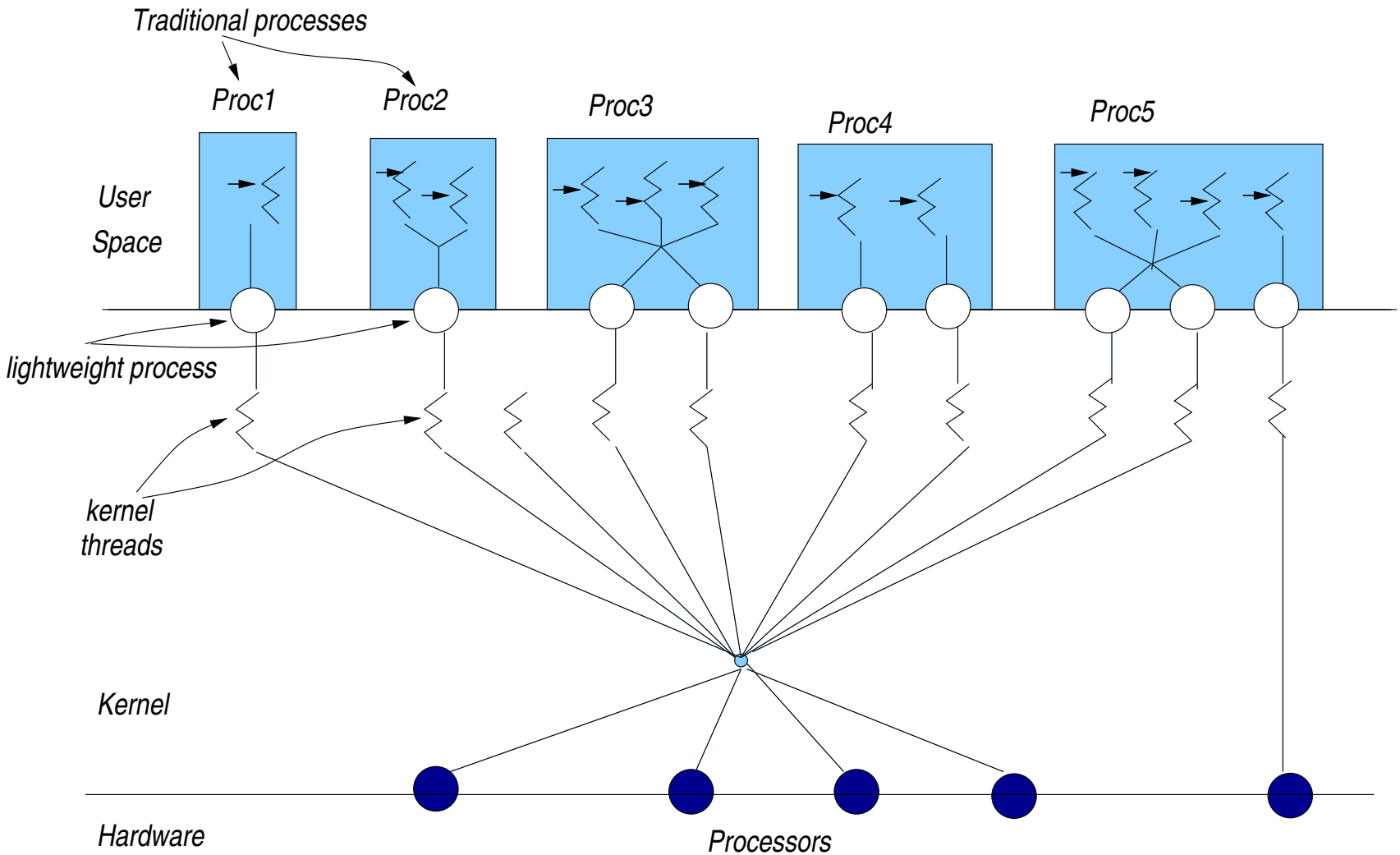
Threads

Threads

- Threads are an alternative to multiple processes.
- Different “flows” (or sequences) of execution operate on the same data (heap).

Thread (Solaris) Model



Thread Highlights

- One or more threads may be executed in the context of a process.
- The entity that is being scheduled is the thread – **not** the process itself.
- In the presence of a single processor, threads are executed by sharing the processor (*time slicing*).
- If there is more than one processor, threads can be assigned to different kernel threads (and, thus, different CPUs) and run in parallel.
- Any thread may create a new thread.

Thread Highlights (continued)

- All threads of a single process share the same address space (static/global variables, heap, file descriptors, etc.) BUT have their own program counter (PC), and stack (incl. registers).
- An OS can switch *faster* from one thread to another than from one process to another.
- The header *#include <pthread.h>* is required by all programs that use threads.
- Programs have to be compiled with the *pthread* library.
  gcc <filename>.c -lpthread

Thread Highlights (continued)

- The functions of the *pthread* library do not set the value of the variable *errno*, so we cannot use the function *perror()* for the printing of a diagnostic message.
- If there is an error in one of the thread functions, *strerror()* is used for the printing of the diagnostic code (which is the "function return" for the thread).
- Function *char *strerror(int errnum)*
  - returns a pointer to a string that describes the error code passed in the argument *errnum*.
  - requires: *#include <string.h>*

Threads vs. Processes

	Threads	*Processes*
Address Space	Common. Any change made to heap or static/globals by one thread is visible to all	Different for each process Afer a *fork* we have different address spaces
File Descriptors	Common. Any two threads can use the same descriptor One *close* on this is sufficient	Two processes use copies of the file descriptors

What happens to threads when...

	What happens..
fork	Only the thread that invoked *fork* is duplicated.
exit	All threads die together (*pthread_exit* for the termination of a single thread).
exec	All threads disappear (the shared/common address space is replaced)
signals	This is somewhat more complex - Section 13.5 of the e-book.

Creation of Threads

- The function that helps generate a thread is:

  *int pthread_create(pthread_t *thread,*
  *const pthread_attrt *attr,*
  *void *(*start_routine)(void*), void *arg);*

- creates a new thread with attributes specified by *attr* within a process.
- if *attr* is NULL, default attributes are used.
- Upon successful completion, *pthread_create()* shall store the ID of the created thread in the location referenced by *thread*.
- Through the *attr* we can change features of the thread but oftentimes we let the default value work, giving a NULL.
- If successful, the function returns zero; otherwise, an error number shall be returned to indicate the error.

Terminating a Thread

- *void pthread_exit(void *value_ptr)*
- terminates the calling thread and makes the value *value_ptr* available to any successful join with the terminating thread.
- After a thread has terminated, the result of access to local (auto) variables of the thread is undefined. So, references to local variables of the exiting thread should not be used for the *value_ptr* parameter value.

pthread_join - waiting for thread termination

- *int pthread_join(pthread_t thread, void **value_ptr)*
- suspends execution of the calling *thread* until the target thread terminates (unless the target thread has already terminated).
- On return from a successful *pthread_join()* call with a non-NULL *value_ptr* argument, the value passed to *pthread_exit()* by the terminating thread shall be made available in the location referenced by *value_ptr*.
- When a *pthread_join()* returns successfully, the target thread has been terminated.
- On successful completion, the function returns 0.

Identifying - Detaching Threads

$\Longrightarrow$ Get the calling thread-ID:

- *pthread_t pthread_self(void)*
- returns the thread-ID of the calling thread.

$\Longrightarrow$ Detaching a thread:

- *int pthread_detach(pthread_t thread)*
- indicates that the thread cannot be joined. Storage for the *thread* can be reclaimed only when the thread terminates.
- If *thread* has not terminated, *pthread_detach()* shall not cause it to terminate.
- If the call succeeds, *pthread_detach()* shall return 0; otherwise, an error number shall be returned.
- Issuing a *pthread_join* on a detached thread fails.

Creating and using threads

```c
#include <stdio.h>
#include <string.h>    /* For strerror */
#include <stdlib.h>    /* For exit     */
#include <pthread.h>   /* For threads  */
#define perror2(s,e) fprintf(stderr, "%s: %s\n", s, strerror(e))

void *thread_f(void *argp){ /* Thread function */
   printf("I am the newly created thread %ld\n", pthread_self());
   pthread_exit((void *) 47); // Not recommended way of "exit"ing
}                             // avoid using automatic variables
                              // use malloc-ed structs to return status
main(){
  pthread_t thr;
  int err, status;
  if (err = pthread_create(&thr, NULL, thread_f, NULL)) { /* New thread */
      perror2("pthread_create", err);
      exit(1);
  }
  printf("I am original thread %ld and I created thread %ld\n",
           pthread_self(), thr);
  if (err = pthread_join(thr, (void **) &status)) { /* Wait for thread */
      perror2("pthread_join", err); /* termination */
      exit(1);
  }
  printf("Thread %ld exited with code %d\n", thr, status);
  printf("Thread %ld just before exiting (Original)\n", pthread_self());
  pthread_exit(NULL);
}
```

Outcome

```
ad@ad-desktop:~/Set007/src$ ./create_a_thread
I am original thread -1216067904 and I created thread
    -1216070800
I am the newly created thread -1216070800
Thread -1216070800 exited with code 47
Thread -1216067904 just before exiting (Original)
ad@ad-desktop:~/Set007/src$
```

Using *pthread_detach*

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

#define perror2(s,e) fprintf(stderr,"%s: %s\n",s,strerror(e))

void *thread_f(void *argp){ /* Thread function */
   int err;
   if (err = pthread_detach(pthread_self())) {/* Detach thread */
       perror2("pthread_detach", err);
       exit(1);
   }
   printf("I am thread %ld and I was called with argument %d\n",
              pthread_self(), *(int *) argp);
   pthread_exit(NULL);
}
```

Using *pthread_detach*

```
main(){
   pthread_t thr;
   int err, arg = 29;

   if (err = pthread_create(&thr,NULL,thread_f,(void *) &arg)){/* New thread */
       perror2("pthread_create", err);
       exit(1);
    }
    printf("I am original thread %d and I created thread %d\n",
              pthread_self(), thr);
    pthread_exit(NULL);
}
```

→ Outcome:

```
ad@ad-desktop:~/Set007/src$ ./detached_thread
I am original thread -1217009984 and I created thread -1217012880
I am thread -1217012880 and I was called with argument 29
ad@ad-desktop:~/Set007/src$
```

Create *n* threads that wait for random secs and then terminate

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <pthread.h>
#define MAX_SLEEP 10 /* Maximum sleeping time in seconds */
#define perror2(s, e) fprintf(stderr, "%s: %s\n", s, strerror(e))

void *sleeping(void *arg) {
   int sl = (int) arg;  /* Horror of horrors! */
   printf("thread %ld sleeping %d seconds ...\n", pthread_self(), sl);
   sleep(sl); /* Sleep a number of seconds */
   printf("thread %ld waking up\n", pthread_self());
   pthread_exit(NULL);
}

main(int argc, char *argv[]){
   int n, i, sl, err;
   pthread_t *tids;
   if (argc > 1) n = atoi(argv[1]); /* Make integer */
   else exit(0);
   if (n > 50) { /* Avoid too many threads */
      printf("Number of threads should be up to 50\n");
      exit(0);
      }

   if ((tids = malloc(n * sizeof(pthread_t))) == NULL) {
      perror("malloc");
      exit(1);
      }
```

n threads waiting for random secs

```
    srandom((unsigned int) time(NULL)); /* Initialize generator */
    for (i=0 ; i<n ; i++) {
    sl = random() % MAX_SLEEP + 1; /* Sleeping time 1..MAX_SLEEP */
    if (err = pthread_create(tids+i, NULL, sleeping, (void *) sl)) {
        /* Create a thread */
        perror2("pthread_create", err);
        exit(1);
        }
    }

    for (i=0 ; i<n ; i++)
    if (err = pthread_join(*(tids+i), NULL)) {
        /* Wait for thread termination */
        perror2("pthread_join", err);
        exit(1);
        }
    printf("all %d threads have terminated\n", n);
}
```

Outcome

```
ad@ad-desktop:~/Set007/src$ ./random_sleeps 3
thread -1216803984 sleeping 6 seconds ...
thread -1225196688 sleeping 8 seconds ...
thread -1233589392 sleeping 7 seconds ...
thread -1216803984 waking up
thread -1233589392 waking up
thread -1225196688 waking up
all 3 threads have terminated
ad@ad-desktop:~/Set007/src$ ./random_sleeps 5
thread -1216611472 sleeping 1 seconds ...
thread -1225004176 sleeping 9 seconds ...
thread -1233396880 sleeping 3 seconds ...
thread -1241789584 sleeping 3 seconds ...
thread -1250182288 sleeping 8 seconds ...
thread -1216611472 waking up
thread -1233396880 waking up
thread -1241789584 waking up
thread -1250182288 waking up
thread -1225004176 waking up
all 5 threads have terminated
ad@ad-desktop:~/Set007/src$
```

Going from single- to multi-threaded programs

```c
#include <stdio.h>
#define NUM 5

void print_mesg(char *);

int     main(){
    print_mesg("hello");
    print_mesg("world\n");
}

void print_mesg(char *m){
int i;
for (i=0; i<NUM; i++){
    printf("%s", m);
    fflush(stdout);
    sleep(1);
    }
}
```

```
ad@ad-desktop:~/Set007/src$ ./print_single
hellohellohellohellohelloworld
world
world
world
world
ad@ad-desktop:~/Set007/src$
```

First Effort in Multi-threading

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

#define NUM 5

main()
{   pthread_t t1, t2;

    void *print_mesg(void *);

    pthread_create(&t1, NULL, print_mesg, (void *)"hello ");
    pthread_create(&t2, NULL, print_mesg, (void *)"world\n");
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
}

void *print_mesg(void *m)
{   char *cp = (char *)m;
    int i;

    for (i=0;i<NUM; i++){
        printf("%s", cp);
        fflush(stdout);
        sleep(2);
        }
    return NULL;
}
```

Outcome

```
ad@ad-desktop:~/Set007/src$
ad@ad-desktop:~/Set007/src$
ad@ad-desktop:~/Set007/src$ ./multi_hello
hello world
hello world
hello world
hello world
hello world
ad@ad-desktop:~/Set007/src$
```

What is “unexpected” here?

```c
#include <stdio.h>
#include <pthread.h>
#define  NUM  5
int      counter=0;

main(){
    pthread_t t1;
    void *print_count(void *);
    int i;

    pthread_create(&t1, NULL, print_count , NULL);
    for(i=0; i<NUM; i++){
        counter++;
        sleep(1);
    }
    pthread_join(t1,NULL);
}

void *print_count(void *m)
{
    /* counter is a shared variable */
    int i;
    for (i=0;i<NUM;i++){
        printf("count = %d\n",counter);
        sleep(1);
        /*changing this 1 -->> 0 has an effect */
    }
    return NULL;
}
```

The "unexpected" outcome:

```
ad@ad-desktop:~/Set007/src$ ./incprint
count = 1
count = 2
count = 3
count = 4
count = 5
ad@ad-desktop:~/Set007/src$
```

⊙ Changing *sleep(1)* $\Longrightarrow$ *sleep(0)*:

```
ad@ad-desktop:~/Set007/src$ vi incprint.c
ad@ad-desktop:~/Set007/src$ gcc incprint.c -o incprint -lpthread
ad@ad-desktop:~/Set007/src$ ./incprint
count = 1
count = 1
count = 1
count = 1
count = 1
ad@ad-desktop:~/Set007/src$
```

$\Rightarrow$ Race Condition!

More problems!

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

int total_words;

int main(int ac, char *av[]){
    pthread_t t1, t2;
    void *count_words(void *);

    if (ac != 3 ) {
        printf("usage: %s file1 file2 \n", av[0]);
        exit(1);
    }
    total_words=0;
    pthread_create(&t1, NULL, count_words , (void *)av[1]);
    pthread_create(&t2, NULL, count_words , (void *)av[2]);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    printf("Main thread with ID: %ld reports %5d total words\n",
                pthread_self(), total_words);
}
```

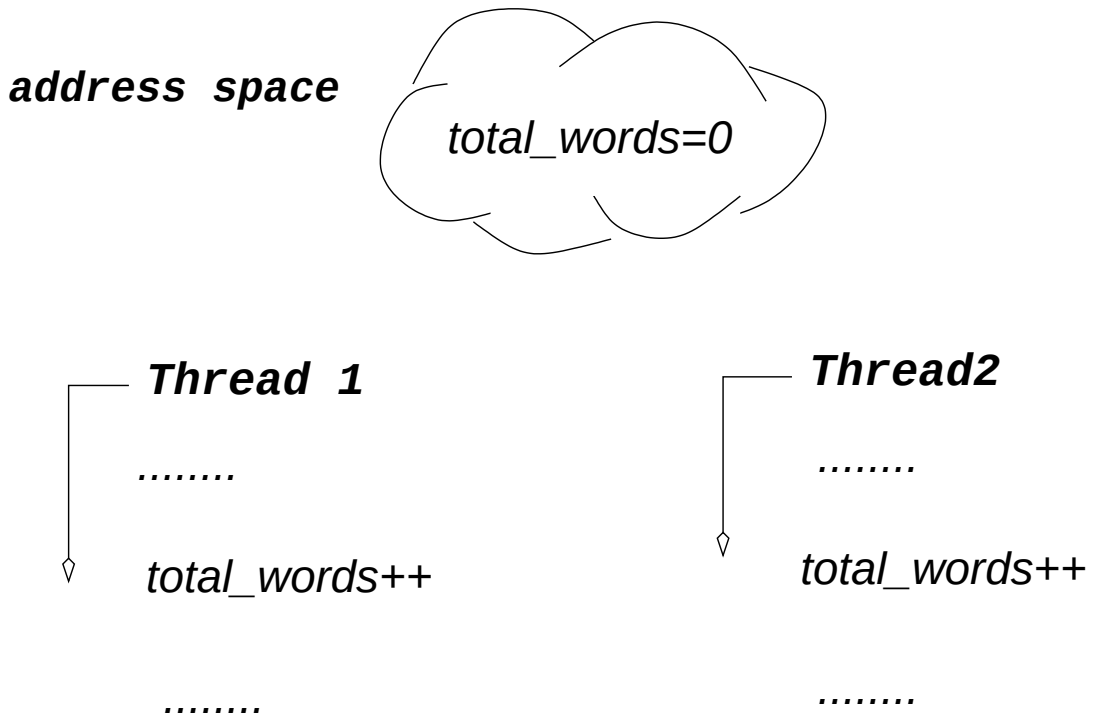
More problems!

```
void *count_words(void *f)
{
    char *filename = (char *)f;
    FILE *fp;    int c, prevc = '\0';
    printf("In thread with ID: %ld counting words.. \n",pthread_self());

    if ( (fp=fopen(filename,"r")) != NULL ){
        while ( ( c = getc(fp) )!= EOF ){
            if ( !isalnum(c) && isalnum(prevc) )
                total_words++;
            prevc = c;
            }
    fclose(fp);
    } else perror(filename);
    return NULL;
}
```

Outcome:

```
ad@ad-desktop:~/Set007/src$
ad@ad-desktop:~/Set007/src$ wc -w fileA fileB
 48 fileA
 61 fileB
109 total
ad@ad-desktop:~/Set007/src$ ./twordcount1 fileA fileB
In thread with ID: -1216558224 counting words..
In thread with ID: -1224950928 counting words..
Main thread with ID: -1216555328 reports   107 total words
ad@ad-desktop:~/Set007/src$ ./twordcount1 fileA fileB
In thread with ID: -1217348752 counting words..
In thread with ID: -1225741456 counting words..
Main thread with ID: -1217345856 reports   105 total words
ad@ad-desktop:~/Set007/src$ ./twordcount1 fileA fileB
In thread with ID: -1217287312 counting words..
In thread with ID: -1225680016 counting words..
Main thread with ID: -1217284416 reports   108 total words
ad@ad-desktop:~/Set007/src$ ./twordcount1 fileA fileB
In thread with ID: -1215718544 counting words..
In thread with ID: -1224111248 counting words..
Main thread with ID: -1215715648 reports   109 total words
ad@ad-desktop:~/Set007/src$
```

Race Condition



- *total_words* might NOT have a consistent value after executing the above two (concurrent) assignments.

POSIX Mutexes

- When theads share common structures (resources), one needs to use a control structure termed a **mutex**.
- A mutex can find itself in only two states: *locked* or *unlocked*.
- *int pthread_mutex_init(pthread_mutex_t *mutex,*
  *const pthread_mutexattr_t *mutexattr)*
  initializes the mutex-object pointed to by *mutex* according to the mutex attributes specified in *mutexattr*.
- A mutex may be initialized only once by setting its value to *PTHREAD_MUTEX_INITIALIZER*

```
static pthread_mutex_t mymutex =
    PTHREAD_MUTEX_INITIALIZER;
```

- *pthread_mutex_init* always returns 0

Locking mutexes

- Locking a mutex is carried out by:
  *int pthread_mutex_lock(pthread_mutex_t *mutex)*
- If the *mutex* is currently unlocked, it becomes locked and owned by the calling thread, and *pthread_mutex_lock* returns immediately.
- If successful, *pthread_mutex_lock* returns 0.
- If the mutex is already locked by another thread, *pthread_mutex_lock* blocks (or "suspends" for the user) the calling thread until the mutex is unlocked.

Unlocking and Destroying mutexes

Unlocking a mutex

- *int pthread_mutex_unlock(pthread_mutex_t *mutex)*
- If the *mutex* has been locked and owned by the calling thread, the *mutex* gets unlocked.
- Upon successful call, it returns 0.

Destroying a Mutex

- *int pthread_mutex_destroy(pthread_mutex_t *mutex)*
- Destroys the *mutex*, freeing resources it might hold.
- In the Linux implementation, the call does nothing except checking that *mutex* is unlocked.
- Upon successful call, it returns 0.

Trying to obtain an lock (discouraged)

Trying to get a lock:

- *int pthread_mutex_trylock(pthread_mutex_t *mutex)*
- behaves identically to *pthread_mutex_lock*, except that it does not block the calling thread if the *mutex* is already locked by another thread.
- Instead, *pthread_mutex_trylock* returns immediately with the error code *EBUSY*.
- If *pthread_mutex_trylock* returns the code *EINVAL*, the mutex was not initialized properly.

Addressing the problem

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <ctype.h>
int             total_words;
pthread_mutex_t  counter_lock = PTHREAD_MUTEX_INITIALIZER;

int main(int ac, char *av[])
{   pthread_t t1, t2;
    void *count_words(void *);
    if ( ac != 3 ) {
        printf("usage: %s file1 file2 \n", av[0]);
        exit(1); }
    total_words=0;
    pthread_create(&t1, NULL, count_words, (void *)av[1]);
    pthread_create(&t2, NULL, count_words, (void *)av[2]);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    printf("Main thread wirth ID %ld reporting %5d total
        words\n",
                pthread_self(),total_words);
}
```

Addressing the problem

```
void *count_words(void *f)
{
    char *filename = (char *)f;
    FILE *fp; int c, prevc = '\0';

    if ( (fp=fopen(filename,"r")) != NULL ){
        while ( ( c = getc(fp) )!= EOF ){
            if ( !isalnum(c) && isalnum(prevc) ){
                pthread_mutex_lock(&counter_lock);
                total_words++;
                pthread_mutex_unlock(&counter_lock);
                }
            prevc = c;
            }
        fclose(fp);
    } else perror(filename);
    return NULL;
}
```

Outcome (correct!)

```
ad@ad-desktop:~/Set007/src$ wc fileA fileB
  1  48 279 fileA
  6  61 344 fileB
  7 109 623 total
ad@ad-desktop:~/Set007/src$ ./twordcount2 fileA fileB
Main thread wirth ID -1215629632 reporting   109 total words
ad@ad-desktop:~/Set007/src$ ./twordcount2 fileA fileB
Main thread wirth ID -1216395584 reporting   109 total words
ad@ad-desktop:~/Set007/src$ ./twordcount2 fileA fileB
Main thread wirth ID -1217239360 reporting   109 total words
ad@ad-desktop:~/Set007/src$ ./twordcount2 fileA fileB
Main thread wirth ID -1216395584 reporting   109 total words
ad@ad-desktop:~/Set007/src$
```

Another Way to Accomplish the Same Correct Operation: no shared data

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <ctype.h>
#define EXIT_FAILURE 1
void *count_words(void *);
struct arg_set{
    char *fname;
    int  count;
    };

int main(int ac, char *av[]) {
       pthread_t t1, t2;
    struct arg_set args1, args2;
    if ( ac != 3 ) {
          printf("usage: %s file1 file2 \n", av[0]); exit (EXIT_FAILURE); }

    args1.fname = av[1]; args1.count = 0;
    pthread_create(&t1, NULL, count_words, (void *) &args1);
    args2.fname = av[2]; args2.count = 0;
    pthread_create(&t2, NULL, count_words, (void *) &args2);

    pthread_join(t1, NULL); pthread_join(t2, NULL);

    printf("In file  %-10s there are %5d words\n", av[1], args1.count);
    printf("In file  %-10s there are %5d words\n", av[2], args2.count);
    printf("Main thread %ld reporting %5d total words\n",
                pthread_self(), args1.count+args2.count);
}
```

Another Way to Accomplish the Same Correct Operation

```
void *count_words(void *a) {
     struct arg_set *args = a;
     FILE *fp; int c, prevc = '\0';
     printf("Working within Thread with ID %ld and counting\n",pthread_self());

     if ( (fp=fopen(args->fname,"r")) != NULL ){
        while ( ( c = getc(fp) )!= EOF ){
            if ( !isalnum(c) && isalnum(prevc) ){
                args->count++;
                }
            prevc = c;
            }
        fclose(fp);
      } else perror(args->fname);
      return NULL;
}
```

$\Rightarrow$ No *mutexes* are used in this function!

Outcome:

```
ad@ad-desktop:~/Set007/src$ wc -w fileA fileB
 48 fileA
 61 fileB
109 total
ad@ad-desktop:~/Set007/src$ ./twordcount3 fileA  fileB
Working within Thread with ID -1224815760 and counting
Working within Thread with ID -1216423056 and counting
In file  fileA      there are    48 words
In file  fileB      there are    61 words
Main thread -1216420160 reporting   109 total words
ad@ad-desktop:~/Set007/src$ ./twordcount3 fileA  fileB
Working within Thread with ID -1215984784 and counting
Working within Thread with ID -1224377488 and counting
In file  fileA      there are    48 words
In file  fileB      there are    61 words
Main thread -1215981888 reporting   109 total words
ad@ad-desktop:~/Set007/src$ ./twordcount3 fileA  fileB
Working within Thread with ID -1216459920 and counting
Working within Thread with ID -1224852624 and counting
In file  fileA      there are    48 words
In file  fileB      there are    61 words
Main thread -1216457024 reporting   109 total words
ad@ad-desktop:~/Set007/src$
```

Things to Remember:

- Every mutex has to be initialized only once.
- *pthread_mutex_unlock* should be called only by the thread holding the mutex.
- NEVER have *pthread_mutex_lock* called by the thread that has already locked the mutex. A deadlock will occur.
- NEVER call *pthread_mutex_destroy* on a locked mutex (*EBUSY*)

Using *pthread_mutex_init*, *pthread_mutex_lock*, *pthread_mutex_unlock*, *pthread_mutex_destroy* (boilerplate)

```c
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <pthread.h> /* For threads */
#define perror2(s, e) fprintf(stderr, "%s: %s\n", s, strerror(e))
pthread_mutex_t mtx;          /* Mutex for synchronization */
char buf[25];                 /* Message to communicate */
void *thread_f(void *);       /* Forward declaration */

main() {
   pthread_t thr;
   int err;
   printf("Main Thread %ld running \n",pthread_self());
   pthread_mutex_init(&mtx, NULL);

   if (err = pthread_mutex_lock(&mtx)) { /* Lock mutex */
      perror2("pthread_mutex_lock", err); exit(1); }
   printf("Thread %ld: Locked the mutex\n", pthread_self());

   if (err = pthread_create(&thr, NULL, thread_f, NULL)) { /* New thread */
      perror2("pthread_create", err); exit(1); }
   printf("Thread %ld: Created thread %ld\n", pthread_self(), thr);

   strcpy(buf, "This is a test message");
   printf("Thread %ld: Wrote message \"%s\" for thread %ld\n",
          pthread_self(), buf, thr);
```

Using *pthread_mutex_init*, *pthread_mutex_lock*, *pthread_mutex_unlock*, *pthread_mutex_destroy*

```
   if (err = pthread_mutex_unlock(&mtx)) { /* Unlock mutex */
      perror2("pthread_mutex_unlock", err); exit(1);
      }
   printf("Thread %ld: Unlocked the mutex\n", pthread_self());

   if (err = pthread_join(thr, NULL)) { /* Wait for thread */
       perror2("pthread_join", err); exit(1); } /* termination */

   printf("Exiting Threads %ld and %ld \n", pthread_self(), thr);

   if (err = pthread_mutex_destroy(&mtx)) { /* Destroy mutex */
      perror2("pthread_mutex_destroy", err); exit(1); }
   pthread_exit(NULL);
}
```

Using *pthread_mutex_init*, *pthread_mutex_lock*, *pthread_mutex_unlock*, *pthread_mutex_destroy*

```
void *thread_f(void *argp){ /* Thread function */
    int err;
    printf("Thread %ld: Just started\n", pthread_self());
    printf("Thread %ld: Trying to lock the mutex\n", pthread_self());

    if (err = pthread_mutex_lock(&mtx)) { /* Lock mutex */
       perror2("pthread_mutex_lock", err); exit(1); }

    printf("Thread %ld: Locked the mutex\n", pthread_self());
    printf("Thread %ld: Read message \"%s\"\n", pthread_self(), buf);

    if (err = pthread_mutex_unlock(&mtx)) { /* Unlock mutex */
       perror2("pthread_mutex_unlock", err); exit(1); }
    printf("Thread %ld: Unlocked the mutex\n", pthread_self());

    pthread_exit(NULL);
}
```

Running the multi-threaded program

```
ad@ad-desktop:~/Set007/src$ ./sync_by_mutex
Main Thread -1217464640 running
Thread -1217464640: Locked the mutex
Thread -1217464640: Created thread -1217467536
Thread -1217464640: Wrote message "This is a test message" for thread
     -1217467536
Thread -1217464640: Unlocked the mutex
Thread -1217467536: Just started
Thread -1217467536: Trying to lock the mutex
Thread -1217467536: Locked the mutex
Thread -1217467536: Read message "This is a test message"
Thread -1217467536: Unlocked the mutex
Exiting Threads -1217464640 and -1217467536
ad@ad-desktop:~/Set007/src$
```

Condition Variables

- A condition (or "condition variable") is a synchronization device/means that allows POSIX threads to suspend execution and relinquish the processors until some predicate on shared data is satisfied.
- The basic operations on conditions are:
  - signal the condition (when the predicate becomes true), and wait for the condition, suspending the thread execution
  - The waiting lasts until another thread signals (or notifies) the condition.
- A condition variable must always be associated with a mutex to avoid a race condition:
  - This race may occur when a thread prepares to wait on a condition variable and another thread signals the condition just before the first thread actually waits on the condition variable.

Initializing a Condition Variable (dynamically)

- *int pthread_cond_init(pthread_cond_t *cond, pthread_condattr_t *cond_attr)*
- initializes the condition variable *cond*, using the condition attributes specified in *cond_attr*, or default attributes if *cond_attr* is simply NULL.
- The call always returns 0 upon completion.
- The LinuxThreads implementation supports no attributes for conditions (*cond_attr* is ignored).
- Variables of type *pthread_cond_t* can also be initialized statically, using the constant PTHREAD_COND_INITIALIZER.

Waiting on a condition

- *int pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex)*
- atomically unlocks the *mutex* and waits for the condition variable *cond* to be signaled.
- The call always returns 0.
- The thread execution is suspended and does not consume any CPU time until the condition variable is signaled (with the help of a *pthread_cond_signal/broadcast*).
- Before returning to the calling thread, *pthread_cond_wait* re-acquires *mutex*.

Signaling variables

$\Rightarrow$ Signaling a variable:

- *int pthread_cond_signal(pthread_cond_t *cond)*
- restarts one of the threads that are waiting on the condition variable *cond*.
- If no threads are waiting on *cond*, nothing happens.
- If several threads are waiting on cond, exactly one is restarted.
- The call always returns 0.

Broadcasting to variables

⇒ Broadcasting to a condition variable:

- *int pthread_cond_broadcast(pthread_cond_t *cond)*
- restarts all the threads that are waiting on the condition variable *cond*.
- Nothing happens if no threads are waiting on *cond*.
- The call always returns 0.

Destroying condition variables

- *int pthread_cond_destroy(pthread_cond_t *cond)*
- destroys a condition variable *cond*, freeing the resources it might hold.
- No threads must be waiting on the condition variable on entrance to *pthread_cond_destroy*.
- In the LinuxThreads, the call does nothing except checking that the condition has no waiting threads.
- Upon successful return the call returns 0.
- In case some threads are waiting on *cond*, *pthread_cond_destroy* returns EBUSY.

While working with mutexes/condition vars keep in mind:

- Associate (in your mind+comments) every piece of shared data in your program with a mutex that protects it.
- For every boolean condition use a separate condition variable.
- For every condition variable, use a single, distinctly-associated with the condition, *mutex*.
- Get the *mutex*, before checking of any condition.
- Always use the same *mutex* when changing variables of a condition.
- Keep a *mutex* for the shortest possible time.
- Do not forget to release locks at the end with *pthread_mutex_unlock*.

Using system calls on condition variables

```c
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <pthread.h>
#define perror2(s, e) fprintf(stderr, "%s: %s\n", s, strerror(e))

pthread_mutex_t mtx = PTHREAD_MUTEX_INITIALIZER;

pthread_cond_t cvar;            /* Condition variable */
char buf[25];                   /* Message to communicate */
void *thread_f(void *);         /* Forward declaration */

main(){
    pthread_t thr; int err;
    pthread_cond_init(&cvar, NULL); /* Initialize condition variable */

    if (err = pthread_mutex_lock(&mtx)) { /* Lock mutex */
        perror2("pthread_mutex_lock", err); exit(1); }
    printf("Thread %ld: Locked the mutex\n", pthread_self());

    if (err = pthread_create(&thr, NULL, thread_f, NULL)) { /* New thread */
        perror2("pthread_create", err); exit(1); }
    printf("Thread %ld: Created thread %ld\n", pthread_self(), thr);

    printf("Thread %ld: Waiting for signal\n", pthread_self());

    pthread_cond_wait(&cvar, &mtx); /* Wait for signal */
    printf("Thread %ld: Woke up\n", pthread_self());
    printf("Thread %ld: Read message \"%s\"\n", pthread_self(), buf);
```

Using system calls on condition variables

```
    if (err = pthread_mutex_unlock(&mtx)) { /* Unlock mutex */
        perror2("pthread_mutex_unlock", err); exit(1); }
    printf("Thread %ld: Unlocked the mutex\n", pthread_self());

    if (err = pthread_join(thr, NULL)) { /* Wait for thread */
        perror2("pthread_join", err); exit(1); } /* termination */
    printf("Thread %ld: Thread %ld exited\n", pthread_self(), thr);

    if (err = pthread_cond_destroy(&cvar)) {
        /* Destroy condition variable */
        perror2("pthread_cond_destroy", err); exit(1); }
    pthread_exit(NULL);
}
```

Using system calls on condition variables

```
void *thread_f(void *argp){ /* Thread function */
    int err;

    printf("Thread %ld: Just started\n", pthread_self());
    printf("Thread %ld: Trying to lock the mutex\n", pthread_self());

    if (err = pthread_mutex_lock(&mtx)) { /* Lock mutex */
        perror2("pthread_mutex_lock", err); exit(1); }
    printf("Thread %ld: Locked the mutex\n", pthread_self());

    strcpy(buf, "This is a test message");

    printf("Thread %ld: Wrote message \"%s\"\n", pthread_self(), buf);
    pthread_cond_signal(&cvar); /* Awake other thread */
    printf("Thread %ld: Sent signal\n", pthread_self());

    if (err = pthread_mutex_unlock(&mtx)) { /* Unlock mutex */
        perror2("pthread_mutex_unlock", err); exit(1); }
    printf("Thread %ld: Unlocked the mutex\n", pthread_self());

    pthread_exit(NULL);
}
```

Using system calls on condition variables

```
ad@ad-desktop:~/Set007/src$
ad@ad-desktop:~/Set007/src$ ./mutex_condvar
Thread -1216870720: Locked the mutex
Thread -1216870720: Created thread -1216873616
Thread -1216870720: Waiting for signal
Thread -1216873616: Just started
Thread -1216873616: Trying to lock the mutex
Thread -1216873616: Locked the mutex
Thread -1216873616: Wrote message "This is a test message"
Thread -1216873616: Sent signal
Thread -1216873616: Unlocked the mutex
Thread -1216870720: Woke up
Thread -1216870720: Read message "This is a test message"
Thread -1216870720: Unlocked the mutex
Thread -1216870720: Thread -1216873616 exited
ad@ad-desktop:~/Set007/src$
ad@ad-desktop:~/Set007/src$
```

Another example:

⊙ Three threads increase the value of a global variable while a fourth one suspends its operation until a *maximum* value is reached.

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <string.h>
#define perror2(s, e) fprintf(stderr, "%s: %s\n", s, strerror(e))

#define COUNT_PER_THREAD 8        /* Count increments by each thread */
#define THRESHOLD 19              /* Count value to wake up thread */
int count = 0;                     /* The counter */
int thread_ids[4] = {0, 1, 2, 3}; /* My thread ids */

pthread_mutex_t mtx;               /* mutex */
pthread_cond_t cv;                 /* the condition variable */

void *incr(void *argp){
    int i, j, *id = argp;
    int err;
    for (i=0 ; i<COUNT_PER_THREAD ; i++) {
        if (err = pthread_mutex_lock(&mtx)) { /* Lock mutex */
            perror2("pthread_mutex_lock", err); exit(1); }
        count++; /* Increment counter */
        if (count == THRESHOLD) { /* Check for threshold */
            pthread_cond_signal(&cv); /* Signal suspended thread */
            printf("incr: thrd %d, count = %d, threshold reached\n",*id,count);
        }
```

Code (Cont'ed)

```
        printf("incr: thread %d, count = %d\n", *id, count);
        if (err = pthread_mutex_unlock(&mtx)) { /* Unlock mutex */
            perror2("pthread_mutex_unlock", err); exit(1); }
        for (j=0 ; j < 1000000000 ; j++);
     } /* Naive: For threads to alternate */
    /* on mutex lock */
    pthread_exit(NULL);
}

void *susp(void *argp){
    int err, *id = argp;
    printf("susp: thread %d started\n", *id);
    if (err = pthread_mutex_lock(&mtx)) { /* Lock mutex */
        perror2("pthread_mutex_lock", err); exit(1);
        }
    while (count < THRESHOLD) { /* If threshold not reached */
        pthread_cond_wait(&cv, &mtx); /* suspend */
        printf("susp: thread %d, signal received\n", *id);
        }
    if (err = pthread_mutex_unlock(&mtx)) { /* Unlock mutex */
        perror2("pthread_mutex_unlock", err); exit(1);
        }
    pthread_exit(NULL);
}
```

Code (Cont'ed)

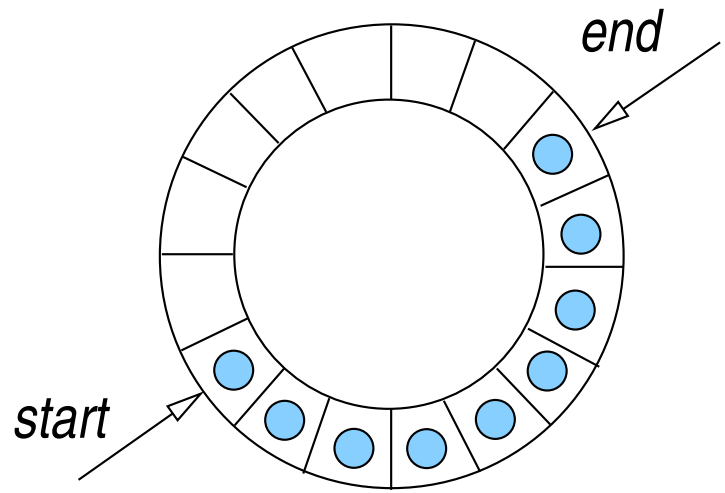
```
main() {
    int i, err;
    pthread_t threads[4];

    pthread_mutex_init(&mtx, NULL); /* Initialize mutex */
    pthread_cond_init(&cv, NULL); /* and condition variable */
    for (i=0 ; i<3 ; i++)
        if (err = pthread_create(&threads[i], NULL, incr,(void *) &thread_ids[i
            ])) { perror2("pthread_create", err); exit(1); /* Create threads 0,
             1, 2 */
           }

    if (err = pthread_create(&threads[3], NULL, susp, (void *) &thread_ids[3]))
        { perror2("pthread_create", err); exit(1); } /* Create thread 3 */

    for (i=0 ; i<4 ; i++)
        if (err = pthread_join(threads[i], NULL)) {
            perror2("pthread_join", err); exit(1);
            };
    /* Wait for threads termination */
    printf("main: all threads terminated\n");
    /* Destroy mutex and condition variable */
    if (err = pthread_mutex_destroy(&mtx)) {
        perror2("pthread_mutex_destroy", err); exit(1); }
    if (err = pthread_cond_destroy(&cv)) {
        perror2("pthread_cond_destroy", err); exit(1); }
    pthread_exit(NULL);
}
```

Outcome:

```
ad@ad-desktop:~/Set007/src$ ./counter
incr: thread 0, count = 1
susp: thread 3 started
incr: thread 1, count = 2
incr: thread 2, count = 3
incr: thread 0, count = 4
incr: thread 1, count = 5
incr: thread 2, count = 6
incr: thread 0, count = 7
incr: thread 1, count = 8
incr: thread 1, count = 9
incr: thread 2, count = 10
incr: thread 0, count = 11
incr: thread 1, count = 12
incr: thread 1, count = 13
incr: thread 2, count = 14
incr: thread 0, count = 15
incr: thread 1, count = 16
incr: thread 0, count = 17
incr: thread 2, count = 18
incr: thread 1, count = 19, threshold reached
incr: thread 1, count = 19
susp: thread 3, signal received
incr: thread 0, count = 20
incr: thread 0, count = 21
incr: thread 2, count = 22
incr: thread 2, count = 23
incr: thread 2, count = 24
main: all threads terminated
ad@ad-desktop:~/Set007/src$
```

The Producer–Consumer Synchronization Problem

- There is one producer and one consumer.
- The producer may produce upto a *maximum* number of goods.
- An item cannot be consumed if the producer has not successfully completed its placement on the buffer.
- If no items exist on the buffer, the consumer has to wait.
- if the buffer is full, the producer has to wait.



A solution for the “bounded buffer” problem

```
#include <stdio.h>                  // from www.mario-konrad.ch
#include <pthread.h>
#include <unistd.h>

#define POOL_SIZE 6

typedef struct {
        int data[POOL_SIZE];
        int start;
        int end;
        int count;
} pool_t;

int num_of_items = 15;

pthread_mutex_t mtx;
pthread_cond_t cond_nonempty;
pthread_cond_t cond_nonfull;
pool_t pool;

void initialize(pool_t * pool) {
        pool->start = 0;
        pool->end = -1;
        pool->count = 0;
}
```

```
void place(pool_t * pool, int data) {
        pthread_mutex_lock(&mtx);
        while (pool->count >= POOL_SIZE) {
                printf(">> Found Buffer Full \n");
                pthread_cond_wait(&cond_nonfull, &mtx);
                }
        pool->end = (pool->end + 1) % POOL_SIZE;
        pool->data[pool->end] = data;
        pool->count++;
        pthread_mutex_unlock(&mtx);
}


int obtain(pool_t * pool) {
        int data = 0;
        pthread_mutex_lock(&mtx);
        while (pool->count <= 0) {
                printf(">> Found Buffer Empty \n");
                pthread_cond_wait(&cond_nonempty, &mtx);
                }
        data = pool->data[pool->start];
        pool->start = (pool->start + 1) % POOL_SIZE;
        pool->count--;
        pthread_mutex_unlock(&mtx);
        return data;
}
```

```
void * producer(void * ptr)
{
        while (num_of_items > 0) {
                place(&pool, num_of_items);
                printf("producer: %d\n", num_of_items);
                num_of_items--;
                pthread_cond_signal(&cond_nonempty);
                usleep(0);
                }
        pthread_exit(0);
}

void * consumer(void * ptr)
{
        while (num_of_items > 0 || pool.count > 0) {
                printf("consumer: %d\n", obtain(&pool));
                pthread_cond_signal(&cond_nonfull);
                usleep(500000);
                }
        pthread_exit(0);
}
```

```
int main(int argc, char ** argv)
{
        pthread_t cons, prod;

        initialize(&pool);
        pthread_mutex_init(&mtx, 0);
        pthread_cond_init(&cond_nonempty, 0);
        pthread_cond_init(&cond_nonfull, 0);
        pthread_create(&cons, 0, consumer, 0);
        pthread_create(&prod, 0, producer, 0);
        pthread_join(prod, 0);
        pthread_join(cons, 0);
        pthread_cond_destroy(&cond_nonempty);
        pthread_cond_destroy(&cond_nonfull);
        pthread_mutex_destroy(&mtx);
        return 0;
}
```

$\Rightarrow$ Outcome:

```
ad@ad-desktop:~/Set007/src$ ./prod-cons
>> Found Buffer Empty
producer: 15
consumer: 15
producer: 14
producer: 13
producer: 12
producer: 11
producer: 10
producer: 9
>> Found Buffer Full
```

```
consumer: 14
producer: 8
>> Found Buffer Full
consumer: 13
producer: 7
>> Found Buffer Full
consumer: 12
producer: 6
>> Found Buffer Full
consumer: 11
producer: 5
>> Found Buffer Full
consumer: 10
producer: 4
>> Found Buffer Full
consumer: 9
producer: 3
>> Found Buffer Full
consumer: 8
producer: 2
>> Found Buffer Full
consumer: 7
producer: 1
consumer: 6
consumer: 5
consumer: 4
consumer: 3
consumer: 2
consumer: 1
ad@ad-desktop:~/Set007/src$
```

Thread Safety

• Problem: a thread may call library functions that are not thread-safe creating spurious outcomes.

- A function is "thread-safe," if multiple threads can simultaneously execute invocations of the same function without *side-effects* (or intereferences of any type!).
- POSIX specifies that all functions (including all those from the Standard C Library) except those (next slide) are implemented in a thread-safe manner.
- Directive: the calls of the table (next slide) *should* have thread-safe implentations denoted with the postfix *_r*.

System calls not required to be thread-safe

asctime	*basename*	*catgets*	*crypt*	*ctime*
dbm_clearerr	*dbm_close*	*dbm_delete*	*dbm_error*	*dbm_fetch*
dbm_firstkey	*dbm_nextkey*	*dbm_open*	*dbm_store*	*dirname*
dlerror	*drand48*	*ecvt*	*encrypt*	*endgrent*
endpwent	*endutxent*	*fcvt*	*ftw*	*gcvt*
getc_unlocked	*getchar_unlocked*	*getdate*	*getenv*	*getgrent*
getgrgid	*getgrname*	*gethostbyaddr*	*gethostbyname*	*getlogin*
getnetbyaddr	*getnetbyname*	*getnetent*	*getopt*	*getprotobyname*
getprotobynumber	*getprotoend*	*getpwent*	*getopwnam*	*getpwuid*
getservbyname	*getservbyport*	*getservent*	*getutxent*	*getutxid*
getutxline	*gmtime*	*hcreate*	*hdestroy*	*hsearch*
inet_ntoa	*l64a*	*lgamma*	*lgammaf*	*lgammal*
localeconv	*localtime*	*lrand48*	*mrand48*	*nftw*
nl_langinfo	*ptsname*	*putc_unlocked*	*putchar_unlocked*	*putenv*
pututxline	*rand*	*readdir*	*setenv*	*setgrent*
setkey	*setpwent*	*setuxent*	*strerror*	*strtok*
ttyname	*unsetenv*	*wcstombs*	*wctomb*	

◇ An easy ("dirty") way to safely use the above calls with threads is to invoke them in conjunction with *mutexes* (i.e., in mutually exclusive fashion).