Intro to GPU Programming with the OpenMP API

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OpenMP Architecture Review Board

The mission of the OpenMP ARB (Architecture Review Board) is to standardize directive-based multi-language high-level parallelism that is performant, productive and portable.

The OpenMP API moves common approaches into an industry standard to simplify a developers' life.

OpenMP

Agenda

- OpenMP device and execution model
- Offload basics
- Exploit parallelism
- Asynchronous offloading
- Summary

OpenMP

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 ☺)

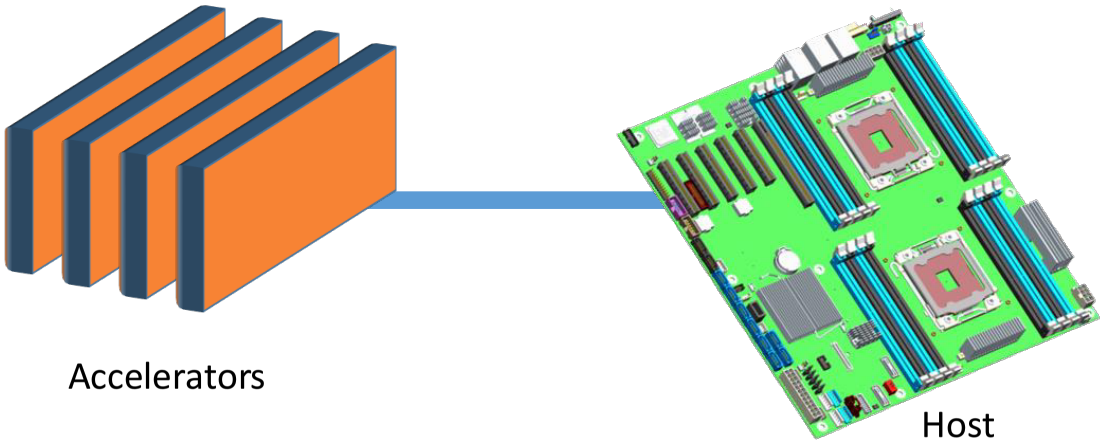
This is the code we want to execute on a target device (i.e., GPU)

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!

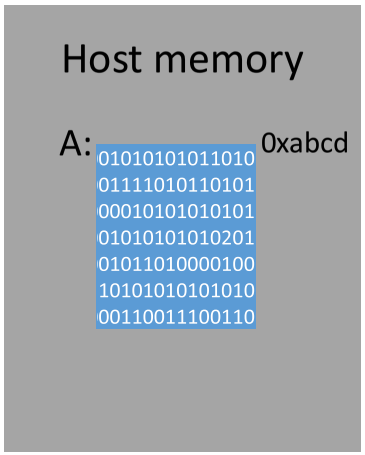
Device Model

- 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)

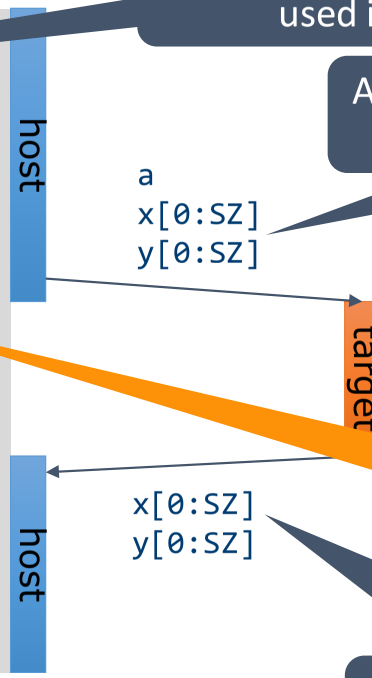
```
!$omp target [clause[[,] clause],…]
structured-block
!$omp end target
```

- 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

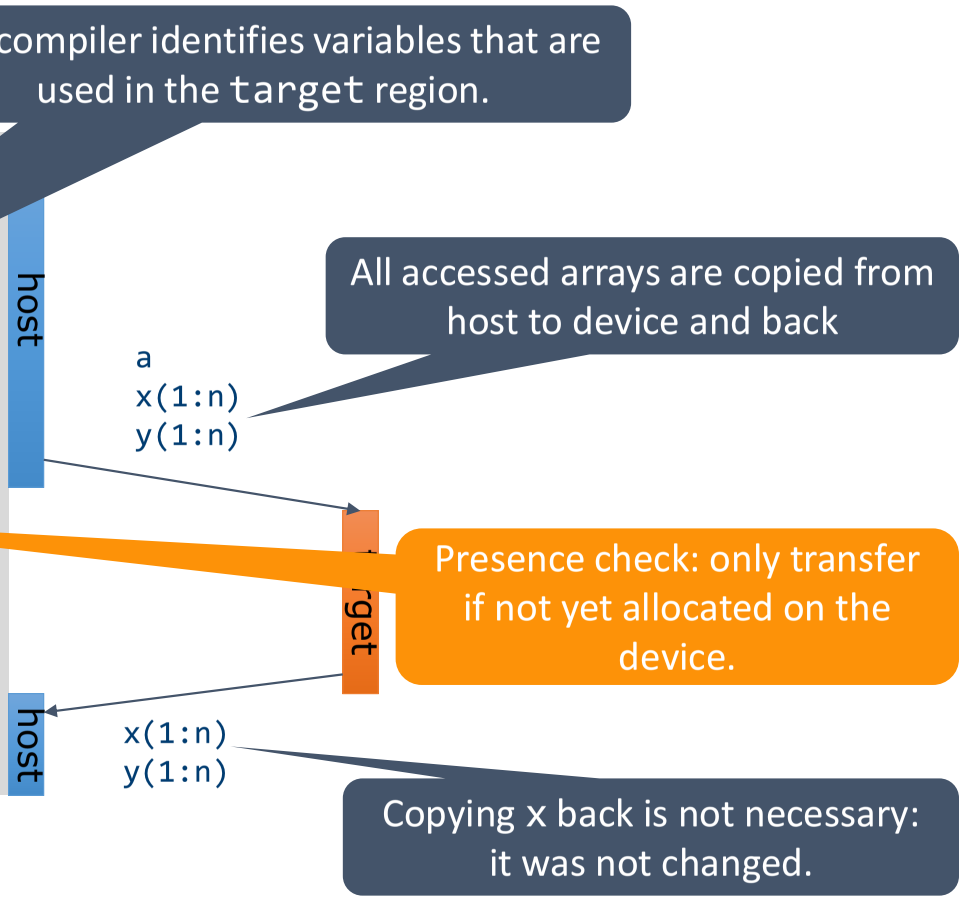
Presence check: only transfer if not yet allocated on the device.

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

clang/LLVM:	`clang -fopenmp -fopenmp-targets=<target triple>`
GNU:	`gcc -fopenmp`
AMD ROCm:	`clang -fopenmp -offload-arch=gfx908`
NVIDIA:	`nvcc –mp=gpu -gpu=cc80`
Intel:	`icx -fiopenmp -fopenmp-targets=spir64`
IBM XL:	`xlc –qsmp –qoffload –qtgtarch=sm_70`

Example: saxpy

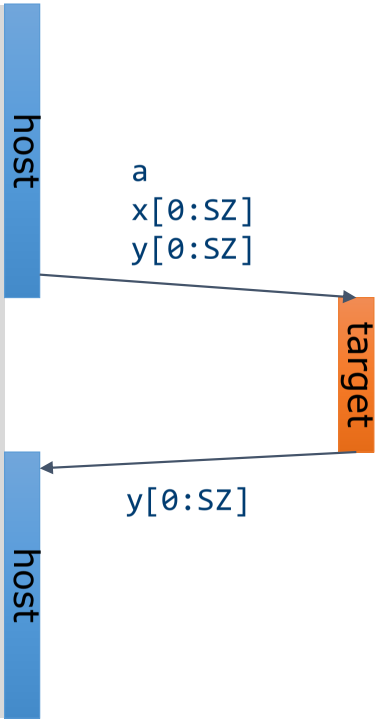
```
subroutine saxpy(a, x, y, n)
    use iso_fortran_env
    integer :: n, i
    real(kind=real32) :: a
    real(kind=real32), dimension(n) :: x
    real(kind=real32), dimension(n) :: y

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



clang/LLVM:	`flang -fopenmp –fopenmp-targets=<target triple>`
GNU:	`gfortran -fopenmp`
AMD ROCm:	`flang -fopenmp –offload-arch=gfx908`
NVIDIA:	`nvfortran –mp=gpu -gpu=cc80`
Intel:	`ifx –fiopenmp -fopenmp-targets=spir64`
IBM XL:	`xlf –qsmp –qoffload –qtgtarch=sm_70`

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);
}
```



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.

Observation when running this: the loop is a sequential loop, and the capabilities of the GPU are not really used! ☹

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

OpenMP

Commercial Break… Community Interaction

Check out openmp.org/news/events-calendar/

OpenMP

Exploiting (Multilevel) Parallelism

OpenMP

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];
    }
}
```

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

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

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
```

`teams` Construct

- Support multi-level parallel devices
- Syntax (C/C++):

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

- Syntax (Fortran):

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

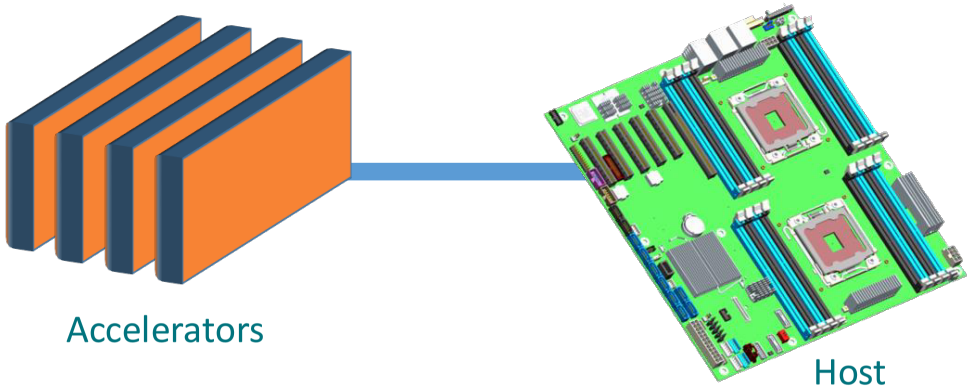
- Clauses

```
num_teams(integer-expression), thread_limit(integer-expression)
default(shared | firstprivate | private none)
private(list), firstprivate(list), shared(list), reduction(operator:list)
```

OpenMP

Optimizing Data Transfers

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.

Role of the Presence Check

- If `map` clauses are not added to `target` constructs, presence checks determine if data is already available in the device data environment:

```
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

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

- OpenMP maintains a mapping table that records what memory pointers have been mapped.
- That table also maintains the translation between host memory and device memory.
- Constructs with no `map` clause for a data item then determine if data has been mapped and if not, a `map(tofrom:…)` is added for that data item.

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.

```
subroutine caller
    ! Declarations omitted

!$omp target data map(to:x) &
                  map(tofrom:y)
    call saxpy(a, x, y, n)
!$omp end target
end subroutine
```

```
subroutine saxpy(a, x, y, n)
    ! Declarations omitted

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

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)
  }
```

`target data` Construct Syntax

- Create scoped data environment and transfer data from the host to the device and back
- Syntax (C/C++)

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

- Syntax (Fortran)

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

- Clauses

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

`target update` Construct Syntax

- Issue data transfers to or from existing data device environment
- Syntax (C/C++)

```
#pragma omp target update [clause[[,] clause],…]
```

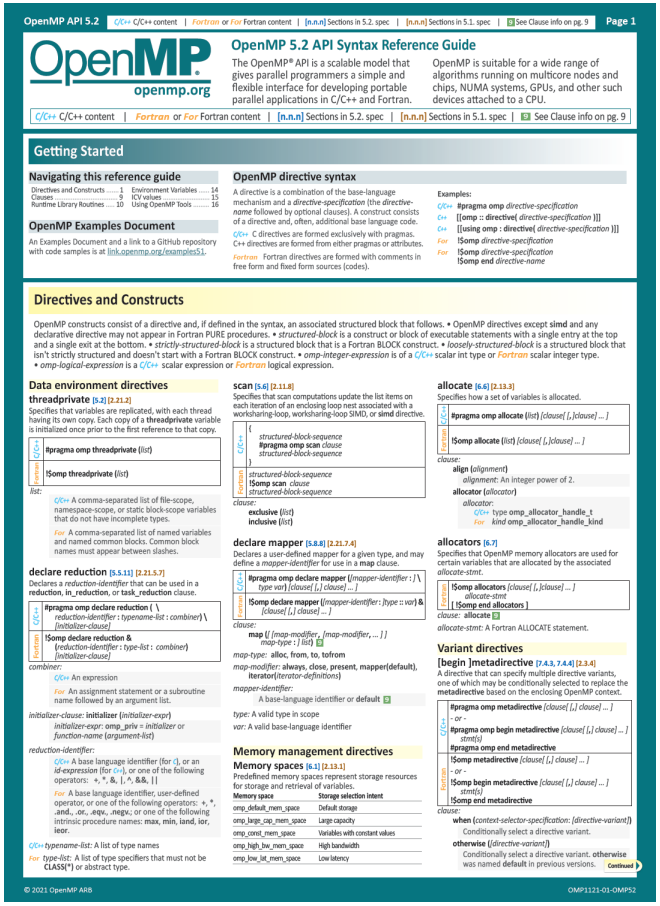
- Syntax (Fortran)

```
!$omp target update [clause[[,] clause],…]
```

- Clauses

```
device(scalar-integer-expression)
to(list)
from(list)
if(scalar-expr)
```

Commerical Break…



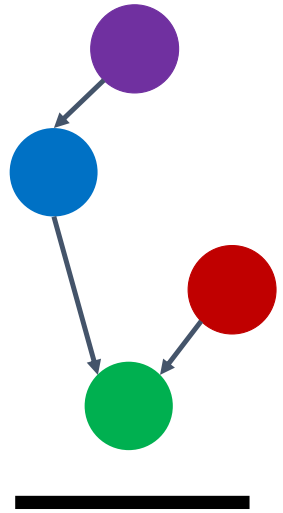
OpenMP

Asynchronous Offloading

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
```



Summary

- OpenMP API is ready to use GPUs for offloading computations
  - Mature offload model w/ support for asynchronous offload/transfer
  - Tightly integrates with OpenMP multi-threading on the host

- More, advanced features (not covered here)
  - Memory management API
  - Interoperability with native data management
  - Interoperability with native streaming interfaces
  - Unified shared memory support

Visit www.openmp.org for more information