Introduction to OpenMP

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Why OpenMP

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- Data duplication across the processors.
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Lack of an industry-wide standard in shared memory high performance computing. The microprocessors are based on the SMP architecture.
POWER5 (IBM) Processor Chip

FXU - Fixed Point (Integer) Unit
ISU - Instruction Sequencing Unit
LSU - Load Store Unit
L2 - Level 2 Cache
MC - Memory Controller

FPU - Floating Point Unit
IDU - Instruction Decoding Unit
IFU - Instruction Fetch Unit
L3 - Level 3 Cache
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  (http://www.redbooks.ibm.com/redpieces/pdfs/sg245768.pdf)
- **UltraSPARC IV** (Sun Fire Servers) Sun Microsystems
  (http://www.sun.com/processors/whitepapers/us4_whitepaper.pdf)
- **PA-8800** (HP 9000 Servers) Hewlett Packard
What is OpenMP

It is an Application Program Interface (API) to provide a model for parallel programming portable across different shared memory architectures.
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What is an API?
Application Program Interface

A set of routines, protocols, and tools for building software applications. A good API makes it easier to develop a program by providing all the building blocks. A programmer puts the blocks together.

Consider the component tasks to print "hello world" on the screen.

1. Outline the shapes of the letters H, e, l, l, o, W, o, r, l, d.
2. Locate a matrix of black and white squares resembling these letters.
3. Program the CPU to put this matrix into the display adapter's frame buffer.
4. Set the graphics card to scan its frame buffer and generate the signal.

A much simpler option is to use an API

1. Write an HTML document containing "hello world".
2. Open the document using a web browser.
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It is an Application Program Interface (API) to provide a model for parallel programming portable across different shared memory architectures and scalable.

Standard is jointly defined by a group with members from major computer hardware and software vendors like IBM, Silicon Graphics, Hewlett Packard, Intel, Sun Microsystems, The Portland Group, etc.
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OpenMP API consists of the following components:

- **Compiler directives**
  Instructs the compiler to process the code section following the directive for parallel execution.

- **Library routines**
  Routines that affect and monitor threads, processors and environment variables. It also has routines to control thread synchronization and get timings.

- **Environment variables**
  Variables controlling the execution of the OpenMP program.
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- **Program execution** begins as a single thread of execution, called the initial thread.
- A thread encountering a `parallel` construct becomes a master, creates a team of itself and additional threads.
- All members of the team execute the code inside `parallel` construct.
Execution and Memory Models

Parallel execution in OpenMP is based on the fork-join model, where the master thread creates a team of threads for parallel execution.

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![Diagram showing thread execution and memory models]

- **Thread 1**
- **Thread 2**
- **Thread 3**

**Memory Models**

- **Private Memory**
- **Temporary View**
- **MEMORY**
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Each thread has a temporary view of the memory, which is like a cache, and a private memory not accessible other threads.

- Relaxed consistency, the thread’s view of memory is not required to be consistent with the memory at all times.
- Flush operation causes the last modified variable in the temporary view to be written to memory.
- Private variables of a thread can be copies of data from memory and cannot be accessed by other threads.

The parallel construct can be nested arbitrary number of times. Thread encountering parallel becomes the master.
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How OpenMP Works

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Parallel is the OpenMP directive which creates a team of threads.

`!$omp` OpenMP directive
`c$omp` OpenMP directive

`!$omp parallel
`$omp parallel

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Work is distributed among the threads using work-sharing OpenMP directives loop, section and single.
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Each of these directives have associated clauses to control data sharing and mode of execution.
### How OpenMP Works

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<td><strong>End</strong> directive terminates the work share and parallel constructs.</td>
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</table>

| !$omp OpenMP directive |
| c$omp OpenMP directive |
| !$omp **parallel** |
| c$omp **parallel** |
| !$omp **parallel** |
| !$omp **do/section/single** |
| !$omp **parallel[clause]** |
| !$omp **workshare[clause]** |
| !$omp **end workshare** |
| !$omp **end parallel** |

---

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Parallel Execution in OpenMP
Parallel Execution in OpenMP

.........................
sequential block

$omp$
parallel [clause[,]clause]...

........................

where clause is one of the following

if(scalar-logical-expression)
private(list)
firstprivate(list)
default(private|shared|none)
shared(list)
copyin(list)
reduction(...)
um_threads(...)
Parallel Execution in OpenMP

............... sequential block

 !$omp parallel [clause[[],clause]...]
 where clause can be if, private, firstprivate, default, shared, copyin, reduction, num_threads

 !$omp do|section|single[clause[...][...]]
 where clause is one of the following
 private(list)
 firstprivate(list)
 lastprivate(list)
 reduction(...)
 ordered
 schedule(kind[,chunk_size])
Parallel Execution in OpenMP

.................
sequential block

!$omp parallel [clause[,clause]...] where clause can be if, private, firstprivate, default, shared, copyin, reduction, num_threads

!$omp do|section|single[clause[...]...] where clause can be private, firstprivate, lastprivate, reduction, ordered, schedule
do ia = 1, N
  structured block
end do

![omp section]
  structured block

![omp section]
  structured block

...
Parallel Execution in OpenMP

...........................
sequential block

!$omp parallel [clause[[[],]clause]...]
where clause can be if, private, firstprivate, default, shared, copyin, reduction, num_threads

!$omp do|section|single[clause[...]...]
where clause can be private, firstprivate, lastprivate, reduction, ordered, schedule
do ia = 1, N
structured block
end do

[!$omp section]
structured block

[!$omp section]
structured block

...

!$omp end do|section[nowait]|
!$& single[end_clause...]}

!$omp end parallel
structured block

.............................
Workshare Directives

Workshare directives follow after a parallel directive or it can occur in a region where there are multiple threads.

There are three possible workshare constructs.

- **loop**
  It distributes the work load of the do which immediately follows it.

- **sections**
  A set of sections follows the directive and these are executed by a team of threads.

- **single**
  The section of code enclosed within this workshare directive is executed by a single thread.

The generic format of the workshare directives is

```
$omp workshare [clause[[[,]clause]...]
lines of code
$omp end workshare
```

where workshare can be one of the three directives.
Data scope attribute clauses allow specifying scope of data to each thread. There are five important data scope attributes.

- **private**
  Each thread in the team has its own uninitialized local copy of the variables and common blocks listed as `private`. A variable should be defined as `private`, if its value is not dependent on any other thread.

- **firstprivate**
  Each thread has its own initialized local copy of the variables and common blocks listed as `firstprivate`.

- **lastprivate**
  Variables or common blocks listed as `lastprivate` can be referred to outside of the construct of the directive. The assigned value is the last calculated in the construct.
Data Scope Attribute Clauses (contd)

- **copyin**
  Variables or common blocks listed in the `copyin` clause are duplicated privately for each thread from the master thread’s copy.

- **shared**
  Variables and common blocks declared as `shared` are available to all the threads.
Synchronization Directives

- **critical**
The blocks of code enclosed within `critical` construct are executed by one thread at a time.

- **barrier**
This directive synchronizes all the threads. When a thread encounters the `barrier` directive, it will wait until all other threads in the team reach the same point.

- **atomic**
The `atomic` ensures that only one thread is writing to a specific memory location. The directive binds to the executable statement which follows immediately.
Synchronization Directives (contd)

- **flush**
  The `flush` directive ensures that each thread has access to data generated by other threads. It makes the memory of the threads consistent.

- **ordered**
  This directive cause the iteration of a block of code within a parallel loop to be executed as it would do sequentially.
Consider the multiplication of two square matrices $A$ and $B$ to get the matrix $C$.

$$C_{ij} = \sum_k A_{ik} B_{kj}$$

```
do ii = 1, nmax
  do jj = 1, nmax
    sum = 0.
    ! +------------+
    ! | Inner Loop |
    ! +------------+
    do kk = 1, nmax
      sum = sum + A(ii,kk)*B(kk,jj)
    enddo
    C(ii,jj) = sum
  enddo
endo```

parallel and do directives
parallel and do directives

!$omp parallel
!$omp do
    do ii = 1, nmax
        do jj = 1, nmax
            sum = 0.
    ! +------------+
    ! | Inner Loop |
    ! +------------+
        do kk = 1, nmax
            sum = sum + A(ii,kk)*B(kk,jj)
        enddo
        C(ii,jj) = sum
    enddo
enddo
!$omp end do
!$omp end parallel

What about the data attributes?
平行和do directives

!$omp parallel private (ii, jj, kk, sum)
!$omp do
  do ii = 1, nmax
    do jj = 1, nmax
      sum = 0.
      +------------+
      | Inner Loop |
      +------------+
      do kk = 1, nmax
        sum = sum + A(ii,kk)*B(kk,jj)
      enddo
      C(ii,jj) = sum
    enddo
  enddo
!$omp end do
!$omp end parallel
Consider the multiplication of two square matrices again.

\[ C_{ij} = \sum_k A_{ik} B_{kj} \]

```
    do ii = 1, nmax
      do jj = 1, nmax
        sum = 0.
        ! +------------+
        ! | Inner Loop |
        ! +------------+
        do kk = 1, nmax
          sum = sum + A(ii,kk)*B(kk,jj)
        enddo
        C(ii,jj) = sum
      enddo
    enddo
```
do ii = 1, nmax
!$omp parallel private (ii, jj, kk, sum)
!$omp sections
!$omp section
  do jj = 1, nmax/2
    sum = 0.
    do kk = 1, nmax
      sum = sum + A(ii,kk)*B(kk,jj)
    enddo
    C(ii,jj) = sum
  enddo
!$omp section
  do jj = 1 + nmax/2, nmax
    sum = 0.
    do kk = 1, nmax
      sum = sum + A(ii,kk)*B(kk,jj)
    enddo
    C(ii,jj) = sum
  enddo
!$omp end sections
!$omp end parallel
end do
In addition to the OpenMP directives, there are library functions to get and set the execution environment control variables.

- **omp_get_thread_num()**
  The function returns the number (integer) of the currently executing thread within the team.

- **omp_get_max_threads()**
  It returns the maximum number (integer) of threads that can execute concurrently in a single parallel section.

- **omp_get_num_procs()**
  It returns the current number (integer) of online processors on the machine.
Library Functions (contd)

- **omp_get_dynamic( ) and omp_set_dynamic( )**
  The first function returns `.TRUE. (logical)`, if dynamic thread adjustment is enabled. The second function can set the status of the dynamic thread adjustment.

- **omp_get_num_threads and omp_set_num_threads**
  The first function returns the number (`integer`) of threads in the current `parallel` section and the second function sets the number of threads to execute the parallel section.

- **omp_get_nested and omp_set_nested**
  The first function returns `.TRUE. (logical)`, if nested parallelism is enabled. The second function can enable or disable nested parallelism.
1. **POWER5** (eSeries Servers) IBM

2. **UltraSPARC IV** (Sun Fire Servers) Sun Microsystems

3. **OpenMP**