LAU
الجامعة اللبنانية الأميركية
Lebanese American University

CSC 447: Parallel Programming for Multi-Core and Cluster Systems

OPENACC

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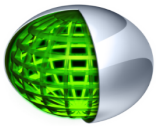
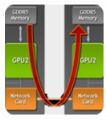
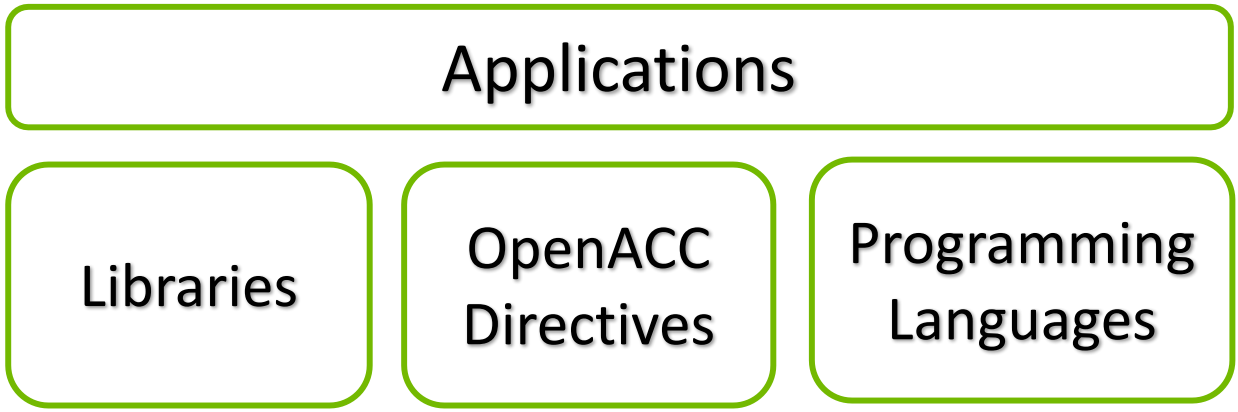
Spring 2016

Programming Approaches	Libraries	OpenACC Directives	Programming Languages
	"Drop-in" Acceleration	Easily Accelerate Apps	Maximum Flexibility
Development Environment		Nsight IDE Linux, Mac and Windows GPU Debugging and Profiling	CUDA-GDB debugger NVIDIA Visual Profiler
Open Compiler Tool Chain		Enables compiling new languages to CUDA platform, and CUDA languages to other architectures	
Hardware Capabilities	SMX 	Dynamic Parallelism 	HyperQ 
			GPUDire 

3 Ways to Accelerate Applications

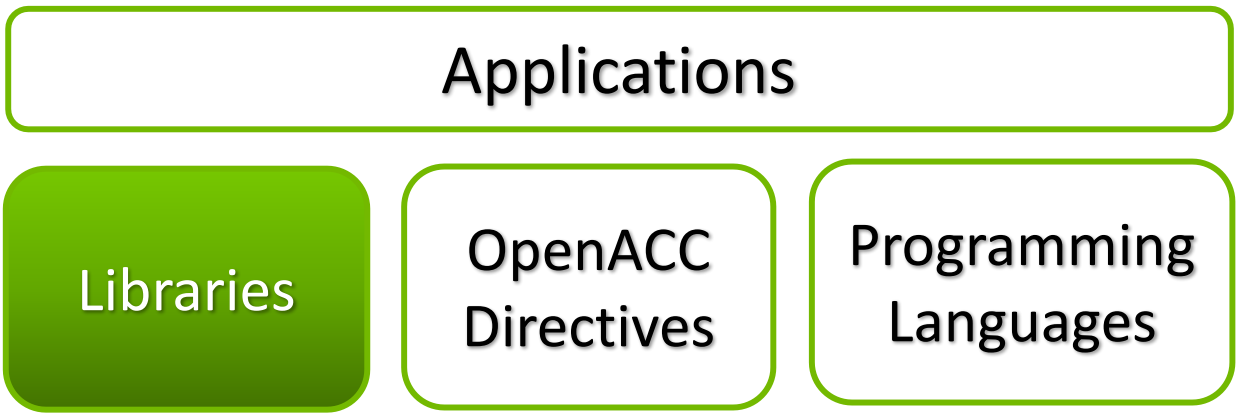


"Drop-in" Acceleration

Easily Accelerate Applications

Maximum Flexibility

3 Ways to Accelerate Applications



"Drop-in" Acceleration

Easily Accelerate Applications

Maximum Flexibility

Libraries: Easy, High-Quality Acceleration

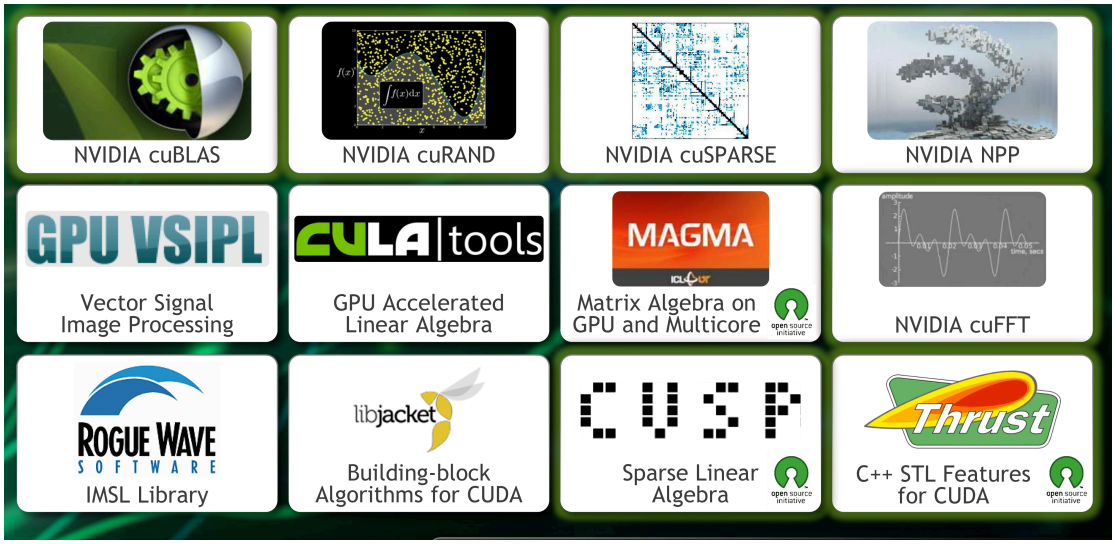
Ease of use: Using libraries enables GPU acceleration without in-depth knowledge of GPU programming

"Drop-in": Many GPU-accelerated libraries follow standard APIs, thus enabling acceleration with minimal code changes

Quality: Libraries offer high-quality implementations of functions encountered in a broad range of applications

Performance: NVIDIA libraries are tuned by experts

Libraries: Easy, High-Quality Acceleration



CUDA Math Libraries

High performance math routines for your applications:

- cuFFT - Fast Fourier Transforms Library
- cuBLAS - Complete BLAS Library
- cuSPARSE - Sparse Matrix Library
- cuRAND - Random Number Generation (RNG) Library
- NPP - Performance Primitives for Image & Video Processing
- Thrust - Templated C++ Parallel Algorithms & Data Structures
- math.h - C99 floating-point Library

Included in the CUDA Toolkit Free download @ www.nvidia.com/getcuda

More information on CUDA libraries:

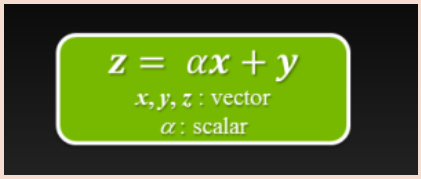
http://www.nvidia.com/object/gtc2010-presentation-archive.html#session2216

Deep Learning: Latest Addition

- NVIDIA cuDNN is a GPU-accelerated library of primitives for deep neural networks
- Designed to be integrated into higher-leve machine learning frameworks

Libraries: Easy, High-Quality Acceleration

```
void saxpy_serial(int n, float a, float *x, float *y)
{
    for (int i = 0; i < n; ++i)
        y[i] = a*x[i] + y[i];
}
```




```
saxpy(1<<20, 2.0, x, y);
```

Standard C Code

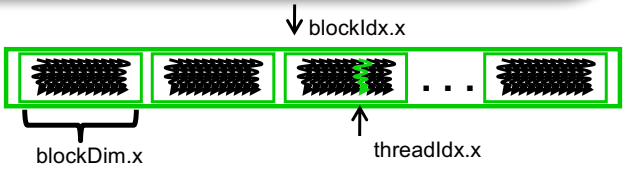
1 << 20 = 1,048,576

Libraries: Easy, High-Quality Acceleration

```
__global__ void saxpy_parallel(int n, float a, float
*x, float *y)
{
    int i = blockIdx.x*blockDim.x + threadIdx.x;
    if (i < n)  y[i] = a*x[i] + y[i];
}
```

```
saxpy<<<4096,256>>>(N, 2.0, x, y);
```

CUDA C Code



Libraries: Easy, High-Quality Acceleration

Copy n elements from a vector x in host memory space to a vector d_x in GPU memory space

```
CublasInit();
cublasSetVector(N, sizeof(x[0]), x, 1, d_x, 1);
cublasSetVector(N, sizeof(y[0]), y, 1, d_y, 1);

// Perform SAXPY on 1M elements
cublasSaxpy(N, 2.0, d_x, 1, d_y, 1);

cublasGetVector(N, sizeof(y[0]), d_y, 1, y, 1);
cublasShutdown();
```

CUBLAS C Code

Libraries: Easy, High-Quality Acceleration

- Step 1: Substitute library calls with equivalent CUDA library calls

  `saxpy ( … )` ▶ `cublasSaxpy ( … )`

- Step 2: Manage data locality

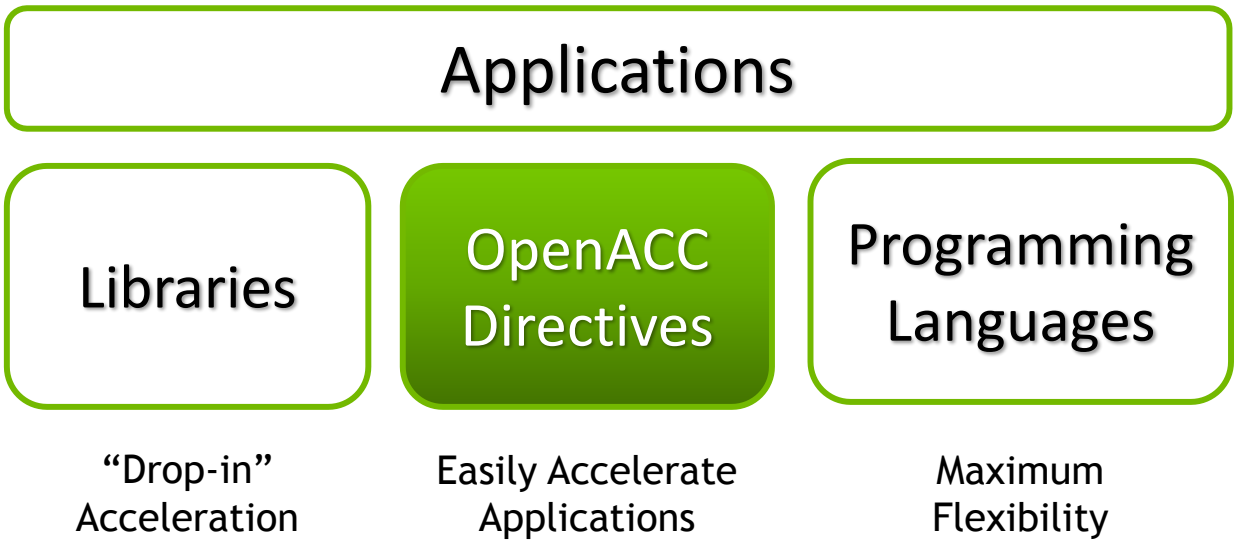
  with CUDA: `cudaMalloc(), cudaMemcpy(), etc.`

  with CUBLAS: `cublasSetVector(), cublasSetVector(), etc.`

- Step 3: Rebuild and link the CUDA-accelerated library

  ```
  nvcc myobj.o –l cublas
  ```

3 Ways to Accelerate Applications



OpenACC Directive Syntax

- `#pragma acc directive [clause [,] clause] …`
  Often followed by a structured code block

C tip: the restrict keyword

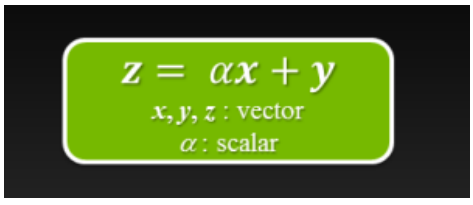
- Declaration of intent given by the programmer to the compiler
  - Applied to a pointer, e.g.

```
float *restrict ptr
```

  - Meaning: "for the lifetime of ptr, only it or a value directly derived from it (such as ptr + 1) will be used to access the object to which it points"*
  - Limits the effects of pointer aliasing
- OpenACC compilers often require restrict to determine independence
  - Otherwise the compiler can't parallelize loops that access ptr
  - Note: if programmer violates the declaration, behavior is undefined

SAXPY Revisited: OpenMP

SAXPY
- Single-Precision A·X Plus Y

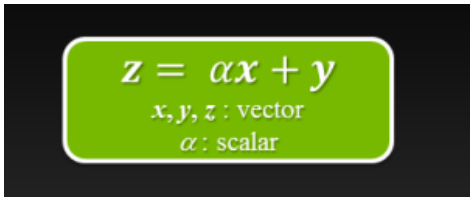



```
void saxpy(int n,
           float a,
           float *x,
           float *restrict y)
{
#pragma omp parallel for
  for (int i = 0; i < n; ++i)
    y[i] = a*x[i] + y[i];
}

...
// Perform SAXPY on 1M elements
saxpy(1<<20, 2.0, x, y);
...
```

SAXPY Revisited: OpenACC

SAXPY
- Single-Precision A·X Plus Y




```
void saxpy(int n,
           float a,
           float *x,
           float *restrict y)
{
#pragma acc parallel loop
  for (int i = 0; i < n; ++i)
    y[i] = a*x[i] + y[i];
}

...
// Perform SAXPY on 1M elements
saxpy(1<<20, 2.0, x, y);
...
```


OpenACC is not *GPU Programming.*

NVIDIA

OpenACC is *Exposing Parallelism* in your code.

Complete SAXPY example code

- Trivial first example
  - Apply a loop directive
  - Learn compiler commands

```
#include <stdlib.h>

void saxpy(int n,
           float a,
           float *x,
           float *restrict y)
{
#pragma acc kernels
  for (int i = 0; i < n; ++i)
    y[i] = a * x[i] + y[i];
}
```

*restrict:
"I promise y does not alias x"

```
int main(int argc, char **argv)
{
  int N = 1<<20; // 1 million floats

  if (argc > 1)
    N = atoi(argv[1]);

  oat *x = (float*)malloc(N * sizeof(float));
  oat *y = (float*)malloc(N * sizeof(float));

  r (int i = 0; i < N; ++i)
  {
    x[i] = 2.0f;
    y[i] = 1.0f;
  }

  saxpy(N, 3.0f, x, y);

  return 0;
}
```


Compile and run

- C:

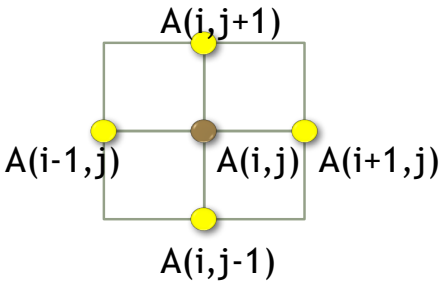
```
pgcc -acc -ta=nvidia -Minfo=accel -o saxpy_acc saxpy.c
```

- Compiler output:

```
pgcc -acc -Minfo=accel -ta=nvidia -o saxpy_acc saxpy.c
saxpy:
      8, Generating copyin(x[:n-1])
         Generating copy(y[:n-1])
         Generating compute capability 1.0 binary
         Generating compute capability 2.0 binary
      9, Loop is parallelizable
         Accelerator kernel generated
          9, #pragma acc loop worker, vector(256) /* blockIdx.x threadIdx.x */
             CC 1.0 : 4 registers; 52 shared, 4 constant, 0 local memory bytes; 100% occupancy
             CC 2.0 : 8 registers; 4 shared, 64 constant, 0 local memory bytes; 100% occupancy
```

Example 2: Jacobi Iteration

- Iteratively converges to correct value (e.g. Temperature), by computing new values at each point from the average of neighboring points.
  - Common, useful algorithm
  - Example: Solve Laplace equation in 2D:



Jacobi Iteration Code

```
while ( error > tol && iter < iter_max )
{
  error=0.0;

  for( int j = 1; j < n-1; j++) {
    for(int i = 1; i < m-1; i++) {

      Anew[j][i] = 0.25 * (A[j][i+1] + A[j][i-1] +
                           A[j-1][i] + A[j+1][i]);


      error = max(error, abs(Anew[j][i] - A[j][i]);
    }
  }
  for( int j = 1; j < n-1; j++) {
    for( int i = 1; i < m-1; i++ ) {
      A[j][i] = Anew[j][i];
    }
  }
  iter++;
}
```

Iterate until converged

Iterate across matrix elements

Calculate new value from neighbors

Compute max error for convergence

Swap input/output arrays

OpenMP C Code

```
while ( error > tol && iter < iter_max ) {
  error=0.0;

#pragma omp parallel for shared(m, n, Anew, A)
  for( int j = 1; j < n-1; j++) {
    for(int i = 1; i < m-1; i++) {

      Anew[j][i] = 0.25 * (A[j][i+1] + A[j][i-1] +
                           A[j-1][i] + A[j+1][i]);

      error = max(error, abs(Anew[j][i] - A[j][i]);
    }
  }

#pragma omp parallel for shared(m, n, Anew, A)
  for( int j = 1; j < n-1; j++) {
    for( int i = 1; i < m-1; i++ ) {
      A[j][i] = Anew[j][i];
    }
  }

  iter++;
}
```

Parallelize loop across CPU threads

Parallelize loop across CPU threads

GPU startup overhead

- If no other GPU process running, GPU driver may be swapped out
  - Linux specific
  - Starting it up can take 1-2 seconds
- Two options
  - Run nvidia-smi in persistence mode (requires root permissions)
  - Run "nvidia-smi –q –l 30" in the background
- If your running time is off by ~2 seconds from results in these slides, suspect this
  - Nvidia-smi should be running in persistent mode for these exercises

First Attempt: OpenACC C

```
while ( error > tol && iter < iter_max ) {
  error=0.0;

#pragma acc kernels
  for( int j = 1; j < n-1; j++) {
    for(int i = 1; i < m-1; i++) {

      Anew[j][i] = 0.25 * (A[j][i+1] + A[j][i-1] +
                           A[j-1][i] + A[j+1][i]);

      error = max(error, abs(Anew[j][i] - A[j][i]);
    }
  }

#pragma acc kernels
  for( int j = 1; j < n-1; j++) {
    for( int i = 1; i < m-1; i++ ) {
      A[j][i] = Anew[j][i];
    }
  }

  iter++;
}
```

Execute GPU kernel for loop nest

Execute GPU kernel for loop nest

First Attempt: Compiler output

```
pgcc  -acc -ta=nvidia -Minfo=accel -o laplace2d_acc laplace2d.c
main:
     57, Generating copyin(A[:4095][:4095])
         Generating copyout(Anew[1:4094][1:4094])
         Generating compute capability 1.3 binary
         Generating compute capability 2.0 binary
     58, Loop is parallelizable
     60, Loop is parallelizable
         Accelerator kernel generated
         58, #pragma acc loop worker, vector(16) /* blockIdx.y threadIdx.y */
         60, #pragma acc loop worker, vector(16) /* blockIdx.x threadIdx.x */
             Cached references to size [18x18] block of 'A'
             CC 1.3 : 17 registers; 2656 shared, 40 constant, 0 local memory bytes; 75% occupancy
             CC 2.0 : 18 registers; 2600 shared, 80 constant, 0 local memory bytes; 100% occupancy
         64, Max reduction generated for error
     69, Generating copyout(A[1:4094][1:4094])
         Generating copyin(Anew[1:4094][1:4094])
         Generating compute capability 1.3 binary
         Generating compute capability 2.0 binary
     70, Loop is parallelizable
     72, Loop is parallelizable
         Accelerator kernel generated
         70, #pragma acc loop worker, vector(16) /* blockIdx.y threadIdx.y */
         72, #pragma acc loop worker, vector(16) /* blockIdx.x threadIdx.x */
             CC 1.3 : 8 registers; 48 shared, 8 constant, 0 local memory bytes; 100% occupancy
             CC 2.0 : 10 registers; 8 shared, 56 constant, 0 local memory bytes; 100% occupancy
```

OpenACC parallel vs. kernels

PARALLEL	KERNELS
Requires analysis by programmer to ensure safe parallelism	Compiler performs parallel analysis and parallelizes what it believes safe
Straightforward path from OpenMP	Can cover larger area of code with single directive

Both approaches are equally valid and can perform equally well.

First Attempt: Performance

Execution	Time (s)	Speedup
CPU 1 OpenMP thread	69.80	--
CPU 2 OpenMP threads	44.76	1.56x
CPU 4 OpenMP threads	39.59	1.76x
CPU 6 OpenMP threads	39.71	1.76x
OpenACC GPU	162.16	0.24x FAIL

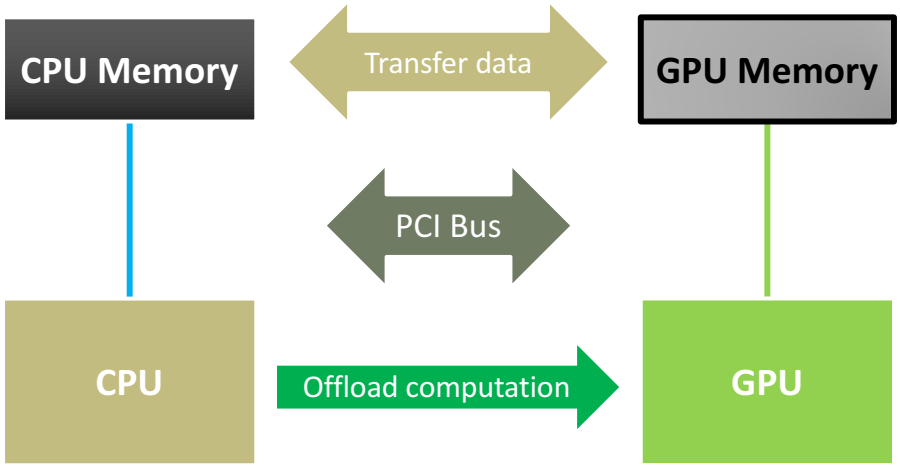
GPU: NVIDIA Tesla M2070

CPU: Intel Xeon X5680
6 Cores @ 3.33GHz

Speedup vs. 1 CPU core

Speedup vs. 6 CPU cores

Basic Concepts



For efficiency, decouple data movement and compute off-load

Excessive Data Transfers

```
while ( error > tol && iter < iter_max )
{
  error=0.0;
```

A, Anew resident on host

Copy

A, Anew resident on accelerator

These copies happen every iteration of the outer while loop!*

```
#pragma acc kernels
for( int j = 1; j < n-1; j++) {
  for( int i = 1; i < m-1; i++) {
    Anew[j][i] = 0.25 * (A[j][i+1] + A[j][i-1] +
                         A[j-1][i] + A[j+1][i]);
    error = max(error, abs(Anew[j][i] - A[j][i]);
  }
}
```

A, Anew resident on accelerator

Copy

A, Anew resident on host

```
  ...
}
```

**Note: there are two #pragma acc kernels, so there are 4 copies per while loop iteration!*

DATA MANAGEMENT

Data Construct

```
#pragma acc data [clause …]
    { structured block }
```

Manage data movement. Data regions may be nested.

Data Clauses

`copy ( list )`	Allocates memory on GPU and copies data from host to GPU when entering region and copies data to the host when exiting region.
`copyin ( list )`	Allocates memory on GPU and copies data from host to GPU when entering region.
`copyout ( list )`	Allocates memory on GPU and copies data to the host when exiting region.
`create ( list )`	Allocates memory on GPU but does not copy.
`present ( list )`	Data is already present on GPU from another containing data region.

and `present_or_copy[in|out]`, `present_or_create`, `deviceptr`.

Array Shaping

- Compiler sometimes cannot determine size of arrays
  - Must specify explicitly using data clauses and array "shape"

```
#pragma acc data copyin(a[0:size-1]), copyout(b[s/4:3*s/4])
```

- Note: data clauses can be used on `data`, `kernels` or `parallel`

Update Construct

```
#pragma acc update [clause …]

if( expression )
async( expression )
```

- Used to update existing data after it has changed in its corresponding copy (e.g. update device copy after host copy changes)
- Move data from GPU to host, or host to GPU.
- Data movement can be conditional, and asynchronous.

Second Attempt: OpenACC C

```
#pragma acc data copy(A), create(Anew)
while ( error > tol && iter < iter_max ) {
  error=0.0;

#pragma acc kernels
  for( int j = 1; j < n-1; j++) {
    for(int i = 1; i < m-1; i++) {

      Anew[j][i] = 0.25 * (A[j][i+1] + A[j][i-1] +
                           A[j-1][i] + A[j+1][i]);

      error = max(error, abs(Anew[j][i] - A[j][i]);
    }
  }

#pragma acc kernels
  for( int j = 1; j < n-1; j++) {
    for( int i = 1; i < m-1; i++ ) {
      A[j][i] = Anew[j][i];
    }
  }

  iter++;
}
```

Copy A in at beginning of loop, out at end. Allocate Anew on accelerator

Second Attempt: Performance

Execution	Time (s)	Speedup
CPU 1 OpenMP thread	69.80	--
CPU 2 OpenMP threads	44.76	1.56x
CPU 4 OpenMP threads	39.59	1.76x
CPU 6 OpenMP threads	39.71	1.76x
OpenACC GPU	13.65	2.9x

GPU: NVIDIA Tesla M2070

CPU: Intel Xeon X5680
6 Cores @ 3.33GHz

Note: same code runs in 9.78s on NVIDIA Tesla M2090 GPU

Speedup vs. 1 CPU core

Speedup vs. 6 CPU cores

Further speedups

- OpenACC gives us more detailed control over parallelization
  - Via gang, worker, and vector clauses
- By understanding more about OpenACC execution model and GPU hardware organization, we can get higher speedups on this code
- By understanding bottlenecks in the code via profiling, we can reorganize the code for higher performance
- Will tackle these later on

Finding Parallelism in your code

- (Nested) for loops are best for parallelization
- Large loop counts needed to offset GPU/memcpy overhead
- Iterations of loops must be independent of each other
  - To help compiler: restrict keyword (C), independent clause
- Compiler must be able to figure out sizes of data regions
  - Can use directives to explicitly control sizes
- Pointer arithmetic should be avoided if possible
  - Use subscripted arrays, rather than pointer-indexed arrays.
- Function calls within accelerated region must be inlineable.

Tips and Tricks

- (PGI) Use time option to learn where time is being spent
  `-ta=nvidia,time`
- Eliminate pointer arithmetic
- Inline function calls in directives regions
  (PGI): `-inline` or `-inline,levels(<N>)`
- Use contiguous memory for multi-dimensional arrays
- Use data regions to avoid excessive memory transfers
- Conditional compilation with `_OPENACC` macro

COMPLETE OPENACC API

Kernels Construct

C

```
#pragma acc kernels [clause …]
    { structured block }
```

Parallel Construct

C

```
#pragma acc parallel [clause …]
    { structured block }
```

```
private( list )
firstprivate( list )
reduction( operator:list )
```

Also any data clause

Parallel Clauses

`num_gangs ( expression )`	Controls how many parallel gangs are created (CUDA `gridDim`).
`num_workers ( expression )`	Controls how many workers are created in each gang (CUDA `blockDim`).
`vector_length ( list )`	Controls vector length of each worker (SIMD execution).
`private( list )`	A copy of each variable in list is allocated to each gang.
`firstprivate ( list )`	`private` variables initialized from host.
`reduction( operator:list )`	`private` variables combined across gangs.

Loop Construct

C

```
#pragma acc loop [clause …]
    { loop }
```

Detailed control of the parallel execution of the following loop.

Loop Clauses

`collapse( n )`	Applies directive to the following `n` nested loops.
`seq`	Executes the loop sequentially on the GPU.
`private( list )`	A copy of each variable in list is created for each iteration of the loop.
`reduction( operator:list )`	`private` variables combined across iterations.

Loop Clauses Inside parallel Region

`Gang`	Shares iterations across the gangs of the parallel region.
`worker`	Shares iterations across the workers of the gang.
`vector`	Execute the iterations in SIMD mode.

Loop Clauses Inside kernels Region

`gang [( num_gangs )]`	Shares iterations across across at most *`num_gangs`* gangs.
`worker [( num_workers )]`	Shares iterations across at most *`num_workers`* of a single gang.
`vector [( vector_length )]`	Execute the iterations in SIMD mode with maximum *`vector_length`*.
`independent`	Specify that the loop iterations are independent.

OTHER SYNTAX

Other Directives

`cache` construct	Cache data in software managed data cache (CUDA shared memory).
`host_data` construct	Makes the address of device data available on the host.
`wait` directive	Waits for asynchronous GPU activity to complete.
`declare` directive	Specify that data is to allocated in device memory for the duration of an implicit data region created during the execution of a subprogram.

Runtime Library Routines

C

```
#include "openacc.h”

acc_async_wait
acc_async_wait_all
acc_shutdown
acc_on_device
acc_malloc
acc_free
```


Environment and Conditional Compilation

`ACC_DEVICE device`	Specifies which device type to connect to.
`ACC_DEVICE_NUM num`	Specifies which device number to connect to.
`_OPENACC`	Preprocessor directive for conditional compilation. Set to OpenACC version

3 Ways to Accelerate Applications