Programming OpenMP for GPUs

Christian Terboven

Michael Klemm

• Agenda (in total 4 days)

- Day 1: OpenMP Introduction
- Day 2: Tasking & Optimizations for NUMA
- **Day 3: Introduction to Offloading with OpenMP**
  - →Welcome
  - →Offloading in OpenMP
  - →Constructs: Teams + Distribute + For
  - →Construct: Loop
  - →Acc: Login and Usage
  - →**Hands-On**
- Day 4: Advanced Offloading Topics

• Material

https://github.com/cterboven/OpenMP-tutorial-CSC GitHub

Introduction to OpenMP Offload Features

Running Example for this Presentation: saxpy

```
void saxpy() {
    float a, x[SZ], y[SZ];
    // left out initialization
    double t = 0.0;
    double tb, te;
    tb = omp_get_wtime();
#pragma omp parallel for firstprivate(a)
    for (int i = 0; i < SZ; i++) {
        y[i] = a * x[i] + y[i];
    }
    te = omp_get_wtime();
    t = te - tb;
    printf("Time of kernel: %lf\n", t);
}
```

Timing code (not needed, just to have a bit more code to show ☺)

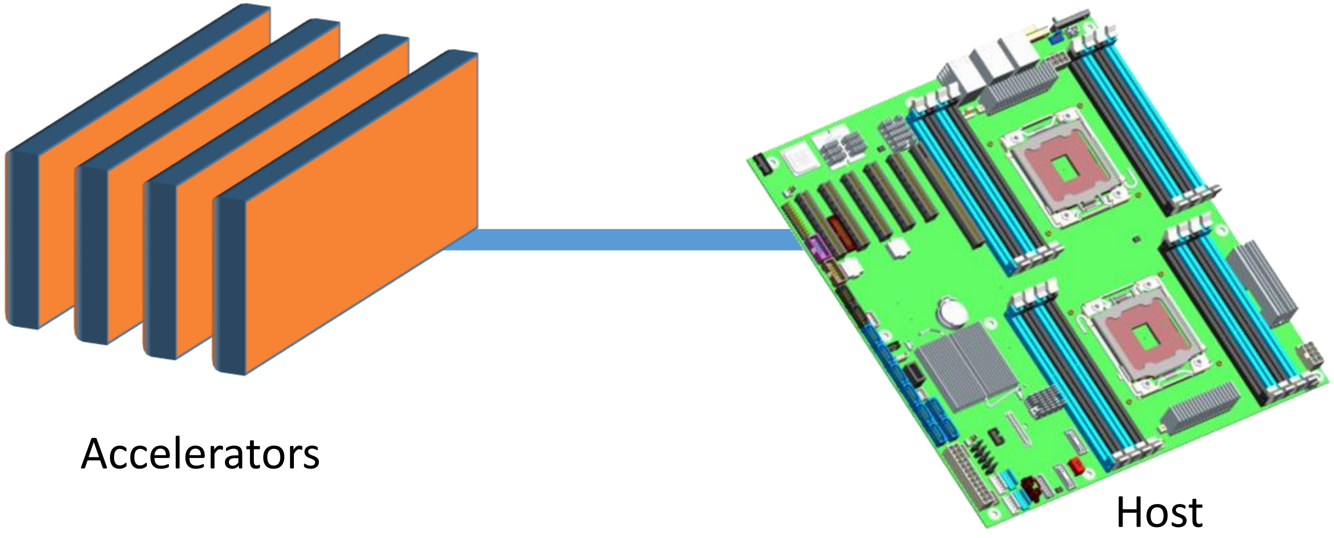
This is the code we want to execute on a target device (i.e., GPU)

Timing code (not needed, just to have a bit more code to show ☺)

Don’t do this at home!
Use a BLAS library for this!

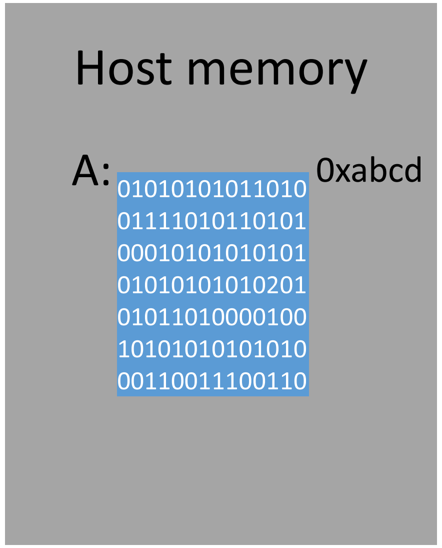
Device Model

- As of version 4.0 the OpenMP API supports accelerators/coprocessors
- Device model:
  - One host for “traditional” multi-threading
  - Multiple accelerators/coprocessors of the same kind for offloading



OpenMP Execution Model for Devices

- Offload region and its data environment are bound to the lexical scope of the construct
  - Data environment is created at the opening curly brace
  - Data environment is automatically destroyed at the closing curly brace
  - Data transfers (if needed) are done at the curly braces, too:
    - Upload data from the host to the target device at the opening curly brace.
    - Download data from the target device at the closing curly brace.




```
!$omp target          &
!$omp   map(alloc:A) &
!$omp   map(to:A)     &
!$omp   map(from:A)   &
   call compute(A)
!$omp end target
```

OpenMP for Devices - Constructs

- Transfer control and data from the host to the device
- Syntax (C/C++)

```
#pragma omp target [clause[[,] clause],…]
structured-block
```

- Syntax (Fortran)

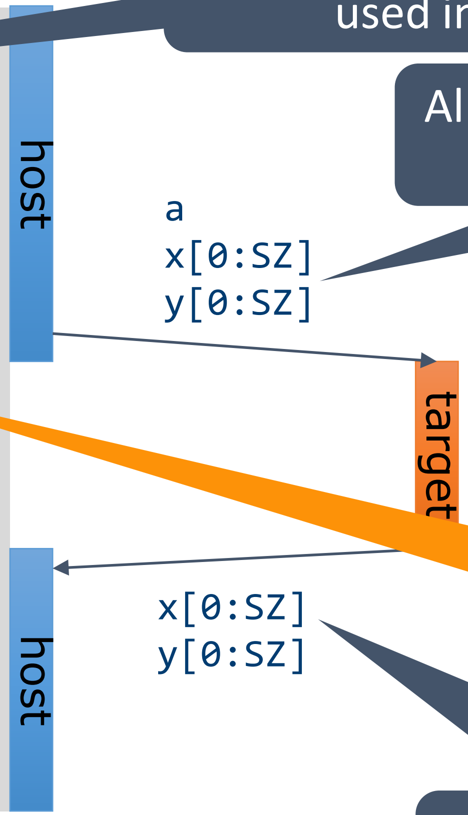
```
!$omp target [clause[[,] clause],…]
structured-block
!$omp end target
```

- Clauses

```
device(scalar-integer-expression)
map([{alloc | to | from | tofrom}:] list)
if(scalar-expr)
```

Example: saxpy

```
void saxpy() {
    float a, x[SZ], y[SZ];
    double t = 0.0;
    double tb, te;
    tb = omp_get_wtime();
#pragma omp target “map(tofrom:y[0:SZ])”
    for (int i = 0; i < SZ; i++) {
        y[i] = a * x[i] + y[i];
    }
    te = omp_get_wtime();
    t = te - tb;
    printf("Time of kernel: %lf\n", t);
}
```



The compiler identifies variables that are used in the `target` region.

All accessed arrays are copied from host to device and back

Presence check: only transfer if not yet allocated on the device.

Copying x back is not necessary: it was not changed.

```
clang -fopenmp -fopenmp-targets=amdgcn-amd-amdhsa -Xopenmp-target=amdgcn-amd-amdhsa -march=gfx908
```

Example: saxpy

The compiler identifies variables that are used in the `target` region.

```
subroutine saxpy(a, x, y, n)
    use iso_fortran_env
    integer :: n, i
    real(kind=real32) :: a
    real(kind=real32), dimension(n) :: x
    real(kind=real32), dimension(n) :: y

!$omp target "map(tofrom:y(1:n))"
    do i=1,n
        y(i) = a * x(i) + y(i)
    end do
!$omp end target
end subroutine
```

host

a
x(1:n)
y(1:n)

All accessed arrays are copied from host to device and back

Presence check: only transfer if not yet allocated on the device.

host

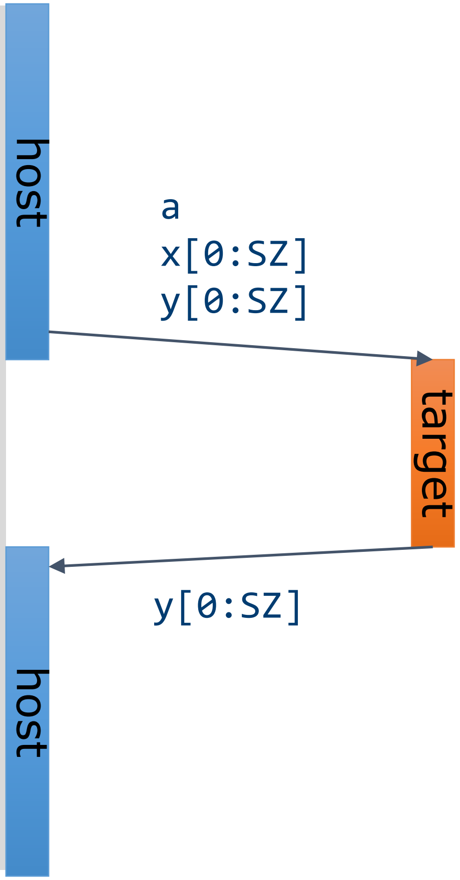
x(1:n)
y(1:n)

Copying x back is not necessary: it was not changed.

```
flang -fopenmp -fopenmp-targets=amdgcn-amd-amdhsa -Xopenmp-target=amdgcn-amd-amdhsa -march=gfx908
```

Example: saxpy

```c
void saxpy() {
    double a, x[SZ], y[SZ];
    double t = 0.0;
    double tb, te;
    tb = omp_get_wtime();
#pragma omp target map(to:x[0:SZ]) \
                   map(tofrom:y[0:SZ])
    for (int i = 0; i < SZ; i++) {
        y[i] = a * x[i] + y[i];
    }
    te = omp_get_wtime();
    t = te - tb;
    printf("Time of kernel: %lf\n", t);
}
```

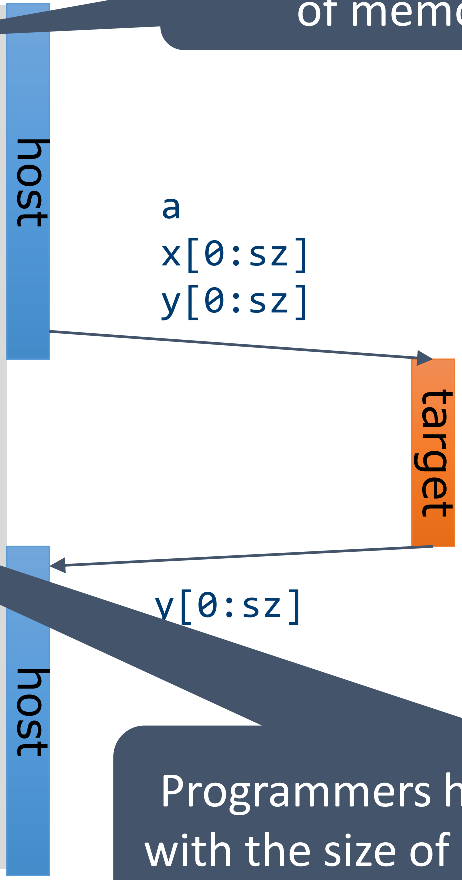



```
clang -fopenmp -fopenmp-targets=amdgcn-amd-amdhsa -Xopenmp-target=amdgcn-amd-amdhsa -march=gfx908
```

Example: saxpy

```c
void saxpy(float a, float* x, float* y,
           int sz) {
    double t = 0.0;
    double tb, te;
    tb = omp_get_wtime();
#pragma omp target map(to:x[0:sz]) \
                   map(tofrom:y[0:sz])
    for (int i = 0; i < sz; i++) {
        y[i] = a * x[i] + y[i];
    }
    te = omp_get_wtime();
    t = te - tb;
    printf("Time of kernel: %lf\n", t);
}
```

The compiler cannot determine the size of memory behind the pointer.



Programmers have to help the compiler with the size of the data transfer needed.

```
clang -fopenmp -fopenmp-targets=amdgcn-amd-amdhsa -Xopenmp-target=amdgcn-amd-amdhsa -march=gfx908
```

Creating Parallelism on the Target Device

- The `target` construct transfers the control flow to the target device
  - Transfer of control is sequential and synchronous
  - This is intentional!

- OpenMP separates offload and parallelism
  - Programmers need to explicitly create parallel regions on the target device
  - In theory, this can be combined with any OpenMP construct
  - In practice, there is only a useful subset of OpenMP features for a target device such as a GPU, e.g., no I/O, limited use of base language features.

Example: saxpy

```c
void saxpy(float a, float* x, float* y,
           int sz) {
#pragma omp target map(to:x[0:sz]) \
                   map(tofrom(y[0:sz])
#pragma omp parallel for simd
    for (int i = 0; i < sz; i++) {
        y[i] = a * x[i] + y[i];
    }
}
```

host

target

host

GPUs are multi-level devices: SIMD, threads, thread blocks

Create a team of threads to execute the loop in parallel using SIMD instructions.

```
clang -fopenmp -fopenmp-targets=amdgcn-amd-amdhsa -Xopenmp-target=amdgcn-amd-amdhsa -march=gfx908
```

Programming OpenMP

GPU: expressing parallelism

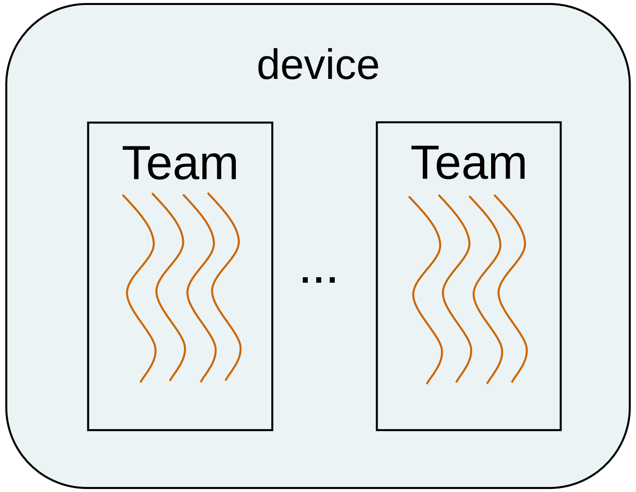
Christian Terboven
Michael Klemm

`teams` and `distribute` constructs

Many slides are taken from the lecture High-Performance Computing at RWTH Aachen University
Authors include: Sandra Wienke, Julian Miller

Terminology

- League:
  the set of threads teams created by a `teams` construct
- Contention group:
  threads of a team in a league and their descendant threads

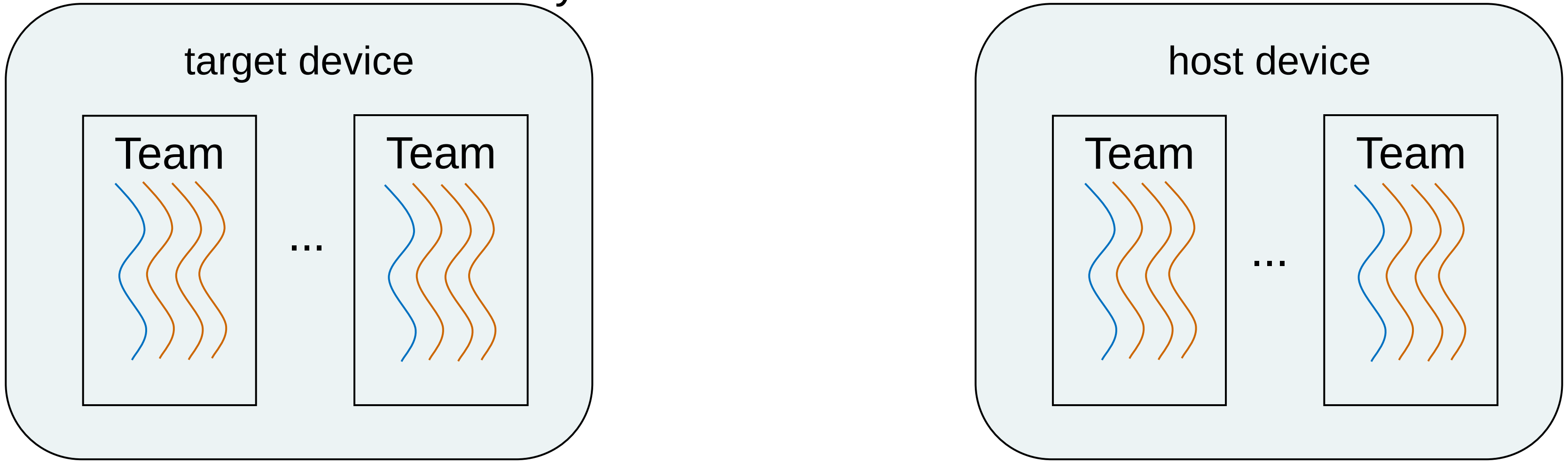


`teams` Construct

The **`teams`** construct creates a *league* of thread teams

- The master thread of each team executes the **`teams`** region
- The number of teams is specified by the **`num_teams`** clause
- Each team executes with **`thread_limit`** threads
- Threads in different teams cannot synchronize with each other

5.0



Only special OpenMP constructs or routines can be strictly nested inside a **`teams`** construct:

- **`distribute [simd]`**, distribute [parallel] worksharing-loop [SIMD]
- **`parallel`** regions (**`parallel for/do`**, **`parallel sections`**)
- **`omp_get_num_teams()`** and **`omp_get_team_num()`**

`distribute` Construct

- work sharing among the teams regions
  - Distribute the iterations of the associated loops across the master threads of each team executing the region

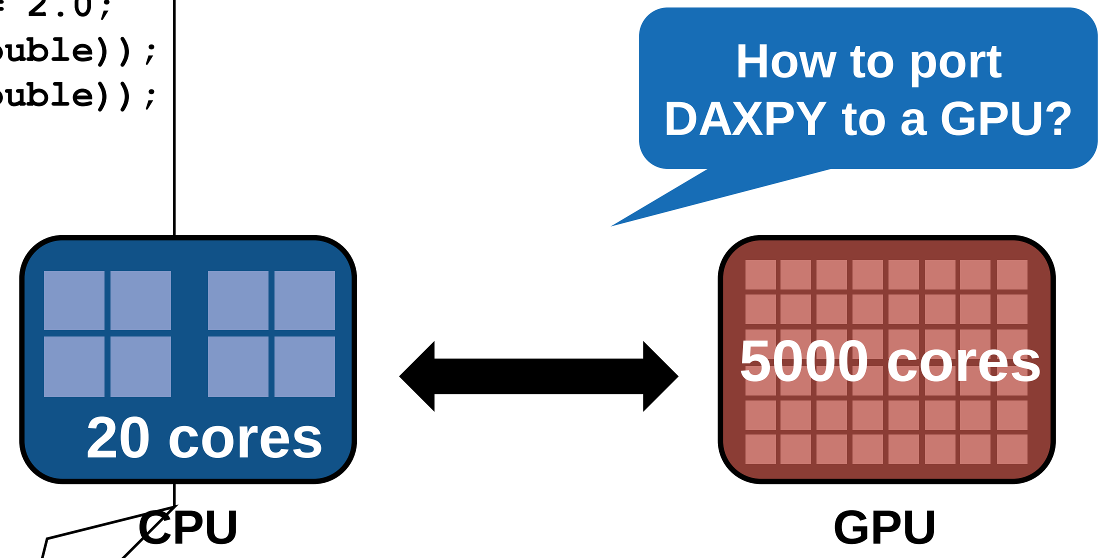
- Strictly nested inside a teams region

- No implicit barrier at the end of the construct

- **`dist_schedule(`***`kind[, chunk_size]`***`)`**
  - The scheduling kind must be **static**
  - Chunks are distributed in round-robin fashion of chunks with size *`chunk_size`*
  - If no chunk size specified, chunks are of (almost) equal size; each team receives at most one chunk

Example DAXPY: How to Port to GPU?

```
void daxpy(int n, double a, double *x, double *y) {
  for (int i = 0; i < n; ++i)
    y[i] = a * x[i] + y[i];
}

int main(int argc, const char* argv[]) {
  static int n = 100000000; static double a = 2.0;
  double *x = (double *) malloc(n * sizeof(double));
  double *y = (double *) malloc(n * sizeof(double));

  // Initialize x, y
  for(int i = 0; i < n; ++i){
    x[i] = 1.0;
    y[i] = 2.0;
  }
  daxpy(n, a, x, y); // Invoke daxpy kernel
  // Check if all values are 4.0

  free(x); free(y);
  return 0;
}
```



Kernel Directives

- Offload kernel code
  - **`target`**: offload work
  - **`teams, parallel`**: create in parallely running threads
  - **`distribute, do, for, simd`**: worksharing across parallel units

- Worksharing
  - **`for`**: offload work
  - **`collapse`**: collapse two or more nested loops to increase parallelism

Compilation

```
clang -fopenmp -Xopenmp-target -fopenmp-targets=nvptx64-nvidia-cuda -march=sm_70
--cuda-path=$CUDA_TOOLKIT_ROOT_DIR daxpy.c
```

- **`clang`** A recent clang compiler with OpenMP target support
- **`-fopenmp`** Enables general OpenMP support
- **`-Xopenmp-target`** Enables OpenMP target support
- **`-fopenmp-targets=nvptx64-nvidia-cuda`** Specifies the target architecture → here: NVIDIA GPUs
- **`-march=sm_70`** Optional. Specifies the target compute architecture
- **`--cuda-path=$CUDA_TOOLKIT_ROOT_DIR`** Optional. Specifies the CUDA path

Example: DAXPY

```
void daxpy(int n, double a, double *x, double *y) {
  #pragma omp target
  for (int i = 0; i < n; ++i)
    y[i] = a * x[i] + y[i];
}

int main(int argc, const char* argv[]) {
  static int n = 100000000; static double a = 2.0;
  double *x = (double *) malloc(n * sizeof(double));
  double *y = (double *) malloc(n * sizeof(double));

  // Initialize x, y
  for(int i = 0; i < n; ++i){
    x[i] = 1.0;
    y[i] = 2.0;
  }
  daxpy(n, a, x, y); // Invoke daxpy kernel
  // Check if all values are 4.0

  free(x); free(y);
  return 0;
}
```

Output:
$ $CC $FLAGS_OFFLOAD_OPENMP daxpy.c
$ a.out
Libomptarget fatal error 1: failure of target construct while offloading is mandatory

Example DAXPY: Debugging

- No compiler error but cryptic runtime error
- NVIDIA Profiler

```
$ nvprof daxpy.exe
==40419== NVPROF is profiling process 40419, command: daxpy.exe
==40419== Profiling application: daxpy.exe
==40419== Profiling result:
No kernels were profiled.

==40419== API calls:
No API activities were profiled.
```

- Cuda-memcheck

```
$ cuda-memcheck daxpy.exe
========= CUDA-MEMCHECK
========= Invalid __global__ read of size 8
=========     at 0x00000d10 in __omp_offloading_4b_f850d140_daxpy_l3
=========     by thread (32,0,0) in block (0,0,0)
=========     Address 0x00000000 is out of bounds
```

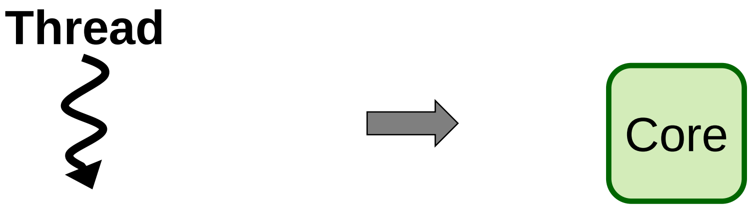
Example DAXPY: Data Management

```c
void daxpy(int n, double a, double *x, double *y) {
  #pragma omp target map(tofrom:y[0:n]) map(to:a,x[0:n])
  for (int i = 0; i < n; ++i)
    y[i] = a * x[i] + y[i];
}

int main(int argc, const char* argv[]) {
  static int n = 100000000; static double a = 2.0;
  double *x = (double *) malloc(n * sizeof(double));
  double *y = (double *) malloc(n * sizeof(double));

  // Initialize x, y
  for(int i = 0; i < n; ++i){
    x[i] = 1.0;
    y[i] = 2.0;
  }
  daxpy(n, a, x, y); // Invoke daxpy kernel
  // Check if all values are 4.0

  free(x); free(y);
  return 0;
}
```

For comparison: ~0.12s on a single CPU core

Output:
$ $CC $FLAGS_OFFLOAD_OPENMP daxpy.c
$ a.out
Max error: 0.00000
Total runtime: 102.50s

Mapping to Hardware



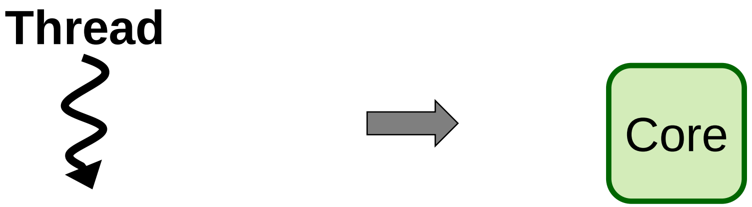
- Each thread is executed by a core

Example DAXPY: Thread Parallelism

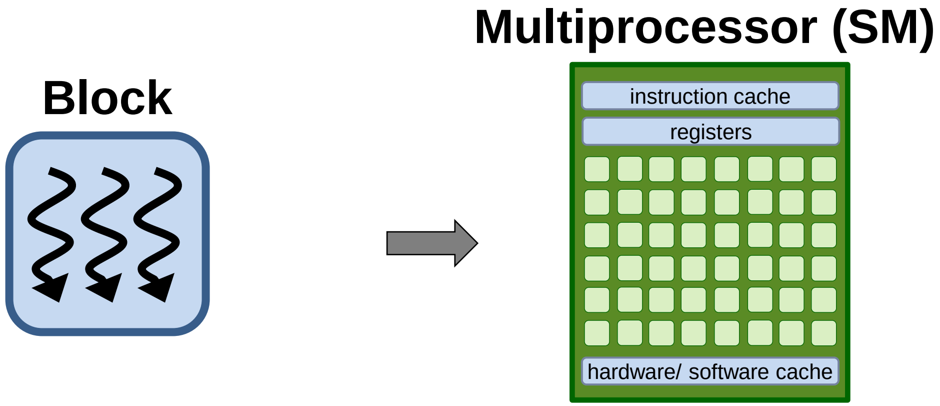
```
void daxpy(int n, double a, double *x, double *y) {
  #pragma omp target parallel for map(tofrom:y[0:n]) map(to:a,x[0:n])
  for (int i = 0; i < n; ++i)
    y[i] = a * x[i] + y[i];
}

int main(int argc, const char* argv[]) {
  static int n = 100000000; static double a = 2.0;
  double *x = (double *) malloc(n * sizeof(double));
  double *y = (double *) malloc(n * sizeof(double));

  // Initialize x, y
  for(int i = 0; i < n; ++i){
    x[i] = 1.0;
    y[i] = 2.0;
  }
  daxpy(n, a, x, y); // Invoke daxpy kernel
  // Check if all values are 4.0

  free(x); free(y);
  return 0;
}
```

```
Output:
$ $CC $FLAGS_OFFLOAD_OPENMP  daxpy.c
$ a.out
Max error: 0.00000
Total runtime: 9.65s
```

Mapping to Hardware



- Each thread is executed by a core



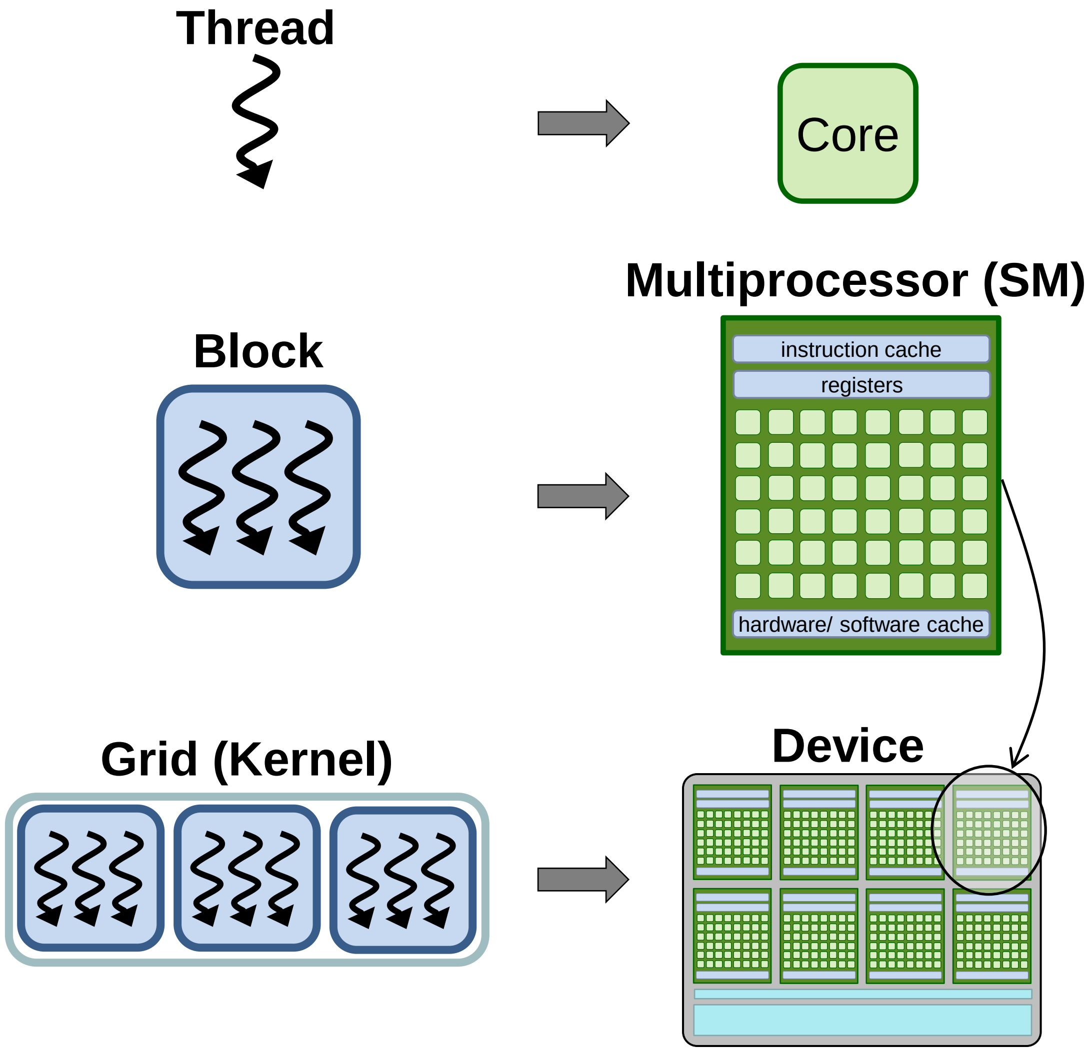
- Each block is executed on a SM
- Several concurrent blocks can reside on a SM depending on shared resources

Example DAXPY: Thread Parallelism

```
void daxpy(int n, double a, double *x, double *y) {
  #pragma omp target teams distribute parallel for map(tofrom:y[0:n]) map(to:a,x[0:n])
for (int i = 0; i < n; ++i)
    y[i] = a * x[i] + y[i];
}

int main(int argc, const char* argv[]) {
  static int n = 100000000; static double a = 2.0;
  double *x = (double *) malloc(n * sizeof(double));
  double *y = (double *) malloc(n * sizeof(double));

  // Initialize x, y
  for(int i = 0; i < n; ++i){
    x[i] = 1.0;
    y[i] = 2.0;
  }
  daxpy(n, a, x, y); // Invoke daxpy kernel
  // Check if all values are 4.0

  free(x); free(y);
  return 0;
}
```

Output:
$ $CC $FLAGS_OFFLOAD_OPENMP daxpy.c
$ a.out
Max error: 0.00000
Total runtime: 0.80s

Mapping to Hardware



- Each thread is executed by a core
- Each block is executed on a SM
- Several concurrent blocks can reside on a SM depending on shared resources
- Each kernel is executed on a device

teams Construct

- Syntax (C/C++):
```
#pragma omp teams [clause[[,] clause]…]
  structured-block
```
- Syntax (Fortran):
```
!$omp teams [clause[[,] clause]…]
  structured-block
```
- Clauses
```
num_teams(integer-expression)
thread_limit(integer-expression)
default(shared | none)  OR
default(shared|private|firstprivate|none)
private(list)
firstprivate(list)
shared(list)
reduction([default,]reduction-identifier : list)
allocate([allocator:]list)
```
5.0

`distribute` Construct

- Syntax (C/C++):

```
#pragma omp distribute [clause[[,] clause]…]
   for-loops
```

- Syntax (Fortran):

```
!$omp distribute [clause[[,] clause]…]
   do-loops
```

- Clauses

```
private(list)
firstprivate(list)
lastprivate(list)
collapse(n)
dist_schedule(kind[, chunk_size])
allocate([allocator:]list)
```

5.0

`loop` constructs

Motivation

- Sometimes, it might be reasonable to shift some burden to the compiler + runtime
  - Discussion: prescriptive vs. descriptive OpenMP
  - OpenACC decided to go the other way

- But: OpenMP has to maintain backwards compatibility

- Loop construct: (IMHO) the first step to introduce descriptivity in OpenMP
  - **`loop`**: specifies that the iterations may be executed concurrently
    - Enables (= permits) the compiler to generated threaded / accelerated code

`loop` construct

- Syntax (C/C++):

```
#pragma omp loop [clause[[,] clause]…]
  for-loops
```

- Syntax (Fortran):

```
!$omp teams [clause[[,] clause]…]
  do-loops
```

- Clauses

`bind`: either `teams`, `parallel` or `thread`: determines parallel execution entity

`collapse(n)`: explained above

`ordered(concurrent)`: (for future extensions: concurrent is currently def.)

`private(list)`: explained above

`firstprivate(list)`: explained above

`reduction([default,]reduction-identifier:list)`: explained above