

# CS475: Project 5

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## OpenCL Array Multiply, Multiply-Add, and Multiply-Reduce

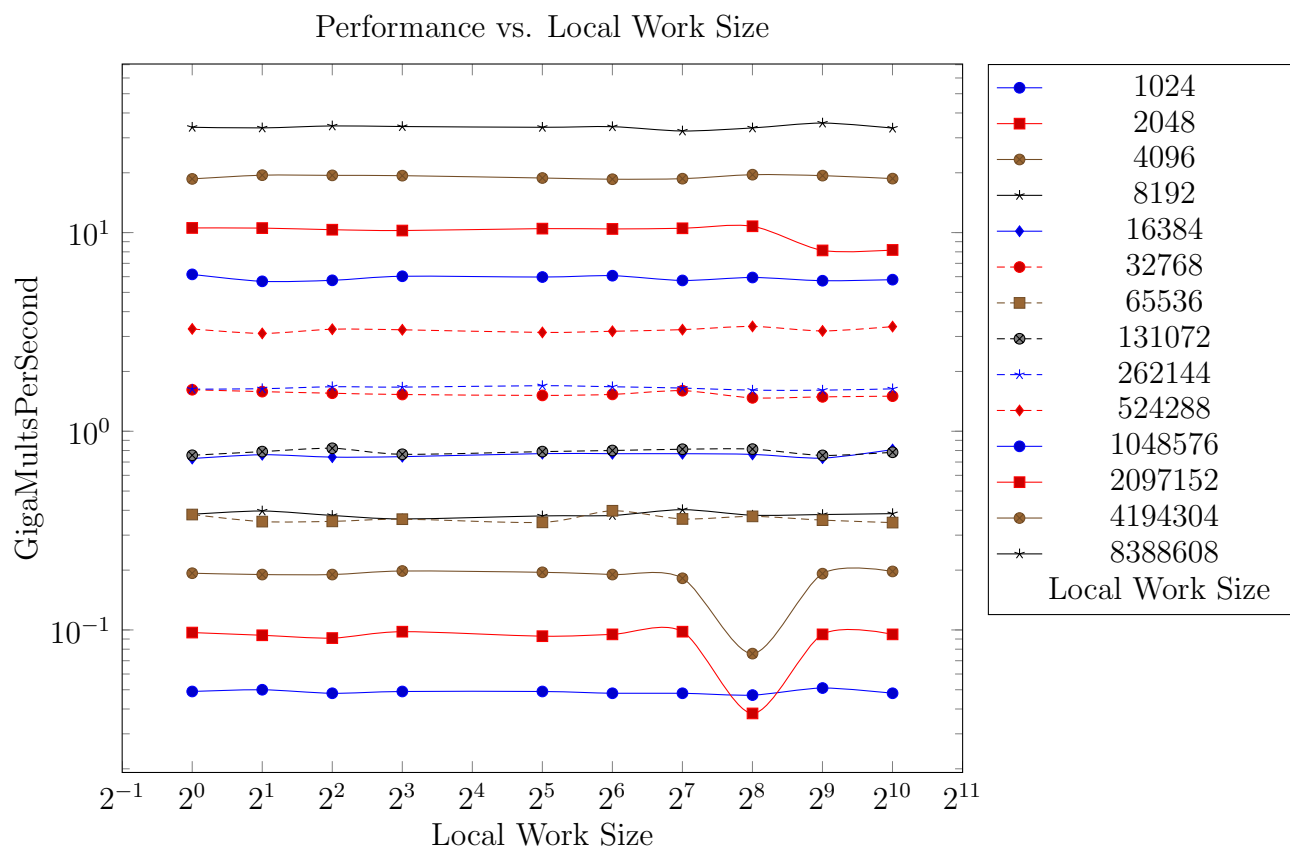
This assignment was compiled on my laptop, a Thinkpad W540 with 8 CPUs (1 sockets, 4 cores, 2 threads per core) and a Nvidia Quadro K1100M.

I had three major problems getting my program to compile and run:

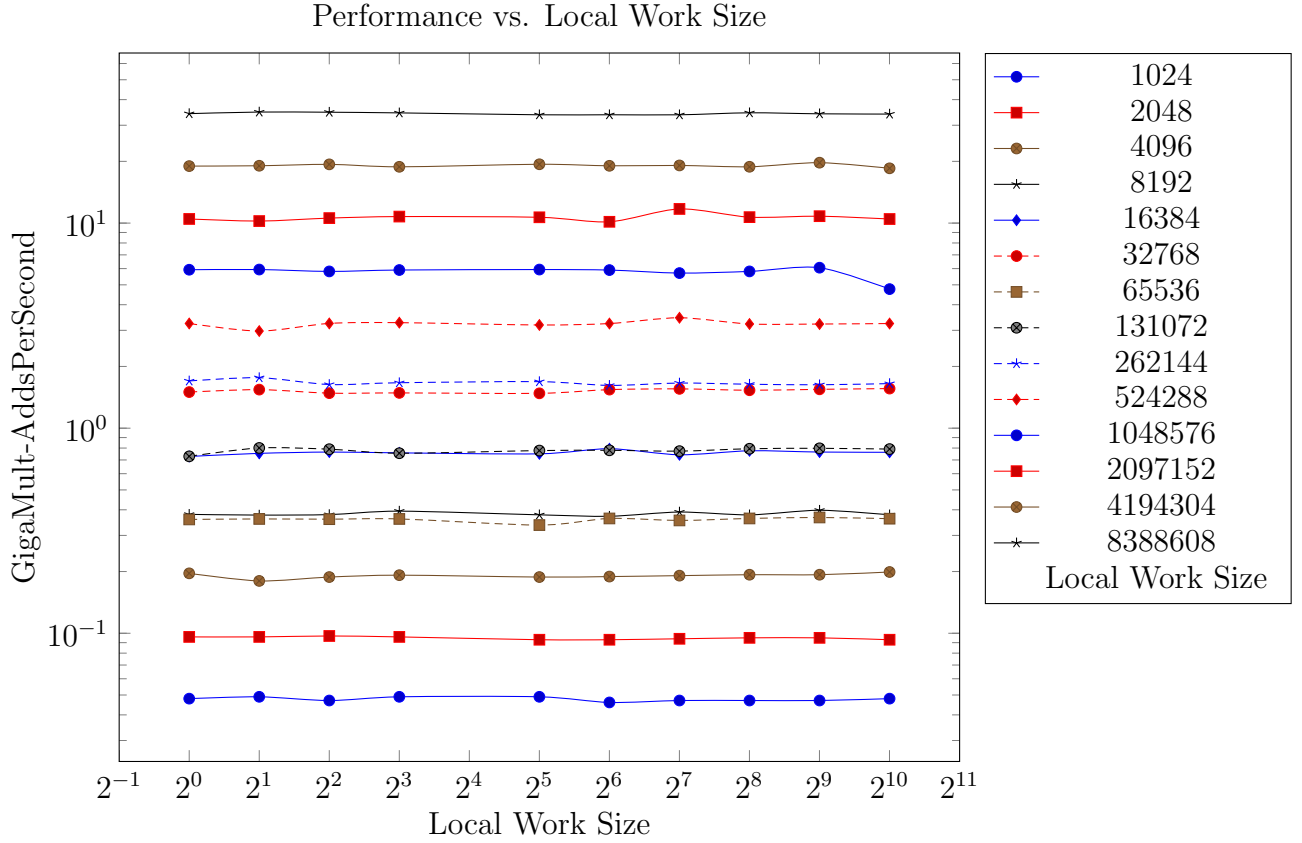
- Proprietary Graphics Though the Nvidia Quadro K1100M supports OpenCL, from my experience the open source drivers do not. There may be CUDA drivers, or an OpenCL SDK in a seperate package, but they are bundled with the open source driver, nor is there any solid information online regarding getting OpenCL working with the open source drivers.
- Link Flags My C programming knowledge is limited, and a lot of time was spent trying to gcc to link the program against the OpenCL library. This most likely worked from the beginning, and my issues was merely having the link flags before the source file, instead of after.
- Multiple GPUs (Bumblebee) The W540 Thinkpad actually contains two GPUs: an integrated Intel graphics processor, and the Quadro K1100M. The printinfo command showed both cards, with only the Quadro supporting OpenCL. I had to change the first.cpp file to query for both devices, and use the second (Quadro) one.

After these hurdles I was able to compile, run, and received data from the program. I did not have time to look into Multiply-reductions, nor was I able to fit everything into two graphs. The graph issue is due to me having too much data.

# Graph: Multiply (Local)

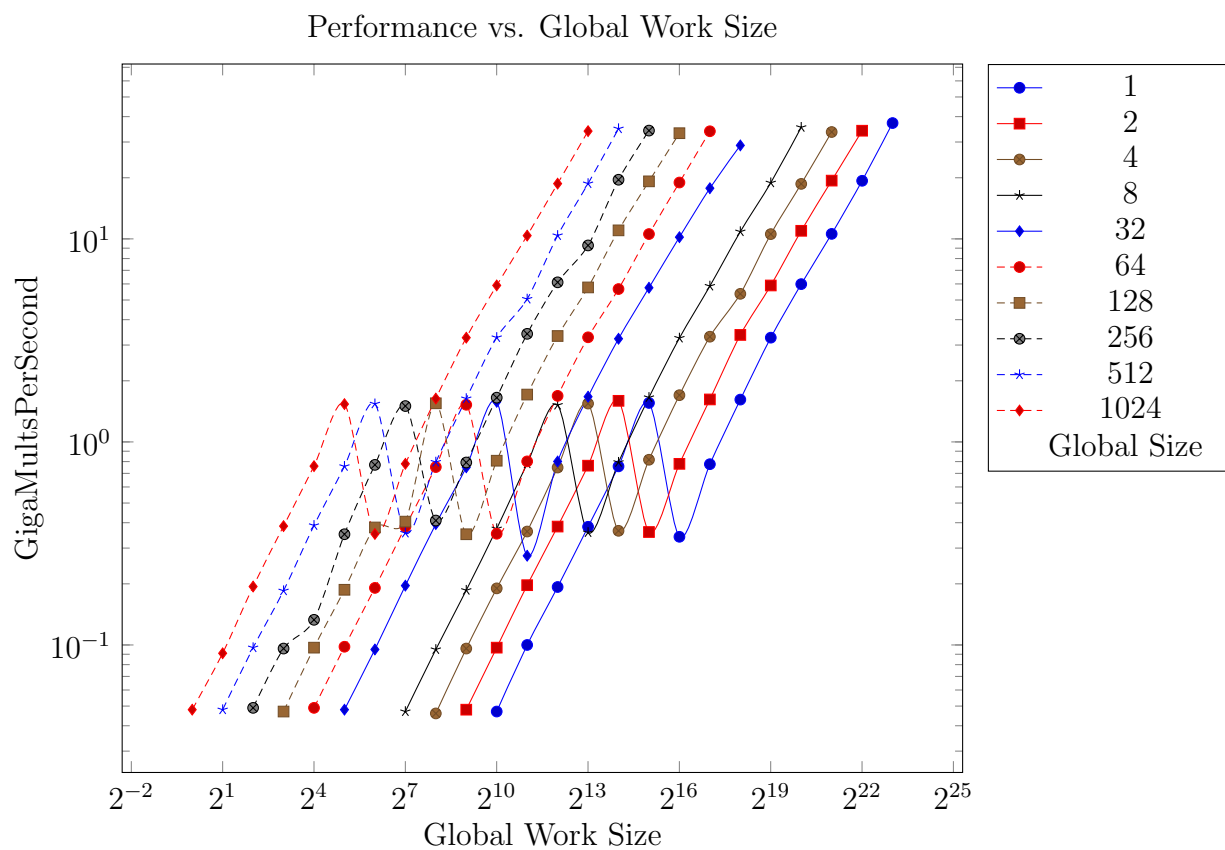


## Graph: Multiply-Add (Local)

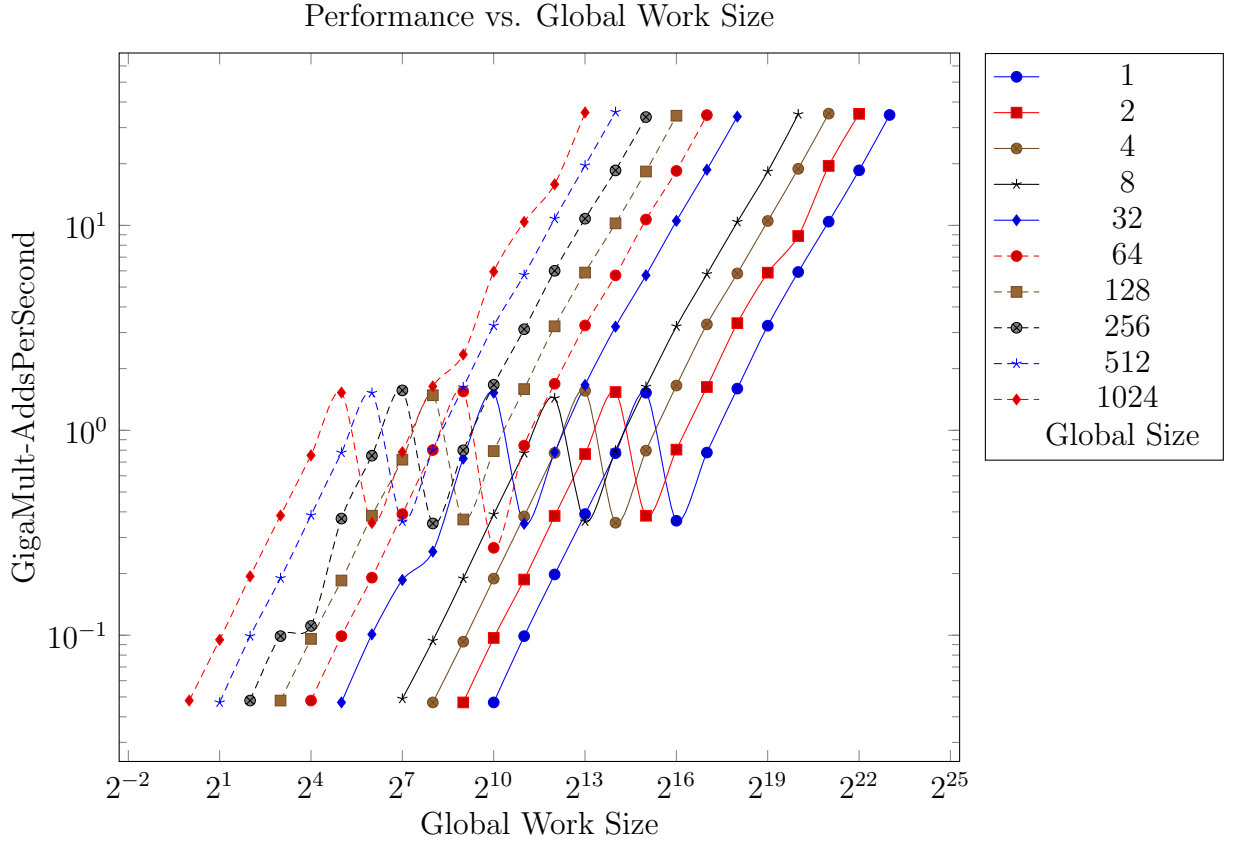


There is very little difference between these two graphs when varying the local work group size. This makes sense as the OpenCL operations being performed are independent of each other, and do not share any data. I have no clues as to why the outliers at  $2^8$  exist only for the non-multiply-and-add.

## Graphs: Multiply (Global)



## Graphs: Multiply-Add (Global)



Both multiply and multiply-add show the same performance changes as the number of elements increases. This shows that the addition of an extra operation (no pun intended) does not affect the GPU performance.

As the global work size increases (as the number of elements increases) the performance continues to improve. This tells us that performance is (again) independent of the local work group size.

When the number of elements reaches 32768 there is a noticeable drop in performance followed by a continual climb across the board. This is most likely due to maxing out the 384 CUDA cores available on the GPU causing the overhead of swapping front/back buffers to be added.

## Tables: Multiply (Local)

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	1	1024	0.049
1024	2	512	0.050
1024	4	256	0.048
1024	8	128	0.049
1024	32	32	0.049
1024	64	16	0.048
1024	128	8	0.048
1024	256	4	0.047
1024	512	2	0.051
1024	1024	1	0.048

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
2048	1	2048	0.097
2048	2	1024	0.094
2048	4	512	0.091
2048	8	256	0.098
2048	32	64	0.093
2048	64	32	0.095
2048	128	16	0.098
2048	256	8	0.038
2048	512	4	0.095
2048	1024	2	0.095

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
4096	1	4096	0.193
4096	2	2048	0.190
4096	4	1024	0.190
4096	8	512	0.198
4096	32	128	0.195
4096	64	64	0.190
4096	128	32	0.182
4096	256	16	0.076
4096	512	8	0.192
4096	1024	4	0.197

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
8192	1	8192	0.382

8192	2	4096	0.397
8192	4	2048	0.377
8192	8	1024	0.362
8192	32	256	0.375
8192	64	128	0.377
8192	128	64	0.403
8192	256	32	0.378
8192	512	16	0.381
8192	1024	8	0.385

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
16384	1	16384	0.729
16384	2	8192	0.762
16384	4	4096	0.741
16384	8	2048	0.745
16384	32	512	0.772
16384	64	256	0.771
16384	128	128	0.771
16384	256	64	0.765
16384	512	32	0.733
16384	1024	16	0.809

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
32768	1	32768	1.618
32768	2	16384	1.583
32768	4	8192	1.554
32768	8	4096	1.531
32768	32	1024	1.515
32768	64	512	1.533
32768	128	256	1.600
32768	256	128	1.473
32768	512	64	1.490
32768	1024	32	1.502

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
65536	1	65536	0.381
65536	2	32768	0.351
65536	4	16384	0.352
65536	8	8192	0.361
65536	32	2048	0.348
65536	64	1024	0.398

65536	128	512	0.362
65536	256	256	0.373
65536	512	128	0.357
65536	1024	64	0.347

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
131072	1	131072	0.757
131072	2	65536	0.790
131072	4	32768	0.821
131072	8	16384	0.766
131072	32	4096	0.790
131072	64	2048	0.800
131072	128	1024	0.812
131072	256	512	0.813
131072	512	256	0.756
131072	1024	128	0.784

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
262144	1	262144	1.629
262144	2	131072	1.637
262144	4	65536	1.675
262144	8	32768	1.668
262144	32	8192	1.696
262144	64	4096	1.675
262144	128	2048	1.650
262144	256	1024	1.610
262144	512	512	1.610
262144	1024	256	1.635

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
524288	1	524288	3.274
524288	2	262144	3.108
524288	4	131072	3.263
524288	8	65536	3.242
524288	32	16384	3.144
524288	64	8192	3.187
524288	128	4096	3.247
524288	256	2048	3.370
524288	512	1024	3.199
524288	1024	512	3.364



NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1048576	1	1048576	6.161
1048576	2	524288	5.684
1048576	4	262144	5.751
1048576	8	131072	6.028
1048576	32	32768	5.974
1048576	64	16384	6.067
1048576	128	8192	5.743
1048576	256	4096	5.942
1048576	512	2048	5.724
1048576	1024	1024	5.795

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
2097152	1	2097152	10.553
2097152	2	1048576	10.534
2097152	4	524288	10.339
2097152	8	262144	10.240
2097152	32	65536	10.470
2097152	64	32768	10.431
2097152	128	16384	10.510
2097152	256	8192	10.759
2097152	512	4096	8.132
2097152	1024	2048	8.176

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
4194304	1	4194304	18.628
4194304	2	2097152	19.451
4194304	4	1048576	19.409
4194304	8	524288	19.343
4194304	32	131072	18.825
4194304	64	65536	18.560
4194304	128	32768	18.678
4194304	256	16384	19.565
4194304	512	8192	19.353
4194304	1024	4096	18.691

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
8388608	1	8388608	33.895
8388608	2	4194304	33.643
8388608	4	2097152	34.425
8388608	8	1048576	34.181

8388608	32	262144	33.884
8388608	64	131072	34.120
8388608	128	65536	32.462
8388608	256	32768	33.635
8388608	512	16384	35.589
8388608	1024	8192	33.556

## Tables: Multiply-Add (Local)

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	1	1024	0.048
1024	2	512	0.049
1024	4	256	0.047
1024	8	128	0.049
1024	32	32	0.049
1024	64	16	0.046
1024	128	8	0.047
1024	256	4	0.047
1024	512	2	0.047
1024	1024	1	0.048

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
2048	1	2048	0.096
2048	2	1024	0.096
2048	4	512	0.097
2048	8	256	0.096
2048	32	64	0.093
2048	64	32	0.093
2048	128	16	0.094
2048	256	8	0.095
2048	512	4	0.095
2048	1024	2	0.093

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
4096	1	4096	0.196
4096	2	2048	0.180
4096	4	1024	0.188
4096	8	512	0.192
4096	32	128	0.188
4096	64	64	0.189

4096	128	32	0.191
4096	256	16	0.193
4096	512	8	0.193
4096	1024	4	0.199

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
8192	1	8192	0.380
8192	2	4096	0.377
8192	4	2048	0.379
8192	8	1024	0.394
8192	32	256	0.378
8192	64	128	0.372
8192	128	64	0.390
8192	256	32	0.378
8192	512	16	0.398
8192	1024	8	0.378

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
16384	1	16384	0.728
16384	2	8192	0.754
16384	4	4096	0.765
16384	8	2048	0.758
16384	32	512	0.750
16384	64	256	0.794
16384	128	128	0.742
16384	256	64	0.776
16384	512	32	0.765
16384	1024	16	0.763

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
32768	1	32768	1.500
32768	2	16384	1.542
32768	4	8192	1.482
32768	8	4096	1.486
32768	32	1024	1.479
32768	64	512	1.542
32768	128	256	1.555
32768	256	128	1.531
32768	512	64	1.547
32768	1024	32	1.560

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
65536	1	65536	0.359
65536	2	32768	0.361
65536	4	16384	0.360
65536	8	8192	0.361
65536	32	2048	0.337
65536	64	1024	0.363
65536	128	512	0.355
65536	256	256	0.363
65536	512	128	0.367
65536	1024	64	0.362

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
131072	1	131072	0.729
131072	2	65536	0.801
131072	4	32768	0.790
131072	8	16384	0.755
131072	32	4096	0.778
131072	64	2048	0.780
131072	128	1024	0.773
131072	256	512	0.794
131072	512	256	0.798
131072	1024	128	0.791

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
262144	1	262144	1.699
262144	2	131072	1.763
262144	4	65536	1.633
262144	8	32768	1.666
262144	32	8192	1.686
262144	64	4096	1.617
262144	128	2048	1.660
262144	256	1024	1.638
262144	512	512	1.628
262144	1024	256	1.650

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
524288	1	524288	3.240
524288	2	262144	2.976
524288	4	131072	3.242
524288	8	65536	3.270

524288	32	16384	3.186
524288	64	8192	3.238
524288	128	4096	3.455
524288	256	2048	3.222
524288	512	1024	3.220
524288	1024	512	3.238

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1048576	1	1048576	5.924
1048576	2	524288	5.937
1048576	4	262144	5.813
1048576	8	131072	5.905
1048576	32	32768	5.936
1048576	64	16384	5.902
1048576	128	8192	5.706
1048576	256	4096	5.814
1048576	512	2048	6.062
1048576	1024	1024	4.766

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
2097152	1	2097152	10.476
2097152	2	1048576	10.231
2097152	4	524288	10.577
2097152	8	262144	10.760
2097152	32	65536	10.674
2097152	64	32768	10.149
2097152	128	16384	11.723
2097152	256	8192	10.691
2097152	512	4096	10.806
2097152	1024	2048	10.468

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
4194304	1	4194304	18.964
4194304	2	2097152	19.039
4194304	4	1048576	19.338
4194304	8	524288	18.816
4194304	32	131072	19.359
4194304	64	65536	19.028
4194304	128	32768	19.108
4194304	256	16384	18.824
4194304	512	8192	19.708

4194304	1024	4096	18.501
NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
8388608	1	8388608	34.174
8388608	2	4194304	34.793
8388608	4	2097152	34.725
8388608	8	1048576	34.468
8388608	32	262144	33.738
8388608	64	131072	33.753
8388608	128	65536	33.734
8388608	256	32768	34.502
8388608	512	16384	34.111
8388608	1024	8192	34.007

## Tables: Multiply (Global)

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	1	1024	0.047
2048	1	2048	0.100
4096	1	4096	0.193
8192	1	8192	0.382
16384	1	16384	0.758
32768	1	32768	1.556
65536	1	65536	0.341
131072	1	131072	0.777
262144	1	262144	1.616
524288	1	524288	3.262
1048576	1	1048576	5.987
2097152	1	2097152	10.583
4194304	1	4194304	19.326
8388608	1	8388608	37.197

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	2	512	0.048
2048	2	1024	0.097
4096	2	2048	0.197
8192	2	4096	0.383
16384	2	8192	0.764
32768	2	16384	1.594
65536	2	32768	0.360

131072	2	65536	0.780
262144	2	131072	1.619
524288	2	262144	3.365
1048576	2	524288	5.896
2097152	2	1048576	10.961
4194304	2	2097152	19.365
8388608	2	4194304	34.100

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	4	256	0.046
2048	4	512	0.096
4096	4	1024	0.190
8192	4	2048	0.362
16384	4	4096	0.748
32768	4	8192	1.545
65536	4	16384	0.365
131072	4	32768	0.817
262144	4	65536	1.699
524288	4	131072	3.298
1048576	4	262144	5.363
2097152	4	524288	10.556
4194304	4	1048576	18.659
8388608	4	2097152	33.601

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	8	128	0.047
2048	8	256	0.095
4096	8	512	0.186
8192	8	1024	0.374
16384	8	2048	0.781
32768	8	4096	1.518
65536	8	8192	0.358
131072	8	16384	0.794
262144	8	32768	1.656
524288	8	65536	3.248
1048576	8	131072	5.857
2097152	8	262144	10.856
4194304	8	524288	18.897
8388608	8	1048576	35.439

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
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1024	32	32	0.048
2048	32	64	0.095
4096	32	128	0.196
8192	32	256	0.394
16384	32	512	0.750
32768	32	1024	1.576
65536	32	2048	0.275
131072	32	4096	0.801
262144	32	8192	1.670
524288	32	16384	3.222
1048576	32	32768	5.745
2097152	32	65536	10.195
4194304	32	131072	17.764
8388608	32	262144	28.870

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	64	16	0.049
2048	64	32	0.098
4096	64	64	0.191
8192	64	128	0.382
16384	64	256	0.752
32768	64	512	1.524
65536	64	1024	0.353
131072	64	2048	0.802
262144	64	4096	1.686
524288	64	8192	3.276
1048576	64	16384	5.661
2097152	64	32768	10.563
4194304	64	65536	18.952
8388608	64	131072	33.892

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	128	8	0.047
2048	128	16	0.097
4096	128	32	0.187
8192	128	64	0.379
16384	128	128	0.405
32768	128	256	1.550
65536	128	512	0.351
131072	128	1024	0.808
262144	128	2048	1.711



524288	128	4096	3.324
1048576	128	8192	5.767
2097152	128	16384	11.015
4194304	128	32768	19.208
8388608	128	65536	33.155

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	256	4	0.049
2048	256	8	0.096
4096	256	16	0.133
8192	256	32	0.351
16384	256	64	0.771
32768	256	128	1.502
65536	256	256	0.410
131072	256	512	0.792
262144	256	1024	1.652
524288	256	2048	3.407
1048576	256	4096	6.110
2097152	256	8192	9.284
4194304	256	16384	19.557
8388608	256	32768	34.148

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	512	2	0.048
2048	512	4	0.097
4096	512	8	0.185
8192	512	16	0.388
16384	512	32	0.758
32768	512	64	1.540
65536	512	128	0.356
131072	512	256	0.796
262144	512	512	1.635
524288	512	1024	3.269
1048576	512	2048	5.054
2097152	512	4096	10.392
4194304	512	8192	18.725
8388608	512	16384	34.895

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	1024	1	0.048
2048	1024	2	0.091

4096	1024	4	0.194
8192	1024	8	0.385
16384	1024	16	0.760
32768	1024	32	1.536
65536	1024	64	0.352
131072	1024	128	0.780
262144	1024	256	1.635
524288	1024	512	3.261
1048576	1024	1024	5.900
2097152	1024	2048	10.378
4194304	1024	4096	18.713
8388608	1024	8192	33.942

## Tables: Multiply-Add (Global)

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	1	1024	0.047
2048	1	2048	0.099
4096	1	4096	0.198
8192	1	8192	0.390
16384	1	16384	0.774
32768	1	32768	1.525
65536	1	65536	0.362
131072	1	131072	0.779
262144	1	262144	1.598
524288	1	524288	3.240
1048576	1	1048576	5.924
2097152	1	2097152	10.427
4194304	1	4194304	18.568
8388608	1	8388608	34.589

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	2	512	0.047
2048	2	1024	0.097
4096	2	2048	0.187
8192	2	4096	0.382
16384	2	8192	0.766
32768	2	16384	1.537
65536	2	32768	0.383
131072	2	65536	0.805

262144	2	131072	1.627
524288	2	262144	3.333
1048576	2	524288	5.879
2097152	2	1048576	8.873
4194304	2	2097152	19.512
8388608	2	4194304	35.036

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	4	256	0.047
2048	4	512	0.093
4096	4	1024	0.189
8192	4	2048	0.380
16384	4	4096	0.776
32768	4	8192	1.559
65536	4	16384	0.354
131072	4	32768	0.796
262144	4	65536	1.654
524288	4	131072	3.288
1048576	4	262144	5.828
2097152	4	524288	10.508
4194304	4	1048576	18.883
8388608	4	2097152	35.106

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	8	128	0.049
2048	8	256	0.094
4096	8	512	0.189
8192	8	1024	0.389
16384	8	2048	0.774
32768	8	4096	1.434
65536	8	8192	0.359
131072	8	16384	0.797
262144	8	32768	1.631
524288	8	65536	3.216
1048576	8	131072	5.784
2097152	8	262144	10.392
4194304	8	524288	18.325
8388608	8	1048576	34.860

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	32	32	0.047

2048	32	64	0.101
4096	32	128	0.186
8192	32	256	0.256
16384	32	512	0.728
32768	32	1024	1.525
65536	32	2048	0.350
131072	32	4096	0.781
262144	32	8192	1.665
524288	32	16384	3.205
1048576	32	32768	5.709
2097152	32	65536	10.523
4194304	32	131072	18.688
8388608	32	262144	33.951

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	64	16	0.048
2048	64	32	0.099
4096	64	64	0.191
8192	64	128	0.390
16384	64	256	0.801
32768	64	512	1.548
65536	64	1024	0.267
131072	64	2048	0.842
262144	64	4096	1.687
524288	64	8192	3.249
1048576	64	16384	5.703
2097152	64	32768	10.683
4194304	64	65536	18.454
8388608	64	131072	34.536

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	128	8	0.048
2048	128	16	0.096
4096	128	32	0.185
8192	128	64	0.383
16384	128	128	0.719
32768	128	256	1.483
65536	128	512	0.367
131072	128	1024	0.792
262144	128	2048	1.589
524288	128	4096	3.218

1048576	128	8192	5.886
2097152	128	16384	10.233
4194304	128	32768	18.328
8388608	128	65536	34.293

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	256	4	0.048
2048	256	8	0.099
4096	256	16	0.111
8192	256	32	0.371
16384	256	64	0.752
32768	256	128	1.566
65536	256	256	0.351
131072	256	512	0.799
262144	256	1024	1.668
524288	256	2048	3.113
1048576	256	4096	6.005
2097152	256	8192	10.784
4194304	256	16384	18.551
8388608	256	32768	33.785

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	512	2	0.047
2048	512	4	0.099
4096	512	8	0.190
8192	512	16	0.385
16384	512	32	0.778
32768	512	64	1.521
65536	512	128	0.359
131072	512	256	0.803
262144	512	512	1.622
524288	512	1024	3.242
1048576	512	2048	5.731
2097152	512	4096	10.770
4194304	512	8192	19.606
8388608	512	16384	35.738

NUM_ELEMENTS	LOCAL_SIZE	NUM_WORK_GROUPS	GMPS
1024	1024	1	0.048
2048	1024	2	0.095
4096	1024	4	0.194

8192	1024	8	0.384
16384	1024	16	0.755
32768	1024	32	1.528
65536	1024	64	0.353
131072	1024	128	0.783
262144	1024	256	1.638
524288	1024	512	2.344
1048576	1024	1024	5.947
2097152	1024	2048	10.401
4194304	1024	4096	15.868
8388608	1024	8192	35.550