Introduction to OpenMP Offload: Part I

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OpenMP Programming Model

It is an Application Program Interface (API) to allow programmers to develop threaded parallel codes on shared memory computational units.

• Directives are understood by OpenMP aware compilers (others are free to ignore)

• Generates parallel threaded code
  – Original thread becomes thread “0”
  – Share resources of the original thread (or rank)
  – Data-sharing attributes of variables can be specified based on usage patterns

Reference: Somewhere from the web
OpenMP Worksharing

#pragma omp parallel
All threads will execute the region

#pragma omp parallel for
All threads will execute a part of the iterations

• Creates a team of OpenMP threads that execute the structured-block that follows

• Number of threads property is generally specified by OMP_NUM_THREADS env variable or num_threads clause (num_threads has precedence)
Recap: OpenMP Worksharing

Serial

```c
for (int i = 0; i < N; ++i) {
    C[i] = A[i] + B[i];
}
```

- 1 thread/process will execute each iteration sequentially
- Total time = time_for_single Iteration * N

Parallel

```c
#pragma omp parallel
for (int i = 0; i < N; ++i) {
    C[i] = A[i] + B[i];
}
```

- Say, OMP_NUM_THREADS = 4
- 4 threads will execute each iteration sequentially (overwriting values of C)
- Total time = time_for_single Iteration * N

Parallel Worksharing

```c
#pragma omp parallel for 
for (int i = 0; i < N; ++i) {
    C[i] = A[i] + B[i];
}
```

- Say, OMP_NUM_THREADS = 4
- 4 threads will distribute iteration space (roughly N/4 per thread)
- Total time = time_for_single Iteration * N/4
Evolution of OpenMP: 1997 – 2022

In spring, 7 vendors and the DOE agree on the spelling of parallel loops and form the OpenMP ARB. By October, version 1.0 of the OpenMP specification for Fortran is released.

1.0
- Minor modifications

1.1
- C/C++ v 1.0. First hybrid applications with MPI* and OpenMP appear.

2.0
- The merge of Fortran and C/C+ specifications begins.

2.5
- Unified Fortran and C/C++. Bigger than both individual specifications combined.

3.0
- Incorporates task parallelism. The OpenMP memory model is defined and codified.

4.0
- Supports offloading execution to accelerator and coprocessor devices, SIMD parallelism, and more. Expands OpenMP beyond traditional boundaries.

4.5
- OpenMP supports taskloops, task priorities, doacross loops, and hints for locks. Offloading now supports asynchronous execution and dependencies to host execution.

5.0
- Supports Memory Management API, Reverse Offload, Loop construct, Detached tasks, Custom Mappers, Tools API, loop transformation (tiling, ...), Improved “omp loop” *, variant overloading, runtime variant selection*, compiler agnostic “built-in assume”

5.1
- Clarifications and deprecations

5.2
- TR11 – Preview of OpenMP 6.0

5.5
- 2016
- 2017
- 2018
- 2019
- 2020
- 2021
- 2022


Adapted from 2021 Exascale Computing Project Virtual Annual Meeting April 12 – 16, 2021
Introduction: OpenMP Offload

- OpenMP offload constructs are a set of directives for C, C++, and Fortran that were introduced in OpenMP 4.0 and further enhanced in later versions. Accelerators
OpenMP Offload Terminology

• **Host device**
  – The device on which the OpenMP program begins execution.

• **Target device**
  – A device with respect to which the current device performs an operation, as specified by a device construct or an OpenMP device memory routine.

• **Parent device**
  – For a given target region, the device on which the corresponding target construct was encountered.
    • A host device may not always be the parent.
OpenMP Offload: Steps

• **Identification** of compute kernels
  – CPU initiates kernel for execution on the device

• Expressing **parallelism** within the kernel

• Manage **data transfer** between CPU and Device
  – relevant data needs to be moved from host to device memory
  – kernel executes using device memory
  – relevant data needs to be moved from device to main memory
Step 1: Identification of Kernels to Offload

• Look for compute intensive code and that can benefit from parallel execution
  – Use performance analysis tools to find bottlenecks/computationally intensive kernels

• Track independent work units with well defined data accesses

• Keep an eye on platform specs
  – GPU memory is a precious resource

• Confirm via Profiling
  – Tools like rocprof and HPCToolkit

• More information regarding rocprof can be found at: [https://docs.olcf.ornl.gov/systems/frontier_user_guide.html#optimization-and-profiling](https://docs.olcf.ornl.gov/systems/frontier_user_guide.html#optimization-and-profiling)

• More information on HPCToolkit can be found at: [http://hpctoolkit.org](http://hpctoolkit.org)
How to Offload using OpenMP?

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<td>#pragma omp target [clause[ [,] clause] ... ] new-line structured-block</td>
<td>!$omp target [clause[ [,] clause] ... ] loosely/tightly-structured-block</td>
<td>The <strong>target</strong> construct offloads the enclosed code to the accelerator.</td>
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<td></td>
<td>!$omp end target</td>
<td></td>
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</table>

- A device data environment is created for the structured block
- The code region is mapped to the device and executed.
OpenMP Offload: Example using `omp target`

/*C code to offload Matrix Addition Code to Device*/

```c
... int A[N][N], B[N][N], C[N][N];
  /* initialize arrays */
  #pragma omp target {
      for (int i = 0; i < N; ++i) {
          for (int j = 0; j < N; ++j) {
              C[i][j] = A[i][j] + B[i][j];
          }
      }
  } // end target
```

The target construct is a task generating construct.
Clauses on target directive

• Clauses allowed on the target directive:
  – device([device-modifier:] integer-expression)
  – if([target:] scalar-expression)
  – thread_limit(integer-expression)
  – private(list)
  – firstprivate(list)
  – in_reduction(reduction-identifier : list)
  – map([[map-type-modifier[,] [map-type-modifier[,] ...]] map-type: ] locator-list)
  – is_device_ptr(list)
  – has_device_addr(list)
  – defaultmap(implicit-behavior[:variable-category])
  – nowait
  – depend([depend-modifier,] dependence-type : locator-list)
  – allocate([allocator:] list)
  – uses Allocators(allocator[allocator-traits-array]) [,allocator[allocator-traits-array] ...])
device clause on target directive

• Use
  – Specify which device should execute the kernel
    • takes device_num or ancestor modifiers

/*C code depicting use of device clause */

#pragma omp target device(device_num:5) //same as device(5)
{
  for (int i = 0; i < N; ++i) {
    for (int j = 0; j < N; ++j) {
      C[i][j] = A[i][j] + B[i][j];
    }
  }
} // end target

Must be a valid device number
device clause to target multiple devices

```c
/*C code to offload Matrix Addition Code to Multiple Devices*/

... int num_dev = omp_get_num_devices();
/* Calculate start array index for each device and elements per device */
for (int dev = 0; dev < num_dev; ++dev)
{
  #pragma omp target map(tofrom: C[lb:len:1]) device(dev)
  {
    for (int i = lb; i < lb+len; ++i) {
      C[i] += A[i] + B[i];
    }
  } // end of omp target
}//end-for
```
device clause on target directive (cont.)

- Using the ancestor modifier

```c
/* C code depicting use of device clause with ancestor modifier */
#pragma omp requires reverse_offload //at filescope
...
...
#pragma omp target
{
    #pragma omp target device(ancestor: 1)
    /*some useful work on parent device*/
    /* Continue with device execution*/
} //end target-1
...
```
if clause on target directive

• Use
  – Conditional execution on target device

```c
/*C code demonstrating conditional offloading */
#pragma omp target if (N > 1024)
{
    for (int i = 0; i < N; ++i) {
        for (int j = 0; j < N; ++j) {
            C[i][j] = A[i][j] + B[i][j];
        }
    }
} // end target
```
nowait clause on target directive

• Use
  – target task may be deferred

```c
/*C code with nowait on target */
/*Use-case: Free host thread*/
...
#pragma omp parallel
{
  #pragma omp masked
  #pragma omp target nowait
  {
    /*independent work unit*/
  } // end target
  #pragma omp for
  for (int i = 0; i < N; ++i) {
    C[i] = A[i] + B[i]
  }
} // end parallel
```
Step 2: Expressing Parallelism

/*C code to offload Matrix Addition Code to Device*/

... int A[N][N], B[N][N], C[N][N];
/* initialize arrays */
#pragma omp target {
    for (int i = 0; i < N; ++i) {
        for (int j = 0; j < N; ++j) {
            C[i][j] = A[i][j] + B[i][j];
        }
    }
} // end target

Target Device

Transfer A, B, C

Compute C

Idle threads

Transfer A, B, C
Expressing Parallelism: using combined constructs

• Combined construct
  – A construct that is a shortcut for specifying one construct immediately nested inside another construct. A combined construct is semantically identical to that of explicitly specifying the first construct containing one instance of the second construct and no other statements.

• Example:
  – `omp parallel{omp for }` == `omp parallel for`
target + parallel construct

/*C code using target parallel*/

... int A[N], B[N], C[N];
/* initialize arrays */
#pragma omp target parallel for
for (int i = 0; i < N; ++i) {
    C[i] = A[i] + B[i];
}
OpenMP teams

• When a `teams` construct is encountered, a league of teams is created.
• Each team is an initial team, and the initial thread “0” in each team executes the teams region.
  – Initial team numbers are consecutive whole numbers (zero to one less than the number of initial teams)
• The number of teams created is determined by the `num_teams` clause. Once the teams are created, the
  – these remain constant for the duration of the teams region.
• The `teams` region must be strictly nested within:
  – the implicit parallel region that surrounds the whole OpenMP program or
  – a target region.
distribute construct

• It is a loop associated construct that binds to the set of initial threads executing an enclosing teams region
  – distribute construct must be strictly nested inside a teams region

• The iterations are distributed across the initial threads of all initial teams that execute the teams region to which the distribute region binds

• Clauses permitted on distribute construct are allocate, collapse, dist_schedule, firstprivate, lastprivate, order, and private
#pragma omp target
for (int i = 0; i < 12; ++i)
{
    C[i] = A[i] + B[i];
}

#pragma omp target teams
num_teams(3)
for (int i = 0; i < 12; ++i)
{
    C[i] = A[i] + B[i];
}

#pragma omp target teams
distribute
num_teams(3)
for (int i = 0; i < 12; ++i)
{
    C[i] = A[i] + B[i];
}

#pragma omp target teams
distribute parallel
for [simd] num_teams(3)
for (int i = 0; i < 12; ++i)
{
    C[i] = A[i] + B[i];
}
**loop construct**

- **Properties:**
  - logical iterations of the associated loops may execute concurrently
  - bind clause determines the binding region
    - orphaned loop needs explicit binding
  - can be nested inside another `loop` construct
  - all iterations are guaranteed to complete at the end of `loop`
    - except when bound to `teams` construct
Offloading using target teams + loop

/*C code with loop enclosed by teams region */

```c
#pragma omp target teams
{
    #pragma omp loop //implicit bind(team)
    for (int i = 0; i < N; ++i) {
        C[i] = A[i] + B[i]
    }
} // end target teams
```

/*C code with orphaned loop */

```c
void fun1(){
#pragma omp loop bind(teams)
for (int i = 0; i < N; ++i) {
    C[i] = A[i] + B[i]
}
#pragma omp target teams
{
    fun1();
}
} // end target teams
```
Summary: Device Execution Directives

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<td><code>#pragma omp target teams [clause[ ,] clause] ... ] new-line structured-block</code></td>
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<td>The <strong>target</strong> construct offloads the enclosed code to the accelerator. The <strong>teams</strong> construct creates a league of teams. The <strong>initial</strong> thread of each team executes the code region.</td>
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<td><code>#pragma omp target teams distribute [clause[ ,] clause] ... ] new-line loop-nest</code></td>
<td><code>!$omp target teams distribute [clause[ ,] clause] ... ] loop-nest</code>  <code>!$omp end target teams distribute</code></td>
<td>The <strong>target</strong> construct offloads the enclosed code to the accelerator. A <strong>league</strong> of thread teams is created, and loop iterations are <strong>distributed</strong> and executed by the initial teams.</td>
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<tr>
<td><code>#pragma omp target teams distribute parallel for [clause[ ,] clause] ... ] new-line loop-nest</code></td>
<td><code>!$omp target teams distribute parallel do [clause[ ,] clause] ... ] loop-nest</code>  <code>!$omp end target teams distribute parallel do</code></td>
<td>The <strong>target</strong> construct offloads the enclosed code to the accelerator. A <strong>league</strong> of thread teams are created, and loop iterations are <strong>distributed</strong> and <strong>executed in parallel</strong> by all threads of the teams.</td>
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<td><code>$omp target parallel do [clause[ [, ] clause] ... ] loop-nest</code></td>
<td>The <code>target</code> construct offloads the enclosed code to the accelerator. The <code>parallel for/do</code> combined construct creates a thread team and distributes the inner loop iterations over threads.</td>
</tr>
<tr>
<td><code>#pragma omp target parallel loop [clause[ [, ] clause] ... ] new-line loop-nest</code></td>
<td><code>$omp target parallel loop [clause[ [, ] clause] ... ] loop-nest</code></td>
<td>The <code>target</code> construct offloads the enclosed code to the accelerator. The <code>parallel</code> construct creates a team of OpenMP threads that execute the region. The <code>loop</code> construct allows concurrent execution of the associated loops.</td>
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<td><code>#pragma omp target simd [clause[ ,] clause] ... ] new-line loop-nest</code></td>
<td>!$omp target simd [clause[ ,] clause] ... ] loop-nest !$omp end target simd]</td>
<td>Semantics are identical to explicitly specifying a target directive immediately followed by SIMD directive.</td>
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<td><code>#pragma omp target parallel for simd \ clause[[,] clause] ... ] new-line loop-nest</code></td>
<td>!$omp target parallel do simd [clause[ ,] clause] ... ] loop-nest !$omp end target parallel do simd]</td>
<td>Semantics are identical to explicitly specifying a target directive immediately followed by a parallel worksharing-loop SIMD directive.</td>
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<td><code>#pragma omp target teams distribute simd \ [clause[ ,] clause] ... ] new-line loop-nest</code></td>
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<td>Semantics are identical to explicitly specifying a target directive immediately followed by a teams distribute simd directive.</td>
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<td><code>#pragma omp target teams distribute parallel for simd \ [clause[ ,] clause] ... ] new-line loop-nest</code></td>
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### Summary: Useful runtime routines for device environment

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<th>Where to call?</th>
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<tr>
<td>int omp_get_num_procs(void);</td>
<td>integer function omp_get_num_procs()</td>
<td><img src="true" alt="Host" /></td>
<td><img src="true" alt="Target" /></td>
</tr>
<tr>
<td>void omp_set_default_device(int device_num);</td>
<td>subroutine omp_set_default_device(device_num) integer device_num</td>
<td><img src="false" alt="Host" /></td>
<td><img src="true" alt="Target" /></td>
</tr>
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<td>int omp_get_default_device(void);</td>
<td>integer function omp_get_default_device()</td>
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<tr>
<td>int omp_get_device_num(void);</td>
<td>integer function omp_get_device_num()</td>
<td><img src="true" alt="Host" /></td>
<td><img src="true" alt="Target" /></td>
</tr>
<tr>
<td>int omp_is_initial_device(void);</td>
<td>logical function omp_is_initial_device()</td>
<td><img src="true" alt="Host" /></td>
<td><img src="true" alt="Target" /></td>
</tr>
<tr>
<td>int omp_get_initial_device(void);</td>
<td>integer function omp_get_initial_device()</td>
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<td><img src="false" alt="Target" /></td>
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### Summary: Useful runtime routines for teams region

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<tr>
<td>int omp_get_num_teams(void);</td>
<td>integer function omp_get_num_teams()</td>
<td>✓</td>
<td>returns the number of initial teams in the current teams region.</td>
</tr>
<tr>
<td>int omp_get_team_num(void);</td>
<td>integer function omp_get_team_num()</td>
<td>✓</td>
<td>returns the initial team number of the calling thread</td>
</tr>
<tr>
<td>void omp_set_num_teams(int num_teams);</td>
<td>subroutine omp_set_num_teams(num_teams)</td>
<td>✓</td>
<td>the number of threads to be used for subsequent teams regions that do not specify a num_teams clause</td>
</tr>
<tr>
<td>int omp_get_max_teams(void);</td>
<td>integer function omp_get_max_teams()</td>
<td>✓</td>
<td>returns an upper bound on the number of teams that could be created by a teams construct</td>
</tr>
<tr>
<td>void omp_set_teams_thread_limit(int thread_limit);</td>
<td>subroutine omp_set_teams_thread_limit(thread_limit)</td>
<td>✓</td>
<td>defines the maximum number of OpenMP threads per team</td>
</tr>
</tbody>
</table>
References

• Examples were adapted from:
  – https://github.com/SOLLVE/sollve_vv
  – OpenMP Examples Document 5.2.1

• OpenMP Specification (5.x)
  – https://www.openmp.org/specifications/

• https://www.nas.nasa.gov/hecc/assets/pdf/training/OpenMP4.5_3-20-19.pdf

• OpenMP Disussion @ 2021 Exascale Computing Project Virtual Annual Meeting (April 12 – 16, 2021)
Thank You