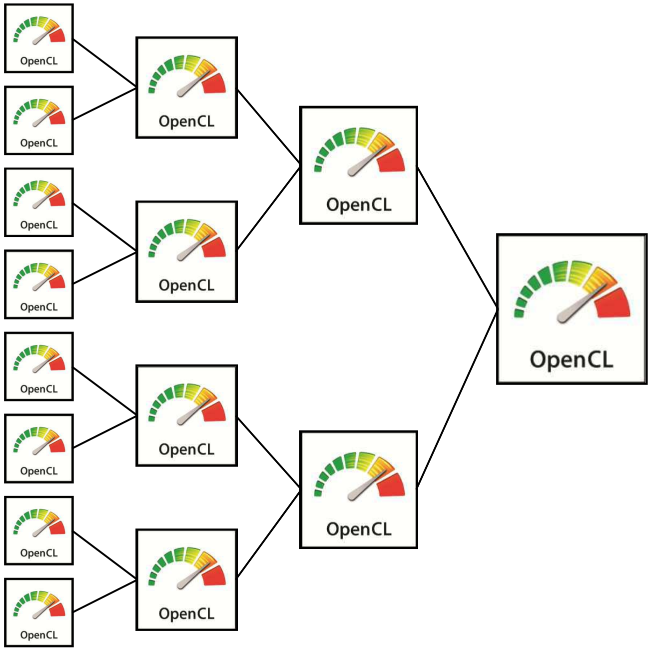
Performing Reductions in OpenCL (and CUDA)

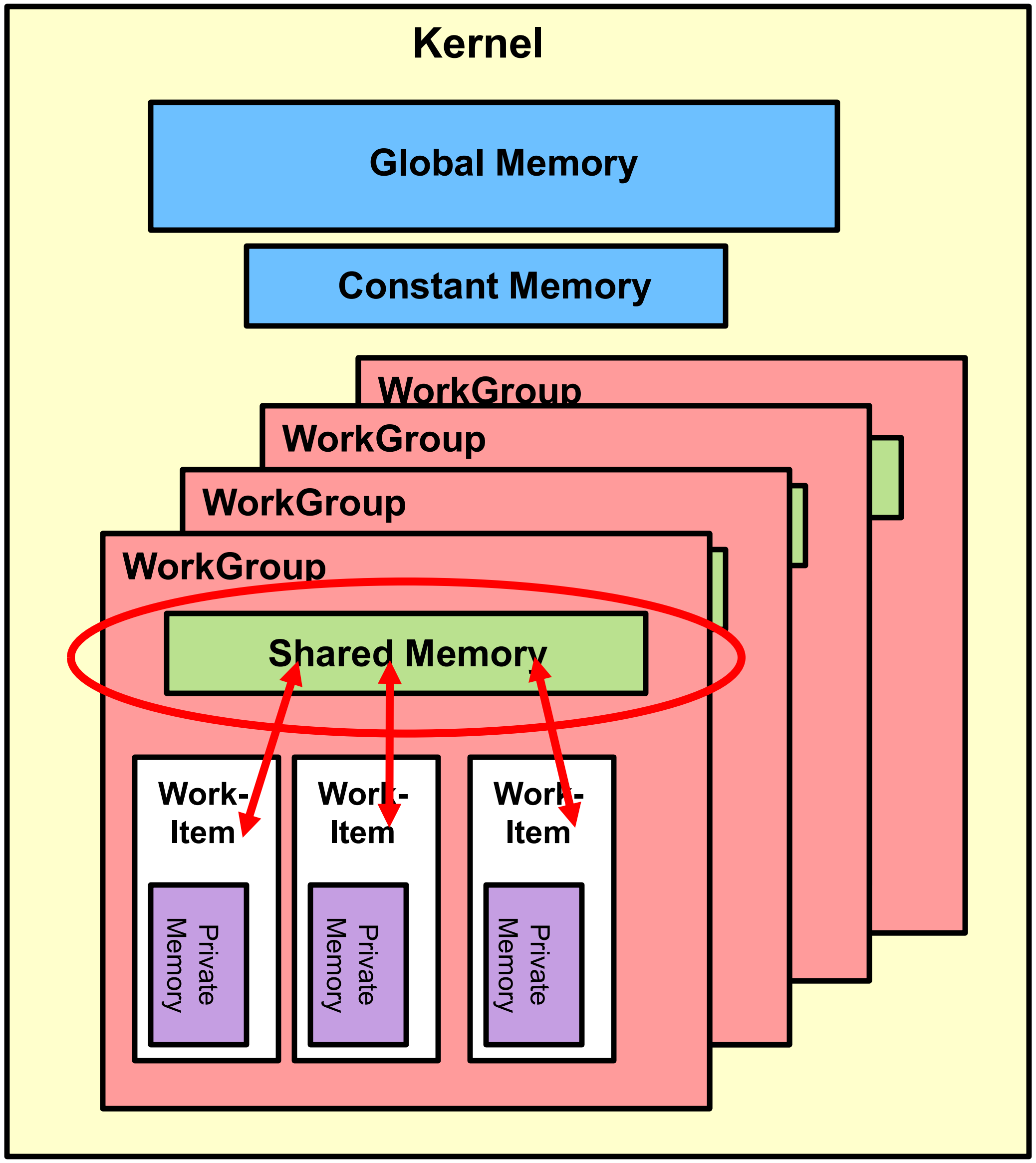
Mike Bailey

mjb@cs.oregonstate.edu

Oregon State University
Computer Graphics



Recall the OpenCL Memory Model



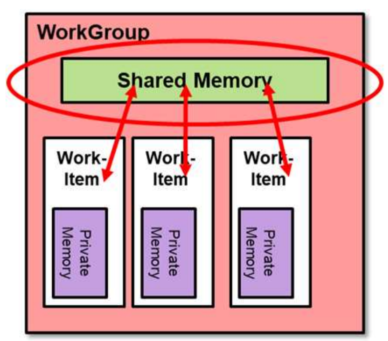
Here's the Problem We're Trying to Solve

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.

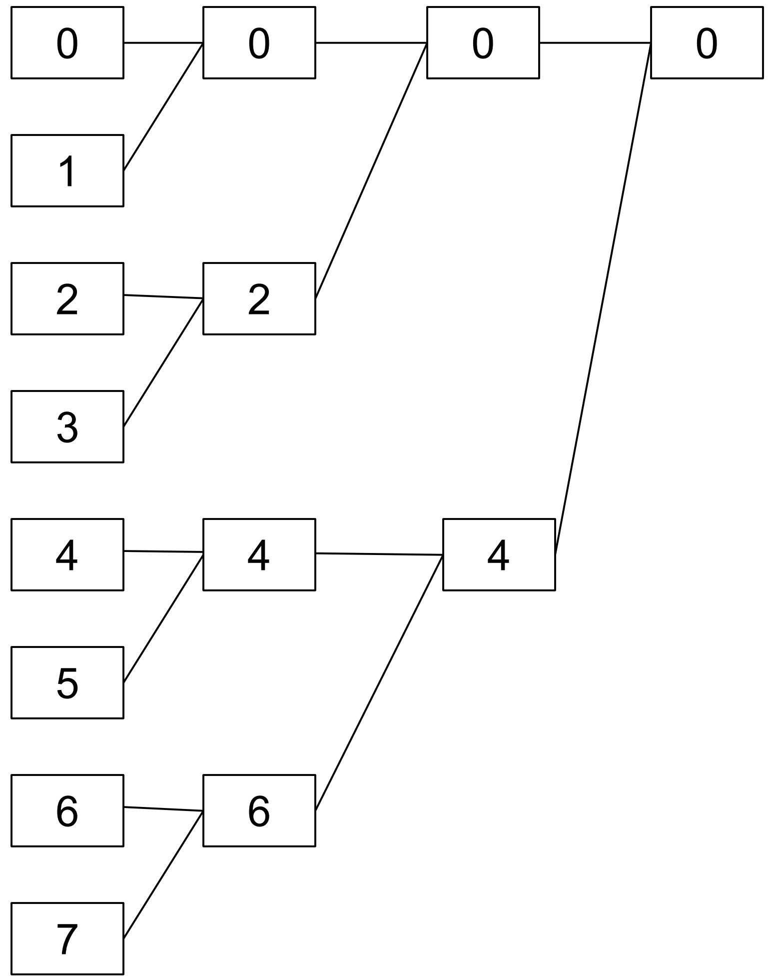
$$A * B \rightarrow \text{prods}$$
$$\sum \text{prods} \rightarrow C$$

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 **prods[ ]** array that is shared within its work-group.



numItems = 8;



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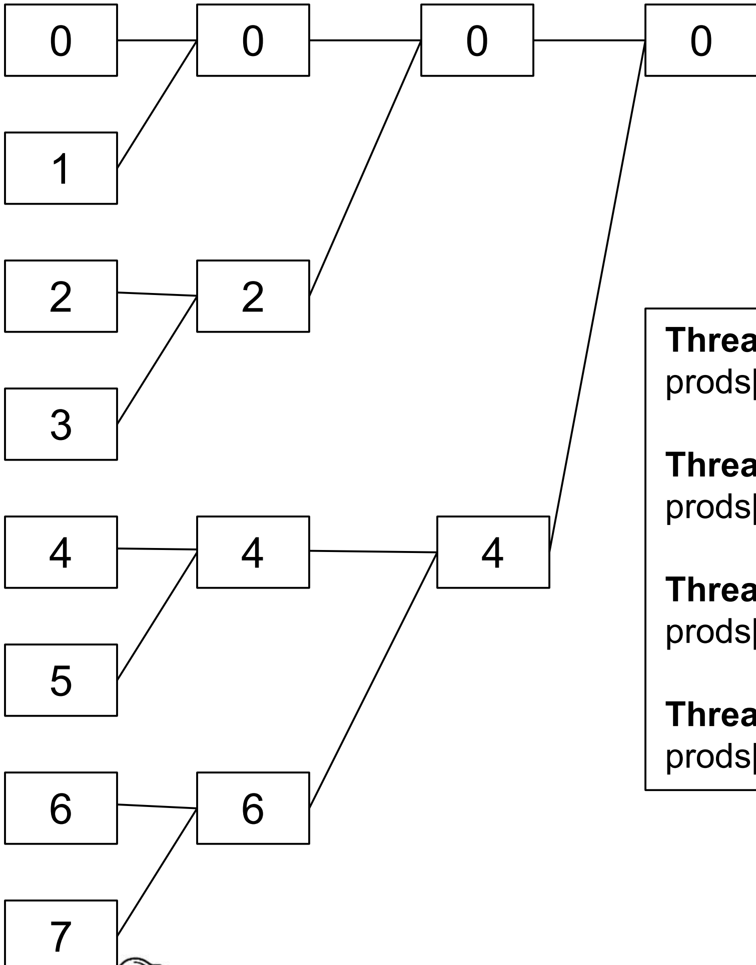
Reduction Takes Place in a Single Work-Group

numItems = 8;



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

Thread #0:
prods[0] += prods[1];
 	
Thread #2:
prods[2] += prods[3];
 	
Thread #4:
prods[4] += prods[5];
 	
Thread #6:
prods[6] += prods[7];
	Thread #0:
	prods[0] += prods[2];
	
	Thread #4:
	prods[4] += prods[6];
		Thread #0:
		prods[0] += prods[4];

. . . but in a more general way than writing them all out by hand.

Here’s What You Would Change in your Host Program

```
#define NUM_WORKGROUPS     ( NUM_ELEMENTS / LOCAL_SIZE )

// global variables:
float hA[ NUM_ELEMENTS ];
float hB[ NUM_ELEMENTS ];
float hC[NUM_WORKGROUPS ];
    • • •
size_t  abSize = NUM_ELEMENTS       * sizeof(float);
size_t    cSize = NUM_WORKGROUPS    * 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 );
```

$A * B \rightarrow$ prods

Σ prods $\rightarrow C$

"cl_mem" is a GPU buffer memory address

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

The Arguments to the Kernel

```
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 );
```

```
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

Reduction Takes Place Within 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;

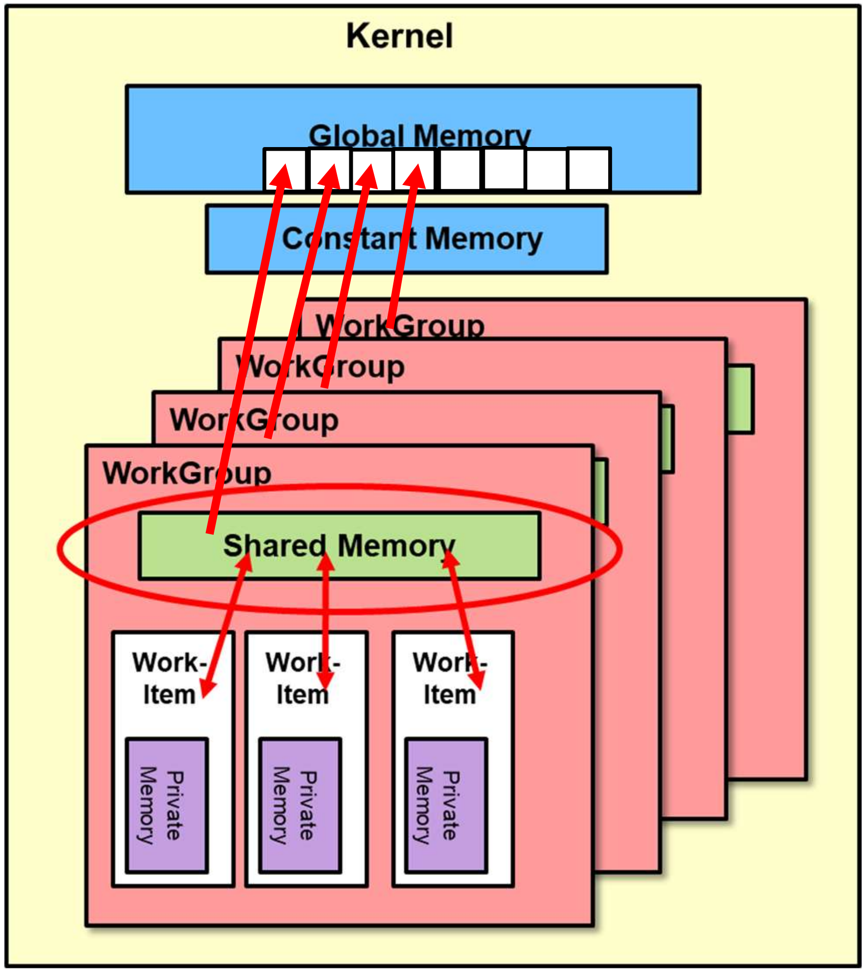
Thread #0:
prods[0] += prods[2];

Thread #4:
prods[4] += prods[6];

offset = 2;
mask = 3;

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

offset = 4;
mask = 7;



A work-group consisting of *numItems* work-items can be reduced to a sum in $log_2(numItems)$ 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*?

F & F	F & T	T & F	T & T
= F	= F	= F	= T

Or, with Bits:

0 & 0	0 & 1	1 & 0	1 & 1
= 0	= 0	= 0	= 1

Or, with Multiple Bits:

000 & 011	001 & 011	010 & 011	011 & 011	100 & 011	101 & 011
= 000	= 001	= 010	= 011	= 000	= 001

If it's been a long time since you have looked at bitmask operators (or never!), here is a good review reference:
https://en.wikipedia.org/wiki/Bitwise_operations_in_C

Reduction Takes Place in a Single *Work-Group*

Each *work-item* is run by a single thread

numItems = 8;

Thread #0:
prods[0] += prods[1];
 	
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prods[2] += prods[3];
 	
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prods[6] += prods[7];
	Thread #0:
	prods[0] += prods[2];
	
	Thread #4:
	prods[4] += prods[6];
		Thread #0:
		prods[0] += prods[4];

offset = 1; mask = 1;	offset = 2; mask = 3;	offset = 4; mask = 7;

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;

Thread #0:
prods[0] += prods[2];

Thread #4:
prods[4] += prods[6];

offset = 2;
mask = 3;

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

offset = 4;
mask = 7;

```
kernel void
ArrayMultReduce( … )
{
        int gid         = get_global_id( 0 );
        int numItems = get_local_size( 0 );
        int tnum        = get_local_id( 0 );     // thread number
        int wgNum     = get_group_id( 0 );   // work-group number

// all threads execute this code simultaneously:
        prods[ tnum ] =  dA[ gid ] * dB[ gid ];
        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 ];
                }
        }

        barrier( CLK_LOCAL_MEM_FENCE );
        if( tnum == 0 )
                dC[ wgNum ] = prods[ 0 ];
}
```

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, NUM_WORKGROUPS*sizeof(float), hC,
                                                        0, NULL, NULL );
PrintCLError( status, "clEnqueueReadBufferl failed: " );
Wait( cmdQueue );


float sum = 0.;
for( int i = 0; i < numWorkgroups; i++ )
{
                sum += hC[ i ];
}
```

Reduction Performance

Work-Group Size = 32