Παράλληλη Επεξεργασία

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«Νήματα Προτύπου POSIX»

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Outline

- POSIX Threads API
  - Thread management
  - Synchronization with mutexes
  - Deadlock and thread safety
  - Barriers
  - Condition variables
  - **Exercises – Examples**
  - Special topics (quick overview)
    - Attribute objects
    - Once-only initialization
    - Thread-private data

Processes vs POSIX Threads

	Processes	**POSIX Threads**
Identifier	pid_t getpid()	pthread_t pthread_self()
Creation	fork()	pthread_create()
Start	exec()	
Wait	wait()	pthread_join()
Exit	exit()	pthread_exit()

POSIX Threads (Pthreads)

- Standardized C language threads programming interface
  - http://pubs.opengroup.org/onlinepubs/9699919799/

- Header file:

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

- Compilation

```
$ gcc -pthread -o hello hello.c
```

- Execution

```
$ ./hello
```

Spawning and Joining Threads

```
void *func(void *arg)
{
   sleep(1);
   return NULL;
}

int main(int argc, char * argv[])
{
   pthread_t id[4];

   for (long i = 0; i < 4; i++)   {
       pthread_create(&id[i], NULL, func, NULL);
   }

   for (long i = 0; i < 4; i++)   {
       pthread_join(id[i], NULL);
    }

   return 0;
}
```

Creating and Joining Threads

```
long x=5;

void *func(void * arg)
{
   long sec = *((long *)arg);
   sleep(x+sec);
   return NULL;
}

int main(int argc, char * argv[])
{
   pthread_t id[4];
   long a[4];

   for (long i = 0; i < 4; i++) {
       a[i] = i;
       pthread_create(&id[i], NULL, func, (void *) &a[i]);
   }

   for (long i = 0; i < 4; i++) {
       pthread_join(id[i], NULL);
   }

   return 0;
}
```

Synchronization

- Consider the following code
  - `next_ticket` is a global variable initialized to 0
  - `ticket` is a local variable, private to each thread

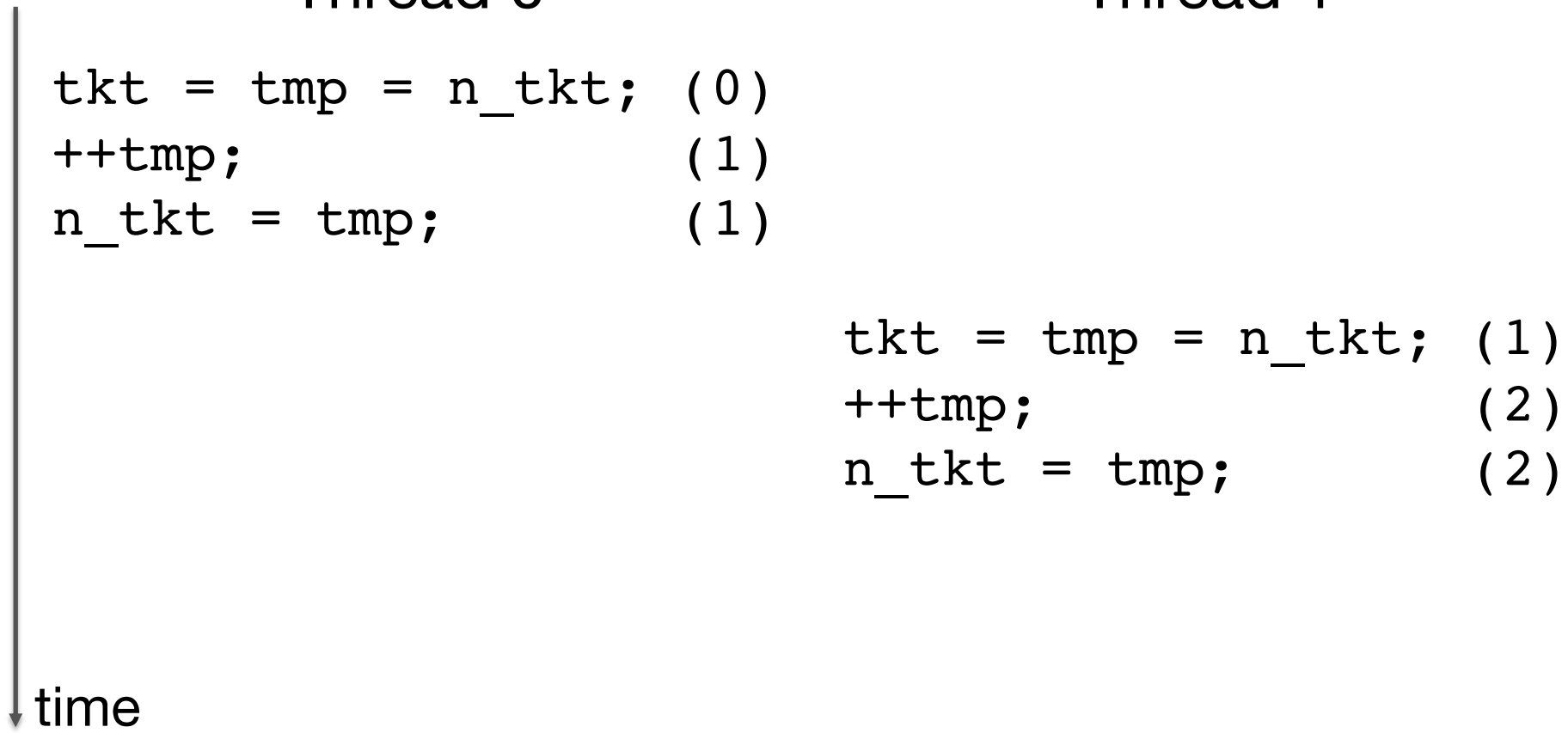
```
ticket = next_ticket++;          /* 0 ⇒ 1 */
```

- In the general case, this is equivalent to the following:

```
ticket = temp = next_ticket; /* 0 */
++temp;                      /* 1 */
next_ticket = temp;          /* 1 */
```

```
R1 ← next_ticket (load)
ticket ← R1      (store)
R1 ← R1+1        (inc)
next_ticket ← R1 (store)
```

Execution with 2 Threads



Another Possible Case

Thread 0		Thread 1	
`tkt = tmp = n_tkt;`	(0)		
		`tkt = tmp = n_tkt;`	(0)
`++tmp;`	(1)		
		`++tmp;`	(1)
`n_tkt = tmp;`	(1)		
		`n_tkt = tmp;`	(1)

time

What we observe here is a race condition
The update of the shared variable is a critical section and must be protected

Synchronization - Mutexes

- POSIX Threads include several synchronization mechanisms
  - Mutexes, Condition variables, Barriers, Reader-Writer locks, Spinlocks, Semaphores
- A Mutex (*Mut*ual *Ex*clusion) is a mechanism that allows multiple threads to synchronize their access to shared resources (e.g. variables)
  - A mutex has two states: *locked* and *unlocked*
  - Only one thread can lock the mutex
  - Once a mutex is locked, any other thread that tries to lock that mutex will suspend its execution, until the thread unlocks the mutex
  - At that point, one of the waiting threads acquires the mutex and continues its execution

Mutex Management

- Declaration and static initialization of a mutex:

```
pthread_mutex_t mymutex = PTHREAD_MUTEX_INITIALIZER;
```

- Declaration and dynamic initialization of a mutex:

```
pthread_mutex_t mymutex;
pthread_mutex_init(&mymutex, NULL);
```

- Locking (acquiring) the mutex:

```
pthread_mutex_lock(&mymutex);
```

- Unlocking (releasing) the mutex after the critical section:

```
pthread_mutex_unlock(&mymutex);
```

Dynamic Allocation of Mutex

- Pointer to mutex

```
pthread_mutex_t *mymutex;
```

- Memory allocation:

```
mymutex = (pthread_mutex_t *)
          malloc(sizeof(pthread_mutex_t));
```

- Mutex intialization:

```
pthread_mutex_init(mymutex, NULL);
```

- Locking and unlocking as before
- Destroying mutex:

```
pthread_mutex_destroy(mymutex);
```

Usage

```
#include <pthread.h>

pthread_mutex_t mutex = PTHREAD_MUTEX_INITIALIZER;
double global_sum = 0.0;

void *work(void *arg)
{
   ...
  pthread_mutex_lock(&mutex);
  global_sum += local_sum;
  pthread_mutex_unlock(&mutex);
   ...
}
```

Check and Lock

```
int pthread_mutex_trylock(pthread_mutex_t *m);
```

- Allows a thread to try to lock a mutex
- If the mutex is available then the thread locks the mutex
- If the mutex is locked then the function informs the user by returning a special value (EBUSY)
- This approach allows for implementations of spinlocks

```
while (pthread_mutex_trylock(&mutex) == EBUSY)
    /*sched_yield()*/;
```

Mutexes - Recap

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

pthread_mutex_t static_mutex = PTHREAD_MUTEX_INITIALIZER;

pthread_mutex_t *dynamic_mutex;

dynamic_mutex = (pthread_mutex_t *)
                malloc(sizeof(pthread_mutex_t));
pthread_mutex_init(&dynamic_mutex, NULL);



pthread_mutex_destroy(&dynamic_mutex);
free(dynamic_mutex);
```

Example: Thread Number

```
#include <pthread.h>

pthread_mutex_t mutex = PTHREAD_MUTEX_INITIALIZER;
int temp_id = 0;

void *work(void *arg)
{
  int id;
  ...
  pthread_mutex_lock(&mutex);
  id = temp_id;
  temp_id = temp_id+1;
  pthread_mutex_unlock(&mutex);
  ...
}
```

Example: try lock

```
pthread_mutex_t mutex1 = PTHREAD_MUTEX_INITIALIZER;

void * func(void *arg) {
   int res;
   res = pthread_mutex_trylock(&mutex1); /* EBUSY */;
   return 0;
}

int main() {
   pthread_t t;
   pthread_mutex_lock(&mutex1);
   pthread_create(&t, NULL, func, NULL);
   sleep(2);
   pthread_mutex_unlock(&mutex1);
   pthread_join(t, NULL);
   return 0;
}
```

Compute Pi - Sequential Version

```
long num_steps = 100000;
double step;

int main()
{
  double x, pi, sum = 0.0;

  step = 1.0/(double) num_steps;

  for (int i=0; i <num_steps; i++){
    x = (i-0.5)*step;
    sum = sum + 4.0/(1.0+x*x);
  }

  pi = step * sum;

  return 0;
}
```

POSIX Threads Version

```
#define NUM_THREADS 2
pthread_t thread[NUM_THREADS];
pthread_mutex_t Mutex;
long num_steps = 100000;
double step;
double global_sum = 0.0;

void *Pi (void *arg) {
  long start;
  double x, sum = 0.0;

  start = (long) (*(int *) arg);
  step = 1.0/(double) num_steps;

  for(long i=start; i<num_steps;
           i+=NUM_THREADS) {
    x = (i+0.5)*step;
    sum = sum + 4.0/(1.0+x*x);
  }
  pthread_mutex_lock (&Mutex);
  global_sum += sum;
  pthread_mutex_unlock(&Mutex);

  return 0;
}
```

```
int main()
{
  double pi;

  int Arg[NUM_THREADS];

  for(int i=0; i<NUM_THREADS; i++)
    Arg[i] = i;

  pthread_mutex_init(&Mutex, NULL);

  for (int i=0; i<NUM_THREADS; i++)
    pthread_create(&thread[i], NULL,
                   Pi, &Arg[i]);

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

  pi = global_sum * step;

  return 0;
}
```

Deadlocks

- Deadlock can occur when multiple mutexes are not locked in the same order.
- The threads cannot continue their execution:

```
        Thread 0                          Thread 1
pthread_mutex_lock(&mut1);      pthread_mutex_lock(&mut2);
pthread_mutex_lock(&mut2);      pthread_mutex_lock(&mut1);
```

- Deadlock can also occur if a mutex is locked twice (recursively) by the same thread

```
pthread_mutex_lock(&mut1);
pthread_mutex_lock(&mut1);
```

Thread Safety

- A function is thread-safe if it can be called safely at the same time by multiple threads
- Reentrant function: can have multiple concurrent active calls, at different points, without side-effects
- Threa-safe function: reentrant or protected with mutual exclusion
- Functions that use static variables are not thread-safe, e.g.: `rand()`, `drand48()`

Solutions

1. Use a mutex inside the function
   - provides an easy but inefficient solution due to the serialization of the code
   - this is the case for rand(), drand48()
2. Use static (per thread) data as function arguments (e.g. strtok_r)
   - not convenient, exposes the internal implementation of the function, requires code rewriting
3. Use thread private data (pthread_key_t)
   - Every thread has its own private data that other threads cannot access

Example 1

- rand_r: thread-safe version of rand()
  - randp is assigned a number from 0 and RAND_MAX
  - returns 0 on success

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

int rand_r(int *ranp){
   static pthread_mutex_t = PTHREAD_MUTEX_INITIALIZER;
   int error;
   if (error = pthread_mutex_lock(&lock))
       return error;
   *ranp = rand();
   return pthread_mutex_unlock(&lock);
}
```

Example 2

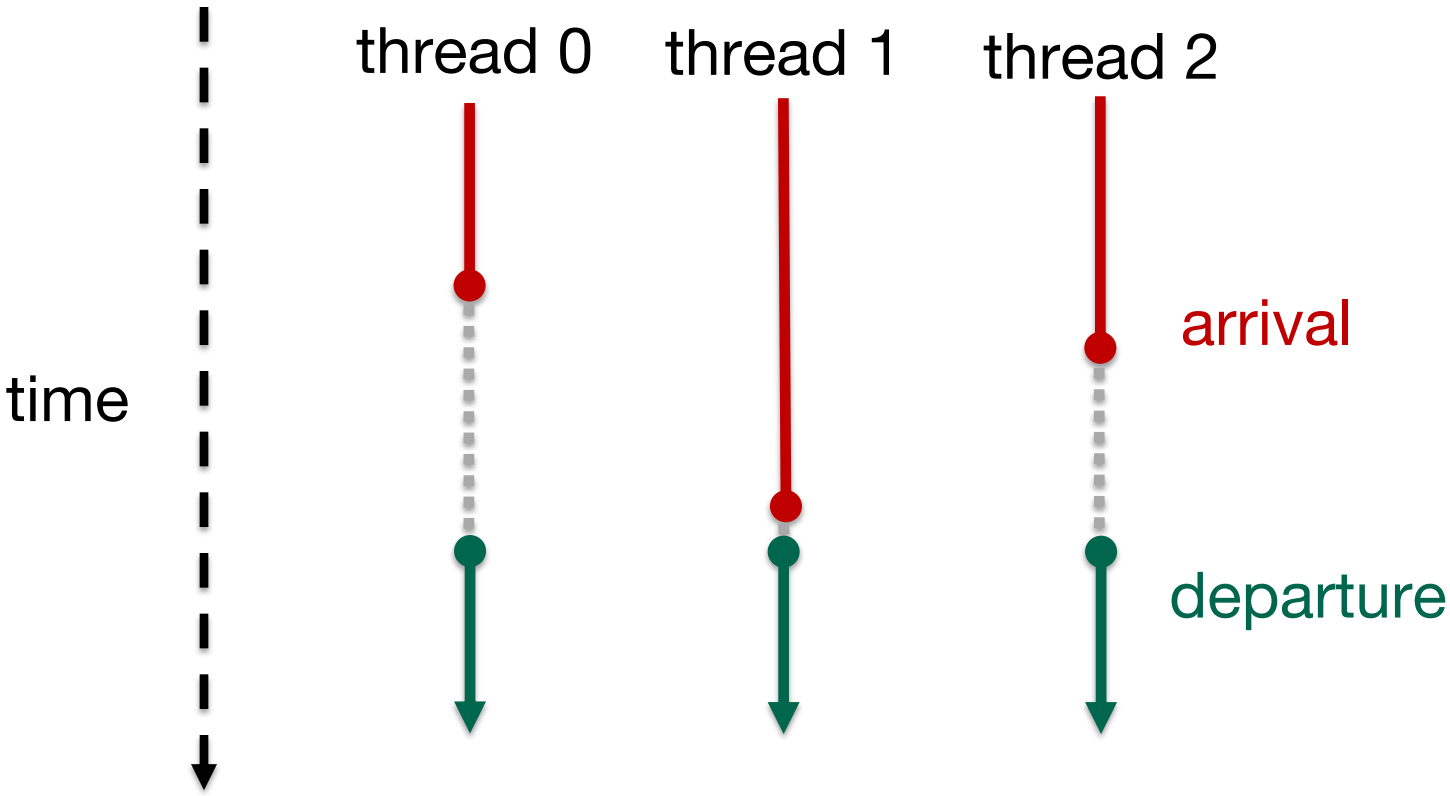
- drand48() vs erand48()
  - "return non-negative, double-precision, floating-point values, uniformly distributed over the interval [0.0 , 1.0]"
  - http://pubs.opengroup.org/onlinepubs/7908799/xsh/drand48.html

```
srand48(10); // initialization
double xi = drand48();
double yi = drand48();


unsigned short buf[3];// random stream
buf[0] = 0; buf[1] = 0; buf[2] = 10; // initialization
double xi = erand48(buf);
double yi = erand48(buf);
```

Barriers

- Barrier: synchronization mechanism that make sures all calling threads in a program
- No thread can cross the barrier until all the threads have reached it



Barriers

```
int pthread_barrier_init(pthread_barrier_t * bar,
                         const pthread_barrierattr_t*attr,
                         usigned int count);
int pthread_barrier_wait(pthread_barrier_t *bar);
int pthread_barrier_destroy(pthread_barrier_t *bar);
```

- pthread_barrier_t: data type
- count: number of threads that must call the barrier

Barrier Example

```
pthread_barrier_t bar;

void *func(void *arg)
{
    int id = *((int *)arg);
    printf("Hello world from thread %d!\n", id);

    pthread_barrier_wait(&bar);
    sleep(id);

    printf("Goodbye world from thread %d!\n", id);

    return NULL;
}

int main(int argc, char * argv[])
{
    ...
    pthread_barrier_init(&bar, NULL, 4);
    ...
```

Condition Variables

- Synchronization mechanism that allows multiple threads to wait on a condition and resume their execution after some time
- Mutexes protect critical code but condition variable protect a more general operation
- A thread waits on a condition variable until it is informed (by the variable) that it can continue
- Another (running) thread signals the condition variable, allowing other threads to continue
- Every condition variable, as shared data, is associated with a specific mutex

Condition Variables

- No need for continuous checking of data
- A thread that modifies the values of data also informs the other threads through the condition variable
- Example: producer-consumer scheme using data queue
  - The consumer thread extracts and processes elements of the queue while this is not empty, otherwise the thread suspends its execution
  - The producer thread adds elements to the queue and informs, through the condition variable, the consumer thread
  - The interaction is based on the number of elements in the queue

Declaration and Initialization

```
int pthread_cond_init(pthread_cond_t * cond,
                      const pthread_condattr_t *attr);
```

- pthread_cond_t: data type
- Static initialization:

```
pthread_cond_t condition = PTHREAD_COND_INITIALIZER;
```

- Dynamic initialization:

```
pthread_cond_init(&condition, NULL);
```

- There must be always an associated mutex

Waiting

```
int pthread_cond_wait(pthread_cond_t *condition,
                      pthread_mutex_t *mutex);
```

- The thread suspends its execution until the condition variable is signaled
- The thread must have locked the associated mutex
- The thread is suspended and the mutex is unlocked automatically in order to be used by other threads
- When the condition variable is singled and the suspended thread wakes up, it automatically locks the mutex

Signaling

```
int pthread_cond_signal(pthread_cond_t *cond);
int pthread_cond_broadcast(pthread_cond_t *cond);
```

- pthread_cond_signal: a thread informs a single thread that waits on the condition variable
- pthread_cond_broadcast: a thread informs all the threads that wait on the condition variable
- The signaling thread has usually locked the associated mutex. In that case, it must release the mutex in order to allow pthread_cond_wait to return

Usage

1. A thread locks the associated mutex m
2. The thread checks the condition and decides if it can continue or not
3. If it can continue (the condition is true):
    1. The thread executes its operation and
    2. Unlocks the mutex
4. If it cannot continue (the condition is false):
    1. The thread suspends itself by calling pthread_cond_wait(&c,&m), and the mutex is automatically unlocked (by the system)
    2. Another thread sets the condition to true and calls pthread_cond_signal(&c)
    3. The thread wakes up with the mutex locked by itself and executes its operation
    4. The thread unlocked the mutex when it completes its operation

Example 1

Thread 0

```
T1: pthread_mutex_lock(&m);
T2: while(!condition_ok)
T3:   while(pthread_cond_wait(&c,&m));
T4:
T5:
T6:
T7:
T8: go_ahead_and_do_it();
T9: pthread_mutex_unlock(&m);
```

Thread 1

```
pthread_mutex_lock(&m);
condition_ok = TRUE;
pthread_cond_signal(&c);
pthread_mutex_unlock(&m);
```

Example 2

Thread 0

```
for(...)
{
 ------------
 pthread_mutex_lock(&mut);
 count++;
 if (count== N){
  /* Wake-up thread 1 */
  pthread_cond_signal(&cond);
}
pthread_mutex_unlock(&mut);
------------
//Do work
}
```

Thread 1

```
-----------
pthread_mutex_lock(&mut);
while(count<N) {
  pthread_cond_wait(&cond, &mut);
}
pthread_mutex_unlock(&mut);
------------

//Do work
```

Example 3

Threads 0,…,N-1

```
for(...)
{
 ------------
 pthread_mutex_lock(&mut);
 count++;
 if (count== N){
  /* Wake-up thread N */
  pthread_cond_signal(&cond);
}
pthread_mutex_unlock(&mut);
------------
//Do work
}
```

Thread N

```
-----------
pthread_mutex_lock(&mut);
while(count<N) {
  pthread_cond_wait(&cond, &mut);
}
pthread_mutex_unlock(&mut);
------------

//Do work
```

Example 4

Thread 0

```
for(...)
{
 ------------
 pthread_mutex_lock(&mut);
 count++;
 if (count== N){
  /* Wake-up threads 1..N */
  pthread_cond_broadcast(&cond);
}
pthread_mutex_unlock(&mut);
------------
//Do work
}
```

Thread 1,2,…,N

```
-----------
pthread_mutex_lock(&mut);
while(count<N) {
  pthread_cond_wait(&cond,&mut);
}
pthread_mutex_unlock(&mut);
------------

//Do work
```

Comments

- Condition variables are used for signaling and not mutual exclusion
- The condition must be always checked if it is true or not
  - Interrupted wake-ups: Before pthread_cond_wait returns with the mutex locked, another thread locks the mutex and changes the condition
  - Loose conditions: an approximation of the real condition (e.g. “there might be available work”)
  - False wakeups: pthread_cond_wait returns but the condition variable has not been signaled (e.g. in multicore systems)

Condition Variables

- Condition variables can be used without a condition
- The mutex must be locked and released before and after wait(), respectively
- Example:

```
pthread_mutex_lock(&mut);
pthread_cond_wait(&cond, &mut);
pthread_mutex_unlock(&mut);
```

Condition Variables - Extension

```
int pthread_cond_timedwait(&condition, &mutex,
                           (struct timespec *)expiration);
```

- Waits on a condition variable but with time constraint. If timeout occurs, the function returns ETIMEDOUT.

==========

```
struct timespec timeout;

/* Wait on the condition variable for 2 seconds */

timeout.tv_sec = time(NULL) + 2;
timeout.tv_nsec = 0;
pthread_cond_timedwait(&condition, &mutex, &timeout);
```

Fibonacci (1/3)

```
/* version 1*/
int fib(int n)
{
   if (n <= 1) return n;
   else return fib(n-1) + fib(n-2);
}


/* version 2*/
void fib(int n, int *res)
{
   int r1, r2;
   if (n <= 1) *res = n;
   else {
        fib(n-1, &r1);
        fib(n-2, &r2);
        *res = r1 + r2;
   }
}
```

Fibonacci (2/3)

```
/* version 3*/
struct fib_arg {
    int n;
    int res;
};

void fib(struct arg *a)
{
    struct fib_arg a1, a2;
   int r1, r2;
   if (a->n <= 1) a->res = a->n;
   else {
        a1.n = a->n-1;
        a2.n = a->n-2;
        fib(&a1);
        fib(&a2);
        a->res = a1.res + a2.res;
   }
}
```

Fibonacci (3/3)

```
/* version 4*/
void *fib(void *arg) {
    struct fib_arg *a = (struct fib_arg *) arg;
    struct fib_arg a1, a2;
    pthread_t t1, t2;

    pthread_mutex_lock(&nthreads_mutex);
    nthreads++;
    pthread_mutex_unlock(&nthreads_mutex);

    if (a->n <= 1) {
       a->res = a->n;
    }
    else {
        a1.n = a->n-1;
        a2.n = a->n-2;
        pthread_create(&t1, NULL, fib, (void *) &a1);
        pthread_create(&t2, NULL, fib, (void *) &a2);
        pthread_join(t1, NULL);
        pthread_join(t2, NULL);
        a->res = a1.res + a2.res;
    }
    return NULL;
}
```

Execution Order (1/2)

```
#define N 10

void *routine(void *arg) {
  int id = (int) arg;
  printf("Hello from thread:%d\n", id);

  return 0;
}

int main() {
  int i;
  pthread_t t[N];
  int a[N];

  for (i = 0; i < N; i++) {
    a[i] = i;
    pthread_create(&t[i], NULL, routine, (void *)&a[i]);
  }

  for (i = 0; i < N; i++)
    pthread_join(t[i], NULL);

  return 0;
}
```

Execution Order (2/2)

```
pthread_mutex_t m[N];  /* initialized in main */
pthread_cond_t c[N];   /* initialized in main */

void *routine(void *arg)
{
  int id = *((int *) arg;)

  if (id > 0) {
    pthread_mutex_lock(&m[id]);
    pthread_cond_wait(&c[id], &m[id]);
  }

  printf("Hello from thread:%d\n", id);

  if (id > 0) pthread_mutex_unlock(&m[id]);
  if (id < N) pthread_cond_signal(&c[id+1]);

  return 0;
}
```

Recursive Locks (1/4)

```
int     othr_init_nest_lock(othr_nest_lock_t *lock);
int     othr_destroy_nest_lock(othr_nest_lock_t *lock);
int     othr_set_nest_lock(othr_nest_lock_t *lock);
int     othr_unset_nest_lock(othr_nest_lock_t *lock);
```

```
typedef struct {
   pthread_mutex_t lock;        /* real lock */
   pthread_mutex_t ilock;       /* data lock */
   pthread_cond_t cond;
   int count;
   othr_t owner;
} othr_nest_lock_t;
```

Recursive Locks (2/4)

```
int othr_init_nest_lock(othr_nest_lock_t *lock)
{
  pthread_mutex_init(&lock->ilock, NULL);
  pthread_mutex_init(&lock->lock, NULL);
  lock->count = 0;
  pthread_cond_init(&lock->cond, 0);
  return (0);
}

int othr_destroy_nest_lock(othr_nest_lock_t *lock)
{
  pthread_mutex_destroy(&lock->lock);
  pthread_cond_destroy(&lock->cond);
  pthread_mutex_destroy(&lock->ilock);
  return (0);
}
```

Recursive Locks (3/4)

```
int othr_set_nest_lock(othr_nest_lock_t *lock)
{
  pthread_mutex_lock(&lock->ilock);
    if (pthread_mutex_trylock(&lock->lock) == 0)    /* lock it */
    {
      lock->owner = pthread_self();                 /* Get ownership */
      lock->count++;
    }
    else
      if (pthread_equal(lock->owner, pthread_self())) /* mine */
        lock->count++;
      else                                  /* someone else */
      {
         while ( pthread_mutex_trylock(&lock->lock) )
           pthread_cond_wait(&lock->cond, &lock->ilock);
         lock->owner = pthread_self();
         lock->count++;
      }
  pthread_mutex_unlock(&lock->ilock);
  return (0);
}
```

Recursive Locks (4/4)

```
int othr_unset_nest_lock(othr_nest_lock_t *lock)
{
  pthread_mutex_lock(&lock->ilock);
    if (pthread_equal(lock->owner,pthread_self()) && lock->count > 0)
    {
      lock->count--;
      if (lock->count == 0)
      {
        pthread_mutex_unlock(&lock->lock);
        pthread_cond_signal(&lock->cond);
      }
    }
  pthread_mutex_unlock(&lock->ilock);
  return (0);
}
```

Special topics

- Attributes objects
  - Thread attributes
  - Mutex attributes
- One-time initialization
- Thread private data

Attribute objects

- Thread creation and mutex, barrier and condition variable initialization routines had the second argument equal to NULL (so far)
- This argument is a pointer to attribute object
- NULL corresponds to the default attribute value
- Attribute object: some kind of private data structure (like C++)
- The members of the object can be accessed through appropriate routines, e.g.:

```
pthread_attr_getstacksize
pthread_attr_setstacksize
```

Thread Attributes

- Declaration, initialization and destruction of a thread attribute object

```
pthread_attr_t attr;
int pthread_attr_init(&attr);
int pthread_attr_destroy(&attr);
```

- Detach state of thread

```
int pthread_attr_getdetachstate(&attr, (int *) &ds);
int pthread_attr_setdetachstate(&attr, (int) ds);
```

`PTHREAD_CREATE_JOINABLE:` joinable thread
`PTHREAD_CREATE_DETACHED:` daemon thread

Thread Attributes

- Stack size of the thread, minimum is PTHREAD_STACK_MIN

```
int pthread_attr_getstacksize(&attr, (size_t *) &ss);
int pthread_attr_setstacksize(&attr, (size_t) ss);
```

- Stack of a thread, allocated explicitly (e.g. malloc)

```
int pthread_attr_getstackaddr(&attr, (void **) &sa);
int pthread_attr_setstacksize(&attr, (void *) sa);
```

Mutex Attributes

- Declaration, initialization and destruction of a mutex attribute object

```
pthread_mutexattr_t attr;
int pthread_mutexattr_init(&attr);
int pthread_mutexattr_destroy(&attr);
```

- Mutex types

```
int pthread_mutexattr_gettype(&attr, (int *) &type);
int pthread_mutexattr_settype(&attr, (int ) type);
```

  - `PTHREAD_MUTEX_NORMAL`: faster implementation
  - `PTHREAD_MUTEX_RECURSIVE`: can be locked several times by the same thread
  - `PTHREAD_MUTEX_ERRORCHECK`: for debugging
  - `PTHREAD_MUTEX_DEFAULT`: usually the first one above

Once-Only Initialization

- Data initialization (e.g.. mutexes) within main()
- Software libraries do not have this option
- A boolean variable that is set when the initialization has been performed is enough for single-threaded applications
- Static initialization of mutexes does not cause any issues
- Dynamic initialization of mutexes requires pthread_once

```
pthread_once_t once_control = PTHREAD_ONCE_INIT;
int pthread_once(pthread_once_t *once_control,
                 void (*init_routine)(void));
```

- Any thread can call the pthread_once function
- The associated variable is first checked, and the initialization routine is then called
- Any other thread waits for the completion of the initialization routine

Once-Only Initialization

```
pthread_once_t once_block = PTHREAD_ONCE_INIT;
pthread_mutex_t mutex;

/* Initialization routine */
void once_init_routine(void) {
    pthread_mutex_init(&mutex, NULL);
}

/* Thread start routine that calls pthread_once */
void *thread_routine(void *arg) {
    pthread_once(&once_block, once_init_routine);
    ...
}

int main() {
    pthread_create(&t, NULL, thread_routine, NULL);
    pthread_once(&once_block, once_init_routine);
    ...
}
```

Thread private data

- Static variables, declared in a file or function, can be accessed by all threads
- Only the register values are private to a thread. Even its stack can be accessed by other threads
- Goal: maintain the value of a variable between calls of different routines on a particular thread
- Creation and destruction of key for management of thread private data:

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

- Access of key values (set, get):

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

Thread private data

```
pthread_key_t key;
pthread_once_t key_once = PTHREAD_ONCE_INIT;

void once_routine(void) {
   pthread_key_create(&key, NULL);
}

void routine() {
   int *value = pthread_getspecific(key);
}

void *func(void *arg) {
    int id = *((int *)arg);
    int *value;
    pthread_once(&key_once, once_routine);

    value = malloc(sizeof(int));
    *value = id;
    pthread_setspecific(key, value);
    routine();
    return NULL;
}
```

References

- Advanced Programming in the Unix Environment, W. Richard Stevens
- Programming with POSIX Threads, David R. Butenhof
  - www.openmp.org
- POSIX threads tutorial at LLNL, Blaise Barney
  - https://computing.llnl.gov/tutorials/pthreads/