a new thread on each iteration, after announcing its intention. If the thread creation fails, it prints an error message and then exits. After creating all the threads, the main program exits.

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

#define NUMBER_OF_THREADS     10

void *print_hello_world(void *tid)
{
      /* This function prints the thread's identifier and then exits. */
      printf("Hello World. Greetings from thread %d\n", tid);
      pthread_exit(NULL);
}

int main(int argc, char *argv[])
{
      /* The main program creates 10 threads and then exits. */
      pthread_t threads[NUMBER_OF_THREADS];
      int status, i;

      for(i=0; i < NUMBER_OF_THREADS; i++) {
            printf("Main here. Creating thread %d\n", i);
            status = pthread_create(&threads[i], NULL, print_hello_world, (void *)i);

            if (status != 0) {
                  printf("Oops. pthread_create returned error code %d\n", status);
                  exit(-1);
            }
      }
      exit(NULL);
}
```

**Figure 2-15.** An example program using threads.

When a thread is created, it prints a one-line message announcing itself, then it exits. The order in which the various messages are interleaved is nondeterminate and may vary on consecutive runs of the program.

The Pthreads calls described above are not the only ones. We will examine some of the others after we have discussed process and thread synchronization.

### 2.2.4 Implementing Threads in User Space

There are two main places to implement threads: user space and the kernel. The choice is a bit controversial, and a hybrid implementation is also possible. We will now describe these methods, along with their advantages and disadvantages.

The first method is to put the threads package entirely in user space. The kernel knows nothing about them. As far as the kernel is concerned, it is managing ordinary, single-threaded processes. The first, and most obvious, advantage is that a user-level threads package can be implemented on an operating system that does not support threads. All operating systems used to fall into this category, and even now some still do. With this approach, threads are implemented by a library.

All of these implementations have the same general structure, illustrated in Fig. 2-16(a). The threads run on top of a run-time system, which is a collection of procedures that manage threads. We have seen four of these already: *pthread_create*, *pthread_exit*, *pthread_join*, and *pthread_yield*, but usually there are more.

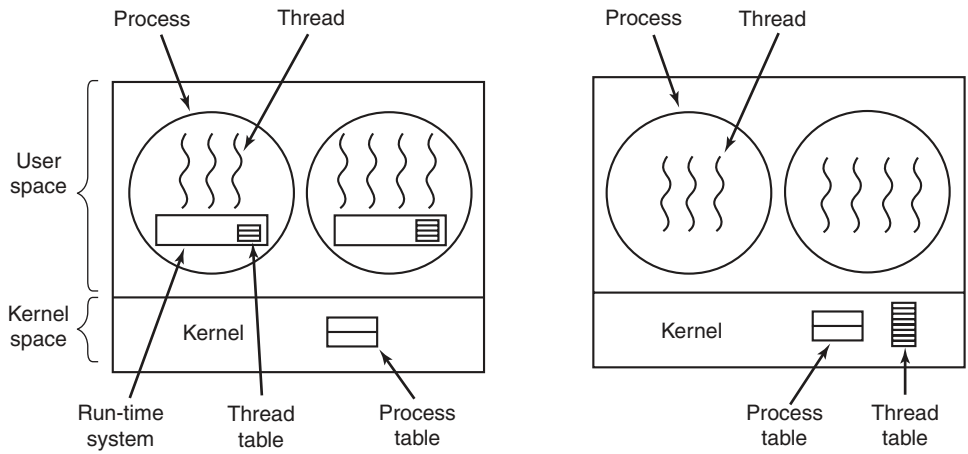


**Figure 2-16.** (a) A user-level threads package. (b) A threads package managed by the kernel.

When threads are managed in user space, each process needs its own private **thread table** to keep track of the threads in that process. This table is analogous to the kernel's process table, except that it keeps track only of the per-thread properties, such as each thread's program counter, stack pointer, registers, state, and so forth. The thread table is managed by the run-time system. When a thread is moved to ready state or blocked state, the information needed to restart it is stored in the thread table, exactly the same way as the kernel stores information about processes in the process table.

When a thread does something that may cause it to become blocked locally, for example, waiting for another thread in its process to complete some work, it calls a run-time system procedure. This procedure checks to see if the thread must be put into blocked state. If so, it stores the thread's registers (i.e., its own) in the thread table, looks in the table for a ready thread to run, and reloads the machine registers with the new thread's saved values. As soon as the stack pointer and program counter have been switched, the new thread comes to life again automatically. If

the machine happens to have an instruction to store all the registers and another one to load them all, the entire thread switch can be done in just a handful of instructions. Doing thread switching like this is at least an order of magnitude—maybe more—faster than trapping to the kernel and is a strong argument in favor of user-level threads packages.

However, there is one key difference with processes. When a thread is finished running for the moment, for example, when it calls *thread_yield*, the code of *thread_yield* can save the thread's information in the thread table itself. Furthermore, it can then call the thread scheduler to pick another thread to run. The procedure that saves the thread's state and the scheduler are just local procedures, so invoking them is much more efficient than making a kernel call. Among other issues, no trap is needed, no context switch is needed, the memory cache need not be flushed, and so on. This makes thread scheduling very fast.

User-level threads also have other advantages. They allow each process to have its own customized scheduling algorithm. For some applications, for example, those with a garbage-collector thread, not having to worry about a thread being stopped at an inconvenient moment is a plus. They also scale better, since kernel threads invariably require some table space and stack space in the kernel, which can be a problem if there are a very large number of threads.

Despite their better performance, user-level threads packages have some major problems. First among these is the problem of how blocking system calls are implemented. Suppose that a thread reads from the keyboard before any keys have been hit. Letting the thread actually make the system call is unacceptable, since this will stop all the threads. One of the main goals of having threads in the first place was to allow each one to use blocking calls, but to prevent one blocked thread from affecting the others. With blocking system calls, it is hard to see how this goal can be achieved readily.

The system calls could all be changed to be nonblocking (e.g., a read on the keyboard would just return 0 bytes if no characters were already buffered), but requiring changes to the operating system is unattractive. Besides, one argument for user-level threads was precisely that they could run with *existing* operating systems. In addition, changing the semantics of read will require changes to many user programs.

Another alternative is available in the event that it is possible to tell in advance if a call will block. In most versions of UNIX, a system call, select, exists, which allows the caller to tell whether a prospective read will block. When this call is present, the library procedure *read* can be replaced with a new one that first does a select call and then does the read call only if it is safe (i.e., will not block). If the read call will block, the call is not made. Instead, another thread is run. The next time the run-time system gets control, it can check again to see if the read is now safe. This approach requires rewriting parts of the system call library, and is inefficient and inelegant, but there is little choice. The code placed around the system call to do the checking is called a **jacket** or **wrapper**.

Somewhat analogous to the problem of blocking system calls is the problem of page faults. We will study these in Chap. 3. For the moment, suffice it to say that computers can be set up in such a way that not all of the program is in main memory at once. If the program calls or jumps to an instruction that is not in memory, a page fault occurs and the operating system will go and get the missing instruction (and its neighbors) from disk. This is called a page fault. The process is blocked while the necessary instruction is being located and read in. If a thread causes a page fault, the kernel, unaware of even the existence of threads, naturally blocks the entire process until the disk I/O is complete, even though other threads might be runnable.01

Another problem with user-level thread packages is that if a thread starts running, no other thread in that process will ever run unless the first thread voluntarily gives up the CPU. Within a single process, there are no clock interrupts, making it impossible to schedule processes round-robin fashion (taking turns). Unless a thread enters the run-time system of its own free will, the scheduler will never get a chance.

One possible solution to the problem of threads running forever is to have the run-time system request a clock signal (interrupt) once a second to give it control, but this, too, is crude and messy to program. Periodic clock interrupts at a higher frequency are not always possible, and even if they are, the total overhead may be substantial. Furthermore, a thread might also need a clock interrupt, interfering with the run-time system's use of the clock.

Another, and really the most devastating, argument against user-level threads is that programmers generally want threads precisely in applications where the threads block often, as, for example, in a multithreaded Web server. These threads are constantly making system calls. Once a trap has occurred to the kernel to carry out the system call, it is hardly any more work for the kernel to switch threads if the old one has blocked, and having the kernel do this eliminates the need for constantly making select system calls that check to see if read system calls are safe. For applications that are essentially entirely CPU bound and rarely block, what is the point of having threads at all? No one would seriously propose computing the first *n* prime numbers or playing chess using threads because there is nothing to be gained by doing it that way.

### 2.2.5 Implementing Threads in the Kernel

Now let us consider having the kernel know about and manage the threads. No run-time system is needed in each, as shown in Fig. 2-16(b). Also, there is no thread table in each process. Instead, the kernel has a thread table that keeps track of all the threads in the system. When a thread wants to create a new thread or destroy an existing thread, it makes a kernel call, which then does the creation or destruction by updating the kernel thread table.

The kernel's thread table holds each thread's registers, state, and other information. The information is the same as with user-level threads, but now kept in the kernel instead of in user space (inside the run-time system). This information is a subset of the information that traditional kernels maintain about their single-threaded processes, that is, the process state. In addition, the kernel also maintains the traditional process table to keep track of processes.

All calls that might block a thread are implemented as system calls, at considerably greater cost than a call to a run-time system procedure. When a thread blocks, the kernel, at its option, can run either another thread from the same process (if one is ready) or a thread from a different process. With user-level threads, the run-time system keeps running threads from its own process until the kernel takes the CPU away from it (or there are no ready threads left to run).

Due to the relatively greater cost of creating and destroying threads in the kernel, some systems take an environmentally correct approach and recycle their threads. When a thread is destroyed, it is marked as not runnable, but its kernel data structures are not otherwise affected. Later, when a new thread must be created, an old thread is reactivated, saving some overhead. Thread recycling is also possible for user-level threads, but since the thread-management overhead is much smaller, there is less incentive to do this.

Kernel threads do not require any new, nonblocking system calls. In addition, if one thread in a process causes a page fault, the kernel can easily check to see if the process has any other runnable threads, and if so, run one of them while waiting for the required page to be brought in from the disk. Their main disadvantage is that the cost of a system call is substantial, so if thread operations (creation, termination, etc.) a common, much more overhead will be incurred.

While kernel threads solve some problems, they do not solve all problems. For example, what happens when a multithreaded process forks? Does the new process have as many threads as the old one did, or does it have just one? In many cases, the best choice depends on what the process is planning to do next. If it is going to call exec to start a new program, probably one thread is the correct choice, but if it continues to execute, reproducing all the threads is probably best.

Another issue is signals. Remember that signals are sent to processes, not to threads, at least in the classical model. When a signal comes in, which thread should handle it? Possibly threads could register their interest in certain signals, so when a signal came in it would be given to the thread that said it wants it. But what happens if two or more threads register for the same signal? These are only two of the problems threads introduce, and there are more.

### 2.2.6 Hybrid Implementations

Various ways have been investigated to try to combine the advantages of user-level threads with kernel-level threads. One way is use kernel-level threads and then multiplex user-level threads onto some or all of them, as shown in Fig. 2-17.

When this approach is used, the programmer can determine how many kernel threads to use and how many user-level threads to multiplex on each one. This model gives the ultimate in flexibility.

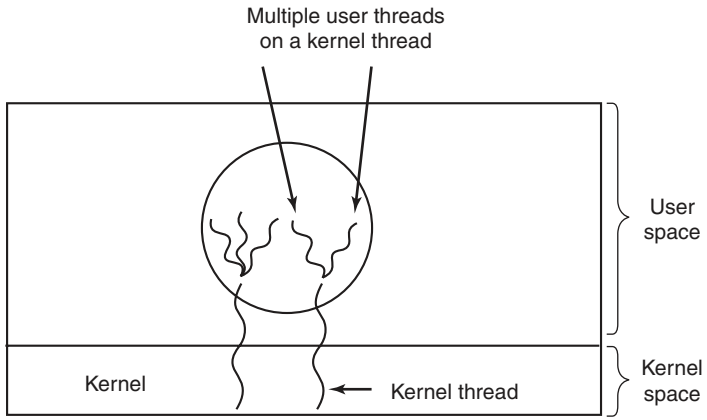


**Figure 2-17.** Multiplexing user-level threads onto kernel-level threads.

With this approach, the kernel is aware of *only* the kernel-level threads and schedules those. Some of those threads may have multiple user-level threads multiplexed on top of them. These user-level threads are created, destroyed, and scheduled just like user-level threads in a process that runs on an operating system without multithreading capability. In this model, each kernel-level thread has some set of user-level threads that take turns using it.

### 2.2.7 Scheduler Activations

While kernel threads are better than user-level threads in some key ways, they are also indisputably slower. As a consequence, researchers have looked for ways to improve the situation without giving up their good properties. Below we will describe an approach devised by Anderson et al. (1992), called **scheduler activations**. Related work is discussed by Edler et al. (1988) and Scott et al. (1990).

The goals of the scheduler activation work are to mimic the functionality of kernel threads, but with the better performance and greater flexibility usually associated with threads packages implemented in user space. In particular, user threads should not have to make special nonblocking system calls or check in advance if it is safe to make certain system calls. Nevertheless, when a thread blocks on a system call or on a page fault, it should be possible to run other threads within the same process, if any are ready.

Efficiency is achieved by avoiding unnecessary transitions between user and kernel space. If a thread blocks waiting for another thread to do something, for example, there is no reason to involve the kernel, thus saving the overhead of the