Using OpenCL™ 2.0 Work-group Functions

Tutorial

Intel® SDK for OpenCL™ Applications - Tutorial

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Among new OpenCL 2.0 features, several new and useful built-ins were introduced, called “work-group functions”. These built-ins provide popular parallel primitives that operate at the workgroup level. This article is a short introduction on work-group functions and their usage. It is also backed with some performance data gathered from Intel HD Graphics OpenCL device.

Work-group functions overview

For novice OpenCL programmers, the OpenCL 2.0 spec chapter dedicated to this topic might look too academic and full of formal notations. In short, work-group functions include three classic work-group level algorithms – **value broadcast**, **reduce**, and **scan**, plus two built-ins that evaluate boolean operation result over entire workgroup. **Reduce** and **scan** algorithms support **add**, **min** and **max** operations.

Functionality of work-group function built-ins is pretty obvious from their names:

- **work_group_broadcast()** built-in duplicates a value from the chosen workitem to all workitems of the workgroup
- **work_group_reduce()** group of built-ins evaluates **sum**, **min** or **max** among all items of workgroup, and then broadcasts it for every work item in the group
- **work_group_scan()** group of built-ins evaluates **sum**, **min** or **max** for all preceding work items, optionally including current
- **work_group_all()** returns logical AND over same boolean expression evaluated for every work-item
- **work_group_any()** is similar to work_group_all(), but logical OR is used instead

An important limitation about the listed built-ins is that they operate on scalar data types only (for example, popular int4 or float4 types are not supported). Also, 8-bit types such as char or uchar are not supported.

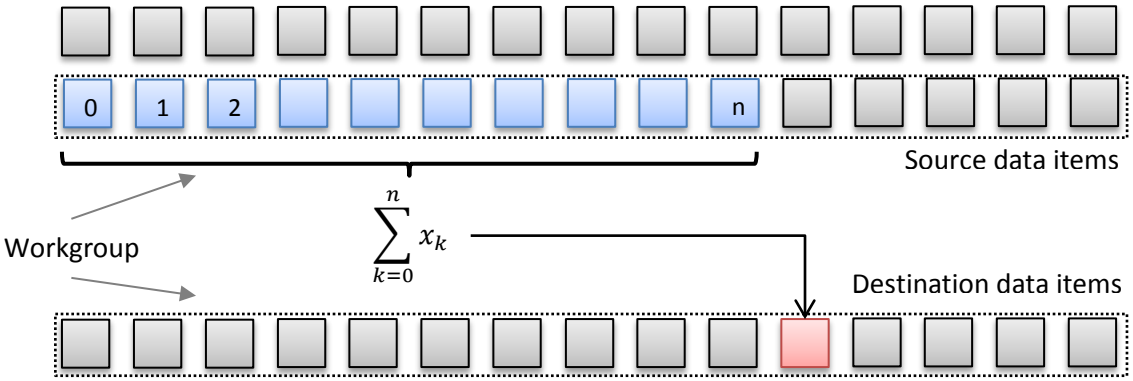
For a complete description, please see chapter 6.13.15 of OpenCL 2.0 C specification.

Work-group functions, as the name implies, always operate in parallel over entire work-group. An implicit consequence from this fact is that any work-group function call acts as a barrier.

Work-group functions usage brings two main benefits. First - work-group functions are convenient. It is much simpler to use a single built-in instead of a bulky piece of code that OpenCL 1.2 user has to write to implement such functionality. Second - work-group functions are more performance efficient, as they use hardware-specific optimizations internally.

Example

For illustration purposes, consider the following task (as a part of some algorithm)- computing prefix sums for equally-sized sub arrays of some larger array. So we have to compute prefix sum for every item of every sub array, and store it to destination memory of the same layout. The source and destination data layout is depicted on the scheme below:



A simple naïve OpenCL kernel for this task might work like this:

- every array (a line on the illustration) will be processed by single workgroup
- for every workitem scan is performed using just plain **for()** loop over preceding items, then cumulative prefix value is added, and finally the result stored to destination
- if workgroup size is smaller than input array for a workgroup, source and destination indices are shifted by workgroup size, cumulative prefix is updated, and process is repeated until the end of source line

The corresponding code is below:

```
__kernel void Calc_wg_offsets_naive(
                    __global const uint* gHistArray,
                    __global uint* gPrefixsumArray,
                    uint bin_size
                    )
{
   uint lid = get_local_id(0);
   uint binId = get_group_id(0);

   //calculate source/destination offset for workgroup
   uint group_offset = binId * bin_size;
   local uint maxval;

   //initialize cumulative prefix
   if( lid == 0 )  maxval = 0;
   barrier(CLK_LOCAL_MEM_FENCE);

   do
   {
      //perform a scan for every workitem
```

```
        uint prefix_sum=0;
        for(int i=0; i<lid; i++)
            prefix_sum += gHistArray[group_offset + i];

        //store result
        gPrefixsumArray[group_offset + lid] = prefix_sum + maxval;
        prefix_sum += gHistArray[group_offset + lid];

        //update group offset and cumulative prefix
        if( lid == get_local_size(0)-1 )  maxval += prefix_sum;
        barrier(CLK_LOCAL_MEM_FENCE);

        group_offset += get_local_size(0);
    }
    while(group_offset < (binId+1) * bin_size);
}
```

This naïve approach is very inefficient in most cases (except probably most tiny workgroup sizes). It is obvious that inner **for()** loop performs too many redundant loads and additions, which actually can be reused. And this redundancy will grow with growing workgroup size. To better utilize Intel HD Graphics hardware capabilities, we need a more work-efficient algorithm, such as Blelloch et al. We won't dive here into algorithm details, since it is perfectly described in classic GPU Gems article - http://http.developer.nvidia.com/GPUGems3/gpugems3_ch39.html.

OpenCL 1.2 code of this work-efficient parallel scan will look like following:

```
#define WARP_SHIFT 4
#define GRP_SHIFT 8
#define BANK_OFFSET(n)     ((n) >> WARP_SHIFT + (n) >> GRP_SHIFT)

__kernel void Calc_wg_offsets_Blelloch(__global const uint* gHistArray,
                        __global uint* gPrefixsumArray,
                        uint bin_size
                        ,__local uint* temp
                       )
{
    int lid = get_local_id(0);
    uint binId = get_group_id(0);
    int n = get_local_size(0) * 2;

    uint group_offset = binId * bin_size;
    uint maxval = 0;
    do
    {
        // calculate array indices and offsets to avoid SLM bank conflicts
        int ai = lid;
        int bi = lid + (n>>1);
        int bankOffsetA = BANK_OFFSET(ai);
        int bankOffsetB = BANK_OFFSET(bi);

        // load input into local memory
        temp[ai + bankOffsetA] = gHistArray[group_offset + ai];
```

```
        temp[bi + bankOffsetB] = gHistArray[group_offset + bi];

        // parallel prefix sum up sweep phase
        int offset = 1;
        for (int d = n>>1; d > 0; d >>= 1)
        {
            barrier(CLK_LOCAL_MEM_FENCE);
            if (lid < d)
            {
                int ai = offset * (2*lid + 1)-1;
                int bi = offset * (2*lid + 2)-1;
                ai += BANK_OFFSET(ai);
                bi += BANK_OFFSET(bi);
                temp[bi] += temp[ai];
            }
            offset <<= 1;
        }

        // clear the last element
        if (lid == 0)
        {
            temp[n - 1 + BANK_OFFSET(n - 1)] = 0;
        }

        // down sweep phase
        for (int d = 1; d < n; d <<= 1)
        {
            offset >>= 1;
            barrier(CLK_LOCAL_MEM_FENCE);

            if (lid < d)
            {
                int ai = offset * (2*lid + 1)-1;
                int bi = offset * (2*lid + 2)-1;
                ai += BANK_OFFSET(ai);
                bi += BANK_OFFSET(bi);

                uint t = temp[ai];
                temp[ai] = temp[bi];
                temp[bi] += t;
            }
        }
        barrier(CLK_LOCAL_MEM_FENCE);

        //output scan result to global memory
        gPrefixsumArray[group_offset + ai] = temp[ai + bankOffsetA] + maxval;
        gPrefixsumArray[group_offset + bi] = temp[bi + bankOffsetB] + maxval;

        //update cumulative prefix sum and shift offset for next iteration
        maxval += temp[n - 1 + BANK_OFFSET(n - 1)] + gHistArray[group_offset + n - 1];
        group_offset += n;
    }
    while(group_offset < (binId+1) * bin_size);
}
```

Generally, this code is more work-efficient and hardware-friendly, but it has its own caveats.

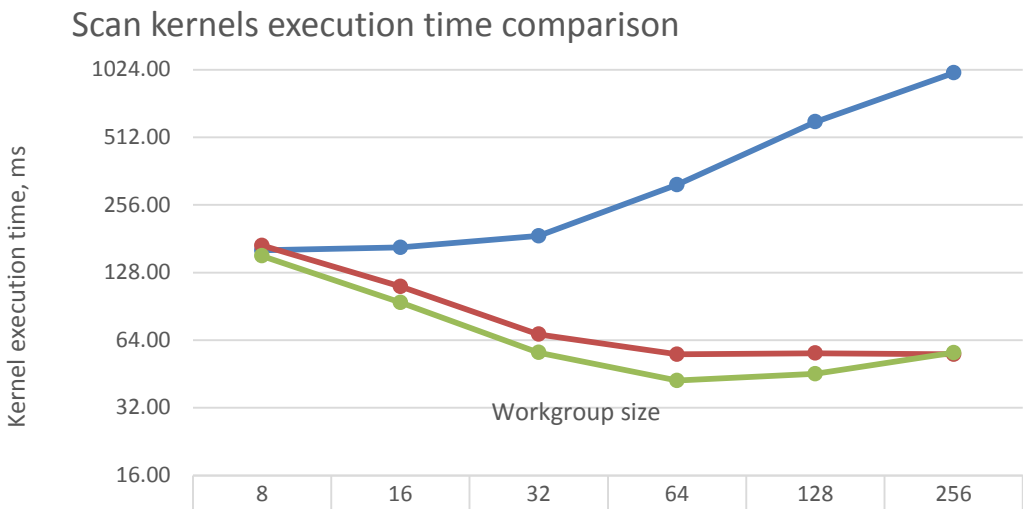
It introduces some overhead on data movement between local and global memory, plus multiple barriers. To amortize them and to be really efficient, this algorithm needs fairly large workgroup size. On tiny workgroup sizes (<16) it unlikely to deliver performance better than naïve loop.

Also note much increased code complexity and additional logic to avoid shared local memory bank conflicts (e.g. BANK_OFFSET macro).

Usage of workgroup functions overcomes all mentioned issues. Corresponding variant of optimized OpenCL code below:

```
__kernel void Calc_wg_offsets_wgf(
                    __global const uint* gHistArray,
                    __global uint* gPrefixsumArray,
                    uint bin_size
                    )
{
   uint lid = get_local_id(0);
   uint binId = get_group_id(0);

   uint group_offset = binId * bin_size;
   uint maxval = 0;

   do
   {
      uint binValue = gHistArray[group_offset + lid];
      uint prefix_sum = work_group_scan_exclusive_add( binValue );
      gPrefixsumArray[group_offset + lid] = prefix_sum + maxval;

      maxval += work_group_broadcast( prefix_sum + binValue, get_local_size(0)-1 );

      group_offset += get_local_size(0);
   }
   while(group_offset < (binId+1) * bin_size);
}
```

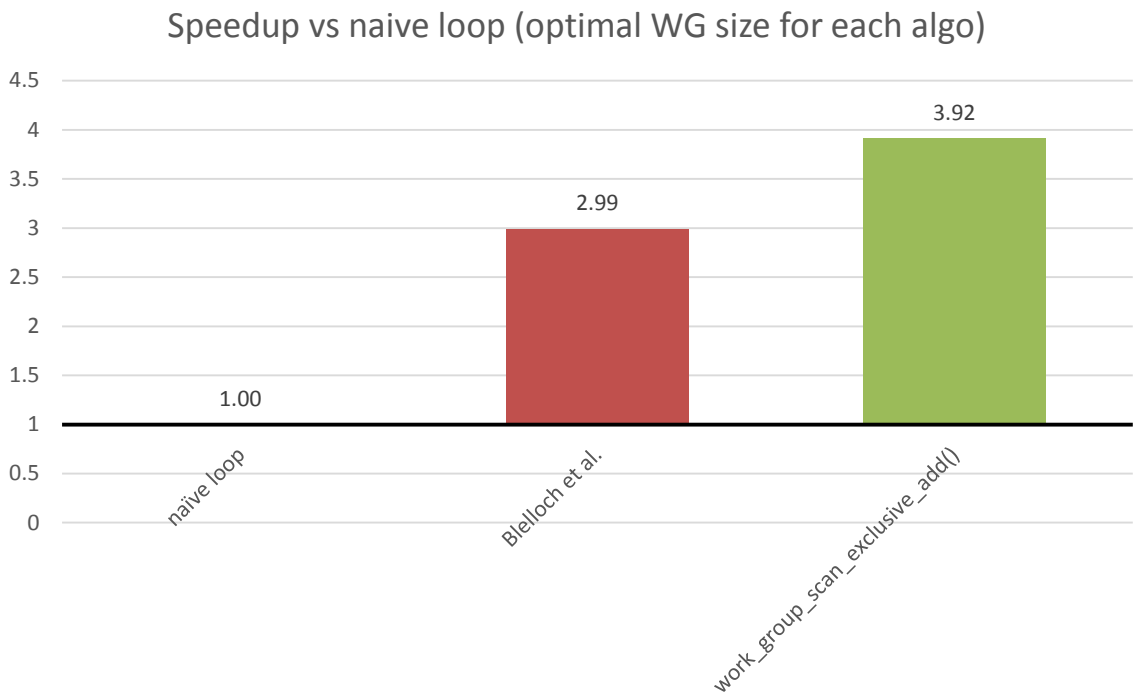
Performance results from both optimizations are measured on fairly large input data (each workgroup scans 65536 items, which corresponds to 8192 … 2048 outer loop iterations, depending on local size):



	8	16	32	64	128	256
naïve loop	160.71	165.64	186.23	314.84	599.30	990.50
Blelloch et al.	168.92	110.95	67.92	55.33	56.04	55.33
work_group_scan_exclusive_add()	151.69	94.20	56.40	42.30	45.31	56.25

As expected, naïve loop performs much worse with growing local size, while both optimized variants improve.

If workgroup size will be set to optimal for given algorithm, kernels comparison will look like this:



Notice how `work_group_scan_exclusive_add()` usage significantly improves performance on any workgroup size, while simultaneously simplifying the code.

Conclusion

Work-group functions addition is an important step forward with OpenCL 2.0 spec, equipping OpenCL developers with new great built-ins. Clever usage of this new feature can save a significant amount of investments in development of complex and performance-efficient OpenCL applications.