Intermediate OpenCL Programming

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Buffer

There are three exclusive types of buffers.

CL_MEM_USE_HOST_PTR

CL_MEM_ALLOC_HOST_PTR

CL_MEM_COPY_HOST_PTR

CL_MEM_USE_HOST_PTR

- OpenCL uses the host memory as the buffer so the `host_ptr` must not be `NULL`.
- If the device is GPU then the access is slow because the buffer is in the host (CPU).

CL_MEM_ALLOC_HOST_PTR

- OpenCL will allocate a buffer in the device and the device will use it directly.
- This memory is accessible from the host by `clEnqueueWriteBuffer` and `clEnqueueReadBuffer`.
- Since the device will allocate the buffer we cannot provide a non-NULL `host_ptr`.
- The access is fast because the buffer is in the device

CL_MEM_COPY_HOST_PTR

- OpenCL will copy the contents of the host buffer to a buffer on the device
- The device will use the device buffer.
- The access is fast because the buffer is in the device (GPU/CPU).

Comparison

buffer type	`host_ptr`	device will use	speed from GPU
`USE`	`!= NULL`	the host buffer directly	slow
`ALLOC`	`== NULL`	the device buffer	fast
`COPY`	`!= NULL`	the device buffer copied from the host buffer	fast

Discussion

- Which of the allcoation mode provides the slowest memory access from a device GPU?

Need not to Retrieve

- We would like to implement the vector addition program without getting the results back from the device.
- The idea is that we copy the vector A and B into device with `CL_MEM_COPY_HOST_PTR` buffer, and put the results in a `CL_MEM_USE_HOST_PTR` buffer.
- When the computation is over then we can get the results in the host buffer directly.

Example 1: (vectorAdd-nofetchC.c)

```
70  cl_mem bufferA =
71    clCreateBuffer(context,
72                   CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR,
73                   N * sizeof(cl_uint), A, &status);
74  assert(status == CL_SUCCESS);
75  cl_mem bufferB =
76    clCreateBuffer(context,
77                   CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR,
78                   N * sizeof(cl_uint), B, &status);
79  assert(status == CL_SUCCESS);
80  cl_mem bufferC =
81    clCreateBuffer(context,
82                   CL_MEM_WRITE_ONLY | CL_MEM_USE_HOST_PTR,
83                   N * sizeof(cl_uint), C, &status);
84  assert(status == CL_SUCCESS);
85  printf("Build buffers completes\n");
```

Execution

- After creating buffers, setting the parameter order, and set up the dimension of `NDRange`, we run the kernel by placing it into the command queue

clFinish

Example 2: (vectorAdd-nofetchC.c)

```
98    size_t globalThreads[] = {(size_t)N};
99    size_t localThreads[] = {1};
100   status =
101     clEnqueueNDRangeKernel(commandQueue, kernel, 1, NULL,
102                            globalThreads, localThreads,
103                            0, NULL, NULL);
104   assert(status == CL_SUCCESS);
105   printf("Kernel execution completes.\n");
```

Demonstration

- Run the `vector-nofetchC-cl` program.

Discussion

- Does it produce the correct answer?

Non-blocking

- The previous program does not produce the correct answer because the function call `clEnqueueNDRangeKernel` is *non-blocking*, which means it will not wait for the completion of the kernel.
- Since we check the contents of `C` before the kernel finishes, the answer is incorrect.
- We need to wait for the commands in the command queue to finish.

Prototype 3: clFinish.h

```
1 cl_int clFinish(cl_command_queue command_queue);
```

Parameters

`command_queue` Wait for the commands in this command queue to finish.

clFinish

Example 4: (vectorAdd-nofetchC-finish.c)

```
 98   size_t globalThreads[] = {(size_t)N};
 99   size_t localThreads[] = {1};
100   status =
101     clEnqueueNDRangeKernel(commandQueue, kernel, 1, NULL,
102                            globalThreads, localThreads,
103                            0, NULL, NULL);
104   assert(status == CL_SUCCESS);
105   printf("Kernel execution completes.\n");
106   /* getcvector */
107   clFinish(commandQueue);
```

Demonstration

- Run the `vector-nofetchC-finish-cl` program.

Discussion

- Does it produce the correct answer?

NDRange

- We can set the dimension of `NDRange` in the `clEnqueueNDRangeKernel` call.
- In the previous example we set the dimension to one, now we want to set it to two.
- Now a work item in `NDRange` will have two indices for two dimensions.

Index

- We can call `get_global_id(i)` to know its index in the i-th dimension.
- The parameter `i` must be within the dimension of `NDRange`

Prototype 5: getGlobalId.h

```
1 size_t get_global_id(uint dimindx);
```

Parameters

`dimindx` The dimension in which we want to know the index.

Domain

- We will use an array to keep track of the global indices a kernel function can see from a work item.
- We declare this array as `int globalId[2][N][N]`, where `N` is 16.
- The first 2 is for two dimensions.

Kernel

Example 6: (get-global-id.cl)

```
1  #define N 16
2
3  __kernel void getGlobalId(__global int globalId[2][N][N])
4  {
5    int id0 = get_global_id(0);
6    int id1 = get_global_id(1);
7    globalId[0][id0][id1] = id0;
8    globalId[1][id0][id1] = id1;
9  }
```

Kernel

- We first call `get_global_id(0)` and `get_global_id(1)` to know the indices of this work item on the two dimensions, and put them into `id0` and `id1`.
- Then we place `id0` and `id1` into corresponding cells of `globalId`.

Discussion

- Google `__global` to and find out what it means.

Buffer

- In the main program we declare a host buffer `bufferGlobalId` to hold the global indices.
- This buffer will link to the `globalId[2][N][N]` parameter in the kernel function.

Buffers

Example 7: (get-global-id.c)

```
73    cl_mem bufferGlobalId =
74      clCreateBuffer(context,
75                     CL_MEM_WRITE_ONLY | CL_MEM_USE_HOST_PTR,
76                     2 * N * N * sizeof(cl_uint), globalId, &status)
77    assert(status == CL_SUCCESS);
78    printf("Build buffers completes\n");
79    /* setarg */
80    status = clSetKernelArg(kernel, 0, sizeof(cl_mem),
81                            (void*)&bufferGlobalId);
82    assert(status == CL_SUCCESS);
83    printf("Set kernel arguments completes\n");
```

Dimension

- Now we set the dimension of `NDRange` to 2, and set the size of each dimension to `N`, as in `globalDim`.
- Since `NDRange` has two dimensions, a work group will also have two dimension. For simplicity we set it to one by one, as in `localDim`.
- We place the kernel into the command queue, then call `clFinish` to wait for the completion.

Buffers

Example 8: (get-global-id.c)

```
85    size_t globalDim[] = {(size_t)N, (size_t)N};
86    size_t localDim[] = {1, 1};
87    status =
88      clEnqueueNDRangeKernel(commandQueue, kernel, 2, NULL,
89                             globalDim, localDim,
90                             0, NULL, NULL);
91    assert(status == CL_SUCCESS);
92    printf("Specify the shape of the domain completes.\n");
93    /* getresult */
94  #ifdef USEclFINSIH
95    clFinish(commandQueue);
96  #else
97    clEnqueueReadBuffer(commandQueue, bufferGlobalId, CL_TRUE,
98                        0, 2 * N * N * sizeof(cl_uint), globalId,
99                        0, NULL, NULL);
100 #endif
101   printf("Kernel execution completes.\n");
102
103   printId("get_global_id(0)", globalId[0]);
```

printId

- We implement a `printId` function to print the contents in any array.
- The first parameter is a string for identification purpose, and the second parameter is the array of indices to print.

Buffers

Example 9: (get-global-id.c)

```
11 void printId(char *title, cl_uint id[N][N])
12 {
13   puts(title);
14   for (int i = 0; i < N; i++) {
15     for (int j = 0; j < N; j++)
16       printf("%2d ", id[i][j]);
17     printf("\n");
18   }
19 }
```

Demonstration

- Run the `get-global-id-cl` program.

Discussion

- Describe the printed indices.
- Will the output be affected if we set the work group size differently?

NDRange

- Local index is the index within a work group.
- We can specify the size of each dimension for a work group in a `clEnqueueNDRangeKernel` call.
- In this example we will set the size of local dimension and observe the results.

Local Index

- We call `get_local_id(i)` to know its index in the i-th dimension.
- The parameter `i` must be within the dimension of `NDRange` because the local and the global index have the same number of dimensions.

Prototype 10: getLocalId.h

```
1 size_t get_local_id(uint dimindx);
```

Parameters

`dimindx` The dimension in which we want to know the index.

Domain

- We will use two arrays to keep track of global and local index a kernel function can see from a work item respectively.
- We declare two arrays as `int globalId[2][N][N]` and `int localId[2][N][N]`.

Kernel

Example 11: (get-global-local-id.cl)

```
1  #define N 16
2
3  __kernel void getGlobalId(__global int globalId[2][N][N],
4            __global int localId[2][N][N])
5  {
6          int id0 = get_global_id(0);
7          int id1 = get_global_id(1);
8          globalId[0][id0][id1] = get_global_id(0);
9          globalId[1][id0][id1] = get_global_id(1);
10         localId[0][id0][id1] = get_local_id(0);
11         localId[1][id0][id1] = get_local_id(1);
12 }
```

Kernel

- We first call `get_global_id(0)` and `get_global_id(1)` to know the indices of this work item in `NDRange`, and put them into `id0` and `id1`.
- Then we call `get_global_id` and `get_local_id` to get the indices.

Buffers

- In the main program we declare two host buffers `bufferGlobalId` and `bufferLocalId` to hold the global and local indices.
- This buffer will link to parameters `globalId[2][N][N]` and `localId[2][N][N]` in the kernel function.

Buffers

Example 12: (get-global-local-id.c)

```
74  cl_mem bufferGlobalId =
75    clCreateBuffer(context,
76                   CL_MEM_WRITE_ONLY | CL_MEM_USE_HOST_PTR,
77                   2 * N * N * sizeof(cl_uint), globalId, &status)
78  assert(status == CL_SUCCESS);
79  cl_mem bufferLocalId =
80    clCreateBuffer(context,
81                   CL_MEM_WRITE_ONLY | CL_MEM_USE_HOST_PTR,
82                   2 * N * N * sizeof(cl_uint), localId, &status);
83  assert(status == CL_SUCCESS);
84  printf("Build buffers completes\n");
85  /* setarg */
86  status = clSetKernelArg(kernel, 0, sizeof(cl_mem),
87                          (void*)&bufferGlobalId);
88  assert(status == CL_SUCCESS);
89  status = clSetKernelArg(kernel, 1, sizeof(cl_mem),
90                          (void*)&bufferLocalId);
91  assert(status == CL_SUCCESS);
92  printf("Set kernel arguments completes\n");
```

Dimension

- Now we set the dimension of `NDRange` to 2, and set the size of each dimension to `N`, as in `globalDim`.
- We set the size of dimension of a work group from the command line arguments, and place the sizes into `localDim`.
- We place the kernel into the command queue, then call `clFinish` to wait for the completion.

Buffers

Example 13: (get-global-local-id.c)

```
94    size_t globalDim[] = {(size_t)N, (size_t)N};
95    int groupRow = atoi(argv[2]);
96    int groupCol = atoi(argv[3]);
97    size_t localDim[] = {groupRow, groupCol};
98    status =
99      clEnqueueNDRangeKernel(commandQueue, kernel, 2, NULL,
100                             globalDim, localDim,
101                             0, NULL, NULL);
102   assert(status == CL_SUCCESS);
103   printf("Specify the shape of the domain completes.\n");
104   /* getresult */
105 #ifdef USEclFINSIH
106   clFinish(commandQueue);
107 #else
108   clEnqueueReadBuffer(commandQueue, bufferGlobalId, CL_TRUE,
109                       0, 2 * N * N * sizeof(cl_uint), globalId,
110                       0, NULL, NULL);
111   clEnqueueReadBuffer(commandQueue, bufferLocalId, CL_TRUE,
112                       0, 2 * N * N * sizeof(cl_uint), localId,
```

Demonstration

- Run the `get-global-id-cl` program by setting the work group size to be 4 by 4.
- Run the `get-global-id-cl` program by setting the work group size to be 2 by 4.

Discussion

- Describe the printed indices under different group sizes.

Matrix Multiplication

- We now use matrix multiplication as an example of using global index.
- We will multiply two N by N matrices using GPU.

Kernel

- The multiplication kernel has three parameters – `A`, `B` and `C`.
- We will multiply `A` with `B`, and place the results in `C`.
- We first get the row and column number of this work item, then preform an inner product.

Kernel

Example 14: (mul-kernel.cl)

```
1  #define N 1024
2
3  __kernel void mul(__global int matrixA[N][N],
4                    __global int matrixB[N][N],
5                    __global int matrixC[N][N])
6  {
7    int row = get_global_id(0);
8    int col = get_global_id(1);
9    int sum = 0;
10   for (int i = 0; i < N; i++)
11     sum += matrixA[row][i] * matrixB[i][col];
12   matrixC[row][col] = sum;
13 }
```

Matrices

- The main program first prepares host memory matrices `A` and `B`.

Buffers

Example 15: (matrixMul.c)

```
61    for (int i = 0; i < N; i++)
62      for (int j = 0; j < N; j++) {
63        A[i][j] = i + j;
64        B[i][j] = i - j;
65      }
```

Buffers

- The main program then creates OpenCL buffers for `A`, `B` and `C`.
- The contents of A and B will be copied into devices (`CL_MEM_COPY_HOST_PTR`), and the GPU will use host memory buffer directly (`CL_MEM_USE_HOST_PTR`).

Buffers

Example 16: (matrixMul.c)

```
67   cl_mem bufferA =
68     clCreateBuffer(context,
69                    CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR,
70                    N * N * sizeof(cl_uint), A, &status);
71   assert(status == CL_SUCCESS);
72   cl_mem bufferB =
73     clCreateBuffer(context,
74                    CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR,
75                    N * N * sizeof(cl_uint), B, &status);
76   assert(status == CL_SUCCESS);
77   cl_mem bufferC =
78     clCreateBuffer(context,
79                    CL_MEM_WRITE_ONLY | CL_MEM_USE_HOST_PTR,
80                    N * N * sizeof(cl_uint), C, &status);
81   assert(status == CL_SUCCESS);
82   printf("Build buffers completes\n");
```

Run Kernel

- We set the size of both dimensions to `N`, as in `globalDim`.
- We set the sizes of dimensions of a work group as 1 by 1 and place the sizes into `localDim`.
- We place the kernel into the command queue, then call `clFinish` to wait for the completion.

Buffers

Example 17: (matrixMul.c)

```
95    size_t globalThreads[] = {(size_t)N, (size_t)N};
96    size_t localThreads[] = {1, 1};
97    status =
98      clEnqueueNDRangeKernel(commandQueue, kernel, 2, NULL,
99                             globalThreads, localThreads,
100                            0, NULL, NULL);
101   assert(status == CL_SUCCESS);
102   printf("Specify the shape of the domain completes.\n");
103   /* getcvector */
104 #ifdef USEclFINSIH
105   clFinish(commandQueue);
106 #else
107   clEnqueueReadBuffer(commandQueue, bufferC, CL_TRUE,
108                       0, N * N * sizeof(cl_uint), C,
109                       0, NULL, NULL);
110 #endif
111   printf("Kernel execution completes.\n");
```

Demonstration

- Run the `matrixMul-cl` program.

Discussion

- Did you notice the significant speed difference in the computation and verification parts?

Time Measurement

- We would like to measure the kernel execution time.
- The kernel is sent to a device through a *command queue*, so we need to enable the command queue for profiling.
- We associate an event with the end of a kernel execution, then wait for the event.
- We retrieve the timing information from the event.

Steps

- We set the property of the command queue to allow profiling.
- We then declare a variable of type `cl_event` for the event.
- We then supply the event as the last parameter when calling `clEnqueueNDRangeKernel`.
- We then wait for this event by calling a function `clWaitForEvents`.
- Finally we extract the timing information from the event by calling `clGetEventProfilingInfo`.

Command Queue

- The kernel is sent to a device through a *command queue*.
- If we want to time (profile) the kernel execution, we need to explicitly set the property of the command queue to `CL_PROFILING_COMMAND_QUEUED`.

Prototype 18: clCreateCommandQueue.h

```
1  cl_command_queue
2  clCreateCommandQueueWithProperties(
3            cl_context context,
4            cl_device_id device,
5            const cl_queue_properties
6            *properties,
7            cl_int *errcode_ret);
```

Property

- We explicitly set the `CL_PROFILING_COMMAND_QUEUED` property of the command queue when we created it.
- Note that the API needs a list of property/value pairs, which must end in 0.
- This *list* is actually an array.

Example 19: (matrixMul-time.c)

```
35    const cl_queue_properties properties[] =
36      {CL_QUEUE_PROPERTIES, CL_QUEUE_PROFILING_ENABLE, 0};
37    cl_command_queue commandQueue =
38      clCreateCommandQueueWithProperties(context, GPU[0],
39                                         properties, &status);
40    assert(status == CL_SUCCESS);
```

Discussion

- Google to find out other properties that can be set for a command queue.

Kernel Execution

- After setting the command queue for profiling, we can start the kernel.
- We supply `event` as the last parameter while calling `clEnqueueNDRangeKernel`, so now we have associated the event with the kernel execution.

Prototype 20: clEnqueueNDRangeKernel.h

```
1  cl_int
2  clEnqueueNDRangeKernel (cl_command_queue command_queue,
3                          cl_kernel kernel,
4                          cl_uint work_dim,
5                          const size_t *global_work_offset,
6                          const size_t *global_work_size,
7                          const size_t *local_work_size,
8                          cl_uint num_events_in_wait_list,
9                          const cl_event *event_wait_list,
10                         cl_event *event);
```

Example 21: (matrixMul-time.c)

```
98   size_t globalThreads[] = {(size_t)N, (size_t)N};
99   size_t localThreads[] = {1, 1};
100  cl_event event;
101  status =
102    clEnqueueNDRangeKernel(commandQueue, kernel, 2, NULL,
103                           globalThreads, localThreads,
104                           0, NULL, &event);
105  assert(status == CL_SUCCESS);
```

Wait for Event

- Now we have submitted the kernel to execution, we just wait for the event to happen.
- We call `clWaitForEvents` to wait for event(s).

clWaitForEvents

Prototype 22: clWaitForEvents.h

```
1 cl_int clWaitForEvents(cl_uint num_events,
2                        const cl_event *event_list);
```

Parameters

`num_events` The number of events to wait for.

`event_list` The array of events to wait for.

Example 23: (matrixMul-time.c)

```
107   status = clWaitForEvents(1, &event);
108   assert(status == CL_SUCCESS);
109   clEnqueueReadBuffer(commandQueue, bufferC, CL_TRUE,
110                       0, N * N * sizeof(cl_uint), C,
111                       0, NULL, NULL);
112   printf("Kernel execution completes.\n");
```

Discussion

- Trace the `matrixMul-time.c` to understand the flow so far.

Three Stages

A kernel execution will go through three stages.

- First the kernel joined the command queue for execution.
- When it is the turn of the kernel, it is submitted to the device for execution.
- When the kernel finished execution, it will trigger the event you associated with it.

Get Information

The event can provide the following four times.

- The time when the kernel joined the command queue.
- The time when the kernel was sent to the device for execution.
- The time when the kernel started execution.
- The time when the kernel finished execution.

Get Information

- We call `clGetEventProfilingInfo` to know the four times.
- The time-stamp is of type `cl_ulong`.

clGetEventProfilingInfo

Prototype 24: clGetEventProfilingInfo.h

```
1 cl_int
2 clGetEventProfilingInfo(cl_event event,
3                          cl_profiling_info param_name,
4                          size_t param_value_size,
5                          void *param_value,
6                          size_t *param_value_size_ret);
```

Parameters

`event` The event that we want to query.

`param_name` The information to query.

`param_value_size` The length of buffer (`param_value`) to store the answer.

`param_value` The buffer to store the answer.

`param_value_size_ret` The actual length of the returned answer.

Four Time Points

- We put the four times in four variables – `timeEnterQueue`, `timeSubmit`, `timeStart`, and `timeEnd`.

Time Calculation

Example 25: (matrixMul-time.c)

```
115   cl_ulong timeEnterQueue, timeSubmit, timeStart, timeEnd;
116   status =
117     clGetEventProfilingInfo(event, CL_PROFILING_COMMAND_QUEUED,
118                             sizeof(cl_ulong), &timeEnterQueue, NUL
119   assert(status == CL_SUCCESS);
120   status =
121     clGetEventProfilingInfo(event, CL_PROFILING_COMMAND_SUBMIT,
122                             sizeof(cl_ulong), &timeSubmit, NULL);
123   assert(status == CL_SUCCESS);
124   status =
125     clGetEventProfilingInfo(event, CL_PROFILING_COMMAND_START,
126                             sizeof(cl_ulong), &timeStart, NULL);
127   assert(status == CL_SUCCESS);
128   status =
129     clGetEventProfilingInfo(event, CL_PROFILING_COMMAND_END,
130                             sizeof(cl_ulong), &timeEnd, NULL);
131   assert(status == CL_SUCCESS);
```

Time Calculation

- We calculate the duration of each stage by the difference of the beginning and the ending time-stamps.
- The unit of time is nano (10^{-9}) second.

Example 26: (matrixMul-time.c)

```
133   printf("kernel queued time %f seconds\n",
134          (timeSubmit - timeEnterQueue) / 1000000000.0);
135   printf("kernel submission time %f seconds\n",
136          (timeStart - timeSubmit) / 1000000000.0);
137   printf("kernel execution time %f seconds\n",
138          (timeEnd - timeStart) / 1000000000.0);
```

Demonstration

- Run the `matrixMul-time-cl` program.

Discussion

- Observe the times of the three stages.

Buffer Comparison

- Now we know how to measure kernel execution time, we can compare the effects of different communication buffers on the execution time.
- We will compare the executive time of using `CL_MEM_COPY_HOST_PTR` and `CL_MEM_USE_HOST_PTR` for creating `A` and `B` buffers.
- We will fix the allocation method of `C` to make a meaningful comparison.

Difference

- The only difference between the following two programs is how they allocate `A` and `B` matrices.

Example 27: (matrixMul-time-copy.c)

```
70  cl_mem bufferA =
71    clCreateBuffer(context,
72                   CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR,
73                   N * N * sizeof(cl_uint), A, &status);
74  assert(status == CL_SUCCESS);
75  cl_mem bufferB =
76    clCreateBuffer(context,
77                   CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR,
78                   N * N * sizeof(cl_uint), B, &status);
79  assert(status == CL_SUCCESS);
80  cl_mem bufferC =
81    clCreateBuffer(context,
82                   CL_MEM_WRITE_ONLY | CL_MEM_USE_HOST_PTR,
83                   N * N * sizeof(cl_uint), C, &status);
84  assert(status == CL_SUCCESS);
85  printf("Build buffers completes\n");
```

Example 28: (matrixMul-time-use.c)

```
70  cl_mem bufferA =
71    clCreateBuffer(context,
72                   CL_MEM_READ_ONLY | CL_MEM_USE_HOST_PTR,
73                   N * N * sizeof(cl_uint), A, &status);
74  assert(status == CL_SUCCESS);
75  cl_mem bufferB =
76    clCreateBuffer(context,
77                   CL_MEM_READ_ONLY | CL_MEM_USE_HOST_PTR,
78                   N * N * sizeof(cl_uint), B, &status);
79  assert(status == CL_SUCCESS);
80  cl_mem bufferC =
81    clCreateBuffer(context,
82                   CL_MEM_WRITE_ONLY | CL_MEM_USE_HOST_PTR,
83                   N * N * sizeof(cl_uint), C, &status);
84  assert(status == CL_SUCCESS);
85  printf("Build buffers completes\n");
```

Demonstration

- Run the `matrixMul-time-copy-cl` and `matrixMul-time-use-cl` programs.

Discussion

- Compare the execution times of the two programs.
- What is the reason for this difference in kernel execution time?

Local Memory

- Local memory is shared by processing units in the same work group.
- Local memory is fast but small.
- We will use local memory to speed up matrix multiplication.

Idea

- Both matrices A and B are N by N.
- We will partition the matrices into Blk by Blk blocks, so each block has N/Blk rows and columns.
- For ease of notation we will use $Block(A, i, j)$ to denote the block in i-th row of blocks and j-th column of blocks in A.

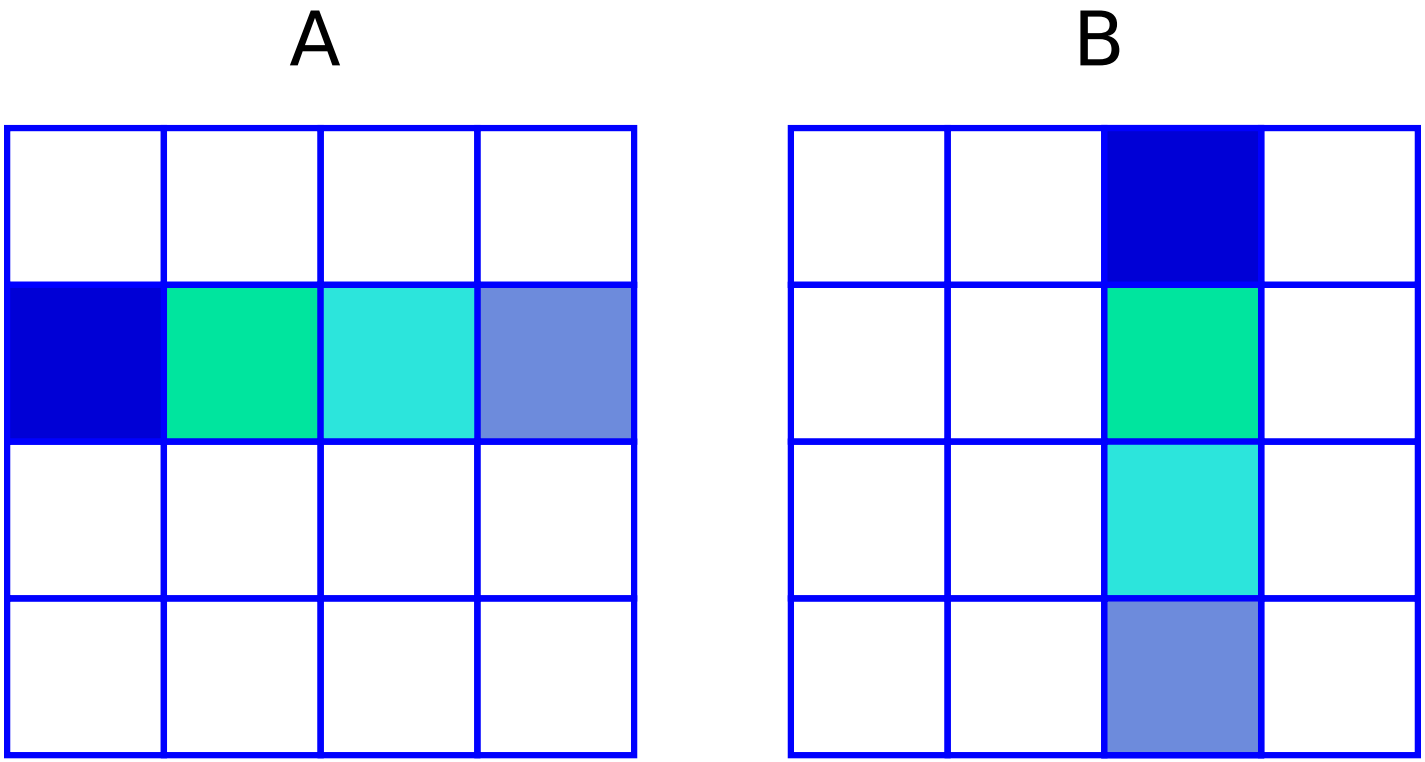
Work Group

- Each work group will compute a block in C.
- Each thread will compute an element of C.

Divide and Conquer

- Now consider the work group that is responsible for computing the $Block(C, i, j)$.
- This work group will first multiply $Block(A, i, 1)$ by $Block(B, 1, j)$.
- This work group will then multiply $Block(A, i, 2)$ by $Block(B, 2, j)$.
- ...
- This work group will then multiply $Block(A, i, N)$ by $Block(B, N, j)$.
- Then $Block(C, i, j)$ is the sum of all these products.

Divide and Conquer



Discussion

- Make sure that you understand this algorithm.

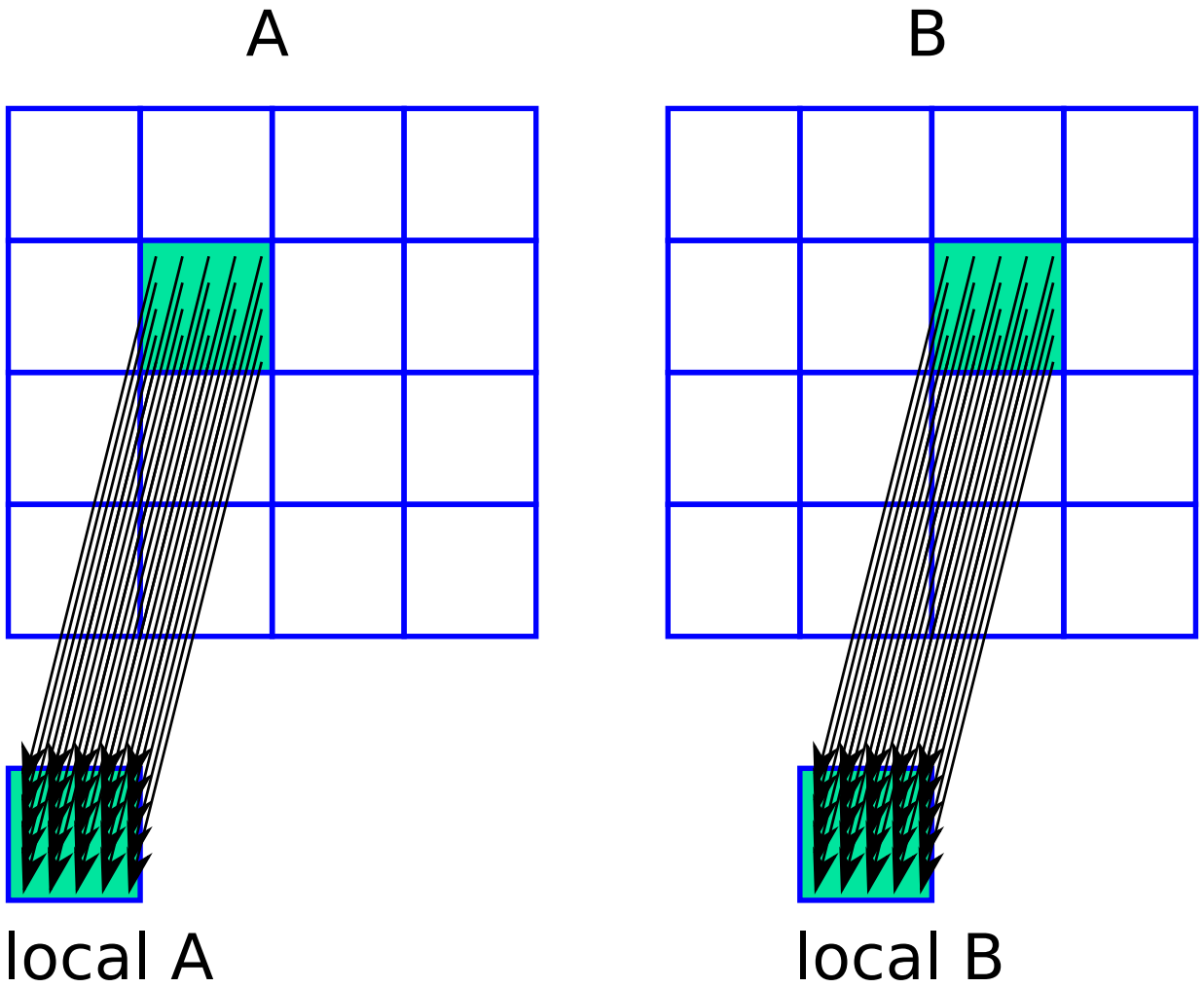
Fast multiplication

- If we know how to do matrix multiplication on two blocks, we know how to solve the whole problem.
- The problem is that if we do this on global memory, it will be slow.
- The idea is to bring $Block(A, i, 1)$ and $Block(B, 1, j)$ into local memory, then we can multiply them fast.
- How??

Memory Movement

- There are $(N/Blk)^2$ elements in $Block(A, i, 1)$.
- There are $(N/Blk)^2$ threads in this work group.
- We make each thread to move an element from both $Block(A, i, 1)$ $Block(B, 1, j)$ into local memory, then from both $Block(A, i, 2)$ and $Block(B, 2, j)$, and so on.
- After each movement each thread computes an element in $Block(C, i, j)$ using the data in local memory.

Move to Local Memory



Profitable

- Why is this profitable?
- Each thread only moves two data.
- Each thread will do a vector inner product on two vector of length (N/Blk).
- That is, every data moved into local memory is shared by (N/Blk) other threads.

Discussion

- Make sure that you understand this profitable theory.

Steps

Now from a thread, or a kernel point of view, it will go through the following steps.

- Get the global and local indices of this work item.
- Go through *Blk* iterations, where each of these iterations multiplies two blocks.
  - Move a data from A in global memory into local memory.
  - Move a data from B in global memory into local memory.
  - After both steps are done compute the inner product and add it to a variable `sum`
- Put sum into the corresponding *C* element.

Constants

- Since the kernel function file cannot include other source files, we can only define these constants here. A more consistent method should be used in the future.
- We define a symbol `BSIDE` for the size of a side of the a block.

Example 29: (mul-local-kernel.cl)

```
2 #define N 1024
3 #define Blk 64
4 #define BSIDE (N / Blk)
```

Interface

- We use global memory as the interface between the kernel and the host, and the interface is the same as before.
- We declare two local matrices in local memory, using the `__local` keyword.

Example 30: (mul-local-kernel.cl)

```
6  __kernel void mul(__global int A[N][N],
7                    __global int B[N][N],
8                    __global int C[N][N])
9  {
10   int globalRow = get_global_id(0);
11   int globalCol = get_global_id(1);
12   int localRow = get_local_id(0);
13   int localCol = get_local_id(1);
14
15   __local int ALocal[BSIDE][BSIDE];
16   __local int BLocal[BSIDE][BSIDE];
```

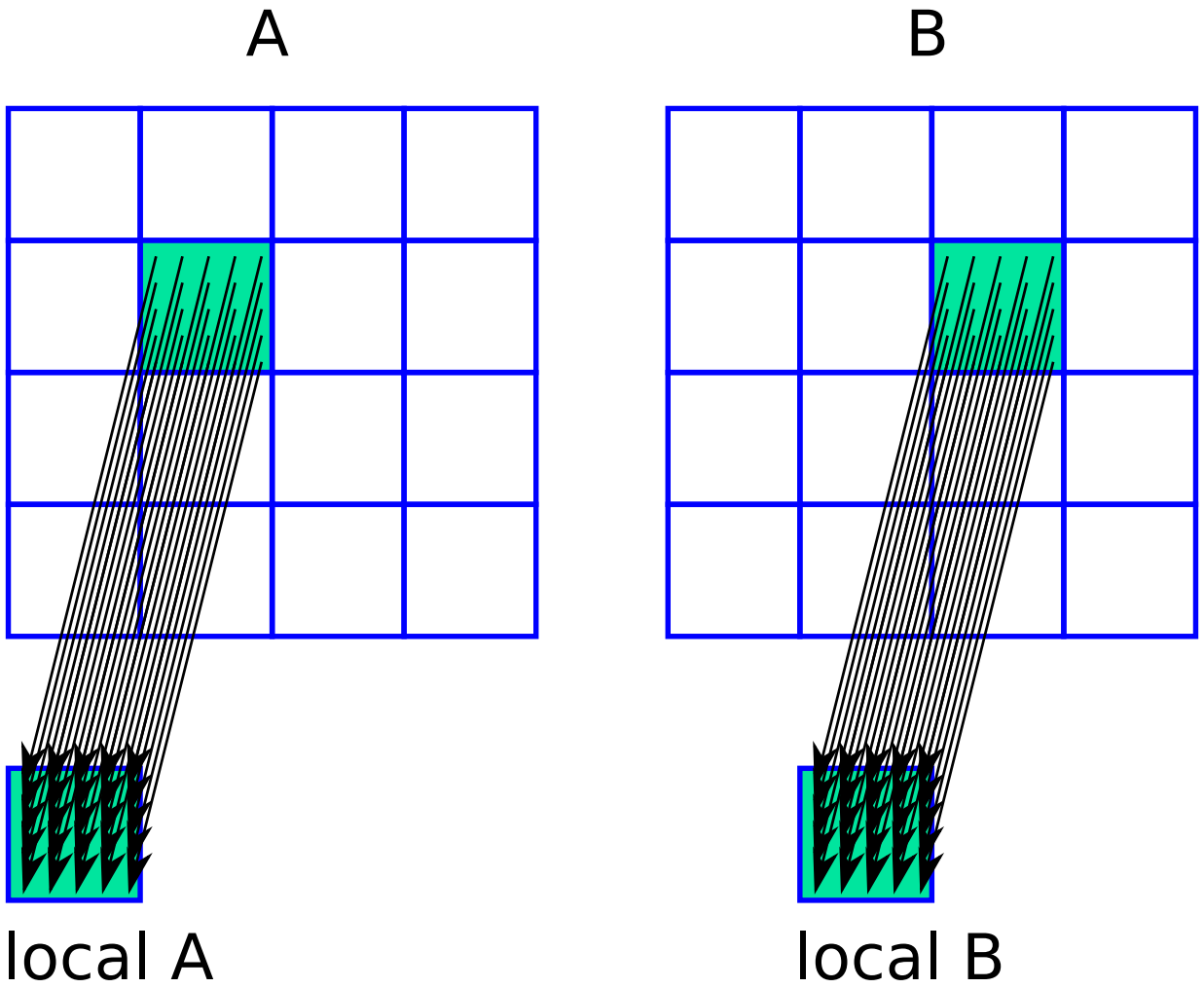
Data Movement

- Each thread (kernel function) moves one data into local A and B.
- However, we need to make sure that when we start the inner product, *all* the data are there.
- Remember a thread only moves two data, other data are moved by other threads – we do not know if they have finished or not.
- We need to synchronize with all other threads in the work group.

Example 31: (mul-local-kernel.cl)

```
18    int sum = 0;
19    for (int block = 0; block < Blk; block++) {
20      ALocal[localRow][localCol] =
21        A[globalRow][block * BSIDE + localCol];
22      BLocal[localRow][localCol] =
23        B[block * BSIDE + localRow][globalCol];
24      barrier(CLK_LOCAL_MEM_FENCE);
```

Move to Local Memory



Discussion

- Do we need to synchronize with threads in other work groups?
- Convince yourself that the index calculation is correct.

Synchronization

- We use `barrier` to synchronize threads.
- All threads in the same group will synchronize.

barrier

Prototype 32: barrier.h

```
1 void barrier(cl_mem_fence_flags flags);
```

Parameters

`flags` The memory level this synchronization guarantees.

`CLK_LOCAL_MEM_FENCE` Guarantees that all local memory operations will finish.

`CLK_GLOBAL_MEM_FENCE` Guarantees that all global memory operations will finish.

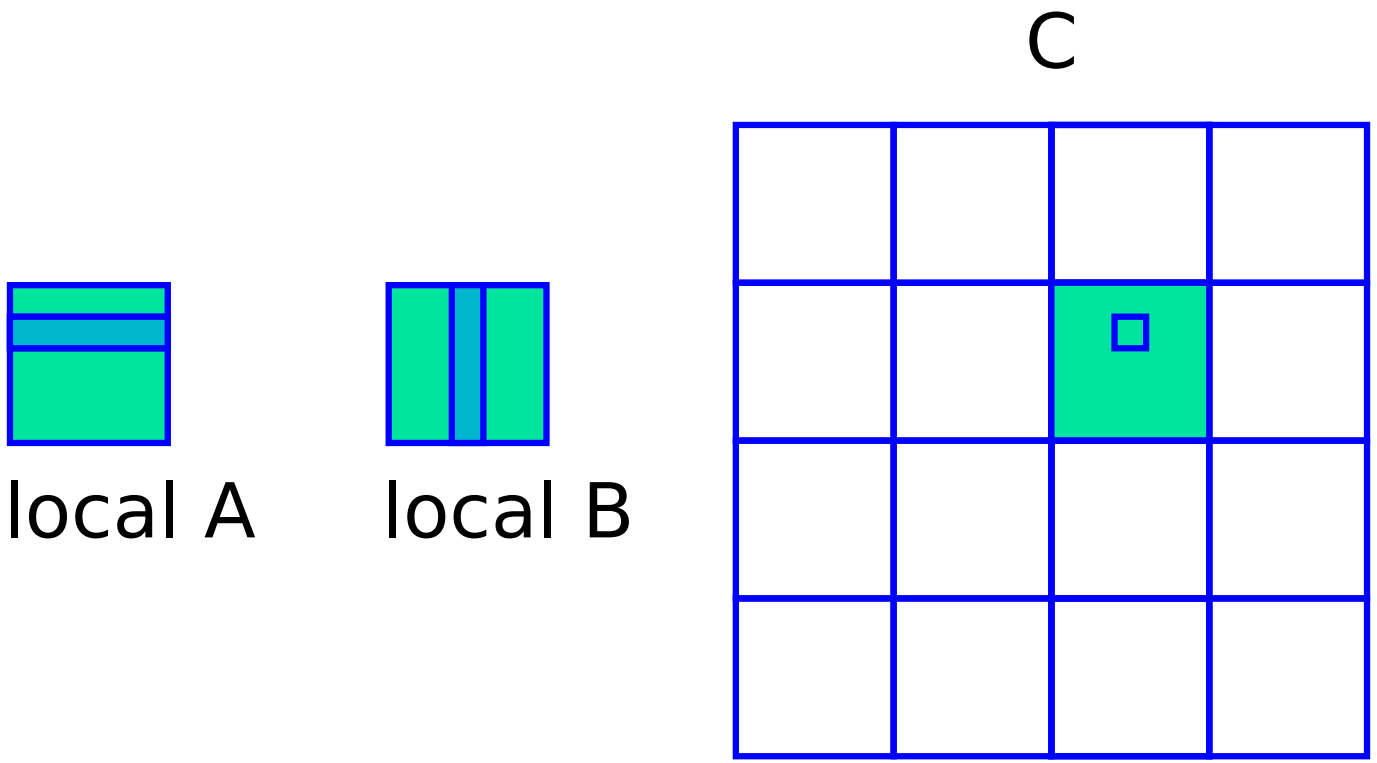
Example 33: (mul-local-kernel.cl)

```
18    int sum = 0;
19    for (int block = 0; block < Blk; block++) {
20      ALocal[localRow][localCol] =
21        A[globalRow][block * BSIDE + localCol];
22      BLocal[localRow][localCol] =
23        B[block * BSIDE + localRow][globalCol];
24      barrier(CLK_LOCAL_MEM_FENCE);
25      /* inner */
26      for (int k = 0; k < BSIDE; k++)
27        sum += ALocal[localRow][k] * BLocal[k][localCol];
28      barrier(CLK_LOCAL_MEM_FENCE);
29    }
30    C[globalRow][globalCol] = sum;
31  }
```

C

- The answer in C is accumulated throughout the iterations in variable `sum`.
- We place another barrier after the inner product.
- We only update local memory so we use `CLK_LOCAL_MEM_FENCE`.

C



Demonstration

- Run the `matrixMul-time-copy-local-cl` program.

Discussion

- Do we need both synchronizations?
- Observe the timing.