Automatically converting C/C++ to OpenCL/CUDA

Introduction by David Williams

Overview

- This presentation provides an introduction to autoparallelisation, focusing on our GPSME toolkit.
- We will cover:
  - What autoparallelisation is and why we want it.
  - How the autoparallelisation process is performed.
  - An introduction to using our toolkit.
  - Benchmarking the toolkit and performance considerations.
  - A demonstration of using the toolkit and frontend.
- Toolkit is available.

Who are we?

- The GPSME project is a collaboration between industry and academia.
  - Multiple partners across Europe.
  - All with different problems to solve.
- Our research project aims to make GPU computing more accessible.
  - Reduce need for expert knowledge.
  - Eliminate need for specialised languages.
  - Avoid rewriting existing code.

Using the GPU

Flexibility / Performance

Ease of use / Speed of development

- Assembly
- OpenCL/CUDA
- Libraries
- Autoparallelisation
- Drag-and-drop

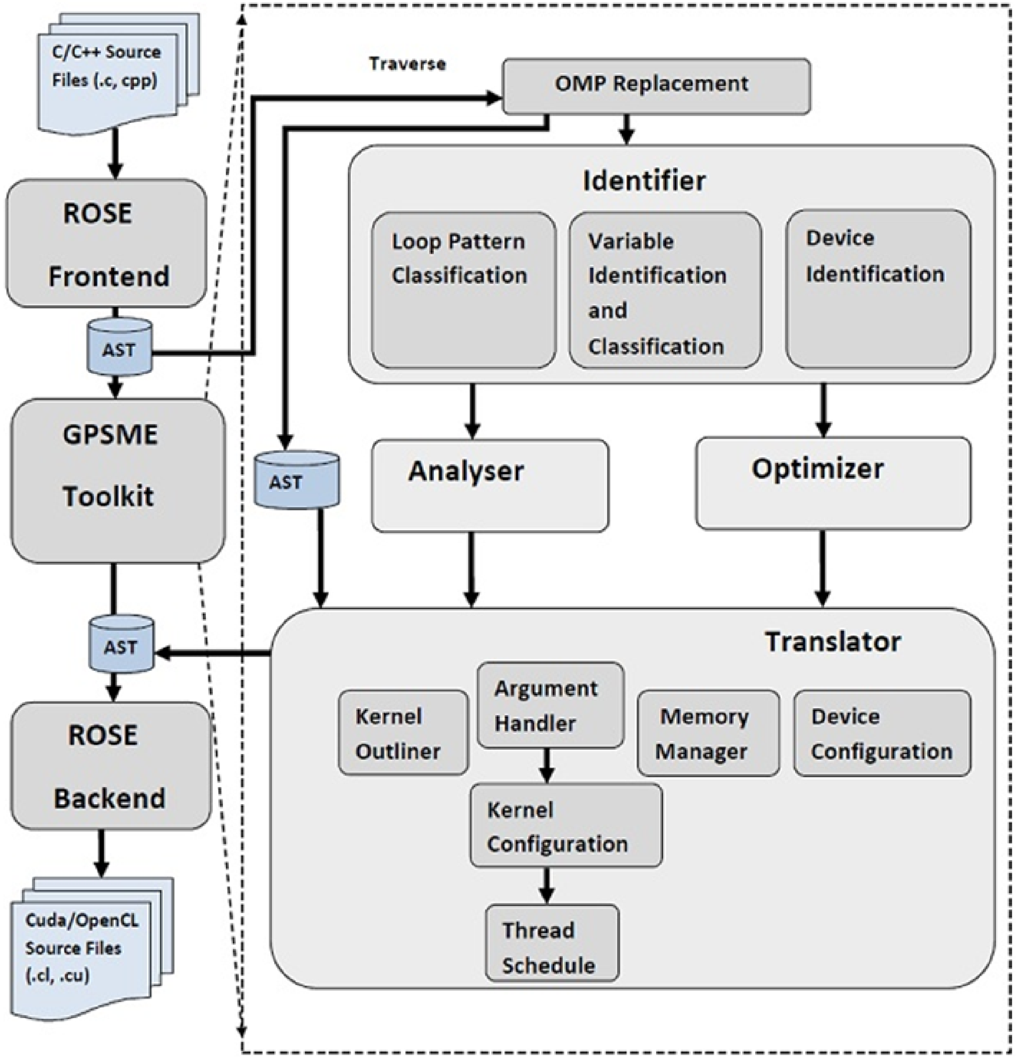
Why autoparallelisation?

- Automatically converting C/C++ to OpenCL/CUDA has a number of advantages:
  - Single codebase – Simplifies the process of targeting machines both with and without GPUS.
  - Reuse existing code.
  - Target a wide range of hardware.
  - Achieve independence from specific backend technologies.
  - Avoid lengthy boilerplate code.

How autoparallelisation works

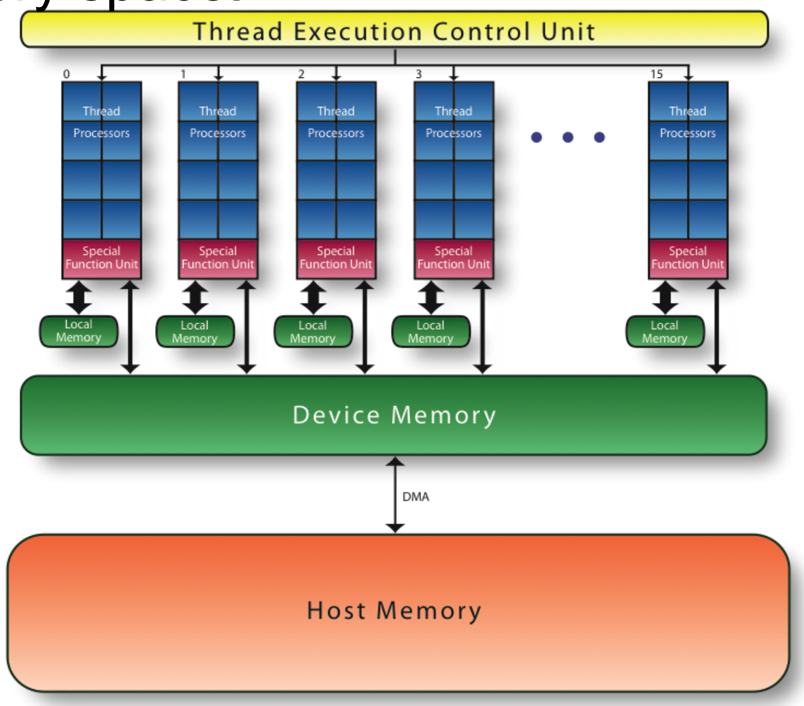
- At its heart, the GPSME toolkit converts C/C++ code into OpenCL/CUDA by following compiler *#pragmas*.
  - Transfer required data to the GPU
  - Copy the body of a loop into an OpenCL/CUDA program.
  - Execute the program on each core simultaneously.
- This is built on a framework called ROSE, by extending a tool called Mint.
  - See www.rosecompiler.org for more information.

How autoparallelisation works



A simple example

- Keep in mind that the GPU has two key architectural differences compared to the CPU:
  - Multiple cores operating in parallel.
  - Separate memory space.



A simple example

- The code below performs a simple low-pass filter (blur) from a source to a destination.

```
for (y = 1; y < imageHeight-1; y++)
{
  for (x = 1; x < imageWidth-1; x++)
  {
    float sum = 0.0f;
    for(offsetY = -1; offsetY <= 1; offsetY++)
    {
      for(offsetX = -1; offsetX <= 1; offsetX++)
      {
        int finalX = x + offsetX;
        int finalY = y + offsetY;
        sum += srcImage[finalY * imageWidth + finalX];
      }
    }
    dstImage[y * imageWidth + x] = sum / 9.0f;
  }
}
```

A simple example

- We can augment this with GPSME directives:

```
#pragma GPSME copy( srcImage,  toDevice, imageWidth, imageHeight)
#pragma GPSME copy( dstImage,  toDevice, imageWidth, imageHeight)
#pragma GPSME parallel
{
  #pragma GPSME for nest(2) tile ( 16, 16 )
  for (y = 1; y < imageHeight-1; y++)
  {
    for (x = 1; x < imageWidth-1; x++)
    {
      float sum = 0.0f;
      for(offsetY = -1; offsetY <= 1; offsetY++)
      {
        for(offsetX = -1; offsetX <= 1; offsetX++)
        {
          //Removed code for brevity
        }
      }
      dstImage[y * imageWidth + x] = sum / 9.0f;
    }
  }
}
#pragma GPSME copy( srcImage, fromDevice, imageWidth, imageHeight)
#pragma GPSME copy( dstImage, fromDevice, imageWidth, imageHeight)
```

A simple example

- The translator is a command line tool which runs under Linux:

```
gpsme inputFile.cpp [options]
```

- Generates output C++ and CUDA in a single file.
- Additional command line options can be provided
  - --shared
  - --register
- For people who don’t run a Linux system the translator can be run via a web interface.

A simple example

- The resulting code can be quite large but here are some core snippets:

```
cudaMemcpy3DParms param_1_dev_1_srcImage = {0};
param_1_dev_1_srcImage.srcPtr = make_cudaPitchedPtr(((void *)
    srcImage),(imageWidth) * sizeof(float ),(imageWidth),(imageHeight));
param_1_dev_1_srcImage.dstPtr = dev_1_srcImage;
param_1_dev_1_srcImage.extent = ext_dev_1_srcImage;
param_1_dev_1_srcImage.kind = cudaMemcpyHostToDevice;
stat_dev_1_srcImage = cudaMemcpy3D(&param_1_dev_1_srcImage);
```

```
if (_gidy >= 0 && _gidy <= imageHeight - 1) {{{
      if (_gidx >= 0 && _gidx <= imageWidth - 1) {{
          if ((((_gidx > 0) && (_gidx < (imageWidth - 1))) &&
            (_gidy > 0)) && (_gidy < (imageHeight - 1))) {
            float sum = 0.0f;
            for (_p_offsetY = -1; _p_offsetY <= 1; _p_offsetY++) {
              _index1D = _gidx;
              for (_p_offsetX = -1; _p_offsetX <= 1; _p_offsetX++) {
                int finalX = (_gidx + _p_offsetX);
                int finalY = (_gidy + _p_offsetY);
                sum += srcImage[(finalY * imageWidth) + finalX];
```

A simple example

- Within your project you can now replace the original C/C++ file with the generated one.
- Also set up your project for OpenCL/CUDA
  - Install software development kit
  - Set up include/linker paths in your project
  - Install runtime/drivers
    - This must also be done on target machines.
- Watch out for naming conflicts if you keep the old code as well.

A simple example

- Several of the GPSME directives are available:
  - #pragma GPSME parallel
    - Marks the region to be parallelised.
  - #pragma GPSME for
    - A ‘for’ loop to be transferred to the GPU. Options are available to control the way this is split across threads.
  - #pragma GPSME barrier
    - Inserts a synchronisation point.
  - #pragma GPSME single
    - Marks a region to be executed serially.
  - #pragma GPSME copy
    - Performs a memory transfer.

A real world example

```
.
.
int iter = 0;
int iX, iY, iZ;
CPU_FLOAT_TYPE* pTemp;


#pragma GPSME copy(pInputData, toDevice, width, height, depth)
#pragma GPSME copy(pOutputData, toDevice, width, height, depth)
#pragma GPSME copy(pFullMaskData, toDevice, width, height, depth)

#pragma GPSME parallel
{
    for(iter=0; iter < 50; iter++)
    {
        #pragma GPSME for  nest(all) tile(8,8,8)
        for(iZ=0; iZ < depth; iZ++)
        {
            .
            .
            E = 1.0f + first[0] * first[0] / (first[2] * first[2]);
            F = first[0] * first[1] / (first[2] * first[2]);
            G = 1.0f + first[1] * first[1] / (first[2] * first[2]);
            L = (2.0f*first[0]*first[2]*second[0 * 3 + 2] - first[0]...
            M = (first[0]*first[2]*second[1 * 3 + 2] +first[1]*first[2]...
            N = (2.0f*first[1]*first[2]*second[1 * 3 + 2] - first[1]...
            .
            .
        }
    }
}

#pragma GPSME copy(pInputData, fromDevice, width, height, depth)
#pragma GPSME copy(pOutputData, fromDevice, width, height, depth)
#pragma GPSME copy(pFullMaskData, fromDevice, width, height, depth)
.
.
```

Practical concerns

- The GPSME toolkit can create huge speedups
  - Depends on underlying code structure.
- The code should:
  - Include (nested) for loops which can be moved to the GPU.
  - Avoid interloop dependencies.
  - Avoid function calls and recursion.
  - Avoid conditional logic.
  - Avoid system operations (allocations, disk access, etc)
  - Avoid dependencies on external libraries.
- The performance increase from parallelism must outweigh the cost of start up and memory transfers.

Interloop dependencies

- What if we want to apply multiple passes of our previous filter?

```
for (count = 0; count < 1000; count++)
{
  for (y = 1; y < imageHeight-1; y++)
  {
    for (x = 1; x < imageWidth-1; x++)
    {
      float sum = 0.0f;
      for(offsetY = -1; offsetY <= 1; offsetY++)
      {
        for(offsetX = -1; offsetX <= 1; offsetX++)
        {
          int finalX = x + offsetX;
          int finalY = y + offsetY;
          sum += srcImage[finalY * imageWidth + finalX];
        }
      }
      dstImage[y * imageWidth + x] = sum / 9.0f;
    }
  }
  swap(srcImage, dstImage);
}
```

Interloop dependencies

- In general such interloop dependencies are problematic for all GPUification approaches as they break parallelism.
  - Techniques exist to reduce them but they are limited.
- You should consider whether you can revise your code to remove the dependencies.
- In some cases it would help to add synchronisation primitives to the toolkit. We're investigating this.

Function calls

- Proper function calls are not supported on all GPU hardware.
  - Functions are usually inlined in the compiled code.
  - GPSME toolkit only supports functions which can be inlined.
  - Recursion is not possible
- Possible workarounds:
  - Make sure the function can be inlined and contains code appropriate for the GPU.
  - Bring the function call outside the loop if it doesn't really need to be executed every iteration.
  - Split the loop in to two loops – one following the other. Only parallelise one of them.

Conditional logic

- GPUs have a *Single Instruction Multiple Data* (SIMD) architecture.
- All threads follow the same execution path.
  - Relevant when testing boundary conditions (e.g. at edge of image)
- Conditional logic is possible but might not deliver the expected benefits.
  - This was relevant for the MedicSight code.

Conditional logic

```
#pragma GPSME 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
        }
    }
}
```

Memory transfers

- GPUs typically have memory which is physically separate from the main system memory.
  - The #pragma GPSME copy directive performs transfers.
- Transfers must be performed immediately before execution of the parallel region.
  - The GPSME toolkit will enforce this.

Memory Transfers

- You should consider:
  - **Bandwidth:** There is a limit to the rate at which data can be transferred to the GPU. This rate varies between cards (typically 10-200 Gb/sec).
  - **Latency:** There is a small delay between requesting a memory transfer and it actually happening. Therefore one large transfer is faster than several small one.
  - **Memory Size:** GPUs typically have between 128Mb to 2Gb of memory, and some is reserved for rendering processes.

Use of External Libraries

- It is common (and generally good practice) to build applications on third-party libraries.
- Unfortunately this causes some problems for parallelisation toolkits.
  - Must be able to see source code to the libraries being used.
  - Libraries must be available on Linux.
  - Libraries cannot be used within parallel regions.
  - Webserver add some extra complications.
- How can we work around these issues?

Use of External Libraries

- This is a problem case:

```
#include <windows.h>
.
.
.
someWindowsFunction();
.
.
.
#pragma GPSME for nest(2) tile(16,16)
for(int x = 0; x < 128; x++)
{
 for(int y = 0; y < 128; y++)
 {
   //Some code here
 }
}
```

Use of External Libraries

- Solve it by splitting the file in two:

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

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

Use of External Libraries

- A more difficult scenario:

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

Use of External Libraries

- When working through the webserver:
  - Make sure the required dependencies are installed.
  - Upload all project-specific headers which are needed.

```
#include "OpenCV.h"
#include "VTK.h"
.
.
#include "MyHeader1.h" // Upload this one
#include "MyHeader2.h" // Upload this one
.
.
int main(int argc, char** argv)
{
        //Some code here
}
```

Now let's see how this works on some harder problems…

Polybench benchmark suite

- Collection of micro-benchmarks
- Originally developed for the CPU
- CUDA/OpenCL versions were developed recently

- Implemented OpenMP, OpenACC and GPSME version
- Recently submitted a paper that presents the results

Polybench benchmark suite

- Convolution:
  2DCONV - 2D convolutional filter
  3DCONV - 3D convolutional filter

- Linear Algebra:
  2MM - 2 Matrix Multiplications (D=A*B; E=C*D)
  3MM - 3 Matrix Multiplications (E=A*B; F=C*D; G=E*F)
  ATAX - Matrix Transpose and Vector Multiplication
  BICG - BiCG Sub Kernel of BiCGStab Linear Solver
  GEMM - Matrix-multiply C=alpha.A.B+beta.C
  GESUMMV - Scalar, Vector and Matrix Multiplication
  GRAMSCHMIDT-Gram-Schmidt decomposition
  MVT - Matrix Vector Product and Transpose
  SYR2K - Symmetric rank-2k operations
  SYRK - Symmetric rank-k operations

- Datamining:
  CORRELATION - Correlation Computation
  COVARIANCE - Covariance Computation

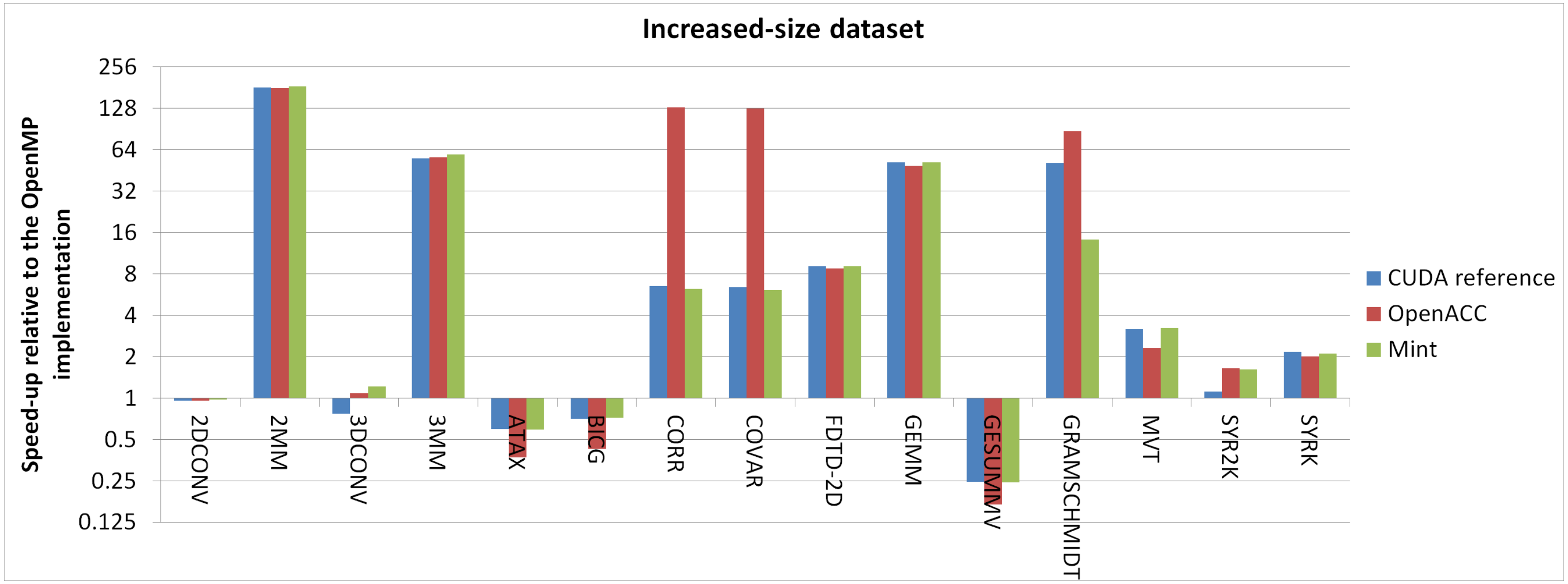
- Stencils:
  FDTD-2D - 2-D Finite Difference Time Domain Kernel

Open standards

- OpenMP
  - Open standard for directive-based multi-core programming
  - Most compilers support it by now
  - Easy to harness shared memory multi-core parallelism
- **OpenACC**
  - Open standard for directive-based GPU computing
  - Announced at SC11 [November 2011]
  - Caps, Cray, and PGI are currently providing OpenACC compilers
  - Version 2.0 is to be released soon…

Polybench initial results

- Most tests benefit from speed-ups compared to the OpenMP version.



Example – GEMM OpenACC

```
#pragma acc data copyin(A[NI*NJ],B[NI*NJ]) copyout(C[NI*NJ]){
   #pragma acc kernels loop independent vector(32)
   for (i = 0; i < NI; i++) {
       #pragma acc loop independent vector(32)
       for (j = 0; j < NJ; j++) {
            C[i*NJ + j] = 0.0;
           for (k = 0; k < NK; ++k)   {
                C[i*NJ + j] += A[i*NK + k] * B[k*NJ + j];
           }
        }
    }
}
```

Example – GEMM GPSME

```
#pragma GPSME copy(A,toDevice, NI, NJ)
#pragma GPSME copy(B,toDevice, NI, NJ)
#pragma GPSME parallel {
#pragma GPSME for  nest(2) tile(32,32)
for (i = 0; i < NI; i++) {
        for (j = 0; j < NJ; j++) {
           C[i*NJ + j] = 0.0;
           for (k = 0; k < NK; ++k)   {
                C[i*NJ + j] += A[i*NK + k] * B[k*NJ + j];
           }
        }
    }
}
#pragma GPSME copy(C,  fromDevice, NI,NJ)
```

Example – GRAMSCHMIDT

```
#pragma GPSME copy(A,toDevice, N, M)
#pragma GPSME copy(R,toDevice, N, M)
#pragma GPSME copy(Q,toDevice, N, M)
#pragma GPSME parallel{
#pragma GPSME for nest(1) tile(128)
for (k = 0; k < N; k++)   {
    nrm = 0;
    for (i = 0; i < M; i++)   {
        nrm += A[i*N + k] * A[i*N + k];
    }
    R[k*N + k] = sqrt(nrm);
    for (i = 0; i < M; i++)   {
        Q[i*N + k] = A[i*N + k] / R[k*N + k];
    }
    for (j = k + 1; j < N; j++)      {
        R[k*N + j] = 0;
        for (i = 0; i < M; i++)       {
            R[k*N + j] += Q[i*N + k] * A[i*N + j];
        }
        for (i = 0; i < M; i++)         {
            A[i*N + j] = A[i*N + j] - Q[i*N + k] * R[k*N + j];
        }
    }
}
}
#pragma GPSME copy(A,fromDevice, N, M)
```

Reduction limits 2^{nd} level parallelization

Example – GRAMSCHMIDT

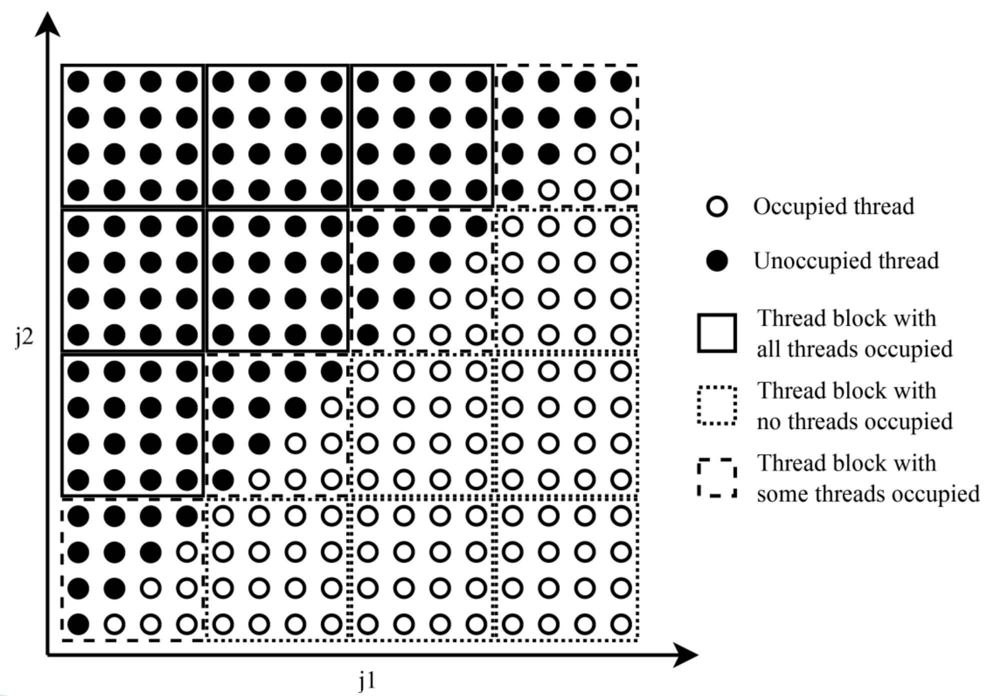
```
for (k = 0; k < N; k++)   {
    nrm = 0;
    for (i = 0; i < M; i++)  {
         nrm += A[i*N + k] * A[i*N + k];
    }
    R[k*N + k] = sqrt(nrm);
    for (i = 0; i < M; i++)  {
         Q[i*N + k] = A[i*N + k] / R[k*N + k];
    }
}
#pragma GPSME copy(A,toDevice, N, M)
#pragma GPSME copy(R,toDevice, N, M)
#pragma GPSME copy(Q,toDevice, N, M)
#pragma GPSME parallel{
#pragma GPSME for nest(2) tile(16,16)
for (k = 0; k < N; k++)   {
    for (j = k + 1; j < N; j++)        {
         R[k*N + j] = 0;
         for (i = 0; i < M; i++)       {
              R[k*N + j] += Q[i*N + k] * A[i*N + j];
         }
        for (i = 0; i < M; i++)         {
              A[i*N + j] = A[i*N + j] - Q[i*N + k] * R[k*N + j];
         }
     }
}
}
#pragma GPSME copy(A,fromDevice, N, M)
```

Triangular loop limits

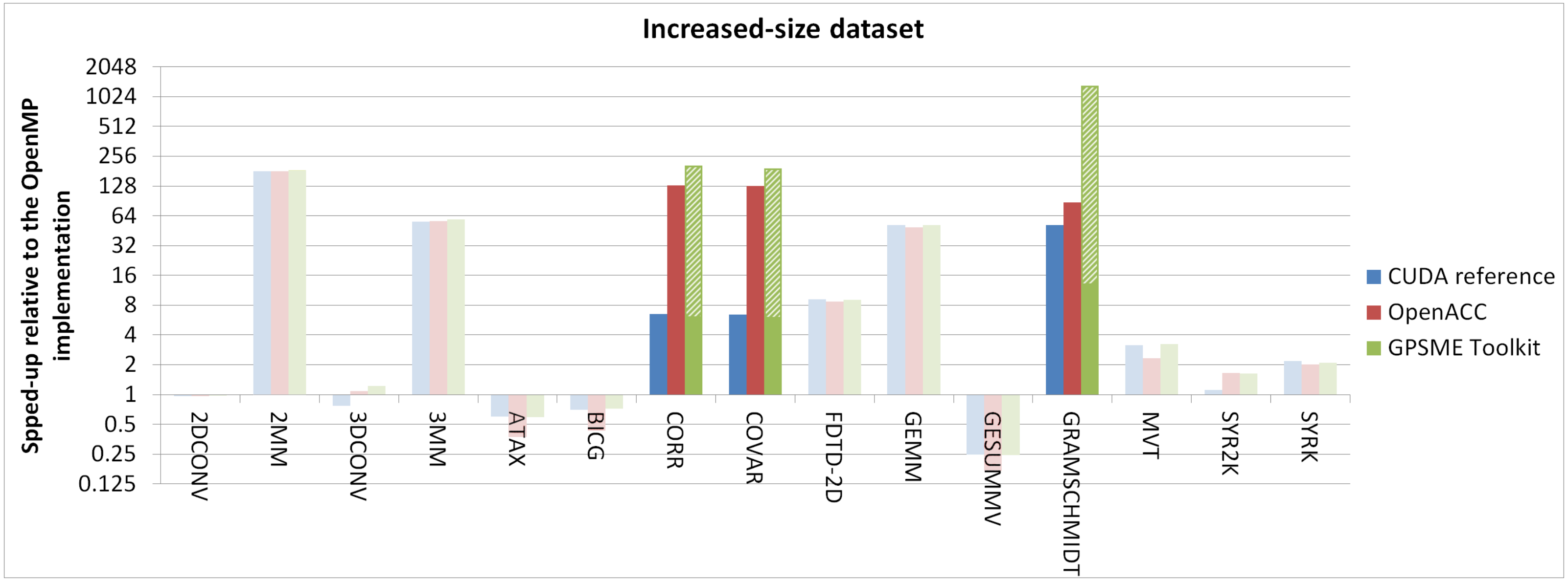
2nd level parallelization

Triangular loop support

- Thread blocks can be:
  - Full: All threads are part of the iteration space. Resources are not wasted.
  - Empty: No thread is part of the iteration space. Resources are not wasted.
  - Half-full: This create divergent branch behavior. Some threads are to be executed, and some are not.



Polybench benchmark suite



- Triangular support increases performance by more than 30 times
- Outperforms OpenACC by a good margin on these tests

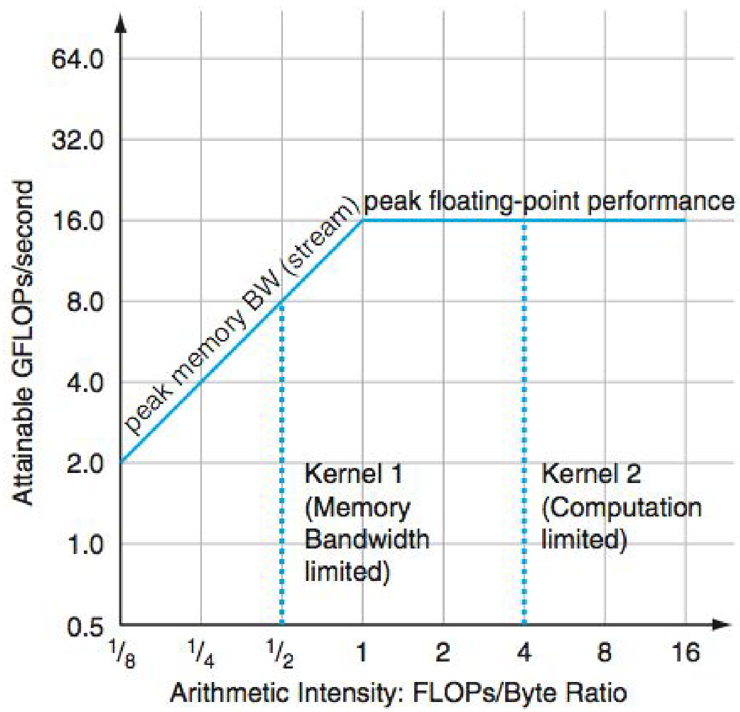
Future work – Multi dimensional arrays

- Tests have been modified to access memory in a 2D manner a[i][j], as opposed to a[i*M+j]
- GPSME finds extra optimization opportunities by exploiting the 2D access pattern
- 25% performance increase when using explicit 2D arrays

	2MM-1D [s]	2MM-2D [s]	SYR2K-1D [s]	SYR2K-2D [s]
OpenACC	3.921	8.927	16.671	32.272
GPSME	3.814	2.812	17.01	12.08

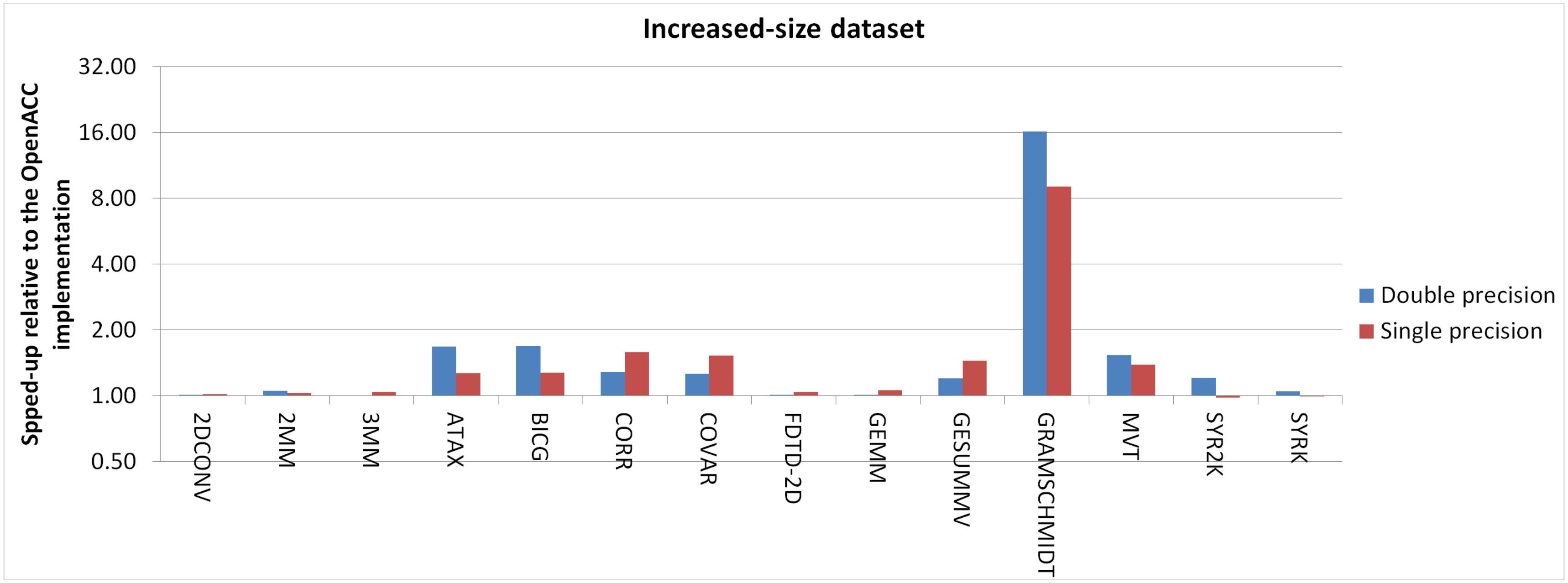
Arithmetic intensity

- Arithmetic intensity is defined as the ratio between computation and memory load/store



Float vs. double

- GPSME is equal or better than OpenACC in all cases



Conclusions on Polybench

- GPSME outperforms OpenACC on the majority of cases:
  - Better register usage
  - Cleaner output code

Memory Space		Bandwidth
Register memory	≈	8,000 GB/s
Shared memory	≈	1,600 GB/s
Global memory	≈	177 GB/s
Mapped memory	≈	8 GB/s

Source: Rob Farber
"CUDA Application Design and Development"

Rotasoft Evaluation

- The ASIFT algorithm for feature extraction
  - Keypoint matching
- Rotasoft have successfully evaluated the ASIFT implementations
  - On their own dataset
  - On a dataset provided by the RTD performers
- Matching accuracy is almost the same as with the CPU version
  - Highly invariant to camera viewpoint change
- Main modification: Replaced Array of Structures with Structure of Arrays

Array of Structures vs Structures of Arrays

- GPU global memory is accessed in chunks and aligned.

```
struct key_aos
{
   int angle;
   int scale;
   int descriptor[128];
};

key_aos *d_keys;
cudaMalloc((void**)&d_keys, ...);
```

```
struct key_soa
{
   int  * angle;
   int  * scale;
   int  * descriptor[128];
};

key_soa d_keys;
cudaMalloc((void**)
  &d_keys.angle, ...);
cudaMalloc((void**)
  &d_keys.scale, ...);
cudaMalloc((void**)
  &d_keys.descriptor, ...);
```

Rotasoft Evaluation – Keypoint matching

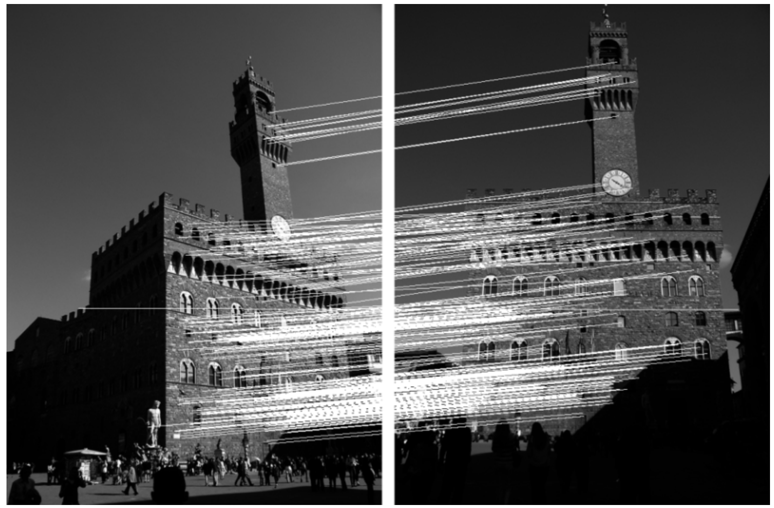
- **Tested on 800x600 image:**
  - Computes matches between two sets of around 11,000 keypoints

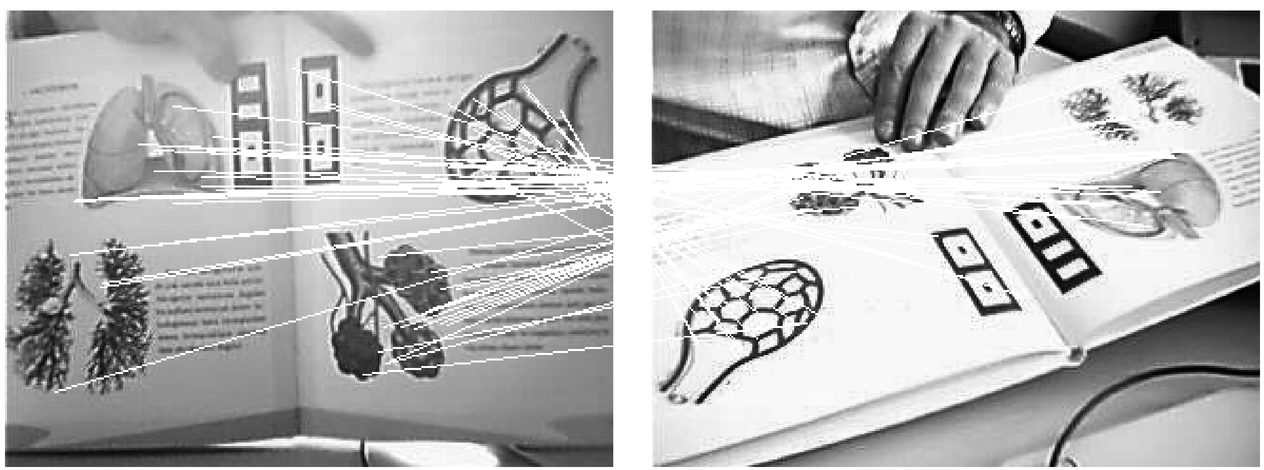
Rotasoft: Core i3@2.1GHz+GT520M **Groningen: Core i7@3.4GHz+GTX680**

	Rotasoft workstation (time in seconds)	Groningen workstation (time in seconds)
Original	69.5	25.9
OpenMP	25.7	6.7
Manual GPU	12.5	1.9
Auto GPU	14.6	3.2

- **Speed-up of 6x for a lower grade system**
- **Speed-up of up to 13.6x for a high-performance system**

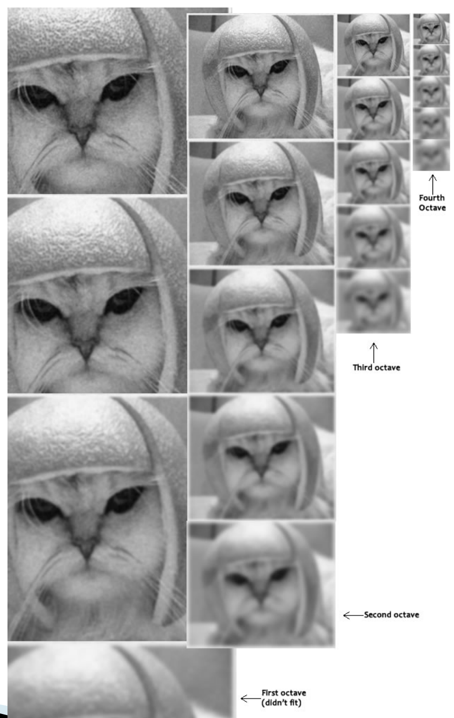
Rotasoft Evaluation – Keypoint matching

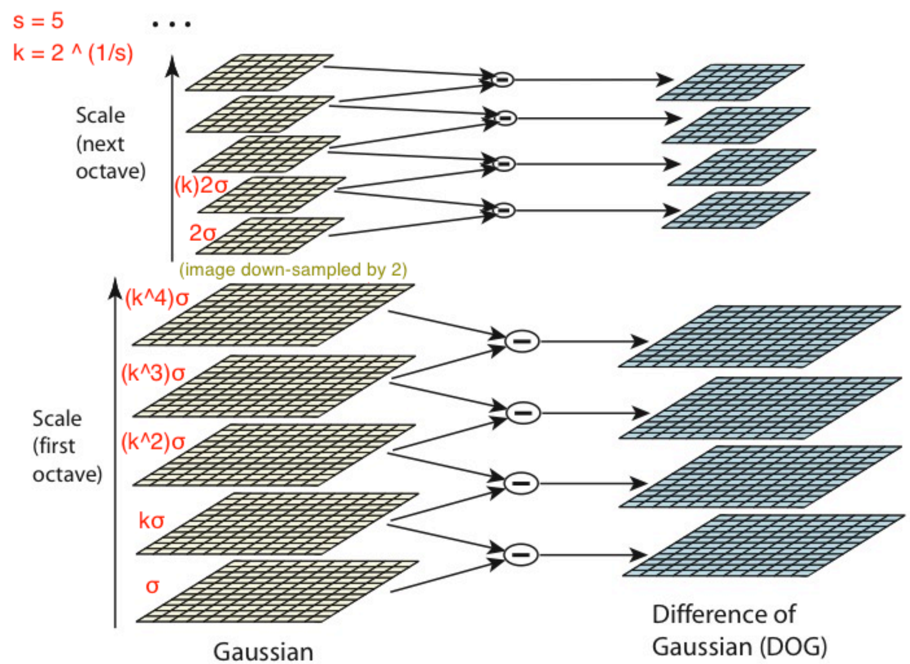




Rotasoft Evaluation

- We continue with evaluating parts of ASIFT keypoint detection, starting with convolution
  - Convolution is about 45-50% of the detection stage





Convolution - GPSME

```
#pragma GPSME copy (A, toDevice,N,M)
#pragma GPSME copy (B, toDevice,N,M)
#pragma GPSME copy (c, toDevice,3,3)
#pragma GPSME parallel  {
#pragma GPSME for  nest(2) tile(32,16)
 for (int i = 1; i < M - 1; ++i)    {
     for (int j = 1; j < N - 1; ++j)     {
        B[i][j] = c[0][0] * A[i - 1][j - 1] + c[0][1] * A[i + 0][j - 1] +
                  c[0][2] * A[i + 1][j - 1] + c[1][0] * A[i - 1][j + 0] +
                  c[1][1] * A[i + 0][j + 0] + c[1][2] * A[i + 1][j + 0] +
                  c[2][0] * A[i - 1][j + 1] + c[2][1] * A[i + 0][j + 1] +
                  c[2][2] * A[i + 1][j + 1];
      }
   }
}
#pragma GPSME copy (B, fromDevice,N,M)
```

Convolution performance

- **Intel i7@3.4GHz ; NVidia GTX680**

	Small data model* 3x3 kernel [Hz]	Small data model* 5x5 kernel [Hz]	Big data model** 3x3 kernel [Hz]	Big data model** 5x5 kernel [Hz]
CPU – GCC	486	64.5	2.94	0.44
PGI OpenACC	4629	2127	26.17	12.33
GPSME	4901	2785	34.6	16.28

- **Speed-up between 10x and 43x vs. CPU code**
- **Between 5%-30% faster than PGI's OpenACC**

* 1024x1024 image
**12288X12288 image

OpenACC vs. GPSME

- OpenACC advantages:
  - It’s an open standard implemented by compiler vendors.
  - Flexibility
    - Synchronisation, memory and device management, caching.
  - Ease of use (integrated into Visual Studio)
- GPSME advantages:
  - Simplicity
  - Generates cleaner output code
    - CUDA, as well as OpenCL code
  - Doesn’t incur performance penalties for the above advantages
  - Full access to source code makes it easily extendable

Conclusions

- GPSME toolkit can deliver large performance gains for some classes of problems.
- Better or equal than PGI OpenACC compiler on Polybench
- For real-world code, usually some revising of is needed:
  - Isolate code you wish to parallelise
  - Try to eliminate library and loop dependencies.
  - Consider memory transfers, especially inside loops
  - Use SoA instead of AoS