Parallel Programming

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Summing n numbers

for(i=1; i++; i<n)
    x[i] += x[i-1];
Summing n numbers in parallel

How does one code this algorithm?
OpenMP
Assume \( n=2^k \)

**Sequential code**
for (\( i=n/2; \ i>1; \ i/=2 \))
  for (\( j=0; \ j<i; \ j++ \))
    \( x[j] += x[j+i]; \)

**Parallel code**
for (\( i=n/2; \ i>1; \ i/=2 \))
  \#pragma omp for
  for (\( j=0; \ j<i; \ j++ \))
    \( x[j] += x[j+i]; \)

- Code is C (or C++) with added pragma statements
- A C compiler will ignore the pragmas (as comments) and will compile second code same as first code
- An OpenMP compiler will understand that pragmas mean that inner loop iterates can be executed in parallel
- If only one thread execute the code, then the code is executed sequentially
- If multiple threads execute the code then
  - execution starts with one thread running
  - when the parallel for is encountered, the other threads start grapping iterates for execution
  - sequential execution resumes when all iterates have executed

*Resulting code will run more slowly than original code if \( n \) is small 😊*
OpenMP

http://www.openmp.org

• Now OpenMP V4 – V4.5 to come soon

• A language used to program code that takes advantage of multicore processors and of simultaneous multithreading
  – Multiple hardware threads run simultaneously
  – They all have access to shared memory

• Has extensions to take advantage of GPUs and vector instructions
How about using multiple processors (cluster, supercomputer)?

• Execution consists of one (or more) process per processor node
  – Each process executes the same code
  – The processes use messages to communicate

• Assume $n = 2^k$ processors and one number per processor
**MPI Code (executed at each processor)**

```c
MPI_Comm_rank(MPI_COMM_WORLD, &myrank);

// processes are numbered with consecutive ranks (0...n-1)
for(i=n/2; i>1; i /= 2)
    if (myrank<i) {
        MPI_Recv(&y, 1, MPI_DOUBLE, myrank+i, tag, MPI_COMM_WORLD, status);
        x += y;
    }
else if (myrank <2*j)
    MPI_Send(&x, 1, MPI_DOUBLE, myrank-i, tag, MPI_COMM_WORLD);

// a receive matches a send according the source rank, tag, communicator)
```
Subtle point

• Second message could arrive at processor 0 before the first message arrives
• Nevertheless, messages will be handled in the right order because of the matching rules
• In general, one may need to make sure that no process starts next iteration before all processes completed the previous iteration

MPI_BARRIER(...)
MPI collective operations

• Replace previous code with

```c
MPI_Reduce(&x, &sum, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_WORLD)
```

• Variable sum at process with rank 0 will be set to the sum of the variables x, one from each process.
  – Internally, the MPI library will execute something similar to the code on previous slide
  – Will handle any number of processes
Alltogether now

• p multicore processes; each process has $2^k$ numbers. Need to compute the sum of all of them

```c
for(i=n/2; i>1; i /=2)
    #pragma omp for
    for(j=0; j<i; j++)
        x[j] += x[j+i];
MPI_Reduce(&x[0], &sum, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_WORLD)
```
MPI

http://www.mpi-forum.org

• Now MPI 3.1
• A library used to program code that runs on multiple processes
  – Each process runs a C (or C++, or OpenMP) code
  – The processes communicate using MPI calls
Is there more than MPI and OpenMP?

- GPU programming – CUDA is often needed
- Work on new languages
  - Data parallel computing: focus on distributed data structures and moving computation to data
    - Chapel: http://chapel.cray.com/
    - Legion: http://legion.stanford.edu/
  - PGAS – Partitioned Global Address Space: Programs can use local references and global references (pointing to an address on another node)
    - UPC: https://upc-lang.org/
- The different world of high-end analytics – Hadoop, Spark...
  - focused on data that does not fit in memory and on coarser-level parallelism
To know more, please take a course in parallel programming

Preferably, at the University of Illinois

Questions?