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A PORTABLE BENCHMARK SUITE FOR HIGHLY PARALLEL DATA INTENSIVE QUERY PROCESSING

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The Need for Accelerated Data Warehousing

Data Warehousing has become a large part of supply chain operations

Analytics of weekly and monthly trends helps to predict future supply needs and ordering patterns

- How many people will buy grills around July 4^{th}?

The explosion of Big Data makes this analytics tougher

New hardware like GPU and Phi accelerators can be used to accelerate queries for data warehousing applications with large amounts of data

- Co-processing with GPUs can provide 2-27x speedup [1]

Our work focuses on mapping a data warehousing benchmark, TPC-H, to a portable accelerator language, OpenCL

[1] B. He, et. al, "Relational query coprocessing on graphics processors," ACM TODS, 2009

Related Work

Currently, there is little work in the area of data analytics on accelerators and no accelerator-based analytics benchmarks

- OmniDB: Kernel-adapter design that uses OpenCL operators as part of larger framework; unclear as to current project status [2]
- Work has also focused on portable database primitives from a software engineering standpoint [3]
- Companies like Map-D are focusing on CUDA-based analytics using SQL queries [4]

[2] S. Zhang, J. He, B. He, and M. Lu. OmniDB: Towards portable and efficient query processing on parallel CPU/GPU architectures. Proceedings of the VLDB Endowment, 6(12):1374–1377, 2013.
[3] D. Broneske, S. Breß, M. Heimel, and G. Saake. Toward hardware-sensitive database operations. EDBT, 2014.
[4] Mostak, Todd. "An overview of MapD (massively parallel database)." White paper. Massachusetts Institute of Technology, 2013.

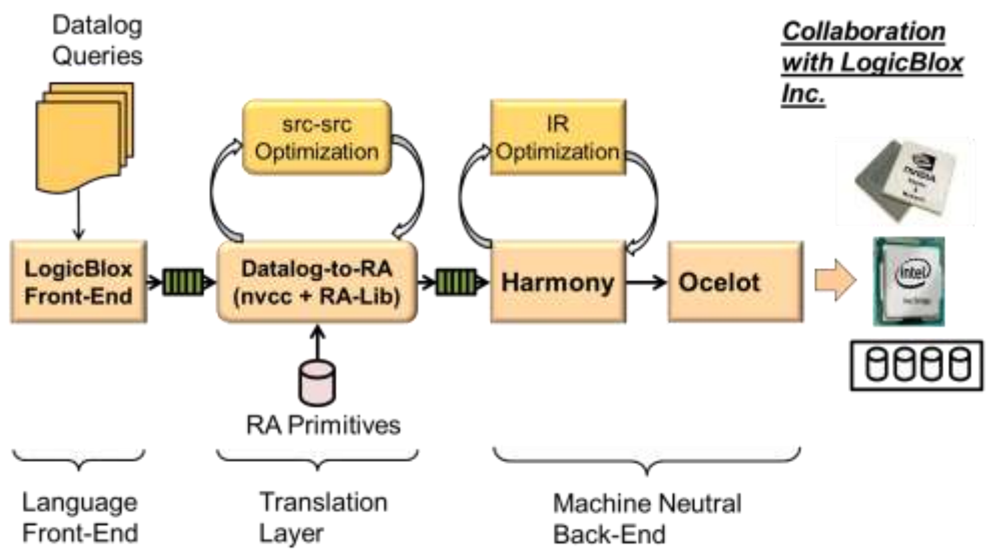
Related Work: Red Fox [5]

Our OpenCL primitives grew out of this GPU-focused project

Red Fox is a collaborative project with LogicBlox that has focused on CUDA implementations of the TPC-H queries using relational algebra (RA).

OpenCL primitives build off the CUDA primitives

- Existing primitives have “GPU slant” – vectorization and testing geared towards Fermi-class GPUs
- Red Fox work demonstrates a path forward for full OpenCL implementation of TPC-H



[5] H. Wu, et al, “Red Fox: An Execution Environment for Relational Query Processing on GPUs”, CGO 2014

Contributions of this work

- Portable database relational algebra primitives using OpenCL for cross-platform compatibility
- A new open-source benchmark that allows these primitives to be run on a variety of systems (extensions for SHOC)
- Evaluation of these primitives and related microbenchmarks on multiple hardware platforms – Intel and AMD CPUs, integrated and discrete GPUs, and Xeon Phi
- An eventual path towards a fully portable, accelerated implementation of the standard data warehousing benchmark, TPC-H [6]

[6] T. P. P. Council. TPC Benchmark H (Decision Support) Standard Specification, Revision 2.17.0 . http://www.tpc.org/tpch/spec/tpch2.17.0.pdf, 2013.

TPC-H Benchmark Suite

Consists of 21 queries meant to represent common data warehousing operations

Benchmark results typically report on the capabilities of a particular hardware system and database setup.

Accelerated versions of TPC-H are complex

Previous Red Fox implementations of queries required many CUDA kernels – the simplest query requires ~15 CUDA kernels and an accompanying scheduler

- For this reason, our work focuses on OpenCL primitives first

```
select
        l_returnflag,
        l_linestatus,
        sum(l_quantity) as sum_qty,
        sum(l_extendedprice) as sum_base_price,
        sum(l_extendedprice*(1-l_discount)) as sum_disc_price,
        sum(l_extendedprice*(1-l_discount)*(1+l_tax)) as sum_charge,
        avg(l_quantity) as avg_qty,
        avg(l_extendedprice) as avg_price,
        avg(l_discount) as avg_disc,
        count(*) as count_order
from
        lineitem
where
        l_shipdate <= date '1998-12-01' - interval '[DELTA]' day (3)
group by
        l_returnflag,
        l_linestatus
order by
        l_returnflag,
        l_linestatus;
```

<u>Q1: Pricing Summary Report Query</u>*: returns a price summary of all items shipped within a certain date range

Scalable HeterOgeneous Computing (SHOC) Suite

Accelerator-based benchmark suite that provides benchmarks written in multiple languages [8]

- Designed as a tool to compare algorithms across software platforms but also to compare hardware systems
- OpenCL, CUDA, Phi (OpenMP), and OpenACC variants include "speeds and feeds" benchmarks as well as parallel benchmarks

Currently there is a focus to add more "Big Data" benchmarks to represent non-scientific workloads

- TPC-H primitives and queries are a good candidate along with ML and graph algorithms

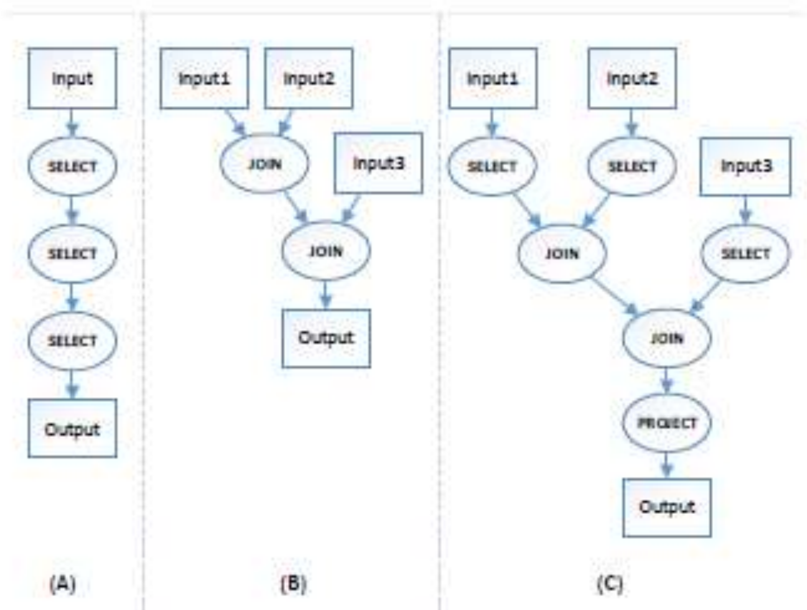
	OpenCL			*CUDA*		
Program	*S*	*EP*	*TP*	*S*	*EP*	*TP*
BusSpeedDownload	x	x		x	x	
BusSpeedReadback	x	x		x	x	
DeviceMemory	x	x		x	x	
KernelCompile	x	x				
MaxFlops	x	x		x	x	
QueueDelay	x	x				
BFS	x	x		x	x	
FFT	x	x		x	x	
MD	x	x		x	x	
MD5Hash	x	x		x	x	
Reduction	x	x	x	x	x	x
QTC				x		x
S3D	x	x		x	x	
SGEMM	x	x		x	x	
Scan	x	x	x	x	x	x
Sort	x	x		x	x	
Spmv	x	x		x	x	
Stencil2D	x		x	x		x
Triad	x	x		x	x	
BusCont		x			x	
MTBusCont		x			x	

[8] A. Danalis, *et al*. The scalable heterogeneous computing (SHOC) benchmark suite. In Proceedings of the 3rd Workshop on General-Purpose Computation on Graphics Processing Units, pages 63–74. ACM, 2010.

TPC-H Primitives and Microbenchmarks

Table 1. Relational Algebra Primitives

Primitive Name	Input Tuple Size	Primitive Name	Input Tuple Size
Project	1	Add	2
Reduce	1	Subtract	2
Reduce by Key	1	Multiply	2
Select	1	Difference	2
Unique	1	Product	2
Inner Join	2		



- This talk focuses on project, select, and join primitives; see [7] for others
- Microbenchmarks A (Chained Select), B (Chained Join), C (Select, Join, Project) represent patterns common in TPC-H queries

[7] I. Saeed. A portable relational algebra library for high performance data-intensive query processing (MS thesis). https://smartech.gatech.edu/handle/1853/51967, 2014.

Basic Design of Primitives

Partition, compute, gather

Values are stored as an array of tuples with key-value pairs

Project:

- Partition, compute, and gather are all combined into one kernel

Select:

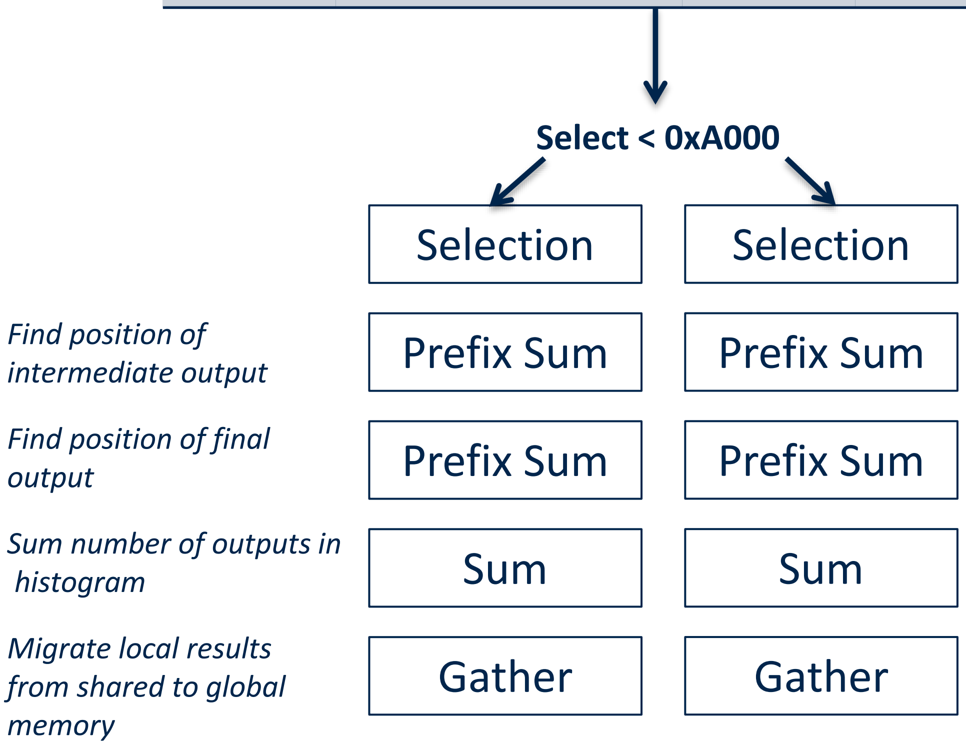
- Partition and compute are combined into "Selection" kernel; separate gather phase

Join:

- Find Bounds kernel is part of partition phase, separate compute and gather stages implemented by different kernels

Select Primitive

Key	0x1235	0x1462	0x1172	0x1903
Value	0xAB23	0xD3F2	0x7213	0x8931



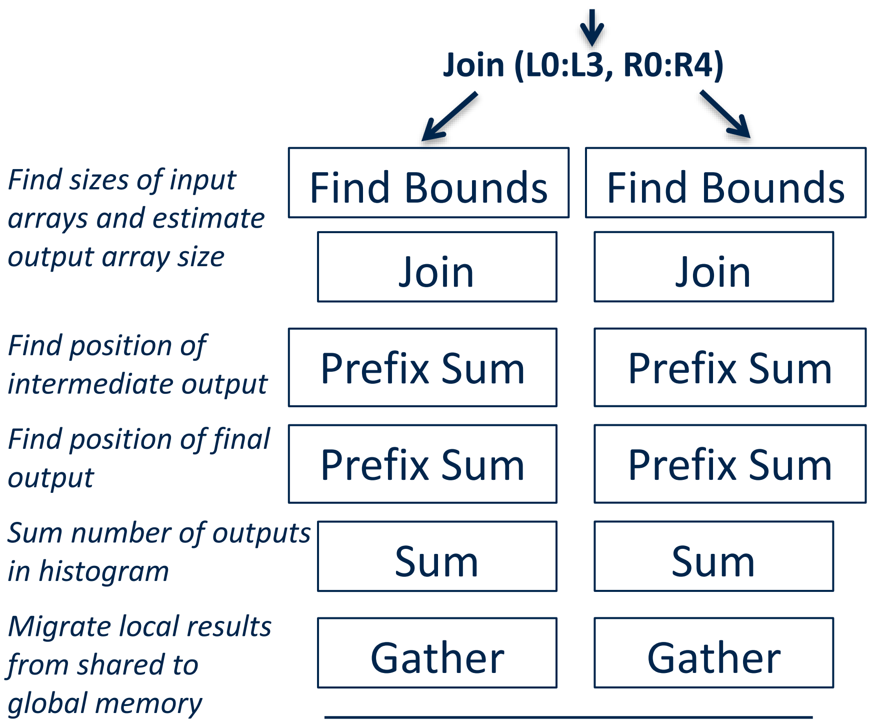
Key	0x1172	0x1903
Value	0x7213	0x8931

```
foreach partition p in parallel do
    foreach work-item w (with local id lw) in parallel do
        keyReg ← input[w].key;
        valueReg ← input[w].value;
        countReg ← 0;
        if keyReg < THRESHOLD then
            countReg ← 1;
        end
        indexReg ←
        positions of selected tuples obtained from Algorithm 3;
        totalReg ←
        number of selected tuples obtained from Algorithm 3;
        if count is equal to 1 then
            local[indexReg].key ← keyReg;
            local[indexReg].value ← valueReg;
        end
        if lw < totalReg then
            globalPartition[lw] ← local[lw];
        end
        if lw is 0 then
            array[p] ← total;
        end
    end
end
```

Join Primitive

Key	0x1235	0x1462	0x1172	0x1903
Value	0xAB23	0xD3F2	0x7213	0x8931

Key	0x1172	0x1235	0x1820	0x1903
Value	0xB723	0x0342	0x6418	0xC298



Key	0x1172	0x1235
Value	0x7213	0xAB23
Value 2	0x8723	0x0342

```
foreach partition p (left and corresponding right) in parallel do
    while one of both left and right partitions not exhausted do
        foreach work-item w (with local id lw) in parallel do
            rightLocal[lw] ← right[w];
            leftLocal[lw] ← left[w];
            if the last tuple key of leftLocal < the first tuple key of
            rightLocal then
                go to the end of leftLocal;
            else
                if the last tuple key of rightLocal < the first tuple
                key of leftLocal then
                    go to the end of the rightLocal;
                else
                    Algorithm 6;
                end
                while right partition end do
                    rightLocal[lw] ← right[w];
                    if the leftLocal last tuple key < the
                    rightLocal first tuple key then
                        break the loop;
                    end
                    Algorithm 6;
                end
            end
        end
    end
    if lw is 0 then
        array[p] ← total;
    end
end
```

Algorithm 5: INNER JOIN

```
rightReg ← right[lw];
lowerReg ← lowerBound for rightReg.key in leftLocal;
upperReg ← upperBound for rightReg.key in leftLocal;
foundCountReg ← upperReg – lowerReg;
indexReg = positions of selected tuples obtained from Algorithm 3;
totalReg = number of selected tuples obtained from Algorithm 3;
if totalReg < size of outputLocal then
    for i ← 0 to foundCountReg do
        outputLocal[indexReg + i] ←
        rightReg and matching left tuple;
    end
    output ← outputLocal;
else
    put in multiple iterations from outputLocal to output;
end
```

Algorithm 6: JOIN Block

Experimental Test bed

Platform	CPU	Accelerator	Device Memory	OS and Software	OpenCL Version
AMD Trinity APU	A10-5800K	HD 7660D	16 GB DDR3	CentOS 7.0	AMD APP 2.9
Intel Ivy Bridge	i5-3470	HD 2500	16 GB DDR3	Ubuntu 14.04	Intel OpenCL 14.2 SDK for Applications and Beignet 1.0
Intel Sandy Bridge	2xE5-2670	Phi 5110	24 GB DDR3, 8 GB DDR	CentOS 6.2, gcc 4.8.2	
Intel Haswell	i7-4770	GT2	16 GB DDR3	Ubuntu 14.04, gcc 4.8.2	
Nvidia Fermi	Xeon X5660	M2090	6 GB	CentOS 6.2, gcc 4.8.2	CUDA 6.0
Nvidia Kepler	Xeon E5520	K40	6 GB	CentOS 6.4, gcc 4.8.2	

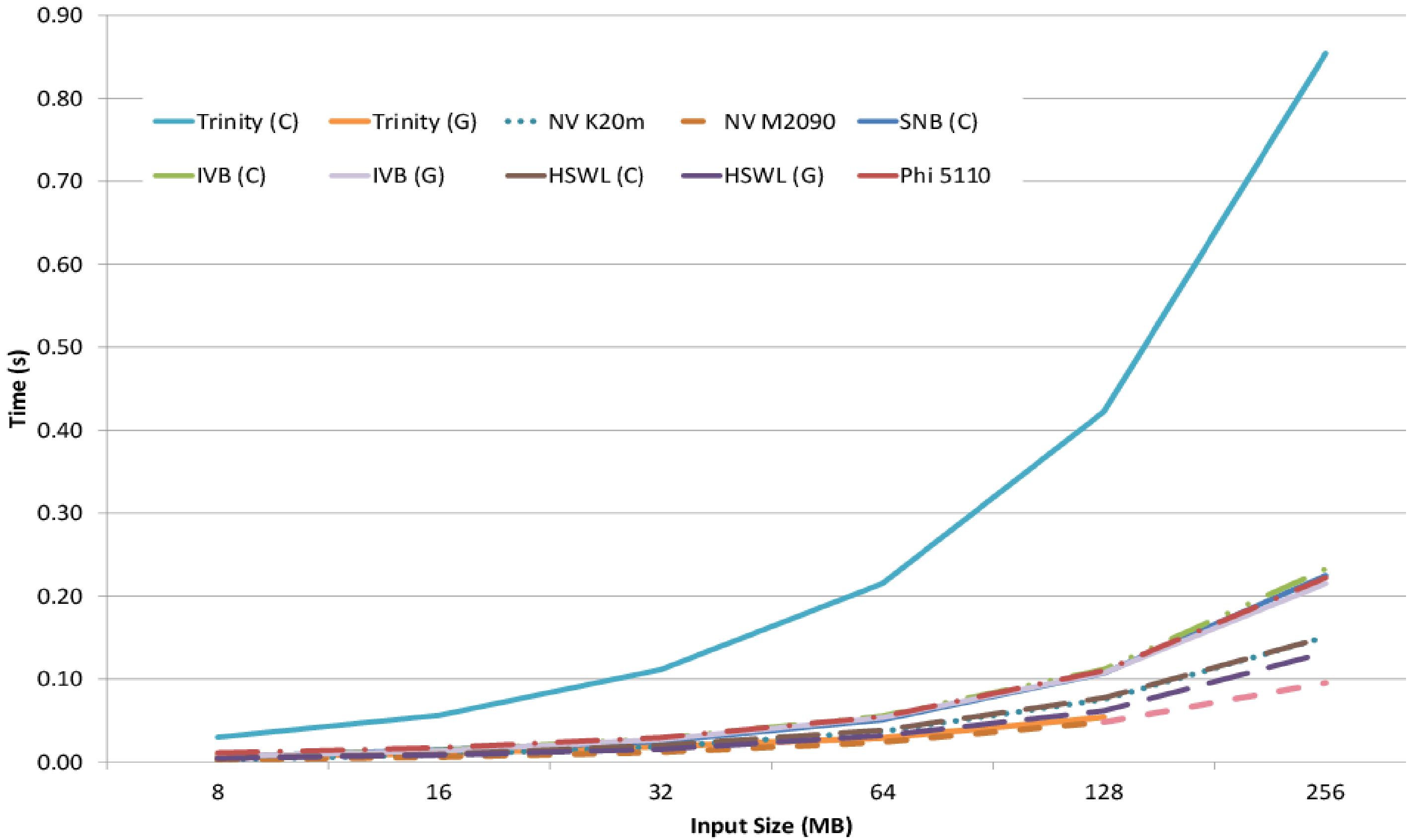
OpenCL 1.2 used because vendor implementations vary

- AMD, Intel support OpenCL 2.0 to a reasonable degree; NVIDIA supports 1.2; Intel discrete GPUs only supported on Linux by "Beignet"

Intel OCL latest version has an issue with vectorizing functionality – this resulted in disabled optimizations for Phi and CPU platforms

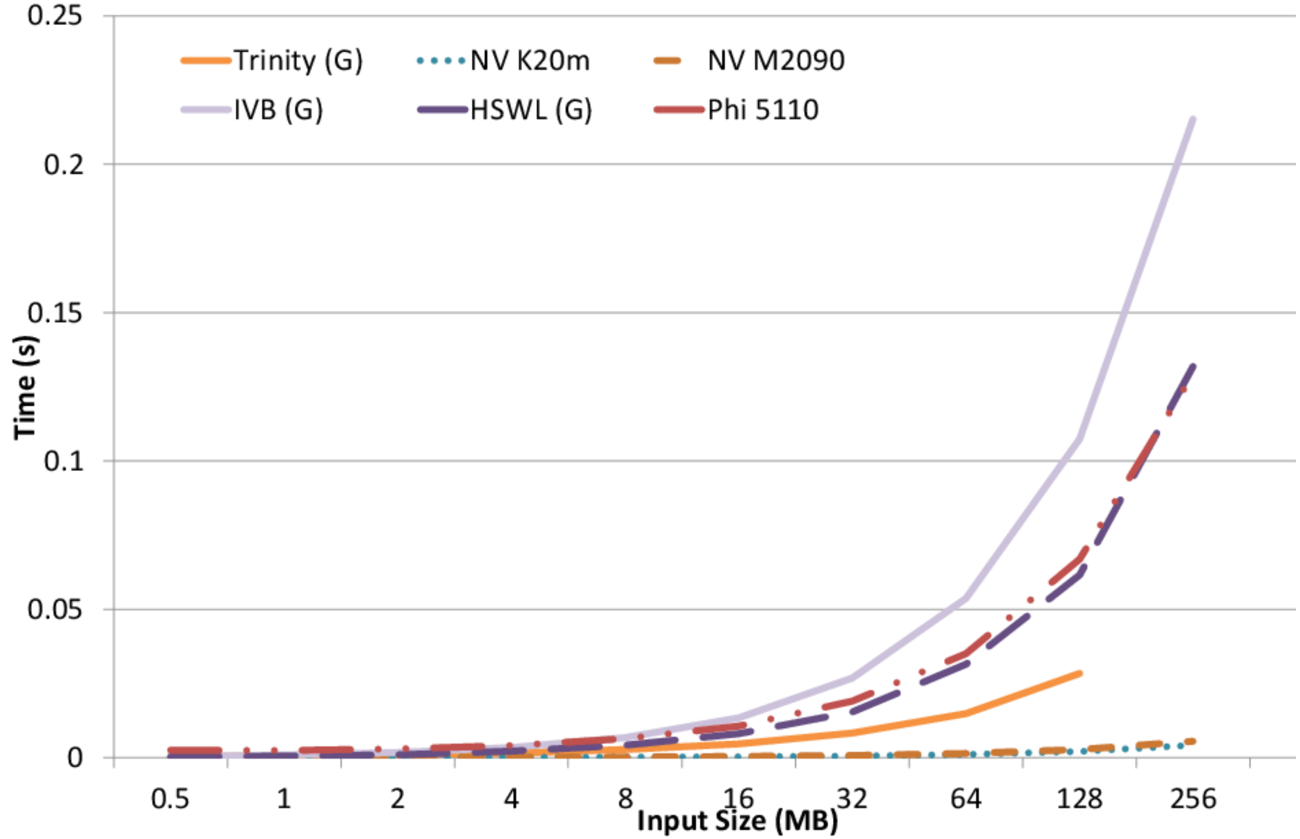
- Beignet is unaffected

Select Total (Compute and Data)



Total time for 256 MB select operation ranges from 95 ms (M2090) to 854 ms (Trinity CPU)

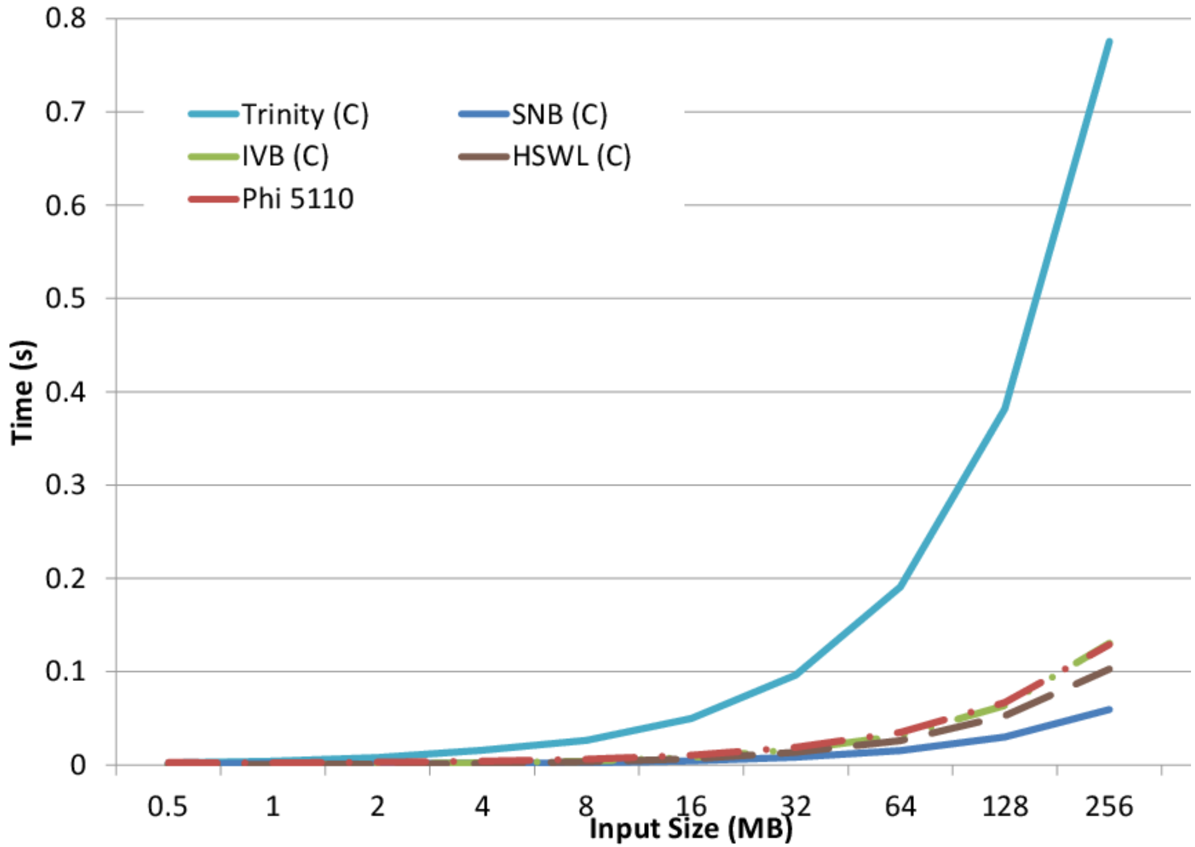
Select Kernel Accelerators (Compute)



Integrated GPUs complete 256 MB Select compute in less than 215 ms

- NVIDIA GPUs and AMD Trinity likely benefit from implicit 256 workgroup size
- Xeon Phi may be penalized by lack of vectorization optimizations

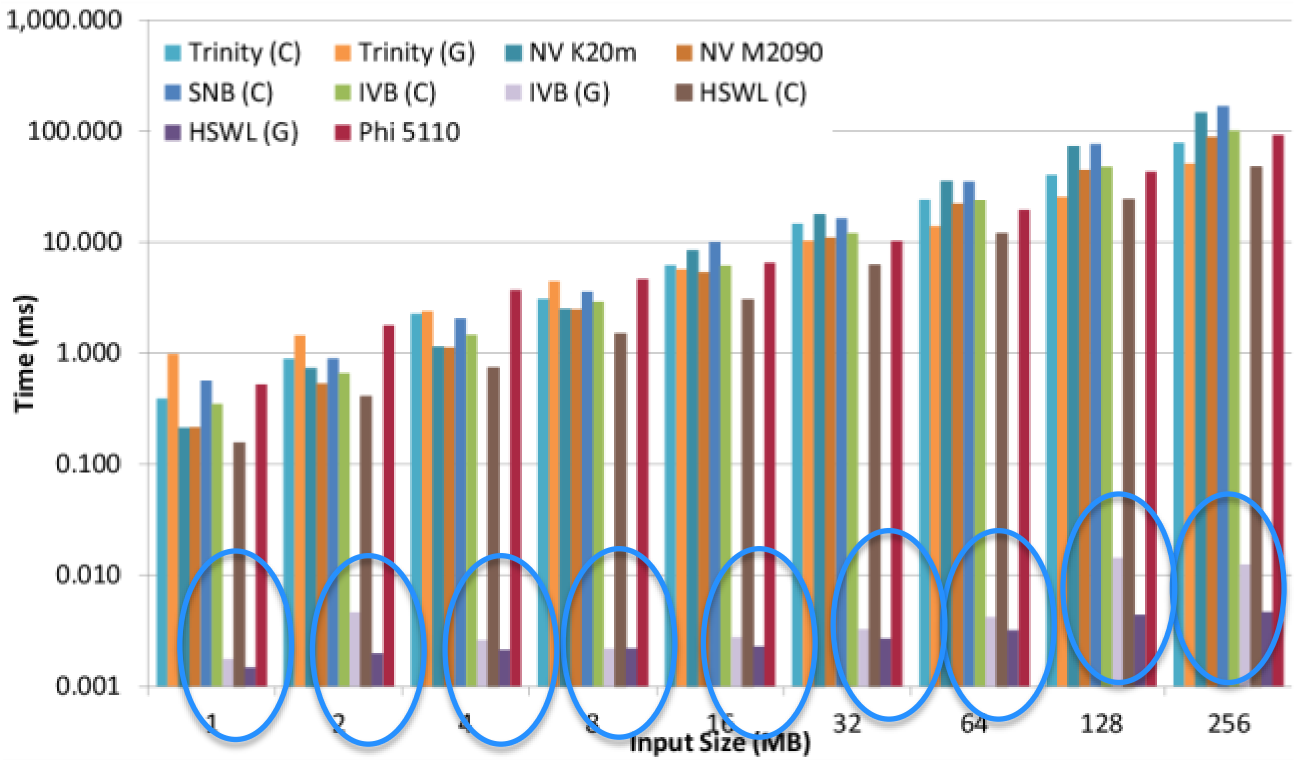
Select Kernel - CPUs (Compute)



Sandy Bridge compute takes just 60 ms compared to total runtime (with data transfer) of 225 ms

- This Xeon CPU has higher clock rates, more threads (16), and more cache than other tested CPUs

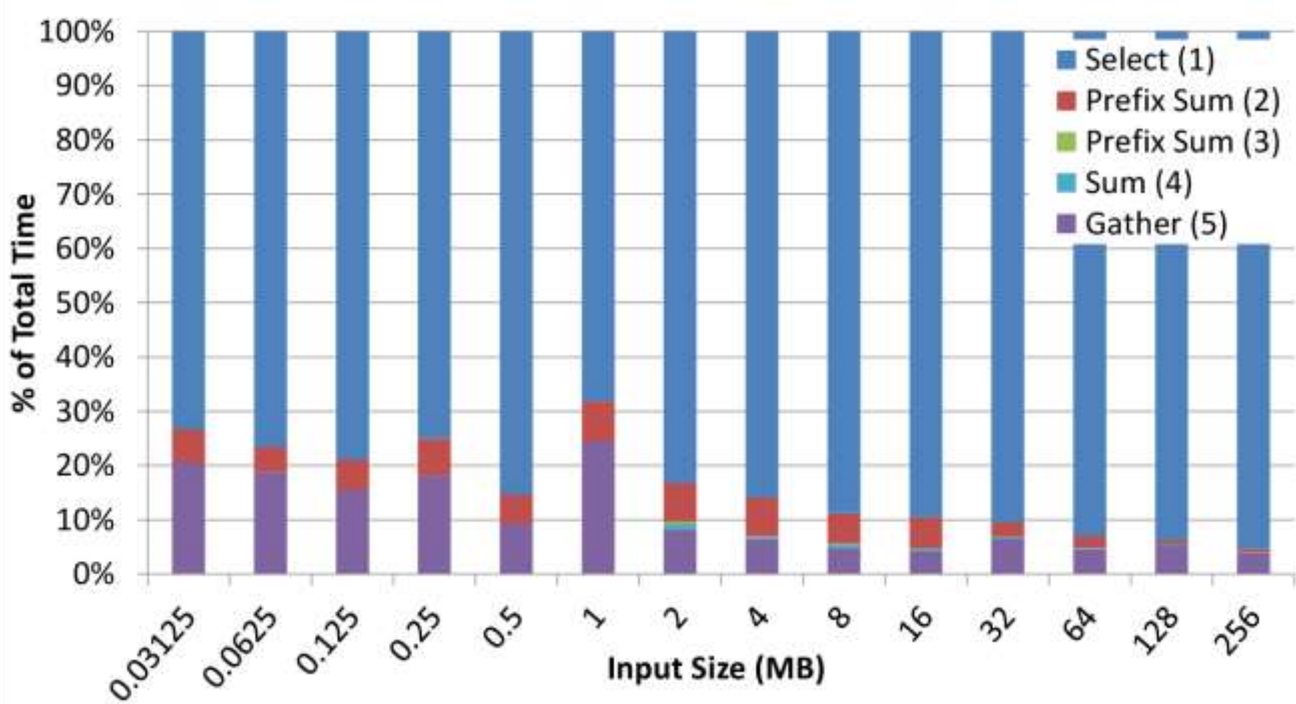
Select Data Transfer (Input/Output)



As expected, data transfer consumes a large amount of execution time

- 165 ms out of 225 ms runtime on Sandy Bridge (74.7%); 48 ms out of 132 on Haswell (31.8%)
- Lower data transfer costs on Ivy Bridge and Haswell GPU are likely due to zero-copy schemes not used for CPU

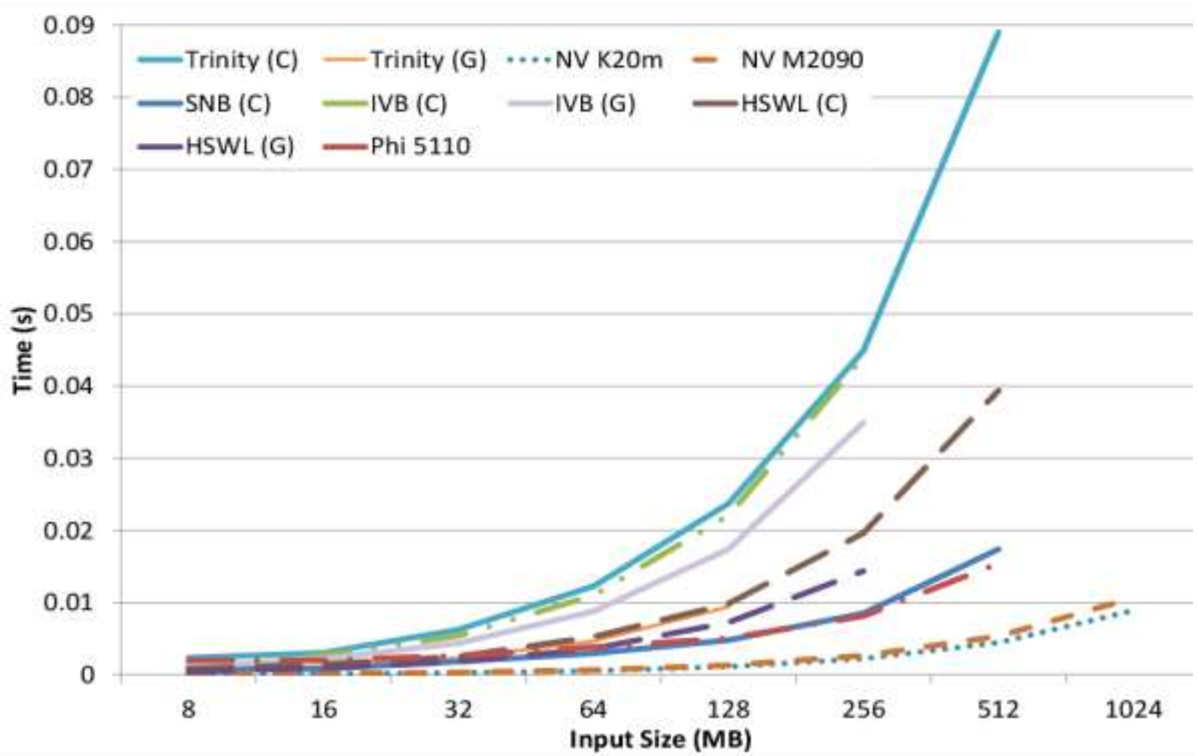
Select Kernel Breakdown – Xeon Phi



Select kernel consumes an increasing portion of kernel runtime

- As described earlier, partitioning and compute were placed into one kernel – good place for future optimization

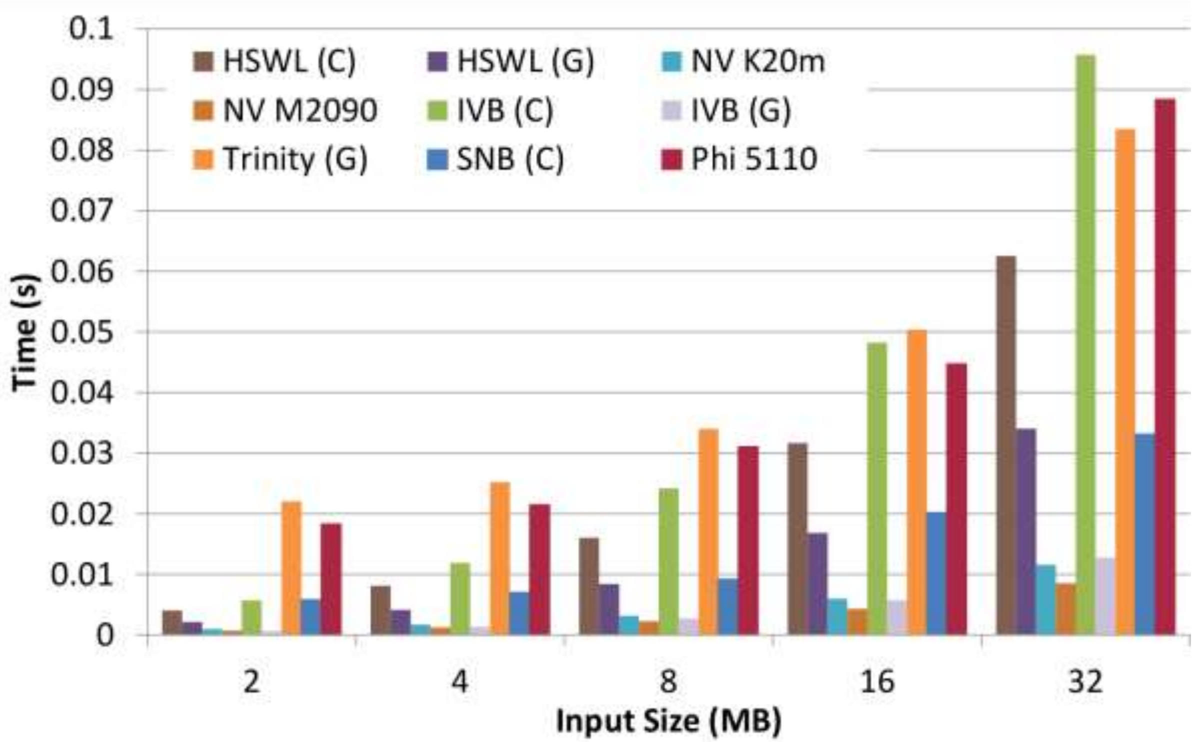
Project Kernel



Project kernel is highly parallel operation – just 1 kernel, no data dependencies

- Discrete GPUs and highly multithreaded architectures (SNB and Xeon Phi) perform best
- 10.6 ms for 1 GB project on K20m; 15.4 ms for 512 MB on Phi; 89 ms for 512 MB on Trinity
- However, total times for 512 MB project range from 139 ms (Haswell CPU) to 336 ms (SNB) with data transfer

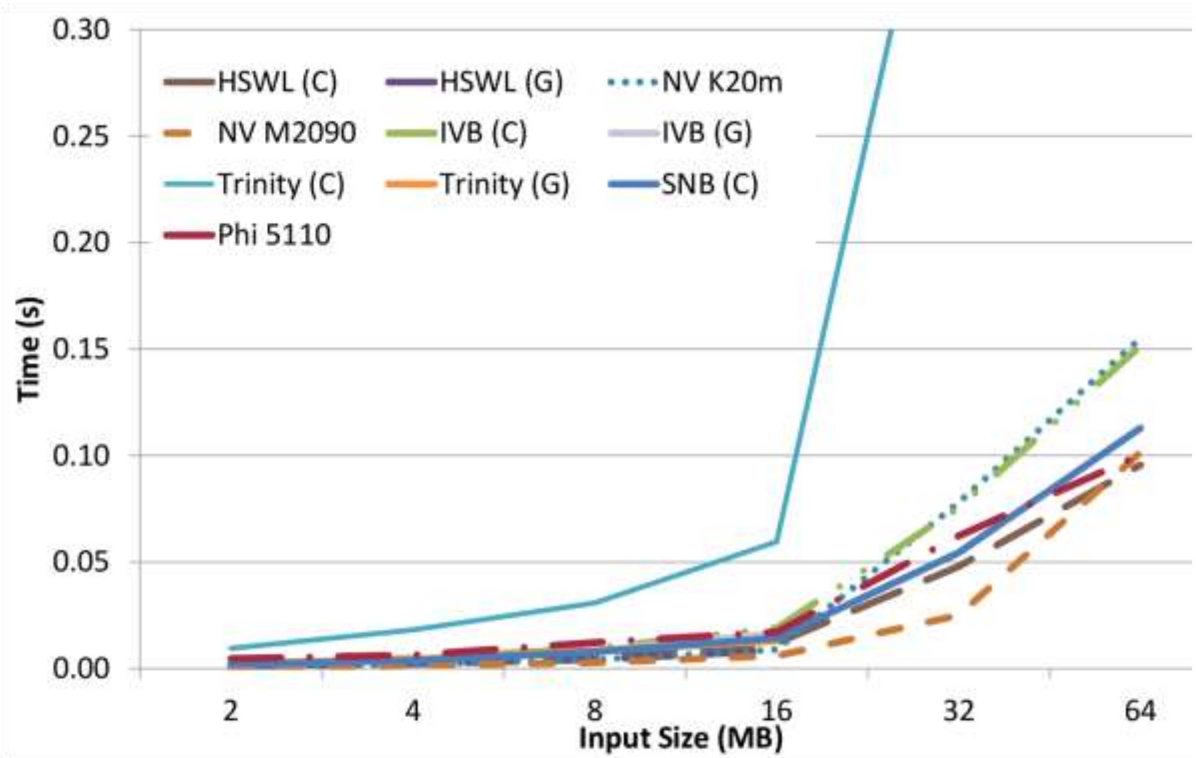
Join Kernel



8.5 ms to 95.7 ms for 2x32 MB join operation

- Workgroup size of 256 (good for GPU, APU) unfairly penalizes Xeon Phi; Phi runs at lower clock speed than CPUs and depends heavily on vectorization for performance

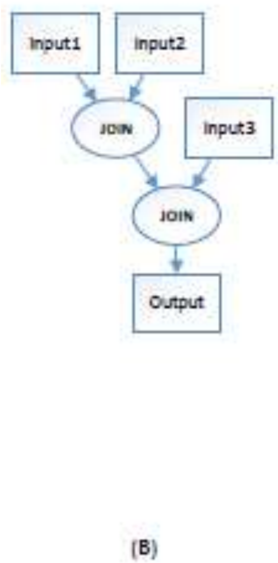
A Microbenchmark (Compute + Data)

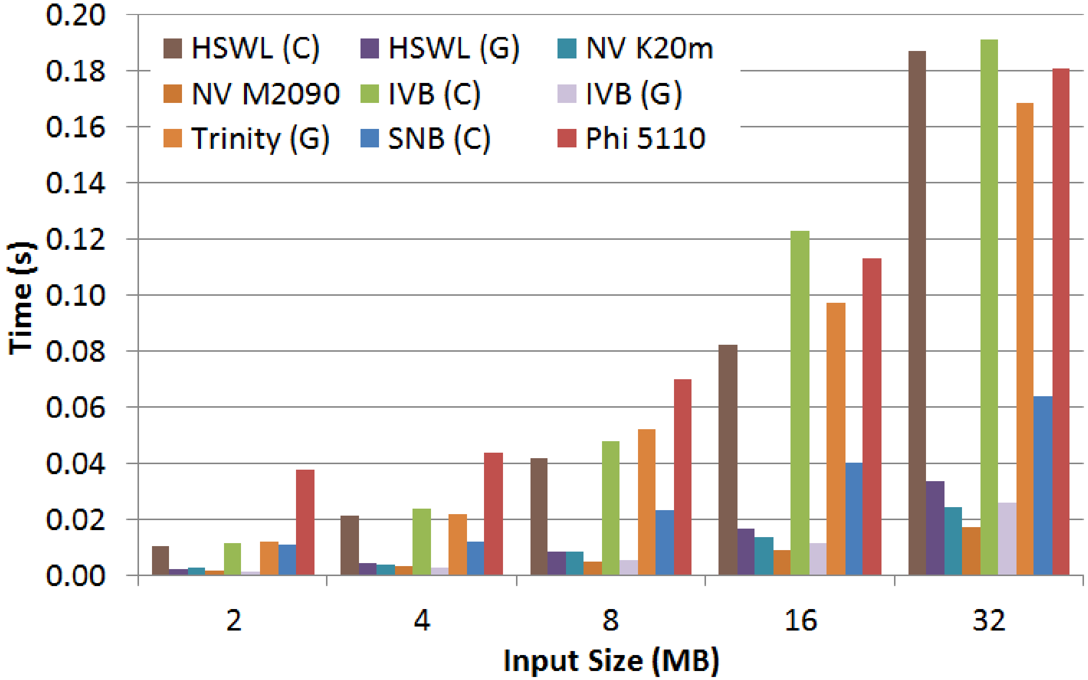


Results mirror select very closely – total runtime of 101 ms (M2090) to 891 ms (Trinity CPU – not shown)

- Subsequent selects operate on device-local data and each iteration, *i*, operates on 0.5i_{-1} input size

B Microbenchmark (Compute)



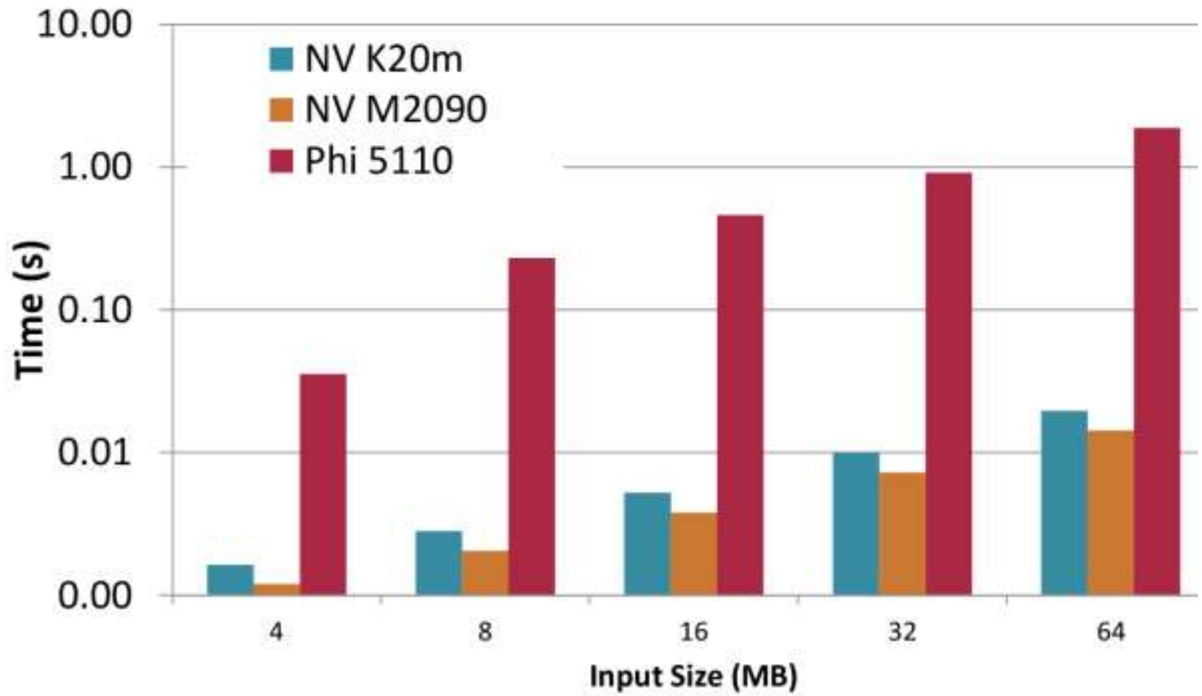


Chained join tracks single Join results linearly due to sequential operations

- 24 ms to 192 ms for 2x32 MB joins

C Microbenchmark (Compute)

(C)



3x64 MB input sets take from less than 20 ms to 1.88 seconds to perform select, join, and project

- Join is the most limiting kernel for Phi performance

Lessons Learned

Common language != optimized code for each platform

- Vendor differences, tuning of code for GPU test platform, bugs in implementations all contribute to widely varied performance across platforms

Architecture trends require further study

- Even in our limited tests, Sandy Bridge compute time was surprisingly low while Xeon Phi was surprisingly slow
- Our speculation is that lack of support for large numbers of work-items and limited vectorization opportunities limited the Phi

Data transfer costs still dominate, especially for small input sets

- In our tests, discrete GPU compute was fastest and data transfer was also relatively low
- However, improved zero-copy semantics make integrated GPUs more appealing for small queries or sub-queries

Future Work

Not just device portability but performance portability

- Needs more profiling!
- Support workgroup sizes specific to each device
- Results demonstrated that initial GPU-focused design limited performance on other platforms

Retest with latest vendor OpenCL stacks

Use primitives to implement full set of TPC-H queries

Investigate scheduling decisions for larger data sets – at what point is crossover from integrated to discrete accelerators worth it?

More Information

Ifrah Saeed's Masters Thesis [7]

More detail on implementation of discussed primitives and all 11 primitives and operators

Red Fox paper [5]

CUDA implementation of TPC-H queries

SHOC alpha release of these benchmarks

www.github.com/jyoung3131/shoc

Still under development, so please feel free to email me if (*when*) you find bugs!

[5] H. Wu, et al, "Red Fox: An Execution Environment for Relational Query Processing on GPUs", CGO 2014
[7] I. Saeed. A portable relational algebra library for high performance data-intensive query processing (MS thesis). https://smartech.gatech.edu/handle/1853/51967, 2014.

Questions?

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F. Schulenburg, https://en.wikipedia.org/wiki/San_Francisco%E2%80%93Oakland_Bay_Bridge#mediaviewer/File:The_two_bridges.jpg