OpenMP Programming

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Goal: Use multiple cores in a computing node via multithreading
OpenMP

- Portable application program interface (API) for shared-memory parallel programming based on multi-threading by compiler directives
- OpenMP = Open specifications for Multi Processing
- OpenMP homepage
  www.openmp.org
- OpenMP tutorial
  computing.llnl.gov/tutorials/openMP
- Process: an instance of program running
- Thread: a sequence of instructions being executed, possibly sharing resources with other threads within a process

MPI (distributed memory)  OpenMP (shared memory)
OpenMP Programming Model

Fork-join parallelism

- **Fork**: master thread spawns a team of threads as needed
- **Join**: when the team of threads complete the statements in the parallel section, they terminate synchronously, leaving only the master thread

- OpenMP threads communicate by sharing variables
#include <stdio.h>
#include <omp.h>
void main () {
    int nthreads,tid;
    nthreads = omp_get_num_threads();
    printf("Sequential section: # of threads = %d\n",nthreads);
    /* Fork multi-threads with own copies of variable */
    #pragma omp parallel private(tid)
    {
        /* Obtain & print thread id */
        tid = omp_get_thread_num();
        printf("Parallel section: Hello world from thread %d\n",tid);
        /* Only master thread does this */
        if (tid == 0) {
            nthreads = omp_get_num_threads();
            printf("Parallel section: # of threads = %d\n",nthreads);
        }
    } /* All created threads terminate */
}

- **Obtain the number of threads & my thread ID** (cf. MPI_Comm_size & MPI_Comm_rank)
- **By default, all variables are shared unless selectively changing storage attributes using private clauses**
OpenMP Example: `omp_example.c`

- **Compilation on** `carc.usc.edu`
  ```
  gcc -o omp_example omp_example.c -fopenmp
  ```

- **Slurm script**
  ```
 #!/bin/bash
  #SBATCH --nodes=1
  #SBATCH --ntasks-per-node=1
  #SBATCH --cpus-per-task=2
  #SBATCH --time=00:00:59
  #SBATCH --output=omp_example.out
  #SBATCH -A anakano_429
  export OMP_NUM_THREADS=2
  ./omp_example
  ```
  Set the # of threads using environment parameter

- **Output**
  - Sequential section: # of threads = 1
  - Parallel section: Hello world from thread 1
  - Parallel section: Hello world from thread 0
  - Parallel section: # of threads = 2
Setting the Number of Threads

- Setting the number of threads to be used in parallel sections within the program (no need to set OMP_NUM_THREADS); see omp_example_set.c
OpenMP Programming Model

- OpenMP is typically used to parallelize (big) loops
- Use synchronization mechanisms to avoid race conditions (i.e., the result changes for different thread schedules)
- Critical section: only one thread at a time can enter

```c
#pragma omp parallel
{
    ...
    #pragma omp critical
    {
        ...
    }
    ...
}
```

Threads wait their turn—only one at a time executes the critical section
Example: Calculating $\pi$

- **Numerical integration**
  \[ \int_0^1 \frac{4}{1 + x^2} \, dx = \pi \]

- **Discretization:**
  \[ \Delta = 1/N: \text{step} = 1/N\text{BIN} \]
  \[ x_i = (i+0.5)\Delta (i = 0, \ldots, N-1) \]
  \[ \sum_{i=0}^{N-1} \frac{4}{1 + x_i^2} \Delta \approx \pi \]

```c
#include <stdio.h>
#define NBIN 100000
void main() {
  long long i; double step,x,sum=0.0,pi;
  step = 1.0/NBIN;
  for (i=0; i<NBIN; i++) {
    x = (i+0.5)*step;
    sum += 4.0/(1.0+x*x);
  }
  pi = sum*step;
  printf("PI = %f\n",pi);
}
```
#include <stdio.h>
#include <omp.h>
#define NBIN 100000

void main() {
    double step, sum = 0.0, pi;
    step = 1.0 / NBIN;
    #pragma omp parallel
    {
        int nthreads, tid; long long i;
        double x;
        nthreads = omp_get_num_threads();
        tid = omp_get_thread_num();
        for (i = tid; i < NBIN; i += nthreads) {
            x = (i + 0.5) * step;
            #pragma omp critical
            sum += 4.0 / (1.0 + x * x);
        }
        pi = sum * step;
        printf("PI = %f\n", pi);
    }
}

Thread-private variables: Either declare private or define within a parallel section
• **Race condition:** Output is dependent on the sequence or timing of how multiple threads are executed

• Race condition arises if the read & write operations below are not atomic (a set of operations is atomic if they are executed without being interrupted by other operations)

```c
sum = sum + 1;
```

Possible scenarios:

- t0 r 0  t0 r 0
- t1 r 0  t0 w 1
- t0 w 1  t1 r 1
- t1 w 2  t1 w 3
Critical Section

- Critical section degrades scalability, cf. Amdahl’s law

\[
T_P = fT_1 + (1-f) \frac{T_1}{P} \\
S_P = \frac{T_1}{T_P} = \frac{1}{f + \frac{1-f}{P}} \to \frac{1}{f} \quad (P \to \infty)
\]

for (i=\text{tid}; \text{i<NBIN}; \text{i+=nthreads}) {
  x = (i+0.5) \times \text{step};
  \#pragma omp critical \quad f \sim 0.5
  \text{sum += } 4.0/(1.0+x\times x);
}

- How to get rid of the critical section?
#include <stdio.h>
#include <omp.h>
#define NBIN 100000
#define MAX_THREADS 8
void main() {  
    int nthreads,tid;
    double step,sum[MAX_THREADS]={0.0},pi=0.0;
    step = 1.0/NBIN;
    #pragma omp parallel private(tid) 
    { 
        long long i;
        double x;
        nthreads = omp_get_num_threads();
        tid = omp_get_thread_num();
        for (i=tid; i<NBIN; i+=nthreads) {
            x = (i+0.5)*step;
            sum[tid] += 4.0/(1.0+x*x);
        }
    } 
    for(tid=0; tid<nthreads; tid++) pi += sum[tid]*step;
    printf("PI = %f\n",pi);
}
Avoid Critical Section: “Wrong” Way

```c
#include <stdio.h>
#include <omp.h>
#define NBIN 100000

void main() {
    double step, sum = 0.0, pi;
    step = 1.0 / NBIN;
    #pragma omp parallel
    {
        int nthreads, tid
        long long i;
        double x;
        nthreads = omp_get_num_threads();
        tid = omp_get_thread_num();
        for (i = tid; i < NBIN; i += nthreads) {
            x = (i + 0.5) * step;
            // #pragma omp critical
            sum += 4.0 / (1.0 + x * x);
        }
    }
    pi = sum * step;
    printf("PI = %f\n", pi);
}
```

Prof. Kunle Olukotun (Stanford)
(Sep. 28, 2017 at USC)

HOGWILD!: A Lock-Free Approach to Parallelizing Stochastic Gradient Descent
F. Niu et al., NIPS11

[anakano@hpc-login3 src]$ ./omp_pi_critical
PI = 3.141593
[anakano@hpc-login3 src]$ ./omp_pi_noncritical
PI = 0.558481 ← 16-thread run
Load Balancing

- Interleaved assignment of loop-index values to threads balances the loads among the threads

```c
for (i=tid; i<NBIN; i+=nthreads) {
    ...
}
```

A bad example
Most Widely Used Construct

- **OpenMP for**: Distribute the loop iterations across the threads; can be combined with OpenMP parallel to achieve multithreading in just one line.

```c
#include <omp.h>
#include <stdio.h>
#define NBIN 100000

void main() {
    long long i;
    double step,x,sum=0.0,pi;
    step = 1.0/NBIN;
    omp_set_num_threads(2);
    #pragma omp parallel for private (i,x) reduction(+:sum)
    for (i=0; i<NBIN; i++) {
        x = (i+0.5)*step;
        sum += 4.0/(1.0+x*x);
    }
    pi = sum*step;
    printf("PI = %f\n",pi);
}
```

Reduction clause performs automatic thread reduction
Where to Go from Here

- **OpenMP tutorial introducing most constructs**
  [https://computing.llnl.gov/tutorials/openMP](https://computing.llnl.gov/tutorials/openMP)

- **OpenMP 4.5 has added many constructs to support modern hardware architectures**
  
  **#pragma omp target**: Offload computation to accelerators like graphics processing units (GPUs)
  
  **#pragma omp simd**: Explicit control over single instruction multiple data (or vector) operations