

ACM/CS 114

Parallel algorithms for scientific applications

Michael A. G. Aïvázis

California Institute of Technology

Winter 2010

Hello world

```
1 #include <pthread.h>
2 #include <stdio.h>
3 #define THREADS 10
4
5 void* hello(void* threadID) {
6     long id = (long) threadID;
7     printf("hello from %02ld/%0d\n", id, THREADS);
8     pthread_exit(NULL);
9     return NULL;
10 }
11
12 int main(int argc, char* argv[]) {
13     long id;
14     int status;
15     pthread_t threads[THREADS];
16
17     for (id=0; id<THREADS; id++) {
18         printf("creating thread %02ld\n", id);
19         status = pthread_create(&threads[id], NULL, hello, (void*) id);
20         if (status) {
21             printf("error %d in pthread_create\n", status);
22         }
23     }
24     /* there is a problem here... */
25     pthread_exit(NULL);
26     return 0;
27 }
```

Joining and detaching

- ▶ in the example in Slide 2, the main thread exits without knowing whether any of the threads it spawned have finished
 - ▶ saying “hello” is asynchronous
 - ▶ but gathering the results of parallel calculations normally isn’t
- ▶ *thread synchronization* can be achieved using `pthread_join`
 - ▶ the `pthread_create` caller saves the thread id
 - ▶ the thread is scheduled, executes, and calls `pthread_exit`
 - ▶ any other thread can wait for this thread to finish by calling `pthread_join` with the saved thread id and also retrieve the termination status
- ▶ for this to work, a thread must be *joinable*
 - ▶ controlled by the thread creation attributes
 - ▶ for portability, you should always mark your joinable threads explicitly
- ▶ a thread that will never be joined may be *detached*
 - ▶ by setting the corresponding attribute during thread creation
 - ▶ or, by calling `pthread_detach` at any point
 - ▶ detaching a thread saves some system resources

Creating mutexes

- ▶ a *mutex* is a locking mechanism that helps guarantee exclusive access to a section of code, most often to control access to shared variables
- ▶ mutexes are created using

```
1 int pthread_mutex_init(  
2   pthread_mutex_t* mutex, const pthread_mutexattr_t* attr);
```

- ▶ they start out unlocked
 - ▶ the `attr` enables more advanced (but perhaps non-portable) use
- ▶ mutexes are destroyed using

```
1 int pthread_mutex_destroy(pthread_mutex_t* mutex);
```

- ▶ destroy mutexes you are no longer using to prevent resource leakage

Locking and unlocking mutexes

- ▶ threads manipulate mutexes through

```
1 int pthread_mutex_lock(pthread_mutex_t* mutex);  
2 int pthread_mutex_trylock(pthread_mutex_t* mutex);  
3 int pthread_mutex_unlock(pthread_mutex_t* mutex);
```

- ▶ `pthread_mutex_lock` attempts to gain exclusive access
 - ▶ if the mutex is unlocked, it locks it and returns
 - ▶ otherwise, it blocks until the mutex is unlocked; when the mutex is unlocked, it locks it and returns
- ▶ `pthread_mutex_unlock` attempts to release a mutex
 - ▶ if it was previously locked by this thread, the mutex is unlocked
 - ▶ if it was not previously locked, the call returns with an error code
 - ▶ if it was locked, but not by the calling thread, the call returns an error code
- ▶ `pthread_mutex_trylock` attempts to lock the mutex
 - ▶ if it is unlocked, the call locks it and returns
 - ▶ if it is locked, the call returns immediately with a *busy* error code
- ▶ locking and unlocking mutexes is explicitly orchestrated by the programmer
- ▶ when multiple threads are blocked waiting for a mutex, there is no way to predict which one will succeed when the mutex becomes available

Example reduction using threads

```
1 #include <pthread.h>
2 #include <stdio.h>
3 #define THREADS 10
4 /* global variables -- yuck! */
5 long sum = 0;
6 pthread_mutex_t mutex;
7 /* worker */
8 void* squares(void* threadID) {
9     long id = (long) threadID;
10    pthread_mutex_lock(&mutex);
11    sum += id*id;
12    pthread_mutex_unlock(&mutex);
13    pthread_exit(NULL);
14    return NULL;
15 }
16 /* main program */
17 int main(int argc, char* argv[]) {
18     long id;
19     pthread_t threads[THREADS];
20     pthread_mutex_init(&mutex, NULL);
21     /* create some threads */
22     for (id=0; id<THREADS; id++) {
23         pthread_create(&threads[id], NULL, squares, (void*) id);
24     }
25     /* wait for them to finish */
26     for (id=0; id<THREADS; id++) {
27         pthread_join(threads[id], NULL);
28     }
29     /* print the result */
30     printf("sum = %ld\n", sum);
31     /* exit */
32     pthread_exit(NULL);
33     return 0;
34 }
```

Condition variables

- ▶ condition variables build upon mutexes to enable threads to signal each other when some condition is met
- ▶ they are created using

```
1 int pthread_cond_init(  
2     pthread_cond_t* condition, const pthread_condattr_t* attr);
```

- ▶ and destroyed using

```
1 int pthread_cond_destroy(pthread_cond_t* condition);
```

Using condition variables

- ▶ the following three routines implement the condition variable semantics

```
1 int pthread_cond_wait(pthread_cond_t* cond, pthread_mutex_t* mutex);  
2 int pthread_cond_signal(pthread_cond_t* cond);  
3 int pthread_cond_broadcast(pthread_cond_t* cond);
```

- ▶ `pthread_cond_wait` blocks the calling thread until the specified condition is *signaled*
 - ▶ it must be called with the mutex locked by the calling thread
 - ▶ `pthread_cond_wait` releases the lock while the thread is blocked
 - ▶ after the matching signal is received, the thread is awakened and the mutex locked
 - ▶ the thread is responsible for releasing the mutex when it is done
- ▶ `pthread_cond_signal` wakes up a thread that is waiting for the given condition variable
 - ▶ mutex must be locked before calling it
 - ▶ mutex must be unlocked after signaling, so blocking threads can be awakened
- ▶ `pthread_cond_broadcast` can be used instead if multiple threads are waiting for a signal

Condition variable caveats

- ▶ be careful with condition variables; make sure that
 - ▶ a thread has called `pthread_cond_wait` before any thread calls `pthread_cond_signal`
 - ▶ the mutex associated with the condition is locked before calling `pthread_cond_wait`, otherwise it might *not block*
 - ▶ the thread that calls `pthread_cond_signal` unlocks the associated mutex, otherwise the threads waiting for the signal will continue to block

Attributes of threads, mutexes and condition variables

- ▶ threads, mutexes and condition variables have associated attribute structures that can be used to tune the default creation parameters
- ▶ they are created and destroyed using

```
1 int pthread_attr_init(pthread_attr_t* attr);
2 int pthread_attr_destroy(pthread_attr_t* attr);
3
4 int pthread_mutexattr_init(pthread_mutexattr_t* attr);
5 int pthread_mutexattr_destroy(pthread_mutexattr_t* attr);
6
7 int pthread_condattr_init(pthread_condattr_t* attr);
8 int pthread_condattr_destroy(pthread_condattr_t* attr);
```

- ▶ typically, the defaults are adequate and tuned to the details of the operating system
- ▶ if you make excessive use of the stack, e.g. large arrays as local variable or deep recursion, you might want to know about

```
1 int pthread_attr_getstacksize(pthread_attr_t* attr, size_t* size);
2 int pthread_attr_setstacksize(pthread_attr_t* attr, size_t size);
```

Other useful routines

- ▶ a thread can access its unique id assigned by the system by calling

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

- ▶ since system thread ids are opaque types, you cannot use == to compare them; instead, use

```
1 int pthread_equal(pthread_t id1, pthread_t id2);
```

- ▶ you can place all thread initialization code in a startup routine and call

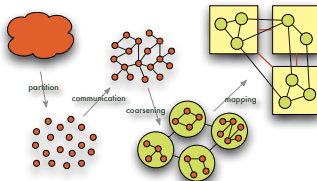
```
1 int pthread_once(pthread_once_t* control_structure, void (*startup_routine)
```

Advanced topics

- ▶ there is quite a bit more in the standard
- ▶ *keys*: creating and accessing per-thread data
 - ▶ as the code get more complicated, it becomes increasingly difficult to pass complete thread-specific information from function to function
 - ▶ possible solutions:
 - ▶ the FORTRAN syndrome, where subroutines end up having dozens of arguments
 - ▶ global variables
 - ▶ an associative container that allows each thread to store and retrieve arbitrary data
- ▶ finer control over thread scheduling
 - ▶ scheduling algorithms and priorities are implementation dependent
 - ▶ there are routines in the standard that enable explicit tuning
 - ▶ the standard guarantees that the routines will be *available*, but they don't have to be *implemented*
- ▶ condition variable sharing across processes
- ▶ explicitly canceling threads
- ▶ the somewhat complicated interactions between threads and signals
- ▶ other synchronization constructs: barriers and read/write locks

Summary

- ▶ well-designed threaded programs must follow the same strategy as any other concurrent program



- ▶ identify the work that can be done concurrently
- ▶ partition it in terms of work units, the fine grain tasks
- ▶ analyze the communication patterns among work units with an eye for critical sections and protecting shared data structures
- ▶ coarsen into threads, define the mutex categories and synchronization points
- ▶ let the OS schedule the threads onto physical processors
- ▶ debugging threaded programs is very difficult
 - ▶ preventing bugs through careful design is critical
 - ▶ so is instrumenting the program to gain confidence in its execution