

GPU Programming with Directives

Introduction to OpenMP offload



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OpenMP Offload to GPU



- GPU offload introduced in OpenMP 4.0
 - fully integrated alongside OpenMP for CPU
 - significant revisions/extensions added in 4.5 and 5.0
 - <https://www.openmp.org/wp-content/uploads/openmp-examples-6.0.pdf>
 - Similar to OpenACC directives
 - OpenACC is an alternative standard for offloading to GPU
 - Developed before OpenMP 4.0
 - <https://www.openacc.org/sites/default/files/inline-images/Specification/OpenACC-3.2-final.pdf>
- Several implementations of OpenMP GPU offload
 - NVIDIA, AMD, GCC, HPE (Cray), IBM, LLVM/clang, Intel
- Hardware agnostic
 - NVIDIA V100/A100/H100
 - AMD MI210/MI250(X)/MI300
 - Intel Xe-HPC

OpenMP Device Model



- Host-centric model with **one host device** and **multiple target devices** of the same type.
- A **device** is a logical execution engine with local storage.
- A **device data environment** is a data environment associated with a target data or target region.
- **target** directives control how data and code are offloaded to devices.
- Data is mapped from a host data environment to a device data environment.

The Target Region



- The **target region** is the basic offloading construct in OpenMP.
 - It defines a section of code, e.g., a loop.
- During execution, when a **target construct** is encountered, the code it contains is executed on a device.
- By default, the code inside the **target construct** executes sequentially.
- Meanwhile, the host thread waits for the **target region** code to finish, before executing the remainder of the code.

The Target Region



- The **target region** is the basic offloading construct in OpenMP.
 - It defines a section of code, e.g., a loop.
- During execution, when a **target construct** is encountered, the code it contains is executed on a device.
- By default, the code inside the **target construct** executes sequentially.
- Meanwhile, the host thread waits for the **target region** to finish, before executing the remainder of the code.

```
// Block A: executed on host
#pragma omp target
{
    // Block B: executed on device
}
// Block C: executed on host
```

C/C++

```
! Block A: executed on host
!$OMP TARGET
    ! Block B: executed on device
!$OMP END TARGET
! Block C: executed on host
```

Fortran

Host and Device Data



- The host and device have separate memory spaces.
- Data declared on the host and accessed within a target region must first be mapped to the device.
- Mapped data must not be accessed by the host until the target region has completed.
- Default behaviour (as from OpenMP 4.5):
 - scalars referenced in the target region are treated as **firstprivate**
 - i.e., scalar is initialised with value on host then copied to device
 - static arrays are copied to the device on entry and back to the host on exit

Map clause



How data is mapped to the device is specified via the **map** clause on the **target** construct.

```
#pragma omp target map(map-type: list)
```

C/C++

```
!$OMP TARGET MAP(map-type: list)
```

Fortran

map-type can be one of the following,

- **to** copy the data to the device on entry;
- **from** copy the data to the host on exit;
- **tofrom** copy the data to the device on entry and back on exit;
- **alloc** allocate an *uninitialised* copy on the device (don't copy values);

and **list** is simply a list of variables.

Map clause example



Two arrays and one scalar

```
#pragma omp target \  
map(to: B, C), map(tofrom: sum)  
{  
    for (int i=0; i<N; i++) {  
        sum += B[i] + C[i];  
    }  
}
```

C/C++

```
!$OMP TARGET  
!$omp& map(to: B(1:N), C(1:N))  
!$omp& map(tofrom: sum)  
DO i = 1,N  
    sum = sum + B(i) + C(i)  
ENDDO  
!$OMP END TARGET
```

Fortran

Map clause example



Two arrays and one scalar

```
#pragma omp target \  
map(to: B, C), map(tofrom: sum)  
{  
    for (int i=0; i<N; i++) {  
        sum += B[i] + C[i];  
    }  
}
```

C/C++

```
!$OMP TARGET  
!$omp& map(to: B(1:N), C(1:N))  
!$omp& map(tofrom: sum)  
DO i = 1,N  
    sum = sum + B(i) + C(i)  
ENDDO  
!$OMP END TARGET
```

Fortran

Execution on device is sequential!

Parallelism on a Device



In principle, we can use all the “normal” OpenMP constructs inside a target region to create and use threads on the device.

- Parallel regions, worksharing, synchronisation, tasks, etc.

However, GPUs are not able to support a full threading model outside of a single streaming multiprocessor (NVIDIA) or compute unit (AMD).

- no synchronization or memory fences possible between SMs
- no coherency between L1 caches
- a parallel region inside a target region will only execute on one SM
- compare with CUDA – can only synchronise threads inside a thread block, not between thread blocks

GPU offload with reduction



```
#pragma omp target \  
map(to: B, C), map(tofrom: sum) \  
parallel for reduction(+:sum)  
    for (int i=0; i<N; i++) {  
        sum += B[i] + C[i];  
    }  
C/C++
```

```
!$OMP TARGET PARALLEL DO  
!$omp& map(to: B(1:N), C(1:N))  
!$omp& map(tofrom: sum)  
!$omp& reduction(+:sum)  
DO i = 1,N  
    sum = sum + B(i) + C(i)  
ENDDO  
!$OMP END TARGET PARALLEL DO  
Fortran
```

Only one GPU SM/CU utilised!

Teams Construct



- Creates multiple master threads inside a target region.
- Each master thread can spawn its own team of threads within separate parallel regions.
- Threads in different teams cannot synchronise with each other.
 - Barriers, critical regions, locks only apply to the threads within a team.
- Can control the number of teams and the number of threads per team.

Teams and Distribute Construct



```
#pragma omp target teams distribute parallel for \  
map(to: B, C), map(tofrom: sum) reduction(+:sum)  
for (int i=0; i<N; i++) {  
    sum += B[i] + C[i];  
}
```

C/C++

Teams and Distribute Construct



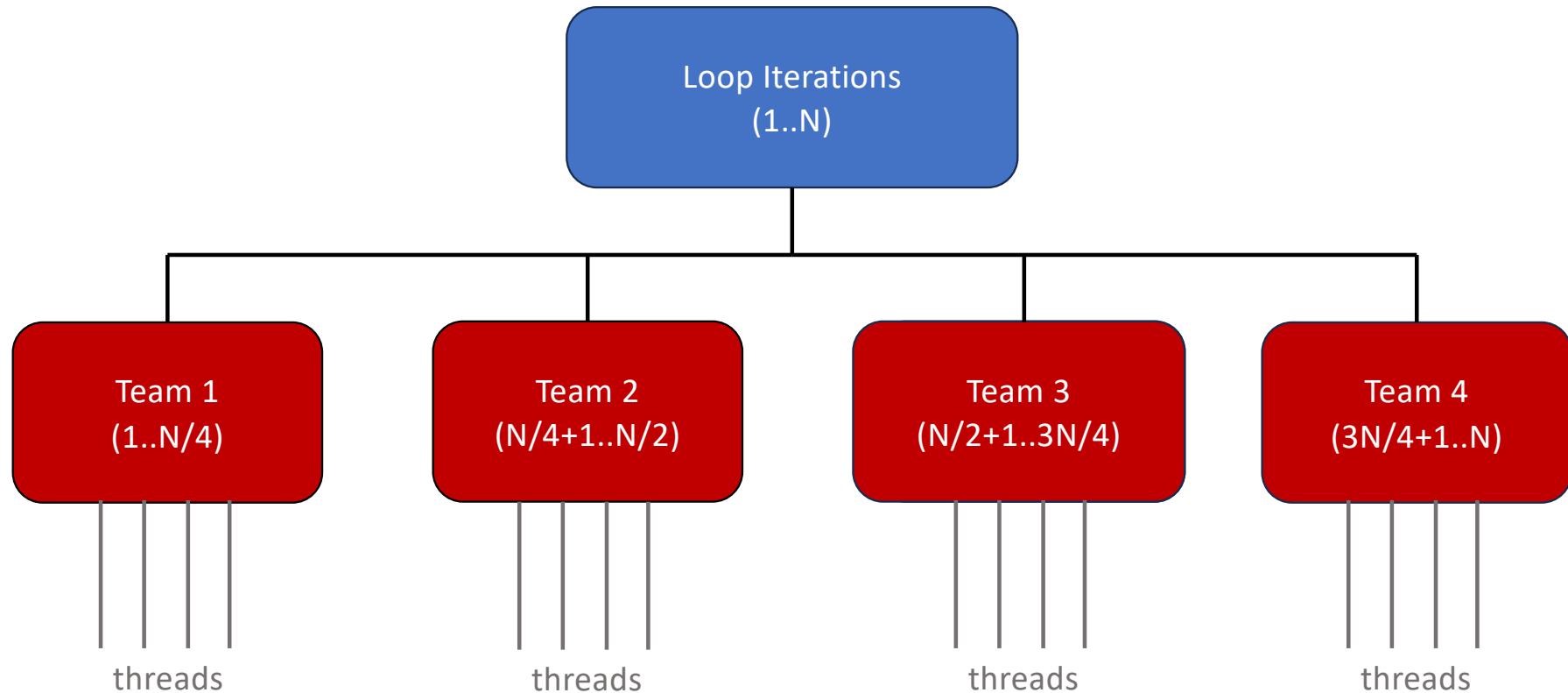
```
#pragma omp target teams distribute parallel for \  
map(to: B, C), map(tofrom: sum) reduction(+:sum)  
for (int i=0; i<N; i++) {  
    sum += B[i] + C[i];  
}
```

C/C++

```
!$OMP TARGET TEAMS DISTRIBUTE PARALLEL DO  
!$omp& map(to: B(1:N), C(1:N))  
!$omp& map(tofrom: sum) reduction(+:sum)  
DO i = 1,N  
    sum = sum + B(i) + C(i)  
ENDDO  
!$OMP END TARGET TEAMS DISTRIBUTE PARALLEL DO
```

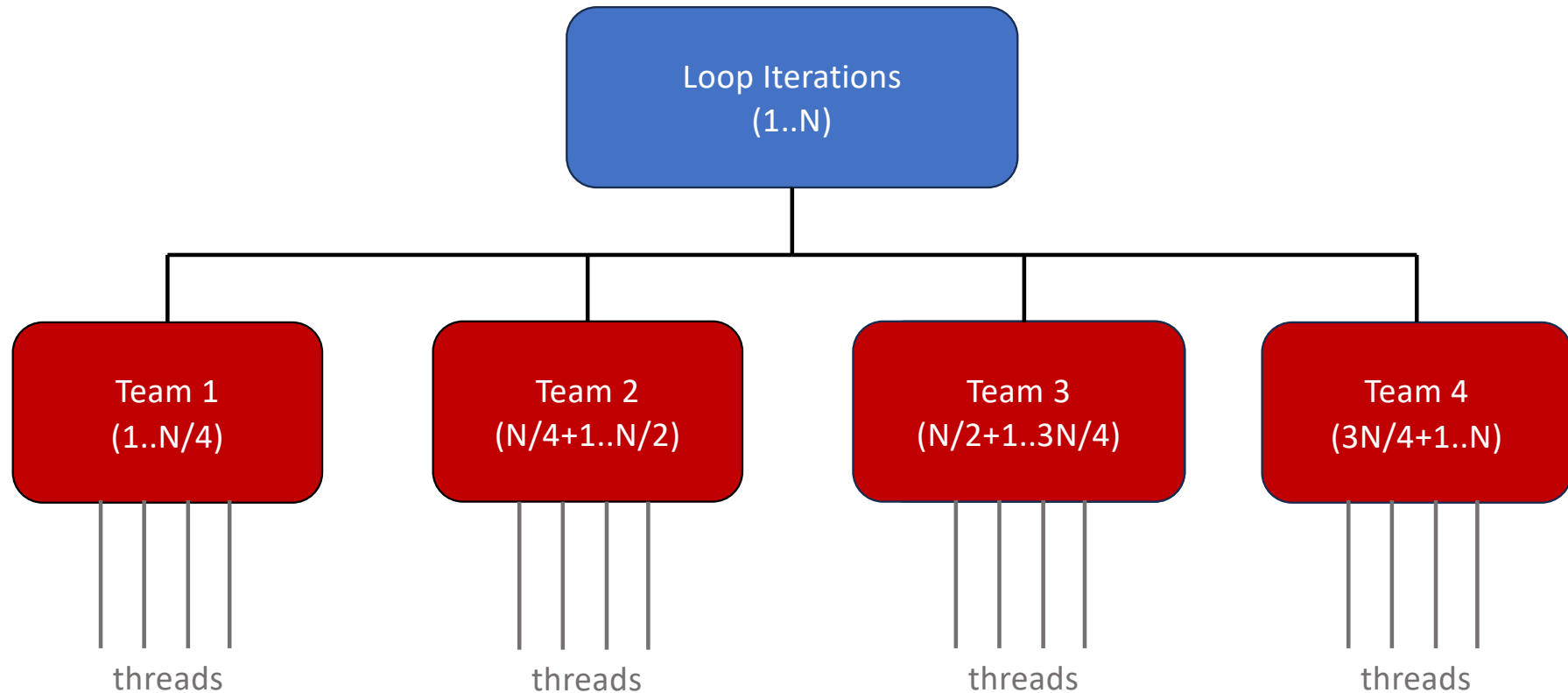
Fortran

Teams and Parallel Regions



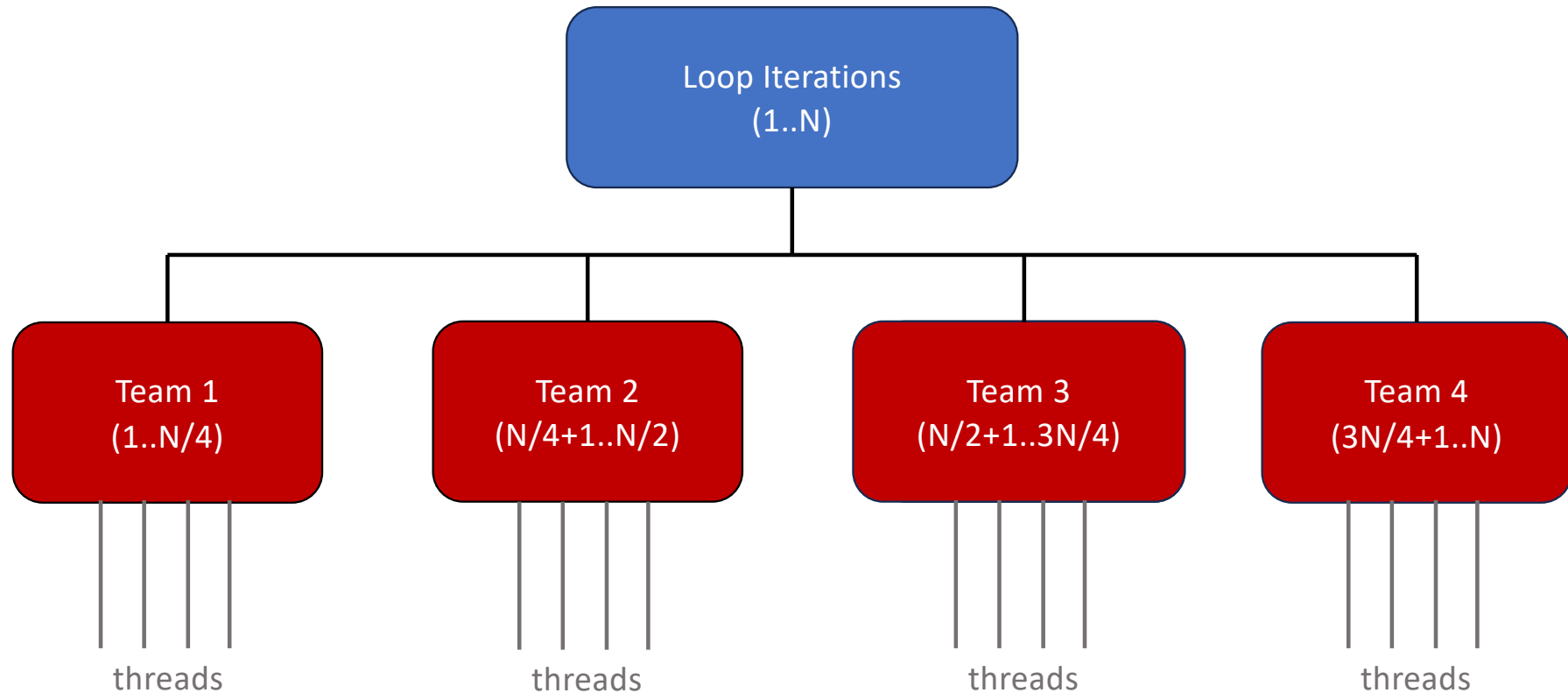
- **distribute** construct: distribute loop iterations across teams.
- **for** or **do** construct: further distribute iterations across team threads.

Teams and Parallel Regions



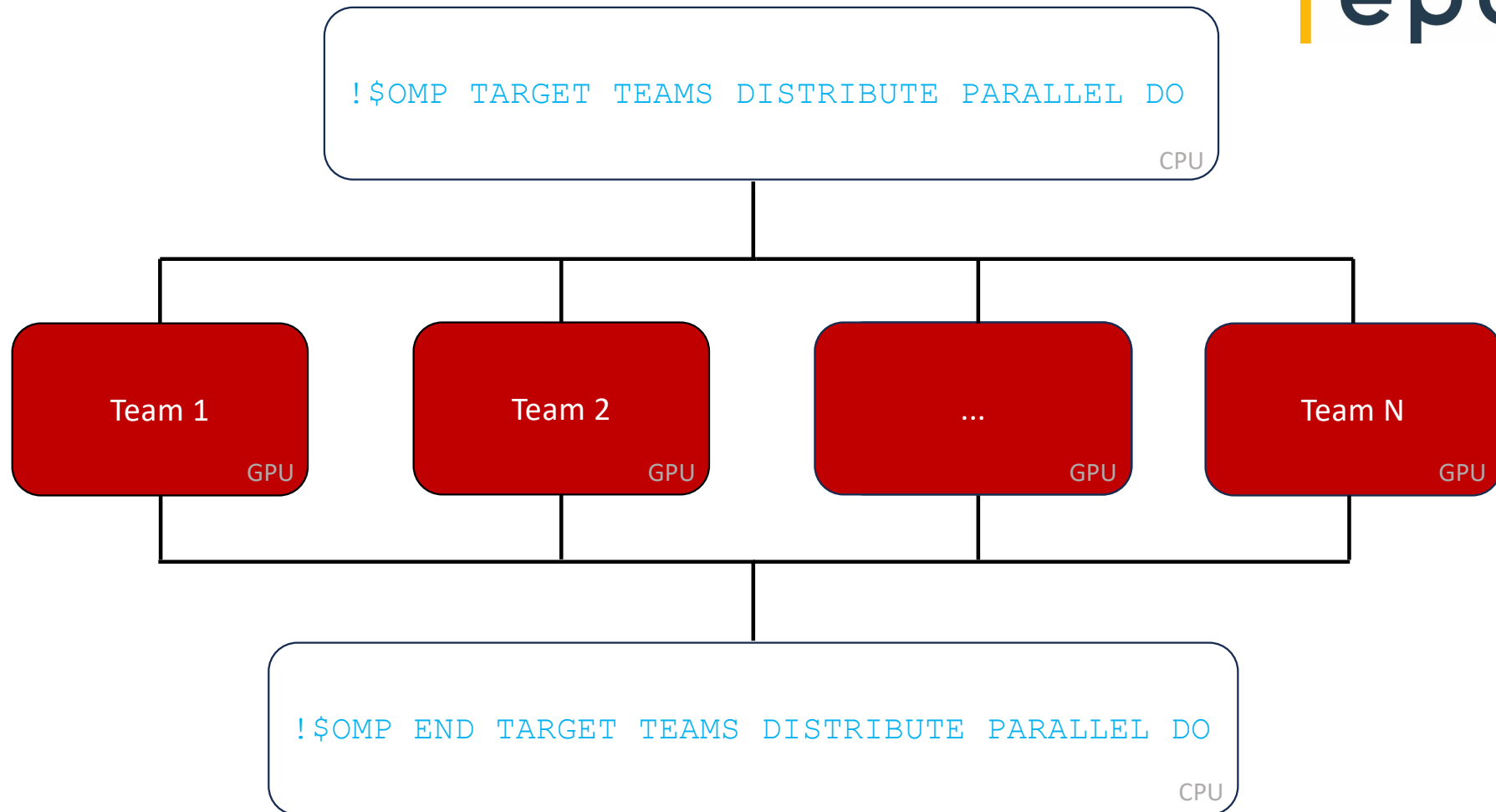
- Each team has its own master thread and runs on a single GPU SM.
- Each team creates a separate parallel region.
 - Typically, a thread runs on a single core within GPU SM.

Teams and Parallel Regions

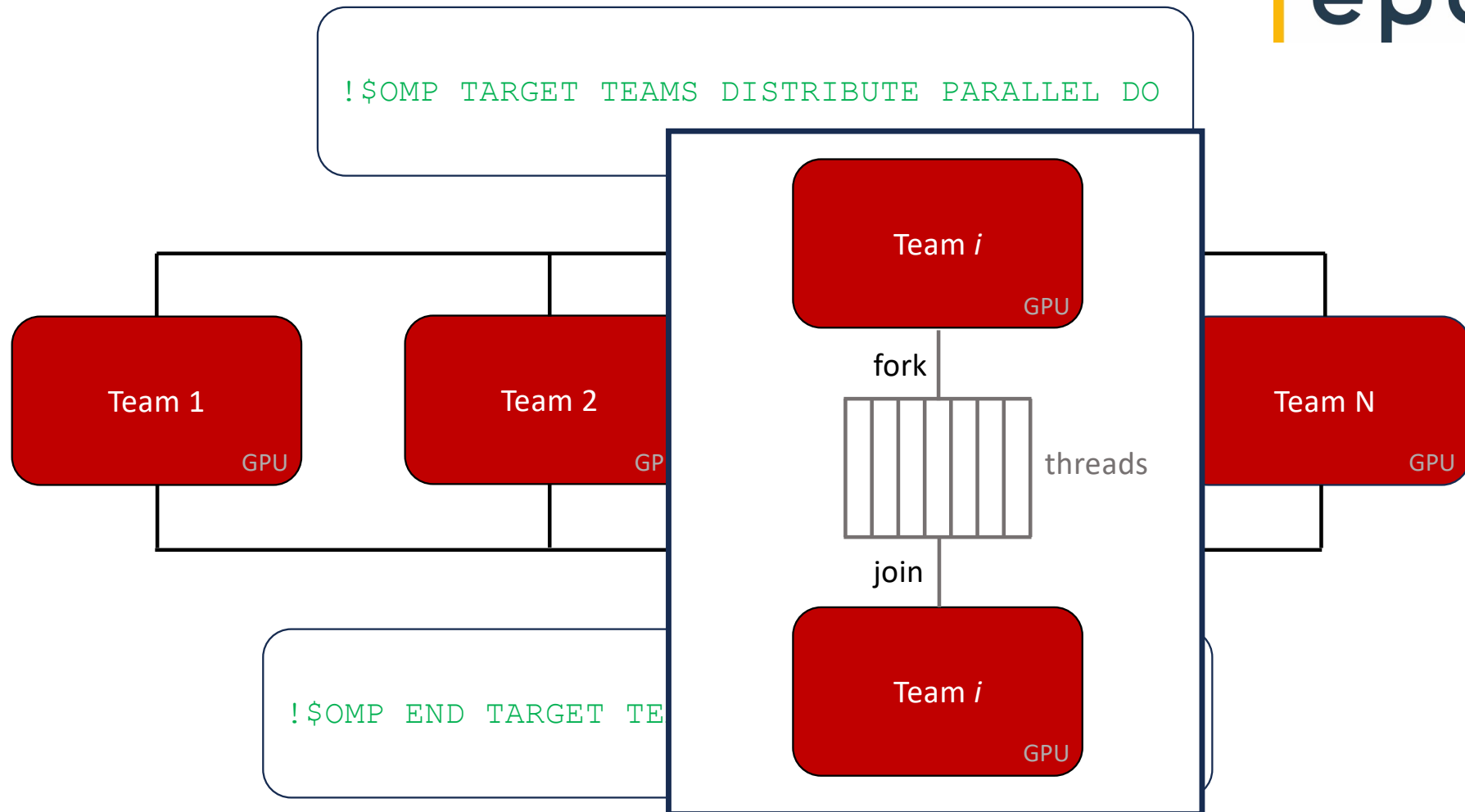


- The number of teams is limited by number of SM/CUs on GPU.
- The number of threads per team depends on number of cores per SM/CU.

Fork Join



Fork Join



Teams Scheduling



```
#pragma omp target teams distribute parallel for \  
map(to: B, C), map(tofrom: sum) \  
dist_schedule(static, 4)  
for (int i=0; i<N; i++) {  
    sum += B[i] + C[i];  
}
```

C/C++

```
!$OMP TARGET TEAMS DISTRIBUTE PARALLEL DO  
!$omp& map(to: B(1:N), C(1:N))  
!$omp& map(tofrom: sum)  
!$omp& dist_schedule(static, 4)  
DO i = 1,N  
    sum = sum + B(i) + C(i)  
ENDDO  
!$OMP END TARGET TEAMS DISTRIBUTE PARALLEL DO
```

Fortran

Teams Scheduling



```
#pragma omp target teams distribute parallel for \  
map(to: B, C), map(tofrom: sum) \  
dist_schedule(static,4)  
for (int i=0; i<N; i++) {  
    sum += B[i] + C[i];  
}
```

C/C++

```
!$OMP TARGET TEAMS DISTRIBUTE PARALLEL DO  
!$omp& map(to: B(1:N), C(1:N))  
!$omp& map(tofrom: sum)  
!$omp& dist_schedule(static,4)  
DO i = 1,N  
    sum = sum + B(i) + C(i)  
ENDDO
```

- Same as schedule clause on worksharing loops, but no dynamic or guided option.
- Iterations grouped into chunks and assigned to teams in a round-robin fashion.
- Number of iterations per chunk can be specified.
- If not specified chunk size per team is approx. equal.

```
!$OMP END TARGET TEAMS DISTRIBUTE PARALLEL DO
```

Fortran

Synchronisation



- All of the “normal” OpenMP synchronisation constructs and routines can be used inside target regions.
- However, most of them, including **barrier**, **critical** and locks only synchronise the threads *within* a team, and not across different teams.
 - means that these are of limited use
- The **atomic** constructs, on the other hand, which protect concurrent accesses to memory locations, do synchronise across the whole device.
 - typically, these are efficiently supported by the hardware

Calling functions inside target regions (C/C++)



loop.c

```
...  
#pragma omp target teams distribute parallel for \  
map(to: B, C), map(tofrom: sum) \  
dist_schedule(static)  
for (int i=0; i<N; i++) {  
    myfunc(i, N, B, C, &sum);  
}  
...
```


Calling functions inside target regions (C/C++)



loop.c

```
...  
#pragma omp target teams distribute parallel for \  
map(to: B, C), map(tofrom: sum) \  
dist_schedule(static)  
for (int i=0; i<N; i++) {  
    myfunc(i, N, B, C, &sum);  
}
```

myfunc.c

```
...  
#pragma omp declare target  
void myfunc(int i, int N, double B, double C, double *sum)  
{  
    ...  
}  
#pragma omp end declare target
```

Calling functions inside target regions (Fortran)



loop.f

```
...  
!$OMP TARGET TEAMS DISTRIBUTE PARALLEL DO  
!$omp& map(to: B(1:N), C(1:N))  
!$omp& map(tofrom: sum)  
!$omp& dist_schedule(static)  
DO i = 1,N  
    call mysub(i, N, B, C, sum)  
ENDDO  
!$OMP END TARGET TEAMS DISTRIBUTE PARALLEL DO  
...
```

Calling functions inside target regions (Fortran)



loop.f

```
...  
!$OMP TARGET TEAMS DISTRIBUTE PARALLEL DO  
!$omp& map(to: B(1:N), C(1:N))  
!$omp& map(tofrom: sum)  
!$omp& dist_schedule(static)  
DO i = 1,N  
    call mysub(i, N, B, C, sum)  
ENDDO  
!$OMP END TARGET TEAMS DISTRIBUTE  
...
```

mysub.f

```
subroutine mysub(i, B, C, N, sum)  
implicit none  
integer i, sum, N  
real*8 B(N), C(N)  
...  
!$omp declare target  
...  
end subroutine mysub
```

Runtime Execution Environment Routines



Name	Description	Location
omp_get_num_devices	the number of non-host devices available for offloading code or data	host only
omp_get_device_num	the device number of the device on which the calling thread is executing	host and device
omp_get_default_device omp_set_default_device	the default target device	host only
omp_get_max_teams	an upper bound on the number of teams that could be created by a team's construct	host and device
omp_get_num_teams omp_set_num_teams	the number of initial teams in the current team's region	host and device
omp_get_team_num	the initial team number of the calling thread	host and device
omp_get_teams_thread_limit omp_set_teams_thread_limit	the maximum number of OpenMP threads per team	host and device

Runtime Execution Environment Routines



```
#include <mpif.h>
#include <omp.h>
void myfunc(...) {
    ...
    int rank, ierr, ndevices;
    ...
    ierr = MPI_comm_rank(MPI_COMM_WORLD, &rank);
    ...
    local_rank = rank % nranks_per_node;
    ...
    ndevices = omp_get_num_devices();
    omp_set_default_device(localrank % ndevices);
    ...
}
```

C/C++

Runtime Execution Environment Routines



```
subroutine mysub(...)
  use omp_lib
  implicit none
  include 'mpif.h'
  ...
  integer rank, ierr, ndevices
  ...
  call MPI_comm_rank(MPI_COMM_WORLD,rank,ierr)
  ...
  local_rank = MOD(rank,nranks_per_node)
  ...
  ndevices = omp_get_num_devices()
  call omp_set_default_device(MOD(localrank,ndevices))
  ...
end subroutine mysub
```

Fortran

Teams Construct Clauses: num_teams and thread_limit



```
#pragma omp target teams distribute parallel for \  
map(to: B, C), map(tofrom: sum) reduction(+:sum) \  
num_teams(4), thread_limit(32)  
for (int i=0; i<N; i++) {  
    sum += B[i] + C[i];  
}
```

C/C++

Teams Construct Clause	Runtime Execution Environment Routine
num_threads	omp_set_num_teams
thread_limit	omp_set_teams_thread_limit

Teams Construct Clauses: num_teams and thread_limit



```
!$OMP TARGET TEAMS DISTRIBUTE PARALLEL DO
!$omp& map(to: B(1:N), C(1:N))
!$omp& map(tofrom: sum) reduction(+:sum)
!$omp& num_teams(4), thread_limit(32)
DO i = 1,N
    sum = sum + B(i) + C(i)
ENDDO
!$OMP END TARGET TEAMS DISTRIBUTE PARALLEL DO
```

Fortran

Teams Construct Clause	Runtime Execution Environment Routine
num_threads	omp_set_num_teams
thread_limit	omp_set_teams_thread_limit

Teams Loop Construct



For convenience, you can use the **teams loop** construct, which will request the compiler to generate the mapping/offload options.

```
#pragma omp target teams loop
for (int i=0; i<N; i++) {
    sum += B[i] + C[i];
}
```

C/C++

```
!$OMP TARGET TEAMS LOOP
DO i = 1,N
    sum = sum + B(i) + C(i)
ENDDO
!$OMP END TARGET TEAMS LOOP
```

Fortran

Teams Loop Construct



For convenience, you can use the **teams loop** construct, which will request the compiler to generate the mapping/offload options.

```
#pragma omp target teams loop
for (int i=0; i<N; i++) {
    sum += B[i] + C[i];
}
```

C/C++

```
!$OMP TARGET TEAMS LOOP
DO i = 1,N
    sum = sum + B(i) + C(i)
ENDDO
!$OMP END TARGET TEAMS LOOP
```

Fortran

Please note, **the compiler might not generate any offload options,**
or **the options generated may not properly parallelise the code for the target device.**

Teams Loop Construct



You can tell the compiler to show which offload options were chosen.

For example, for NVIDIA nvfortran/nvcc use the "-Minfo=mp" setting.

```
1  !$OMP TARGET TEAMS LOOP
2  DO i = 1,N
3      sum = sum + B(i) + C(i)
4  ENDDO
5  !$OMP END TARGET TEAMS LOOP
```

Fortran

```
...
1, !$omp target teams loop
    1, Generating "nvkernel_cpt_dat_vals_p__F1L160_6" GPU kernel
        Generating NVIDIA GPU code
            2, Loop parallelized across teams, threads(128)
                Generating implicit reduction(+:sum)
1, Generating implicit map(tofrom:c(:),b(:))
...
```

Teams Loop Construct



You can tell the compiler to show which offload options were chosen.

For example, for NVIDIA nvfortran/nvcc use the "-Minfo=mp" setting.

```
1  !$OMP TARGET TEAMS LOOP
2  DO i = 1,N
3      sum = sum + B(i) + C(i)
4  ENDDO
5  !$OMP END TARGET TEAMS LOOP
```

Fortran

Such diagnostics can be obtained using other compilers...

```
gfortran -O3 -cpp -fopenmp -fdump-tree-all \
        -foffload=nvptx-none -foffload="-lm -lgfortran -latomic" ...
```

```
crayftn -O3 -cpp -h omp -h list=a ...
```

... but, some grepping may be required...

...search through generated "<source file name>.f.*" files.

Further Study



OpenMP API Examples v6.0 Nov 2024

<https://www.openmp.org/wp-content/uploads/openmp-examples-6.0.pdf>

See the Devices chapter (No. 6)

Gives the OpenMP version when particular feature was introduced.