Topic 6: Threads*

Threads - Νήματα

- Lightweight Processes (LWPs)
  - share single address space,
  - each has its own flow control

- Try to overcome penalties
  - separate process for every flow of of control is costly

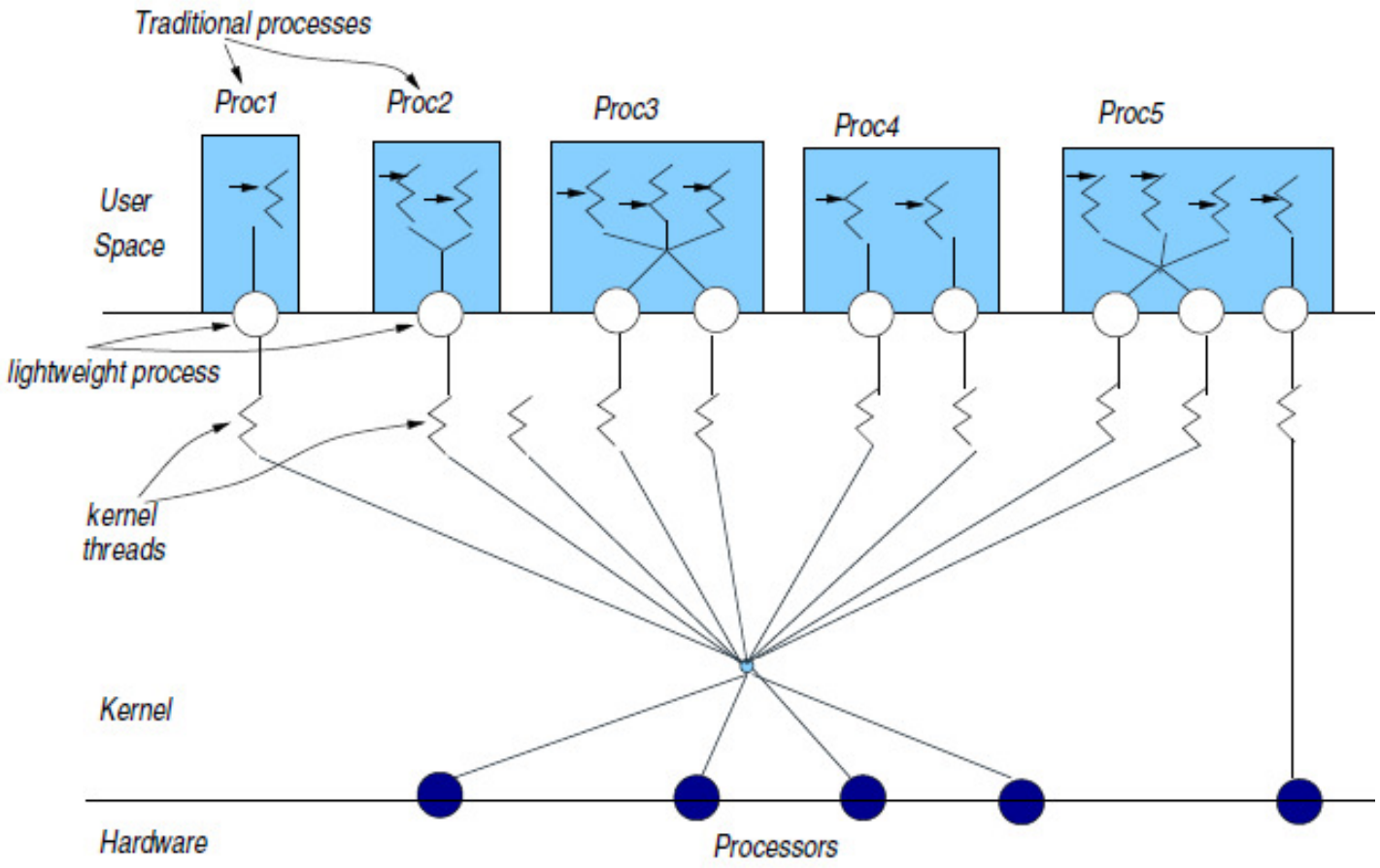
Why Threads?

- Offer a more efficient way to develop apps
  - on uniprocessor, one thread blocks on a syscall (e.g., read), another grabs CPU and does useful processing (faster user interface, lower program execution time)
  - on multiprocessor, separate thread on each CPU (program finishes faster)

•Question: In our network server example, if creating multiple processes is a performance issue, why not just use select()?

•What do threads give us over select()-based network server?

Thread (Solaris) Model



Threads Overview

- 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 concurrently.
- If there are more than one processors, threads can be assigned to different kernel thread (and so different CPUs) and run in parallel.
- Any thread may create a new thread.

Threads Overview

- All threads of a single process share the same address space (address space, file descriptors etc.) BUT they have their own PC, stack and set of registers.
- The kernel can perform content switches from one thread to another faster 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

Threads Overview

- The functions of the pthread library do not set the value of the variable *errno* and 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).

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 by one thread is visible to all (i.e., mallon()/free())	Different for each process. After a fork() we have different address spaces
File descriptors	Common. Any two threads can use the same descriptor. One close() on this descriptor is sufficient	Two processes use copies of the file descriptors
fork()	On a fork(), only the thread that invoked the fork is duplicated.	
exit()	On 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. See textbook.	

POSIX Thread Management

POSIX function	description
`pthread_create`	create a thread
`pthread_self`	find out own thread ID
`pthread_equal`	test 2 thread IDs for equality
`pthread_exit`	exit thread without existing process
`pthread_detach`	set thread to release resources
`pthread_join`	wait for a thread
`pthread_cancel`	terminate another thread
`pthread_kill`	send a signal to a thread

Thread creation

```
int pthread_create(pthread_t *thread,
                   const   pthread_attr_t *attr,
                   void *(*start_func) (void *), void *arg);
```

- Creates a new thread with attributes specified by attr within a process.
- Thread executes the function at address start_func
- Upon successful completion, pthread create() shall store the ID of the created thread in the location referenced by *thread*.
- Through *attr* we can change features of the thread but oftentimes we use the default attribute values work, by setting *attr* to NULL.
- If successful, returns 0; otherwise, an error number shall be returned to indicate the error.

Thread termination

void pthread_exit (void *retval);

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

pthread join - waiting for thread termination

```
int pthread_join (pthread_t thread,
                  void ** retval );
```

- suspends execution of the calling thread until the target thread terminates (unless the target thread has already terminated).
- When a pthread join() returns successfully, the target thread has been terminated.
- On successful completion, the function returns 0.
- If retval is not NULL, then pthread join() copies the exit status of the target thread into the location pointed to by *retval.

Identifying – Detaching Threads

pthread_t pthread_self(void);

- Returns the thread-ID of the calling thread

int pthread_detach(pthread_t thread);

- indicates that the 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.
- Calling pthread_join() on a detached thread fails.

Χρήση pthread_create, pthread_exit, pthread_join και pthread_self

```
#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);
}
main(){
  pthread_t thr;
  int err, status;
  /* New thread */
  if (err = pthread_create(&thr, NULL, thread_f, NULL)) {
      perror2("pthread_create", err);
      exit(1);
      }
  printf("I am original thread %ld and I created
             thread %ld\n", pthread_self(), thr);
  /* Wait for thread */
  if (err = pthread_join(thr, (void **) &status)) {
      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); }
```

Not recommended way of "exit"ing.. avoid using automatic values; use malloc(ed) structs to return status

Run output

```
mema@bowser> ./create_a_thread
I am the newly created thread 134558720
I am original thread 134557696 and I created thread 134558720
Thread 134558720 exited with code 47
Thread 134557696 just before exiting (Original)
mema@bowser>
```

whichexit() can be executed as a thread

```
void *whichexit(void *arg){
    int n;
    int np1[1];
    int *np2;
    char s1[10];
    char s2[] = "I am done";
    n = 3;
    np1 = n;
    np2 = (int *)malloc(sizeof(int *));
    *np2 = n;
    strcpy(s1,"Done");
    return(NULL);
    }
```

1. n
2. &n
3. (int *)n
4. np1
5. np2
6. s1
7. s2
8. "This works"
9. strerror(EINTR)

Which of the above options could be *safe* replacement for NULL as return value in whichexit function?
(Or as a parameter to pthread_exit?)

whichexit() can be executed as a thread

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void *whichexit(void *arg){
    int n;
    int np1[1];
    int *np2;
    char s1[10];
    char s2[] = "I am done";
    n = 3;
    np1 = n;
    np2 = (int *)malloc(sizeof(int *));
    *np2 = n;
    strcpy(s1,"Done");
    return(NULL);
    }
```

1. n
2. &n
3. (int *)n
4. np1
5. np2
6. s1
7. s2
8. "This works"
9. strerror(EINTR)

Which of the above options could be *safe* replacement for NULL as return value in whichexit function? (Or as a parameter to pthread_exit?)

1. No, return value is a pointer not an int
2. No – automatic variable
3. Might work (but not in all impls- avoid)
4. No – automatic variable
5. Yes – dynamically allocated
6. No – automatic variable
7. No – automatic storage
8. Yes – In C, string literals have static storage
9. No – The string produced by strerror might not exist

Χρήση pthread_detach

```
#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 %d and I was called with
            argument %d\n",
           pthread_self(), *(int *) argp);
   pthread_exit(NULL);
}
main(){
   pthread_t thr;
   int err, arg = 29;
   /*New Thread */
   if (err = pthread_create(&thr,NULL,thread_f,(void *) &arg)){
       perror2("pthread_create", err);
       exit(1);
       }
    printf("I am original thread %d and I created thread %d\n",
           pthread_self(), thr);
    pthread_exit(NULL);
}
```

Print “detached” thread

Run output

```
mema@bowser> ./detached_thread
I am thread 134558720 and I was called with argument 29
I am original thread 134557696 and I created thread 134558720
mema@bowser>
```

Create *n* threads that wait for a random number of seconds and then terminate

```
#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))
#define MAX_SLEEP 10

void *sleeping(void *arg) {
   int sl = (int) arg;
   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 no more
                than 50\n");  exit(0); }
   if ((tids = malloc(n * sizeof(pthread_t))) == NULL) {
      perror("malloc");  exit(1); }
```

```
srandom((unsigned int) time(NULL));  /* Initialize generator */
   for (i=0 ; i<n ; i++) {
        /* Sleeping time 1..MAX_SLEEP */
        sl = random() % MAX_SLEEP + 1;
        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++) {
      /* Wait for thread termination */
      if (err = pthread_join(*(tids+i), NULL)) {
          perror2("pthread_join", err);
          exit(1);
      }
   }
   printf("all %d threads have terminated\n", n);
}
```

Sample output

```
mema@bowser> ./create_many_threads 12
thread 134685184 sleeping 8 seconds ...
thread 134559232 sleeping 3 seconds ...
thread 134685696 sleeping 7 seconds ...
thread 134686208 sleeping 1 seconds ...
thread 134558720 sleeping 2 seconds ...
thread 134559744 sleeping 2 seconds ...
thread 134560256 sleeping 5 seconds ...
thread 134560768 sleeping 8 seconds ...
thread 134561280 sleeping 5 seconds ...
thread 134684672 sleeping 4 seconds ...
thread 134686720 sleeping 2 seconds ...
thread 134687232 sleeping 8 seconds ...
thread 134686208 waking up
thread 134558720 waking up
thread 134559744 waking up
thread 134686720 waking up
thread 134559232 waking up
thread 134684672 waking up
thread 134560256 waking up
thread 134561280 waking up
thread 134685696 waking up
thread 134685184 waking up
thread 134560768 waking up
thread 134687232 waking up
all 12 threads have terminated
mema@bowser>
```

Going from a single-threaded program to multi-threading

```
#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);
}
}
```

```
mema@bowser> ./print_single
hellohellohellohellohelloworld
world
world
world
world
mema@bowser>
```

First attempt..

```
#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;
}
```

Output of 4 runs

```
mema@bowser> ./multi_hello
hello world
hello world
hello world
hello world
hello world

mema@bowser>   ./multi_hello
hello world
world
hello hello world
hello world
hello world

mema@bowser> ./multi_hello
world
hello world
hello hello world
hello world
hello world

mema@bowser> ./multi_hello
world
hello hello world
hello world
world
hello world
hello mema@bowser>
```

Another Example: Synchronization attempt (via *sleep()*)

```
#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 to something else has an effect */
        }
        return NULL;
}
```

Output

```
mema@bowser> ./incprint
count = 0
count = 1
count = 2
count = 3
count = 4
mema@bowser> ./incprint
count = 1
count = 1
count = 3
count = 4
count = 5
mema@bowser> ./incprint
count = 1
count = 2
count = 3
count = 4
count = 5
mema@bowser> ./incprint
count = 1
count = 1
count = 3
count = 4
count = 5
mema@bowser>
```

Changing the *sleep(1)* to *sleep(0)* within *print_count()* we get the following:

```
mema@bowser> ./incprint
count = 0
count = 0
count = 0
count = 0
count = 0
mema@bowser>
```

Counting words from two distinct files

```
#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);
}
```

```
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;
}
```

Output

```
mema@bowser> wc file1 file2
    1       4      15 file1
    1       4      17 file2
    2       8      32 total
mema@bowser> ./wordcount1 file1 file2
In thread with ID: 134559232 counting words..
In thread with ID: 134558720 counting words..
Main thread with ID: 134557696 reports     8 total words
mema@bowser> ./wordcount1 file1 file2
In thread with ID: 134559232 counting words..
In thread with ID: 134558720 counting words..
Main thread with ID: 134557696 reports   6 total words
mema@bowser>
```

Concurrent Access

Potential Problem:

Thread1	Thread2
.....	.....
.....	.....
total_words++	total_words++
.....	.....

Race-condition: total_words might not have *consistent value* after executing the above two assignments.
Never allow concurrent access to data without protection (when at least one access is write)!

Binary POSIX Mutexes

- When threads share common structures (resources), the POSIX library offers a simplified version of semaphores termed binary semaphores or mutexes.
- A binary semaphore 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.
  - pthread_mutex_init always returns 0
- A mutex may also be initialized by setting its value by the macro
- **static pthread_mutex_t mymutex =**
  PTHREAD_MUTEX_INITIALIZER;
- Initialization of a mutex should occur only once

Locking a mutex

- 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.

Locking a mutex

- 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 error code *EINVAL,* the mutex was not initialized properly.

Unlocking and destroying 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.

int pthread_mutex_destroy(pthread_mutex_t *mutex)

- Destroys the mutex, freeing resources it might hold.
- In the LinuxThreads implementation, the call does nothing except checking that mutex is unlocked.
- Upon successful call, it returns 0.

Counting (corretly) words in two files

```
/* add all header files */
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);
}
```

```
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;
}
```

Another program that counts words in two files correctly

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <ctype.h>
#define EXIT_FAILURE 1

struct arg_set{
        char *fname;
        int  count;
        };

int     main(int ac, char *av[]) {
        pthread_t t1, t2;
        struct arg_set args1, args2;
        void *count_words(void *);

        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);

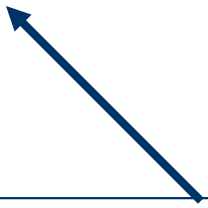
        args2.fname = av[2]; args2.count = 0;
        pthread_create(&t2, NULL,
                        count_words, (void *) &args2);

        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);
}
```

```
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;
}
```



No mutex in this function!

```
mema@bowser> ./twordcount3 \
      /etc/dictionaries-common/words \
     /etc/dictionaries-common/ispell-default
Working within Thread with ID 1210238064 and counting
Working within Thread with ID 1218630768 and counting
In file  /etc/dictionaries-common/words there are 123261 words
In file  /etc/dictionaries-common/ispell-default there are     3 words
Main thread 1210235216 reporting 123264 total words
mema@bowser>
```

Tips

- *pthread_mutex_trylock()* returns *EBUSY* if the mutex is already locked by another thread
- Every mutex must 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
- If *EINVAL* is returned when trying to lock a mutex, then the mutex has not been initialized properly
- NEVER call *pthread_mutex_destroy()* on a locked mutex (*EBUSY*)

Using: pthread_mutex_init, pthread_mutex_lock, pthread_mutex_unlock, pthread_mutex_destroy

```
.............
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 %d: Locked the mutex\n", pthread_self());

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

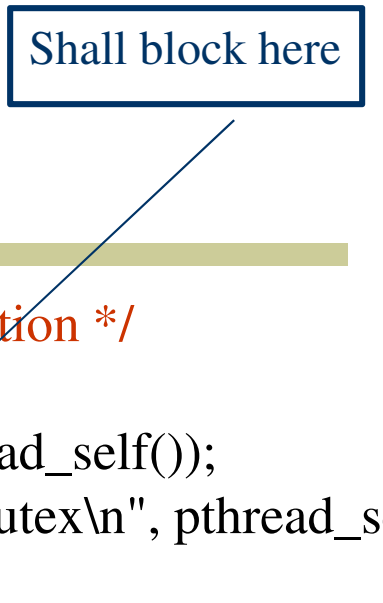
   strcpy(buf, "This is a test message");
   printf("Thread %ld: Wrote message \"%s\" for thread %ld\n",
          pthread_self(), buf, thr);
```

```
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);
}
```




```
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);
}
```

```
mema@linux01> ./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
mema@linux01>
```

Sum the squares of *n* integers using *m* threads

```
.................
#include <pthread.h>
#define perror2(s, e) fprintf(stderr, "%s: %s\n", s, strerror(e))
#define LIMITUP 100

pthread_mutex_t mtx;      /* Mutex for synchronization */
int n, nthr, mtxfl;       /* Variables visible by thread function */
double sqsum;             /* Sum of squares */
void *square_f(void *);  /* Forward declaration */

main(int argc, char *argv[]){
    int i, err;
    pthread_t *tids;
    if (argc > 3) {
        n = atoi(argv[1]);        /* Last integer to be squared */
        nthr = atoi(argv[2]);     /* Number of threads */
        mtxfl = atoi(argv[3]); }/* with lock (1)? or without lock (0) */
    else exit(0);

    if (nthr > LIMITUP) { /* Avoid too many threads */
        printf("Number of threads should be up to 100\n"); exit(0); }
    if ((tids = malloc(nthr * sizeof(pthread_t))) == NULL) {
        perror("malloc"); exit(1); }
```

```
sqsum = (double) 0.0; /* Initialize sum */
   pthread_mutex_init(&mtx, NULL); /* Initialize mutex */

   for (i=0 ; i<nthr ; i++) {
      if (err = pthread_create(tids+i, NULL, square_f, (void *) i)) {
      /* Create a thread */
      perror2("pthread_create", err); exit(1); } }

   for (i=0 ; i<nthr ; i++)
      if (err = pthread_join(*(tids+i), NULL)) {
      /* Wait for thread termination */
          perror2("pthread_join", err); exit(1); }
```

```
    if (!mtxfl) printf("Without mutex\n");
    else printf("With mutex\n");

    printf("%2d threads: sum of squares up to %d is %12.9e\n",
            nthr,n,sqsum);
    sqsum = (double) 0.0; /* Compute sum with a single thread */
    for (i=0 ; i<n ; i++)
        sqsum += (double) (i+1) * (double) (i+1);
    printf("Single thread: sum of squares up to %d is %12.9e\n",
            n, sqsum);
    printf("Formula based: sum of squares up to %d is %12.9e\n",
           n, ((double) n)*(((double) n)+1)*(2*((double) n)+1)/6);
    pthread_exit(NULL);
}

void *square_f(void *argp){ /* Thread function */
    int i, thri, err;
    thri = (int) argp;

    for (i=thri ; i<n ; i+=nthr) {
        if (mtxfl) /* Is mutex used? */
            if (err = pthread_mutex_lock(&mtx)) { /* Lock mutex */
                perror2("pthread_mutex_lock", err); exit(1); }

        sqsum += (double) (i+1) * (double) (i+1);

        if (mtxfl) /* Is mutex used? */
            if (err = pthread_mutex_unlock(&mtx)) { /*Unlock mutex */
                perror2("pthread_mutex_unlock", err); exit(1); } }
    pthread_exit(NULL); }
```

Execution outcome

mema@bowser> ./sum_of_squares 12345678 99 1
With mutex
99 threads: sum of squares up to 12345678 is 6.272253963e+20
Single thread: sum of squares up to 12345678 is 6.272253963e+20
Formula based: sum of squares up to 12345678 is 6.272253963e+20
mema@bowser> ./sum_of_squares 12345678 99 0
Without mutex
99 threads: sum of squares up to 12345678 is 4.610571900e+20
Single thread: sum of squares up to 12345678 is 6.272253963e+20
Formula based: sum of squares up to 12345678 is 6.272253963e+20

Synchronization & Performance

- Two threads, A and B
- A reads data from net and places in buffer, B reads data from buffer and computes with it

A: 1) Ανάγνωση δεδομένων
2) Κλείδωμα mutex
3) Τοποθέτηση στην ουρά
4) Ξεκλείδωμα mutex
5) Επιστροφή στο 1)

B: 1) Κλείδωμα mutex
2) If buffer not empty, αφαίρεση δεδομένων
3) Ξεκλείδωμα mutex
4) Επιστροφή στο 1)

Αυτό δουλεύει μια χαρά. Βλέπετε κάποιο πιθανό πρόβλημα;

Condition Variables

- A condition variable is a synchronization mechanism that allows POSIX threads to suspend execution and relinquish the processors until some predicate on the shared data is satisfied.
- Basic operations on condition variables:
  - signal the condition (when the predicate becomes true)
  - wait for the condition, suspending execution
  - The waiting lasts until another thread "signals" (also called "notifies") the condition

- A condition variable must always be associated with a mutex to avoid a race condition:
  - 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

```
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 of cond_attr is simply NULL
- Always returns 0
- The LinuxThreads implementation does not support attributes for condition variables (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.
- Before calling pthread_cond_wait() the thread must have *mutex locked
- The thread's execution is suspended and the thread does not consume any CPU time until the condition variable is signaled (via a call by another thread to pthread_cond_ signal() or pthread_cond_broadcast()
- Before returning to the calling thread, pthread_cond_wait re-acquires mutex
- Always returns 0

Signaling a condition 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
- Always returns 0

Broadcasting 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.
- Always returns 0.

Destroying a condition variable

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 when pthread_cond_destroy() is called
- In LinuxThreads, the call does nothing except checking that the condition has no waiting threads
- On success, the call returns 0
- In case some threads are waiting on cond, pthread_cond_destroy returns EBUSY
- No need to call this function for statically initialized condition variables

Tips for using condition variables

- For every condition, use a single, distinctly-associated with the condition, condition variable
- Associate/use a **single, unique mutex** with **every condition variable**
- Lock the mutex before checking the condition protected by that mutex
- 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()

Use of: pthread_cond_init, pthread_cond_wait, pthread_cond_signal, pthread_cond_destroy

```
#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;
   /* Initialize condition variable */
   pthread_cond_init(&cvar, NULL);

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

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

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

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

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

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

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

   printf("Thread %d: Just started\n", pthread_self());
   printf("Thread %d: 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 %d: Locked the mutex\n", pthread_self());

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

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

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

   pthread_exit(NULL);
}
```

Execution output

```
mema@bowser> ./mutex_condvar
Thread 1210546512: Locked the mutex
Thread 1210549360: Just started
Thread 1210549360: Trying to lock the mutex
Thread 1210546512: Created thread 1210549360
Thread 1210546512: Waiting for signal
Thread 1210549360: Locked the mutex
Thread 1210549360: Wrote message "This is a test message"
Thread 1210549360: Sent signal
Thread 1210549360: Unlocked the mutex
Thread 1210546512: Woke up
Thread 1210546512: Read message "This is a test message"
Thread 1210546512: Unlocked the mutex
Thread 1210546512: Thread 1210549360 exited
mema@bowser>
```

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

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.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, err, *id = argp;
    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: thread %d, count = %d, threshold reached\n",
                    *id,count);
            }
```

```
        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++);  /* For threads to alternate */
      }
    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); }
```

Always use a while loop and re-check the condition after receiving signal and returning from pthread_cond_wait; Why?

```
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])) {
            /* Create threads 0, 1, 2 */
            perror2("pthread_create", err); exit(1);
            }
        if (err = pthread_create(&threads[3], NULL, susp,
                                 (void *) &thread_ids[3])) {
        /* Create thread 3 */
        perror2("pthread_create", err); exit(1); }

    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);  }
```

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

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 intereference of any type!)
- POSIX specifies that all functions (including all those from the Standard C Library) except those listed on next slide are implemented in a thread-safe manner
- Directive: the calls listed on the next slide should have thread-safe implementations denoted with the postfix _r

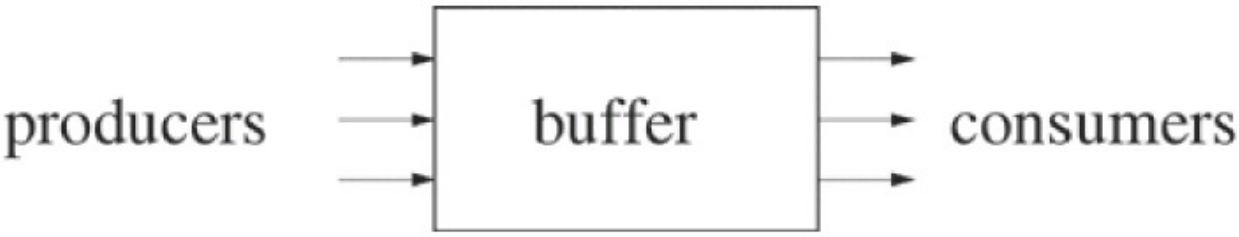
System calls not required to be thread-safe

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*	*getprotobynam*
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*	

Thread safety

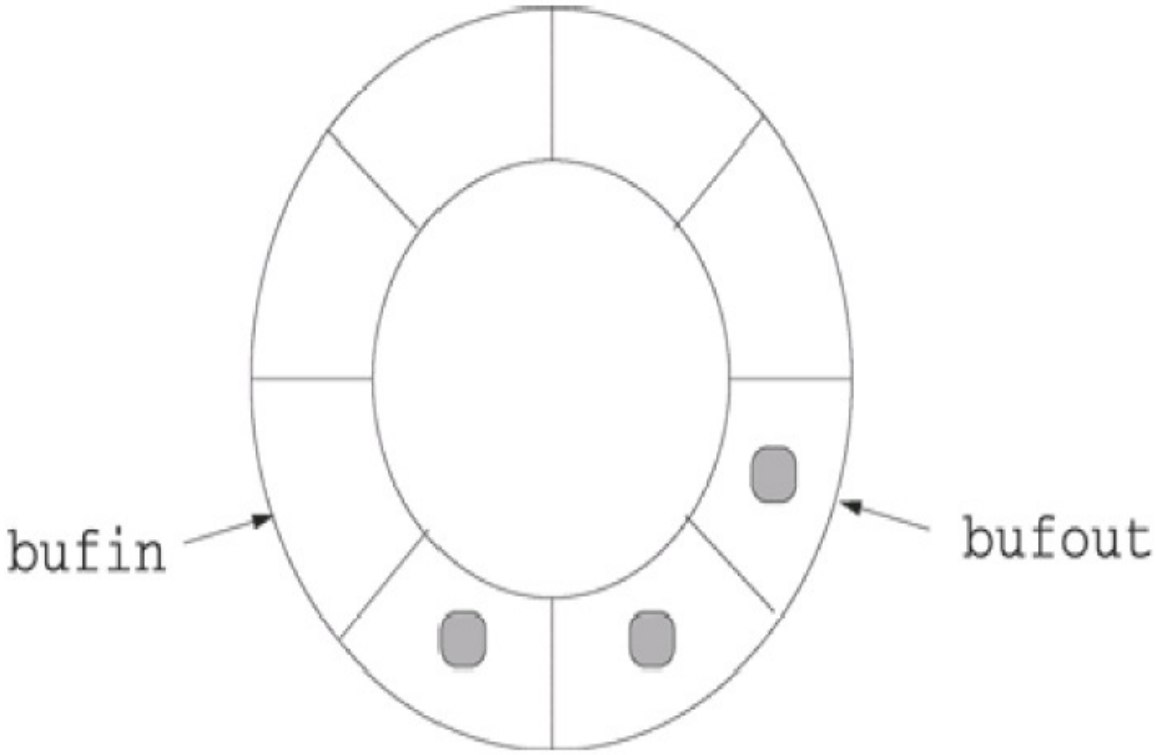
- An easy ("dirty") way to safely use the above calls with threads is to invoke them in conjunction with mutexes (i.e., in mutually exclusive fashion)
- Can convert non-thread-safe functions to safe as follows:
  - 1) Lock a mutex, 2) call the function, 3) use data returned (e.g., pointer to a struct allocated somewhere), 4) unlock mutex
  - 1) Lock mutex, 2) call function 3) copy struct pointed to by returned pointer for later use 4) unlock
- Remember: _r at end of function name means it is re-entrant (i.e., thread-safe)

Producer-Consumer Problem



- Producers (P) insert data into buffer
- Consumers (C) read data from the buffer
- **What do we want to avoid?**
  - C starts reading an object that a producer has not yet finished inserting
  - C reads an object from the buffer that does not exist
  - C reads an object that has already been removed from the buffer
  - P places an item in the buffer, when buffer is full
  - P overwrites an item in the buffer that has not yet been read by a consumer

Example: Bounded cyclical buffer



bufin: points at next available slot for storing item
bufout: points at slot where next reader should read from

Solution to bounded buffer problem

```
#include <errno.h>
#include <pthread.h>
#include "buffer.h"
static buffer_t buffer[BUFSIZE];
static pthread_mutex_t bufferlock =
            PTHREAD_MUTEX_INITIALIZER;
static int bufin = 0;
static int bufout = 0;
static int totalitems = 0;
int getitem(buffer_t *itemp) { /* remove item from buffer
                                  and put in *itemp */
  int error;
  int erroritem = 0;
  if (error = pthread_mutex_lock(&bufferlock))
     /* no mutex, give up */
     return error;
  if (totalitems > 0) {    /* buffer has something to remove */
     *itemp = buffer[bufout];
      bufout = (bufout + 1) % BUFSIZE;
      totalitems--;
  } else
     erroritem = EAGAIN;
  if (error = pthread_mutex_unlock(&bufferlock))
      return error;  /* unlock error more serious than no item*/
  return erroritem;
}
```

Πόσα υπάρχουν στο buffer. Χρειάζεται?

Τι επιστρέφει αν δεν υπάρχουν δεδομένα?

```
int putitem(buffer_t item) { /* insert item into buffer */
  int error;
  int erroritem = 0;
  if (error = pthread_mutex_lock(&bufferlock))
     /* no mutex, give up */
     return error;
  if (totalitems < BUFSIZE) {    /* buffer has room for another item */
      buffer[bufin] = item;
      bufin = (bufin + 1) % BUFSIZE;
      totalitems++;
  } else
     erroritem = EAGAIN;
  if (error = pthread_mutex_unlock(&bufferlock))
      return error;  /* unlock error more serious than no slot*/
  return erroritem;
}
```

fetching items from the buffer

The following piece of code attempts to retrieve 10 items from the buffer[8] ring...

```
int error, i, item;

for (i=0; i<10; i++){
    while ( (error = getitem(&item)) &&  (error== EAGAIN)) ;
    if (error) break;
    printf("Retrieved item %d: %d\n", i, item);
    }
```

Problems??

fetching items from the buffer

The following piece of code attempts to retrieve 10 items from the buffer[8] ring...

```
int error, i, item;

for (i=0; i<10; i++){
    while ( (error = getitem(&item)) &&  (error== EAGAIN)) ;
    if (error) break;
    printf("Retrieved item %d: %d\n", i, item);
    }
```

Problem??

1) busy waiting
2) producers might get blocked --
   (readers might continuously grab lock first)

Solution:

Use condition variables

Another producer-consumer example

```
// from www.mario-konrad.ch, changed slightly
#include <stdio.h>
#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(300000);
                }
        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(){
        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;
}
```

```
mema@bowser> ./producer-consumer
>> Found Buffer Empty
producer: 15
consumer: 15
producer: 14
consumer: 14
producer: 13
producer: 12
consumer: 13
producer: 11
consumer: 12
producer: 10
producer: 9
consumer: 11
producer: 8
producer: 7
consumer: 10
producer: 6
consumer: 9
producer: 5
producer: 4
consumer: 8
producer: 3
producer: 2
consumer: 7
producer: 1
consumer: 6
consumer: 5
consumer: 4
consumer: 3
consumer: 2
consumer: 1
mema@bowser>
```

```
mema@bowser> ./producer-consumer
>> 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
```

Outcome - usleep(0)

```
>> 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
mema@bowser>
```

Outcome - usleep(0) (cont'd)

Food for Thought

- Anything wrong with this example? Hint: what data are protected by mutexes?
- With one producer/consumer, can we use if instead while in the condition check?
- With multiple producers/consumers where multiple items can be added/removed at a time, does code need to be changed?