Introduction to CUDA Programming

Jian Tao

jtao@tamu.edu

Fall 2023 HPRC Short Course

10/13/2023

TEXAS A&M UNIVERSITY
School of Performance, Visualization & Fine Arts

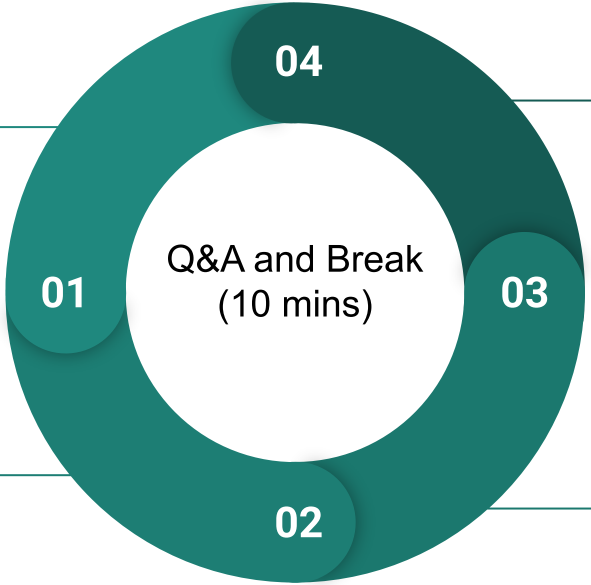
High Performance Research Computing
DIVISION OF RESEARCH

TEXAS A&M
Institute of Data Science

Introduction to CUDA Programming

Part I. Getting Started with Grace (~10 mins)

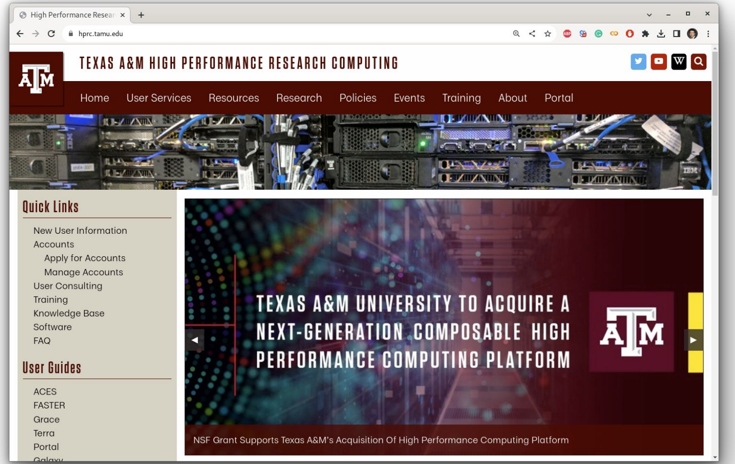
Part II. GPU as an Accelerator (~40 mins)



Part IV. CUDA C/C++ Basics (~50 mins)

Part III. Running CUDA Code on Grace (~30 mins)

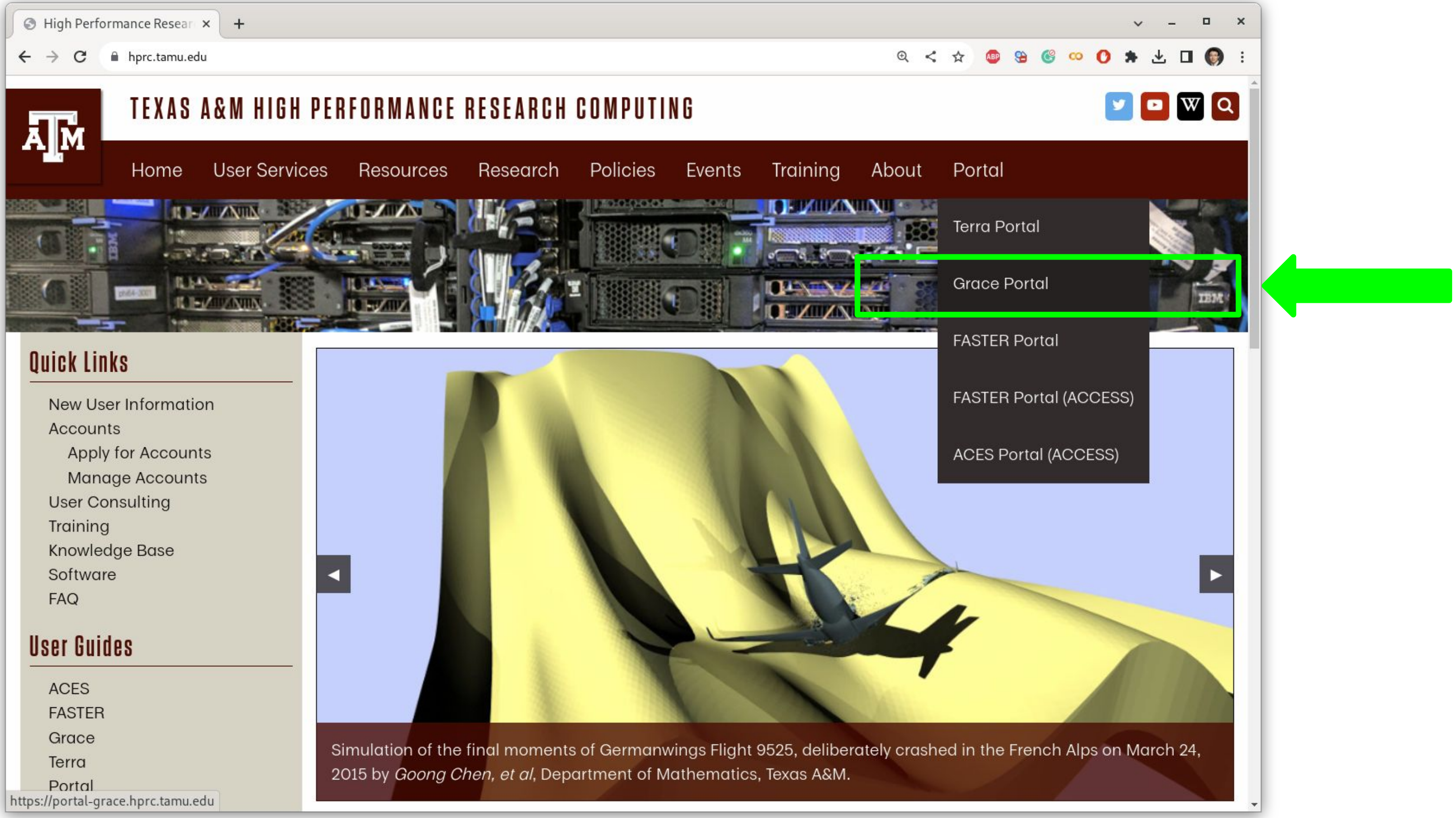
Part I. Working Environment



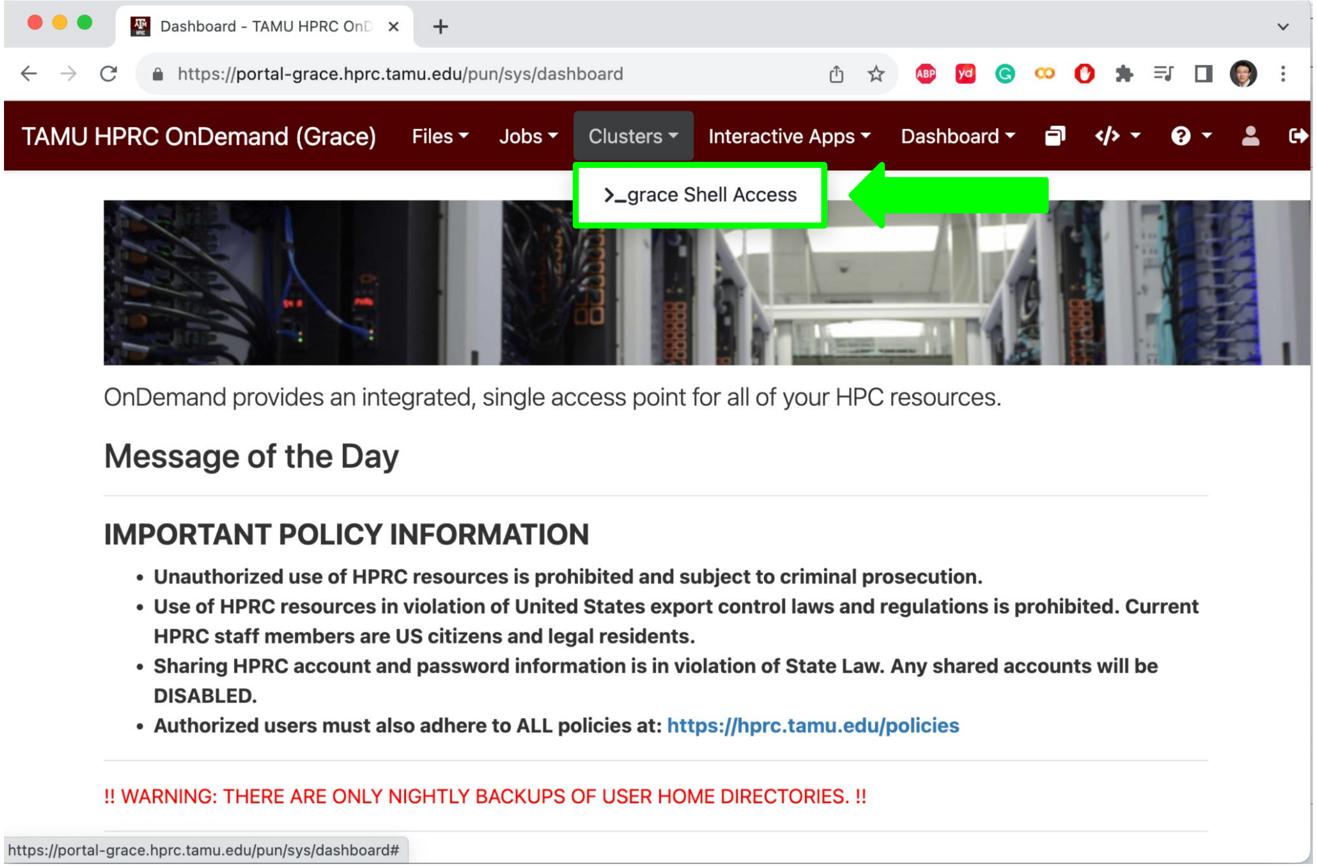
HPRC Portal

*** VPN is required for off-campus users.**

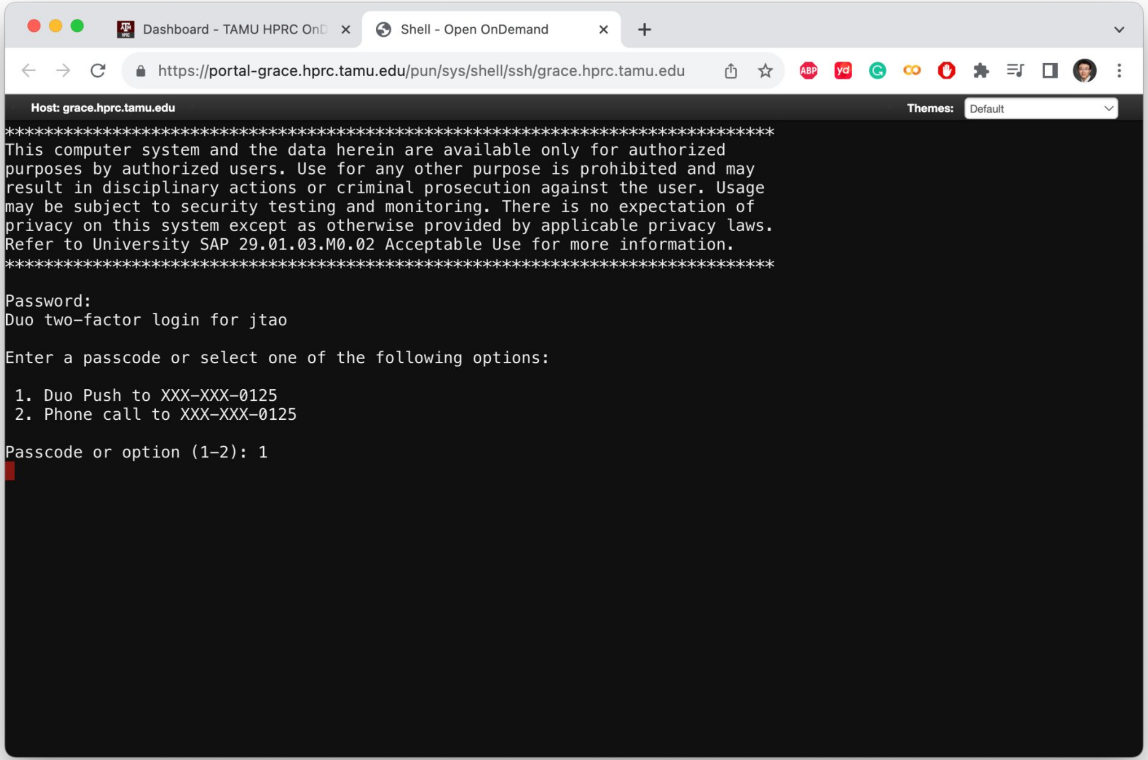
Login HPRC Portal (Grace)



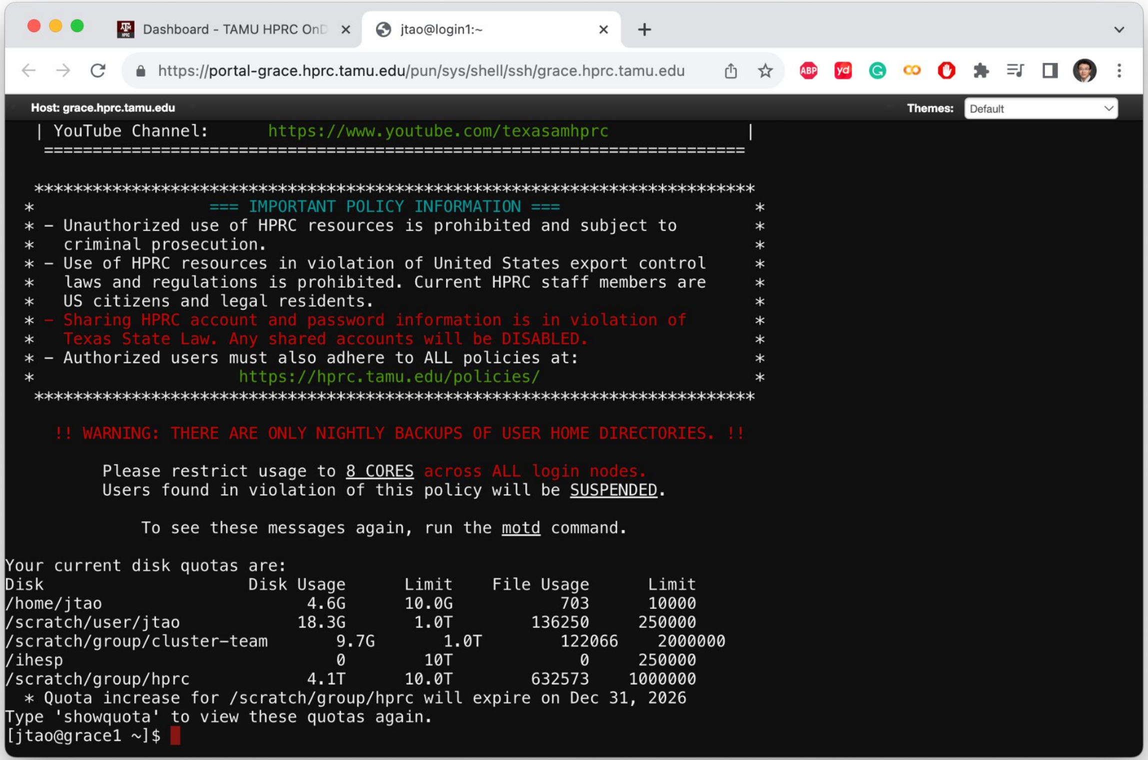
Grace Shell Access - I



Grace Shell Access - II



Grace Shell Access - II



Commands to Copy Examples

- Navigate to your personal scratch directory

```
$ cd $SCRATCH
```

- Files for this course are located at

  `/scratch/training/cuda.exercise.tgz`

  Make a copy in your personal scratch directory

```
$ cp /scratch/training/cuda.exercise.tgz $SCRATCH/
```

  Extract the files

```
$ tar -zxvf cuda.exercise.tgz
```

- Enter this directory (your local copy)

```
$ cd CUDA
```

```
$ cd hello_world
```

Load CUDA Module, Compile, and Run

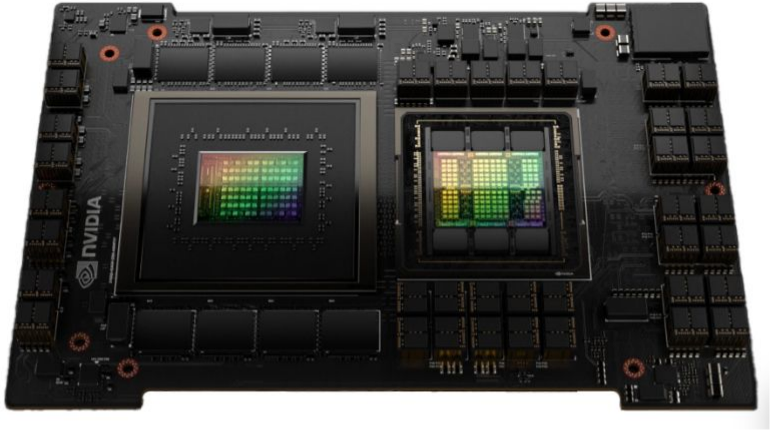
```
[jtao@grace1 ~]$ cd $SCRATCH
[jtao@grace1 jtao]$ cp /scratch/training/cuda.exercise.tgz .
[jtao@grace1 jtao]$ tar -zxvf cuda.exercise.tgz
CUDA/
CUDA/vector_add/
CUDA/vector_add/vecadd_par.cu
CUDA/vector_add/faster_cuda_run.sh
CUDA/vector_add/vecadd_ser.cu
CUDA/vector_add/vecadd_par_block.cu
CUDA/vector_add/grace_cuda_run.sh
CUDA/faster_cuda_run.sh
CUDA/hello_world/
CUDA/hello_world/faster_cuda_run.sh
CUDA/hello_world/hello_world_host.cu
CUDA/hello_world/hello_world_device.cu
CUDA/hello_world/grace_cuda_run.sh
CUDA/grace_cuda_run.sh
CUDA/unified_memory/
CUDA/unified_memory/faster_cuda_run.sh
CUDA/unified_memory/uni_mem.cu
CUDA/unified_memory/grace_cuda_run.sh
CUDA/README
[jtao@grace1 jtao]$ cd CUDA/hello_world/
[jtao@grace1 hello_world]$ ml CUDA
[jtao@grace1 hello_world]$ nvcc --version
nvcc: NVIDIA (R) Cuda compiler driver
Copyright (c) 2005-2023 NVIDIA Corporation
Built on Tue_Aug_15_22:02:13_PDT_2023
Cuda compilation tools, release 12.2, V12.2.140
Build cuda_12.2.r12.2/compiler.33191640_0
[jtao@grace1 hello_world]$ nvcc hello_world_device.cu
[jtao@grace1 hello_world]$ ./a.out
Hello World!
```

Part II. GPU as an Accelerator

CPU

GPU Accelerator

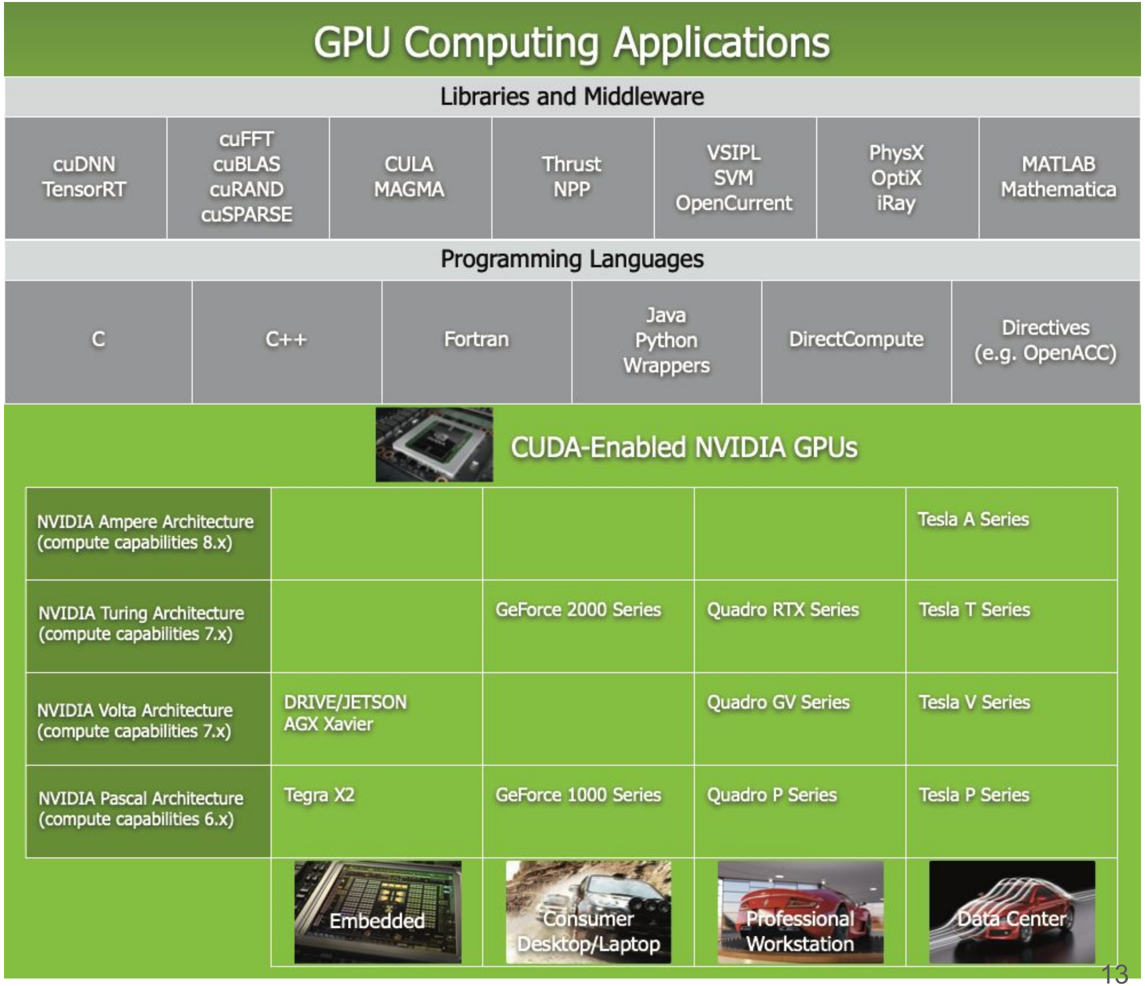
NVIDIA Tesla H100 with 80 Billion Transistors



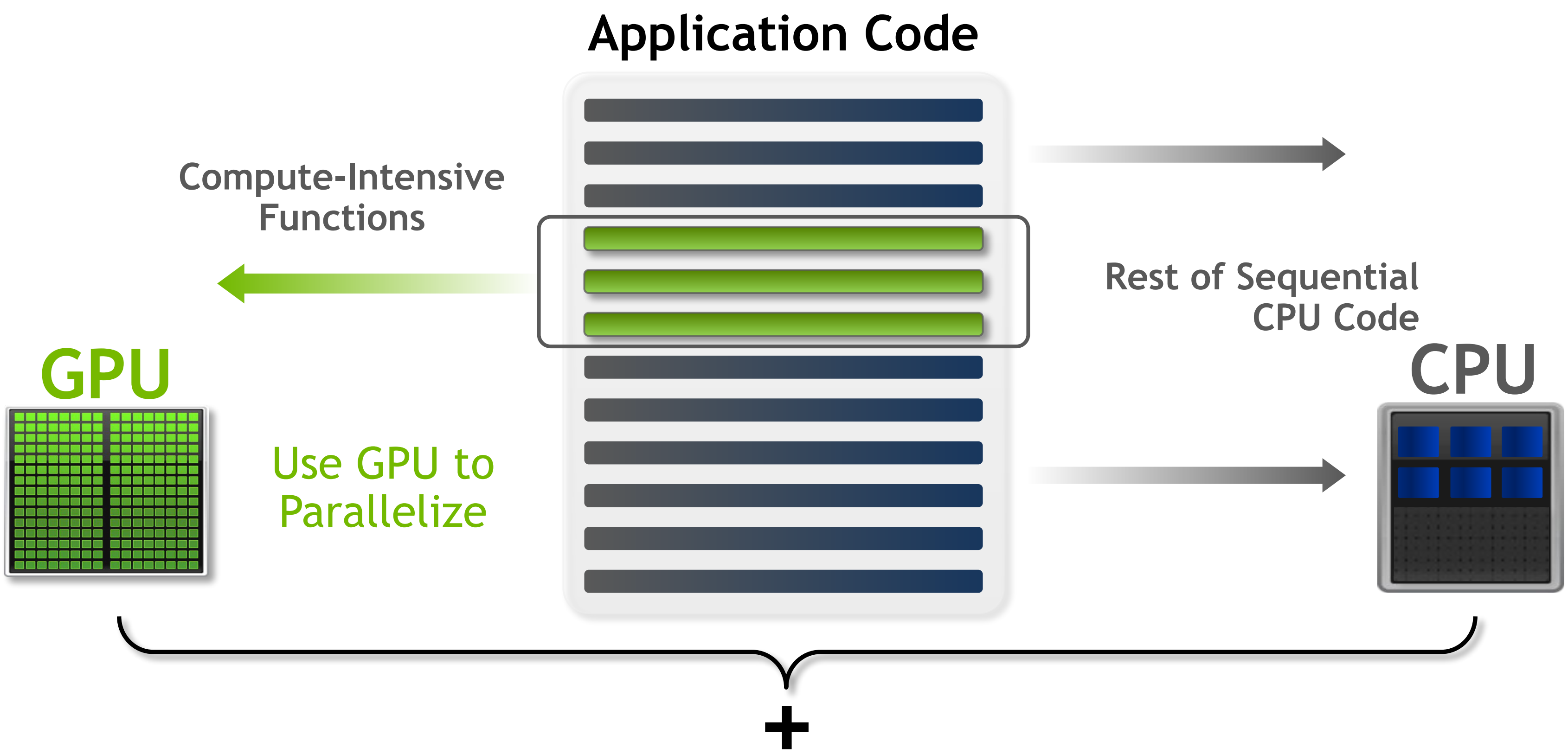
During the 2022 Nvidia GTC, Nvidia officially announced Hopper, its latest microarchitecture. The Nvidia Hopper H100 GPU is implemented using the TSMC 5nm process with 80 billion transistors. It consists of up to 144 streaming multiprocessors.

GPU Computing Applications

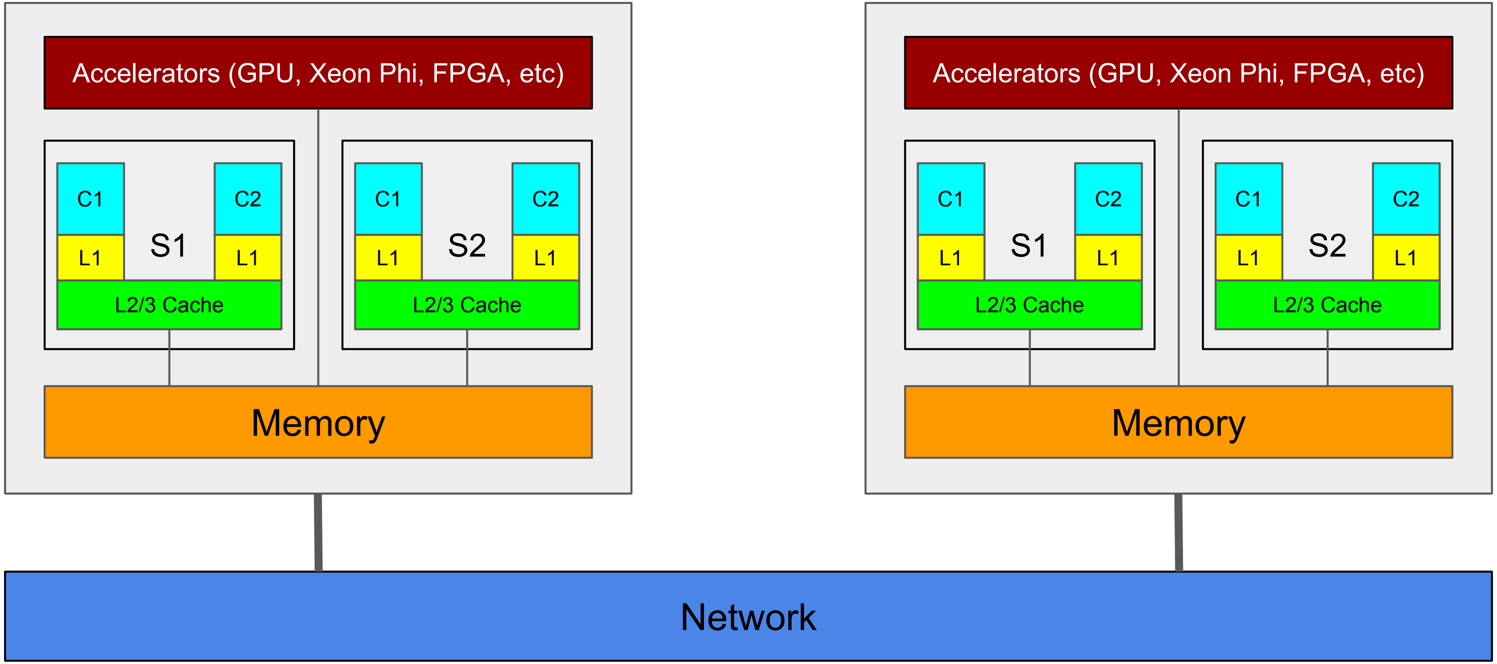
A catalog of GPU-accelerated applications can be found at https://www.nvidia.com/en-us/gpu-accelerated-applications/.



Add GPUs: Accelerate Science Applications



HPC - Distributed Heterogeneous System



Programming Models: MPI + (CUDA, OpenCL, OpenMP, OpenACC, etc.)

CUDA Parallel Computing Platform

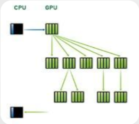
https://developer.nvidia.com/cuda-toolkit

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

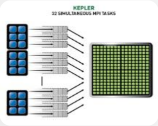
Hardware Capabilities

SMX

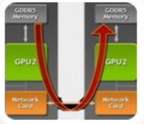
Dynamic Parallelism



HyperQ



GPUDirect



3 Ways to Accelerate Applications

Applications

Libraries	OpenACC Directives	Programming Languages
"Drop-in" Acceleration	Easily Accelerate Applications	Maximum Flexibility

3 Ways to Accelerate Applications

Applications

Libraries	OpenACC Directives	Programming Languages
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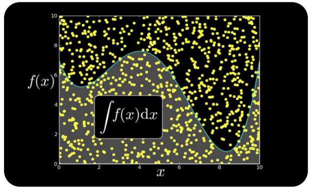
Libraries: Easy, High-Quality Acceleration

- **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

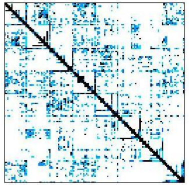
NVIDIA CUDA-X GPU-Accelerated Libraries

https://developer.nvidia.com/gpu-accelerated-libraries


NVIDIA cuBLAS



NVIDIA cuRAND

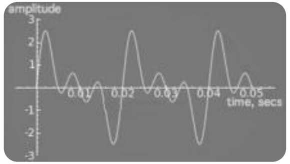

NVIDIA cuSPARSE


NVIDIA NPP

GPU VSIPL
Vector Signal Image Processing

CULA tools
GPU Accelerated Linear Algebra

MAGMA
Matrix Algebra on GPU and Multicore



NVIDIA cuFFT

ROGUE WAVE SOFTWARE
IMSL Library

ArrayFire Matrix Computations

CUSP
Sparse Linear Algebra

Thrust
C++ STL Features for CUDA

CUDA-accelerated Application with Libraries

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

  `saxpy ( … )` ► **`cublasSaxpy ( … )`**

- **Step 2:** Manage data locality

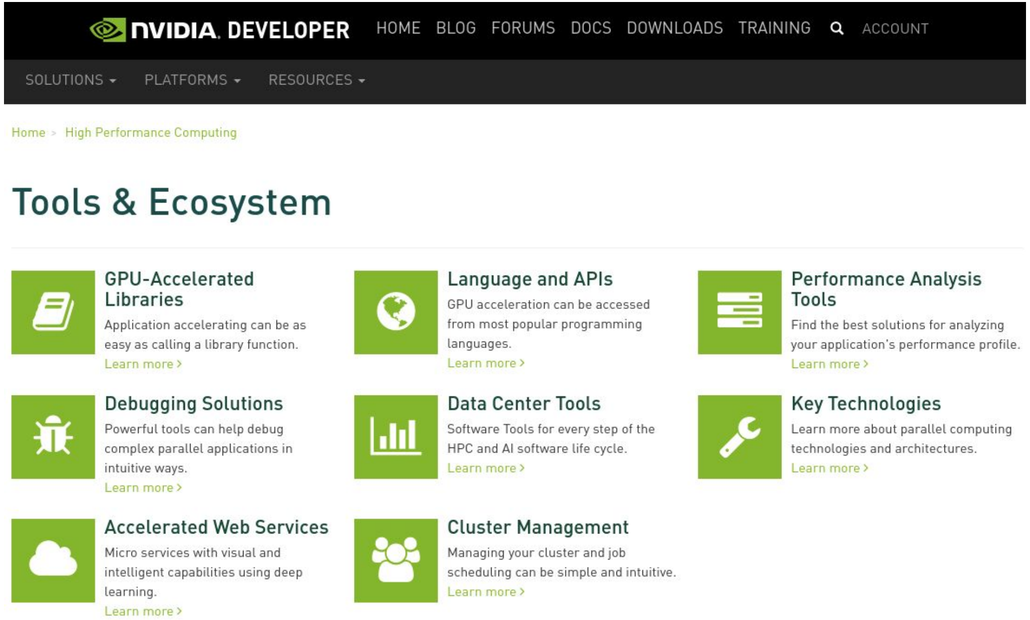
  - with CUDA: **`cudaMalloc()`**, **`cudaMemcpy()`**, `etc.`
  - with CUBLAS: **`cublasAlloc()`**, **`cublasSetVector()`**, `etc.`

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

```
$nvcc myobj.o –l cublas
```

Explore the CUDA (Libraries) Ecosystem

- CUDA Tools and Ecosystem described in detail on NVIDIA Developer Zone.



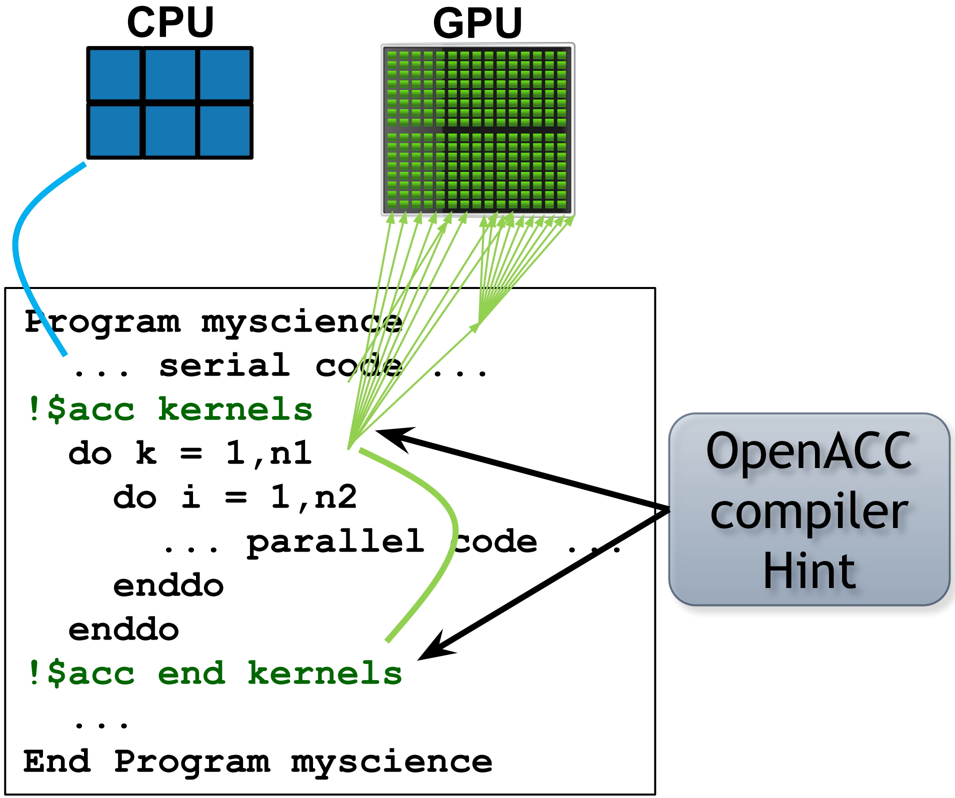
[NVIDIA CUDA Tools & Ecosystem]

3 Ways to Accelerate Applications

Applications

Libraries	OpenACC Directives	Programming Languages
"Drop-in" Acceleration	Easily Accelerate Applications	Maximum Flexibility

OpenACC Directives



Simple Compiler hints

Compiler Parallelizes code

Works on many-core GPUs & multicore CPUs

OpenACC

The Standard for GPU Directives

- **Easy:** Directives are the easy path to accelerate compute intensive applications
- **Open:** OpenACC is an open GPU directives standard, making GPU programming straightforward and portable across parallel and multi-core processors
- **Powerful:** GPU Directives allow complete access to the massive parallel power of a GPU

Directives: Easy & Powerful

Real-Time Object Detection

Global Manufacturer of Navigation Systems

5x in 40 Hours

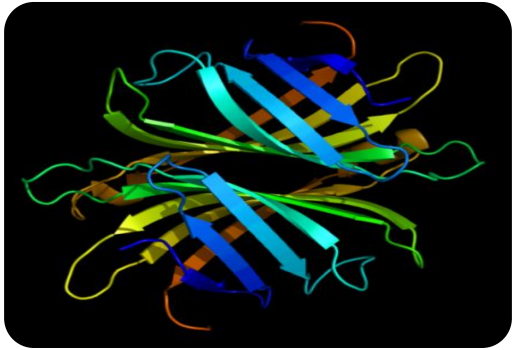
Valuation of Stock Portfolios using Monte Carlo

Global Technology Consulting Company

2x in 4 Hours

Interaction of Solvents and Biomolecules

University of Texas at San Antonio



5x in 8 Hours

3 Ways to Accelerate Applications

Applications

Libraries	OpenACC Directives	Programming Languages
"Drop-in" Acceleration	Easily Accelerate Applications	Maximum Flexibility

GPU Programming Languages

Numerical analytics	MATLAB, Mathematica, LabVIEW
Fortran	OpenACC, CUDA Fortran
C	OpenACC, CUDA C, OpenCL
C++	Thrust, CUDA C++, OpenCL
Python	PyCUDA, PyOpenCL, CuPy
Julia / Java	JuliaGPU/CUDA.jl, jcuda

Rapid Parallel C++ Development

- Resembles C++ STL
- High-level interface
  - Enhances developer productivity
  - Enables performance portability between GPUs and multicore CPUs
- Flexible
  - CUDA, OpenMP, and TBB backends
  - Extensible and customizable
  - Integrates with existing software
- Open source

Thrust

```
// generate 32M random numbers on host
thrust::host_vector<int> h_vec(32 << 20);
thrust::generate(h_vec.begin(),
                 h_vec.end(),
                 rand);

// transfer data to device (GPU)
thrust::device_vector<int> d_vec = h_vec;

// sort data on device
thrust::sort(d_vec.begin(), d_vec.end());

// transfer data back to host
thrust::copy(d_vec.begin(),
             d_vec.end(),
             h_vec.begin());
```

https://thrust.github.io/

Learn More

These languages are supported on all CUDA-capable GPUs.

You might already have a CUDA-capable GPU in your laptop or desktop PC!

CUDA C/C++
http://developer.nvidia.com/cuda-toolkit

PyCUDA (Python)
https://developer.nvidia.com/pycuda

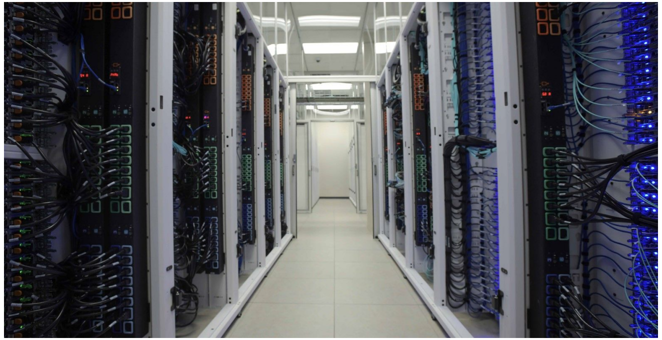
Thrust C++ Template Library
http://developer.nvidia.com/thrust

MATLAB
http://www.mathworks.com/discovery/matlab-gpu.html

CUDA Fortran
https://developer.nvidia.com/cuda-fortran

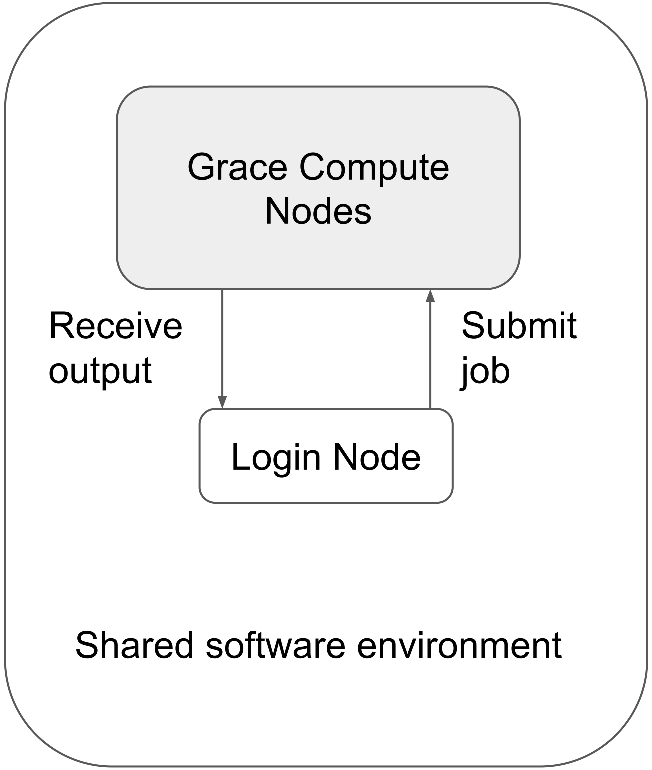
Mathematica
http://www.wolfram.com/mathematica/new-in-8/cuda-and-opencl-support/

Part III. Running CUDA Code on Grace



Running CUDA Code on Grace

```
# load CUDA module
$ml CUDA

# copy sample code to your scratch space
$tar -zxvf cuda.exercise.tgz

# compile CUDA code
$cd CUDA
$cd hello_world
$nvcc hello_world_host.cu
$./a.out

# edit job script & submit your GPU job
$sbatch grace_cuda_run.sh
```



Part IV. CUDA C/C++ BASICS

What is CUDA?

- CUDA Architecture
  - Used to mean “Compute Unified Device Architecture”
  - Expose GPU parallelism for general-purpose computing
  - Retain performance
- CUDA C/C++
  - Based on industry-standard C/C++
  - Small set of extensions to enable heterogeneous programming
  - Straightforward APIs to manage devices, memory etc.

A Brief History of CUDA

- Researchers used OpenGL APIs for general purpose computing on GPUs before CUDA.
- In 2007, NVIDIA released first generation of Tesla GPU for general computing together their proprietary CUDA development framework.
- Current stable version of CUDA is 12.2.2 (as of Oct 2023).

Heterogeneous Computing

- Terminology:
  - ***Host*** The CPU and its memory (host memory)
  - ***Device*** The GPU and its memory (device memory)

Host

Device

Heterogeneous Computing

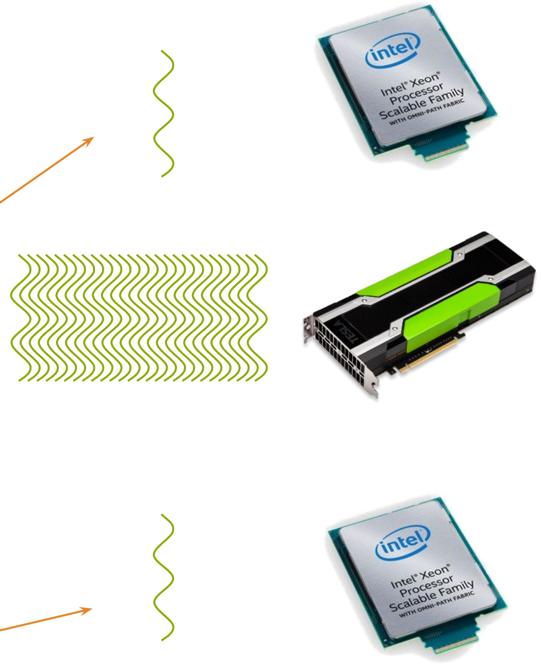
```
#include <iostream>
#include <algorithm>

using namespace std;

#define N          1024
#define RADIUS     3
#define BLOCK_SIZE 16

__global__ void stencil_1d(int *in, int *out) {
                __shared__ int temp[BLOCK_SIZE + 2 * RADIUS];
                int gindex = threadIdx.x + blockIdx.x * blockDim.x;
                int lindex = threadIdx.x + RADIUS;

                // Read input elements into shared memory
                temp[lindex] = in[gindex];
                if (threadIdx.x < RADIUS) {
                                temp[lindex - RADIUS] = in[gindex - RADIUS];
                                temp[lindex + BLOCK_SIZE] = in[gindex +
BLOCK_SIZE];
                }

                // Synchronize (ensure all the data is available)
                __syncthreads();

                // Apply the stencil
                int result = 0;
                for (int offset = -RADIUS ; offset <= RADIUS ; offset++)
                                result += temp[lindex + offset];

                // Store the result
                out[gindex] = result;
}

void fill_ints(int *x, int n) {
                fill_n(x, n, 1);
}

int main(void) {
                int *in, *out;            // host copies of a, b, c
                int *d_in, *d_out;        // device copies of a, b, c
                int size = (N + 2*RADIUS) * sizeof(int);

                // Alloc space for host copies and setup values
                in  = (int *)malloc(size); fill_ints(in,  N + 2*RADIUS);
                out = (int *)malloc(size); fill_ints(out, N + 2*RADIUS);

                // Alloc space for device copies
                cudaMalloc((void **)&d_in,  size);
                cudaMalloc((void **)&d_out, size);

                // Copy to device
                cudaMemcpy(d_in,  in,  size, cudaMemcpyHostToDevice);
                cudaMemcpy(d_out, out, size, cudaMemcpyHostToDevice);

                // Launch stencil_1d() kernel on GPU
                stencil_1d<<<N/BLOCK_SIZE,BLOCK_SIZE>>>(d_in + RADIUS, d_out +
RADIUS);

                // Copy result back to host
                cudaMemcpy(out, d_out, size, cudaMemcpyDeviceToHost);

                // Cleanup
                free(in); free(out);
                cudaFree(d_in); cudaFree(d_out);
                return 0;
}
```

parallel function

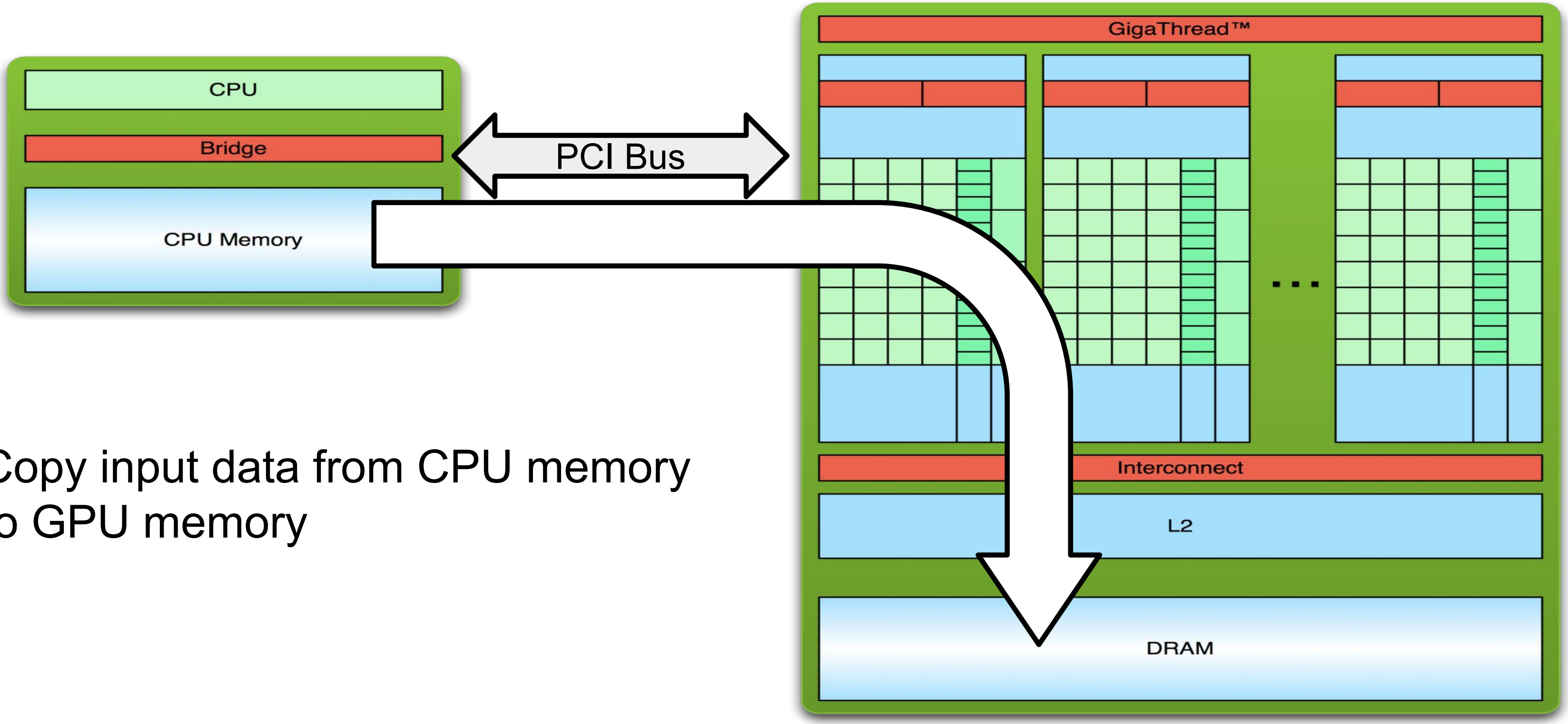
serial code

parallel code

serial code

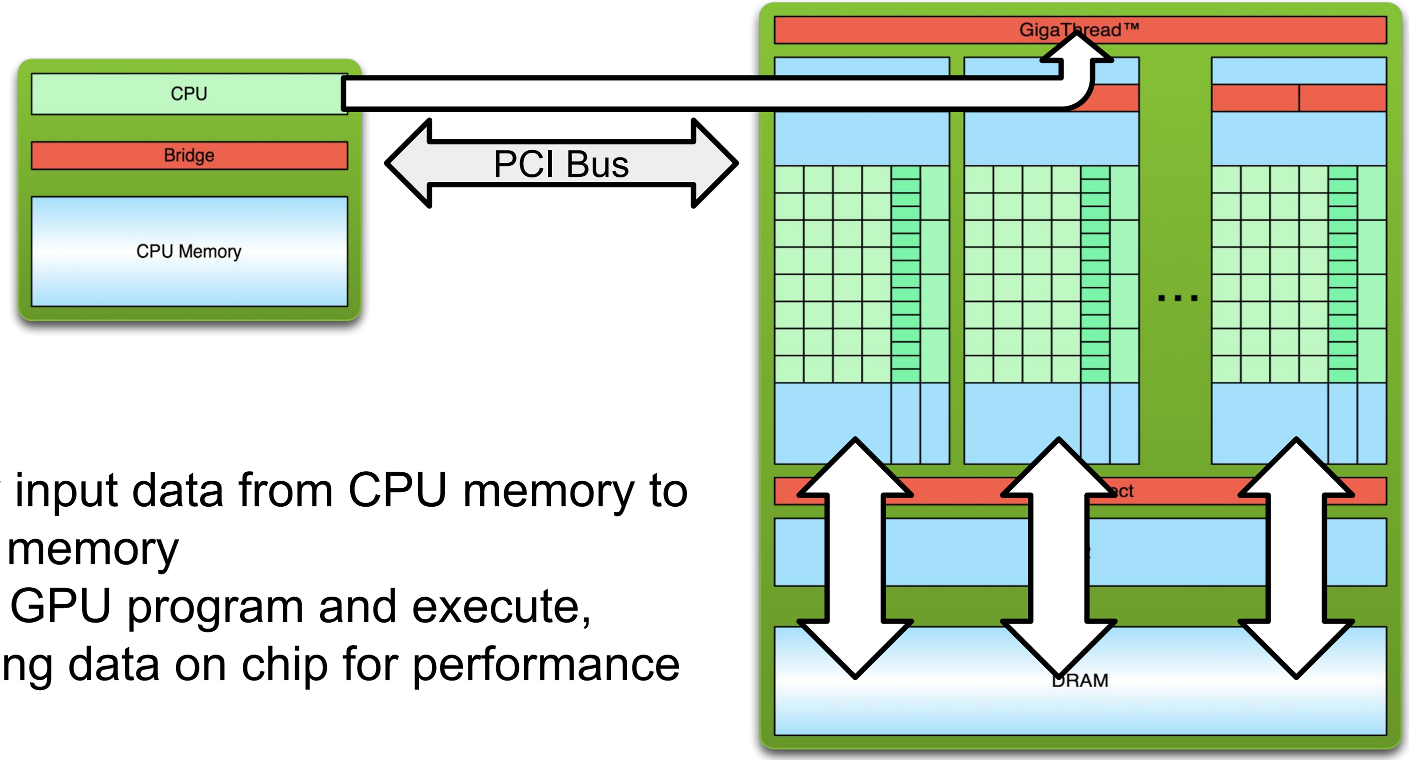


Simple Processing Flow



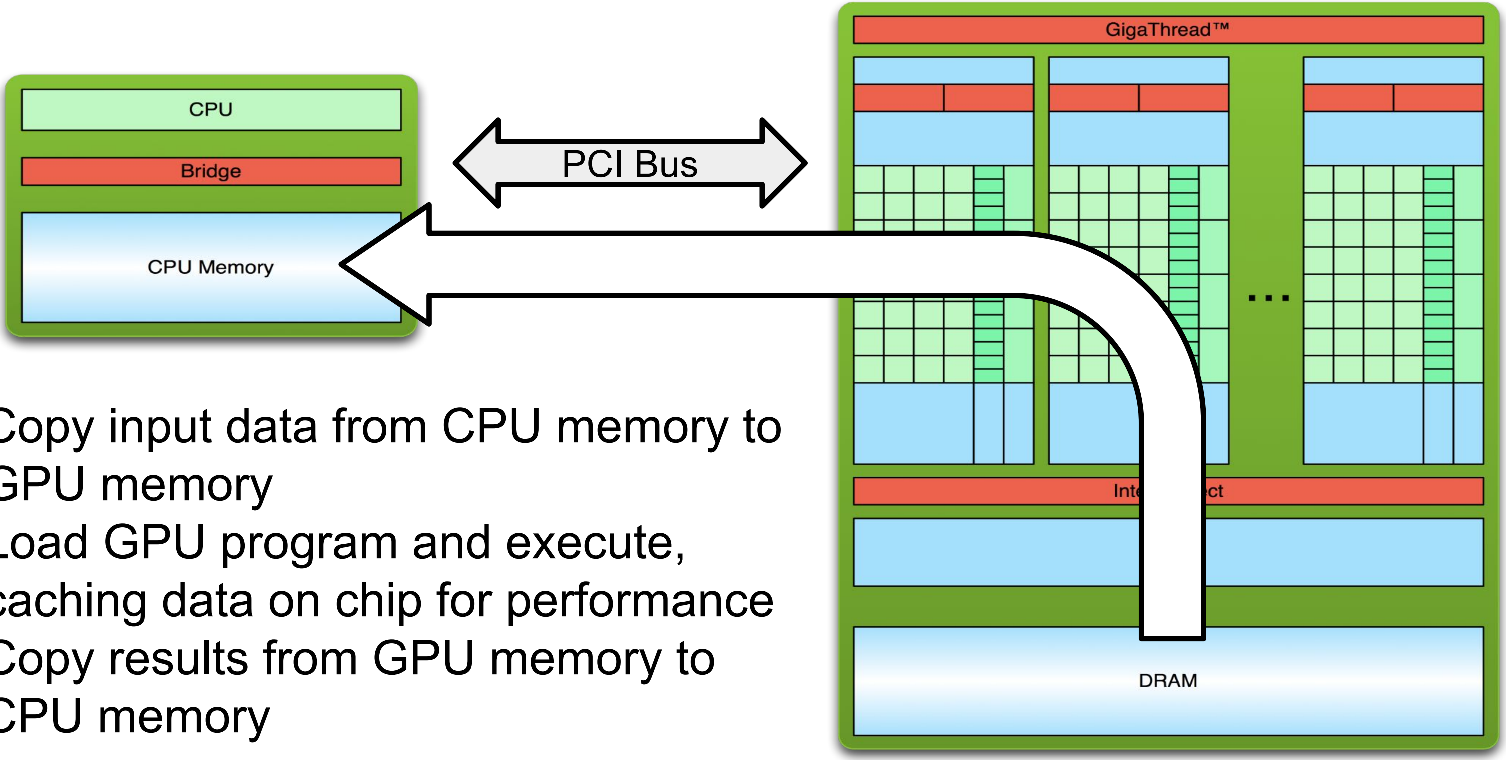
1. Copy input data from CPU memory to GPU memory

Simple Processing Flow



1. Copy input data from CPU memory to GPU memory
2. Load GPU program and execute, caching data on chip for performance

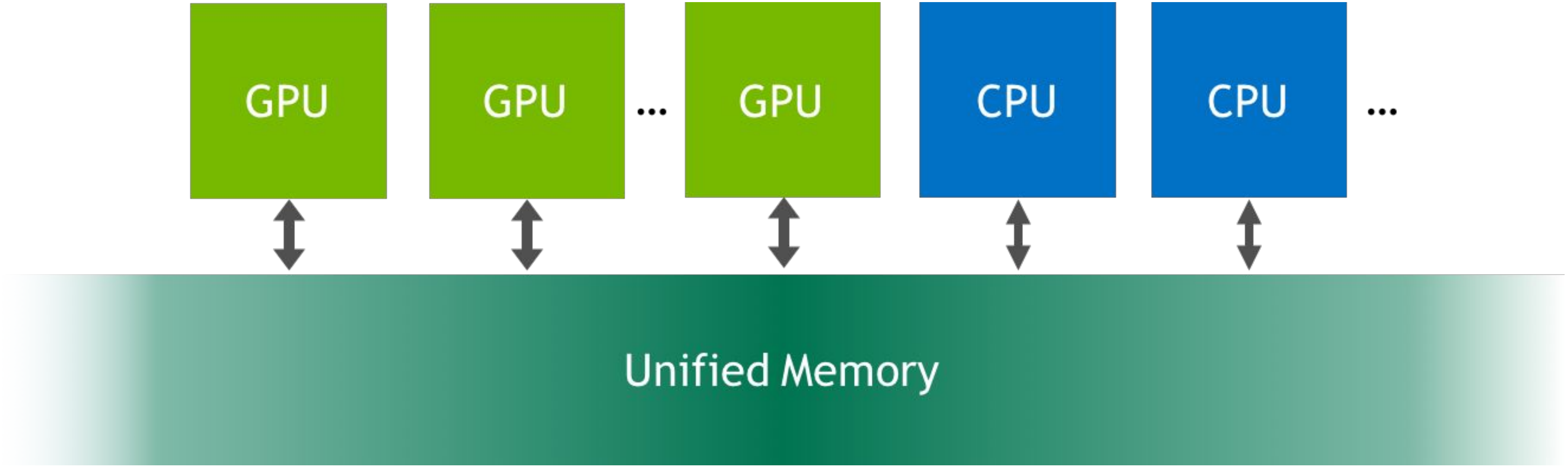
Simple Processing Flow



1. Copy input data from CPU memory to GPU memory
2. Load GPU program and execute, caching data on chip for performance
3. Copy results from GPU memory to CPU memory

Unified Memory

Software: CUDA 6.0 in 2014 **Hardware: Pascal GPU in 2016**



Unified Memory

- A managed memory space where all processors see a single coherent memory image with a common address space.
- Memory allocation with **`cudaMallocManaged()`**.
- Synchronization with **`cudaDeviceSynchronize()`**.
- Eliminates the need for **`cudaMemcpy()`**.
- Enables simpler code.
- Hardware support since Pascal GPU.

Hello World!

```
int main(void) {
    printf("Hello World!\n");
    return 0;
}
```

Output:

```
$ nvcc hello_world.cu
$ ./a.out
$ Hello World!
```

- Standard C that runs on the host
- NVIDIA compiler (nvcc) can be used to compile programs with no *device* code

Hello World! with Device Code

```
__global__ void mykernel(void) {
}

int main(void) {
    mykernel<<<1,1>>>();
    printf("Hello World!\n");
    return 0;
}
```

- Two new syntactic elements…

Hello World! with Device Code

```
__global__ void mykernel(void) {
}
```

- CUDA C/C++ keyword `__global__` indicates a function that:
  - Runs on the device
  - Is called from host code
- `nvcc` separates source code into host and device components
  - Device functions (e.g. **`mykernel()`**) processed by NVIDIA compiler
  - Host functions (e.g. **`main()`**) processed by standard host compiler
    - **gcc, icc, etc.**

Hello World! with Device Code

```
mykernel<<<1,1>>>();
```

- Triple angle brackets mark a call from ***host*** code to ***device*** code
  - Also called a “kernel launch”
  - We’ll return to the parameters (1, 1) in a moment
- That’s all that is required to execute a function on the GPU!

Hello World! with Device Code

```
__global__ void mykernel(void){
}
int main(void) {
    mykernel<<<1,1>>>();
    printf("Hello World!\n");
    return 0;
}
```

Output:

```
$nvcc hello.cu
$./a.out
Hello World!
```

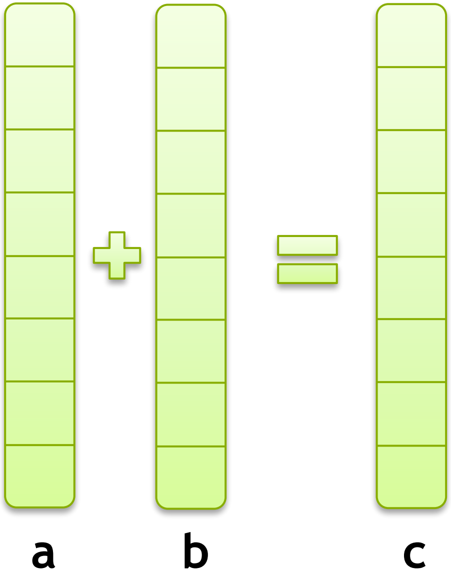
- `mykernel()` does nothing!

Parallel Programming in CUDA C/C++

- But wait… GPU computing is about massive parallelism!

- We need a more interesting example…

- We'll start by adding two integers and build up to vector addition



Addition on the Device

- A simple kernel to add two integers

```
__global__ void add(int *a, int *b, int *c) {
    *c = *a + *b;
}
```

- As before `__global__` is a CUDA C/C++ keyword meaning
  - `add()` will execute on the device
  - `add()` will be called from the host

Addition on the Device

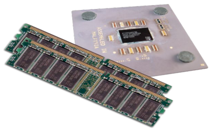
- Note that we use pointers for the variables

```
__global__ void add(int *a, int *b, int *c) {
    *c = *a + *b;
}
```

- `add()` runs on the device, so `a`, `b`, and `c` must point to device memory
- We need to allocate memory on the GPU.

Memory Management

- Host and device memory are separate entities
  - *Device* pointers point to GPU memory
    - May be passed to/from host code
    - May *not* be dereferenced in host code
  - *Host* pointers point to CPU memory
    - May be passed to/from device code
    - May *not* be dereferenced in device code



- Simple CUDA API for handling device memory
  - **`cudaMalloc()`**, **`cudaFree()`**, **`cudaMemcpy()`**
  - Similar to the C equivalents **`malloc()`**, **`free()`**, **`memcpy()`**

Addition on the Device: add()

- Returning to our `add()` kernel

```
__global__ void add(int *a, int *b, int *c) {
    *c = *a + *b;
}
```

- Let’s take a look at main()…

Addition on the Device: `main()`

```
int main(void) {
    int a, b, c;                // host copies of a, b, c
    int *d_a, *d_b, *d_c;      // device copies of a, b, c
    int size = sizeof(int);

    // Allocate space for device copies of a, b, c
    cudaMalloc((void **)&d_a, size);
    cudaMalloc((void **)&d_b, size);
    cudaMalloc((void **)&d_c, size);

    // Setup input values
    a = 2;
    b = 7;
```

Addition on the Device: `main()`

```
    // Copy inputs to device
    cudaMemcpy(d_a, &a, size, cudaMemcpyHostToDevice);
    cudaMemcpy(d_b, &b, size, cudaMemcpyHostToDevice);

    // Launch add() kernel on GPU
    add<<<1,1>>>(d_a, d_b, d_c);

    // Copy result back to host
    cudaMemcpy(&c, d_c, size, cudaMemcpyDeviceToHost);

    // Cleanup
    cudaFree(d_a); cudaFree(d_b); cudaFree(d_c);
    return 0;
}
```

Moving to Parallel

- GPU computing is about massive parallelism
  - So how do we run code in parallel on the device?

```
add<<< 1, 1 >>>();
```

```
add<<< N, 1 >>>();
```

- Instead of executing `add()` once, execute N times in parallel

Vector Addition on the Device

- With **`add()`** running in parallel we can do vector addition
- Terminology: each parallel invocation of **`add()`** is referred to as a **block**
  - The set of blocks is referred to as a **grid**
  - Each invocation can refer to its block index using **`blockIdx.x`**

```
__global__ void add(int *a, int *b, int *c) {
    c[blockIdx.x] = a[blockIdx.x] + b[blockIdx.x];
}
```

- By using **`blockIdx.x`** to index into the array, each block handles a different element of the array.

Vector Addition on the Device

```
__global__ void add(int *a, int *b, int *c) {
    c[blockIdx.x] = a[blockIdx.x] + b[blockIdx.x];
}
```

- On the device, each block can execute in parallel:

Block 0	Block 1	Block 2	Block 3
`c[0] = a[0] + b[0];`	`c[1] = a[1] + b[1];`	`c[2] = a[2] + b[2];`	`c[3] = a[3] + b[3];`

Vector Addition on the Device: `add()`

- Returning to our parallelized `add()` kernel

```
__global__ void add(int *a, int *b, int *c) {
    c[blockIdx.x] = a[blockIdx.x] + b[blockIdx.x];
}
```

- Let’s take a look at main()…

Vector Addition on the Device: `main()`

```
#define N 512
int main(void) {
 int *a, *b, *c;            // host copies of a, b, c
 int *d_a, *d_b, *d_c;      // device copies of a, b, c
 int size = N * sizeof(int);

 // Alloc space for device copies of a, b, c
 cudaMalloc((void **)&d_a, size);
 cudaMalloc((void **)&d_b, size);
 cudaMalloc((void **)&d_c, size);

 // Alloc space for host copies of a, b, c and set up input values
 a = (int *)malloc(size); random_ints(a, N);
 b = (int *)malloc(size); random_ints(b, N);
 c = (int *)malloc(size);
```

Vector Addition on the Device: `main()`

```
    // Copy inputs to device
    cudaMemcpy(d_a, a, size, cudaMemcpyHostToDevice);
    cudaMemcpy(d_b, b, size, cudaMemcpyHostToDevice);

    // Launch add() kernel on GPU with N blocks
    add<<<N,1>>>(d_a, d_b, d_c);

    // Copy result back to host
    cudaMemcpy(c, d_c, size, cudaMemcpyDeviceToHost);

    // Cleanup
    free(a); free(b); free(c);
    cudaFree(d_a); cudaFree(d_b); cudaFree(d_c);
    return 0;
}
```

Vector Addition with Unified Memory

```
__global__ void VecAdd(int *ret, int a, int b) {
    ret[blockIdx.x] = a + b + blockIdx.x;
}
int main() {
    int *ret;
    cudaMallocManaged(&ret, 1000 * sizeof(int));
    VecAdd<<< 1000, 1 >>>(ret, 10, 100);
    cudaDeviceSynchronize();
    for(int i=0; i<1000; i++)
        printf("%d: A+B = %d\n", i, ret[i]);
    cudaFree(ret);
    return  0;
}
```

Vector Addition with Managed Global Memory

```
__device__ __managed__  int  ret[1000];

__global__ void VecAdd(int *ret, int a, int b) {
    ret[blockIdx.x] = a + b + blockIdx.x;
}
int main() {
    VecAdd<<< 1000, 1 >>>(ret, 10, 100);
    cudaDeviceSynchronize();
    for(int i=0; i<1000; i++)
        printf("%d: A+B = %d\n", i, ret[i]);
    return  0;
}
```

* compile with nvcc -arch=sm_80 to avoid segment fault on Grace.

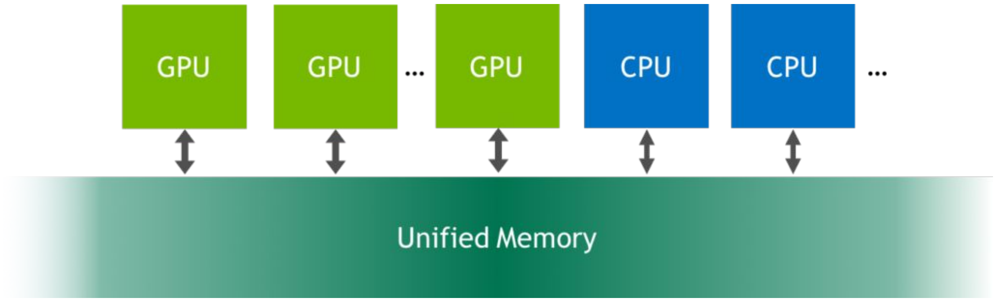
Review (1 of 2)

- Difference between *host* and *device*
  - *Host* CPU
  - *Device* GPU
- Using `__global__` to declare a function as device code
  - Executes on the device
  - Called from the host
- Passing parameters from host code to a device function

Review (2 of 2)

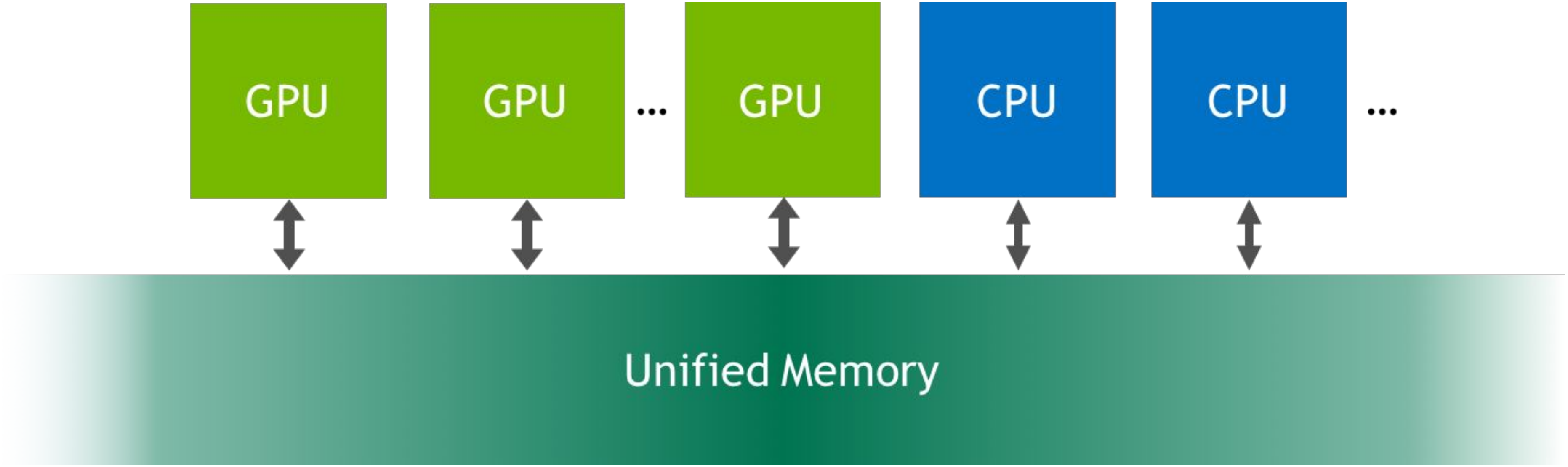
- Basic device memory management
  - **cudaMalloc()**
  - **cudaMemcpy()**
  - **cudaFree()**
- Launching parallel kernels
  - Launch **N** copies of **add()** with **add<<<N,1>>>(…)**.
  - Use **blockIdx.x** to access block index.
  - Use **nvprof** for collecting & viewing profiling data.

Unified Memory Programming



Unified Memory

Software: CUDA 6.0 in 2014 **Hardware: Pascal GPU in 2016**



Unified Memory

- A managed memory space where all processors see a single coherent memory image with a common address space.
- Eliminates the need for **`cudaMemcpy()`**.
- Enables simpler code.

- Equipped with hardware support since Pascal.

Example - Vector Addition w/o UM

```
__global__  void  VecAdd( int  *ret,  int  a,  int  b) {
    ret[threadIdx.x] = a + b + threadIdx.x;
}
int main() {
    int *ret;
    cudaMalloc(&ret, 1000 * sizeof(int));
    VecAdd<<< 1, 1000 >>>(ret, 10, 100);
    int *host_ret = (int *)malloc(1000 * sizeof(int));
    cudaMemcpy(host_ret, ret, 1000 * sizeof(int), cudaMemcpyDefault);
    for(int i=0; i<1000; i++)
        printf("%d: A+B = %d\n", i, host_ret[i]);
    free(host_ret);
    cudaFree(ret);
    return  0;
}
```

Example - Vector Addition with UM

```
__global__ void VecAdd(int *ret, int a, int b) {
    ret[threadIdx.x] = a + b + threadIdx.x;
}
int main() {
    int *ret;
    cudaMallocManaged(&ret, 1000 * sizeof(int));
    VecAdd<<< 1, 1000 >>>(ret, 10, 100);
    cudaDeviceSynchronize();
    for(int i=0; i<1000; i++)
        printf("%d: A+B = %d\n", i, ret[i]);
    cudaFree(ret);
    return  0;
}
```

Example - Vector Addition with Managed Global Memory

```
__device__ __managed__  int  ret[1000];

__global__ void VecAdd(int *ret, int a, int b) {
    ret[threadIdx.x] = a + b + threadIdx.x;
}
int main() {
    VecAdd<<< 1, 1000 >>>(ret, 10, 100);
    cudaDeviceSynchronize();
    for(int i=0; i<1000; i++)
        printf("%d: A+B = %d\n", i, ret[i]);
    return  0;
}
```

Managing Devices

Coordinating Host & Device

- Kernel launches are asynchronous
  - Control returns to the CPU immediately
- CPU needs to synchronize before consuming the results

`cudaMemcpy()`	Blocks the CPU until the copy is complete. Copy begins when all preceding CUDA calls have completed
`cudaMemcpyAsync()`	Asynchronous, does not block the CPU
`cudaDeviceSynchronize()`	Blocks the CPU until all preceding CUDA calls have completed

Reporting Errors

- All CUDA API calls return an error code (`cudaError_t`)
  - Error in the API call itself or
  - Error in an earlier asynchronous operation (e.g. kernel)
- Get the error code for the last error:

```
cudaError_t cudaGetLastError(void)
```

- Get a string to describe the error:

```
char *cudaGetErrorString(cudaError_t)
printf("%s\n",cudaGetErrorString(cudaGetLastError()));
```

Device Management

- Application can query and select GPUs

```
cudaGetDeviceCount(int *count)
cudaSetDevice(int device)
cudaGetDevice(int *device)
cudaGetDeviceProperties(cudaDeviceProp *prop, int device)
```

- Multiple threads can share a device
- A single thread can manage multiple devices

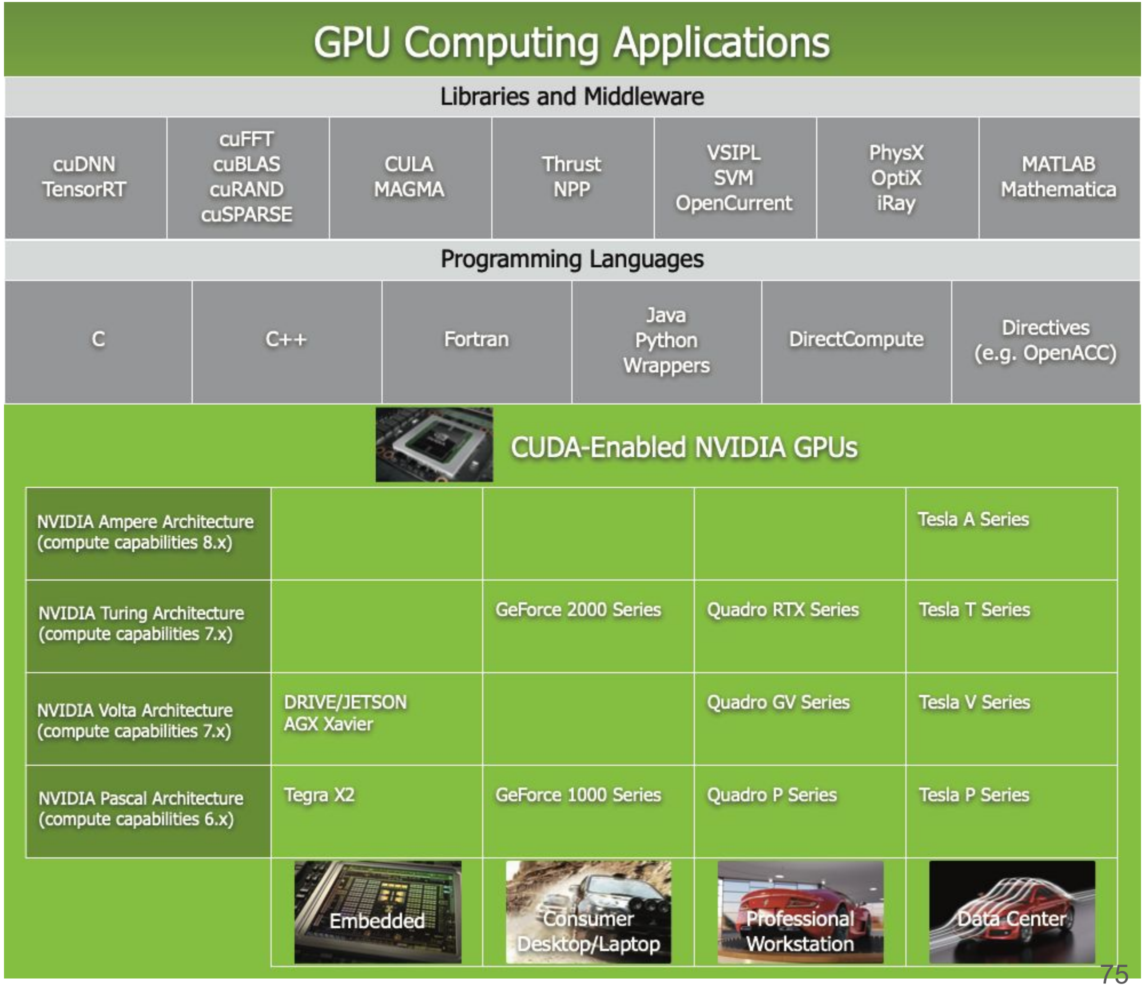
  Select current device: `cudaSetDevice(i)`

  For peer-to-peer copies: `cudaMemcpy(…)`

† requires OS and device support

GPU Computing Capability

The compute capability of a device is represented by a version number that identifies the features supported by the GPU hardware and is used by applications at runtime to determine which hardware features and/or instructions are available on the present GPU.



More Resources

You can learn more about CUDA at

– CUDA Programming Guide (docs.nvidia.com/cuda)

– CUDA Zone – tools, training, etc. (developer.nvidia.com/cuda-zone)

– Download CUDA Toolkit & SDK (www.nvidia.com/getcuda)

– Nsight IDE (Eclipse or Visual Studio) (www.nvidia.com/nsight)

Acknowledgments

- Educational materials from NVIDIA Deep Learning Institute via its University Ambassador Program.
- Support from Texas A&M Engineering Experiment Station (TEES), Texas A&M Institute of Data Science (TAMIDS), and Texas A&M High Performance Research Computing (HPRC).
- Support from NSF OAC Award #2019129 - MRI: Acquisition of FASTER - Fostering Accelerated Sciences Transformation Education and Research
- Support from NSF OAC Award #2112356 - Category II: ACES - Accelerating Computing for Emerging Sciences

Tesla A100 GPU Node

```
Device 0: "A100-PCIE-40GB"
  CUDA Driver Version / Runtime Version          11.2 / 11.0
  CUDA Capability Major/Minor version number:   8.0
  Total amount of global memory:                40536 MBytes (42505273344 bytes)
  (108) Multiprocessors, ( 64) CUDA Cores/MP:   6912 CUDA Cores
  GPU Max Clock rate:                           1410 MHz (1.41 GHz)
  Memory Clock rate:                            1215 Mhz
  Memory Bus Width:                             5120-bit
  L2 Cache Size:                                41943040 bytes
  Warp size:                                    32
  Maximum number of threads per multiprocessor: 2048
  Maximum number of threads per block:          1024
  Max dimension size of a thread block (x,y,z): (1024, 1024, 64)
  Max dimension size of a grid size    (x,y,z): (2147483647, 65535, 65535)
  Concurrent copy and kernel execution:         Yes with 3 copy engine(s)
  Run time limit on kernels:                    No
  Device has ECC support:                       Enabled
  Device supports Unified Addressing (UVA):     Yes
  Supports Cooperative Kernel Launch:           Yes
```