Lecture 6:
Intro to shared memory programming

David Bindel

15 Sep 2011

Logistics

- For HW 1:
  - Remember it's due by midnight tomorrow!
  - If you can't get to CMS or the cluster, let me know today.
- For Project 1:
  - I've mailed initial pairings. Groups of up to 3.
  - I'll post some suggested optimizations (probably tomorrow).
  - I will look for two things when grading:
    - Did you find some optimization strategy that made the code faster? Getting 2 Gflop/s (say) should be reasonable.
    - Did you write a correct and comprehensible description of your strategy, telling me what did or did not work?
  - If you copy over the files one at a time to `crocus` and are getting a "permission denied" error when you try `make run`, make sure that `make_sge.sh` is executable:
    `chmod +x make_sge.sh`

Preliminary list of Proj 1 notes

- Play nice. Use `make run` to run your timer.
- Play with the compiler flags!
- Spend some time thinking about memory patterns, including:
  - Loop prders
  - Different blocking factors
  - Dealing with edge blocks
  - Copy optimizations
- May want to play with low-level (SSE)
  - Probably via a different timing framework
- Could be fun to automatically test ideas (code generator)

Reminder: Shared memory programming model

Program consists of *threads* of control.

- Can be created dynamically
- Each has private variables (e.g. local)
- Each has shared variables (e.g. heap)
- Communication through shared variables
- Coordinate by synchronizing on variables
- Examples: pthreads, OpenMP, Cilk, Java threads

Mechanisms for thread birth/death

- Statically allocate threads at start
- Fork/join (pthreads)
- Fork detached threads (pthreads)
- Cobegin/coend (OpenMP?)
  - Like fork/join, but lexically scoped
- Futures (?)
  - `v = future(somefun(x))`
  - Attempts to use `v` wait on evaluation

Mechanisms for synchronization

- Locks/mutexes (enforce mutual exclusion)
- Monitors (like locks with lexical scoping)
- Barriers
- Condition variables (notification)

Concrete code: pthreads

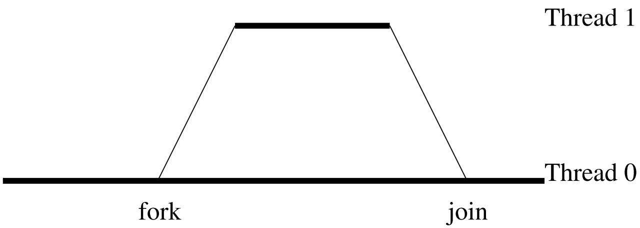
- pthreads = POSIX threads
- Standardized across UNIX family
- Fairly low-level
- Heavy weight?

Wait, what's a thread?

Processes have *state*. Threads share some:

- Instruction pointer (per thread)
- Register file (per thread)
- Call stack (per thread)
- Heap memory (shared)

Thread birth and death



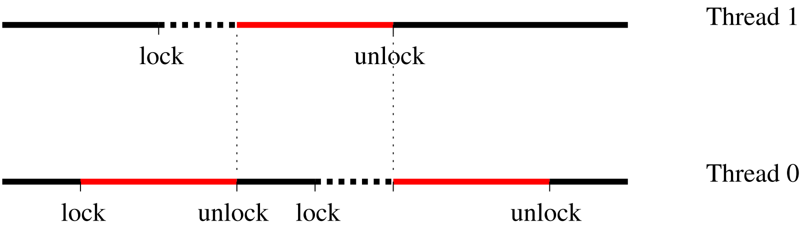
Thread is created by *forking*.
When done, *join* original thread.

Thread birth and death

```
void thread_fun(void* arg);

pthread_t thread_id;
pthread_create(&thread_id, &thread_attr,
               thread_fun, &fun_arg);
...
pthread_join(&thread_id, NULL);
```

Mutex

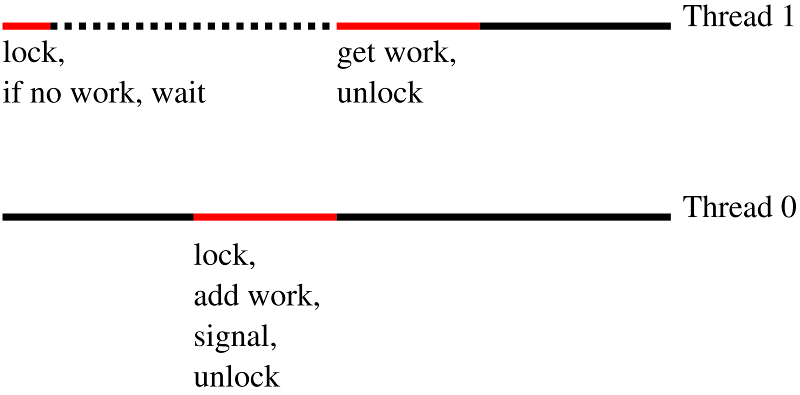


Allow only one process at a time in *critical section* (red).
Synchronize using locks, aka mutexes (*mutual exclusion vars*).

Mutex

```
pthread_mutex_t l;
pthread_mutex_init(&l, NULL);
...
pthread_mutex_lock(&l);
/* Critical section here */
pthread_mutex_unlock(&l);
...
pthread_mutex_destroy(&l);
```

Condition variables



Allow thread to wait until condition holds (e.g. work available).

Condition variables

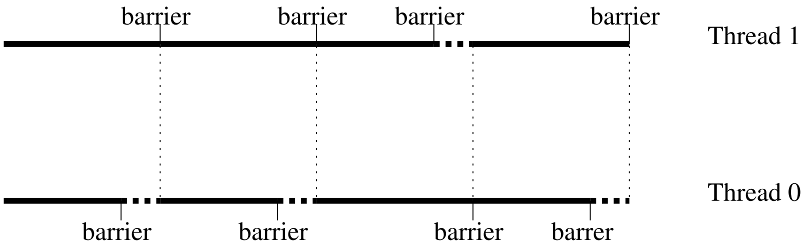
```
pthread_mutex_t l;
pthread_cond_t cv;
pthread_mutex_init(&l)
pthread_cond_init(&cv, NULL);
```

```
/* Thread 0 */
mutex_lock(&l);
add_work();
cond_signal(&cv);
mutex_unlock(&l);
```

```
/* Thread 1 */
mutex_lock(&l);
if (!work_ready)
    cond_wait(&cv, &l);
get_work();
mutex_unlock();
```

```
pthread_cond_destroy(&cv);
pthread_mutex_destroy(&l);
```

Barriers



Computation phases separated by barriers.
Everyone reaches the barrier, then proceeds.

Barriers

```
pthread_barrier_t b;
pthread_barrier_init(&b, NULL, nthreads);
...
pthread_barrier_wait(&b);
...
```

Synchronization pitfalls

- Incorrect synchronization $\implies$ *deadlock*
  - All threads waiting for what the others have
  - Doesn't always happen! $\implies$ hard to debug
- Too little synchronization $\implies$ data races
  - Again, doesn't always happen!
- Too much synchronization $\implies$ poor performance
  - ... but makes it easier to think through correctness

Deadlock

Thread 0:

lock(l1); lock(l2);
Do something
unlock(l2); unlock(l1);

Thread 1:

lock(l2); lock(l1);
Do something
unlock(l1); unlock(l2);

Conditions:

1. Mutual exclusion
2. Hold and wait
3. No preemption
4. Circular wait

The problem with pthreads

Portable standard, but...

- Low-level library standard
- Verbose
- Makes it easy to goof on synchronization
- Compiler doesn't help out much

OpenMP is a common alternative.

Example: Work queues

- Job composed of different tasks
- Work gang of threads to execute tasks
- Maybe tasks can be added over time?
- Want dynamic load balance

Example: Work queues

Basic data:

- Gang of threads
- Work queue data structure
- Mutex protecting data structure
- Condition to signal work available
- Flag to indicate all done?

Example: Work queues

```
task_t get_task() {
  task_t result;
  pthread_mutex_lock(&task_l);
  if (done_flag) {
    pthread_mutex_unlock(&task_l);
    pthread_exit(NULL);
  }
  if (num_tasks == 0)
    pthread_cond_wait(&task_ready, &task_l);
  ... Remove task from data struct ...
  pthread_mutex_unlock(&task_l);
  return result;
}
```

Example: Work queues

```
void add_task(task_t task) {
  pthread_mutex_lock(&task_l);
  ... Add task to data struct ...
  if (num_tasks++ == 0)
    pthread_cond_signal(&task_ready);
  pthread_mutex_unlock(&task_l);
}
```

Monte Carlo

Basic idea: Express answer a as

$$a = E[f(X)]$$

for some random variable(s) X.

Typical toy example:

$$\pi/4 = E[\chi_{[0,1]}(X^2 + Y^2)] \text{ where } X, Y \sim U(-1, 1).$$

We'll be slightly more interesting...

A toy problem

Given ten points (X_i, Y_i) drawn uniformly in $[0, 1]^2$, what is the expected minimum distance between any pair?

Toy problem: Version 1

Serial version:

```
sum_fX = 0;
for i = 1:ntrials
  x = rand(10,2);
  fX = min distance between points in x;
  sum_fX = sum_fX + fx;
end
result = sum_fX/ntrials;
```

Parallel version: run twice and average results?!
No communication — *embarrassingly parallel*

Need to worry a bit about `rand`...

Error estimators

Central limit theorem: if R is computed result, then

$$R \sim N\left(E[f(X)], \frac{\sigma_{f(X)}}{\sqrt{n}}\right).$$

So:

- Compute sample standard deviation $\sigma_{\hat{f(X)}}$
- Error bars are $\pm\sigma_{\hat{f(X)}}/\sqrt{n}$
- Use error bars to monitor convergence

Toy problem: Version 2

Serial version:

```
sum_fX = 0;
sum_fX2 = 0;
for i = 1:ntrials
  x  = rand(10,2);
  fX = min distance between points in x;
  sum_fX  = sum_fX + fX;
  sum_fX2 = sum_fX + fX*fX;
  result = sum_fX/i;
  errbar = sqrt(sum_fX2-sum_fX*sum_fX/i)/i;
  if (abs(errbar/result) < reltol), break; end
end
result = sum_fX/ntrials;
```

Parallel version: ?

Pondering parallelism

Two major points:

- How should we handle random number generation?
- How should we manage termination criteria?

Some additional points (briefly):

- How quickly can we compute `fX`?
- Can we accelerate convergence (variance reduction)?