# CRAY COMPILER AND OPENMP OFFLOADING

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Frontier Application Readiness
Kick-Off Workshop

October 9, 2019

CRAY®

a Hewlett Packard Enterprise company

## Outline

- Cray Compiling Environment (CCE) introduction
- CCE OpenMP overview
- CCE OpenMP offloading best practices
- Future CCE OpenMP roadmap

# Cray Compilation Environment (CCE)

- Fortran compiler
  - Proprietary front end and optimizer; Cray-modified LLVM
  - Fortran 2018 support, excluding coarray teams
- Two C and C++ compiler options
  - Default option: Cray-modified Clang+LLVM complier
  - “Classic” option: EDG front end; proprietary optimizer; Cray-modified LLVM
  - C11 and C++17 support
  - gcc 8.1 compatibility
  - UPC support
- OpenMP 4.5 support, including offloading for NVIDIA GPUs

## CCE Motivation

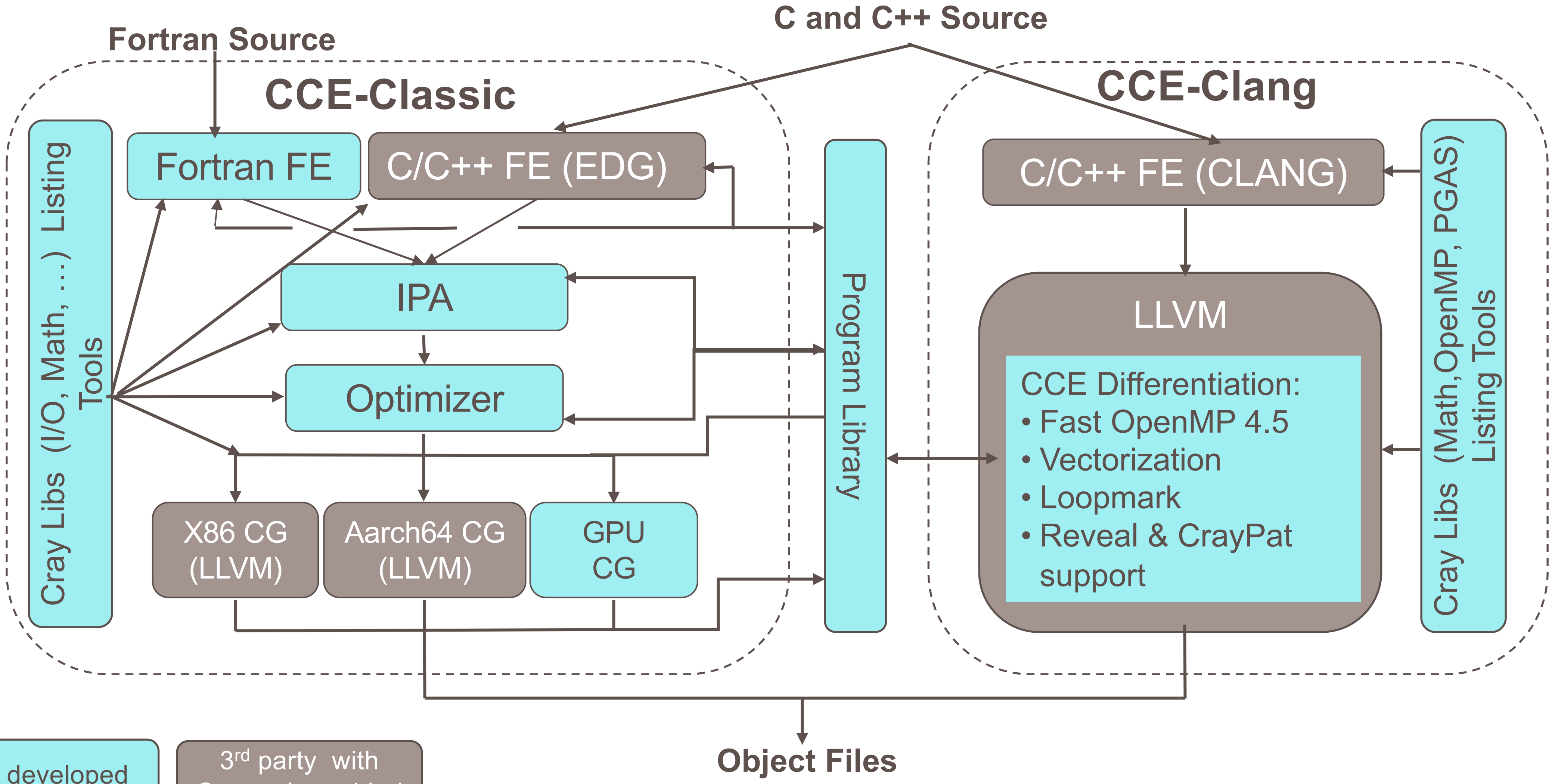
- Why does Cray develop a compiler at all?
  - Performance
  - Customer support
- Why build on Clang/LLVM?
  - Clang leads C & C++ compilers in standards support and diagnostics
  - Clang’s compile time is much faster than Cray’s existing compiler
  - Cray can contribute non-differentiating work upstream
  - Cray can keep some differentiating work proprietary

*A solid base compiler infrastructure frees up Cray compiler developers to focus more narrowly on HPC and customer-driven features and optimizations*

## CCE Clang Differentiation

- Loopmark
- Decompile
- CrayPat support
- Cray OpenMP runtime (CPU and GPU)
- Cray libm (optimized versions of select math functions)
- UPC
- *Reveal support (in development)*
- *Enhanced FP trap support (in development)*

# CCE 9.0



CCE Differentiation:
- Fast OpenMP 4.5
- Vectorization
- Loopmark
- Reveal & CrayPat support

## CCE Release and Versioning

- Moving to two major releases a year (~Q2 and ~Q4)
  - CCE codebase and version based off latest Clang major release
  - Monthly minor updates will continue for ~5 months after each major release
- CCE 9.0 – June 2019
  - Based on development Clang 9.0
- CCE 9.1 – Nov 2019
  - Based on released Clang 9.0
- CCE 10.0 – May 2020 (tentative)
  - Based on released Clang 10.0

## Invoking CCE

- Different CCE modules for Clang or Classic C/C++
  - `module load PrgEnv-cray`
  - `module avail cce`
  - `module swap cce/9.0.2`
  - `module swap cce/9.0.2-classic`
- Fortran compiler is the same for both modules
- Invoke compiler through CrayPE driver

```
cc  <CFLAGS>   source.c
CC  <CXXFLAGS> source.cpp
ftn <FFLAGS>   source.f90
```

# Common CCE Compiler Flags

| CCE Classic 9.0 | CCE 9.0 | Purpose |
|---|---|---|
| -O0 | -O0 *(default)* | No optimization |
| -O1 | -O1 -ffast-math | Light optimization |
| -O2 *(default)* | -O2 -ffast-math | Moderate optimization |
| -O3 | -O3 -ffast-math<br>-Ofast *(recommended starting point)* | Heavy optimization |
| -hpic, -hPIC | -fpic, -fPIC | Generate position-independent code |
| -hlist=m | -fsave-loopmark | Emit Loopmark (.lst) |
| -hlist=d | -fsave-decompile | Emit Decompile (.dc and .ll) |

- CCE Clang is a drop-in replacement for upstream Clang
  - Cray adds options for new features but keeps existing options
  - Special –*fno-cray* option disables Cray changes
- CCE Clang is NOT a drop-in replacement for CCE Classic – options differ

# CCE OPENMP OVERVIEW

# CCE OpenMP Flags

| General OpenMP | CCE 8.7 | CCE 9.0 Fortran and Classic | CCE 9.0 Clang C/C++ |
|---|---|---|---|
| Enable OpenMP | **-homp (default)** | -homp<br>-fopenmp (alias) | -fopenmp<br>-fopenmp=libcraymp (Cray runtime)<br>-fopenmp=libomp (Clang runtime) |
| Disable OpenMP | -hnoomp | **-hnoomp (default)**<br>-fno-openmp (alias) | **-fno-openmp (default)** |

| OpenMP Offloading | All CCE Compilers (accel modules) | CCE 9.0 Clang C/C++ (optional flags) |
|---|---|---|
| Native Host CPU | craype-accel-host | (default without flags; no warning) |
| NVIDIA Pascal | craype-accel-nvidia60 | -fopenmp-targets=nvptx64 -Xopenmp-target -march=sm_60 |
| NVIDIA Volta | craype-accel-nvidia70 | -fopenmp-targets=nvptx64 -Xopenmp-target -march=sm_70 |
| AMD Vega20* | craype-accel-amd-gfx906 | -fopenmp-targets=amdgcn-amd-amdhsa<br>-Xopenmp-target=amdgcn-amd-amdhsa -march=gfx906 |

**AMD GPU support under development*

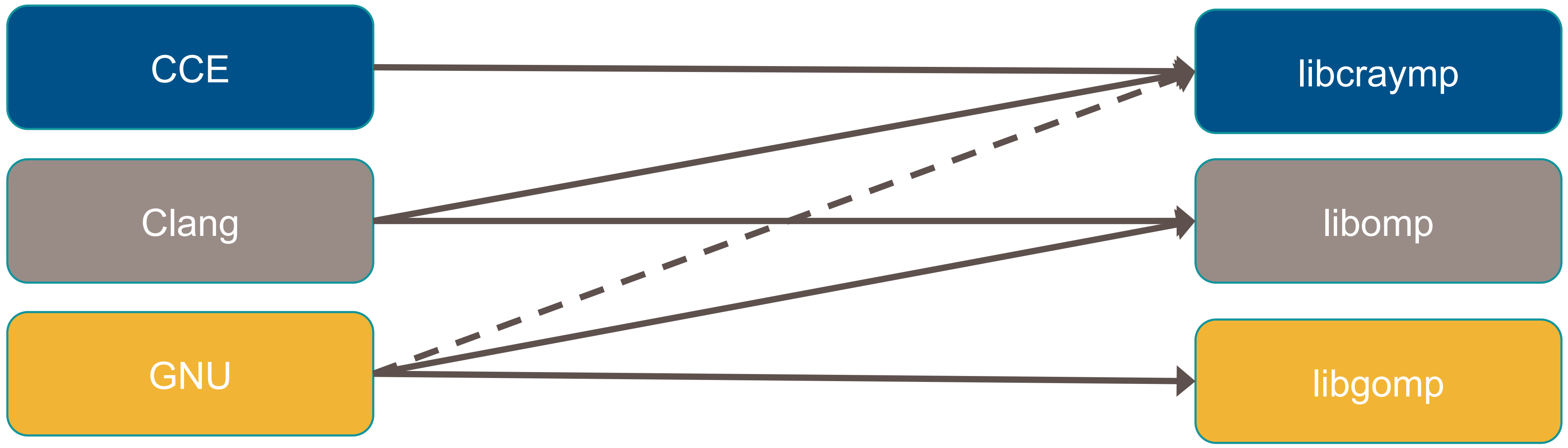
## CCE 9.0 Clang C/C++ OpenMP Plan

- Fully support OpenMP 4.5 (CPU and GPU)
  - NVIDIA support today, AMD GPU support under development
- Use CCE OpenMP runtime libraries
  - Offers interoperability with CCE Fortran (and Classic C/C++)
  - Provides a lightweight, HPC-optimized runtime
  - Requires a thin “adapter” layer in Cray’s runtime
- Implement Cray-optimized Clang code generation for accelerator regions
  - Mimics the CCE Classic implementation
  - Leverages compiler analysis/translation with ultra-lightweight device runtime
  - Offers significant performance advantage over upstream Clang

# CCE OpenMP Limitations on GPU

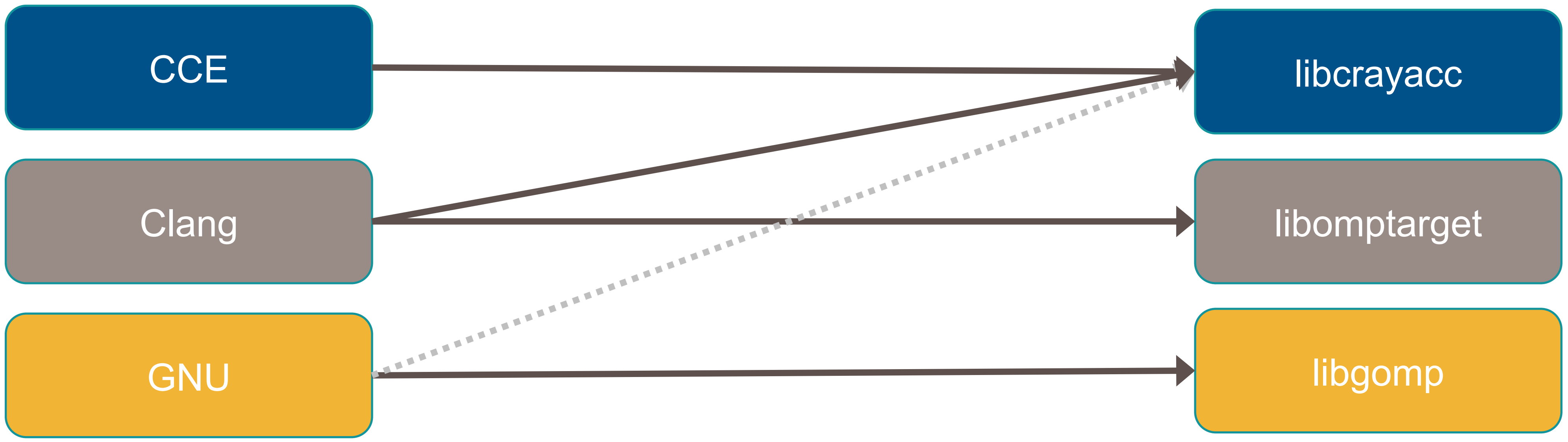
- CCE currently handles these core constructs
  - `target, teams, distribute, parallel, do/for, barrier, simd`
- Support for other constructs is under development
  - E.g., `master, single, critical`
- Some constructs may be implemented to be “functionally compliant”
  - E.g., `task, taskloop, cancel, doacross`
- Our implementation is driven by user feedback
- *More feedback is always appreciated*

# CCE OpenMP CPU Interoperability



*The libcraymp GNU interface is currently limited to OpenMP 3.1 constructs*

# CCE OpenMP GPU Interoperability



*Accesses to global variables and calls to functions cannot cross a "compiler boundary"*

*Additional pre-link steps may need to be added to the application build process if not linked by CCE.*

*The libcrayacc GNU offloading interface is not yet supported*

## CCE OPENMP OFFLOADING BEST PRACTICES

# OpenMP Offloading Strategy

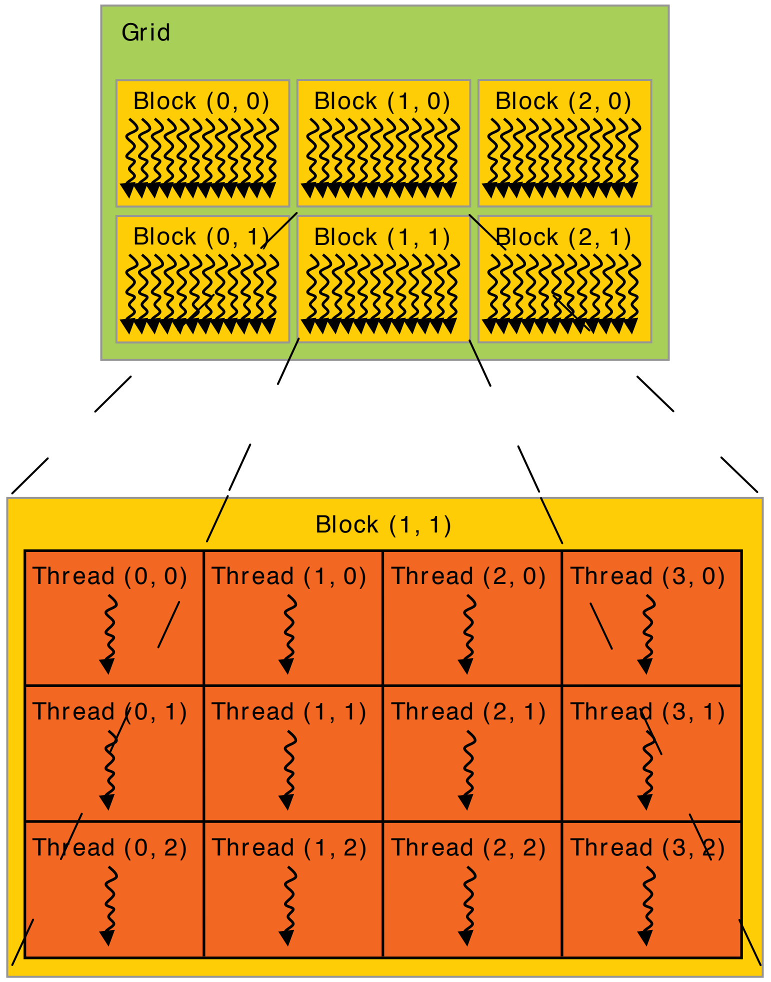
1. Offload time-intensive parallel loops
   - Focus on functional correctness
   - Rely on “point-of-use” data transfers
2. Optimize kernel computation
   - Temporarily ignore data transfer overheads
3. Optimize data transfers
   - Add enclosing data regions and updates where necessary
   - Communicate directly to/from GPU memory
4. Use device asynchronously
   - Fill device “queue” with a “stream” of dependent work
   - Execute multiple kernels in parallel

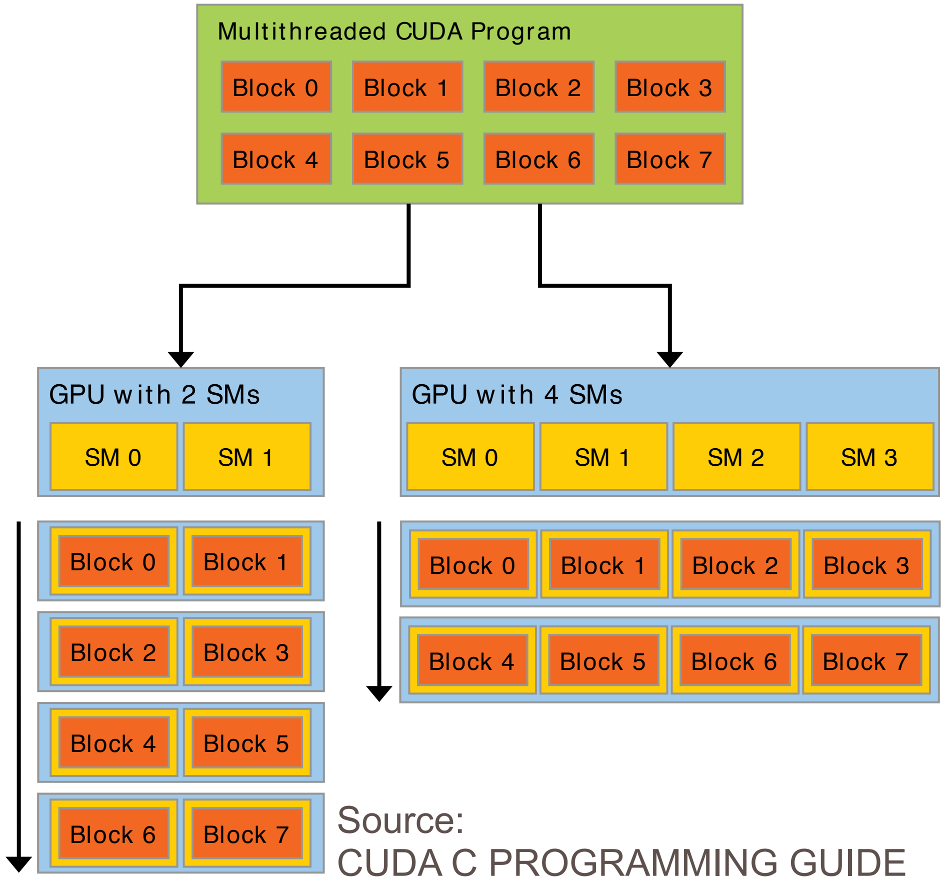
## Step 1: Offload Code to GPU with `omp target`

- “omp target” offloads region of code to an accelerator
  - Does not express any parallelism
- “Map” clauses move data to/from accelerator memory
  - Scalars are made “firstprivate” at default
  - Non-scalars are mapped “tofrom” at default
- “declare target” makes functions and global variables available on accelerator
- “`nowait`” and “depend” clauses express asynchronous operations

```
!$omp target
  ... ! This code runs serially on the GPU
!$omp end target
```

# Step 2: Express Parallelism on GPU





Source:
CUDA C PROGRAMMING GUIDE
PG-02829-001_v9.1 | March 2018

## GPU Terminology (Secret Decoder Ring)

| NVIDIA | AMD | Description |
|---|---|---|
| Threadblock / CTA | Work group | • Loosely-coupled, course-grained parallelism<br>• ***Collective synchronization prohibited***<br>• Performs best with massive parallelism<br>• Performance scales with more powerful GPUs |
| Warp | Wavefront | • Fine-grained, independent parallelism<br>• NVIDIA warp/wavefront size is 32 threads<br>• AMD warp/wavefront size is 64 threads |
| Thread | Work item | • Fine-grained, lock-step parallelism<br>• Performs best with stride-1 data accesses<br>• Performs best with non-divergent control flow |

## `omp teams`

- Specifies fork/join parallelism, like “`omp parallel`”
  - API calls support querying “team num” and “num teams”
- Collective synchronization prohibited (i.e., no barriers)
  - Allows mapping directly to GPU threadblocks
- Must appear directly within “`omp target`”

```
!$omp target
!$omp teams
  ... ! This code runs on the GPU using multiple “teams”
!$omp end teams
!$omp end target
```

## omp distribute

- Loop partitioning construct, like “omp do/for”
  - Iterations are partitioned across “teams”
- **There is no implied barrier at end of loop**
- Best practice: combine as “target teams distribute”

```
!$omp target teams
!$omp distribute
do i=1,n
  ... ! Iterations are partitioned across “teams”
end do
!$omp end target teams
```

# OpenMP Construct Mapping to GPU

| Construct | CCE Classic | CCE 9.0 Clang | Upstream Clang |
|---|---|---|---|
| `omp teams` | • Threadblocks<br>• Threadblocks+threads | • Threadblocks<br>• Threadblocks+threads | • Threadblocks |
| `omp parallel` | • Unused (aggressive autothreading on GPU) | • Threads (with limitations) | • Threads |
| `omp simd` | • Threads | • Threads | • Unused |

- `teams` is required to map to GPU threadblocks, for all implementations
- `parallel` and `simd` are inconsistent across implementations
  - CCE `parallel` limitations: called functions are visible; only contains `barrier`, `for` with `static` schedule, and `omp_get_thread_num` / `omp_get_num_threads` queries
  - Current Best practice: specify the composite `parallel do/for simd`
- **Long term CCE goal: let users express parallelism with any construct they think makes sense, and CCE will map to available hardware parallelism**

## omp parallel for simd

- Best practice: combine with "teams" to express two-level GPU parallelism
  - "teams" maps to GPU threadblocks
  - CCE-Classic maps "simd" to GPU threads (skips "parallel for")
  - Clang maps "parallel for" to GPU threads (skips "simd")

```
!$omp target teams distribute
parallel for simd
do i=1,n
 ... ! 2-level parallelism
end do
!$omp end target teams
```

```
!$omp target teams distribute
do i=1,n
 !$omp parallel for simd
 do j=1,n
  ... ! 2-level parallelism
 end do
end do
```

# Debugging Construct Mapping

```
   16.          #pragma omp target teams distribute
   17.    gG--<     for (int i = 0 ; i < 1000 ; i++) {
   18.    gG          a[i] = b[i] + c[i];
   19.    gG-->     }
   20.            }
```

```
$ cc -hmsgs -hlist=m -homp test.c
```

```
CC-6405 craycc: ACCEL File = test.c, Line = 17
  A region starting at line 17 and ending at line 19 was placed on the accelerator.
CC-6430 craycc: ACCEL File = test.c, Line = 17
  A loop was partitioned across the threadblocks and the 128 threads within a
threadblock.
```

**CCE-Classic only; CCE-Clang is under development*

# Step 3: Add Data Regions

```
#pragma omp target data map(from:a) map(alloc:b,c)
{
  #pragma omp target teams distribute
  for (int i = 0 ; i < 1000 ; i++) {
     b[i] = c[i] = 1.0;

  #pragma omp target teams distribute
  for (int i = 0 ; i < 1000 ; i++)
     a[i] = b[i] + c[i];
}
```

## Debugging Data Directives

- CRAY_ACC_DEBUG
  - Recommended values: 1 or 2
  - Emits messages for all offloading operations (e.g., allocate, transfer, launch)
  - File/line/var info for CCE-Clang coming in CCE 9.1.0
- Debug code with ”host” accelerator target
  - All maps/updates become noops

# CRAY_ACC_DEBUG=1

```
$ CRAY_ACC_DEBUG=1 ./a.out
ACC: Transfer 3 items (to acc 12000 bytes, to host 0 bytes) from
test.c:16
ACC: Execute kernel main$ck_L16_1 async(auto) from test.c:16
ACC: Wait async(auto) from test.c:18
ACC: Transfer 3 items (to acc 0 bytes, to host 4000 bytes) from test.c:18
```

# CRAY_ACC_DEBUG=2

```
$ CRAY_ACC_DEBUG=2 ./a.out
ACC: Start transfer 3 items from test.c:16
ACC:       allocate, copy to acc 'a' (4000 bytes)
ACC:       allocate, copy to acc 'b' (4000 bytes)
ACC:       allocate, copy to acc 'c' (4000 bytes)
ACC: End transfer (to acc 12000 bytes, to host 0 bytes)
ACC: Execute kernel main$ck_L16_1 blocks:8 threads:128 async(auto) from test.c:16
ACC: Wait async(auto) from test.c:18
ACC: Start transfer 3 items from test.c:18
ACC:       copy to host, free 'a' (4000 bytes)
ACC:       free 'b' (4000 bytes)
ACC:       free 'c' (4000 bytes)
ACC: End transfer (to acc 0 bytes, to host 4000 bytes)
```

## MPI Communication on GPU Memory

```
#pragma omp target data map(buffer[:n])
{
#pragma omp target teams distribute
  for (int i = 0; i < n; i++) buffer[i] = ...;

#pragma omp target data use_device_ptr(buffer)
  {
    MPI_Send(buffer,n,...); // requires GPU-aware MPI
    // gpu_function(buffer, ...); // Or other GPU-aware function
  }
}
```

## Step 4: Use GPU Asynchronously

```
void target_nowait_example(int N, double *A, double *B, double *C) {
  #pragma omp target enter data map(alloc:A[:N], B[:N], C[:N])

  #pragma omp target teams distribute nowait depend(out:A)
  for(int i=0; i<N; i++) A[i] = i*4; // Kernel A

  #pragma omp target teams distribute nowait depend(out:B)
  for(int i=0; i<N; i++) B[i] = i*2; // Kernel B

  #pragma omp target teams distribute nowait depend(in:A,B) depend(out:C)
  for(int i=0; i<N; i++) C[i] = A[i] + B[i]; // Kernel C

  #pragma omp target exit data depend(in:C) map(from:C[:N]) map(delete:A[:N],B[:N])
}
```

## CCE OPENMP ROADMAP

# CCE OpenMP Roadmap

- *2019 Jun*: **CCE 9.0**
  - Alpha CCE Clang OpenMP 4.5 for NVIDIA GPUs
- *2019 Nov*: **CCE 9.1**
  - Full CCE Clang OpenMP 4.5 for NVIDIA GPUs
- *2020 Feb*: **CCE 9.1.x**
  - Pre-alpha OpenMP 4.5 for AMD GPUs *(CORAL-2 only)*
- *2020 May*: **CCE 10.0**
  - Partial OpenMP 5.0 support
- *2020 Nov*: **CCE 11.0**
  - Full OpenMP 5.0 support

## FORWARD LOOKING STATEMENTS

## THANK YOU

QUESTIONS?

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“

THE FUTURE IS SELDOM THE SAME AS THE PAST.

”

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