GPU programming made easier

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Introduction

- We created a tool that reduces the development time of GPU code.
- The input is a loop nest which is parsed into an internal representation.
- We generate code which makes the loop executable on a GPU.
- We apply optimizations to the code and perform benchmarks on CPU and GPU architectures.
- Our code is 2-258X faster than code generated by an OpenACC compiler, 1-37X faster than optimized CPU code, and attains up to 25% of peak performance.

Ideas

- We want to reduce errors and the development time, while ensuring high performance.
- Optimizations on OpenCL code are regular and the same optimization can be applied to many different pieces of code.
- A tool with a catalogue of optimizations which can be performed semi-automatically by the programmer.
- Move toward fully-automatic optimizations to make the tool usable for novices in GPU programming.

Overview

- Front end and code generation
- OpenCL background
- GPU background
- Transformations
- Pattern-matching rules
- Performance experiments
- Conclusion

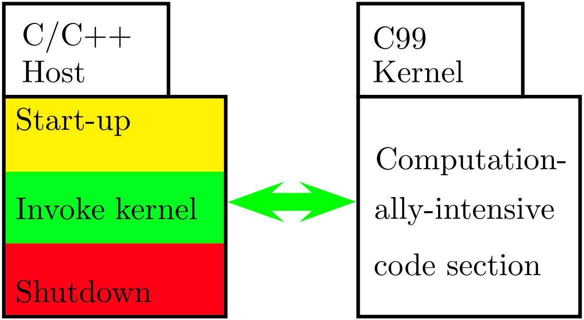
Front end and code generation


```
t_PLUS = r'\+'

def p_native_type(p):
    """ native_type : VOID
                    | SIZE_T
                    | ...
    """
    p[0] = p[1]

def p_for_loop(p):
    """ for_loop : FOR LPAREN assignment_expression SEMI binop SEMI
                              increment RPAREN compound
    """
    p[0] = ForLoop(p[3], p[5], p[7], p[9])
class ForLoop(Node):
    def __init__(self, init, cond, inc, compound):
        self.init = init
        self.cond = cond
        self.inc = inc
        self.compound = compound
```

OpenCL background



- The host code sets up data structures and manages the GPU execution.

GPU (GK110) background

- Warps: 32 threads which execute the same instructions in a Single Instruction Multiple Threads (SIMT) fashion.
- Registers: 255 private to each thread. Use as cache for data with time locality.
- Local memory: scratchpad shared between local work group. Effective when data is shared/broadcasted.
- Memory coalescing: data accessed by threads with consecutive thread IDs should be located consecutively in memory.

Transformations

- DefineArg: Similar to constant propagation, we can compile the values of variables into the kernel code, in order to allow the compiler to do more optimizations.
- Transposition: We transpose the data in an array in order to create coalesced memory access.

HoistToReg and HoistToRegLoop

- Read data once, save it in registers, and reread the data from there, similar to loop-invariant code motion.

```
for (unsigned j = 0; j < N; j++) {
    float a_x = Pos[0][get_global_id(0)];
    float a_y = Pos[1][get_global_id(0)];
    float a_m = Mas[get_global_id(0)];
    ...
}
```

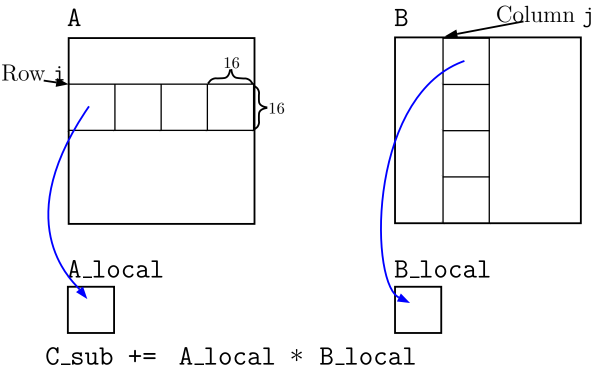
Original code

```
float Mas0_reg = Mas[get_global_id(0)];
float Pos0_reg = Pos[0][get_global_id(0)];
float Pos1_reg = Pos[1][get_global_id(0)];
for (unsigned j = 0; j < N; j++) {
    float a_x = Pos0_reg;
    float a_y = Pos1_reg;
    float a_m = Mas0_reg;
    ...
}
```

Transformed code

TileInLocal

- Load shared data into local memory once and let each thread read the data they need from local memory.



TileInLocal

Original code

```
float C_sub = 0;
for (unsigned k = 0; k < wA; k++) {
    C_sub += A[get_global_id(1)][k] * B[k][get_global_id(1)];
}
C[get_global_id(1)][get_global_id(0)] = C_sub;
```

Transformed code

```
float C_sub = 0;
for (unsigned k = 0; k < wA; k+=16) {
    A_local[get_local_id(1)][get_local_id(0)] =
                          A[get_global_id(1)][k + get_local_id(0)];
    B_local[get_local_id(1)][get_local_id(0)] =
                          B[k + get_local_id(1)][get_global_id(0)];
    barrier(CLK_LOCAL_MEM_FENCE);
    for (unsigned kk = 0; kk < 16; kk++) {
        C_sub += A_local[get_local_id(1)][kk] *
                          B_local[kk][get_local_id(0)];
    }
    barrier(CLK_LOCAL_MEM_FENCE);
}
C[get_global_id(1)][get_global_id(0)] = C_sub;
```

Pattern matching

- We link each transformations to a pattern. The presence of the pattern in the code, means that the linked transformation is applicable.
- We iterate over the array references and search for patterns. For each found pattern we check a set of conditions, and if met, we perform the linked transformation.
- The conditions are not exhaustive, but sufficiently thorough to make them usable in practice.
- The running time is linear in the number of array references.

DefineArg and Transposition

- For DefineArg we do no pattern matching, and perform the transformation always.
- For Transposition we divide the pattern-matching rule into two cases: 1D- and 2D-parallelization.

For 1D:

```
A[get_global_id(0)][d]
```

For 2D:

```
A[get_global_id(0)][get_global_id(1)]
```

HoistToReg and HoistToRegLoop

- For HoistToReg: an array reference that is inside one or more loops, but contains no loop index.
- For HoistToRegLoop: an array reference that is inside two loops, and the loop index of the outermost loop is not in the subscript of the reference.
- We use at most 20 registers.
- We decide at run-time whether to include the transformation.

For HoistToReg

```
for (unsigned k = 0; k < N; k++) {
    ... = A[10];
    ... = B[get_global_id(0)][l];
    for (unsigned g = 0; g < dim; g++) {
        ... = C[get_global_id(1)];
        ... = D[l][10];
    }
}
```

For HoistToRegLoop

```
for (unsigned k = 0; k < N; k++) {
    for (unsigned g = 0; g < dim; g++) {
        ... = A[10][g];
        ... = B[g][get_global_id(0)];
        ... = C[get_global_id(1)][g];
        ... = D[g][l];
    }
}
```

TileInLocal

- An array with two subscripts where one contains a loop index and the other a global thread identifier.
- Additional conditions:
  - The loop index must have a stride of one.
  - The number of loop iterations must be divisable by a tiling factor.
- Check last condition at run-time.

```
for (unsigned k = 0; k < N; k++) {
     ... = A[get_global_id(1)][k];
     ... = B[k][get_global_id(0)];
}
```

Performance experiments

We compare the performance against:

1. Frameworks with comparative capabilities
2. The theoretical peak performance of the test hardware
3. The performance of CPUs

- We found one framework, the OpenACC API, which has similar capabilities as our tool.
- We extended our tool to generate optimized code for CPUs.
- The benchmarks were run on an NVIDIA K20 GPU, and a machine with two Intel Xeon E5-2670 clocked at 2.6 GHz.

Performance experiments (2)

We have a mix of programs: compute/memory bound, small/high N.

	MatMul	**Squared Euclid**	**NBody**	**Laplace**	**Gaussian kernels**	**Jacobi**
DEFINEARG	x	x	x	x	x	x
TRANSPOSITION		x		x		
HOISTTOREG			x			
HOISTTOREGLOOP		x		x		
TILEINLOCAL	x				x	
TILEINLOCALSTENCIL						x

Tabel: Applicability of the transformations.

Performance experiments (3)

	MatMul	Jacobi	Squared Euclid	NBody	Laplace	Gaussian kernels
GPU OPTIMIZED to GPU BASIC	3.1	1	55.7	3.4	3.6	1.7
GPU BASIC to PGI	0.9	1.9	4.6	2.2	–	–
GPU OPTIMIZED to PGI	2.8	1.9	257.4	7.5	–	–

Tabel: Speedup in the execution time of the code generated by the different frameworks.

Performance experiments (4)

	MatMul	**Jacobi**	**Squared Euclid**	**NBody**	**Laplace**	**Gaussian kernels**
Performance [GFlop/s]	205	4	611	872	245	104
% of peak performance	6	1	18	25	21	3

	MatMul	**Jacobi**	**Squared Euclid**	**NBody**	**Laplace**	**Gaussian kernels**
CPU Optimized to CPU Basic	6.8	0.7	1.1	1.1	1.1	15.6
GPU Optimized to CPU Optimized	3.3	0.6	36.1	10.9	6.5	1.8

Conclusion

- Design of a model of how data can be reused.
- We found pattern-matching rules which allow the transformations to be performed automatically.
- Conditions pertaining to the applicability of a transformations needs to be checked at compile time and at run-time.
- Benchmarks show significant improvements, up to one order of magnitude, in time-to-solution when comparing to OpenACC and optimized CPU code.
- For three programs, the generated code attained close to 25% of peak performance of the GPU. For the others, further transformations would be needed to obtain higher performance.