Programming Models for OpenPOWER Systems

Productive, Portable, High-Level GPU Acceleration

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XL Compiler Suite

- IBM XL C/C++ for Linux, V13.1.6 and IBM XL Fortran for Linux, V15.1.6
- Architectures: IBM POWER8 and POWER9
- Language support:
    - C11, C++11, and partial C++14
    - Fortran 2003, and partial F2008
    - OpenMP 3.1, most of OpenMP 4.5, some TR6
    - CUDA Fortran

Compiler Reference: http://ibm.biz/XLC1316
http://ibm.biz/XLFortran1516

How to use

- OpenMP programs: `> xlC_r -qsmp=omp [-qoffload]`
  `> xlf_r -qsmp=omp [-qoffload]`
- CUDA Fortran: `> xlf_r -qcuda` (or just `xlcuf`)
- CUDA Fortran + OMP: `> xlf_r -qcuda -qsmp=omp -qoffload`

- Options:
  - Best performance: `-Ofast`
  - Debugging OpenMP: `-qsmp=noopt -g -qfullpath`
  - To get line number info only: `-g1 -qfullpath`
  - Offloading device arch: `-qtgtarch=[auto|sm_35|sm_60|sm_70]`

-qoffload enables GPU offloading of OpenMP target regions

-qtgtarch is needed if you are cross compiling or the sm level changed after the compiler was installed.

Debugging and Profiling

- Tools:
  - cuda-gdb
  - cuda-memcheck
  - nvprof
  - nvvp

- Debugging Tips:
  - Reduce testcase size.
  - Reduce parallelism: `num_threads` clause for parallel region, and `thread_limit` and `num_teams` clauses for teams region.
  - Reduce array sizes to rule out memory limit issues.
  - CUDA Fortran only: `-qcudaerr=all` to check return codes from all CUDA API calls.
  - Fortran only: `-qcheck` to check for array bounds.
    Control per-device malloc limit by compiling with -qcuda option and exporting XLCUF_GPU_DATA_LIMIT=*bytes.*
  - Use -qport=c_loc if you get errors about C_LOC and the missing TARGET attribute.
  - Use printf (C/C++) and print (Fortran).

Fortran support and CUDA interop

CUDA C/C++

- Use XL C/C++ as host compiler for POWER CPUs when using nvcc:
  - Fully leverage advanced compiler optimizations for POWER
  - Sample invocation
    `> nvcc -ccbin xlC_r -Xcompiler -Ofast t.cu`

- Interoperability with OpenMP
  - Use `is_device_ptr` to access CUDA-allocated device memory in OpenMP
  - Use `use_device_ptr` to access OpenMP allocated device memory in CUDA
  - Calling OpenMP procedures from CUDA and vice-versa is not supported.

Fortran Language Support

- XL Fortran supports
  - Most of Technical specification 29113: interoperability of assumed-length, assumed-rank, assumed-type, allocatable, pointer, and optional arguments
  - Partial Fortran 2008: submodules, do concurrent, contiguous attribute, BLOCK construct, enhancement to ALLOCATE, STOP/ERROR STOP
  - Full Fortran 2003.

Reference: https://ibm.biz/Fortran2008Status
https://ibm.biz/FortranTS29113Status

CUDA Fortran support

- XL Fortran supports most of CUDA Fortran, with CUF kernels being the main missing feature.
- We intend our CUDA Fortran support to be fully compatible with PGI's, and we test our compiler against the PGI test suite to ensure compatibility.
- More details on the known issues and limitations with our CUDA Fortran implementation can be found at: http://ibm.biz/XLCUF_Limitations

CUDA Fortran and OMP

- A Fortran application can include both CUDA Fortran and OpenMP.
- CUDA Fortran variables can appear on OMP clauses.

```
program p
integer, parameter :: n = 1000000
integer i
integer, allocatable, pinned :: arr_p(:)
integer, allocatable, managed :: arr_m(:)

allocate(arr_p(n), arr_m(n))
arr_m = 0

!$omp target teams distribute parallel do map(from: arr_p) is_device_ptr(arr_m)
  do i = 1, n
    arr_p(i) = arr_m(i) + 1
  end do
end program p
```

Good Programming Patterns

Good Programming Patterns for OpenMP

- Compiler has a generic (runtime-library-dependent) and an SPMD (little to no runtime) codegen schemes.
- SPMD scheme is the closest to a CUDA kernels with least runtime calls.
- Help the compiler generate “SPMD” programs by:
  - Using `#pragma omp distribute parallel do [simd]` for target teams and `#pragma omp parallel do [simd]` for target regions.
  - Calls to unknown functions (definition not in CU) causes generic codegen.
  - Give the compiler inlining opportunities, e.g. making sure hot functions are defined in same compilation unit (CU) as their call sites.
  - Use -qinline+<function-name> to force inlining (mangled name for C++). For example -qinline+foo or -qinline+_Z3fooi

Compiler-friendly Code pattern

- Compiler can generate better code when functions can be inlined in an OMP TARGET construct. For inlining to happen, caller and callee must be in the same compilation unit.
- The following code-pattern prohibits SPMD code generation.

```
module m
  integer, parameter :: N = 10
  contains
  subroutine mod_sub(x, y, z)
    integer :: x, y, z
    !$omp declare target
      z = 24 * x + y
  end subroutine
end module m
```

```
use m
integer :: x(N), y(N), z(N)
x = 10
y = 20
!$omp target teams distribute parallel do map(to: x, y) map(from: z)
  do i = 1, N
    call mod_sub(x(i), y(i), z(i)) ! This call can not be inlined
  end do
end
```

Compiler-friendly Code pattern

- Placing caller and callee in the same module allows SPMD code generation.

```
module m
  integer, parameter :: N = 10
  contains
  subroutine mod_sub(x, y, z)
    integer :: x, y, z
    !$omp declare target
      z = 24 * x + y
  end subroutine
  subroutine driver(x, y, z)
    integer :: x(N), y(N), z(N)
    !$omp target teams distribute parallel do map(to: x, y) map(from: z)
    do i = 1, N
      call mod_sub(x(i), y(i), z(i)) ! This call can be inlined
    end do
  end subroutine
end module m
```

```
use m
integer :: x(N), y(N), z(N)
x = 10
y = 20
call driver(x, y, z)
end
```

Good Programming Patterns for OpenMP (Part 2)

- Use good-coalescing access patterns:
  - Use static schedule with chunk size of 1 for `distribute` and `do` loops.
  - Mind the loop order (example in next slide)
- Tune grid and block size using the `num_teams` and `thread_limit` clauses.
- Team private/local variable are put into shared memory by the compiler.

Good Programming Patterns for OpenMP (Part 2)

```
int ar[2][3];
#pragma omp target teams thread_limit(4) num_teams(1)
                              // ar in memory:
{                             //                            [0,0] [0,1] [0,2] [1,0] [1,1] [1,2]
 #pragma omp parallel for     // i=0,1 distributed
 for (int i = 0; i < 2; ++i)  // among 4 threads
  for (int j = 0; j < 3; ++j) //
   ar[i][j] += x;             //                            t0    t0    t0    t1    t1    t1

 #pragma omp parallel for     // j=0,1,2 distributed
 for (int j = 0; j < 3; ++j)  // among 4 threads
  for (int i = 0; i < 2; ++i) //
   ar[i][j] += x;             //                            t0    t1    t2    t0    t1    t2

 #pragma omp parallel for \   // [i,j]=[0,0],[0,1],[0,2]
     collapse(2)              //       [1,0],[1,1],[1,2]
 for (int i = 0; i < 2; ++i)  // distributed among
  for (int j = 0; j < 3; ++j) // 4 threads
   ar[i][j] += x;             //                            t0    t1    t2    t3    t0    t1

 #pragma omp parallel for \   // [j,i]=[0,0],[0,1],[1,0],
     collapse(2)              //       [1,1],[2,0],[2,1]
 for (int j = 0; j < 3; ++j)  // distributed among          t0    t2    t0    t1    t4    t1
  for (int i = 0; i < 2; ++i) // 4 threads
   ar[i][j] += x;             //
```

Fortran Array-access

- Accessing assumed-size and deferred-shape arrays involves overhead.
  - In general, bounds are not known at compile-time.
  - Bounds and storage of a deferred-shape array can change at runtime.
- Compiler can generate better code for assumed-shape arrays in case they are known to be contiguous at compile-time.

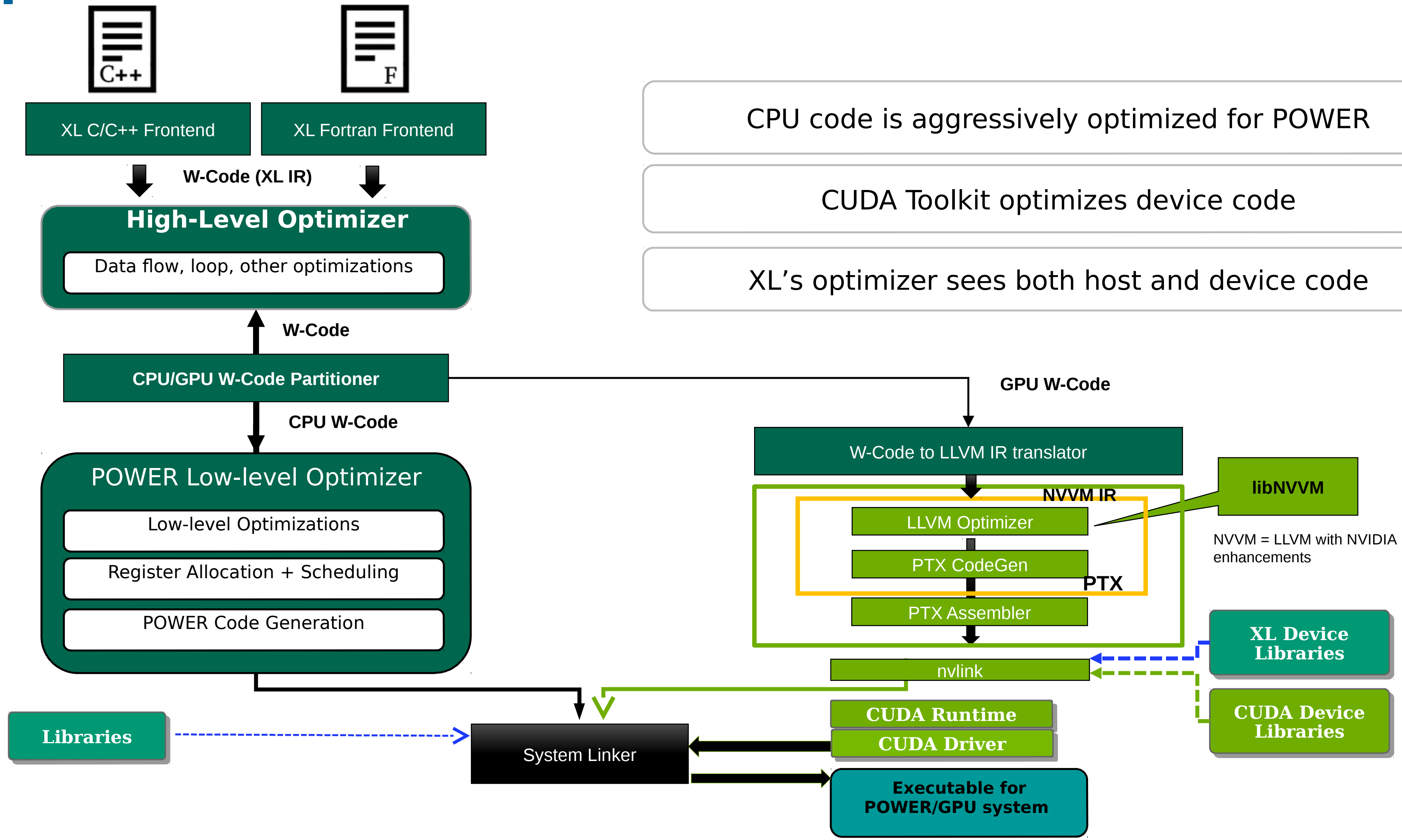
```
subroutine zaxpy_explicit_shape(start,end,len,x,y,z)
  integer(kind=8), intent(in) :: start,end,len
  real(kind=8),    intent(in)  :: x(len), y(len)
  real(kind=8),    intent(out) :: z(len)
  integer(kind=8) :: i

  !$omp target teams map(to: x, y) map(from: z)
  !$omp distribute parallel do
  do i = start, end
     z(i) = 24 * x(i) + y(i)
  end do
  !$omp end target teams

end subroutine zaxpy_explicit_shape
```

```
subroutine zaxpy_deferred_shape(start,end, x,y,z)
  integer(kind=8), intent(in) :: start,end
  real(kind=8), intent(in), contiguous :: x(:), y(:)
  real(kind=8), intent(out), contiguous :: z(:)
  integer(kind=8) :: i

  !$omp target teams map(to: x, y) map(from: z)
  !$omp distribute parallel do
  do i = start, end
     z(i) = 24 * x(i) + y(i)
  end do
  !$omp end target teams

end subroutine zaxpy_deferred_shape
```

Questions

Extra slides (not part of presentation)

Compiler architecture



CPU code is aggressively optimized for POWER

CUDA Toolkit optimizes device code

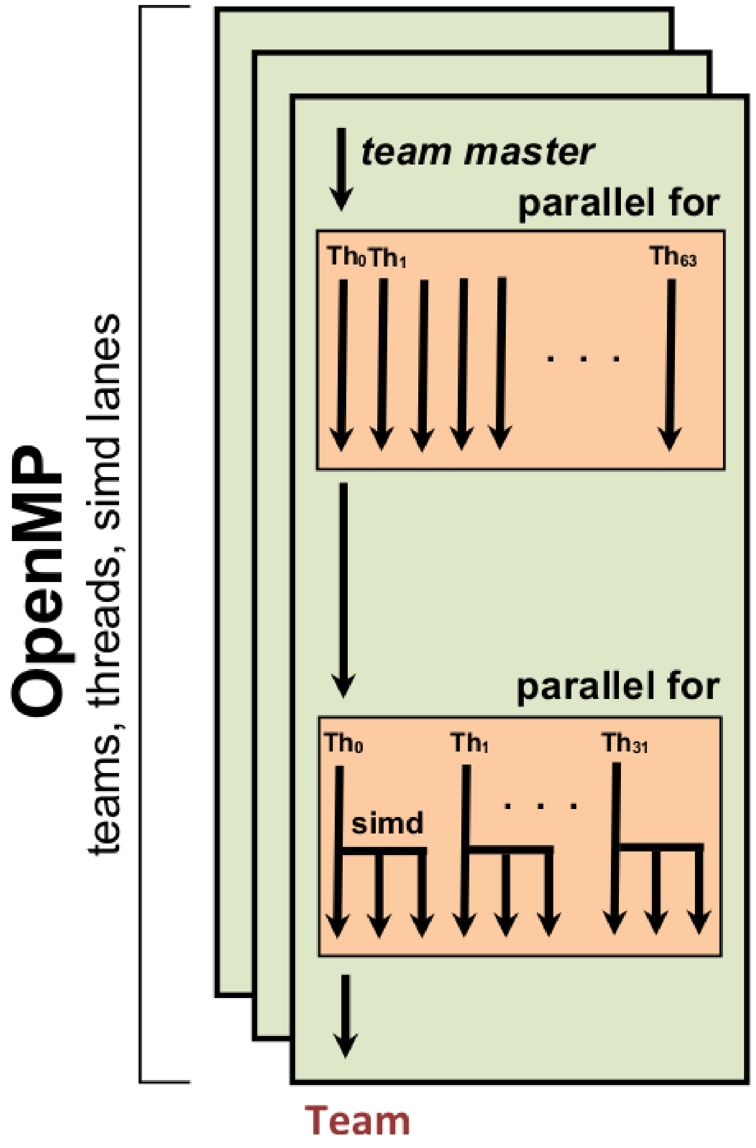
XL's optimizer sees both host and device code

OpenMP for everything

- Extracting maximum performance:
  - To program a GPU: you have to use CUDA, OpenCL, OpenGL, DirectX, Intrinsics, C++AMP, OpenACC.
  - To program a host SIMD unit: you have to use Intrinsics, OpenCL, or auto-vectorization (possibly aided by compiler hints)
  - To program the CPU threads, you might use pthreads, C/C++11, OpenMP, TBB, Cilk, Apple GCD, Google executors

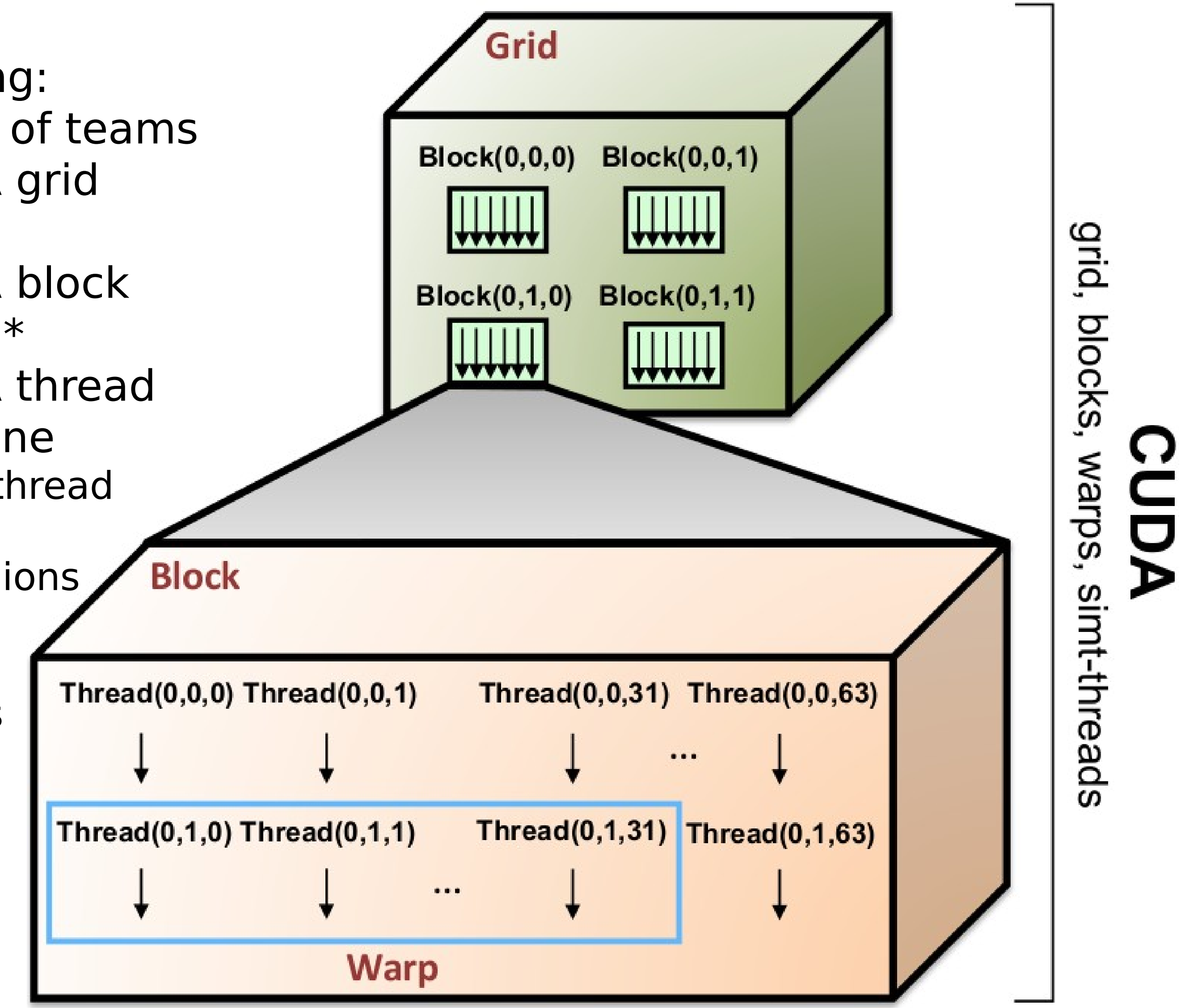
- With OpenMP 4.0:
  - You can use the same standard to program the **GPU**, the **SIMD** units, and the **CPU** threads.

OpenMP program mapping to CPU+GPU hardware



Generally speaking:
  OpenMP League of teams
    => CUDA grid
  OpenMP team
    => CUDA block
  OpenMP Thread *
    => CUDA thread
  OpenMP SIMD lane
    => CUDA thread

*Nested parallel regions do not spawn new threads; instead work sharing occurs among the CUDA threads in our OpenMP impl.

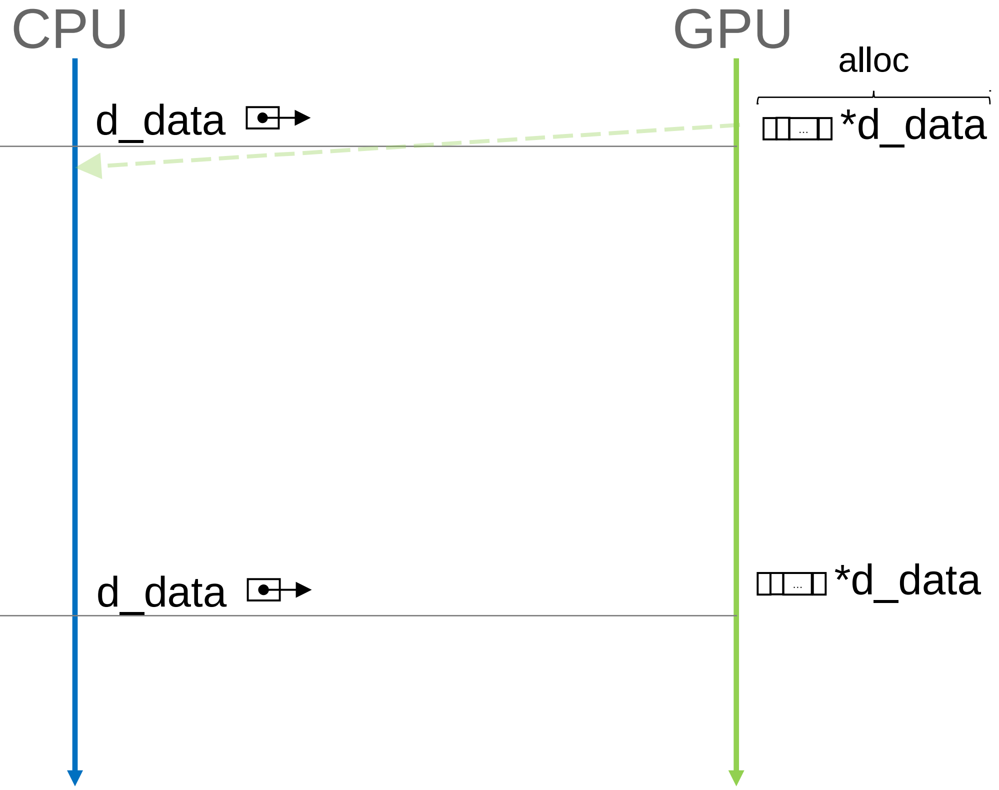


OpenMP and CUDA: is_device_ptr

- Use **is_device_ptr** to pass device allocated memory (e.g. from cudaMalloc) to an OpenMP target region
- Also useful for passing unified memory pointers to a target region

```
// cuda_alloc.cu
int * AllocAndInitialize(int init, int length) {
  int *d_data;
  cudaMalloc(&d_data, length * sizeof(*d_data));

  InitKernel<<<nBlk, nThd>>>(data, init, length); //Set all to init
  return d_data;
}

// omp_kernel.cc
void DoSomething() {
  const int length = 1024;
  int *devMemFromCuda = AllocAndInitialize(5, length);

  #pragma omp target is_device_ptr(devMemFromCuda)
   for (int i = 0; i < length; ++ i) {
     devMemFromCuda[i] = devMemFromCuda[i] * 2;
   }
}
```

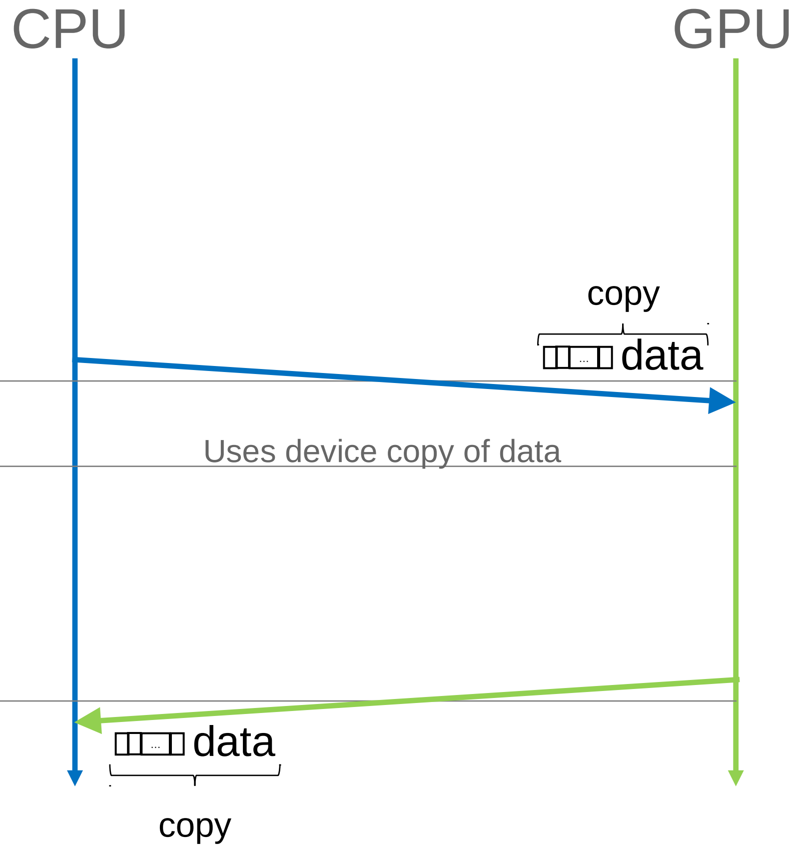
Example: Sharing device storage between OpenMP and CUDA with is_device_ptr



OpenMP and CUDA: use_device_ptr

- Use **use_device_ptr** to pass mapped device memory from OpenMP to another programming model (e.g. CUDA)

```
// cuda_launch_kernel.cu
void LaunchCUDAIncrement(int *data, int length) {
  …
  IncrementKernel<<<nBlk, nThd>>>(data, length);
}

// omp_map_and_call_cuda.cc
void DoSomething() {
  const int len = 1024;
  int data[len] = {0,};

  #pragma omp target data map(data[:len]) use_device_ptr(data[:len])
  {
    LaunchCudaIncrement(&data, len);

    #pragma omp map(data[:len])
    for (int i = 0; i < len; ++i) {
      data[i] = data[i] * 2;
    }
  }
}
```



Example: Sharing device storage between OpenMP and CUDA with is_device_ptr