

CMSC 714
Lecture 6
OpenMP

Alan Sussman

Notes

- MPI project due week from Monday, Sept. 26
 - Send any questions about project spec, or running on zaratan cluster to Dr. Sussman
- Don't forget to send questions for readings
 - additional readings posted recently, with who should send questions

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 available to run on more than one node in a cluster

- **Example**

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

More on OpenMP

- **Characteristics**

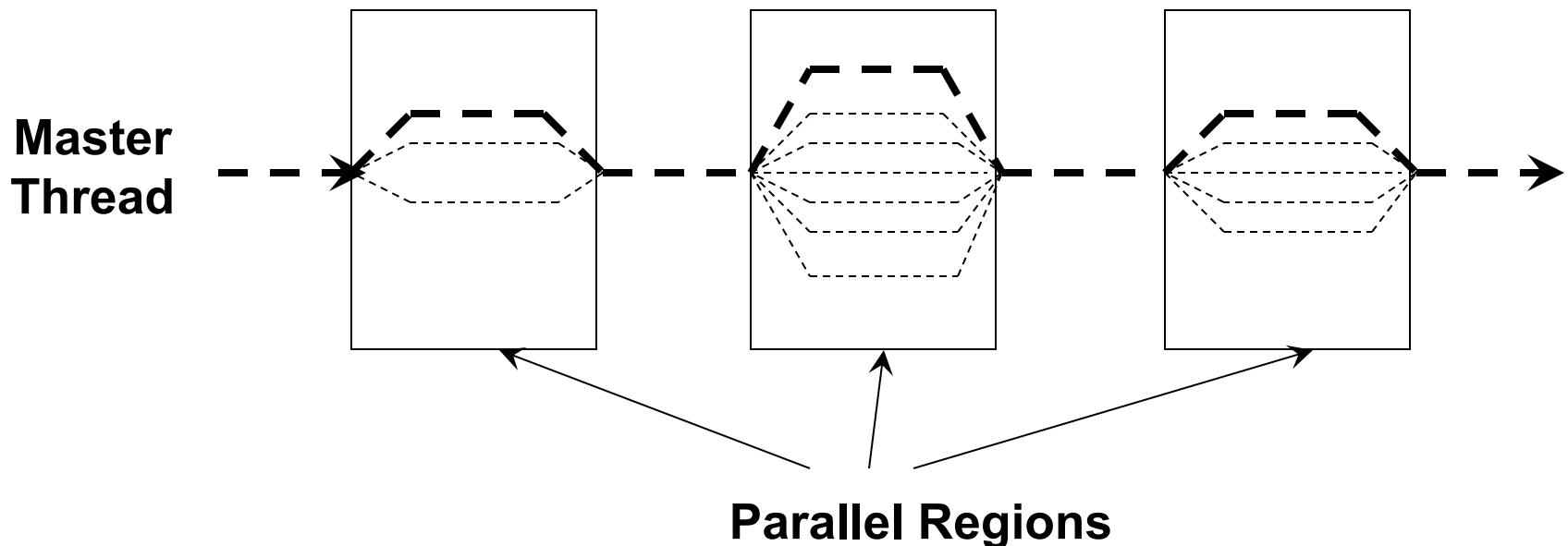
- Not a full parallel language, but a language extension
- A set of standard compiler directives and library routines
- Used to create parallel Fortran, C and C++ programs
- Usually used to parallelize loops
- Standardizes last ~20 years of SMP practice

- **Implementation**

- C 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 (master)
 - Worker threads spawned when parallel region encountered
 - Barrier synchronization required at end of parallel region

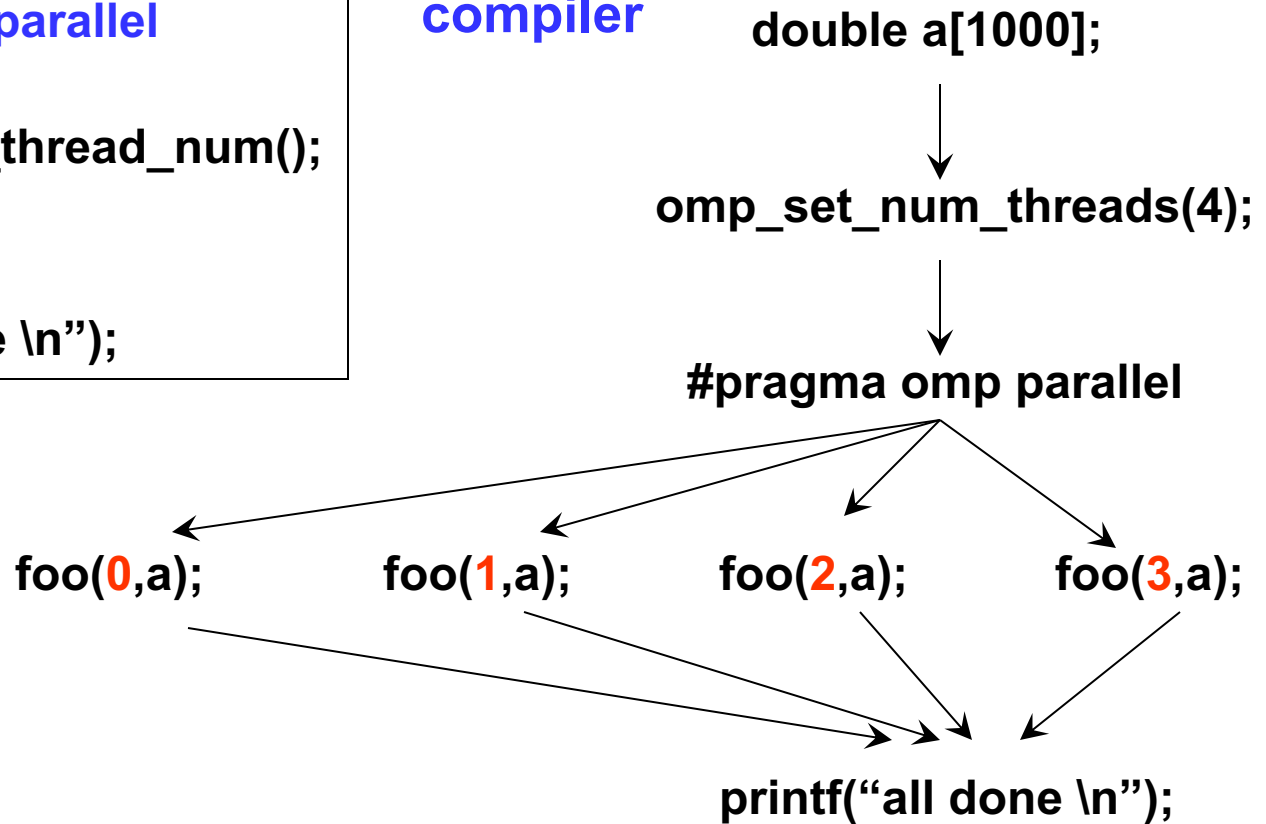


OpenMP – Example Parallel Region

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

```
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



OpenMP – Example Parallel Loop

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

OpenMP
compiler



```
#pragma omp parallel for  
for (i=0;i<N;i++) {  
    foo(i);  
}
```

```
#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

```
#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:**

```
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

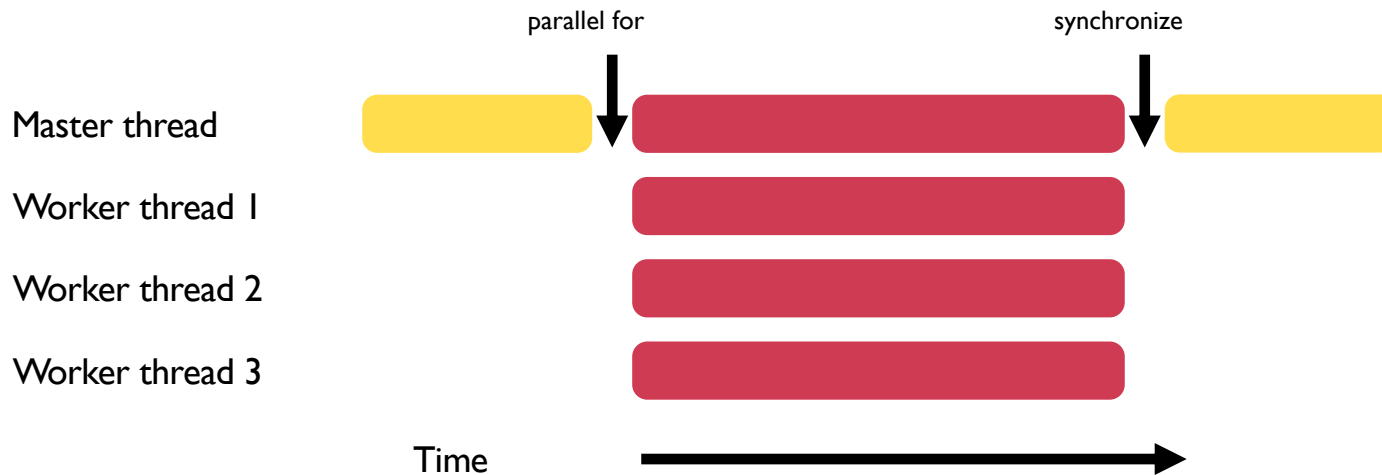
```
int main(int argc, char **argv)
{
    ...

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

    ...
}
```

Parallel for execution

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



Number of threads

- Use environment variable in shell

```
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/openmpsul06.html#x139-5540002.19.4>

firstprivate clause

- Initializes each thread's private copy to the value of the master 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 master's copy
- Last iteration determined by sequential order

```
#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

```
#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/openmpsul07.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

<https://software.intel.com/content/www/us/en/develop/articles/openmp-loop-scheduling.html>

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 $\pi = \int_0^1 \frac{4}{1+x^2}$

```
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

<https://software.intel.com/content/www/us/en/develop/documentation/advisor-user-guide/top/appendix/adding-parallelism-to-your-program/replacing-annotations-with-openmp-code/adding-openmp-code-to-synchronize-the-shared-resources.html>