Lecture 10

Programming Shared Memory IV

Controlling Thread, OpenMP (Open Multi-Processing)

Ceng505 *Parallel Computing* at December 13, 2010

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Controlling Thread and Synchronization Attributes I

- Threads and synchronization variables can have several attributes associated with them.
  - Different threads may be scheduled differently (round-robin, prioritized, etc.),
  - They may have different stack sizes, and so on.
  - A synchronization variable such as a mutex-lock may be of different types.
- An attributes object is a data-structure that describes entity (thread, mutex, condition variable) properties.
- When creating a thread or a synchronization variable, we can specify the attributes object that determines the properties of the entity.
- Pthreads allows the user to change the priority of the thread.
- Subsequent changes to attributes objects do not change the properties of entities created using the attributes object prior to the change.

Controlling Thread and Synchronization Attributes II

- There are several advantages of using attributes objects.

1. It separates the issues of program *semantics and implementation*.
    - Thread properties are specified by the user.
    - How these are implemented at the system level is transparent to the user.
    - This allows for greater portability across operating systems.
2. Using attributes objects improves modularity and readability of the programs.
3. It allows the user to modify the program easily.
    - For instance, if the user wanted to change the scheduling from round robin to time-sliced for all threads,
    - they would only need to change the specific attribute in the attributes object.

- To create an attributes object with the desired properties,
- we must first create an object with default properties and then modify the object as required.

Attributes Objects for Threads I

- **pthread_attr_init**;

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

- This function initializes the attributes object *attr* to the default values.
- Upon successful completion, the function returns a 0, otherwise it returns an error code.
- The attributes object may be destroyed.
- **pthread_attr_destroy**;

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

- The call returns a 0 on successful removal of the attributes object *attr*.

Attributes Objects for Threads II

- Individual properties associated with the attributes object can be changed using the following functions:
- **pthread_attr_setdetachstate** $\Longrightarrow$ to set the detach state
- **pthread_attr_setguardsize_np** $\Longrightarrow$ to set the stack guard size
- **pthread_attr_setstacksize** $\Longrightarrow$ to set the stack size
- **pthread_attr_setstackaddr** $\Longrightarrow$ to set the stack address
- **pthread_attr_setinheritsched** $\Longrightarrow$ to set whether scheduling policy is inherited from the creating thread
- **pthread_attr_setschedpolicy** $\Longrightarrow$ to set the scheduling policy (in case it is not inherited)
- **pthread_attr_setschedparam** $\Longrightarrow$ to set the scheduling parameters
- **pthread_attr_setprio** $\Longrightarrow$ to set the priority
- **pthread_attr_default, pthread_attr_init**
- For most parallel programs,
  default thread properties are generally adequate.

Composite Synchronization Constructs I

- While the Pthreads API provides a **basic set of synchronization constructs**, often, there is a need for higher level constructs.
- These higher level constructs can be built using basic synchronization constructs.
- An important and often used construct in threaded (as well as other parallel) programs is a *barrier*.
- A barrier call is used to hold a thread until all other threads participating in the barrier have reached the barrier.
- Barriers can be implemented using a *counter*, a *mutex* and a *condition variable*.
- A single integer is used to keep track of the number of threads that have reached the barrier.
  - If the *count* is less than the total number of threads, the threads execute a *condition wait*.
  - The last thread entering (and setting the count to the number of threads) wakes up all the threads using a condition broadcast.

Composite Synchronization Constructs II

The code for accomplishing this is as follows:

```
typedef struct {
    pthread_mutex_t count_lock;
    pthread_cond_t ok_to_proceed;
    int count;
} mylib_barrier_t;

void mylib_init_barrier(mylib_barrier_t *b) {
    b -> count = 0;
    pthread_mutex_init(&(b -> count_lock), NULL);
    pthread_cond_init(&(b -> ok_to_proceed), NULL);
}

void mylib_barrier (mylib_barrier_t *b, int num_threads) {
    pthread_mutex_lock(&(b -> count_lock));
    b -> count ++;
    if (b -> count == num_threads) {
        b -> count = 0;
        pthread_cond_broadcast(&(b -> ok_to_proceed));
    }
    else
        while (pthread_cond_wait(&(b -> ok_to_proceed),
            &(b -> count_lock)) != 0);
    pthread_mutex_unlock(&(b -> count_lock));
}
```

Composite Synchronization Constructs III

- In the above implementation of a barrier, threads enter the barrier and stay until the broadcast signal releases them.
- The threads are released one by one since the mutex *count_lock* is passed among them one after the other.
- The trivial lower bound on execution time of this function is therefore $O(n)$ for n threads.
- This implementation of a barrier can be speeded up using multiple barrier variables.

Tips for Designing Asynchronous Programs I

- When designing multithreaded applications, it is important to remember that one cannot assume any order of execution with respect to other threads.
- Any such order must be explicitly established using the synchronization mechanisms discussed above: *mutexes*, *condition variables*, and *joins*.
- In many thread libraries, threads are switched at *semi-deterministic* intervals.
- Such libraries (*slightly asynchronous* libraries) are more forgiving of synchronization errors in programs.
- On the other hand, **kernel threads** (threads supported by the kernel) and threads scheduled on multiple processors are less forgiving.
- The programmer must therefore **not make any assumptions** regarding the level of asynchrony in the threads library.

Tips for Designing Asynchronous Programs II

- The following rules of thumb which help minimize the errors in threaded programs are recommended.
- Set up all the requirements for a thread before actually creating the thread. This includes
  - initializing the data,
  - setting thread attributes,
  - thread priorities,
  - mutex-attributes, etc.
- Once you create a thread, it is possible that the newly created thread actually runs to completion before the creating thread gets scheduled again.

Tips for Designing Asynchronous Programs III

- When there is a producer-consumer relation between two threads for certain data items,
- At the producer end, make sure the data is placed before it is consumed and that intermediate buffers are guaranteed to not overflow.
- At the consumer end, make sure that the data lasts at least until all potential consumers have consumed the data.
- This is particularly relevant for stack variables.
- Where possible, define and use group synchronizations and data replication.
- This can improve program performance significantly.
- **While these simple tips provide guidelines for writing error-free threaded programs, extreme caution must be taken to avoid race conditions and parallel overheads associated with synchronization.**

OpenMP: a Standard for Directive Based Parallel Programming I

- While standardization and support for these threaded APIs has come a long way,
- their use is still predominantly restricted to **system programmers** as opposed to **application programmers**.
- One of the reasons for this is that APIs such as Pthreads are considered to be **low-level primitives**.
- Conventional wisdom indicates that a large class of applications can be efficiently supported by **higher level constructs** (**or directives**)
- which rid the programmer of the mechanics of manipulating threads.
- Such **directive-based languages** have existed for a long time,
- but only recently have standardization efforts succeeded in the form of OpenMP.

The OpenMP Programming Model I

- OpenMP is an API that can be used with FORTRAN, C, and C++ for programming shared address space machines.
- OpenMP directives provide support for **concurrency**, **synchronization**, and **data handling** while avoiding the need for explicitly setting up mutexes, condition variables, data scope, and initialization.
- OpenMP directives in C and C++ are based on the *#pragma* compiler directives.
- The directive itself consists of a directive name followed by clauses.

```
#pragma omp directive [clause list]
```

- OpenMP programs execute serially until they encounter the *parallel* directive.
- This directive is responsible for **creating a group of threads**.

The OpenMP Programming Model II

- The exact number of threads can be specified in the directive, set using an environment variable, or at runtime using OpenMP functions.
- The main thread that encounters the *parallel* directive becomes the *master* of this group of threads with id 0.
- The *parallel* directive has the following prototype:

```
#pragma omp parallel [clause list]
/* structured block */
```

- Each thread created by this directive executes the *structured block* specified by the parallel directive.
- It is easy to understand the concurrency model of OpenMP when viewed in the context of the corresponding Pthreads translation.
- In Figure 1, one possible translation of an OpenMP program to a Pthreads program is shown.

The OpenMP Programming Model III

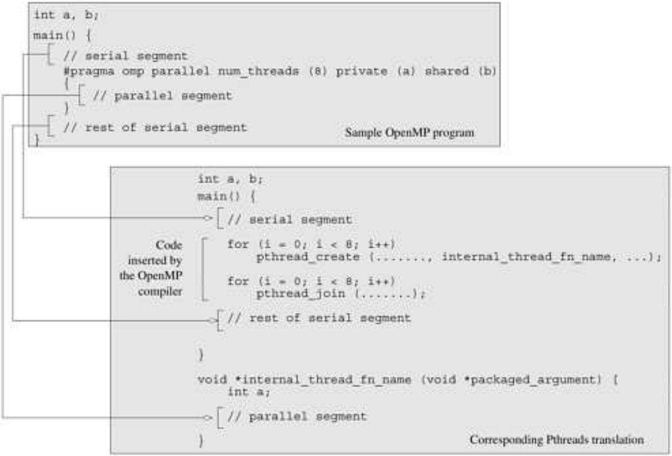

Figure: A sample OpenMP program along with its Pthreads translation that might be performed by an OpenMP compiler.

The OpenMP Programming Model IV

- The <u>clause list</u> is used to specify **conditional parallelization**, **number of threads**, and **data handling**.
- **Conditional Parallelization:** The clause *if (scalar expression)* determines whether the parallel construct results in creation of threads.
  - Only one *if* clause can be used with a parallel directive.
- **Degree of Concurrency:** The clause *num_threads (integer expression)* specifies the number of threads that are created by the *parallel* directive.
- **Data Handling:** The clause *private (variable list)* indicates that the set of variables specified is local to each thread.
  - i.e., each thread has its own copy of each variable in the list.
  - The clause *firstprivate (variable list)* is similar to the private clause, except the values of variables on entering the threads are <u>initialized</u> to corresponding values before the parallel directive.
  - The clause *shared (variable list)* indicates that all variables in the list are shared across all the threads,
  - i.e., there is only one copy. Special care must be taken while handling these variables by threads to ensure serializability.

The OpenMP Programming Model V

```
#include <omp.h>
main ()  {
int var1, var2, var3;
Serial code
Beginning of parallel section. Fork a team of threads.
Specify variable scoping
#pragma omp parallel private(var1, var2) shared(var3)
  {
  Parallel section executed by all threads
  All threads join master thread and disband
  }
Resume serial code
}
***********************************************************
#include <omp.h>
int a,b,num_threads;
int main()
{
  printf("I am in sequential part.\n");
#pragma omp parallel num_threads (8) private (a) shared (b)
  {
    num_threads=omp_get_num_threads();
    printf("I am openMP parellized part and thread %d \n",
                                   omp_get_thread_num());
  }
}
```

The OpenMP Programming Model VI

Using the parallel directive;

```
#pragma omp parallel if (is_parallel == 1) num_threads(8)
            private (a) shared (b) firstprivate(c)
{
    /* structured block */
}
```

- Here, if the value of the variable *is_parallel* equals one, eight threads are created.
- Each of these threads gets private copies of variables a and c, and shares a single value of variable b.
- Furthermore, the value of each copy of c is initialized to the value of c before the parallel directive.
- The clause *default (shared)* implies that, by default, a variable is shared by all the threads.
- The clause *default (none)* implies that the state of each variable used in a thread must be explicitly specified.
- This is generally recommended, to guard against errors arising from unintentional concurrent access to shared data.

The OpenMP Programming Model VII

- Just as *firstprivate* specifies how multiple local copies of a variable are initialized inside a thread,
- the *reduction* clause specifies how multiple local copies of a variable at different threads are combined into a single copy at the master when threads exit.
- The usage of the *reduction* clause is *reduction (operator: variable list)*.
- This clause performs a reduction on the scalar variables specified in the list using the *operator*.
- The variables in the list are implicitly specified as being private to threads.
- The *operator* can be one of

`+, *, -, &, |, ^, &&, and ||.`

The OpenMP Programming Model VIII

Using the reduction clause;

```
#pragma omp parallel reduction(+: sum) num_threads(8)
 {
 /* compute local sums here */
  }
 /* sum here contains sum of all local instances of sums */
```

- In this example, each of the eight threads gets a copy of the variable *sum*.
- When the threads exit, the sum of all of these local copies is stored in the single copy of the variable (at the master thread).

The OpenMP Programming Model IX

- **Computing PI** using OpenMP directives (presented a Pthreads program for the same problem).
- The *omp_get_num_threads()* function returns the number of threads in the parallel region
- The *omp_get_thread_num()* function returns the integer id of each thread (recall that the master thread has an id 0).
- The parallel directive specifies that all variables except *npoints*, the total number of random points in two dimensions across all threads, are local.
- Furthermore, the directive specifies that there are eight threads, and the value of sum after all threads complete execution is the sum of local values at each thread.
- A for loop generates the required number of random points (in two dimensions) and determines how many of them are within the prescribed circle of unit diameter.

The OpenMP Programming Model X

```
/* *****************************************************
 An OpenMP version of a threaded program to compute PI.
 ***************************************************** */

 #pragma omp parallel default(private) shared (npoints) \
                      reduction(+: sum) num_threads(8)
   {
    num_threads = omp_get_num_threads();
     sample_points_per_thread = npoints / num_threads;
     sum = 0;
     for (i = 0; i < sample_points_per_thread; i++) {
  rand_no_x =(double)(rand_r(&seed))/(double)((2<<14)-1);
  rand_no_y =(double)(rand_r(&seed))/(double)((2<<14)-1);
       if (((rand_no_x - 0.5) * (rand_no_x - 0.5) +
           (rand_no_y - 0.5) * (rand_no_y - 0.5)) < 0.25)
          sum ++;
     }
   }
```

Note that this program is <u>much easier</u> to write in terms of specifying creation and termination of threads compared to the corresponding POSIX threaded program.