Pthreads

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Pthreads

The standard thread package on Unix/Linux systems. To use it on Linux,

- Include the header file <pthread.h> in your program.
- Compile your program with the "-pthread" flag.

Useful Routines:

```
pthread_create(&thread, attributes, func, arg);
pthread_exit(status);
pthread_join(thread, &status);   // sync back a thread
pthread_cancel(thread);          // force termination a thread
pthread_self();                  // return the self thread
pthread_equal(thread1, thread2); // compare two threads
sched_yield();                   // yield to another thread
```

- The pthread_join() routine is for synchronizing a *terminated* thread back to its parent.
- Not all threads are joinable — a thread can be created as *detached*; when it terminates, it is destroyed and its resource released.

Synchronizations in Pthreads

- Mutex Locks:

```
pthread_mutex_t mutex;

pthread_mutex_init(&mutex, attributes);
pthread_mutex_lock(&mutex);
pthread_mutex_trylock(&mutex);
pthread_mutex_destroy();
```

- Condition Variables:

```
pthread_cond_t cond;

pthread_cond_init(&cond, attributes);
pthread_cond_signal(cond);
pthread_cond_broadcast(cond);
pthread_cond_wait(cond, mutex);
```


Attributes

Various attributes can be set for threads, locks, and condition variables. For normal cases, the default values work just fine.

- For threads:
  - scheduling policy, stack size, detached state
- For mutexes:
  - *normal* — only a single thread is allowed to lock it; if a threads tries to lock it twice a deadlock occurs.
  - *recursive* — a thread can lock the mutex multiple time; each successive lock/unlock increments/decrements a counter; another thread can lock a mutex only if its counter is zero.
- For condition variables:
  - can enable cross-process sharing

A Simple Example

```
#include <pthread.h>

void child(long id) {
  printf("Child %ld\n", id);
}

main() {
  long i=1, j=2;
  pthread_t thread1, thread2;
  pthread_create(&thread1, NULL,
                 (void*) child, (void*)i);
  pthread_create(&thread2, NULL,
                 (void*) child, (void*)j);
  printf("Parent: waiting for child 1\n");
  pthread_join(thread1, NULL);
  printf("Parent: waiting for child 2\n");
  pthread_join(thread2, NULL);
  printf("Parent: done\n");
}
```

Output:

```
Parent: waiting for child 1
Child 1
Child 2
Parent: waiting for child 2
Parent: done
```


Mutexes

Locks are implemented in Pthreads with "mutex" variables.

- To use a mutex, first it must be declared and initialized:

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

  NULL specifies a default attribute for the mutex.

- A critical section can then be protected with the mutex:

```
pthread_mutex_lock(&mutex);
<critical section>
pthread_mutex_unlock(&mutex);
```

  - If a thread reaches a mutex lock and finds it locked, it will wait for the lock to open.
  - If more than one thread is waiting for the lock to open when it opens, the system will select one thread to be allowed to proceed.

Mutexes (cont.)

- Only the thread that locks a mutex can unlock it.
- Pthreads offers a routine that can test whether a lock is locked without blocking the thread:

```
pthread_mutex_trylock()
```

  - It will lock an unlocked mutex and return 0 or will return with EBUSY if the mutex is locked — useful in overcoming deadlock.
- A mutex can be destroyed with

```
pthread_mutex_destroy()
```


Condition Variables

- Condition variables also need to be initialized before use:

```
pthread_cond_t cond;
pthread_cond_init(&cond, NULL);
```

- Each condition variable must be associated with a mutex, since the checking and setting of the condition must be done inside a critical section. The "wait" routine, in particular, takes a mutex as one of its arguments:

```
pthread_cond_wait(cond, mutex);
```

- Signals that are sent out by "signal" or "broadcast" routines are not remembered, which means that threads must already be waiting for a signal to receive it.

Condition Variable Example

Decrement a count; if value reaches 0, send a signal.

```
counter() {
  pthread_mutex_lock(&mutex);
  c--;
  if (c == 0)
    pthread_cond_signal(cond);
  pthread_mutex_unlock(&mutex);
}
```

Compare with two other versions:

```
counter_v2() {
  pthread_mutex_lock(&mutex);
  c--;
  if (c == 0)
    pthread_cond_broadcast(cond);
  pthread_mutex_unlock(&mutex);
}
```

```
counter_v3() {
  pthread_mutex_lock(&mutex);
  c--;
  pthread_mutex_unlock(&mutex);
  if (c == 0)
    pthread_cond_signal(cond);
}
```


Condition Variable Example (cont.)

```
action() {
  pthread_mutex_lock(&mutex);
  while (c <> 0)
    pthread_cond_wait(cond, mutex);
  pthread_mutex_unlock(&mutex);
  take_action();
}
```

Compare with the following version:

```
action_v2() {
  pthread_mutex_lock(&mutex);
  if (c <> 0)
    pthread_cond_wait(cond, mutex);
  pthread_mutex_unlock(&mutex);
  take_action();
}
```

Array-Sum Example

```c
#include <pthread.h>

int arraySize = 1000;           // default array size
int numThreads = 10;            // default number of threads
int *array;                     // shared array
int sum = 0, idx = 0;           // global sum and idx
pthread_mutex_t sumLock;

int main(int argc, char **argv) {
  pthread_t thread[numThreads];
  array = init_array(arraySize);        // initialize array
  pthread_mutex_init(&sumLock, NULL);   // initialize mutex

  for (long k = 0; k < numThreads; k++) {        // create threads
    pthread_create(&thread[k], NULL, (void*)slave, (void*)k);
  }
  for (long k = 0; k < numThreads; k++) {        // join threads
    pthread_join(thread[k], NULL);
  }
  printf("The sum of 1 to %i is %d\n", arraySize, sum);
}
```


Array-Sum Example (cont.)

```c
int *init_array(int size) {
  int *array = (int *) malloc(sizeof(int) * size);
  for (int i = 0; i<size; i++)
    array[i] = i + 1;
  return array;
}

void slave(long tid) {
  printf("Thread %ld started\n", tid);

  int i, psum = 0;
  do {
    pthread_mutex_lock(&sumLock);     // read and increment idx
    i = idx++;
    pthread_mutex_unlock(&sumLock);
    if (i < arraySize)                // add one array element
      psum += array[i];
  } while (i < arraySize);
  pthread_mutex_lock(&sumLock);       // add local psum to global sum
  sum += psum;
  pthread_mutex_unlock(&sumLock);
}
```

Array-Sum Version 2

Show where threads are executed.

```
#define _GNU_SOURCE
#include <pthread.h>
#include <sched.h>               // for getting cpu id

void slave(long tid) {
  printf("Thread %ld started on %d\n", tid, sched_getcpu());

  ...
}
```

Question: Can we have more control over where threads execute?

Array-Sum Version 3

Control where threads are executed.

```
#define _GNU_SOURCE
#include <pthread.h>
#include <sched.h>               // for getting cpu id
#include <unistd.h>              // for getting nprocs

int main(int argc, char **argv) {
  pthread_t thread[numThreads];
  array = init_array(arraySize);                // initialize array
  pthread_mutex_init(&sumLock, NULL);           // initialize mutex
  int nprocs = sysconf(_SC_NPROCESSORS_ONLN);
  cpu_set_t cpuset;
  int cid = 0;
  for (long k = 0; k < numThreads; k++) {       // create threads
    pthread_create(&thread[k], NULL, (void*)slave, (void*)k);
    CPU_ZERO(&cpuset);
    CPU_SET(cid++ % nprocs, &cpuset);
    pthread_setaffinity_np(thread[k], sizeof(cpu_set_t), &cpuset);
  }
  ...
}
```

Array-Sum Version 4

Add command-line arguments for parameter configurations.

```
int arraySize;                // array size, given by user
int numThreads = 1;           // default number of threads

int main(int argc, char **argv) {
  if (argc < 2) {
    printf ("Usage: ./arraysum4 <arraySize> [<numThreads>]\n");
    exit(0);
  } else if (argc > 2) {
    if ((numThreads=atoi(argv[2])) < 1) {
      printf ("<numThreads> must be greater than 0\n");
      exit(0);
    }
  }
  if ((arraySize=atoi(argv[1])) < 1) {
    printf ("<arraySize> must be greater than 0\n");
    exit(0);
  }
  ...
}
```


Producer-Consumer with Bounded Buffer

Problem Description:

- One producer, multiple consumers, and a bounded task queue.
- The producer creates tasks and adds them one by one to the end of the task queue. If the queue is full, it waits for new space to open up.
- Each consumer removes tasks one by one from the head of the task queue. If the queue is empty, it waits for new task to appear.

Programming Issues:

- Task and queue representations
- Threads creation and management
- Synchronization
- Termination

Producer-Consumer: Task and Queue Representations

```
typedef struct task_ task_t;
struct task_ {
  int val;          // each task holds an integer value
  task_t *next;     // and a pointer to next task
};

typedef struct queue_ queue_t;
struct queue_ {
  task_t *head;
  task_t *tail;
  int limit;        // queue size limit
  int length;       // current number of tasks
};
```

Supporting Routines:

```
task_t *create_task(int val) { ... }
queue_t *init_queue(int limit) { ... }
void add_task(queue_t *queue, task_t *task) { ... }
task_t *remove_task(queue_t *queue) { ... }
```


Producer-Consumer: Threads Creation and Management

```
int main(int argc, char **argv) {

  // create consumer threads
  pthread_t *threads =
    (pthread_t *) malloc(sizeof(pthread_t) * numConsumers);
  for (long k = 0; k < numConsumers; k++)
    pthread_create(&threads[k], NULL, (void*)consumer, (void*)k);

  // execute the producer code
  producer();

  // wait for consumer threads to terminate
  for (long k = 0; k < numConsumers; k++)
    pthread_join(threads[k], NULL);
}
```

Producer-Consumer: Synchronization

```
void producer() {
  while (<there is still task>) {
    <try to add a task to the queue>
    <wait if no space available>
  }
}

void consumer(long tid) {
  while (1) {
    <try to get a task from the queue>
    <wait if none available>
  }
}
```

Questions:

1. Other than the two `waits`, is there a need for additional synchronizations?
2. Who is/are responsible for sending signals to the waiting threads?

Producer-Consumer: Termination

```
void producer() {
  while (<there is still task>) {
    <try to add a task to the queue>
    <wait if no space available>
  }
}

void consumer(long tid) {
  while (1) {
    <try to get a task from the queue>
    <wait if none available>
  }
}
```

Questions:

1. Can the producer thread terminate on its own?
2. Can the consumer threads ternimate on their own?
3. If not, what additional mechanism is needed?

Quicksort Program Framework

```
// A global array of size N contains the integers to be sorted.
// A global task queue is initialized with the sort range [0,N-1].
//
int main(int argc, char **argv) {
  // 1. read in command-line arguments, N and numThreads;
  // 2. initialize array, queue, and other shared variables

  // 3. create numThreads-1 worker threads, each executes a copy
  //    of the worker() routine
  for (long k = 0; k < numThreads-1; k++)
    pthread_create(&thread[k], NULL, (void*)worker, (void*)k);

  // 4. the main thread also runs a copy of the worker() routine;
  //    its copy has the last id, numThreads-1
  worker(numThreads-1);

  // 5. the main thread waits for worker threads to join back
  for (long k = 0; k < numThreads-1; k++)
    pthread_join(thread[k], NULL);

  // 6. verify the result
}
```


Quicksort Program Framework (cont.)

```
void worker(long wid) {
  while (<termination condition is not met>) {
    task = remove_task();
    quicksort(array, task->low, task->high);
  }
}

void quicksort(int *array, int low, int high, long wid) {
  // 1. find a pivot and partition the array into two segments
  int middle = partition(array, low, high);
  // 2. add the first segment to the task queue
  if (low < middle)
    <add task [low, middle-1] to queue>
  // 3. recursively sort on the second segment
  if (middle < high)
    quicksort(array, middle+1, high, wid);
}
```

Questions:

1. What synchronizations are needed?
2. What should the termination condition be?