CSE 599 I Accelerated Computing - Programming GPUS

Multi-GPU Programming

Objective

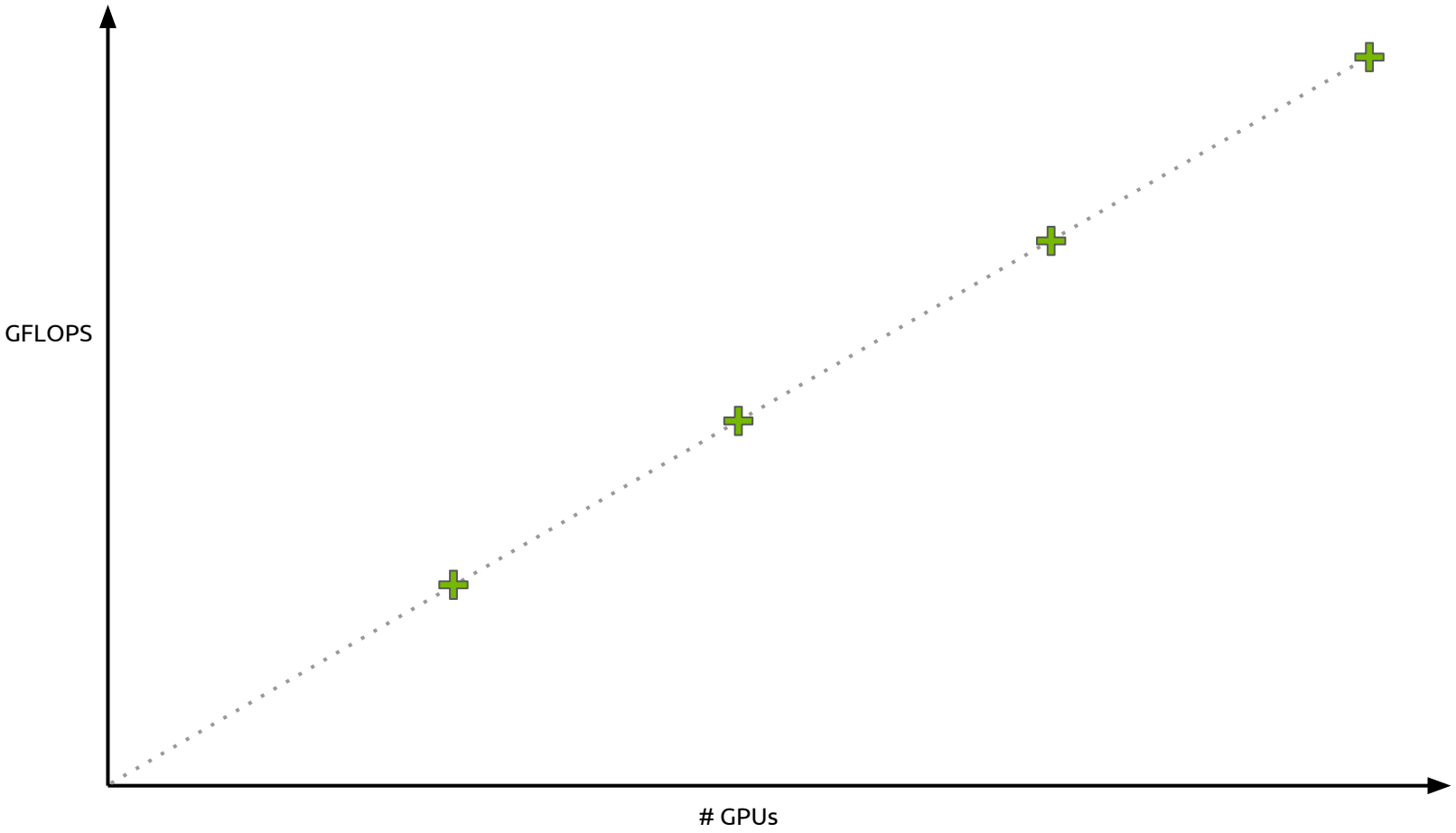
- Look at patterns for multi-gpu computation, including:
  - Multiple GPUs hosted in the same PC
  - Multiple GPUs hosted in multiple PCs on the same network

When is it Time to Scale to Multiple GPUs?

- The data to be processed doesn't fit in the global memory of a single GPU memory and is accessed too frequently and / or irregularly for zero-copy
- Using a single GPU results in many "waves" of blocks which are serialized
- The latencies involved in inter-GPU communication can be hidden by computation done by each GPU

Done properly (and applied to the right problem), bandwidth of multi-GPU programs can grow almost exactly linearly with the number of GPUs (i.e. approach 100% efficiency)

The Ideal Situation



Data-Parallel Multi-GPU Programming

For truly massive N and fully-independent computation, simply distribute N/M input elements to M devices

In the simplest case, all devices are connected via PCIe to the same node

How Many Devices are Available?

```
int numGpus;
cudaGetDeviceCount(&numGpus);

printf("There are %d CUDA-capable devices available\n", numGpus);

for (int i = 0; i < numGpus; ++i) {

     cudaDeviceProp deviceProperties;

     cudaGetDeviceProperties(&deviceProperties, i);

     printf("Device %d has compute capability %d.%d\n",
             i, deviceProperties.major, deviceProperties.minor);

}
```

VectorAdd with Multiple GPUs

```
void superMassiveVectorAdd(const float * h_A, const float * h_B, float * h_C, const int N) {

        const int nPerGpu = (N - 1) / NUM_GPUS + 1;

        float * d_As[NUM_GPUS];
        float * d_Bs[NUM_GPUS];
        float * d_Cs[NUM_GPUS];
        cudaStream_t streams[NUM_GPUS];

        for (int i = 0; i < NUM_GPUS; ++i) {

                // set current device
                cudaSetDevice(i);
                // allocate memory on current device
                cudaMalloc(&d_As[i], nPerGpu * sizeof(float));
                cudaMalloc(&d_Bs[i], nPerGpu * sizeof(float));
                cudaMalloc(&d_Cs[i], nPerGpu * sizeof(float));

                cudaStreamCreate(&streams[i]);

        }
        for (int i = 0; i < NUM_GPUS; ++i) {

                cudaSetDevice(i);
                cudaMemcpyAsync(d_As[i], h_A + i * nPerGpu, nPerGpu * sizeof(float), cudaMemcpyHostToDevice, streams[i]);
                cudaMemcpyAsync(d_Bs[i], h_B + i * nPerGpu, nPerGpu * sizeof(float), cudaMemcpyHostToDevice, streams[i]);

                vectorAddKernel<<<(nPerGpu-1)/256+1,256,0,streams[i]>>>(d_As[i], d_Bs[i], d_Cs[i], nPerGpu);

                cudaMemcpyAsync(h_C + nPerGpu, d_Cs[i], nPerGpu * sizeof(float), cudaMemcpyDeviceToHost, streams[i]);

        }

        ...
}
```

Non-blocking!

Streams and Synchronization with Multiple GPUs

- Streams are specific to a device (the current device when it was created)
  - Kernels can only be launched in a stream if the associated device is current
  - Events can only be recorded in a stream if the associated device is current

- Any stream can query or synchronize with an event on any other stream, even if the stream is associated with another device
  - This allows for inter-device synchrony

UVA and Multiple GPUs

Uniform Virtual Addressing (UVA) maps all global device memory into the same address space

This means any pointer to global memory on any device can be used to determine the location within the device memory, as well as **which device**

```
int whichDevice(const void * ptr) {

	cudaPointerAttributes ptrAttributes;

	cudaPointerGetAttributes(&ptAttributes, ptr);

	return ptrAttributes.device;

}
```

This also means cudaMemcpy can be used to copy to/from any device at any time, regardless of the current device

Enabling Peer-to-Peer Access

```
void enableAllPossibleP2PAccess(const int numGpus) {

	for (int device = 0; device < numGpus; ++device) {

		cudaSetDevice(device);

		for (int peerDevice = 0; peerDevice < numGpus; ++peerDevice) {

			int accessIsPossible = 0;
			cudaDeviceCanAccessPeer(&accessIsPossible, device, peerDevice);

			if (accessIsPossible) {
				cudaDeviceEnablePeerAccess(peerDevice);
				printf(“Device %d now has access to device %d\n”, device, peerDevice);
			}

		}

	}

}
```

This will allow to GPUs attached to the same PCI-e root node to communicate directly over PCI-e

Other inter-device communications must go through the host

Direct Peer-to-Peer Access

With UVA, devices for which peer access has been enabled can read and write directly to the global memory of a peer device

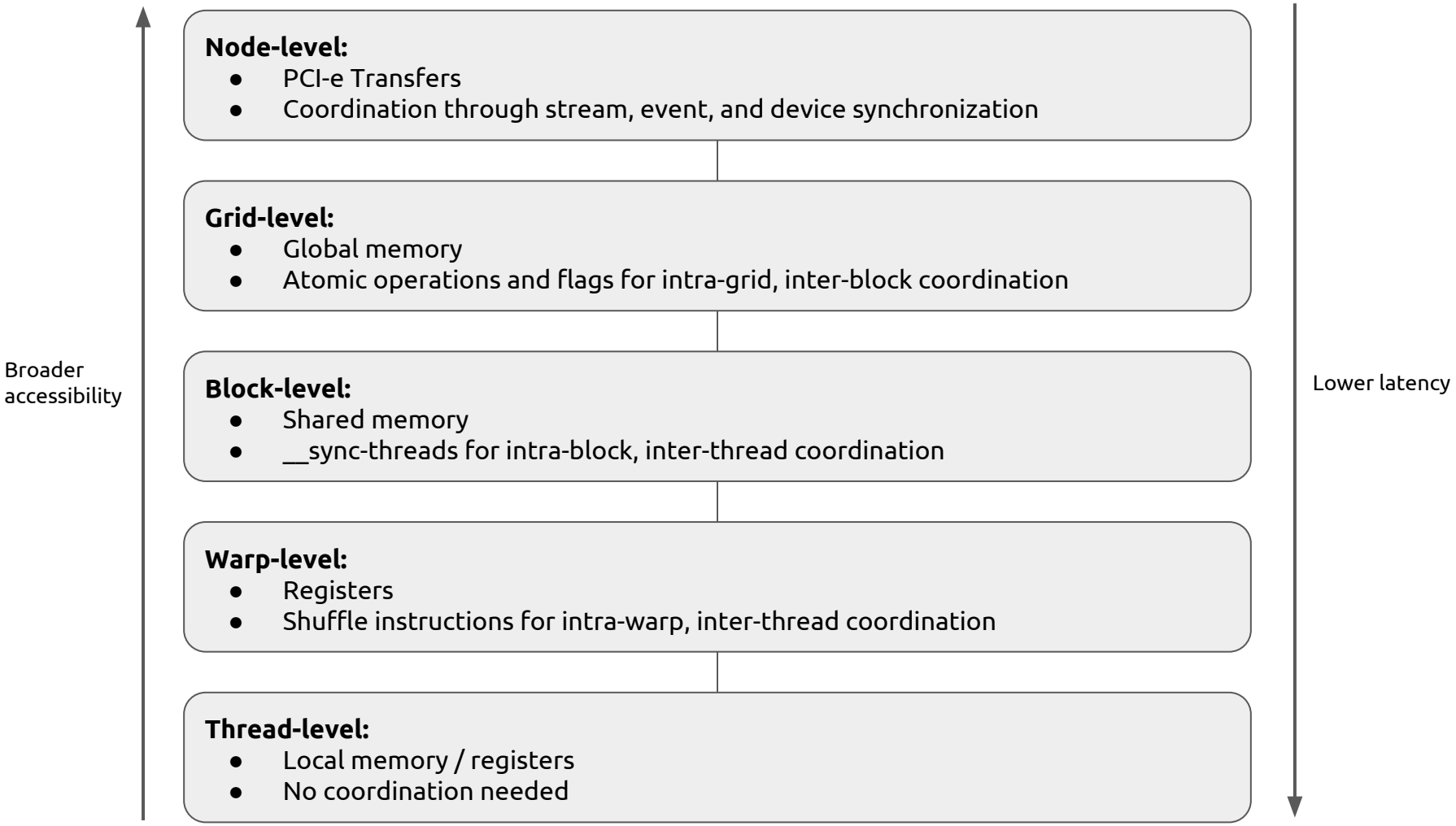
These reads and writes happen directly over PCI-e, similarly to zero-copy memory reads and writes between device and host

Peer-to-peer Memory Copy

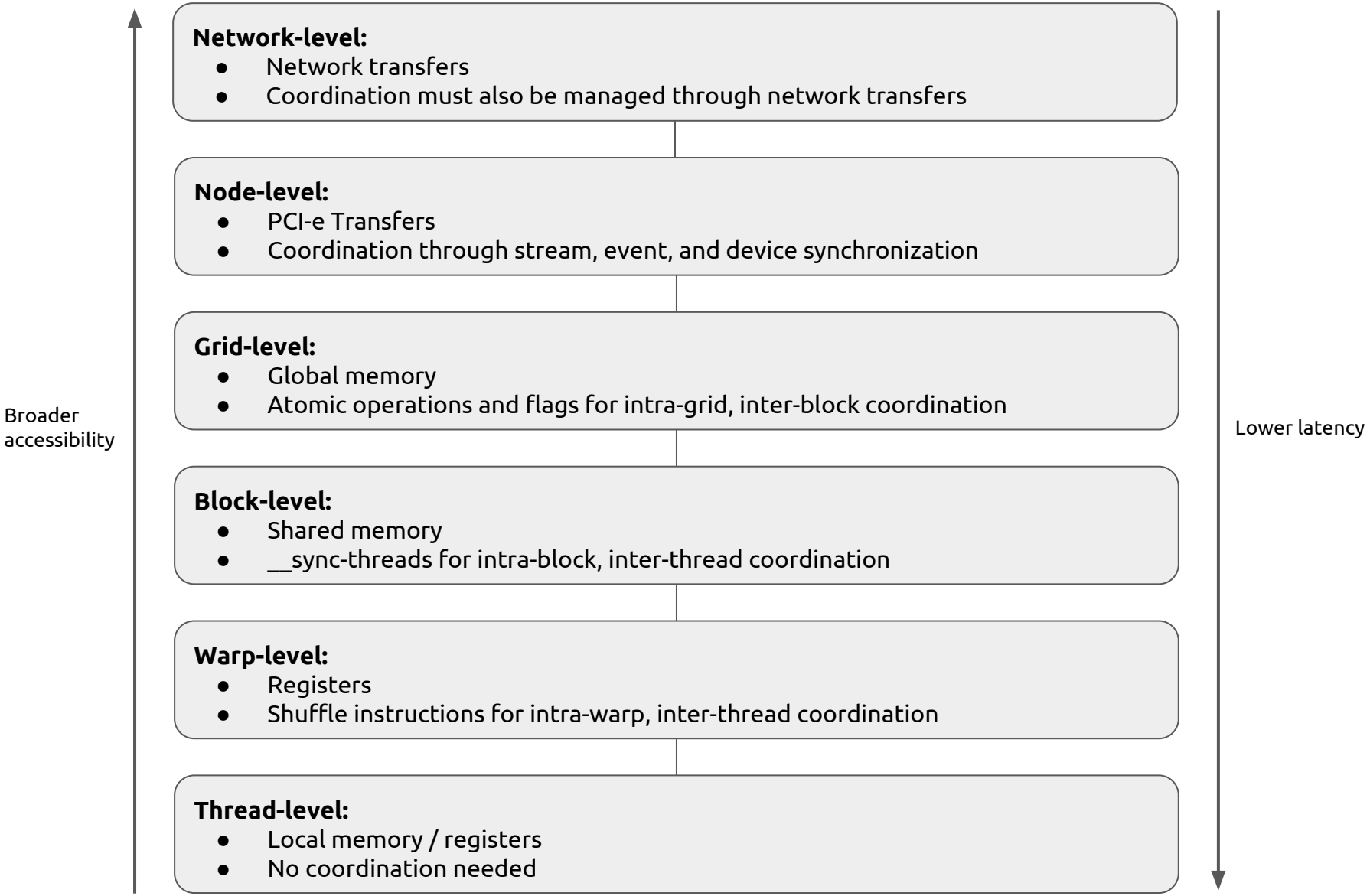
`cudaMemcpy` can also be used to explicitly transfer data from one device to another

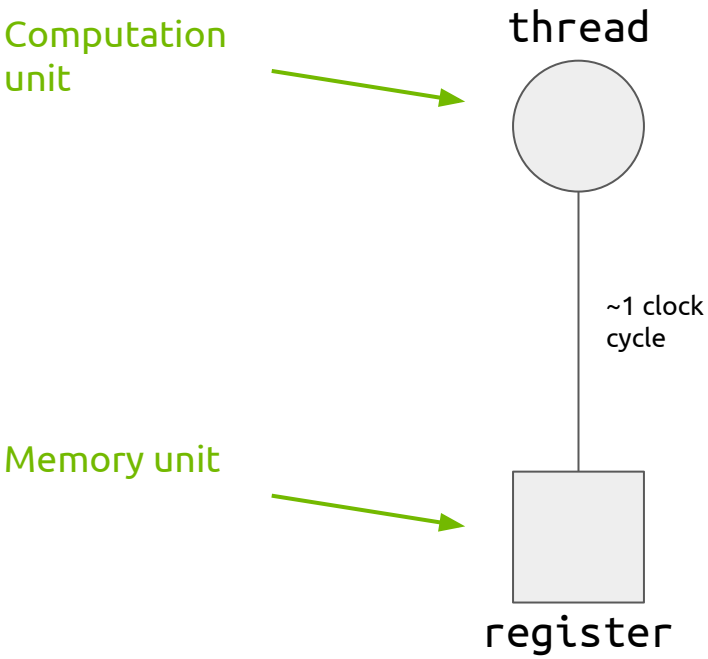
This is done in the same way as any other data transfer, and uses the `cudaMemcpyDeviceToDevice` flag

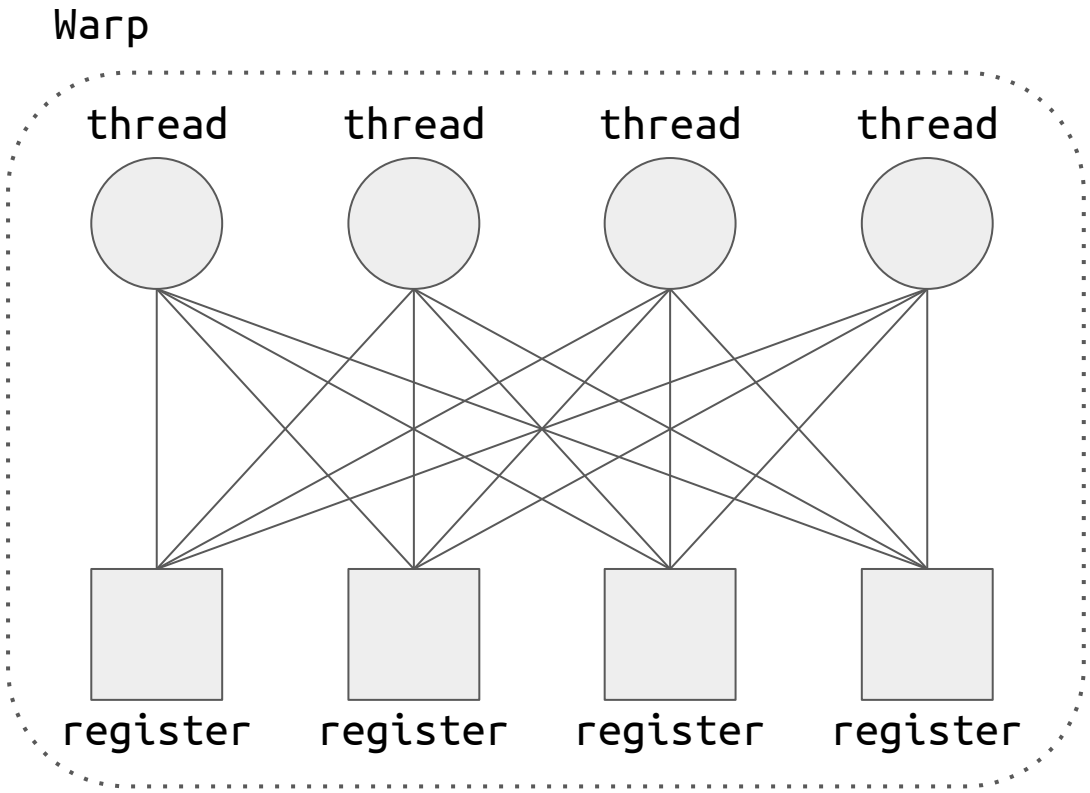
Five-Level Processing Hierarchy

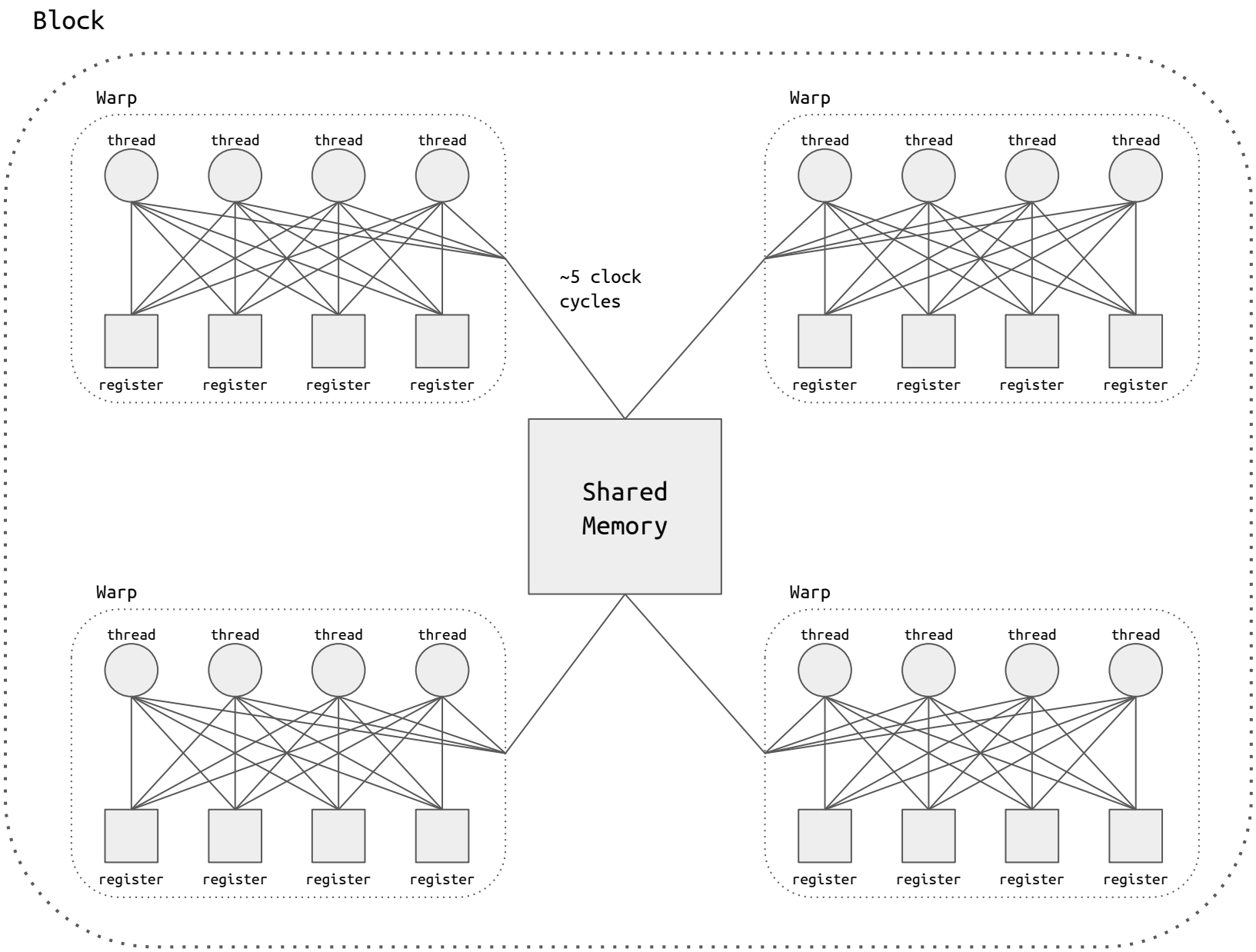


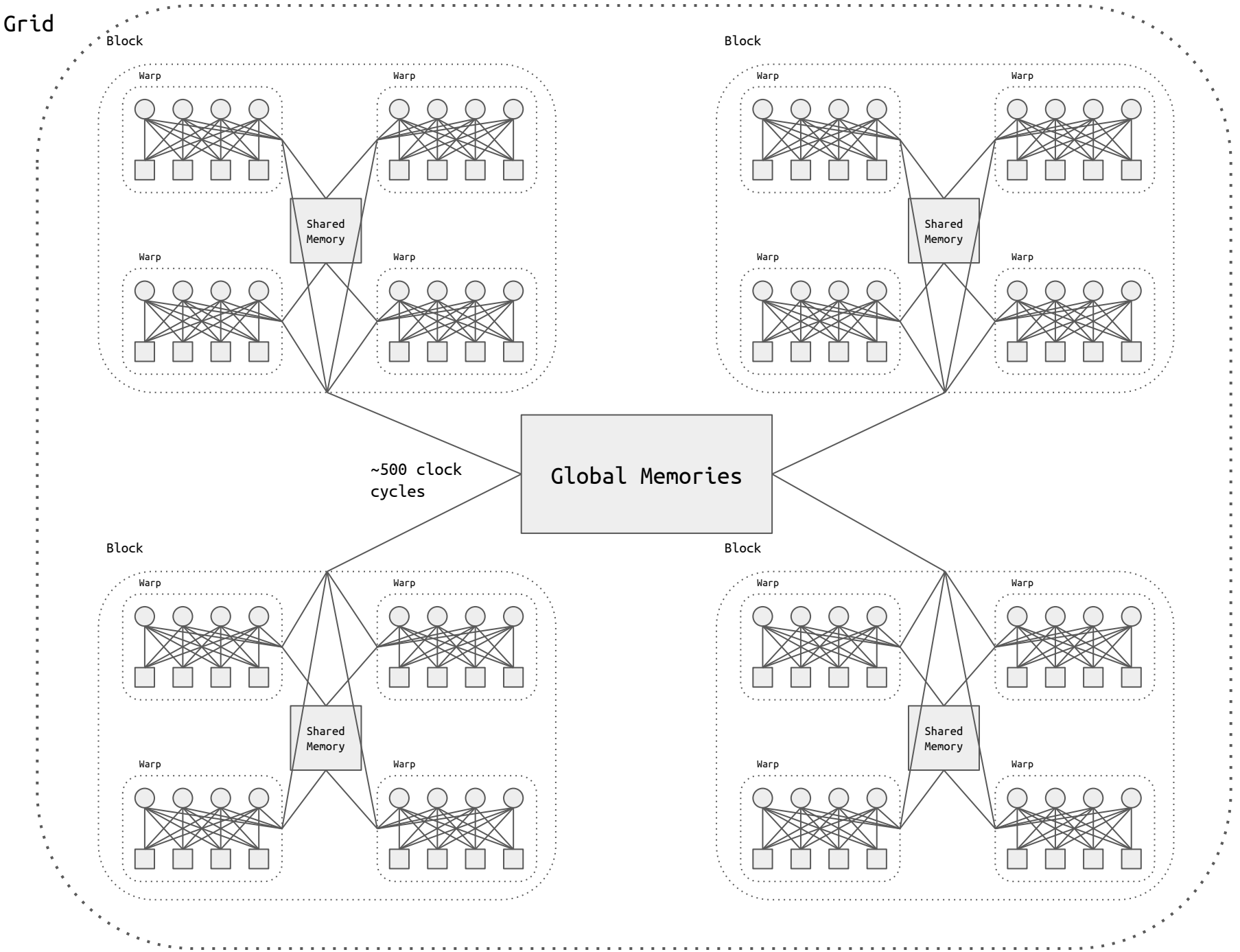
Six-Level Processing Hierarchy

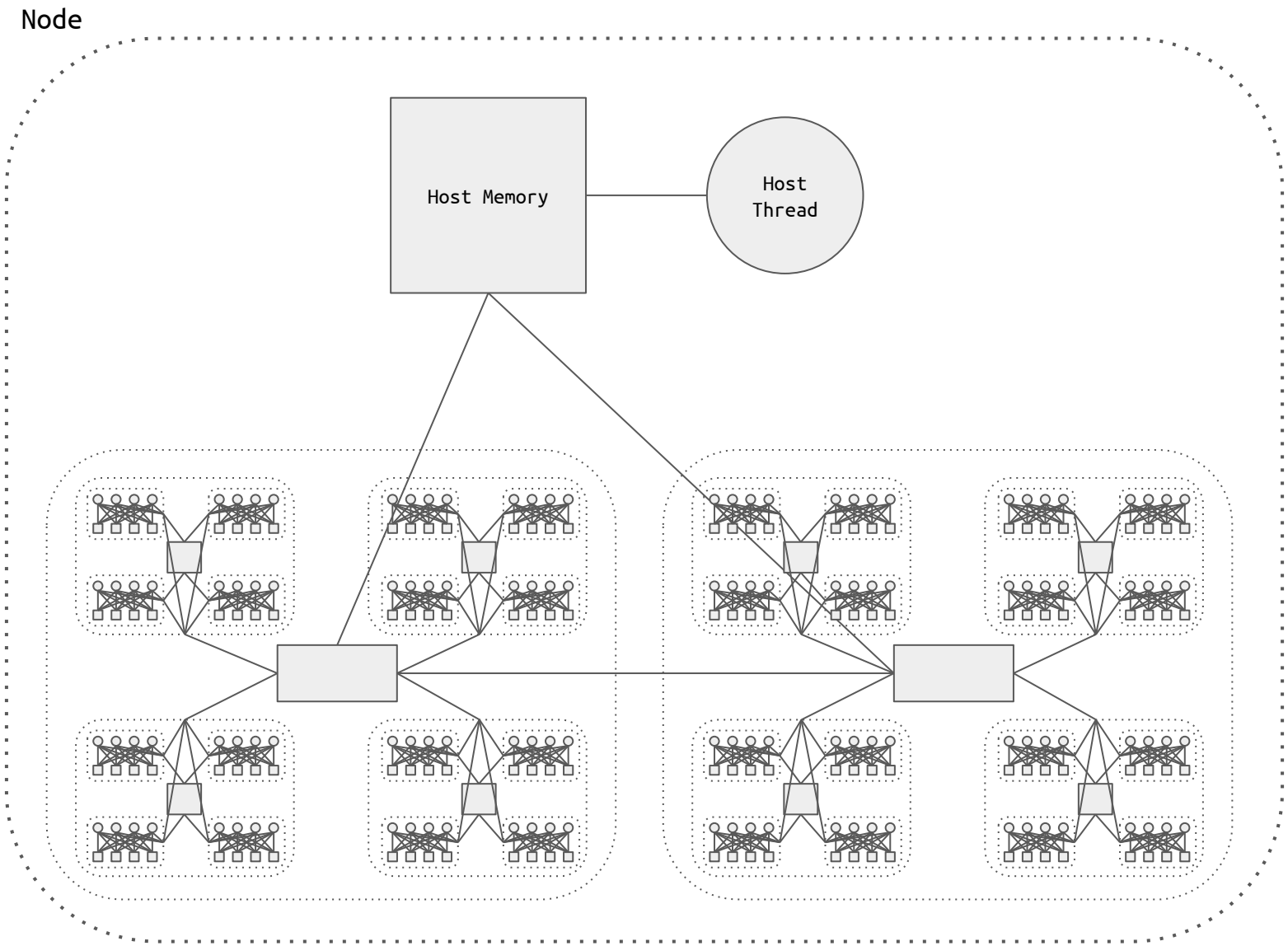


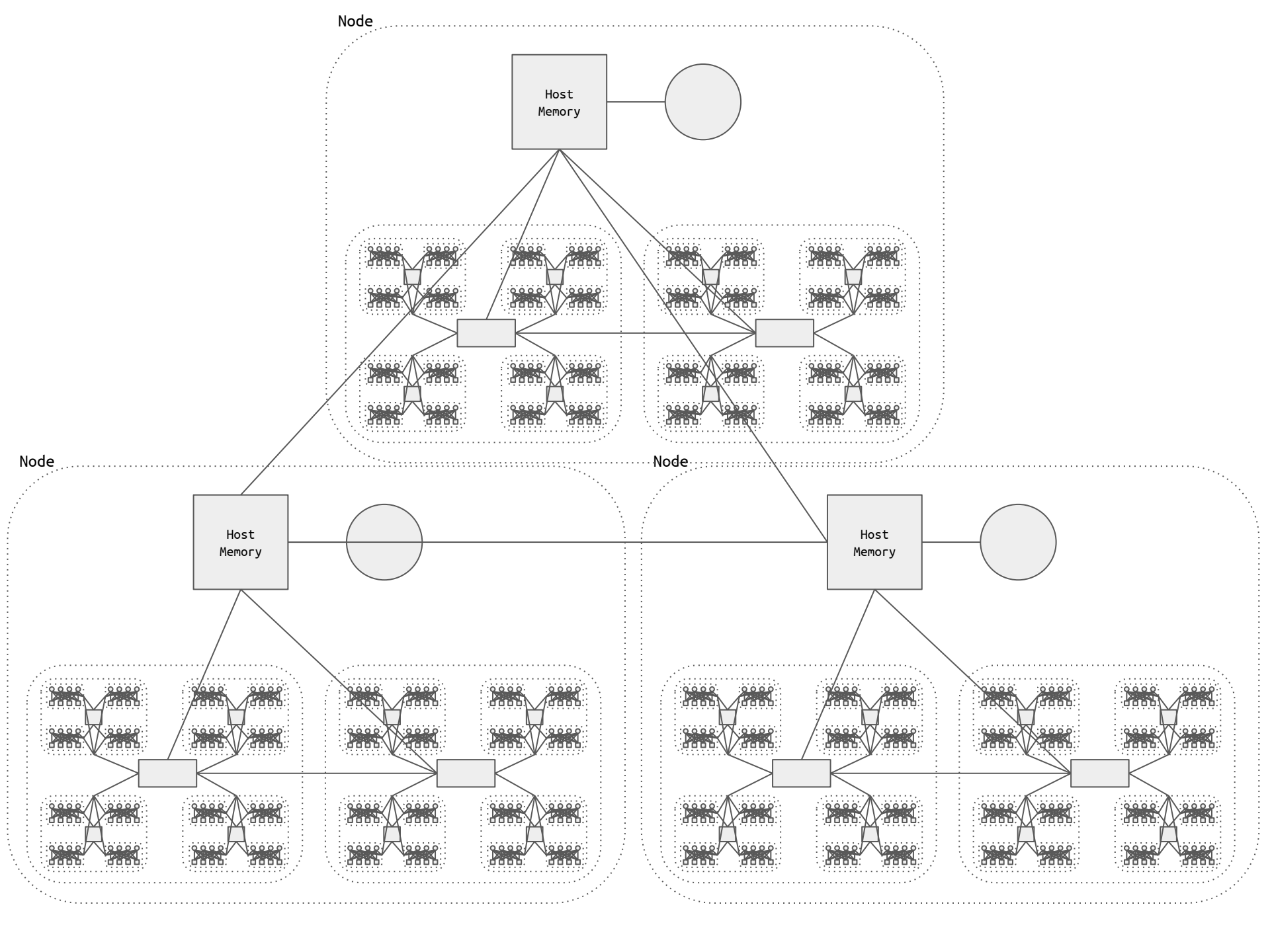

Computation unit
thread
~1 clock cycle
Memory unit
register


Warp
thread
thread
thread
thread
register
register
register
register


Block
Warp
thread
thread
thread
thread
register
register
register
register
Warp
thread
thread
thread
thread
register
register
register
register
~5 clock
cycles
Shared
Memory
Warp
thread
thread
thread
thread
register
register
register
register
Warp
thread
thread
thread
thread
register
register
register
register


Grid
Block
Warp
Warp
Shared Memory
Warp
Warp
Block
Warp
Warp
Shared Memory
Warp
Warp
~500 clock cycles
Global Memories
Block
Warp
Warp
Shared Memory
Warp
Warp
Block
Warp
Warp
Shared Memory
Warp
Warp


Node
Host Memory
Host
Thread


Node
Host Memory
Node
Host Memory
Node
Host Memory

GPU Teaching Kit

Accelerated Computing

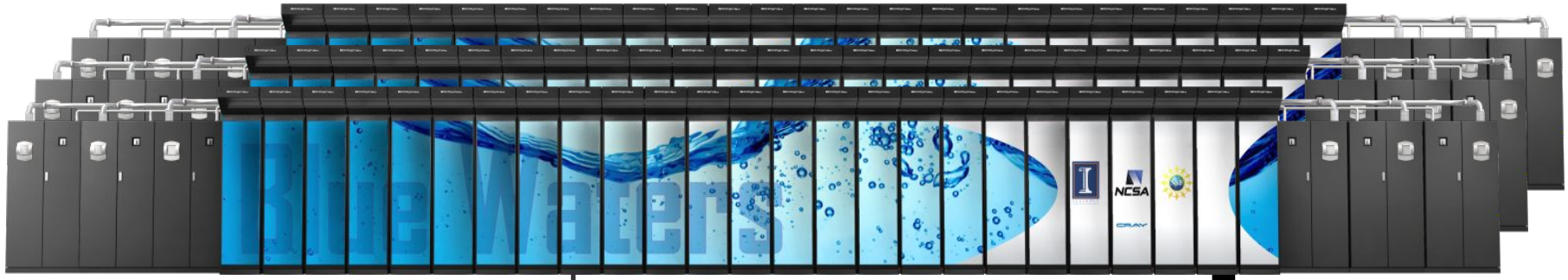
Module 18 – Related Programming Models: MPI

Lecture 18.1 - Introduction to Heterogeneous Supercomputing and MPI

Objective

- To learn the basics of an MPI application
  - Blue Waters, a supercomputer clusters with heterogeneous CPU-GPU nodes
  - MPI initialization, message passing, and barrier synchronization API functions
  - Vector addition example

Blue Waters - Operational at Illinois since 3/2013



12.5 PF
1.6 PB DRAM
$250M

10/40/100 Gb Ethernet Switch

IB Switch

120+ Gb/sec

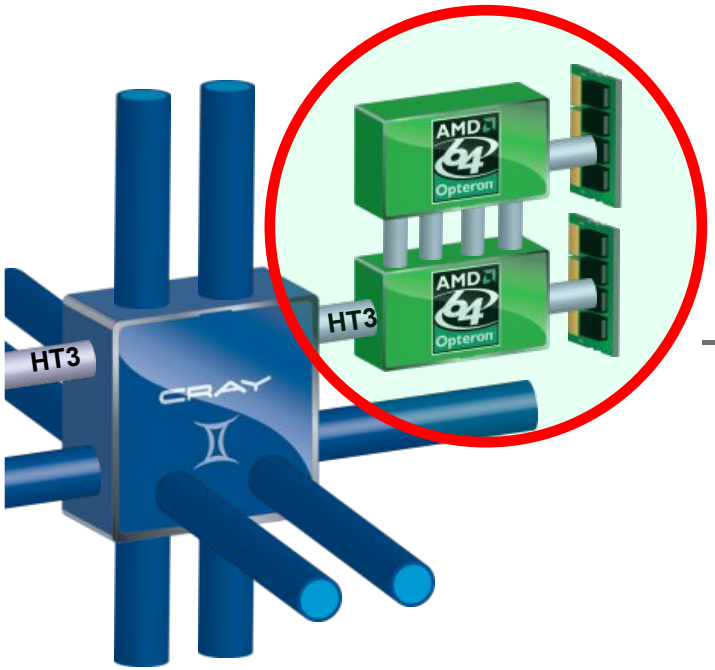
100 GB/sec

WAN

Spectra Logic: 300 PBs

Sonexion: 26 PBs

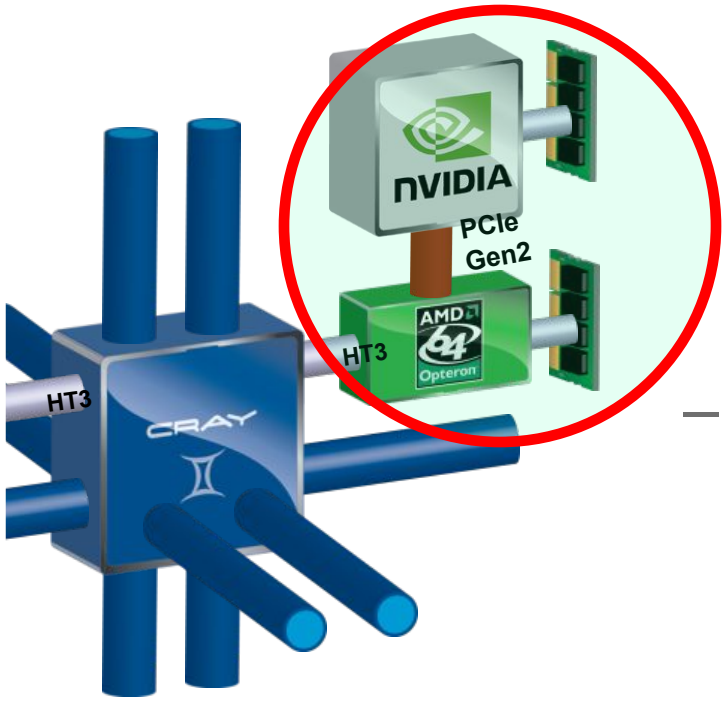
Cray **XE6** Dual Socket Nodes



- Two AMD Interlagos chips
  - 16 core modules, 64 threads
  - 313 GFs peak performance
  - 64 GBs memory
    - 102 GB/sec memory bandwidth
- Gemini Interconnect
  - Router chip & network interface
  - Injection Bandwidth (peak)
    - 9.6 GB/sec per direction

Blue Waters contains 22,640 Cray XE6 compute nodes.

Cray **XK7** Dual Socket Nodes

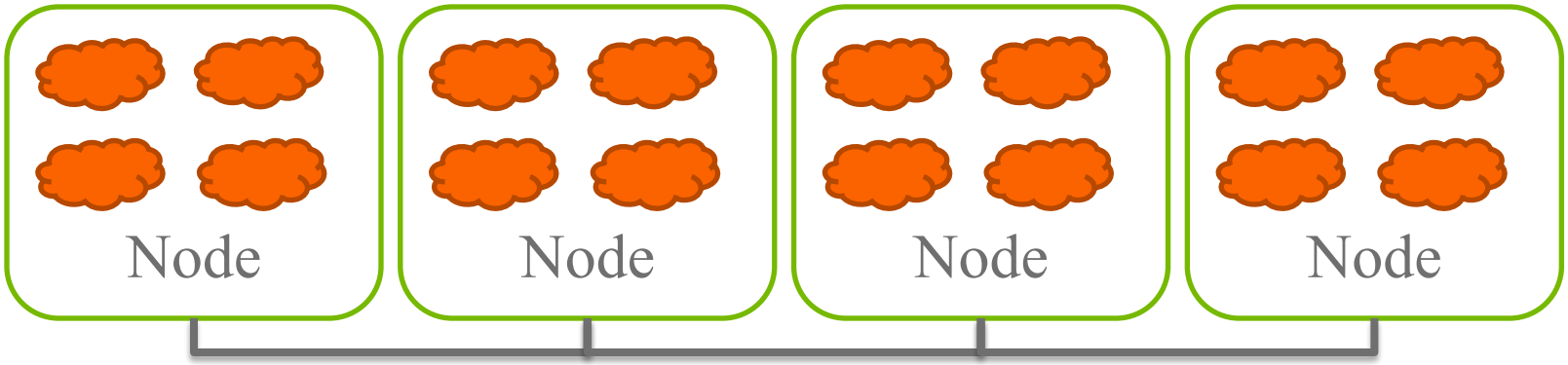


- One AMD Interlagos chip
  - 8 core modules, 32 threads
  - 156.5 GFs peak performance
  - 32 GBs memory
    - 51 GB/s bandwidth
- One NVIDIA Kepler chip
  - 1.3 TFs peak performance
  - 6 GBs GDDR5 memory
    - 250 GB/sec bandwidth
- Gemini Interconnect
  - Same as XE6 nodes

Blue Waters contains 4,224 Cray XK7 compute nodes.

MPI – Programming and Execution Model

– Many processes distributed in a cluster



– Each process computes part of the output
– Processes communicate with each other
– Processes can synchronize

26

MPI Initialization, Info and Sync

- `int MPI_Init(int *argc, char ***argv)`
  - Initialize MPI

- `MPI_COMM_WORLD`
  - MPI group with all allocated nodes

- `int MPI_Comm_rank (MPI_Comm comm, int *rank)`
  - Rank of the calling process in group of comm

- `int MPI_Comm_size (MPI_Comm comm, int *size)`
  - Number of processes in the group of comm

27

Vector Addition: Main Process

```
int main(int argc, char *argv[]) {
  int vector_size = 1024 * 1024 * 1024;
  int pid=-1, np=-1;

  MPI_Init(&argc, &argv);
  MPI_Comm_rank(MPI_COMM_WORLD, &pid);
  MPI_Comm_size(MPI_COMM_WORLD, &np);

  if(np < 3) {
    if(0 == pid) printf("Need 3 or more processes.\n");
    MPI_Abort( MPI_COMM_WORLD, 1 ); return 1;
  }
```

Vector Addition: Main Process

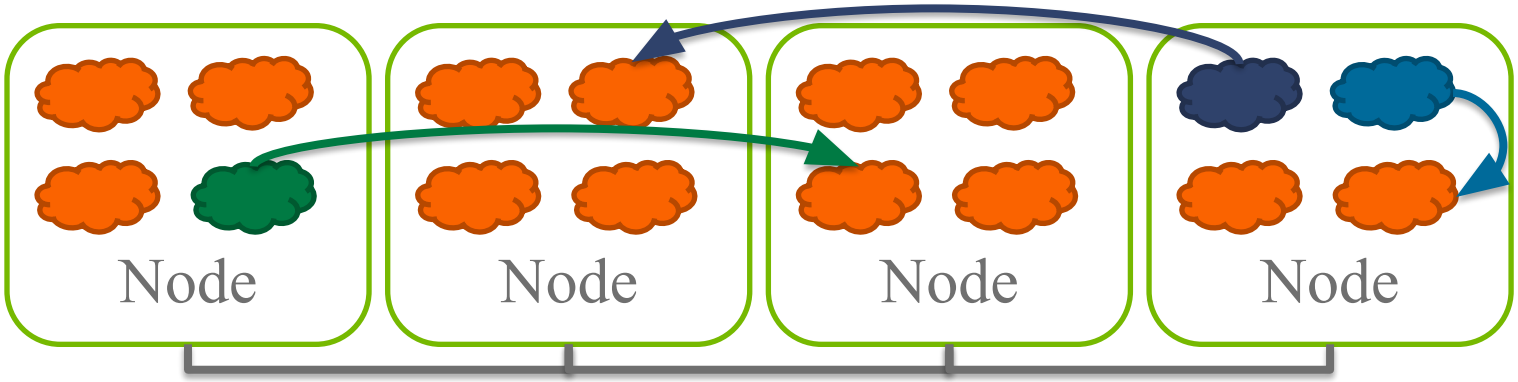
```
  if(pid < np - 1)
    compute_node(vector_size / (np - 1));
  else
    data_server(vector_size);

  MPI_Finalize();
  return 0;
}
```

MPI Sending Data

- `int MPI_Send(void *buf, int count, MPI_Datatype datatype, int dest, int tag, MPI_Comm comm)`
  - Buf: Initial address of send buffer (choice)
  - Count: Number of elements in send buffer (nonnegative integer)
  - Datatype: Datatype of each send buffer element (handle)
  - Dest: Rank of destination (integer)
  - Tag: Message tag (integer)
  - Comm: Communicator (handle)

MPI Sending Data

- `int MPI_Send(void *buf, int count, MPI_Datatype datatype, int dest, int tag, MPI_Comm comm)`
  - Buf: Initial address of send buffer (choice)
  - Count: Number of elements in send buffer (nonnegative integer)
  - Datatype: Datatype of each send buffer element (handle)
  - Dest: Rank of destination (integer)
  - Tag: Message tag (integer)
  - Comm: Communicator (handle)



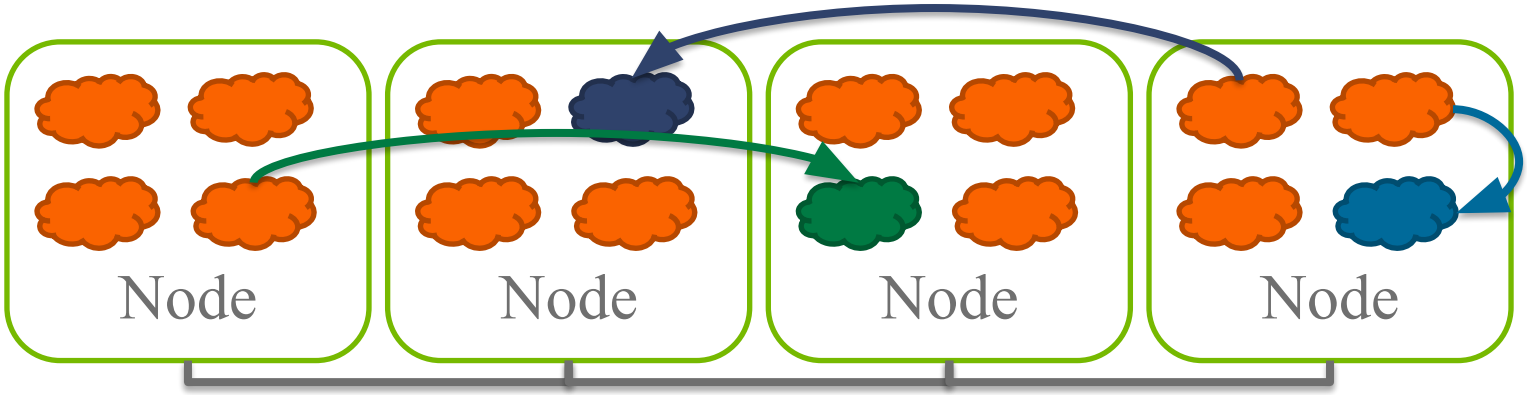
MPI Receiving Data

- `int MPI_Recv(void *buf, int count, MPI_Datatype datatype, int source, int tag, MPI_Comm comm, MPI_Status *status)`
  - Buf: Initial address of receive buffer (choice)
  - Count: Maximum number of elements in receive buffer (integer)
  - Datatype: Datatype of each receive buffer element (handle)
  - Source: Rank of source (integer)
  - Tag: Message tag (integer)
  - Comm: Communicator (handle)
  - Status: Status object (Status)

32

MPI Receiving Data

- `int MPI_Recv(void *buf, int count, MPI_Datatype datatype, int source, int tag, MPI_Comm comm, MPI_Status *status)`
  - Buf: Initial address of receive buffer (choice)
  - Count: Maximum number of elements in receive buffer (integer)
  - Datatype: Datatype of each receive buffer element (handle)
  - Source: Rank of source (integer)
  - Tag: Message tag (integer)
  - Comm: Communicator (handle)
  - Status: Status object (Status)



33

Vector Addition: Server Process (I)

```
void data_server(unsigned int vector_size) {
    int np, num_nodes = np - 1, first_node = 0, last_node = np - 2;
    unsigned int num_bytes  = vector_size * sizeof(float);
    float *input_a = 0, *input_b = 0, *output = 0;

    /* Set MPI Communication Size */
    MPI_Comm_size(MPI_COMM_WORLD, &np);

    /* Allocate input data */
    input_a = (float *)malloc(num_bytes);
    input_b = (float *)malloc(num_bytes);
    output = (float *)malloc(num_bytes);
    if(input_a == NULL || input_b == NULL || output == NULL) {
        printf("Server couldn't allocate memory\n" );
        MPI_Abort( MPI_COMM_WORLD, 1 );
    }
    /* Initialize input data */
    random_data(input_a, vector_size , 1, 10);
    random_data(input_b, vector_size , 1, 10);
```

Vector Addition: Server Process (II)

```
/* Send data to compute nodes */
float *ptr_a = input_a;
float *ptr_b = input_b;

for(int process = 0; process < num_nodes; process++) {
    MPI_Send(ptr_a, vector_size / num_nodes, MPI_FLOAT,
            process, DATA_DISTRIBUTE, MPI_COMM_WORLD);
    ptr_a += vector_size / num_nodes;

    MPI_Send(ptr_b, vector_size / num_nodes, MPI_FLOAT,
            process, DATA_DISTRIBUTE, MPI_COMM_WORLD);
    ptr_b += vector_size / num_nodes;
}

/* Wait for nodes to compute */
MPI_Barrier(MPI_COMM_WORLD);
```

Vector Addition: Server Process (III)

```
    /* Wait for previous communications */
    MPI_Barrier(MPI_COMM_WORLD);

    /* Collect output data */
    MPI_Status status;
    for(int process = 0; process < num_nodes; process++) {
        MPI_Recv(output + process * vector_size / num_nodes,
            vector_size / num_nodes, MPI_REAL, process,
            DATA_COLLECT, MPI_COMM_WORLD, &status );
    }

    /* Store output data */
    store_output(output, vector_size);

    /* Release resources */
    free(input_a);
    free(input_b);
    free(output);
}
```

Vector Addition: Compute Process (I)

```
void compute_node(unsigned int vector_size ) {
    int np;
    unsigned int num_bytes = vector_size * sizeof(float);
    float *input_a, *input_b, *output;
    MPI_Status status;

    MPI_Comm_size(MPI_COMM_WORLD, &np);
    int server_process = np - 1;

    /* Alloc host memory */
    input_a = (float *)malloc(num_bytes);
    input_b = (float *)malloc(num_bytes);
    output = (float *)malloc(num_bytes);

    /* Get the input data from server process */
    MPI_Recv(input_a, vector_size, MPI_FLOAT, server_process,
            DATA_DISTRIBUTE, MPI_COMM_WORLD, &status);
    MPI_Recv(input_b, vector_size, MPI_FLOAT, server_process,
            DATA_DISTRIBUTE, MPI_COMM_WORLD, &status);
```

MPI Barriers

- int MPI_Barrier (MPI_Comm comm)
  - Comm: Communicator (handle)

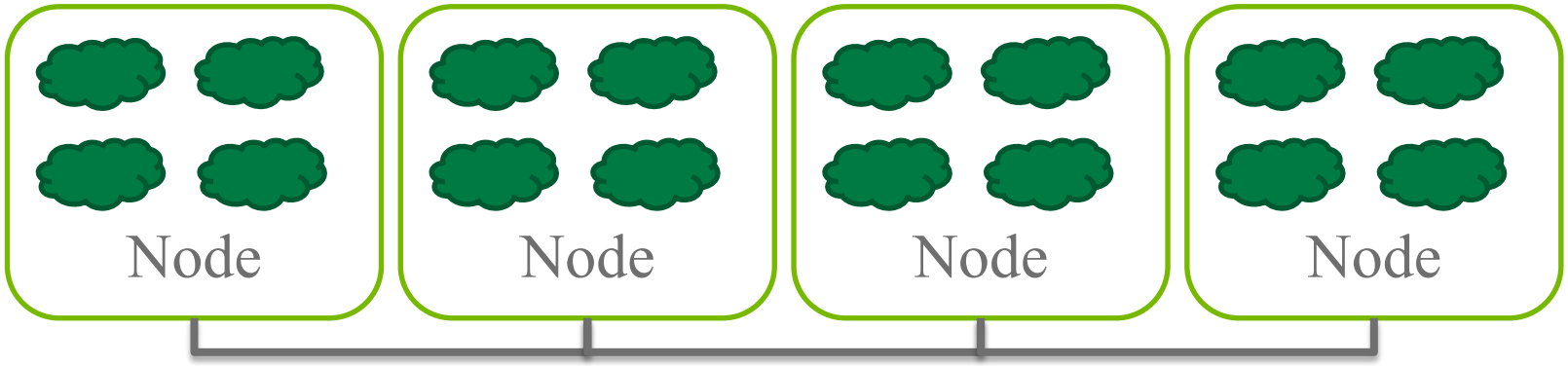
- Blocks the caller until all group members have called it; the call returns at any process only after all group members have entered the call.

MPI Barriers

- Wait until all other processes in the MPI group reach the same barrier
  - All processes are executing Do_Stuff()
  - Some processes reach the barrier and the wait in the barrier until all reach the barrier

Example Code

```
Do_stuff();

MPI_Barrier();

Do_more_stuff();
```



Vector Addition: Compute Process (II)

```
    /* Compute the partial vector addition */
    for(int i = 0; i < vector_size; ++i) {
        output[i] = input_a[i] + input_b[i];
    }

    /* Report to barrier after computation is done*/
    MPI_Barrier(MPI_COMM_WORLD);


    /* Send the output */
    MPI_Send(output, vector_size, MPI_FLOAT,
             server_process, DATA_COLLECT, MPI_COMM_WORLD);

    /* Release memory */
    free(input_a);
    free(input_b);
    free(output);
}
```

GPU Teaching Kit

Accelerated Computing

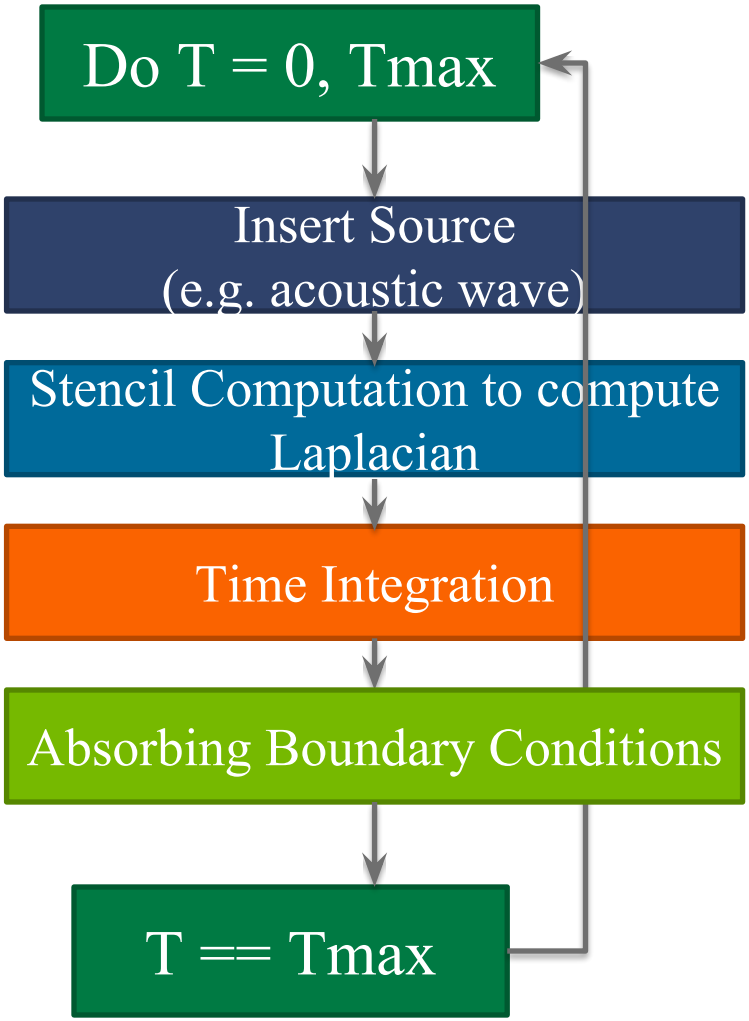
GPU Teaching Kit

Accelerated Computing

Module 18 – Related Programming Models: MPI

Lecture 18.2 – Introduction to MPI-CUDA Programming

A Typical Wave Propagation Application

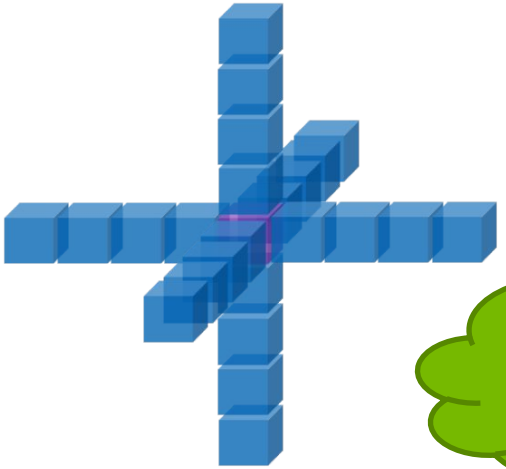


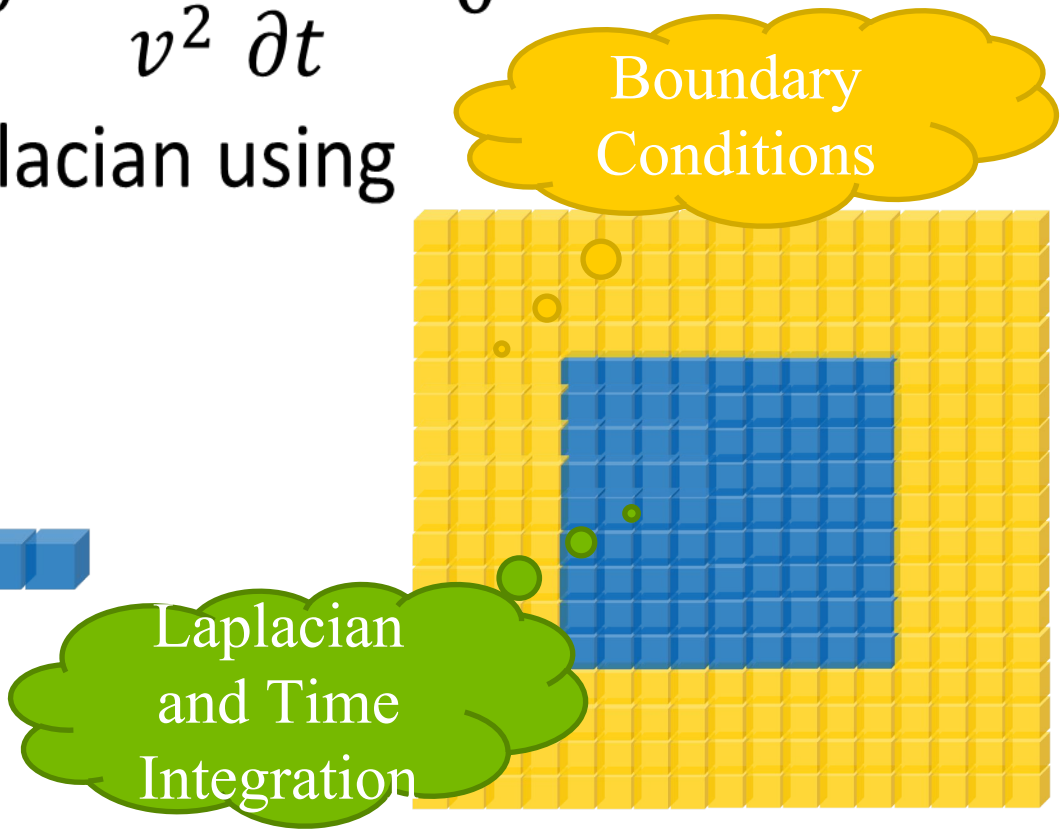
Review of Stencil Computations

- Example: wave propagation modeling

$$\nabla^2 U - \frac{1}{v^2}\frac{\partial U}{\partial t} = 0$$

- Approximate Laplacian using finite differences





Wave Propagation: Kernel Code

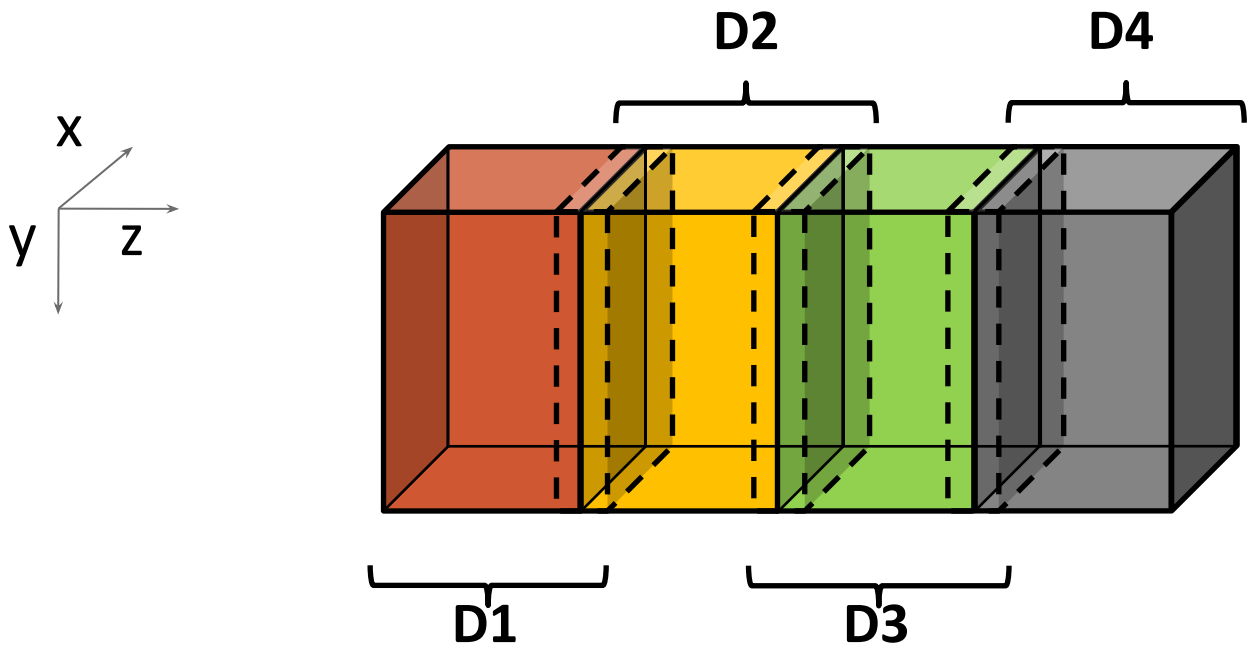
```
/* Coefficients used to calculate the laplacian */
__constant__ float coeff[5];

__global__ void wave_propagation( float *next, float *in,
                  float *prev, float *velocity, dim3 dim)
{
    unsigned x = threadIdx.x + blockIdx.x * blockDim.x;
    unsigned y = threadIdx.y + blockIdx.y * blockDim.y;
    unsigned z = threadIdx.z + blockIdx.z * blockDim.z;

    /* Point index in the input and output matrixes */
    unsigned n = x + y * dim.z + z * dim.x * dim.y;

    /* Only compute for points within the matrixes */
    if(x < dim.x && y < dim.y && z < dim.z) {

        /* Calculate the contribution of each point to the laplacian */
        float laplacian = coeff[0] + in[n];
```

Wave Propagation: Kernel Code

```
        for(int i = 1; i < 5; ++i) {
            laplacian += coeff[i] *
                                (in[n - i] + /* Left */
                                in[n + i] + /* Right */
                                in[n - i * dim.x] + /* Top */
                                in[n + I * dim.x] + /* Bottom */
                                in[n - i * dim.x * dim.y] + /* Behind */
                                in[n + i * dim.x * dim.y]);   /* Front */
        }

        /* Time integration */
        next[n] = velocity[n] * laplacian + 2 * in[n] - prev[n];
    }
}
```

Stencil Domain Decomposition

- Volumes are split into tiles (along the Z-axis)
  - 3D-Stencil introduces data dependencies



Wave Propagation: Main Process

```
int main(int argc, char *argv[]) {
    int pad = 0, dimx  = 480+pad, dimy  = 480, dimz  = 400, nreps = 100;
    int pid=-1, np=-1;

    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &pid);
    MPI_Comm_size(MPI_COMM_WORLD, &np);

    if(np < 3) {
        if(0 == pid) printf("Needed 3 or more processes.\n");
        MPI_Abort( MPI_COMM_WORLD, 1 ); return 1;
    }
    if(pid < np - 1)
        compute_node(dimx, dimy, dimz / (np - 1), nreps);
    else
        data_server( dimx,dimy,dimz, nreps );

    MPI_Finalize();
    return 0;
}
```

Stencil Code: Server Process (I)

```
void data_server(int dimx, int dimy, int dimz, int nreps) {
    int np, num_comp_nodes = np - 1, first_node = 0, last_node = np - 2;
    unsigned int num_points = dimx * dimy * dimz;
    unsigned int num_bytes  = num_points *  sizeof(float);
    float *input=0, *output = NULL, *velocity = NULL;
    /* Set MPI Communication Size */
    MPI_Comm_size(MPI_COMM_WORLD, &np);
    /* Allocate input data */
    input = (float *)malloc(num_bytes);
    output = (float *)malloc(num_bytes);
    velocity = (float *)malloc(num_bytes);
    if(input == NULL || output == NULL || velocity == NULL) {
        printf("Server couldn't allocate memory\n" );
        MPI_Abort( MPI_COMM_WORLD, 1 );
    }
    /* Initialize input data and velocity */
    random_data(input, dimx, dimy ,dimz , 1, 10);
    random_data(velocity, dimx, dimy ,dimz , 1, 10);
```

Stencil Code: Server Process (II)

```
/* Calculate number of shared points */
int edge_num_points = dimx * dimy * (dimz / num_comp_nodes + 4);
int int_num_points  = dimx * dimy * (dimz / num_comp_nodes + 8);
float *input_send_address = input;

/* Send input data to the first compute node */
MPI_Send(send_address, edge_num_points, MPI_REAL, first_node,
         DATA_DISTRIBUTE, MPI_COMM_WORLD );
send_address += dimx * dimy * (dimz / num_comp_nodes - 4);

/* Send input data to "internal" compute nodes */
for(int process = 1; process < last_node; process++) {
    MPI_Send(send_address, int_num_points, MPI_FLOAT, process,
             DATA_DISTRIBUTE, MPI_COMM_WORLD);
    send_address += dimx * dimy * (dimz / num_comp_nodes);
}

/* Send input data to the last compute node */
MPI_Send(send_address, edge_num_points, MPI_REAL, last_node,
         DATA_DISTRIBUTE, MPI_COMM_WORLD);
```

Stencil Code: Server Process (III)

```
float *velocity_send_address = velocity;

/* Send velocity data to compute nodes */
for(int process = 0; process < num_comp_nodes; process++) {
    MPI_Send(velocity + process * num_points / num_comp_nodes,
             num_points / num_comp_nodes, MPI_FLOAT,
             process, DATA_DISTRIBUTE, MPI_COMM_WORLD);
}

/* Wait for nodes to compute */
MPI_Barrier(MPI_COMM_WORLD);

/* Collect output data */
MPI_Status status;
for(int process = 0; process < num_comp_nodes; process++)
    MPI_Recv(output + process * num_points / num_comp_nodes,
        num_points / num_comp_nodes, MPI_FLOAT, process,
        DATA_COLLECT, MPI_COMM_WORLD, &status );
}
```

Stencil Code: Server Process (IV)

```
        /* Store output data */
    store_output(output, dimx, dimy, dimz);

    /* Release resources */
    free(input);
    free(velocity);
    free(output);
}
```

Stencil Code: Compute Process (I)

```
void compute_node_stencil(int dimx, int dimy, int dimz, int nreps ) {
    int np, pid;
    MPI_Comm_rank(MPI_COMM_WORLD, &pid);
    MPI_Comm_size(MPI_COMM_WORLD, &np);

    unsigned int num_points       = dimx * dimy * (dimz + 8);
    unsigned int num_bytes        = num_points * sizeof(float);
    unsigned int num_ghost_points = 4 * dimx * dimy;
    unsigned int num_ghost_bytes  = num_ghost_points * sizeof(float);

    int left_ghost_offset   = 0;
    int right_ghost_offset  = dimx * dimy * (4 + dimz);

    float *input = NULL, *output = NULL, *prev = NULL, *v = NULL;

    /* Allocate device memory for input and output data */
    gmacMalloc((void **)&input,  num_bytes);
    gmacMalloc((void **)&output, num_bytes);
    gmacMalloc((void **)&prev, num_bytes);
    gmacMalloc((void **)&v, num_bytes);
```

Stencil Code: Compute Process (II)

```
MPI_Status status;
int left_neighbor  = (pid > 0) ? (pid - 1) : MPI_PROC_NULL;
int right_neighbor = (pid < np - 2) ? (pid + 1) : MPI_PROC_NULL;
int server_process = np - 1;

/* Get the input data from server process */
float *rcv_address = input + num_ghost_points * (0 == pid);
MPI_Recv(rcv_address, num_points, MPI_FLOAT, server_process,
         DATA_DISTRIBUTE, MPI_COMM_WORLD, &status );

/* Get the velocity data from server process */
rcv_address = h_v + num_ghost_points * (0 == pid);
MPI_Recv(rcv_address, num_points, MPI_FLOAT, server_process,
         DATA_DISTRIBUTE, MPI_COMM_WORLD, &status );
```

GPU Teaching Kit

Accelerated Computing

Module 18 – Related Programming Models: MPI

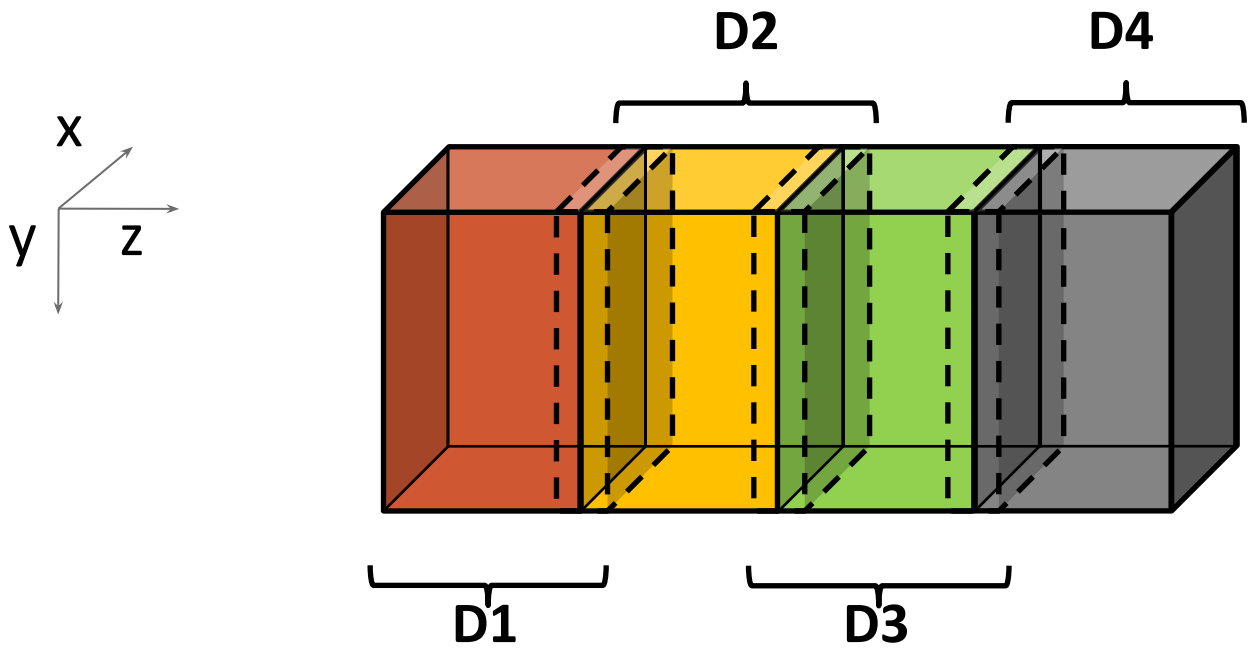
Lecture 18.3 – Overlapping Computation with Communication

Ojective

- To learn how to overlap computation with communication in a MPI+CUDA application
  - Stencil example
  - CUDA Stream as an enabler of overlap
  - MPI_SendRecv() function

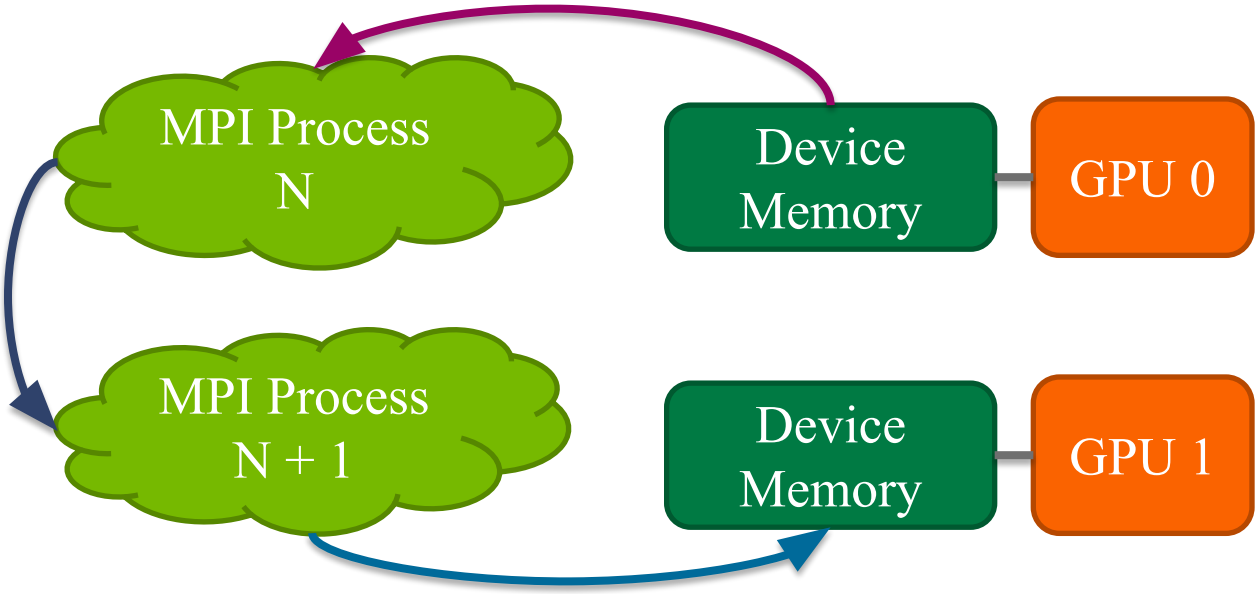
Stencil Domain Decomposition

- Volumes are split into tiles (along the Z-axis)
  - 3D-Stencil introduces data dependencies



CUDA and MPI Communication

- Source MPI process:
  - cudaMemcpy(tmp,src, cudaMemcpyDeviceToHost)
  - MPI_Send()
- Destination MPI process:
  - MPI_Recv()
  - cudaMemcpy(dst, src, cudaMemcpyDeviceToDevice)



Data Server Process Code (I)

```
void data_server(int dimx, int dimy, int dimz, int nreps) {
    int np,
    /* Set MPI Communication Size */
    MPI_Comm_size(MPI_COMM_WORLD, &np);

    num_comp_nodes = np - 1, first_node = 0, last_node = np - 2;
    unsigned int num_points = dimx * dimy * dimz;
    unsigned int num_bytes  = num_points *  sizeof(float);
    float *input=0, *output=0;
        /* Allocate input data */
    input = (float *)malloc(num_bytes);
    output = (float *)malloc(num_bytes);
    if(input == NULL || output == NULL) {
        printf("server couldn't allocate memory\n");
        MPI_Abort( MPI_COMM_WORLD, 1 );
    }
    /* Initialize input data */
    random_data(input, dimx, dimy ,dimz , 1, 10);
    /* Calculate number of shared points */
    int edge_num_points = dimx * dimy * (dimz / num_comp_nodes + 4);
    int int_num_points  = dimx * dimy * (dimz / num_comp_nodes + 8);
    float *send_address = input;
```

Data Server Process Code (II)

```
/* Send data to the first compute node */
MPI_Send(send_address, edge_num_points, MPI_FLOAT, first_node,
        0, MPI_COMM_WORLD );

send_address += dimx * dimy * (dimz / num_comp_nodes - 4);
/* Send data to "internal" compute nodes */
for(int process = 1; process < last_node; process++) {
    MPI_Send(send_address, int_num_points, MPI_FLOAT, process,
            0, MPI_COMM_WORLD);
    send_address += dimx * dimy * (dimz / num_comp_nodes);
}

/* Send data to the last compute node */
MPI_Send(send_address, edge_num_points, MPI_FLOAT, last_node,
        0, MPI_COMM_WORLD);
```

Compute Process Code (I).

```
void compute_node_stencil(int dimx, int dimy, int dimz, int nreps ) {
    int np, pid;
    MPI_Comm_rank(MPI_COMM_WORLD, &pid);
     MPI_Comm_size(MPI_COMM_WORLD, &np);
    int server_process = np - 1;

    unsigned int num_points       = dimx * dimy * (dimz + 8);
    unsigned int num_bytes        = num_points * sizeof(float);
    unsigned int num_halo_points = 4 * dimx * dimy;
    unsigned int num_halo_bytes  = num_halo_points * sizeof(float);

    /* Alloc host memory */
    float *h_input  = (float *)malloc(num_bytes);
        /* Allocate device memory for input and output data */
    float *d_input = NULL;
    cudaMalloc((void **)&d_input,  num_bytes );
    float *rcv_address = h_input + num_halo_points * (0 == pid);
    MPI_Recv(rcv_address, num_points, MPI_FLOAT, server_process,
            MPI_ANY_TAG, MPI_COMM_WORLD, &status );
    cudaMemcpy(d_input, h_input, num_bytes, cudaMemcpyHostToDevice);
```

Stencil Code: Kernel Launch

```
void launch_kernel(float *next, float *in, float *prev, float *velocity,
                   int dimx, int dimy, int dimz)
{
    dim3 Gd, Bd, Vd;

    Vd.x = dimx; Vd.y = dimy; Vd.z = dimz;

    Bd.x = BLOCK_DIM_X; Bd.y = BLOCK_DIM_Y; Bd.z = BLOCK_DIM_Z;

    Gd.x = (dimx + Bd.x - 1) / Bd.x;
    Gd.y = (dimy + Bd.y - 1) / Bd.y;
    Gd.z = (dimz + Bd.z - 1) / Bd.z;

    wave_propagation<<<Gd, Bd>>>(next, in, prev, velocity, Vd);
}
```

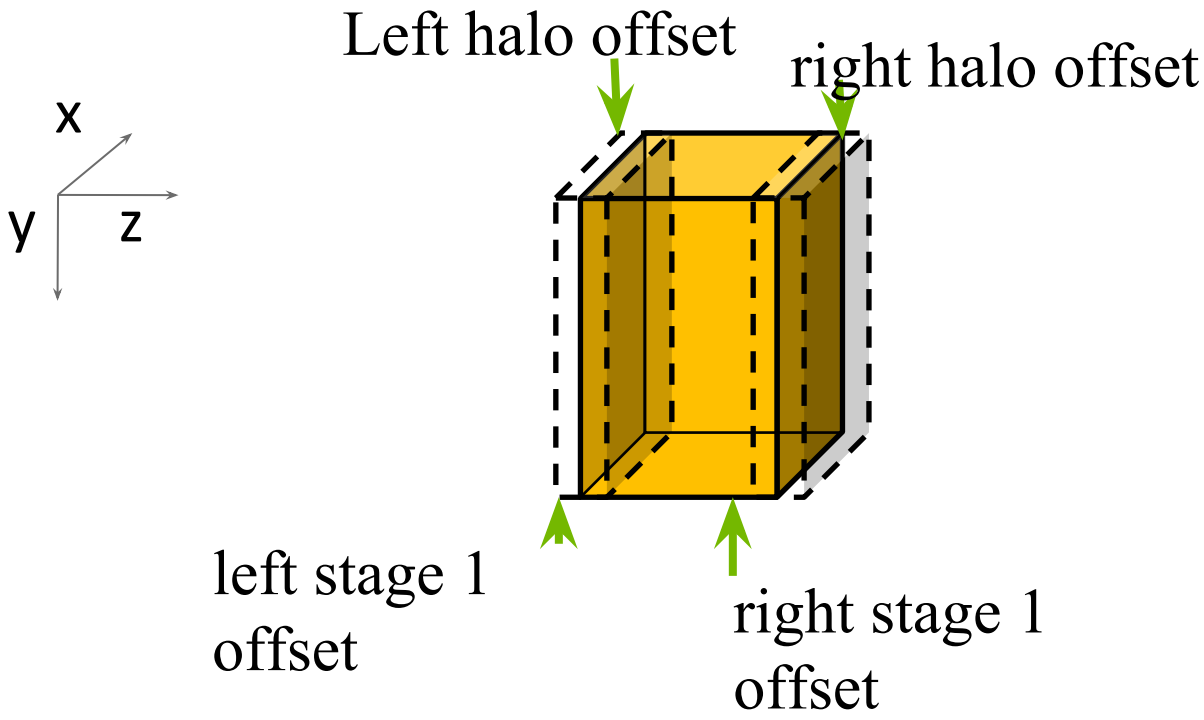
MPI Sending and Receiving Data

- int MPI_Sendrecv(void *sendbuf, int sendcount, MPI_Datatype sendtype, int dest, int sendtag, void *recvbuf, int recvcount, MPI_Datatype recvtype, int source, int recvtag, MPI_Comm comm, MPI_Status *status)
  - Sendbuf: Initial address of send buffer (choice)
  - Sendcount: Number of elements in send buffer (integer)
  - Sendtype: Type of elements in send buffer (handle)
  - Dest: Rank of destination (integer)
  - Sendtag: Send tag (integer)
  - Recvcount: Number of elements in receive buffer (integer)
  - Recvtype: Type of elements in receive buffer (handle)
  - Source: Rank of source (integer)
  - Recvtag: Receive tag (integer)
  - Comm: Communicator (handle)
  - Recvbuf: Initial address of receive buffer (choice)
  - Status: Status object (Status). This refers to the receive operation.

Compute Process Code (II)

```
float *h_output = NULL, *d_output = NULL, *d_vsq = NULL;
float *h_output = (float *)malloc(num_bytes);
cudaMalloc((void **)&d_output, num_bytes );

float *h_left_boundary = NULL, *h_right_boundary = NULL;
float *h_left_halo = NULL, *h_right_halo = NULL;

/* Alloc host memory for halo data */
cudaHostAlloc((void **)&h_left_boundary, num_halo_bytes);
cudaHostAlloc((void **)&h_right_boundary,num_halo_bytes);
cudaHostAlloc((void **)&h_left_halo,     num_halo_bytes);
cudaHostAlloc((void **)&h_right_halo,    num_halo_bytes);

/* Create streams used for stencil computation */
cudaStream_t stream0, stream1;
cudaStreamCreate(&stream0);
cudaStreamCreate(&stream1);
```

Device Memory Offsets Used for Data Exchange with Neighbors



Compute Process Code (III)

```
MPI_Status status;
int left_neighbor  = (pid > 0)     ? (pid - 1) : MPI_PROC_NULL;
int right_neighbor = (pid < np - 2) ? (pid + 1) : MPI_PROC_NULL;

/* Upload stencil cofficients */
upload_coefficients(coeff, 5);

int left_halo_offset   = 0;
int right_halo_offset  = dimx * dimy * (4 + dimz);
int left_stage1_offset  = 0;
int right_stage1_offset = dimx * dimy * (dimz - 4);
int stage2_offset       = num_halo_points;

MPI_Barrier( MPI_COMM_WORLD );
for(int i=0; i < nreps; i++) {
    /* Compute boundary values needed by other nodes first */
    launch_kernel(d_output + left_stage1_offset,
        d_input + left_stage1_offset, dimx, dimy, 12, stream0);
    launch_kernel(d_output + right_stage1_offset,
        d_input + right_stage1_offset, dimx, dimy, 12, stream0);

    /* Compute the remaining points */
    launch_kernel(d_output + stage2_offset, d_input + stage2_offset,
                  dimx, dimy, dimz, stream1);
```

Compute Process Code (IV)

```
/* Copy the data needed by other nodes to the host */
cudaMemcpyAsync(h_left_boundary, d_output + num_halo_points,
       num_halo_bytes, cudaMemcpyDeviceToHost, stream0 );
cudaMemcpyAsync(h_right_boundary,
           d_output + right_stage1_offset + num_halo_points,
           num_halo_bytes, cudaMemcpyDeviceToHost, stream0 );
cudaStreamSynchronize(stream0);
```

Compute Process Code (V)

```
    /* Send data to left, get data from right */
    MPI_Sendrecv(h_left_boundary, num_halo_points, MPI_FLOAT,
                 left_neighbor,  i, h_right_halo,
                 num_halo_points, MPI_FLOAT, right_neighbor, i,
                 MPI_COMM_WORLD, &status );
    /* Send data to right, get data from left */
    MPI_Sendrecv(h_right_boundary, num_halo_points, MPI_FLOAT,
                 right_neighbor, i, h_left_halo,
                 num_halo_points, MPI_FLOAT, left_neighbor,  i,
                 MPI_COMM_WORLD, &status );

    cudaMemcpyAsync(d_output+left_halo_offset,  h_left_halo,
                 num_halo_bytes, cudaMemcpyHostToDevice, stream0);
    cudaMemcpyAsync(d_output+right_ghost_offset, h_right_ghost,
                 num_halo_bytes, cudaMemcpyHostToDevice, stream0 );
    cudaDeviceSynchronize();

    float *temp = d_output;
    d_output = d_input; d_input = temp;
}
```

Compute Process Code (VI)

```
    /* Wait for previous communications */
    MPI_Barrier(MPI_COMM_WORLD);

    float *temp = d_output;
    d_output = d_input;
    d_input = temp;

    /* Send the output, skipping halo points */
    cudaMemcpy(h_output, d_output, num_bytes,
               cudaMemcpyDeviceToHost);
    float *send_address = h_output + num_ghost_points;
    MPI_Send(send_address, dimx * dimy * dimz, MPI_REAL,
           server_process, DATA_COLLECT, MPI_COMM_WORLD);
    MPI_Barrier(MPI_COMM_WORLD);

    /* Release resources */
    free(h_input); free(h_output);
    cudaFreeHost(h_left_ghost_own); cudaFreeHost(h_right_ghost_own);
    cudaFreeHost(h_left_ghost); cudaFreeHost(h_right_ghost);
    cudaFree( d_input ); cudaFree( d_output );
}
```

Data Server Code (III)

```
    /* Wait for nodes to compute */
    MPI_Barrier(MPI_COMM_WORLD);

    /* Collect output data */
    MPI_Status status;
    for(int process = 0; process < num_comp_nodes; process++)
        MPI_Recv(output + process * num_points / num_comp_nodes,
            num_points / num_comp_nodes, MPI_REAL, process,
            DATA_COLLECT, MPI_COMM_WORLD, &status );

    /* Store output data */
    store_output(output, dimx, dimy, dimz);

    /* Release resources */
    free(input);
    free(output);
}
```

More on MPI Message Types

- Point-to-point communication
  - Send and Receive
- Collective communication
  - Barrier
  - Broadcast
  - Reduce
  - Gather and Scatter

GPU Teaching Kit

Accelerated Computing

MPI Communication Groups

Using `MPI_COMM_WORLD` all the time can be expensive

Smaller communication groups can be defined

Synchronization and message passing within the smaller groups is faster

This is analogous to the division of a CUDA thread grid into blocks

MPI Communication Groups

```
int MPI_Comm_split(MPI_Comm comm, int color, int key, MPI_Comm *newcomm)
```

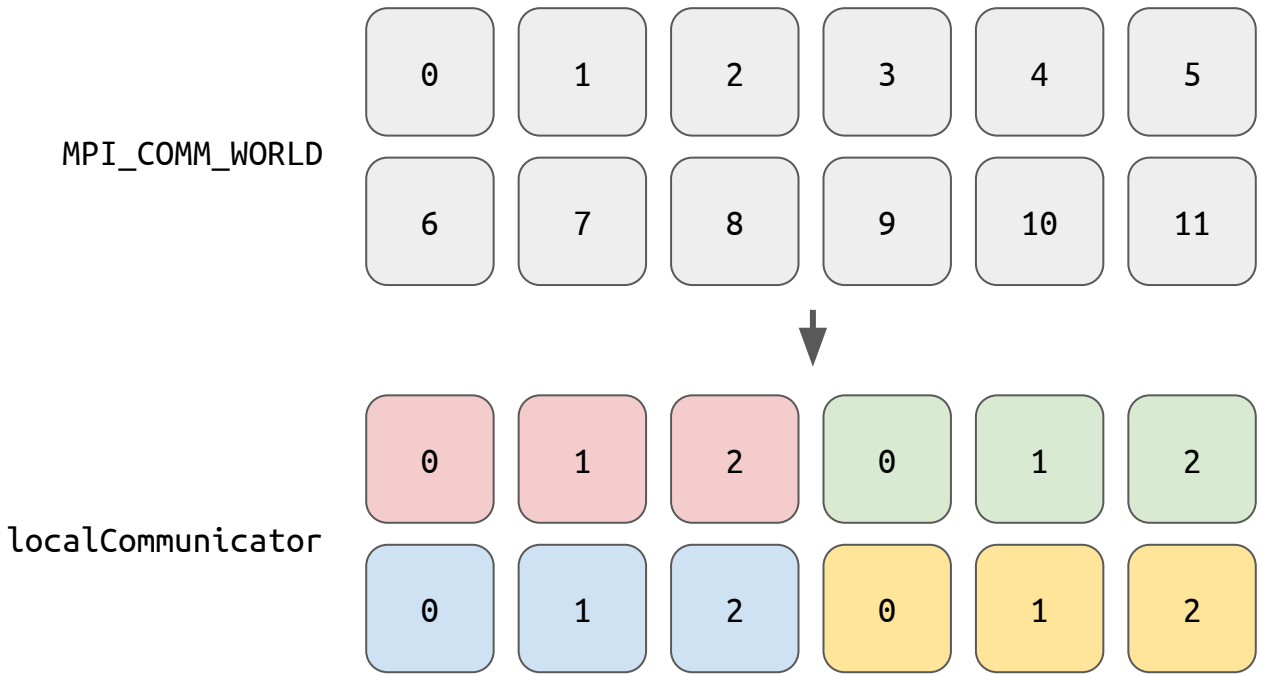
All nodes that pass the same `color` value to `MPI_Comm_split` will get back the same `newcomm` communicator

The rank of nodes in the new communicators will be determined by `key`

All nodes still participate in communications using the original `comm`

MPI Communication Groups

```
MPI_Comm localCommunicator;

MPI_Comm_split(MPI_COMM_WORLD, nodeID / 3, nodeID, &localCommunicator);
```



Conclusion / Takeaways

- Programming for multiple GPUs on the same node is a relatively straightforward extension of single-GPU programming, where the host manages memory transfers between host and device and device and device
- Programming for multiple nodes involves network communication, potentially introducing large latencies to be hidden
- MPI (Message Passing Interface) is a useful API for managing memory transfer and synchronization between multiple nodes

Sources

Cheng, John, Max Grossman, and Ty McKercher. *Professional Cuda C Programming*. John Wiley & Sons, 2014.

Kirk, David B., and W. Hwu Wen-Mei. *Programming massively parallel processors: a hands-on approach*. Morgan Kaufmann, 2016.