IHPC 2011, June 1-3rd 2011
Parallel Programming with GPUs

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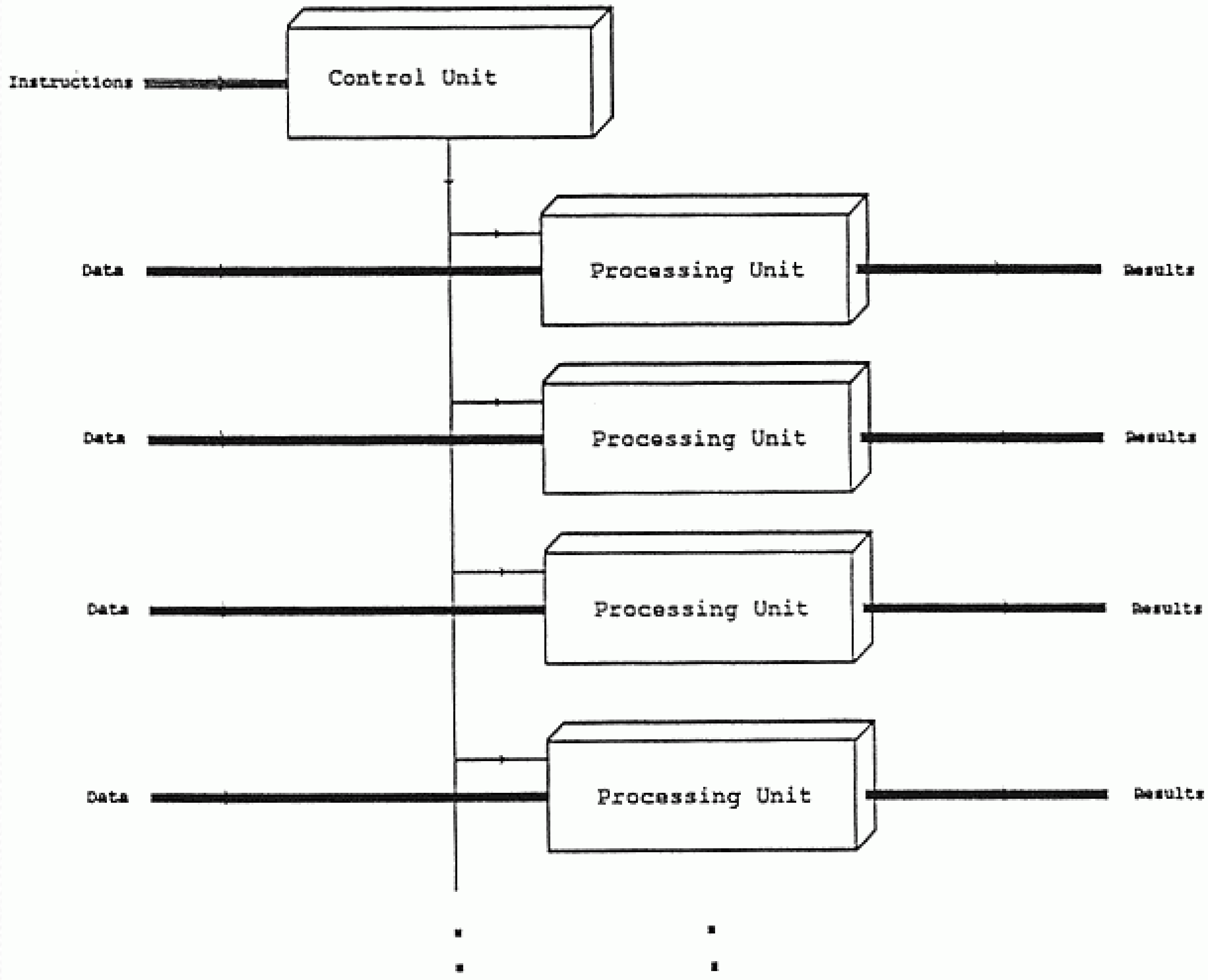
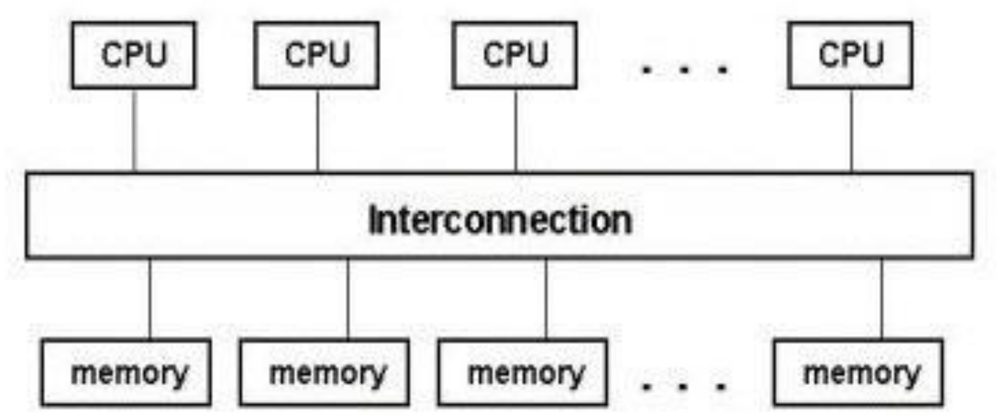
SIMD



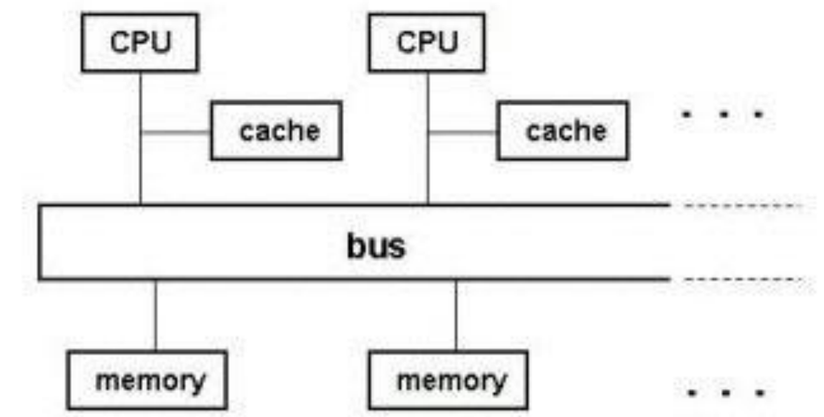
Instructions
Control Unit
Data
Processing Unit
Results
Data
Processing Unit
Results
Data
Processing Unit
Results
Data
Processing Unit
Results

MIMD Shared Memory

- Virtual view - single globally addressable memory
- May be a single memory or several memories
- Access time can vary (NUMA) based on how close a memory is to the referencing processor



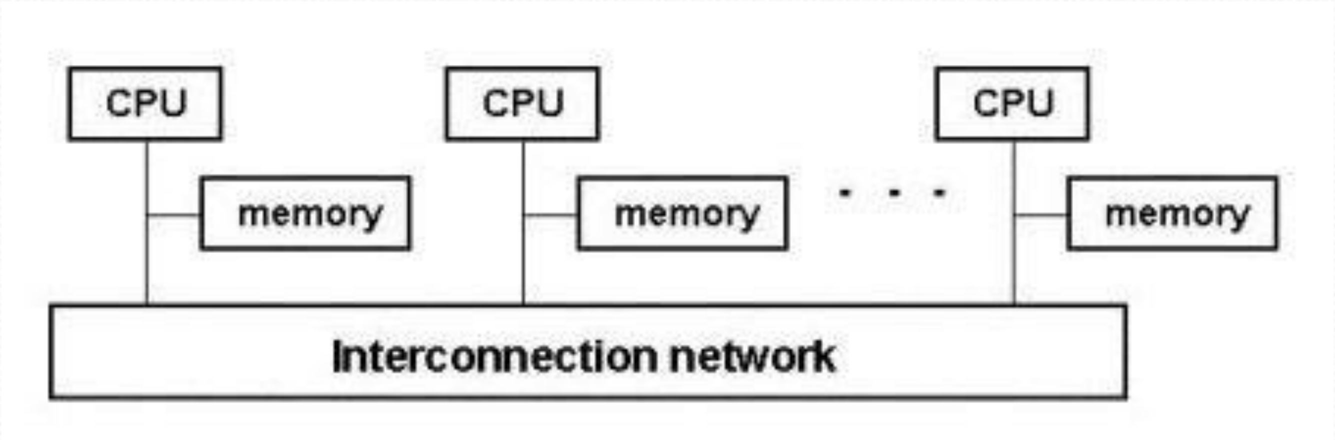
Shared-memory MIMD architecture



Bus-based shared-memory MIMD architecture

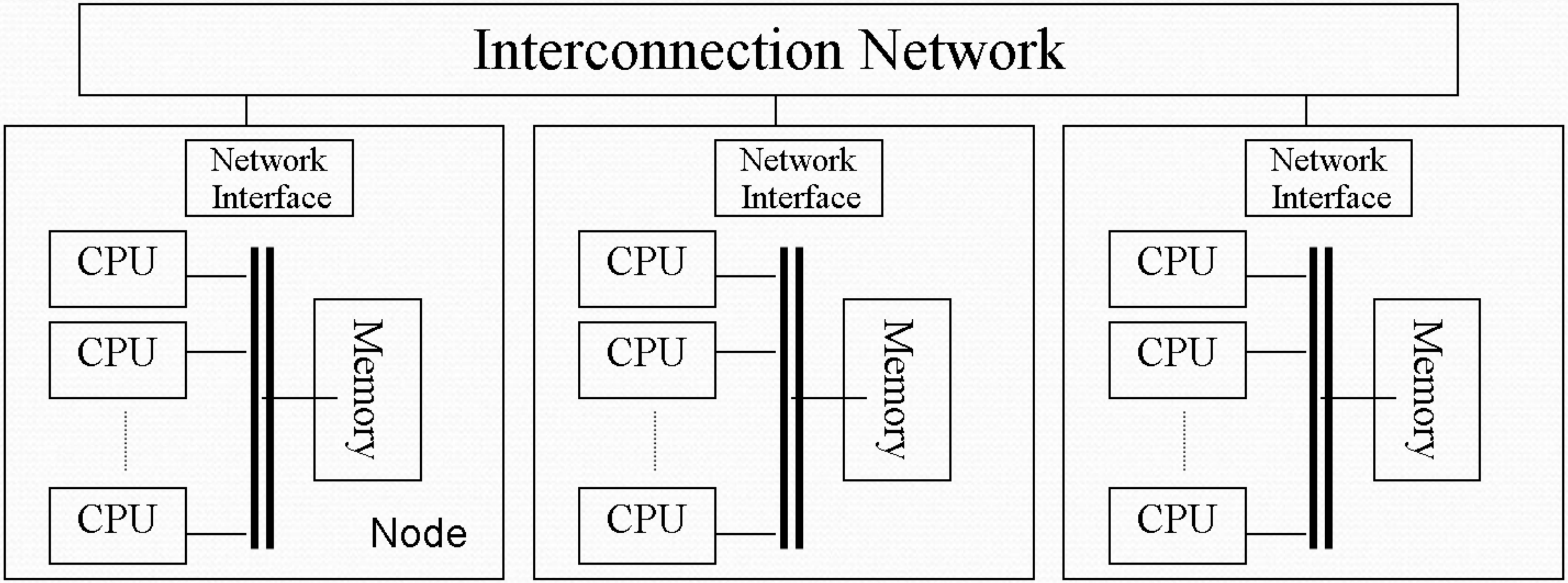
MIMD Distributed Memory

- Each processor has its own private memory
- Data must be explicitly sent from one processor to another over the network to share data

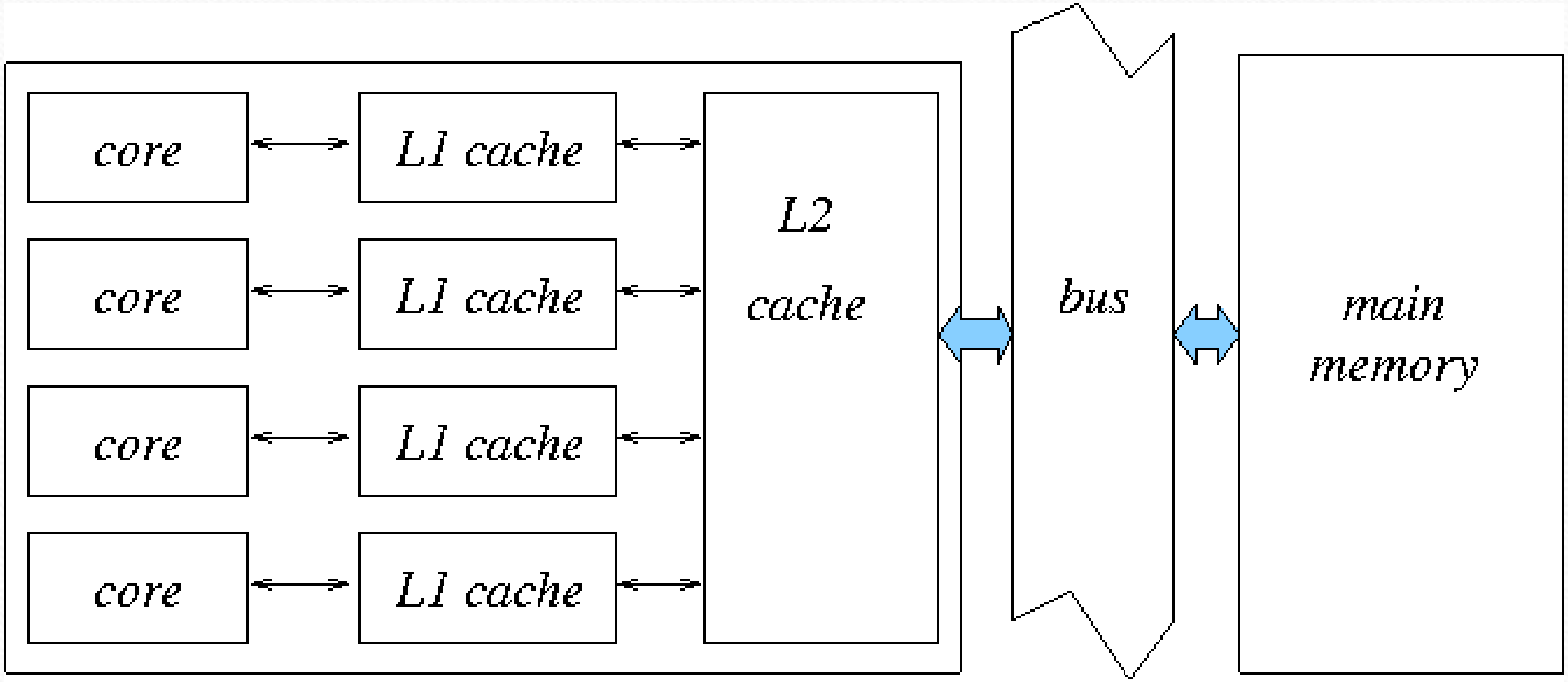


Symmetric Multi-Processing

- Shared memory within a node
  - Multiple sockets
  - Multicore chip in each socket
- Distributed memory across nodes



Multicore Processor

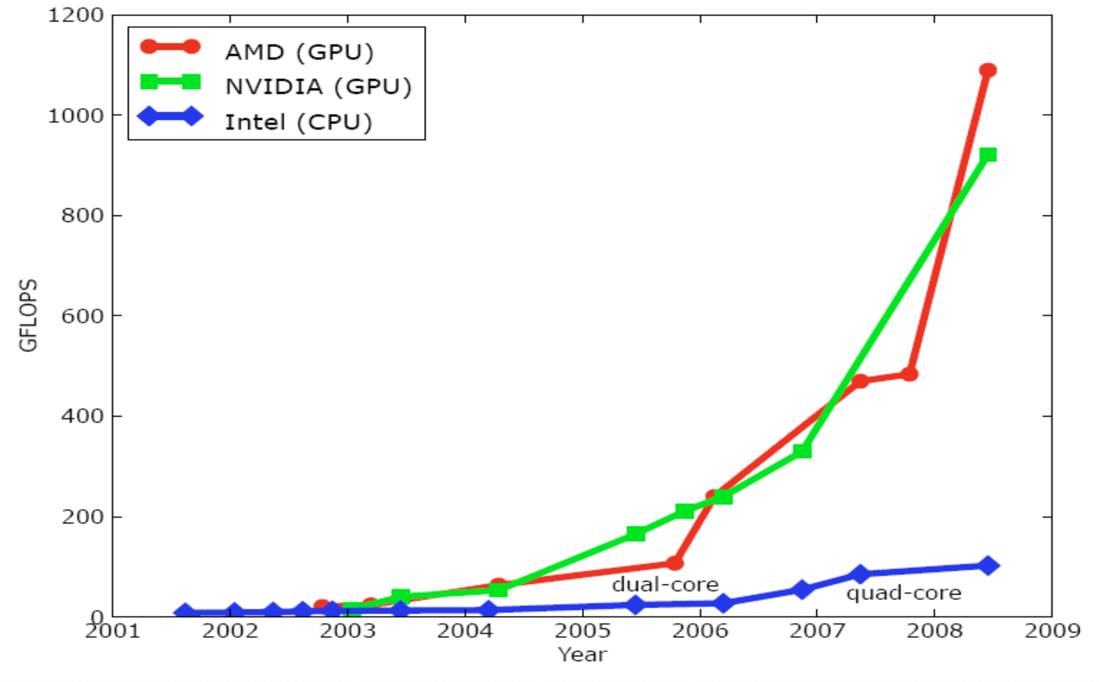


Tools for parallel Programming

- In 1997 MPI (message Passing Interface) for distributed memory systems. In 2008 OpenMPI (open source version) was made available.
- Pthreads or OpenMP (1997) for shared memory programming on computers and processors. OpenMP application programming interface (API) was developed by the OpenMP ARB (arch. Review board)
- CUDA (2003) for host-device architectures GPU's and also recently Intel's OpenCL. Graphics GPU's used OpenGL which is good for graphics application but very difficult for numerical software development.

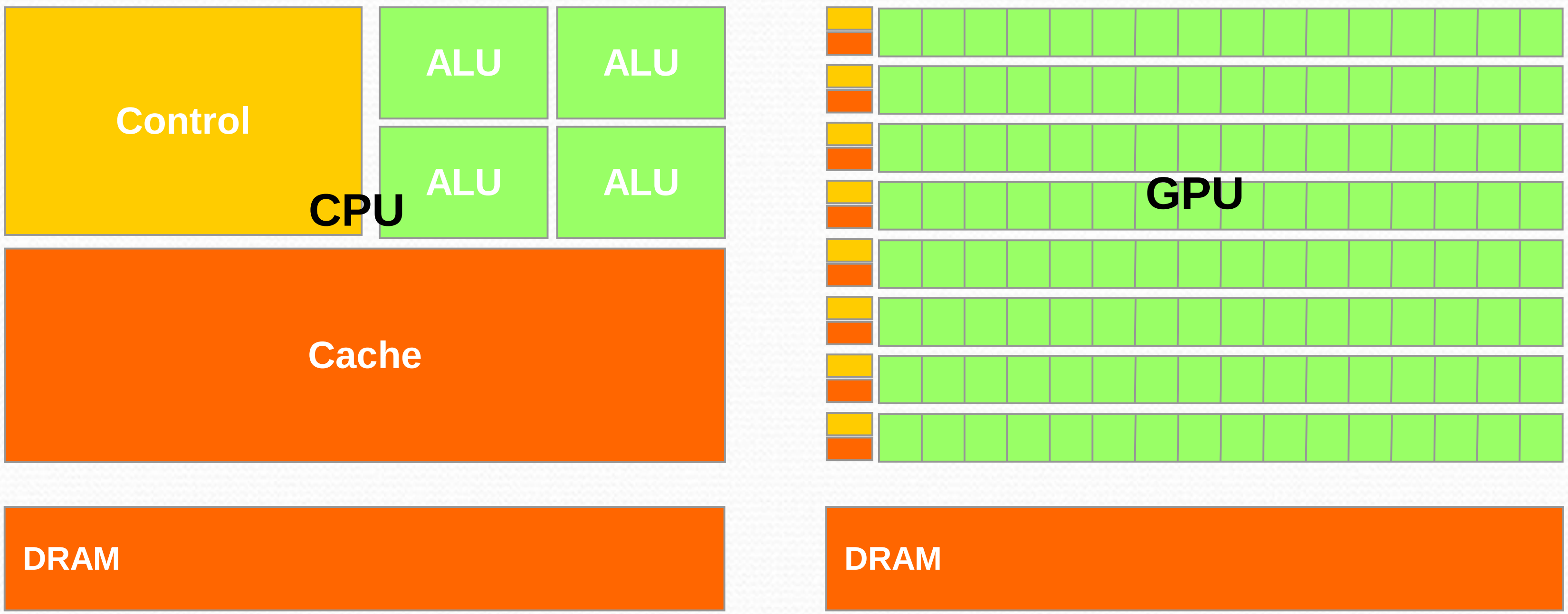
Massively Parallel Processor with GPUs

- A quiet revolution and potential build-up
  - Calculation: 367 GFLOPS vs. 32 GFLOPS
  - Memory Bandwidth: 86.4 GB/s vs. 8.4 GB/s
  - Until 2007, programmed through graphics API

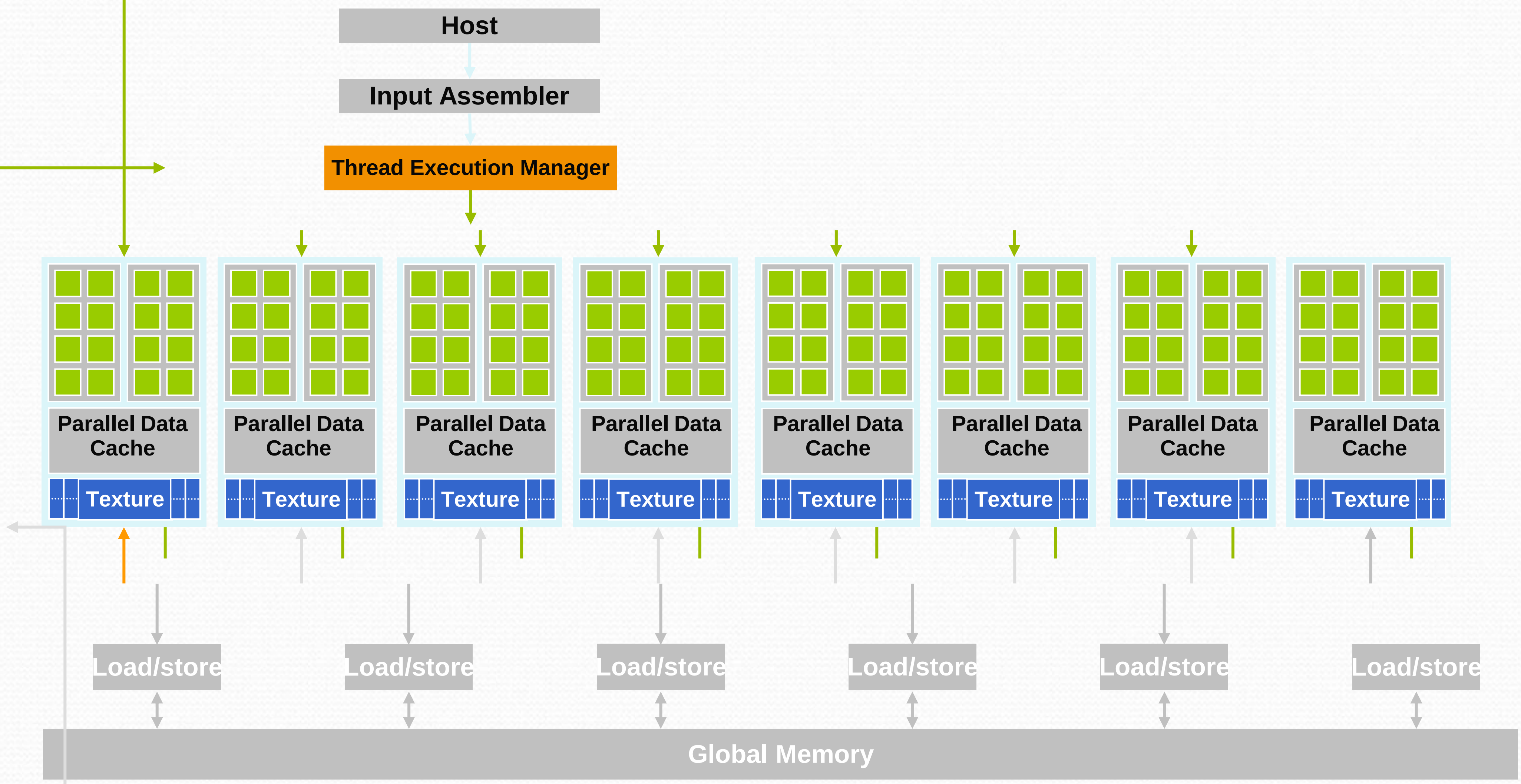


  - GPU in every PC and workstation – massive volume and potential impact

CPUs and GPUs have fundamentally different design philosophies

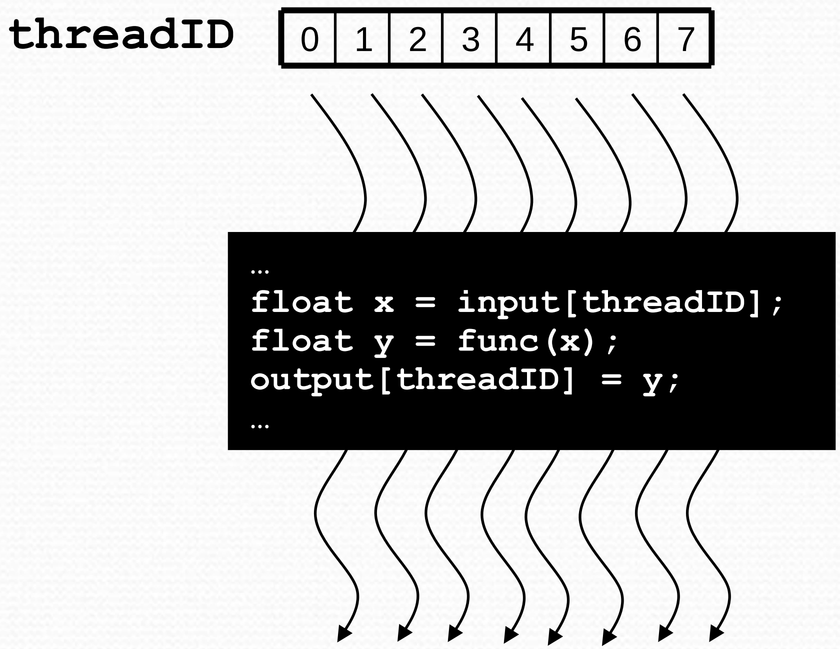


Architecture of a CUDA GPU(2007 on)



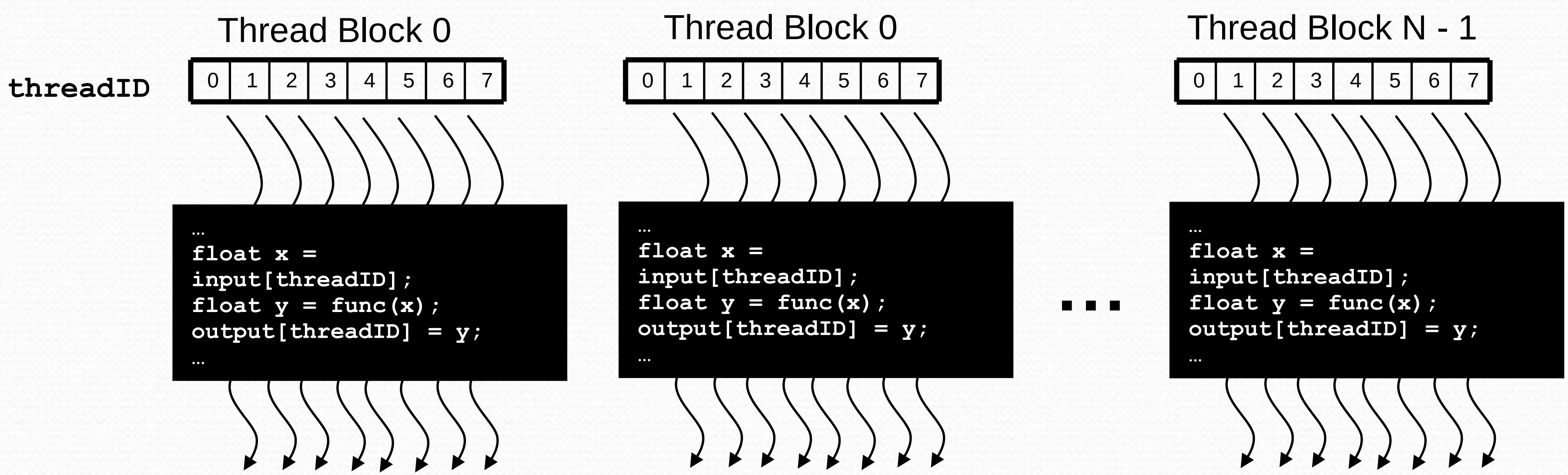
Arrays of Parallel Threads

- A CUDA kernel is executed by an array of threads
  - All threads run the same code (SPMD)
  - Each thread has an ID that it uses to compute memory addresses and make control decisions



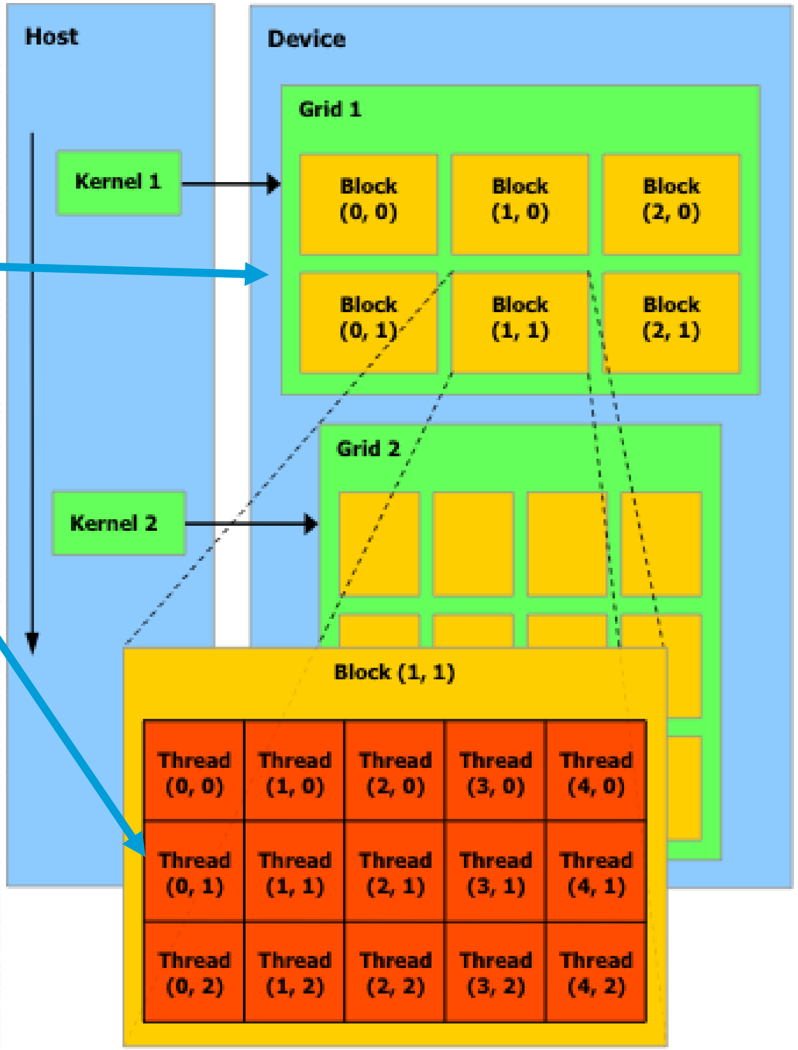
Cooperation

- Divide monolithic thread array into multiple blocks
  - Threads within a block cooperate via **shared memory, atomic operations** and **barrier synchronization**
  - Threads in different blocks cannot cooperate



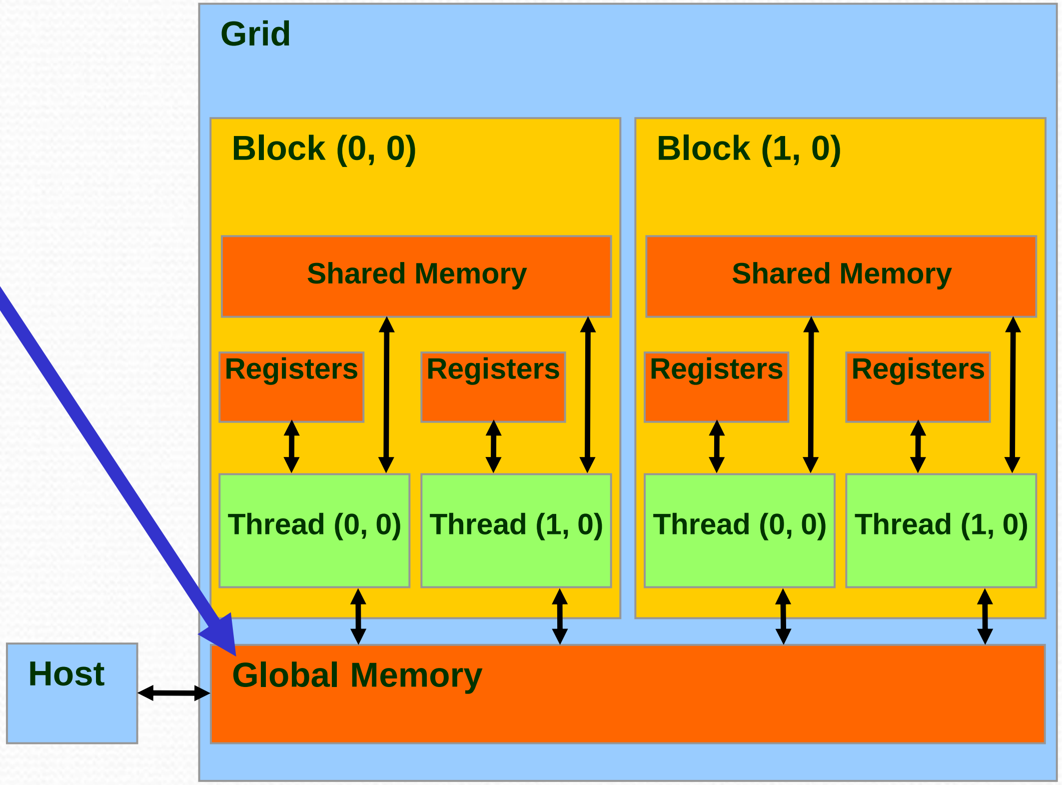
Block IDs and Thread IDs

- Each thread uses IDs to decide what data to work on
  - Block ID: 1D or 2D
  - Thread ID: 1D, 2D, or 3D
- Simplifies memory addressing when processing multidimensional data
  - Image processing
  - Solving PDEs on volumes
  - …



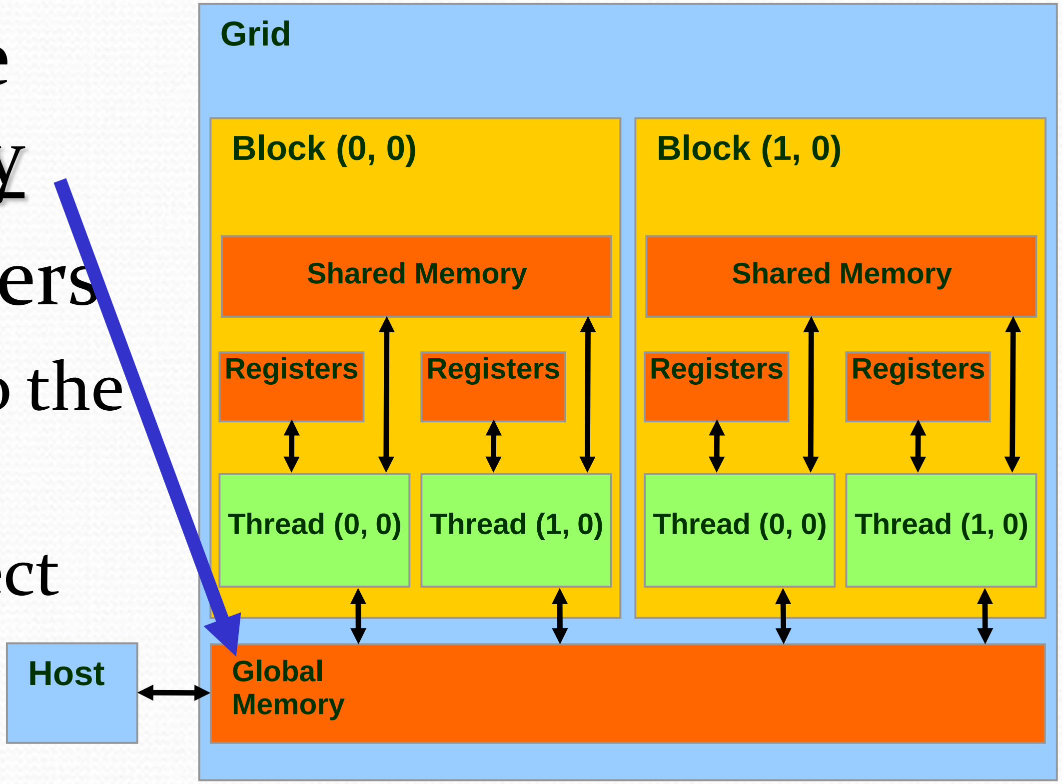
CUDA Memory Model Overview

- Global memory
  - Main means of communicating R/W Data between host and device
  - Contents visible to all threads
  - Long latency access
- We will focus on global memory for now



CUDA Device Memory

- cudaMalloc()
  - Allocates object in the device Global Memory
  - Requires two parameters
    - **Address of a pointe**r to the allocated object
    - **Size of** of allocated object
- cudaFree()
  - Frees object fromdevice Global Memory



CUDA Device Memory Allocation (cont.)

- Code example:
  - Allocate a 64 * 64 single precision float array
  - Attach the allocated storage to Md
  - “d” is often used to indicate a device data structure

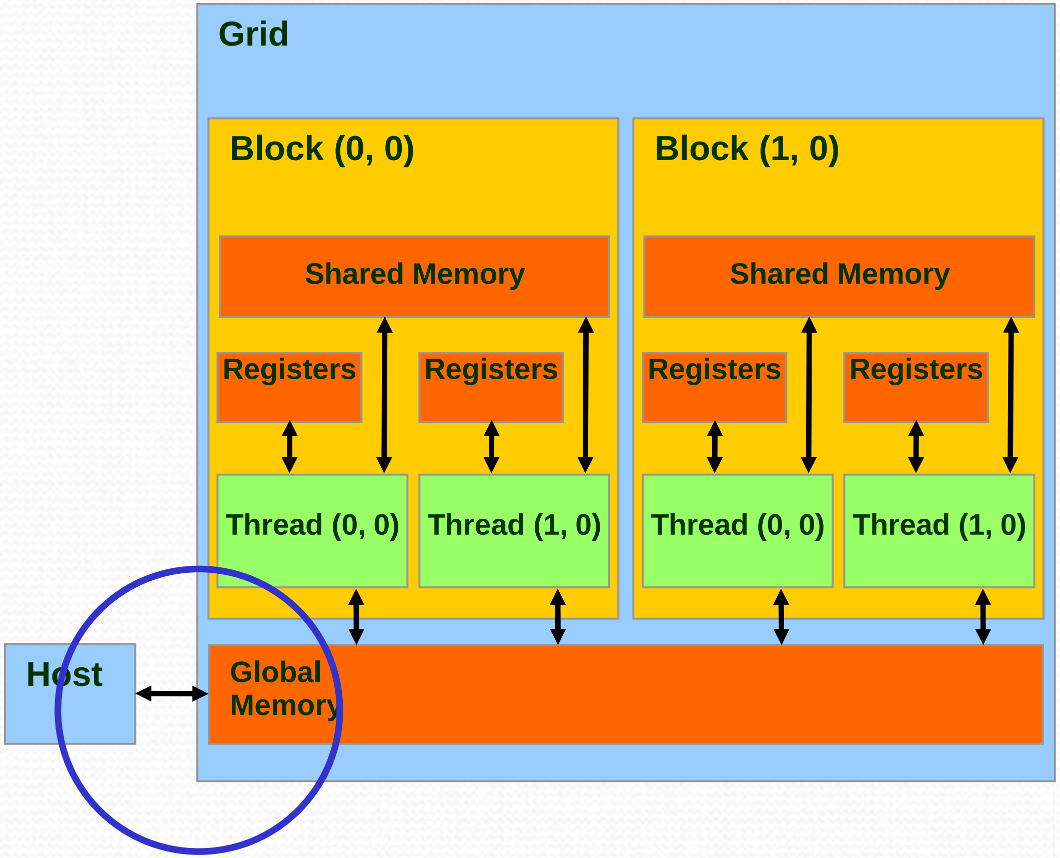
```
TILE_WIDTH = 64;
Float* Md;
int size = TILE_WIDTH * TILE_WIDTH * sizeof(float);
```

cudaMalloc((void)&Md, size);**

cudaFree(Md);

CUDA Host-Device Data Transfer

- cudaMemcpy() - synchronous
  - memory data transfer
  - Requires four parameters
    - Pointer to destination
    - Pointer to source
    - Number of bytes copied
    - Type of transfer
      - Host to Host
      - Host to Device
      - Device to Host
      - Device to Device
- Asynchronous transfer
  - cudaMemcpyAsync()



CUDA Host-Device Data Transfer

- Code example:
  - Transfer a 64 * 64 single precision float array
  - M is in host memory and Md is in device memory
  - cudaMemcpyHostToDevice and cudaMemcpyDeviceToHost are symbolic constants

```
cudaMemcpy(Md, M, size, cudaMemcpyHostToDevice);

cudaMemcpy(M, Md, size, cudaMemcpyDeviceToHost);
```

- **Declspecs**
  - **global, device, shared, constant**
- **Keywords**
  - **threadIdx, blockIdx**
- **Intrinsics**
  - **__syncthreads**
- **Runtime API**
  - **Memory, symbol, execution management**
- **Function launch**

```
__device__ float filter[N];

__global__ void convolve (float *image)  {

  __shared__ float region[M];
  ...

  region[threadIdx] = image[i];

  __syncthreads()
  ...

  image[j] = result;
}

// Allocate GPU memory
cudaMalloc((void **)&myimage, bytes);



// 100 blocks, 10 threads per block
convolve<<<100, 10>>> (myimage);
```

- `__device__` functions cannot have their address taken
- For functions executed on the device:
  - No recursion
  - No static variable declarations inside the function
  - No variable number of arguments

CUDA Function Declarations

	Executed on the:	Only callable from the:
`__device__ float DeviceFunc()`	device	device
`__global__ void KernelFunc()`	device	host
`__host__ float HostFunc()`	host	host

- `__global__` defines a kernel function
  - Must return `void`
- `__device__` and `__host__` can be used together

Calling a Kernel Function – Thread Creation

- A kernel function must be called with an execution configuration:

```
__global__ void KernelFunc(...);
dim3   DimGrid(100, 50);     // 5000 thread blocks
dim3   DimBlock(4, 8, 8);    // 256 threads per block
size_t SharedMemBytes = 64; // 64 bytes of shared
   memory
KernelFunc
<<< DimGrid, DimBlock, SharedMemBytes >>>(...);
```

- Any call to a kernel function is asynchronous – host can continue processing after the kernel call

Choosing the GPU

```
int main( void ) {
    cudaDeviceProp  prop;
    int dev;

    cudaGetDevice( &dev );
    printf( "ID of current CUDA device:  %d\n", dev );

    memset( &prop, 0, sizeof( cudaDeviceProp ) );
    prop.major = 1;
    prop.minor = 3;
    cudaChooseDevice( &dev, &prop );
    printf( "ID of CUDA device closest to revision 1.3:  %d\n", dev );

    cudaSetDevice( dev );
}
```

Adding two vectors on GPU

```
// Example 1: Uses 1 thread per block
#define N   100  // size of vectors

__global__ void add( int *a, int *b, int *c ) {
    int tid = blockIdx.x;    // tid = block index for 1 thread/block (N blocks)
    int tid = threadIdx.x;  // tid = thread index for 1 block kernel launch
    if (tid < N)
        c[tid] = a[tid] + b[tid];
}

int main( void ) {
    int a[N], b[N], c[N];
    int *dev_a, *dev_b, *dev_c;

    // allocate the memory on the GPU
    cudaMalloc( (void**)&dev_a, N * sizeof(int) );
    cudaMalloc( (void**)&dev_b, N * sizeof(int) );
    cudaMalloc( (void**)&dev_c, N * sizeof(int) );
```

```
// copy the arrays 'a' and 'b' to the GPU
    cudaMemcpy( dev_a, a, N * sizeof(int), cudaMemcpyHostToDevice );
    cudaMemcpy( dev_b, b, N * sizeof(int), cudaMemcpyHostToDevice );

    add<<<N,1>>>( dev_a, dev_b, dev_c );   // kernel launch: 1 thread/block, N blocks
    add<<<1,N>>>( dev_a, dev_b, dev_c);    // kernel launch: N threads/block, 1 block

    // copy the array 'c' back from the GPU to the CPU
    cudaMemcpy( c, dev_c, N * sizeof(int), cudaMemcpyDeviceToHost );

    // and display the results...

    // free the memory allocated on the GPU
    cudaFree( dev_a );
    cudaFree( dev_b );
    cudaFree( dev_c );

    return 0;
}
```

General case: B blocks, T threads/block

```
#define N  (32 * 1024)
#define B 128
#define T 128

__global__ void add( int *a, int *b, int *c ) {
    int tid = threadIdx.x + blockIdx.x*blockDim.x;
    while (tid < N) {
        c[tid] = a[tid] + b[tid];
        tid += blockDim.x*gridDim.x;
    }
}
```

Max # blocks = 65,535

Max # threads/block usually = 512

Choosing 128 threads/block: B = (N+127)/128

Using the kernel

```
int main( void ) {
    int a[N], b[N], c[N];
    int *dev_a, *dev_b, *dev_c;
    // allocate memory on device
    cudaMalloc( (void**)&dev_a, N * sizeof(int) );
    cudaMalloc( (void**)&dev_b, N * sizeof(int) );
    cudaMalloc( (void**)&dev_c, N * sizeof(int) );

    // initialize vectors a & b…
    // copy a & b to device (dev_a & dev_b)
    cudaMemcpy( dev_a, a, N * sizeof(int), cudaMemcpyHostToDevice );
    cudaMemcpy( dev_b, b, N * sizeof(int), cudaMemcpyHostToDevice );

     add<<<B,T>>>( dev_a, dev_b, dev_c );  // kernel launch: T threads/block, B blocks

    // copy from device and use results
   cudaMemcpy( c, dev_c, N * sizeof(int), cudaMemcpyDeviceToHost);
}
```

Inner products

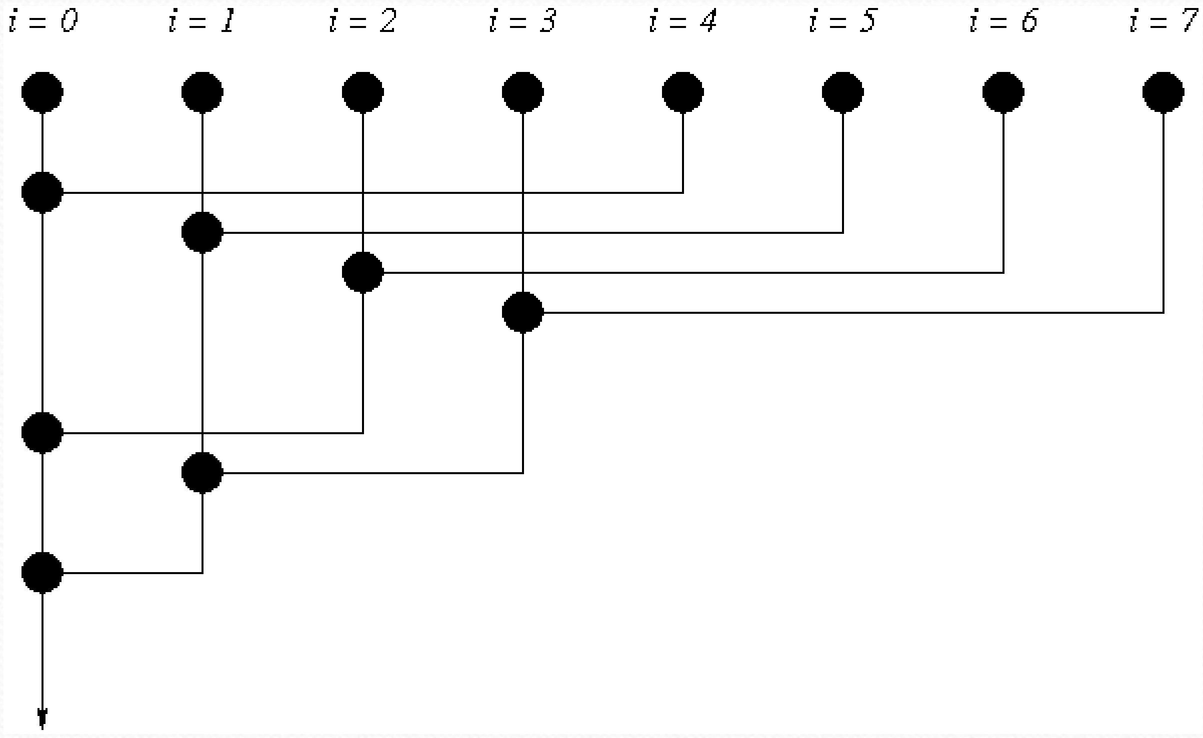
```
__global__ void dot(float *a, float *b, float *c) {
    __shared__ float cache[threadsPerBlock];
    int tid = threadIdx.x + blockIdx.x*blockDim.x;
    int cacheIndex = threadIdx.x;

    float temp = 0;
    while ( tid < N )  {
        temp += a[tid]*b[tid];
        tid     += blockDim.x * gridDim.x;
    }
    cache[cacheIndex] = temp;

    __syncthreads();
```

```
 // parallel reduction: threadsPerblock must be a power of two!
    int i = blockDim.x / 2;
    while ( i != 0 ) {
        if ( cacheIndex < i )
            cache[cacheIndex] += cache[cacheIndex + i];
        __syncthreads();
        i /= 2;
    }
    // cache[0]  is now the sum of a[i]*b[i] for all i for this thread block

    if ( cacheIndex == 0 )
        c[blockIdx.x] = cache[0];
}
```



More on this…

22C:177 High performance and Parallel Computing (cross-listed with 22M:178) Fall 2011

Covers:

- MPI
- OpenMP
- CUDA (OpenCL?)

See http://www.cs.uiowa.edu/~oliveira/C177-F11/C177-F11-description.html

Dr. Oliveira Current Research

- Granular flow simulation on GPU’s
  simulating interactions between rocks or balls as they slide and roll; highly dynamic sparse interact’ns
- Clustering for large databases: algorithms for grouping PPN functional modules, grouping genes activated simultaneously in CNS of rats
- Issues about GPUs
  Redesigning algorithms; ML algorithms
- Other applications using MPI and OpenMP
  Applications involving PDEs, ODEs, linear and no linear solvers, preconditioners (recursive algorithms)

Some references……

- *Using OpenMP*, Chapman, Jost and van der Pas, MIT Press (2008)
- *Art of Concurrency*, Clay Breshears (2009)
- *CUDA by Example: An Introduction to General-Purpose GPU Programming*, Sanders & Kandrot (2010)
- *Programming Massively Parallel Computers*, Kirk & Hwu, Morgan Kauffman (2010)
- *Writing Scientific Software*, Oliveira & Stewart, Cambridge University Press (2006)
- *Parallel Programming with MPI*, Pacheco, Morgan Kauffman (1996)