Introducing OpenMP in a Data Structures (CS2) or Systems Class

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SIGCSE 2019 Workshop on Modernizing Early CS Courses with Parallel and Distributed Computing

Goals

- Introduce basic ideas of OpenMP shared memory parallelism
  - At a level suitable for teaching in an intro programming or systems class
  - Mainly targeting loop level parallelism
- Provide examples of using OpenMP for some simple problems

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
  - lots of other things we won't talk about today

OpenMP

- Characteristics
  - Both local & shared memory (depending on directives)
  - Parallelism: directives for parallel loops, functions
  - Compilers convert programs into multi-threaded (i.e. pthreads)
  - Not available on clusters
- Example

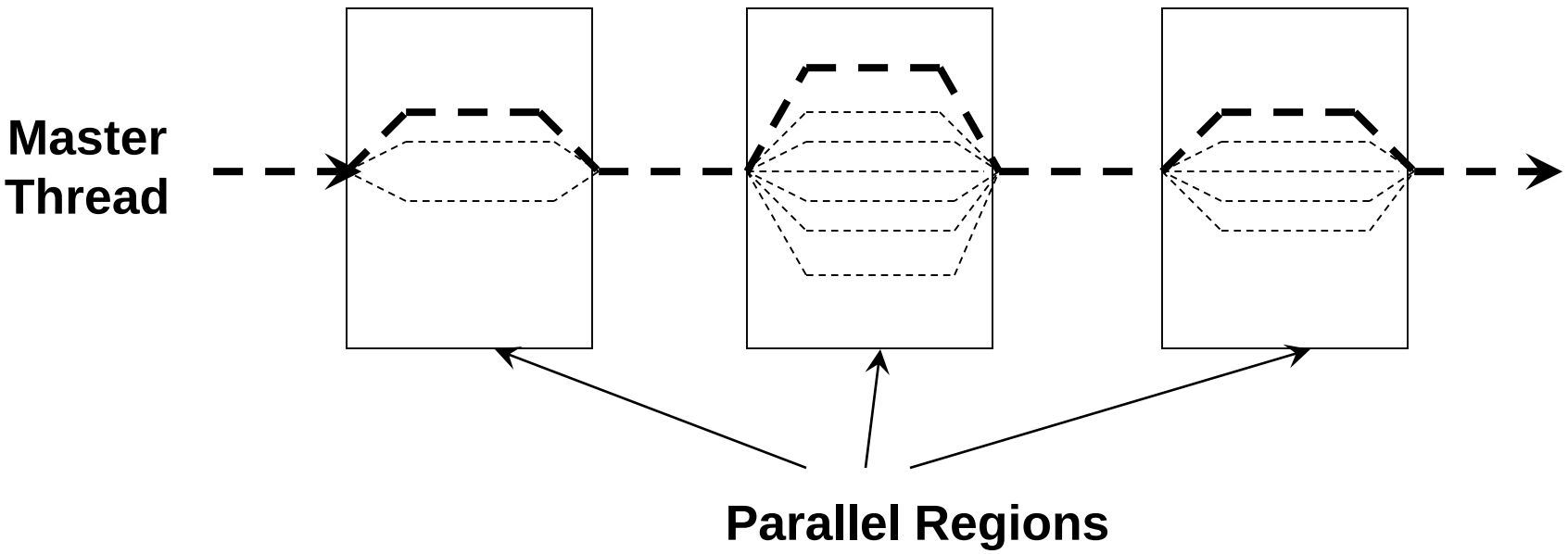
```
#pragma omp parallel for private(i)
for (i=0; i<NUPDATE; i++) {
        int ran = random();
        table[ ran & (TABSIZE-1) ] ^= stable[ ran >> (64-LSTSIZE) ];
}
```

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/C++, Java programs
  - Usually used to parallelize loops
  - Standardizes last >20 years of SMP practice
- Implementation
  - C/C++ compiler directives using #pragma omp <directive>
    - Somewhat different syntax for Java or Fortran
  - 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

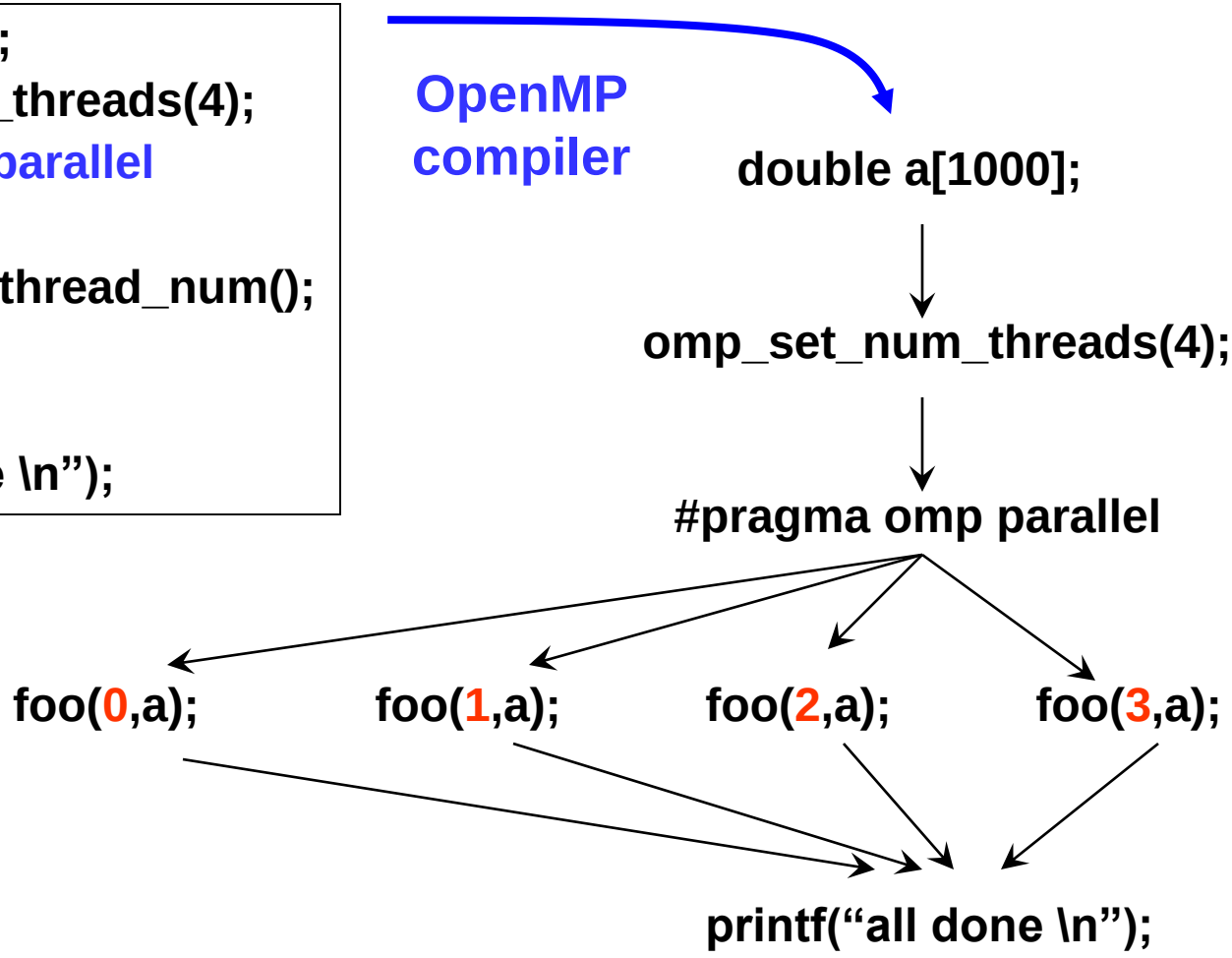
- Fork-join parallelism (restricted form of MIMD)
  - Normally single thread of control (master)
  - Worker threads spawned when parallel region encountered
  - Barrier synchronization required at end of parallel region



OpenMP – Example Parallel Region

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

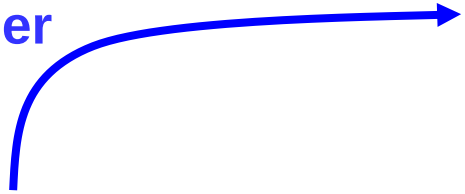
```
double a[1000];
omp_set_num_threads(4);
#pragma omp parallel
{
  int id = omp_thread_num();
  foo(id,a);
}
printf("all done \n");
```



OpenMP – 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);
   }
}
```

Sample C OpenMP Code

```
int main() {
    int n, i;
    double w, x, sum, pi;
    printf(“Enter number of intervals: \n”);
    scanf(“%d”, &n);
    /* calculate the interval size */
    w = 1.0;
    sum = 0.0;
#pragma omp parallel for private(x), reduction(+: sum)
    for (i = 1; i <= n; i++) {
        x = w * (i - 0.5);
        sum = sum + f(x);
    }
    pi = w * sum;
    printf (“computed pi = %f\n”, pi);
}
/* function to integrate */
double f(double a) {
    return (2.0 / (1.0 + a*a));
}
```

Execution Context

- Every thread has its own execution context
- Execution context: address space containing all of the variables a thread may access
- Contents of execution context:
  - static variables
  - dynamically allocated data structures in the heap
  - variables on the run-time stack
  - additional run-time stack for functions invoked by the thread

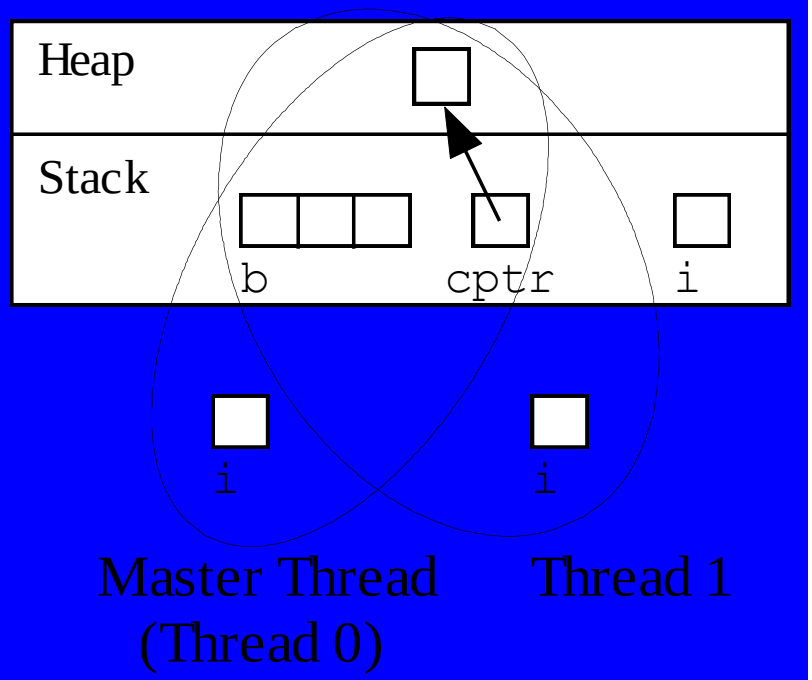
Shared and Private Variables

- Shared variable: has same address in execution context of every thread
- Private variable: has different address in execution context of every thread
- A thread cannot access the private variables of another thread

Shared and Private Variables

```
int main (int argc, char *argv[])
{
   int b[3];
   char *cptr;
   int i;

   cptr = malloc(1);
#pragma omp parallel for
   for (i = 0; i < 3; i++)
      b[i] = i;
```



Race Condition

- Consider this C program segment to compute π using the rectangle rule (should look familiar):

```
double area, pi, x;
int i, n;
...
area = 0.0;
for (i = 0; i < n; i++) {
   x = (i+0.5)/n;
   area += 4.0/(1.0 + x*x);
}
pi = area / n;
```

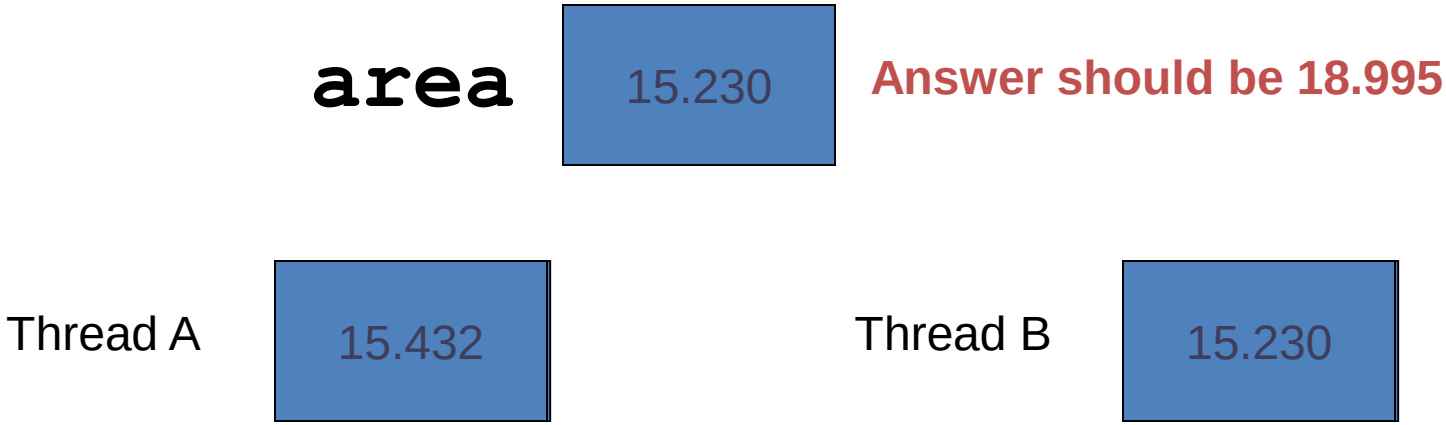
Race Condition (cont.)

- If we simply parallelize the loop...

```
double area, pi, x;
int i, n;
...
area = 0.0;
#pragma omp parallel for private(x)
for (i = 0; i < n; i++) {
   x = (i+0.5)/n;
   area += 4.0/(1.0 + x*x);
}
pi = area / n;
```

Race Condition (cont.)

- ... we set up a race condition in which one process may “race ahead” of another and not see its change to shared variable **`area`**



Reductions

- Reductions are so common that OpenMP provides support for them
- May add reduction clause to **`parallel for`** pragma
- Specify reduction operation and reduction variable
- OpenMP takes care of storing partial results in private variables and combining partial results after the loop

reduction Clause

- The reduction clause has this syntax:
  `reduction (<op> :<variable>)`
- Operators
  - `+` Sum
  - `*` Product
  - `&` Bitwise and
  - `|` Bitwise or
  - `^` Bitwise exclusive or
  - `&&` Logical and
  - `||` Logical or

π-finding Code with Reduction Clause

```
double area, pi, x;
int i, n;
...
area = 0.0;
#pragma omp parallel for \
        private(x) reduction(+:area)
for (i = 0; i < n; i++) {
   x = (i + 0.5)/n;
   area += 4.0/(1.0 + x*x);
}
pi = area / n;
```

Logistics

- OpenMP is supported by modern C, C++, Fortran compilers
  - gcc has supported it since version 4.2
  - Use the **–fopenmp** argument to gcc to enable processing OpenMP directives and link the library
  - Set the environment variable OMP_NUM_THREADS to set the initial number of threads in parallel sections
- For Java support, try pyjama (at U. Auckland) or omp4j (at www.omp4j.org)

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