

Distributed/Cluster Computing for Data Stream Mining: Draft Notes

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Abstract

The thesis is focused on elucidating GPU computing feasibility for clustering tasks

Acknowledgements

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Introduction

In real world applications such as industrial monitoring, sensor networks, financial data generate large unbounded streams of data which has to be processed with pre-defined response time. The processors capabilities limit the bandwidth of the stream which can be processed. Parallelizing processing algorithm will increase maximum bandwidth while maintaining the response time requirement.

Chapter 1

General Purpose GPU Computing

Introduction

The modern Graphical Processing Units (GPU) greatly outpace CPUs in arithmetic throughput and memory bandwidth for data-parallel tasks. Since 2001 the efforts were made to port data parallel algorithms to GPUs - first using shader languages such as HLSL, then with the release of Nvidia G80 in 2006 using extensions to C programming language - CUDA[12]. Presently there is a number of programming frameworks targetting specifically GPU architecture such as CUDA[35], OpenCL[11], RenderScript[16], DirectCompute[5] and more generic parallel-processing frameworks such as OpenMP[14] and AMP[3] which provide GPU backend as one of the targets. The differences in the hardware architecture between CPU and GPU is reflected in the programming model of the traditional GPU-specific languages which contain hardware architecture specific language constructs. This chapter provides an overview of GPU architecture, most known programming frameworks, lists limitations of the traditional GP GPU programming, discusses OpenCL 2.0 standard which addresses some of the limitations and Heterogenous System Architecture (HSA) an optimized platform architecture for OpenCL 2.0.

GPU Architecture

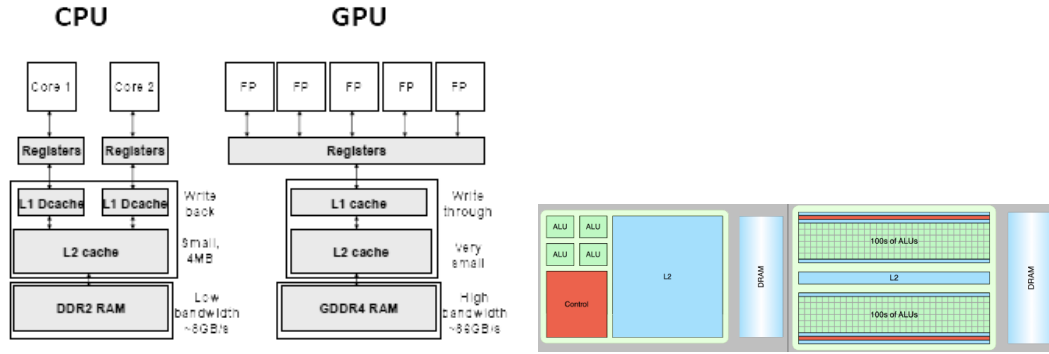


Figure 1.1: CPU versus GPU hardware architecture. Reproduced from NVIDIA GPU ARCHITECTURE and CUDA PROGRAMMING ENVIRONMENT by Alan Tatourian[44]

The main differences between modern CPU and GPU architectures are the level of parallelism and ability to directly address tiered memory. Modern CPU with 2 hex-cores support maximum of 12 threads (24 with hyperthreading) and minimal unit of execution for the NVIDIA GPU (called *wavefront*) is 32 threads. Modern GPUs implement SIMT (Single Instruction - Multiple Thread) execution model (AMD/NVIDIA desktop GPUs) first introduced by NVIDIA in G80 model[12]. The single unit of scalar instructions called *kernel* is scheduled to execute in blocks of data-parallel threads on SIMT hardware. Each instruction in a block is executed in a lock-step. The control divergence is emulated by *masking* - the device executes instructions from both branches of the conditional statement[17][35]. The CPU thread is a heavy-weight entity which is centered around execution of a specific task for an extended period of time. Whenever CPU needs to preempt the thread, the register state is stored and another thread takes over. This makes a context switch a costly operation and operating systems attempt to minimize number of context switches per second. The GPU context switch is an extremely lightweight operation and is routinely used for the latency-hiding - whenever the wavefront is waiting on data, the GPU schedules another wavefront for execution. The GPU registers are private for each thread and are not reallocated until thread execution completes.

Modern CPUs provide a flat view of the operating system memory while GPUs divide memory in tiers based on the access speed:

- *private/register* - private to the current thread
- *local* - shared within a *threadblock*
- *global* - accessible by every thread

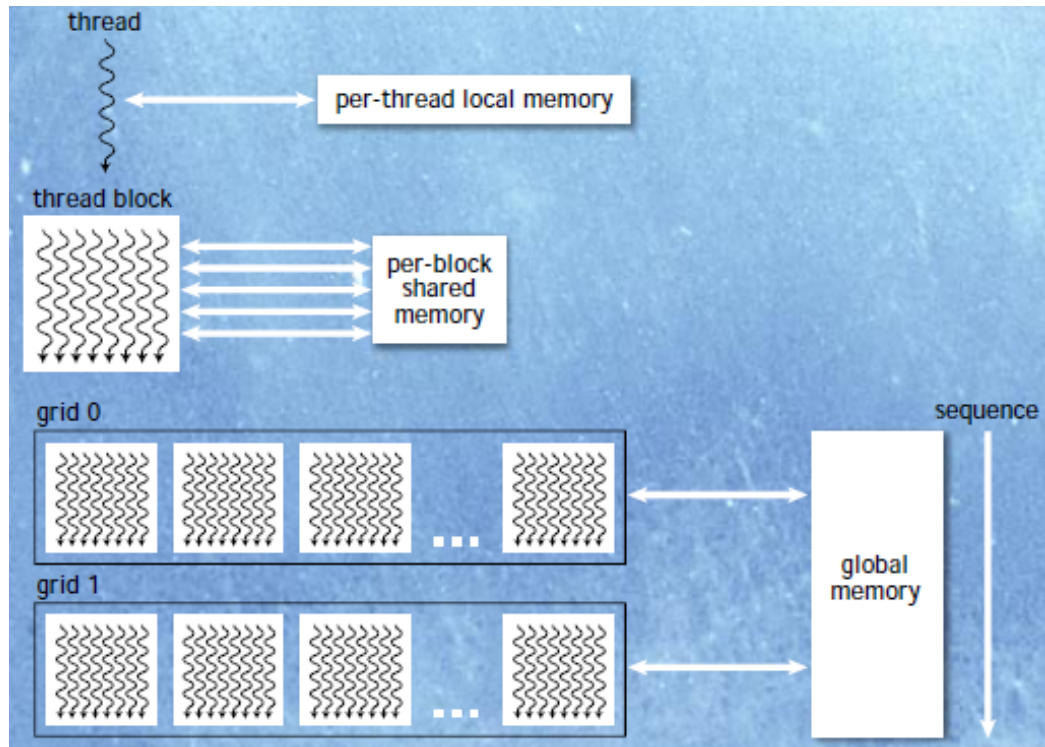


Figure 1.2: GPU Memory Tiers. Reproduced from NVIDIA GPU ARCHITECTURE and CUDA PROGRAMMING ENVIRONMENT by Alan Tatourian[44]

The GPU programming following abstractions:

- *Kernel* - a unit of execution
- *Thread* - a single unit of processed data
- *Threadblock* - a group of *threads* sharing same *kernel* and *local* memory.

The unit of scheduling is called *wavefront* in AMD terminology or *warp* in NVIDIA and typically consists of 32 threads on NVIDIA and 64 on AMD hardware. The GPU chip is equipped with a number of SIMT cores which

execute same instruction for each *warp*. Divergence of control results in under-load of the processing units and reduces performance. The branching should be reduced to wavefront granularity to avoid wasting execution cycles[41][35] It should be noted that the wavefront size is a hardware specific feature and the optimization should be performed at the run-time.

General Purpose GPU Computing Frameworks

Existing General Purpose GPU (GP GPU) computing frameworks can be classified by the level of provided hardware abstraction: high-level frameworks integrate with existing high-level programming language such as Java to provide parallel computing capabilities without exposing any hardware details[13], traditional GPU languages such as CUDA[35] expose task scheduling and memory management giving the expert user fine-tuning capabilities, low level languages provide intermediate binary format compatible with multiple hardware targets. The tree of the GP-GPU technologies is presented in the Figure 1.

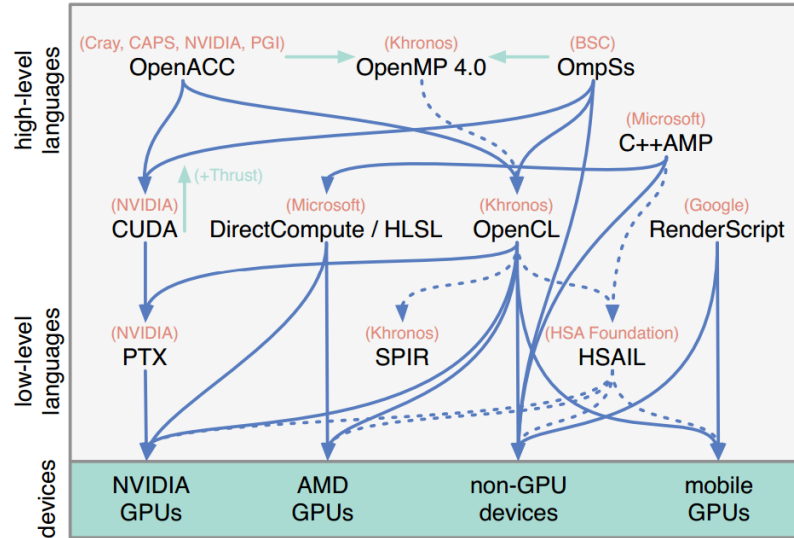


Figure 1.3: GP GPU technologies tree. Reproduced from C. Nugteren, Improving the Programmability of GPU Architecture, p. 21 [37]

High Level Languages

OpenACC and OpenMP are high level parallel programming frameworks that specify a set of annotations, environment variables and library routines for shared memory parallelism in C/C++ and Fortran programs[?][14]. Microsoft C++ AMP[3] is a C++ library which enables parallel computations for CPU and GPUs (using Microsoft DirectX Shading Language) Rootbear GPU compiler provides a transparent compilation of Java code into CUDA[38]. Aparapi provides a way to generate OpenCL kernel code from Java, theoretically allowing code which can be executed on CPU and offloaded to GPU if needed[1]. Project Sumatra is a OpenJDK project which focuses on development of the Hotspot virtual machine capable of offloading JDK 8 Stream API[10] computations to the GPU[13].

GPU-specific Languages

GPU-specific languages provide a programming model consistent with the GPU hardware implementation.

- CUDA - A programming language for NVIDIA hardware based on C language. Kernels are expressed as C-functions for one thread with parallelism defined at run-time by specifying dimensions of execution grid and thread blocks[35]
- OpenCL 1.X builds upon ideas implemented in CUDA by adding device management APIs and providing hardware-agnostic programming specification. OpenCL gives *write once-run anywhere* guarantee but does not give any performance consistency guarantees across different hardware[43].
- RenderScript - Android GPU computing component which uses OpenCL with Java binding programming model - C-style kernels and Java-based control code. RenderScript does not provide any APIs for the *work-*

group size control in the bid to provide performance portability between different devices[16].

- DirectCompute/HLSL - Microsoft Parallel Computing.

Low-Level Languages

The low level assembly representation is used to abstract compiler implementation from the actual hardware since each model or even revision may have a different instruction set. The translation is performed by *Just-In-Time* compiler before the kernel execution. Each vendor provides different low level specifications: NVIDIA CUDA uses Parallel Thread Execution and Instruction Set Architecture (PTX ISA)[15], Khronos Group specifies Standard Portable Intermediate Representation(SPIR)[18], and HSA Foundation specifies Heterogenous System Architecture Intermediate Language (HSAIL)[19].

Limitations

Input Size The massively parallel nature of GPU platforms require a certain amount of data to be passed to the kernel to achieve maximum performance. Table 1.1 shows execution time of a kernel which assigns index to each array element $X_i = i$ on AMD A8-7600. The execution time starts to increase when input size is above 1024 and remains constant for lower values. To maximum performance on AMD A8-7600 will be achieved when input size will exceed 1024 elements.

Global Size	256	512	768	1024	1280	2560	3072	3584	4608	4864
Execution Time (μ sec)	8	8	8	8	9	9	10	11	11	12

Table 1.1: Input Size and Execution Time

GPU Memory Size and Host-GPU Transfer The discrete GPU requires transfer of data from the host to the GPU memory which adds additional overhead to the computations and requires task partitioning according to the mem-

ory specification of GPU[40]. Memory transfer is a bottleneck for Aparapi and its developers allow explicit memory management[1]. This effectively reduces framework which promises CPU-GPU interoperability to the Java wrapper of the OpenCL API.

Kernel Launch There is a constant time needed to setup kernel launch which might offset any gain from parallelization if the data can be processed sequentially faster.(NB. Amdahl's law) It is impossible to schedule kernel execution from within the kernel itself requiring a mix of kernel and host code if several iterations are required.

OpenCL 2.0

OpenCL 2.0 standard[11] introduces several features which attempt to address limitations of GPU programming:

- Shared Virtual Memory - both host and kernel code share same address space thus either hiding memory transfers (discreet GPU driver stack) or if backed by the hardware architecture such as HSA eliminate its need[19]
- Dynamic Parallelism - OpenCL 2.0 allows scheduling of kernels from within a kernel without host interaction reducing host CPU bottleneck.
- Pipes - pipes feature allows passing data from kernel to kernel without processing the whole input which allows to obtain the results of computation faster.

HSA Platform

AMD introduced Heterogeneous System Architecture platform as an optimized platform architecture for OpenCL 2.0. Its specification introduces a set of requirements that allow both GPUs and CPU share same memory space, synchronize execution using signals and atomics and schedule execution both from

GPU and CPU[19]. Task execution is performed by *agents* which represent CPU or GPU nodes. The task execution is scheduled via *queues* and synchronized using *signals*. HSA memory model guarantees sequential consistency for the correctly synchronized programs.

Software Available: At the moment (Feb 2014) there is a OpenCL 2.0- \mathcal{H} SAIL compiler available[8] and a Linux-based runtime environment[7].

HSA Queues

HSA uses queues to schedule code execution. A HSA *queue* is a ringbuffer which contains *packets* with either call or synchronization parameters. The queue maintains two indexes - read index and write index. Write index is modified by the user and used to submit packets to the queue. The read index is updated by the packet processor whenever the packet is taken for execution. As soon as packet is written to the queue the ownership is taken by the HSA packet processor and it may change packet contents at any time[19]. Compared to traditional dispatch where the execution is scheduled via user-mode and kernel-mode driver layers the HSA dispatch intends to be lightweight and source-agnostic way of scheduling execution. The HSA Queues support work-stealing that is several HSA agents may be attached to the queue to share the workload.

HSA Signals

HSA uses *signals* to perform synchronization between host and kernels being executed or to signal completion of the task. A *signal* is essentially a shared memory variable modified by the HSA agent. Runtime environment provides a way to check the value of the signal or wait for the specific value.

HSA Memory Model

The sequential consistency was first defined by L. Lamport as “..the result of any execution is the same as if the operations of all the processors were

executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program.” Modern processors (ARM, x86, Itanium, POWER) introduce relaxed memory model to allow a range of the hardware optimizations to provide better performance by reordering load and store operations[31]. Platform specification states

The HSA memory consistency model is a relaxed model based around RCsc semantics on a set of synchronizing operations. The standard RCsc model is extended to include fences and relaxed atomic operations. In addition HSA includes concepts of memory segments and scopes.

[19] Similiar to Java Memory Model[?] it guarantees sequential consistency for the correctly synchronized programs, that is 'synchronizing operations meet the requirements for sequential consistency within each scope/segment instance'[19]. The specification introduces several memory segments: “

- Global segment, shared between all agents.
- Group segment, shared between work-items in the same work-group in a HSAIL kernel dispatch.
- Private, private to a single work-item in a HSAIL kernel dispatch.
- Kernarg, read-only memory visible to all work-items in a HSAIL kernel dispatch.
- Readonly, read-only memory visible to all agents

” Each particular memory location is always associated with one and only one segment and all operations apply to only one segment with the exception of fence operations[19]. In addition to memory segments HSA memory model introduces *scopes* : wavefront, work-group, component and system. They can be used to reduce visibility of the memory operation compared to the default supported by the segment. The global segment may use any of the specified scopes and group segment is limited to wavefront and workgroup scopes[19]. Different workgroups accessing a global variable with the workgroup scope

will work with different instances of the variable. The write serialization only applies to the operations within the segment/scope that they specify.

Implementation Notes

Sequential execution of several packets sometimes may be faster than submission of all packets and waiting for the barrier packet. For instance first scenario runs in 8 μsec per packet on AMD A8-7600 and second results in 193 μsec per packet. According to AMD support this is caused by the CPU going into power-saving mode while kernel is running. There is a constant time needed to setup kernel launch, e.g. for AMD A8-7600, it is 6 μsec using HSA.

Conclusion

The modern specifications such as OpenCL 2.0 and HSA attempt to address some of the latency issues of the GPU programming by introduction of the shared memory and lightweight dispatch and data passing mechanisms. This work will focus on the evaluation of suitability of those technologies for the latency-sensitive data stream processing.

Chapter 2

System Architecture

The implemented data stream processing library provides a set of classification algorithms for Massively Online Analysis(MOA)[21]. The library uses existing linear algebra package ViennaCL[45] which allows multiple backends such as CUDA, OpenCL, CPU and extends it with the machine learning algorithms such as nearest neighbours search and stochastic gradient descent.

MOA interface The ViennaCL library is implemented in C++ and as such requires Java Native Interface[9] to be used to interface from the Java Virtual Machine. Java Virtual Machine manages its own memory space and garbage collector may move the data at any time. JNI provides two mechanisms to access the array data from the native code. First is copying - the java pointer is locked by the critical section array content is copied to the native array. Second skips the copying and provides direct access to the java pointer. Both involve entering and exiting a critical and impose significant performance loss due to the copying and locking overhead. *add data* Those costs can not be avoided but can be minimized by moving them to the instance creation/modification time - the object constructor will call the native method which allocates the native data structures and moves data from the Java storage to the native one.

Native Storage The library implementation stores the instance data as the native ViennaCL types. This implies that for GPU ViennaCL backends the data

will be stored in GPU memory that may be insufficient for the larger problems. In such case the partitioning will be used - the problem data is kept in the main memory and offloaded to GPU-backed context on as needed basis.

HSA Backend This work adds a new HSA backend to the ViennaCL library based on the HSA Runtime[19]. This implementation is tuned for Kaveri AMD APU and uses the same set of OpenCL kernels as the OpenCL backend. In HSA backend the main system memory is transparently mapped to GPU and vice-versa, allowing to use vector or matrix element-addressing operations without first copying data to the CPU memory space.

OpenCL 2.0 features At the time of writing (driver version 1642.5) the OpenCL 2.0 features such as workgroup functions and device enqueue impose significant performance impact and can not be used for the performance computing. Atomic locks do not result in significant performance impact. ViennaCL should be extended to provide pre-processor option to compile with Shared Virtual Memory buffers.

Chapter 3

k-Nearest Neighbours

Problem Statement

k-Nearest Neighbours method is a non-parametric method used for the classification and regression. It computes a given instance distance to the examples with the known label and either provides a class membership for the classification which is a class most common among nearest neighbours or an object property value which is an average of the nearest neighbours. The error rate bound by the twice the Bayes error if the number of examples approaches infinity. The naive approach computes distance to each example and has computational complexity $O(N^d)$ where N - number of examples and d - cardinality of the example. The method optimizations deal with organizing the search space to reduce complexity associated with distance calculation. Examples would be branch and bounds methods such as kd-tree that partition search space, and approximate methods, e.g. locality sensitivity hash that simplifies the distance function by mapping instances into lower dimensional space. In relation to data stream classification there are two problems:

- Forward k-NN - for an given sliding window of examples find classification of the variable query
- Reverse k-NN - for a given fixed query form a window of examples nearest to it. This approach is discussed in Efficiently Processing Continuous k-

NN Queries on Data Streams[22].

There is a number of implementations of the offline k-NN algorithm for GP-GPU: brute force approach[24][28][27][40], kd-tree[26][46] and approximate [33][29].

Brute force The brute force approach consists of distance calculation and selection phase. The distances to the query are computed as a vector-matrix multiplication or if several queries are processed at once as a matrix-matrix multiplication. GPU implementation of those routines is available as a part of libraries implementing BLAS[6][4][45]. The selection phase finds nearest to the query out of all the computed distances. Sismanis et. al[40] provide time complexity of reduced sort algorithms and evaluates their performance on GPU, proposes to interleave distance calculation and sorting phases to hide latency - the data for the distance calculation should be offloaded to GPU while it performs the sorting phase. The input data in the brute-force approach is partitioned according to the GPU memory capabilities and does not use examples's spatial information.

KD-tree The massive parallelism of GPU can be exploited by using breadth-first approach when building the kd-tree. The space is first partitioned into regions and then the local subtrees are constructed in parallel[46][39]. The kd-tree approach presented by Gieske et. al focuses on parallel execution of nearest neighbour queries in a lazy fashion. The query points are accumulated in the leaf nodes of the kd-tree until enough of them is present and then processed as a batch. This solves an issue of the GPU underutilization and low performance if leaf nodes are processed sequentially for each example[26].

Locality Sensitive Hashing

Algorithm Implementations

Brute-Force Approach The algorithm maintains a sliding window of examples, calculates distance to the query point for each example and sorts them according to the least distance selecting nearest k neighbours.

Sliding Window The sliding window is implemented as a FIFO cyclic buffer. The OpenCL implementation uses partial mapping of the buffer to reduce memory transfers.

Distance Calculation The distance calculation between query vector and sliding window is a vector by matrix multiplication operation. For the dense matrices the implementation performs a serial computation of the distance, each thread working on its own example. Since all the threads process attributes in exactly same order there is no wavefront divergence. This is not the case for the sparse matrices and this approach will cause GPU underutilization.

The optimal implementation depends on the size of the window and number of attributes present[42]. For the small instance size (≤ 100) and windows less than 10^4 elements naive implementation will provide the best solution. Best all around distance calculation should apply different strategies depending on the window size and number of attributes[42]. The alternatives are presented in the Figure 3.1.

Selection Alabi, et.al evaluated different selection strategies based on bucket sort algorithm and Merrill-Grimshaw implementation of radix sort[20].

The selection phase may be interleaved with the distance calculation to utilize both CPU and GPU cores and benefit from the better sort performance on low window sizes[34].

The work needs to provide several alternative selection strategies such as Merrill-Grimshaw radix sort[32] or k-bucket Selection[20] to provide alternative GPU selection strategy.

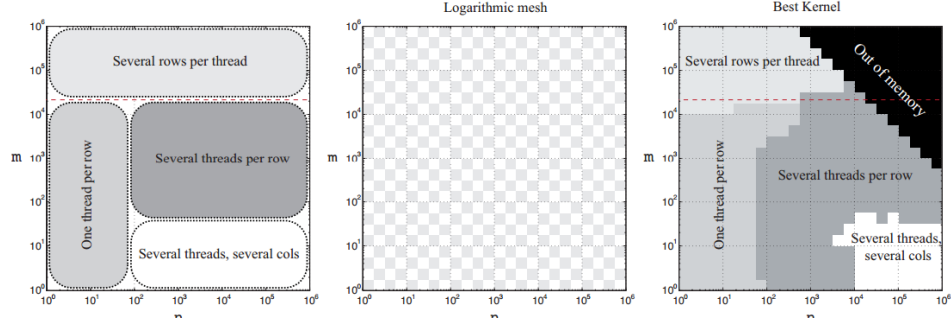


Figure 3.1: Left; Four matrix-vector multiplication kernels designed to perform well at different shapes $m \times n$ of A . Middle; Tuning mesh. Right; Best kernel in practice. The dashed line indicates the minimum 21504 rows needed in A for full occupancy of the Nvidia Tesla C2050 card in a one-thread-per-row kernel. Note the logarithmic axes.. Reproduced from High-Performance Matrix-Vector Multiplication on the GPU by Hans Henrik Brandenburg Sørensen[42]

Figure 3.2 shows measured performance of different selection strategies - merge sort from AMD Bolt library[2], bitonic sort similar to reference AMD implementation and radix select based on Alabi, et. al. implementation[20]. The CPU sort and choose is a clear winner for small (≤ 535) window sizes. The merge sort should be applied to sub 2^{25} windows and radix select (with data copy) should be used for larger window sizes. *TODO*: The work should investigate in-place radix select and device enqueue for radix select optimization. *TODO*: Radix select shows a semi-flat line up to 2^{23} window size. The implementation should be checked for excessive setup.

KD-Tree based k-Nearest Neighbours Search The KD-Tree nearest neighbours search is composed of parallel tree construction over fixed set of instances and evaluation.

Parallel Tree Construction The input to the algorithm is the matrix containing example instances and the desired tree depth. The tree nodes contain row numbers of the associated instances, split attribute, split value and ranges for the associated instances. The tree split is performed iteratively until the desired tree depth is reached. First the ranges are updated for each tree node using kernel based on Bolt max element kernel[2]. The kernel finds

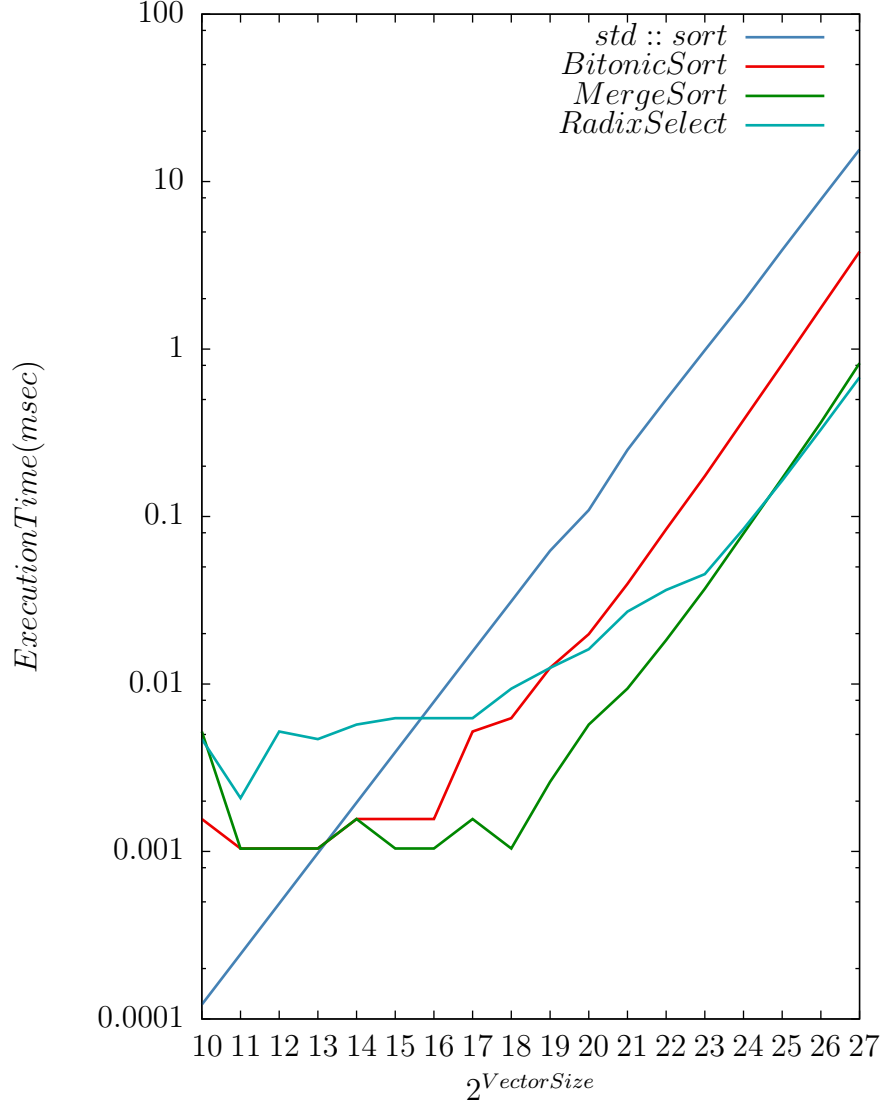


Figure 3.2: Selection Algorithm Performance for K=128. Test configuration GPU R9 390, CPU AMD A8-7600, AMD Catalyst version 15.20.

ranges for a given attribute for each of the nodes in a tree. A split dimension and point is chosen using the CPU routine. A mark kernel composes two flag vectors - one for the left child, other for the right one, a scan is performed to compute offsets and then the child nodes are populated with the indices of the instances belonging to them. *TODO Picture*

Evaluation The evaluation uses same distance calculation kernel as the Naive Implementation. The evaluation can be either performed sequentially - a recursive algorithm similar to the [21] implementation or several query instances can be scheduled at once. In this case the progress of each individual

query instance is tracked by the bit vector containing the tree path processed so far, current node number and current found nearest neighbours. The algorithm alternates between invoking kernels for leaf node distance calculation and split plane distance calculation until all query instances are fully processed. *TODO Diagram*

LHS based k-Nearest Neighbours Search *TODO*

Chapter 4

Stochastic Gradient Descent

Problem Statement

The stochastic gradient descent is a iterative optimization method which approximates a gradient of the function by a gradient of a single example. The stochastic gradient descent is widely in many machine learning tasks and is a standard algorithm used in training neural networks.

The parallel implementations of the algorithm use either assumption that data in the training batch is loosely coupled and it is possible to loose some of the individual updates thus the batch can processed in parallel - Hogwild! algorithm [36] or extract independent data blocks from the traing batch - DSGD[25], FPSGD[23] or arbitrary divide the examples into parts processed in parallel and approximate the direction of the gradient descent [30] using weight update vectors produced by them.

Algorithm Implementation

The implementation relies on the fact that the weights vector can be updated without locking since the training instances are sparse and each instance contributes to a different part of the weights vector[36].

Chapter 5

Experimental Results

k-Nearest Neighbours

kNN Naive implementation

The first version of k-NN algorithm used Java implementation with JavaCL library. The results in Figure 5.1 provide overview of the achieved speedups.

TODO

Stochastic Gradient Descent

Good benchmarks: HSA Hogwild! with batching
Bad benchmarks: HSA Hogwild! without batching

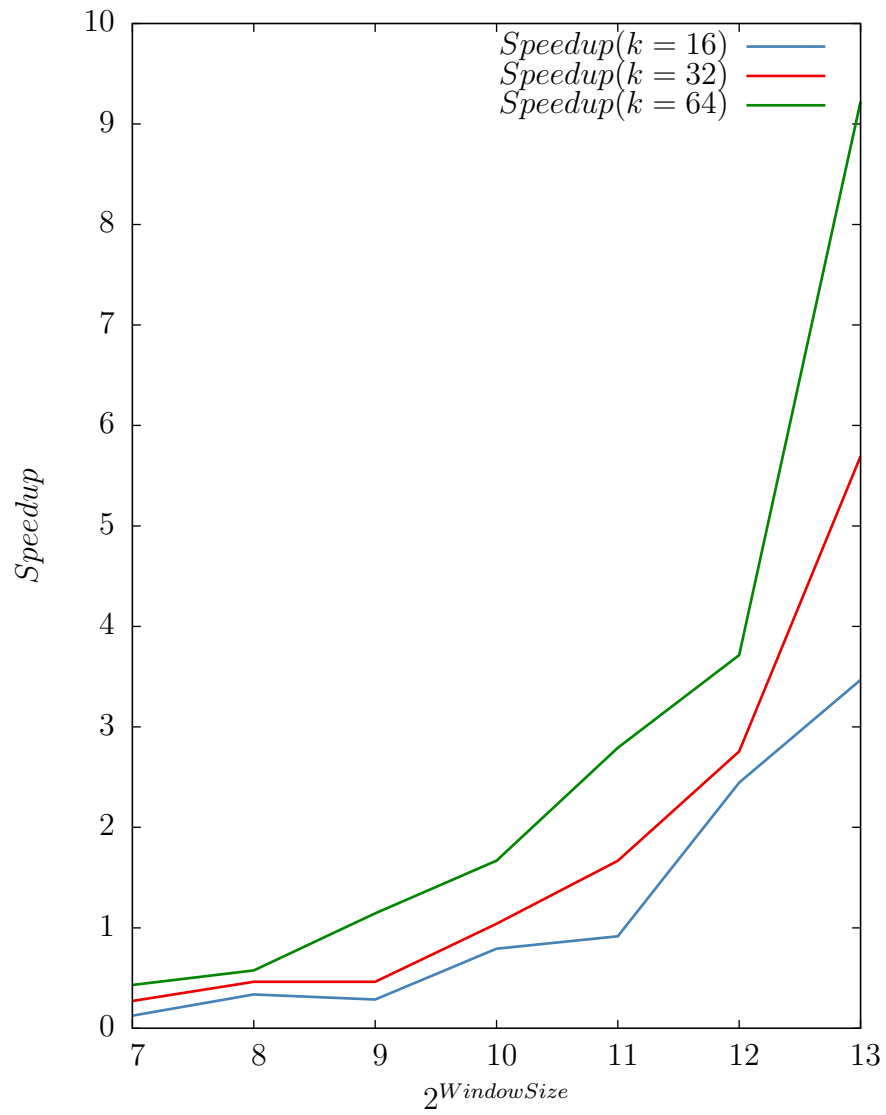


Figure 5.1: Naive KNN implementation (Radeon Mobility HD5730)

Chapter 6

Conclusions and Future Work

TODO

References

- [1] aparapi - api for data parallel java. allows suitable code to be executed on gpu via opencl.
- [2] Bolt c++ template library.
- [3] C++ amp overview.
- [4] clmath - amd.
- [5] Compute shader overview.
- [6] cublas.
- [7] Hsafoundation.
- [8] Hsafoundation/cloc.
- [9] Java se 7 java native interface-related apis and developer guides.
- [10] java.util.stream (java platform se 8).
- [11] Khronos opencl registry.
- [12] Nvidias next generation cuda(tm) compute architecture:fermi.
- [13] Openjdk: Project sumatra.
- [14] Openmp.org.
- [15] Ptx isa :: Cuda toolkit documentation.
- [16] Renderscript—android developers.
- [17] Single instruction, multiple threads.
- [18] Spir - the first open standard intermediate language for parallel compute and graphics.
- [19] Hsa platform system architecture specification, 2014.

-
- [20] Tolu Alabi, Jeffrey D. Blanchard, Bradley Gordon, and Russel Steinbach. Fast k-selection algorithms for graphics processing units. *J. Exp. Algorithmics*, 17:4.2:4.1–4.2:4.29, October 2012.
 - [21] Albert Bifet, Geoff Holmes, Richard Kirkby, and Bernhard Pfahringer. Moa: Massive online analysis. *J. Mach. Learn. Res.*, 11:1601–1604, August 2010.
 - [22] C. Bohm, Beng Chin Ooi, C. Plant, and Ying Yan. Efficiently processing continuous k-nn queries on data streams. In *Data Engineering, 2007. ICDE 2007. IEEE 23rd International Conference on*, pages 156–165, April 2007.
 - [23] Wei-Sheng Chin, Yong Zhuang, Yu-Chin Juan, and Chih-Jen Lin. A fast parallel stochastic gradient method for matrix factorization in shared memory systems. *ACM Trans. Intell. Syst. Technol.*, 6(1):2:1–2:24, March 2015.
 - [24] A. Dashti. Efficient computation of k-nearest neighbor graphs for large high-dimensional data sets on gpu clusters.
 - [25] Rainer Gemulla, Erik Nijkamp, Peter J. Haas, and Yannis Sismanis. Large-scale matrix factorization with distributed stochastic gradient descent. In *Proceedings of the 17th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, KDD '11*, pages 69–77, New York, NY, USA, 2011. ACM.
 - [26] Fabian Gieseke, Justin Heinermann, Cosmin Oancea, and Christian Igel. Buffer kd trees: Processing massive nearest neighbor queries on gpus. In *Proceedings of The 31st International Conference on Machine Learning*, page 172180, 2014.
 - [27] Kimikazu Kato and Tikara Hosino. Solving k-nearest neighbor problem on multiple graphics processors. In *Proceedings of the 2010 10th IEEE/ACM International Conference on Cluster, Cloud and Grid Computing, CC-GRID '10*, pages 769–773, Washington, DC, USA, 2010. IEEE Computer Society.
 - [28] Quansheng Kuang and Lei Zhao. L.: A practical gpu based knn algorithm. In *In Proceedings of the Second Symposium on International Computer Science and Computational Technology (ISCST 09) (Dec. 2009)*, Academy Publisher, pages 151–155.
 - [29] Tieu Lin Loi, Jae-Pil Heo, Junghwan Lee, and Sung-Eui Yoon. Vlsh: Voronoi-based locality sensitive hashing. In *Intelligent Robots and Systems*

- (*IROS*), *2013 IEEE/RSJ International Conference on*, pages 5345–5352, Nov 2013.
- [30] Dhruv Mahajan, S. Sathiya Keerthi, S. Sundararajan, and Léon Bottou. A parallel SGD method with strong convergence. *CoRR*, abs/1311.0636, 2013.
 - [31] Luc Maranget, Susmit Sarkar, and Peter Sewell. A tutorial introduction to the arm and power relaxed memory models, 2012.
 - [32] Duane Merrill and Andrew S. Grimshaw. High performance and scalable radix sorting: a case study of implementing dynamic parallelism for gpu computing. *Parallel Processing Letters*, 21(2):245–272, 2011.
 - [33] Marius Muja and David G. Lowe. Scalable nearest neighbor algorithms for high dimensional data. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 36, 2014.
 - [34] Jatin Chhugani Anthony D. Nguyen Victor W. Lee Daehyun Kim Pradeep Dubey Nadathur Satish, Changkyu Kim. Fast sort on cpus,gpus and intel mic architectures.
 - [35] John Nickolls, Ian Buck, Michael Garland, and Kevin Skadron. Scalable parallel programming with cuda. *Queue*, 6(2):40–53, March 2008.
 - [36] Feng Niu, Benjamin Recht, Christopher R, and Stephen J. Wright. Hogwild: A lock-free approach to parallelizing stochastic gradient descent. In *In NIPS*, 2011.
 - [37] C. Nugteren. Improving the programmability of gpu architectures, 2014.
 - [38] P.C. Pratt-Szeliga, J.W. Fawcett, and R.D. Welch. Rootbeer: Seamlessly using gpus from java. In *High Performance Computing and Communication 2012 IEEE 9th International Conference on Embedded Software and Systems (HPCC-ICESSE)*, *2012 IEEE 14th International Conference on*, pages 375–380, June 2012.
 - [39] Maxim Shevtsov, Alexei Soupikov, and Er Kapustin. Highly parallel fast kd-tree construction for interactive ray tracing of dynamic scenes.
 - [40] N. Sismanis, N. Pitsianis, and Xiaobai Sun. Parallel search of k-nearest neighbors with synchronous operations. In *High Performance Extreme Computing (HPEC)*, *2012 IEEE Conference on*, pages 1–6, Sept 2012.
 - [41] T. Aila S.Laine, T. Karras. Megakernels considered harmful: Wavefront path tracing on gpus.

- [42] Hans Henrik Brandenborg Sørensen. High-performance matrix-vector multiplication on the gpu. In *Proceedings of the 2011 International Conference on Parallel Processing*, Euro-Par'11, pages 377–386, Berlin, Heidelberg, 2012. Springer-Verlag.
- [43] John E Stone, David Gohara, and Guochun Shi. Opencl: A parallel programming standard for heterogeneous computing systems. *Computing in science & engineering*, 12(1-3):66–73, 2010.
- [44] Alan Tatourian. Nvidia gpu architecture and cuda programming environment.
- [45] Philippe Tillet, Karl Rupp, Siegfried Selberherr, and Chin-Teng Lin. Towards performance-portable, scalable, and convenient linear algebra. In *Presented as part of the 5th USENIX Workshop on Hot Topics in Parallelism*, Berkeley, CA, 2013. USENIX.
- [46] Kun Zhou, Qiming Hou, Rui Wang, and Baining Guo. Real-time kd-tree construction on graphics hardware. *ACM Trans. Graph.*, 27(5):126:1–126:11, December 2008.