Introduction to OpenMP Tasking and Offloading

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based on work by
R. Bader (LRZ), G. Hager (RRZE), V. Weinberg (LRZ),
and R. v. d. Pas, E. Stotzer, C. Terboven: **Using OpenMP – The Next Step**. MIT Press, 2017, ISBN 978-0-262-53478-9

Shared-Memory Parallelization With Tasking

Tasks in OpenMP

- tasks in OpenMP refer to an instance of executable code and associated data environment
- we already used tasks unknowingly, e.g.:
  - internally `parallel` construct creates an **implicit** task of the associated structured block for each thread

- **explicit** tasks allow for greater flexibility
  - parallelize workloads which cannot be mapped to worksharing constructs
  - allow for dependencies between tasks

Creating Tasks

```
task [clauses…]
structured-block
```

```
#pragma omp parallel
{
  #pragma omp single
  {
    for (...) {
      #pragma omp task
      { /* work */ }
    }
  } /* implicit barrier */
}
```

- encountering thread creates a task from associated *structured block*
- task can be executed
  - **undeferred**: executed immediately
  - **deferred**: possibly executed later
- deferred tasks are enqueued to be processed by (waiting) threads
- tasks are executed in unspecified order
- barrier is only left iff
  - all threads have arrived
  - and **all tasks have been processed**

Data Sharing (Attributes) with Tasks

- specify explicitly with clauses:
  - **`default`**, **`private`**, **`shared`**, **`firstprivate`**
- rules (as already known):
  - static/global variables → shared
  - automatic (stack) variables inside region → private
- referenced variables become **`firstprivate`** iff:
  - no default clause present
  - variable not explicitly listed
  - variable not determined shared in enclosing constructs
  - ensures data is still alive when task is executed

```
#pragma omp parallel
#pragma omp single
{
  double d[100] = ...;
  #pragma omp task
  work(d, 100);
}
```

d **`firstprivate`** as determined **`private`** inside **`single`**

```
double d[100] = ...;
#pragma omp parallel
#pragma omp single
{

  #pragma omp task
  work(d, 100);
}
```

d **shared**

Task Clauses

```
if(expression)
```

- `if(true)`:
  - **deferred** task created, possibly executed later
  - the default
- `if(false)`:
  - **undeferred** task is created, executed immediately
  - only applies to task at hand
  - optimization:
    - stop generating tasks if enough have been generated, see `final`
    - reduce overhead
  - all other task semantics still apply

Task Synchronization

- waiting for completion of tasks:
  - explicit **`barrier`**
  - implicit barriers (does not apply for **`nowait`**)
- with explicit task synchronization constructs
  - **`taskwait`**
  - **`taskgroup`** (see later)

- **`taskwait`**: wait until all child tasks of current (implicit) task are completed
  - **NOTE**: child tasks include only direct children, not grandchildren

```
#pragma omp parallel
#pragma omp single
{
  #pragma omp task
  work1();

  #pragma omp taskwait

  #pragma omp task
  work2();
}
```

continue when **`work1`** has finished

wait in impl. barrier until **`work2`** has finished

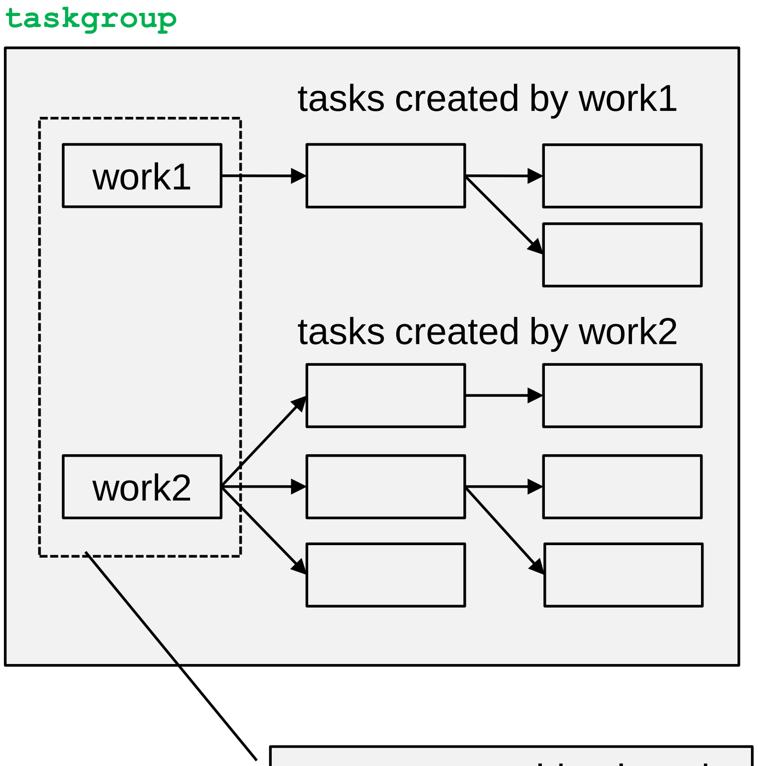
Task Synchronization with `taskgroup`

- wait for **all** tasks created within `taskgroup` region
  - not only the direct children as with `taskwait`

```
#pragma omp parallel
#pragma omp single
{
   #pragma omp taskgroup
   {
       #pragma omp task
       work1() /* spawns more tasks */

       #pragma omp task
       work2() /* spawns more tasks */
   }
}
```

wait here for **all** tasks in `taskgroup` region to finish



`taskwait` would only wait for work1 and work2

Task Synchronization with taskgroup

- allows for dedicated waiting on tasks

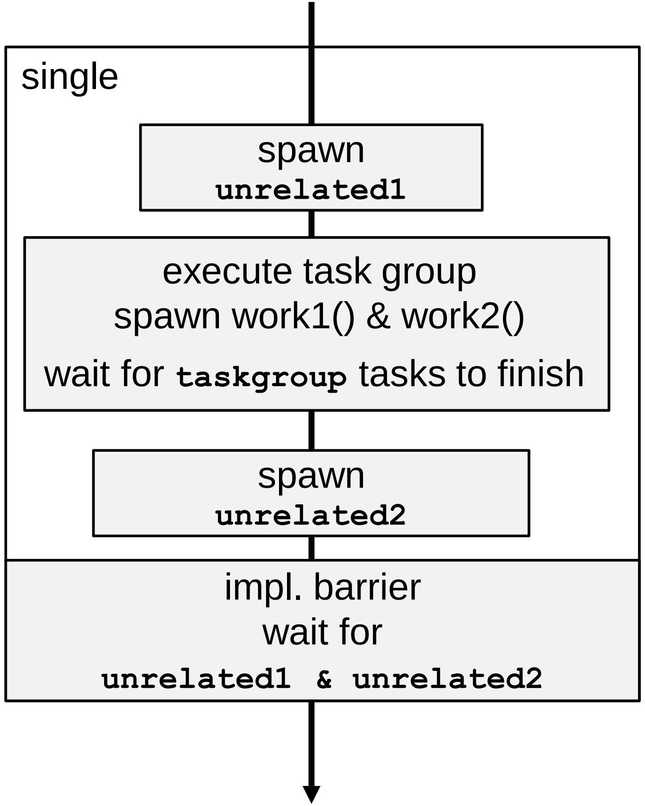
```
#pragma omp parallel
#pragma omp single
{
  #pragma omp task
  unrelated1();

  #pragma omp taskgroup
  {
      #pragma omp task
      work1() /* spawns more tasks */

      #pragma omp task
      work2() /* spawns more tasks */
  } /* wait for tasks */

  #pragma omp task
  unrelated2();
} /* implicit barrier */
```

no waiting for `unrelated1`



Task Scheduling Points

- threads can suspend execution of tasks and switch to another task (*task switch*), and also start new tasks
- **only** at predefined task scheduling points (TSPs):
  - `task` construct
  - end of task
  - at `taskyield` and `taskwait`
  - end of `taskgroup` construct
  - at implicit/explicit barrier
  - (`target` related constructs & API)
- `taskyield` introduces an explicit TSP

task scheduling points

```
#pragma omp parallel
#pragma omp single
{
  double d[100] = ...

  #pragm omp task
  {
    work(d, 100);

    #pragma omp taskyield

    more_work(d, 100)
  }

  #pragma omp taskwait
}
```

uninterrupted * (around `work(d, 100);` and around `more_work(d, 100)`)

- `#pragm omp task` — task construct
- `#pragma omp taskyield` — `taskyield`
- closing `}` of the task — end of task
- `#pragma omp taskwait` — `taskwait`
- closing `}` of the single region — impl. barrier

*assuming in `work()`/`more_work()` no TSPs occur

Task Scheduling Points

- best:
  - do not hold locks when crossing task scheduling points
  - avoid task scheduling points in critical regions

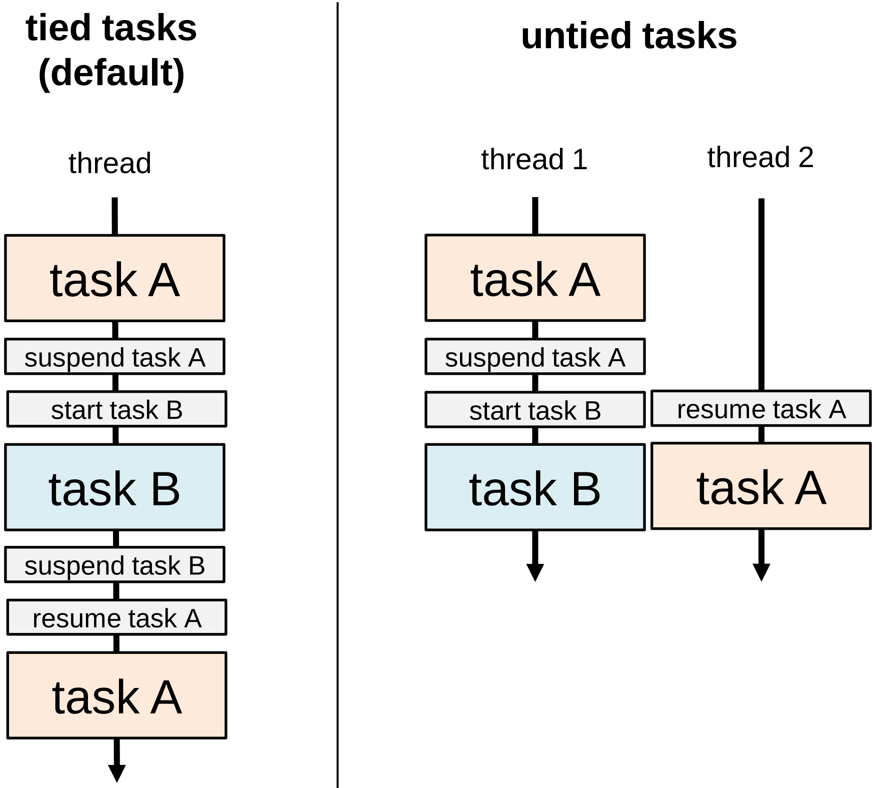
- deadlocks can occur
  - task A holds a lock/is inside a critical region
  - task A is suspended due to reaching a task scheduling point
  - task B is resumed by the same thread
  - task B tries to acquire the lock/enter the critical region
  - deadlock occurs

Tied and Untied Tasks

- tied tasks (default)
  - cannot leave thread that first started execution of task (≠ encountering thread)
- untied tasks
  - can be resumed by any thread in team

NOTE: tied might be desired if cache/NUMA locality is needed

```
#pragma omp task untied
task_a();
#pragma omp task untied
task_b();
```



Reductions with Tasks

≥ v5.0

- requires two components
- `taskgroup` with `task_reduction` clause
- `in_reduction` clause of `task`

```
#pragma omp parallel
#pragma omp single
{
  int sum = 0;
  #pragma omp taskgroup \
              task_reduction(+:sum)
  {
    #pragma omp task in_reduction(+:sum)
    { /* might spawn tasks that also have
           in_reduction(+:sum)  */
    }

    #pragma omp task { }
    /* does not take part */

  } /* implicit barrier */
  /* sum available */
}
```

Task Dependencies

- introduce dependencies between **sibling** tasks
- dependency types:
  - `in`: “read” from variables
  - `out/inout`: “read” from and “write” to variables
  - not covering: **`mutexinoutset`**, **`inoutset`**, **`depobj`**

- task graph is built by matching dependencies to dependencies of already submitted tasks

```
task depend(in:…) \
     depend(out:…) \
     depend(inout:…)
```

list of variables, array elements and sections

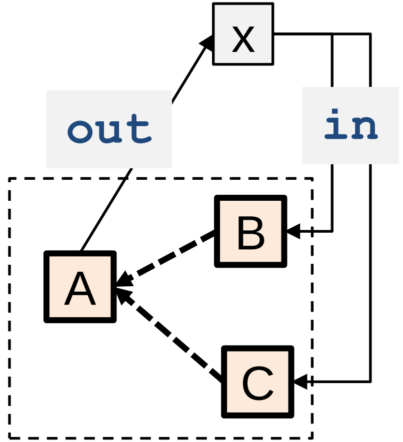
NOTE: tasks do not necessarily have to use the variables specified in dependencies

`in` dependency

- depends on last `out` dependency of the listed variables, if any
- can be scheduled parallel to other tasks with the same `in` dependency
- if no previous `out` dependency to listed variable exists, it is assumed as fulfilled

```
#pragma omp task depend(out:x) /*A*/
/*…*/
#pragma omp task depend(in:x)  /*B*/
/*…*/
#pragma omp task depend(in:x)  /*C*/
/*…*/
```

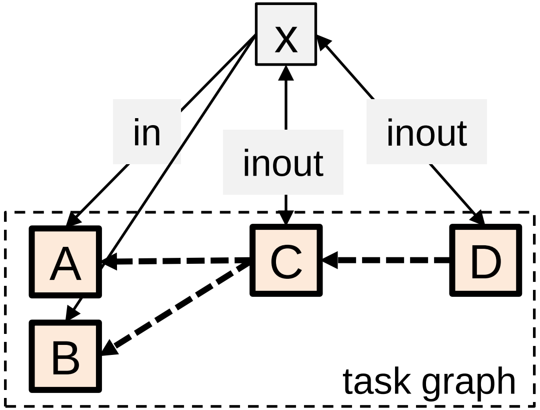
task graph



`out`/`inout` dependency

- depends on
  - last **`out`** dependency of the listed variables, if any
  - all **`in`** dependencies scheduled directly before
- if no previous **`in`/`inout`/`out`** dependency to listed variable exists, it is assumed as fulfilled
- **`out`** and **`inout`** are effectively the same

```
#pragma omp task depend(in:x) /*A*/
/*…*/
#pragma omp task depend(in:x) /*B*/
/*…*/
#pragma omp task depend(inout:x)  /*C*/
/*…*/
#pragma omp task depend(inout:x)  /*D*/
/*…*/
```



Oder of Creation Matters

```
int v = 0;
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(out:x)   /*A*/
  v = 1;

  #pragma omp task depend(inout:x) /*B*/
  v += 2;

  #pragma omp task depend(inout:x) /*C*/
  v *= 2;
}
```

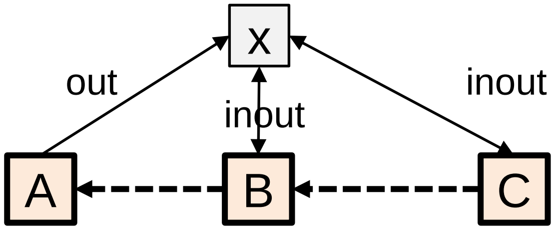
$x = ((1) + 2) * 2 = 6$

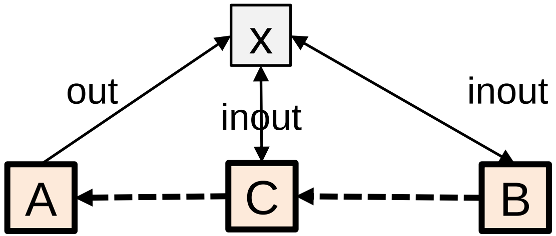
```
int v = 0;
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(out:x)   /*A*/
  v = 1;

  #pragma omp task depend(inout:x) /*C*/
  v *= 2;

  #pragma omp task depend(inout:x) /*B*/
  v += 2;
}
```

$x = ((1) * 2) + 2 = 4$





Dependencies between Siblings only

```
int x;

#pragma omp task depend(in: x)
{
  #pragma omp task depend(out: x)
  { … }
}

#pragma omp task depend(out: x)
{ … }
```

related, as tasks are siblings

unrelated as tasks are no siblings

`taskloop` construct

```
taskloop [clauses]
do-/for-loop
```

- wraps chunks of iterations of assoc. loops into tasks and executes them
  - **not** a worksharing construct
  - however: created tasks can be executed by all threads in current team

- advantages
  - can be arbitrarily nested
    - worksharing loops require nested parallelism
  - explicit tasks cannot encounter worksharing loops
  - automatic load balancing

```
#pragma omp parallel num_threads(2)
#pragma omp single
{
  int from = omp_get_thread_num();
  #pragma omp taskloop
  for (int i = 0; i < 5; ++i) {
    printf("%d %d %d\n",
      i, omp_get_thread_num(), from);
  }
}
```

one thread encounters it, all threads execute tasks, 5 lines of output

possible output:

```
3 0 0
4 0 0
0 1 0
1 1 0
2 1 0
```

`taskloop` is executed 2 times

```
#pragma omp parallel num_threads(2)
{
  #pragma omp taskloop
  for (int i = 0; i < 5; ++i) {…}
}
```

`taskloop` clauses

- loop related:
  - **`collapse`**, **`reduction`**
- task related clauses are applied to the created tasks:
  - **`final`**, **`if`**, **`in_reduction`**, **`mergeable`**, **`priority`**, **`untied`**
- chunk size related:
  - **`grainsize`**, **`num_tasks`**
- data sharing attributes:
  - **`firstprivate`**, **`private`**, **`shared`**, **`lastprivate`**
- **`taskloop`** is implicitly wrapped into a **`taskgroup`**:
  - **`nogroup`** removes impl. **`taskgroup`**

`taskloop` clauses

- **`grainsize([strict:]n)`**
  - task has between **`n`** and **`2n`** iterations
  - with **`strict`** each task has **`n`** iterations
  - last chunk can have less than **`n`** iterations

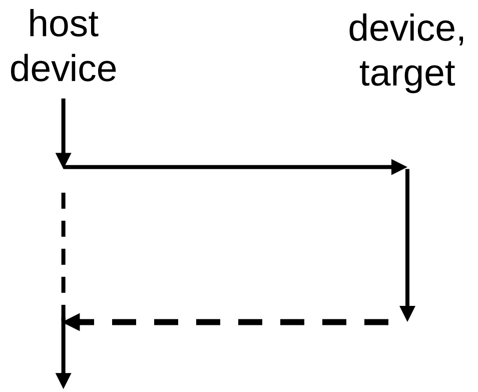
- **`num_tasks([strict:]n)`**
  - generated no. of tasks will be = **`min(n,`** ***`no. of iterations`*****`)`**

Offloading

Introduction

- execute code on a device, typically an accelerator
  - not necessarily a GPU, can also be an FPGA, DSP, …
  - OpenMP tries to abstract from the targeted device's architecture
- **target**: device where code and data is offloaded to
- execution always starts on the **host device**

- here only a small fraction of the standard is covered



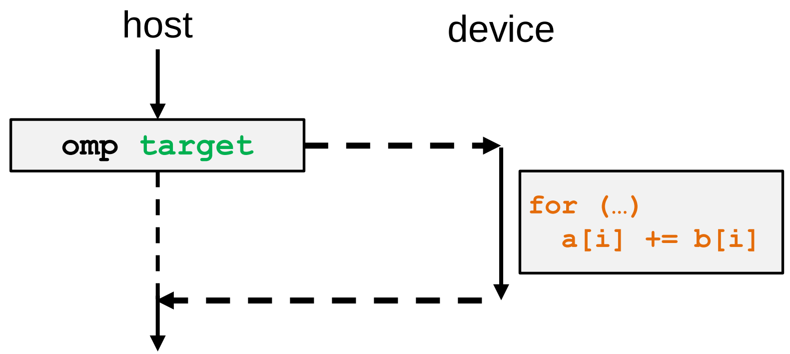
target construct

```
target [clauses…]
<structured block>
```

- execute associated structured block on the device
- on the target:
  - execution is initially single threaded
- on the host:
  - wait until offloaded code completes

- `target` construct cannot be nested inside another `target` construct

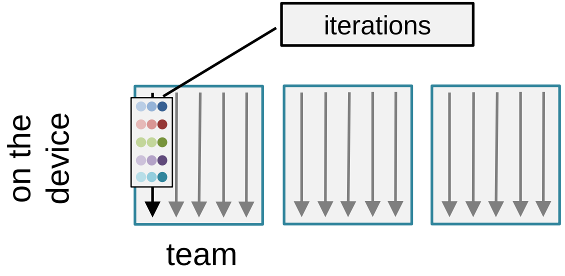
```
int a[1024], b[1024];
/* init a and b */
#pragma omp target
{
  for (int i = 0; i < 1024; ++i)
    a[i] += b[i];
} /* wait until complete */
```



Generating Parallelism

- **`target`** construct alone does not generate parallelism

```
#pragma omp target
for (int i = 0; i < 1024; ++i)
  a[i] += b[i];
```

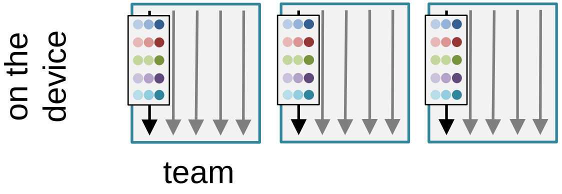


visualization idea based on: Using OpenMP 4.5 Target Offload for Programming Heterogeneous Systems, NASA Advanced Supercomputing Division, Mar 20, 2019

Generating Parallelism

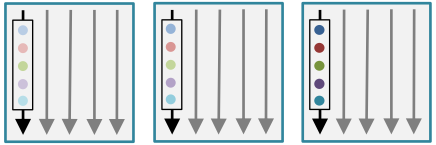
- `teams` construct
  - generate **league of teams**
  - a team has only one initial thread
  - each team executes the same code
  - how many teams: impl. defined
    - `num_teams(n)` clause

```
#pragma omp target teams
for (int i = 0; i < 1024; ++i)
  a[i] += b[i];
```



- `distribute` construct
  - distributes iteration space of associated loop(s) over teams

```
#pragma omp target teams distribute
for (int i = 0; i < 1024; ++i)
  a[i] += b[i];
```



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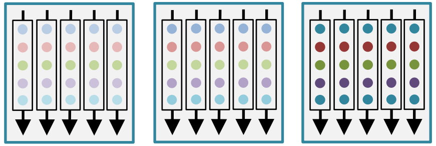
Generating Parallelism

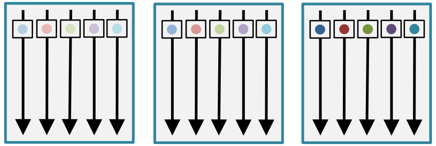
- `parallel` construct
  - gen. parallel region with multiple threads inside each team

```
#pragma omp target teams distribute \
                       parallel
for (int i = 0; i < 1024; ++i)
  a[i] += b[i];
```



- worksharing loop
  - distribute team's iteration space over all threads inside a team

```
#pragma omp target teams distribute \
                       parallel for
for (int i = 0; i < 1024; ++i)
  a[i] += b[i];
```



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Generating Parallelism

- **`simd`** construct
  - use SIMD lanes in each thread

```
#pragma omp target teams distribute \
                          parallel for simd
for (int i = 0; i < 1024; ++i)
  a[i] += b[i];
```

- how each directive maps to a GPU entity depends on the compiler

Generating Parallelism

- some possible combinations

```
omp target <sb>
omp target parallel <sb>
omp target parallel for/do <ln>
omp target parallel for/do simd <ln>
omp target simd <ln>
omp target teams <sb>
omp target teams distribute <ln>
omp target teams distribute parallel for/do <ln>
omp target teams distribute parallel for/do simd <ln>
omp target teams distribute simd <ln>
```

```
sb: structured block
ln: loop nest
```

not covered: section, loop construct

`target teams` construct

- each team has a new initial thread
- teams are loosely coupled
  - in contrast to the `parallel` construct
- no synchronization across teams

```
#pragma omp target teams
{ … }
```

```
#pragma omp target
#pragma omp teams
{ … }
```

`target teams` must be a compound construct or directly nested

clauses:

- `num_teams(expr)` clause
  - no. of teams to create
  - if unspecified gen. no. of teams is implementation defined
- `thread_limit(expr)` clause
  - max. no. of active threads in a team
- `if(expr)` clause
  - evaluate to true: create teams
  - evaluate to false: create only 1 team
- `shared, private, firstprivate, default:`
  - usual meaning
- `reduction` clause: see later

`distribute` construct

- distribute iterations of associated loop over teams
  - must be strictly nested inside a **`teams`** construct
  - iteration space must be the same for all teams
  - no implicit barrier at the end

```
#pragma omp target teams distribute
<loop>
```

```
#pragma omp target teams
#pragma omp distribute
<loop>
```

`distribute` must be a compound construct or strictly nested

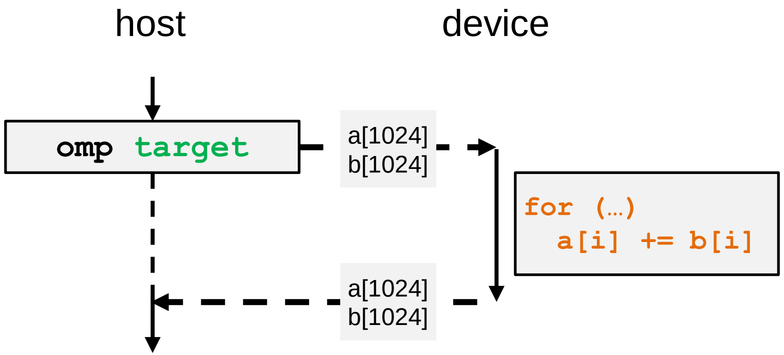
- **`dist_schedule(static[,chunk_size])`** clause
  - if unspecified: implementation defined
  - w/o **`chunk_size`**: each team gets one equally sized chunk
- **`collapse(n)`** clause
  - same as for **`for`**/**`do`** construct
  - associate and collapse iteration space of n nested loops

Data Mapping

- host and device memory can be separate
- mapping of variables ensures
  - a variable is accessible on the target, e.g. by copy or allocation
  - a consistent memory view
- what can be mapped:
  - variables, array sections, members of structures
- mapping causes a presence check
  - copy to device only if not already present
- mapping attributes can be
  - implicit or explicit

```
int a[1024], b[1024];
/* init a and b */
#pragma omp target
{
  for (int i = 0; i < 1024; ++i)
    a[i] += b[i];
} /* wait until complete */
```

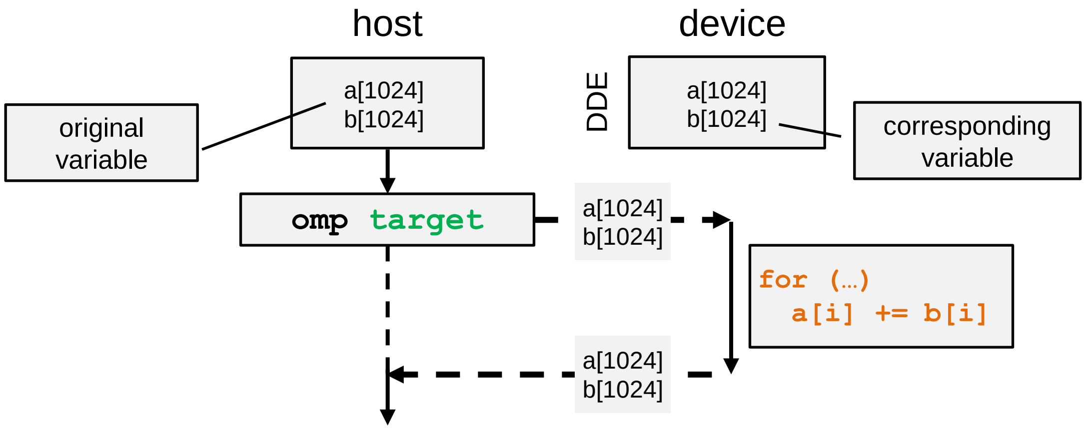
here, implicit mapping attributes cause variables to be mapped, note a[1024], b[1024]



Device Data Environment (DDE)

- exists for each device
  - exists beyond a single target region
- contains all variables accessible by threads running on the device
- mapping ensures a variable is in a device's DDE

```
int a[1024], b[1024];
/* init a and b */
#pragma omp target
{
  for (int i = 0; i < 1024; ++i)
    a[i] += b[i];
} /* wait until complete */
```



`map` clause

- map clause

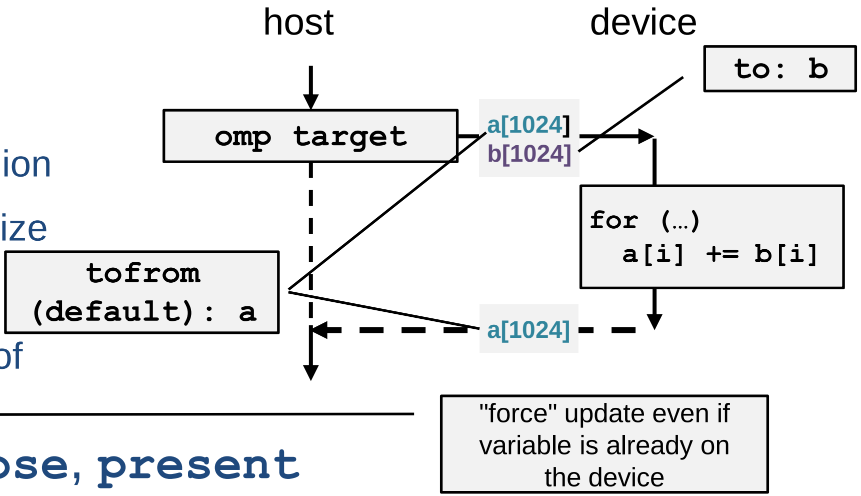
```
map([<mtm>,]<map-type>: <variables>)
```

- `map-type`: how a variable is mapped

`tofrom`	default, copy to device on entry of target region and back at the end
`to`	copy to device on entry of target region
`from`	allocate on entry of target region, copy from device to host on exit of target region
`alloc`	on entry, allocate on device, but do not initialize
`release`	counterpart to `alloc`
`delete`	removes variable from device (independent of RC)

- `mtm`: `map-type-modifier`: `always`, `close`, `present`

```
int a[1024], b[1024];
/* init a and b */
#pragma omp target map(a) map(to:b)
{
  for (int i = 0; i < 1024; ++i)
    a[i] += b[i];
} /* wait until complete */
```



Allocating on the Device

- map-type `alloc`
  - allocate variable/array on device
  - no initialization is performed
  - no copy back to host
- useful, e.g. when an array is only used on the device

`tmp` allocated on the device

```
int tmp[1024];

#pragma omp target map(alloc:tmp)
{
  for (int i = 0; i < 1024; ++i)
    tmp[i] = compute(i);

  for (int i = 0; i < 1024; ++i)
    work(tmp[i]);

  for (int i = 0; i < 1024; ++i)
    work2(tmp[i]);
}
```

`tmp` not copied back

How to map dynamically allocated arrays in C/C++

- map dynamically allocated arrays via array section syntax

```
array[[lower-bound]:length]
```

```
double * a = malloc(sizeof(double) * n_el);
double * b = malloc(sizeof(double) * n_el);
/* init a */

#pragma omp target map(to:a[:n_el]) \
                   map(alloc:b[:n_el])
for (int i = 0; i < n_el; ++i) {
  b[i] = a[i];
}
```

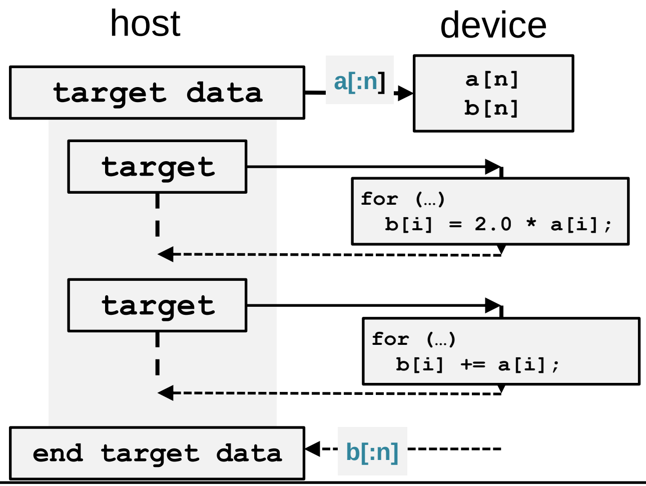
target data construct

```
target data [clauses]
<block>
```

- map data for the duration of the associated block to the DDE
  - **<block>** still executed on host
  - **<block>** typically includes multiple **target** regions
- clauses:
  - **map()** with **to**, **from**, **tofrom**, **alloc**
  - not covered: **device**, **if**, **use_device_addr**, **use_device_ptr**

```
#pragma omp target data map(to:a[:n]) \
                        map(from:b[:n])
{
  #pragma omp target
  for (int i = 0; i < n; ++i)
  { b[i] = 2.0 * a[i]; }

  #pragma omp target
  for (int i = 0; i < n; ++i)
  { b[i] += a[i]; }
}
```



`target update` Construct

```
target update [clauses]
```

- copy data between host and device
  - runs on the host
  - cannot appear inside a `target` construct
  - copy is always performed
    - in contrast to `target map(…)`

```
#pragma omp target data map(to:a[:n]) \
                        map(from:b[:n])
{
  #pragma omp target
  for (int i = 0; i < n; ++i)
  { b[i] = 2.0 * a[i]; }

  #pragma omp target update from(b[:n])
  /* do something with b */

  #pragma omp target
  for (int i = 0; i < n; ++i)
  { b[i] += a[i]; }
}
```

- clauses
  - `to(var-list)` copy vars. to device
  - `from(var-list)` copy vars. to host
  - not covered: device, if, nowait, depend

`enter data`/`exit data` directives

```
target enter data map(…) [clauses]
target exit data map(…)  [clauses]
```

→ map data

→ unmap data

- **unstructured**
- can be called at any point on host
- at **`exit data`**: listed variables not present on the device are ignored
- clauses not covered: **`device`**, **`if`**, **`depend`**, **`nowait`**

allowed: to, alloc

```
double * vec_allocate(int n_el)
{
  double * a = malloc(…);
  #pragma omp target enter data \
              map(alloc:a[:n_el])
  return a;
}

void vec_free(double * a)
{
  #pragma omp target exit data \
              map(release:a[:n_el])
  free(a);
}
```

allowed: from, release, delete

Selecting a Device

- without specification the default device is used
- default device:
  - get: **`omp_get_default_device()`**
- logical device ids in the range from
  `0` to **`omp_get_num_devices() - 1`**
- use specific device with id:
  - env. var. **`OMP_DEFAULT_DEVICE`**
  - **`omp_set_default_device(id)`**
  - **`device(id)`** clause of **`target`** … clauses

Useful Runtime API Calls

- get default device
  - `int omp_get_default_device()`
  - `integer function omp_get_default_device()`

  H

- set default device
  - `void omp_set_default_device(int device)`
  - `subroutine omp_set_default_device(device) integer device`

  H

- return no. of non-host offload devices
  - `int omp_get_num_devices();`
  - `integer function omp_get_num_devices()`

  H

- return no. of initial/host device
  - `int omp_get_initial_device()`
  - `integer function omp_get_initial_device()`

  H

- return calling thread's device no.
  - `int omp_get_device_num()`
  - `integer function omp_get_device_num()`
  - on host returns the value of `omp_get_initial_device()`

  H/D

- return if calling thread runs on host
  - `int omp_is_initial_device()`
  - `integer function omp_is_initial_device()`

  H/D

callable from host H, device D

Env. Vars. related to Offloading

- **`OMP_DEFAULT_DEVICE=<n>`** **with n ≥ 0**
  - set the default device used for executing `target` constructs
- **`OMP_TARGET_OFFLOAD=mandatory | disabled | default`**
  - `mandatory`: usage of unsupported or unavailable device or invalid device number causes termination
  - `disabled`: if supported by the OpenMP RT, the only device available is the host
- **`OMP_TEAMS_THREAD_LIMIT=<n>`**
  - maximum no. of threads each team can have

Performance Aspects

- need to know what underlying architecture/RT will do
  - copy or not copy
  - avoid unnecessary copies
- mapped variables require a presence check on the device
  - hence: **`private`**/**`firstprivate`** variables are faster
- determine how your compiler maps directives to GPU entities
  - check how **`num_teams`**/**`thread_limit`** are interpreted

Inspecting Transfers

- GCC
  - **`GOMP_DEBUG=1 ./a.out`**
  - prints a lot of information
- LLVM/clang
  - env. var. **`LIBOMPTARGET_INFO`**
  - from https://openmp.llvm.org/design/Runtimes.html#llvm-openmp-target-host-runtime-libomptarget
    - **`0x01`**: show data args. when entering device kernel
    - **`0x02`**: show when a mapped address already exists on device
    - **`0x04`**: Dump the contents of the device pointer map at kernel exit
    - **`0x08`**: Indicate when an entry is changed in the device mapping table
    - **`0x10`**: Print OpenMP kernel information from device plugins
    - **`0x20`**: Indicate when data is copied to and from the device
  - **`LIBOMPTARGET_INFO=$((0x01 | 0x02)) ./a.out`**
- NVHPC
  - env. var. **`PGI_ACC_DEBUG=1`**
  - env. var. **`NVCOMPILER_ACC_NOTIFY=1`**