Notes

• MPI project posted
  • due 2 weeks from Thursday, Sept. 28
  • Send any questions about project spec, or running on zaratan cluster, to me or Keon, or post on Piazza
• Don't forget to send questions for readings
  • additional readings posted last week, with who should send questions (check again, since class roster has changed)
• We will finish OpenMP next class
  • Other readings/lectures pushed back – see Readings web page
OpenMP

• Support Parallelism for SMPs
  • provide a simple portable model
  • allows both shared and private data
  • provides parallel do loops

• Includes
  • automatic support for fork/join parallelism
  • reduction variables
  • atomic statement
    • one process executes at a time
  • plus a lot more
OpenMP

• Characteristics
  • Both thread-local & shared memory (depending on directives)
  • Parallelism: directives for parallel loops, functions
  • Compilers convert programs into multi-threaded (i.e. pthreads)
  • Not able to run on more than one node in a cluster

• Example

```c
#pragma omp parallel for private(i)
for (i=0; i<NUPDATE; i++) {
    int ran = random();
    table[ ran & (TABSIZE-1) ] ^= stable[ ran >> (64-LSTSIZE) ];
}
```
More on OpenMP

• **Characteristics**
  • Not a full parallel language, but a language extension
  • A set of standard compiler directives and library routines
  • Used to create parallel Fortran, C and C++ programs
  • Usually used to parallelize loops
  • Standardizes last ~20 years of SMP practice

• **Implementation**
  • C/C++ compiler directives using `#pragma omp <directive>`
  • Parallelism can be specified for regions & loops
  • Data can be
    • Private – each thread has local copy
    • Shared – single copy for all threads
OpenMP – Programming Model

• Fork-join parallelism (restricted form of MIMD)
  • Normally single thread of control (primary)
  • Worker threads spawned when parallel region encountered
  • Barrier synchronization required at end of parallel region
OpenMP – Example Parallel Region

- Task level parallelism – #pragma omp parallel { ... }

```c
double a[1000];
omp_set_num_threads(4);
#pragma omp parallel
{
    int id = omp_thread_num();
    foo(id, a);
}
printf(“all done \n”);```

OpenMP compiler

```c
double a[1000];
omp_set_num_threads(4);
#pragma omp parallel

foo(3, a);
foo(2, a);
foo(1, a);
foo(0, a);
printf(“all done \n”);```
OpenMP – Example Parallel Loop

- **Loop level parallelism** – `#pragma omp parallel for`
  - Loop iterations are assigned to threads, invoked as functions

```c
#pragma omp parallel
{
    int id, i, nthreads,start, end;
    id = omp_get_thread_num();
    nthreads = omp_get_num_threads();
    start = id * N / nthreads ;  // assigning
    end = (id+1) * N / nthreads ;  // work
    for (i=start; i<end; i++) {
        foo(i);
    }
}
```
Race conditions when threads interact

• Unintended sharing of variables can lead to race conditions

• Race condition: program outcome depends on the scheduling order of threads

• How can we prevent data races?
  • Use synchronization
  • Change how data is stored
OpenMP details
OpenMP pragmas

• Pragma: a compiler directive in C or C++
• Mechanism to communicate with the compiler
• Compiler may ignore pragmas

```
#pragma omp construct [clause [clause] ... ]
```
Hello World in OpenMP

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

int main(void)
{
    #pragma omp parallel
    printf("Hello, world.\n");
    return 0;
}
```

• Compiling:
  
gcc -fopenmp hello.c -o hello

• Setting number of threads:
  
```bash
export OMP_NUM_THREADS=2
```
Parallel for

• Directs the compiler that the immediately following for loop should be executed in parallel

```
#pragma omp parallel for [clause [clause] ... ]
for (i = init; test_expression; increment_expression) {
    ...
    do work
    ...
}
```
Parallel for example

• saxpy (single precision a*x+y) example

```c
int main(int argc, char **argv)
{
    ...

#pragma omp parallel for
    for (int i = 0; i < n; i++) {
        z[i] = a * x[i] + y[i];
    }

    ...
}
```
Parallel for execution

- Primary thread creates worker threads
- All threads divide iterations of the loop among themselves
Number of threads

• Use environment variable in shell

```bash
export OMP_NUM_THREADS=X
```

• Use `omp_set_num_threads(int num_threads)`
  • Set the number of OpenMP threads to be used in parallel regions

• `int omp_get_num_procs(void)`
  • Returns the number of available processors/cores
  • Can be used to decide the number of threads to create
Data sharing defaults

• Most variables are shared by default
• Global variables are shared
• Exception: loop index variables are private by default
• Stack variables in function calls from parallel regions are also private to each thread (thread-private)
Overriding defaults using clauses

- Specify how data is shared between threads executing a parallel region
  - private(list)
  - shared(list)
  - default(shared | none)
  - reduction(operator: list)
  - firstprivate(list)
  - lastprivate(list)

https://www.openmp.org/spec-html/5.0/openmp/s106.html#x139-5540002.19.4
firstprivate clause

• Initializes each thread’s private copy to the value of the primary thread’s copy

val = 5;

#pragma omp parallel for firstprivate(val)
for (int i = 0; i < n; i++) {
    ... = val + 1;
}
lastprivate clause

- Writes the value belonging to the thread that executed the last iteration of the loop to the primary’s copy
- Last iteration determined by sequential order

```c
#pragma omp parallel for lastprivate(val)
for (int i = 0; i < n; i++) {
    val = i + 1;
}

printf("%d\n", val);
```
reduction(operator: list) clause

• Reduce values across private copies of a variable
• Operators: +, -, *, &, |, ^, &&, ||, max, min
  • User-defined operators can be created

```c
#pragma omp parallel for reduction(+: val)
for (int i = 0; i < n; i++) {
    val += i;
}

printf("%d\n", val);
```

https://www.openmp.org/spec-html/5.0/openmpsu107.html#x140-5800002.19.5
Loop scheduling

• Assignment of loop iterations to different worker threads
• Default schedule tries to balance iterations among threads
• User-specified schedules are also available
User-specified loop scheduling

• Schedule clause

    schedule (type[, chunk])

• type: static, dynamic, guided, runtime

• static: iterations divided as evenly as possible (#iterations/#threads)
  • chunk size < #iterations/#threads can be used to interleave threads

• dynamic: assign a chunk size block to each thread
  • When a thread is finished, it retrieves the next block from an internal work queue, so requires a scheduler thread
  • Default chunk size = 1
Other schedules

• **guided**: similar to dynamic but start with a large chunk size and gradually decrease it for handling load imbalance between iterations
• **auto**: scheduling delegated to the compiler
• **runtime**: use the OMP_SCHEDULE environment variable

Calculate the value of  \[ \pi = \int_0^1 \frac{4}{1 + x^2} \]  

int main(int argc, char *argv[]) 
{  
    ...  

    n = 10000;  

    h   = 1.0 / (double) n;  
    sum = 0.0;  

    for (i = 1; i <= n; i += 1) {  
        x = h * ((double)i - 0.5);  
        sum += (4.0 / (1.0 + x * x));  
    }  
    pi = h * sum;  

    ...  
}
Calculate the value of $\pi = \int_0^1 \frac{4}{1 + x^2}$

```c
int main(int argc, char *argv[]) {
    ...

    n = 10000;
    h = 1.0 / (double) n;
    sum = 0.0;

    #pragma omp parallel for private(x) reduction(+: sum)
    for (i = 1; i <= n; i += 1) {
        x = h * ((double) i - 0.5);
        sum += (4.0 / (1.0 + x * x));
    }
    pi = h * sum;

    ...
}
```
Synchronization

• Concurrent access to shared data may result in inconsistencies
• Use mutual exclusion to avoid that
• critical directive
• atomic directive
• Library lock routines