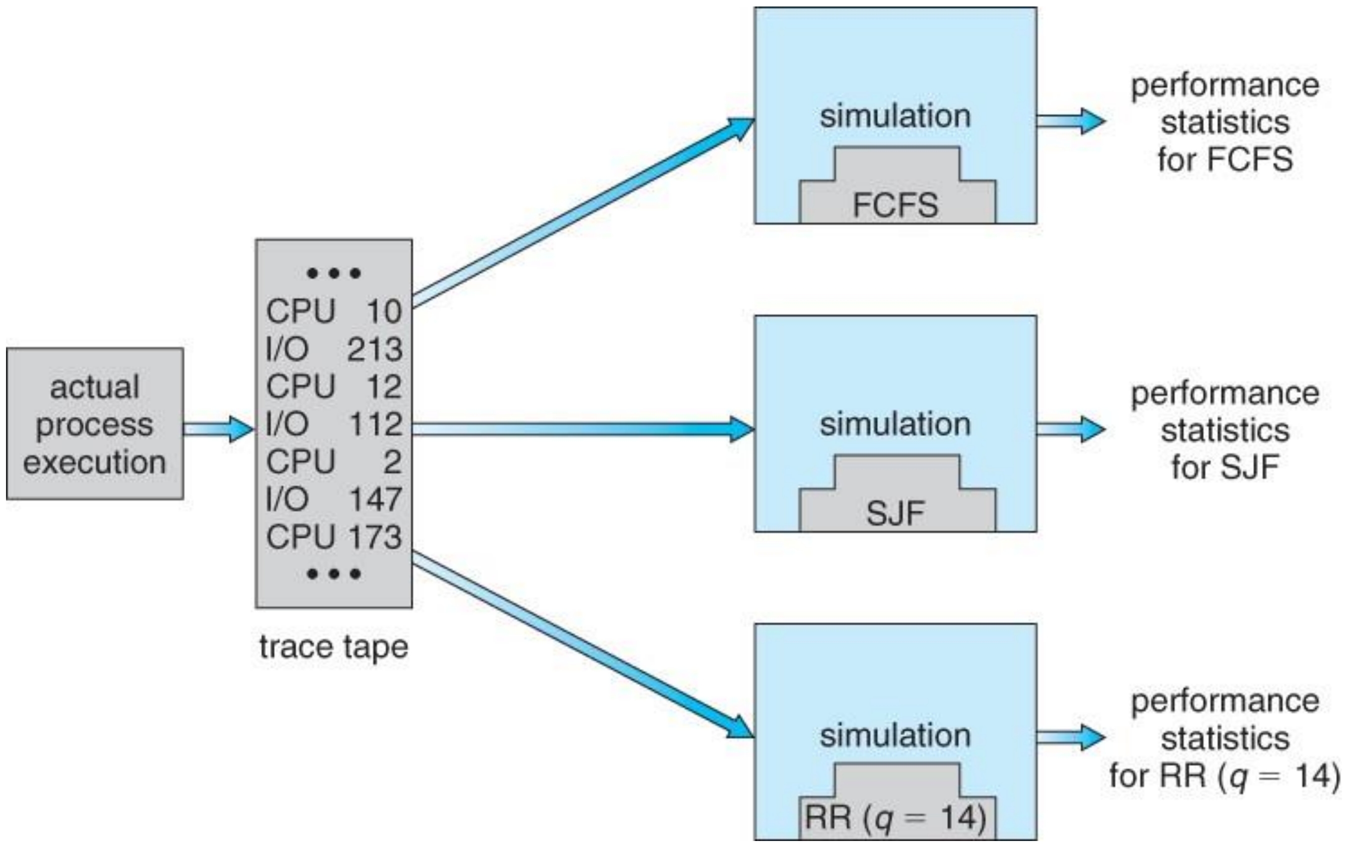


Figure 6.25 - Evaluation of CPU schedulers by simulation.

Implementation

- The only real way to determine how a proposed scheduling algorithm is going to operate is to implement it on a real system.
- For experimental algorithms and those under development, this can cause difficulties and resistance among users who don't care about developing OSes and are only trying to get their daily work done.
- Even in this case, the measured results may not be definitive, for at least two major reasons: (1) System work loads are not static, but change over time as new programs are installed, new users are added to the system, new hardware becomes available, new work projects get started, and even societal changes. (For example the explosion of the Internet has drastically changed the amount of network traffic that a system sees and the importance of handling it with rapid response times.) (2) As mentioned above, changing the scheduling system may have an impact on the work load and the ways in which users use the system. (The book gives an example of a programmer who modified his code to write an arbitrary character to the screen at regular intervals, just so his job would be classified as interactive and placed into a higher priority queue.)

- Most modern systems provide some capability for the system administrator to adjust scheduling parameters, either on the fly or as the result of a reboot or a kernel rebuild.

Summary

Material Omitted from the Eighth Edition:

Was 5.4.4 Symmetric Multithreading (Omitted from 8th edition)

- An alternative strategy to SMP is ***SMT, Symmetric Multi-Threading,*** in which multiple virtual (logical) CPUs are used instead of (or in combination with) multiple physical CPUs.
- SMT must be supported in hardware, as each logical CPU has its own registers and handles its own interrupts. (Intel refers to SMT as ***hyperthreading technology.)***
- To some extent the OS does not need to know if the processors it is managing are real or virtual. On the other hand, some scheduling decisions can be optimized if the scheduler knows the mapping of virtual processors to real CPUs. (Consider the scheduling of two CPU-intensive processes on the architecture shown below.)

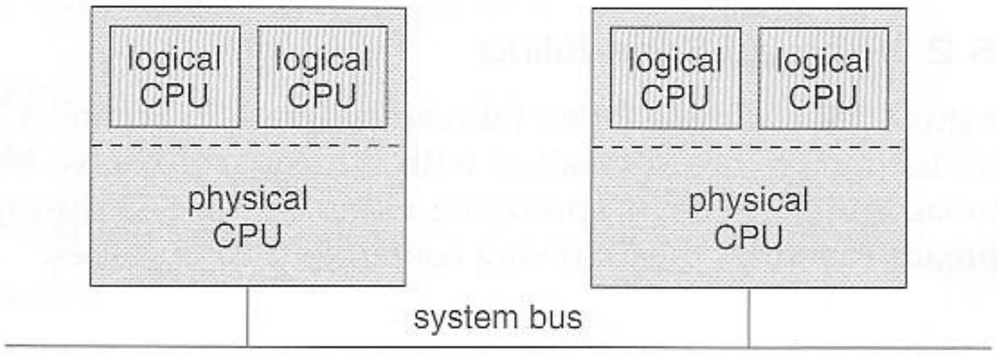


Figure 5.8 A typical SMT architecture

omitted