Performing Reductions in OpenCL

Recall the OpenCL Memory Model

Kernel

- Global Memory
- Constant Memory

WorkGroup

- Shared Memory

Work Item

- Private Memory
Here's the Problem We are Trying to Solve

Like the first.cpp demo program, we are piecewise multiplying two arrays. Unlike the first demo program, we want to then add up all the products and return the sum.

\[ A \times B \rightarrow \text{prods} \]
\[ \Sigma \text{prods} \rightarrow C \]

After the array multiplication, we want each work-group to sum the products within that work-group, then return them to the host in an array for final summing.

To do this, we will not put the products into a large global device array, but into a \text{prods[]} array that is shared within its work-group.

Reduction Takes Place in a Single Work-Group

If we had 8 work-items in a work-group, we would like the threads in each work-group to execute the following instructions . . .

\[
\begin{align*}
\text{Thread \#0:} & \quad \text{prods[0]} += \text{prods[1]}; \\
\text{Thread \#2:} & \quad \text{prods[2]} += \text{prods[3]}; \\
\text{Thread \#4:} & \quad \text{prods[4]} += \text{prods[5]}; \\
\text{Thread \#6:} & \quad \text{prods[6]} += \text{prods[7]}; \\
\end{align*}
\]

. . . but in a more general way than writing them all out by hand.
Here's What You Would Change in your Host Program

```c
size_t numWorkGroups = NUM_ELEMENTS / LOCAL_SIZE;

float * hA = new float [ NUM_ELEMENTS ];
float * hB = new float [ NUM_ELEMENTS ];
float * hC = new float [ numWorkGroups ];
size_t abSize = NUM_ELEMENTS * sizeof(float);
size_t cSize = numWorkGroups * sizeof(float);
cl_mem dA = clCreateBuffer( context, CL_MEM_READ_ONLY , abSize, NULL, &status );
cl_mem dB = clCreateBuffer( context, CL_MEM_READ_ONLY , abSize, NULL, &status );
cl_mem dC = clCreateBuffer( context, CL_MEM_WRITE_ONLY , cSize, NULL, &status );
status = clEnqueueWriteBuffer( cmdQueue, dA, CL_FALSE, 0, abSize, hA, 0, NULL, NULL );
status = clEnqueueWriteBuffer( cmdQueue, dB, CL_FALSE, 0, abSize, hB, 0, NULL, NULL );
cl_kernel kernel = clCreateKernel( program, "ArrayMultReduce", &status );
status = clSetKernelArg( kernel, 0, sizeof(cl_mem), &dA );
status = clSetKernelArg( kernel, 1, sizeof(cl_mem), &dB );
status = clSetKernelArg( kernel, 2, LOCAL_SIZE * sizeof(float), NULL );
// local "prods" array is dimensioned the size of each work-group
status = clSetKernelArg( kernel, 3, sizeof(cl_mem), &dC );
```

This NULL is how you tell OpenCL that this is a local (shared) array, not a global array.

The Arguments to the Kernel

```c
status = clSetKernelArg( kernel, 0, sizeof(cl_mem), &dA );
status = clSetKernelArg( kernel, 1, sizeof(cl_mem), &dB );
status = clSetKernelArg( kernel, 2, LOCAL_SIZE * sizeof(float), NULL );
// local "prods" array – one per work-item
status = clSetKernelArg( kernel, 3, sizeof(cl_mem), &dC );
```

```c
kernel void ArrayMultReduce( global const float *dA, global const float *dB, local float *prods, global float *dC )
{
    int gid = get_global_id( 0 ); // 0 .. total_array_size-1
    int numItems = get_local_size( 0 ); // # work-items per work-group
    int tnum = get_local_id( 0 ); // thread (i.e., work-item) number in this work-group
    // 0 .. numItems-1
    int wgNum = get_group_id( 0 ); // which work-group number this is in
    prods[ tnum ] = dA[ gid ] * dB[ gid ]; // multiply the two arrays together
    // now add them up – come up with one sum per work-group
    // It is a big performance benefit to do it here while "prods" is still available – and is local
    // It would be a performance hit to pass "prods" back to the host then bring it back to the device for reduction
    A * B → prods
    Σ prods → C
}```
A work-group consisting of numItems work-items can be reduced to a sum in \( \log_2(\text{numItems}) \) steps. In this example, numItems=8.

The reduction begins with the individual products in prods[0] .. prods[7]. The final sum will end up in prods[0], which will then be copied into dC[wgNum].

## A Review of Bitmasks

Remember Truth Tables?

<table>
<thead>
<tr>
<th>F &amp; F</th>
<th>F &amp; T</th>
<th>T &amp; F</th>
<th>T &amp; T</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>F</td>
<td>F</td>
<td>T</td>
</tr>
</tbody>
</table>

Or, with Bits:

<table>
<thead>
<tr>
<th>0 &amp; 0</th>
<th>0 &amp; 1</th>
<th>1 &amp; 0</th>
<th>1 &amp; 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>= 0</td>
<td>= 1</td>
<td>= 0</td>
<td>= 1</td>
</tr>
</tbody>
</table>

Or, with Multiple Bits:

<table>
<thead>
<tr>
<th>000 &amp; 011</th>
<th>001 &amp; 011</th>
<th>010 &amp; 011</th>
<th>011 &amp; 011</th>
<th>100 &amp; 011</th>
<th>101 &amp; 011</th>
</tr>
</thead>
<tbody>
<tr>
<td>= 000</td>
<td>= 001</td>
<td>= 010</td>
<td>= 011</td>
<td>= 000</td>
<td>= 001</td>
</tr>
</tbody>
</table>
Reduction Takes Place in a Single Work-Group

Each work-item is run by a single thread

Thread #0:
prods[ 0 ] += prods[ 1 ];

Thread #2:
prods[ 2 ] += prods[ 3 ];

Thread #4:
prods[ 4 ] += prods[ 5 ];

Thread #6:
prods[ 6 ] += prods[ 7 ];

offset = 1;
mask = 1;

// all threads execute this code simultaneously:
for( int offset = 1; offset < numItems; offset *= 2 )
{
    int mask = 2*offset - 1;
    barrier( CLK_LOCAL_MEM_FENCE );  // wait for all threads to get here
    if( ( tnum & mask ) == 0 ) // bit-by-bit and’ing tells us which
{                              // threads need to do work now
        prods[ tnum ] += prods[ tnum + offset ];
    }
}

offset = 4;
mask = 7;

Thread #0:
prods[ 0 ] += prods[ 4 ];

Thread #8:
prods[ 8 ] += prods[ 10 ];

Thread #10:
prods[ 10 ] += prods[ 12 ];

offset = 8;
mask = 15;

// wait for all threads to get here
if( ( tnum & mask ) == 0 ) // bit-by-bit and’ing tells us which
{                          // threads need to do work now
        prods[ tnum ] += prods[ tnum + offset ];
}

Anding bits

Σ prods → C

And, Finally, in your Host Program

Wait( cmdQueue );
double time0 = omp_get_wtime( );

status = clEnqueueNDRangeKernel( cmdQueue, kernel, 1, NULL, globalWorkSize, localWorkSize, 0, NULL, NULL);
PrintCLError( status, "clEnqueueNDRangeKernel failed: " );

Wait( cmdQueue );
double time1 = omp_get_wtime( );

status = clEnqueueReadBuffer( cmdQueue, dC, CL_TRUE, 0, numWorkGroups*sizeof(float), hC, 0, NULL, NULL);
PrintCLError( status, "clEnqueueReadBuffer failed: " );

Wait( cmdQueue );

float sum = 0.;
for( int i = 0; i < numWorkgroups; i++ )
{
    sum += hC[ i ];
}
Reduction Performance
Work-Group Size = 32

Array Size (MegaNumbers)

GigaNumbers Multiplied and Reduced Per Second

0 50 100 150 200 250 300

0 1 2 3 4 5 6

Computer Graphics