CARP: Correct and Efficient Accelerator Programming

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Introduction - CARP

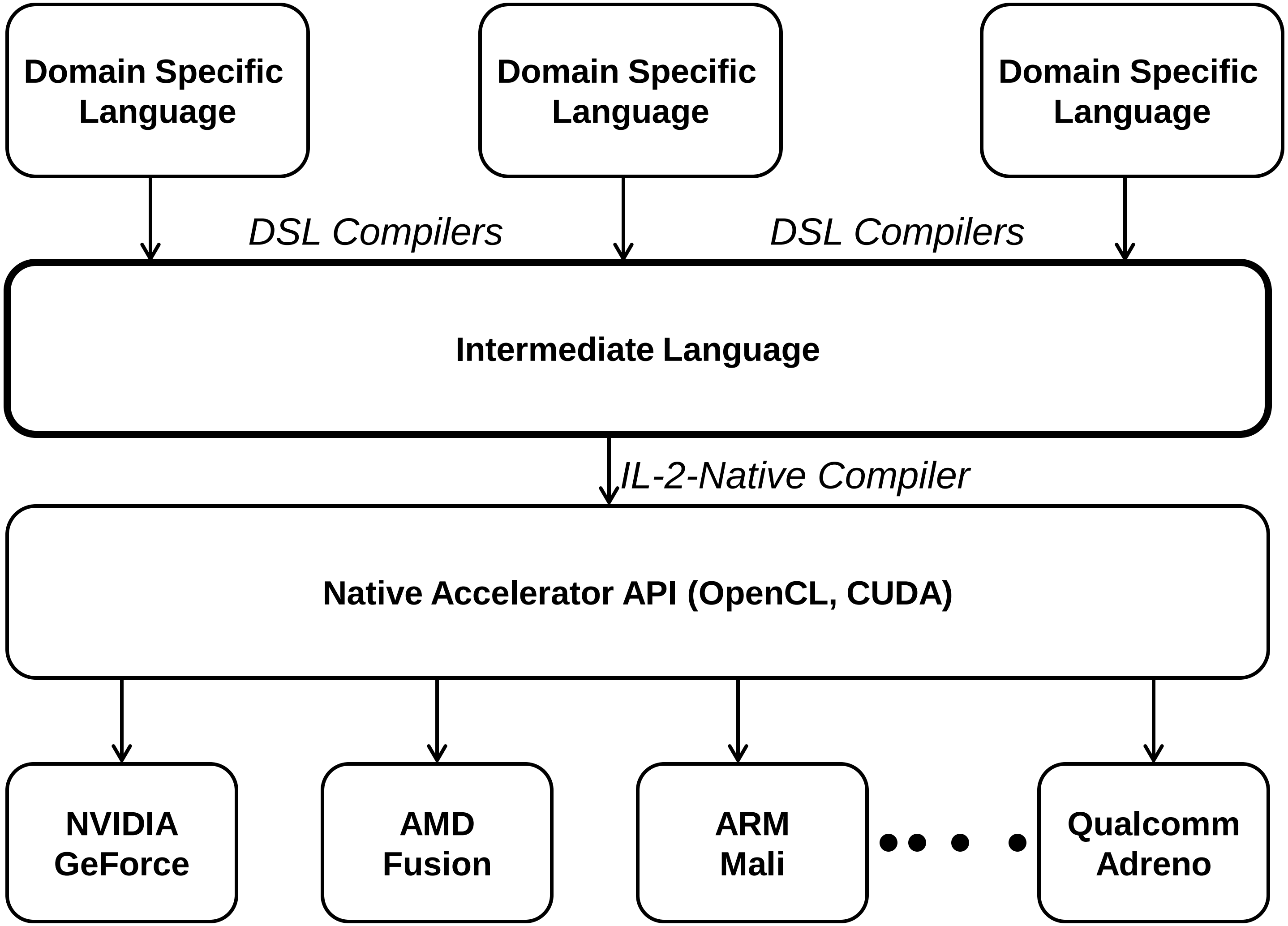
- **Objective**
  - To design compilation and verification techniques and tools for **C**orrect and Efficient **A**ccelerato**R** **P**rogramming

- **European Commission funded project**
  - Funded through FP7 Scheme
  - Started on 1 Dec, 2011
  - European Commission contribution : 2.8 million Euros
  - Partners: ARM, ENS, Imperial College London, Realeyes, RWTH Aachen, Monoidics, Twente University, Rightware

Introduction - Motivation

- **Native Accelerator programming is low-level**
  - Hard to program
  - Lack of performance portability
- **Many researchers focussing on ease of programming**
  - Domain-specific languages (DSLs) – Halide, OptiML
  - High-level programming models
- **Compiling directly to low-level code is inadvisable**
  - Implementers duplicate work and compromise on quality
- **Need an intermediate language**
  - For *n* input languages and *m* architectures, build *n+m* rather than *n*m* compilers.
  - The right approach to achieve performance portability
- **Wish to leverage Polyhedral Magic for GPUs**
  - Polyhedral techniques for arrays and loop transformation sync well with GPU architecture and GPU targeting applications

Compilation Framework



Domain Specific Language

Domain Specific Language

Domain Specific Language

DSL Compilers

DSL Compilers

Intermediate Language

IL-2-Native Compiler

Native Accelerator API (OpenCL, CUDA)

NVIDIA GeForce

AMD Fusion

ARM Mali

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Qualcomm Adreno

Compilation Framework

1. Design VOBLA, a domain-specific language for linear algebra

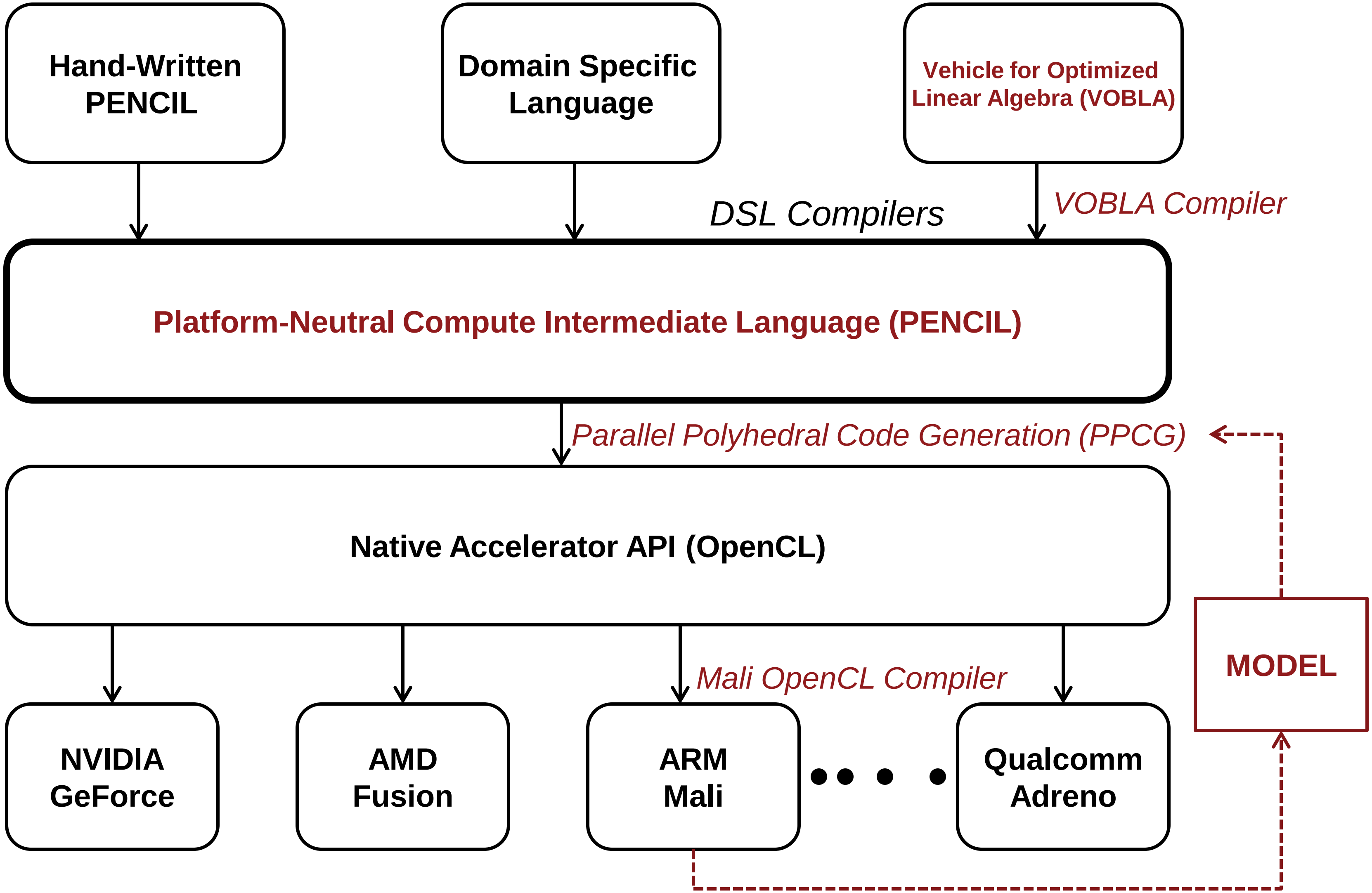
2. Design PENCIL, a platform-neutral computer intermediate language, to be used either by DSL compilers as their target language or by expert programmers

3. Contribute to designing and implementing advanced compilation techniques (based on the polyhedral model) for translating platform-independent PENCIL code into efficient platform-specific OpenCL code

4. Develop a performance-portable implementation of Basic Linear Algebra Subroutines (BLAS) based on the DSL-to-PENCIL-to-OpenCL flow

5. Devise a performance and energy model of the Mali-T600. Validate that it allows the compiler to make useful predictions for optimizing OpenCL code.

CARP Compilation Framework


Hand-Written PENCIL

Domain Specific Language

Vehicle for Optimized Linear Algebra (VOBLA)

DSL Compilers

VOBLA Compiler

Platform-Neutral Compute Intermediate Language (PENCIL)

Parallel Polyhedral Code Generation (PPCG)

Native Accelerator API (OpenCL)

Mali OpenCL Compiler

MODEL

NVIDIA GeForce

AMD Fusion

ARM Mali

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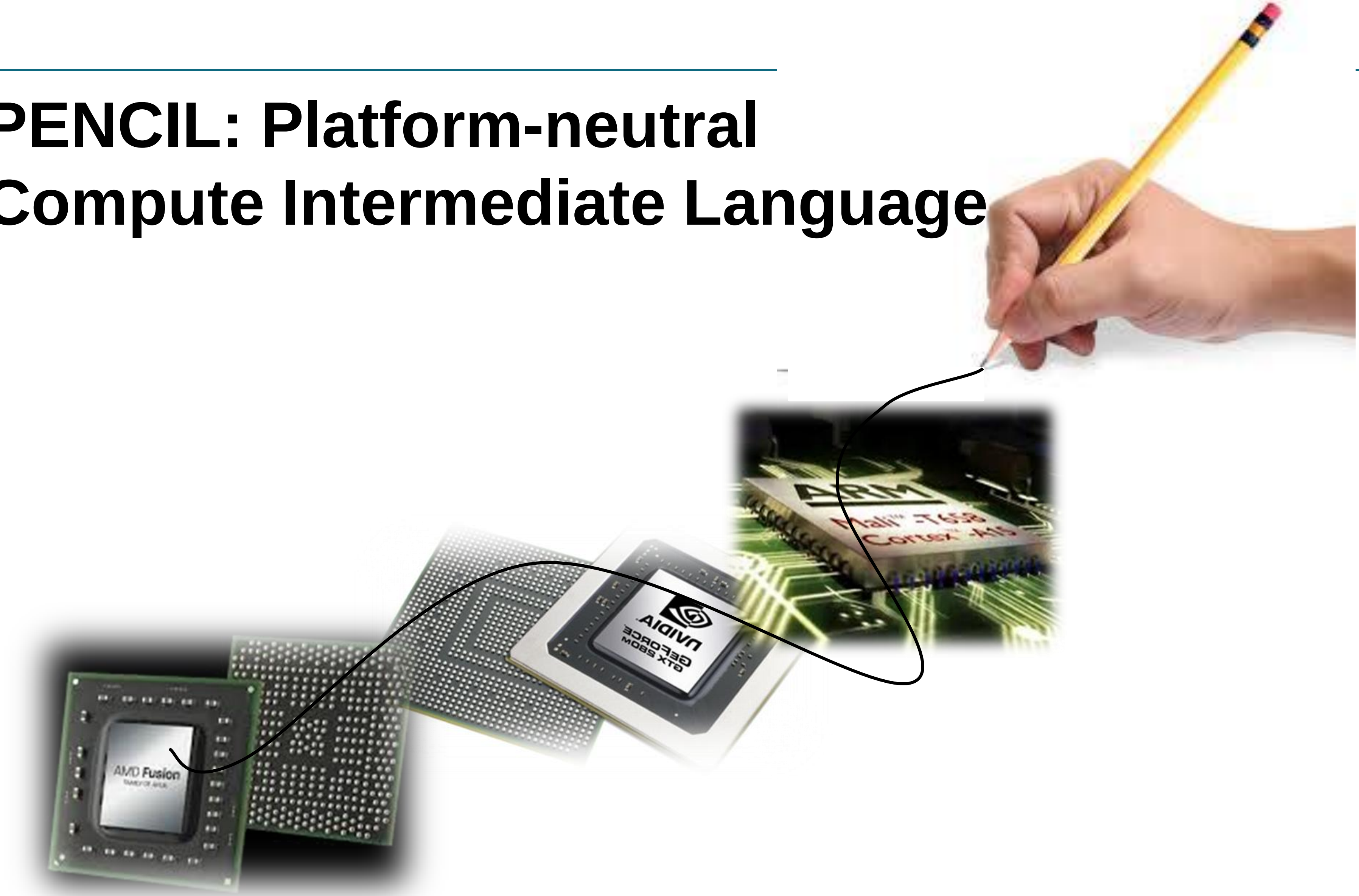
Qualcomm Adreno

PENCIL: Platform-neutral Compute Intermediate Language



PENCIL Features

- **Facilitate Parallelism: Declarative rather than Imperative**
  - Convey information on parallelism in the code. Not specify how exactly to parallelise and schedule
- **PENCIL code should be source compatible with C99 compiler**
  - Important for checking sequential correctness
- **Key Directives**
  - __pencil_assume, __pencil_assert
  - pragmas – pencil independent (reduction) , ivdep
  - Summary function – DEF, USE
- **Other PENCIL Features**
  - Restricted use of pointers
  - Use of *const restrict static*
  - Canonical forms for loops

PENCIL Language

```
void foo1 (int n, int m, int S, int D[const restrict static S]){
  __pencil_assume( m > n);
  for (int k = 0; k < n; k++) { D[i] = D[i+m]; }
}
```

```
void foo1 (int m, int S, int D[const restrict static S],
           int E[const restrict static S]){
  #pragma pencil independent
  for (int k = 0; k < m; k++)  D[E[i]] = i*i;
}
```

```
int foo1 ( int m, int S, int D[const restrict static S],
           int E[const restrict static S]){
  double ret = 0.0;
  #pragma pencil independent reduction (+:ret)
  for (int k = 0; k < m; k++)  ret += D[i]*E[i];
   return ret;
}
```

PENCIL Language

- **SUMMARY FUNCTION**
  - To capture complex or unknown memory access information

```
int foo( int N, int A[const restrict static N]) ACCESS(foo_summary);

int foo_summary( int N, int A[const restrict static N]){
   USE(A);
}

void bar( int N, int A[const restrict static N]){
  foo(N,A);
  for (int k = 0; k < m; k++) A[i]++;
}
```

VOBLA - Introduction

- **VOBLA: Vehicle for Optimizing Basic Linear Algebra**
  - Domain Specific Language (DSL) to handle dense and sparse matrices
  - Enables concise specification of linear algebra codes
    - LAPACK and BLAS
  - Generate rich PENCIL code

- **VOBLA Features**
  - Compact code when describing complex matrix operations
  - Array shape support
    - Single function can handle various access pattern (transpose, conjugate)
  - VOBLA functions are generic which can be exported to different types
  - Easily iterate over different data layout (e.g. sparse matrices)

VOBLA Language

- **Control flow operators** - `for, forall, while, if`
  - each iteration of `forall` is independent
  - `for/forall` specify multi-dimensional iteration space
  - Compact representation for loops over assignment

```
x[i] = i forall i in 0:n-1;
```

- **Expressions**
  - Basic operators are available for vectors and vector-scalar operands
  - `len`: returns size of different dimensions of an array
  - `sum`: operator to sum over sequence of scalars

```
let norm2 = sum(x*x forall _, x in X);
```

- **Re, Im** and **Conjugate** built-in function

VOBLA Language

- **Template Functions**
  - To manage different versions – floating (floating point precision, array storage)of same function
  - To improve ease of programming and compactness by exposing only the algorithm part of code
  - Help compiler by preventing obfuscation through implementation details

```
function scal(a: Value, out X: Value[]) { ... }

export scal<Complex Double>(X is Column) as zscal;

export scal<Float>(X is Reversed Column) as sscal;
```

VOBLA Language

- **Array Access Pattern**
  - Hide complexity of storage, provide generality and simplify code generation

- **Iterate access pattern**
  - Enumerate the elements in an undefined pattern

```
Aij = i * j forall i, j, Aij in A;
```

- **Sparse iterate**
  - Skips elements that are zero

```
let norm2 = 0;
norm2 += Xi * Xi for _, Xi in X.sparse;
```

- **Indexed**
  - Cannot be implemented for every storage format

```
let dot = 0;
dot += xi * y[i] forall i, xi in X.sparse;
```

VOBLA Language

- **Array Operators**
  - Allow compact representation of array operations

```
//X += 2*Y
X[i] += 2*Yi forall i, Yi in Y.sparse;
```

- **Array Views**
  - Help decouple algorithm from the way array is stored
  - Avoids copying of data

```
//VOBLA
..X[2:4]..  // Take elements of X between 2 and 4
..A[*][2].. // Take the third column of A
let a = Transpose(A)[i][j]; //float a = A[j][i];
```

VOBLA Language

- **User Defined Access Patterns**
  - In addition to iterate, sparse iterate and indexed

- **Four objects to define access pattern**
  - Interface
    - Specifies which access pattern is implemented by the array
    - During compilation each interface will have a layout implementing its interface specifying how to access the data
    - To access data, a method defined in by Interface object is called
  - Storage
    - Storage object contains the storage layout
  - Layout
    - Specifies how to access data for a given storage
  - View
    - Create new layouts from existing ones using inheritance

VOBLA Language

- **Storages**
  - Storage object represents the part of an array that is independent of the way it is accessed

```
//storage object- coordinate list(COO) sparse format
storage CooStorage {
        nRows: Index;
        nCols: Index;
        nNonZeros: Index;
        rowIdx: Index[nNonZeros];
        colIdx: Index[nNonZeros];
        data: Value[nNonZeros];
}
```

$$\begin{bmatrix} 5 & 0 & 0 \\ 9 & 0 & 7 \\ 0 & 0 & 3 \end{bmatrix}$$

ROW	0	1	1	2
COL	0	0	2	2
VALUE	5	9	7	3

VOBLA Language

- **Layout** definition contains
  - Name of storage object
  - List of interfaces implemented by the layout
  - An implementation for each of teh methods defined in the interfaces

```
layout Coo: CooStorage implements
               SparseIterable<Value>[][] {
parameter:
interface:
   getLen1(): Index { return nRows; }
   getLen2(): Index { return nCols; }

   sparseIterate(): range<Index, Index, &Value> {
     yield rowIdx[k], colIdx[k], data[k]
                 forall k in 0:nNonZeros;
   }
}
```

VOBLA Language

- **Views**
  - Enables layouts from existing layouts
  - Acts as wrapper around a layout

- TransposeMat on base interface Accessible

```
view TransposedMat: Accessible<Value>[][]
   implements Accessible<Value>[][] {

     access(i: Index, j: Index): &Value{
     return base.access(j, i);
  }
}
```

- To access sparse transpose matrix in COO format

```
export gemm<Float>(A is TransposedMat(COO))
```

BLAS Implementation

- **Basic Linear Algebra Subprograms library**
  - Level 1: vector-vector operations
  - Level 2: matrix-vector operations
  - Level 3: matrix-matrix operations

- **BLAS in VOBLA**
  - Data types
    - Most BLAS functions are defined on 4 data types – single and double precision real numbers, single and double precision complex numbers
  - Matrix view
    - For each matrix BLAS takes in an additional flag indicating if matrix is to be interpreted as normal, transposed, or conjugate transpose
  - Storage layout
    - Level 2 and 3 BLAS functions support dense matrix storage layouts and pre-defined compressed or triangular layouts

BLAS Implementation

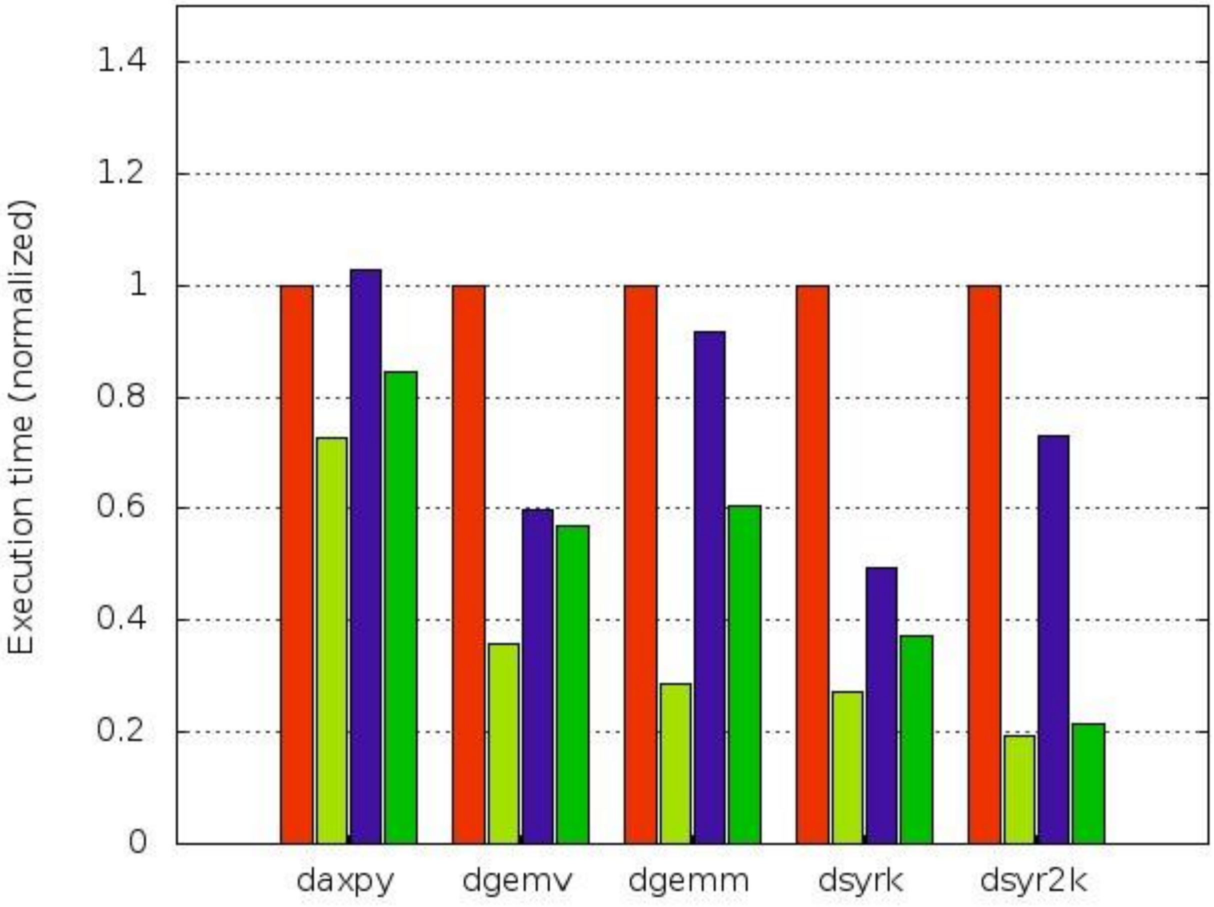
- **GEMM:** $C \leftarrow \alpha AB + \beta C$

```
function gemm(alpha: Value,
               in A: SparseIterable<Value>[m][k],
               in B: Value[k][n],
               beta: Value,
               out C: Value[m][n])
{
   Cij *= beta forall _, _, Cij in C.sparse;

   C[i][j] += alpha*Ail*B[l][j]
       for i, l, Ail in A.sparse, j in 0:n-1;
}
```

- 50 export statements to obtain all BLAS variants

Results


Execution time (normalized)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
daxpy
dgemv
dgemm
dsyrk
dsyr2k

Conclusion

- VOBLA – A DSL for efficient linear algebra programming
- PENCIL – special constructs to carry meta-data for polyhedral code generator
- VOBLA based BLAS on average 2.5x better than basic OpenCL implementation
- A step closer to solving programmer productivity and performance portability

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