CS4961 Parallel Programming

Lecture 5: More OpenMP, Introduction to Data Parallel Algorithms

Mary Hall
September 4, 2012

Administrative

- Mailing list set up, everyone should be on it
  - You should have received a test mail last night to your umail account. Let me know if you prefer a different account.
- TA: Axel Rivera, axel.rivera@utah.edu

  Office hours: Wednesday, Friday, 10-10:30AM in undergrad lounge

Homework 2: Mapping to Architecture

Due before class, Thursday, September 6

Objective: Begin thinking about architecture mapping issues

Turn in electronically on the CADE machines using the handin program: "handin cs4230 hw2 <probfile>"

- Problem 1: (2.3 in text) [Locality]
- Problem 2: (2.8 in text) [Caches and multithreading]
- Problem 3: [Amdahl's Law] A multiprocessor consists of 100 processors, each capable of a peak execution rate of 20 Gflops. What is performance of the system as measured in Gflops when 20% of the code is sequential and 80% is parallelizable?
- Problem 4: (2.16 in text) [Parallelization scaling]
- Problem 5: [Buses and crossbars] Suppose you have a computation that uses two vector inputs to compute a vector output, where each vector is stored in consecutive memory locations. Each input and output location is unique, but data is loaded/stored from cache in 4-word transfers. Suppose you have P processors and N data elements, and execution time is a function of time L for a load from memory and time C for the computation. Compare parallel execution time for a shared memory architecture with a bus (Nehalem) versus a full crossbar (Niagara) from Lecture 3, assuming a write back cache that is larger than the data footprint.

Programming Assignment 1: Due Friday, Sept. 14, 11PM MDT

To be done on water.eng.utah.edu (you all have accounts – passwords available if your CS account doesn't work)

1. Write a program to calculate π in OpenMP for a problem size and data set to be provided. Use a block data distribution.
2. Write the same computation in Pthreads.

Report your results in a separate README file.

- What is the parallel speedup of your code? To compute parallel speedup, you will need to time the execution of both the sequential and parallel code, and report speedup = Time(seq) / Time (parallel)
- If your code does not speed up, you will need to adjust the parallelism granularity, the amount of work each processor does between synchronization points. You can do this by either decreasing the number of threads or increasing the number of iterations.
- Report results for two different # of threads, holding iterations fixed, and two different # of iterations holding threads fixed. Also report lines of code for the two solutions.

Extra credit: Rewrite both codes using a cyclic distribution and measure performance for same configurations.

Programming Assignment 1, cont.

- A test harness is provided in pi-test-harness.c that provides a sequential pi calculation, validation, speedup timing and substantial instructions on what you need to do to complete the assignment.
- Here are the key points:
  - You'll need to write the parallel code, and the things needed to support that. Read the top of the file, and search for "TODO".
  - Compile w/ OpenMP: cc –o pi-openmp –O3 –xopenmp pi-openmp.c
  - Compile w/ Pthreads:
    cc -o pi-pthreads -O3 pi-pthreads.c -lpthread
  - Run OpenMP version: ./pi-openmp > openmp.out
  - Run Pthreads version: ./pi-pthreads > pthreads.out
- Note that editing on water is somewhat primitive – I'm using vim. You may want to edit on a different CADE machine.

Estimating π

$$\pi = 4\left[1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \cdots\right] = 4\sum_{k=0}^{\infty} \frac{(-1)^k}{2k+1}$$

```
double factor = 1.0;
double sum = 0.0;
for (k = 0; k < n; k++) {
   sum += factor/(2*k+1);
   factor = -factor;
}
pi_approx = 4.0*sum;
```


Today's Lecture

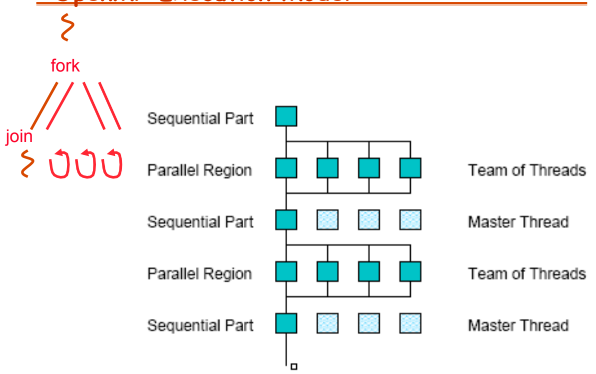
- Data Parallelism in OpenMP
  - Expressing Parallel Loops
  - Parallel Regions (SPMD)
  - Scheduling Loops
  - Synchronization
- Sources of material:
  - Textbook
  - https://computing.llnl.gov/tutorials/openMP/

OpenMP: Prevailing Shared Memory Programming Approach

- Model for shared-memory parallel programming
- Portable across shared-memory architectures
- Scalable (on shared-memory platforms)
- Incremental parallelization
  - Parallelize individual computations in a program while leaving the rest of the program sequential
- Compiler based
  - Compiler generates thread program and synchronization
- Extensions to existing programming languages (Fortran, C and C++)
  - mainly by directives
  - a few library routines

See http://www.openmp.org

OpenMP Execution Model



OpenMP parallel region construct

- Block of code to be executed by multiple threads in parallel
- Each thread executes the **same code redundantly (SPMD)**
  - Work within work-sharing constructs is distributed among the threads in a team
- Example with C/C++ syntax

  `#pragma omp parallel` [clause [clause] ...] new-line

  structured-block
- clause can include the following:

  `private` (list)

  `shared` (list)

Programming Model – Data Sharing

- Parallel programs often employ two types of data
  - Shared data, visible to all threads, similarly named
  - Private data, visible to a single thread (often stack-allocated)
- PThreads:
  - Global-scoped variables are shared
  - Stack-allocated variables are private
- OpenMP:
  - **shared** variables are shared
  - **private** variables are private
  - Default is **shared**
  - Loop index is **private**

```
// shared, globals
int bigdata[1024];

void* foo(void* bar) {
  int tid;

  #pragma omp parallel \
   shared ( bigdata ) \
   private ( tid )
  {
    /* Calc. here */
  }
}
```

OpenMP Data Parallel Construct: Parallel Loop

- All pragmas begin: #pragma
- Compiler calculates loop bounds for each thread directly from *serial* source (computation decomposition)
- Compiler also manages data partitioning of Res
- Synchronization also automatic (barrier)

Serial Program:	Parallel Program:

void main()
{
double Res[1000];
 	
for(int i=0;i<1000;i++) {
do_huge_comp(Res[i]);
}
}
	void main()
	{
	double Res[1000];
	#pragma omp parallel for
	for(int i=0;i<1000;i++) {
	do_huge_comp(Res[i]);
	}
	}

Limitations and Semantics

- Not all "element-wise" loops can be ||ized

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

  - Loop index: signed integer
  - Termination Test: <,<=,>,=> with loop invariant int
  - Incr/Decr by loop invariant int; change each iteration
  - Count up for <,<=; count down for >,>=
  - Basic block body: no control in/out except at top
- Threads are created and iterations divvied up; requirements ensure iteration count is predictable
- What would happen if one thread were allowed to terminate early?

OpenMP implicit semantics (sum version 5)

- Implicit barrier at the end of each loop
- Without a directive, code executes sequentially

OpenMP critical directive (sum version 3)

- Enclosed code
- executed by all threads, but
- **restricted to only one thread at a time**

```
#pragma omp critical [ ( name ) ] new-line
  structured-block
```

- A thread waits at the beginning of a critical region until no other thread in the team is executing a critical region with the same name.
- All unnamed `critical` directives map to the same unspecified name.

OpenMp Reductions

- OpenMP has reduce operation

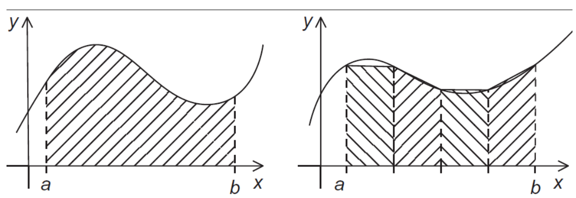
```
sum = 0;
#pragma omp parallel for reduction(+:sum)
for (i=0; i < 100; i++)   {
sum += array[i];
}
```

- Reduce ops and init() values (C and C++):

+	0	bitwise &	~0	logical &	1
-	0	bitwise |	0	logical |	0
*	1	bitwise ^	0		

FORTRAN also supports min and max reductions

The trapezoidal rule

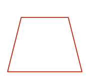


Serial algorithm

```
/* Input:  a, b, n */
h = (b-a)/n;
approx = (f(a) + f(b))/2.0;
for (i = 1; i <= n-1; i++) {
   x_i = a + i*h;
   approx += f(x_i);
}
approx = h*approx;
```



```
h = (b-a)/n;
approx = (f(a) + f(b))/2.0;
for (i = 1; i <= n-1; i++)
   approx += f(a + i*h);
approx = h*approx;
```



```
   h = (b-a)/n;
   approx = (f(a) + f(b))/2.0;
#  pragma omp parallel for num_threads(thread_count) \
      reduction(+: approx)
   for (i = 1; i <= n-1; i++)
      approx += f(a + i*h);
   approx = h*approx;
```



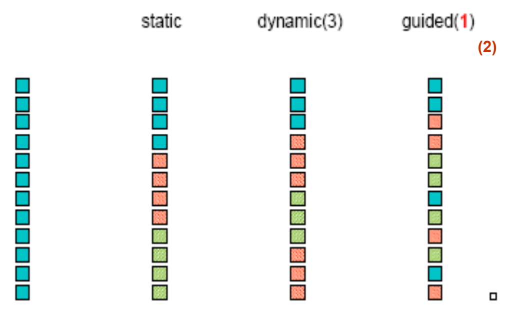
```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>

void Trap(double a, double b, int n, double* global_result_p);

int main(int argc, char* argv[]) {
   double  global_result = 0.0;  /* Store result in global_result */
   double  a, b;                 /* Left and right endpoints      */
   int     n;                    /* Total number of trapezoids    */
   int     thread_count;

   thread_count = strtol(argv[1], NULL, 10);
   printf("Enter a, b, and n\n");
   scanf("%lf %lf %d", &a, &b, &n);
#  pragma omp parallel num_threads(thread_count)
   Trap(a, b, n, &global_result);

   printf("With n = %d trapezoids, our estimate\n", n);
   printf("of the integral from %f to %f = %.14e\n",
      a, b, global_result);
   return 0;
}  /* main */
```

```c
void Trap(double a, double b, int n, double* global_result_p) {
   double  h, x, my_result;
   double  local_a, local_b;
   int  i, local_n;
   int my_rank = omp_get_thread_num();
   int thread_count = omp_get_num_threads();

   h = (b-a)/n;
   local_n = n/thread_count;
   local_a = a + my_rank*local_n*h;
   local_b = local_a + local_n*h;
   my_result = (f(local_a) + f(local_b))/2.0;
   for (i = 1; i <= local_n-1; i++) {
     x = local_a + i*h;
     my_result += f(x);
   }
   my_result = my_result*h;

#  pragma omp critical
   *global_result_p += my_result;
}  /* Trap */
```


Programming Model – Loop Scheduling

- `schedule` clause determines how loop iterations are divided among the thread team
  - **`static([chunk])`** divides iterations statically between threads
    - Each thread receives `[chunk]` iterations, rounding as necessary to account for all iterations
    - Default **`[chunk]`** is **`ceil( # iterations / # threads )`**
  - **`dynamic([chunk])`** allocates **`[chunk]`** iterations per thread, allocating an additional **`[chunk]`** iterations when a thread finishes
    - Forms a logical work queue, consisting of all loop iterations
    - Default **`[chunk]`** is 1
  - **`guided([chunk])`** allocates dynamically, but **`[chunk]`** is exponentially reduced with each allocation

Loop scheduling



More loop scheduling attributes

- RUNTIME The scheduling decision is deferred until runtime by the environment variable OMP_SCHEDULE. It is illegal to specify a chunk size for this clause.
- AUTO The scheduling decision is delegated to the compiler and/or runtime system.
- **NO WAIT / nowait**: If specified, then threads do not synchronize at the end of the parallel loop.
- **ORDERED**: Specifies that the iterations of the loop must be executed as they would be in a serial program.
- **COLLAPSE**: Specifies how many loops in a nested loop should be collapsed into one large iteration space and divided according to the schedule clause (collapsed order corresponds to original sequential order).

Impact of Scheduling Decision

- Load balance
  - Same work in each iteration?
  - Processors working at same speed?
- Scheduling overhead
  - Static decisions are cheap because they require no run-time coordination
  - Dynamic decisions have overhead that is impacted by complexity and frequency of decisions
- Data locality
  - Particularly within cache lines for small chunk sizes
  - Also impacts data reuse on same processor

A Few Words About Data Distribution

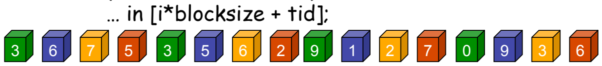
- Data distribution describes how global data is partitioned across processors.
  - Recall the CTA model and the notion that a portion of the global address space is physically co-located with each processor
- This data partitioning is implicit in OpenMP and may not match loop iteration scheduling
- Compiler will try to do the right thing with static scheduling specifications

Common Data Distributions

- Consider a 1-Dimensional array to solve the global sum problem, 16 elements, 4 threads

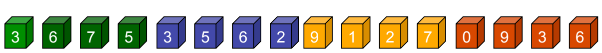
CYCLIC (chunk = 1):

```
for (i = 0; i<blocksize; i++)
    … in [i*blocksize + tid];
```

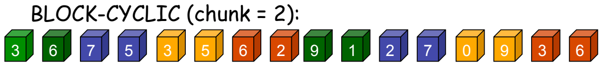


BLOCK (chunk = 4):

```
for (i=tid*blocksize; i<(tid+1) *blocksize; i++)
   … in[i];
```



BLOCK-CYCLIC (chunk = 2):



The Schedule Clause

- Default schedule:

```
   sum = 0.0;
#  pragma omp parallel for num_threads(thread_count) \
      reduction(+:sum)
   for (i = 0; i <= n; i++)
      sum += f(i);
```

```
   sum = 0.0;
#  pragma omp parallel for num_threads(thread_count) \
      reduction(+:sum) schedule(static,1)
   for (i = 0; i <= n; i++)
      sum += f(i);
```

OpenMP Synchronization

- Implicit barrier
  - At beginning and end of parallel constructs
  - At end of all other control constructs
  - Implicit synchronization can be removed with `nowait` clause
- Explicit synchronization
  - `critical`
  - `atomic (single statement)`
  - `barrier`

Variation: OpenMP parallel and for directives

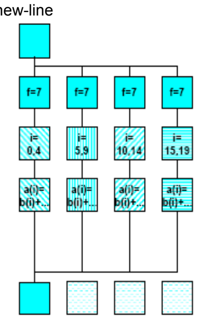
Syntax:

`#pragma omp for` [clause [clause] ...] new-line

for-loop

clause can be one of the following:

`shared (list)`
`private(` list`)`
`reduction(` operator`:` list`)`
`schedule(` type [, chunk] `)`
`nowait` (C/C++: on `#pragma omp for`)




```
#pragma omp parallel private(f) {
  f=7;
#pragma omp for
    for (i=0; i<20; i++)
    a[i] = b[i] + f * (i+1);
} /* omp end parallel */
```


OpenMP environment variables

OMP_NUM_THREADS

- sets the number of threads to use during execution
- when dynamic adjustment of the number of threads is enabled, the value of this environment variable is the maximum number of threads to use
- For example,

  `setenv OMP_NUM_THREADS 16` **[csh, tcsh]**

  `export OMP_NUM_THREADS=16` **[sh, ksh, bash]**

OMP_SCHEDULE

- applies only to `do/for` and `parallel do/for` directives that have the schedule type `RUNTIME`
- sets schedule type and chunk size for all such loops
- For example,

  `setenv OMP_SCHEDULE GUIDED,4` **[csh, tcsh]**

  `export OMP_SCHEDULE= GUIDED,4` **[sh, ksh, bash]**

Summary of Lecture

- OpenMP, data-parallel constructs only
  - Task-parallel constructs later
- What's good?
  - Small changes are required to produce a parallel program from sequential (parallel formulation)
  - Avoid having to express low-level mapping details
  - Portable and scalable, correct on 1 processor
- What is missing?
  - Not completely natural if want to write a parallel code from scratch
  - Not always possible to express certain common parallel constructs
  - Locality management
  - Control of performance