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Harnessing Aspect Oriented Programming on GPU: Application to Warp-Level Parallelism (WLP)

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Abstract: *Stochastic simulations involve multiple replications in order to build confidence intervals for their results, and Designs Of Experiments (DOEs) to explore their parameters set. In this paper, we propose Warp-Level Parallelism (WLP), a GPU-enabled solution to compute Multiple Replications In Parallel (MRIP) on GPUs (Graphics Processing Units). GPUs are intrinsically tuned to process efficiently the same operation on several data, which is not suited to parallelize MRIP or DOEs. Our approach proposes to rely on small thread groups, called warps, to perform independent computations such as replications. This approach has proved to be efficient on three classical simulation models, but originally lacked the transparency users might expect. In this work, we enhance WLP using Aspect Oriented Programming (AOP). Our work describes the way to combine CUDA and AOP, and brings forward the techniques available to exploit AOP in a CUDA-enabled development.*

Keywords: Aspect Oriented Programming (AOP); Stochastic Simulation; Multiple Replications In Parallel (MRIP); GPU, CUDA; Warp-Level Parallelism (WLP)

1 INTRODUCTION

Replications are a widespread method to obtain confidence intervals for stochastic simulation results. It consists in running the same stochastic simulation with different random sources and averaging the results. According to the Central Limit Theorem, the average result is approximated in an accurate enough way by a Gaussian Law, for a number of replications greater than 30. Thus, for a number of replications greater than 30, we can obtain a confidence interval with a satisfactory precision. This average result depends on the stochastic variability of the application. Some applications can settle for fewer replications, but are consequently less keen to take advantage of MRIP.

There are many cases where a single simulation can last for a while, so 30 of them run sequentially may represent a very long computation time. Because of this overhead, 30 replications are hardly run in most simulations. Instead, a good practice is often to run 3 replications when debugging, and 10 replications are commonly used to compute a confidence interval. To maintain an acceptable computation time while running 30 or more replications, many scientists proposed to run in parallel these independent simulations. This approach has been named Multiple Replication in Parallel (MRIP) in the nineties Pawlikowski et al. (1994). As its name suggests, its main idea is to run each replication in parallell Hill (1997); Pawlikowski (2003). In addition, when we explore an experimental plan we have to run different sets of replications, with different factor levels according to the experimental framework Hill (1996); Amblard et al. (2003). In this paper, we will not consider any constraints that need to be satisfied when implementing MRIP. One of the main barriers that often prevents simulationists to achieve a decent amount of replications is the lack of knowledge in the parallelization techniques. Another common hindrance is the amount of parallel computing facilities available. Our work tackles this problem by introducing a way to harness the computational power of GPUs (Graphics Processing Units) to process MRIP or DOEs faster than on a scalar CPU (Central Processing Unit).

GPUs deliver such an overwhelming power at a low cost that they now play an important role in the High Performance Computing world. However, this kind of devices display major constraints, tied to its intrinsic architecture. Basically, GPUs have been designed to deal with computation intensive applications such as image processing. One of their well-known limits are the slow memory accesses. Indeed, since GPUs are designed to be efficient at computation, they badly cope with applications frequently accessing memory. Except by choosing the right applications, the only thing we can do to overcome this drawback is to wait for the hardware to evolve in such a way. Since the NVIDIA generation codenamed Fermi, GPUs have shown a move in this way by improving cache memories available on the GPU. This leads to better performances for most applications at no development cost, only by replacing the old hardware by the state-of-the-art one (Kepler at the time of writing).

Now, what we can actually think about is the way we program GPUs. Whatever the programming language or architecture chosen to develop an application with, CUDA (Compute Unified Device Architecture) or OpenCL, the underlying paradigm is the same: SIMT (Single Instruction, Multiple Threads). Thus, applications are tuned to exploit the hardware configuration, which is a particular kind of SIMD architecture (Single Instruction, Multiple Data). To obtain speed- ups, parallel applications must be implemented in an SIMD-compliant way. This point reduces the scope of GPU-enabled applications.

The SIMT paradigm automatically groups into 32-wide bundles called warps. Warps are the base unit used to schedule both computation on Arithmetic and Logic Units (ALUs) and mem-

ory accesses. Threads within the same warp follow the SIMD pattern, i.e. they are supposed to execute the same operation at a given clock cycle. If they do not, a different execution branch is created and executed sequentially every time a thread needs to compute differently from its neighbours. The latter phenomenon is called branch divergence, and leads to significant performance drops. However, threads contained in different warps do not suffer the same constraint. They are executed independently, since they belong to different warps.

In this paper, we describe Warp-Level Parallelism (WLP), a paradigm to evaluate the approach of using GPUs to compute MRIP, using an independent warp for each replication. In order make it easier to use, we introduce an Aspect Oriented Programming (AOP) declination of WLP using an handcrafted preprocessor. As a matter of fact, this paper also details the different solutions to couple AOP with CUDA. It shows what AOP can bring to CUDA-enabled applications, in terms of software engineering and extensibility. In the further sections, we will:

- Describe a mechanism to run MRIP on GPU;
- Propose an implementation of our approach: WLP;
- Introduce the different approaches to implement AOP and those compatible with CUDA;
- Detail the AOP version of WLP;
- Benchmark WLP with three different simulation models.

2 GENERAL CONCEPTS OF GPU PROGRAMMING AND ARCHITECTURE

This section does a brief recall of the major concepts introduced by GPU programming and especially by CUDA. It also basically describes how a GPU architecture is organized, since these aspects are directly tied to our approach.

2.1 The Single Instruction Multiple Threads (SIMT) paradigm

SIMT is the underlying paradigm of any CUDA application. It is based on the well-known SIMD paradigm. While using SIMD, the same instruction is executed in parallel on multiple computational units, but takes different data flows in input. Instead of viewing SIMT as a simple SIMD variant, one needs to understand that it has been created to simplify applications development on GPU. The main idea is first to allow developers to deal with a unique function, named kernel, which will be run in parallel on the GPU. Second, developers manipulate threads in SIMT, which are a much more common tool nowadays than traditional vectors enabling SIMD parallelization.

In order to handle SIMT more easily, CUDA introduces different bundles of threads. As a matter of fact, threads are grouped into blocks, which size and 3D-geometry are defined by the user. The whole blocks of a kernel form a 2D grid. Each thread will be uniquely identified in the kernel thanks to an identifier computed from a combination of its own coordinates and of its belonging block's. More precisely, in addition to grid and blocks, CUDA devices automatically split threads into fixed-size bundles called warps. Currently, warps contain 32 threads. They are extremely important in the low-level mechanisms ruling execution on a GPU.

As long as NVIDIA has defined both CUDA-enabled GPUs' architecture and the SIMT paradigm, the latter is not only convenient, it also perfectly fits the device. Its sole purpose is to be used on a GPU architecture, which is quite different from other multi-core architectures, especially from CPU ones, as we will see in the next part.

2.2 Basic architecture of a GPU

While a CPU possesses few cores, each of them allowing the execution of one thread at a time, a GPU possesses a small number of Streaming Multiprocessors (SM) (for instance an NVIDIA Fermi C2050 has 14 SMs). Each SM embeds an important number of computational units (there are 32 floating point computational units - called Streaming Processor (SP) - on each SM of a Fermi C2050). In theory, the floating-point computation power of a GPU device is equal to the number of SMs multiplied by the number of SPs. Another figure that needs to be considered in the architecture is the number of warp schedulers. The latter are key elements of CUDA performance. In fact, memory accesses are done per warp. However, because of memory latency, the warps-schedulers select the warps that have their data ready to process. Consequently, the more warps can be scheduled, the more the memory latency can be hidden.

While the first generation of NVIDIA GPUs was issued with a single warp-scheduler per SM Lindholm et al. (2008), later generations, such as Fermi and Kepler, own respectively two and four warp schedulers per SM Wittenbrink et al. (2011). Figure 1 shows a simplified representation of a SM of the Fermi architecture. Warps are first employed when threads need to be scheduled on the SM they have been assigned to. In fact, threads within a warp also achieve memory accesses in parallel, before processing the same instruction on this data. To sum up, threads are bound to each other, and must execute the same instructions according to SIMD machinery. Meanwhile, warps are the smallest unit that run in parallel on the different SMs of a GPU, and are the smallest GPU element that is able to process independent code sections. Indeed, given that different warps either run on different SMs, or on the same but at different clock ticks, they are fully independent to each other.

2.3 Blocks dispatching and warps scheduling on NVIDIA GPUs

Now that we have introduced the basic functioning of CUDA-enabled GPUs, let us detail the particular features that will help us to achieve MRIP on such architectures. We will see in this part how our GPU-enabled MRIP implementation relies on the scheduling features provided by NVIDIA CUDA devices. The first generation of NVIDIA GPUs were only able to run a single kernel at a time. Thus, blocks of threads were dispatched through all the available SMs in a more or less logical way: SMs were activated in turn, striding indices four by four. When every SM had been activated, the process started again.

One of the key features of architectures from Fermi and more recent is the ability to run several kernels in parallel on the same device. To do so, the way blocks of threads are dispatched through the device has been redesigned in a new fashion. Now, every block of threads, no matter which kernel it belongs to, is first handled by a top-level scheduler referred to as the GigaThread Engine. It is supposed to dispatch blocks of threads to the Streaming Multiprocessors (SMs). The point is CUDA has always proposed asynchronous kernel calls to developers. Now that devices can run several kernels in parallel, GigaThread needs to take into account any potential upcoming kernel. Consequently, the dispatcher cannot reserve all the SMs to run a first kernel, given that a second one could be launched at any time. When the second kernel appears, some resources will still be available so that they can be assigned to the new kernel blocks.

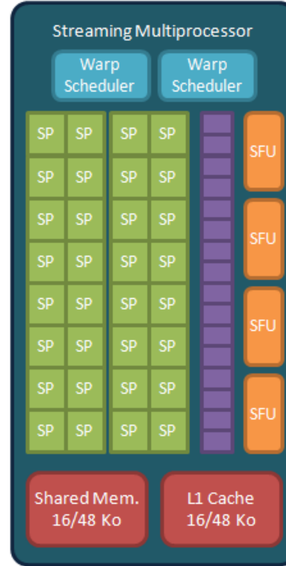

Figure 1: Simplified architecture of an NVIDIA Fermi C2050 streaming multiprocessor

Moreover, GigaThread enables immediate replacement of blocks on an SM when one completes executing. Since context switching has been fastened with recent architectures, blocks of threads can fully take advantage of the hardware device thanks to GigaThread dispatching capabilities. From an external point of view, and since we do not have the real specifications, we have noted that the dispatching of blocks does not seem to be deterministic. NVIDIA uses a specific way to place blocks on SMs: indeed, SMs will not be enabled in order. SMs bearing non-consecutive identifiers will in fact run consecutively ordered blocks.

3 A WARP MECHANISM TO SPEED UP REPLICATIONS

Two problems arise when trying to port replications to GPU threads, considering a replication per thread. First, we generally compute few replications, whereas we have seen that GPUs needed to achieve large amounts of computations to hide their memory latency. Second, replications of stochastic simulations are not renowned for their SIMD-friendly behaviour. Usually, replications fed with different random sources will draw different random numbers at the same point of the execution. If a condition result is based on this draw, divergent execution paths are likely to appear, forcing threads within a same warp to be executed sequentially because of the intrinsic properties of the device.

The idea that we propose in this paper is to take advantage of the previously introduced warp mechanism to enable fast replications of a simulation. Instead of having to deal with Thread-Level Parallelism (TLP) and its constraints mentioned above, we place ourselves at a slightly higher scope to manipulate warps only. Let this paradigm be called Warp-Level Parallelism (WLP), as opposed to TLP. Now running only one replication per warp, it is possible to have each replication to execute different instructions without being faced to the branch divergence problem.

But to successfully enable easy development of simulation replications on GPU using one thread per warp, two mechanisms are needed.

First, it is necessary to restrict each warp to use only one valid thread. By doing so, we ensure not to have divergent paths within a warp. Moreover, we artificially increase the device's occupancy, and consequently, we take advantage of the quick context switching between warps to hide slow memory accesses. Theoretically, we should use the lowest block size maximizing occupancy. For instance, a C2050 board owns 14 SMs, and can schedule at most 8 blocks per SM. In this case, the optimal block size when running 50 replications would be 32 threads per block. This situation is represented in Figure 2, where we can see two warps running their respective first threads only. The 31 remaining threads are disabled, and will stall until the end of the kernel. Unfortunately, the GigaThread scheduler, introduced in the previous section, does not always enable a kernel to run on every available SM. In addition, SMs' memory constraints might compromise this ideal case by reducing the number of available blocks per SM.

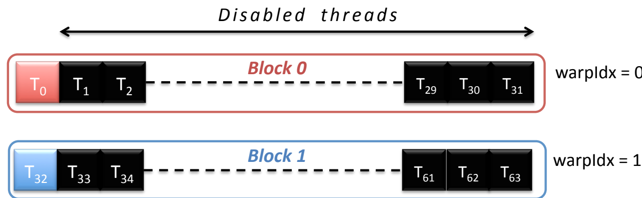

Figure 2: Representation of thread disabling to place the application at a warp-level

Second, there has to be an easy solution to get a unique index for each warp. TLP relies essentially on threads identifiers to retrieve or write data back. Thus, WLP needs to propose an equivalent mechanism so that warps can be distinguished to access and compute their own data.

Thanks to the two tools introduced in this section, it is possible to create a kernel where only one thread per warp will be valid, and where it will be easy to make each valid thread compute different instructions, or work on different data depending on the new index.

Although we could not figure out the real behavior of the GigaThread Engine dispatcher, the characteristics noticed in this part are sufficient to evaluate the performance of the dispatching policy. Furthermore, the new scheduling features introduced of NVIDIA GPUs benefit the overall performance of our warp-based approach, given that it highly relies on warp scheduling and block dispatching.

4 IMPLEMENTATION

Now that we have defined our solution, we will propose an implementation in this section. To do so, we need to focus on two major constraints: first, we should keep a syntax close to C++ and CUDA, so that users are not confused when they use our approach. Second, we need to propose compile-time mechanisms as much as possible. Indeed, since WLP only exploits a restricted amount of the device's processing units, we have tried to avoid any overhead implied by our paradigm.

This paper intends to prove that our approach is up and running. Thus, this section will only introduce a restricted number of keywords used by WLP. As we have seen previously, we first

have to be able to identify the different warps, in the same way SIMT does with threads. One way to obtain the warp identifier is to compute it at runtime. Indeed, we know that warps are formed by 32 threads in current architectures NVIDIA (2011b). Thus, knowing the running kernel configuration thanks to CUDA defined data-structures, the warp identifier can be determined using simple operations only, similarly to what Hong et al. (2011) have done. The definition of a `warpIdx` variable containing the warp's identifier can be written as in Figure 3:

```
const unsigned int warpIdx = (
   threadIdx.x + blockDim.x * (
        threadIdx.y + blockDim.y * (
                threadIdx.z + blockDim.z * (
                        blockIdx.x + gridDim.x * blockIdx.y
   ) ) ) ) / warpSize;
```

Figure 3: Const-definition of warpIdx

Conceptually, this definition is ideal because `warpIdx` is declared as a 'constant variable', and the warp identifier does not change during a kernel execution. This formula fits with the CUDA way to number threads, which first considers threads' x indices, then y and finally z, within a block. The same organization is applied to blocks numbering Kirk and Hwu (2010). Please note that the `warpSize` variable is provided by CUDA. This makes our implementation lasting since warp sizes may evolve in future CUDA architectures.

Although this method introduces superfluous computations to figure out the kernel's configuration, we find it easier to understand for developers. Another way to compute the warp's identifier would have been to write CUDA PTX assemblyNVIDIA (2011a). The latter is the Instruction Set Architecture (ISA) currently used by CUDA-enabled GPUs. CUDA enables developers to insert inlined PTX assembly into CUDA high-level code, as explained in NVIDIA (2011b). However, this method is far less readable than ours, and would not be more efficient since we only compute `warpIdx` once: at initialization.

This warp identifier will serve as a base in WLP. When classical CUDA parallelism makes a heavy use of the runtime-computed global thread identifier, WLP proposes `warpIdx` as an equivalent.

Now that we are able to figure out threads' parent warp, let us restrain the execution of the kernel to a warp scope. Given that we need to determine whether or not the current thread is the first within its belonging warp, we will be faced to problems similar to those encountered when trying to determine the warp identifier. In fact, a straightforward solution relying on our knowledge of the architecture quickly appears. It consists in determining the global thread identifier within the block to ensure it is a multiple of the current warp size. Once again, the kernel configuration is issued by CUDA intrinsic data structures, but we still need a reliable way to get the warp size to take into account any potential evolution. Luckily, we can figure out this size at runtime thanks to the aforementioned `warpSize` variable. Consequently, here is how we begin a warp-scope kernel in WLP:

```
if ( ( threadIdx.x + blockDim.x *
    ( threadIdx.y + blockDim.y * threadIdx.z ) )
 % warpSize == 0 )
```

Figure 4: Directive enabling warp-scope execution

We now own the bricks to perform WLP, but still lack a user-friendly API. Indeed, it would not be adapted to ask our users to directly use complex formulas without having wrapped them up before in higher-level calls. A first attempt to do so is implemented though macros. As compile-time mechanisms, macros do not cause any runtime overhead. They are also perfectly handled by *nvcc*, the CUDA compiler. Our previous investigations result in two distinct macros: `WARP_BEGIN` and `WARP_INIT`, which respectively mark the beginning of the warp-scope code portion, and correctly fill the warp identifier variable. When `WARP_INIT` presents no particularities, except the requirement to be called before any operations bringing into play `warpIdx`, `WARP_BEGIN` voluntary forgets the block-starting brace following the *if* statement. By doing so, we expect users to place both opening and closing braces of their WLP code if needed, just as they would do with any other block-initiating keyword.

To sum up, please note once again that this implementation mainly targets to validate our approach. Still, it lays the foundation of a more complete API dedicated to WLP. Unfortunately, macros are not convenient to use. They do not provide control check until compilation. Macros are also quite hard to debug, because they are inlined in the code. Thus, they are not suited to write production codes. Macros were useful in our case to validate the concept though.

5 AOP DECLINATION OF WLP

In this section, we study the possibility to take advantage of the inputs brought by Aspect Oriented Programming (AOP) Kiczales et al. (1997) in GPU programming, and especially when using CUDA.

AOP consists in defining entry points where code is inserted in order to modify the program's behavior. These entry points are called pointcuts in AOP. A traditional example of aspects usage is the insertion of a pointcut to wrap a function call. For instance, the function call can be wrapped around the verification of a pointer, or an exception catching block. The point is this change has a small impact on the code thanks to the way aspects are handled. Indeed, the specific operations are externalized, and usually inserted at compile time. This way, operations can be done without being inserted directly in the code.

AOP generally involves a third-party software that will preprocess the source code in order to actually add the equivalent parts matching the aspect directives. For C++, a preprocessor was released in 2002 and is called AspectC++ Spinczyk et al. (2002). AspectC++ comes with lots of features but is still experimental, and thus does not fully support the C++ syntax and standard constructs. The aspect has to be defined in an "aspect header" (*.ah* extension) that will be used by the AspectC++ preprocessor (*ac++*) to weave the C++ code matching the pointcuts.

Our first attempt has been to try to implement WLP through pointcut matching any function called `wlp_*()`. In our case, we expected to obtain a similar behavior to what plain macros delivered. The conditional statement, previously achieved by the *WARP_BEGIN* macro, would

have been added with the aspect specific code. The *warpIdx* variable, previously declared and initialized by *WARP_INIT*, would have been defined through an inlined function. Unfortunately, such an approach could not be completed for several reasons. First WLP would have been available at a kernel scope only, whereas the original implementation allows to turn each programming block into a WLP-run operation. Second, AspectC++ displays troubles parsing CUDA code and the Thrust library, making it unavailable within a CUDA project.. This led us to abandon AspectC++ and to head towards another aspect implementation.

A classic way to implement handcrafted aspects in C++ is by using templates. This design is close to policy classes Alexandrescu (2001) where each new behavior that is intended to be inserted is implemented at the heart of a new template class. This class is seen as a component, which can be plugged into the base class or into other components. In order to support this feature, each involved class must accept a template parameter. Moreover, when using C++03, the template function's prototype has to match the wrapped function's to enhance it. This forces the user to write its own aspect any time he wants to use WLP. This is why we abandoned this method. A new feature from C++11 called variadic templates would enable us to provide aspect facilities through templates without the need for the user to write its own template aspect class. However, *nvcc*, the CUDA compiler, does not support C++11 at the time of writing. In the same way, a third approach could have been considered by harnessing variadic macros. Yet, the latter are not standard in C++03 either.

Other languages, such as Java for instance, implement aspects through annotations inserted in the code. The latter are understood by a preprocessor that makes them part of the language keywords. As long as the C-style fashion to deal with aspects has shown unavailable or awkward in a CUDA-enabled project, we turned to annotations. This implied to write our own preprocessor, which is designed to adopt the same behavior as Java annotations. The preprocessor itself is a simple Perl script that will rapidly parse the code to find the annotations. Its behavior is simple and focuses on detecting the annotations in the original code, and neither evaluates the whole code, nor builds a full syntax tree. This which prevents issues with unsupported C++/CUDA features that are encountered by more complete pieces of software like AspectC++.

Macros make the code harder to debug because they are inlined. An aspect preprocessor can workaround this issue by taking advantage of the `#line` pragma. This pragma can be used to point to the compiler what will be the next line number to consider, no matter the previous line number. By doing so, when our preprocessor weaves the code, it also inserts the said pragma. The aspect is then totally transparent for the user in case of a build error or when debugging. He will be warned of problems in his code at the exact line they were before any aspect code was inserted.

Concretely, in order to define a WLP kernel, the "// @warp" annotation just needs to be added before the kernel implementation. Two others annotations have been defined to enable WLP on part of the code only. The code parts that need WLP are delimited by "// @warp: begin" and "// @warp: end" at, respectively, the beginning and end of the block. Equivalent keywords from the macro WLP implementation and the AOP version are summed up in Table 1. Obviously, this preprocessing phase occurs prior to the classical building stages from CUDA.

In a more concrete way, Listings 1 and 2 expose dummy code snippets using aspects to enable WLP. Listing 1 shows an example of code for a whole WLP kernel, while Listing 2 presents a code where WLP is bounded to part of the code only.

<table>
<tr><th>Aspect code</th><th>Macro equivalence</th></tr>
<tr><td>// @warp</td><td>WARP_BEGIN {
WARP_INIT
// actual code
}</td></tr>
<tr><td>// @warp: begin</td><td>WARP_BEGIN {
WARP_INIT</td></tr>
<tr><td>// @warp: end</td><td>}</td></tr>
</table>

Table 1: Equivalence between original WLP through macros and aspect implementation

Listing 1: A whole WLP kernel

```
// @warp
__global__ void TestKernel(float * deviceArray) {
  deviceArray[0] = 0.;
  deviceArray[warpIdx] = 1.;
}
```

6 RESULTS

In this part, we introduce three well-known stochastic simulation models in order to benchmark our solution. We have compared WLP's performances on a Tesla C2050 board to those of a state-of-the-art scalar CPU: an Intel Westemere running at 2.527 GHz. For all of the three following models, each replication runs in a different warp when considering the GPU, whereas the CPU runs the replications sequentially. The following implementations use L'Ecuyer's Tausworthe three-component PRNG, which is available on both CPU and GPU respectively through Boost.Random and Thrust.Random Hoberock and Bell (2010) libraries. Random streams issued from this PRNG are then split into several sub-sequences according to the Random Spacing distribution technique Hill (2010).

6.1 Description of the models

First, we have a classical Monte Carlo simulation used to approximate the value of Pi. The application draws a succession of random points' coordinates. The number of random points present in the quarter of a unit circle are counted and stored. At the end of the simulation, the Pi approximation corresponds to the ratio of points in a quarter of the unit circle to the total number of drawn points. The output of the simulation is therefore an approximate Pi value.

Listing 2: WLP on part of the code only

```
__global__ void TestKernel2(float * deviceArray) {
  deviceArray[0] = 0.;
  // @warp: begin
  deviceArray[warpIdx] = 1.;
  // @warp: end
}
```

This model takes two input parameters: the number of random points to draw and the number of replications to compute.

The second simulation is a M/M/1 queue. For each client, the time duration before its arrival and the service time is randomly drawn. All other statistics are computed from these values. The program outputs are the average idle time, the average time in queue of the clients and the average time spent by the clients in the system. Because it did not impact the performances, the parameters of the random distribution are static in our implementation. Only the number of clients in the system and the number of replications, which modify the execution time, can be specified when running the application.

The last simulation is an adaptation of the random walk tests for PNRGs exposed in Vattulainen and Ala-Nissila (1995). The idea is to simulate a walker moving randomly on a chessboard-like map. The original application tests the independence of multiple flows of the same PRNG. To achieve this, multiple random walkers are run with different initializations of a generator on identically configured maps. Basically, each walker computes a replication. In the end, we count the number of walkers in every area of the map. Depending on the PRNG quality, we should find an equivalent number of walkers in each area. When the original version splits the map in four quarters, our implementation uses 30 chunks to put the light on the opportunity of our approach when there are many divergent branches in an application.

6.2 Comparison CPU versus GPU warp

As we can see in Figure 5, the CPU computation time of the Monte Carlo application approximating the value of Pi grows linearly with the number of replications. The GPU computation time increases only by steps. This behaviour is due to the huge parallel capability of the device. Until the GPU is fully loaded, adding another replication does not impact the computation time, because they are all done in parallel. So, when the device is full, any new iteration will increase the computation time. This only happens on the 65th replication because the GPU saved some resources in case a new kernel would have to be computed simultaneously. The same mechanism explains that after this first overhead, a new threshold appears and so on.

Due to this behaviour, GPUs are less efficient than CPUs when the board is nearly empty. When less than 30 replications are used, more than two-thirds of the board computational power is idle. Because sequential computation on CPU is widely faster than sequential computation on GPU, if only a little of the parallel capability of the device is used, the GPU runs slower. But when the application uses more of the device parallel computation power, the GPU becomes more efficient than the CPU.

The pattern is very similar for the second model: the M/M/1 queue (see Figure 6). When the board does not run enough warps in parallel, the CPU computation is faster than the GPU one. But with this model, the number of replications needed for the GPU approach to outperform the CPU is smaller than what we obtained with the previous simple model. The GPU computation is here faster as soon as 20 replications are performed, when it required 30 replications to show its efficiency with the first model. This can be explained by GPUs' architecture, where memory accesses are far more costly than floating point operations in terms of processing time. If the application has a better computational operations per memory accesses ratio, it will run more efficiently on GPU. Thus, the GPU approach will catch with the CPU one faster.

This point is very important because it means that depending on the application characteristics, it can be adequate to use this approach from a certain number of replications, or not. A

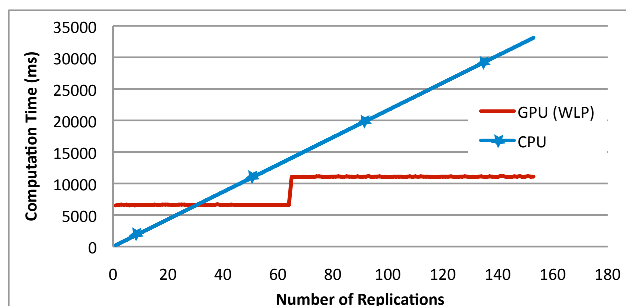

Figure 5: Computation time versus number of replications for the Monte Carlo Pi approximation with 10000000 draws

solution is to consider the warp approach only when the number of replications is big enough to guaranty that most of the applications will run faster.

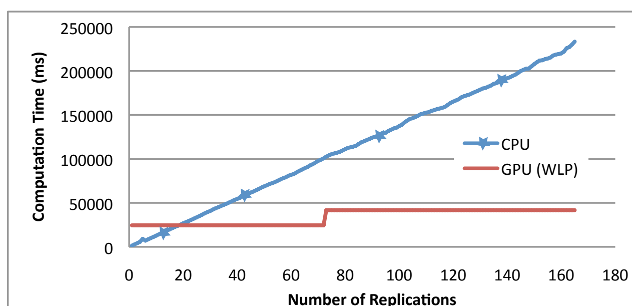

Figure 6: Computation time versus number of replications for a M/M/1 queue model with 10000 clients

6.3 Comparison GPU warp versus GPU thread

If the advantages of WLP-enabled replications compared to CPU ones in terms of computation time have been demonstrated with the previous examples, it is necessary to determine if WLP outperforms the classic TLP.

This case study has been achieved using the last model introduced: our adaptation of the random walk. Figure 7 shows the computation time noticed for each approach: CPU, GPU with WLP and GPU with TLP (named *thread* in the caption). Obviously, CPU and WLP results confirm the previous pattern: the CPU computation time increases linearly when the WLP one increases by steps. TLP follows logically the same evolution shape as WLP. Although it is impossible to see it here because the number of replications is too small, it also evolves step by step, similarly to the warp approach. WLP consumes a whole warp for each replication. In the same time, TLP activates 32 threads per warp. Thus, the latter's steps will be 32 times as long as WLP's. Having said that, we easily conclude that the first step in TLP will occur after the 2048th replication.

As we can see in Figure 7, the computation time needed by the thread approach is significantly more important than the computation time of the warp approach (about 6 times bigger

for the first 64 replications). But WLP catches up with TLP when the number of replications increases. When more than 700 replications are performed, the benefit of using the warp approach is greatly reduced. The best use of the warp approach for this model is obtained when running between 20 and 700 replications. Please note that this perfectly matches our replications amount requirement. It even allows the user to run another set of replications according to an experimental plan, or to run another set of replications with a different high quality PRNG. The latter practice is a good way to ensure that the input pseudo-random streams do not bias the results.

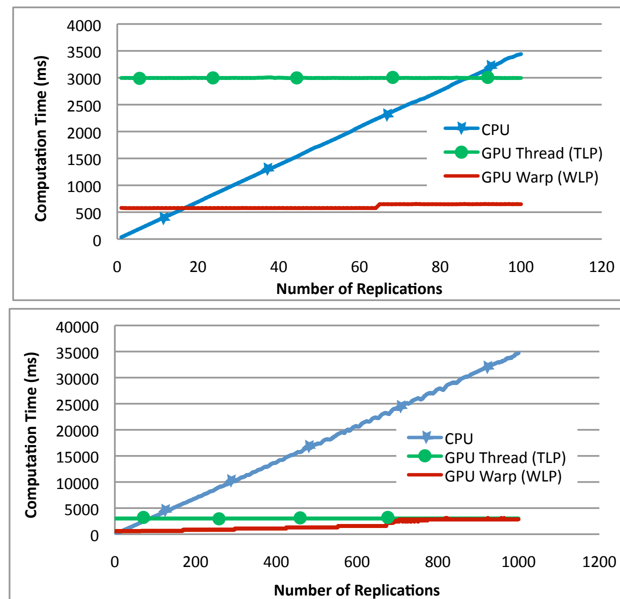

Figure 7: Computation time versus number of replications for a random walk model with 1000 steps *(above: 100 replications, below: 1000 replications)*

These results are backed up by the output of the NVIDIA Compute Profiler for CUDA applications. The latter tool allows developers to visualize many data about their applications. In our case, we have studied the ratio between the time spent accessing global memory versus computing data. Such figures are displayed in Figure 8 for both TLP and WLP versions of the random walk simulation. Our approach obviously outperforms TLP, given that the ratio of overall Global Memory access time versus computation time is about 2.5 times bigger for TLP.

To explain this ratio, let us recall that computation time was lower for WLP. Since the same algorithm is computed by the two different approaches, we should have noticed the same amount of Global Memory accesses in the two cases. In the same way, the profiler indicates significant differences between Global Memory reads and writes for TLP and WLP. These figures are summed up in Table 2:

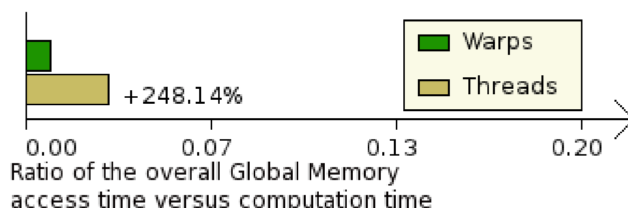

Figure 8: Comparison of TLP and WLP ratio of the overall Global Memory access time versus computation time

	TLP	***WLP***
Reads	225	18
Writes	302	104

Table 2: Number of read and write accesses to Global Memory for TLP and WLP versions of the Random Walk

7 CONCLUSION

This paper has shown that using GPUs to compute MRIP was both possible and relevant. Having depicted nowadays GPUs' architecture, we have detailed how warp scheduling was achieved on such devices, and especially how we could take advantage of this feature to process codes with a high rate of branch divergent parts. Our approach, WLP (Warp-Level Parallelism), can also help users to easily distribute their DOE experimental plans with replications on GPU.

WLP has been implemented thanks to simple arithmetic operations. Consequently, WLP displays a minimalist impact on the overall runtime performance. In order to validate the approach, the internal mechanisms enabling WLP have first been wrapped in macros. Then, for the sake of user-friendliness, another high level version has been proposed following an aspect-oriented approach. Aspects are implemented through annotations, preprocessed by a Perl script to generate the corresponding WLP blocks. At the time of writing, our version is functional and allows users to create blocks of code that will be executed independently on the GPU. Each warp will run an independent replication of the same simulation, determined by the warp identifier figured out at runtime. By doing so, we prevent performances to drop as they would do in an SIMT environment confronted to branch-divergent execution paths. WLP also tackles the GPU underutilization problem by artificially increasing the occupancy.

To demonstrate our approach performances, we have compared the execution times of a sequence of independent replications for three different stochastic simulations. Results show that WLP is at least twice as fast as a thread running on a cutting-edge CPU when asked to compute a reasonable amount of replications, that is to say more than 30 replications. This will always be the case when a stochastic simulation is studied with a design of experiments, where for each combination of deterministic factors, at least 30 replications shall be run, according to the previously mentioned Central Limit Theorem. WLP also overcomes the traditional CUDA SIMT performances by up to 6 to compute the same set of replications. Here, SIMT suffers of an underutilized GPU, whereas WLP takes advantage of the fast scheduling of warps.

Insofar performances of WLP increase with the Fermi architecture compared to Tesla, but it is difficult to forecast the same behaviour on new architectures without adapting the approach.

The lack of information regarding the hardware and especially the schedulers ruling threads execution on a CUDA GPU forces us to perform new experiments and possibly adapt WLP.

Still the aspect-oriented declination of WLP opens new perspective in terms of software engineering for GPU devices. We have shown that AOP could be harnessed for such devices, provided an handcrafted preprocessor is available. Future releases of the CUDA toolkit should even withdraw this constraint by allowing established solutions such as AspectC++ and C++11 to fully match CUDA's specificities. Aspect could then deliver their full potential, and in our case, allow us to implement an OpenCL declination of WLP without changing the way it is used in client source code.

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