Parallel Programming
in C with MPI and OpenMP

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Chapter 17

Shared-memory Programming
Outline

- OpenMP
- Shared-memory model
- Parallel `for` loops
- Declaring private variables
- Critical sections
- Reductions
- Performance improvements
- More general data parallelism
- Functional parallelism

OpenMP

- OpenMP: An application programming interface (API) for parallel programming on multiprocessors
  - Compiler directives
  - Library of support functions
- OpenMP works in conjunction with Fortran, C, or C++
What’s OMP/MPI/CUDA good for?

- C+OpenMP shared memory multiprocessors
- C+MPI(+OpenMP) distributed machines (built out of shared memory machines)
  - for us:
    ISTeC Cray:
    - 52 nodes, each with
      - 4 processors, each with 6 cores
- C+CUDA for GPUs
  - for us: Nvidia Tesla 30 processors, 240 cores, on a chip

Shared-memory Model

Processors interact and synchronize with each other through shared variables.
Fork/Join Parallelism

- Initially only master thread is active
- Master thread executes sequential code
- Fork: Master thread creates or awakens additional threads to execute parallel code
- Join: At end of parallel code created threads die or are suspended
Incremental Parallelization

- Sequential program a special case of a shared-memory parallel program
- Parallel shared-memory programs may only have a single parallel loop
- Incremental parallelization: process of converting a sequential program to a parallel program a little bit at a time

Parallel for Loops

- C programs often express data-parallel operations as `for` loops
  ```c
  for (i = first; i < size; i += prime)
  marked[i] = 1;
  ```
- OpenMP makes it easy to indicate when the iterations of a loop may execute in parallel
- Compiler takes care of generating code that forks/joins threads and allocates the iterations to threads
Pragmas

-Pragma: a compiler directive in C or C++
- Stands for “pragmatic information”
- A way for the programmer to communicate with the compiler
- Compiler free to ignore pragmas
- Syntax:
  ```
  #pragma omp <rest of pragma>
  ```

Parallel for Pragma

- Format:
  ```
  #pragma omp parallel for
  for (i = 0; i < N; i++)
  a[i] = b[i] + c[i];
  ```
- There is a data dependence between the iterations, but it can be resolved. HOW??
Parallel for Pragma

Format:

```c
#pragma omp parallel for
for (i = 0; i < N; i++)
a[i] = b[i] + c[i];
```

- There is a data dependence between the iterations, but it can be resolved. HOW??
  - Blocking: compute #iterations, group them, compute start index of each group.
- Compiler must be able to verify the run-time system will have information it needs to schedule loop iterations. What can we NOT have?
  - Dynamic control, e.g. conditional exit out of the loop.
**Canonical Shape of for Loop Control Clause**

\[
\text{for(index = start; index } \geq \begin{cases} < \\ \leq \\ \geq \\ > \end{cases} \text{ end; } \left\{ \begin{array}{l}
\text{index}++ \\
+ \text{index} \\
\text{index}-- \\
- \text{index} \\
\text{index}+ \text{ = inc} \\
\text{index}-- \text{ = inc} \\
\text{index} = \text{ index} + \text{ inc} \\
\text{index} = \text{ inc +index} \\
\text{index} = \text{ index} - \text{ inc}
\end{array} \right. \}
\]

**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

C memory structure recap

- Data variables in C can be:
  - In registers (compiler directive, may not always be followed, and may spill)
  - On the stack (activation record of the current execution context)
  - On the heap – dynamically allocated through malloc
Shared and Private Variables

```c
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;
}
```

Single and Multithreaded Processes

- **Single-threaded process**
  - Code
  - Data
  - Files
  - Registers
  - Stack

- **Multithreaded process**
  - Code
  - Data
  - Files
  - Registers
  - Registers
  - Registers
  - Stack
  - Stack
  - Stack
Function omp_get_num_procs

- Returns number of processors available for use by the parallel program

    int omp_get_num_procs (void)

Function omp_set_num_threads

- Uses the parameter value to set the number of threads to be active in parallel sections of code
- May be called at multiple points in a program

    void omp_set_num_threads (int t)

- Can you set the #threads > OMP_NUM_THREADS?
  - try it
Declaring Private Variables

```c
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[i][j] = MIN(a[i][j], a[i][k]+tmp);
```

- Either loop could be executed in parallel
- We prefer to make outer loop parallel, to reduce number of forks/joins
- We then must give each thread its own private copy of variable \( j \), **WHY?**

### private Clause

- **Clause:** an optional, additional component to a pragma
- **Private clause:** directs compiler to make one or more variables private

```c
private ( <variable list> )
```
Example Use of private Clause

```c
#pragma omp parallel for private(j)
for (i = 0; i < n; i++)
    for (j = 0; j < n; j++)
        a[i][j] = MIN(a[i][j], a[i][k] + tmp);
```

firstprivate Clause

- Used to create private variables having initial values identical to the variable controlled by the master thread as the loop is entered
- Variables are initialized once per thread, not once per loop iteration
- If a thread modifies a private variable's value in an iteration, subsequent iterations that are executed by this thread will get the modified value, other threads will work with their own private copy
lastprivate Clause

- Sequentially last iteration: iteration that occurs last when the loop is executed sequentially
- lastprivate clause: used to copy back to the master thread’s copy of a variable the private copy of the variable from the thread that executed the sequentially last iteration

Race Condition

- Consider this C program segment to compute $\pi$ using the rectangle rule:

```c
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...

  what happens?

  ```
  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 two processes may both read `area`, then compute the rhs, then write back

<table>
<thead>
<tr>
<th>area</th>
<th>Answer should be 18.995</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.230</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thread A</th>
<th>Thread B</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.432</td>
<td>15.230</td>
</tr>
</tbody>
</table>

  `area += 4.0/(1.0 - x*x)`
# Race Condition Time Line

<table>
<thead>
<tr>
<th>Value of area</th>
<th>Thread A</th>
<th>Thread B</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.667</td>
<td>+ 3.765</td>
<td></td>
</tr>
<tr>
<td>11.667</td>
<td></td>
<td>+ 3.563</td>
</tr>
<tr>
<td>15.432</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.230</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

##_critical Pragma

- Critical section: a portion of code that only one thread at a time may execute
- We denote a critical section by putting the pragma

```c
#pragma omp critical
```

in front of a block of C code
Correct, but inefficient, code

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;
#pragma omp critical
    area += 4.0/(1.0 - x*x);
}
pi = area / n;

Source of Inefficiency
- Update to area inside a critical section
- Only one thread at a time may execute the statement; i.e., it is sequential code
- Time to execute statement significant part of loop, made worse by the need for synchronization
- Speedup will be severely constrained
- Can you see a solution?
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
\[ \pi \text{ code with Reduction Clause} \]

```c
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;
```

---

**Performance Improvement #1**

- Too many fork/joins can lower performance
- Inverting loops may help performance if
  - Parallelism is in inner loop
  - After inversion, the outer loop can be made parallel
  - Inversion does not significantly lower cache hit rate
Performance Improvement #2

- If loop has too few iterations, fork/join overhead is greater than time savings from parallel execution.
- The `if` clause instructs compiler to insert code that determines at run-time whether loop should be executed in parallel; e.g.,

```
#pragma omp parallel for if(n > 5000)
```

Performance Improvement #3

- We can use `schedule` clause to specify how iterations of a loop should be allocated to threads.
- Static schedule: all iterations allocated to threads before any iterations executed.
- Dynamic schedule: only some iterations allocated to threads at beginning of loop’s execution. Remaining iterations allocated to threads that complete their assigned iterations.
Static vs. Dynamic Scheduling

- Static scheduling
  - Low overhead
  - May exhibit high workload imbalance
- Dynamic scheduling
  - Higher overhead
  - Can reduce workload imbalance

Chunks

- A chunk is a contiguous range of iterations
- Increasing chunk size reduces overhead and may increase cache hit rate
- Decreasing chunk size allows finer balancing of workloads
schedule Clause

- Syntax of schedule clause
  \[ \text{schedule} \ (<\text{type}>[,<\text{chunk}>] ) \]
- Schedule type required, chunk size optional
- Allowable schedule types
  - static: static allocation
  - dynamic: dynamic allocation
  - guided
  - runtime: type chosen at run-time based on value of environment variable OMP_SCHEDULE

Scheduling Options

- schedule(static): block allocation of about \( n/\#\text{threads} \) contiguous iterations to a thread
- schedule(static,\( C \)): interleaved allocation of chunks of size \( C \) to threads
- schedule(dynamic): dynamic one-at-a-time allocation of iterations to threads
- schedule(dynamic,\( C \)): dynamic allocation of \( C \) iterations at a time to threads
Scheduling Options (cont.)

- schedule(guided, C): dynamic allocation of chunks to tasks using guided self-scheduling heuristic. Initial chunks are bigger, later chunks are smaller, minimum chunk size is C.
- schedule(guided): guided self-scheduling with minimum chunk size 1
- schedule(runtime): schedule chosen at run-time based on value of OMP_SCHEDULE; Unix example: `setenv OMP_SCHEDULE "static,1"`

More General Data Parallelism

- Our focus has been on the parallelization of `for` loops
- Other opportunities for data parallelism
  - processing items on a “to do” list
  - `for` loop + additional code outside of loop
Processing a “To Do” List

parallel Pragma

- The `parallel` pragma precedes a block of code that should be executed by all of the threads
- Note: execution is replicated among all threads
Use of **parallel** Pragma

```c
#pragma omp parallel private(task_ptr)
{
    task_ptr = get_next_task (&job_ptr);
    while (task_ptr != NULL) {
        complete_task (task_ptr);
        task_ptr = get_next_task (&job_ptr);
    }
}
```

Critical Section for **get_next_task**

```c
char *get_next_task(struct job_struct **head) {
    struct task_struct *nextTask;
    #pragma omp critical
    {
        if (*head == NULL) nextTask = NULL;
        else {
            nextTask = (*head)->task;
            *head = (*head)->next;
        }
    }
    return nextTask;
}
```
Functions for SPMD-style Programming

- The parallel pragma allows us to write SPMD-style programs
- In these programs we often need to know number of threads and thread ID number
- OpenMP provides functions to retrieve this information

Function `omp_get_thread_num`

- This function returns the thread identification number
- If there are $t$ threads, the ID numbers range from 0 to $t-1$
- The master thread has ID number 0

```c
int omp_get_thread_num (void)
```
Function `omp_get_num_threads`

- Function `omp_get_num_threads` returns the number of active threads.
- If call this function from sequential portion of program, it will return 1.

```c
int omp_get_num_threads (void)
```

**forPragma**

- The `parallel` pragma instructs every thread to execute all of the code inside the block.
- If we encounter a `for` loop that we want to divide among threads, we use the `for` pragma.

```
#pragma omp for
```
Example Use of for Pragma

```c
#pragma omp parallel private(i,j)
for (i = 0; i < m; i++) {
    low = a[i];
    high = b[i];
    if (low > high) {
        printf("Exiting (%d)\n", i);
        break;
    }
}  
#pragma omp for
for (j = low; j < high; j++)
    c[j] = (c[j] - a[i])/b[i];
```

single Pragma

- Suppose we only want to see the output once
- The `single` pragma directs compiler that only a single thread should execute the block of code the pragma precedes
- Syntax:
  ```c
  #pragma omp single
  ```
Use of single Pragma

```c
#pragma omp parallel private(i,j)
for (i = 0; i < m; i++) {
    low = a[i];
    high = b[i];
    if (low > high) {
#pragma omp single
        printf("Exiting (%d)\n", i);
        break;
    }
#pragma omp for
    for (j = low; j < high; j++)
        c[j] = (c[j] - a[i])/b[i];
}
```

nowait Clause

- Compiler puts a barrier synchronization at end of every parallel for statement
- In our example, this is necessary: if a thread leaves loop and changes **low** or **high**, it may affect behavior of another thread
- If we make these private variables, then it would be okay to let threads move ahead, which could reduce execution time
Use of nowait Clause

```c
#pragma omp parallel private(i,j,low,high)
for (i = 0; i < m; i++) {
    low = a[i];
    high = b[i];
    if (low > high) {
#pragma omp single
        printf("Exiting (%d)\n", i);
        break;
    }
#pragma omp for nowait
    for (j = low; j < high; j++)
        c[j] = (c[j] - a[i])/b[i];
}
```

Functional Parallelism

- To this point all of our focus has been on exploiting data parallelism
- OpenMP allows us to assign different threads to different portions of code (functional parallelism)
Functional Parallelism Example

\[ v = \text{alpha}(); \]
\[ w = \text{beta}(); \]
\[ x = \text{gamma}(v, w); \]
\[ y = \text{delta}(); \]
\[ \text{printf} \left( \"%6.2f\n\", \text{epsilon}(x,y) \right); \]

May execute alpha, beta, and delta in parallel

**parallel sections Pragma**

- Precedes a block of \( k \) (sub) blocks of code that may be executed concurrently by (up to) \( k \) threads
- Syntax:

  \[
  \#\text{pragma omp parallel sections}
  \]
section Pragma

- Precedes each block of code within the encompassing block preceded by the parallel sections pragma
- May be omitted for first parallel section after the parallel sections pragma
- Syntax:

```
#pragma omp section
```

Example of parallel sections

```c
#pragma omp parallel sections
{
#pragma omp section /* Optional */
    v = alpha();
#pragma omp section
    w = beta();
#pragma omp section
    y = delta();
}
    x = gamma(v, w);
    printf("%6.2f\n", epsilon(x, y));
```
Another Approach

Execute alpha and beta in parallel.
Execute gamma and delta in parallel.

sections Pragma

- Appears inside a parallel block of code
- Has same meaning as the parallel sections pragma
- If multiple sections pragmas inside one parallel block, may reduce fork/join costs
Use of sections Pragma

```c
#pragma omp parallel
{
  #pragma omp sections
  {
    v = alpha();
    #pragma omp section
    w = beta();
  }
  #pragma omp sections
  {
    x = gamma(v, w);
    #pragma omp section
    y = delta();
  }
}
printf("%.2f\n", epsilon(x,y));
```

Summary (1/3)

- OpenMP is an API for shared-memory parallel programming
- Shared-memory model based on fork/join parallelism
- Data parallelism
  - parallel for pragma
  - reduction clause
Summary (2/3)

- Functional parallelism (parallel sections pragma)
- SPMD-style programming (parallel pragma)
- Critical sections (critical pragma)
- Enhancing performance of parallel for loops
  - Inverting loops
  - Conditionally parallelizing loops
  - Changing loop scheduling

Summary (3/3)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>OpenMP</th>
<th>MPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suitable for multiprocessors</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Suitable for multicomputers</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Supports incremental parallelization</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Minimal extra code</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Explicit control of memory hierarchy</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>