Parallel Programming using OpenMP

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OpenMP Multithreaded Programming

- OpenMP stands for “Open Multi-Processing”
- OpenMP is a multi-vendor standard to perform shared-memory multithreading
- OpenMP uses the fork-join model
- OpenMP is both directive- and library-based
- OpenMP threads share a single executable, global memory, and heap (malloc, new)
- Each OpenMP thread has its own stack (function arguments, local variables)
- Using OpenMP requires no dramatic code changes
- OpenMP probably gives you the biggest multithread benefit per amount of work you have to put in to using it

Much of your use of OpenMP will be accomplished by issuing C/C++ “pragmas” to tell the compiler how to build the threads into the executable

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

What OpenMP Isn’t:

- OpenMP doesn’t check for data dependencies, data conflicts, deadlocks, or race conditions. You are responsible for avoiding those yourself
- OpenMP doesn’t check for non-conforming code sequences
- OpenMP doesn’t guarantee identical behavior across vendors or hardware
- OpenMP doesn’t guarantee the order in which threads execute, just that they do execute
- OpenMP is not overhead-free
- OpenMP does not prevent you from writing false-sharing code (in fact, it makes it really easy)

Memory Allocation in a Multithreaded Program

One-thread
- Stack
- Program
- Executable
- Globals
- Heap

Multiple-threads
- Stack
- Program
- Executable
- Common
- Global
- Heap

Using OpenMP in Linux

```
g++ -o proj proj.cpp -O3 -lm -fopenmp
```

Using OpenMP in Microsoft Visual Studio

1. Go to the Project menu → Project Properties
2. Change the setting Configuration Properties → C/C++ → Language → OpenMP Support to “Yes (openmp)”

Seeing if OpenMP is Supported on Your System

```
#ifndef _OPENMP
fprintf(stderr, "OpenMP is not supported – sorry/in");
#endif
```

Number of OpenMP threads

Two ways to specify how many OpenMP threads you want to have available:

1. Set the OMP_NUM_THREADS environment variable
2. Call omp_set_num_threads(num);

Asking how many cores this program has access to:

```
num = omp_get_num_procs();
```

Setting the number of threads to the exact number of cores available:

```
num = omp_set_num_threads(omp_get_num_procs());
```

Asking how many OpenMP threads this program is using right now:

```
um = omp_get_num_threads();
```
Asking which thread this one is:

```
me = omp_get_thread_num();
```
Creating an OpenMP Team of Threads

```
#pragma omp parallel default(none)
{
  ... 
}
```

Each thread would then execute all lines of code in this block.

```
#include <omp.h>
int i;
#pragma omp parallel for default(none),private(i)
for( i = 0; i < num; i++ )
{
  ... 
}
```

This tells the compiler to parallelize the for loop into multiple threads, and to give each thread its own personal copy of the variable i. But, you don’t have to do this for variables defined in the loop body:

```
#pragma omp parallel for default(none)
for( int i = 0; i < num; i++ )
{
  ... 
}
```

This is probably the biggest parallel benefit per programming effort!

OpenMP for-Loop Rules

- The index must be an int or a pointer
- The start and end conditions must have compatible types
- Neither the start nor the end conditions can be changed during the execution of the loop
- The index can only be modified by the “changed” expression (i.e., not modified inside the loop itself)
- There can be no between-loop data dependencies

```
for( index = start ; index < end ; index++)
```

```
index += incr
```

```
index = index + incr
```

```
index = index - decr
```

```
private(x)
```

Means that each thread will have its own copy of the variable x.

```
shared(x)
```

Means that each thread will share a common x. This is potentially dangerous.

OpenMP Directive Data Types

I recommend that you use:

```
default(none)
```

in all your OpenMP directives. This will force you to explicitly flag all of your inside variables as shared or private. This will help prevent mistakes.

```
private(x)
```

Means that each thread will have its own copy of the variable x.

```
shared(x)
```

Means that each thread will share a common x. This is potentially dangerous.
Static Threads
- All work is allocated and assigned at runtime

Dynamic Threads
- Consists of one Master and a pool of threads
- The pool is assigned some of the work at runtime, but not all of it
- When a thread from the pool becomes idle, the Master gives it a new assignment
  * "Round-robin assignments"

OpenMP Allocation of Work to Threads

```
#pragma omp parallel for default(none),schedule(static,chunksize)
for( int index = 0 ; index < 12 ; index++ )
    chunksize = 1
    Each thread is assigned one iteration, then the assignments start over
chunksize = 2
Each thread is assigned two iterations, then the assignments start over
chunksize = 4
Each thread is assigned four iterations, then the assignments start over
```

Arithmetic Operations Among Threads – A Problem
```
#pragma omp parallel for private(myPartialSum),shared(sum)
for( int i = 0; i < N; i++ )
{  
  float myPartialSum = ...  
  sum = sum + myPartialSum;  
  if ( scheduler has other threads ready before i has finished )
    scheduler decides to execute i on a different thread 
  if ( some other thread finishes before i )
    scheduler decides to execute i on a different thread
  This is non-deterministic!
```

```
Assembly code:
Load sum, Add myPartialSum, Store sum
What if the scheduler decides to switch threads right here?
Conclusion: Don’t do it this way!
```

Arithmetic Operations Among Threads – Three Solutions
```
#pragma omp atomic
sum += myPartialSum;  
• Fixes the non-deterministic problem
• But, serializes the code
• Operators include +, -, *, /, ++, --

#pragma omp critical
sum = sum + myPartialSum;  
• Also serializes the code

#pragma omp parallel for reduction(+:sum) private(myPartialSum)
  sum += myPartialSum;  
• Performs (sum, product, and, or, |, &,...) in O(log2N) time instead of O(N)
• Operators include +, -, *, /, ++, --, ^=, |=, &=
```

Here’s a trapezoid integration example (covered in another section).
The partial sums are added up, as shown on the previous page.
The integration was done 30 times.
The answer is supposed to be exactly 2.
None of the 30 answers is even close.
And, not only are the answers bad, they are not even consistently bad!

Conclusion: Don’t do it this way!

If You Understand Basketball Brackets, You’ll Understand Reduction

```
Source: ESPN
```

If You Understand Basketball Brackets, You’ll Understand Reduction

```
Source: ESPN
```
Mutual Exclusion Locks (Mutexes)

omp_init_lock(omp_lock_t*);
omp_set_lock(omp_lock_t*);
omp_unset_lock(omp_lock_t*);
omp_test_lock(omp_lock_t*);

(omp_lock_t is really an array of 4 unsigned chars)

Critical sections

#pragma omp critical
Restricts execution to one thread at a time

#pragma omp single
Restricts execution to a single thread ever

Barriers

#pragma omp barrier
Forces all threads to wait here until all threads arrive

(Note: there is an implied barrier after parallel for loops and OpenMP sections, unless the nowait clause is used)

OpenMP Tasks

• An OpenMP task is a single line of code or a structured block which is immediately assigned to one thread in the current thread team
• If the tied clause is used, it is assigned to the same thread. If the untied clause is used, it can be assigned to any thread.
• The task can be executed immediately or it can be placed on its thread’s list of things to do.
• If the if clause is used and the argument evaluates to 0, then the task is executed immediately, superceding whatever else that thread is doing.
• There has to be an existing parallel thread team for this to be effective. Otherwise one thread ends up doing all tasks.
• One of the best uses of this is to make a function call. That function then runs concurrently until it completes.

#pragma omp task
Watch_For_Internet_Input();

You can create a task barrier with:

#pragma omp taskwait

These are very much like OpenMP Sections, but Sections are more static, that is, they are setup when you write the code, whereas Tasks can be created anytime, and in any number, under control of your program’s logic.

OpenMP Task Example:

Processing each element of a linked list

#pragma omp parallel
{
#pragma omp single default(none)
{
 element "p = listHead;
 while( p != NULL )
{
 #pragma omp task
 Process( p );
 p = p->next;
 }
}
}
Single Program Multiple Data (SPMD) in OpenMP

```
#define NUM 1000000
float A[NUM], B[NUM], C[NUM];
total = omp_get_num_threads();
#pragma omp parallel default(none),private(me),shared(total)
{
    me = omp_get_thread_num();
    DoWork(me, total);
}

void DoWork(int me, int total)
{
    int first = NUM * me / total;
    int last = NUM * (me+1)/total - 1;
    for(int i = first; i <= last; ++i)
    {
        C[i] = A[i] * B[i];
    }
}
```