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# Threads: Basic Theory and Libraries

This chapter examines aspects of threads and multiprocessing (and multithreading). We will first study a little theory of threads and also look at how threading can be effectively used to make programs more efficient. The C thread libraries will then be introduced. The following chapters will look at further thread issues such as synchronisation and practical examples.

## Processes and Threads

We can think of a **thread** as basically a *lightweight* process. In order to understand this let us consider the two main characteristics of a process:

### Unit of resource ownership

- A process is allocated:
  - a virtual address space to hold the process image
  - control of some resources (files, I/O devices...)

### Unit of dispatching

- A process is an execution path through one or more programs:
  - execution may be interleaved with other processes
  - the process has an execution state and a dispatching priority

If we treat these two characteristics as being independent (as does modern OS theory):

- The unit of resource ownership is usually referred to as a **process** or task. This Processes have:
  - a virtual address space which holds the process image.
  - protected access to processors, other processes, files, and I/O resources.
- The unit of dispatching is usually referred to a **thread** or a lightweight process. Thus a thread:
  - Has an execution state (running, ready, etc.)
  - Saves thread context when not running
  - Has an execution stack and some per-thread static storage for local variables
  - Has access to the memory address space and resources of its process
- all threads of a process share this when one thread alters a (non-private) memory item, all other threads (of the process) sees that a file open with one thread, is available to others

## Benefits of Threads vs Processes

If implemented correctly then threads have some advantages of (multi) processes, They take:

- Less time to create a new thread than a process, because the newly created thread uses the current process address space.
- Less time to terminate a thread than a process.
- Less time to switch between two threads within the same process, partly because the newly created thread uses the current process address space.
- Less communication overheads -- communicating between the threads of one process is simple because the threads share everything: address space, in particular. So, data produced by one thread is immediately available to all the other threads.

## Multithreading vs. Single threading

Just as we can have multiple processes running on some systems we can have multiple threads running:

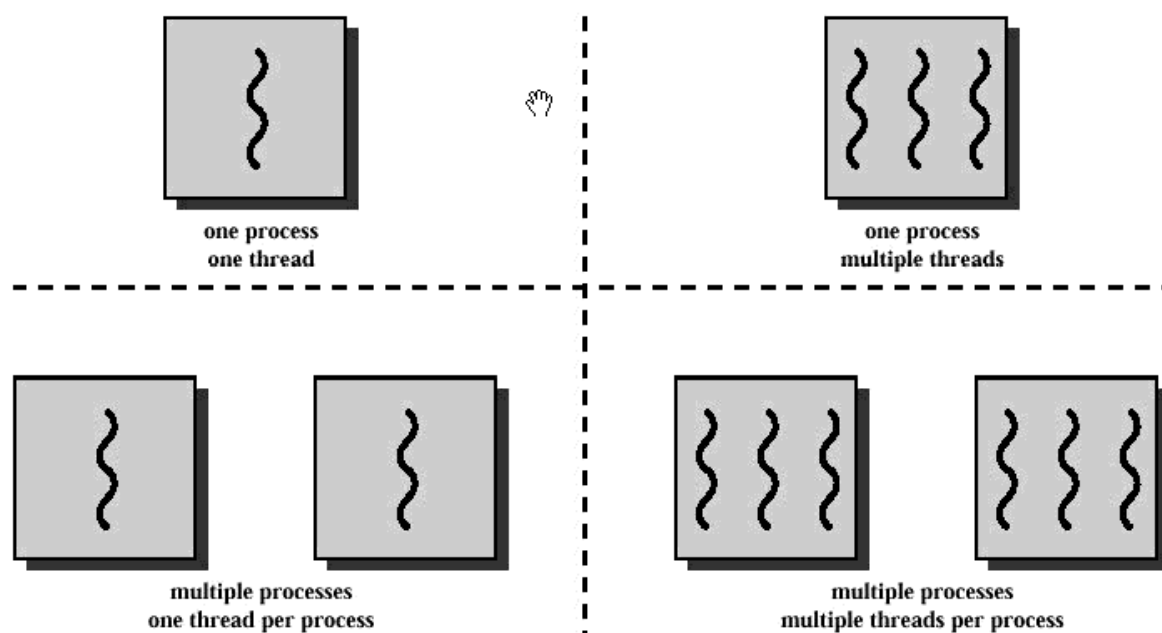
### Single threading

- when the OS does not recognize the concept of thread

### Multithreading

- when the OS supports multiple threads of execution within a single process

Figure [28.1](#) shows a variety of models for threads and processes.



**Fig. 28.1 Threads and Processes** Some example popular OSs and their thread support is:

**MS-DOS**

-- support a single user process and a single thread

**UNIX**

-- supports multiple user processes but only supports one thread per process

**Solaris**

-- supports multiple threads

Multithreading your code can have many benefits:

- Improve application responsiveness -- Any program in which many activities are not dependent upon each other can be redesigned so that each activity is defined as a thread. For example, the user of a multithreaded GUI does not have to wait for one activity to complete before starting another.
- Use multiprocessors more efficiently -- Typically, applications that express concurrency requirements with threads need not take into account the number of available processors. The performance of the application improves transparently with additional processors. Numerical algorithms and applications with a high degree of parallelism, such as matrix multiplications, can run much faster when implemented with threads on a multiprocessor.
- Improve program structure -- Many programs are more efficiently structured as multiple independent or semi-independent units of execution instead of as a single, monolithic thread. Multithreaded programs can be more adaptive to variations in user demands than single threaded programs.
- Use fewer system resources -- Programs that use two or more processes that access common data through shared memory are applying more than one thread of control. However, each process has a full address space and operating systems state. The cost of creating and maintaining this large amount of state information makes each process much more expensive than a thread in both time and space. In addition, the inherent separation between processes can require a major effort by the programmer to communicate between the threads in different processes, or to synchronize their actions.

Figure 28.2 illustrates different process models and thread control in a single thread and multithreaded application.

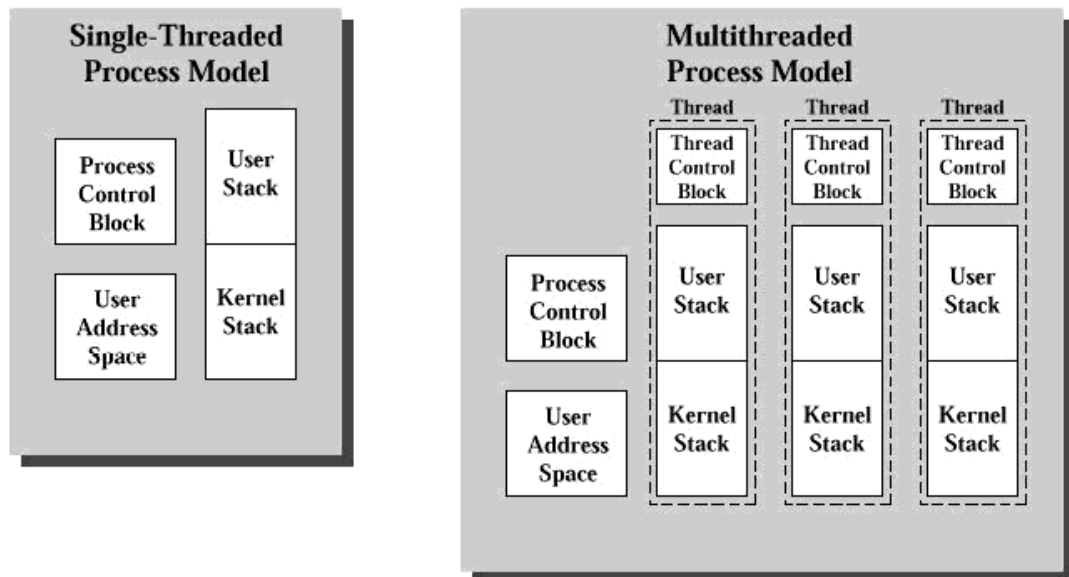


Fig. 28.2 Single and Multi- Thread Applications

## Some Example applications of threads

:

**Example : A file server on a LAN**

- It needs to handle several file requests over a short period
- Hence more efficient to create (and destroy) a single thread for each request
- Multiple threads can possibly be executing simultaneously on different processors

**Example 2: Matrix Multiplication**

Matrix Multiplication essentially involves taking the rows of one matrix and multiplying and adding corresponding columns in a second matrix *i.e.*:

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix} =$$

$$\begin{pmatrix} a_{11}.b_{11} + a_{12}.b_{21} + a_{13}.b_{31} & a_{11}.b_{12} + a_{12}.b_{22} + a_{13}.b_{32} & a_{11}.b_{13} + a_{12}.b_{23} + a_{13}.b_{33} \\ a_{21}.b_{11} + a_{22}.b_{21} + a_{23}.b_{31} & a_{21}.b_{12} + a_{22}.b_{22} + a_{23}.b_{32} & a_{21}.b_{13} + a_{22}.b_{23} + a_{23}.b_{33} \\ a_{31}.b_{11} + a_{32}.b_{21} + a_{33}.b_{31} & a_{31}.b_{12} + a_{32}.b_{22} + a_{33}.b_{32} & a_{31}.b_{13} + a_{32}.b_{23} + a_{33}.b_{33} \end{pmatrix}$$

Fig. 28.3 Matrix Multiplication (3x3 example) Note that each *element* of the resultant matrix can be computed independently, that is to say by a different thread.

We will develop a C++ example program for matrix multiplication later (see Chapter [14](#)).

## Thread Levels

There are two broad categories of thread implementation:

- User-Level Threads -- Thread Libraries.
- Kernel-level Threads -- System Calls.

There are merits to both, in fact some OSs allow access to both levels (*e.g.* Solaris).

## User-Level Threads (ULT)

In this level, the kernel is not aware of the existence of threads -- All thread management is done by the application by using a thread library. Thread switching does not require kernel mode privileges (no mode switch) and scheduling is application specific

Kernel activity for ULTs:

- The kernel is not aware of thread activity but it is still managing process activity
- When a thread makes a system call, the whole process will be blocked but for the thread library that thread is still in the running state
- So thread states are independent of process states

### Advantages and inconveniences of ULT

#### *Advantages:*

- Thread switching does not involve the kernel -- no mode switching
- Scheduling can be application specific -- choose the best algorithm.
- ULTs can run on any OS -- Only needs a thread library

#### *Disadvantages:*

- Most system calls are blocking and the kernel blocks processes -- So all threads within the process will be blocked
- The kernel can only assign processes to processors -- Two threads within the same process cannot run simultaneously on two processors

## Kernel-Level Threads (KLT)

In this level, All thread management is done by kernel No thread library but an API (system calls) to the kernel thread facility exists. The kernel maintains context information for the process and the threads, switching between threads requires the kernel Scheduling is performed on a thread basis.

### Advantages and inconveniences of KLT

#### *Advantages*

- the kernel can simultaneously schedule many threads of the same process on many processors blocking is done on a thread level
- kernel routines can be multithreaded

#### *Disadvantages:*

- thread switching within the same process involves the kernel, *e.g* if we have 2 mode switches per thread switch this results in a significant slow down.

## Combined ULT/KLT Approaches

Idea is to combine the best of both approaches

Solaris is an example of an OS that combines both ULT and KLT (Figure [28.4](#):

- Thread creation done in the user space
- Bulk of scheduling and synchronization of threads done in the user space
- The programmer may adjust the number of KLTs
- Process includes the user's address space, stack, and process control block
- User-level threads (threads library) invisible to the OS are the interface for application parallelism
- Kernel threads the unit that can be dispatched on a processor
- Lightweight processes (LWP) each LWP supports one or more ULTs and maps to exactly one KLT

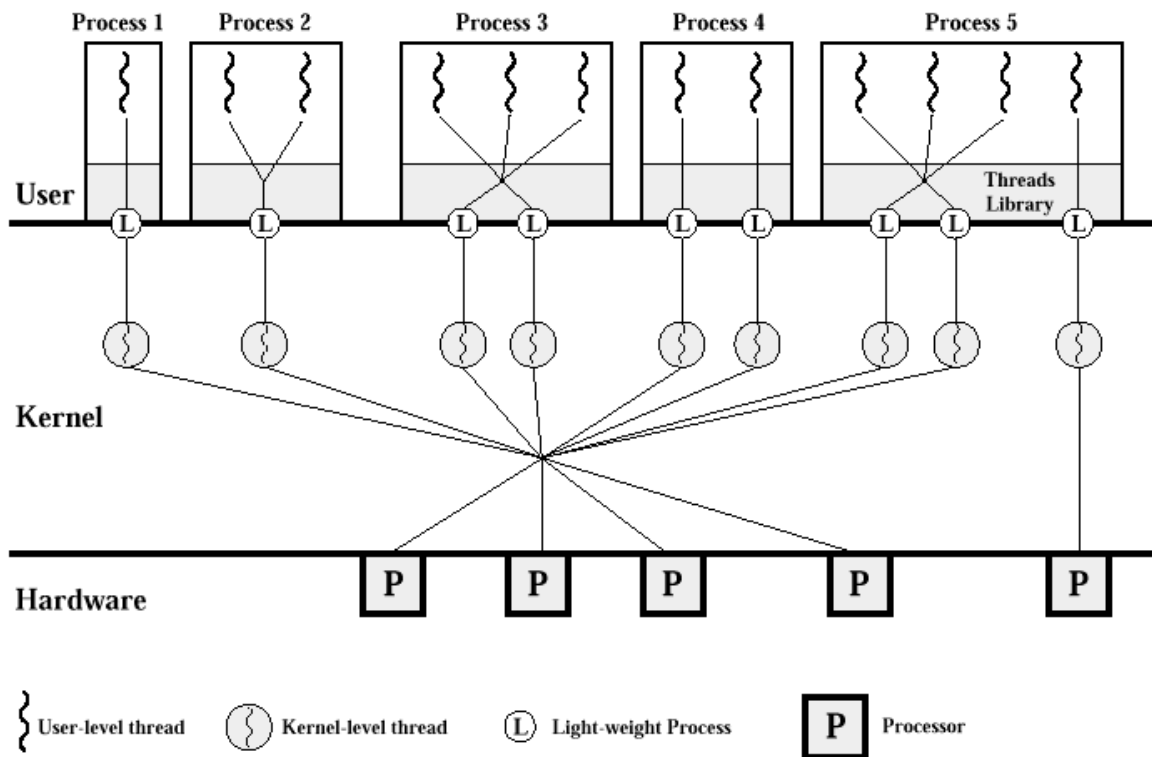


Fig. 28.4 Solaris Thread Implementation

## Threads libraries

The interface to multithreading support is through a subroutine library, `libpthread` for POSIX threads, and `libthread` for Solaris threads. They both contain code for:

- creating and destroying threads
- passing messages and data between threads
- scheduling thread execution
- saving and restoring thread contexts

## The POSIX Threads Library: `libpthread`, `<pthread.h>`

### Creating a (Default) Thread

Use the function `pthread_create()` to add a new thread of control to the current process. It is prototyped by:

```
int pthread_create(pthread_t *tid, const pthread_attr_t *tattr,
void* (*start_routine)(void *), void *arg);
```

When an attribute object is not specified, it is `NULL`, and the **default** thread is created with the following attributes:

- It is unbounded
- It is nondetached
- It has a default stack and stack size
- It inherits the parent's priority

You can also create a default attribute object with `pthread_attr_init()` function, and then use this attribute object to create a default thread. See the Section [29.2](#).

An example call of default thread creation is:

```
#include <pthread.h>
pthread_attr_t tattr;
```

```
pthread_t tid;
extern void *start_routine(void *arg);
void *arg;
int ret;
/* default behavior*/
ret = pthread_create(&tid, NULL, start_routine, arg);

/* initialized with default attributes */
ret = pthread_attr_init(&tattr);
/* default behavior specified*/
ret = pthread_create(&tid, &tattr, start_routine, arg);
```

The `pthread_create()` function is called with `attr` having the necessary state behavior. `start_routine` is the function with which the new thread begins execution. When `start_routine` returns, the thread exits with the exit status set to the value returned by `start_routine`.

When `pthread_create` is successful, the ID of the thread created is stored in the location referred to as `tid`.

Creating a thread using a `NULL` attribute argument has the same effect as using a default attribute; both create a default thread. When `tattr` is initialized, it acquires the default behavior.

`pthread_create()` returns a zero and exits when it completes successfully. Any other returned value indicates that an error occurred.

## Wait for Thread Termination

Use the `pthread_join` function to wait for a thread to terminate. It is prototyped by:

```
int pthread_join(pthread_t tid, void **status);
```

An example use of this function is:

```
#include <pthread.h>
pthread_t tid;
int ret;
int status;
/* waiting to join thread "tid" with status */
ret = pthread_join(tid, &status);
/* waiting to join thread "tid" without status */
ret = pthread_join(tid, NULL);
```

The `pthread_join()` function blocks the calling thread until the specified thread terminates. The specified thread must be in the current process and must not be detached. When `status` is not `NULL`, it points to a location that is set to the exit status of the terminated thread when `pthread_join()` returns successfully. Multiple threads cannot wait for the same thread to terminate. If they try to, one thread returns successfully and the others fail with an error of `ESRCH`. After `pthread_join()` returns, any stack storage associated with the thread can be reclaimed by the application.

The `pthread_join()` routine takes two arguments, giving you some flexibility in its use. When you want the caller to wait until a specific thread terminates, supply that thread's ID as the first argument. If you are interested in the exit code of the defunct thread, supply the address of an area to receive it. Remember that `pthread_join()` works only for target threads that are `nondetached`. When there is no reason to synchronize with the termination of a particular thread, then that thread should be detached. Think of a detached thread as being the thread you use in most instances and reserve `nondetached` threads for only those situations that require them.

## A Simple Threads Example

In this Simple Threads fragment below, one thread executes the procedure at the top, creating a helper thread that executes the procedure `fetch`, which involves a complicated database lookup and might take some time.

The main thread wants the results of the lookup but has other work to do in the meantime. So it does those other things and then waits for its helper to complete its job by executing `pthread_join()`. An argument, `pbe`, to the new thread is passed as a stack parameter. This can be done here because the main thread waits for the spun-off thread to terminate. In general, though, it is better to `malloc()` storage from the heap instead of passing an address to thread stack storage, which can disappear or be reassigned if the thread terminated.

The source for `thread.c` is as follows:

```
void mainline (...)
{
```

```

struct phonebookentry *pbe;
pthread_attr_t tattr;
pthread_t helper;
int status;
pthread_create(&helper, NULL, fetch, &pbe);
/* do something else for a while */
pthread_join(helper, &status);
/* it's now safe to use result */
}
void fetch(struct phonebookentry *arg)
{
    struct phonebookentry *npbe;
    /* fetch value from a database */
    npbe = search (prog_name)
    if (npbe != NULL)
        *arg = *npbe;
    pthread_exit(0);
}
struct phonebookentry {
    char name[64];
    char phonenumber[32];
    char flags[16];
}

```

## Detaching a Thread

The function `pthread_detach()` is an alternative to `pthread_join()` to reclaim storage for a thread that is created with a detachstate attribute set to `PTHREAD_CREATE_JOINABLE`. It is prototyped by:

```
int pthread_detach(pthread_t tid);
```

A simple example of calling this function to detach a thread is given by:

```

#include <pthread.h>
pthread_t tid;
int ret;
/* detach thread tid */
ret = pthread_detach(tid);

```

The `pthread_detach()` function is used to indicate to the implementation that storage for the thread `tid` can be reclaimed when the thread terminates. If `tid` has not terminated, `pthread_detach()` does not cause it to terminate. The effect of multiple `pthread_detach()` calls on the same target thread is unspecified.

`pthread_detach()` returns a zero when it completes successfully. Any other returned value indicates that an error occurred. When any of the following conditions are detected, `pthread_detach()` fails and returns the an error value.

## Create a Key for Thread-Specific Data

Single-threaded C programs have two basic classes of data: local data and global data. For multithreaded C programs a third class is added: *thread-specific data (TSD)*. This is very much like global data, except that it is private to a thread.

Thread-specific data is maintained on a per-thread basis. TSD is the only way to define and refer to data that is private to a thread. Each thread-specific data item is associated with a key that is global to all threads in the process. Using the key, a thread can access a pointer (`void *`) that is maintained per-thread.

The function `pthread_keycreate()` is used to allocate a key that is used to identify thread-specific data in a process. The key is global to all threads in the process, and all threads initially have the value `NULL` associated with the key when it is created.

`pthread_keycreate()` is called once for each key before the key is used. There is no implicit synchronization. Once a key has been created, each thread can bind a value to the key. The values are specific to the thread and are maintained for each thread independently. The per-thread binding is deallocated when a thread terminates if the key was created with a destructor function. `pthread_keycreate()` is prototyped by:

```
int pthread_key_create(pthread_key_t *key, void (*destructor) (void *));
```

A simple example use of this function is:

```

#include <pthread.h>
pthread_key_t key;
int ret;

```



```
/* key create without destructor */
ret = pthread_key_create(&key, NULL);
/* key create with destructor */
ret = pthread_key_create(&key, destructor);
```

When `pthread_keycreate()` returns successfully, the allocated key is stored in the location pointed to by `key`. The caller must ensure that the storage and access to this key are properly synchronized. An optional destructor function, `destructor`, can be used to free stale storage. When a key has a non-NULL destructor function and the thread has a non-NULL value associated with that key, the destructor function is called with the current associated value when the thread exits. The order in which the destructor functions are called is unspecified.

`pthread_keycreate()` returns zero after completing successfully. Any other returned value indicates that an error occurred. When any of the following conditions occur, `pthread_keycreate()` fails and returns an error value.

## Delete the Thread-Specific Data Key

The function `pthread_keydelete()` is used to destroy an existing thread-specific data key. Any memory associated with the key can be freed because the key has been invalidated and will return an error if ever referenced. (There is no comparable function in Solaris threads.)

`pthread_keydelete()` is prototyped by:

```
int pthread_key_delete(pthread_key_t key);
```

A simple example use of this function is:

```
#include <pthread.h>
pthread_key_t key;
int ret;
/* key previously created */
ret = pthread_key_delete(key);
```

Once a key has been deleted, any reference to it with the `pthread_setspecific()` or `pthread_getspecific()` call results in the `EINVAL` error.

It is the responsibility of the programmer to free any thread-specific resources before calling the delete function. This function does not invoke any of the destructors.

`pthread_keydelete()` returns zero after completing successfully. Any other returned value indicates that an error occurred. When the following condition occurs, `pthread_keycreate()` fails and returns the corresponding value.

## Set the Thread-Specific Data Key

The function `pthread_setspecific()` is used to set the thread-specific binding to the specified thread-specific data key. It is prototyped by :

```
int pthread_setspecific(pthread_key_t key, const void *value);
```

A simple example use of this function is:

```
#include <pthread.h>
pthread_key_t key;
void *value;
int ret;

/* key previously created */
ret = pthread_setspecific(key, value);
```

`pthread_setspecific()` returns zero after completing successfully. Any other returned value indicates that an error occurred. When any of the following conditions occur, `pthread_setspecific()` fails and returns an error value.

**Note:** `pthread_setspecific()` does *not* free its storage. If a new binding is set, the existing binding must be freed; otherwise, a *memory leak can occur*.

## Get the Thread-Specific Data Key

Use `pthread_getspecific()` to get the calling thread's binding for key, and store it in the location pointed to by value. This function is prototyped by:

```
int pthread_getspecific(pthread_key_t key);
```

A simple example use of this function is:

```
#include <pthread.h>
pthread_key_t key;
void *value;
/* key previously created */
value = pthread_getspecific(key);
```

## Global and Private Thread-Specific Data Example

### Thread-Specific Data Global but Private

Consider the following code:

```
body() {
...
while (write(fd, buffer, size) == -1) {
if (errno != EINTR) {
fprintf(mywindow, "%s\n", strerror(errno));
exit(1);
}
}
...
}
```

This code may be executed by any number of threads, but it has references to two global variables, `errno` and `mywindow`, that really should be references to items private to each thread.

References to `errno` should get the system error code from the routine called by this thread, not by some other thread. So, references to `errno` by one thread refer to a different storage location than references to `errno` by other threads. The `mywindow` variable is intended to refer to a stdio stream connected to a window that is private to the referring thread. So, as with `errno`, references to `mywindow` by one thread should refer to a different storage location (and, ultimately, a different window) than references to `mywindow` by other threads. The only difference here is that the threads library takes care of `errno`, but the programmer must somehow make this work for `mywindow`. The next example shows how the references to `mywindow` work. The preprocessor converts references to `mywindow` into invocations of the `mywindow` procedure. This routine in turn invokes `pthread_getspecific()`, passing it the `mywindow_key` global variable (it really is a global variable) and an output parameter, `win`, that receives the identity of this thread's window.

**Turning Global References Into Private References** Now consider this code fragment:

```
thread_key_t mywin_key;
FILE *_mywindow(void) {
FILE *win;
pthread_getspecific(mywin_key, &win);
return(win);
}
#define mywindow _mywindow()

void routine_uses_win( FILE *win) {
...
}
void thread_start(...) {
...
make_mywin();
...
routine_uses_win( mywindow )
...
}
```

The `mywin_key` variable identifies a class of variables for which each thread has its own private copy; that is, these variables are thread-specific data. Each thread calls `make_mywin` to initialize its window and to arrange for its instance of `mywindow` to refer to it. Once this routine is called, the thread can safely refer to `mywindow` and, after `mywindow`, the thread gets the reference to its private window. So, references to `mywindow` behave as if they were direct references to data private to the thread.

We can now set up our initial Thread-Specific Data:

```

void make_mywindow(void) {
FILE **win;
static pthread_once_t mykeycreated = PTHREAD_ONCE_INIT;
pthread_once(&mykeycreated, mykeycreate);
win = malloc(sizeof(*win));
create_window(win, ...);
pthread_setspecific(mywindow_key, win);
}
void mykeycreate(void) {
pthread_keycreate(&mywindow_key, free_key);
}
void free_key(void *win) {
free(win);
}

```

First, get a unique value for the key, `mywin_key`. This key is used to identify the thread-specific class of data. So, the first thread to call `make_mywin` eventually calls `pthread_keycreate()`, which assigns to its first argument a unique key. The second argument is a destructor function that is used to deallocate a thread's instance of this thread-specific data item once the thread terminates.

The next step is to allocate the storage for the caller's instance of this thread-specific data item. Having allocated the storage, a call is made to the `create_window` routine, which sets up a window for the thread and sets the storage pointed to by `win` to refer to it. Finally, a call is made to `pthread_setspecific()`, which associates the value contained in `win` (that is, the location of the storage containing the reference to the window) with the key. After this, whenever this thread calls `pthread_getspecific()`, passing the global key, it gets the value that was associated with this key by this thread when it called `pthread_setspecific()`. When a thread terminates, calls are made to the destructor functions that were set up in `pthread_key_create()`. Each destructor function is called only if the terminating thread established a value for the key by calling `pthread_setspecific()`.

## Getting the Thread Identifiers

The function `pthread_self()` can be called to return the ID of the calling thread. It is prototyped by:

```
pthread_t pthread_self(void);
```

Its use is very straightforward:

```

#include <pthread.h>
pthread_t tid;
tid = pthread_self();

```

## Comparing Thread IDs

The function `pthread_equal()` can be called to compare the thread identification numbers of two threads. It is prototyped by:

```
int pthread_equal(pthread_t tid1, pthread_t tid2);
```

Its use is straightforward to use, also:

```

#include <pthread.h>
pthread_t tid1, tid2;
int ret;
ret = pthread_equal(tid1, tid2);

```

As with other comparison functions, `pthread_equal()` returns a non-zero value when `tid1` and `tid2` are equal; otherwise, zero is returned. When either `tid1` or `tid2` is an invalid thread identification number, the result is unpredictable.

## Initializing Threads

Use `pthread_once()` to call an initialization routine the first time `pthread_once()` is called -- Subsequent calls to have no effect. The prototype of this function is:

```

int pthread_once(pthread_once_t *once_control,
void (*init_routine)(void));

```

## Yield Thread Execution

The function `sched_yield()` to cause the current thread to yield its execution in favor of another thread with the same or greater priority. It is prototyped by:

```
int sched_yield(void);
```

It is clearly a simple function to call:

```
#include <sched.h>
int ret;
ret = sched_yield();
```

`sched_yield()` returns zero after completing successfully. Otherwise -1 is returned and `errno` is set to indicate the error condition.

## Set the Thread Priority

Use `pthread_setschedparam()` to modify the priority of an existing thread. This function has no effect on scheduling policy. It is prototyped as follows:

```
int pthread_setschedparam(pthread_t tid, int policy,
const struct sched_param *param);
```

and used as follows:

```
#include <pthread.h>
pthread_t tid;
int ret;
struct sched_param param;
int priority;
/* sched_priority will be the priority of the thread */
sched_param.sched_priority = priority;
/* only supported policy, others will result in ENOTSUP */

policy = SCHED_OTHER;
/* scheduling parameters of target thread */
ret = pthread_setschedparam(tid, policy, &param);
```

`pthread_setschedparam()` returns zero after completing successfully. Any other returned value indicates that an error occurred. When either of the following conditions occurs, the `pthread_setschedparam()` function fails and returns an error value.

## Get the Thread Priority

`pthread_getschedparam(pthread_t tid, int policy, struct schedparam *param)` gets the priority of the existing thread.

An example call of this function is:

```
#include <pthread.h>
pthread_t tid;
struct sched_param param;
int priority;
int policy;
int ret;
/* scheduling parameters of target thread */
ret = pthread_getschedparam (tid, &policy, &param);
/* sched_priority contains the priority of the thread */
priority = param.sched_priority;
```

`pthread_getschedparam()` returns zero after completing successfully. Any other returned value indicates that an error occurred. When the following condition occurs, the function fails and returns the error value set.

## Send a Signal to a Thread

Signal may be sent to threads in a similar fashion to those for process as follows:

```
#include <pthread.h>
#include <signal.h>
int sig;
pthread_t tid;
int ret;
ret = pthread_kill(tid, sig);
```

`pthread_kill()` sends the signal `sig` to the thread specified by `tid`. `tid` must be a thread within the same process as the calling thread. The `sig` argument must be a valid signal of the same type defined for `signal()` in `<signal.h>` (See Chapter 23)

When `sig` is zero, error checking is performed but no signal is actually sent. This can be used to check the validity of `tid`.

This function returns zero after completing successfully. Any other returned value indicates that an error occurred. When either of the following conditions occurs, `pthread_kill()` fails and returns an error value.

## Access the Signal Mask of the Calling Thread

The function `pthread_sigmask()` may be used to change or examine the signal mask of the calling thread. It is prototyped as follows:

```
int pthread_sigmask(int how, const sigset_t *new, sigset_t *old);
```

Example uses of this function include:

```
#include <pthread.h>
#include <signal.h>
int ret;
sigset_t old, new;
ret = pthread_sigmask(SIG_SETMASK, &new, &old); /* set new mask */
ret = pthread_sigmask(SIG_BLOCK, &new, &old); /* blocking mask */
ret = pthread_sigmask(SIG_UNBLOCK, &new, &old); /* unblocking */
```

`how` determines how the signal set is changed. It can have one of the following values:

**SIG\_SETMASK**  
-- Replace the current signal mask with `new`, where `new` indicates the new signal mask.

**SIG\_BLOCK**  
-- Add `new` to the current signal mask, where `new` indicates the set of signals to block.

**SIG\_UNBLOCK**  
-- Delete `new` from the current signal mask, where `new` indicates the set of signals to unblock.

When the value of `new` is `NULL`, the value of `how` is not significant and the signal mask of the thread is unchanged. So, to inquire about currently blocked signals, assign a `NULL` value to the `new` argument. The `old` variable points to the space where the previous signal mask is stored, unless it is `NULL`.

`pthread_sigmask()` returns a zero when it completes successfully. Any other returned value indicates that an error occurred. When the following condition occurs, `pthread_sigmask()` fails and returns an error value.

## Terminate a Thread

A thread can terminate its execution in the following ways:

- By returning from its first (outermost) procedure, the threads start routine; see `pthread_create()`
- By calling `pthread_exit()`, supplying an exit status
- By termination with POSIX cancel functions; see `pthread_cancel()`

The void `pthread_exit(void *status)` is used to terminate a thread in a similar fashion to the `exit()` for a process:

```
#include <pthread.h>
int status;
pthread_exit(&status); /* exit with status */
```

The `pthread_exit()` function terminates the calling thread. All thread-specific data bindings are released. If the calling thread is not detached, then the thread's ID and the exit status specified by `status` are retained until the thread is waited for (blocked). Otherwise, `status` is ignored and the thread's ID can be reclaimed immediately.

The `pthread_cancel()` function to cancel a thread is prototyped:

```
int pthread_cancel(pthread_t thread);
```

and called:

```
#include <pthread.h>
pthread_t thread;
int ret;
ret = pthread_cancel(thread);
```

How the cancellation request is treated depends on the state of the target thread. Two functions,

`pthread_setcancelstate()` and `pthread_setcanceltype()` (see `man` pages for further information on these functions), determine that state.

`pthread_cancel()` returns zero after completing successfully. Any other returned value indicates that an error occurred. When the following condition occurs, the function fails and returns an error value.

## Solaris Threads: `<thread.h>`

Solaris have many similarities to POSIX threads. In this section focus on the Solaris features that are not found in POSIX threads. Where functionality is virtually the same for both Solaris threads and for pthreads, (even though the function names or arguments might differ), only a brief example consisting of the correct include file and the function prototype is presented. Where return values are not given for the Solaris threads functions, see the appropriate `man` pages.

The Solaris threads API and the pthreads API are two solutions to the same problem: building parallelism into application software. Although each API is complete in itself, you can safely mix Solaris threads functions and pthread functions in the same program.

The two APIs do not match exactly, however. Solaris threads supports functions that are not found in pthreads, and pthreads includes functions that are not supported in the Solaris interface. For those functions that do match, the associated arguments might not, although the information content is effectively the same.

By combining the two APIs, you can use features not found in one to enhance the other. Similarly, you can run applications using Solaris threads, exclusively, with applications using pthreads, exclusively, on the same system.

To use the Solaris threads functions described in this chapter, you must link with the Solaris threads library `-lthread` and include the `<thread.h>` in all programs.

## Unique Solaris Threads Functions

Let us begin by looking at some functions that are unique to Solaris threads:

- Suspend Thread Execution
- Continue a Suspended Thread
- Set Thread Concurrency Level
- Get Thread Concurrency

### Suspend Thread Execution

The function `thr_suspend()` immediately suspends the execution of the thread specified by a target thread, (`tid` below). It is prototyped by:

```
int thr_suspend(thread_t tid);
```

On successful return from `thr_suspend()`, the suspended thread is no longer executing. Once a thread is suspended, subsequent calls to `thr_suspend()` have no effect. Signals cannot awaken the suspended thread; they remain pending until the thread resumes execution.

A simple example call is as follows:

```
#include <thread.h>

thread_t tid; /* tid from thr_create() */
/* pthreads equivalent of Solaris tid from thread created */
/* with pthread_create() */
pthread_t ptid;
int ret;
ret = thr_suspend(tid);
/* using pthreads ID variable with a cast */
ret = thr_suspend((thread_t) ptid);
```

**Note:** `pthread_t tid` as defined in `pthread` is the same as `thread_t tid` in Solaris threads. `tid` values can be used interchangeably either by assignment or through the use of casts.

## Continue a Suspended Thread

The function `thr_continue()` resumes the execution of a suspended thread. It is prototypes as follows:

```
int thr_continue(thread_t tid);
```

Once a suspended thread is continued, subsequent calls to `thr_continue()` have no effect.

A suspended thread will **not** be awakened by a signal. The signal stays pending until the execution of the thread is resumed by `thr_continue()`.

`thr_continue()` returns zero after completing successfully. Any other returned value indicates that an error occurred. When the following condition occurs, `thr_continue()` The following code fragment illustrates the use of the function:

```
thread_t tid; /* tid from thr_create() */
/* pthreads equivalent of Solaris tid from thread created */
/* with pthread_create() */
pthread_t ptid;
int ret;
ret = thr_continue(tid);
/* using pthreads ID variable with a cast */
ret = thr_continue((thread_t) ptid)
```

## Set Thread Concurrency Level

By default, Solaris threads attempt to adjust the system execution resources (LWPs) used to run unbound threads to match the real number of active threads. While the Solaris threads package cannot make perfect decisions, it at least ensures that the process continues to make progress. When you have some idea of the number of unbound threads that should be simultaneously active (executing code or system calls), tell the library through `thr_setconcurrency(int new_level)`. To get the number of threads being used, use the function `thr_getconcurrencyint(void)`:

`thr_setconcurrency()` provides a hint to the system about the required level of concurrency in the application. The system ensures that a sufficient number of threads are active so that the process continues to make progress, for example:

```
#include <thread.h>
int new_level;
int ret;

ret = thr_setconcurrency(new_level);
```

Unbound threads in a process might or might not be required to be simultaneously active. To conserve system resources, the threads system ensures by default that enough threads are active for the process to make progress, and that the process will not deadlock through a lack of concurrency. Because this might not produce the most effective level of concurrency, `thr_setconcurrency()` permits the application to give the threads system a hint, specified by `new_level`, for the desired level of concurrency. The actual number of simultaneously active threads can be larger or smaller than `new_level`. Note that an application with multiple compute-bound threads can fail to schedule all the runnable threads if `thr_setconcurrency()` has not been called to adjust the level of execution resources. You can also affect the value for the desired concurrency level by setting the `THR_NEW_LW` flag in `thr_create()`. This effectively increments the current level by one.

`thr_setconcurrency()` a zero when it completes successfully. Any other returned value indicates that an error occurred. When any of the following conditions are detected, `thr_setconcurrency()` fails and returns the corresponding value to `errno`.

## Readers/Writer Locks

Readers/Writer locks are another unique feature of Solaris threads. They allow simultaneous read access by many threads while restricting write access to only one thread at a time.

When any thread holds the lock for reading, other threads can also acquire the lock for reading but must wait to acquire the lock for writing. If one thread holds the lock for writing, or is waiting to acquire the lock for writing, other threads must wait to acquire the lock for either reading or writing. Readers/writer locks are slower than mutexes, but can improve performance when they protect data that are not frequently written but

that are read by many concurrent threads. Use readers/writer locks to synchronize threads in this process and other processes by allocating them in memory that is writable and shared among the cooperating processes (see `mmap(2)`) and by initializing them for this behavior. By default, the acquisition order is not defined when multiple threads are waiting for a readers/writer lock. However, to avoid writer starvation, the Solaris threads package tends to favor writers over readers. Readers/writer locks must be initialized before use.

### Initialize a Readers/Writer Lock

The function `rwlock_init()` initialises the readers/writer lock. It is prototypes in `<synch.h>` or `<thread.h>` as follows:

```
int rwlock_init(rwlock_t *rwlp, int type, void * arg);
```

The readers/writer lock pointed to by `rwlp` and to set the lock state to unlocked. `type` can be one of the following

#### **USYNC\_PROCESS**

-- The readers/writer lock can be used to synchronize threads in this process and other processes.

#### **USYNC\_THREAD**

-- The readers/writer lock can be used to synchronize threads in this process, only.

**Note:** that `arg` is currently ignored.

`rwlock_init()` returns zero after completing successfully. Any other returned value indicates that an error occurred. When any of the following conditions occur, the function fails and returns the corresponding value to `errno`.

Multiple threads must not initialize the same readers/writer lock simultaneously. Readers/writer locks can also be initialized by allocation in zeroed memory, in which case a type of `USYNC_THREAD` is assumed. A readers/writer lock must not be reinitialized while other threads might be using it.

An example code fragment that initialises Readers/Writer Locks with Intraprocess Scope is as follows:

```
#include <thread.h>

rwlock_t rwlp;
int ret;
/* to be used within this process only */
ret = rwlock_init(&rwlp, USYNC_THREAD, 0);
Initializing Readers/Writer Locks with Interprocess Scope
#include <thread.h>
rwlock_t rwlp;
int ret;
/* to be used among all processes */
ret = rwlock_init(&rwlp, USYNC_PROCESS, 0);
```

### Acquire a Read Lock

To acquire a read lock on the readers/writer lock use the `rw_rdlock()` function:

```
int rw_rdlock(rwlock_t *rwlp);
```

The readers/writer lock pointed to by `rwlp`. When the readers/writer lock is already locked for writing, the calling thread blocks until the write lock is released. Otherwise, the read lock is acquired.

`rw_rdlock()` returns zero after completing successfully. Any other returned value indicates that an error occurred. When any of the following conditions occur, the function fails and returns the corresponding value to `errno`.

A function `rw_tryrdlock(rwlock_t *rwlp)` may also be used to attempt to acquire a read lock on the readers/writer lock pointed to by `rwlp`. When the readers/writer lock is already locked for writing, it returns an error. Otherwise, the read lock is acquired. This function returns zero after completing successfully. Any other returned value indicates that an error occurred.

### Acquire a Write Lock

The function `rw_wrlock(rwlock_t *rwlp)` acquires a write lock on the readers/writer lock pointed to by `rwlp`. When the readers/writer lock is already locked for reading or writing, the calling thread blocks until all the read locks and write locks are released. Only one thread at a time can hold a write lock on a readers/writer lock.



`rw_wrlock()` returns zero after completing successfully. Any other returned value indicates that an error occurred.

Use `rw_trywrlock(rwlock_t *rwlp)` to attempt to acquire a write lock on the readers/writer lock pointed to by `rwlp`. When the readers/writer lock is already locked for reading or writing, it returns an error.

`rw_trywrlock()` returns zero after completing successfully. Any other returned value indicates that an error occurred.

### Unlock a Readers/Writer Lock

The function `rw_unlock(rwlock_t *rwlp)` unlocks a readers/writer lock pointed to by `rwlp`. The readers/writer lock must be locked and the calling thread must hold the lock either for reading or writing. When any other threads are waiting for the readers/writer lock to become available, one of them is unblocked.

`rw_unlock()` returns zero after completing successfully. Any other returned value indicates that an error occurred.

### Destroy Readers/Writer Lock State

The function `rwlock_destroy(rwlock_t *rwlp)` destroys any state associated with the readers/writer lock pointed to by `rwlp`. The space for storing the readers/writer lock is not freed.

`rwlock_destroy()` returns zero after completing successfully. Any other returned value indicates that an error occurred.

### Readers/Writer Lock Example

The following example uses a bank account analogy to demonstrate readers/writer locks. While the program could allow multiple threads to have concurrent read-only access to the account balance, only a single writer is allowed. Note that the `get_balance()` function needs the lock to ensure that the addition of the checking and saving balances occurs atomically.

```
rwlock_t account_lock;
float checking_balance = 100.0;
float saving_balance = 100.0;
...
rwlock_init(&account_lock, 0, NULL);
...
float
get_balance() {
    float bal;
    rw_rdlock(&account_lock);
    bal = checking_balance + saving_balance;
    rw_unlock(&account_lock);
    return(bal);
}
void
transfer_checking_to_savings(float amount) {
    rw_wrlock(&account_lock);
    checking_balance = checking_balance - amount;
    saving_balance = saving_balance + amount;
    rw_unlock(&account_lock);
}
```

## Similar Solaris Threads Functions

Here we simply list the similar thread functions and their prototype definitions, except where the complexity of the function merits further exposition. .

### Create a Thread

The `thr_create()` routine is one of the most elaborate of all the Solaris threads library routines.

It is prototyped as follows:

```
int thr_create(void *stack_base, size_t stack_size,
void *(*start_routine) (void *), void *arg, long flags,
thread_t *new_thread);
```

This function adds a new thread of control to the current process. Note that the new thread does not inherit

pending signals, but it does inherit priority and signal masks.

`stack_base` contains the address for the stack that the new thread uses. If `stack_base` is `NULL` then `thr_create()` allocates a stack for the new thread with at least `stack_size` bytes. `stack_size` Contains the size, in number of bytes, for the stack that the new thread uses. If `stack_size` is zero, a default size is used. In most cases, a zero value works best. If `stack_size` is not zero, it must be greater than the value returned by `thr_min_stack(void)` inquiry function.

There is no general need to allocate stack space for threads. The threads library allocates one megabyte of virtual memory for each thread's stack with no swap space reserved.

`start_routine` contains the function with which the new thread begins execution. When `start_routine` returns, the thread exits with the exit status set to the value returned by `start_routine`

`arg` can be anything that is described by `void`, which is typically any 4-byte value. Anything larger must be passed indirectly by having the argument point to it.

Note that you can supply only one argument. To get your procedure to take multiple arguments, encode them as one (such as by putting them in a structure).

`flags` specifies attributes for the created thread. In most cases a zero value works best. The value in `flags` is constructed from the bitwise inclusive OR of the following:

#### **THR\_SUSPENDED**

-- Suspends the new thread and does not execute `start_routine` until the thread is started by `thr_continue()`. Use this to operate on the thread (such as changing its priority) before you run it. The termination of a detached thread is ignored.

#### **THR\_DETACHED**

-- Detaches the new thread so that its thread ID and other resources can be reused as soon as the thread terminates. Set this when you do not want to wait for the thread to terminate. Note - When there is no explicit synchronization to prevent it, an unsuspended, detached thread can die and have its thread ID reassigned to another new thread before its creator returns from `thr_create()`.

#### **THR\_BOUND**

-- Permanently binds the new thread to an LWP (the new thread is a bound thread).

#### **THR\_NEW\_LWP**

-- Increases the concurrency level for unbound threads by one. The effect is similar to incrementing concurrency by one with `thr_setconcurrency()`, although `THR_NEW_LWP` does not affect the level set through the `thr_setconcurrency()` function. Typically, `THR_NEW_LWP` adds a new LWP to the pool of LWPs running unbound threads.

When you specify both `THR_BOUND` and `THR_NEW_LWP`, two LWPs are typically created -- one for the bound thread and another for the pool of LWPs running unbound threads.

#### **THR\_DAEMON**

-- Marks the new thread as a daemon. The process exits when all nondaemon threads exit. Daemon threads do not affect the process exit status and are ignored when counting the number of thread exits.

A process can exit either by calling `exit()` or by having every thread in the process that was not created with the `THR_DAEMON` flag call `thr_exit()`. An application, or a library it calls, can create one or more threads that should be ignored (not counted) in the decision of whether to exit. The `THR_DAEMON` flag identifies threads that are not counted in the process exit criterion.

`new_thread` points to a location (when `new_thread` is not `NULL`) where the ID of the new thread is stored when `thr_create()` is successful. The caller is responsible for supplying the storage this argument points to. The ID is valid only within the calling process. If you are not interested in this identifier, supply a zero value to `new_thread`.

`thr_create()` returns a zero and exits when it completes successfully. Any other returned value indicates that an error occurred. When any of the following conditions are detected, `thr_create()` fails and returns the corresponding value to `errno`.

## **Get the Thread Identifier**

The `int thr_self(void)` to get the ID of the calling thread.

## **Yield Thread Execution**

`void thr_yield(void)` causes the current thread to yield its execution in favor of another thread with the same or greater priority; otherwise it has no effect. There is no guarantee that a thread calling `thr_yield()` will do so.

## Signals and Solaris Threads

The following functions exist and operate as do pthreads.

`int thr_kill(thread_t target_thread, int sig)` sends a signal to a thread.

`int thr_sigsetmask(int how, const sigset_t *set, sigset_t *oset)` to change or examine the signal mask of the calling thread.

## Terminating a Thread

The `void thr_exit(void *status)` to terminates a thread.

The `int thr_join(thread_t tid, thread_t *departedid, void **status)` function to wait for a thread to terminate.

Therefore to join specific threads one would do:

```
#include <thread.h>
thread_t tid;
thread_t departedid;
int ret;
int status;
/* waiting to join thread "tid" with status */
ret = thr_join(tid, &departedid, (void **)&status);
/* waiting to join thread "tid" without status */
ret = thr_join(tid, &departedid, NULL);
/* waiting to join thread "tid" without return id and status */
ret = thr_join(tid, NULL, NULL);
```

When the `tid` is (`thread_t`) 0, then `thread_join()` waits for any undetached thread in the process to terminate. In other words, when no thread identifier is specified, any undetached thread that exits causes `thread_join()` to return.

To join any threads:

```
#include <thread.h>
thread_t tid;
thread_t departedid;
int ret;
int status;
/* waiting to join thread "tid" with status */
ret = thr_join(NULL, &departedid, (void **)&status);
```

By indicating `NULL` as thread id in the `thr_join()`, a join will take place when any non detached thread in the process exits. The `departedid` will indicate the thread ID of exiting thread.

## Creating a Thread-Specific Data Key

Except for the function names and arguments, thread specific data is the same for Solaris as it is for POSIX.

`int thr_keycreate(thread_key_t *keyp, void (*destructor) (void *value))` allocates a key that is used to identify thread-specific data in a process.

`int thr_setspecific(thread_key_t key, void *value)` binds value to the thread-specific data key, key, for the calling thread.

`int thr_getspecific(thread_key_t key, void **valuep)` stores the current value bound to key for the calling thread into the location pointed to by valuep.

In Solaris threads, if a thread is to be created with a priority other than that of its parent's, it is created in `SUSPEND` mode. While suspended, the threads priority is modified using the `int thr_setprio(thread_t tid, int newprio)` function call; then it is continued.

An unbound thread is usually scheduled only with respect to other threads in the process using simple priority levels with no adjustments and no kernel involvement. Its system priority is usually uniform and is inherited from the creating process.

The function `thr_setprio()` changes the priority of the thread, specified by `tid`, within the current process to the priority specified by `newprio`.

By default, threads are scheduled based on fixed priorities that range from zero, the least significant, to the largest integer. The `tid` will preempt lower priority threads, and will yield to higher priority threads. For example:

```
#include <thread.h>
thread_t tid;
int ret;
int newprio = 20;
/* suspended thread creation */
ret = thr_create(NULL, NULL, func, arg, THR_SUSPEND, &tid);
/* set the new priority of suspended child thread */
ret = thr_setprio(tid, newprio);
/* suspended child thread starts executing with new priority */

ret = thr_continue(tid);
```

Use `int thr_getprio(thread_t tid, int *newprio)` to get the current priority for the thread. Each thread inherits a priority from its creator. `thr_getprio()` stores the current priority, `tid`, in the location pointed to by `newprio`.

## Example Use of Thread Specific Data: Rethinking Global Variables

Historically, most code has been designed for single-threaded programs. This is especially true for most of the library routines called from C programs. The following implicit assumptions were made for single-threaded code:

- When you write into a global variable and then, a moment later, read from it, what you read is exactly what you just wrote.
- This is also true for nonglobal, static storage.
- You do not need synchronization because there is nothing to synchronize with.

The next few examples discuss some of the problems that arise in multithreaded programs because of these assumptions, and how you can deal with them.

Traditional, single-threaded C and UNIX have a convention for handling errors detected in system calls. System calls can return anything as a functional value (for example, `write` returns the number of bytes that were transferred). However, the value `-1` is reserved to indicate that something went wrong. So, when a system call returns `-1`, you know that it failed.

Consider the following piece of code:

```
extern int errno;

...

if (write(file_desc, buffer, size) == -1)
{ /* the system call failed */
    fprintf(stderr, "something went wrong, error code = %d\n", errno);
    exit(1);
}
```

Rather than return the actual error code (which could be confused with normal return values), the error code is placed into the global variable `errno`. When the system call fails, you can look in `errno` to find out what went wrong.

Now consider what happens in a multithreaded environment when two threads fail at about the same time, but with different errors.

- Both expect to find their error codes in `errno`,
- **but** one copy of `errno` cannot hold both values.

This global variable approach simply does not work for multithreaded programs. Threads solves this problem through a conceptually new storage class: *thread-specific data*.

This storage is similar to global storage in that it can be accessed from any procedure in which a thread might be running. However, it is private to the thread: when two threads refer to the thread-specific data location of the same name, they are referring to two different areas of storage.

So, when using threads, each reference to `errno` is thread-specific because each thread has a private copy of `errno`. This is achieved in this implementation by making `errno` a macro that expands to a function call.

# Compiling a Multithreaded Application

There are many options to consider for header files, define flags, and linking.

## Preparing for Compilation

The following items are required to compile and link a multithreaded program.

- A standard C compiler (`cc`, `gcc` *etc*)
- Include files:
  - `<thread.h>` and `<pthread.h>`
  - `<errno.h>`, `<limits.h>`, `<signal.h>`, `<unistd.h>`
- The Solaris threads library (`libthread`), the POSIX threads library (`libpthread`), and possibly the POSIX realtime library (`libposix4`) for semaphores
- MT-safe libraries (`libc`, `libm`, `libw`, `libintl`, `libnsl`, `libsocket`, `libmalloc`, `libmapmalloc`, and so on)

The include file `<thread.h>`, used with the `-lthread` library, compiles code that is upward compatible with earlier releases of the Solaris system. This library contains both interfaces: those with Solaris semantics and those with POSIX semantics. To call `thr_setconcurrency()` with POSIX threads, your program needs to include `<thread.h>`.

The include file `<pthread.h>`, used with the `-lpthread` library, compiles code that is conformant with the multithreading interfaces defined by the POSIX 1003.1c standard. For complete POSIX compliance, the define flag `_POSIX_C_SOURCE` should be set to a (long) value  $\geq 199506L$ , as follows:

```
cc [flags] file... -D_POSIX_C_SOURCE=N (where N 199506L)
```

You can mix Solaris threads and POSIX threads in the same application, by including both `<thread.h>` and `<pthread.h>`, and linking with either the `-lthread` or `-lpthread` library. In mixed use, Solaris semantics prevail when compiling with `-D_REENTRANT` flag set  $\geq 199506L$  and linking with `-lthread`, whereas POSIX semantics prevail when compiling with `_POSIX_C_SOURCE` flag set  $\geq 199506L$  and linking with `-lpthread`.

Defining `_REENTRANT` or `_POSIX_C_SOURCE`

### Linking With `libthread` or `libpthread`

For POSIX threads behavior, load the `libpthread` library. For Solaris threads behavior, load the `libthread` library. Some POSIX programmers might want to link with `-lthread` to preserve the Solaris distinction between `fork()` and `fork1()`. All that `-lpthread` really does is to make `fork()` behave the same way as the Solaris `fork1()` call, and change the behavior of `alarm()`.

To use `libthread`, specify `-lthread` last on the `cc` command line.

To use `libpthread`, specify `-lpthread` last on the `cc` command line.

Do not link a *nonthreaded* program with `-lthread` or `-lpthread`. Doing so establishes multithreading mechanisms at link time that are initiated at run time. These *slow down* a single-threaded application, waste system resources, and produce misleading results when you debug your code.

**Note:** For C++ programs that use threads, use the `-mt` option, rather than `-lthread`, to compile and link your application. The `-mt` option links with `libthread` and ensures proper library linking order. ( Using `-lthread` might cause your program to crash (core dump).

### Linking with `-lposix4` for POSIX Semaphores

The Solaris semaphore routines (see Chapter [30.3](#)) are contained in the `libthread` library. By contrast, you link with the `-lposix4` library to get the standard POSIX semaphore routines (See Chapter [25](#))

## Debugging a Multithreaded Program

The following list points out some of the more frequent oversights and errors that can cause bugs in multithreaded programs.

- Passing a pointer to the caller's stack as an argument to a new thread.
- Accessing global memory (shared changeable state) without the protection of a synchronization mechanism.
- Creating deadlocks caused by two threads trying to acquire rights to the same pair of global resources in alternate order (so that one thread controls the first resource and the other controls the second resource and neither can proceed until the other gives up).
- Trying to reacquire a lock already held (recursive deadlock).
- Creating a hidden gap in synchronization protection. This is caused when a code segment protected by a synchronization mechanism contains a call to a function that frees and then reacquires the synchronization mechanism before it returns to the caller. The result is that it appears to the caller that the global data has been protected when it actually has not.
- Mixing UNIX signals with threads -- it is better to use the `sigwait()` model for handling asynchronous signals.
- Forgetting that default threads are created `PTHREAD_CREATE_JOINABLE` and must be reclaimed with `pthread_join()`. **Note**, `pthread_exit()` does not free up its storage space.
- Making deeply nested, recursive calls and using large automatic arrays can cause problems because multithreaded programs have a more limited stack size than single-threaded programs.
- Specifying an inadequate stack size, or using non-default stacks. And, note that multithreaded programs (especially those containing bugs) often behave differently in two successive runs, given identical inputs, because of differences in the thread scheduling order.

In general, multithreading bugs are statistical instead of deterministic. Tracing is usually a more effective method of finding order of execution problems than is breakpoint-based debugging.

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1/5/1999