LRZ Workshop June 2023

Parallelizing heterogenous applications with Intel ® OpenMP and OpenMP offloading

Advanced Topics

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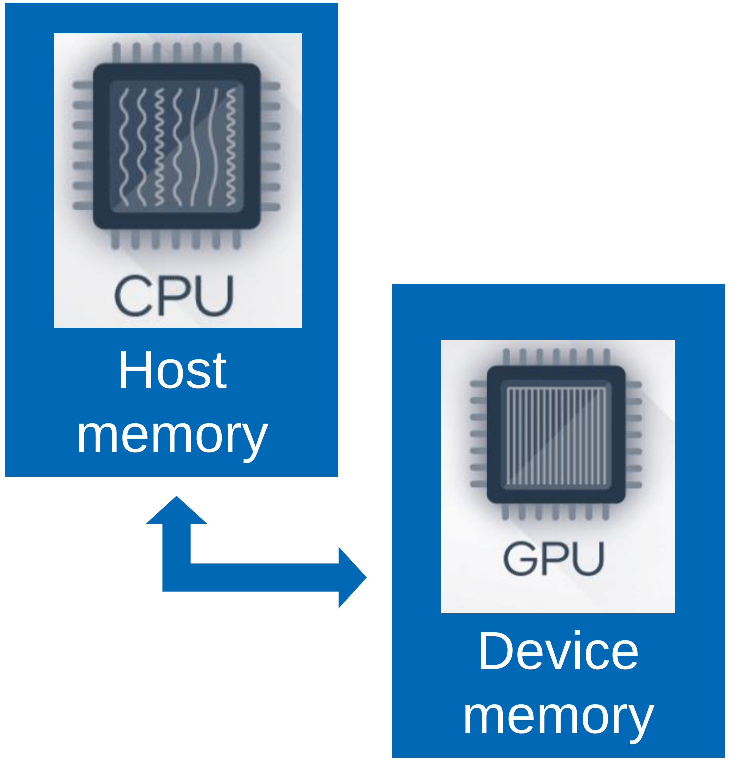
Agenda

- OpenMP* Offload Compiler Support
- Environment variables
- OpenMP* Target Construct
- Managing Device Data
- Demo
- Using openMP Offload with Intel® oneAPI Math Kernel Library (MKL)

OpenMP* Offload Compiler Support

Device Model

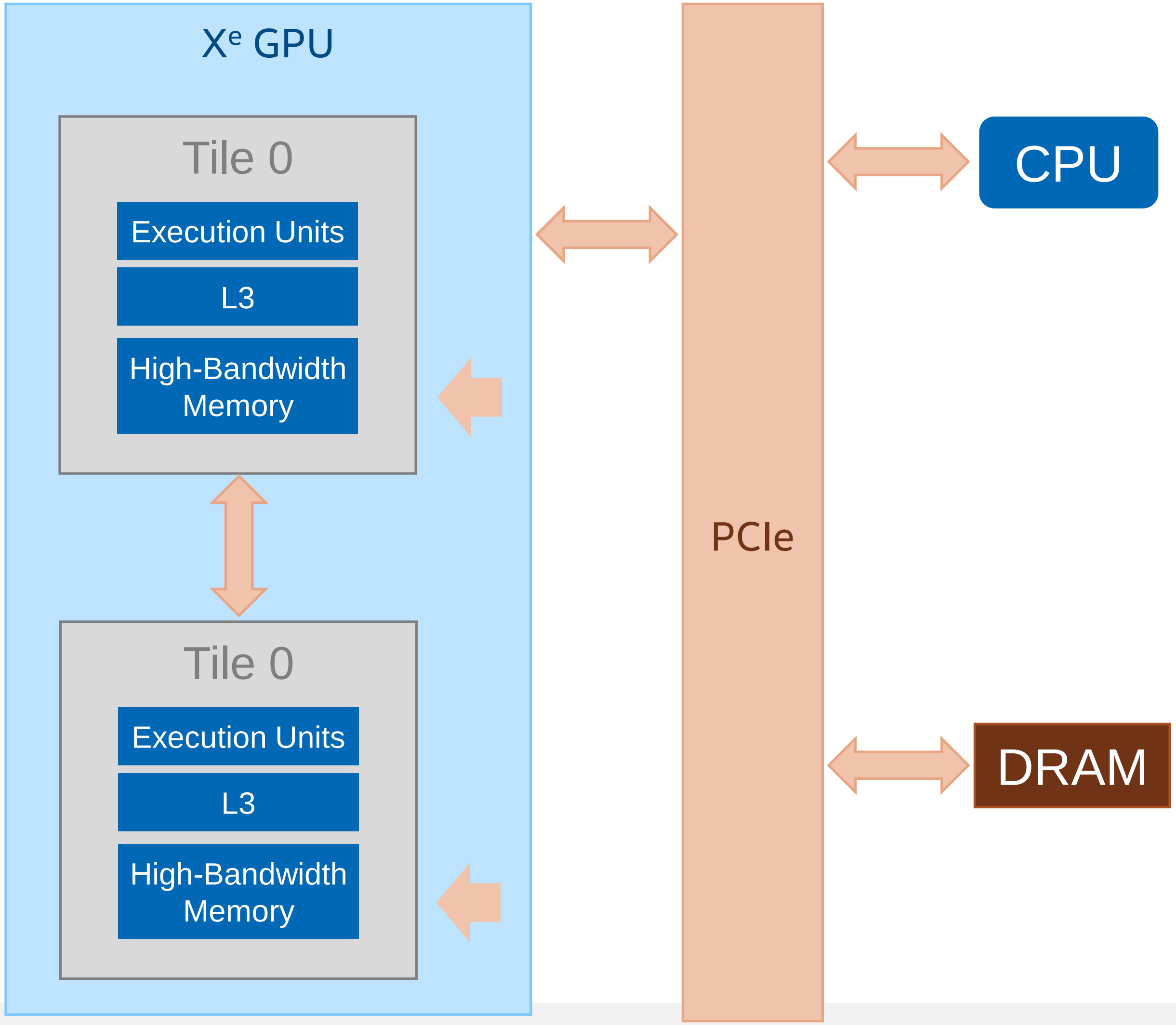


Host memory

Device memory

- Host-centric model
- Host and Device have separate memory spaces
- Device data environment
- We need to move data from host to device to access data inside target region
- We need constructs to offload code to device

Intel X^e Multi-Tile GPU Architecture



- Tiles are independent
  - No global schedulers
  - No global commands affecting all tiles
  - No global state
  - Can work concurrently
- Tiles can communicate over memory
  - Use GPU semaphores for synchronization

OpenMP* Offload Compiler Support

- Intel® C++ Compiler

```
icx -fiopenmp -fopenmp-targets=spir64 <source>.c
```

```
icpx -fiopenmp -fopenmp-targets=spir64 <source>.cpp
```

- Intel® Fortran Compiler

```
ifx -fiopenmp -fopenmp-targets=spir64 <source>.f90
```

- Hardware Supported: Intel® Gen9
- OpenMP directives supported in the icx and ifx compilers for GPU and CPU
- On Linux*, GCC* 4.8.5 or higher must be installed for host code compilation. This is to avoid any incompatibilities due to a changed C++ Application Binary Interface (ABI).

OpenMP* Offload Compiler Support

- Ahead-of-Time compilation supported

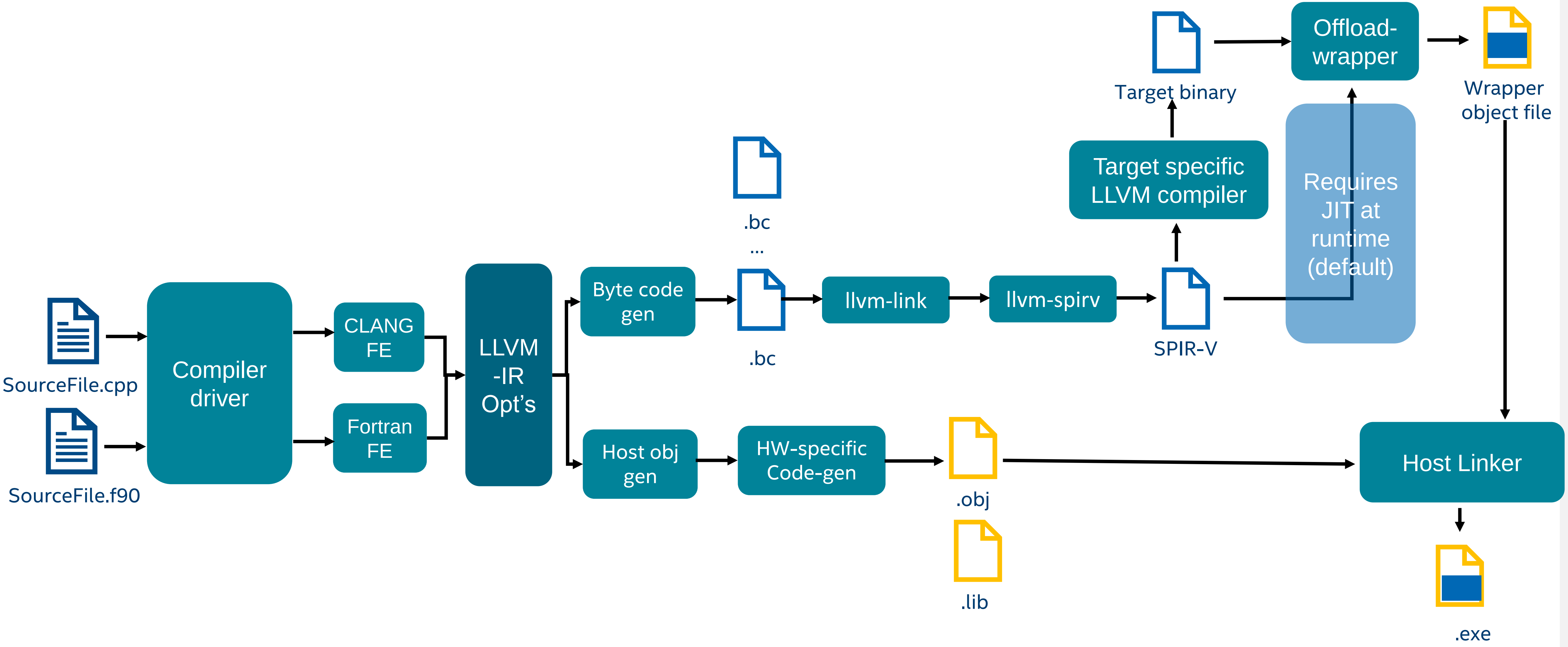
```
icx -fiopenmp -fopenmp-targets=spir64_gen -Xopenmp-target-backend "-device *"
<source>.cpp
```

- -Xopenmp-target-frontend=T"options“
- -Xopenmp-target-backend=T"options“
- -Xopenmp-target-linker=T"options“

Xopenmp-target

Offload Compilation Flow

-fopenmp-targets=spir64_gen
-Xopenmp-target-backend "-device *"



Environment variables

- OMP_TARGET_OFFLOAD : Control offload on device or host
  - Set `MANDATORY` to start offloading
  - Set `DISABLED` to ‘emulate’ offloading on CPU (implementation defined!)
- LIBOMPTARGET_PLUGIN : Choose runtime backend
  - Choose `OpenCL™` or `Level0`
- LIBOMPTARGET_DEBUG : Display debug information
  - Gives you a long and detailed log!
  - Use `1` as value
- LIBOMPTARGET_PLUGIN_PROFILE: Add profiling info
  - Try `T,usec`
  - LIBOMPTARGET_PROFILE is deprecated
- LIBOMPTARGET_INFO: data-mappings and kernel execution
  - 32-bit field to enable or disable different types of information
  - -1 – enable every bit set

oneAPI Level Zero Specification

Supported Environment Variables

OpenMP Offload Constructs

Device Code

- **omp target** *[clause[[,]clause]…] structured-block*
- **omp declare target** *[function-definitions-or-declarations]*
- **omp declare target** [variable-definitions-or-declarations]

Worksharing

- **omp teams** *[clause[[,]clause]…] structured-block*
- **omp distribute** *[clause[[,]clause]…] for-loops*

Memory operations

- **map** *([[map-type-modifier[,]]map-type:] list) map-type :=* ***alloc*** | ***tofrom*** | ***to*** | ***from*** | ***release*** | ***delete*** *map-type-modifier :=* ***always***
- **omp target data** *clause[[[,] clause]…] structured-block*
- **omp target enter data** *clause[[[,]clause]…]*
- **omp target exit data** clause[[[,]clause]…]
- **omp target update** clause[[[,]clause]…]

OpenMP Offload Language

C++	Fortran
#pragma omp target *[clause[[,]clause]…]* *structured-block*	**!$omp target** *[clause[[,]clause]…]* *structured-block* **!$omp end target**
#pragma omp target data *[clause[[,]clause]…]* *structured-block*	**!$omp target** *[clause[[,]clause]…]* *structured-block* **!$omp end target data**
#pragma omp teams *[clause[[,]clause]…]* *structured-block*	**!$omp teams** *[clause[[,]clause]…]* *structured-block*
#pragma omp distribute *[clause[[,]clause]…]* *structured-block*	**!$omp distribute** *[clause[[,]clause]…]* *structured-block*

OpenMP* 5.1 - What's new?

- Fortran 2008 is now fully supported and initial support for Fortran 2018 has been added
- C++11 attributes in addition to pragmas
  - [[omp::directive (parallel for)]] -   #pragma omp parallel for

- New directives

Scope	Improve teams performance
Assume	Optimization invariants
Interop	interoperability
Dispatch	Variant substitution
Error	compiler or runtime to display a messages
nothing	utility

- Deprecated and replaced:
  - omp_target_is_accessible
  - omp_get_mapped_ptr
  - omp_calloc
  - omp_aligned_alloc
  - omp_realloc
  - omp_set_num_teams
  - omp_set_teams_thread_limit
  - omp_get_max_teams
  - omp_get_teams_thread_limit

Press Release: OpenMP ARB releases OpenMP 5.1 with Vital Usability Enhancements

OpenMP* Target Construct
Fortran

Target construct

```
integer :: a(100),  b(100), c(100)
do k=1,100
        a(k) = 1
        b(k) = 1
end do
```

Host code

```
 !$omp target
         do k=1,100
                 c(k) =  a(k) + b(k)
         end do
 !$omp end target
```

Device code

```
do k=1,100
        write (*,*) c(k)
end do
```

Host code

`target [clause]`

- Offloads a code region to a target device
- Sequential and synchronous by default

clause : device, private, firstprivate, in_reduction, map, allocate, if
Sync: nowait, depend

`if` - When an `if` clause is present and the `if` clause expression evaluates to *false*, the target region is executed by the **host device in the host data environment.**

2.12.5 `target` Construct

Target Device Construct

```
integer :: a(100),  b(100), c(100)
do k=1,100
        a(k) = 1
        b(k) = 1
end do
```

Host code

```
 !$omp target device (0)
        do k=1,100
                c(k) =  a(k) + b(k)
        end do
 !$omp end target
```

Device code

```
do k=1,100
        write (*,*) c(k)
end do
```

Host code

`target device`

- Specify which device to offload to in a multi-device environment

- Device number an integer
  - Assignment is implementation-specific
  - Usually start at 0 and sequentially increments
- Works with **`target`**, **`target data`**, **`target enter \ exit data`**, **`target update`** directives

2.12.5 `target` Construct

Target Device Construct for Multi-Tile GPUs

```
integer :: a(100),  b(100), c(100)
do k=1,100
        a(k) = 1
        b(k) = 1
end do
```

Host code

```
!$omp target device(0) subdevice (0, 2:5)
        do k=1,100
                c(k) =  a(k) + b(k)
        end do
!$omp end target
```

runs on tiles 2, 3, 4, and 5

Device code

```
do k=1,100
        write (*,*) c(k)
end do
```

Host code

`target device`

- Specify which device to offload to in a multi-device environment
- How to utilize multi-tile GPU?
- **`SUBDEVICE  ( [level,] start [:length [:stride]] )`**
  - Level - non-negative int constant; default 0
  - Start - non-negative int expression.
  - Length - positive int expression; default 1
  - Stride - positive int expression; default 1

Intel® Fortran Compiler Classic and Intel® Fortran Compiler Developer Guide and Reference: SUBDEVICE

OpenMP* Device Parallelism

```
integer :: a(100),  b(100), c(100)
do k=1,100
        a(k) = 1
        b(k) = 1
end do
```

Host code

```
 !$omp target device (0)
        !$omp parallel do
        do k=1,100
                c(k) =  a(k) + b(k)
        end do
        !$omp end parallel do
 !$omp end target
```

???

Device code

```
do k=1,100
        write (*,*) c(k)
end do
```

Host code

`target [clause]`

- Offloads a code region to a target device
- Sequential and synchronous by default

Why NOT parallel for?

- CPU parallelism differs from GPU – shared memory systems
- `omp parallel for` threads will use only 1 Streaming Multiprocessor (SM) to synchronize
- Need a different level of parallelism to step over multiple SM

GPU device architecture

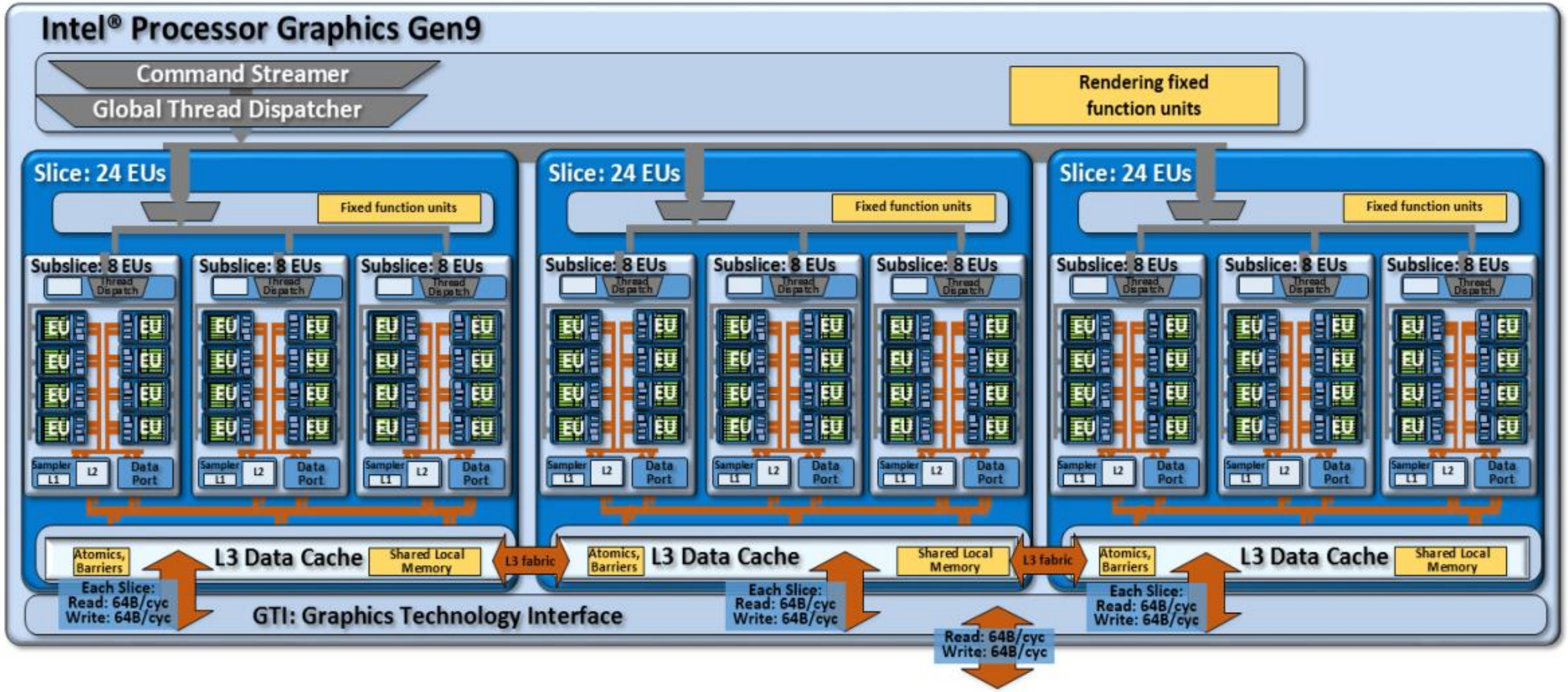


Figure 8: Another potential product design that instantiates the compute architecture of Intel® processor graphics gen9. This design is composed of three slices, of three subslices each for a total of 72 EUs.

[The Compute Architecture of Intel(R) Processor Graphics Gen9. Version 1.0]()

OpenMP* Device Parallelism

```
integer :: a(100),  b(100), c(100)
do k=1,100
        a(k) = 1
        b(k) = 1
end do
```

Host code

```
 !$omp target teams
      !$omp parallel do
          do k=1,100
                   c(k) =  a(k) + b(k)
          end do
      !$omp end parallel do
 !$omp end target
```

Device code

```
do k=1,100
        write (*,*) c(k)
end do
```

Host code

`target [clause]`

Offloads a code region to a target device

Sequential by default

`target teams`

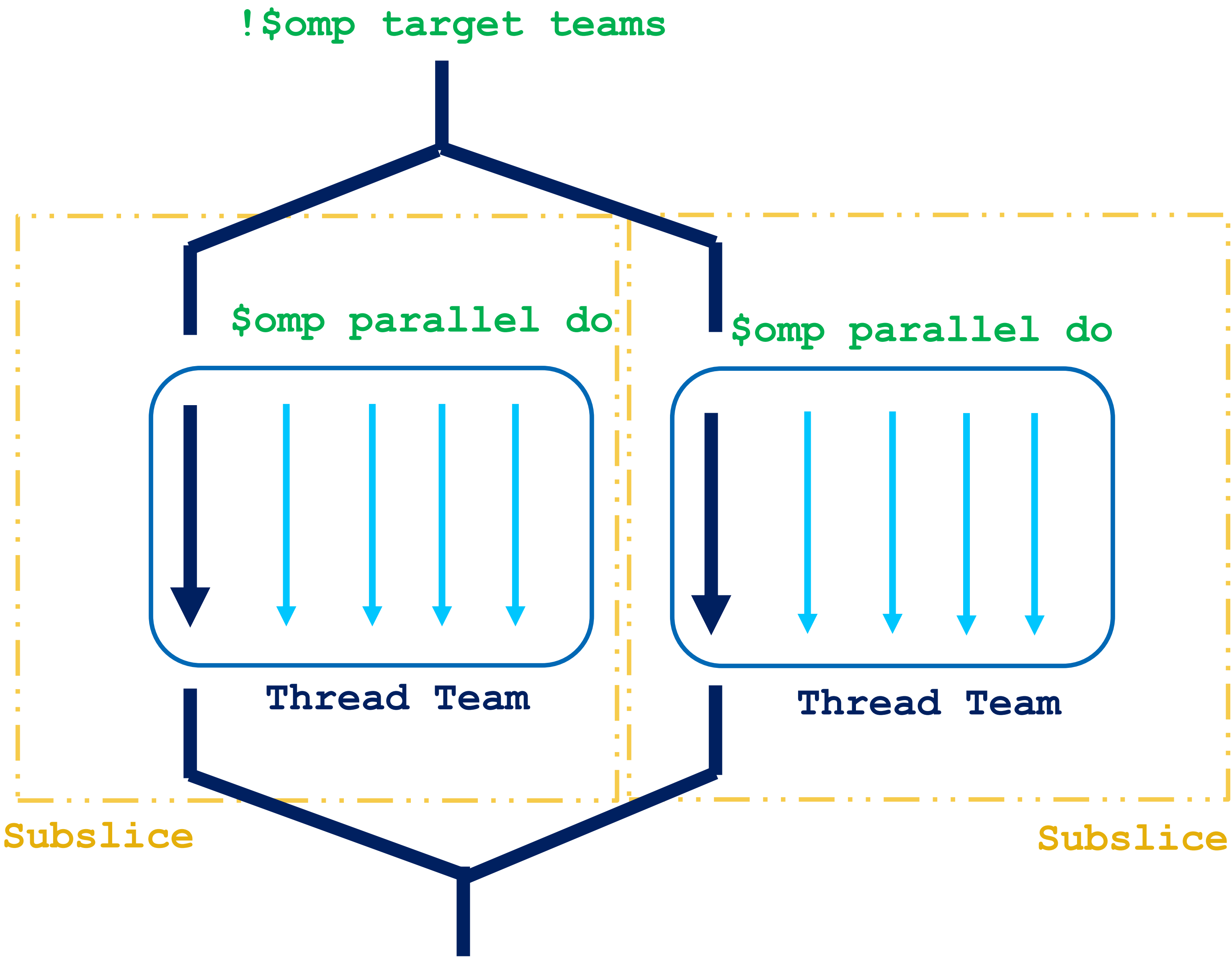
creates a *league* of teams where the primary thread of each team executes the `teams` region.

number of teams = number of work groups **`(clinfo)`**

2.13.21 `target teams` Construct

Teams Construct

OpenMP	GPU Hardware
SIMD	SIMD Lane (Channel)
Thread	SIMD Thread mapped to an EU
Team	Group of threads mapped to a Subslice
League	Multiple Teams mapped to a GPU



2.7 teams Construct

OpenMP* Worksharing

```
integer :: a(100),  b(100), c(100)
do k=1,100
        a(k) = 1
        b(k) = 1
end do
```

Host code

```
 !$omp target teams distribute parallel do
         do k=1,100
                 c(k) =  a(k) + b(k)
         end do
 !$omp end target teams distribute parallel do
```

Device code

```
do k=1,100
        write (*,*) c(k)
end do
```

Host code

`target teams distribute`

shortcut for specifying a target construct containing a teams distribute construct and no other statements.

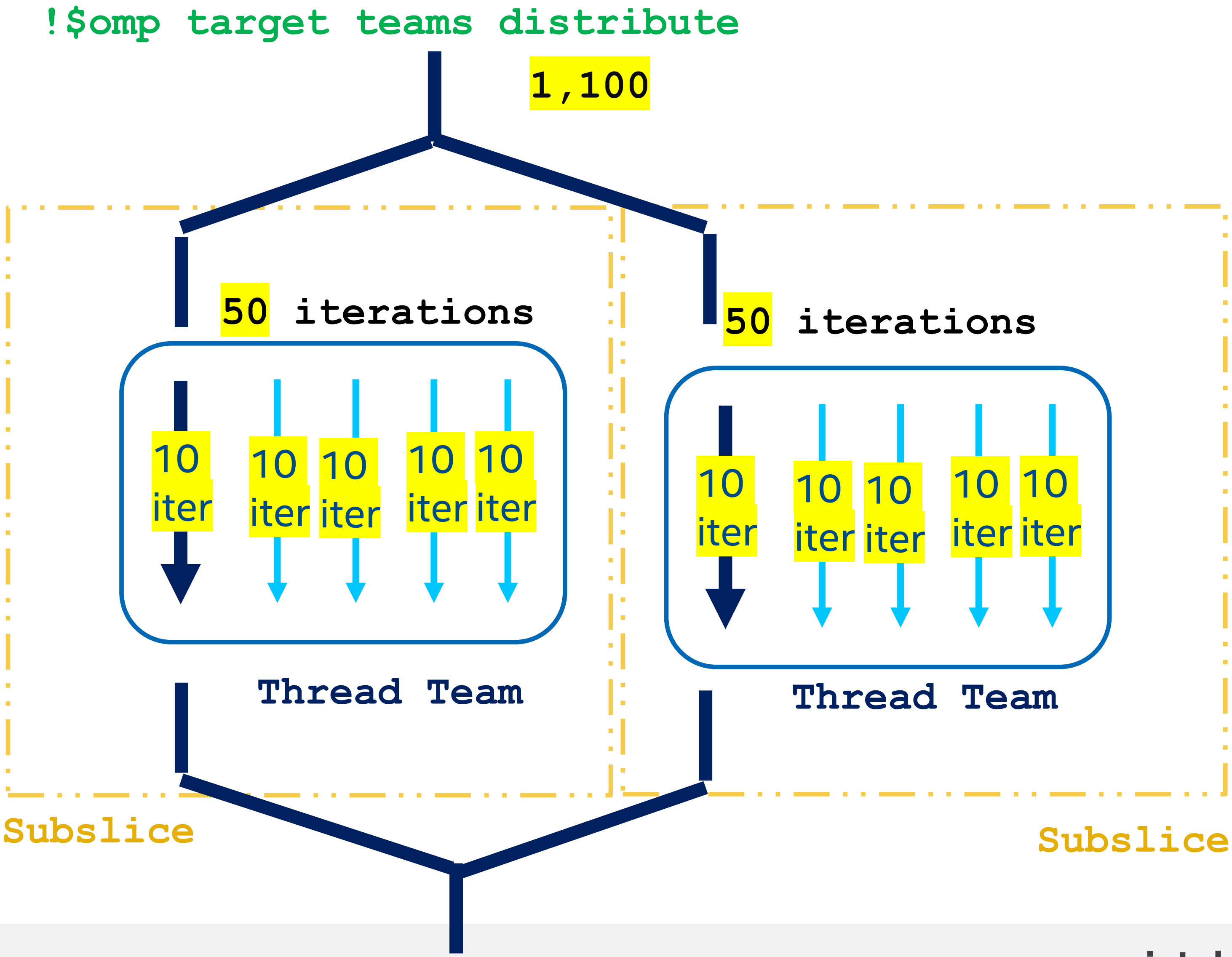
`target teams distribute parallel do`

parallel worksharing-loop construct is a shortcut for specifying a target construct containing a teams distribute parallel worksharing-loop construct and no other statements

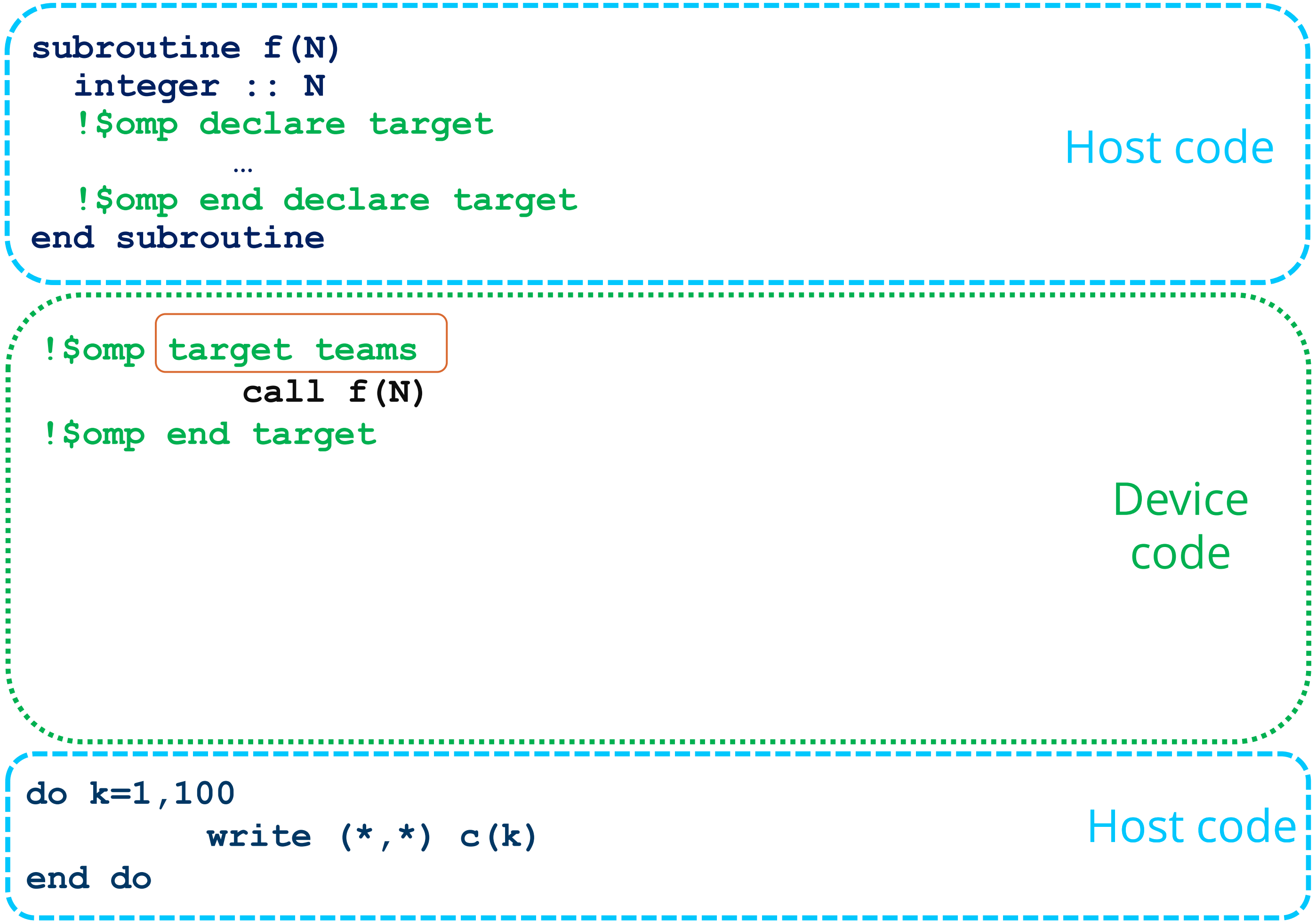
2.13.11 `teams distribute` Construct
2.13.25 Target Teams Distribute Parallel Worksharing-Loop Construct

Teams Distribute Construct

```
!$omp target teams
distribute parallel
do
      do k=1,100
         c(k) =  a(k) + b(k)
      end do
!$omp end target
teams distribute
parallel do
```



Calling functions inside Target region



```
subroutine f(N)
  integer :: N
  !$omp declare target
        …
  !$omp end declare target
end subroutine
```

Host code

```
 !$omp target teams
          call f(N)
 !$omp end target
```

Device code

```
do k=1,100
        write (*,*) c(k)
end do
```

Host code

`declare target`

compiles a version of the function/subroutine for the target device

Function compiled for both host execution and target execution by default

`device_type(host | nohost | any)`

2.12.7 `declare target` Directive

Asynchronous Target Regions

```
integer :: a(100),  b(100), c(100)
do k=1,100
        a(k) = 1
        b(k) = 1
end do
```

Host code

```
!$omp task depend(out: a)
    call init_vector(a,  N)
!$omp end task
!$omp task depend(out: b)
    call init_vector(b,  N)
!$omp end task
!$omp target map(to:a, b) map(tofrom:c) nowait depend(in:a, b)
depend(out:c)
     call vector_add(a, b, c, N);
!$omp end target
!$omp targetmap(to:c) map(tofrom:c) nowait depend(in:c)
depend(out:c)
   call vector_increment(c, N)
!$omp end target
!$omp taskwait
```

Device code

```
do k=1,100
        write (*,*) c(k)
end do
```

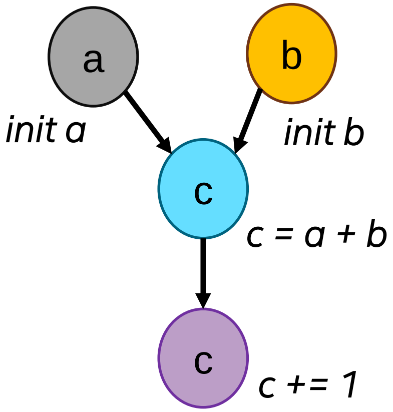
Host code

`target [clause]`

Offloads a code region to a target device

Synchronous by default

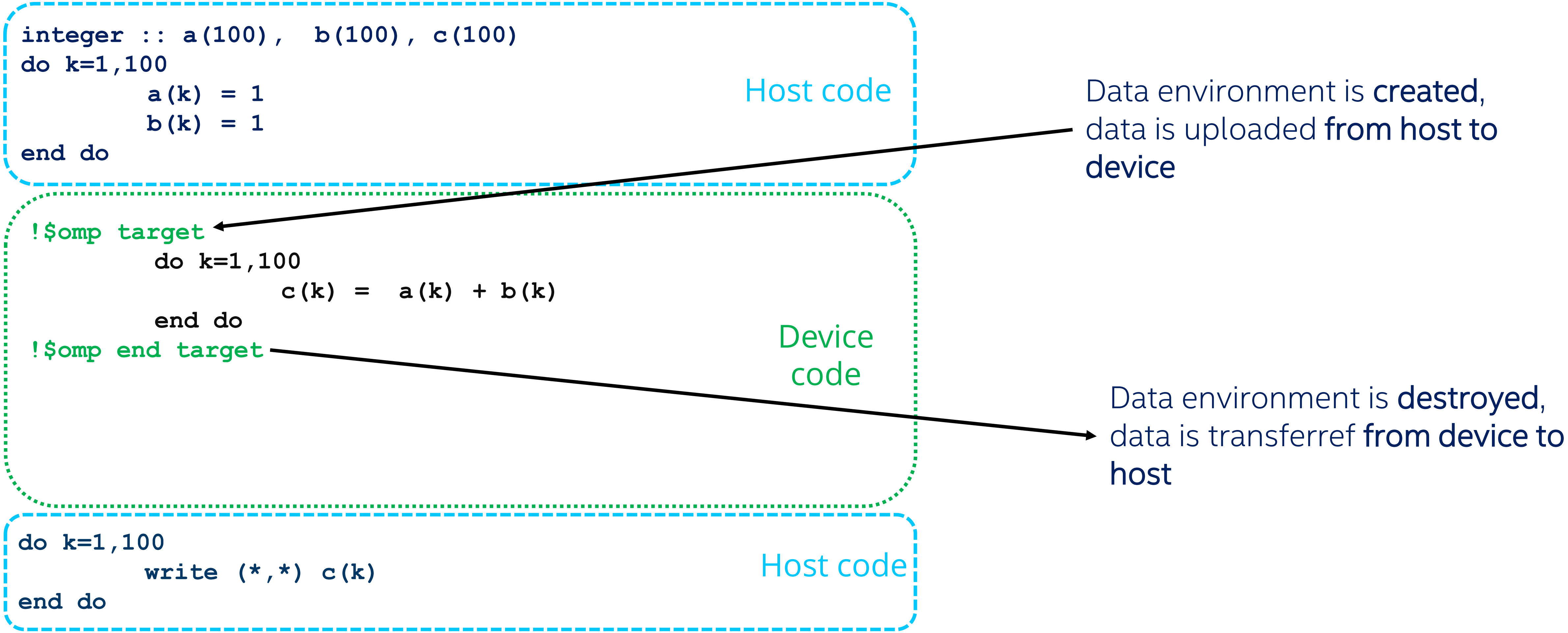
- nowait
- depend ([depend-modifier,]dependence-type : locator-list)



[2.17.11 depend Clause](#)
[15.6 nowait Clause](#)

Managing Device Data
Fortran

Device Data Environment



```
integer :: a(100),  b(100), c(100)
do k=1,100
        a(k) = 1
        b(k) = 1
end do
```

Host code

```
!$omp target
        do k=1,100
                c(k) =  a(k) + b(k)
        end do
!$omp end target
```

Device code

```
do k=1,100
        write (*,*) c(k)
end do
```

Host code

Data environment is **created**, data is uploaded **from host to device**

Data environment is **destroyed**, data is transferref **from device to host**

[1.4.6 OpenMP Memory Consistency]

Target map construct

```
integer :: a(100),  b(100), c(100)
do k=1,100
        a(k) = 1
        b(k) = 1
end do
```

Host code

```
!$omp target teams distribute parallel do
 map(to:a) map(to:b) map(tofrom:c)
         do k=1,100
                 c(k) =  a(k) + b(k)
         end do
     !$omp end parallel do
!$omp end target
```

Device code

```
do k=1,100
        write (*,*) c(k)
end do
```

Host code

`target map (map_type)`

Map variables to a device data environment and execute the construct on that device.

map_type : to, from, tofrom, alloc, release, delete

modifier: always, close, <mapper identifier>

2.19.7 Data-Mapping Attribute Rules, Clauses, and Directives

Dynamically Allocated Data

```
integer :: a(100),  b(100), c(100)
do k=1,100
        a(k) = 1
        b(k) = 1
end do
```

Host code

```
!$omp target teams distribute parallel do
  map(to:a[0:N]) map(to:b [0:N]) map(tofrom:c [0:N])
        do k=1,100
                c(k) =  a(k) + b(k)
        end do
!$omp end target teams distribute parallel do
```

Device code

```
do k=1,100
        write (*,*) c(k)
end do
```

Host code

`target map (map_type)`

When pointers are dynamically allocated, number of elements to be mapped must be explicitly specified

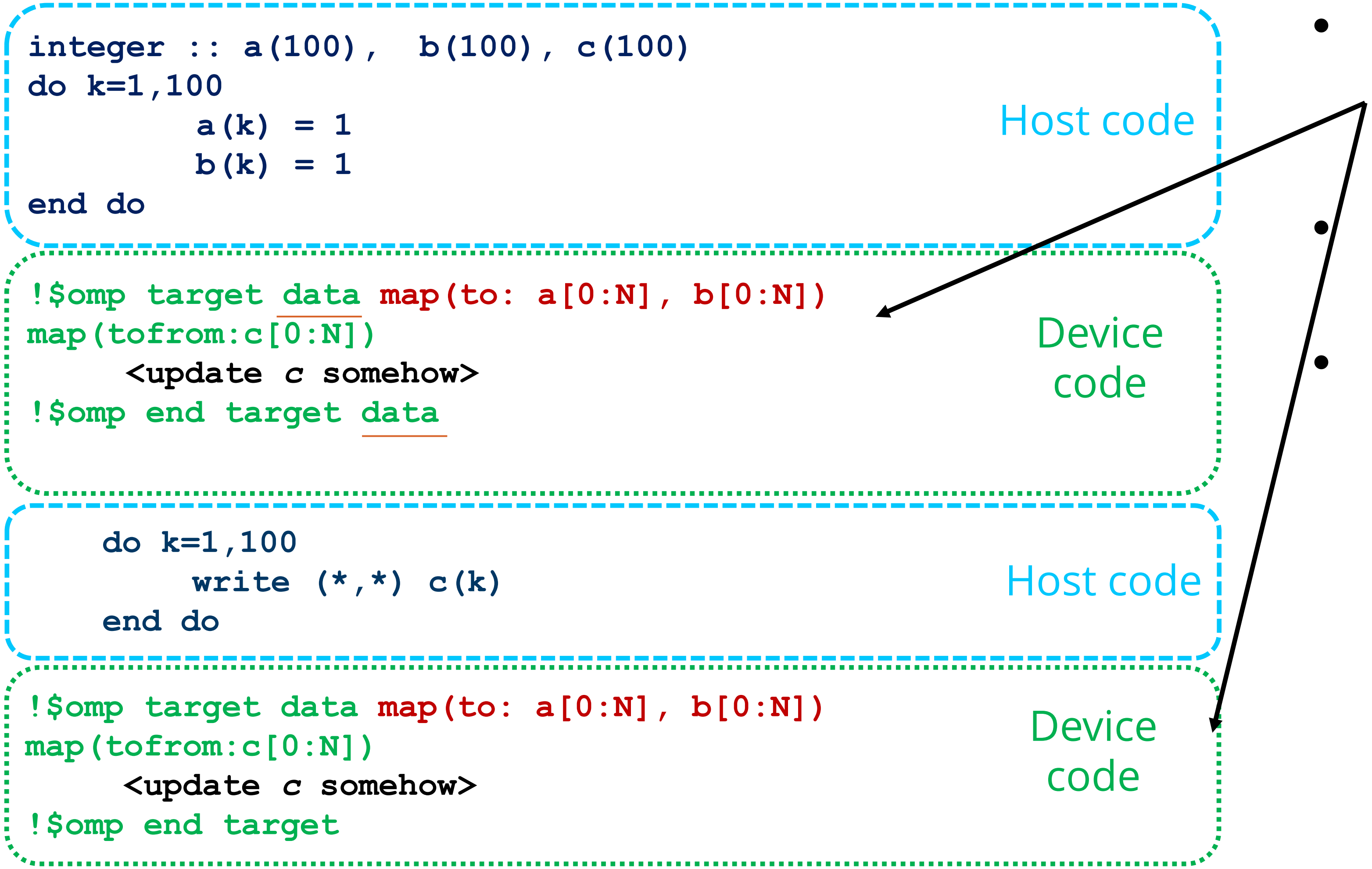
N – the number of elements to be copied

Note:

C++ : array[start : length]
Fortran: array[start : end]

2.19.7 Data-Mapping Attribute Rules, Clauses, and Directives

Minimize Copy Overhead



```
integer :: a(100),  b(100), c(100)
do k=1,100
        a(k) = 1
        b(k) = 1
end do
```

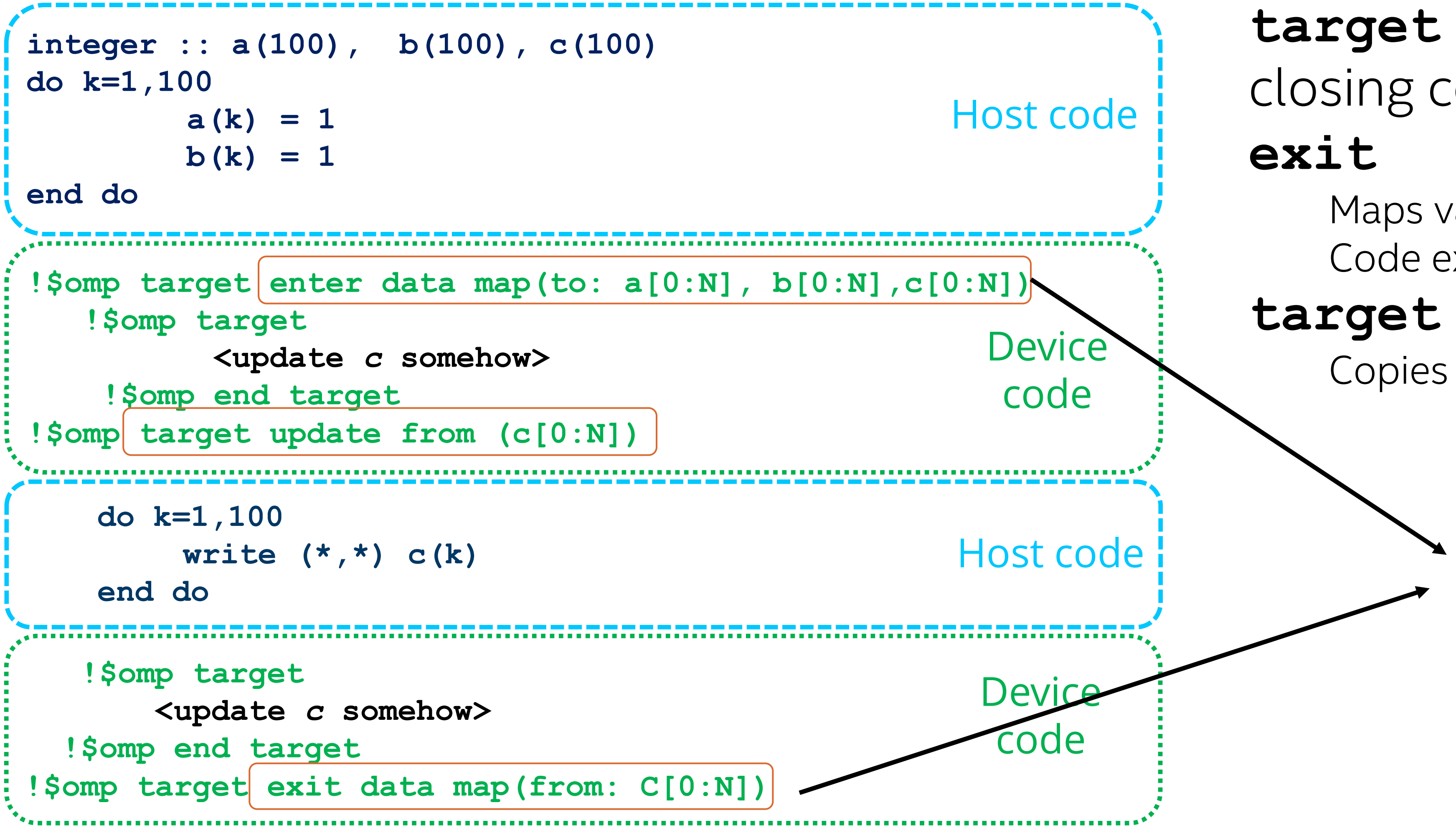
```
!$omp target data map(to: a[0:N], b[0:N])
map(tofrom:c[0:N])
     <update c somehow>
!$omp end target data
```

```
    do k=1,100
         write (*,*) c(k)
    end do
```

```
!$omp target data map(to: a[0:N], b[0:N])
map(tofrom:c[0:N])
     <update c somehow>
!$omp end target
```

- What if we need a and b in multiple target regions?
- Data movement overhead
- Solution:
  - **`target enter data`**
  - **`target update`**

Target data enter construct



```
integer :: a(100),  b(100), c(100)
do k=1,100
        a(k) = 1
        b(k) = 1
end do
```

```
!$omp target enter data map(to: a[0:N], b[0:N],c[0:N])
   !$omp target
          <update c somehow>
    !$omp end target
!$omp target update from (c[0:N])
```

```
    do k=1,100
         write (*,*) c(k)
    end do
```

```
   !$omp target
       <update c somehow>
  !$omp end target
!$omp target exit data map(from: C[0:N])
```

`target enter` requires closing construct, **`target exit`**

Maps variables

Code execution not offloaded

`target update`

Copies data between host and device

enter data and **exit data** are standalone directives

[2.12.3 `target enter data` Construct]

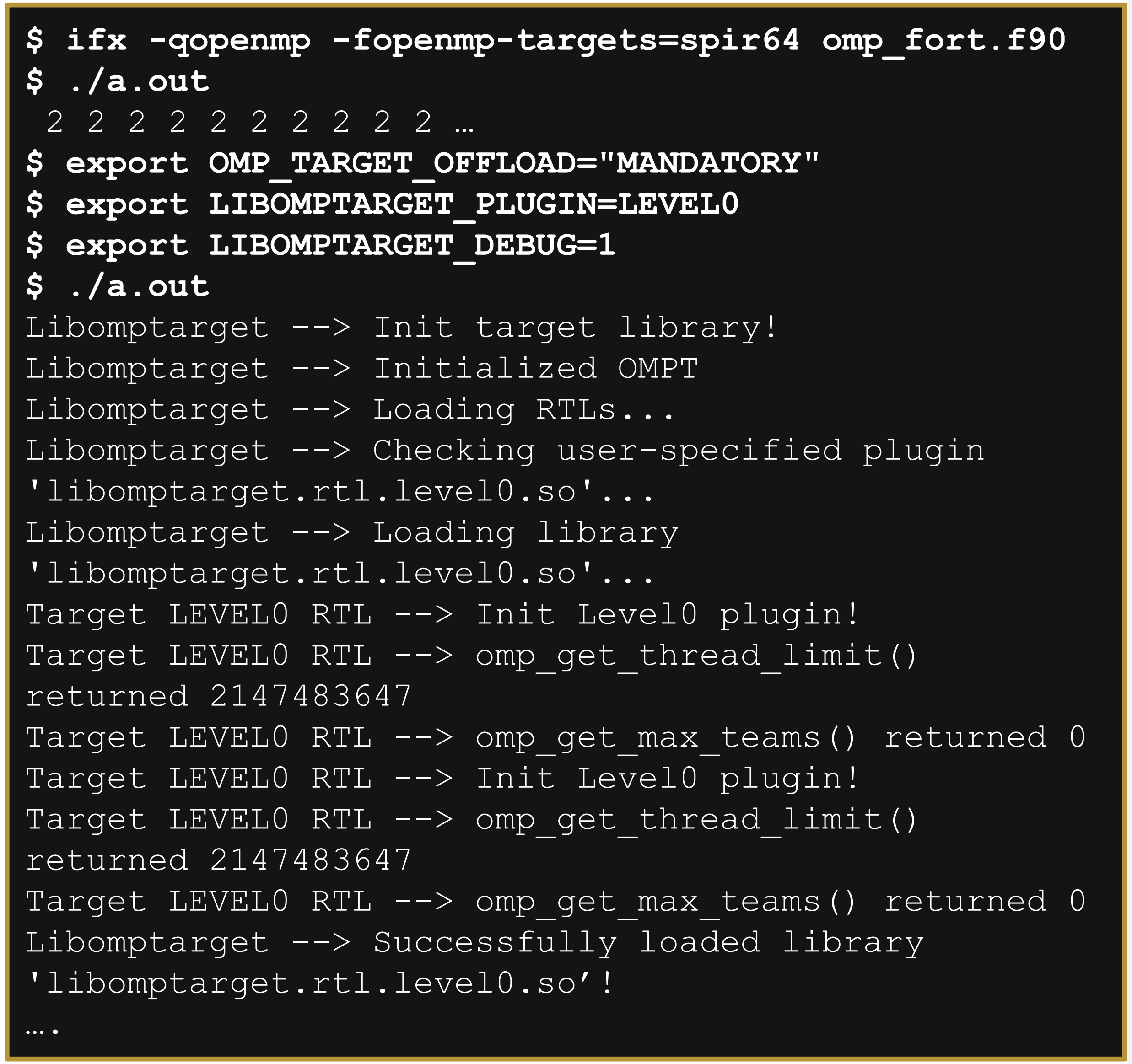
Demo

Fortran Code Sample

```fortran
program vector_add
 use omp_lib
 integer :: a(100), b(100), c(100)
  do k=1,100
   a(k) = 1
   b(k) = 1
 end do

!$omp target teams distribute parallel do
map (to:a) map(to:b) map(tofrom:c)
   do k=1,100
     c(k) = a(k) + b(k)
   end do
!$omp end target teams distribute parallel do

 do k=1,10
   write (*,'(1x,i0)',advance='no') c(k)
 end do
 write (*,*) '...’
end program vector_add
```



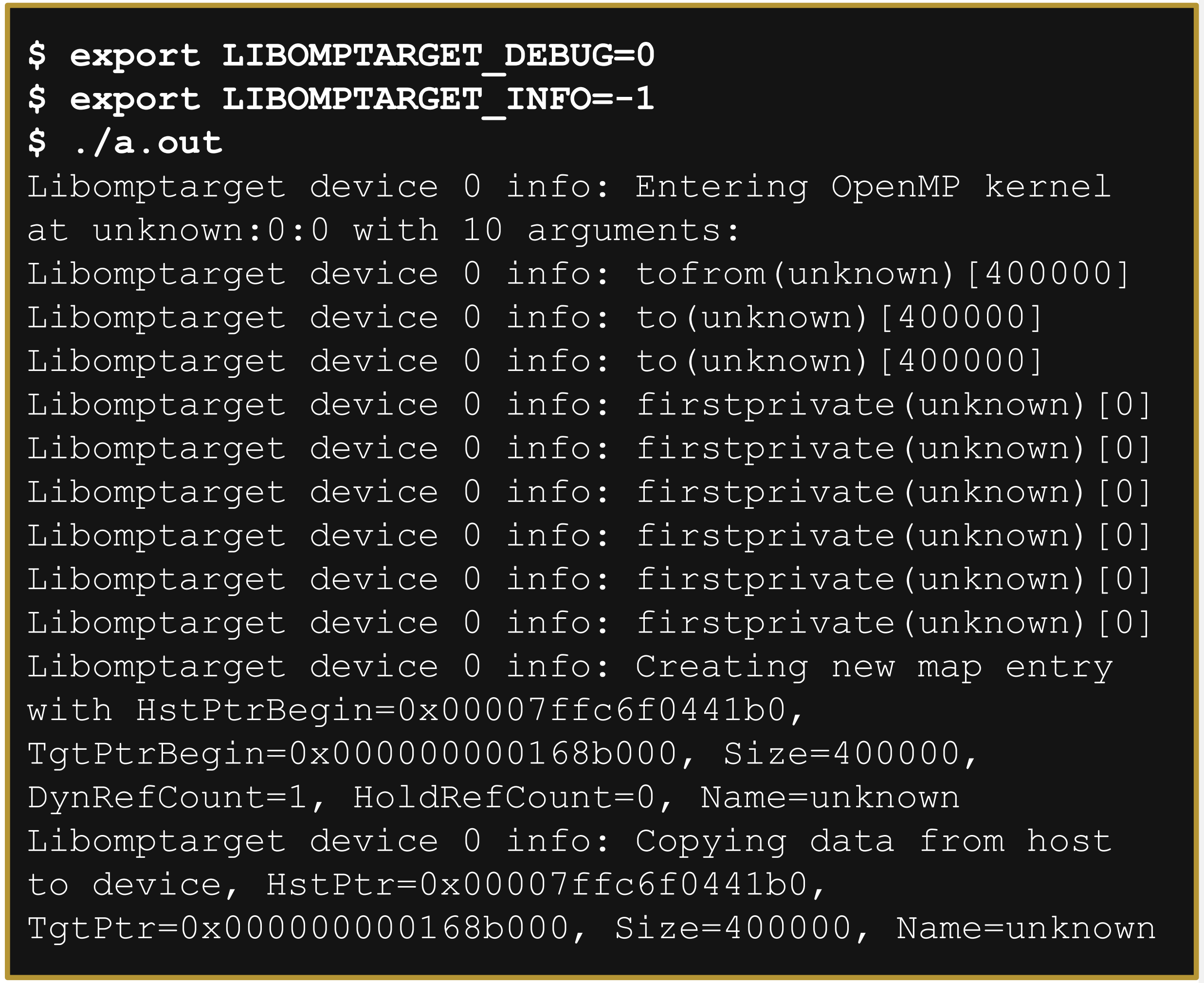
```
$ ifx -qopenmp -fopenmp-targets=spir64 omp_fort.f90
$ ./a.out
 2 2 2 2 2 2 2 2 2 2 …
$ export OMP_TARGET_OFFLOAD="MANDATORY"
$ export LIBOMPTARGET_PLUGIN=LEVEL0
$ export LIBOMPTARGET_DEBUG=1
$ ./a.out
Libomptarget --> Init target library!
Libomptarget --> Initialized OMPT
Libomptarget --> Loading RTLs...
Libomptarget --> Checking user-specified plugin
'libomptarget.rtl.level0.so'...
Libomptarget --> Loading library
'libomptarget.rtl.level0.so'...
Target LEVEL0 RTL --> Init Level0 plugin!
Target LEVEL0 RTL --> omp_get_thread_limit()
returned 2147483647
Target LEVEL0 RTL --> omp_get_max_teams() returned 0
Target LEVEL0 RTL --> Init Level0 plugin!
Target LEVEL0 RTL --> omp_get_thread_limit()
returned 2147483647
Target LEVEL0 RTL --> omp_get_max_teams() returned 0
Libomptarget --> Successfully loaded library
'libomptarget.rtl.level0.so’!
….
```

Fortran Code Sample

```fortran
program vector_add
 use omp_lib
 integer :: a(100), b(100), c(100)
  do k=1,100
   a(k) = 1
   b(k) = 1
 end do

!$omp target teams distribute parallel do
map (to:a) map(to:b) map(tofrom:c)
   do k=1,100
     c(k) = a(k) + b(k)
   end do
!$omp end target teams distribute parallel do

 do k=1,10
   write (*,'(1x,i0)',advance='no') c(k)
 end do
 write (*,*) '...’
end program vector_add
```



```
$ export LIBOMPTARGET_DEBUG=0
$ export LIBOMPTARGET_INFO=-1
$ ./a.out
Libomptarget device 0 info: Entering OpenMP kernel
at unknown:0:0 with 10 arguments:
Libomptarget device 0 info: tofrom(unknown)[400000]
Libomptarget device 0 info: to(unknown)[400000]
Libomptarget device 0 info: to(unknown)[400000]
Libomptarget device 0 info: firstprivate(unknown)[0]
Libomptarget device 0 info: firstprivate(unknown)[0]
Libomptarget device 0 info: firstprivate(unknown)[0]
Libomptarget device 0 info: firstprivate(unknown)[0]
Libomptarget device 0 info: firstprivate(unknown)[0]
Libomptarget device 0 info: firstprivate(unknown)[0]
Libomptarget device 0 info: Creating new map entry
with HstPtrBegin=0x00007ffc6f0441b0,
TgtPtrBegin=0x000000000168b000, Size=400000,
DynRefCount=1, HoldRefCount=0, Name=unknown
Libomptarget device 0 info: Copying data from host
to device, HstPtr=0x00007ffc6f0441b0,
TgtPtr=0x000000000168b000, Size=400000, Name=unknown
```

What else?

- OpenMP* Offload Basics in DevCloud (with lab!)
- openMP Specification
- C/C++ OpenMP* and SYCL* Composability
- Three Quick, Practical Examples of OpenMP* Offload to GPUs

Using openMP Offload with Intel® oneAPI Math Kernel Library (MKL)

Calling MKL OpenMP offload (OpenMP => 5.1)

```
#include <mkl.h>
int main()
{
   /* Allocate memory. */
   MKL_INT n = 1337;
   double *A = malloc(sizeof(double) * n*n );
   double *B = malloc( sizeof(double) * n*n );
   double *C = malloc( sizeof(double) * n*n );
   /* Initialise A and B with your favourite values here. */
   for ( int i = 0; i < n; ++i )
   for ( int j = 0; j < n; ++j )
   {
      A[ i + j*n ] = i*j;
      B[ i + j*n ] = i+j;
   }
   /* Form matrix-matrix product C = A*B */
   cblas_dgemm(CblasColMajor, CblasNoTrans, CblasNoTrans,
               n, n, n, 1.0, A, n, B, n, 0.0, C, n);
   return 0;
}
```

- Starting point: Classic C code calling the standard CBLAS MKL interface.

Shall be executed on GPU

Calling MKL OpenMP offload (OpenMP => 5.1)

```
cblas_dgemm(CblasColMajor, CblasNoTrans, CblasNoTrans,
               n, n, n, 1.0, A, n, B, n, 0.0, C, n);
```

```
#pragma omp target data map(to:A[0:n*n],B[0:n*n]) map(from:C[0:n*n])
{
/* This will run the CPU version! */
   cblas_dgemm(CblasColMajor, CblasNoTrans, CblasNoTrans,
               n, n, n, 1.0, A, n, B, n, 0.0, C, n);
}
```

- Remember: omp target data map only creates a data environment on the GPU.
- A and B get transferred to the GPU, C is allocated on the GPU.
- Cblas_dgemm will be calculated on the CPU.
- C gets overwritten by uninitialized data from the GPU.

Calling MKL OpenMP offload (OpenMP => 5.1)

```
cblas_dgemm(CblasColMajor, CblasNoTrans, CblasNoTrans,
               n, n, n, 1.0, A, n, B, n, 0.0, C, n);
```

```
#include <mkl.h>
#include <mkl_omp_offload.h>
```

```
#pragma omp target data map(to:A[0:n*n],B[0:n*n]) map(from:C[0:n*n])
{
#pragma omp dispatch
cblas_dgemm(CblasColMajor, CblasNoTrans, CblasNoTrans,
               n, n, n, 1.0, A, n, B, n, 0.0, C, n);
}
```

- Include mkl_omp_offload.h header file
- Instruct the compiler to use the offload version by “omp dispatch” (available since OpenMP 5.1)
- Compile with –fopenmp-version=51

Calling MKL OpenMP offload (OpenMP => 5.1)

- Compile:

```
icx -fiopenmp -fopenmp-version=51 -fopenmp-targets=spir64 -qmkl \
   -o dgemm_sample.o -c dgemm_sample.c
```

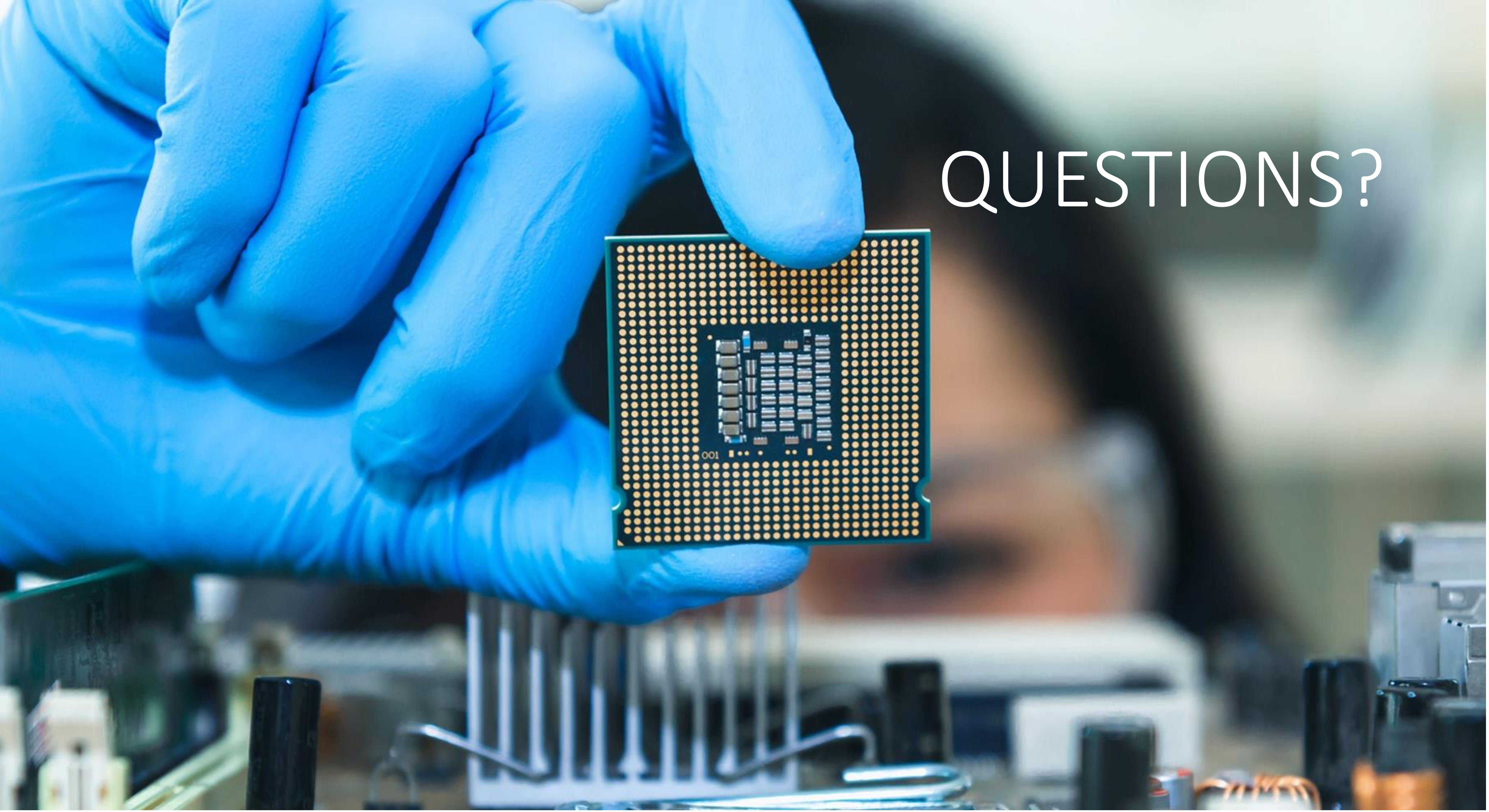
- Link:

```
icx -fiopenmp -fopenmp-version=51 -fopenmp-targets=spir64 -qmkl \
   -o dgemm_sample dgemm_sample.o
```

- Many more options (64/32-bit integers, static/dynamic linking, Linux*/Windows*, etc.) are available through the:

Intel® oneAPI Math Kernel Library Link Line Advisor

QUESTIONS?



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