Wavefront Parallel Processing on GPUs with an Application to Video Encoding Algorithms

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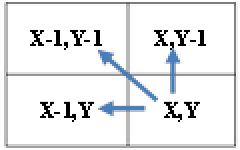
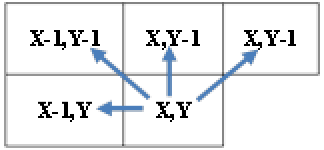
Wavefront Parallel Processing (WPP)

- Efficient Parallel Processing technique for problems characterized by specific patterns of data dependencies across an n-dimension grid
- Patterns referred to as Wavefront Dependency Patterns



45° dependencies



26° dependencies

- Key observations:
  - Data dependencies satisfied by ordered traversals along diagonals a.k.a *wavefronts*
  - Independent computations in a wavefront

0,0 [0]	1,0 [1]	2,0 [2]	3,0 [3]	4,0 [4]	5,0 [5]	6,0 [6]
0,1 [1]	1,1 [2]	2, 1 [3]	3, 1 [4]	4, 1 [5]	5, 1 [6]	6,1 [7]
0,2 [2]	1,2 [3]	2, 2 [4]	3, 2 [5]	4, 2 [6]	5, 2 [7]	6,2 [8]
0,3 [3]	1,3 [4]	2, 3 [5]	3, 3 [6]	4, 3 [7]	5, 3 [8]	6,3 [9]
0,4 [4]	1,4 [5]	2, 4 [6]	3, 4 [7]	4, 4 [8]	5, 4 [9]	6,4 [10]
0,5 [5]	1,5 [6]	2, 5 [7]	3, 5 [8]	4, 5 [9]	5, 5 [10]	6,5 [11]

45° wavefront traversal

0,0 [0]	1,0 [1]	2,0 [2]	3,0 [3]	4,0 [4]	5,0 [5]	6,0 [6]
0,1 [2]	1, 1 [3]	2, 1 [4]	3, 1 [5]	4, 1 [6]	5, 1 [7]	6,1 [8]
0,2 [4]	1, 2 [5]	2, 2 [6]	3, 2 [7]	4, 2 [8]	5, 2 [9]	6,2 [10]
0,3 [6]	1, 3 [7]	2, 3 [8]	3, 3 [9]	4, 3 [10]	5, 3 [11]	6,3 [12]
0,4 [8]	1, 4 [9]	2, 4 [10]	3, 4 [11]	4, 4 [12]	5, 4 [13]	6,4 [14]
0,5 [10]	1, 5 [11]	2, 5 [12]	3, 5 [13]	4, 5 [14]	5, 5 [15]	6,5 [16]

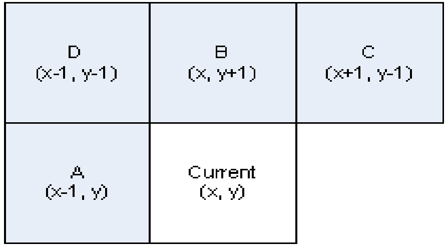
26° wavefront traversal

Applications Of WPP

- Scientific algorithms based on dynamic programming – Smith-Waterman for genome sequencing
  - Large grids & less computation at grid points
- Modern video encoding algorithms – AVC & HEVC
  - Small grids & much computation at grid points
- Image analysis – Morphological Reconstruction
  - Large grids & dynamic dependencies at grid points

-	-	A	T	C	G	A	A
-	0	0	0	0	0	0	0
C	0	0	0	5	1	0	0
A	0	5	1	1	2	5	5
T	0	1	10	6	2	1	2
A	0	5	6	7	3	7	6
C	0	1	2	11	7	3	4

Smith-Waterman sequence alignment



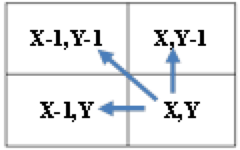
Differential encoding of motion vectors in video encoding

Video Encoding Algorithms

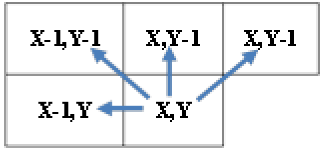
- Video encoding algorithms exploit temporal (inter frame) and spatial (intra frame) similarities across and within frames
- Modern video encoding algorithms employ block based video motion estimation (VME) to do this
- Dominant compute intensive component
- Critical to efficiently extract parallelism for performance
- Exhibits 26˚ and 45˚ wavefront patterns for *“Predicted Motion Vector”* (PMV) and *“Most Probable Mode”* (MPM)

[4]

Inter and Intra frame motion estimation

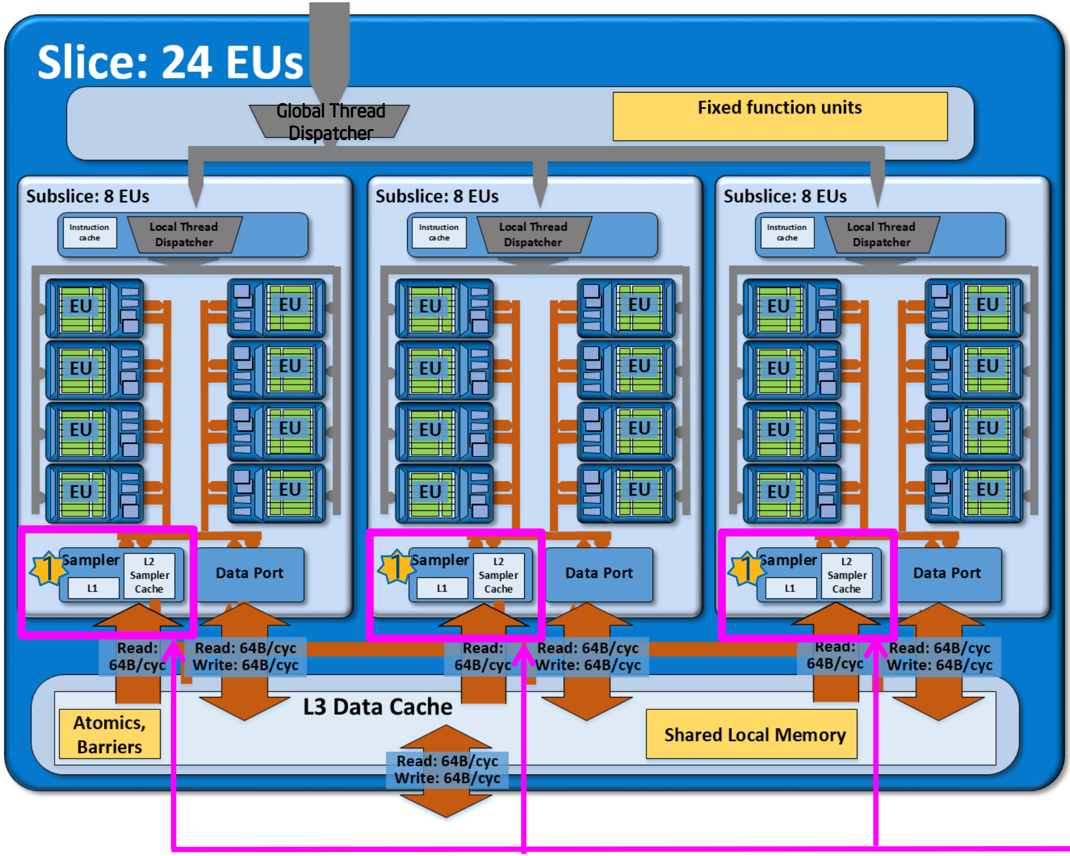


45° dependencies



26° dependencies

Intel® Graphics 530 GPU Architecture



Sub-slice

- SLM shared by sub-slice EU threads
- Barrier synchronization in sub-slice
- One VME engine

Programmable VME Engine

- Optimized for memory bandwidth
- Provides configurable raw compute
- Smarts in the hands of the programmer

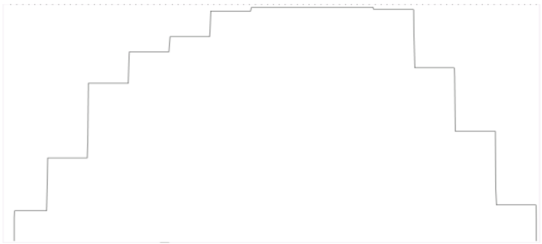
1 Powerful Video Motion Estimation (VME) Engine in Sampler

OpenCL SW Interface

- Device-side VME vendor extension - exposes programmable VME functionality in GPU
- Set of built-in functions **callable from user written OpenCL kernels** – maps closely with exposed HW interface
    - Essentially provides a very low-level motion estimation library with a underlying HW implementation – think of it as Inter Performance Primitives (IPP).
- Subgroups functions for block API

Challenges with WPP on GPUs with OpenCL

- Challenges with synchronization between WGs
  - GPU schedulers not particularly designed to handle dependencies across work-groups (WGs)
  - OpenCL spec allows launch order of WGs to be implementation specific
  - Non-preemptable nature of WGs
- Challenges with expanding and contracting parallelism
  - Not having enough compute to saturate machine
  - Idle polling

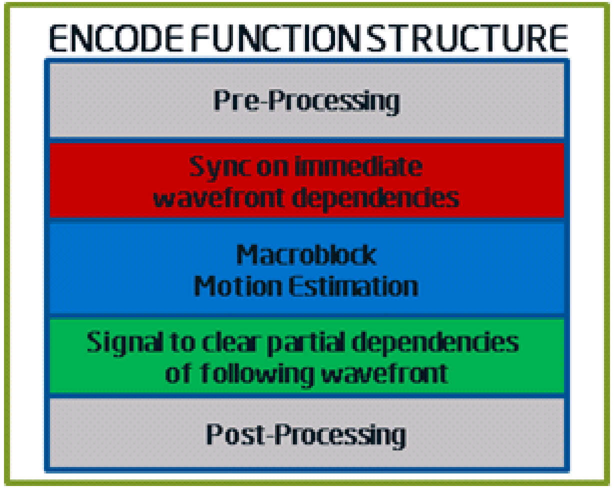


Plot of parallelism as wavefront progresses

IMPLEMENTED SOLUTIONS

Implemented Solutions

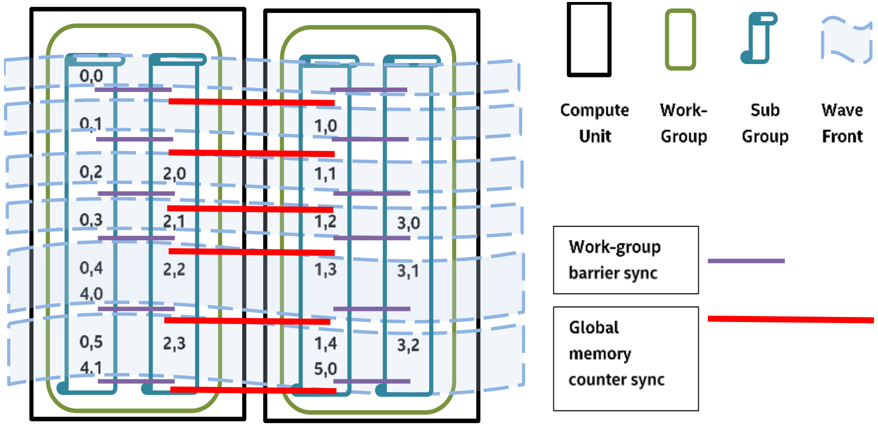
- Four WPP OpenCL solutions implemented and evaluated on Intel® Processor Graphics (Intel® Graphics 530)
  - Same basic encode kernel structure
    - Uses custom global memory barriers
    - No data dependencies for pre and post-processing stages
    - Per Amdahl's law the Motion Estimation stage is the performance critical part
    - Pre and post-processing part move work out of the performance critical part
  - Up to 9 forward reference frames searched per MB.
  - VME operations leveraged through Intel OpenCL device-side VME extensions



- Major considerations
  - Maximally utilize achievable parallelism
  - Efficient synchronization

Persistent Threads with Distributed Wavefront Sweep

- Subgroups active for entire kernel duration – w/a launch order issues
- One work-group runs on a compute unit
- Maximal launch of subgroups
- Work-queues process ordered wavefronts
- Subgroups with work-group sync efficiently using barriers
- Inter work-group sync using global memory counter
- Efficient sync



0,0 [0]	1,0 [1]	2,0 [2]	3,0 [3]	4,0 [4]	5,0 [5]	6,0 [6]
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0,2 [2]	1,2 [3]	2, 2 [4]	3, 2 [5]	4, 2 [6]	5, 2 [7]	6,2 [8]
0,3 [3]	1,3 [4]	2, 3 [5]	3, 3 [6]	4, 3 [7]	5, 3 [8]	6,3 [9]
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0,5 [5]	1,5 [6]	2, 5 [7]	3, 5 [8]	4, 5 [9]	5, 5 [10]	6,5 [11]

45˚ wavefront data distribution

Persistent Threads with Distributed Wavefront Sweep

```
void poll(__global atomic_int* counter, int threshold) {
    int entry = threshold - 1;
    // Only one representative work-item from representative subgroup
    // needs to poll.
    if (get_sub_group_local_id()==0&&  get_sub_group_id() == 0) {
        while (entry != threshold) {
            entry = atomic_load_explicit(
                counter, memory_order_acquire, memory_scope_device);
        }
    }
   work_group_barrier(CLK_LOCAL_MEM_FENCE);
}

void signal(__global atomic_int* counter) {
    // Only one representative work-item from representative subgroup
    // needs to signal.
    if (get_sub_group_local_id() == 0) {
        atomic_fetch_add_explicit(
            counter, 1, memory_order_acq_rel, memory_scope_device);
    }
}
```

Synchronization functions

- OpenCL 2.0 memory model atomics needed to guarantee correctness
  - Polls with acquire semantics
  - Signal with acquire-release semantics
  - Writes from subgroups signaling a counter update need to be visible in subgroups polling for the same counter update
- Major drawback is inability to extract partial parallelism across wavefronts.

Persistent Threads with Cyclic Computation

- Data partitioned into unit intervals along an axis and assigned to persistent threads in round-robin
- Only works if no forward dependency across intervals
- For 45° wavefront, cyclic distribution along x or y axis
- For 26° wavefront, cyclic distribution only along y because of top-right dependency
- Persistent threads - one subgroup per WG

WG0	WG1	WG2	WG3	WG0	WG1	WG2
0,0 [0]	1,0 [1]	2,0 [2]	3,0 [3]	4,0 [4]	5,0 [5]	6,0 [6]
0,1 [1]	1,1 [2]	2, 1 [3]	3, 1 [4]	4, 1 [5]	5, 1 [6]	6,1 [7]
0,2 [2]	1,2 [3]	2, 2 [4]	3, 2 [5]	4, 2 [6]	5, 2 [7]	6,2 [8]
0,3 [3]	1,3 [4]	2, 3 [5]	3, 3 [6]	4, 3 [7]	5, 3 [8]	6,3 [9]
0,4 [4]	1,4 [5]	2, 4 [6]	3, 4 [7]	4, 4 [8]	5, 4 [9]	6,4 [10]
0,5 [5]	1,5 [6]	2, 5 [7]	3, 5 [8]	4, 5 [9]	5, 5 [10]	6,5 [11]

1-step intervals

45° wavefront data distribution

WG0	0,0 [0]	1,0 [1]	2,0 [2]	3,0 [3]	4,0 [4]	5,0 [5]	6,0 [6]
WG1	0,1 [2]	1, 1 [3]	2, 1 [4]	3, 1 [5]	4, 1 [6]	5, 1 [7]	6,1 [8]
WG2	0,2 [4]	1, 2 [5]	2, 2 [6]	3, 2 [7]	4, 2 [8]	5, 2 [9]	6,2 [10]
WG3	0,3 [6]	1, 3 [7]	2, 3 [8]	3, 3 [9]	4, 3 [10]	5, 3 [11]	6,3 [12]
WG0	0,4 [8]	1, 4 [9]	2, 4 [10]	3, 4 [11]	4, 4 [12]	5, 4 [13]	6,4 [14]
WG1	0,5 [10]	1, 5 [11]	2, 5 [12]	3, 5 [13]	4, 5 [14]	5, 5 [15]	6,5 [16]

2-step intervals

26° wavefront data distribution

Persistent Threads with Cyclic Computation

```
int2 mbid = { get_group_id(0), 0 };
do {
  int2 imgsize = get_image_dim(srcimg);
  int2 framembsize = (imgsize + (int2)(15, 15)) / 16;
   preprocess(…);
   if (mbid.x > 0) {
       poll(scoreboard + mbid.x - 1, mbid.y + 1);
   }
   if (!skip_block) {
       block_motion_estimate_process(...);
   }
   signal(scoreboard + mbid.x);
   postprocess(…); mbid.y += 1;
   // Cycle computation in interval
   if (mbid.y == framembsize.y) {
       mbid.y = 0; mbid.x += get_num_groups(0);
   }
 } while (mbid.x < framembsize.x);
```

Poll neighbor interval counter

Signal current interval counter

Cyclic computation of wavefronts

- Subgroups process intervals
- Synch using global memory counters – one per WG
- Similar pair of sync functions
- Enables overlapped partial execution of multiple wavefronts
- Drawback is not having enough threads to saturate GPU for lower resolutions

Distributed Computation of Wavefronts

- Similar to cyclic computation approach
- Proposed extension for OpenCL runtime to fill GPU deterministically using pre-defined pattern
  - *reqd_launch_pattern(pattern)*
  - ‘native’ or ‘raster’, or ‘custom’ patterns
- Eliminates cycling step
- Enables WG-level pre-emption if in an environment with context switch latency requirements

WG0	WG1	WG2	WG3	WG4	WG5	WG6
0,0 [0]	1,0 [1]	2,0 [2]	3,0 [3]	4,0 [4]	5,0 [5]	6,0 [6]
0,1 [1]	1,1 [2]	2, 1 [3]	3, 1 [4]	4, 1 [5]	5, 1 [6]	6,1 [7]
0,2 [2]	1,2 [3]	2, 2 [4]	3, 2 [5]	4, 2 [6]	5, 2 [7]	6,2 [8]
0,3 [3]	1,3 [4]	2, 3 [5]	3, 3 [6]	4, 3 [7]	5, 3 [8]	6,3 [9]
0,4 [4]	1,4 [5]	2, 4 [6]	3, 4 [7]	4, 4 [8]	5, 4 [9]	6,4 [10]
0,5 [5]	1,5 [6]	2, 5 [7]	3, 5 [8]	4, 5 [9]	5, 5 [10]	6,5 [11]

1-step wavefronts

45˚ wavefront data distribution

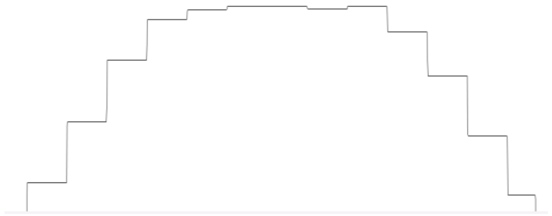
WG0	0,0 [0]	1,0 [1]	2,0 [2]	3,0 [3]	4,0 [4]	5,0 [5]	6,0 [6]
WG1	0,1 [2]	1, 1 [3]	2, 1 [4]	3, 1 [5]	4, 1 [6]	5, 1 [7]	6,1 [8]
WG2	0,2 [4]	1, 2 [5]	2, 2 [6]	3, 2 [7]	4, 2 [8]	5, 2 [9]	6,2 [10]
WG3	0,3 [6]	1, 3 [7]	2, 3 [8]	3, 3 [9]	4, 3 [10]	5, 3 [11]	6,3 [12]
WG4	0,4 [8]	1, 4 [9]	2, 4 [10]	3, 4 [11]	4, 4 [12]	5, 4 [13]	6,4 [14]
WG5	0,5 [10]	1, 5 [11]	2, 5 [12]	3, 5 [13]	4, 5 [14]	5, 5 [15]	6,5 [16]

2-step wavefronts

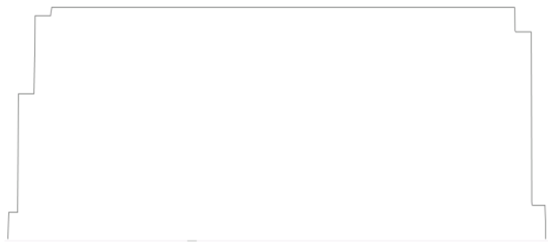
26˚ wavefront data distribution

Persistent Threads with Cyclic Computation of Multiple Independent Wavefronts

- Enhancement of basic cyclic computation to address key drawbacks
  - Unable to saturate GPU for smaller frames
  - Lesser parallelism during wavefront expansion/contraction phases
- Process multiple independent wavefronts
  - from independent encode streams, or
  - from independent slices within same stream
  - we chose 3 wavefronts from different streams



Plot of parallelism as single wavefront progresses



Plot of parallelism with multiple wavefronts

Persistent Threads with Cyclic Computation of Multiple Independent Wavefronts

```
int2 mbid = { 0, get_sub_group_id() };
int2 imgsize = get_image_dim(src0img);
int2 framembsize = (imgsize + (int2)(15, 15)) / 16;
do {
   preprocess(…);
   if (mbid.y > 0) {
      uint threshold = mbid.x + wavefront_step_size;
      threshold = (threshold>framembsize.x)? framembsize.x: threshold;
      poll(scoreboard + mbid.y - 1, threshold, mbid);
   }
   if (get_group_id(0) == 0) {
      if (!skip_block[0])  block_motion_estimate_process(..., src0img, ...)
   } else if (get_group_id(0) == 1) {
      if (!skip_block[1])  block_motion_estimate_process(..., src1img, ...)
   } else if (get_group_id(0) == 2) {
      if (!skip_block[2])   block_motion_estimate_process(..., src2img, ...)
   }
   signal(scoreboard + mbid.y);
   postprocess(…); mbid.x += 1;
   if (mbid.x == framembsize.x) {
      mbid.x = 0;  mbid.y += get_num_sub_groups();
   }
} while (mbid.y < framembsize.y);
```

Poll wavefront neighbor thread counter

Signal wavefront current thread counter

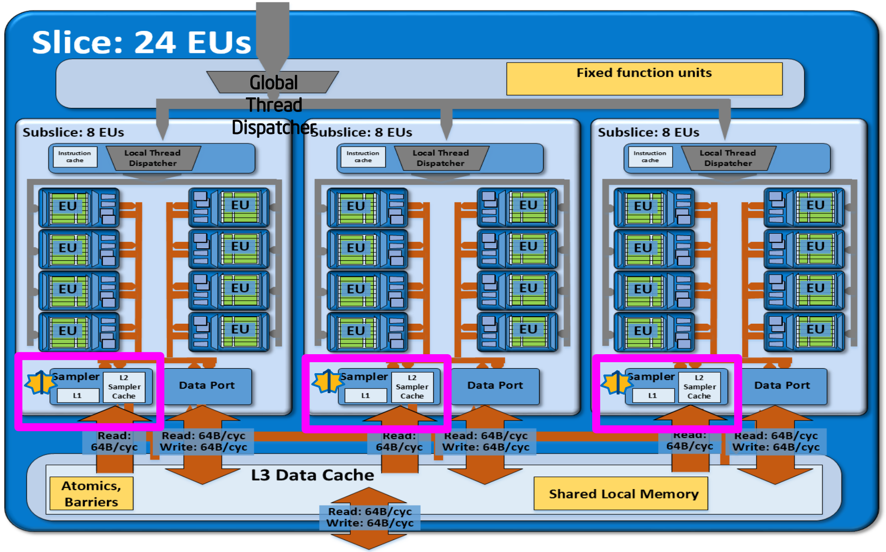
Cyclic computation of multiple independent wavefronts

- Scaled version of basic cyclic approach
  - One persistent WG processing intervals from one set of independent wavefronts
  - Three WGs
  - Maximal launch of subgroups in WGs
- Difference global counters across WGs for sync
- Other benefits
  - Better L1/L2 sampler cache locality

PERFORMANCE EVALUATIONS

Performance Evaluation – Experiment Setup

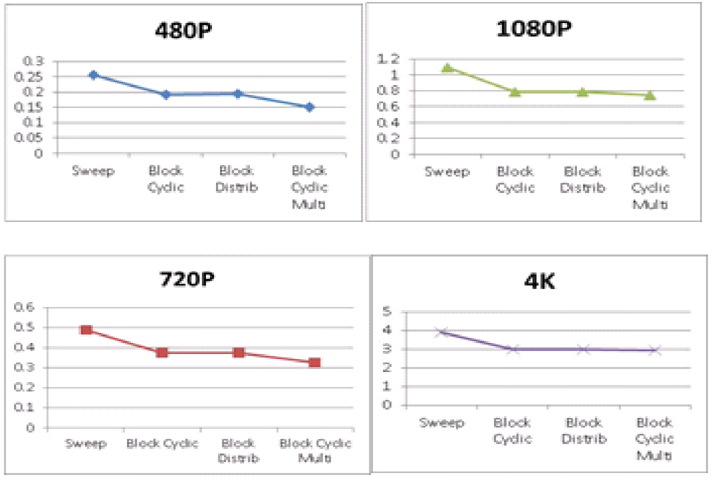
- Key performance metrics
  - GPU execution time per frame
    - Overall performance
  - VME engine busyness
    - Parallelism extracted
  - Count of atomic operations
    - Efficiency of sync



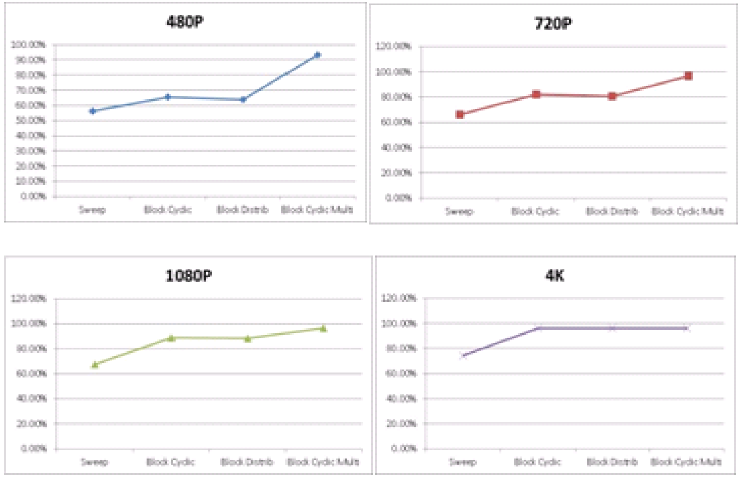
Intel® Graphics 530 Architecture

- Test sequences
  - 480p (858x480), 72-p (1280x720), 1080p (1920x1080), 4k (3840x2160)
    - 15 planar YUV frames
- Force max workgroup size to be 896

Performance Evaluation – Key Observations



GPU execution times comparison

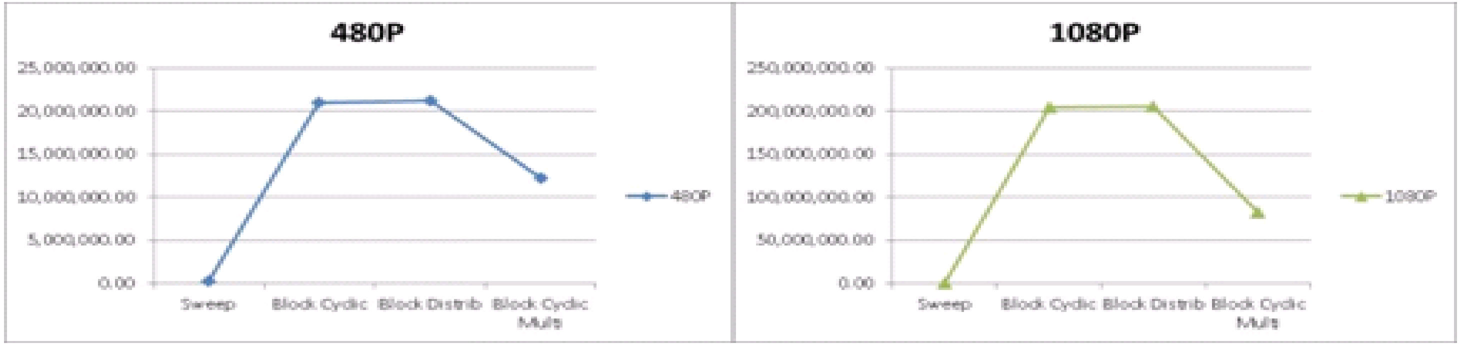


GPU media samples busyness comparison

- Distributed wavefront sweep performed poorly despite most efficient sync
  - Low sampler utilization
  - Extracting parallelism more important
- Cyclic & Distributed computation solutions performed identically

- Multiple independent wavefront solution performed best specially for lower resolutions
  - For 480p 21% over basic cyclic solution; sampler utilization up to 96% from 65%
  - For 4K no noticeable improvement over basic

Performance Evaluation – Key Observations



GPU atomic operation comparison

- Distributed wavefront sweep performed most efficient sync as expected
- Cyclic & Distributed computation solutions had quite of but of idle polling and bandwidth utilization
- Multiple independent wavefront solution performed well
  - Lesser threads per independent wavefront; but enough to keep sampler busy
  - Ergo lesser idle polling load per set of global sych counters

SUMMARY

Summary

- Background and Challenges with WPP on GPUs
- Evaluated 4 WPP solutions for video encoding on Intel® Processor Graphics
  - Cost of sync is not as significant when compared to the efficiency of extracting parallelism
  - Efficiency of sync improved by running just as many threads to keep the VME engine busy
  - Cyclic computation with multiple independent wavefronts solution performed best overall particularly for 720p resolutions and below
  - In cases where only one encode stream is available basic cyclic computation solution is recommended unless multi-slice is an option

Acknowledgements

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