**PENCIL: Towards a Platform-Neutral Compute Intermediate Language for DSLs**

Riyadh Baghdadi†, Albert Cohen†, Serge Guelton†, Sven Verdoolaege†, Jun Inoue†, Tobias Grosser†,
Georgia Kouveli*, Alexey Kravets*, Anton Lokhmotov*, Cedric Nugteren*, Fraser Waters*†,
Alastair F. Donaldson‡

* ARM, Media Processing Division, 110 Fulbourn Road, Cambridge, CB1 9NJ, UK
† INRIA and École Normale Supérieure, Département d’Informatique, 45 Rue d’Ulm, 75005 Paris, France
‡ Imperial College London, Department of Computing, 180 Queen’s Gate, London, SW7 2BZ, UK

**Abstract**—We motivate the design and implementation of a platform-neutral compute intermediate language (PENCIL) for productive and performance-portable accelerator programming.

I. INTRODUCTION

Many systems – from supercomputer installations to embedded systems-on-chip – benefit from using special-purpose accelerators which can significantly outperform general-purpose processors in terms of energy efficiency as well as in terms of execution speed.

Software for accelerated systems, however, is currently written using low-level APIs, such as OpenCL and CUDA, which increases the cost of its development and maintenance. On the other hand, general-purpose programming languages like C, C++ and Java do not directly leverage features of accelerators, such as data-level parallelism, or support common accelerator programming idioms, such as iteration space tiling. Furthermore, in many application domains for which accelerators show promise, such as image processing and computational fluid dynamics, it is common to program in domain-specific languages (DSLs).

Compiling DSLs directly into OpenCL or CUDA is possible but not advisable. For example, to target accelerated platforms effectively the DSL implementers must develop sophisticated code generation and optimization techniques. Given typical budget constraints, they will likely limit their efforts to a set of techniques useful for a small number of target platforms (e.g. accelerated by NVIDIA GPUs), thus compromising on performance portability. Moreover, the implementers of different DSLs will likely spend their efforts on implementing an overlapping set of techniques. Clearly, both teams would benefit if they could target an efficiently implemented intermediate language.

Beside enhancing productivity, DSLs have the advantage of using high level constructs that have rich semantics. These constructs provide a wealth of information that enable the compiler to optimize and parallelize the code even for algorithms that are considered to be irregular when expressed in languages like C. DSL compilers keep a close control on the generated code, eliminating many of the problems faced by general-purpose optimizing compilers.

In this article, we present our work in progress on a platform-neutral compute intermediate language for DSLs called PENCIL. We give an early overview of PENCIL and some of the design guidelines that will help in its definition. We show some coding rules, language extensions and directives that we envisage to include in PENCIL along with a preliminary syntax. And finally, we present two examples of DSLs and show how they can be expressed in PENCIL.

II. OVERVIEW OF PENCIL

PENCIL will be a platform-neutral intermediate language for multiple high performance DSLs. An optimization framework will take care of optimizing and parallelizing the intermediate language. In this paper we use the polyhedral framework [?] as an example of a static optimization framework. The polyhedral framework uses an algebraic representation and abstraction of programs to reason about loop transformations, allowing the modeling and application of complex loop nest transformations addressing most of the parallelism and locality-enhancing challenges.

The PENCIL language is meant to facilitate automatic parallelization and optimization for execution on multi-threaded SIMD hardware; it will thus have sequential semantics. The syntax presented in this work is a preliminary syntax based on C, and benefiting from C99 and the GNU extensions.

PENCIL will be suitably high-level to allow straightforward DSL-to-PENCIL compilation, but will provide direct support for common accelerator features and programming idioms, to allow downstream compilation into extremely efficient low-level code. In particular, its features will include extensions and directives (pragmas) allowing users to supply information about dependences and memory access patterns that may be difficult or impossible to analyze automatically, and a low-level API allowing expert programmers to exert control over performance-related aspects such as scheduling, vectorization, placement and data layout, when desired.

The information captured by PENCIL extensions and directives (pragmas) are similar to Æcute metadata [?], which have proved successful in proof-of-concept implementations. We plan to extend this initial work in two ways.
First, we will ensure that PENCIL can represent both regular and irregular algorithms suitable for accelerators, by systematically studying algorithmic ‘motifs’ (originally called ‘dwarfs’) proposed by researchers from Berkeley [8]. Acute metadata are a close fit for regular algorithms which typically have static iteration spaces and memory access patterns, such as dense linear algebra and stencil computations. We have used similar techniques to generate efficient OpenCL code for an irregular algorithm – sparse matrix-vector product – for several state-of-the-art sparse matrix formats suited for GPUs [2].

Second, we will investigate the use of directives and extensions in cross-component optimizations, where dependence information associated with several computational kernels is collectively exploited to perform transformations to increase parallelism and locality. In addition to being useful as a compilation target, PENCIL will remain sufficiently high-level and structured to be used directly as an efficiency language, particularly for library implementers. Thus, the cross-component optimizer will be designed to support linking and transformation of a mixture of PENCIL code compiled from DSLs, hand-written user and library code.

Figure 1 shows the DSL compilation flow involving PENCIL. First, a program written in a domain specific language is translated into PENCIL. The PENCIL design aims to make the task of writing a DSL→PENCIL compiler (the job of the DSL implementer) as straightforward as possible. Domain specific optimizations are applied during this translation. Second, the generated PENCIL code is combined with hand-written PENCIL codes that implement specific library functions. This combination of codes is then optimized and parallelized (using the polyhedral framework for example). Finally highly specialized OpenCL code is generated. The generated code is tuned through profile-based iterative compilation and auto-tuning.

A. PENCIL design

In order to guarantee the correctness of optimizations, compilers usually take conservative assumptions. These conservative assumptions reduce the ability of the compiler to find optimizations. The compiler may assume, for example, that two pointers may alias, whereas the pointers do not actually alias. The fact that the two pointers do not alias is in general well known to the programmer and to the DSL compiler, but this information is not transmitted, in general, to the compiler.

To address this problem, PENCIL sets coding rules that may be used by DSL compilers and by expert PENCIL programmers in order to enhance the ability of the compiler to perform static code analysis. Some of these rules will be checked and enforced by the PENCIL compiler, while some others are left up to the programmer or DSL compiler.

The current syntax of PENCIL uses C annotations and extensions where possible. As such, a PENCIL program, in the current state, retains the standard syntax and semantics of a C program and can be processed by an ordinary C compiler. Semantical additions to C make use of custom GNU extensions and directives.

While designing PENCIL, we are putting a strong emphasis on the definition of annotation syntaxes and coding rules that may be easily lowered to compiler intermediate representations using attributes and built-in functions, mainly because we are considering an equivalent LLVM IR syntax for PENCIL.

B. Examples of PENCIL coding rules, extensions and directives

1) Coding rules: One of the main characteristics of PENCIL is its restriction on pointer usage in order to eliminate aliasing. PENCIL will accept only non-array variables to be passed by value, and will accept only non-array variables to be passed by pointer. Array parameters must be passed using the C99 VLA syntax and must be qualified restrict, const, and static with the same syntax and semantics as in C99. For example:

```c
/* The following function is PENCIL-compliant. */
void foo (int a[restrict const static 5]) {
    /* `a[]` is const but its elements are not. */
    a[0] = 1;
    /* Here const is not required. Local variables are not coerced to pointers. */
    int c[2];
}
```

Fig. 1: The DSL compilation flow involving PENCIL.
Readers may recall that C99 coerces the type of a in function foo to int*, but we require the explicit array declaration syntax to reinforce that PENCIL disallows pointer arithmetic. We may also find ways to leverage the declared array size information in PENCIL compilers in the future.

A pass-by-pointer parameter should be declared in the receiving functions prototype as a const restrict pointer. These restrictions guarantee that a pointer can only point to a fixed memory region throughout its lifetime and that different pointers never point to the same memory region.

Other coding rules that we envisage to enforce in PENCIL programs include the constraint that recursion (whether direct or indirect) and unstructured control flow (via gotos) are not allowed.

2) Extensions: PENCIL provides access summary functions for describing the data access patterns of a function. This mechanism may be applied to any function, including those whose behaviors are too complex for the compiler to infer accurately, as well as library functions whose source code is not available to the PENCIL compiler and/or which internally uses features of C that are banned in PENCIL. In the following example, ACCESS declares that foo performs the same data access as foo_summary (array qualifiers are omitted for brevity):

```c
void foo_summary (int n, int A[n], int B[n],
       int C[n])
{
   for (int i=0; i<n; i++) {
      DEF(A[i]); USE(B[i]); MAY_DEF(B[i]);
   }
   if (n < 4) DEF(C[0]); // one-element def
       USE(A[n-1]);
}
```

```c
void foo(int n, int A[n], int B[n], int C[n])
{
   ACCESS(foo_summary(n, A, B, C))
   int i;
   for (i=0; i<n; i++) {
      A[i] = B[i];
      B[rand()] % n = 42;
   }
   if (n < 4) C[0] = A[n-1];
}
```

The macros DEF, USE, and MAY_DEF expand to built-in functions that modify, use, or may modify their argument, respectively, but which are guaranteed not to be accidentally optimized out in upstream compiler passes. The actual accesses summarized by the function are defined by the array elements traversed along the execution of the summary function. Control flow and C instructions are only meant to drive the enumeration of these accesses. Since these summaries are meant to be processed by a static analyzer, non-affine control flow may lead to further discrepancies between may-write and must-write access sets. For example, the result of such a static analysis could take the form of three distinct access relations, mapping each iteration of the summarized function call and/or its parameters to a set of may-write, must-write, and read accesses respectively.

3) Directives: PENCIL uses directives inspired by OpenMP, OpenACC and advanced vectorizing compilers.

The restrictions presented in the previous section simplify data and control dependence analysis, which gives PENCIL compilers a boost in loop optimizations. When this falls short of providing the compiler with necessary static information, however, dependence information can be explicitly supplied as directives. One such directive is

```c
#pragma pencil independent [(l_1, ..., l_n)]
```

The list $l_1, ..., l_n$ indicates the labeled statements on which the loop independence is guaranteed. A statement that appears in an independent clause is assumed not to have any loop-carried dependence with any other statement in the loop. If this list is omitted then all statements in the loop body are free of dependences carried by the annotated loop. In the following example:

```c
#pragma pencil independent
for (int i=0; i<n; i++)
   A[t[i]]++;
```

different iterations of the loop may write to the same array location. The write location depends on the value of $t[i]$. In order to parallelize the loop, the compiler needs to make sure that there is no loop-carried dependence, but proving this property is not possible at compile time. Thus, the compiler considers conservatively that there may be a dependence between the different iterations and the loop is not parallelized. If the DSL compiler or the expert PENCIL programmer know that all values of $t[i]$ are different then she should insert an independent pragma to indicate that different iterations of the loop are independent. This will not only enable the parallelization of the loop, but also provide valuable static information to other loop transformations and optimizations.

Unlike the OpenMP parallel pragma, it is possible to use the independent pragma on while loops to indicate that there is no dependence between the different iterations of the while loop. It is up to the compiler to use this information to optimize the code. Moreover, the independent pragma allows fine grain code description as its scope may be limited to only one statement in the loop body.

PENCIL also defines a reduction directive equivalent to the reduction directive defined in OpenMP and OpenACC. It has the following syntax:

```c
#pragma pencil reduction (operator : scalars)
```

Note that PENCIL does not compete with OpenMP, actually PENCIL complements OpenMP and, in general, the coding rules defined by PENCIL are useful for compiler optimizations even if they are used outside PENCIL.

All in all, this feature set provides a language whose overall semantics is sequential but which places conventions and restrictions that increase the static information available to the compiler, thus enabling the compiler to do more aggressive loop nest optimizations and parallelization. Although the language is sequential, the information about parallelism available at the DSL level is not lost, because this information is expressed in PENCIL through directives like independent which indicates the absence of dependences in a given loop.
Any lower level compiler can use this information not only to parallelize the loop but to apply other optimizations as well. Expressing the absence of dependences is more powerful than expressing only parallelism.

### III. Examples of DSL translation into PENCIL

This section provides examples of DSLs that can be mapped into PENCIL, and benefit from the optimizations provided by PENCIL compilers, including polyhedral compilation methods. Some DSLs are mostly designed for programmer productivity, and their compilation flow typically combines specific passes for abstraction penalty removal with more generic optimization passes. Such DSLs should immediately benefit from PENCIL with minor modifications to their compilation flow. Other DSLs involve a lot of domain-specific information available for compile-time optimizations. Since a large number of these optimizations are actually generic ones, expressible as loop transformations and storage mapping choices, PENCIL will also contribute to the simplification of their tool flow.

In all of the following examples, memory access information should be used to annotate functions called from within the kernels. Moreover, the coding rules are mandatory to enable a precise dependence analysis.

#### A. OP2 library

OP2 [?] is a state-of-the-art library for parallelizing unstructured mesh computations. It restricts the computational kernel’s data-access pattern, simplifying dependence analyses and facilitating task decomposition, scheduling, and data layout. While a great deal of OP2’s innovations lies in its efficient backend implementations, it is noteworthy how PENCIL captures OP2’s most important restrictions. Let us illustrate this with the following program using OP2’s C++ binding, adapted from [?]. Functions named with the op_ prefix constitute OP2’s API. For the sake of conciseness we have omitted string parameters that are used for dynamic type checking and OP2’s API. For the sake of conciseness we have omitted string parameters that are used for dynamic type checking and OP2’s API.

```c
void main_loop (int ncells, int nedges,
    double *cell_data)
{
    int i0, i1;
    void kernel (double *cell0, double *cell1)
    {
        cell0 += edge; cell1 += edge;
    }

    void op_par_loop (int ncells, int nedges,
        double *edge_data,
        double *cell_data)
    {
        op_set cells = op_decl_set (ncells);
        op_set edges = op_decl_set (nedges);
        op_map pecell = op_decl_map (edges, cells, 2,
            edge_to_cells);
        op_dat dcells = op_decl_dat (cells, 1, cell_data);
        op_dat dedges = op_decl_dat (edges, 1, edge_data);
        op_par_loop (kernel, edges,
            op_arg(edges, -1, OP_ID, 1, OP_READ),
            op_arg(dcells, 0, pecell, 1, OP_INC),
            op_arg(dcells, 1, pecell, 1, OP_INC));
    }
```

In this example, we assume a 2D mesh with `ncells` cells, numbered (or indexed) from 0 through `ncells`-1, and a total of `nedges` edges also numbered from 0. We ignore boundary edges for simplicity and assume that each edge falls between exactly two cells. The input `edge_to_cells` is a 1-to-2 mapping that indicates which edge touches which cells – the edge with index `i` touches the cells with indices `edge_to_cells[2*i]` and `edge_to_cells[2*i+1]`. Every edge or cell carries one double-precision floating point data, specified by `edge_data` or `cell_data`, respectively. The main computational kernel adds to each cell all data coming in from its edges; we wish to do this for all cells.

The first six lines of `main_loop()` just communicate this setup to OP2. `op_decl_set()` is used to declare the set of cells and the set of edges, while `op_decl_map()` defines the relationship between them using `edge_to_cells`. The argument 2 indicates to OP2 that this is a 1-to-2 mapping. Conceptually `pecell` is just a copy of `edge_to_cells`, made opaque so that OP2 is not constrained by the layout or location of `edge_to_cells`. Finally `op_decl_dat()` attaches data to the cells and edges.

The most interesting part is `op_par_loop()`, which is conceptually equivalent to the following plain C loop:

```
for (int i = 0; i < nedges; ++i)
    kernel (&dedges[i],
        &dcells[pecell[2*i]],
        &dcells[pecell[2*i+1]]);
```

In words, `op_par_loop()` iterates over the indices of `edges`, calling a kernel on the data associated with each index. The three calls to `op_arg()` are used to indicate the arguments of `kernel()`, and to describe how each argument is being accessed.

For example

```
void kernel (double edge[], int ie,
    double cell0[], int i0)
{
    cell0[i0] += edge[ie];
}
```

lets `op_par_loop()` to that the first argument of `kernel()` is `dcells`; and that the index used to access `dcells` is calculated by looking up `pecell` at the loop index `i` and adding the offset 0; the number of data elements passed to the kernel is 1 starting at the translated index. `OP_ID` is used to indicate that the loop index should be used directly to address the data. The last argument `OP_INC` is a hint on how the kernel function accesses this data; it means the data is the subject of a global-reduction sum, as seen for `cell0` and `cell1` in the above example. The other possible hints are `OP_READ`, `OP_WRITE`, and `OP_RW`. For the last two, the kernel code must ensure that no data conflict is possible between different iterations.

It should be clear that OP2’s semantics is correctly captured in PENCIL by translation to a for loop like the one above, with the caveat that `kernel` must be either inlined or modified to

```
void kernel (double edge[], int ie,
    double cell0[])
{
    cell0[i0] += edge[ie];
}
```

(because PENCIL does not allow pointers). The translated for loop is legal PENCIL. The other parts – the first six lines of `main_loop()` – simply reify and constrain the input data, which is unnecessary in PENCIL.
This is not surprising, as OP2 is a more aggressively restricted DSL than PENCIL. The more interesting fact is how much of OP2’s static information can be captured in PENCIL. The single greatest benefit from OP2’s programming model is probably elimination of pointer analysis. This is built into PENCIL. Of OP2’s access hints, OP INC can be expressed with a reduction pragma, the conflict-freedom requirement of OP_WRITE/OP_RW can be expressed with #pragma independent, and OP_READ should be inferable from the source code.

One aspect of OP2 that is not currently captured explicitly by PENCIL is allowing the un-associativity of floating point arithmetic to compromise bit-wise reproducibility of results. The example program above suffers from the problem that parallelizing the loop in any way compromises numerical precision to some extent. This is a long-standing and well-known issue, often handled by providing a switch or pragma to allow trading precision for efficiency. We plan to follow this well-accepted practice.

B. Delite/OptiML

OptiML [?] is a DSL for machine learning built on top of Delite [?], a framework for creating implicitly parallel DSLs. An OptiML program is actually a program generator embedded in Scala. It uses meta-programming to construct a symbolic representation of the DSL program as it is executed. Each program expression, such as if(c) a else b, constructs an IR node when the program is run. Instead of using a control flow graph (CFG) for the different statements with fixed basic blocks, Delite uses a “sea of nodes” [?] as an IR representation. Nodes are connected with respect to their (input and control) dependences but are allowed to float freely otherwise.

The Delite IR provides several operators. A given DSL may use a subset of these operators and may also extend existing operators to create new ones.

OptiML programs operate on the high-level mutable types Vector[T] and Matrix[T] and provides 4 main control structures: sum, vector construction, untilconverged and gradient. We enumerate these structures and show how they can be mapped to PENCIL.

- **sum**: expresses generic summations over an indexed range. It calculates \( \sum f(i) \) where \( f(i) \) is a user-defined function. For example

```scala
val x = sum(0,100) { i => exp(i) }
```

calculates

```
x = exp(0) + exp(1) + exp(2) + ...
```

sum is implemented as a parallel tree-reduce and can be translated into PENCIL using a for loop and a reduction directive.

```scala
x = exp(0)
#pragma pencil reduction (+:x)
for (i=1; i<=100; i++)
x += exp(i);
```

- **vector construction**: implemented as a parallel map in Delite. It has the following form

```scala
val my_vector = (0::end) { i => 0 }
```

and can be translated into PENCIL using a simple for loop. There is no need in this case to use the independent pragma, as the loop nest is always affine and the underlying optimization tools that operate on PENCIL will be able to recover the parallelism and generate a parallel code.

```scala
for (i=0; i<end; i++)
my_vector[i] = 0;
```

- **untilconverged**: an iterative control structure that iterates until reaching a convergence criterion. Each iteration produces a value, and the loop converges when the difference between values in consecutive iterations falls below a supplied threshold. This control structure is implemented in PENCIL as a sequential loop.

- **gradient descent**: is a specialized version of untilconverged that implements the gradient descent algorithm for exponential family models. It provides batch and stochastic variants. The batch variant uses a parallel algorithm and thus it can be mapped, in PENCIL, into a for loop annotated with the independent pragma to indicate that there is no loop carried dependence. The stochastic variant is mapped into a sequential for loop as the algorithm is not parallel.

IV. Conclusion

We proposed PENCIL, a platform-neutral compute intermediate language for productive and performance-portable accelerator programming. This intermediate language facilitates the design and implementation of high-level programming environments for parallel architectures. In particular, we believe PENCIL reduces the complexity and costs of exploiting heterogeneous systems.

*Acknowledgments*: This work was partly supported by the European FP7 project CARP id. 287767.