LAU
الجامعة اللبنانية الأميركية
Lebanese American University

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

CUDA Memory and Blocks

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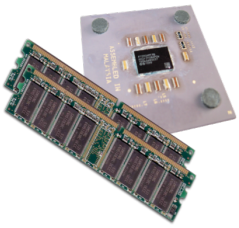
CONCEPTS

- Heterogeneous Computing
- Hello World!
- Compiling

Heterogeneous Computing

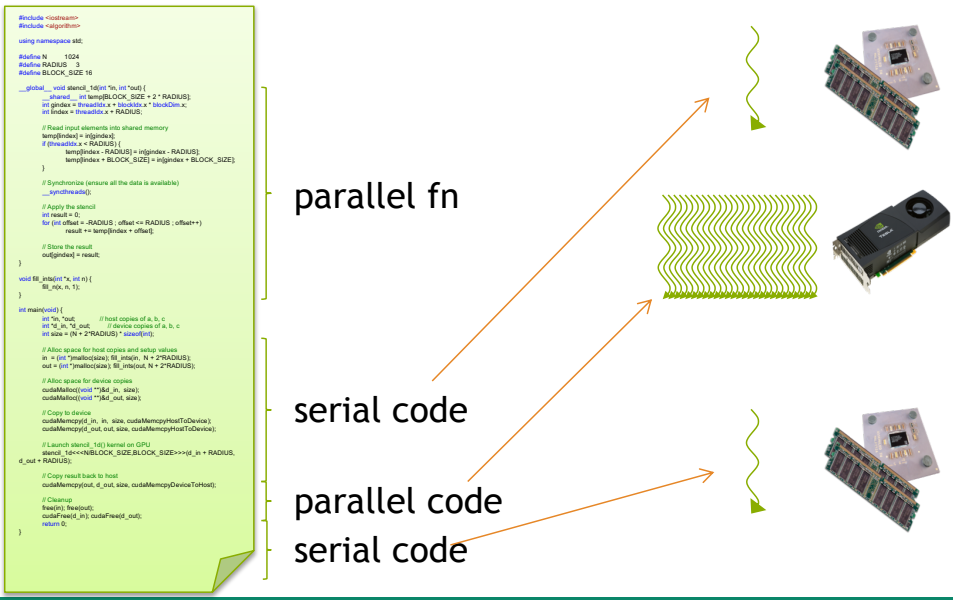
- Terminology:
  - *Host* The CPU and its memory (host memory)
  - *Device* The GPU and its memory (device memory)



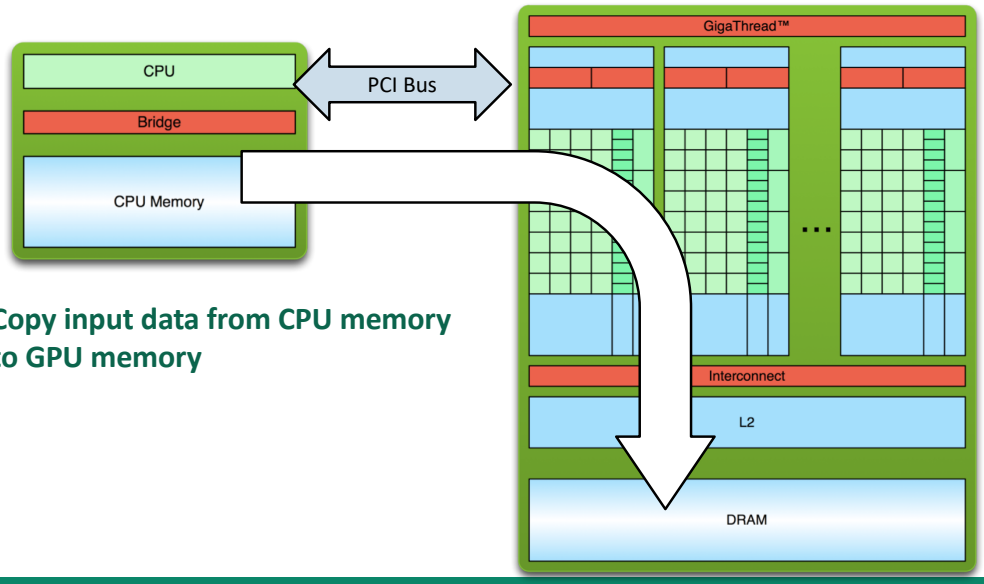
Host

Device

Heterogeneous Computing

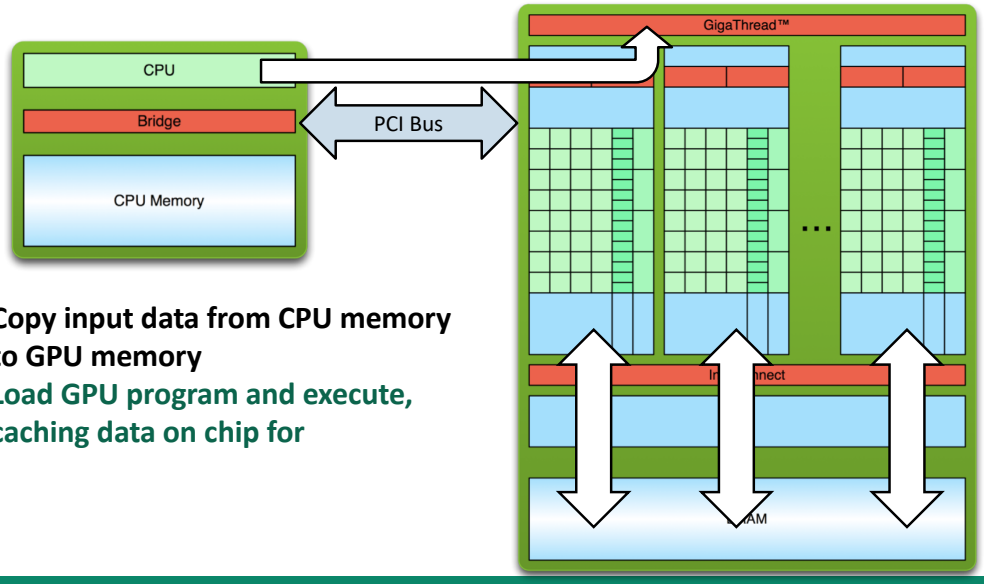


Simple Processing Flow



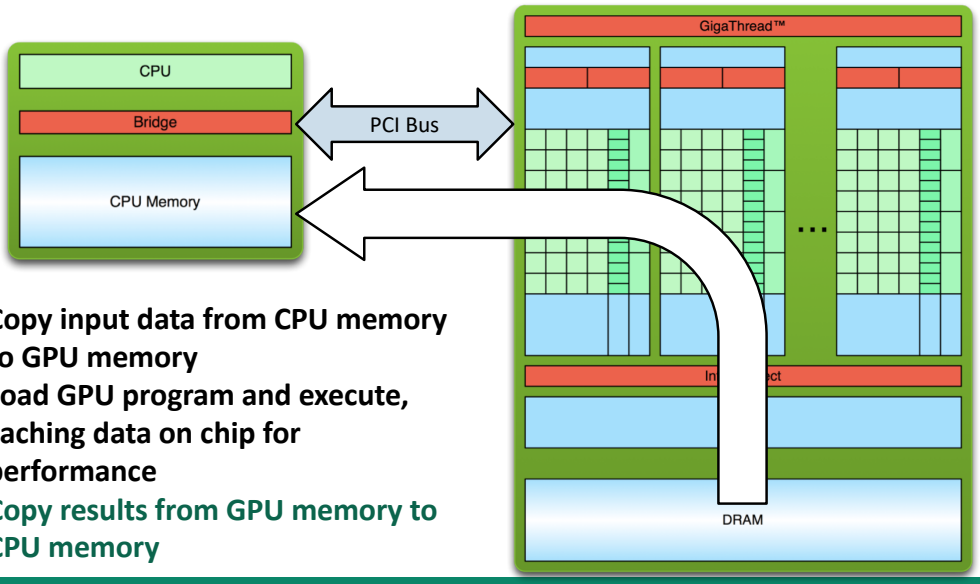
1. Copy input data from CPU memory to GPU memory

Simple Processing Flow



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

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**

Heterogeneous Computing

Hello World!

Compiling

Hello World!

CUDA

- CUDA provides a simple grid model
  - Can decompose into CUDA blocks
- A linear distribution of work within a single block leads to an ideal decomposition into CUDA blocks.
  - Can assign up to sixteen blocks per SM and we can have up to 16 SMs (32 on some GPUs), any number of blocks of 256 or larger is fine.
  - In practice, limit the number of elements within the block to 128, 256, or 512

Blocks, Threads, and Grids

- CUDA C allows the definition of a group of blocks in two dimensions
- Use two-dimensional indexing for problems such as matrix math or image processing
  - Avoid annoying translations from linear to rectangular indices
- A collection of parallel blocks is called a grid
- No dimension of a launch of blocks may exceed 65,535

CUDA Hello World

- We will discuss over the following few slides a couple of simple examples
- We will start with the classical `hello_world` example

Hello World (Host Only)

- Recall
  - *Host*–The CPU and its memory (host memory)
  - *Device*–The GPU and its memory (device memory)

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

Hello World (Device Code)

- Recall
  - *Host*–The CPU and its memory (host memory)
  - *Device*–The GPU and its memory (device memory)

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

Output:

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


Hello World (Device Code)

- CUDA C keyword `__global__` indicates that a function
  - Runs on the device
  - Called from host code
- `kernel<<< 1, 1 >>>();`
  - Triple angle brackets mark a call from hostcode to devicecode
  - Sometimes called a "kernel launch"
- nvcc splits the source file into host and device components
  - NVIDIA's compiler handles device functions like kernel()
  - Standard host compiler handles host functions like main()
    - gcc
    - Microsoft Visual C

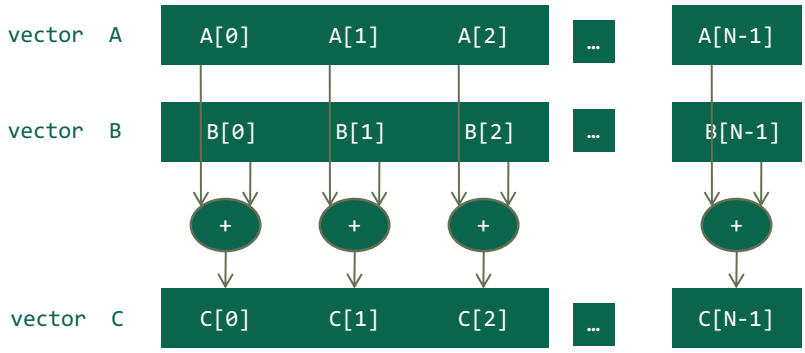
Introduction to CUDA C

- Memory Management
- Blocks
- Threads
- Indexing
- Shared memory
- __syncthreads()
- Asynchronous operation
- Handling errors
- Managing devices

Memory Management

- **`host`** and **`device`** memory are distinct entities in CUDA:
  - Device pointers point to GPU memory
  - May be passed to and from host code
  - May not be dereferenced from host code
- Host pointers point to CPU memory
  - May be passed to and from device code
  - May not be dereferenced from device code
- Basic CUDA API for dealing with device memory
  - `cudaMalloc(), cudaFree(), cudaMemcpy()`
  - Similar to their C equivalents, `malloc(), free(), memcpy()`

Vector Addition



Vector Addition: Typical Solution

```
// Compute vector sum C = A + B
void vecAdd(float *h_A, float *h_B, float *h_C, int n)
{
    int i;
    for (i = 0; i<n; i++)
        h_C[i] = h_A[i] + h_B[i];
}
int main()
{
   // Memory allocation for h_A, h_B, and h_C
   // I/O to read h_A and h_B, N elements
   …
    vecAdd(h_A, h_B, h_C, N);
}
```

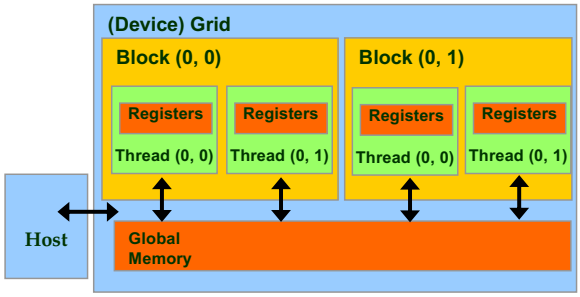
Memory Management

- 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()`

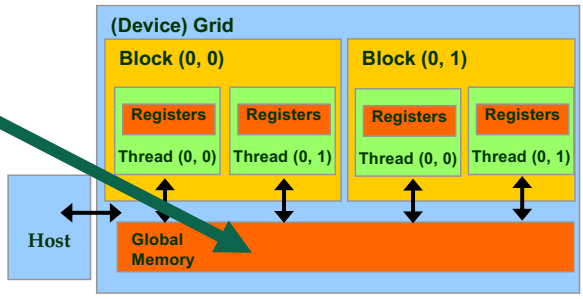
Partial Overview of CUDA Memories

- Device code can:
  - R/W per-thread registers
  - R/W all-shared global memory
- Host code can
  - Transfer data to/from per grid global memory



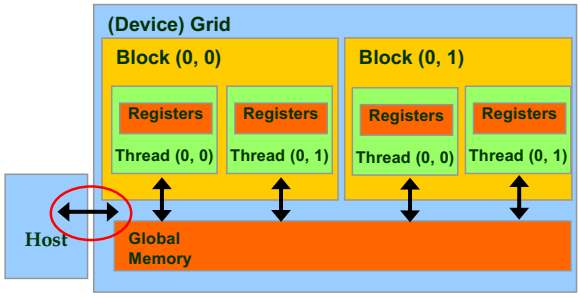
CUDA Device Memory Management API functions

- cudaMalloc()
  - Allocates an object in the device global memory
  - Two parameters
    - **Address of a pointer** to the allocated object
    - **Size of** allocated object in terms of bytes
- cudaFree()
  - Frees object from device global memory
  - One parameter
    - **Pointer** to freed object



Host-Device Data Transfer API functions

- cudaMemcpy()
  - memory data transfer
  - Requires four parameters
    - Pointer to destination
    - Pointer to source
    - Number of bytes copied
    - Type/Direction of transfer
  - Transfer to device is asynchronous



Adding two numbers on the GPU

```
int main( void )
{
      int a, b, c;                          // host copies of a, b, c
      int *dev_a, *dev_b, *dev_c;           // device copies of a, b, c
      int size = sizeof( int);              // we need space for an integer

      // allocate device copies of a, b, c
      cudaMalloc( (void**)&dev_a, size );
      cudaMalloc( (void**)&dev_b, size );
      cudaMalloc( (void**)&dev_c, size );
      a = 2;lock
      b = 7;
      // copy inputs to device
      cudaMemcpy( dev_a, &a, size, cudaMemcpyHostToDevice);
      cudaMemcpy( dev_b, &b, size, cudaMemcpyHostToDevice);

    // launch add() kernel on GPU, passing parameters
      vecAdd<<< 1, 1 >>>( dev_a, dev_b, dev_c);

    // copy device result back to host copy of c
    cudaMemcpy( &c, dev_c, size, cudaMemcpyDeviceToHost);
    cudaFree( dev_a);
    cudaFree( dev_b);
    cudaFree( dev_c);
    return 0;
}
```

We can do without this as of CUDA 6

Kernel Launch for one block with one thread

Vector Addition on the GPU

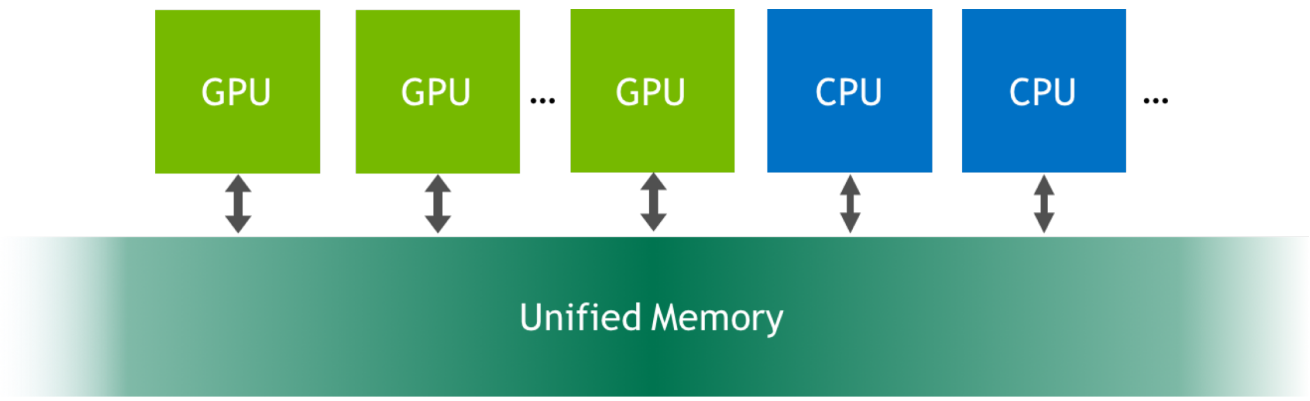
```
__global__ void vecAdd( int *a, int *b, int *c)
{
    *c= *a+ *b;
}
```

- vecAdd()
  - __global__ indicates that the function runs on the device and called from host code
  - …so a, b, and c must point to device memory

Unified Memory in CUDA 6

- GPU and CPU memproes are physically distinct and separated by the PCI-Express bus.
- As of CUDA 6 and starting with the Kepler, NVidia bridged the CPU-GPU divide
  - Unified Memory creates a pool of managed memory that is shared between the CPU and GPU
  - Managed memory is accessible to both the CPU and GPU using a single pointer.
  - The system automatically migrates data between the CPU and the GPU memories

Unified Memory



CPU Code

```
void sortfile(FILE *fp, int N) {
  char *data;
  data = (char *)malloc(N);

  fread(data, 1, N, fp);

  qsort(data, N, 1, compare);


  use_data(data);

  free(data);
}
```

CUDA 6 Code with Unified Memory

```
void sortfile(FILE *fp, int N) {
  char *data;
  cudaMallocManaged(&data, N);

  fread(data, 1, N, fp);

  qsort<<<...>>>(data,N,1,compare);
  cudaDeviceSynchronize();

  use_data(data);

  cudaFree(data);
}
```


"cudaMallocManaged" vs. "cudaMalloc"

- Some have benchmarked both and noted that is slightly "cudaMallocManaged" slower than "cudaMalloc"
- The following can be noted:
  - The main bottleneck is on the PCIE bus
  - cudaMallocManaged is of interest to a non-proficient CUDA programmer
    - Simpler learning curve
  - The Maxwell and Pascal architectures provide HW support for unified memory so cudaMallocManaged() provides better performance on those architectures

Back to Our Addition Example: Unified Memory (CUDA 6 and beyond)

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

int main( void )
{
      int *a, *b, *c;              // host copies of a, b, c
      int size = sizeof (int);     // The total number of bytes per vector

   // Allocate memory
   cudaMallocManaged(&a, size);
   cudaMallocManaged(&b, size);
   cudaMallocManaged(&c, size);

  // launch add() kernel on GPU, passing parameters
   vecAdd<<< 1, 1 >>> ( a, b, c);

   cudaDeviceSynchronize(); // Wait for the GPU to finish

    // Free all our allocated memory
    cudaFree( a ); cudaFree( b ); cudaFree( c );
}
```

Run one block with one thread

Blocks until the device has completed all preceding requested tasks.

In Practice, Check for API Errors in Host Code

```
cudaError_t  err = cudaMalloc((void **) &d_A, size);

if (err != cudaSuccess)  {
   printf("%s in %s at line %d\n", cudaGetErrorString(err), __FILE__, __LINE__);
   exit(EXIT_FAILURE);
}
```

CUDA Blocks

- Memory Management
- Blocks
- Threads
- Indexing
- Shared memory
- __syncthreads()
- Asynchronous operation
- Handling errors
- Managing devices

Moving to Parallel

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

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

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

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

Vector Addition on the GPU

- Well, since GPUs are about massive parallelism we will rewrite the add() method such that
  - Each invocation of add() is referred to as a *block*
  - Kernel can refer to its block's index with the variable blockIdx.x
  - Each block adds a value from a[] and b[], storing the result in c[]
- By using `blockIdx.x` to index into the array, each block handles a different index

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


Vector Addition on the GPU


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

Vector Addition on the GPU: N Blocks

```
#define N 512
int main( void )
{
      int *a, *b, *c;                       // a, b, c
      int size = N * sizeof( int);          // The total number of bytes per vector

      // Allocate memory
      cudaMallocManaged(&a, size);
      cudaMallocManaged(&b, size);
      cudaMallocManaged(&c, size);

      random_ints( a, N );
      random_ints( b, N );


      // launch add() kernel on GPU using N Parallel Blocks
      vecAdd<<< N, 1 >>>( a, b, d);

      cudaDeviceSynchronize(); // Wait for the GPU to finish


      // Free all our allocated memory
      cudaFree( a ); cudaFree( b ); cudaFree( c );
}
```

Launch N blocks with 1 thread each