Lecture: Manycore GPU Architectures and Programming, Part 4

-- Introducing OpenACC for Accelerators

CSCE 569 Parallel Computing

Department of Computer Science and Engineering
Yonghong Yan
yanyh@cse.sc.edu
https://passlab.github.io/CSCE569/

Manycore GPU Architectures and Programming: Outline

- Introduction
  - GPU architectures, GPGPUs, and CUDA
- GPU Execution model
- CUDA Programming model
- Working with Memory in CUDA
  - Global memory, shared and constant memory
- Streams and concurrency
- CUDA instruction intrinsic and library
- Performance, profiling, debugging, and error handling
- ☛ **Directive-based high-level programming model**
  - **OpenMP and OpenACC**

OpenACC

- OpenACC's guiding principle is simplicity
  - Want to remove as much burden from the programmer as possible
  - No need to think about data movement, writing kernels, parallelism, etc.
  - OpenACC compilers automatically handle all of that

- In reality, it isn't always that simple
  - Don't expect to get massive speedups from very little work

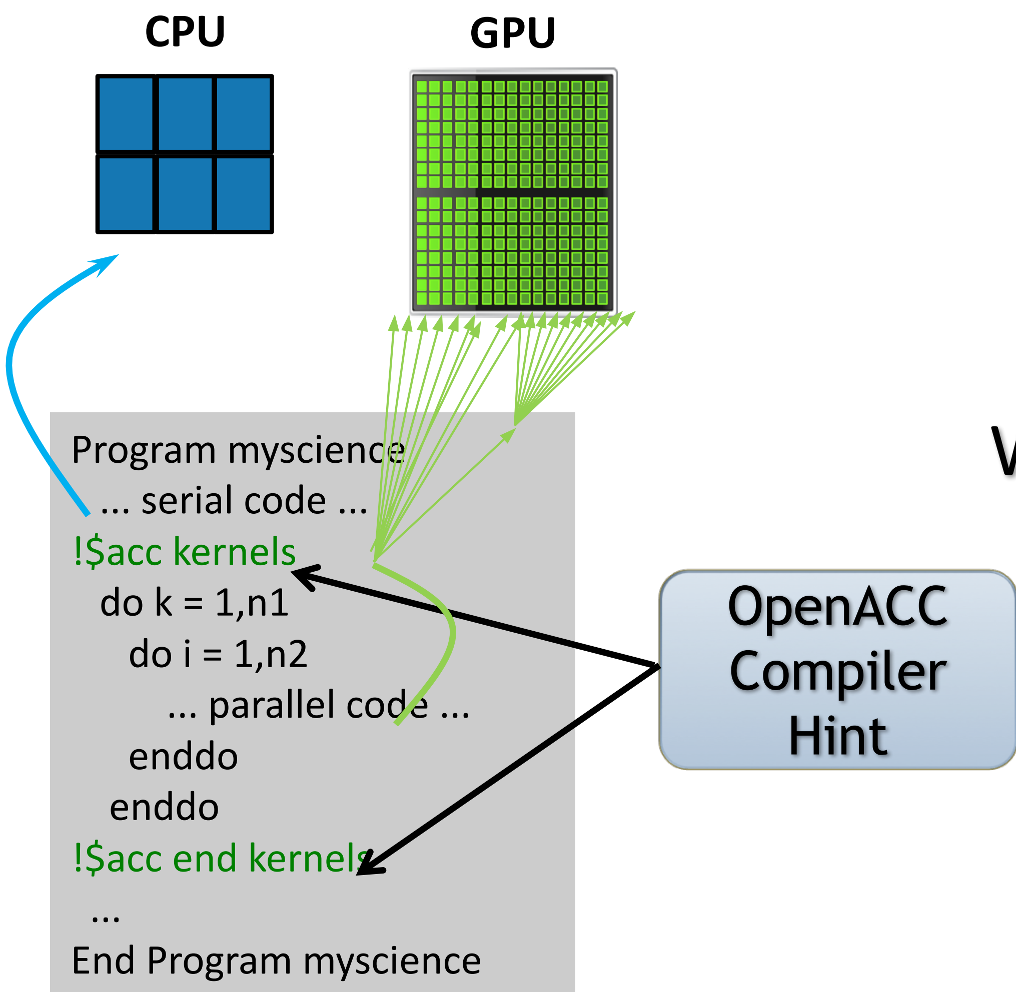
- However, OpenACC can be an easy and straightforward programming model to start with
  - http://www.openacc-standard.org/

OpenACC

- OpenACC shares a lot of principles with OpenMP
  - Compiler `#pragma` based, and requires a compiler that supports OpenACC
  - Express the type of parallelism, let the compiler and runtime handle the rest
  - OpenACC also allows you to express data movement using compiler `#pragmas`

```
#pragma acc
```

OpenACC Directives



Simple Compiler hints

Compiler Parallelizes code

Works on many-core GPUs & multicore CPUs

OpenACC

- Creating parallelism in OpenACC is possible with either of the following two compute directives:

```
#pragma acc kernels
#pragma acc parallel
```

- `kernels` and `parallel` each have their own strengths
  - `kernels` is a higher abstraction with more automation
  - `parallel` offers more low-level control but also requires more work from the programmer

OpenACC Compute Directives

- The `kernels` directive marks a code region that the programmer wants to execute on an accelerator
  - The code region is analyzed for parallelizable loops by the compiler
  - Necessary data movement is also automatically generated

```
#pragma acc kernels
{
    for (i = 0; i < N; i++)
        C[i] = A[i] + B[i];

    for (i = 0; i < N; i++)
        D[i] = C[i] * A[i];
}
```

OpenACC Compute Directives

- Like OpenMP, OpenACC compiler directives support clauses which can be used to modify the behavior of OpenACC `#pragmas`

```
#pragma acc kernels clause1 clause2 ...
```

- `kernels` supports a number of clauses, for example:
  - `if(cond)`: Only run the parallel region on an accelerator if cond is true
  - `async(id)`: Don't wait for the parallel code region to complete on the accelerator before returning to the host application. Instead, id can be used to check for completion.
  - `wait(id)`: wait for the async work associated with id to finish first
  - ...

OpenACC Compute Directives

- Take a look at the `simple-kernels.c` example

  - Compile with an OpenACC compiler, e.g. PGI:

    ```
    $ pgcc -acc simple-kernels.c -o simple-kernels
    ```

  - You may be able to add compiler-specific flags to print more diagnostic information on the accelerator code generation, e.g.:

    ```
    $ pgcc -acc simple-kernels.c -o simple-kernels -Minfo=accel
    ```

We donot have this compiler on our systems

OpenACC Compute Directives

- On the other hand, the `parallel` compute directive offers much more control over exactly how a parallel code region is executed

  - With just `kernels`, we have little control over which loops are parallelized or how they are parallelized
  - Think of `#pragma acc parallel` similarly to `#pragma omp parallel`

```
#pragma acc parallel
```

OpenACC Compute Directives

- With `parallel`, all parallelism is created at the start of the parallel region and does not change until the end
  - The execution mode of a parallel region changes depending on programmer-inserted `#pragmas`

- `parallel` supports similar clauses to `kernels`, plus:
  - `num_gangs(g)`, `num_workers(w)`, `vector_length(v)`: Used to configure the amount of parallelism in a `parallel` region
  - `reduction(op:var1, var2, ...)`: Perform a reduction across gangs of the provided variables using the specified operation
  - ...

OpenACC

- Mapping from the abstract GPU Execution Model to OpenACC concepts and terminology
  - ***OpenACC Vector element* = a thread**
    - The use of "vector" in OpenACC terminology emphasizes that at the lowest level, OpenACC uses vector-parallelism
  - ***OpenACC Worker* = SIMT Group**
    - Each worker has a vector width and can contain many vector elements
  - ***OpenACC Gang* = SIMT Groups on the same SM**
    - One gang per OpenACC PU
    - OpenACC supports multiple gangs executing concurrently

OpenACC

- Mapping to CUDA threading model:
  - Gang Parallelism: Work is run across multiple OpenACC Pus
    - **CUDA Blocks**
  - Worker Parallelism: Work is run across multiple workers (i.e. SIMT Groups)
    - **Threads per Blocks**
  - Vector Parallelism: Work is run across vector elements (i.e. threads)
    - **Within Wrap**

OpenACC Compute Directives

- In addition to `kernels` and `parallel`, a third OpenACC compute directive can help control parallelism (but does not actually create threads):

```
#pragma acc loop
```

- The `loop` directive allows you to explicitly mark loops as parallel and control the type of parallelism used to execute them

OpenACC Compute Directives

- Using `#pragma acc loop gang/worker/vector` allows you to explicitly mark loops that should use gang, worker, or vector parallelism in your OpenACC application
  - Can be used inside both `parallel` and `kernels` regions

- Using `#pragma acc independent` allows you to explicitly mark loops as parallelizable, overriding any automatic compiler analysis
  - Compilers must naturally be conservative when auto-parallelizing, the `independent` clause allows you to use detailed knowledge of the application to give hints to the compiler

OpenACC Compute Directives

- Consider `simple-parallel.c`, in which the `loop` and `parallel` directives are used to implement the same computation as `simple-kernels.c`

```
#pragma acc parallel
{
  #pragma acc loop
  for (i = 0; i < N; i++)
    ...
  #pragma acc loop
  for (i = 0; i < N; i++)
    ...
}
```

OpenACC Compute Directives

- As a syntactic nicety, you can combine `parallel/kernels` directives with `loop` directives:

```
#pragma acc kernels loop
for (i = 0; i < N; i++) {
    ...
}

#pragma acc parallel loop
for (i = 0; i < N; i++) {
    ...
}
```

OpenACC Compute Directives

- This combination has the same effect as a `loop` directive immediately following a `parallel/kernels` directive:

```
#pragma acc kernels
#pragma acc loop
for (i = 0; i < N; i++) { ... }

#pragma acc parallel
#pragma acc loop
for (i = 0; i < N; i++) { ... }
```

OpenACC Compute Directives

- In summary, the `kernels`, `parallel`, and `loop` directives all offer different ways to control the OpenACC parallelism of an application
  - `kernels` is highly automated, but your rely heavily on the compiler to create an efficient parallelization strategy
    - A short-form of parallel/loop for GPU
  - `parallel` is more manual, but allows programmer knowledge about the application to improve the parallelization strategy
    - Like OpenMP parallel
  - `loop` allows you to take more manual control over both
    - Like OpenMP worksharing

Suggested Readings

1. The sections on *Using OpenACC* and *Using OpenACC Compute Directives* in Chapter 8 of *Professional CUDA C Programming*
2. *OpenACC Standard*. 2013. http://www.openacc.org/sites/default/files/ OpenACC.2.0a_1.pdf
3. Jeff Larkin. *Introduction to Accelerated Computing Using Compiler Directives*. 2014. http:// on-demand.gputechconf.com/gtc/2014/presentations/S4167-intro-accelerated- computing-directives.pdf
4. Michael Wolfe. *Performance Analysis and Optimization with OpenACC*. 2014. http:// on-demand.gputechconf.com/gtc/2014/presentations/S4472-performance-analysis- optimization-openacc-apps.pdf

OpenACC Data Directives

- `#pragma acc data` can be used to explicitly perform communication between a host program and accelerators

- The `data` clause is applied to a code region and defines the communication to be performed at the start and end of that code region

- The `data` clause alone does nothing, but it takes clauses which define the actual transfers to be performed

OpenACC Data Directives

- Common clauses used with `#pragma acc data`:

Clause	Description
`copy(list)`	Transfer all variables in **`list`** to the accelerator at the start of the **`data`** region and back to the host at the end.
`copyin(list)`	Transfer all variables in **`list`** to the accelerator at the start of the **`data`** region.
`copyout(list)`	Transfer all variables in **`list`** back to the host at the end of the **`data`** region.
`present_or_copy(list)`	If the variables specified in **`list`** are not already on the accelerator, transfer them to it at the start of the **`data`** region and back at the end.
`if(cond)`	Only perform the operations defined by this data directive if **`cond`** is true.

OpenACC Data Directives

- Consider the example in `simple-data.c`, which mirrors `simple-parallel.c` and `simple-kernels.c`:

```
#pragma acc data copyin(A[0:N], B[0:N])
copyout(C[0:N], D[0:N])
{
#pragma acc parallel
  {
#pragma acc loop
    for (i = 0; i < N; i++)
      ...
#pragma acc loop
    for (i = 0; i < N; i++)
      ...
  }
}
```

OpenACC Data Directives

- OpenACC also supports:

```
#pragma acc enter data
#pragma acc exit data
```

- Rather than bracketing a code region, these `#pragmas` allow you to copy data to and from the accelerator at arbitrary points in time
  - Data transferred to an accelerator with `enter data` will remain there until a matching `exit data` is reached or until the application terminates

OpenACC Data Directives

- Finally, OpenACC also allows you to specify data movement as part of the compute directives through data clauses

```
#pragma acc data copyin(A[0:N], B[0:N])
copyout(C[0:N], D[0:N])
{
#pragma acc parallel
  {
  }
}
```

↓

```
#pragma acc parallel copyin(A[0:N], B[0:N])
copyout(C[0:N], D[0:N])
```

OpenACC Data Specification

- You may have noticed that OpenACC data directives use an unusual array dimension specification, for example:

```
#pragma acc data copy(A[start:length])
```

- In some cases, data specifications may not even be necessary as the OpenACC compiler can infer the size of the array:

```
int a[5];
#pragma acc data copy(a)
{
    ...
}
```

OpenACC Data Specification

- If the compiler is unable to infer an array size, error messages like the one below will be emitted
  - Example code:

```
int *a = (int *)malloc(sizeof(int) * 5);
#pragma acc data copy(a)
{
    ...
}
```

  - Example error message:

```
PGCC-S-0155-Cannot determine bounds for array a
```

OpenACC Data Specification

- Instead, you must specify the full array bounds to be transferred

```
int *a = (int *)malloc(sizeof(int) * 5);
#pragma acc data copy(a[0:5])
{
    ...
}
```

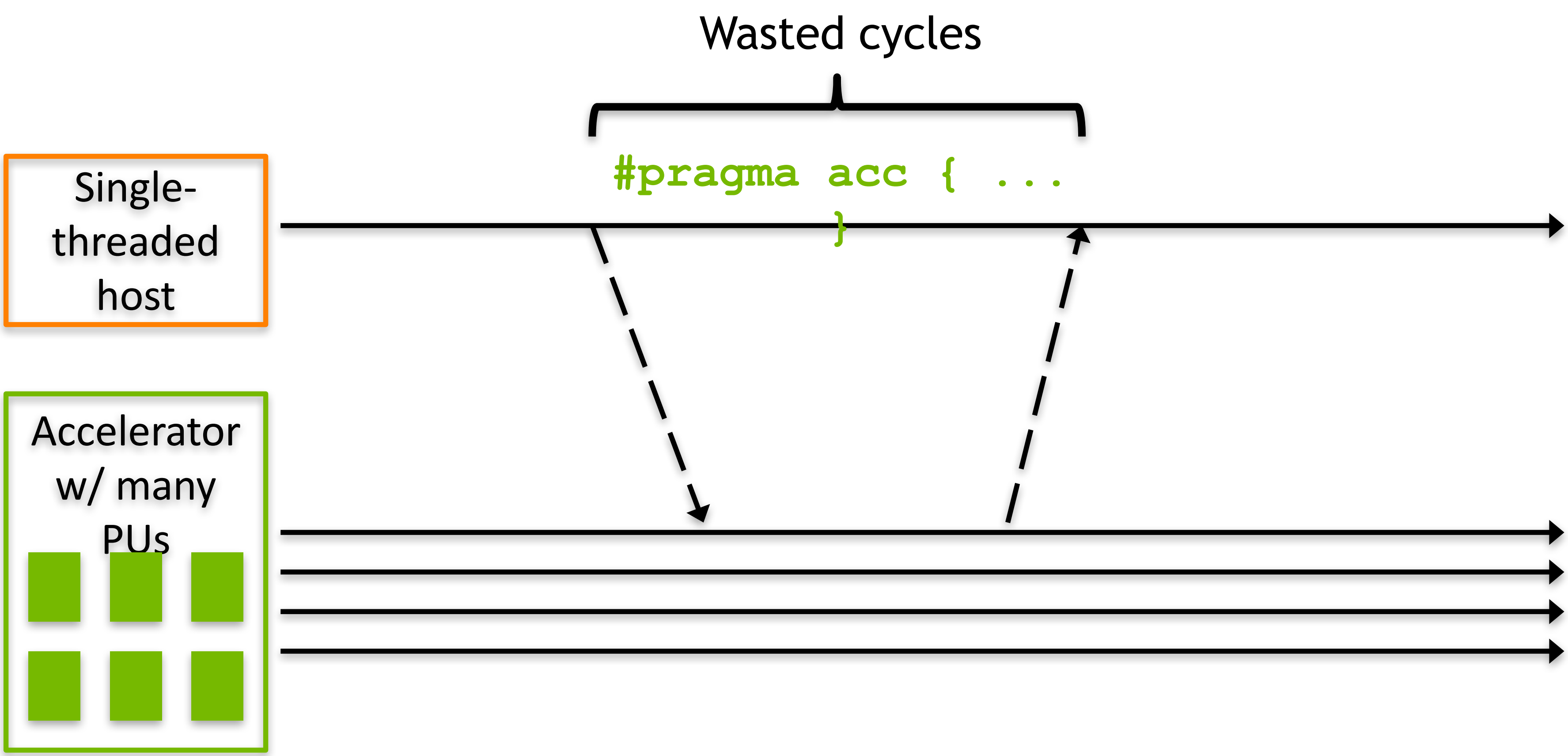
  - The lower bound is inclusive and, if not explicitly set, will default to 0
  - The length must be provided if it cannot be inferred

Asynchronous Work in OpenACC

- In OpenACC, the default behavior is always to block the host while executing an acc region
  - Host execution does not continue past a `kernels/parallel` region until all operations within it complete
  - Host execution does not enter or exit a data region until all prescribed data transfers have completed

Asynchronous Work in OpenACC

- When the host blocks, host cycles are wasted:



Asynchronous Work in OpenACC

- In many cases this default can be overridden to perform operations asynchronously
  - Asynchronously copy data to the accelerator
  - Asynchronously execute computation
- As a result, host cycles are not wasted idling while the accelerator is working

Asynchronous Work in OpenACC

- Asynchronous work is created using the `async` clause on compute and data directives, and every asynchronous task has an `id`
  - Run a `kernels` region asynchronously:
    ```
    #pragma acc kernels async(id)
    ```
  - Run a `parallel` region asynchronously:
    ```
    #pragma acc parallel async(id)
    ```
  - Perform an `enter data` asynchronously:
    ```
    #pragma acc enter data async(id)
    ```
  - Perform an `exit data` asynchronously:
    ```
    #pragma acc exit data async(id)
    ```
  - `async` is not supported on the `data` directive

Asynchronous Work in OpenACC

- Having asynchronous work means we also need a way to wait for it
  - Note that every `async` clause on the previous slide took an `id`
  - The asynchronous task created is uniquely identified by that `id`

- We can then wait on that `id` using either:
  - The `wait` clause on compute or data directives
  - The OpenACC Runtime API's Asynchronous Control functions

Asynchronous Work in OpenACC

- Adding a `wait(id)` clause to a compute or data directive makes the associated data transfer or computation wait until the asynchronous task associated with that `id` completes

- The OpenACC Runtime API supports explicitly waiting using:

```
void acc_wait(int id);
void acc_wait_all();
```

- You can also check if asynchronous tasks have completed using:

```
int acc_async_test(int id);
int acc_async_test_all();
```

Asynchronous Work in OpenACC

- Let's take a simple code snippet as an example:

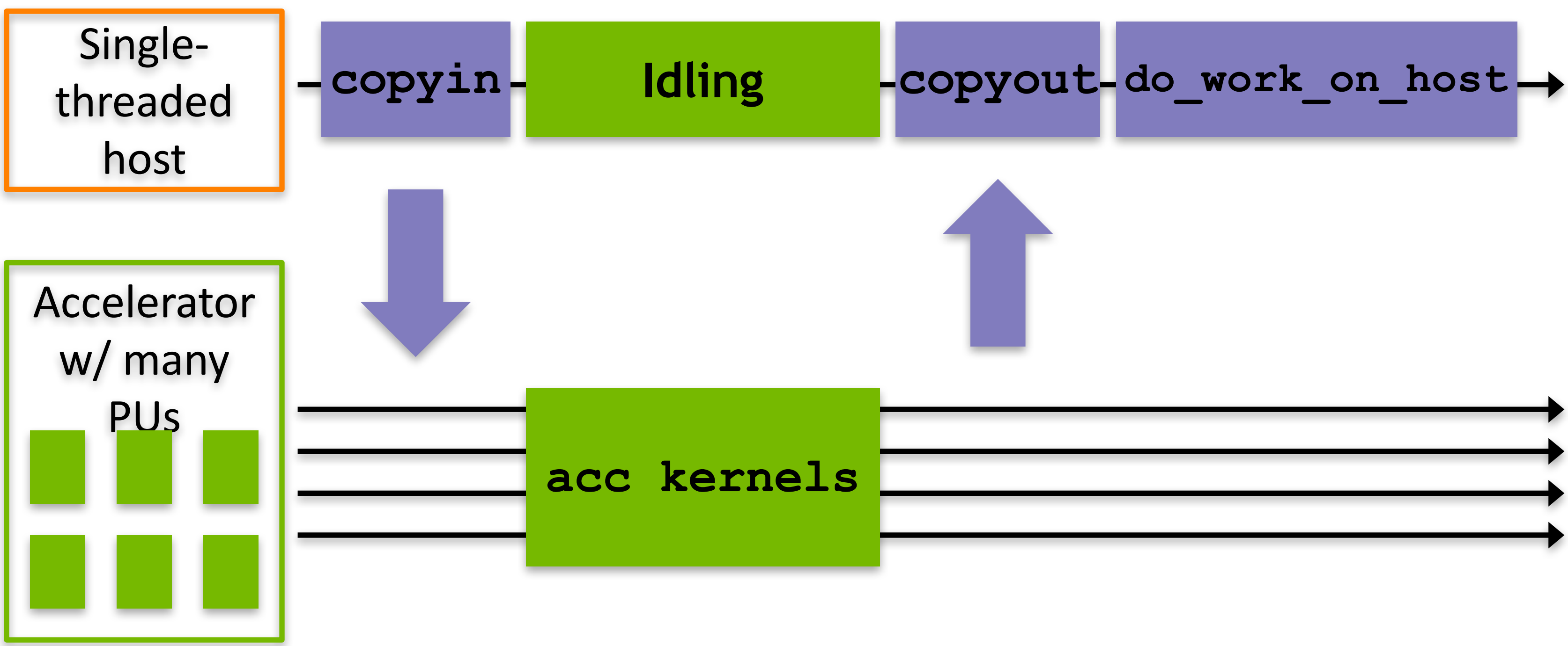
Host is blocked

```
#pragma acc data copyin(A[0:N])
copyout(B[0:N])
{
#pragma acc kernels
   {
     for (i = 0; i < N; i++)
       B[i] = foo(A[i]);
   }
}
```

Host is working

```
do_work_on_host(C);
```

Asynchronous Work in OpenACC



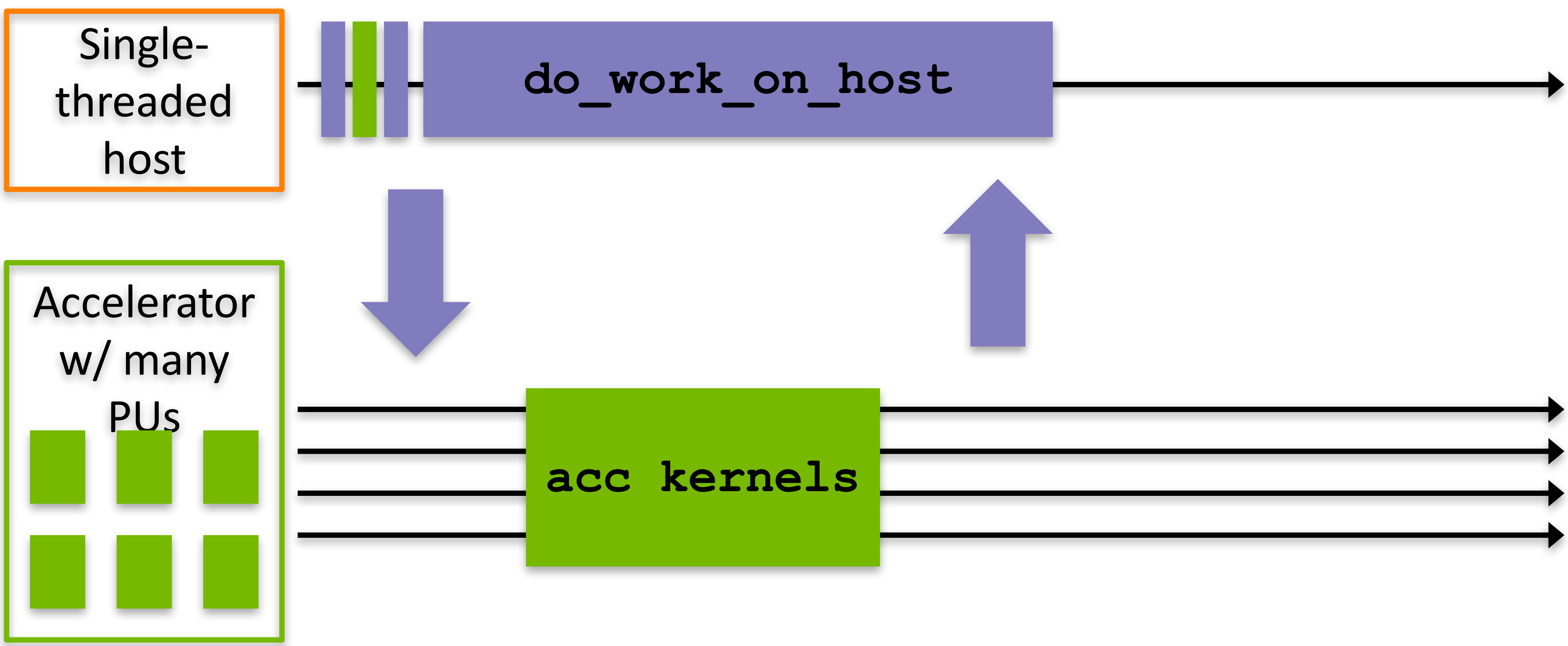
Asynchronous Work in OpenACC

- Performing the transfer and compute asynchronously allows us to overlap the host and accelerator work:

```
#pragma acc enter data async(0)
copyin(A[0:N]) create(B[0:N])
#pragma acc kernels wait(0) async(1)
{
  for (i = 0; i < N; i++)
    B[i] = foo(A[i]);
}
#pragma acc exit data wait(1) async(2)
copyout(B[0:N])
do_work_on_host(C);

acc_wait(2);
```

Asynchronous Work in OpenACC



Reductions in OpenACC

- OpenACC supports the ability to perform automatic parallel reductions
  - The `reduction` clause can be added to the `parallel` and `loop` directives, but has a subtle difference in meaning on each

```
#pragma acc parallel reduction(op:var1, var2, ...)
#pragma acc loop reduction(op:var1, var2, ...)
```

  - `op` defines the reduction operation to perform
  - The variable list defines a set of private variables created and initialized in the subsequent compute region

Reductions in OpenACC

- When applied to a `parallel` region, `reduction` creates a private copy of each variable for **each gang** created for that `parallel` region

- When applied to a `loop` directive, `reduction` creates a private copy of each variable for **each vector element** in the loop region

- The resulting value is transferred back to the host once the current compute region completes

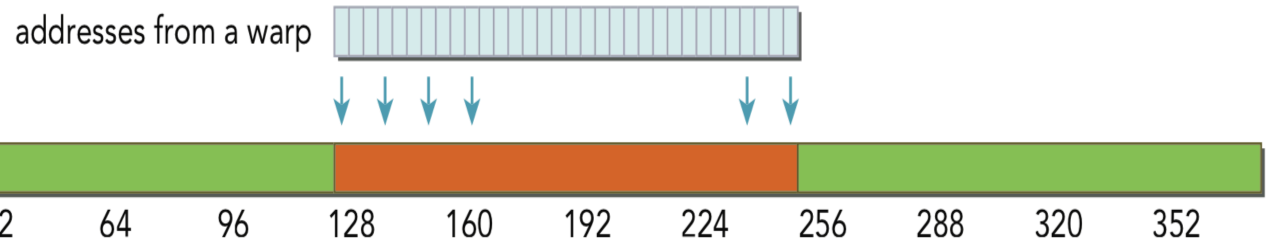
OpenACC Parallel Region Optimizations

- To some extent, optimizing the parallel code regions in OpenACC is contradictory to the whole OpenACC principle
  - OpenACC wants programmers to focus on writing application logic and worry less about nitty-gritty optimization tricks
  - Often, low-level code optimizations require intimate understanding of the hardware you are running on

- In OpenACC, optimizing is more about avoiding symptomatically horrible scenarios so that the compiler has the best code to work with, rather than making very low-level optimizations
  - Memory access patterns
  - Loop scheduling

OpenACC Parallel Region Optimizations

- GPUs are optimized for aligned, coalesced memory accesses
  - Aligned: the lowest address accessed by the elements in a vector to be 32- or 128-bit aligned (depending on architecture)
  - Coalesced: neighboring vector elements access neighboring memory cells



OpenACC Parallel Region Optimizations

- Improving alignment in OpenACC is difficult because there is less visibility into how OpenACC threads are scheduled on GPU

- Improving coalescing is also difficult, the OpenACC compiler may choose a number of different ways to schedule a loop across threads on the GPU

- In general, try to ensure that neighboring iterations of the innermost parallel loops are referencing neighboring memory cells

OpenACC Parallel Region Optimizations

- Vecadd example using coalescing and noncoalescing access

CLI Flag	Average Compute Time
Without `-b` (coalescing)	122.02us
With `-b` (noncoalescing)	624.04ms

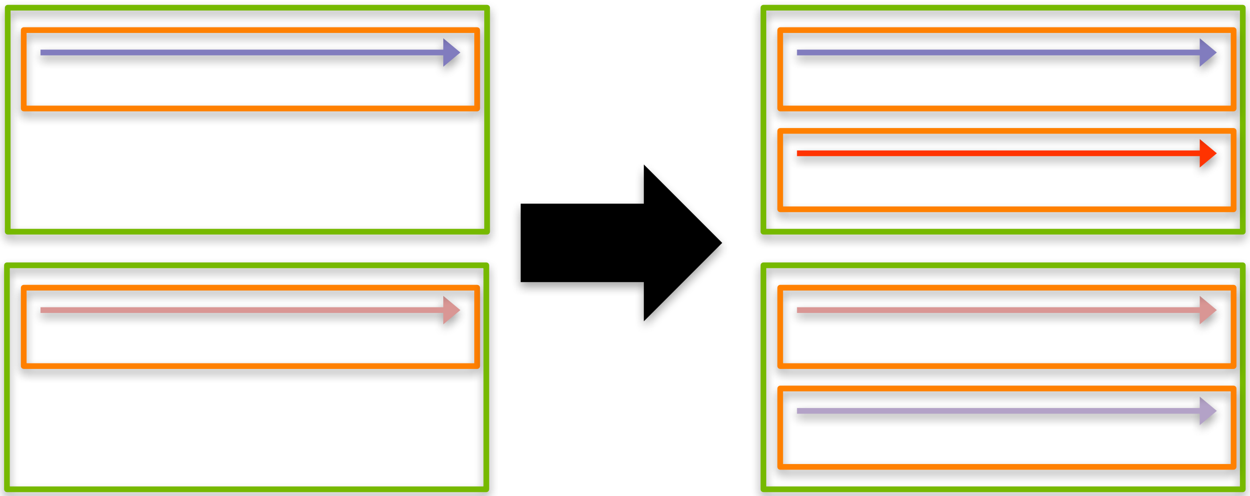
OpenACC Parallel Region Optimizations

- The `loop` directive supports three special clauses that control how loops are parallelized: `gang`, `worker`, and `vector`
  - The meaning of these clauses changes depending on whether they are used in a `parallel` or `kernels` region

- The `gang` clause:
  - In a `parallel` region, causes the iterations of the loop to be parallelized across gangs created by the `parallel` region, transitioning from gang-redundant to gang-partitioned mode.
  - In a `kernels` region, does the same but also allows the user to specify the number of gangs to use, using `gang(ngangs)`

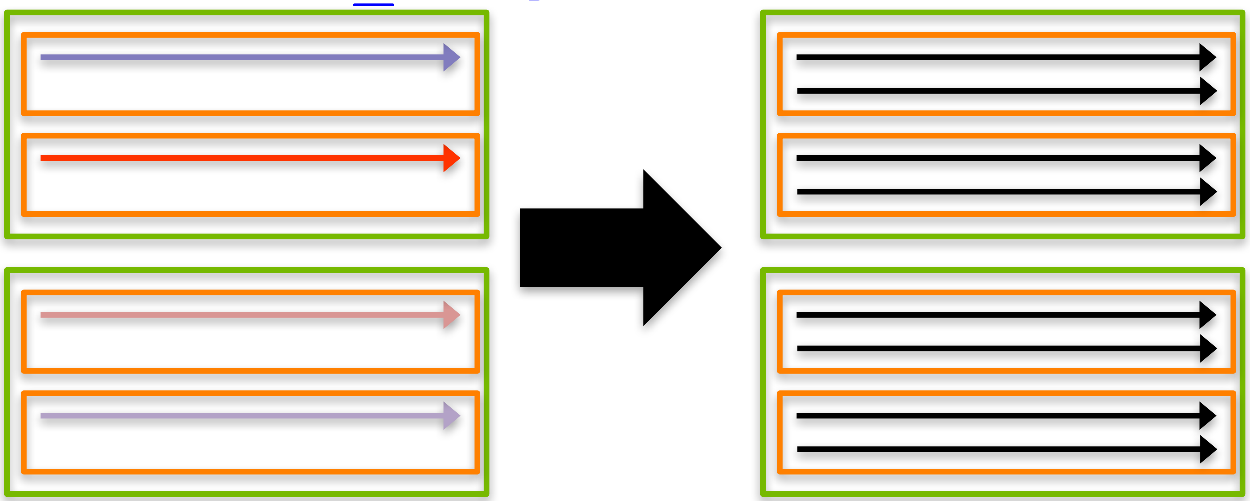
OpenACC Parallel Region Optimizations

- The `worker` clause:
  - In a `parallel` region, causes the iterations of the loop to be parallelized across workers created by the `parallel` region, transitioning from worker-single to worker-partitioned modes.
  - In a `kernels` region, does the same but also allows the user to specify the number of workers per gang, using `worker(nworkers)`



OpenACC Parallel Region Optimizations

- The `vector` clause:
  - In a `parallel` region, causes the iterations of the loop to be parallelized using vector/SIMD parallelism with the vector length specified by `parallel`, transitioning from vector-single to vector-partitioned modes.
  - In a `kernels` region, does the same but also allows the user to specify the vector length to use, using `vector(vector_length)`



OpenACC Parallel Region Optimizations

- Manipulating the `gang`, `worker`, and `vector` clauses results in different scheduling of loop iterations on the underlying hardware
  - Can result in significant performance improvement or loss

- Consider the example of loop schedule
  - The `gang` and `vector` clauses are used to change the parallelization of two nested loops in a `parallel` region
  - The # of gangs is set with the command-line flag `-g`, vector width is set with `-v`

OpenACC Parallel Region Optimizations

- Try playing with `-g` and `-v` to see how `gang` and `vector` affect performance
  - Options for gang and vector sizes

```
#pragma acc parallel copyin(A[0:M * N], B[0:M *
N]) copyout(C[0:M * N])
#pragma acc loop gang(gangs)
        for (int i = 0; i < M; i++) {
#pragma acc loop vector(vector_length)
            for (int j = 0; j < N; j++) {
                ...
            }
        }
```

OpenACC Parallel Region Optimizations

Example results:

-g	-v (constant)	Time
1	128	5.7590ms
2	128	2.8855ms
4	128	1.4478ms
8	128	730.11us
16	128	373.40us
32	128	202.89us
64	128	129.85us

-g (constant)	-v	Time
32	2	9.3165ms
32	8	2.7953ms
32	32	716.45us
32	128	203.02us
32	256	129.76us
32	512	125.16us
32	1024	124.83us

OpenACC Parallel Region Optimizations

- Your options for optimizing OpenACC parallel regions are fairly limited
  - The whole idea of OpenACC is that the compiler can handle that for you
- There are some things you can do to avoid poor code characteristics on the GPU that that compiler can't optimize you out of (memory access patterns)
- There are also tunables you can tweak which may improve performance (e.g. `gang`, `worker`, `vector`)

The Tile Clause

- Like the `gang`, `worker`, and `vector` clauses, the `tile` clause is used to control the scheduling of loop iterations
  - Used on `loop` directives only

- It specifies how you would like loop iterations grouped across the iteration space
  - Iteration grouping (more commonly called loop tiling) can be beneficial for locality on both CPUs and GPUs

The Tile Clause

- Suppose you have a loop like the following:

```
#pragma loop
for (int i = 0; i < N; i++) {
    ...
}
```

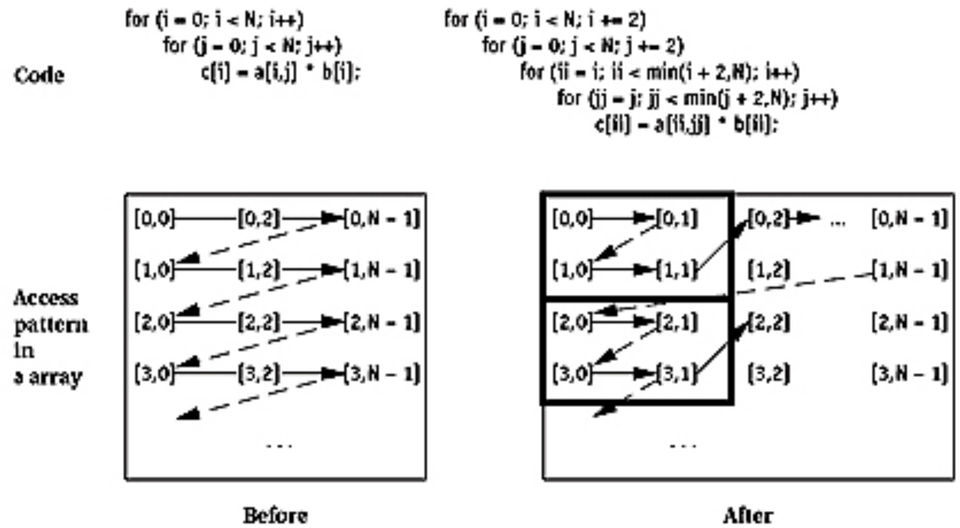
- The `tile` clause can be added like this:

```
#pragma loop tile(8)
for (int i = 0; i < N; i++) {
    ...
}
```

The Tile Clause

- Analogous to adding a second inner loop:

```
#pragma loop
for (int i = 0; i < N; i+=8) {
    for (int ii = 0; ii < 8; ii++) {
        ...
    }
}
```



  – The same iterations are performed, but the compiler may choose to schedule them differently on hardware threads

The Cache Directive

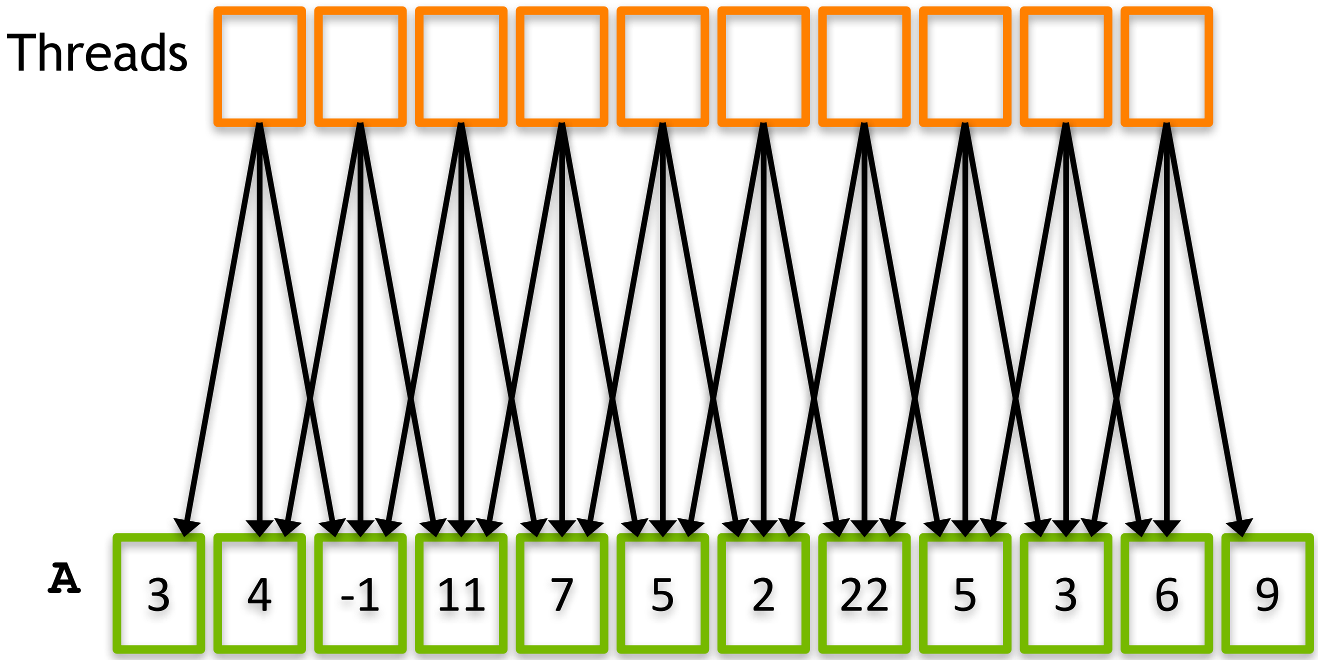
- The `cache` directive is used to optimize memory accesses on the accelerator. It marks data which will be frequently accessed, and which therefore should be kept close in the cache hierarchy

- The `cache` directive is applied immediately inside of a loop that is being parallelized on the accelerator:
  - Note the same data specification is used here as for data directives

```
#pragma acc loop
for (int i = 0; i < N; i++) {
    #pragma acc cache(A[i:1])
    ...
```

The Cache Directive

- For example, suppose you have an application where every thread `i` accesses cells `i-1`, `i`, and `i+1` in a vector `A`



The Cache Directive

- This results in lots of wasted memory accesses as neighboring elements in the vector reference the same cells in the array `A`

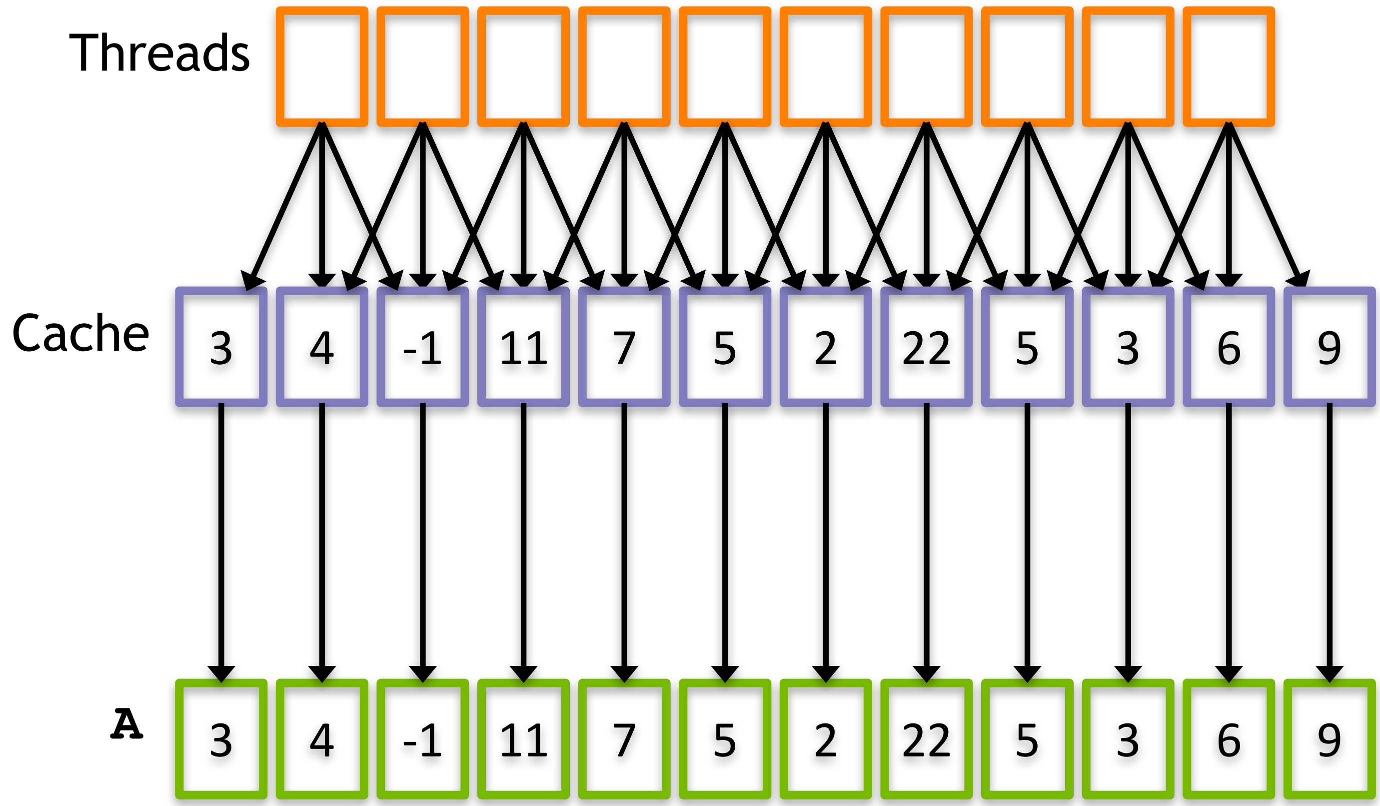
- Instead, we can use the cache directive to indicate to the compiler which array elements we expect to benefit from caching:

```
#pragma acc parallel loop
for (int i = 0; i < N; i++)
{
    B[i] = A[i-1] + A[i] +
A[i+1];
}
```

```
#pragma acc parallel loop
for (int i = 0; i < N; i++) {
    #pragma acc cache(A[i-1:2])
    B[i] = A[i-1] + A[i] +
A[i+1];
}
```

The Cache Directive

- Now, the compiler will automatically cache `A[i-1]`, `A[i]`, and `A[i+1]` and only load them from accelerator memory once



The Cache Directive

- The `cache` directive requires a lot of complex code analysis from the compiler to ensure this is a safe optimization

- As a result, it is not always possible to use the `cache` optimization with arbitrary application code
  - Some restructuring may be necessary before the compiler is able to determine how to effectively use the `cache` optimization

The Cache Directive

- The `cache` directive can result in significant performance gains thanks to much improved data locality

- However, for complex applications it generally requires significant code refactoring to expose the cache-ability of the code to the compiler
  - Just like to use shared memory in CUDA

Suggested Readings

1. *OpenACC Standard*. 2013. http://www.openacc.org/sites/default/files/ OpenACC.2.0a_1.pdf
2. Peter Messmer. *Optimizing OpenACC* Codes. http://on-demand.gputechconf.com/gtc/2013/presentations/S3019-Optimizing-OpenACC-Codes.pdf