CS4961 Parallel Programming

Lecture 4: Memory Systems and Introduction to Threads (Pthreads and OpenMP)

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August 30, 2012

Homework 1: Parallel Programming Basics

Due before class, Thursday, August 30

Turn in electronically on the CADE machines using the handin program: "handin cs4230 hw1 <probfile>"

- Problem 1: (from today's lecture) We can develop a model for the performance behavior from the versions of parallel sum in today's lecture based on sequential execution time S, number of threads T, parallelization overhead O (fixed for all versions), and the cost B for the barrier or M for each invocation of the mutex. Let N be the number of elements in the list. For version 5, there is some additional work for thread 0 that you should also model using the variables above. (a) Using these variables, what is the execution time of valid parallel versions 2, 3 and 5; (b) present a model of when parallelization is profitable for version 3; (c) discuss how varying T and N impact the relative profitability of versions 3 and 5.

Homework 1: Parallel Programming Basics

- Problem 2: (#1.3 in textbook): Try to write pseudo-code for the tree-structured global sum illustrated in Figure 1.1. Assume the number of cores is a power of two (1, 2, 4, 8, …).

Hints: Use a variable `divisor` to determine whether a core should send its sum or receive and add. The `divisor` should start with the value 2 and be doubled after each iteration. Also use a variable `core_difference` to determine which core should be partnered with the current core. It should start with the value 1 and also be doubled after each iteration. For example, in the first iteration `0 % divisor = 0` and `1 % divisor = 1`, so 0 receives and adds, while 1 sends. Also in the first iteration `0 + core_difference = 1` and `1 – core_difference = 0`, so 0 and 1 are paired in the first iteration.

Homework 1, cont.

- Problem 3: What are your goals after this year and how do you anticipate this class is going to help you with that? Some possible answers, but please feel free to add to them. Also, please write at least one sentence of explanation.
  - A job in the computing industry
  - A job in some other industry that uses computing
  - As preparation for graduate studies
  - To satisfy intellectual curiosity about the future of the computing field
  - Other

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.

Reading for Today

- Chapter 2.4-2.4.3 (pgs. 47-52)

2.4 Parallel Software
- Caveats
- Coordinating the processes/threads
- Shared-memory

- Chapter 4.1-4.2 (pgs. 151-159)

4.0 Shared Memory Programming with Pthreads
- Processes, Threads, and Pthreads
- Hello, World in Pthreads

- Chapter 5.1 (pgs. 209-215)

5.0 Shared Memory Programming with OpenMP
- Getting Started

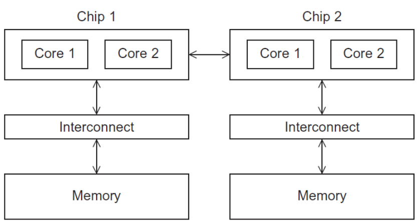
Today's Lecture

- Discussion of Memory Systems
- Review Shared Memory and Distributed Memory Programming Models
- Brief Overview of POSIX Threads (Pthreads)
- Data Parallelism in OpenMP
  - Expressing Parallel Loops
  - Parallel Regions (SPMD)
  - Scheduling Loops
  - Synchronization
- Sources of material:
  - Textbook
  - Jim Demmel and Kathy Yelick, UCB
  - openmp.org

Shared Memory vs. Distributed Memory Programs

- Shared Memory Programming
  - Start a single process and fork threads.
  - Threads carry out work.
  - Threads communicate through shared memory.
  - Threads coordinate through synchronization (also through shared memory).
- Distributed Memory Programming
  - Start multiple processes on multiple systems.
  - Processes carry out work.
  - Processes communicate through message-passing.
  - Processes coordinate either through message-passing or synchronization (generates messages).

Non-uniform Memory Access (NUMA) multicore system



A memory location a core is directly connected to can be accessed faster than a memory location that must be accessed through another chip.

Figure 2.6

Cache coherence

- Programmers have no direct control over caches and when they get updated.
- However, they can organize their computation to access memory in a different order.

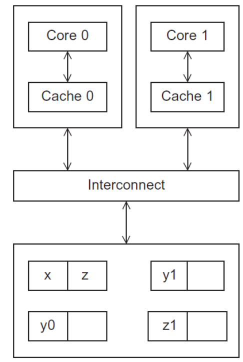


Figure 2.17

A shared memory system with two cores and two caches

Cache coherence

y0 privately owned by Core 0

y1 and z1 privately owned by Core 1

x = 2; /* shared variable */

Time	Core 0	Core 1
0	`y0 = x;`	`y1 = 3*x;`
1	`x = 7;`	Statement(s) not involving x
2	Statement(s) not involving x	`z1 = 4*x;`

y0 eventually ends up = 2

y1 eventually ends up = 6

z1 = ???

Snooping Cache Coherence

- The cores share a bus.
- Any signal transmitted on the bus can be "seen" by all cores connected to the bus.
- When core 0 updates the copy of x stored in its cache it also broadcasts this information across the bus.
- If core 1 is "snooping" the bus, it will see that x has been updated and it can mark its copy of x as invalid.

Directory Based Cache Coherence

- Uses a data structure called a directory that stores the status of each cache line.
- When a variable is updated, the directory is consulted, and the cache controllers of the cores that have that variable's cache line in their caches are invalidated.

False Sharing

- A cache line contains more than one machine word.
- When multiple processors access the same cache line, it may look like a potential race condition, even if they access different elements.
- Can cause coherence traffic.

Shared memory interconnects

- Bus interconnect
  - A collection of parallel communication wires together with some hardware that controls access to the bus.
  - Communication wires are shared by the devices that are connected to it.
  - As the number of devices connected to the bus increases, contention for use of the bus increases, and performance decreases.

Shared memory interconnects

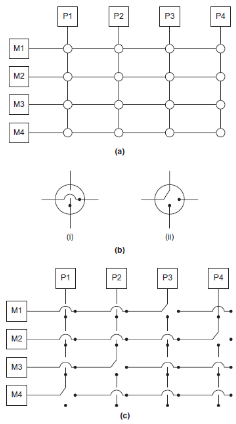
- Switched interconnect
  - Uses switches to control the routing of data among the connected devices.
  - Crossbar –
    - Allows simultaneous communication among different devices.
    - Faster than buses.
    - But the cost of the switches and links is relatively high.
    - Crossbars grow as n^2 *making them impractical for large n*

Figure 2.7

(a)
A crossbar switch connecting 4 processors (P_i) and 4 memory modules (M_j)

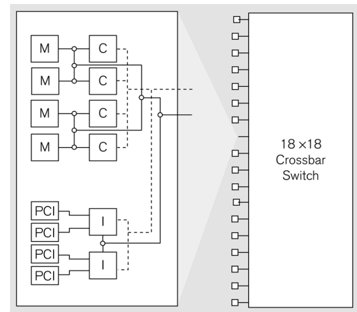
(b)
Configuration of internal switches in a crossbar

(c) Simultaneous memory accesses by the processors



SunFire E25K

- 4 UltraSparcs
- Dotted lines represent snooping
- 18 boards connected with crossbars
  - Basically the limit
  - Increasing processors per node will, on average, increase congestion



Shared Memory

- Dynamic threads
  - Master thread waits for work, forks new threads, and when threads are done, they terminate
  - Efficient use of resources, but thread creation and termination is time consuming.
- Static threads
  - Pool of threads created and are allocated work, but do not terminate until cleanup.
  - Better performance, but potential waste of system resources.

Thread Safety

- Chapter 2 mentions thread safety of shared-memory parallel functions or libraries.
  - A function or library is thread-safe if it operates "correctly" when called by multiple, simultaneously executing threads.
  - Since multiple threads communicate and coordinate through shared memory, a thread-safe code modifies the state of shared memory using appropriate synchronization.
  - Some features of sequential code that may not be thread safe?

Programming with Threads

Several thread libraries, more being created

- PThreads is the POSIX Standard
  - Relatively low level
    - Programmer expresses thread management and coordination
    - Programmer decomposes parallelism and manages schedule
  - Portable but possibly slow
  - Most widely used for systems-oriented code, and also used for some kinds of application code
- OpenMP is newer standard
  - Higher-level support for scientific programming on shared memory architectures
    - Programmer identifies parallelism and data properties, and guides scheduling at a high level
    - System decomposes parallelism and manages schedule
  - Arose from a variety of architecture-specific pragmas

Overview of POSIX Threads (Pthreads)

- POSIX: *Portable **O**perating **S**ystem **I**nterface for **UNIX***
  - Interface to Operating System utilities
- PThreads: The POSIX threading interface
  - System calls to create and synchronize threads
  - Should be relatively uniform across UNIX-like OS platforms
- PThreads contain support for
  - Creating parallelism
  - Synchronizing
  - No explicit support for communication, because shared memory is implicit; a pointer to shared data is passed to a thread

Slide source: Jim Demmel and Kathy Yelick

Forking Pthreads

Signature:

```
int pthread_create(pthread_t *,
                   const pthread_attr_t *,
                   void * (*)(void *),
                   void *);
```

Example call:

```
errcode = pthread_create(&thread_id,
                         &thread_attribute,
                         &thread_fun, &fun_arg);
```

- thread_id is the thread id or handle (used to halt, etc.)
- thread_attribute various attributes
  - standard default values obtained by passing a NULL pointer
- thread_fun the function to be run (takes and returns void*)
- fun_arg an argument can be passed to thread_fun when it starts
- errorcode will be set to nonzero if the create operation fails

Slide source: Jim Demmel and Kathy Yelick

Forking Pthreads, cont.

- The effect of pthread_create
  - Master thread actually causes the operating system to create a new thread
  - Each thread executes a specific function, thread_fun
    - The same thread function is executed by all threads that are created, representing the thread's *computation decomposition*
  - For the program to perform different work in different threads, the arguments passed at thread creation distinguish the thread's "id" and any other unique features of the thread.

Simple Threading Example

```
int main() {
  pthread_t threads[16];
  int tn;
  for(tn=0; tn<16; tn++) {
    pthread_create(&threads[tn], NULL, ParFun, NULL);
  }
  for(tn=0; tn<16 ; tn++) {
    pthread_join(threads[tn], NULL);
  }
  return 0;
}
```

Compile using gcc … –lpthread

This code creates 16 threads that execute the function "ParFun".

Note that thread creation is costly, so it is important that ParFun do a lot of work in parallel to amortize this cost.

Slide source: Jim Demmel and Kathy Yelick

Shared Data and Threads

- Variables declared outside of main are shared
- Object allocated on the heap may be shared (if pointer is passed)
- Variables on the stack are private: passing pointer to these around to other threads can cause problems
- Shared data often a result of creating a large "thread data" struct
  - Passed into all threads as argument
  - Simple example:

```
char *message = "Hello World!\n";
pthread_create( &thread1,
        NULL,
        (void*)&print_fun,
        (void*) message);
```

Slide source: Jim Demmel and Kathy Yelick

"Hello World" in Pthreads

- Some preliminaries
  - Number of threads to create (threadcount) is set at runtime and read from command line
  - Each thread prints "Hello from thread <X> of <threadcount>"
- Also need another function
  - `int pthread_join(pthread_t *, void **value_ptr)`
  - From Unix specification: "suspends execution of the calling thread until the target thread terminates, unless the target thread has already terminated."
  - The second parameter allows the exiting thread to pass information back to the calling thread (often NULL).
  - Returns nonzero if there is an error

Hello World! (1)

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

/* Global variable:  accessible to all threads */
int thread_count;

void *Hello(void* rank);  /* Thread function */

int main(int argc, char* argv[]) {
   long      thread;  /* Use long in case of a 64-bit system */
   pthread_t* thread_handles;

   /* Get number of threads from command line */
   thread_count = strtol(argv[1], NULL, 10);

   thread_handles = malloc (thread_count*sizeof(pthread_t));
```

declares the various Pthreads functions, constants, types, etc.

Hello World! (2)

```
   for (thread = 0; thread < thread_count; thread++)
      pthread_create(&thread_handles[thread], NULL,
          Hello, (void*) thread);

   printf("Hello from the main thread\n");

   for (thread = 0; thread < thread_count; thread++)
      pthread_join(thread_handles[thread], NULL);

   free(thread_handles);
   return 0;
}  /* main */
```


Hello World! (3)

```
void *Hello(void* rank) {
   long my_rank = (long) rank;  /* Use long in case of 64-bit system */

   printf("Hello from thread %ld of %d\n", my_rank, thread_count);

   return NULL;
}  /* Hello */
```


Explicit Synchronization: Creating and Initializing a Barrier

- To (dynamically) initialize a barrier, use code similar to this (which sets the number of threads to 3):

```
pthread_barrier_t b;
pthread_barrier_init(&b,NULL,3);
```

- The second argument specifies an object attribute; using NULL yields the default attributes.
- To wait at a barrier, a process executes:

```
pthread_barrier_wait(&b);
```

- This barrier could have been statically initialized by assigning an initial value created using the macro `PTHREAD_BARRIER_INITIALIZER(3)`.

Slide source: Jim Demmel and Kathy Yelick

Mutexes (aka Locks) in Pthreads

- To create a mutex:

```
#include <pthread.h>
pthread_mutex_t amutex = PTHREAD_MUTEX_INITIALIZER;
pthread_mutex_init(&amutex, NULL);
```

- To use it:

```
int pthread_mutex_lock(amutex);
int pthread_mutex_unlock(amutex);
```

- To deallocate a mutex

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

- Multiple mutexes may be held, but can lead to deadlock:

```
thread1        thread2
lock(a)        lock(b)
lock(b)        lock(a)
```

Slide source: Jim Demmel and Kathy Yelick

Additional Pthreads synchronization described in textbook

- Semaphores
- Condition variables
- More discussion to come later in the semester, but these details are not needed to get started programming

Summary of Programming with Threads

- Pthreads are based on OS features
  - Can be used from multiple languages (need appropriate header)
  - Familiar language for most programmers
  - Ability to shared data is convenient
- Pitfalls
  - Data races are difficult to find because they can be intermittent
  - Deadlocks are usually easier, but can also be intermittent
- OpenMP is commonly used today as a simpler alternative, but it is more restrictive
  - OpenMP can parallelize many serial programs with relatively few annotations that specify parallelism and independence

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

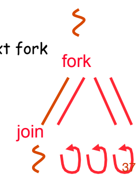
See http://www.openmp.org

A Programmer's View of OpenMP

- OpenMP is a portable, threaded, shared-memory programming *specification* with "light" syntax
  - Exact behavior depends on OpenMP implementation!
  - Requires compiler support (C/C++ or Fortran)
- OpenMP will:
  - Allow a programmer to separate a program into *serial regions* and *parallel regions,* rather than concurrently-executing threads.
  - Hide stack management
  - Provide synchronization constructs
- OpenMP will not:
  - Parallelize automatically
  - Guarantee speedup
  - Provide freedom from data races

OpenMP Execution Model

- Fork-join model of parallel execution
- Begin execution as a single process (**master thread**)
- Start of a parallel construct:
  - Master thread creates team of threads (**worker threads**)
- Completion of a parallel construct:
  - Threads in the team synchronize -- **implicit barrier**
- Only master thread continues execution
- Implementation optimization:
  - Worker threads spin waiting on next fork



OpenMP uses Pragmas

- Pragmas are special preprocessor instructions.
- Typically added to a system to allow behaviors that aren't part of the basic C specification.
- Compilers that don't support the pragmas ignore them.
- The interpretation of OpenMP pragmas
  - They modify the statement immediately following the pragma
  - This could be a compound statement such as a loop

#pragma omp …

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 directive format C (also Fortran and C++ bindings)

- Pragmas, format

  `#pragma omp` directive_name [clause [clause] ...] new-line
- Conditional compilation

```
#ifdef _OPENMP
  block,
  e.g., printf("%d avail.processors\n",omp_get_num_procs());
#endif
```

- Case sensitive
- Include file for library routines

```
#ifdef _OPENMP
#include <omp.h>
#endif
```

OpenMP runtime library, Query Functions

`omp_get_num_threads`:

Returns the number of threads currently in the team executing the parallel region from which it is called

```
int omp_get_num_threads(void);
```

`omp_get_thread_num`:

Returns the thread number, within the team, that lies between `0` and `omp_get_num_threads()-1`, inclusive. The master thread of the team is thread `0`

```
int omp_get_thread_num(void);
```


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)

Hello World in OpenMP

- Let's start with a parallel region construct
- Things to think about
  - As before, number of threads is read from command line
  - Code should be correct without the pragmas and library calls
- Differences from Pthreads
  - More of the required code is managed by the compiler and runtime (so shorter)
  - There is an implicit thread identifier

gcc –fopenmp …


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

void Hello(void);  /* Thread function */

int main(int argc, char* argv[]) {
   /* Get number of threads from command line */
   int thread_count = strtol(argv[1], NULL, 10);

#  pragma omp parallel num_threads(thread_count)
   Hello();

   return 0;
}  /* main */

void Hello(void) {
   int my_rank = omp_get_thread_num();
   int thread_count = omp_get_num_threads();

   printf("Hello from thread %d of %d\n", my_rank, thread_count);

}  /* Hello */
```

In case the compiler doesn't support OpenMP

```
# include <omp.h>

        #ifdef _OPENMP
        # include <omp.h>
        #endif
```


In case the compiler doesn't support OpenMP

```
# ifdef _OPENMP
   int my_rank = omp_get_thread_num ( );
   int thread_count = omp_get_num_threads ( );
# e l s e
   int my_rank = 0;
   int thread_count = 1;
# endif
```


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

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`

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