


PENCIL

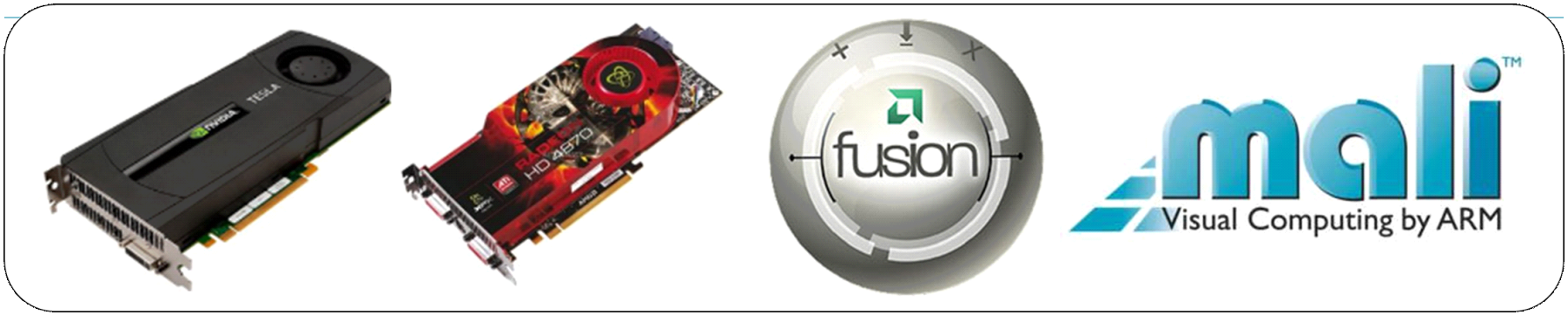
A Platform-Neutral Compute Intermediate Language for DSL Compilers

Riyadh Baghdadi[1,2] Javed Absar[3] Ulysse Beaugnon[1,2]
Adam Betts[4] Albert Cohen[1,2] Róbert Dávid[5]
Alastair Donaldson[4] Tobias Grosser[1,2] Sven Van Haastregt[3]
Elnar Hajiyev[5] Jeroen Ketema[4] Alexey Kravets[3]
Michael Kruse[1] Anton Lokhmotov[3] Chandan Reddy[1]
Sven Verdoolaege[2,6]

[1]École Normale Supérieure, [2]INRIA, [3]ARM, [4]Imperial College London, [5]RealEyes, [6]KU Leuven

9th February 2016

Obligatory Motivational Slide About Accelerators



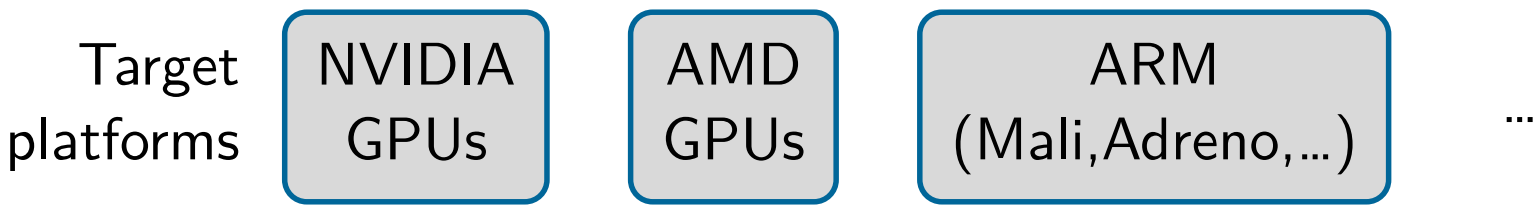
Advantages

- Impressive raw performance
- Massive parallelism
- Low energy consumption per operation

Problems

- Highly optimized code is hard to write
- Non-portable performance
- Maintaining multiple sources for different architectures not easy

Compilers



Compilers

Domain languages

VOBLA

```
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;
}
```

Target platforms

NVIDIA GPUs

AMD GPUs

ARM (Mali,Adreno,...)

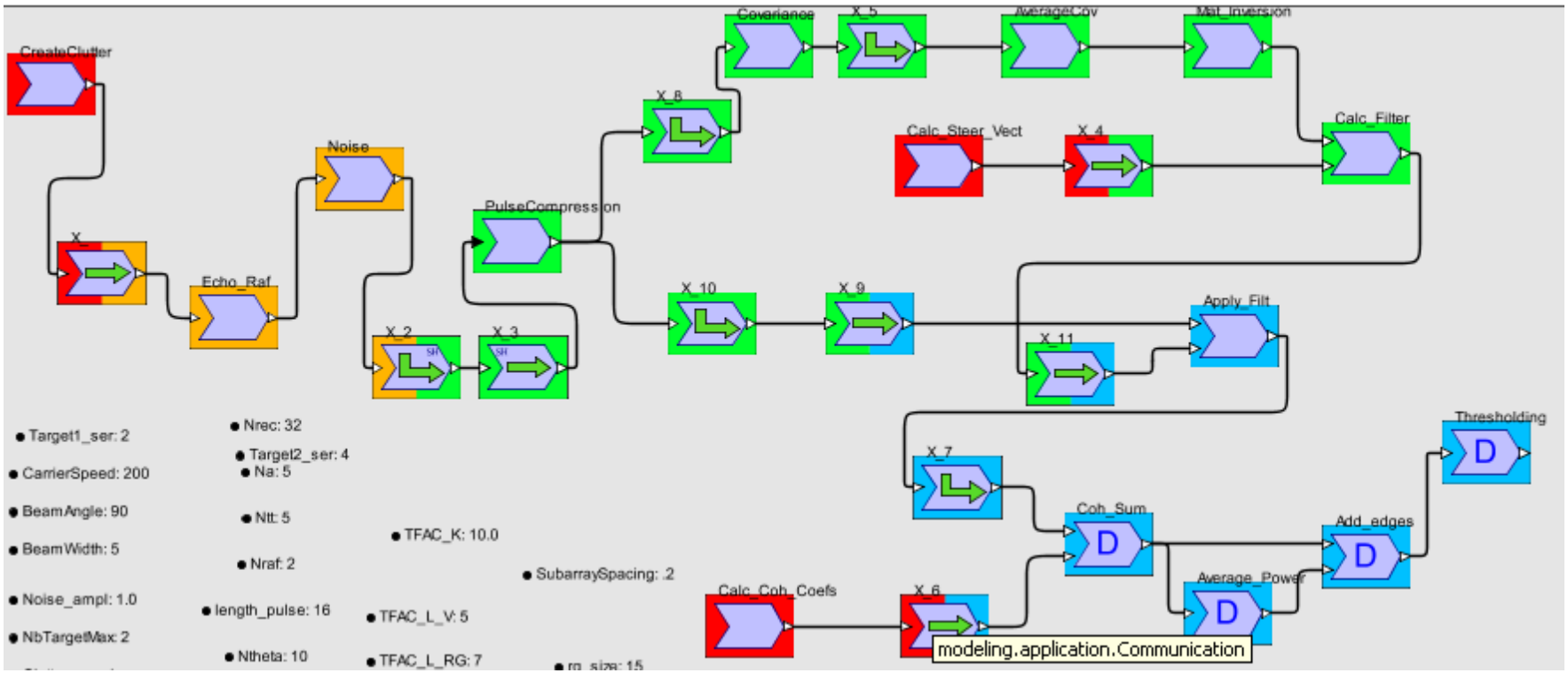
...

Compilers

Domain languages

VOBLA

SpearDE



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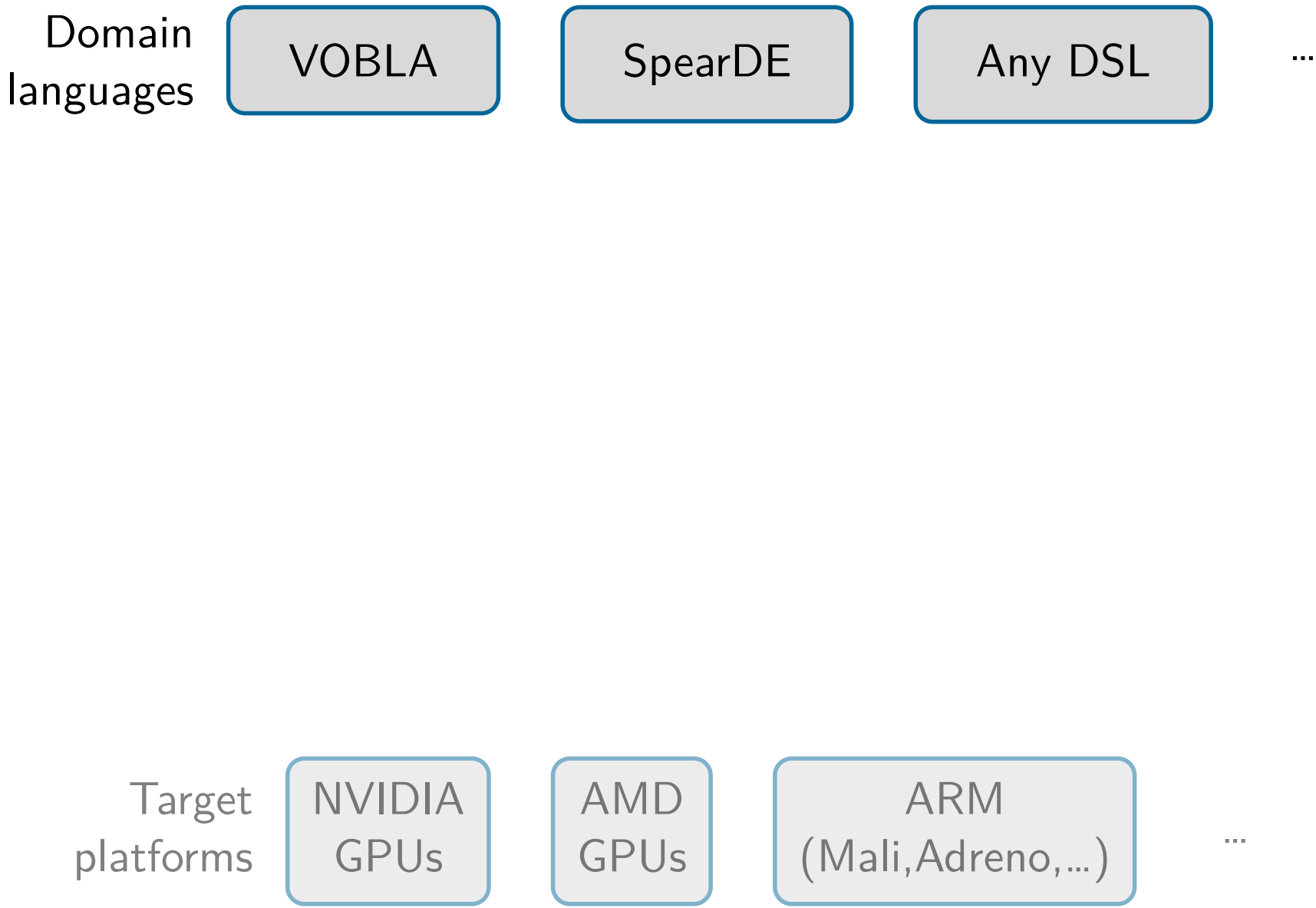
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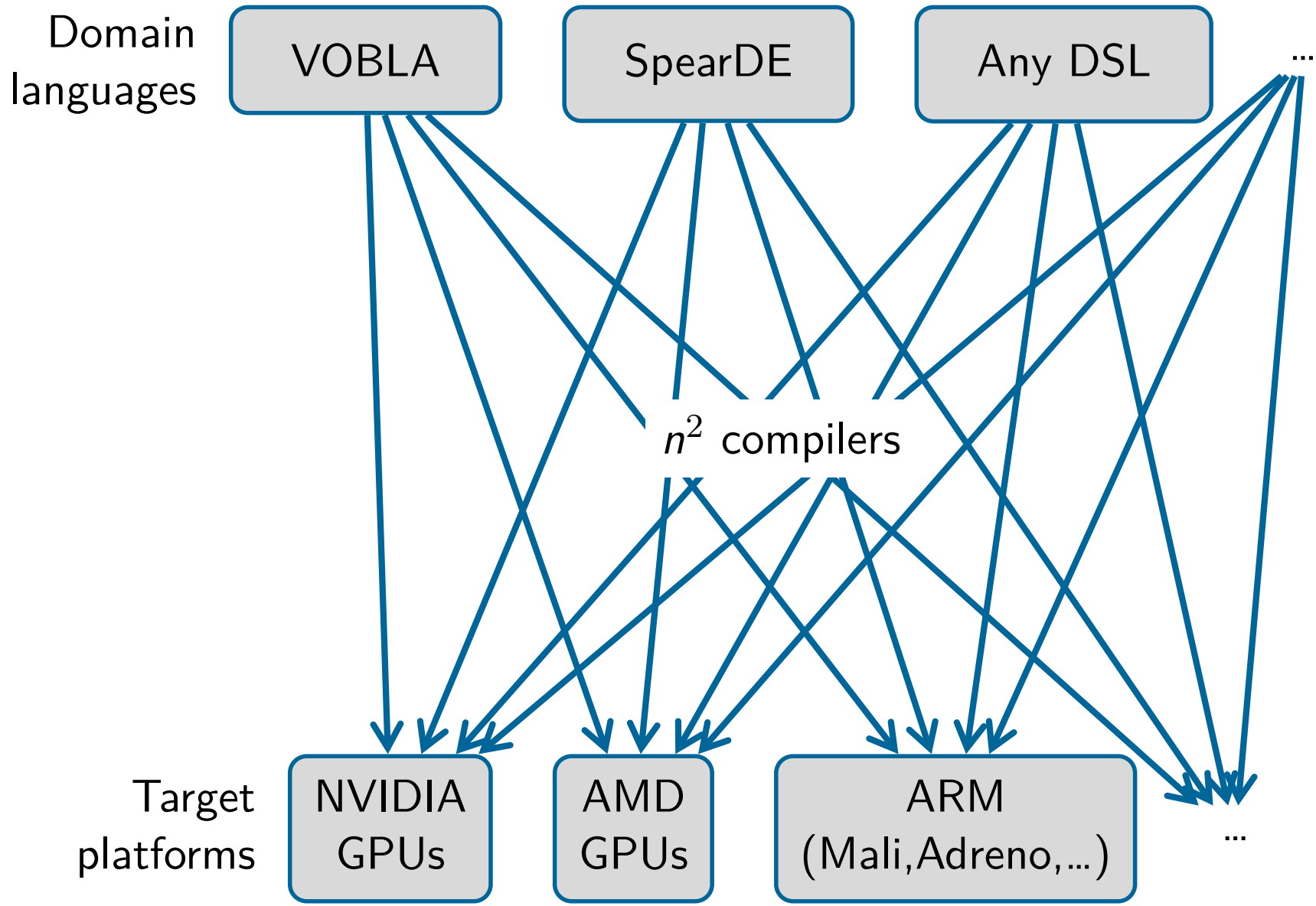
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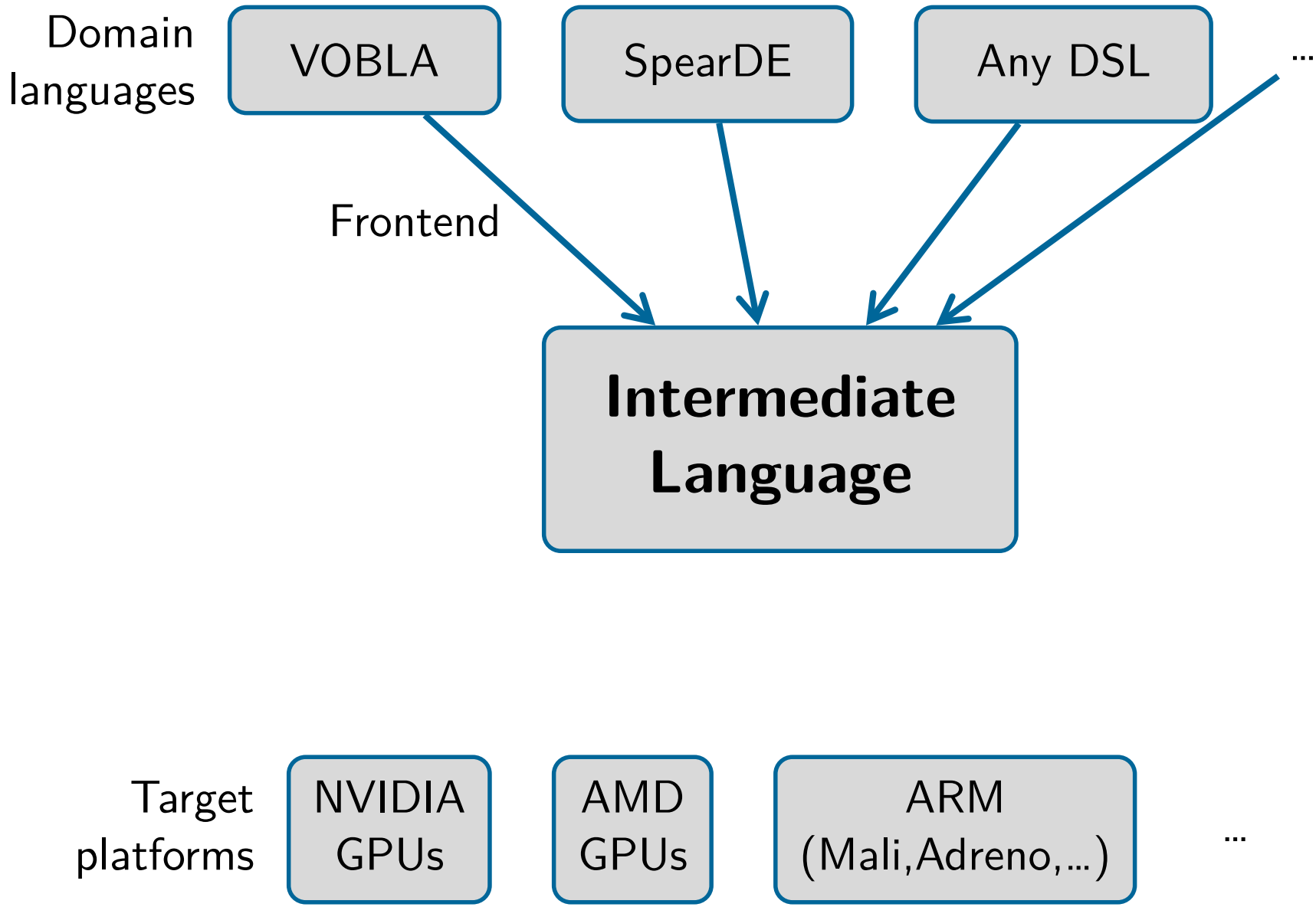
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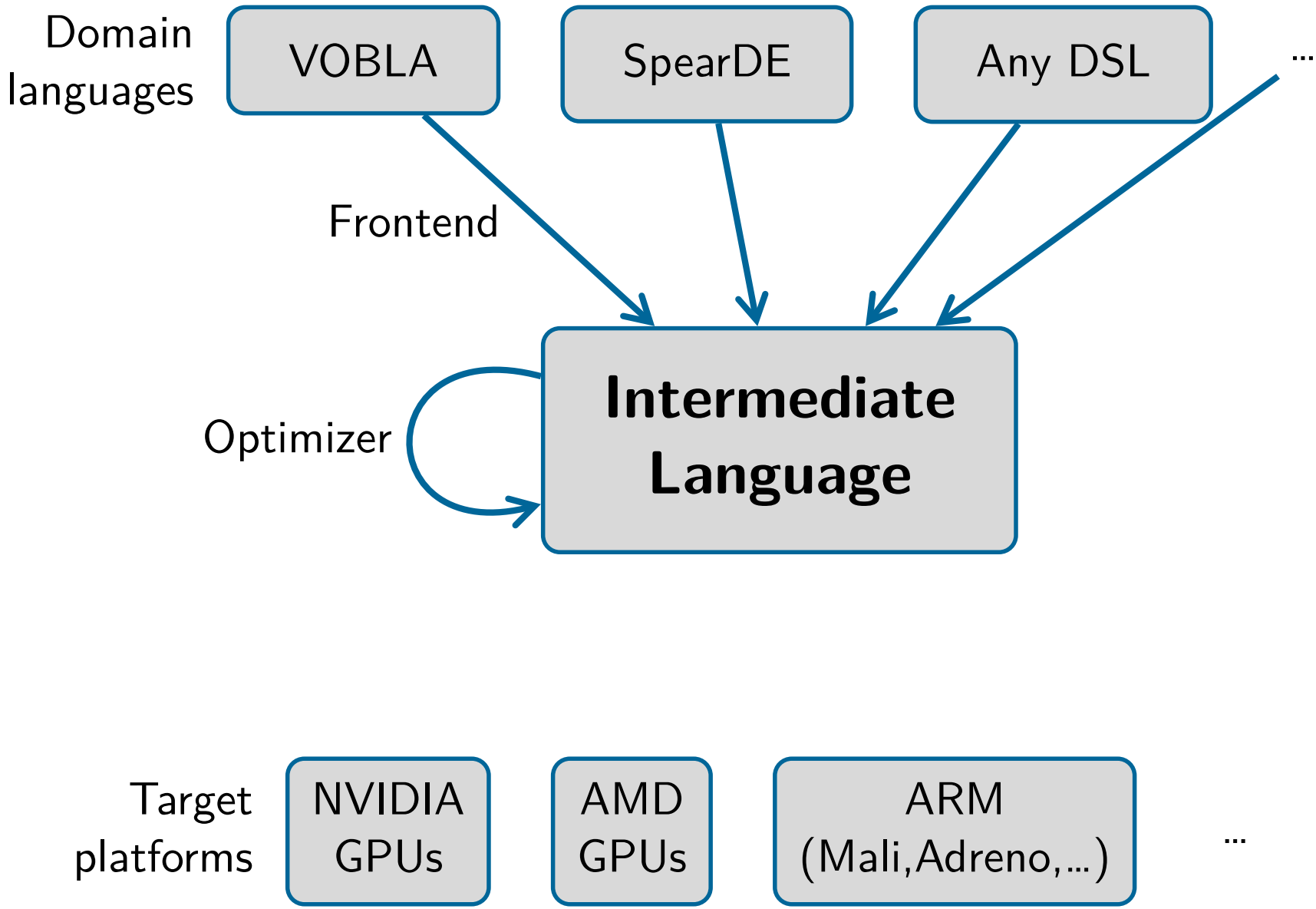
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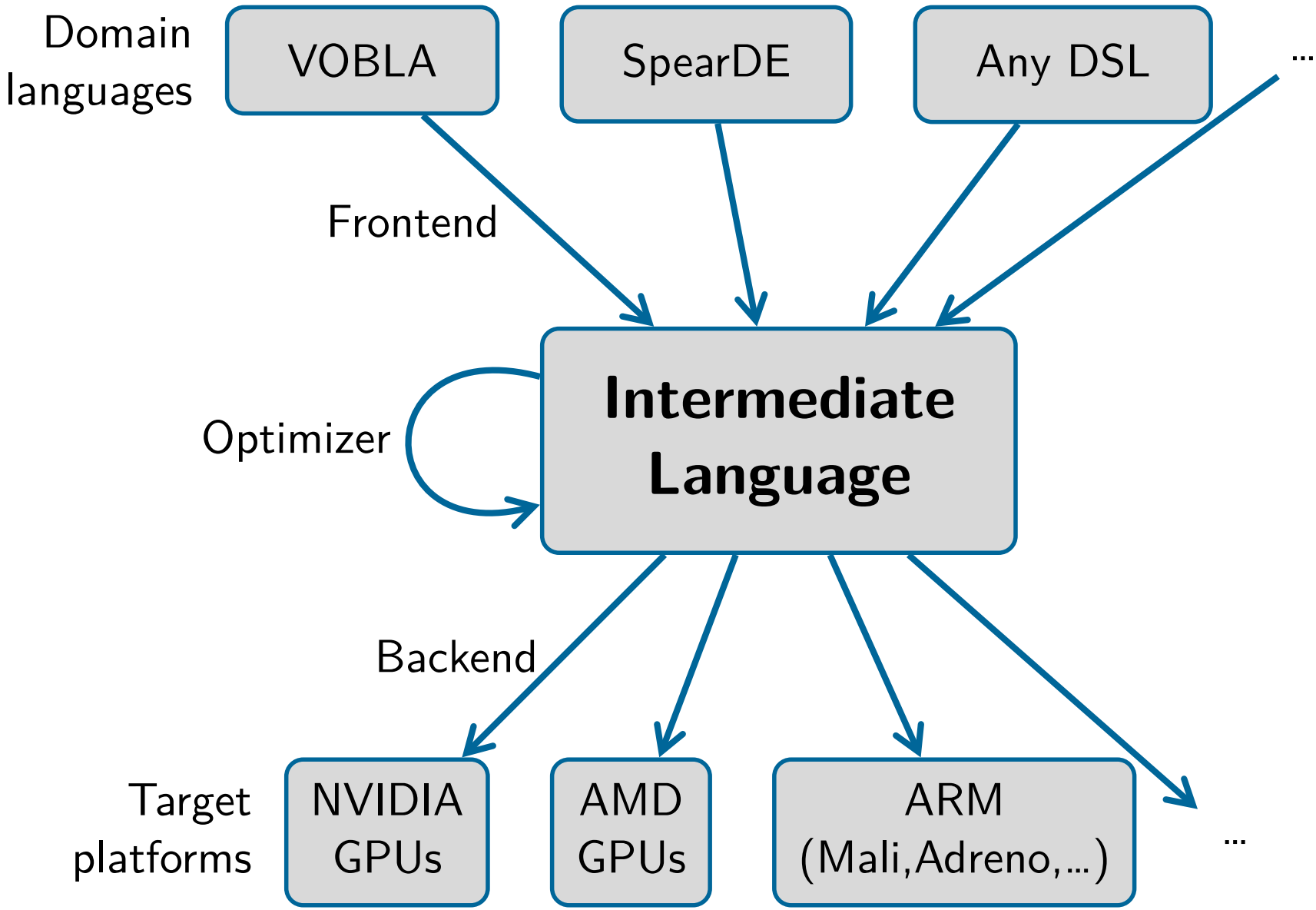
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Overview

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- Intermediate language
  Any frontend language possible

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- Intermediate language
  Any frontend language possible
- Polyhedral compiler friendly
  Powerful static analysis and optimizations
- Meta-level specification
  Code properties not derivable from code itself (helps pessimistic optimizers)
- OpenCL output
  Multiple target platforms

General Flow

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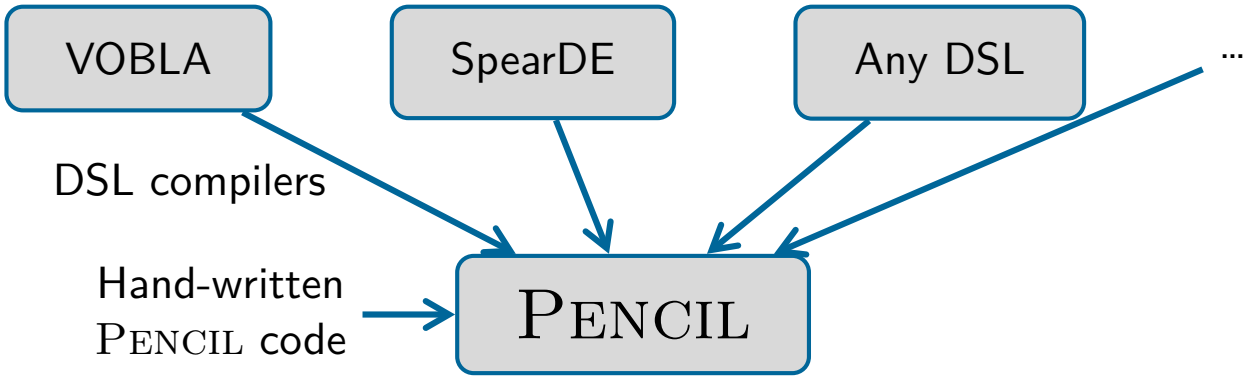

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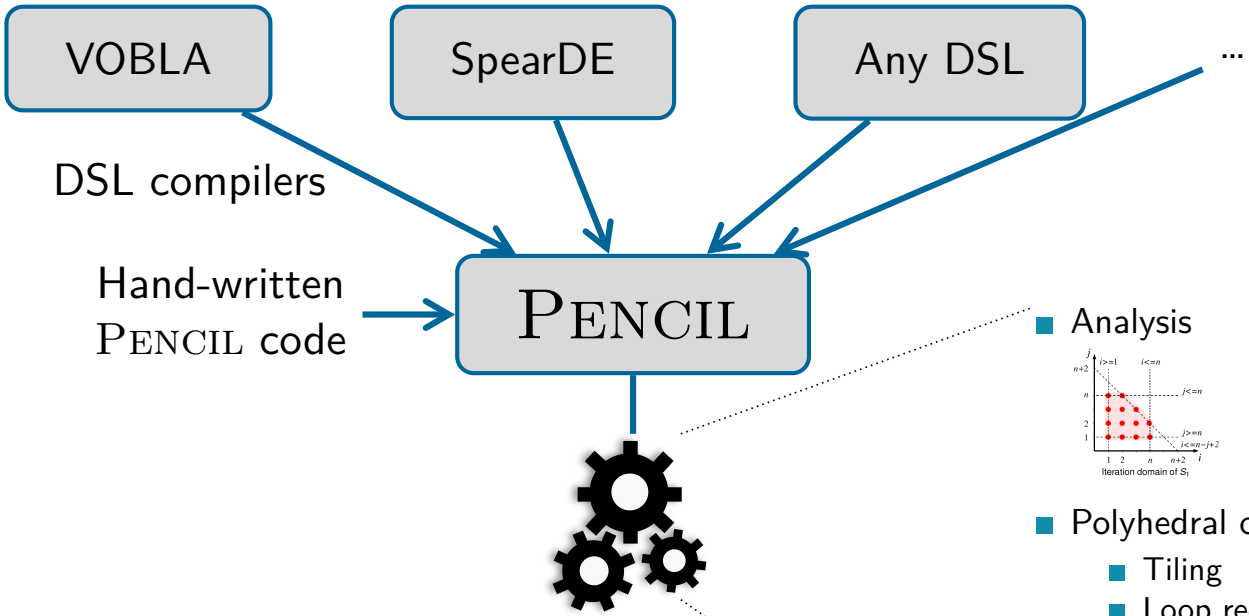
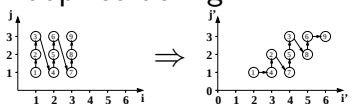


- Analysis

- Polyhedral optimizer
  - Tiling
  - Loop reordering



  - Parallelization
  - Data localization
  - ...

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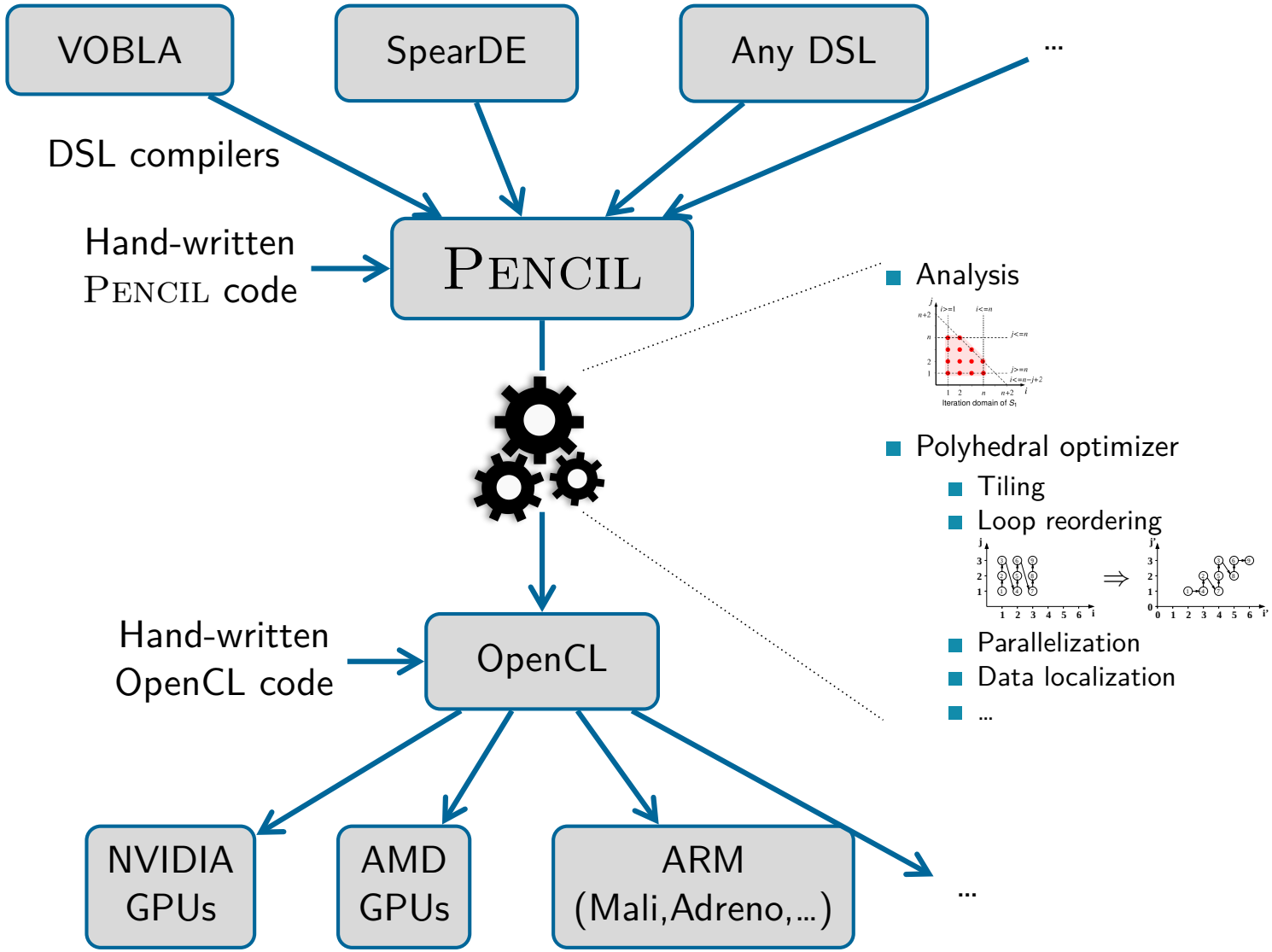

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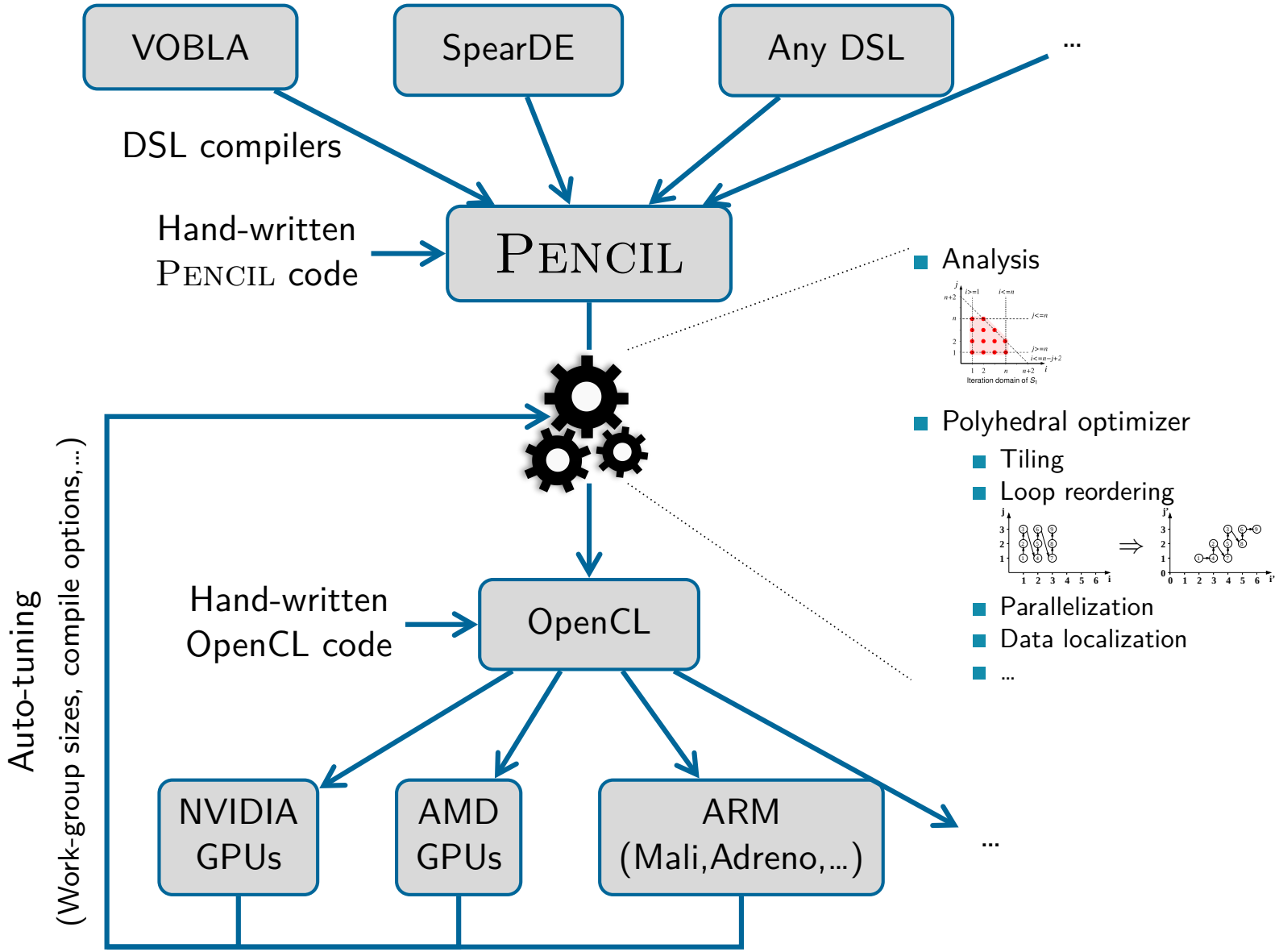

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```
void foo(int * const restrict A)
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$\Rightarrow$

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void foo(int n, int A[static const restrict n])
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    Invalidate data currently helt by an array

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  - `__pencil_assume`
    Make assumption violations undefined behviour
  - Summary functions
    Describe the memory access pattern of a function

General Syntax

Example: Finite Impulse Response

```
1 #include <pencil.h>
2
3 void fir(int n, float in[static const restrict n],
4           float out[static const restrict n])
5 {
6     for (int i = 1; i < n-1; ++i) {
7         out[i] = (in[i-1] + in[i] + in[i+1])/3;
8     }
9 }
```

General Syntax

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Declarations & plain C compatibility

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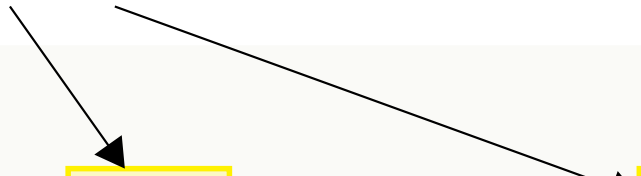
At least `n` elements (and non-null if $n > 0$)



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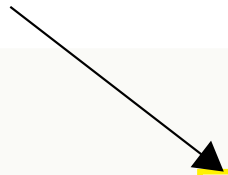
Pointer `in` does not change in function body



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No aliasing

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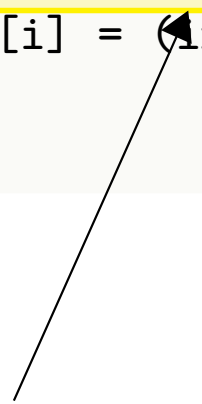

Canonical `for`-loop

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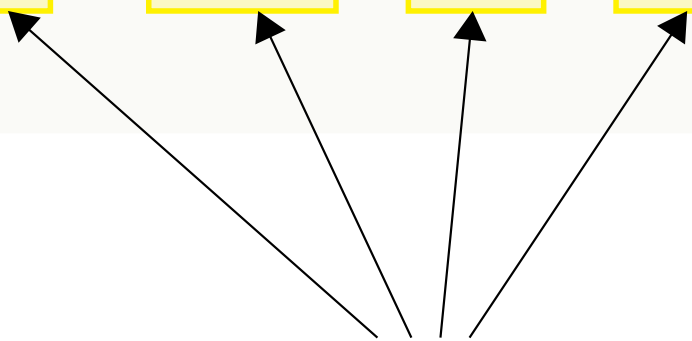

Array subscripts (syntactically different from `*(out + i)`)

Kill Statement

Example: Finite Impulse Response

```
1  void doublefir_inplace(int n, float in[static const restrict n],
2                         float tmp[static const restrict n],
3                         float out[static const restrict n])
4  {
5
6
7
8      for (int i = 1; i < n-1; ++i) {
9          tmp[i] = (in[i-1] + in[i] + in[i+1])/3;
10     }
11     tmp[0] = (in[0] + in[1])/2;
12     tmp[n-1] = (in[n-2] + in[n-1])/2;
13
14     for (int i = 1; i < n-1; ++i) {
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16     }
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18     __pencil_kill(tmp); // Avoid copy to host
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4  {
5      __pencil_kill(tmp); // Avoid copy to device
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Independent Directive

Example: Basic Histogram

```
1  void basic_histogram(int n, int m,
2                       unsigned char image[static const restrict n][m],
3                       int hist[static const restrict 256]) {
4
5      for (int i=0; i<N; i++)
6
7          for (int j=0; j<M; j++) {
8              int idx = image[i][j];
9              atomic_add(hist[idx], 1);
10         }
11 }
```

Independent Directive

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1  void basic_histogram(int n, int m,
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4  #pragma pencil independent
5      for (int i=0; i<N; i++)
6  #pragma pencil independent
7          for (int j=0; j<M; j++) {
8              int idx = image[i][j];
9              atomic_add(hist[idx], 1);
10         }
11 }
```

Assume Statement

Example: Matrix-Vector Multiplication

```
1  void gemv(int n, int m, float mat[static const restrict m][n],
2            float vec[static const restrict n],
3            float out[static const restrict m]) {
4
5
6
7      for (int i = 0; i < m; ++i) {
8          out[i] = 0;
9          for (int j = 1; j < n; ++j)
10             out[i] += mat[i][j] * vec[j];
11     }
12 }
```

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Example: Matrix-Vector Multiplication

```
1  void gemv(int n, int m, float mat[static const restrict m][n],
2            float vec[static const restrict n],
3            float out[static const restrict m]) {
4      __pencil_assume(n > 0 && m > 0);
5
6
7      for (int i = 0; i < m; ++i) {
8          out[i] = 0;
9          for (int j = 1; j < n; ++j)
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- Avoid code generation and checking for special cases

Assume Statement

Example: Matrix-Vector Multiplication

```
1  void gemv(int n, int m, float mat[static const restrict m][n],
2            float vec[static const restrict n],
3            float out[static const restrict m]) {
4      __pencil_assume(n > 0 && m > 0);
5      __pencil_assume(n <= 16);
6
7      for (int i = 0; i < m; ++i) {
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11     }
12 }
```

- Promote vec to local memory

Summary Function

```
1
2
3
4
5
6
7
8  void blackbox(int n, float in[static const restrict n],
9      float out[static const restrict n]);
10
11 void foo(int m, int n, float in[static const restrict n],
12         float out[static const restrict m][n]) {
13     for (int j=0; j<m; ++j)
14         blackbox(n, in, out[j]);
15 }
```

Summary Function

```
1  static void blackbox_summary(int n, float in[static const restrict n],
2                               float out[static const restrict n]) {
3      for (int i=0; i<n; ++i)
4          USE(in[i]);
5      for (int i=0; i<n; ++i)
6          DEF(out[i]);
7  }
8  void blackbox(int n, float in[static const restrict n],
9       float out[static const restrict n]) ACCESS(blackbox_summary);
10
11 void foo(int m, int n, float in[static const restrict n],
12          float out[static const restrict m][n]) {
13     for (int j=0; j<m; ++j)
14         blackbox(n, in, out[j]);
15 }
```

Summary Functions

Example: Fast Fourier Transformation

```
1  static void fftKernel32_summary(int n, int start, struct float2 a[static const restrict n]) {
2      for (int i=start; i<start+32; ++i)
3          USE(a[i]);
4      for (int i=start; i<start+32; ++i)
5          DEF(a[i]);
6  }
7
8  void fftKernel32(int n, int start, struct float2 a[static const restrict n])
9          ACCESS(fftKernel32_summary);
10
11 void fft64(struct float2 a[static const restrict 64]) {
12     for (int k = 0; k < 2; ++k) {
13         fftKernel32(64, k*32, a);
14     }
15     for (int k = 0; k < 32; ++k) {
16         float2 t = a[k];
17         float2 s = a[32+k];
18
19         a[k].x = s.x + cos(-2*PI*k/64)*t.x - sin(-2*PI*k/64)*t.y;
20         a[k].y = s.y + sin(-2*PI*k/64)*t.x + cos(-2*PI*k/64)*t.x;
21         a[32+k].x = s.x - cos(-2*PI*k/64)*t.x + sin(-2*PI*k/64)*t.y;
22         a[32+k].y = s.y - sin(-2*PI*k/64)*t.x - cos(-2*PI*k/64)*t.x;
23     }
24 }
```

Summary/Conclusion

- PENCIL language
  - Polyhedral-friendly subset of C99
  - `__pencil_kill(expr)`
  - `__pencil_assume(expr)`
  - `#pragma pencil independent`
  - Summary functions
- Versatile intermediate step
- Competitive performance using PPCG
- PPCG also compiles to CUDA and OpenMP

References

- PPCG
  http://freecode.com/projects/ppcg
- VOBLA
  Beaugnon et. al. *VOBLA: A vehicle for optimized basic linear algebra*. LCTES '14
- SpearDE
  Lenormand and Edelin. *An industrial perspective: A pragmatic high end signal processing design environment at Thales*. SAMOS '03

Compile and Install

Requirements:

- gcc/clang
- GNU Autotools
- clang-dev
- Python 3
- OpenCL/nvcc in system default paths

```
$ git clone https://github.com/Meinersbur/pencilcc.git --recursive
$ cd pencilcc
$ ./autogen.sh
$ ./configure
$ make
$ sudo make install
```

Usage I

- Show command options

```
$ pencilcc -h
$ ppcg -h
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```
$ pencilcc source.c -o program --target=cuda
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- Show what it does

```
$ pencilcc source.c -o program --show-commands
```

Usage II

- Set tile size

```
$ pencilcc source.c -o program -S 32
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- Dump effective optimization parameters

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$ pencilcc source.c -o program --dump-sizes
{kernel[0]->tile[32];kernel[0]->block[64];kernel[0]->grid[1024]}
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- Don't use shared (OpenCL: `__local`) memory:

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```

- Don't use shared (OpenCL: `__local`) memory:

```
$ pencilcc source.c -o program --no-shared-memory
```

- Don't use private (thread-local) memory:

```
$ pencilcc source.c -o program --private-memory
```

Ideal Loop Nesting

```
1  void foo(int n, int m, float A[static const restrict m][n],
2                         float B[static const restrict m][n]) {
3  #pragma scop
4    for (int i = 0; i < m; ++i) {
5      for (int j = 0; j < n; ++j) {
6        A[i][j] = B[i][j];
7      }
8    }
9  #pragma endscop
10 }
```

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DO use idiomatic for-loops

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DOs

DO use idiomatic for-loops

DO use C99 VLAs

DO use `static const restrict` in declarations

DO use `__pencil_assume` (lower/upper bound for each parameter)

DO use `__pencil_kill`

DO declare local arrays right after `#pragma scop`

DONTs

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DONTs

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AVOID non-affine array subscripts

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DONT alias

DONT exceed an array's dimensions's size

DONT declare structs/arrays variables inside loops (SROA them!)

AVOID extra statements to compute subexpressions

AVOID reductions

DONT write unusual code (Assign `n,m`; Shadowing; Assign multiple values in one statements; ...)

Use Multidimensional Arrays

```
1 #define INDEX(i,j) ((i)*n+(j))
2 void foo(int n, int m, float *A, float *B) {
3   for (int i = 0; i < m; ++i)
4     for (int j = 0; j < n; ++j)
5       A[INDEX(i,j)] = B[INDEX(i,j)];
6 }
```

$\Rightarrow$

```
1 void foo(int n, int m, float A[static const restrict m][n],
2                         float B[static const restrict m][n]) {
3   for (int i = 0; i < m; ++i)
4     for (int j = 0; j < n; ++j)
5       A[i][j] = B[i][j];
6 }
```

Use __pencil_assume

```
1 void foo(int m, float A[static const restrict m],
2               float B[static const restrict m]) {
3 #pragma scop
4   for (int i = 0; i < m; ++i)
5     A[i] = B[i];
6 #pragma endscop
7 }
```

⇒

```
1 void foo(int m, float A[static const restrict m],
2               float B[static const restrict m]) {
3 #pragma scop
4     __pencil_assume(m > 0);
5     __pencil_assume(m <= 128);
6   for (int i = 0; i < m; ++i)
7     A[i] = B[i];
8 #pragma endscop
9 }
```

Use __pencil_kill

```
1 void foo(int m, float A[static const restrict m],
2               float B[static const restrict m]) {
3 #pragma scop
4   for (int i = 0; i < m; ++i)
5     A[i] = B[i];
6 #pragma endscop
7 }
```

⇒

```
1 void foo(int m, float A[static const restrict m],
2               float B[static const restrict m]) {
3 #pragma scop
4   __pencil_kill(A);
5   for (int i = 0; i < m; ++i)
6     A[i] = B[i];
7 #pragma endscop
8 }
```

Declare Local Arrays within SCoP

```
1  void foo(int m, float A[static const restrict m],
2               float B[static const restrict m]) {
3    float tmp[m];
4  #pragma scop
5    for (int i = 0; i < m; ++i) {
6      tmp[i] = B[i];
7      A[i] = tmp[i];
8    }
9  #pragma endscop
10 }
```

$\Rightarrow$

```
1  void foo(int m, float A[static const restrict m],
2               float B[static const restrict m]) {
3  #pragma scop
4    float tmp[m];
5    for (int i = 0; i < m; ++i) {
6      tmp[i] = B[i];
7      A[i] = tmp[i];
8    }
9  #pragma endscop
```

No Iteration Over Pointers

```
1 for (float *p = A; p <= A+n; ++p)
2   *p = 0;
```

$\Rightarrow$

```
1 for (int i = 0; i < m; ++i)
2   A[i] = 0;
```

Avoid If-Conditions using Ternary Operator

```
1  for (int i = 0; i < m; ++i)
2    for (int j = 0; j < n; ++j)
3      if (x)
4        c = 5;
5      else
6        c = 6;
7      A[i][j] = c * B[i][j];
```

⇒

```
1  for (int i = 0; i < m; ++i) {
2    for (int j = 0; j < n; ++j) {
3      c = x ? 5 : 6;
4      A[i][j] = c * B[i][j];
5    }
```

Avoid Precomputing Common Subexpressions

```
1 for (int i = 0; i < m; ++i) {
2   c = i * i;
3   for (int j = 0; j < n; ++j)
4     A[i][j] = c * B[i][j];
5 }
```

$\Rightarrow$

```
1 for (int i = 0; i < m; ++i) {
2   for (int j = 0; j < n; ++j)
3     A[i][j] = (i*i) * B[i][j];
```

(except computing `c` is very complex)

Avoid Loop-Local Structs/Arrays I

```
1 for (int i = 0; i < m; ++i) {
2   for (int j = 0; j < n; ++j) {
3     struct float2 c = {1.0f, 0.0f};
4     A[i][j] = c.x * c.x + c.y * c.y;
5   }
6 }
```

$\Rightarrow$

```
1 for (int i = 0; i < m; ++i) {
2   for (int j = 0; j < n; ++j) {
3     float x = 1.0f;
4     float y = 0.0f;
5     A[i][j] = x * x + y * y;
6   }
7 }
```

Avoid Loop-Local Arrays II

```
1  void foo(int n, int m, float A[static const restrict m][n],
2                         float B[static const restrict m][n]) {
3    for (int i = 0; i < m; ++i) {
4      float tmp[n];
5      for (int j = 0; j < n; ++j) {
6        tmp[j] = B[i][j];
7        A[i][j] = tmp[j];
8      }
9    }
10 }
```

$\Rightarrow$

```
1  void foo(int n, int m, float A[static const restrict m][n],
2                         float B[static const restrict m][n]) {
3    float tmp[m][n];
4    for (int i = 0; i < m; ++i)
5      for (int j = 0; j < n; ++j) {
6        tmp[i][j] = B[i][j];
7        A[i][j] = tmp[i][j];
8      }
9  }
```

Help: PPCG did not parallelize my code!

- Add `#pragma pencil parallel`
- Contains a function call? Add a summary function
- Is there a locally declared struct/array variable?
- Non-affine array subscripts?
- Non-affine if-conditions?
- While loops?
- True serial dependency?

Help: PPCG takes too long!

- `-isl-schedule-max-coefficient=1`
- Use fewer statements (`a = b; ++a` ⇒ `a = b+1`)
- [Last resort] Translate code sections yourself in OpenCL/CUDA
- [If you feel experimental] Decorate code sections with tautological non-affine if-conditions (e.g. `if ((double)i*i>=0)`)