Aspect-Driven Mixed-Precision Tuning Targeting GPUs

Ricardo Nobre∗,+, Luís Reis∗,+, João Bispo∗,+, Tiago Carvalho∗,+, João M.P. Cardoso∗,+,
Stefano Cherubin×, Giovanni Agosta×
∗University of Porto, Portugal ∗INESC-TEC, Portugal ×Politecnico di Milano, Italy

ABSTRACT

Writing mixed-precision kernels allows to achieve higher throughput together with outputs whose precision remain within given limits. The recent introduction of native half-precision arithmetic capabilities in several GPUs, such as NVIDIA P100 and AMD Vega 10, contributes to make precision-tuning even more relevant as of late. However, it is not trivial to manually find which variables are to be represented as half-precision instead of single- or double-precision. Although the use of half-precision arithmetic can speed up kernel execution considerably, it can also result in providing non-usable kernel outputs, whenever the wrong variables are declared using the half-precision data-type. In this paper we present an automatic approach for precision tuning. Given an OpenCL kernel with a set of inputs declared by a user (i.e., the person responsible for programming and/or tuning the kernel), our approach is capable of deriving the mixed-precision versions of the kernel that are better improve upon the original with respect to a given metric (e.g., time-to-solution, energy-to-solution). We allow the user to declare and/or select a metric to measure and to filter solutions based on the quality of the output. We implement a proof-of-concept of our approach using an aspect-oriented programming language called LARA. It is capable of generating mixed-precision kernels that result in considerably higher performance when compared with the original single-precision floating-point versions, while generating outputs that can be acceptable in some scenarios.

CCS CONCEPTS

• Computing methodologies → Parallel programming languages; • Software and its engineering → Source code generation;

KEYWORDS

GPGPU, aspect-driven, mixed-precision

1 INTRODUCTION

High Performance Computing (HPC) is evolving towards a stage where resources, in particular energy, cannot be considered expendables. Exascale HPC systems challenge the boundaries of the power supply, and therefore energy and power efficiency are paramount to exploit effectively such huge amount of resources. To address this issue, heterogeneity is currently the most interesting option from an architectural point of view. Nowadays most supercomputers support heterogeneous accelerators and often they feature General Processing Units (GPUs). GPUs allow HPC systems to significantly improve their FLOPS/Watt metrics, as testified by their strong presence in the Green500. In this scenario, it is worth to consider the impact of data precision on GPU computations.

Modern GPUs with support for native half-precision (i.e., 16-bit floating point) arithmetic with up to 2× the peak arithmetic throughput of single-precision include the NVIDIA P100 (Pascal architecture) and V100 (Volta architecture), the AMD Vega 10 XT/XL (Vega architecture), and integrated GPUs within the Intel CPUs with the Skylake, Kaby Lake, and Coffee Lake micro-architectures (Gen9+ architecture). These GPUs can be used to accelerate a number of applications that can work with 16-bit floating-points, which have less precision and range than 32-bit and 64-bit precision floating-points.

The use of data-types smaller than 32-bit can be useful in a broad selection of applications such as deep neural network training [7, 29] and inferencing [30], some image processing kernels [28] and radioastronomy [16].

The benefit potential is not limited to the higher arithmetic throughput of the GPUs, we should also consider the benefit of performing memory operation on a reduced amount of data. This consideration is valid for various memory levels, from the local memory to all the levels of the cache, from the GPU memory to the host memory. For instance, using a 16-bit float instead of a 32-bit float can make data accesses faster, both for reading and for writing.

In this paper, we present a LARA-based [17] approach for precision-tuning and we evaluate it in the context of compilation of OpenCL kernels for a GPU. We present our work-in-progress in terms of the development of a tool for automatically generating and evaluating (considering both performance and the quality of the generated outputs) alternative versions of given GPU code. The purpose of this easy-to-use tool is to help GPGPU programmers to better use the floating-point capabilities of their GPUs.

This work was partially supported by the TEC4Growth project, NORTE-01-0145-FEDER-000620, financed by NORTE 2020, under the PORTUGAL 2020 Partnership Agreement, through the European Regional Development Fund (ERDF), and by Fundação para a Ciência e a Tecnologia (FCT) through PD/BD/118211/2016. In addition, this work was partially supported in part by EU H2020-FET HPC program through the ANTAREX project under grant 671623. Finally, Ricardo Nobre acknowledges support from the HiPEAC4 Network of Excellence, financed by the EU H2020 research and innovation programme under grant agreement number 687698.

Permission to make digital or hard copies of part or all of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for third-party components of this work must be honored. For all other uses, contact the owner/author(s).

PARMA-DITAM’18, January 2018, MAN, United Kingdom
© 2018 Copyright held by the owner/author(s).
ACM ISBN 123-4567-24-567/08/06… $15.00
https://doi.org/10.475/123_4
Section 2 presents our approach. The methodology behind the experiments presented in this paper is described in detail in section 3. Section 4 presents experimental results and a brief discussion. Related work in the context of precision tuning is presented in section 5. Finally, section 6 presents concluding remarks about the work presented in this paper.

2 PROPOSED APPROACH

We use the LARA language [17] to develop a dedicated tool. Our tool takes an OpenCL kernel as input, it generates and evaluates multiple versions of the input kernel. Those versions exploit mixed-precision data types to achieve performance improvements over the original kernel, while they satisfy a user-defined constraint on the quality of the output. The tool supports specifying the following parameters:

- A set (or multiple sets) of inputs to the kernel;
- A metric for evaluating the quality of the outputs of the generated kernels;
- A threshold value which represents the maximum difference between the outputs of the original kernel and the candidates generated during exploration which is considered acceptable;
- A goal metric, such as execution performance.

The overall flow for the user is as follows. First, the user decides which metric they want to use to measure the quality of the output. They can pick a metric available from our library, or they can write a custom metric. Then, the user has to define an initialization routine for the GPU kernel under inspection. Our tool runs the original GPU kernel to generate a reference for the output. Then, it uses a Design Space Exploration (DSE) loop to evaluate several versions of the kernel. Our tool uses the selected goal metric as the target of a DSE optimization. Different OpenCL versions are automatically generated by our tool by mixing different combinations of data types for the declarations of variables in the GPU kernel. We target half-, single-, and double-precision floating-point. At the end, the tool reports the solution(s) that achieves best score according to the given quality metric. The tool excludes from the report the solution(s) that achieves best score according to the given quality metric. The tool supports specifying the following parameters:

- A set (or multiple sets) of inputs to the kernel;
- A metric for evaluating the quality of the outputs of the generated kernels;
- A threshold value which represents the maximum difference between the outputs of the original kernel and the candidates generated during exploration which is considered acceptable;
- A goal metric, such as execution performance.

The source-code code of the Clava compiler is available at https://github.com/specs-feup/specs-lara/tree/master/ANTAREX/HalfPrecisionOpenCL.

An extended version of this example is available at https://github.com/specs-feup/specs-lara/tree/master/ANTAREX/HalfPrecisionOpenCL.
```plaintext
aspectdef HalfPrecisionOpenCL
input
numIndependParams,
maxVersions = undefined,
combinationFilter = []
end

// Get the list of float and double variables
defclared in the OpenCL kernel (including parameters)
call result : OpenCLVariablesToTest;
var variablesToTest = result.variablesToTest;

generate combinations of variables
var sequenceGenerator = new SequentialCombinations(
variablesToTest.length, maxVersions);

var counter = 8;
while(sequenceGenerator.hasNext()) {

// Get a new combination of variables
var combination = sequenceGenerator.next();

// Number that was used to generate the sequence
var lastSeed = sequenceGenerator.getLastSeed();

// Check if combination passes the filter
if(!isCombinationValid(lastSeed, combinationFilter)) {
    continue;
}

// Save original kernel version
Clava.pushAst();

// Change the builtin type of the variables
for(var index of combination) {
    var $vardecl = Clava.findJp(variablesToTest[index]);
    changeTypeToHalf($vardecl);
}

// Add to the OpenCL kernel the pragma that enables half-precision
addHalfPragma();

// Choose output folder based on the
// number of independent parameters of the kernel
var baseFolder = getBaseFolder(lastSeed, numIndependParams);
var kernelFolder = "half_version_" + counter;
var outputFolder = Io.getPath(baseFolder, kernelFolder);

// Generate code
Clava.writeCode(outputFolder);

// Discard modified kernel and restore original one
Clava.popAst();

counter++;
}
end
```

Figure 1: LARA aspect that generates alternative versions of OpenCL kernels using different types for the input parameters and the kernel body variables.

3 EXPERIMENTAL METHODOLOGY

In this section we describe the setup of the experiment we present in this paper. It includes a description of the hardware, the benchmarks, the validation approach, and validation metrics.

3.1 Target Platform

We execute our experiments on a Sapphire Radeon Vega 64 Limited Edition graphics card (part number 21275-01-20G), which features an AMD Vega 10 XT GPU [2]. The GPU has a peak compute performance of 12,759, 12, 874, and 815 GFLOPS respectively with single-, half-, and double-precision scalar data-types. The use of vector data-types with width 2 – i.e., f16, f16 and d16 – results in performance improvement that brings the previous metrics to 12,690, 24,294 and 808 GFLOPS. As expected, the use of vector data-types results in a peak performance boost of 2× for half-precision computations, and a non-improvement for the others. In the case of single-precision and of double-precision data-types, the peak compute performance does not increase with the use of any of the vector data-types. It is also worth mentioning that using the half scalar data-type results in similar peak compute performance as using f16. The use of half4, half8, and half16 results in performance close to when using half2, as operating on two half-precision floats at a given time per OpenCL kernel instance saturates the GPUs. We extract the peak performance metrics through clpeak [4], a tool for profiling OpenCL devices.

Notice that, on GPUs such as the one we used, half-precision arithmetic peak performance can only be achieved if vectorization is used. Otherwise, the performance of single- and half-precision versions of the same code can be identical for some OpenCL kernels. Although vectorization is an important part of accelerating half-precision applications – i.e., the use of the packed half-precision floating-point arithmetic capabilities of the GPU – we consider auto-vectorization to be outside the scope of this paper. Nevertheless, a tool implementing the approach described in this paper can be a key component in a mapping strategy for generating high-performance vectorized implementations of OpenCL kernels, as using half-precision data-types is required for vectorization to have a considerable impact on GPU kernel code.

The graphics card is installed on a desktop computer with an Intel Xeon E3-1245 V3 @3.6GHz and 16GB of DDR3 @2400MHz in a dual channel configuration. We use Ubuntu 16.04 64-bit with the ROCm [1] driver stack (ver. 1.6). The GPU is set to high performance mode using the ROCm System Management Interface (rocm-smi), in order to reduce the variability introduced by the more aggressive dynamic frequency scaling of other more energy efficient modes.

3.2 Kernels and Goal Metric

In this paper we use kernels from the Polybench/GPU benchmark suite [26] to evaluate our approach. We selected this particular benchmark suite as it is freely available and thus contributes to making the results presented in this paper reproducible. Polybench/GPU is a collection of codes implemented for GPUs using CUDA, OpenCL, and HMPP. This benchmark suite includes kernels from benchmarks from different domains which represent computations that would be performed on GPUs in the context of applications.
of HPC. We rely on the OpenCL kernels from the 2DCONV and the GEMM benchmarks for the purpose of demonstrating our approach.

Table 1 shows a number of metrics related with the design space of the possible solutions. For the experiments presented in this paper, we allow each floating-point variable to be either a float or an half.

For instance, the OpenCL kernel of the 2DCONV benchmark has 2 floating-point parameters, matrices $A$ and $B$. Therefore, there are four possible kernel signatures, as such: $A$ and $B$ float, $A$ and $B$ half, $A$ float and $B$ half and vice-versa. The 2 floating-point inputs, combined with the fact that there are 9 floating-point variables in the kernel body, and that each variable is allowed to assume one of two different data-types (float or half) results in 2048 ($= 2^{2+9}$) possible solutions. The GEMM kernel has no floating-point variables in it’s body, therefore, considering it has 5 floating-point parameters (matrices $A$, $B$ and $C$, and alpha and beta) the number of possible OpenCL kernel versions is 32 ($= 2^5$), each having a unique function signature.

In this paper, when representing an OpenCL kernel signature, we use 0 or 1 at a given position $n$ to denote that input number $n$ of the kernel is of data type float or half, respectively. For instance, sig_{01101} represents a function kernel where the first and fourth inputs are of data type float and all other are of data type half.

The goal metric in the experiments presented in this paper is the minimization of execution time of a given OpenCL kernel, through evaluation of alternative versions of the kernel. The performance reported in this paper are averaged over 30 executions. We kept the computer load as low as possible to avoid interferences from other processes.

To determine whether the obtained error is within an acceptable margin, we compute the relative solution error [12], computed as:

$$\eta = \frac{\|A_{\text{approx}} - A\|_F}{\|A\|_F}$$

(1)

Where $\|X\|_F$ is defined as the Frobenius matrix norm, computed as the square root of the sum of the squares of all elements of the specified matrix:

$$\|X\|_F = \sqrt{\sum_{i=1}^{m} \sum_{j=1}^{n} (X_{ij})^2}$$

(2)

Note that $\|X\|_F = 0$ when the matrix is composed entirely of zeros, so if $A_{\text{approx}} = A$ (i.e., if the results are exact), then the relative solution error will be 0.

4 RESULTS

In this section, we present results that can be used to infer the performance/error trade-offs of the different versions generated by our tool from the OpenCL codes considered for demonstrating our approach.

Figure 2 depicts the results for 2DCONV, for the four possible signatures this OpenCL convolution kernel can have when each of its floating-point parameters is allowed the freedom to be a float or a half. The cases where both $A$ and $B$ input matrices are half-precision (i.e., signature sig_{11}) results generally in higher performance than the original solution (data-point most at left with error of 0.0) at the cost of a larger difference between the output from execution of the original kernel and the output from execution of the modified kernels (see, section 3.2). However, some of these solutions result in a smaller output error than some of the solutions with each of the other possible signatures, therefore increasing the merit of performing an exploration on the data-types of both the kernel parameters and the variables in the kernel body. Some of the solutions that have some of the variables declared as half might be useful in scenarios where some loss of accuracy in the output of the kernel is allowed, resulting in a speedup up to 1.13× (0.46 seconds for the fastest version and 0.51 seconds for the original version). The OpenCL version with all variables (both input and kernel body variables) declared as half was the solution measured to achieve higher performance. However, it results in a large error (see, section 3) of 0.000702 when compared with the other versions (error of 0.000716 was the highest registered). Other solutions that differ from the former by having some of the kernel body variables declared as float can result in smaller output error while having close to the same performance. For instance, there is a solution that results on an output error of 0.000489 while having close to the same execution time as the fastest solution (0.47 vs. 0.46 seconds).

Compared with 2DCONV, the GEMM kernel lead to more problems when using half-precision when using the original PolyBench/C initialization data. There were many instances where some half-precision floating-point variables represented inf, which is indicative of an overflow. This resulted in inf being also reported as error measurement (see, section 3.2).
We opted to, for the experiments presented here, reduce both the initialization values for the positions of matrices A, B and C, as well as alpha and beta by a factor of 1000x. Figure 3 depicts the results for GEMM, for the 32 possible versions the OpenCL matrix multiplication kernel can have.

In the case of GEMM, all four mixed-precision variations of the original kernel that have matrix A and matrix B as half and matrix C as float (i.e., sig_11000, sig_11001, sig_11010 and sig_11011) take close to 0.5 seconds to execute, while incurring in a smaller output error than many other versions in the solution space. This experimental result is particularly interesting: with respect to these four mixed-precision versions not only result in smaller error, but also have considerably higher performance and than the four versions where all three input matrices are of the data type half. This consideration includes the version where all input floating-point input matrices and scalars of data type half (i.e., sig_11111), which is arguably the solution that at first would be intuitively expected to result in the highest performance compared with other versions. This occurs due to strict aliasing, a concept from the C language standard which indicates that two pointers to different base types never alias. When matrix C points to half values and matrices A and B point to float values, or vice-versa, then the compiler may assume that matrix C never aliases with the other pointers (as doing so would be undefined behavior). The GEMM benchmarks contains a loop where the same position of C is continuously overwritten. If C is known to never alias with A and B, then the store instruction can be moved out of the loop, resulting in significantly fewer memory instructions. The same optimization can be enabled by explicitly marking C as restrict. When this happens, the version where all vectors are of data type half (i.e., sig_11110) executes in roughly the same performance as sig_11000 (approximately 0.5 seconds). Versions using only single-precision floating point also benefit from restrict. For instance, the version where all inputs are of data type float takes approximately 1.3 seconds to execute if the C matrix is declared with the restrict keyword (the original takes 2.0 seconds).

The version measured to execute faster (sig_11010) (although very close in terms of execution performance to the other three versions with signature sig_110XX) results in an improvement of 4.06x over the original version (the generated mixed-precision version takes 0.49 seconds and the original single-precision version takes 2 seconds), in cases the error that results from using that version is acceptable. With respect to the effect of the data-type of the two input scalars on the quality of the output of this specific matrix multiplication kernel, the declaration of alpha as a half floating-point always results in considerably increasing the output error, while declaring beta as a half has a much smaller effect.

5 RELATED WORK

Approximate computing have been investigated at several levels, from energy-efficient hardware design [15] to software tools for high performance computing [12, 21]. Researchers developed entire frameworks [5] to analyze the effects of several approximate computing techniques. However, the effectiveness of such frameworks has yet to be proved.

A large share of the work in this field is related to the adaptation of the data to hardware and energy constraints. In the embedded system domain, floating point values are usually converted to fixed point one [24] to limit the area cost and power consumption of the architecture. Hardware designers developed tools to support the automatic conversion of floating point values to fixed point ones [3, 13, 19, 27]. More recent work in this field aims at exploiting fixed point arithmetics on FPGA accelerators to speedup floating point applications, such as [20].

In high performance computing the effects of reduced precision has yet to be proved. A common approach to apply reduced and mixed precision on GPU requires the programmer to manually substitute the data type in the problem as presented in [22]. More complex frameworks can provide an automated approach to reduced precision. Lam introduces in [21] an automated procedure to identify portions of code which can be safely computed with reduced floating point precision without affecting result accuracy. In order to be able to select the best precision configuration, the work presented in [21] requires to generate and execute several versions of the same program.

Analysis and profiling tools, such as Precimonius [6] and later works [11], provide hints to the programmer on which data type is the most efficient while satisfying a given error threshold on the output. However, their implementations focus only on CPUs and do not deal with accelerators neither they support OpenCL.

An holistic approach described in [8] merges the error requirements introduced by reduced precision with a contract-based programming model which supports both floating point and fixed point
We presented a LARA-based approach for precision-tuning and we evaluated it in the context of compilation of OpenCL kernels for GPU. Our tool generated alternative versions of the GPU kernels resulted in improving performance over the original single-precision versions on an AMD Vega 10 XT GPU. These versions also produced outputs which have a difference from the original outputs that might be acceptable for some use-cases. Moreover, some of the solutions obtained in our experiments clearly demonstrate the importance of using mixed-precision when striving to increase the performance of a given OpenCL kernel while also having requirements in terms of the quality of the generated output.

We are confident that our approach and the tool we are currently developing can be useful, especially given the ease-of-use, to GPGPU programmers. It helps programmers to better use the floating-point capabilities of modern GPUs with support for native half-precision arithmetic with 2x peak performance throughput compared with peak the performance arithmetic throughput with single-precision, such as the NVIDIA P100 (Pascal architecture) and V100 (Volta architecture), the AMD Vega 10 XT/XX (Vega architecture) and current Intel integrated GPUs that are part of the Intel CPUS with the Skylake, Kaby Lake and Coffee Lake micro-architectures.

In the current implementation, our tool generates all OpenCL versions for evaluation, which corresponds to performing a full search in the design space during the exploration. As a future direction, we will work on integrating with specialized DSE tools to allow for faster exploration. Finally, we plan to add support for CUDA in our tool in a near future.

6 CONCLUSIONS

We presented a LARA-based approach for precision-tuning and we evaluated it in the context of compilation of OpenCL kernels for GPU. Our tool generated alternative versions of the GPU kernels resulting in improved performance over the original single-precision versions on an AMD Vega 10 XT GPU. These versions also produced outputs which have a difference from the original outputs that might be acceptable for some use-cases. Moreover, some of the solutions obtained in our experiments clearly demonstrate the importance of using mixed-precision when striving to increase the performance of a given OpenCL kernel while also having requirements in terms of the quality of the generated output.

We are confident that our approach and the tool we are currently developing can be useful, especially given the ease-of-use, to GPGPU programmers. It helps programmers to better use the floating-point capabilities of modern GPUs with support for native half-precision arithmetic with 2x peak performance throughput compared with peak the performance arithmetic throughput with single-precision, such as the NVIDIA P100 (Pascal architecture) and V100 (Volta architecture), the AMD Vega 10 XT/XX (Vega architecture) and current Intel integrated GPUs that are part of the Intel CPUS with the Skylake, Kaby Lake and Coffee Lake micro-architectures.

In the current implementation, our tool generates all OpenCL versions for evaluation, which corresponds to performing a full search in the design space during the exploration. As a future direction, we will work on integrating with specialized DSE tools to allow for faster exploration. Finally, we plan to add support for CUDA in our tool in a near future.

REFERENCES