Asynchronous GPU Programming in OpenMP

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Agenda

- Who are Michael and Christian?
- Review: OpenMP device and execution model
- Review: Offloading in OpenMP
- Optimizing data transfers and asynchronous offloading
- Hybrid OpenMP and HIP (or CUDA)
- Advanced Task Synchronization

Who are Michael and Christian?

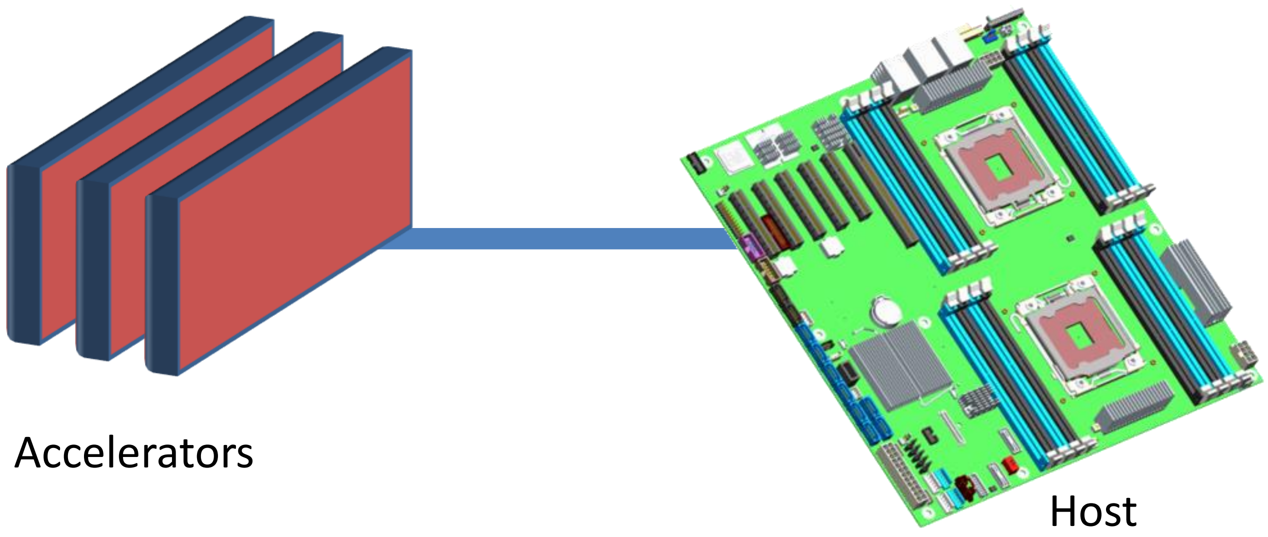
Michael and Christian

- Michael …
  - → Principal Member of Technical Staff at AMD
  - → Works in HPC since 2003
  - → Works on the Fortran OpenMP offload compiler for AMD Instinct™ Accelerators
  - → Is a member of the OpenMP language committee since 2009
  - → Chief Executive Officer of the OpenMP ARB since April 2016
- Christian …
  - → … is a senior scientist at RWTH Aachen University and leads the HPC group
  - → … does research on Parallel Programming and Performance
  - → … is a member of the OpenMP language committee since 2008 and co-chair of the Affinity subcom.
  - → is co-author of the book "Using OpenMP - The Next Step", published by MIT Press

Review: OpenMP device and execution model

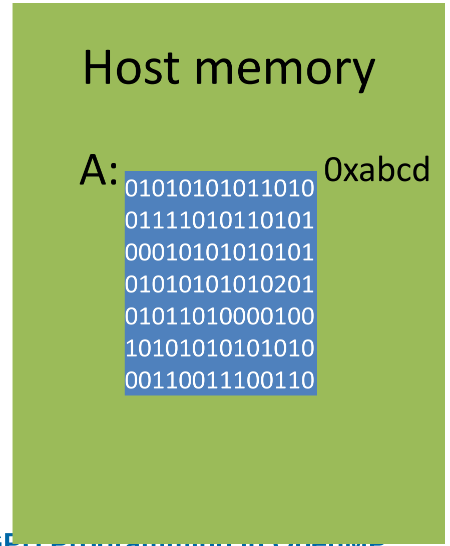
Device Model

- 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 / begin of target
  - → Data environment is automatically destroyed at the closing curly brace / end target
  - → Data transfers (if needed) are done at the curly braces / begin or end, 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
```

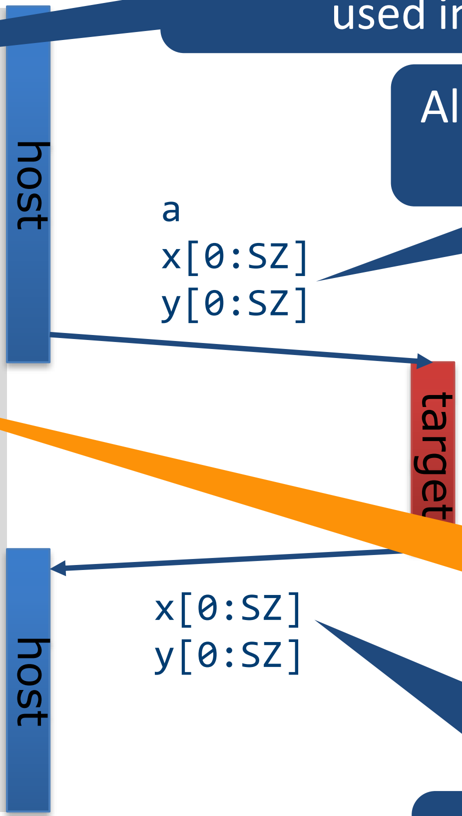
Review: Offloading in OpenMP

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



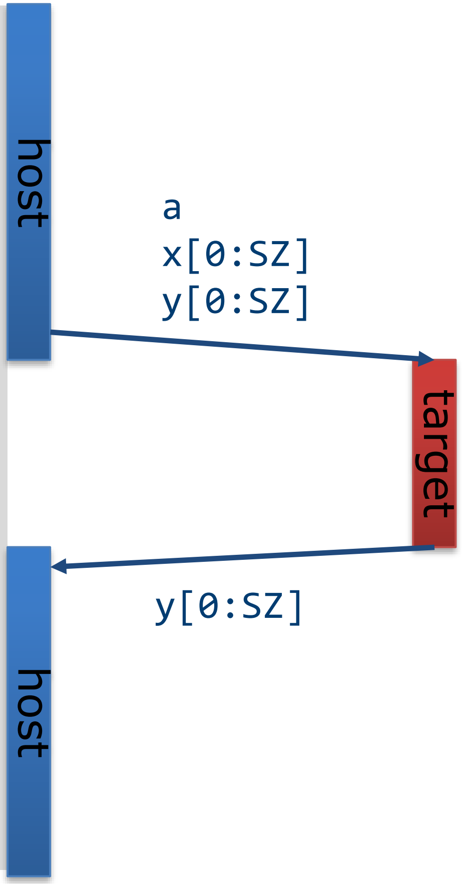
Presence check: only transfer if not yet allocated on the device.

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

```
clang -fopenmp --offload-arch=gfx90a ...
```

Example: saxpy

```
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);
}
```

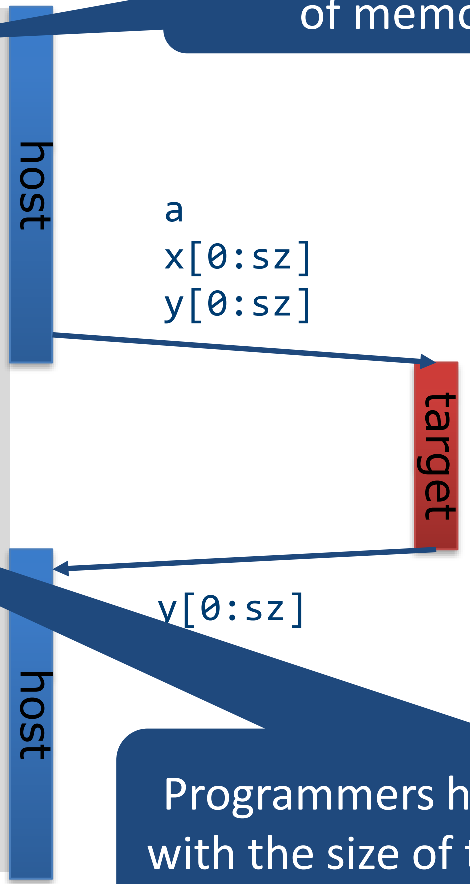



```
clang -fopenmp --offload-arch=gfx90a ...
```

Example: saxpy

```
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 --offload-arch=gfx90a
```

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

```
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 --offload-arch=gfx90a
```

Multi-level Parallel saxpy

- Manual code transformation
  - → Tile the loop into an outer loop and an inner loop.
  - → Assign the outer loop to “teams”.
  - → Assign the inner loop to the “threads”.
  - → (Assign the inner loop to SIMD units.)

```
void saxpy(float a, float* x, float* y, int sz) {
    #pragma omp target teams map(to:x[0:sz]) map(tofrom:y[0:sz]) num_teams(nteams)
    {
        int bs = n / omp_get_num_teams();   // n assumed to be multiple of #teams
        #pragma omp distribute
        for (int i = 0; i < sz; i += bs) {
            #pragma omp parallel for simd firstprivate(i,bs)
            for (int ii = i; ii < i + bs; ii++) {
                y[ii] = a * x[ii] + y[ii];
}   }   }   }
```

Multi-level Parallel saxpy

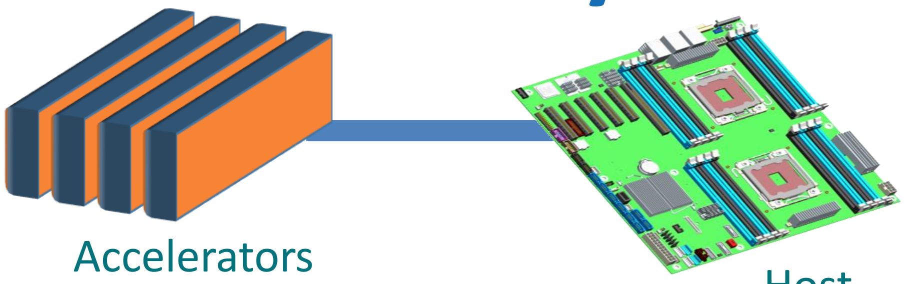
- For convenience, OpenMP defines composite constructs to implement the required code transformations

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

```
subroutine saxpy(a, x, y, n)
    ! Declarations omitted
!$omp omp target teams distribute parallel do simd &
!$omp&          num_teams(num_blocks) map(to:x) map(tofrom:y)
    do i=1,n
        y(i) = a * x(i) + y(i)
    end do
!$omp end target teams distribute parallel do simd
end subroutine
```

Optimizing data transfers and asynchronous offloading

Optimizing Data Transfers is Key to Performance



- Connections between host and accelerator are typically lower-bandwidth, higher-latency interconnects
  - → Bandwidth host memory: hundreds of GB/sec
  - → Bandwidth accelerator memory: TB/sec
  - → PCIe Gen 4 bandwidth (16x): tens of GB/sec

- Unnecessary data transfers must be avoided, by
  - → only transferring what is actually needed for the computation, and
  - → making the lifetime of the data on the target device as long as possible.

Optimize Data Transfers

- Reduce the amount of time spent transferring data:
  - → Use `map` clauses to enforce direction of data transfer.
  - → Use `target data`, `target enter data`, `target exit data` constructs to keep data environment on the target device.

```
void example() {
    float tmp[N], data_in[N], float data_out[N];
#pragma omp target data map(alloc:tmp[:N]) \
                        map(to:a[:N],b[:N]) \
                        map(tofrom:c[:N])
    {
        zeros(tmp, N);
        compute_kernel_1(tmp, a, N); // uses target
        saxpy(2.0f, tmp, b, N);
        compute_kernel_2(tmp, b, N); // uses target
        saxpy(2.0f, c, tmp, N);
}   }
```

```
void zeros(float* a, int n) {
#pragma omp target teams distribute parallel for
    for (int i = 0; i < n; i++)
        a[i] = 0.0f;
}
```

```
void saxpy(float a, float* y, float* x, int n) {
#pragma omp target teams distribute parallel for
    for (int i = 0; i < n; i++)
        y[i] = a * x[i] + y[i];
}
```

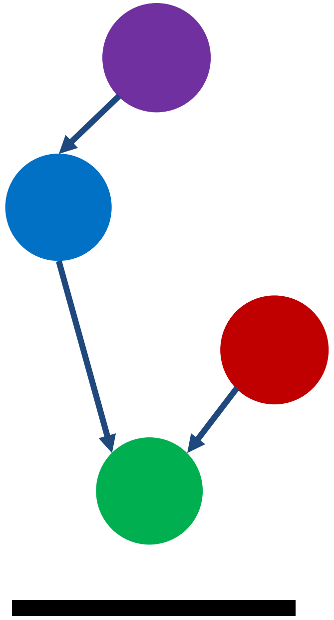
Example: target data and target update

```
#pragma omp target data device(0) map(alloc:tmp[:N]) map(to:input[:N)) map(from:res)
  {
#pragma omp target device(0)
#pragma omp parallel for
    for (i=0; i<N; i++)
      tmp[i] = some_computation(input[i], i);

    update_input_array_on_the_host(input);

#pragma omp target update device(0) to(input[:N])

#pragma omp target device(0)
#pragma omp parallel for reduction(+:res)
    for (i=0; i<N; i++)
      res += final_computation(input[i], tmp[i], i)
  }
```

Asynchronous Offloads

- OpenMP `target` constructs are synchronous by default
  - → The encountering host thread awaits the end of the `target` region before continuing
  - → The `nowait` clause makes the target constructs asynchronous (in OpenMP speak: they become an OpenMP task)

```
#pragma omp task                                                       depend(out:a)
    init_data(a);

#pragma omp target map(to:a[:N]) map(from:x[:N])  nowait      depend(in:a) depend(out:x)
    compute_1(a, x, N);

#pragma omp target map(to:b[:N]) map(from:z[:N])  nowait      depend(out:y)
    compute_3(b, z, N);

#pragma omp target map(to:y[:N]) map(to:z[:N])    nowait      depend(in:x) depend(in:y)
    compute_4(z, x, y, N);

#pragma omp taskwait
```



Hybrid OpenMP and HIP (or CUDA)

Hybrid Programming

- Hybrid programming here stands for the interaction of OpenMP with a lower-level programming model, e.g.
  - → OpenCL
  - → CUDA
  - → HIP

- OpenMP supports these interactions
  - → Calling low-level kernels from OpenMP application code
  - → Calling OpenMP kernels from low-level application code

Example: Calling saxpy

```
void example() {
    float a = 2.0;
    float * x;
    float * y;

    // allocate the device memory
    #pragma omp target data map(to:x[0:count]) map(tofrom:y[0:count])
    {
        compute_1(n, x);
        compute_2(n, y);
        saxpy(n, a, x, y)
        compute_3(n, y);
    }
}
```

```
void saxpy(size_t n, float a,
           float * x, float * y) {
#pragma omp target teams distribute \
                  parallel for simd
    for (size_t i = 0; i < n; ++i) {
        y[i] = a * x[i] + y[i];
    }
}
```

Let's assume that we want to implement the saxpy() function in a low-level language.

HIP Kernel for saxpy()

- Assume a HIP version of the SAXPY kernel:

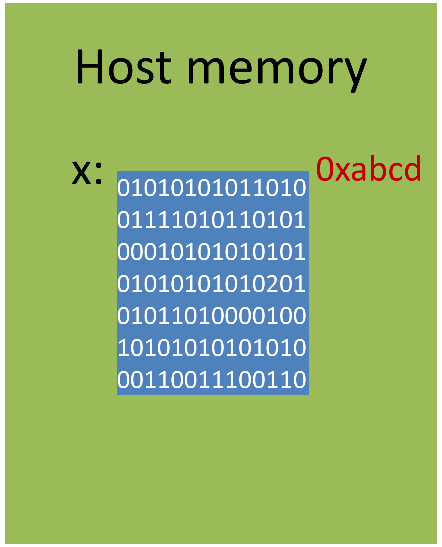
```
__global__ void saxpy_kernel(size_t n, float a, float * x, float * y) {
    size_t i = threadIdx.x + blockIdx.x * blockDim.x;
    y[i] = a * x[i] + y[i];
}

void saxpy_hip(size_t n, float a, float * x, float * y) {
    assert(n % 256 == 0);
    saxpy_kernel<<<n/256,256,0,NULL>>>(n, a, x, y);
}
```

These are device pointers!

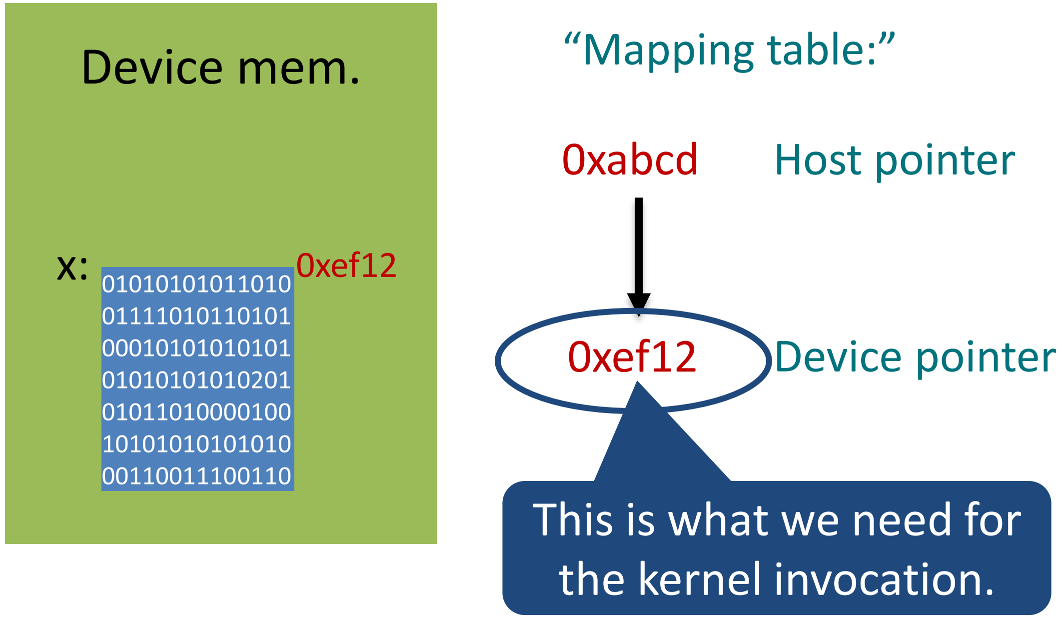
- We need a way to translate the host pointer that was mapped by OpenMP directives and retrieve the associated device pointer.

Pointer Translation /1

- When creating the device data environment, OpenMP creates a mapping between
  - → the (virtual) memory pointer on the host and
  - → the (virtual) memory pointer on the target device.
- This mapping is established through the data-mapping directives and their clauses.




```
#pragma omp target data \
        map(to:x[0:n])
    ...
!$omp end target data
```



Pointer Translation /2

- The target data construct defines the `use_device_addr` clause to perform pointer translation.
  - → The OpenMP implementation searches for the host pointer in its internal mapping tables.
  - → The associated device pointer is then returned.

```
type * x = 0xabcd;
#pragma omp target data use_device_addr(x[:0])
{
    example_func(x);   // x == 0xef12
}
```

- Note: the pointer variable shadowed within the `target data` construct for the translation.

Putting it Together…

```
void example() {
    float a = 2.0;
    float * x = ...;   // assume: x = 0xabcd
    float * y = ...;

    // allocate the device memory
    #pragma omp target data map(to:x[0:count]) map(tofrom:y[0:count])
    {
        compute_1(n, x);  // mapping table: x:[0xabcd,0xef12], x = 0xabcd
        compute_2(n, y);
        #pragma omp target data use_device_addr(x[:0],y[:0])
        {
            saxpy_hip(n, a, x, y) // mapping table: x:[0xabcd,0xef12], x = 0xef12
        }
        compute_3(n, y);
    }
}
```

Advanced Task Synchronization

Asynchronous API Interaction

- Some APIs are based on asynchronous operations
  - → MPI asynchronous send and receive
  - → Asynchronous I/O
  - → HIP, CUDA and OpenCL stream-based offloading
  - → In general: any other API/model that executes asynchronously with OpenMP (tasks)
- Example: HIP memory transfers

```
do_something();
hipMemcpyAsync(dst, src, nbytes, hipMemcpyDeviceToHost, stream);
do_something_else();
hipStreamSynchronize(stream);
do_other_important_stuff(dst);
```

- Programmers need a mechanism to marry asynchronous APIs with the parallel task model of OpenMP
  - → How to synchronize completions events with task execution?

Try 1: Use just OpenMP Tasks

```
void hip_example() {
#pragma omp task      // task A
    {
        do_something();
        hipMemcpyAsync(dst, src, nbytes, hipMemcpyDeviceToHost, stream);
    }
    #pragma omp task // task B
    {
        do_something_else();
    }
    #pragma omp task // task C
    {
        hipStreamSynchronize(stream);
        do_other_important_stuff(dst);
    }
}
```

Race condition between the tasks A & C,
task C may start execution before
task A enqueues memory transfer.

- This solution does not work!

Try 2: Use just OpenMP Tasks Dependences

```
void hip_example() {
#pragma omp task depend(out:stream)    // task A
    {
        do_something();
        hipMemcpyAsync(dst, src, nbytes, hipMemcpyDeviceToHost, stream);
    }
    #pragma omp task                    // task B
    {
        do_something_else();
    }
    #pragma omp task depend(in:stream) // task C
    {
        hipStreamSynchronize(stream);
        do_other_important_stuff(dst);
    }
}
```

Synchronize execution of tasks through dependence. May work, but task C will be blocked waiting for the data transfer to finish

- This solution may work, but
  - → takes a thread away from execution while the system is handling the data transfer.
  - → may be problematic if called interface is not thread-safe

Detachable

- OpenMP 5.0 introduces the concept of a detachable task
  - → Task can detach from executing thread without being "completed"
  - → Regular task synchronization mechanisms can be applied to await completion of a detached task
  - → Runtime API to complete a task

- Detached task events: `omp_event_handle_t` datatype
- Detached task clause: `detach(event)`
- Runtime API:

```
void omp_fulfill_event(omp_event_handle_t *event)
```

Detaching Tasks

```
omp_event_handle_t  *event;
void detach_example() {
#pragma omp task detach(event)
    {
        important_code();
    } ①

    #pragma omp taskwait ② ④
}
```

Some other thread/task:

```
omp_fulfill_event(event); ③
```

1. Task detaches
2. `taskwait` construct cannot complete
3. Signal event for completion
4. Task completes and `taskwait` can continue

Putting It All Together

```
void callback(hipStream_t stream, hipError_t status, void *cb_dat) {
  ③ omp_fulfill_event(* (omp_event_handle_t *) cb_data);
}
void hip_example() {
    omp_event_handle_t hip_event;
#pragma omp task detach(hip_event) // task A
    {
        do_something();
        hipMemcpyAsync(dst, src, nbytes, hipMemcpyDeviceToHost, stream);
        hipStreamAddCallback(stream, callback, &hip_event, 0);
  ① }
#pragma omp task                      // task B
        do_something_else();

#pragma omp taskwait ② ④
#pragma omp task                      // task C
    {
        do_other_important_stuff(dst);
}   }
```

1. Task A detaches
2. `taskwait` does not continue
3. When memory transfer completes, callback is invoked to signal the event for task completion
4. `taskwait` continues, task C executes

Removing the taskwait Construct

```
void callback(hipStream_t stream, hipError_t status, void *cb_dat) {
  ② omp_fulfill_event(* (omp_event_handle_t *) cb_data);
}
void hip_example() {
    omp_event_handle_t hip_event;
#pragma omp task depend(out:dst) detach(hip_event) // task A
    {
        do_something();
        hipMemcpyAsync(dst, src, nbytes, hipMemcpyDeviceToHost, stream);
  ①     hipStreamAddCallback(stream, callback, &hip_event, 0);
    }
#pragma omp task                        // task B
        do_something_else();

#pragma omp task depend(in:dst)      ③  // task C
    {
        do_other_important_stuff(dst);
}   }
```

1. Task A detaches and task C will not execute because of its unfulfilled dependency on A
2. When memory transfer completes, callback is invoked to signal the event for task completion
3. Task A completes and C's dependency is fulfilled

Performance Optimisation and Productivity 3

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