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Exploratory research on embedding CUDA code into heterogeneous MP-SOC architectures programmed with the Daedalus framework

Rick van der Zwet

BACHELOR’S THESIS
Leiden Institute of Advanced Computer Science (LIACS)
Leiden University
Niels Bohrweg 1
2333 CA Leiden
The Netherlands
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Rick van der Zwet
<hvdzwet@liacs.nl>
Leiden Institute of Advanced Computer Science, The Netherlands
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Abstract

The objective of this Bachelor Thesis is to explore the possibilities of using NVIDIA CUDA enabled GPU Processors within the HDPC framework. The HDPC framework is one of the heterogeneous MP-SoC architectures programmed with the Daedalus framework.

This paper will focus on the transfer overhead introduced by using the GPU and how to best cope with this introduced latency.

In this study it was found that using the GPU instead of the CPU, the overall execution times will decrease if the execution pattern has specific characteristics with regards to token size and processing complexity.

1 Introduction

Traditionally computation is the domain of the general purpose CPUs, but new computation stars are arising on the horizon. Starting from 2007 NVIDIA has released the NVIDIA Compute Unified Device Architecture (CUDA)
framework. This framework allows programming on a CUDA enabled NVIDIA Graphics Processing Unit (GPU).

The GPU uses specialized co-processors to offer specialized computation methods for highly parallel computations claiming faster computation times with regards to the CPU. The faster computation time is achieved by partitioning a (multi-threaded) program into blocks of threads that execute independently from each other.

The GPU is not meant as replacement for the CPU, but to be used in Stream Processing. This means that the GPU needs a supporting CPU for control and setup. The supporting CPU offloads specific computing tasks to the GPU and processes the results from the GPU. This specific computing tasks on the GPU are based on Single Instruction, Multiple Data (SIMD). SIMD is used to exploit data level parallelism [Flynn1972].

The co-processors on the GPU do not share memory with the CPU. The CPU has its DDR memory located on the motherboard \( (^1}\) (Host Memory) and the GPU has its own dedicated DDR memory which is located on the GPU itself (Device Memory).

As the GPU and the CPU do not share memory, memory transfers are needed to transfer the data from the Host Memory to the Device Memory and back. These transfers need to be processed by the communication channel between the GPU and the mainboard.

There are multiple technologies in use to connect the GPU to the mainboard. The GPU is normally connected to the motherboard using a The Peripheral Component Interconnect Express (PCIe) bus or Accelerated Graphics Port bus (AGP). The AGP GPU cards are not worth considering as their (Device to Host) bandwidth is roughly 10 times lower than the PCIe. \(^2\)

To make sure the GPU processing is faster than the CPU equivalent, the time needed by the PCIe communication channel to transfer the data should not exceed the speedup gained by the highly parallel execution on the GPU.

The GPU has a fixed amount of Device Memory available. A computation which needs more memory requires the data to be split. The resulting data chunks need to be well-balanced with regards to transfer time and com-

\(^1\)The motherboard is also called mobo, mainboard, system board or logic board.

\(^2\)http://en.wikipedia.org/wiki/List_of_device_bandwidths
putation time. Making the data chunks too big will cause the GPU to spend most of the time waiting for the data to transfer. Making the data chunks too small will cause the GPU being busy doing many small transfers and not actually making efficient computations.

Now consider a program designed as a Kahn Process Network (KPN), a model of computation introduced by Dr. Gilles Kahn [Kahn1974]. This KPN has computation components (processes) which are connected via communication channels. In a KPN there is no notion of a global schedule that dictates the relative order of execution.

To make the program running as fast as possible it is advised to run a process on the most suitable hardware platform available. This takes both communication speed and the type of the communication channel into account.

Now consider a KPN which has two processes which are connected via one communication channel. Both processes are scheduled to run on the CPU sharing the Host Memory. Passing a Host Memory pointer between two CPU processes reduces the communication channel overhead to almost 0. However, if one process is scheduled on the GPU and the other is scheduled on the CPU the communication channel time overhead is non-trivial.

The right chunk size of data which is transferred at ones and the number of such data chunks, transferred during the execution of the program have (great) impact on the performance of the GPU. Finding the right balance between these factors is critical to consider the GPU as computation platform next to the alternatives available.

To allow every computation component in the KPN to be executed on a specific platform, glue-code is needed to connect them together. For a general purpose computer architecture such as Intel and AMD x86(-64) this glue-code is provided by the Heterogeneous Desktop Parallel Computing (HDPC) framework developed at LIACS [Far08]. HDPC currently supports the hardware platforms CPU, GPU, Field Programmable Gate Array (FPGA) and Cell Broadband Engine Architecture (Cell BE) to be used for process execution. The HDPC framework is depicted in Figure 1 and discussed in more detail in Section 2.1.

The HDPC framework uses as input a generated KPN by the Daedalus framework developed at LIACS [DAC2008]. The Daedalus framework is able to convert a sequential C/C++ program to parallel KPN. The Daedalus
framework in this paper will be used to generate our experiment KPN. The HDPC framework has to choose on which platform to place a process for execution. Due to the balance problem mentioned above, the choice to use the GPU or CPU for execution of a process is challenging.

This Bachelor Thesis will explore the proposed techniques of embedding CUDA code into the Daedalus framework by [Far08]. By exploration this Bachelor Thesis will find out if the CUDA enabled NVIDIA GPU can be used in the Daedalus framework to speedup the overall computation time.

The results of this exploratory research can also be used by programmers who want to take maximum advantage of the capacities of the GPU architecture.

The document is organized as follows; Section 2 will introduce the CUDA and HDPC terminology. The problem itself will be explained in Section 3 to continue with computation of theoretical values in Section 4. Testing will be done with the test setup depicted in Section 5 and implemented using Section 6. All experimental results are found in Section 7 explaining the differences between the theoretical values and the experiment results. Experiment conclusions are found in Section 8. And finally recommendations will be given for further research in Section 9.

2 Background

2.1 HDPC

Specifying an application using a parallel Model of Computation (MoC) such as the KPN MoC, is a time-consuming and error prone task which is currently not well understood by developers. Therefore, we need tools that allow us to continue writing sequential programs and automatically derive parallel specifications.

The Daedalus framework tools developed at LIACS are designed for this purpose. The pn tool generates a KPN from a sequential C/C++ program. The Embedded System-level Platform Synthesis and Application Mapping (Espam) tool will use the generated KPN together with the platform and mapping specification as input. The Espam tool generates several autonomous
Figure 1: An HDPC framework example. A KPN running on our framework with three interconnected processes, A, B, and C all execute their functions on a device connected to the same machine. Communication channels and the FIFO mechanism are implemented in main system memory (Host Memory) and are under control of HDPC code. Transfer of data between different devices happens by reading from the Device Memory associated with the processing node into Host Memory, then writing this data in due time to the Device Memory of the consuming node. In the case of execution on the CPU this transfer is either simply a memory copy or a pointer change as all data is in the same address space. Picture taken from [Far08, pg.4]

processes that transfers data between each other through FIFO communication channels. The Daedalus framework is depicted in Figure 2.

HDPC uses above mentioned tools and generates code for a general purpose computer such as the Intel or AMD x86(-64). The processes of a KPN can then execute on a heterogeneous multitude of platforms.

HDPC extends upon Espam by generating back-end code for a desktop computer that acts as the controlling and coordinating arbiter between the processes of a KPN. The processes can then execute not only on the CPU cores but also on various computing devices like the FPGA, Graphics Pro-
Figure 2: Daedalus grand overview

ccessing Unit (GPU), or the Cell B.E. to take advantage of their respective strengths.

For each process in a KPN, a thread on the host CPU is created. If computations inside the node are executed on the host machine, the CPU (of a multi-core system) is used for the actual computation. For external devices like the GPU, the host thread is only responsible for control flow, transfer of data to- and from the device and starting execution of the computation on the device; nothing more.
2.2 CUDA

NVIDIA offers the CUDA Software SDK allowing programming on the GPU free of charge in binary format, the source code is not provided. The binary format introduces some difficulties with regards to optimizations and limit calculations as the CUDA Software SDK is essentially a black box, where internal implementation on new releases might change without notice [Hallhill2008].

CUDA is a general purpose parallel computing architecture that leverages the Parallel Compute Engine in NVIDIA GPUs using the CUDA Instruction Set Architecture (ISA) and the Parallel Compute Engine in the GPU.

The ISA and the Parallel Compute Engine vary between releases of GPUs. To provide a unified programming interface with backward compatibility the CUDA GPU driver and the CUDA SDK provides a programming interface for the developer. This allows the developers to perform parallel programming on NVIDIA CUDA enabled GPUs, without the need of releasing a new version for every new release of the CUDA driver or software.

The more cores the GPU has the less time it needs to execute the program as threads can be scheduled on more cores. This advantage is shown in Figure 3.

To program the CUDA architecture you will have to use C with CUDA specific extensions, which will be processed by NVIDIA provided PathScale Open64 C compiler and you will also need to have a NVIDIA compatible GPU installed with the correct driver version. For debugging purposes the software can be compiled to run in a simulation mode, which is executed on the CPU only. The simulation mode executes very slow on the CPU, but makes it possible to follow the execution path and spot errors on memory reference for example.

There are 2 levels on which you can program CUDA code, the so called high-level API and the low-level API. As those names suggest, the low-level is used for more control over the code, but it also requires a fair amount of bookkeeping to make sure the processes keep data synchronized and consistent.

In order for the CUDA GPU to allow calculation it (1) needs to transfer the data from the Host Memory to its own Device Memory (2) Initiate the
Figure 3: A GPU with more cores will automatically execute the program in less time than a GPU with fewer cores.

computation (3) and do the actual computation. (4) On completion transfer the data back from the Device Memory to the Host Memory. This flow is depicted in Figure 4.

For more background information refer to the CUDA Getting Started Guide [CUDA-GS] and CUDA C Programming Guide [CUDA-PG].

3The original figure is CC-BY Tosaka and found at [http://en.wikipedia.org/wiki/File:CUDA_processing_flow_%28En%29.png](http://en.wikipedia.org/wiki/File:CUDA_processing_flow_%28En%29.png)
3 Problem description

We want to execute a simple program Producer ⇒ Calculator ⇒ Consumer, modeled as KPN, with processes and communication channels as depicted.
Figure 5: The design of Producer ⇒ Calculator ⇒ Consumer using 3 processes (Consumer, Calculator and Consumer) and 2 FIFO communication channels, including pseudo-code implementation of the processes.

In Figure 5, in this program there is single process Producer and a single process Consumer which will be executed on the CPU. The single process Calculator in the Producer ⇒ Calculator ⇒ Consumer program however will be executed either on the GPU or the CPU.

Within the program Producer ⇒ Calculator ⇒ Consumer the Producer generates a fixed amount of entries (ENTRY_COUNT). These entries are packed in tokens with each token containing a specific amount of entries (TOKEN_SIZE). As soon as a token is ready it will be written to the first communication channel. The Producer will repeat this process till a fixed amount of entries is reached (TOKEN_COUNT).

The first communication channel transfers the tokens from the Producer to the Calculator acting as First-In-First-Out (FIFO) buffer with limited token capacity (BUFFER_SIZE).
The Calculator on its part performs a *blocking read* on the first communication channel. A *blocking read* will read a token from the communication channel if there are tokens waiting, else it will wait for one token to arrive. Next, the Calculator will perform a computation on every individual entry within a token. This computation has a constant workload set for all entries. This workload is specified in number of loop iterations by parameter `LOAD_SIZE`. When the computation is done the result is written in the second communication channel. The Calculator will repeat the process, so the Calculator will proceed processing a new entry if one is available in the first communication channel, else it will perform the *blocking read* on the first communication channel.

This computations of the Calculator (on all entries within a token) do not share any dependency and can thus be executed in any order. This property is needed as the operations within the Calculator need to be (highly) parallel in order to be a suitable candidate for GPU computing.

The second communication channel has the same characteristics as the first communication channel, but different end-point. The second FIFO buffer will transfer tokens from the Calculator to the Consumer.

The Consumer will do a *blocking read* on the second communication channel and will make sure the result calculated by the Calculator is actually valid.

Please observe that there is a strict execution order between tokens. The Calculator can only process one token at a time and there is only one Calculator process connected to the first and second FIFO communication channels. The FIFO buffer of the communication channels enforces a strict order in the tokens by design.

For the Calculator there are two platforms considered to run the code on. First the GPU will be discussed and secondly the CPU. Both the GPU and the CPU have two communication types for the attached FIFO channels. Data can be transferred by either physically movement of data (*COPY*) or by pointer reference type (*POINTER*) as defined by the HDPC framework [Far08, pg. 6].

As the CUDA GPU is not able to access the Host Memory directly, the GPU needs to be prepared by the supporting CPU before execution. The two strategies of preparing memory for the CUDA GPU are implemented as follows:
1) **COPY**: Assign memory on the GPU device and copy the content from *Host Memory* to *Device Memory*. When the computation is done copy the result stored in *Device Memory* back to *Host Memory*.

2) **POINTER**: Assign special CUDA allocated memory in *Host Memory* which can be used for both the *CPU* and the *GPU*. Next give the pointers to the newly allocated source and target address spaces to the *CUDA GPU*, the back-end driver will dynamically transfer the data to the *GPU* when needed.

“Preparing” the *CUDA* will cause an initial start-up penalty, the same applies for memory transfers between the *CUDA GPU* and the *Host Memory*. This “setup-overhead” can eventually become larger than the gained computation speedup, causing the overall computation to be slower.

The drawback of the *COPY* method comes with choosing the “wrong” transfer sizes, which causes unnecessary many *COPY* transfers being initiated. “Minimize data transfer between the host and the device” is advised by *CUDA* [CUDA-BPG][pg. 15] but no estimation is given on the best transfer sizes to use, in order to make best use of the *GPU*.

The drawback of the *POINTER* method comes with the fact that the transfer logic is handled in the back-end, which cannot be given any hints on what kind of data to expect with regards to size and type. This will cause the build-in optimizer to guess the best transfer sizes making it potentially (very) inefficient.

For our program *Producer ⇒ Calculator ⇒ Consumer* we now have four different execution strategies we can choose from when executing the program, namely the executing strategies *CPU COPY*, *CPU POINTER*, *GPU COPY* and *GPU POINTER*. But which execution strategy leads to the lowest execution time?

Finding the answer to this question requires finding a *Tipping Point* where the extra communication overhead time needed by different execution strategies will be less than the gain achieved by the computation speedup.

Finding this *Tipping Point* is not-trivial as it requires writing code for specific hardware architectures with the same software architecture in mind. The HDPC framework can help here structuring the code in such a way that both cases will be comparable.
In order to make the decision about the execution strategy, two questions emerge: 1) Would it matter if we know the amount of entries to process (ENTRY_COUNT) and the complexity of the computation (LOAD_SIZE) in advance? 2) Giving this knowledge can we apply basic design rules when developing KPN process nodes which need to run on the GPU?

4 Theoretical Calculation

The interface between the GPU card and the CPU is the PCIe x16 bus. The Bandwidth of the PCIe x16 bus operates at a theoretical maximum of 5GHz. This gives a theoretical maximum bandwidth of $500MB/s \times 16 = 8GB/s$.\(^4\) This theoretical maximum causes for example a transfer of 8GB to the GPU Device Memory and back into the Host Memory to add a 2 seconds overhead in transfer time.

The amount of Clock Cycles an arbitrary operation takes on the GPU Cores is found at [CUDA-PG][pg. 94, table 5-1]. The Clock Cycles per arbitrary operation is ranging from 8 to 48, depending on the Computation Capacity of the GPU.

To calculate the time needed for transfer and computation on the GPU, a variety of constants are needed in the calculation. These constants are found in the [CUDA-PG], [CUDA-BPG] and the data-sheet found on the manufacturer website. The Experiments in Section 7 uses the NVIDIA GeForce GTX 295 GPU card, thus the theoretical computations below are based on this card.

The Theoretical Bandwidth on the NVIDIA GeForce GTX 295 is calculated using[CUDA-BPG, pg. 13] and the values given by NVIDIA\(^5\)

\[999MHz \times 10^6 \times 488bit/8bit \times 4/10^9 = 223.8GBps\]  

(1)

In Formula (1) the Memory Clock is 999MHz, the Memory Interface Width is 448 bits. The multiplier 4 comes from the quad data rate configuration, which is derived from the SLI feature. This concludes that the internal

\(^4\)http://en.wikipedia.org/wiki/PCI_Express
bandwidth for the NVIDIA GeForce GTX 295 is much higher (≈ 25 times) than the PCIe Bandwidth.

Accessing the global memory costs between 400 to 600 Clock Cycles as found in [CUDA-BPG, pg. 47], the NVIDIA GeForce GTX 295 runs at 1242MHz, has 30 Multiprocessors (MP) and 8 Cores/MP making a total of 240 cores. The Compute Capability is 1.3, so it will execute 8 additions/comparisons per Clock Cycle per Multiprocessor [CUDA-PG, pg. 94].

For the calculations below, the memory access is assumed to be perfect. Perfect memory accesses on both the GPU and CPU are achieved if the data is aligned properly and accesses are sequential to avoid misses and extra transfers/calculations to make it fit in the architecture. For the CUDA GPU the differences can be as large as ≈ 8 times [CUDA-PG][pg. 164, figure G-1].

Consider processing 2 million int32_t integers = 64 million bits = 8 million bytes. Every entry will be processed by a single thread, this requires an total of 2 million threads. An single thread will perform 1 addition (ex: output = input + 1).

Assume the process is able to transfer the whole memory content (all 2 million integers) from Host Memory to Device Memory (and back) at ones. The process will then take the following approach: 1) Transfer all integers to the Device Memory. 2) compute concurrently for every single integer; a) load the value from memory b) Perform one addition and c) store the result. 3) When all computations are done transfer the result to Host Memory. Looking at the time needed for every individual step of the computation:

1) The transfer from Host Memory to Device Memory will take 0.5ns per entry:
\[ 4\text{byte}/8\text{GBps} = 0.5\text{ns} \] (2a)

2) One Memory Access (read or write) operation takes as much as 600 clock cycles whereas one addition operation only takes 1 clock cycle. Due this big differences the addition clock cycles will not be considered in the calculation. This makes the total needed for Memory Access read and write using 30 Multiprocessors to be:
\[ 2 \times 2 \times 10^6 \times 600/30 = 1 \times 10^7 \text{ Clock Cycles} \] (2b)

the cores are running at 1242MHz so this will take in total:
\[ \frac{1 \times 10^7}{1242 \times 10^6} = 8 \times 10^6\text{ns} = 8\text{ms} \] (2c)
The total internal transfer time to the GPU is very small:

\[
\frac{0.008\text{GB}}{223.8\text{GB}} = 0.03\text{ms} \quad (2d)
\]

For that matter the transfer time to the GPU can be ignored with respect to the calculation times. Which makes an average time to perform an addition on 1 integer to be:

\[
\frac{8\text{ms}}{2 \times 10^6 \text{sec}} = 4\text{ns} \quad (2e)
\]

3) The transfer from Device Memory to Host Memory will takes per integer 0.5\text{ns}:

\[
\frac{4\text{byte}}{8\text{GBps}} = 0.5\text{ns} \quad (2f)
\]

The sum of all answers in Formula (2) will be 0.5\text{ns} + 4\text{ns} + 0.5\text{ns} = 5\text{ns} per integer.

If the GPU time is reduced to 0\text{ns}, the average time will still be 1\text{ns} for transfer only. However, the average time does not equal the latency time. The latency is significant as it cannot start computing before all integers have been transferred. For this example it causes a 1\text{ms}(!) delay before the computation on the GPU can start.

The actual average time will increase as the theoretical average time does not yet include the following details; 1) The “setup costs” on the supporting CPU. One example of “setup costs” is the GPU driver initialization. 2) The time needed on GPU for context switches and thread initialization. 3) Overhead caused by (multiple) Memory Transfers if data is not transferred at ones. 4) Overhead caused by hardware not fully utilized e.g. waiting for data or instructions. 5) Overhead caused by the HDPC framework used for programming.

**NOTE:** In the theoretical example of processing 2 million integers the GPU computation power is not fully utilized. For a best case scenario all memory fetches are pipe-lined on the GPU and during the “waiting” time the GPU executes an addition. Best case scenario the computation load could be increased to 600 clock cycles. This way a Multiprocessor can fire off half of its cores to fetch Memory and the other half to run the computation and “flip” between this configurations.
5 Construction of Test Environment

NVIDIA CUDA enabled (consumer) GPU cards are available in numerous architectures and variety of cards with regards to main factors such as number of MultiProcessors, Compute Capability and Clock Speed. Building a uniform test environment is preferred to rule out operating system and software/toolkit differences.

In this experiment the Producer and Consumer run on the CPU and the Calculator can either be a CPU process or a GPU process. This approach will eliminate any difference in the setup. The Calculator will simulate its load by using a simple addition on the entry. The Consumer will validate the output of the Consumer to ensure the Consumer is not cheating or generating errors in memory transfers.

The experiment Scheduling and Memory transfer code is automatically generated by the Daedalus framework with target HDPC framework, which for this experiment is Producer ⇒ Calculator ⇒ Consumer as shown in Figure 5.

The functions that the three processes (Producer, Calculator, Consumer) implement are manually coded, with maximum execution speed in mind.

During the compilation some compiler optimizations are disabled, to ensure that the compiler does not ‘trick’ the results by applying secret (unwanted) optimizations. Disabling the specific (loop) optimizations, makes sure the profiling code will run as intended.

The total execution time will be calculated and divided by the number of entries (ENTRY_COUNT) to get the execution time for a single entry. This will include the Producer and Consumer execution time which is an unknown constant for all setups. Converting all results to single entry execution times is merely a practical usage, as it is easier to vary total entry counts and still make comparisons.

There will be 4 different setups to experiment with, as mentioned in Section 3. This 4 setups are the result of combinations of the 2 architectures (GPU, CPU) and the 2 memory transfer strategies (COPY, POINTER). This gives the 4 combinations GPU COPY, GPU POINTER, CPU COPY and CPU POINTER.
The **BUFFER_SIZE** of the two Communication Channels be kept constant to the given value of 3 tokens. The Communication Channels are by design always available for the **Calculator**. The **Calculator** code also has an error check implemented for blocking pipes. This check will raise an error if the **Calculator** fails to read from the First **FIFO** Communication Channel (underflow) or fails to write to the Second **FIFO** Communication Channel (overflow).

In addition to test for the efficiency of the **HDPC** framework and allowing to benchmark the overhead of the **HDPC** framework a second test setup is manually coded. The second test setup mimics the behavior of the explained Processes, but without the use of the **HDPC** framework for the Communication Channels synchronization and concurrency for example.

### 6 Implementation

Using an Ubuntu 10.10 32 bit USB boot-able test environment, together with **CUDA** Toolkit 3.2 allows us to run on systems without the need of installing software on the test systems, to avoid issues like porting the code to a different Operating System and have the flexibility to test on any **CUDA** enabled system, without altering the system installed state.

The code is written in **C++** compiled using **gcc 4.4.5** and **CUDA** compilation tools 3.2 and **NVIDIA CUDA** Driver 260.19.26. Using compilation the code has been build with all compiler optimization possible, except for loop-enrolling to ensure the “dummy load” will be valid.

The subset of options on the GPU has been limited to **TOKEN_SIZE**, **ENTRY_COUNT** and **LOAD_SIZE**.

A “framework” in **sh** shell provides caches of already compiled binaries and allows displaying results in a reproducible matter. More on this “framework” is found in Appendix A.

The “framework” also avoid endless running experiments. If a configuration is running longer than (the configured) 10 seconds the configuration will be terminated and there will be no results for the specific configuration. This behavior is implemented to allow running the computations in batch without the need of waiting for useless configurations. A (very) badly configured
configuration can take more than 1 hour of computation time.

CUDA device information has been inquired using the deviceQuery Utility provided in the CUDA Examples Toolkit, whereas facter\textsuperscript{6} 1.5.7 did gather system specific information.

7 Experiments

The experiment was run on 2 different platforms (GPU, CPU) using 2 different strategies (COPY, POINTER) testing 1500 different configurations. The most important configurations variables are shown in Table 1.

The parameters are determined based on try and error as exploring the whole scope requires the setup to be running for years. This is caused by the 10 seconds needed to compile and execute a single configuration. This (re)compiling is required for each experiment setup as values like TOKEN SIZE and BUFFER_SIZE in the HDPC framework are set during compile time. All experiments setup are repeated at least 10 times to ensure consistency in results.

<table>
<thead>
<tr>
<th>Configuration Flag</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOAD_SIZE</td>
<td>10, 100</td>
</tr>
<tr>
<td>TOKEN_SIZE</td>
<td>100.000, 1.000.000, 10.000.000, 16.777.216</td>
</tr>
<tr>
<td>ENTRY_COUNT</td>
<td>100.000, 1.000.000, 10.000.000</td>
</tr>
</tbody>
</table>

Table 1: Main configuration inputs used for experiments

Specification for machine used to conduct experiments; CUDA GPU GeForce GTX 295, Capability 1.3, 30 (MP) x 8 (Cores/MP) = 240 (Cores) @ 1.24 GHz. The CPU specification 8 * Intel Core\textsuperscript{TM} i7 CPU 920 @ 2.67GHz, 3GB Memory.

For the sake of simplicity in the upcoming calculations assume that the overhead generated by the Producer and Consumer is 0\(\text{ns}\) per entry. In practice this overhead is a fixed constant per entry, causing the actual time spend by the Calculator alone to be lower.

The y-axis on all Figures are set to the time needed in nanoseconds to

\textsuperscript{6}\url{http://www.puppetlabs.com/puppet/related-projects/facter/}
process a single entry, where lower means better.

An important property to consider is the so called *Tipping Point*. A *Tipping Point* is the intersection point between two graphs. The *Tipping Point* indicates when to consider an alternative architecture (CPU or GPU).

**NOTE:** Not all graphs can be (visually) compared to each-other as the input parameters differ, take good care of the type used on the x-axis of the graph. The x-axis type is either **TOKEN_SIZE** or **ENTRY_COUNT**. Also take care of the different values of the fixed parameters **ENTRY_COUNT**, **LOAD_SIZE** and **TOKEN_SIZE**. The actual values used for the fixed parameters are shown in the title of the graph.

![Figure 6: Experiment Result - The small value of the parameter LOAD_SIZE causes the CPU COPY and CPU POINTER to be almost equal.](image)

Figure 6: Experiment Result - The small value of the parameter **LOAD_SIZE** causes the **CPU COPY** and **CPU POINTER** to be almost equal.
Figure 7: Experiment Result - Larger value of \texttt{LOAD\_SIZE} causes the \textit{COPY} and \textit{POINTER} strategy for the \textit{GPU} to be significantly different.

For small value of the \texttt{LOAD\_SIZE} as shown Figure 6 there are almost no differences between the \textit{COPY} or \textit{POINTER} strategy on \textit{CPU} except for the small \texttt{TOKEN\_SIZE} values whereas the caches and context-switches are causing variances. For the \textit{GPU} the \textit{POINTER} strategy is always faster than the \textit{COPY} strategy. This behavior is consistent for larger \texttt{LOAD\_SIZE} values. The difference gets more obvious if the \texttt{LOAD\_SIZE} increases as shown in Figure 7.

The reason the \textit{GPU POINTER} and \textit{COPY} graphs in Figure 7 are not shown for \texttt{TOKEN\_SIZE} < 50 is because execution takes longer than the pre-defined cut-off time of 10 seconds.

Close inspection of the \textit{GPU POINTER} graph in Figure 7 shows missing results in the range 50 < \texttt{TOKEN\_SIZE} < 500. These values are missing as the program is unable to execute correctly this small \texttt{TOKEN\_SIZE} input values. The reason for the behavior is unexplained.

Increasing the \texttt{LOAD\_SIZE} causes the \textit{Tipping Point} to “shift-to-the-left” in the graphs, seen relatively to the \texttt{TOKEN\_SIZE} values (x-axis). For example on \texttt{ENTRY\_COUNT} 1,000,000 and \texttt{LOAD\_SIZE} 10 the tripping point is roughly at \texttt{TOKEN\_SIZE} 3000 as shown in Figure 6, whereas for \texttt{LOAD\_SIZE} 100 the
tripping is roughly at \text{TOKEN\_SIZE} 750 as shown in Figure 7.

The best result found in Figure 6 is found at \text{TOKEN\_SIZE} 2000 and is 14\text{ns} for the \text{GPU \ POINT\_ER} strategy, all the other strategies are in the same range 14 – 16\text{ns}. The best result in Figure 7 is again with the \text{GPU \ POINT\_ER} strategy and is 42\text{ns}. The \text{GPU \ COPY} is pretty competitive with 45\text{ns}, but the \text{CPU} strategies are falling behind with 120\text{ns}.

Figure 8: Experiment Result - Variants in the \text{ENTRY\_COUNT} makes the execution stable after a while.

Figure 8 shows the hyperbola graph quickly approaches “a-stable-execution-time-per-entry-under-limit” no matter how many entries it get inserted. This gives best result, starting from 2M entries, for the \text{GPU} strategies of 14 – 16\text{ns} and for the \text{CPU} strategies 110\text{ns}.

In Figure 9 it is shown that the \text{Tipping Point} for the HDPC implementation is better than the non-HDPC implementation (2500 vs 10000). A better \text{Tipping Point} allows the \text{TOKEN\_SIZE} to be smaller with respect to the point where the \text{GPU} implementations is faster than the \text{CPU} implementations. The fact that the HDPC implementation is faster is because it uses a multiple \text{CPU} setup unlike the non-HDPC implementation, so the extra work done by scheduling and planning done by the HDPC pays off in a better performing program. In this experiment the HDPC version is almost 4 times more effi-
cient with regards to \texttt{TOKEN\_SIZE} values. Even for small \texttt{TOKEN\_SIZE} values (ranging from 2500 to 10000) the \textit{GPU POINTER} strategy will speedup the computation. Looking in absolute values the \textit{GPU POINTER} strategy will achieve a speedup of 2 times from 10 ns to 5 ns per entry.

The non-HDPC \textit{CPU POINTER} graph in Figure 9 is lower in absolute execution time than the HDPC equivalent (10 ns vs 12 ns). The reason for this behavior is unexplained.
Figure 9: Experiment Result - The non-HDPC version lacks of multiple CPU support.
Figure 10: Experiment Result - CPU or Compiler optimization using int16 for small TOKEN_SIZEs and int32 for bigger ones, which only get detected in the non-HDPC.
The expected theoretical value for LOAD_SIZE 10 is calculated using the method discussed in Section 4: 
\[0.5 \text{ns} + 4 \text{ns} \times 10 + 0.5 \text{ns} = 41 \text{ns}\]. For LOAD_SIZE 100 this will become \[0.5 \text{ns} + 4 \text{ns} \times 100 + 0.5 \text{ns} = 401 \text{ns}\]. Table 2 summarized the best results found in the experiments. The theoretical values are (much) higher than the best results found in Figures 6, 7, 8, 9a and 9b.

The reason for the (big) difference between the theoretical calculated values and the actual values is likely to be caused by better alignments of data on the GPU. The theoretical value calculated comes with the worst-case scenario of all data miss aligned. If the data were to be perfectly aligned, 1 read operation (600 clock cycles) would seeds \([488 \text{bits} / 32 \text{bits}] = 15 \text{threads}\). This makes the computation \(\approx 15\) times faster. These experiments come with partially aligned data, making it roughly 4 till 10 times faster.

The differences between the theoretical best values and the experiment best values also shows that determining accurate theoretical values (to be used in some analysis) is quite difficult and challenging. Systematic and (semi-)automated practical experiments are important to reliably validate the design decisions made with the theoretical calculations.

Looking at the experimental results there are three important observations; 1) The LOAD_SIZE has a more significant impact if the TOKEN_SIZE is small. 2) Calculation with LOAD_SIZE 100 seems to take roughly 3.5 times longer than the same experiment setup with LOAD_SIZE 10. The value 3.5 is likely tight to the specific GPU used, computing the exact value is unknown. 4) The best result is achieved with the largest number of entries and the largest TOKEN_SIZE and a moderate LOAD_SIZE.

NOTE: The CPU COPY and CPU POINTER strategies test results from the HDPC setup have a higher deviation than the non-HDPC graphs. The line plotted through the points in the graph is more irregular for the HDPC graph than for the non-HDPC graph as seen in Figure 9. This irregularity is best seen.

Table 2: Best experiment results found for the GPU POINTER strategy. Column “time” list the time needed to process a single entry.

<table>
<thead>
<tr>
<th>Fig. #</th>
<th>Type</th>
<th>ENTRY_COUNT</th>
<th>LOAD_SIZE</th>
<th>TOKEN_SIZE</th>
<th>time</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>HDPC</td>
<td>1.000.000</td>
<td>10</td>
<td>2.000</td>
<td>14ns</td>
</tr>
<tr>
<td>7, 8</td>
<td>HDPC</td>
<td>1.000.000</td>
<td>100</td>
<td>2.000</td>
<td>42ns</td>
</tr>
<tr>
<td>9a, 9b</td>
<td>HDPC</td>
<td>16.777.216</td>
<td>10</td>
<td>10.000</td>
<td>4ns</td>
</tr>
<tr>
<td></td>
<td>non-HDPC</td>
<td>16.777.216</td>
<td>10</td>
<td>10.000</td>
<td>10ns</td>
</tr>
</tbody>
</table>
in the \texttt{TOKEN\_SIZE} range 0 till 1000. This deviation is most likely caused by the extra work required in the HDPC framework for Communication Channels synchronization, various statistics and context switching between CPUs. Pinpointing the exact component causing the spread turned out to be hard as adding more profiling code extra calls to the HDPC timer functions caused the program to behave differently and introduced even more spread. This gives a strong indication that the actual context switches are causing this spread.

\textbf{NOTE:} The compiler or hardware optimization can play tricks during the experiments. A specific \textit{CPU} optimization was not detected in the HDPC code whereas it was detected in the non-HDPC code as this program was more simple for the compiler to understand. Figure 10b shows the interesting “jump” for the from 120\(\text{ns}\) to 150\(\text{ns}\) for the \textit{CPU} based strategies at the non-HDPC exactly at the value of a short integer (\texttt{int16}) boundary \(2^{15}−1 = 32767\).

\section{Conclusion}

The \textit{KPN} generated by HDPC for Producer $\Rightarrow$ Calculator $\Rightarrow$ Consumer can use the \textit{GPU} to speedup execution, if the amount of data to process is sufficiently high. A minimum 100,000 items (\texttt{ENTRY\_COUNT}) is needed when using the NVIDIA GeForce GTX 295.

Choose the \texttt{TOKEN\_SIZE} as large as possible. Every extra memory transfer from \textit{Host Memory} to \textit{Device Memory} or back has a negative impact on performance. Choose at least 1000 items to transfer on every memory transfer (\texttt{TOKEN\_SIZE}), anything less is worthless on the \textit{GPU} as alternative.

The dummy \texttt{LOAD\_SIZE} used in the experiments is equivalent to a \textit{very} large computation as global memory access was used to mimic high-load computations. A \texttt{LOAD\_SIZE} of 10 is equivalent of roughly \(600\times2\times10 = 12,000\) clock cycles on the \textit{GPU}.

When you like to deploy your own code on \textit{CUDA} run on initial check to test for complexity. The complexity (\texttt{LOAD\_SIZE}) should together with your \texttt{TOKEN\_SIZE} value give a “fair” amount of work for the \textit{GPU} to compute.

To answer the first question formulated at the end of Section 3 (on page 14): Knowing in advance the amount of entries to process (\texttt{ENTRY\_COUNT}) and the complexity of the computation (\texttt{LOAD\_SIZE}) gives an indication of
whether to use the GPU at all. However, it does not give a definitive answer of the configuration parameter (TOKEN_SIZE) to use.

To answer the second question; The TOKEN_SIZE is the most important parameter during the process of designing and implementation of running (some) KPN nodes on the GPU. Determining the optimal TOKEN_SIZE during run-time is preferred, but requires more research of finding an algorithm able to make this run-time optimizations. Determining the (semi-)optimal TOKEN_SIZE in advance for a specific configuration, by means of exploration, allows significant speedups during run-time.

The Daedalus tools and the HDPC framework has been proved to be a useful tool to quickly and efficiently build a framework application. The KPN and the choice of HDPC for having a dedicated CPU thread for controlling the GPU implementation of a KPN process has a positive effect on the performance of the program. The HDPC has proven to be a flexible framework allowing model variations of the TOKEN_SIZE parameters in a consistent and controlled way.

One downside of the HDPC implementation is the static TOKEN_SIZE assignment during compile time, which require knowledge of the target architecture in advance.

The GPU is a very powerful co-processor, but its application area is somehow limited within general purpose computing. Off-loading “standard” CPU based processes and try to run them on the GPU without modification is not going to work. Significant effort needs to be spend in order to rewrite a process to fit in the highly parallel architecture of the GPU. Thus it is better to look at the data parallelism as basic-building block during the development of the application.

For the two GPU memory transfer strategies tested, the GPU POINTER strategy is preferred over the GPU COPY variant. 1) The GPU POINTER is equal or faster in overall execution. This makes the implementation in particular more interesting if smaller TOKEN_SIZE values are needed. 2) The GPU POINTER strategy has the advantage that memory transfer management is hidden in the CUDA framework making programming the code potentially faster and more dynamic. The wide variety of NVIDIA GPU cards around causes the GPU COPY code to be fairly specific as it requires knowledge of the card it is going to be executed on. The GPU POINTER implementation does not have this limitation.
9 Future Work

The CUDA Framework 4.0 has made improvements in concurrent computation, memory transfer and streamed transfers from one GPU to another GPU without invoking main memory, this is in line with the Daedalus framework, but is currently not implemented in the HDPC framework.

The CUDA Framework provides GPU-accelerated libraries for Basic Linear Algebra Subprograms (BLAS), Fourier Transform (FT), Sparse Matrix and Random Number Generation (RNG) calculations. Using this libraries as basic building blocks in the KPN allows to use the power of the GPU more easily.

The POINTER strategy proved sufficient for simple programs with our Producer ⇒ Calculator ⇒ Consumer example. However for more complex concurrent examples the efficiency is still unknown.

The card used in this experiments is a high-end GPU Card, but not specially tailored for CUDA computations. The NVIDIA Tesla Cards are specially tailored for computations, running the experiments should give a whole different Tipping Point.

10 Acknowledgments

I would like to thank Hristo Nikolov at LIACS who was always ready to answer my questions and actively participating throughout my research with suggestions towards a better experiment setup and being a highly valuable knowledge in explaining the optimization quirks in the background both for the GPU and CPU as the system as whole.

References

[CUDA-PG] CUDA Programming Guide 3.2,
A Re-run the experiment

In order to redo the experiment you need to setup a work environment. And Ubuntu USB Hard-Drive setup is preferred. This setup is out of the scope of this Appendix but can be summarized as follows: 1) Run the standard Ubuntu Installer on a USB Hard-Drive. 2) Install the NVIDIA CUDA Driver and Development Tools. Find extra Ubuntu install hints in Appendix B. 3) Checkout the source code from the LIACS CVS Repository at docs/students/hvdzwet/bachelor-thesis/experiment.

7USB Pen-Drive cannot be used, as the I/O is too slow when using it for compiling
8A public snapshot is found at http://rickvanderzwet.nl/svn/briareus/
The HDPC variant is found at boost-hdpc, the manual Implementation is found at manualImp.

You will first need to populate id2device.txt using the values you get from deviceQuery and facter, this file is used at a later stage for graphing purposes. Now run new-experiment.sh. This will execute all the variants used in this paper.

Next, to view the graphs run view-plots.sh. The output will point you to a directory where the graphs are stored. For settings boundaries on the graphs you can use the following environment settings YMIN=0 YMAX=500 XMIN=30000 XMAX=35000.

Please note that almost all scripts take a (ridiculous) set of (optional) environment variables to tweak running the experiments one way or the other to speedup execution times. So if you are planning to re-do experiments or run “interactively” look through the headers of the *.sh files to see what kind of flags you can set.

B Ubuntu Installation Hints

B.1 General Notes

1. You will get errors about libcuda missing if you have not installed the NVIDIA CUDA driver and using the standard Ubuntu provider driver instead.
2. If you do not want to remove your (default) Operating System, you can use a USB-DISK on modern computers. During the install of Ubuntu make sure to select the proper USB-DISK. Refer to your BIOS manual for instructions to boot from a USB-DISK.

B.2 Ubuntu 10.10

Make sure to install the packages to get started:

$ sudo apt-get install libboost-thread-dev libboost-dev build-essential */ facter gnuplot
The Ubuntu provided driver does NOT work with downloaded CUDA framework, neither the nouveau (open source driver) nor the provided proprietary driver. Install the dev-driver from NVIDIA found at [http://developer.nvidia.com/cuda-downloads](http://developer.nvidia.com/cuda-downloads). Make sure to remove the nouveau first:

# <GOTO ttyv1 (CTRL+ALT+F1) and login>
$ sudo service gdm stop
$ sudo apt-get remove xserver-xorg-video-nouveau nvidia--*
$ <install DEV driver>
$ sudo reboot


### B.3 CUDA

Your profile need to be setup correctly to allow compiling:

$ export LD_LIBRARY_PATH=$LB_LIBRARY_PATH:/usr/local/cuda/lib
$ export LD_LIBRARY_PATH=$LB_LIBRARY_PATH:/usr/local/cuda/lib64
$ export PATH=$PATH:/usr/local/cuda/bin

The examples require a additional set of libraries:

$ sudo apt-get install libgl1-mesa-dev libxmu-dev libx11-dev
$ sudo apt-get install libglu1-mesa-dev libxi-dev libglut3-dev

Make sure to compile the helper libraries and the debug version of it:

$ make -C ~/NVIDIA_GPU_Computing_SDK/C
$ make -C ~/NVIDIA_GPU_Computing_SDK/C dbg=1