CSCI-GA.3033-004

Graphics Processing Units (GPUs): Architecture and Programming

Lecture : OpenACC

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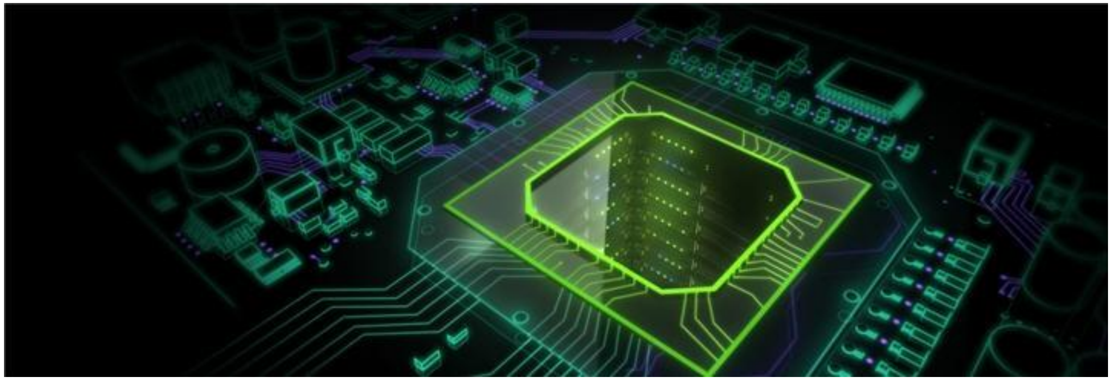
Some slides for this lecture are adopted (and slightly edited) from

- David Kirk and Wei-mei W. Hwu



What is OpenACC?

- The OpenACC Application Programming Interface provides a set of
  - compiler directives (pragmas)
  - library routines and
  - environment variables

  that can be used to write data parallel FORTRAN, C and C++ programs that run on accelerator devices.

http://www.openacc.org/

What is OpenACC?

- Initially developed by Portland Group (PGI), CRAY, NVIDIA with support from CAPS enterprise
- Announced at the Supercomputing Conference (SC11), Nov 2011.

The Main Strategy

OpenACC is based on programmers inserting hints into their programs on how the code is to be parallelized.

The compiler runs the code on the hardware platform that is specified at the time of compilation.

#pragma

- In C and C++: the #pragma directive is:

the method to provide, to the compiler, information that is not specified in the standard language.

MatrixMultiplication

```
void computeAcc(float *P, const float *M, const float *N, int Mh, int Mw, int Nw)
{


 for (int i=0; i<Mh; i++) {

     for (int j=0; j<Nw; j++) {
         float sum = 0;
         for (int k=0; k<Mw; k++) {
             float a = M[i*Mw+k];
             float b = N[k*Nw+j];
             sum += a*b;
         }
         P[i*Nw+j] = sum;
     }
 }
}
```

MatrixMultiplication in OpenACC

```
void computeAcc(float *P, const float *M, const float *N, int Mh, int Mw, int Nw)
{

 #pragma acc parallel loop copyin(M[0:Mh*Mw]) copyin(N[0:Nw*Mw])
             copyout(P[0:Mh*Nw])
 for (int i=0; i<Mh; i++) {
    #pragma acc loop
    for (int j=0; j<Nw; j++) {
       float sum = 0;
       for (int k=0; k<Mw; k++) {
           float a = M[i*Mw+k];
           float b = N[k*Nw+j];
           sum += a*b;
       }
       P[i*Nw+j] = sum;
    }
 }
}
```

MatrixMultiplication in OpenACC

```
void computeAcc(float *P, const float *M, const float *N, int Mh, int Mw, int Nw)
{

 #pragma acc parallel loop copyin(M[0:Mh*Mw]) copyin(N[0:Nw*Mw])
             copyout(P[0:Mh*Nw])
 for (int i=0; i<Mh; i++) {
    #pragma acc loop
    for (int j=0; j<Nw; j++) {
       float sum = 0;
       for (int k=0; k<Mw; k++) {
          float a = M[i*Mw+k];
          float b = N[k*Nw+j];
          sum += a*b;
       }
       P[i*Nw+j] = sum;
    }
 }
}
```

The copyin clause and the copyout clause specify how the matrix data should be transferred between the host and the accelerator.

The parallel loop means the 'i' loop is mapped to the 1st level of parallelism on the accelerator

instructs the compiler to map the inner 'j' loop on the 2nd level of parallelism on the accelerator.

Motivation

OpenACC programmers can often start with writing a sequential version and then annotate their sequential program with OpenACC directives.

- leave most of the details in generating a kernel and data transfers to the OpenACC compiler.

OpenACC Directives

#pragma acc <directive> [clause …]

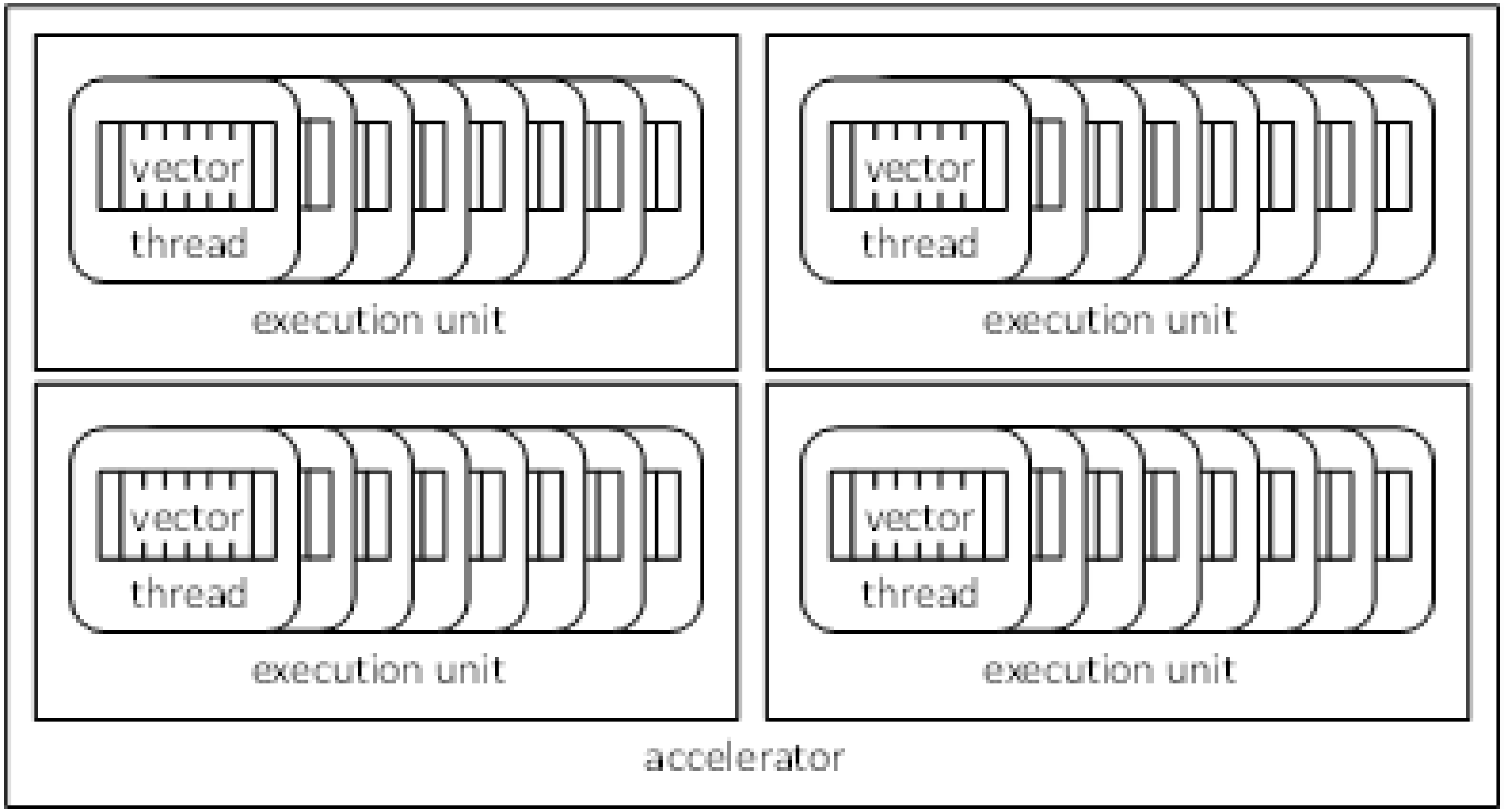
Directive is applied to the immediately following statement

Directive + statement = OpenACC Construct

Frequently Encountered Issues

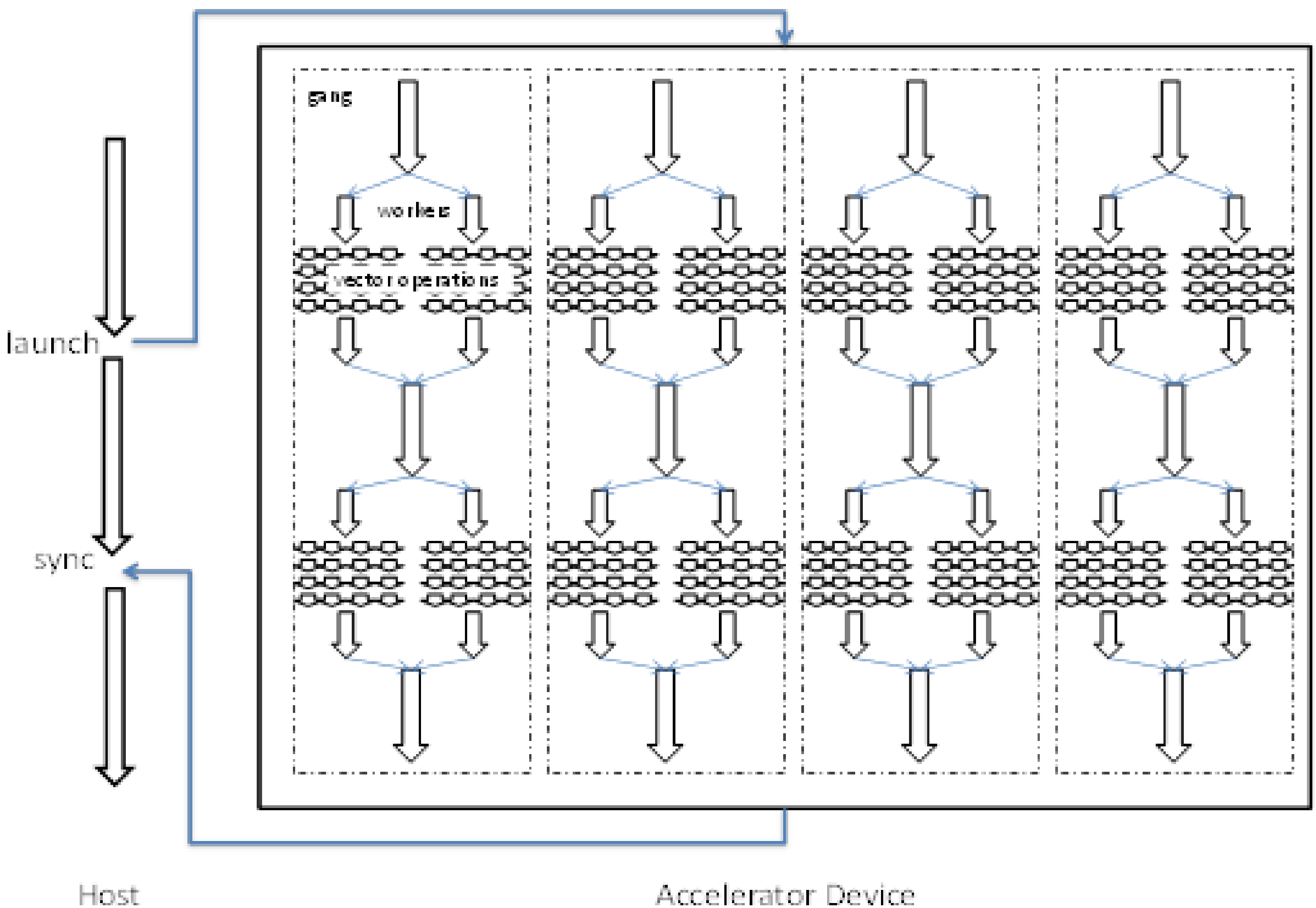
- Some OpenACC pragmas are hints to the OpenACC compiler, which may or may not be able to act accordingly
  - The performance of an OpenACC depends heavily on the quality of the compiler.
  - Much less so in CUDA or OpenCL
- Some OpenACC programs may behave differently or even incorrectly if pragmas are ignored

OpenACC Device Model



Currently OpenACC does not allow synchronization across threads.

OpenACC Execution Model



OpenACC has two main directives

- Compute directives
  - Marks block of code to be accelerated
- Data management directives
  - For data movement
  - Can be used within compute directives

Compute Directives: Two main constructs

Parallel Construct

The programmer does most of the work.

Kernels Construct

- Tells the compiler that this region should be placed on the accelerator.
- The compiler does most of the heavy lifting.

Loop Construct

Tells the compiler that loop iterations are independent.

Parallel Construct

```
#pragma acc parallel loop copyin(M[0:Mh*Mw]) copyin(N[0:Nw*Mw]) \
copyout(P[0:Mh*Nw])
for (int i=0; i<Mh; i++) {
...
}
```

is equivalent to:

```
#pragma acc parallel copyin(M[0:Mh*Mw]) copyin(N[0:Nw*Mw])
copyout(P[0:Mh*Nw])
{
    #pragma acc loop
    for (int i=0; i<Mh; i++) {
        ...
    }
}
```

(a parallel region that consists of just a loop)

Parallel Construct

- A parallel construct is executed on an accelerator
- Parallel directive by itself is relatively useless.
- One can specify the number of gangs and number of workers in each gang

```
#pragma acc parallel copyout(a) num_gangs(1024) num_workers(32)
{
        a = 23;
}
```

1024*32 workers will be created.

a=23 will be executed redundantly by all 1024 gang leads

Gangs Loop

```
#pragma acc parallel
num_gangs(1024)
{
    for (int i=0; i<2048; i++) {
        ...
    }
}
```

One worker within each gang
will execute the parallel region.
So, the 2048 iterations
will be executed redundantly
and sequentially by 1024 gang leaders.

```
#pragma acc parallel
num_gangs(1024)
{
#pragma acc loop gang
    for (int i=0; i<2048; i++) {
        ...
    }
}
```

The 2048 loop iterations will be
distributed among the 1024 gangs.
Each gang leader will execute 2 iterations.

Worker Loop

```
#pragma acc parallel num_gangs(1024) num_workers(32)
{
    #pragma acc loop gang
    for (int i=0; i<2048; i++) {
        #pragma acc loop worker
        for (int j=0; j<512; j++) {
            foo(i,j);
        }
    }
}
```

1024*32=32K workers will be created, each executing 1M/32K = 32 instance of foo()

```
#pragma acc parallel num_gangs(32)
{
    Statement 1;
    Statement 2;
    #pragma acc loop gang
    for (int i=0; i<n; i++) {
        Statement 3; Statement 4;
    }
    Statement 5;
    Statement 6;
    #pragma acc loop gang
    for (int i=0; i<m; i++) {
        Statement 7;
        Statement 8;
    }
    Statement 9;
    if (condition)
        Statement 10;
}
```

- Statements 1 and 2 are redundantly executed by 32 gang leaders (32)
- The n for-loop iterations are distributed to 32 gangs, each gang will distribute its share to a number of workers.
- Number of workers is determined by compiler/runtime.

What if statements: 1, 2, 5, 6, 9, and 10 must be executed only once for the correctness of the program?

```
#pragma acc parallel num_gangs(1)
num_workers(32)
{
    Statement 1;
    Statement 2;
    #pragma acc loop worker
    for (int i=0; i<n; i++) {
        Statement 3;
        Statement 4;
    }
    Statement 5;
    Statement 6;
    #pragma acc loop worker
    for (int i=0; i<m; i++) {
        Statement 7;
        Statement 8;
    }
    Statement 9;
    if (condition)
       Statement 10;
}
```

Multiple level of Parallelism

```
{
        for(int i =0; i < 2048; i++){
                for( j = 0; j < 512; j++){
                        for( k = 0; k < 1024; k++) {
                                foo(i, j, k);
                        }
                }
        }
}
```

Multiple level of Parallelism

```
#pragma acc parallel num_gangs(1024) num_workers(32)
vector_length(32)
{
        #pragma acc loop gang
        for(int i =0; i < 2048; i++){
                #pragma acc loop worker
                for( j = 0; j < 512; j++){
                        #pragma acc loop vector
                        for( k = 0; k < 1024; k++) {
                                foo(i, j, k);
                        }
                }
        }
}
```

Kernel Constructs

```
#pragma acc kernels
{
    #pragma acc loop num_gangs(1024)
    for (int i=0; i<2048; i++) {
        a[i] = b[i];
    }
    #pragma acc loop num_gangs(512)
    for (int j=0; j<2048; j++) {
        c[j] = a[j]*2;
    }
    for (int k=0; k<2048; k++) {
        d[k] = c[k];
    }
}
```

- Kernel constructs tells the compiler to execute the code in the accelerator if possible.
- Kernel region may be broken into a series of kernels, each of which executed on the accelerator.

Example

```
int a[n][m], b[n][m], c[n][m];
...
#pragma acc kernels
for(int j = 0; j < n; j++) {
   for(int k = 0; k < m; k++) {
    c[j][k] = a[j][k];
    a[j][k] = c[j][k] + n[j][k];
  }
 }
```

Compiler is free to parallelize the code in any way it sees, or run it sequentially, to ensure correctness.

```
int a[n][m], b[n][m], c[n][m];
...
#pragma acc kernels
{
        for(int j = 0; j < n; j++) {
          for(int k = 0; k < m; k++) {
              c[j][k] = a[j][k];
              a[j][k] = c[j][k] + n[j][k];
            }
          }

        for(int j = 0; j < n; j++) {
          for(int k = 0; k < m; k++) {
              d[j][k] = a[j][k] - 5;
            }
          }
}
```

```
int a[n][m], b[n][m], c[n][m];
...
#pragma acc kernels
{
        for(int j = 0; j < n; j++) {
          for(int k = 0; k < m; k++) {
              c[j][k] = a[j][k];
              a[j][k] = c[j][k] + n[j][k];
              d[j][k] = a[j][k] - 5;
            }
          }
}
```

```
int a[n][m], b[n][m], c[n][m];
…
#pragma acc kernels
{
        for(int j = 0; j < n; j++) {
          for(int k = 0; k < m; k++) {
              c[j][k] = a[j][k];
              a[j][k] = c[j][k] + n[j][k];
            }
          }

        for(int j = 0; j < n; j++) {
          for(int k = 0; k < m; k++) {
              d[j][k] = a[j][k] - 5;
            }
          }
}
```

```
int a[n][m], b[n][m], c[n][m];
…
#pragma acc parallel loop
        for(int j = 0; j < n; j++) {
          for(int k = 0; k < m; k++) {
              c[j][k] = a[j][k];
              a[j][k] = c[j][k] + n[j][k];
            }
          }
#pragma acc parallel loop
        for(int j = 0; j < n; j++) {
          for(int k = 0; k < m; k++) {
              d[j][k] = a[j][k] - 5;
            }
          }
```

```
void foo(int * x, int * y, int n, int m){
  int a[2048], b[2048];

  #pragma acc kernels copy(x[0:2048], y[0:2048], a, b)
  {
      //no data dependence
      #pragma acc loop
      for( int i =0; i < 2047; i++){
                  a[i] = b[i+1] + 1;
      }

     //data dependence
     #pragma acc loop
      for( int j =0; j < 2047; j++){
                  a[j] = a[j+1] + 1;
      }

     // Data dependence if x[] is not aliased with y[]
     #pragma acc loop
      for( int k =0; k < 2047; k++){
                  x[i] = y[i+1] + 1;
      }

     //no data dependence if n >= m
     #pragma acc loop
      for( int l =0; l < m; l++){
                  x[l] = x[l+n] + 1;
      }


  }
}
```

```
void foo(int * x, int * y, int n, int m){
  int a[2048], b[2048];

  #pragma acc kernels copy(x[0:2048], y[0:2048], a, b)
  {
     //no data dependence
     #pragma acc loop
     for( int i =0; i < 2047; i++){
                a[i] = b[i+1] + 1;
     }

    //data dependence
    #pragma acc loop
     for( int j =0; j < 2047; j++){
                a[j] = a[j+1] + 1;
     }

    // Data dependence if x[] is not aliased with y[]
    #pragma acc loop
     for( int k =0; k < 2047; k++){
                x[i] = y[i+1] + 1;
     }

    //no data dependence if n >= m
    #pragma acc loop
     for( int l =0; l < m; l++){
                x[l] = x[l+n] + 1;
     }


  }
}
```

OpenACC compiler has no problem parallelizing this loop.

```
void foo(int * x, int * y, int n, int m){
  int a[2048], b[2048];

  #pragma acc kernels copy(x[0:2048], y[0:2048], a, b)
  {
      //no data dependence
      #pragma acc loop
      for( int i =0; i < 2047; i++){
                  a[i] = b[i+1] + 1;
      }

     //data dependence
     #pragma acc loop
      for( int j =0; j < 2047; j++){
                  a[j] = a[j+1] + 1;
      }

     // Data dependence if x[] is not aliased with y[]
     #pragma acc loop
      for( int k =0; k < 2047; k++){
                  x[i] = y[i+1] + 1;
      }

     //no data dependence if n >= m
     #pragma acc loop
      for( int l =0; l < m; l++){
                  x[l] = x[l+n] + 1;
      }


  }
}
```

OpenACC compiler has no problem deciding that this loop is not parallelizable.

```
void foo(int * x, int * y, int n, int m){
 int a[2048], b[2048];

 #pragma acc kernels copy(x[0:2048], y[0:2048], a, b)
 {
     //no data dependence
     #pragma acc loop
     for( int i =0; i < 2047; i++){
                  a[i] = b[i+1] + 1;
     }

    //data dependence
    #pragma acc loop
     for( int j =0; j < 2047; j++){
                  a[j] = a[j+1] + 1;
     }

    // Data dependence if x[] is not aliased with y[]
    #pragma acc loop
     for( int k =0; k < 2047; k++){
                  x[i] = y[i+1] + 1;
     }

    //no data dependence if n >= m
    #pragma acc loop
     for( int l =0; l < m; l++){
                  x[l] = x[l+n] + 1;
     }


 }
}
```

The compiler will take the conservative approach and not parallelize this loop.
If you are sure that x[] and y[] are not aliased then use:

foo(int * restricted x, int * restricted y, ….)

```
void foo(int * x, int * y, int n, int m){
 int a[2048], b[2048];

 #pragma acc kernels copy(x[0:2048], y[0:2048], a, b)
 {
    //no data dependence
    #pragma acc loop
    for( int i =0; i < 2047; i++){
                a[i] = b[i+1] + 1;
    }

   //data dependence
   #pragma acc loop
    for( int j =0; j < 2047; j++){
                a[j] = a[j+1] + 1;
    }

   // no data dependence if x[] is not aliased with y[]
   #pragma acc loop
    for( int k =0; k < 2047; k++){
                x[i] = y[i+1] + 1;
    }

   //no data dependence if n >= m
   #pragma acc loop
    for( int l =0; l < m; l++){
                x[l] = x[l+n] + 1;
    }


 }
}
```

The compiler will take the conservative approach and not parallelize this loop.

If you are sure that it can be parallelized, then use:

#pragma acc loop independent

Some Words About Data Constructs

- Loop control variable is private to each thread.
- copyin: to the device
- copyout: from the device
- copy: both and automatically
- Example: **#pragma acc data copy(array[i:n])**
  - i: the start index (can be anything)
  - n: number of elements to be copied

Some Words About Data Constructs

```
#pragma acc loop
for(int j = 0; j < m; j++)
#pragma acc cache (b[j])
  b[j] = b[j] *c;
```

Tells the compiler that each iteration of the for-loop uses one element of array b.
→
The compiler will try to move n elements to fast memory.

Is this Code Correct?

```
#pragma acc parallel{
   #pragma acc loop
   for(int i = 0; i < 1000; i++){
        a[i] = b[i];
   }
   #pragma acc loop
   for(int i = 0; i < 1000; i++){
        b[i] = b[i] * 2;
         c[i] = n[i] + a[i];
   }
}
```

Is this Code Correct?

```
#pragma acc kernels{
  #pragma acc loop
  for(int i = 0; i < 1000; i++){
      a[i] = b[i];
  }
  #pragma acc loop
  for(int i = 0; i < 1000; i++){
      b[i] = b[i] * 2;
      c[i] = n[i] + a[i];
  }
}
```

OpenACC CIMS Machines

module load pgi

For GPU:

pgcc -acc -Minfo filename.c

For multicore:

pgcc -acc -ta=multicore -Minfo filename.c

Conclusions

- OpenACC is easy to learn and gets you to a fast start to use an accelerators.
- Directives on top of C, C++, and Fortran
- Compared with CUDA, OpenACC gives you less control of how the final code on the accelerator will be.
- OpenACC can be used fairly fine with CUDA and its libraries.