ACM/CS 114
Parallel algorithms for scientific applications

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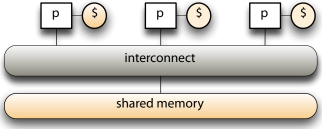
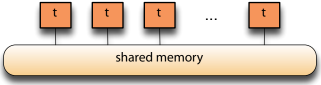
Threads and shared memory parallelism

- recall the shared memory architecture



  - processors are connected to a memory pool with a global address space
  - processors have their own cache but no private memory
- model is relevant for *threads*
  - lightweight processes that can be scheduled independently, but share many OS resources
    - CPU
    - memory
    - but also file descriptors, process environment, etc.
  - supported by most modern operating systems



Processes and threads

- in most operating systems, a process has
  - process id and group id, user id and group id
  - environment variables
  - working directory
  - scheduling information
  - registers, stack, heap, instruction stream
  - file descriptors, signal handlers, other process dependent structures
- threads
  - share many of the per-process properties
    - they are lightweight since they incur low overhead
  - have their own copy of
    - registers, stack, instruction stream
    - scheduling information
- threads are important programming constructs
  - every vendor supports a proprietary interface
  - *pthreads*, the POSIX standard API specification brought portability
  - standardized creation, management, synchronization

The pthreads API

- threads require support from the compiler, the linker, the loader, and the OS kernel
  - thread safety
- special command line argument to most compliant compilers
  - changes the instruction strategy
  - adds the pthread runtime library to the link line
  - links against the thread safe runtime
- naming conventions

Prefix	Functional group
`pthread_`	access to the threads, and some miscellaneous routines
`pthread_attr_`	thread attribute objects
`pthread_mutex_`	mutexes
`pthread_mutexattr_`	mutex attribute objects
`pthread_cond_`	condition variables
`pthread_condattr_`	condition variable attribute objects
`pthread_key_`	thread-specific data keys
`pthread_rwlock_`	read/write locks
`pthread_barrier_`	synchronization barriers

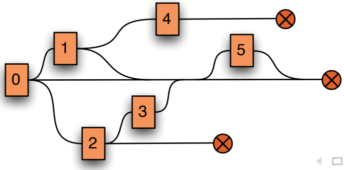
- the standard specifies the API for `C` only; `FORTRAN` support varies
  - must include `pthread.h`
- lots of good books; see **http://acm114.caltech.edu/references**

Creating threads

- create threads by calling

```c
int pthread_create(
    pthread_t* id, const pthread_attr_t* attr,
    void* (*startup)(void*), void* arg);
```

- initially a process has one thread; every other thread must be explicitly created by calling `pthread_create` and passing
  - `id`: the location where a unique thread identifier will be stored
  - `attr`: an opaque attribute object with thread initialization options
  - `startup`: a pointer to a `C` function that will be executed by the thread once it gets scheduled
  - `arg`: user defined data to be passed to `startup`; may be `NULL`
- once scheduled, threads are first class citizens
- the maximum number of threads per process depends on the implementation



Terminating threads

- several ways to terminate a thread
  - the thread returns from `main`
  - the thread explicitly calls `pthread_exit`
  - the thread is killed when another thread calls `pthread_cancel`
  - the process terminates due to some system call, e.g. `exit`, `exec`, etc.
- use `pthread_exit` to kill a thread when it is no longer needed

```c
int pthread_exit(void * status);
```

- if `main` finishes and any threads remain
  - they get killed unless `main` has called `pthread_exit`
  - otherwise they continue to run
- thread routines do not have to call `pthread_exit` unless they intend to pass their termination status to their creator
- `pthread_exit` does not perform any process cleanup: it doesn't flush/close files, release other resources, signal the process parent, etc.

Hello world

```
#include <pthread.h>
#include <stdio.h>
#define THREADS 10

void* hello(void* threadID) {
   long id = (long) threadID;
   printf("hello from %02ld/%0d\n", id, THREADS);
   pthread_exit(NULL);
   return NULL;
}

int main(int argc, char* argv[]) {
   long id;
   int status;
   pthread_t threads[THREADS];

   for (id=0; id<THREADS; id++) {
      printf("creating thread %02ld\n", id);
      status = pthread_create(&threads[id], NULL, hello, (void*) id);
      if (status) {
         printf("error %d in pthread_create\n", status);
      }
   }

   pthread_exit(NULL);
   return 0;
}
```

Joining and detaching

- in the example in Slide 7, 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

```
int pthread_mutex_init(
   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

```
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

```
int pthread_mutex_lock(pthread_mutex_t* mutex);
int pthread_mutex_trylock(pthread_mutex_t* mutex);
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

Condition variables

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

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

- and destroyed using

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

Using condition variables

- the following three routies implement the condition variable semantics

```
int pthread_cond_wait(pthread_cond_t* cond, pthread_mutex_t* mutex);
int pthread_cond_signal(pthread_cond_t* cond);
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

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

int pthread_mutexattr_init(pthread_mutexattr_t* attr);
int pthread_mutexattr_destroy(pthread_mutexattr_t* attr);

int pthread_condattr_init(pthread_condattr_t* attr);
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

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

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

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

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

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

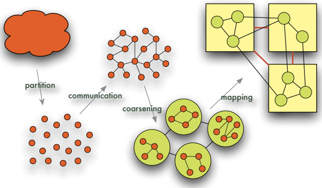
```
int pthread_once(pthread_once_t* control_structure, void (*startup_routine)
```

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