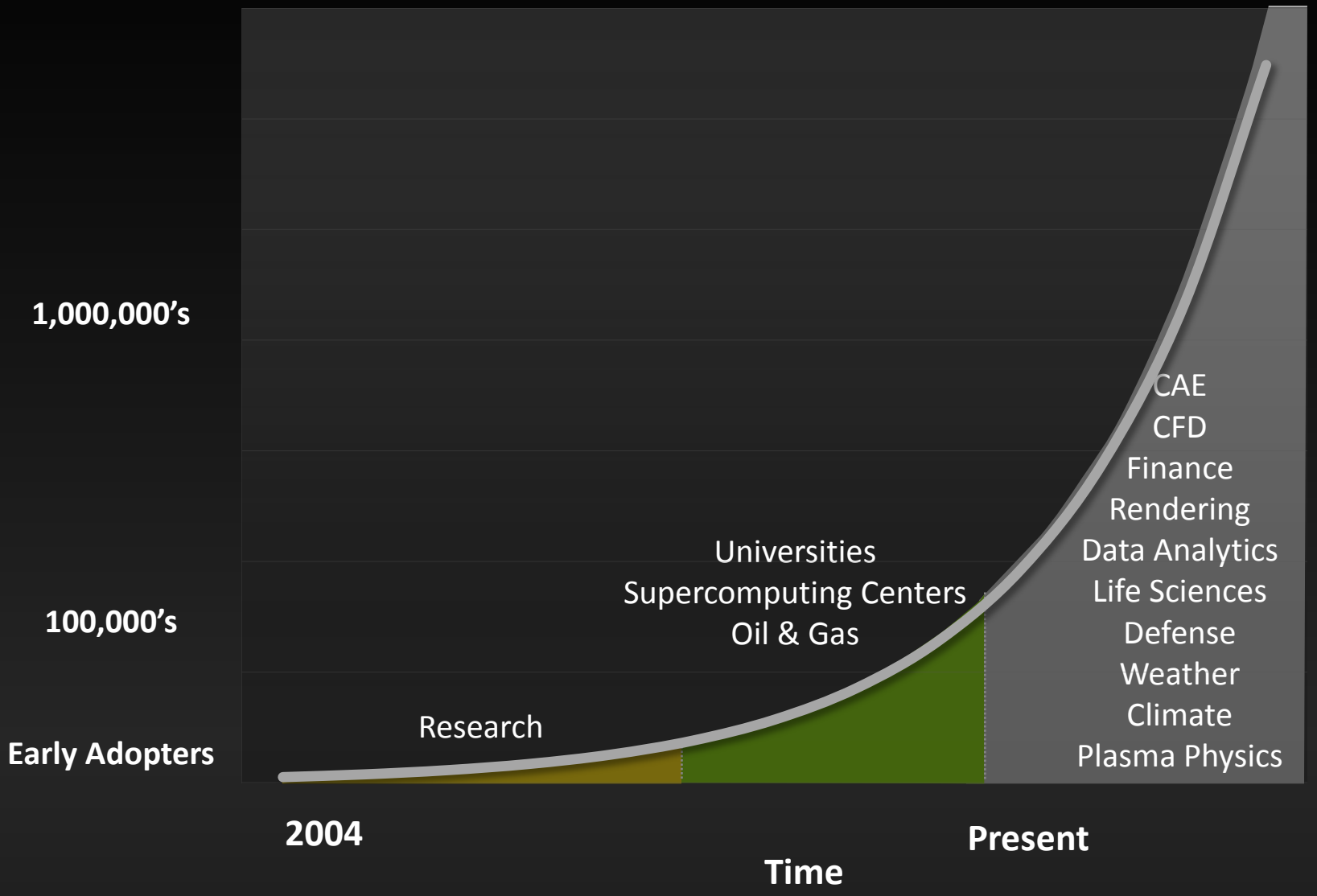
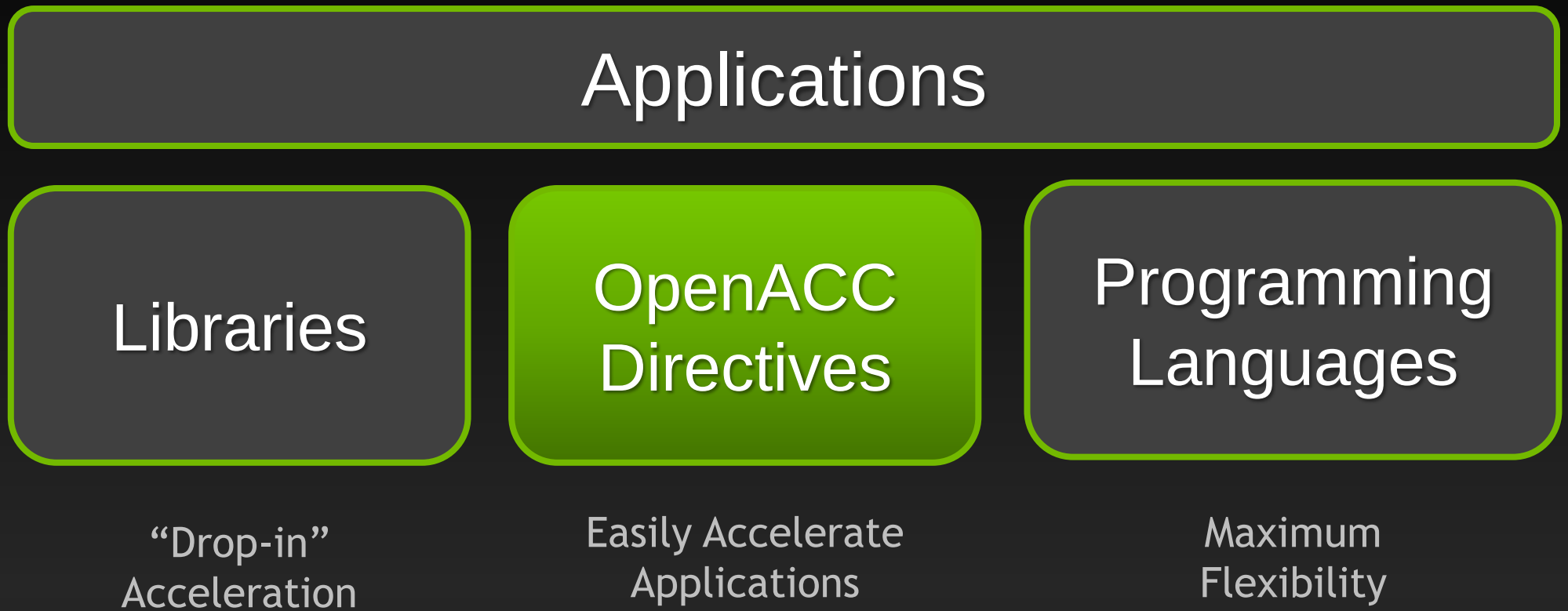

Introduction to
OpenACC
16 May 2013
NVIDIA

# GPUs Reaching Broader Set of Developers



# 3 Ways to Accelerate Applications



# Introducing OpenACC
## The Standard for GPU Directives

- OpenACC allows programmers to provide simple hints, known as “directives” to the compiler.
- These directives identify which areas of code to accelerate, without requiring programmers to modify or adapt the underlying code itself.
- By exposing parallelism to the compiler, directives allow the compiler to do the detailed work of mapping the computation onto the accelerator.

# Advantages of OpenACC

- **Easy:** OpenACC directives supply an easy path to accelerate compute intensive applications.
  - Modelled on the familiar OpenMP directives format.
- **Open:** OpenACC is an open GPU directives standard, making GPU programming straightforward and portable.
  - Currently Nvidia GPUs and multicore CPUs. More to come…
- **Powerful:** GPU Directives allow complete access to the massively parallel power of a GPU.

OpenACC®
DIRECTIVES FOR ACCELERATORS

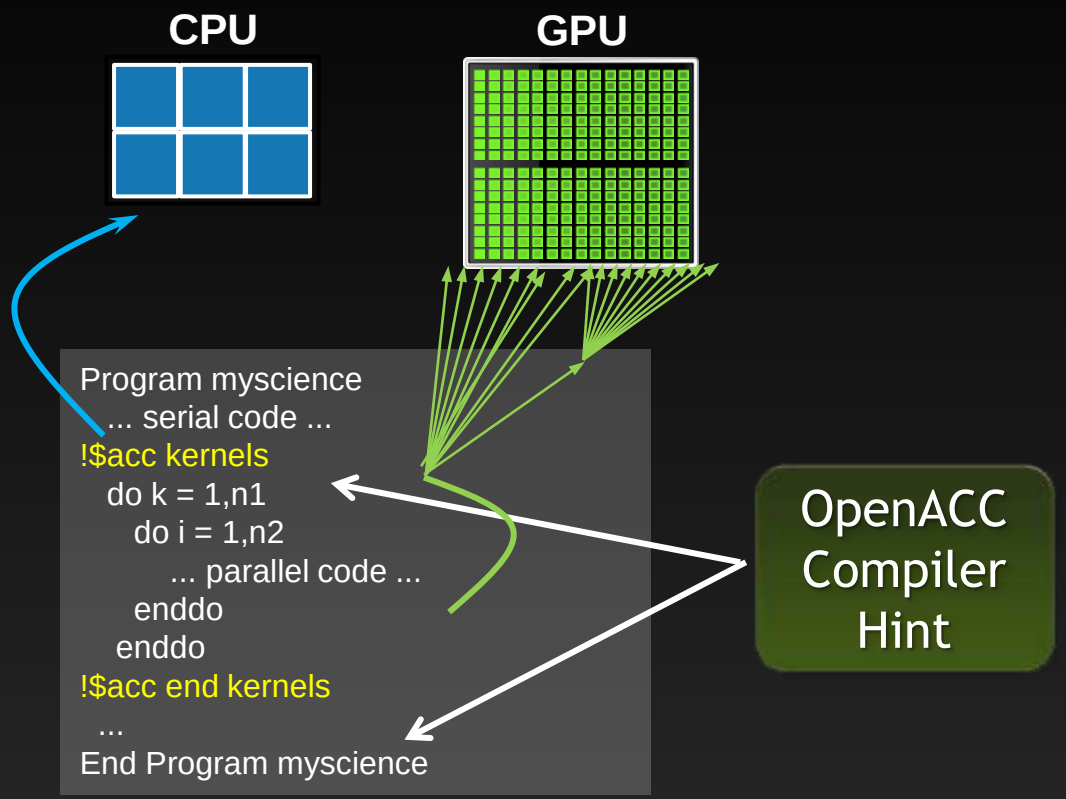
# High-Level Language...

- Compiler directives to specify parallel regions in C & Fortran.
  - Offload parallel regions.
  - Portable across OSes, host CPUs, accelerators, and compilers.
- Create high-level heterogeneous programs.
  - Without explicit accelerator initialization.
  - Without explicit data or program transfers between host and accelerator.

# …Low-Level Access

- Programming model allows programmers to start simple.
  - Compiler gives additional guidance.
- Loop mappings, data location, and other performance details.
- Compatible with other GPU languages and libraries.
  - Interoperate between CUDA C/Fortran and GPU libraries.
  - e.g. CUFFT, CUBLAS, CUSPARSE, etc.

# OpenACC Directives Overview




Your original
Fortran or C code

Simple Compiler hints

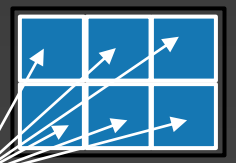
Compiler Parallelises code

Works on many-core GPUs & multicore CPUs

# Familiar to OpenMP Programmers

## OpenMP

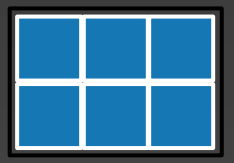
CPU



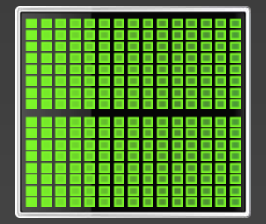
```
main() {
  double pi = 0.0; long i;

  #pragma omp parallel for reduction(+:pi)
  for (i=0; i<N; i++)
  {
    double t = (double)((i+0.05)/N);
    pi += 4.0/(1.0+t*t);
  }

  printf("pi = %f\n", pi/N);
}
```

## OpenACC

CPU



GPU



```
main() {
  double pi = 0.0; long i;

  #pragma acc kernels
  for (i=0; i<N; i++)
  {
    double t = (double)((i+0.05)/N);
    pi += 4.0/(1.0+t*t);
  }

printf("pi = %f\n", pi/N);
}
```

# Benefits of CUDA vs Time to Implement

- CUDA C/C++ or Fortran are powerful techniques, offering dramatic performance increases.
- While it has become increasingly user friendly, there are many programmers who can't afford the time to learn and apply a parallel programming language.
- Scientists and engineers also work with huge existing code bases and can only make minor changes to their code that are portable across hardware and operating systems.

# Directives: Easy & Powerful

## Real-Time Object Detection

Global Manufacturer of Navigation Systems


**5x in 40 Hours**

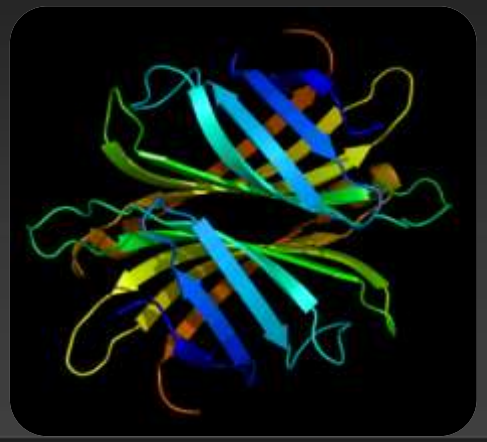
## Valuation of Stock Portfolios using Monte Carlo

Global Technology Consulting Company


**2x in 4 Hours**

## Interaction of Solvents and Biomolecules

University of Texas at San Antonio



**5x in 8 Hours**

# Local Success with OpenACC

**The University of Melbourne**

**Department of Zoology**

Professor Kerry Black

65x in 48 hours

Better understand complex reasons by lifecycles of snapper fish in Port Phillip Bay


* Achieved using the PGI Accelerator Compiler

# OpenACC Specification and Website

- Full OpenACC 1.0 Specification available online.
- Public Comment Draft of 2.0 Specification now available online.

www.openacc.org

- Quick reference card also available.

- Beta implementations available now from PGI, Cray, and CAPS.

# How does it work?

- Programmers provide simple hints to the compiler.
- In C/C++ these hints are implemented using the `#pragma acc` directive (`!$acc` in Fortan).
- The '`acc`' identifier directives tell the compiler to enable accelerator functions during the compilation of your program code.
- A fully defined accelerator directive should look as follows:

  `#pragma acc` *`directive-name`* `[`*`clause`* `[[,]` *`clause`*`]…]`

# OpenACC Directives

- There *directive-name* specifies the type of accelerator action you want to perform.
- For example, `#pragma acc kernels` is an OpenACC directive that compiles a region of your program into a sequence of kernels to execute on your GPU device.
- The *clause* provides specific instructions for the chosen directive.
- For example, `#pragma acc kernels copyin(A[0:n])` declares that array A has values that need to be copied to the device memory.

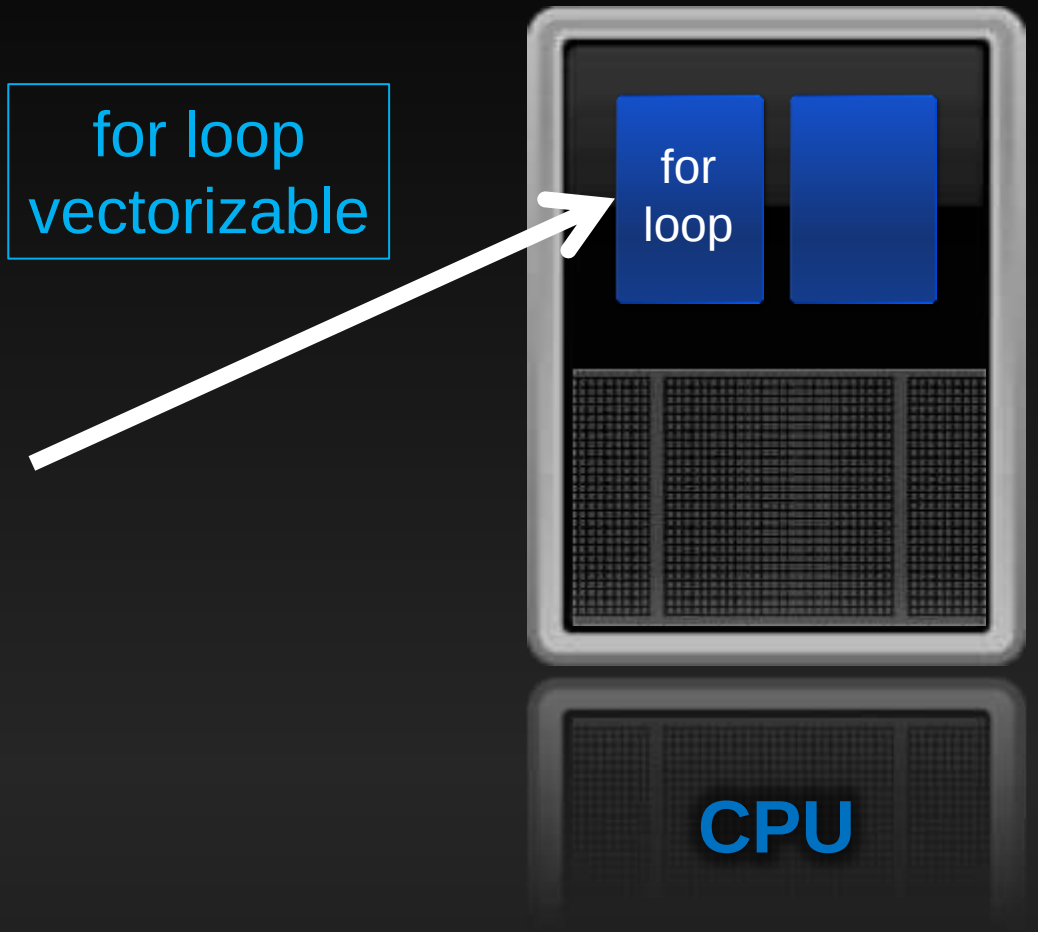
# OpenACC Directives

- There *directive-name* specifies the type of accelerator action you want to perform.
- For example, `#pragma acc kernels` is an OpenACC directive that compiles a region of your program into a sequence of kernels to execute on your GPU device.
- The *clause* provides specific … directive.
- For example, `#pragma acc kernels copyin(A[0:n])` declares that array A has values that need to be copied to the device memory.

**NB: This is NOT array 'slice' notation (Python, MATLAB, Fortran users beware!!)**
**This means start at idx 0 and copy the following n elements**

# Example: Vector Addition Serial Code

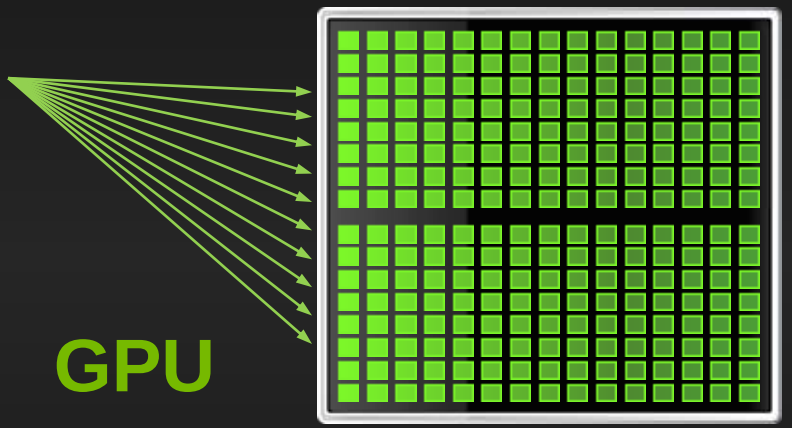
```
int main ()
{
  ...serial code...

  for( i=0; i < n; i++) {
      c[i] = a[i] + b[i]
  }

  ...serial code...
}
```



# Vector Addition Device Code (CUDA)

Launch a CUDA kernel for the Vector addition

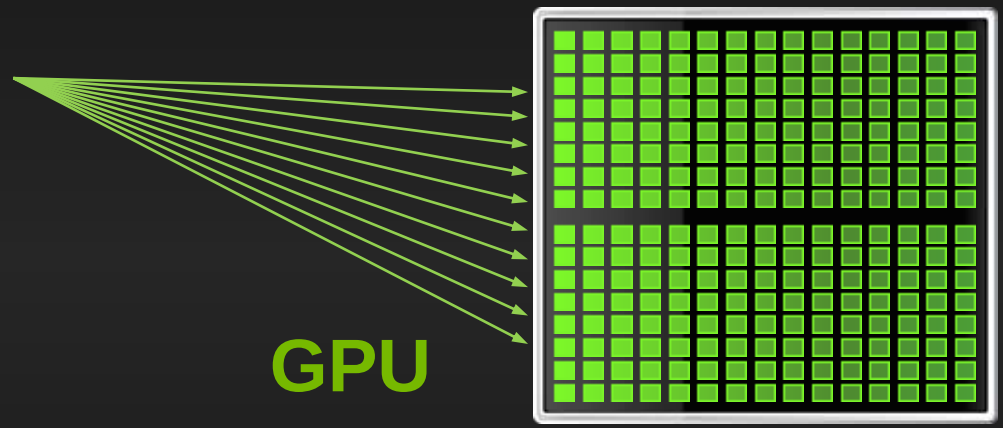
```
__global__ void vecaddgpu(float *r, float *a, float *b, int n)
{
    // Get global thread ID
    int id = blockIdx.x*blockDim.x+threadIdx.x;

    // Make sure we do not go out of bounds
    if (id < n)
        c[id] = a[id] + b[id];
}
```



# Vector Addition Device Code (OpenACC)

Accelerator Kernel launched with #pragma acc

```
void vecaddgpu( float *restrict r, float *a, float *b, int n )
{
   //Launch GPU Accelerator Kernel
   #pragma acc kernels copyin(a[0:n],b[0:n]) copyout(c[0:n])

       for( int i = 0; i < n; ++i ) {
       c[i] = a[i] + b[i];
       }
}
```



# Device Code: What's Similar?

- Both techniques require an accelerator (i.e. GPU) kernel to be launched on the device.
- The host variables (e.g. arrays) need to be copied from the host memory to the device memory.
- Values in the device memory need to be copied back to the host memory at the end of the accelerator region.

# Device Code: What's Changed?

- `#pragma acc` directive replaces `__global__` as the GPU kernel generator.
- Variables are copied from host to device (and vice versa) using `#pragma acc (copyin() & copyout())` directive clauses instead of using `cudaMemcpy()` in the host code.
- Thread id allocation (`blockIdx.x*blockDim.x+threadIdx.x`) is handled 'behind the scenes' by OpenACC.
- A `restrict` keyword is placed on array 'r' (explained later).

# OpenACC parallel vs. kernels


**PARALLEL**

- Requires analysis by programmer to ensure safe parallelism
- Straightforward path from OpenMP

**KERNELS**

- Compiler performs parallel analysis and parallelizes what it believes safe
- Can cover larger area of code with single directive

Both approaches are equally valid and can perform equally well.

# Kernels Construct

Each loop is executed as a separate kernel on the GPU.

```
#pragma acc kernels
   for (i=0; i<n; i++){
        a(i) = 0.0
        b(i) = 1.0
        c(i) = 2.0
   }

   for (i=0; i<n; i++){
        a(i) = b(i) + c(i)
   }
```

kernel 1

kernel 2

The two kernels will execute synchronously by default

# Kernels Clauses

- `if( condition )`

Generates two copies of the construct (host and device) and executes one of the copies when an IF condition is reached.

- `async [( scalar-integer-expression )]`

The kernels region will be executed by the accelerator device asynchronously while the host process continues with the code following the region.

- `copy( list )`

Allocates memory on the GPU and copies the data from the host when entering the region, and copies data back to the host when exiting region.

- `copyin( list )`

Allocates GPU memory and copies data from the host when entering the region.

# Kernels Clauses

- `copyout( list )`

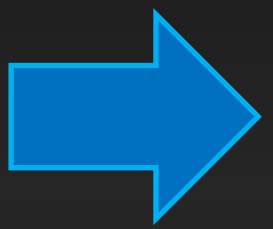
Allocates host memory copies data to the host when exiting the region.

- `create( list )`

Allocates memory on the GPU but does not copy.

Other clauses include:

- `present( list )`
- `present_or_copy( list )`
- `present_or_copyin( list )`
- `present_or_copyout( list )`
- `present_or_create( list )`
- `deviceptr( list )`



For more information on clauses:

http://www.openacc.org/sites/default/files/OpenACC.1.0_0.pdf

# The restrict keyword

- Applied to a pointer. For example:

```
float* restrict r
```

- Without the `restrict` keyword, pointer aliasing may occur, whereby the same memory location can be accessed using different names.

- OpenACC compilers often require the `restrict` keyword to determine independence of memory locations.
  - Otherwise the compiler can't parallelize loops that access `r`.

http://en.wikipedia.org/wiki/Restrict

# Vector Addition Host Code (CUDA)

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>

// CUDA kernel. Each thread takes care of one element of c
__global__ void vecaddgpu(float *d_a, float *d_b, float *d_c, int n)
{
    //Device Code
}

int main( int argc, char* argv[] )
{
    // Size of vectors
    int n = 100000;
    float *h_a;
    float *h_b;
    float *h_c;
    float *d_a;
    float *d_b;
    float *d_c;

    // Allocate memory for each vector on host
    size_t bytes = n*sizeof(float);
    h_a = (float*)malloc(bytes);
    h_b = (float*)malloc(bytes);
    h_c = (float*)malloc(bytes);

    // Allocate memory for each vector on GPU
    cudaMalloc(&d_a, bytes);
    cudaMalloc(&d_b, bytes);
    cudaMalloc(&d_c, bytes);

    // Initialize vectors on host
    int i;
    for( i = 0; i < n; i++ ) {
        h_a[i] = sinf(i)*sinf(i);
        h_b[i] = cosf(i)*cosf(i);
    }

    // Copy host vectors to device
    cudaMemcpy( d_a, h_a, bytes, cudaMemcpyHostToDevice);
    cudaMemcpy( d_b, h_b, bytes, cudaMemcpyHostToDevice);

    // Execute the kernel
    int blockSize, gridSize;
    blockSize = 1024;
    gridSize = (int)ceil((float)n/blockSize);
    vecaddgpu<<<gridSize, blockSize>>>(d_a, d_b, d_c, n);

    // Copy array back to host
    cudaMemcpy( h_c, d_c, bytes, cudaMemcpyDeviceToHost );

    // Sum up vector c and print result divided by n, this should equal 1 within
error
    float sum = 0;
    for(i=0; i<n; i++)
        sum += h_c[i];
    printf("final result: %f\n", sum/n);

    // Release device memory
    cudaFree(d_a);
    cudaFree(d_b);
    cudaFree(d_c);

    // Release host memory
    free(h_a);
    free(h_b);
    free(h_c);

    return 0;
}
```

- Device kernel `__global__ void vecAddGpu( ... )`
- Explicitly define separate host `h_x` and device `d_x` vectors
- Allocate host vector memory using `malloc()`
- Allocate device vector memory using `cudaMalloc()`
- Initialise vectors on host (`for loop`)
- Copy initialised values to device using `cudaMemcpy()`
- Launch kernel to do work `vecaddgpu<<< ... >>>`
- Copy result vector from device to host using `cudaMemcpy()`
- Free device memory using `cudaFree()`
- Free host memory using `free()`

# Host Code: OpenACC

- What is one of the most significant differences between host-only and combined host+accelerator based programs?

## MEMORY

- In accelerator programming languages such as CUDA, data movement between the memories can dominate the user's host code.
- In the OpenACC model, data movement between the memories is implicit and managed by the compiler.
- Controlled by the directives from the programmer (e.g. `copyin(list)`)

# Host Code: OpenACC

- While less code-intensive, programmers must be aware of the potentially separate memories for reasons including (but not limited to):
- Memory bandwidth between host and device, which determines the compute intensity required to accelerate a region of code.
- Device memory size, which can prohibit offloading regions of code that operate on very large amounts of data.

# Vector Addition Host Code (OpenACC)

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>

// CUDA kernel. Each thread takes care of one element of c
void vecaddgpu(float *d_a, float *d_b, float *restrict d_c, int n)
{
    #pragma acc kernels copyin(d_a[0:n],d_b[0:n]) copyout(d_c[0:n])
    for (int i = 0; i < n; ++i)
        d_c[i] = d_a[i] + d_b[i]; "regular" for loop
}

int main( int argc, char* argv[] )
{
    // Size of vectors
    int n = 100000;
    float *h_a;
    float *h_b;
    float *h_c;
    float *d_a;
    float *d_b;
    float *d_c;

    // Allocate memory for each vector on host
    size_t bytes = n*sizeof(float);
    h_a = (float*)malloc(bytes);
    h_b = (float*)malloc(bytes);
    h_c = (float*)malloc(bytes);

    // Allocate memory for each vector on GPU
    cudaMalloc(&d_a, bytes);
    cudaMalloc(&d_b, bytes);
    cudaMalloc(&d_c, bytes);

    // Initialize vectors on host
    int i;
    for( i = 0; i < n; i++ ) {
        h_a[i] = sinf(i)*sinf(i);
        h_b[i] = cosf(i)*cosf(i);
    }

    // Copy host vectors to device
    cudaMemcpy( d_a, h_a, bytes, cudaMemcpyHostToDevice);
    cudaMemcpy( d_b, h_b, bytes, cudaMemcpyHostToDevice);

    // Execute the kernel
    int blockSize, gridSize;
    blockSize = 1024;
    gridSize = (int)ceil((float)n/blockSize);
    vecaddgpu<<<gridSize, blockSize>>>(d_a, d_b, d_c, n);

    // Copy array back to host
    cudaMemcpy( h_c, d_c, bytes, cudaMemcpyDeviceToHost );

    // Sum up vector c and print result divided by n, this should equal 1 within
error
    float sum = 0;
    for(i=0; i<n; i++)
        sum += h_c[i];
    printf("final result: %f\n", sum/n);

    // Release device memory
    cudaFree(d_a);
    cudaFree(d_b);
    cudaFree(d_c);

    // Release host memory
    free(h_a);
    free(h_b);
    free(h_c);

    return 0;
}
```

- Remove `__global__` and replace device code with `#pragma acc kernels copyin(...) copyout(...)`
- Define host `h_x` and device `d_x` vectors
- Allocate host vector memory using `malloc()`
- Allocate device vector memory using `cudaMalloc()`
- Initialise vectors on host (`for loop`)
- Copy initialised values to device using `cudaMemcpy()`
- Launch kernel to do work `vecaddgpu<<< ... >>>`
- Copy result vector from device to host using `cudaMemcpy()`
- Free device memory using `cudaFree()`
- Free host memory using `free()`

# Vector Addition Host Code (OpenACC)

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>

// CUDA kernel. Each thread takes care of one element of c
void vecaddgpu(float *a, float *b, float *restrict c, int n)
{
    #pragma acc kernels copyin(a[0:n],b[0:n]) copyout(c[0:n])
    for (int i = 0; i < n; ++i)
        c[i] = a[i] + b[i];}
}

int main( int argc, char* argv[] )
{
    // Size of vectors
    int n = 100000;
    float *a;
    float *b;
    float *c;



    // Allocate memory for each vector on host
    size_t bytes = n*sizeof(float);
    a = (float*)malloc(bytes);
    b = (float*)malloc(bytes);
    c = (float*)malloc(bytes);




    // Initialize vectors on host
    int i;
    for( i = 0; i < n; i++ ) {
        a[i] = sinf(i)*sinf(i);
        b[i] = cosf(i)*cosf(i);
    }



    // Execute the kernel
    vecaddgpu(a, b, c, n);




    // Sum up vector c and print result divided by n, this should equal 1 within
error
    float sum = 0;
    for(i=0; i<n; i++)
        sum += c[i];
    printf("final result: %f\n", sum/n);




    // Release host memory
    free(a);
    free(b);
    free(c);

    return 0;
}
```

"regular" for loop

Remove `__global__` and replace device code with `#pragma acc kernels copyin(...) copyout(...)`

Allocate host vector memory using `malloc()`

Initialise vectors on host (`for loop`)

Call `vecaddgpu()` function normally to run on GPU

Free host memory using `free()`

# Vector Addition Host Code (OpenACC)

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>

// CUDA kernel. Each thread takes care of one element of c
void vecaddgpu(float *a, float *b, float *restrict c, int n)
{
    #pragma acc kernels copyin(a[0:n],b[0:n]) copyout(c[0:n])
    for (int i = 0; i < n; ++i)
        c[i] = a[i] + b[i];}
}

int main( int argc, char* argv[] )
{
    // Size of vectors
    int n = 100000;
    float *a;
    float *b;
    float *c;

    // Allocate memory for each vector on host
    size_t bytes = n*sizeof(float);
    a = (float*)malloc(bytes);
    b = (float*)malloc(bytes);
    c = (float*)malloc(bytes);

    // Initialize vectors on host
    int i;
    for( i = 0; i < n; i++ ) {
        a[i] = sinf(i)*sinf(i);
        b[i] = cosf(i)*cosf(i);
    }

    // Execute the kernel
    vecaddgpu(a, b, c, n);

    // Sum up vector c and print result divided by n, this should equal 1 within
error
    float sum = 0;
    for(i=0; i<n; i++)
        sum += [i];
    printf("final result: %f\n", sum/n);

    // Release host memory
    free(a);
    free(b);
    free(c);

    return 0;
}
```

- Remove `__global__` and replace device code with `#pragma acc kernels copyin(...) copyout(...)`
- Allocate host vector memory using `malloc()`
  - Device memory allocated inside the `copyin()` clause
- Initialise vectors on host (`for loop`)
  - Values copied to device using the `copyin()` clause
- Call `vecaddgpu` function normally to run on GPU
  - Vectors copied back to host using the `copyout()` clause
- Free host memory using `free()`
  - Device memory is automatically freed

# OpenACC compliant compilers

- OpenACC requires a compliant compiler that understands OpenACC directives.
- GCC is NOT one of them (yet…)
- The examples used the PGI Accelerator that is part of a software toolkit called *PGI Workstation* by The Portland Group.
  - OpenACC directives in C and Fortran: target GPU + multicore CPU
  - Also compiles “CUDA Fortran”
  - Other advanced compiler optimisation routines: often 2x over gcc or VS
  - See http://www.pgroup.com/ for more information.

# Compile and run

- **Compile your code by entering the following at the command line.**

```
pgcc –acc -ta=nvidia,host -Minfo vecaddgpu.c
```

| | |
|---|---|
| `pgcc` | Command to invoke the C Compiler. |
| `–acc` | Flag to enable the OpenACC `#pragma`'s and includes the OpenACC runtime library (i.e. `#include "openacc.h"`). |
| `-ta=nvidia,host` | Flag to set the NVIDIA GPU or CPU as the target accelerator device. Falls back to CPU if no compatible GPU at runtime! |
| `-Minfo` | Flag that displays compile-time optimization listings. |

# -Minfo output can be helpful…

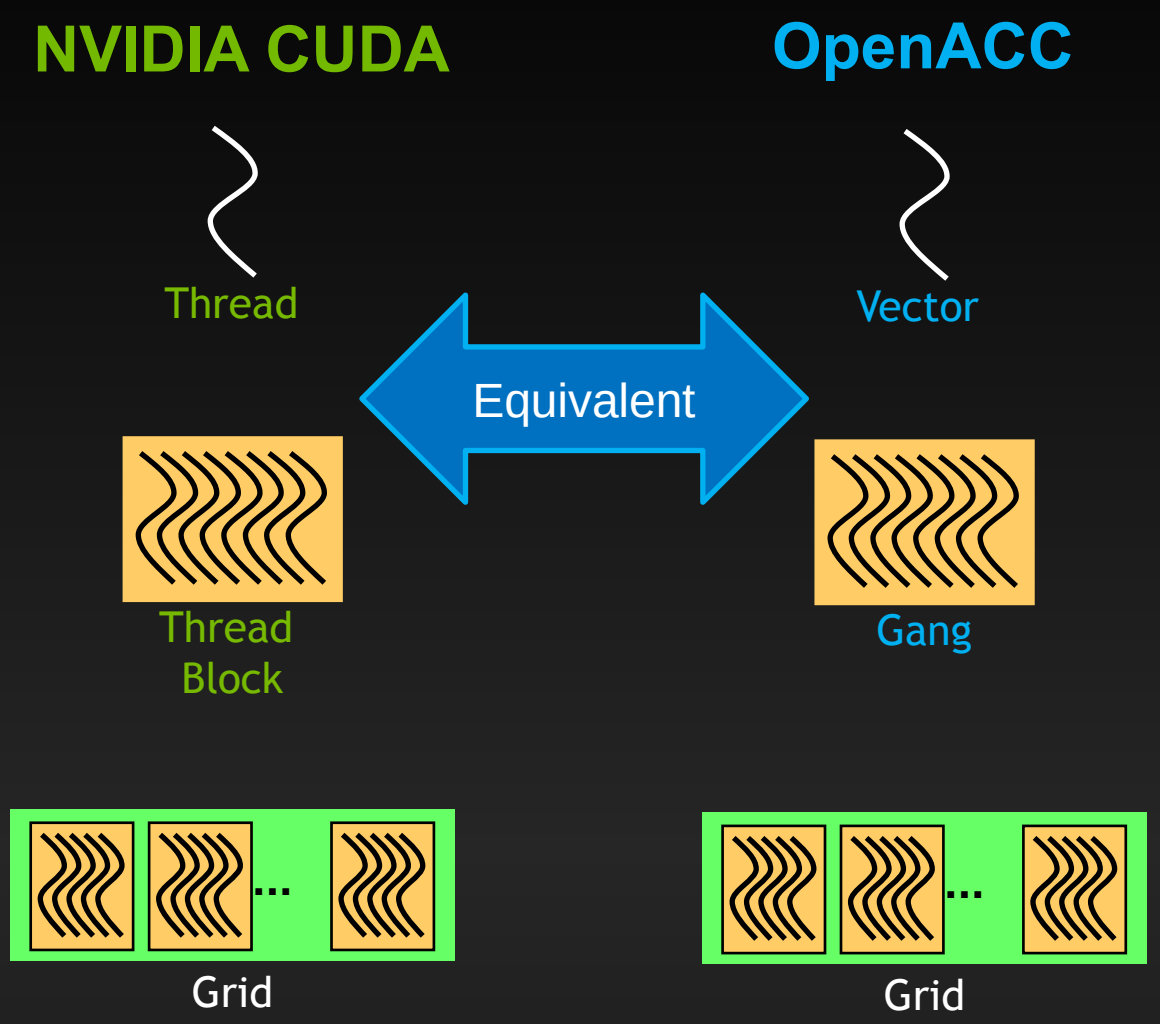
```
pgcc –acc -ta=nvidia -Minfo vecaddgpu.c
vecaddgpu:

5,Generating copyout(c[:n])
Generating copyin(a[:n])
Generating copyin(b[:n])
Generating compute capability 1.0 binary
Generating compute capability 2.0 binary

6, Loop is parallelizable
Accelerator kernel generated

6, #pragma acc loop gang, vector(256) /* blockIdx.x threadIdx.x */

CC 1.0 : 5 registers; 60 shared, 4 constant, 0 local memory bytes; 100% occupancy
CC 2.0 : 8 registers; 8 shared, 68 constant, 0 local memory bytes; 100% occupancy
```

Generates multiple versions

Successful parallelisation

Sets gangs & vectors

# What are gangs and vectors?




The OpenACC execution model has three levels:

- Gang - Thread block
- Worker - Warp
- Vector - Threads in a Warp

The OpenACC compiler directives can automatically setup gangs, workers & vectors when running your code.

Advantage: Less coding effort

Disadvantage: Potentially lower speed-ups

# Controlling Gangs and Vectors Inside a ‘kernels’ directive

- To improve speed-ups, it is possible to control block and thread configurations in OpenACC by using the gang and vector clauses.

Example:

‘loop’ construct:
Parallelises only the immediately proceeding loop after this directive

```
#pragma acc kernels loop gang(100) vector(128)
    for (i = 0; i < N; ++i) { ... }
```

- Translation: Use a up to 100 gangs, and up to a vector length of 128 within each gang.

# Controlling Gangs and Vectors Inside a 'parallel' directive

- To improve speed-ups, it is possible to control block and thread configurations in OpenACC by using the gang and vector clauses.

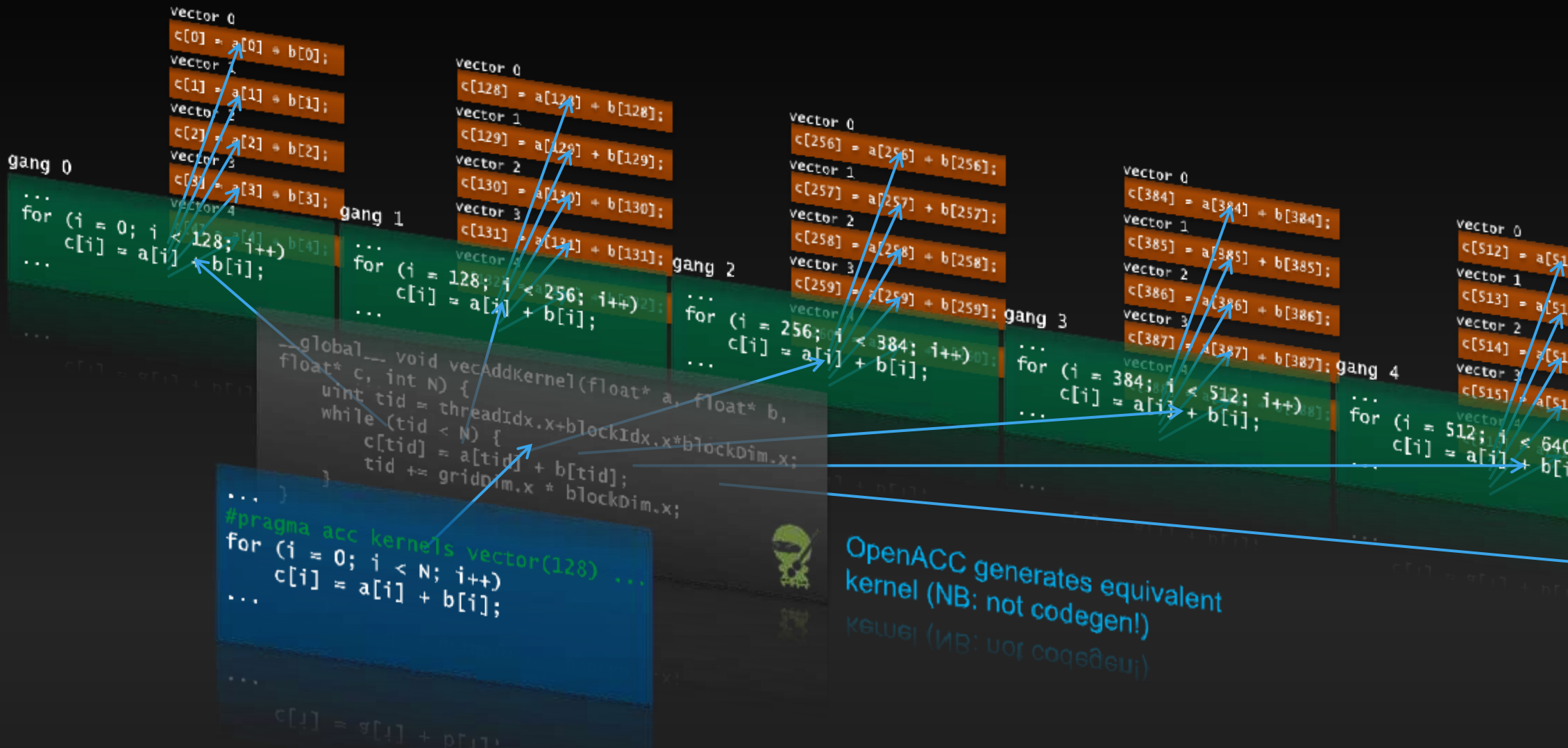
Example:

'parallel' directive only fires up the requested workers… requires you to explicitly identify which loops to use them on!

```
#pragma acc parallel num_gangs(100) vector_length(128)
    #pragma acc loop
        for (i = 0; i < N; ++i) { ... }
```

- Translation: 1st pragma: Use 100 gangs, each with vector length 128.
  2nd pragma: Share the work in the loop across workers

# OpenACC Process Flow



# Useful environment variables

```
C:\Working_Dir\vecaddgpu.exe

11: region entered 1 time
        time(us): total=404,000 init=45,000 region=359,000
                  kernels=47,555 data=300,934
        w/o init: total=359,000 max=359,000 min=359,000 avg=359,000


13: kernel launched 1 times
            grid: [65535]  block: [256]
            time(us): total=47,555 max=47,555 min=47,555 avg=47,555
```

PGI_ACC_TIME=1

PGI_ACC_NOTIFY=1

# Vector addition results

| n | Total (μs) | Init (μs) | region (μs) | kernels (μs) | data (μs) | CPU (μs) |
|---|---|---|---|---|---|---|
| 1000 | 48000 | 45200 | 2800 | 7 | 225.6 | 0 |
| 10000 | 46800 | 43800 | 3000 | 10.4 | 303.6 | 0 |
| 100000 | 49000 | 45400 | 3600 | 54.4 | 994.6 | 0 |
| 1000000 | 53400 | 46000 | 7400 | 480.6 | 4298.6 | 1400 |
| 10000000 | 82600 | 43200 | 39400 | 4707.6 | 31800 | 16200 |
| 100000000 | 403800 | 46000 | 357800 | 47562.4 | 299881.6 | 160400 |

- GPU initialisation is fixed; therefore it dominates for small n.
- Data transfer dominates for large n.

# Vector addition speedups

| n | GPU Speedup (kernel) | GPU Speedup (kernel+data) | Data(%) |
|---|---|---|---|
| 1000 | 0 | 0 | 0.970 |
| 10000 | 0 | 0 | 0.967 |
| 100000 | 0 | 0 | 0.948 |
| 1000000 | 2.913 | 0.293 | 0.899 |
| 10000000 | 3.441 | 0.444 | 0.871 |
| 100000000 | 3.372 | 0.462 | 0.863 |

- A 3x speedup achieved without data transfer.
- Worse performance when data transfer times are considered.
- Need to have higher compute intensity to offset data transfer overheads.
  - Each thread needs to do more work to justify the data transfer overhead!

# In summary

- OpenACC is easy, powerful and portable.
- Can target Nvidia GPUs and multicore CPUs.
  - Use, `-ta=nvidia,host` flag at the command line.
- Can use the `kernels` directive to automatically parallelise code regions or the `parallel` directive or more fine-grained control.
- Currently all function calls must be in-lineable.
  - Changing in OpenACC 2.0.
- Important: Find where bottlenecks in your code are.
  - Use profiling tools (PGPROF, gprof, etc…)
  - Ask for help ☺


Thank You
NVIDIA