A General Toolkit for “GPUtilisation” in SME Applications

Deliverable 4.7

GPUtilisation Toolkit

User Manual

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Executive summary

This document presents the User Manual of the GPSME Toolkit. The GPSME Toolkit is part of the FP7 project entitled “A General Toolkit for “GPUtilisation” in SME Applications”. The project is developed by a consortium composed of two research groups (University of Bedfordshire, UK and Rijksuniversiteit Groningen, the Netherlands) and 4 SME partners. The goal of the project is to develop a toolkit that will help SMEs improve the quality and reduce the time-to-market for their new and existing products. The GPUtilisation toolkit will automate the conversion of existing sequential CPU code to an optimal GPU implementation. The initiative of this project came from the demands of the 4 SME participants. While providing services in different areas, they all face a common problem: the quality of their products has been inhibited by a lack of computing power. The lack of computing power is not an inherent limitation for the actual SMEs, but is mostly a limitation imposed by the equipment that the users of their products are expected to have – in other words, the product developed is constrained by the computational resources of the likely user base. Hence, the availability and affordability of the equipment necessary to use the SME’s products can affect their marketing and become a major obstacle to their competitiveness in the future.

From a technological point of view, through the GPSME toolkit the consortium will research and develop techniques based on automatic parallelization for modern day GPUs. As a foundation for the GPSME toolkit, the consortium will use a sophisticated open source complier platform ROSE (www.rosecompiler.org), and improve the functions and optimize the algorithms of an existing C-to-CUDA translator MINT. In the proposed GPSME software structure, the input to the toolkit is C/C++ source code, which would be read and transferred as an AST (Abstract Syntax Tree) by the ROSE frontend. At the base of the GPSME toolkit is a set of ***#pragma*** user annotations that are meant to guide the toolkit to a closer-to-optimal tailor-made implementation. By using the information provided by the user through the annotations, the toolkit will carry out different transformations on the AST. The output from the toolkit is CUDA/OpenCL source code obtained by unparsing the transformed AST through the ROSE back-end. The toolkit will operate by creating optimized GPU kernels out of annotated parallelizable loops.

In this document, Section 1 provides a brief introduction of the GPSME toolkit andthe purpose of this document. Section 2 presents the installation instructions for the toolkit, as well as some of the key concepts. Section 3 gives two use-cases for the GPUtilisation toolkit. In Section 4, a specification of each important component of this toolkit is presented. Section 5 describes the current limitations and the future improvements of the toolkit.

1. Introduction

1.1 Purpose of this document

This document is the User Manual (UM) for the GPSME Toolkit developed under the FP7 EU project entitled: A *General Toolkit for "GPUtilisation" in SME Applications (GPSME)*. This document is meant to help SME users become more familiar with the GPSME toolkit and with its programming model. The set of user-annotations will also be explained, and some working examples will be given later in this text.

1.2 Document Overview

This document is intended for the SME developers. In Section 2, the design overview of the GPUtilisation toolkit is provided. Section 3 gives a general description of the system architecture of the GPUtilisation toolkit. In section 4, the detailed design of each component in this toolkit is presented. Section 5 describes the testing strategy of this toolkit.

1.3 Target audience

The target audience of the User Manual are the developers and scientists from the SMEs who want to learn how to use the toolkit. They are shown the handles by which they can tune their existing and future algorithms towards the efficient use of GPGPU hardware.

1.4 Terminology and definitions

Throughout this document, certain terms have a very specific meaning:

- ROSE – open-source compiler infrastructure developed at LLNL (Lawrence Livermore National Laboratory) with the goal to help the research community in designing source-to-source translators
- GPU (Graphics Processing Unit) – highly data-parallel processing hardware, typically used for games, but lately used more extensively in scientific applications
- CUDA is the parallel computing platform and programming model supported by NVIDIA on its range of GPUs
- OpenCL is a parallel computing platform and programming model promoted by the Khronos group and supported by NVIDIA, AMD, Intel and other hardware vendors on GPUs or on multi-core CPUs
- Mint is a basic C-to-CUDA translator, based on ROSE, that is optimized towards sequential C – to – parallel CUDA source-to-source translation for stencil-based applications

1.5 Key Stakeholders

The key stakeholders are:

- **Biocomputing Competence Center**,
  Italy
  http://www.b3c.it/
- **ImageMetry Ltd.**
  Czech Republic
  http://www.imagemetry.com/

- **Medicsight**
  United Kingdom
  http://www.medicsight.com/
- **RotaSoft Ltd.**
  Turkey
  http://www.rotasoft.com.tr/
- **AnSmart Ltd.**
  United Kingdom
  http://www.ansmart.co.uk/
- **University of Bedfordshire**
  United Kingdom
  http://www.beds.ac.uk
- **University of Groningen**
  Netherlands
  http://www.rug.nl/

2. Getting started

In this chapter we outline the first steps in using the GPSME toolkit. In the first part of the chapter information about the toolkit's installation is provided, while in the second part some basic command-line usage of the tool is presented.

2.1 Installation requirements

The GPUtilisation toolkit is designed to work in the Linux environment, and is based on the foundation provided by the ROSE platform. Below we list the requirements from both a hardware and software standpoint:

Hardware requirements:

- X86/x64 CPU 1.5GHz CPU
- Graphic card supporting CUDA (http://developer.nvidia.com/cuda/cuda-gpus) or a computing platform supporting OpenCL - multi-core CPU or supported GPU (http://www.khronos.org/conformance/adopters/conformant-products/)
- Ram size over 4GB
- Hard disk space of over 1GB

Software requirements:

- Linux Ubuntu (10.04 or higher)
- ROSE infrastructure
- git
- subversion
- wget
- g++ version 4.0.x to 4.4.x
- gfortran version 4.2.x to 4.4.x
- BOOST version 1.36.0 to 1.45.0
- JAVA version >=1.5.0_11
- Autoconf version >=2.59
- Automake version >= 1.96
- GNU Libtool version >= 1.5.6
- GNU Flex, GNU Bison, Doxygen, ghostscript, DOT(GraphViz), LaTex, zgrviewer.

Note: The majority of the software listed above is actually used for the successful installation of ROSE. Once the ROSE library has been generated, the GPSME toolkit only requires BOOST and JAVA on the Ubuntu platform. However, considering the diversity of ROSE versions, it is recommended that users download and install ROSE on their machine before using the toolkit.

2.2 Installing the toolkit

The steps required to have a working installation of the GPSME toolkit are summarized below:

1. Download and install a version of the Boost library (between 1.36 and 1.45) from www.boost.org/users/download. More information about the specific issues with installing the different versions of Boost can be found in: www.boost.org.
2. Download and install one of the recent versions of ROSE. The GPSME toolkit development started with the ROSE toolkit version 16568 from 3/10/2011. This version is recommended, but newer versions will typically be supported also. Instructions for the ROSE installation can be found in the ROSE user manual (http://rosecompiler.org/ROSE_UserManual/ROSE-UserManual.pdf) under Section 2.
3. Download and untar the GPSME toolkit. To successfully install the toolkit, the rose.mk file has to be modified to reflect the specific pre-required installation paths. The following paths should be provided:
    a. ROSE_INSTALL_DIR
    b. BOOST_INSTALL_DIR
    c. JAVA_INCLUDE
4. **cd** to the GPSME *src* directory and type **make** to compile the GPSME toolkit
5. Set up the LD_LIBRARY_PATH environment variable to include the paths to the boost library and java library. For example:
    a. *export BOOST_INSTALL= /yourpath/boost_1_4*
    b. *export LD_LIBRARY_PATH=$BOOST_INSTALL/lib:$LD_LIBRARY_PATH*
    c. *export JAVA_HOME= /usr/lib/jvm/java-6-openjdk*
    d. *export LD_LIBRARY_PATH=$JAVA_HOME/jre/lib/amd64/server:$LD_LIBRARY_PATH*

After successfully completing these steps the GPSME toolkit installation should be complete. The next step is to experiment with the GPSME programming model.

2.3 Using the command-line options

The toolkit is used to generate a CUDA or OpenCL output from an annotated C/C++ source file. The output code does not rely on any external library that should be loaded at runtime, as the GPSME toolkit solely relies on the libraries of the target language, namely the CUDA runtime library when targeting CUDA, or the OpenCL runtime library when targeting OpenCL. These libraries should be present at the locations contained in the LD_LIBRARY_PATH environment variable.

The GPSME toolkit uses the command-line interface (CLI) to invoke the program in the Linux environment. Each command for the GPSME toolkit starts with the executable name, which is "GPSMETranslator". The executable name is followed by the name of the source file that should be translated and also by an option flag that controls the output of the translator. These are the three mandatory fields, with other fields being optional.

Use the following rules when specifying command line options:

- Enter options in any order. Each option is separated by spaces.
- Be consistent with upper case and lower case.
- Enter file names in the specified order that is prescribed by the command line program.
- Use lower case for all file extensions.
- There is an "options" modifier at the end of the command line, which controls the various options of the translator.

An example for the usage of the toolkit is:

$ ./GPSMETranslator <input_source_file>.<extension> <output_format> [options]

Where:

- <input_source_file> - represents the filename of the source code to be processed.
- <extension> can currently be either .c or .cpp. Based on the provided extension, the GPSME toolkit will call the necessary front-end parser from the ROSE infrastructure, and will generate the AST for the input source.
- <output_format> is a mandatory parameter that selects whether the output format is CUDA or OpenCL. The toolkit can thus be called like:
    - $ ./GPSMETranslator matMul.c –cl to generate an OpenCL version of the matMul.c input C program
    - $ ./GPSMETranslator Heat3D.cpp –cu to generate a CUDA version of the Heat3D.cpp input C++ program
- [options] is an optional list of arguments that trigger certain optimizations, or guide the compiler with extra knowledge. These set of options will further be extended during the development of the project. Some of the options are:
    - Optimization options:
        - opt:shared turns on shared memory usage to improve performance
        - opt:register turns on register reuse to avoid register fill/spill
    - Platform-specific:
        - platform:xxx helps the translator produce a code tailored to a specific output platform (e.g. platform:cc30 tunes the output to an NVIDIA compute-capability 3.0 compatible device)

Apart from this simple use-case, users can also make use of Makefiles, in order to compile multi-file, multi-rule projects. A sample Makefile will be shown farther in this document.

Besides this Linux client-based usage scenario, the toolkit will be provided with a web-server front-end. In the first versions of the toolkit the web-service will be accessible by the SMEs through normal web queries, with later versions increasing the automation and providing scripted access to the web-server. The purpose of this web-server approach is to provide platform independence to the SMEs. This way, even if the toolkit is normally usable only in the UNIX environment, SMEs who have their application on other platforms (e.g. Windows, Mac OSX) can still use it. Some further constraints will be applied for this approach (e.g. target operating system-specific libraries must not be used in the files that need to be parallelized, as they will not be found on the source Linux system by the front-end parser).

2.4 Key concepts/resources used within GPSME

Below are listed some of the most important concepts and the resources used within the GPSME project.

ROSE Infrastructure: Open source compiler infrastructure to build source-to-source program transformation and analysis tools.

- Particularly well suited for building custom tools for static analysis, program optimization, arbitrary program transformation, domain-specific optimizations, complex loop optimizations, and performance analysis.
- ROSE builds and provides access to an abstract syntax tree (AST) that is well suited to source-to-source transformation (ROSE does not lose any information about the structure of the original source code).
- Nearly all types of optimizations are included in ROSE and can be used via simple function calls to some interfaces from the translators. Examples of packages within ROSE which can be used:
  - Call Graph analysis library
  - CFG analysis
  - Alias analysis
  - Extensive loop transformation API with capabilities including:
    - Dependence and transitive dependence analysis
    - Profitability analysis
    - Transformation framework
- More information about the ROSE infrastructure can be found at http://rosecompiler.org

Mint Translator: A domain-specific source-to-source translator between C and CUDA.

- Based on ROSE and targeting CUDA.
- Domain-specific targeting stencil-based methods. Stencil-based methods are the base for many algorithms that numerically solve partially differential equations (PDEs), and are thus widely used in scientific applications.
- Uses some user-guided annotations in the form of pragmas**.** These pragmas give more specific knowledge to the translator.
- Achieves about 80% of hand-optimized code performance for stencil methods when targeting the latest NVIDIA boards.

AST manipulation:

- The GPSME toolkit works by modifying the input files' abstract syntax tree (AST).
- The AST is passed to the GPSME toolkit in the mid-end of ROSE, after the input file is parsed by the EDG front-end (C/C++ front-end from ROSE). The resulting AST is complete, incorporating all the semantics from the input source-file. This is due to the vast number of the ROSE intermediate representation nodes (IR nodes) that are required to model every aspect of the input source-file inside the AST.

Loop transformations:
- The GPSME toolkit relies on the dependency testing from ROSE to check if a particular loop is safely parallelizable or not.
- Apart from checking the safeness of parallelization, ROSE also provides an API for loop dependency elimination that employs techniques such as: loop skewing, loop reversal, loop interchange, loop fusion, etc.
- Each transformation modifies the AST accordingly, and after the dependency has been eliminated, the loop nest can be safely parallelized.

CUDA/OpenCL runtime:
- Based on the user-provided pragma annotations, the GPSME translator will issue CUDA or OpenCL runtime calls in the output programs.

- These runtime calls control the creation of the data structures on the GPU, the copying between the host processor's memory and the device memory, and the copying of results from device memory to the host memory.
- Launching of compute kernels on the accelerator device.
- Communication with the various command and data queues from the OpenCL runtime.

2.5 Current status

The development environment of the GPSME toolkit has been built on top of the ROSE platform for designing source-to-source translation. The ROSE platform is designed solely for Linux, and thus this is the operating system of choice for the GPSME toolkit. A web-service scenario that extends this initial limitation to multiple platforms has been described in Section 2.3 Using the command-line options. The general architecture of the GPSME toolkit is presented in Figure 1: General architecture of the GPSME toolkit. The first version of the GPSME toolkit to support C/C++ input source files and capable of outputting a CUDA/OpenCL source file has been implemented. This version of the GPMSE toolkit is built on top of a similar toolkit called "Mint". Mint is only capable of translating a single C source file into a CUDA file. Also, Mint is limited to some domain-specific problems, namely stencil computation. The extended functions proposed so far in the GPSME toolkit make it capable of reading basic C++ files and generating OpenCL files.

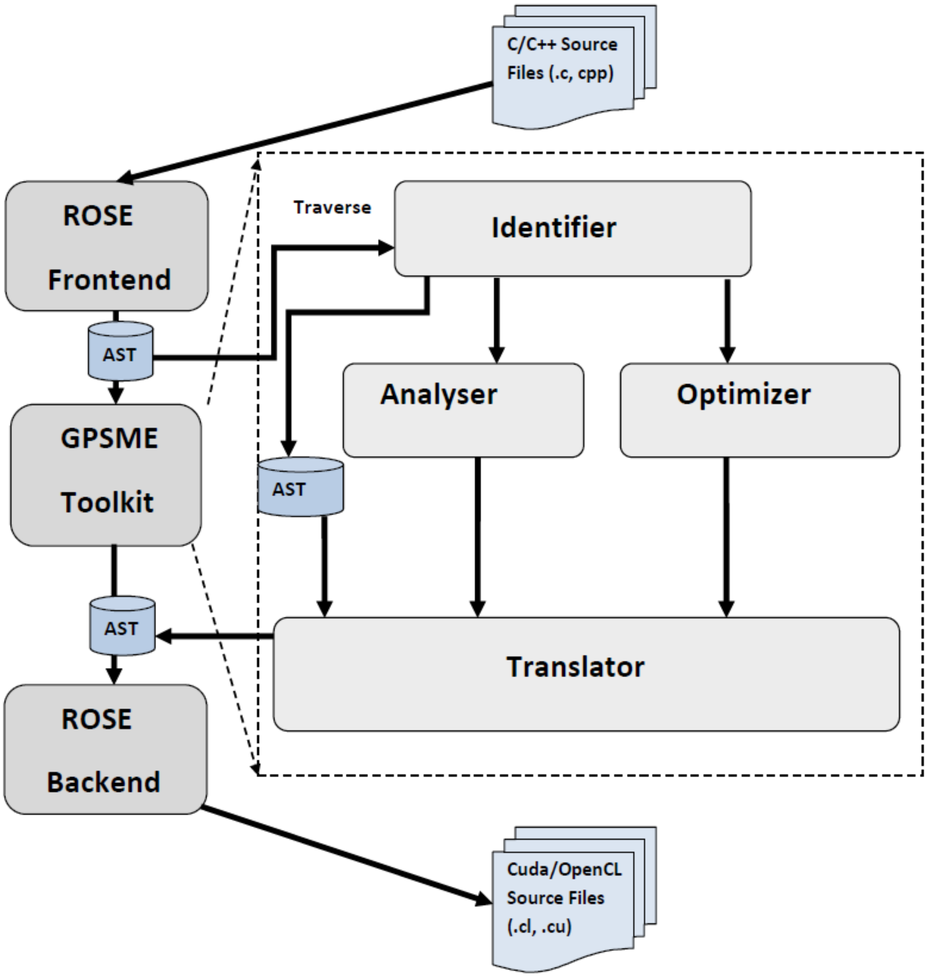


Figure 1: General architecture of the GPSME toolkit

2.6Constraints

The main constraints of the current version of the GPSME toolkit are:

- Only works natively on the Linux platform due to the availability of ROSE libraries
- Unable to support all the features of the C++ programming language
- Unable to parallelize multiple types of loop patterns, being limited to a 3D type of loop pattern as will be seen in the source examples from Section

3. Using the GPSME toolkit.

3. Using the GPSME toolkit

3.1 7-point 3D heat equation using the GPSME toolkit

```
void Heat3D::execute(void)
{
  int n = 256;
  int m = 256;
  int k = 256;

  float c0=0.5;
  float c1=-0.25;

  float*** Unew; float*** Uold;

  Unew= alloc3D(n+2, m+2, k+2);
  Uold= alloc3D(n+2, m+2, k+2);

  init(Unew, n+2, m+2, k+2);
  init(Uold, n+2, m+2, k+2);

  int T= 20;
  int nIters = 0;
  double time_elapsed ;
  double Gflops=0.0;

#pragma mint copy(Uold, toDevice, (n+2), (m+2), (k+2))
#pragma mint copy(Unew, toDevice, (n+2), m+2, (k+2))

#pragma mint parallel
  {
    time_elapsed = getTime();
    int t=0;

    while( t < T ){
      t++;
      int x, y, z;

      //7-point stencil
#pragma mint for nest(all) tile(16,16,16) chunksize(1,1,16)
      for (z=1; z<= k; z++){
         for (y=1; y<= m; y++){
           for (x=1; x<= n; x++) {
             Unew[z][y][x] = c0* Uold[z][y][x]  + c1 * (Uold[z][y][x-1] + Uold[z][y][x+1]+
                                                Uold[z][y-1][x] + Uold[z][y+1][x] +
                                                Uold[z-1][y][x] + Uold[z+1][y][x]);
           }
      }
    }
#pragma mint single
    {
      REAL*** tmp;
      tmp = Uold; Uold = Unew; Unew = tmp;
      nIters = t ;
    }
```

Figure 2: GPSME toolkit example for a 3D heat equation

This section aims at providing the user an understanding of using the GPSME toolkit pragmas. Currently, the pragmas involved are inherited from the Mint project, but they will be further extended during the lifetime of the project, in order to provide increased flexibility and the ability to fine-tune the output code.

As can be seen in the modified source file, only 4 pragmas are needed to optimally transform the 3D heat equation from its CPU to an optimal GPU implementation. The used pragmas have the following meaning:

- #pragma mint copy
  - First two pragmas of type **copy** command the transfer of the input arrays from the host to the device memory ($U_{\mathbf{new}}$ and U_{old}). *toDevice* is the direction of transfer and ***n+2,m+2,k+2*** are the three dimensions of each array.
  - The last pragma of type **copy** transfers the result back to host-memory space by using the modifier *fromDevice.*
- #pragma mint parallel
  - This pragma indicates the start of a parallel region. This region encloses the kernel that should be parallelized.
- #pragma mint for
  - This pragma indicates that the following statement is a series of nested for-loops.
  - The ***all*** modifier lets GPSME know that all the levels of the loop nest should be parallelized.
  - The **tilesize** and **chunksize** parameters control the thread block dimensions. The direct relation between the thread block size and these parameters is: dim3 blockDim(tx/cx,ty/cy,tz/cz), where tilesize=(tx,ty,tz) and chunksize= (cx,cy,cz).
- #pragma mint single
  - The part of code that is enclosed in a **pragma mint single block** is executed either on the device by a single GPU-thread, or on the host. It is a sequential region.

After annotating the code in this manner, we run the **GPSMETranslator** executable as shown in Section 2.3 Using the command-line options. In case we target CUDA, the output will be the following:

- A *.cu CUDA file that contains:
  - The transformed kernel - This function will be compiled with the device compiler and executed on the GPU.
  - The host-code. This code will issue all the commands to the runtime system. It will issue memory allocation, memory copying, kernel launches, as well as other commands to the device.

An example of the output from the GPSME toolkit is outlined in the figures below:

```
  Unew = alloc3D((n + 2),(m + 2),(k + 2));
  Uold = alloc3D((n + 2),(m + 2),(k + 2));
  init(Unew,(n + 2),(m + 2),(k + 2));
  init(Uold,(n + 2),(m + 2),(k + 2));
  int T = 20;
  int nIters = 0;
  double time_elapsed;
  double Gflops = 0.0;
/* Mint: Replaced Pragma: #pragma mint copy( Uold, toDevice,( n + 2 ),( m + 2
),( k + 2 ) ) */
  cudaError_t stat_dev_1_Uold;
  cudaExtent ext_dev_1_Uold = make_cudaExtent(((n+2)) * sizeof(double
),((m+2)),((k+2)));
/* Mint: Malloc on the device */
  cudaPitchedPtr dev_1_Uold;
  stat_dev_1_Uold = cudaMalloc3D(&dev_1_Uold,ext_dev_1_Uold);
  if (stat_dev_1_Uold != cudaSuccess)
    fprintf(stderr,"%s\n",cudaGetErrorString(stat_dev_1_Uold));
/* Mint: Copy host to device */
  cudaMemcpy3DParms param_1_dev_1_Uold = {0};
  param_1_dev_1_Uold.srcPtr = make_cudaPitchedPtr(((void *)Uold[0][0]),((n+2))
* sizeof(double ),((n+2)),((m+2)));
  param_1_dev_1_Uold.dstPtr = dev_1_Uold;
  param_1_dev_1_Uold.extent = ext_dev_1_Uold;
  param_1_dev_1_Uold.kind = cudaMemcpyHostToDevice;
  stat_dev_1_Uold = cudaMemcpy3D(&param_1_dev_1_Uold);
……………………

#pragma mint for nest ( all ) tile ( 16, 16, 16 ) chunksize ( 1, 1, 16 )
      int num3blockDim_1_1527 = (k - 1 + 1) % 16 == 0?(k - 1 + 1) / 16 : (k -
1 + 1) / 16 + 1;
      int num2blockDim_1_1527 = (m - 1 + 1) % 16 == 0?(m - 1 + 1) / 16 : (m -
1 + 1) / 16 + 1;
      int num1blockDim_1_1527 = (n - 1 + 1) % 16 == 0?(n - 1 + 1) / 16 : (n -
1 + 1) / 16 + 1;
      float invYnumblockDim_1_1527 = 1.00000F / num2blockDim_1_1527;
      dim3 blockDim_1_1527(16,16,1);
      dim3
gridDim_1_1527(num1blockDim_1_1527,num2blockDim_1_1527*num3blockDim_1_1527);

mint_1_1527<<<gridDim_1_1527,blockDim_1_1527>>>(n,m,k,c0,c1,dev_2_Unew,dev_1_U
old,num2blockDim_1_1527,invYnumblockDim_1_1527);
      cudaThreadSynchronize();
      cudaError_t err_mint_1_1527 = cudaGetLastError();
```

Figure 3: GPSME generated host code

```
__global__ void mint_1_1527(int n,int m,int k,double c0,double
c1,cudaPitchedPtr dev_2_Unew,cudaPitchedPtr dev_1_Uold,int
num2blockDim_1_1527,float invYnumblockDim_1_1527)
{
  double *Unew = (double *)dev_2_Unew.ptr;
  int _width = dev_2_Unew.pitch / sizeof(double );
  int _slice = dev_2_Unew.ysize * _width;
  double *Uold = (double *)dev_1_Uold.ptr;
  float blocksInY = num2blockDim_1_1527;
  float invBlocksInY = invYnumblockDim_1_1527;
  int _p_x;
  int _p_y;
  int _p_z;
{
    int _upperb_y = m;
    int _upperb_x = n;
    int _idx = threadIdx.x + 1;
    int _gidx = _idx + blockDim.x * blockIdx.x;
    int _idy = threadIdx.y + 1;
    int _gidy = _idy + blockDim.y * 1 * blockIdx.y;
    int _idz = threadIdx.z + 1;
    int blockIdxz = blockIdx.y * invBlocksInY;
    int blockIdxy = blockIdx.y - blockIdxz * blocksInY;
    _gidy = _idy + blockIdxy * blockDim.y;
    int _gidz = _idz + blockIdxz * 16;
    int _index3D = _gidx + _gidy * _width + _gidz * _slice;
{
      int _upper_gidz = _gidz + 16 < k?_gidz + 15 : k;
{
        if (_gidy >= 1 && _gidy <= m) {{
            if (_gidx >= 1 && _gidx <= n)
              for (_gidz = _gidz; _gidz <= _upper_gidz; _gidz += 1) {
                _index3D = _gidx + _gidy * _width + _gidz * _slice;
{
                  Unew[_index3D] = ((c0 * Uold[_index3D]) + (c1 *
(((((Uold[_index3D - 1] + Uold[_index3D + 1]) + Uold[_index3D - _width]) +
Uold[_index3D + _width]) + Uold[_index3D - _slice]) + Uold[_index3D +
_slice])));
                }
              }
          }
        }
      }
    }
  }
}
```

3.2 SME code working example

In this section a sample code from one of the SME partners in the project is presented. As can be seen also from this sample, the effort necessary to annotate the code is much less than the effort needed to write an optimal parallel implementation. As can be seen in the input source code from Figure 5, in order to pass through the toolkit, the third dimension of the arrays has to be “artificially created”. Other samples of code can also be transformed in this manner.

```
int getartiblocks(int image_width,int image_height,double
***imDenoised_GPU,double ***oneChannelImage_GPU,int fv_size, double
***fv_GPU,int intraBlockRelativeOffset)
{
  int counter = 0;
  int row;
  int column;
  int row_offset;
  int column_offset;
  float denoised_value;
  double ***imDenoised = imDenoised_GPU;
  double ***oneChannelImage = oneChannelImage_GPU;
  double ***fv = fv_GPU;
  int   index_z = 1;

#pragma mint copy(imDenoised, toDevice, index_z, image_width, image_height)
#pragma mint copy(oneChannelImage, toDevice, index_z, image_width,
image_height)
#pragma mint copy(fv, toDevice, index_z, index_z, fv_size)

#pragma mint parallel
  {
  #pragma mint for nest(all) tile(16,16,16) chunksize(1,1,16)
  for (int j = 1 ; j <=1 ; j++){
    for (int t = 1 ; t <=1 ; t++){
      for (int i = 0; i < (image_height * image_width); i++) {
        row = (i / image_width);
        column = (i % image_width);
        row_offset = (row % 8);
        column_offset = (column % 8);
        if ((((row_offset >= intraBlockRelativeOffset) && (row_offset <= ((8 -
intraBlockRelativeOffset) - 1))) && (column_offset >=
intraBlockRelativeOffset)) && (column_offset <= ((8 -
intraBlockRelativeOffset) - 1))) {
              denoised_value = imDenoised[0][row][column];
              fv[0][0][counter++] = (oneChannelImage[0][row][column] -
denoised_value);
        }
       }
     }
   }
 }

#pragma mint copy(imDenoised, fromDevice, index_z, image_width, image_height)
#pragma mint copy(oneChannelImage, fromDevice, index_z, image_width,
image_height)
#pragma mint copy(fv, fromDevice, index_z, index_z, fv_size)

  return 1 ;
}
```

Figure 5: SME code passing through GPSME toolkit

3.3 Example Makefile for multi-file support

Until this example, we have only used a single source file for input to the GPSME toolkit. However, one Makefile is provided below as a basis for creating C++ multi-file projects by the users of the tool:

```
#Input/outputs
SOURCES=MemoryManagement.cpp Timings.cpp Poisson19.cpp Heat3D.cpp main.cpp
CPU_EXECUTABLE=MultiCpp_cpu
GPU_EXECUTABLE=MultiCpp_gpu

#Compiler settings
CC=g++
CFLAGS=-c -Wall
LDFLAGS=

#Generated variables
OBJECTS=$(SOURCES:.cpp=.o)
TEMP=$(basename $(SOURCES))
TEMP2=$(addprefix gpsme_, $(TEMP))
CUDASRCS=$(addsuffix .cu, $(TEMP2))
CUDAOBJS=$(CUDASRCS:.cu=.o)

# Stops make deleting the intermediate (.cu) files after compiling them.
# http://darrendev.blogspot.nl/2008/06/stopping-make-delete-intermediate-
files.html
.SECONDARY:

#Default target
all: gpu cpu

#Target for CPU version
cpu: $(SOURCES) $(CPU_EXECUTABLE)

$(CPU_EXECUTABLE): $(OBJECTS)
        $(CC) $(LDFLAGS) $(OBJECTS) -o $@

#Taget for GPU version
gpu: $(SOURCES) $(GPU_EXECUTABLE)

$(GPU_EXECUTABLE): $(CUDAOBJS)
        nvcc $(CUDAOBJS) -o $@

%.o : %.cu
        nvcc -c $< -o $@

gpsme_%.cu : %.cpp
        GPSMETranslator $< -o $@

clean:
        #rm -rf $(OBJECTS) $(CUDAOBJS) $(CPU_EXECUTABLE) $(GPU_EXECUTABLE)
$(CUDASRCS) $(ROSEFILES)
        rm -rf $(CPU_EXECUTABLE)
        rm -rf $(GPU_EXECUTABLE)
        rm -rf a.out
        rm -rf gpsme_*
```

When calling **make** in the directory in which the Makefile resides, two versions will be created, one for the CPU, and a different CUDA one for the GPU. In the case of the GPU one, the GPSMETranslator is firstly called to translate the annotated input files to CUDA. Then, the NVIDIA compiler nvcc is used to compile the *.cu generated file to a *.o object file. Finally, after this process is repeated for all the input files, nvcc is again invoked in order to link all the object files together and create the GPU executable. For the CPU version, the input files are compiled directly with the g++ UNIX C++ compiler. This script was provided as a model, and can be further extended to provide compile options specific to OpenCL.

4. Detailed Design

Technically, GPSME features techniques to adapt automatic parallelization to the latest GPU compute architecture to deliver optimal performance. This is expected to greatly improve on traditional CPU-based automatic parallelization. The literature review has suggested that the techniques in this area are still very much in their infancy and that there is no existing toolkit that can benefit the SMEs immediately.

Among others, the product shall support:

- Automatic parallelization under Linux natively and under other OS through the use of a web-service;
- C++ programming language;
- Parallelization of all parallelizable types of loops in the code;
- Specific semi-automated directives/clauses (like OpenMP).

4.1 System and execution model

The system structure and translation flow of the GPSME toolkit is illustrated in Figure 1. The input to the toolkit is C/C++ source code annotated with GPSME pragmas. Once the source file is read, the ROSE frontend constructs the AST and passes it to the core of the GPSME toolkit. The core of the toolkit traverses the AST and queries the parallel regions containing data-parallel for-loops. Directives in a parallel region go through the components of the identifier, analyser and optimizer in the toolkit core. The translator component uses the conducted rules from the above components to transform the AST. The output from the toolkit is CUDA/OpenCL source code generated by unparsing the transformed AST. The GPSME-generated source file follows the CUDA (OpenCL is similar) system assumptions as seen in Figure 6. These assumptions are as follows:

- The host (CPU) has a different address space from the device (GPU) address space.
- The host is typically a multi-core CPU, coupled to the system main memory.
- The device is typically a many-core GPU with a complex memory hierarchy and with at least two levels of parallelism.
- The host issues commands and data to the device. The execution of a kernel takes place on the device, and the host reads back the results by again issuing a command to the device.

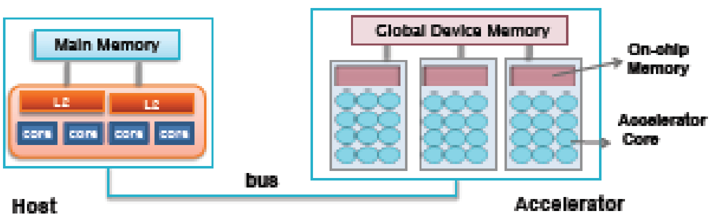


Figure 6: Mint system model

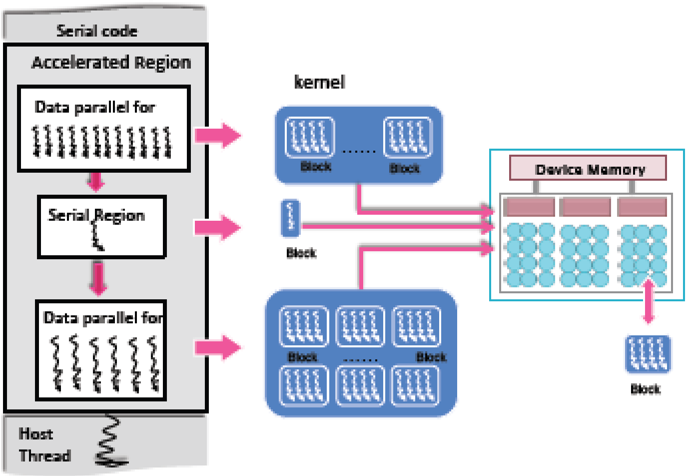


Figure 7: Mint execution model

4.2 GPSME Pragmas

The design of the toolkit starts from the defined user annotations. GPSME has inherited a set of 5 **pragmas** from the Mint project. This minimal set of **pragmas** will be extended during the course of the project, with some more specialized **pragmas** that will have the role of fine-tuning the code transformation process (e.g. improving the memory management).

- **#pragma mint parallel [clauses]**: indicates the start of a structured block of code representing the region containing parallel work. This region implies the use of a different address space (device address space) and creates an accelerator scope for the variables. These regions will be accelerated. Before control enters the parallel region, any data used in the region must have previously been transferred using the copy directive. It is the programmer's responsibility to specify the variable names, the size and the number of dimensions in case of a copy. This should be provided by the prior use of a **#pragma copy** directive. Currently, it is not supported to have a parallel region nested inside another parallel region.

- **#pragma mint for [clauses]**: marks the succeeding for-loop for GPU acceleration and manages data decomposition and work assignment. Each such parallel for-loop becomes a CUDA or OpenCL kernel. After the kernel returns, there is an implicit barrier, synchronizing all the device threads to the host thread. This is the most powerful annotation, having also a few clauses that extend its capabilities:

  - *nest(#|all)*: indicates the depth of for-loop parallelization within a loop nest. It can be an integer or it can be *all* to specify that all the loops from within the loop nest are parallelizable. If the *nest* clause is omitted, only the outer-most for-loop is parallelized.

  - *tile(tx,ty,tz)*: specifies how the iteration space of a loop nest is to be subdivided into tiles. A data tile is a group of threads. In particular for the NVIDIA notation, a tile corresponds to the number of data points computed by a thread block.
  - *chunksize(cx,cy,cz)*: aggregates logical threads into a single CUDA or OpenCL thread. For some applications, if each point is calculated by a device thread, the workload for each thread is not sufficient to obtain high performance. For this kind of applications, the granularity of the separation of work into threads is controlled using this clause. Together with the tile clause, the chunksize clause specifies the number of threads residing in a thread clock. This number is *threads(tx/cx,ty/cy,tz/cz).*
- **#pragma mint copy (src|dst, toDevice|fromDevice,[Nx,Ny,Nz,…]):** expresses data transfers between the host and device. The programmer should manually handle all the transfers to/from device memory using this pragma. Users should be careful when needing data back from the device. At the exit from a parallel region, the data on the device is destroyed, and thus has to be read with a copy directive. The specific modifiers of this pragma are:
  - **src|dst** is the variable name that should be transferred.
  - **toDevice|fromDevice** represents the direction of the data copy.
  - **[Nx,Ny,Nz,…]** represent the dimension of the array from the fastest to slowest varying dimension.
- **#pragma mint barrier**: synchronizes all the threads.
- **#pragma mint single**: indicates serial regions. Depending on the requirements, either a host or a single device thread executes the region.

4.2.1 New pragmas

The pragmas listed above have been inherited from the Mint project, but in addition to these we have defined some new pragmas to help with different code structures such as those found in the code from IME. These pragmas particularly aim at solving 2D image processing problem. Before using these pragmas, it is necessary to revise CPU code into an acceptable format of auto-processing CPU code. It assumes that the 2D Image data is stored into a 2D float pointer : Image[width][height], and a known size window would be created into a 1D array to process some operations in this image, such as median filter, sobel filter, etc.

Therefore, the general steps of 2D image processing operations are below:

1. To define the required 1D array before traveling the image data stored in 2D float pointer.
2. For each selected window, to transfer the relevant image data in buffer to the 1D array.
3. To do any necessary image processing operations on this 1D array.
4. To find the required value into 1D array and assign to image data.

In order to achieve these steps, four pragmas are designed in GPSME toolkit:

#pragma GPSME single remaininloop

This pragma is used to put the definition statement of 1D array into CUDA kernels. It is because in revised CPU code, the definition statement of 1D array usually is putted outside the “for” Loop, but in CUDA kernel, it should be defined inside the kernel. This pragma is to put the definition statement from outside “for” loop into inside “for” loop. Ideally, it would be not limited the number of 1D or 2D arrays are defined, in IME case, one 1D array is required.

#pragma GPSME single transfer

This pragma is used to parse the codes of transferring image data from buffer into 1D array in CUDA kernel. One code transferring is on the initialization, condition statement and increment of “for” loop during the traveling image data. Another code transferring is on replacing 2D pointer image buffer on host by CUDA Texture Array on device. The thread calculation process should be generated at the beginning of CUDA kernel.

#pragma GPSME single remain

This pragma is used to remain the codes of operating 1D array in CPU code as same as in CUDA kernel. It requires the codes in this pragma are variable-independent; the referenced 1D or 2D arrays should be already defined into GPSME single remaininloop pragma. Meanwhile, the operations in the code should be simple calculation and suitable for GPU threads.

#pragma GPSME single assign

This pragma is used to parse the codes of transferring image data from 1D array into texture buffer in CUDA kernel. Code transferring is on replacing 2D pointer image buffer on host by CUDA Texture Array on device. The thread calculation process should be generated at the beginning of CUDA kernel.

4.3 Input languages

In this section the input possibilities of the GPSME toolkit are presented. Initially, Mint supported only C annotated code. After some modifications to the front-end, now C++ code can pass through the toolkit. The parallel loop can now be in member functions, so the code palette that can pass through the toolkit is further extended. However, not all C++ OOP constructs are supported. Inside of the parallel constructs delimited by the pragmas, there are also some limitations. These will be discussed in section 5.2 Known limitations, and some of them will be resolved in further revisions.

4.4 Output languages

Initially, Mint had support for the CUDA backend. Because this is a project involving multiple SMEs, each one with its particular GPU in mind, the palette of output languages had to be extended. The current version of the GPSME toolkit offers an OpenCL backend, increasing the use of the toolkit to platforms like AMD or Intel.

Below is the most important information about the OpenCL backend.

```
/* Mint_num_platforms: Device Configuration. */
  printf("------ Start to get PlatformIDs \n");
  cl_platform_id platform_id = (NULL);
  cl_device_id device_id = (NULL);
  cl_uint ret_num_devices;
  cl_uint ret_num_platforms;
  cl_int ret;
  cl_context context = (NULL);
  cl_command_queue command_queue = (NULL);
  ret =
clGetPlatformIDs(1,&platform_id,&ret_num_platforms);
  printf("------ Get PlatformIDs \n");

  ret =
clGetDeviceIDs(platform_id,CL_DEVICE_TYPE_DEFAULT,1,&device_id,&ret_num_platfor
ms);
  context = clCreateContext((NULL),1,&device_id,(NULL),(NULL),&ret);
  printf("------ Start Loading the kernel .cl file \n");

/* Mint: Loading the kernel. */
  cl_program program;
```

Figure 8: OpenCL configuration generated by GPSME OpenCL backend

A mapping has been realized between CUDA and OpenCL for device configuration, kernel parameters, allocate structures, create structures and others, but a complete mapping is not yet achieved.

4.5 Loop management

For the majority of the algorithms encountered in the SMEs codebase, there are only slight loop dependencies. So typically, loop nests are transformed directly to kernel bodies, and a kernel call is issued instead. This is also the case for stencil methods. However, if there are some loops that have dependencies, GPSME has the ability to use the Loop Transformation API from ROSE, remove the dependencies by rearranging the AST, and then rewrite the modified AST. This will assure the input to the GPSME toolkit will be as free as possible of dependencies. Some of the loop types are described below.

4.5.1 Loop pattern classification

In this class, several types of loops would be recognized, and then we can use some techniques to optimize them, e.g. skewing, interchanging, stencil.

- *Standard Single Loop*: This is a typical singe loop type as below:

  do I = 0, N
  S1 : A(I) = B(I) + 1
  S2: C(I) = A(I) + 1
  enddo

- *Single Loop with dependency*: can be transformed to standard single loop by skewing

do I = 0, N	*do I = 0, N*
S1 : A(I) = B(I) + 1	*S1 : A(I) = B(I) + 1*
S2: C(I) = A(I-1) + 1	*S2: C(I) = A(I+1) + 1*

```
enddo                          enddo
```

- *Standard Double Loop*: This is a typical double loop type as below:

```
do  I = 0, N                   do  I = 1, N
do J = 0, M                    do J = 1, M
S1 : A(I,J) = F(B(I,J) )       S1 : A(I,J) = F((I-1,J) )
enddo                          enddo
enddo                          enddo
```

- *Double Loop with dependencies*: can be transferred to standard double loop by interchanging

```
Do  I = 1, N                   Do  I = 1, N
Do J = 1, M                    Do J = 1, M
S1 : A(J,I) = F(B(J-1,I))      S1 : A(I,J) = F(B(I-1,J) )
Enddo                          Enddo
Enddo                          Enddo

do  I = 1, N                   do  I = 0, N
do J = 1, M                    do J = 0, 1
S1 : A(J,I) = F(B(J-1,I-1))    S1 : A(I,J) = F(B(I-1,J+1) )
enddo                          enddo
enddo                          enddo

do  I = 0, 1
do J = 0, M
S1 : A(J,1-I) = F(B(J-1,1-I+1))
enddo
enddo
```

- *Standard Three Loops*: There is a typical triple loop type as below:

```
do  I  = 0, N
do  J = 0, M
do  T = 0, K
S1 :   A(I,J,K) = F(B(I,J,K) )
enddo
enddo
enddo
```

The stencil computing technique can solve the more complex three nested loops.

The identification of these loops uses *Data Dependency Analysis (DDA)* techniques. We will use the functions provided by ROSE to traverse the parallel regions of the AST, and then classify the type of the loop. In order to reach this aim, some data has to be collected:

- *Number of Loops*: Number of “For” nodes in the AST.
- *Loop Parameters*: parameters used in each “For” loop.
- *Local Variable*: variable defined in the loop bodies.
- *Reference Variable*: variable used in the loop bodies.

Note: this sub-component is under further investigation.

4.6 Memory management

The memory management mechanisms are triggered by the #pragma copy pragmas present in the user code. First, the array is created on the target device, and afterwards the data is copied from the source to the specified target destination. All the allocation and copying is made through the CUDA and OpenCL runtime. However, this pragma should be extended in order to select between creation and copying. Maybe the data is already on the device, and it doesn't make sense to create/allocate it again. This could also facilitate the data persistence on the device between subsequent kernel calls, hence improving performance. It is known that the biggest problem in GPGPU computing is the low-speed PCIe copies between host and device.

5. Implemented features

5.1 Extended Mint's input and output

In this initial version of the toolkit, the main addition to Mint was the added support for C++ input files, and added support for OpenCL output. This greatly extends the capabilities of this research initiative, increasing the possibility of experimenting with a big codebase while targeting a bigger number of platforms.

5.2 Known limitations

One of the biggest limitations we have determined so far when working with SME code in Mint is exactly what Mint was designed for: it is a domain-specific translator. It works and gives the best results when targeting 3D stencil methods.
Also, memory management is a bit limiting at this moment, making unnecessary copies for specific algorithmic cases.
The following is a list of limitations:

- Unable to parallelize function calls inside of parallel regions.
- Cannot work on other domains (only 3D stencil-based methods) without tweaking.
- Memory management is inefficient for given types of algorithms. Extra memory copies are generated.

5.3 In future releases

In order to reach these objectives, the test strategy is:

- Adding more execution patterns that can be detected, besides the 3D stencil-pattern
- Improve memory management
- Improve support for function calls inside parallel regions
- Improve support for pointer arithmetic

6. Writing code for parallelisation

Automatic parallelisation of source code is a complex process and the GPSME toolkit needs a good understanding of the code which is being converted. Ideally the toolkit would be able to handle arbitrary C++ code as input, but the state-of-the-art in automatic parallelisation is still a long way from this goal. Therefore, the purpose of this section is to guide the user on how to best write code which can be parallelised by the GPSME toolkit.

There are two fundamental limitations which must be kept in mind when writing code to be processed by the toolkit:

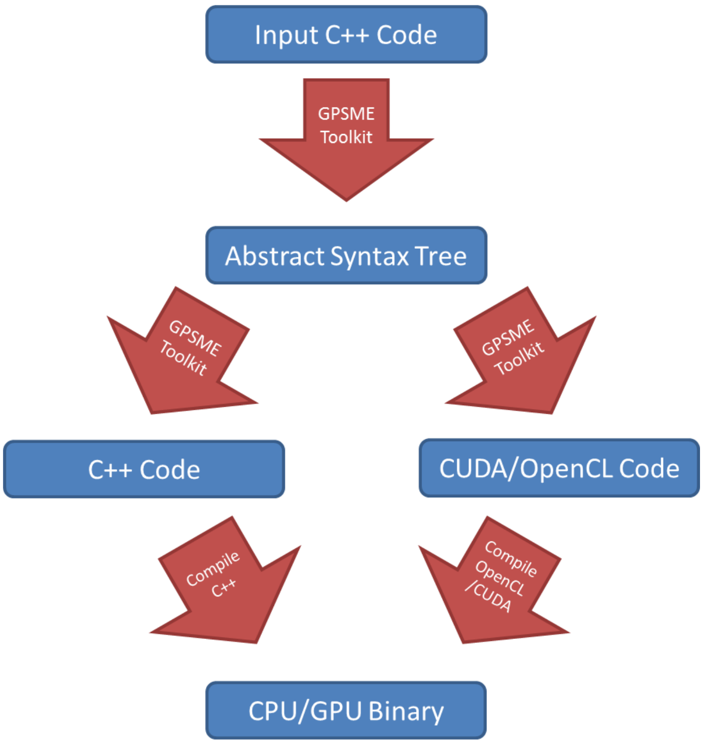
1. The GPSME toolkit is a source-to-source translator, which means it needs the source code to the algorithm being parallelised. This prohibits the use of external libraries to which the toolkit cannot see the source code when conversion is performed.

2. Not all constructs which can be expressed in C++ can be translated to GPU equivalents. In particular the regions to be parallelised should be simple nested loops which do not contain interdependencies, complex conditional logic, or most types of function call.

Guidelines for dealing with these limitations are further discussed in the sections below.

6.1 Dealing with external dependencies

When trying to understand the behaviour of the toolkit with regard to external dependencies it is useful to have a basic understanding of the parallelisation process. The process is as follows:



The input to the toolkit is C++ source code, and the output is also source code (C++/OpenCL/CUDA) with transformations applied. Internally the toolkit builds an abstract syntax tree from the source code, applies parallelising transformations to this, and then generates the corresponding output source code. It is this need to build an abstract syntax tree which underpins the requirement to have the source code to parts of the algorithm which are being parallelised.

Of course, most applications do have some form of external dependencies as software reuse is a strong principle of good engineering. To some degree it is indeed possible to parallelise such applications if the code can be revised according to the guidelines below.

6.1.1 Working with the toolkit locally

Using the toolkit locally under Linux offers the most flexibility as it is possible to configure the host to have the required dependencies installed, and this can ease the code revising process. However you should watch out for the following scenarios.

Let's say you have an application which you wish to parallelise but which makes use of the OpenCV toolkit for image processing operations. You might have a nested for loop which contains a call to an OpenCV function:

```
#pragma mint for nest(2) tile(16,16)
for(int x = 0; x < 128; x++)
{
      for(int y = 0; y < 128; y++)
      {
            .
            .
            // External function call
            cvSomeFunction();
            .
            .
      }
}
```

In this case the code is not suitable for parallelisation because the function 'cvSomeFunction()' is contained within a shared library (.dll or .so) and is implemented in CPU machine code. It is not possible to move this function to the GPU because GPUs have a different instruction set and architecture.

In this case the only option is to remove the call to cvSomeFunction() and replace it with your own implementation, but only if you believe that the algorithm being implemented matches the parallel nature of the GPU.

Another important example is when dependencies are outside the region being parallelised but within the same source file. Consider the case when we have a call to a Windows system function before the nested loop:

```
#include <windows.h>
.
.
.
someWindowsFunction();
.
.
.
```

```
#pragma mint for nest(2) tile(16,16)
for(int x = 0; x < 128; x++)
{
      for(int y = 0; y < 128; y++)
      {
            .
            .
            .
      }
}
```

Because the toolkit runs on Linux the use of Windows functions (even just including 'windows.h') represents an external dependency. The GPSME translator is unable to see the definitions of these Windows functions and so is not able to build the abstract syntax tree. Fortunately in this case it is possible to work around the limitation by splitting the code to be parallelised into a separate file and only running the GPSME toolkit on that:

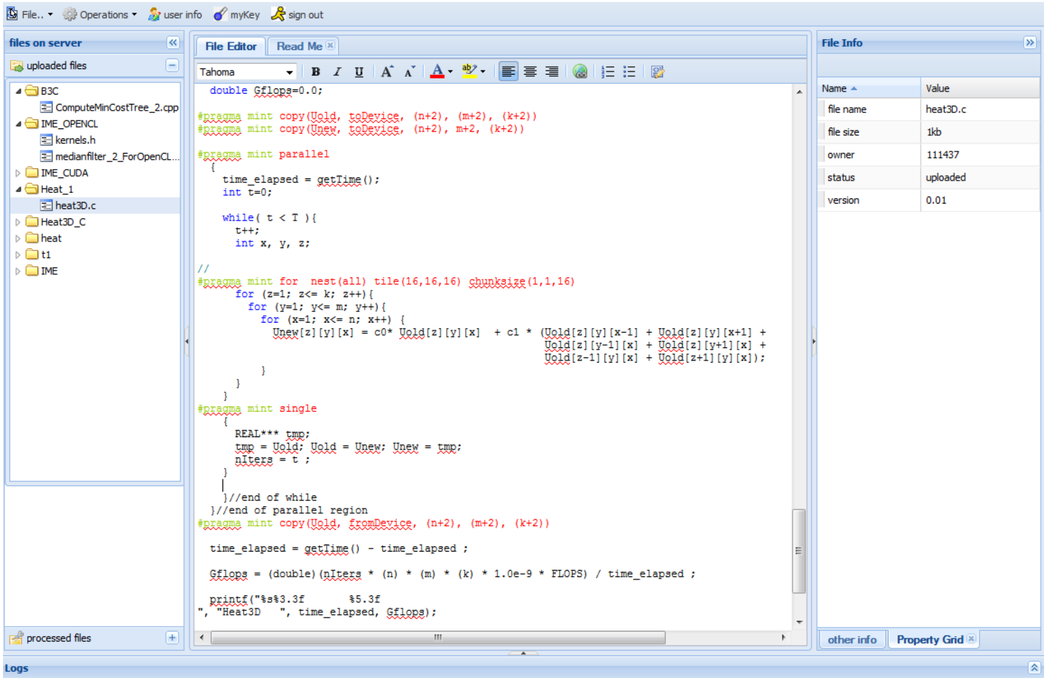
```
// In 'parallelisable.cpp' (for example)
#pragma mint for nest(2) tile(16,16)
for(int x = 0; x < 128; x++)
{
      for(int y = 0; y < 128; y++)
      {
            .
            .
            .
      }
}

//In main.cpp
#include <windows.h>
#include "parallelisable.h"
.
.
someWindowsFunction();
.
.
//Now call parallelised function in parallelisable.cpp
```

With this approach the GPSME toolkit never sees the code which it can't handle and so parallelisation is possible.

6.1.2 Working with the remote server

Driven by the potential difficulties of having a local GPSME installation, and also to increase the visibility of the toolkit, we include access to the toolkit through a remote web server. The web server can be accessed at http://gp-sme.co.uk/web_face/.

This service facilitates the translation of the user source code, not needing anything related to the toolkit locally installed on the users' machines. A screenshot from the online translator is given in the image below.



The typical usage of the GPSME web application is as follows:

- The user creates and account with their details.
- The user uploads a C/C++ file
- The users upload the necessary header files.
- The user selects the desired output type.
- The user initiates the code translation process.
- It takes a few seconds for the GPSME remote server to process the user files.
- The results can be retrieved under the 'Processed files' tab.

Many users will not be running the toolkit locally on a Linux machine but will instead be making use this remote web server. In this case you should keep the following points in mind in addition to those raised previously:

- If you have an external dependency then it must be installed on the remote webserver in addition to your local machine. You will need to contact you server administrator to get this set up.
- When uploading a C++ file for parallelisation you must also upload any of your own headers on which the C++ file is dependant. It is assumed that these belong in the same directory as the C++ source file, so avoid paths in your #include statements.

The webserver can also be installed locally on SME servers and act as a demo for the eventual customers.

6.2 Handling difficult C++ constructs

The architecture of the GPU is inherently different from the CPU architectures with which most programmers are familiar. As a result there are often differences between the programming constructs exposed by languages aimed at the two architectures, and forming a mapping between the constructs is often non-trivial.

In this section we give some tips and tricks to keep in mind when writing C++ code which is intended to be parallelised for the GPU, and also provides some background as to why the various differences exist.

6.2.1 Loop parallelisation

It is hopefully clear by now that the main application of the GPSME toolkit is to parallelise source code which contains nested loops. The toolkit works by extracting the contents of these loops and running it across a number of GPU cores simultaneously. This means that loop iterations which would have been processed serially by the CPU can now be processed in parallel.

The code snippet below provides an example of the kind of nested loop which is well suited for parallelisation by the toolkit:

```
#pragma mint for nest(2) tile(16,16)
for(int x = 0; x < 128; x++)
{
	for(int y = 0; y < 128; y++)
	{
		// Double the value of all inputs, this is fine.
		someArray[x][y] = someArray[x][y] * 2.0f;
	}
}
```

Of course, real world code is often more complex than that shown above and may contain loop interdependencies which impede the parallelisation process. A typical example is when the results of one iteration are used in the next iteration, and so it is not possible to execute the iterations in parallel because the required data is not available. For example:

```
#pragma mint for nest(2) tile(16,16)
for(int x = 0; x < 128; x++)
{
	for(int y = 0; y < 128; y++)
	{
		// This is not possible because we depend on previous 'x'
		someArray[x][y] = someArray[x-1][y] * 2.0f;
	}
}
```

If you have such code in your application then you may want to consider rewriting the algorithm in such a way that these interdependencies do not exist, or perhaps choose a different algorithm which is more amicable to parallelisation.

6.2.2 Data transfer and memory constraints

It is important to realise that GPUs have their own memory which is separate from the main system memory and which is typically both smaller and faster. In order for GPUs to operate on data it must first be transferred into GPU memory using the **`#pragma mint copy`** directive already discussed, and the results must be transferred back to the main system memory after the transfer is complete.

This architecture has a significant effect on the kinds of algorithms which can be moved to the GPU and on the benefit obtained by doing so. In particular you should keep the following points in mind:

- **Bandwidth:** There is a limit to the rate at which data can be transferred to the GPU and back again, and this limit varies between system. Typically the rate at which data can be sent to the GPU is higher than the rate at which it can be retrieved. If an application does not do significant work on each piece of data then it is possible for the application to be limited by this rate of data transfer, and so a significant speedup might not be obtained.

- **Latency:** Each time a data transfer is requested there is a small delay before it actually occurs. If an application is performing a lot of small transfers between the GPU and system memory then these accumulated delays can have a noticeable effect on the speed of the application. In general it is better to perform a single large data transfer rather than several small ones.

- **Memory size:** The amount of memory available on a GPU can vary from approx. 128Mb up to 2Gb, but it is always significantly less than the available system memory. You should also be aware that some memory is already taken up for purposes such as holding the frame buffer which is used during rendering. With this in mind, you may want to optimise your algorithm to work on smaller amount if data, for example by braking large images down into a number of tiles (which also has cache benefits).

6.2.3 Conditional logic

GPUs utilise a *Single Instruction Multiple Data (SIMD)* pipeline in order to effectively achieve parallelism. Execution of programs is performed by a large number of threads which each operate on a separate piece of the data set. Due to the architecture of GPUs it is important for all threads to be executing the same instruction at the same time.

This architecture can be problematic for algorithms which contain conditional branches. While valid, these branches do not map well to the GPU architecture because they can cause the threads to exhibit divergent behaviour. Consider the following example:

```
#pragma mint for nest(2) tile(16,16)
for(int x = 0; x < 128; x++)
{
      for(int y = 0; y < 128; y++)
      {
            float val = someArray[x][y];
            if(val < 0.001f)
            {
                  continue; // Optimisation
            }
            else
            {
                  .
                  . // Some expensive code here
                  .
```

```
            }
        }
}
```

In this code the conditional test 'if(val < 0.001f)' has been added as an intended optimisation because it skips the expensive code for certain values of 'val'. However, on the GPU this optimisation does not work as expected because all threads must take the same path and so threads cannot return early. Instead the execution time for a group of threads is determined by the slowest thread in that group.

6.2.5 Function calls

Function calls are one of the fundamental building blocks of C/C++ programs, but their implementation in GPU languages such as CUDA or OpenCL is different to what might be expected.

In a modern CPU function calls are implemented by saving the current program state onto the stack and then using a 'jump' instruction which transfers execution of a program from one point to another. This approach does not match the architecture of GPUs (for similar reasons to the issues with conditional logic) and so current GPUs do not support jumps or function calls.

That said, programming languages such as OpenCL and CUDA do allow functions to be defined and called from the main kernel but a different implementation is used. In particular the function call is actually inlined into the function that called it. This is done during the compilation stage.

The impact of this on the GPSME toolkit is that parallel regions can include function calls provided that those functions can be inlined by the compiler. This requires a definition of the function to be available to be available to the toolkit at the time it processes the callsite. Functions definitions should not exist in external libraries or separate compilation units.

As a concrete example the following code will give difficulties to the GPSME toolkit:

```
// In functions.h
float addOne(float val);

// In functions.cpp
#include "functions.h"

float addOne(float val)
{
      return val + 1.0f;
}

// In main.cpp
#include "functions.h"
.
.
.
#pragma mint for nest(2) tile(16,16)
for(int x = 0; x < 128; x++)
{
      for(int y = 0; y < 128; y++)
      {
```

```
            // ERROR: No definition for addOne()
            float result = addOne(someArray[x][y]);
      }
}
```

But these difficulties can be resolved by rearranging the code as follows:

```
// In main.cpp
float addOne(float val)
{
      return val + 1.0f;
}
.
.
.
#pragma mint for nest(2) tile(16,16)
for(int x = 0; x < 128; x++)
{
      for(int y = 0; y < 128; y++)
      {
            // OK: addOne() is in this compilation unit.
            float result = addOne(someArray[x][y]);
      }
}
```

A related problem is recursion because a recursive function cannot be inlined (at least not if the termination a criterion is being determined at runtime). For this reason it is not possible to parallelise regions containing recursive function calls.

Appendix A. GPSME programs

```
/*
   by Didem Unat
   3D 7-point jacobi
   Written to be used as an input program to mint translator

 */

//#include "common.h"
#include <stdio.h>
#include <math.h>
#include <omp.h>
#include <stdlib.h>
#include <assert.h>
#include <sys/time.h>
#define REAL double
#define FLOPS 8
#define chunk 64
const double kMicro = 1.0e-6;

REAL ***alloc3D(int n, int m,int k)
{
  REAL ***m_buffer=NULL;

  int nx=n, ny=m, nk = k;

  m_buffer = (REAL***)malloc(sizeof(REAL**)* nk);
  assert(m_buffer);

  REAL** m_tempzy = (REAL**)malloc(sizeof(REAL*)* nk * ny);
  REAL *m_tempzyx = (REAL*)malloc(sizeof(REAL)* nx * ny * nk );

  int z, y;
  for ( z = 0 ; z < nk ; z++, m_tempzy += ny ) {
    m_buffer[z] = m_tempzy;
    for (  y = 0 ; y < ny ; y++, m_tempzyx += nx ) {
      m_buffer[z][y] = m_tempzyx;
    }
  }

  return m_buffer;
}

double getTime()
{
  struct timeval TV;

  const int RC = gettimeofday(&TV, NULL);
  if(RC == -1)
    {
      printf("ERROR: Bad call to gettimeofday\n");
      return(-1);
    }

  return( ((double)TV.tv_sec) + kMicro * ((double)TV.tv_usec) );
```

```
}  // end getTime()

//allocate 3D array
REAL ***alloc3D_(int n, int m,int k){

  REAL ***E=NULL;

  int nx=n, ny=m, nk = k;

  E = (REAL***)malloc(sizeof(REAL**)* nk);
  assert(E);

  E[0] = (REAL**)malloc(sizeof(REAL*)* nk * ny);
  E[0][0] = (REAL*)malloc(sizeof(REAL)*nx * ny * nk );

  int jj,kk;

  for(kk=0 ; kk < nk ; kk++){

    if(kk > 0)
      {
       E[kk] = E[kk-1] + ny ;
       E[kk][0] = E[kk-1][0] + ny*nx ;
      }

    for(jj=1; jj< ny; jj++) {
      E[kk][jj] = E[kk][jj-1] + nx ;
    }
    }
  return(E);
}

void free3D(REAL*** E)
{
  //int k=0;
  /*  for(k=0 ; k < m ; k++)
    {
      free(E[k]);
      }*/
  free(E[0][0]);
  free(E[0]);
  free(E);

}
void init(REAL*** E, int N, int M, int K)
{
  int i,j,k;

  for(k=0 ; k < K ; k++)
    for(i=0 ; i < M ; i++)
      for(j=0 ; j < N ; j++){

      E[k][i][j]=1.0;

      if(i==0 || i == M-1 || j == 0 || j == N-1 || k==0 || k == K-1 )
        E[k][i][j]=0.0;
    }
}

//calculate l2norm for comparison
```

```
void calculatel2Norm(REAL*** E, int N, int M, int K, int nIters)
{
  int i, j, k  =0;

  float mx = -1;
  float l2norm = 0;

  for (k=1; k<= K ; k++){
    for (j=1; j<= M; j++){
      for (i=1; i<= N; i++) {
        l2norm += E[k][j][i]*E[k][j][i];

        if (E[k][j][i] > mx)
          mx = E[k][j][i];
      }
    }
  }
  l2norm /= (float) ((N)*(M)*(K));
  l2norm = sqrt(l2norm);
  printf(":N %d M %d K %d , iteration %d\n", N, M, K , nIters);
  printf(":max: %20.12e, l2norm: %20.12e\n",mx,l2norm);
}

int main (int argc, char* argv[])
{

  int n = 256;
  int m = 256;
  int k = 256;

  REAL c0=0.5;
  REAL c1=-0.25;

  REAL*** Unew; REAL*** Uold;

  Unew= alloc3D(n+2, m+2, k+2);
  Uold= alloc3D(n+2, m+2, k+2);

  init(Unew, n+2, m+2, k+2);
  init(Uold, n+2, m+2, k+2);

  int T= 20;

  printf("\n=====Timings (sec) for 7-Point Jacobi, Solving Heat Eqn ");
  if(sizeof(REAL) == 4)
    printf(" (Single Precision) =====\n");
  if(sizeof(REAL) == 8)
    printf(" (Double Precision) =====\n");

  printf("Kernel\t Time(sec)\tGflops  \tBW-ideal(GB/s)\tBW-algorithm
(N=(%d,%d) ite\
rs=%d)\n", n,n, T);
  printf("------\t----------\t--------\t--------------\t------------\n");


  int nIters = 0;
  double time_elapsed ;
  double Gflops=0.0;

#pragma mint copy(Uold, toDevice, (n+2), (m+2), (k+2))
#pragma mint copy(Unew, toDevice, (n+2), m+2, (k+2))
```

```
#pragma mint parallel
  {
    time_elapsed = getTime();
    int t=0;

    while( t < T ){
      t++;
      int x, y, z;

      //7-point stencil
#pragma mint for  nest(all) tile(16,16,16) chunksize(1,1,16)
      for (z=1; z<= k; z++){
        for (y=1; y<= m; y++){
          for (x=1; x<= n; x++) {
            Unew[z][y][x] = c0* Uold[z][y][x]  + c1 * (Uold[z][y][x-1] +
Uold[z][y][x+1] +
                                                        Uold[z][y-1][x] +
Uold[z][y+1][x] +
                                                        Uold[z-1][y][x] +
Uold[z+1][y][x]);
          }
        }
      }
#pragma mint single
      {
        REAL*** tmp;
        tmp = Uold; Uold = Unew; Unew = tmp;
        nIters = t ;
      }

    }//end of while
  }//end of parallel region
#pragma mint copy(Uold, fromDevice, (n+2), (m+2), (k+2))

  time_elapsed = getTime() - time_elapsed ;

  Gflops = (double)(nIters * (n) * (m) * (k) * 1.0e-9 * FLOPS) /
time_elapsed ;

  printf("%s%3.3f \t%5.3f\n", "Heat3D   ", time_elapsed, Gflops);

  calculatel2Norm(Uold, n, m, k, T);


  free3D(Uold);
  free3D(Unew);

  return 0;
}
```

Wiener denoising - IME

```
#include "wiennerdenosing.h"
#include <fstream>
#include <windows.h>

double getTime_2()
{
```

```
  DWORD t1 ;
  t1 = timeGetTime();
  return (double)t1 ;
}  // end getTime()

double meandenosing(int image_width,int image_height,double
***imDenoised_GPU, double ***oneChannelImage_GPU, int window_size)
{
  double ***imDenoised = imDenoised_GPU;
  double ***oneChannelImage = oneChannelImage_GPU;
  float tmp = 0.0 ;
  float win = 1.0/window_size ;
  int   max_index = 0 ;
  int   index_z = 1;
  int   i, j, m ;
  double time_elapsed = 0.0 ;
  time_elapsed = getTime_2();

#pragma mint copy(imDenoised, toDevice, image_width,
image_height,window_size)
#pragma mint copy(oneChannelImage, toDevice, image_width,
image_height,window_size)

#pragma mint parallel
{
 //7-point stencil
 #pragma mint for  nest(all) tile(16,16,16) chunksize(1,1,16)
        //for(int n = 1 ; n < 256 ; n++){
  for (m = 1 ; m < window_size - 1; m++){
  for (i = 1; i < image_height - 1; i++) {
   for(j = 1; j < image_width - 1; j++){

     imDenoised[m][i][j] = (oneChannelImage[m][i-1][j-1] +
oneChannelImage[m][i-1][j] + oneChannelImage[m][i-1][j+1] +
                              oneChannelImage[m][i][j-1] +
oneChannelImage[m][i][j] + oneChannelImage[m][i][j+1] +
                              oneChannelImage[m][i+1][j-1] +
oneChannelImage[m][i+1][j] + oneChannelImage[m][i+1][j+1])*win
                                                         +
(oneChannelImage[m-1][i-1][j-1] + oneChannelImage[m-1][i-1][j] +
oneChannelImage[m-1][i-1][j+1] +
                              oneChannelImage[m-1][i][j-1] +
oneChannelImage[m-1][i][j] + oneChannelImage[m-1][i][j+1] +
                              oneChannelImage[m-1][i+1][j-1] +
oneChannelImage[m-1][i+1][j] + oneChannelImage[m-1][i+1][j+1])*win
                                                        ;


     }
   }
  }
  //}
}

#pragma mint copy(imDenoised, fromDevice, image_width,
image_height,window_size)

 time_elapsed = getTime_2() - time_elapsed ;
 return time_elapsed ;
}
```

```
int getartiblocks(int image_width,int image_height,double
***imDenoised_GPU,double ***oneChannelImage_GPU,int fv_size, double
***fv_GPU,int intraBlockRelativeOffset)
{
  int counter = 0;
  int row;
  int column;
  int row_offset;
  int column_offset;
  float denoised_value;
  double ***imDenoised = imDenoised_GPU;
  double ***oneChannelImage = oneChannelImage_GPU;
  double ***fv = fv_GPU;
  int   index_z = 1;

  printf("start getartiblocks \n");

#pragma mint copy(imDenoised, toDevice, image_width, image_height,index_z)
#pragma mint copy(oneChannelImage, toDevice, image_width,
image_height,index_z)
#pragma mint copy(fv, toDevice, fv_size, index_z, index_z)

#pragma mint parallel
  {
 //7-point stencil
 #pragma mint for  nest(all) tile(16,16,16) chunksize(1,1,16)
  for (int j = 1 ; j <=1 ; j++){
    for (int t = 1 ; t <=1 ; t++){
  for (int i = 0; i < (image_height * image_width); i++) {
    row = (i / image_width);
    column = (i % image_width);
    row_offset = (row % 8);
    column_offset = (column % 8);
    if ((((row_offset >= intraBlockRelativeOffset) && (row_offset <= ((8 -
intraBlockRelativeOffset) - 1))) && (column_offset >=
intraBlockRelativeOffset)) && (column_offset <= ((8 -
intraBlockRelativeOffset) - 1))) {
      denoised_value = imDenoised[0][row][column];
      fv[0][0][counter++] = (oneChannelImage[0][row][column] -
denoised_value);
    }
  }
}
}
}

#pragma mint copy(imDenoised, fromDevice, index_z, image_height,
image_width)
#pragma mint copy(oneChannelImage, fromDevice, index_z, image_height,
image_width)
#pragma mint copy(fv, fromDevice, index_z, index_z, fv_size)

  return 1 ;
}


int wiennerdenosing(int image_width,int image_height,double
***oneChannelImage_GPU, int window_size, double ***win_GPU)
{
  //double ***imDenoised = imDenoised_GPU;
```

```
  double ***oneChannelImage = oneChannelImage_GPU;
  double ***v = win_GPU; // win_GPU has to be initlized
  float tmp = 0.0 ;
  int   max_index = 0 ;
  int   index_z = 1;
  int   i, j, m ;

//#pragma mint copy(imDenoised, toDevice, image_width,
image_height,index_z)
#pragma mint copy(oneChannelImage, toDevice, image_width,
image_height,index_z)
#pragma mint copy(v, toDevice, window_size, image_width, image_height)

//printf("start wiennerdenosing %d , %d \n", image_height, image_width);
#pragma mint parallel
{
 //7-point stencil
 #pragma mint for  nest(all) tile(16,16,16) chunksize(1,1,16)
  for (m = 0 ; m < 1 ; m++){
  for (i = 1; i < image_height - 1; i++) {
   for(j = 1; j < image_width - 1; j++){

     v[i][j][0] = oneChannelImage[m][i-1][j-1];
     v[i][j][1] = oneChannelImage[m][i-1][j];
     v[i][j][2] = oneChannelImage[m][i-1][j+1];
     v[i][j][3] = oneChannelImage[m][i][j-1];
     v[i][j][4] = oneChannelImage[m][i][j];
     v[i][j][5] = oneChannelImage[m][i][j+1];
     v[i][j][6] = oneChannelImage[m][i+1][j-1];
     v[i][j][7] = oneChannelImage[m][i+1][j];
     v[i][j][8] = oneChannelImage[m][i+1][j+1];

         //printf("start wiennerdenosing m %d, i %d, j %d \n", m, i, j);
     }
   }
  }
}

 //printf("start wiennerdenosing i %d , j %d, m %d \n", i, j, m);
#pragma mint copy(oneChannelImage, fromDevice, image_width,
image_height,index_z)
#pragma mint copy(v, fromDevice, window_size, image_width, image_height)

 return 1 ;
}




int wiennerdenosing2(int image_width,int image_height,double
***imDenoised_GPU, int window_size, double ***win_GPU)
{

  double ***imDenoised = imDenoised_GPU;
  //double ***oneChannelImage = oneChannelImage_GPU;
  double ***v = win_GPU; // win_GPU has to be initlized
  float tmp = 0.0 ;
  int   max_index = 0 ;
  int   index_z = 1;
  int   i, j ,m ;
```

```
#pragma mint copy(imDenoised, toDevice, image_width, image_height,index_z)
//#pragma mint copy(oneChannelImage, toDevice, image_width,
image_height,index_z)
#pragma mint copy(v, toDevice, window_size, image_width, image_height)

#pragma mint parallel
{
 //7-point stencil
 #pragma mint for  nest(all) tile(16,16,16) chunksize(1,1,16)

  for (i = 1; i < image_height - 1; i++) {
   for(j = 1; j < image_width - 1; j++){
       for (m = 9 ; m <=90 ; m++){

     // To make a order
        if((m % 9 >= 9 - m/9) && (v[i][j][m % 9] < v[i][j][m % 9 -1]))
        {
               tmp = v[i][j][m % 9];
               v[i][j][m % 9] = v[i][j][m % 9 - 1];
               v[i][j][m % 9 - 1] = tmp ;
        }


     //oneChannelImage[i][j] = v[4] ;
     imDenoised[0][i][j] = v[i][j][4] ;
     //imDenoised[0][ii][jj] = 0.5 ;

     }
   }
  }
}

//printf("start wiennerdenosing i %d , j %d, m %d \n", i, j, m);

#pragma mint copy(imDenoised, fromDevice, image_width,
image_height,index_z)
#pragma mint copy(v, fromDevice, window_size, image_width, image_height)

 return 1 ;
}


// Fixed the bug
int wiennerdenosing1(int image_width,int image_height,double
***oneChannelImage_GPU, int window_size, double ***win_GPU)
{
  //double ***imDenoised = imDenoised_GPU;
  double ***oneChannelImage = oneChannelImage_GPU;
  double ***v = win_GPU; // win_GPU has to be initlized
  float tmp = 0.0 ;
  int   max_index = 0 ;
  int   index_z = 1;
  int   i, j, m ;

//#pragma mint copy(imDenoised, toDevice, image_width,
image_height,index_z)
#pragma mint copy(oneChannelImage, toDevice, image_width, image_height,
window_size)
#pragma mint copy(v, toDevice,image_width, image_height, window_size)

//printf("start wiennerdenosing %d , %d \n", image_height, image_width);
```

```
#pragma mint parallel
{
 //7-point stencil
 #pragma mint for  nest(all) tile(16,16,16) chunksize(1,1,16)
  for (m = 0 ; m < window_size ; m++){
  for (i = 1; i < image_height - 1; i++) {
   for(j = 1; j < image_width - 1; j++){

           if(m==0)
                   v[m][i][j]= oneChannelImage[m][i-1][j-1];
           else if(m==1)
            v[m][i][j] = oneChannelImage[m][i-1][j];
           else if(m==2)
            v[m][i][j] = oneChannelImage[m][i-1][j+1];
           else if(m==3)
            v[m][i][j] = oneChannelImage[m][i][j-1];
           else if(m==4)
            v[m][i][j] = oneChannelImage[m][i][j];
           else if(m==5)
            v[m][i][j] = oneChannelImage[m][i][j+1];
           else if(m==6)
            v[m][i][j] = oneChannelImage[m][i+1][j-1];
           else if(m==7)
            v[m][i][j] = oneChannelImage[m][i+1][j];
           else if(m==8)
            v[m][i][j] = oneChannelImage[m][i+1][j+1];

         //printf("start wiennerdenosing m %d, i %d, j %d \n", m, i, j);
     }
   }
  }
}

 //printf("start wiennerdenosing i %d , j %d, m %d \n", i, j, m);
#pragma mint copy(oneChannelImage, fromDevice, image_width, image_height,
window_size)
#pragma mint copy(v, fromDevice, image_width, image_height, window_size)

 return 1 ;
}




int wiennerdenosing22(int image_width,int image_height, int window_size,
double ***win_GPU)
{

  //double ***imDenoised = imDenoised_GPU;
  //double ***oneChannelImage = oneChannelImage_GPU;
  double ***v = win_GPU; // win_GPU has to be initlized
  float tmp = 0.0 ;
  int   max_index = 0 ;
  int   index_z = 1;
  int   i, j ,m ;

  //printf("start wiennerdenosing 22 \n");

//#pragma mint copy(imDenoised, toDevice, image_width, image_height,
window_size)
```

```
//#pragma mint copy(oneChannelImage, toDevice, image_width,
image_height,index_z)
#pragma mint copy(v, toDevice, image_width, image_height, window_size)

#pragma mint parallel
{
 //7-point stencil
 #pragma mint for  nest(all) tile(16,16,16) chunksize(1,1,16)

  for (m = 9 ; m < 90 ; m++){
  for (i = 1; i < image_height - 1; i++) {
   for(j = 1; j < image_width - 1; j++){

            //if(m == 81)
        //printf("start wiennerdenosing 22 m %d \n",  m);
     // To make a order
        if((m % 9 > 9 - m/9) && (v[m % 9][i][j] < v[m % 9 -1][i][j]))
        {
               tmp = v[m % 9][i][j];
               v[m % 9][i][j] = v[m % 9 - 1][i][j];
               v[m % 9 - 1][i][j] = tmp ;

                             //printf("start wiennerdenosing 22 i %d , j %d, m
%d \n", i, j, m);

        }

        }
           //oneChannelImage[i][j] = v[4] ;
     //imDenoised[m % 9 - 1][i][j] = v[4][i][j] ;
     //imDenoised[0][ii][jj] = 0.5 ;
   }
  }
}

//printf("start wiennerdenosing 22  %f , %f, %f , %f , %f, %f, %f , %f,
%f\n", v[0][100][100], v[1][100][100], v[2][100][100], v[3][100][100],
v[4][100][100], v[5][100][100], v[6][100][100], v[7][100][100],
v[8][100][100]);

//#pragma mint copy(imDenoised, fromDevice, image_width, image_height,
window_size)
#pragma mint copy(v, fromDevice, image_width, image_height, window_size)

 return 1 ;
}


int wiennerdenosing23(int image_width,int image_height,double
***imDenoised_GPU, int window_size, double ***win_GPU)
{

  double ***imDenoised = imDenoised_GPU;
  //double ***oneChannelImage = oneChannelImage_GPU;
  double ***v = win_GPU; // win_GPU has to be initlized
  float tmp = 0.0 ;
  int   max_index = 0 ;
  int   index_z = 1;
  int   i, j ,m ;
```

```
#pragma mint copy(imDenoised, toDevice, image_width, image_height,
window_size)
//#pragma mint copy(oneChannelImage, toDevice, image_width,
image_height,index_z)
#pragma mint copy(v, toDevice, image_width, image_height, window_size)

#pragma mint parallel
{
 //7-point stencil
 #pragma mint for  nest(all) tile(16,16,16) chunksize(1,1,16)

 for (m = 0 ; m < window_size ; m++){
  for (i = 1; i < image_height - 1; i++) {
   for(j = 1; j < image_width - 1; j++){


      //// To make a order
      //   if((m % 9 >= 9 - m/9) && (v[i][j][m % 9] < v[i][j][m % 9 -1]))
      //   {
      //          tmp = v[i][j][m % 9];
      //          v[i][j][m % 9] = v[i][j][m % 9 - 1];
      //          v[i][j][m % 9 - 1] = tmp ;
      //   }


      //oneChannelImage[i][j] = v[4] ;
      imDenoised[m][i][j] = v[4][i][j] ;
      //imDenoised[0][ii][jj] = 0.5 ;

      }
    }
   }
}

//printf("start wiennerdenosing i %d , j %d, m %d \n", i, j, m);

#pragma mint copy(imDenoised, fromDevice, image_width, image_height,
window_size)
#pragma mint copy(v, fromDevice, image_width, image_height, window_size)

 return 1 ;
}


int getartiblocks1(int image_width,int image_height,double
***imDenoised_GPU,double ***oneChannelImage_GPU,int fv_size, double
***fv_GPU,int intraBlockRelativeOffset)
{
  int counter = 0;
  int row;
  int column;
  int row_offset;
  int column_offset;
  float denoised_value;
  double ***imDenoised = imDenoised_GPU;
  double ***oneChannelImage = oneChannelImage_GPU;
  double ***fv = fv_GPU;
  int   index_z = 1;

  printf("start getartiblocks 1\n");
```

```
#pragma mint copy(imDenoised, toDevice, image_width, image_height,fv_size)
#pragma mint copy(oneChannelImage, toDevice, image_width,
image_height,fv_size)
#pragma mint copy(fv, toDevice, image_width, image_height,fv_size)

#pragma mint parallel
  {
 //7-point stencil
 #pragma mint for  nest(all) tile(16,16,16) chunksize(1,1,16)
                 for (int i = 0; i < image_height ; i++) {
                        for(int j = 0; j < image_width ; j++){
                               for( int m = 0 ; m < fv_size ; m++) {
  //for (int i = 0; i < (image_height * image_width); i++) {
    //row = (i / image_width);
    //column = (i % image_width);
    row_offset = (i % 8);
    column_offset = (j % 8);
    if ((((row_offset >= intraBlockRelativeOffset) && (row_offset <= ((8 -
intraBlockRelativeOffset) - 1))) && (column_offset >=
intraBlockRelativeOffset)) && (column_offset <= ((8 -
intraBlockRelativeOffset) - 1))) {
      denoised_value = imDenoised[m][i][j];
      //fv[0][0][counter++] = (oneChannelImage[m][i][j] - denoised_value);
          fv[m][i][j] = (oneChannelImage[m][i][j] - denoised_value);

          //printf("start getartiblocks 1 i %d , j %d, m %d \n", i, j, m);
    }
  }
}
}
}

#pragma mint copy(imDenoised, fromDevice, image_width,
image_height,fv_size)
#pragma mint copy(oneChannelImage, fromDevice, image_width,
image_height,fv_size)
#pragma mint copy(fv, fromDevice, image_width, image_height,fv_size)

  return 1 ;
}
```

Appendix B. GPSME interface descriptions

The GPSME toolkit uses the command-line interface (CLI) to invoke the program in the Linux environment. Each command for the GPSME toolkit starts with the executable name, which is “GPSMETranslator”. The executable name is followed by the name of the source file that should be translated and also by an option flag that controls the output of the translator. These are the three mandatory fields, with other fields being optional.
Use the following rules when specifying command line options:

- Enter options in any order. Each option is separated by spaces.
- Be consistent with upper case and lower case.
- Enter file names in the specified order that is prescribed by the command line program.
- Use lower case for all file extensions.
- There is an “options” modifier at the end of the command line, which controls the various options of the translator.

An example for the usage of the toolkit is:

- $ ./GPSMETranslator <input_source_file>.<extension> <output_format> [options]

Where:

- <input_source_file> - represents the filename of the source code to be processed.
- <extension> can currently be either .c or .cpp. Based on the provided extension, the GPSME toolkit will call the necessary front-end parser from the ROSE infrastructure, and will generate the AST for the input source
- <output_format> is a mandatory parameter that selects whether the output format is CUDA or OpenCL. The toolkit can thus be called like:
    - $ ./GPSMETranslator matMul.c –cl to generate an OpenCL version of the matMul.c input C program
    - $ ./GPSMETranslator Heat3D.cpp –cu to generate a CUDA version of the Heat3D.cpp input C++ program

[options] is an optional list of arguments that trigger certain optimization, or guide the compiler with extra knowledge. These set of options will further be extended during the development of the project.

Reference

1. GPSME User Requirements Specification Document.
2. Domain-Specific Translator and Optimizer for Massive On-Chip Parallelism, Didem Unat, Ph.D. Dissertation, San Diego, 2012