Lecture 7: Shared memory programming

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Logistics

- Still have a couple people looking for groups – help out?
- Check out this week's CS colloquium:
  "Trumping the Multicore Memory Hierarchy with Hi-Spade"

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)?

Pseudo-random number generation

- Pretend *deterministic* and process is random.
  $\Longrightarrow$ We lose if it doesn't *look* random!
- RNG functions have *state*
  $\Longrightarrow$ Basic `random()` call is *not* thread-safe!
- Parallel strategies:
  - Put RNG in critical section (slow)
  - Run independent RNGs per thread
    - Concern: correlation between streams
  - Split stream from one RNG
    - E.g. thread 0 uses even steps, thread 1 uses odd steps
    - Helpful if it's cheap to skip steps!
- Good libraries help! Mersenne twister, SPRNG, ...?

One solution

- Use a version of Mersenne twister with no global state:

```
void sgenrand(long seed,
              struct mt19937p* mt);
double genrand(struct mt19937p* mt);
```

- Choose pseudo-random seeds per thread at startup:

```
long seeds[NTHREADS];
srandom(clock());
for (i = 0; i < NTHREADS; ++i)
    seeds[i] = random();
...
/* sgenrand(seeds[i], mt) for thread i */
```

Toy problem: Version 2.1p

```
sum_fX = 0; sum_fX2 = 0; n = 0;
for each thread in parallel
  do
    fX = result of one random trial
    ++n;
    sum_fX += fX;
    sum_fX2 += fX*fX;
    errbar = ...
    if (abs(errbar/result) < reltol), break; end
  loop
end
result = sum_fX/n;
```

Toy problem: Version 2.2p

```
sum_fX = 0; sum_fX2 = 0; n = 0; done = false;
for each thread in parallel
  do
    fX = result of one random trial
    get lock
      ++n;
      sum_fX = sum_fX + fX;
      sum_fX2 = sum_fX2 + fX*fX;
      errbar = ...
      if (abs(errbar/result) < reltol)
        done = true;
      end
    release lock
  until done
end
result = sum_fX/n;
```

Toy problem: Version 2.3p

```
sum_fX = 0; sum_fX2 = 0; n = 0; done = false;
for each thread in parallel
  do
    batch_sum_fX, batch_sum_fX2 = B trials
    get lock
      n += B;
      sum_fX += batch_sum_fX;
      sum_fX2 += batch_sum_fX2;
      errbar = ...
      if (abs(errbar/result) < reltol)
        done = true;
      end
    release lock
  until done or n > n_max
end
result = sum_fX/n;
```

Toy problem: actual code (pthreads)

Some loose ends

- Alternative: “master-slave” organization
  - Master sends out batches of work to slaves
  - Example: SETI at Home, Folding at Home, ...
- What is the right batch size?
  - Large $B \implies$ amortize locking/communication overhead (and variance actually helps with contention!)
  - Small B avoids too much extra work
- How to evaluate $f(X)$?
  - For p points, obvious algorithm is $O(p^2)$
  - Binning points better? No gain for p small...
- Is $f(X)$ the right thing to evaluate?
  - Maybe $E[g(X)] = E[f(X)]$ but $\mathrm{Var}[g(X)] \ll \mathrm{Var}[f(X)]$?
  - May make much more difference than parallelism!

The problem with pthreads revisited

pthreads can be painful!

- Makes code verbose
- Synchronization is hard to think about

Would like to make this more automatic!

- ... and have been trying for a couple decades.
- OpenMP gets us *part* of the way

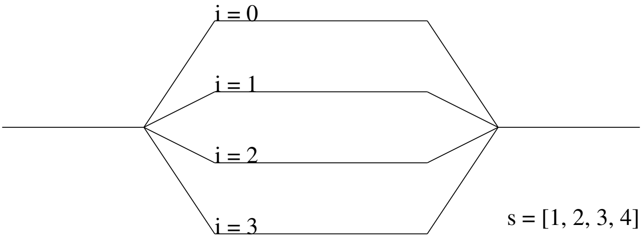
OpenMP: Open spec for MultiProcessing

- Standard API for multi-threaded code
  - Only a spec — multiple implementations
  - Lightweight syntax
  - C or Fortran (with appropriate compiler support)
- High level:
  - Preprocessor/compiler directives (80%)
  - Library calls (19%)
  - Environment variables (1%)

Parallel “hello world”

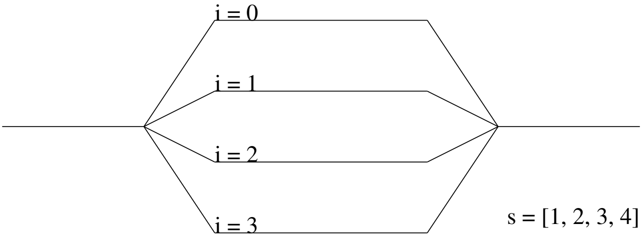
```
#include <stdio.h>
#include <omp.h>

int main()
{
    #pragma omp parallel
    printf("Hello world from %d\n",
           omp_get_thread_num());

    return 0;
}
```

Parallel sections



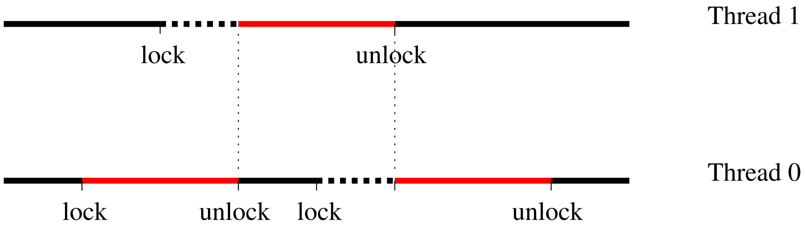
- Basic model: fork-join
- Each thread runs same code block
- Annotations distinguish shared (*s*) and private (*i*) data
- *Relaxed consistency* for shared data

Parallel sections



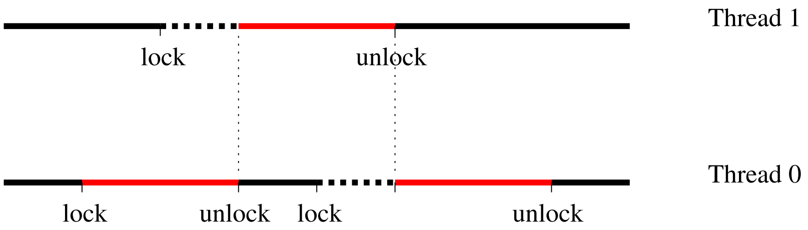

```
...
double s[MAX_THREADS];
int i;
#pragma omp parallel shared(s) private(i)
{
  i = omp_get_thread_num();
  s[i] = i;
}
...
```

Critical sections



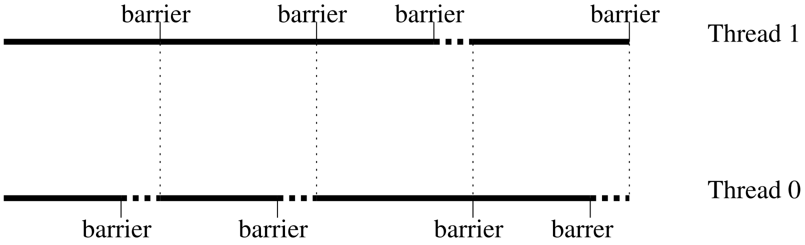
- Automatically lock/unlock at ends of *critical section*
- Automatically memory flushes for consistency
- Locks are still there if you really need them...

Critical sections




```
#pragma omp parallel {
  ...
  #pragma omp critical my_data_cs
  {
    ... modify data structure here ...
  }
}
```

Barriers




```
#pragma omp parallel
for (i = 0; i < nsteps; ++i) {
  do_stuff
  #pragma omp barrier
}
```

Toy problem: actual code (OpenMP)

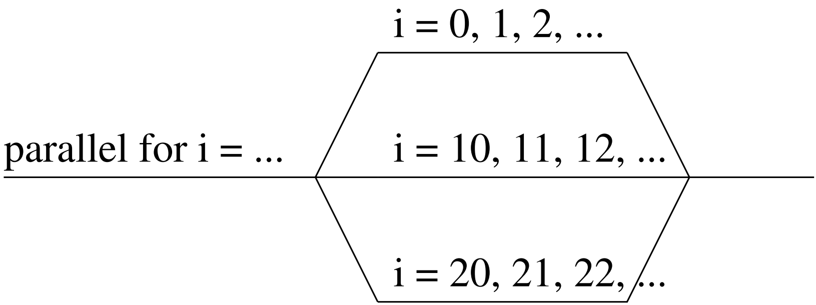
Toy problem: actual code (OpenMP)

A practical aside...

- GCC 4.3+ has OpenMP support by default
  - Earlier versions may support (e.g. latest Xcode `gcc-4.2`)
  - GCC 4.4 (prerelease) for my laptop has buggy support!
  - `-O3 -fopenmp` == death of an afternoon
- Need `-fopenmp` for both compile and link lines

```
gcc -c -fopenmp foo.c
gcc -o -fopenmp mycode.x foo.o
```

Parallel loops



- Independent loop body? At least order doesn't matter[1].
- Partition index space among threads
- Implicit barrier at end (except with `nowait`)

[1] If order matters, there's an `ordered` modifier.

Parallel loops

```
/* Compute dot of x and y of length n */
int i, tid;
double my_dot, dot = 0;
#pragma omp parallel \
        shared(dot,x,y,n) \
        private(i,my_dot)
{
  tid = omp_get_thread_num();
  my_dot = 0;

  #pragma omp for
  for (i = 0; i < n; ++i)
    my_dot += x[i]*y[i];

  #pragma omp critical
  dot += my_dot;
}
```

Parallel loops

```
/* Compute dot of x and y of length n */
int i, tid;
double dot = 0;
#pragma omp parallel \
        shared(x,y,n) \
        private(i) \
        reduction(+:dot)
{
  #pragma omp for
  for (i = 0; i < n; ++i)
    dot += x[i]*y[i];
}
```

Parallel loop scheduling

Partition index space different ways:

- `static[(chunk)]`: decide at start of loop; default chunk is `n/nthreads`. Lowest overhead, most potential load imbalance.
- `dynamic[(chunk)]`: each thread takes `chunk` iterations when it has time; default `chunk` is 1. Higher overhead, but automatically balances load.
- `guided`: take chunks of size unassigned iterations/threads; chunks get smaller toward end of loop. Somewhere between `static` and `dynamic`.
- `auto`: up to the system!

Default behavior is implementation-dependent.

Other parallel work divisions

- `single`: do only in one thread (e.g. I/O)
- `master`: do only in one thread; others skip
- `sections`: like cobegin/coend

Essential complexity?

Fred Brooks (*Mythical Man Month*) identified two types of software complexity: essential and accidental.

Does OpenMP address accidental complexity? Yes, somewhat!

Essential complexity is harder.

Things to still think about with OpenMP

- Proper serial performance tuning?
- Minimizing false sharing?
- Minimizing synchronization overhead?
- Minimizing loop scheduling overhead?
- Load balancing?
- Finding enough parallelism in the first place?

Let's focus again on memory issues...

Memory model

- Single processor: return last write
  - What about DMA and memory-mapped I/O?
- Simplest generalization: *sequential consistency* – as if
  - Each process runs in program order
  - Instructions from different processes are interleaved
  - Interleaved instructions ran on one processor

Sequential consistency

A multiprocessor is sequentially consistent if the result of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program.

– Lamport, 1979

Example: Spin lock

Initially, `flag = 0` and `sum = 0`

Processor 1:

```
sum += p1;
flag = 1;
```

Processor 2:

```
while (!flag);
sum += p2;
```

Example: Spin lock

Initially, `flag = 0` and `sum = 0`

Processor 1:

```
sum += p1;
flag = 1;
```

Processor 2:

```
while (!flag);
sum += p2;
```

Without sequential consistency support, what if

1. Processor 2 caches `flag`?
2. Compiler optimizes away loop?
3. Compiler reorders assignments on P1?

Starts to look restrictive!

Sequential consistency: the good, the bad, the ugly

Program behavior is “intuitive”:

- Nobody sees garbage values
- Time always moves forward

One issue is *cache coherence*:

- Coherence: different copies, same value
- Requires (nontrivial) hardware support

Also an issue for optimizing compiler!

There are cheaper *relaxed* consistency models.

Snoopy bus protocol

Basic idea:

- Broadcast operations on memory bus
- Cache controllers “snoop” on all bus transactions
  - Memory writes induce serial order
  - Act to enforce coherence (invalidate, update, etc)

Problems:

- Bus bandwidth limits scaling
- Contending writes are slow

There are other protocol options (e.g. directory-based).
But usually give up on *full* sequential consistency.

Weakening sequential consistency

Try to reduce to the *true* cost of sharing

- `volatile` tells compiler when to worry about sharing
- Memory fences tell when to force consistency
- Synchronization primitives (lock/unlock) include fences

Sharing

True sharing:

- Frequent writes cause a bottleneck.
- Idea: make independent copies (if possible).
- Example problem: malloc/free data structure.

False sharing:

- Distinct variables on same cache block
- Idea: make processor memory contiguous (if possible)
- Example problem: array of ints, one per processor

Take-home message

- Sequentially consistent shared memory is a useful idea...
  - "Natural" analogue to serial case
  - Architects work hard to support it
- ... but implementation is costly!
  - Makes life hard for optimizing compilers
  - Coherence traffic slows things down
  - Helps to limit sharing

Have to think about these things to get good performance.