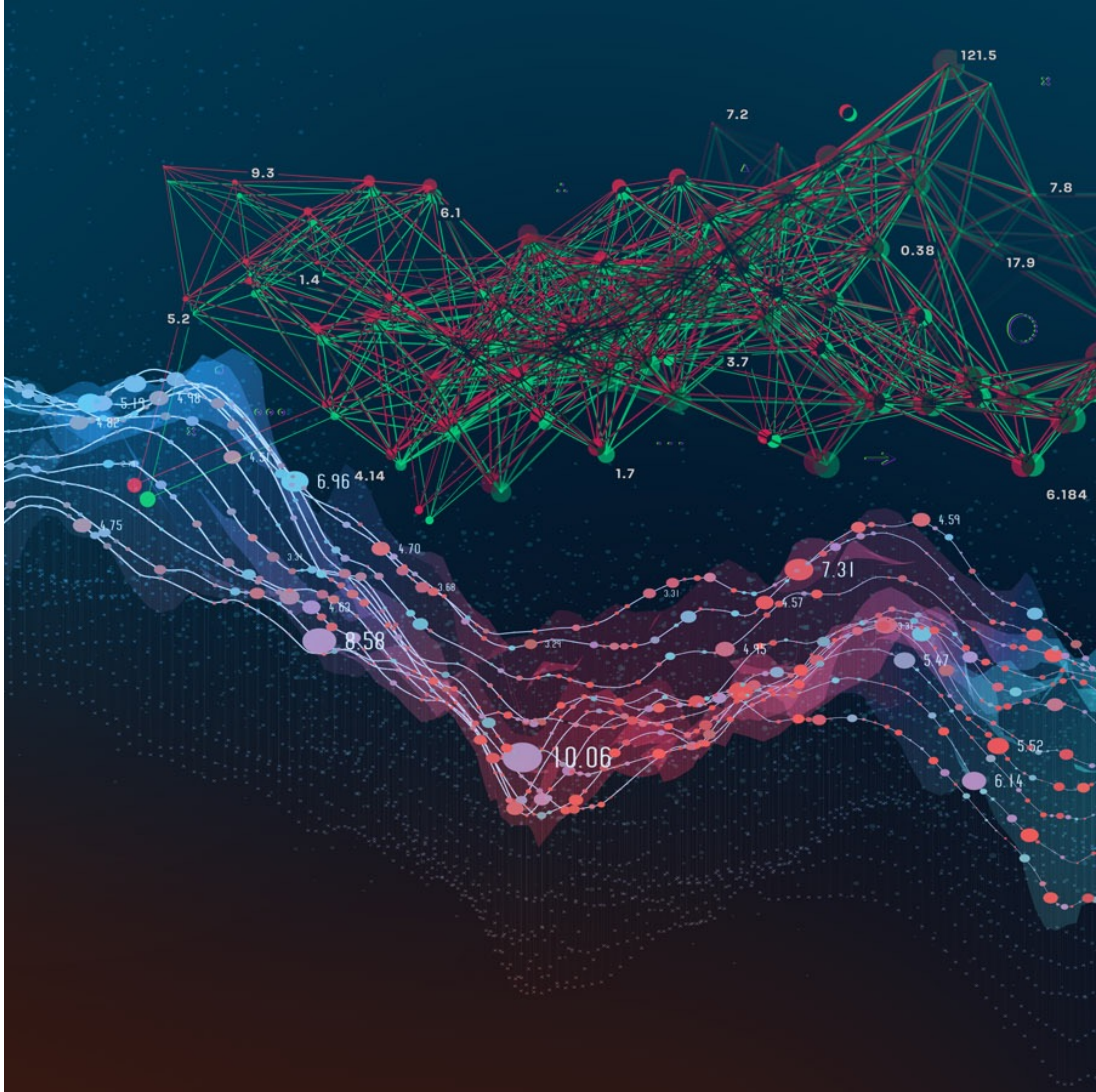
Pacific Northwest NATIONAL LABORATORY

COMET: Domain Specific COMpiler for Extreme Targets in Multi-Level IR

October 25, 2022

Gokcen Kestor, **Rizwan Ashraf**, Zhen Peng, Ruiqin Tian, Luanzheng Guo, Ryan Friese

Pacific Northwest National Laboratory



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Agenda

Time (CDT)	Topic	Presenter	Duration
9.00-9.10	Logistic	G. Kestor	10 minutes
9.10-9.50	Dense and Sparse Tensor Algebra	G. Kestor	40 minutes
9.50-10.30	Hands-on Session	G. Kestor	40 minutes
10.30-11.00	Break		
11.00-11.10	Kernel Fusion	G. Kestor	10 minutes
11.10-11.20	Semiring Support	R. Ashraf	10 minutes
11.20-11.35	FPGA Codegen	R. Ashraf	15 minutes
11.35-12.15	Hands-on Session	R. Ashraf	40 minutes
12.15-12.30	Conclusions and Q&A	All	15 minutes

COMET Kernel Fusion

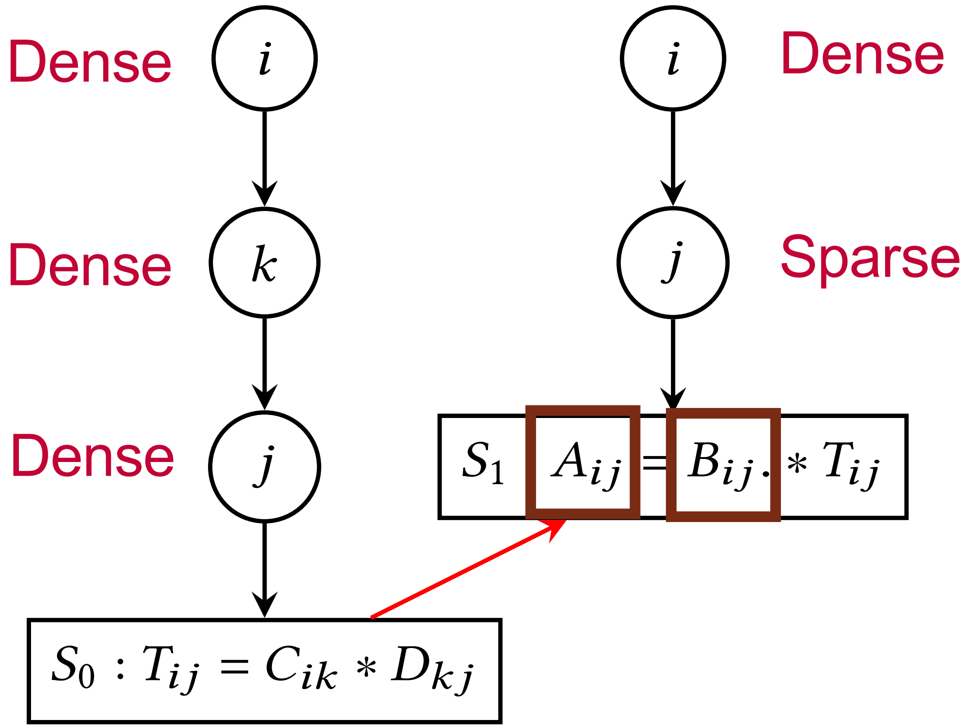
April 4th, 2023

Redundancy-Aware Kernel Fusion[1]

- Compound sparse tensor expressions are commonly used in many domains, including graph analytics, machine learning, and other scientific domain.
- Efficient kernel fusion is needed to eliminate redundant computation
- An expression can be broken into basic operator and each operator can be represented as an index tree

$$A_{ij} = B_{ij} .* (C_{ik} * D_{kj})$$

SDDMM (Sampled Dense-Dense Matrix Multiplication)



[1] ReACT: Redundancy-Aware Code Generation for Tensor Expressions. Tong Zhou, Ruiqin Tian, Rizwan A Ashraf, Roberto Gioiosa, Gokcen Kestor, Vivek Sarkar. 2022 31st International Conference on Parallel Architectures and Compilation Techniques (PACT). October 2022.

Redundancy-Aware Fusion

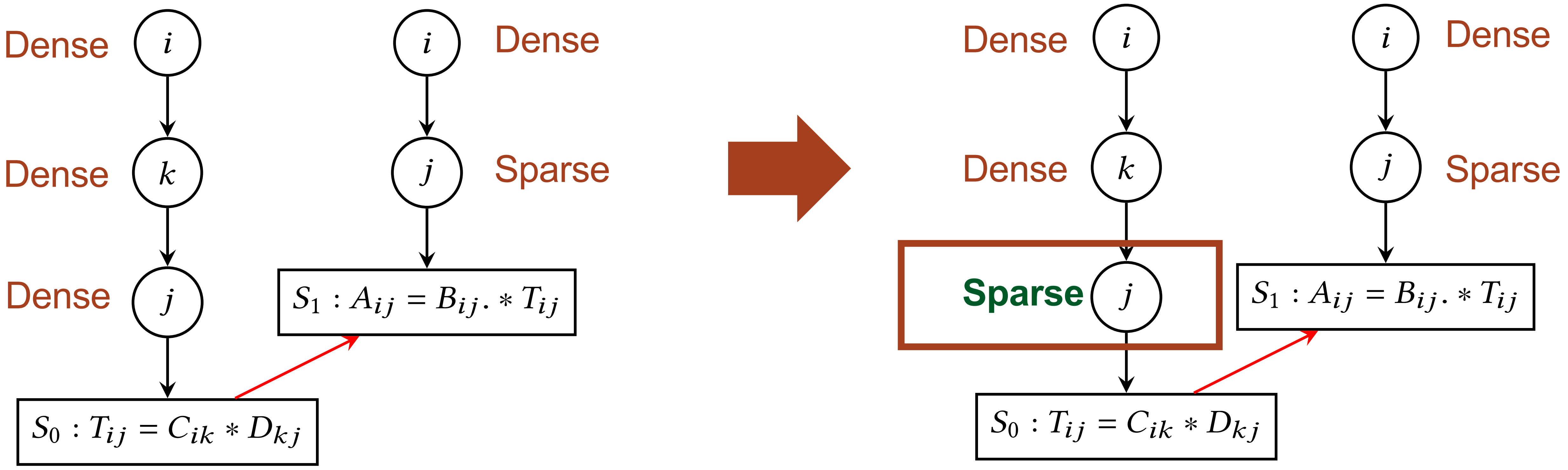
- Two step approach
  1. Propagate sparse iteration spaces
     ✓eliminate dead-value redundancy
  2. Trie-like fusion
     ✓eliminate reduction and loop invariant redundancy

- Memory optimizations
  - Reduce the size of the intermediate tensors wherever possible

Propagate sparse iteration spaces

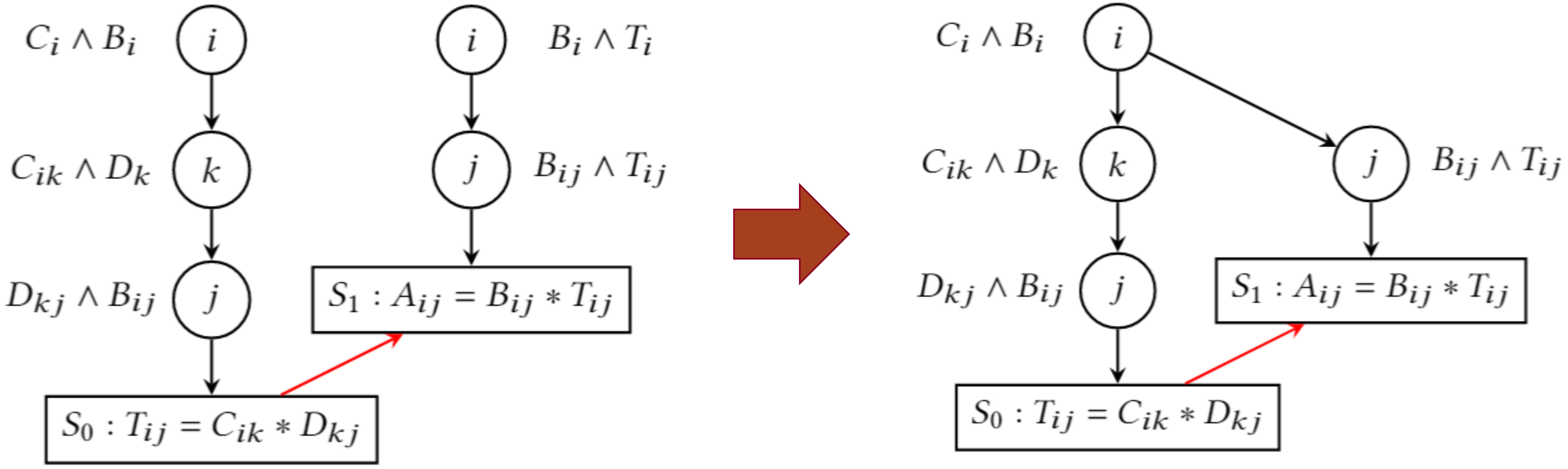
Propagate sparsity from consumer to producer

SDDMM $$A_{ij} = B_{ij} .* (C_{ik} * D_{kj})$$



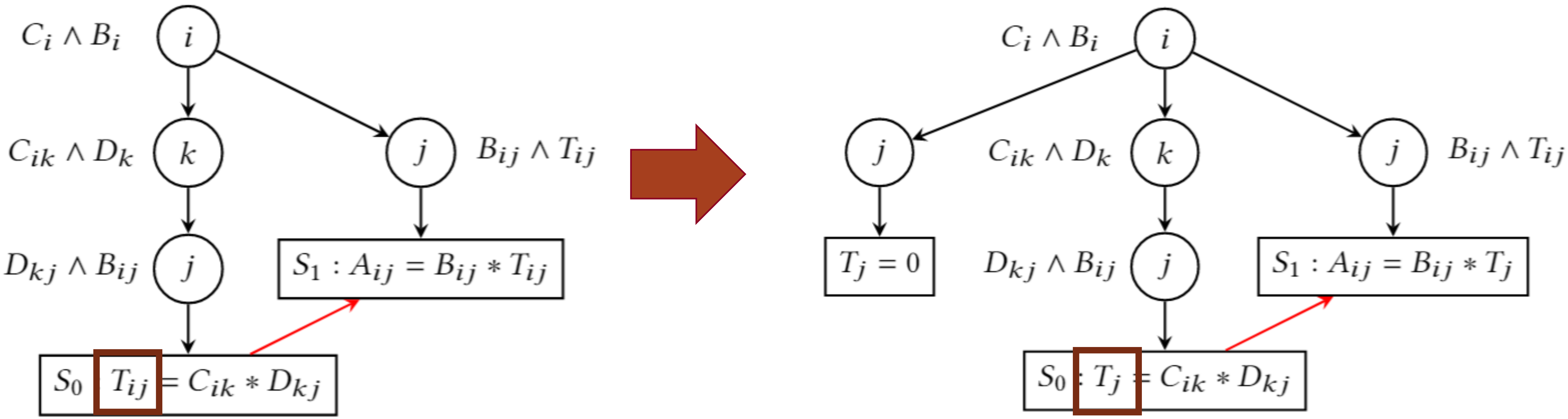
Trie-like fusion

- Fusion is like inserting a key into a trie (prefix tree)



Memory optimization

- Reduce the size of the intermediate tensors wherever possible
- For example SDDMM, we can reduce T_{ij} to an 1-D array

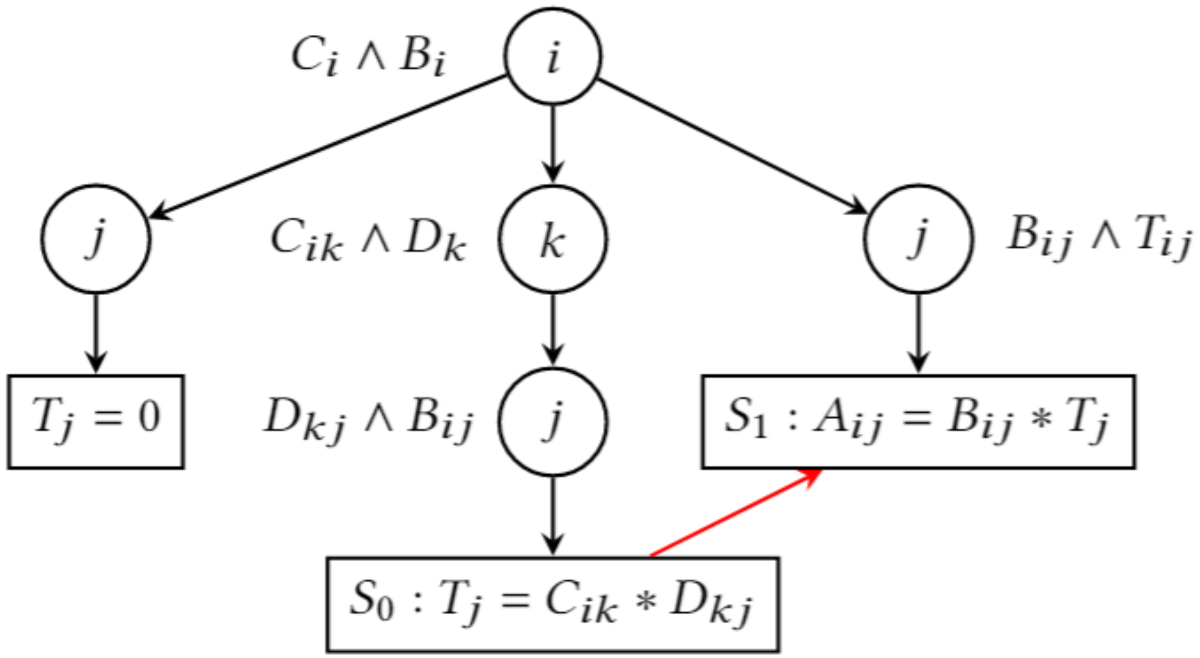


2-D tensor **1-D tensor**

Low-Level codegen

- General loop structure can be generated by traversing the tree
- Generate dense/sparse loop ranges depending on if the loop is dense or sparse

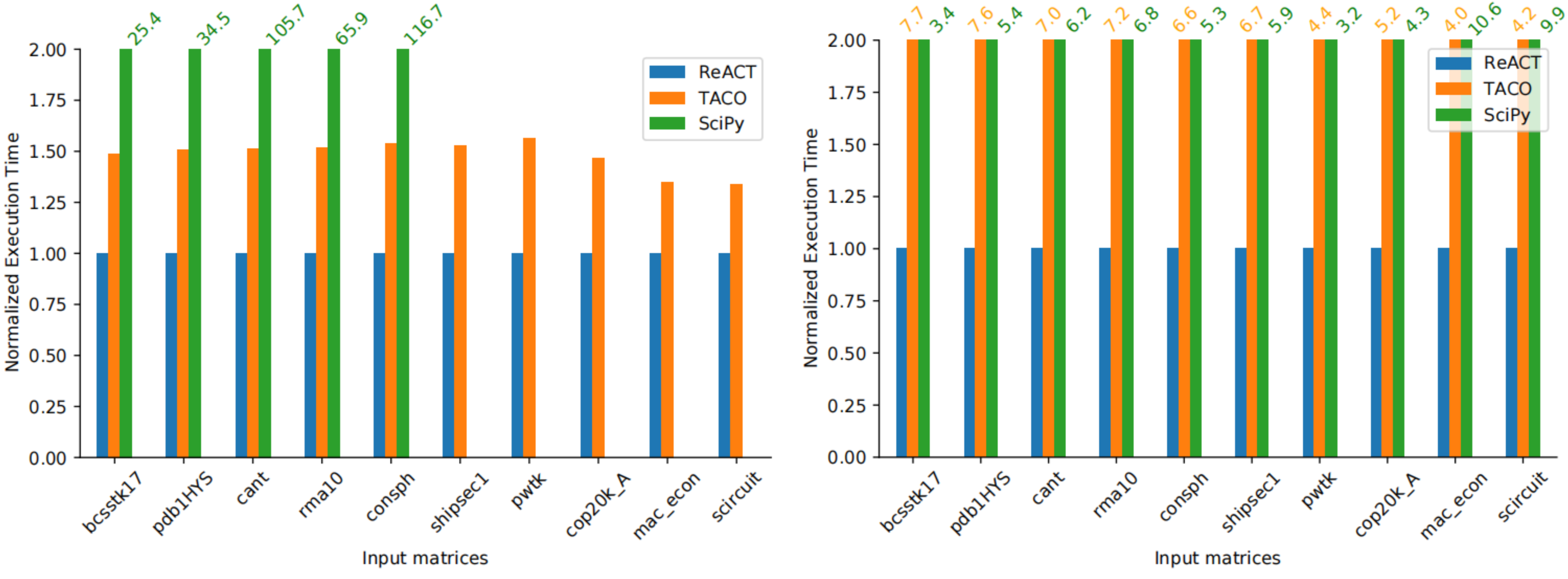
Final index tree




```
auto T = new double[D2_dimension]();
int jT = 0;
for (int32_t i = 0; i < C1_dimension; i++) {
  for (int32_t k = 0; k < D1_dimension; k++) {
    int32_t kC = i * C2_dimension + k;
    jT = 0;
    for (int32_t jB = B2_pos[i]; jB < B2_pos[(i + 1)]; jB++) {
      int32_t j = B2_crd[jB];
      int32_t jD = k * D2_dimension + j;
      T[jT] += C_vals[kC] * D_vals[k * D2_dimension + j];
      jT++;
    }
  }

  jT = 0;
  for (int32_t jB = B2_pos[i]; jB < B2_pos[(i + 1)]; jB++) {
    int32_t j = B2_crd[jB];
    A_vals[jB] += B_vals[jB] * T[jT];
    T[jT] = 0;
    jT++;
  }
}
```

SDDMM and GNN results (16 cores)



(a) SDDMM (NK=64)

(b) GNN-kernel1 (NH=256, NJ=16)

- TACO code generation produces maximal fused code, which introduces redundant computation

COMET Semiring Support

Semiring

- A semiring is an algebraic structure that allows us to perform special operations beyond addition and multiplication to elements in a generic matrix multiplication
- Some constructs found in graph algorithms cannot be represented by standard linear algebra operations but can by semirings
  - Better programming expressiveness
  - Better performance
- Semirings are included in representative libraries like GraphBLAS and Intel MKL

Represent in **semirings** by GraphBLAS:

```
LAGr_mxv (mngp, NULL, GrB_MIN_UINT32,
GxB_MIN_SECOND_UINT32, S, gp, NULL);
```

Connected Components: Hooking & shortcutting

Represent in **normal linear algebra operations** by TACO:

```
// for all edges do hooking and linking
for (int i=0; i < coors.size(); i++) {
    int v_idx = coors[i].x, u_idx = coors[i].y;
    // update u, v:
    v(v_idx) = 1; u(u_idx) = 1;
    // calculate f_u, f_v, ff_u
    f_u(n) = F(n, m) * u(m);
    f_v(p) = F(p, q) * v(q);
    ff_u(x) = F(x, y) * f_u(y);
    if (equall(f_u, ff_u) && larger(f_u, f_v)){
        // hooking - assign f_v to ff_u
        int fu_idx = getF(F, u_idx);
        assignColumn(F, v_idx, fu_idx);
    }
}
// shortcutting
for (int j = 0; j < F.getDimension(1); ++j) {
    int j_f = getF(F, j);
    int j_ff = getF(F, j_f);
    if (j_f != j_ff) {
        assignColumn(F, j_f, j);
    }
}
```

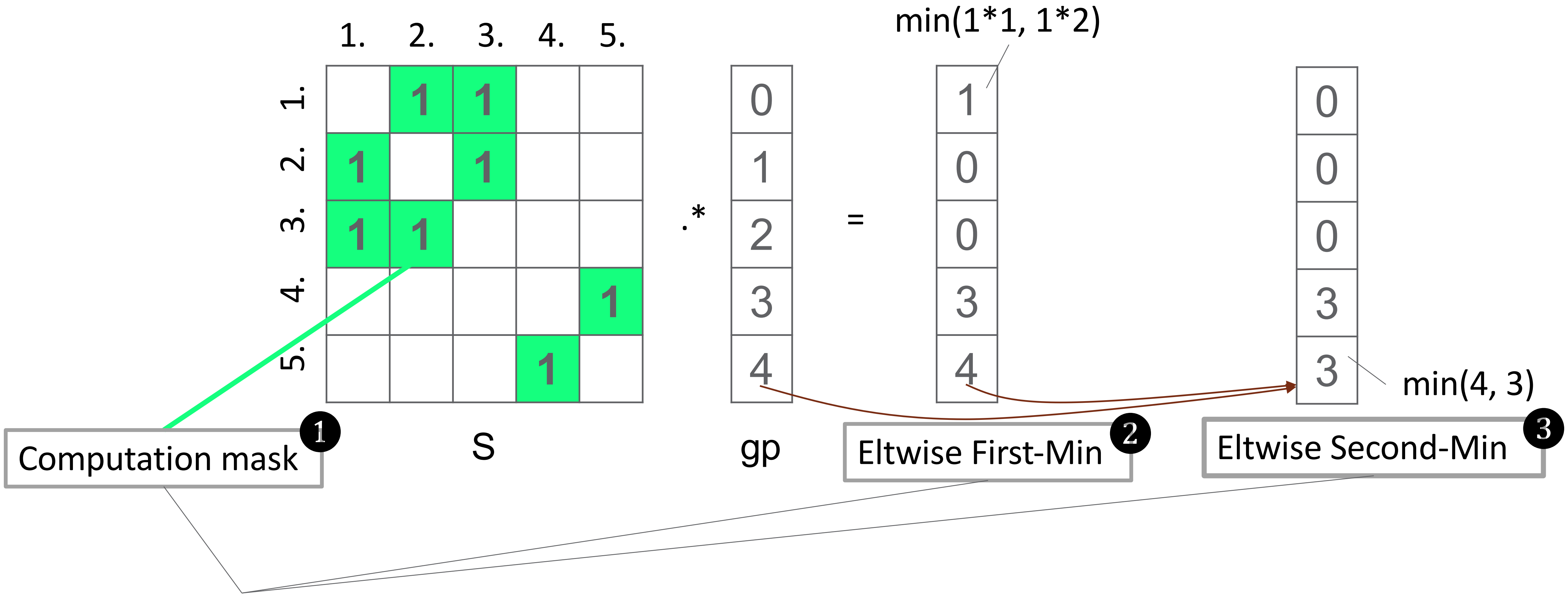
Cannot represent in LA

Cannot represent in LA

Cannot represent in LA

Challenges to represent semirings in LA

- *MIN_SECOND* Semirings cannot be represented in normal Linear Algebra



Cannot be represented in normal LA, and must be represented in special LA

Some semiring examples in DSL

```
def main() {
    #IndexLabel Declarations
    IndexLabel [a] = [?];
    IndexLabel [b] = [?];
    IndexLabel [c] = [?];

    #Tensor Declarations
    Tensor<double> A([a, b], {CSR});
    Tensor<double> B([b, c], {CSR});
    Tensor<double> C([a, c], {CSR});

    #Tensor Data Initialization
    A[a, b] = read_from_file(0);
    B[b, c] = read_from_file(1);

    #PlusTimes semiring
    C[a, c] = A[a, b] @(+,*) B[b, c];
}
```

```
def main() {
    #IndexLabel Declarations
    IndexLabel [a] = [?];
    IndexLabel [b] = [?];


    #Tensor Declarations
    Tensor<double> A([a, b], {CSR});
    Tensor<double> B([a, b], {CSR});

    #Tensor Data Initialization
    A[a, b] = read_from_file(0);
    B[a, b] = read_from_file(1);


    #Min monoid
    C[a, b] = A[a, b] @(min) B[a, b];
}
```

Semiring Operations* in COMET

Semirings	Operation	Explanation
Lor-land	s(|, &)	'lor' means logical OR; 'land' means logical AND.
Min-first	s(min, first)	'min' means the minimal value; 'first' means first(x, y) = x: output the value of the first in the pair.
Plus-times	s(+,x)	'+' means addition; 'x' means multiplication.
Any-pair	s(any, pair)	'any' means "if there is any; if yes return true". 'pair' means pair(x, y) = 1: x and y both have defined value at this intersection.
Min-plus	s(min, +)	'min' means the minimal value; '+' means addition.
Plus-pair	s(+, pair)	'+' means addition; 'pair' means pair(x, y) = 1: x and y both have defined value at this intersection.
Min-second	s(min, second)	'min' means the minimal value; 'second' means second(x, y) = x: output the value of the second in the pair.
Plus-second	s(+, second)	'+' means addition; 'second' means second(x, y) = x: output the value of the second in the pair.
Plus-first	s(+, first)	'+' means addition; 'first' means first(x, y) = x: output the value of the first in the pair.

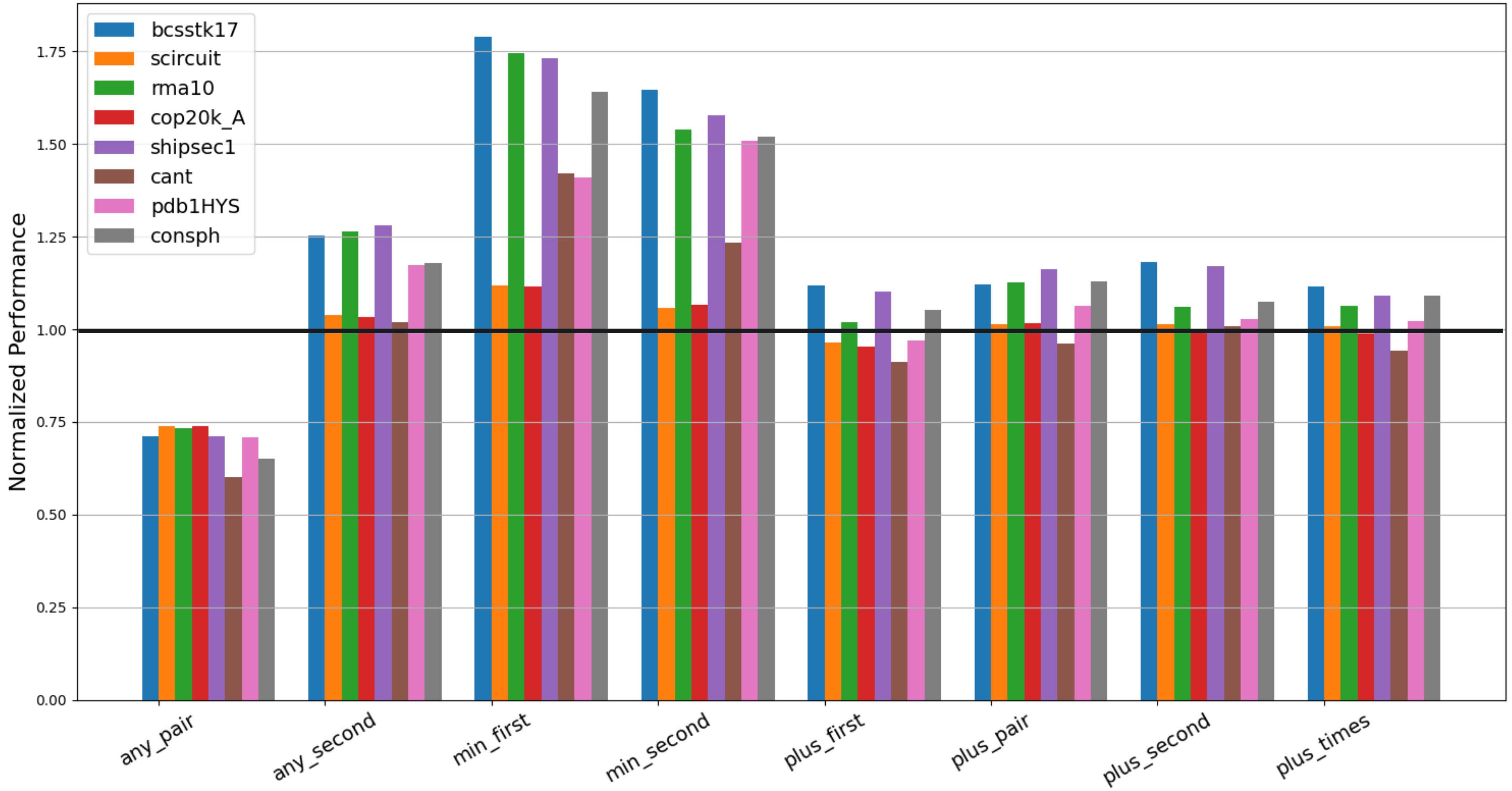
* COMET supports arbitrary combinations of operators for semiring

Semiring Operations per application

	Semirings	Operation	Description
BFS	Lor-land	s(|, &)	Compute traversal level for each vertex
	Min-first	s(min, first)	Compute parent for each vertex
	Plus-mul	s(+,x)	Number of paths
	Any-pair	s(any, pair)	Reachability
	Min-plus	s(min, +)	Shortest path
SSSP	Min-plus	s(min, +)	Shortest path without mask (Bellman-Ford Algorithm)
TC	Plus-pair	s(+, pair)	Number of triangles
CC	Min-second	s(min, second)	Hooking and shortcutting
PR	Plus-second	s(+, second)	Outbound pagerank score
BC	Plus-first	s(+, first)	Accumulate path count

Semiring Performance (unjumbled)

- A method returns a matrix in an *unjumbled* state, with indices sorted
  - if the matrix will be immediately exported in unjumbled form, or
  - if the matrix is provided as input to a method that requires it to not be jumbled

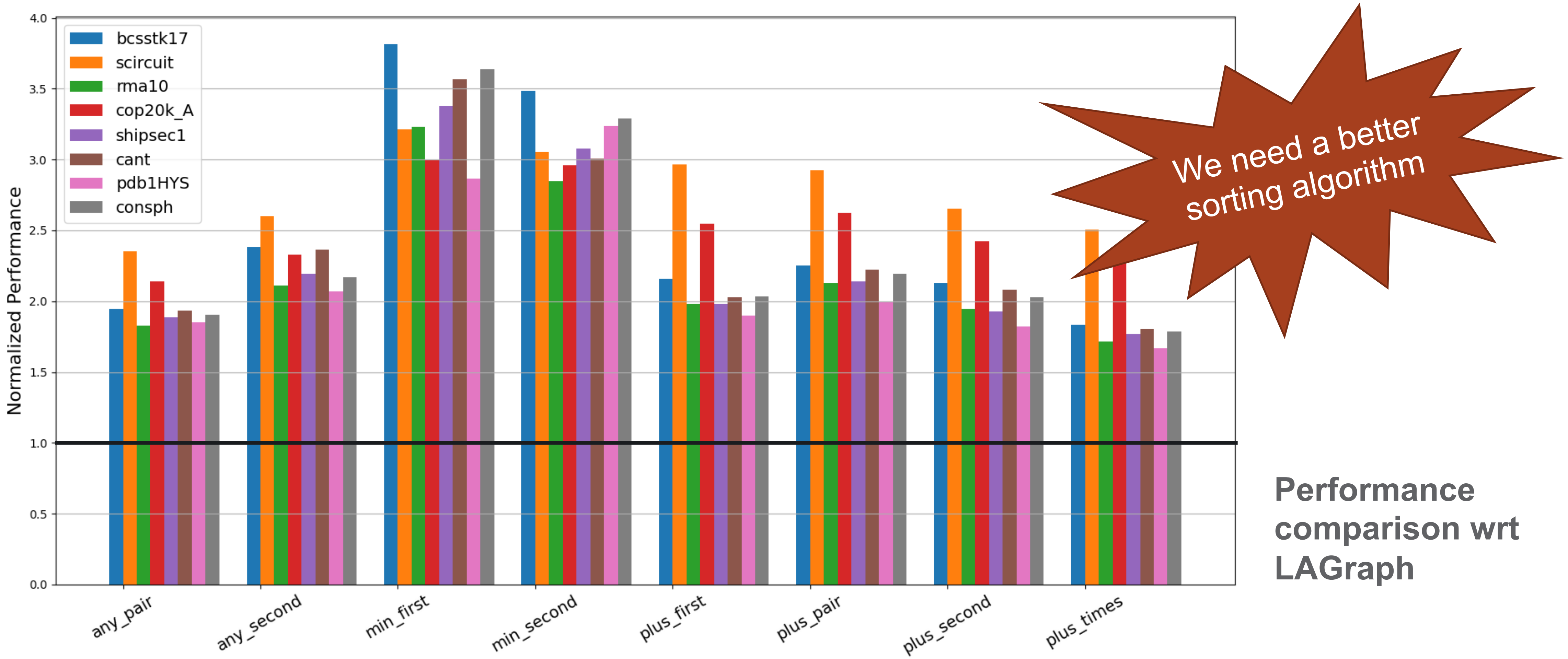


Performance comparison wrt LAGraph[1]

[1] Tim Mattson; Timothy A. Davis; Manoj Kumar; Aydin Buluc; Scott McMillan; Jose Moreira; Carl Yang. "LAGraph: A Community Effort to Collect Graph Algorithms Built on Top of the GraphBLAS", IEEE International Parallel and Distributed Processing Symposium Workshops (IPDPSW), 2019.

Semiring Performance (jumbled)

- A method returns a matrix in a *jumbled* state, with indices out of order
  - If some methods can tolerate jumbled matrices on input, the sorting of the indices is left pending



Performance comparison wrt LAGraph

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COMET Heterogenous Target

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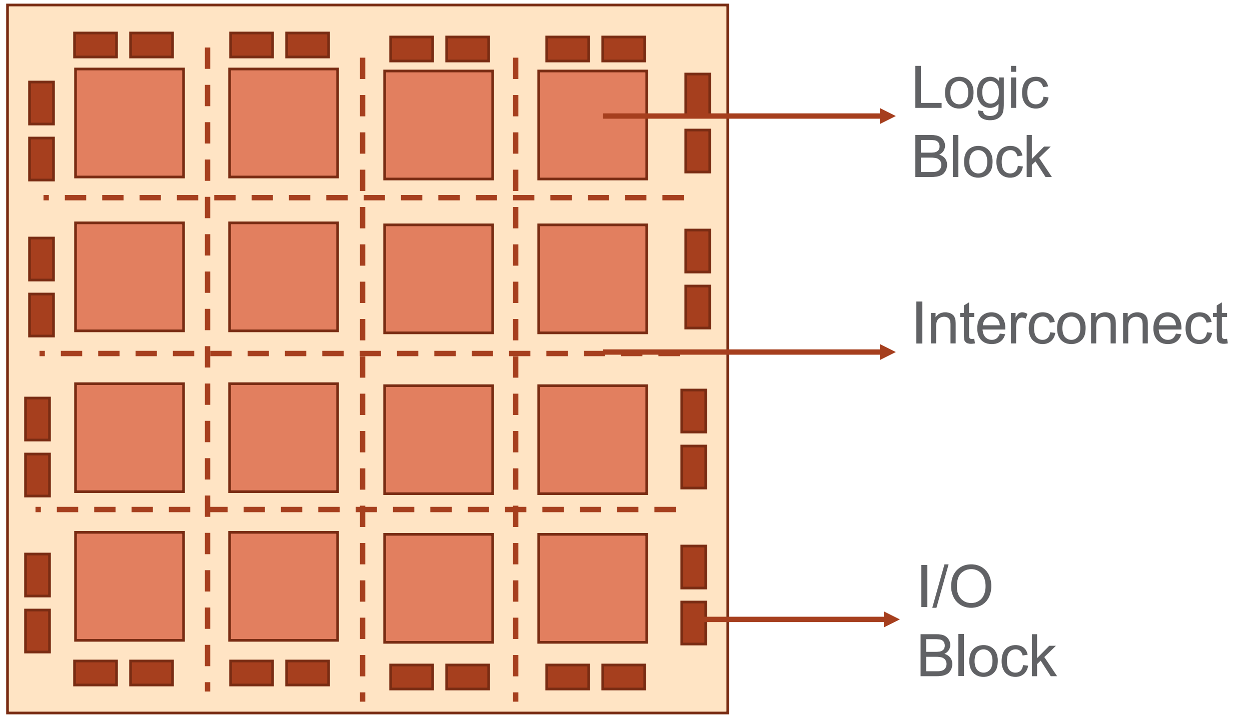
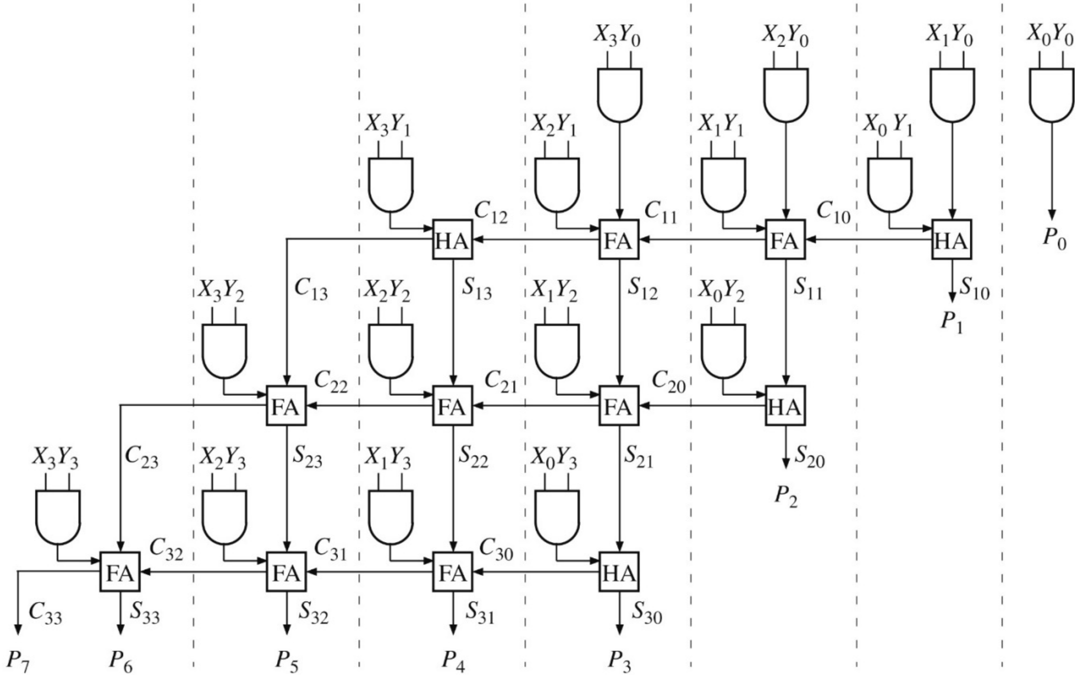
What does an FPGA Accelerator look like?

- Field Programmable Gate Arrays (FPGAs) are reconfigurable hardware devices that can be programmed to provide desired functionality.
  - Challenge: The accelerator design needs to be synthesized (blank slate).
  - Gain: Energy efficient compared to a GPU.
  - Potential: High degree of parallelism.



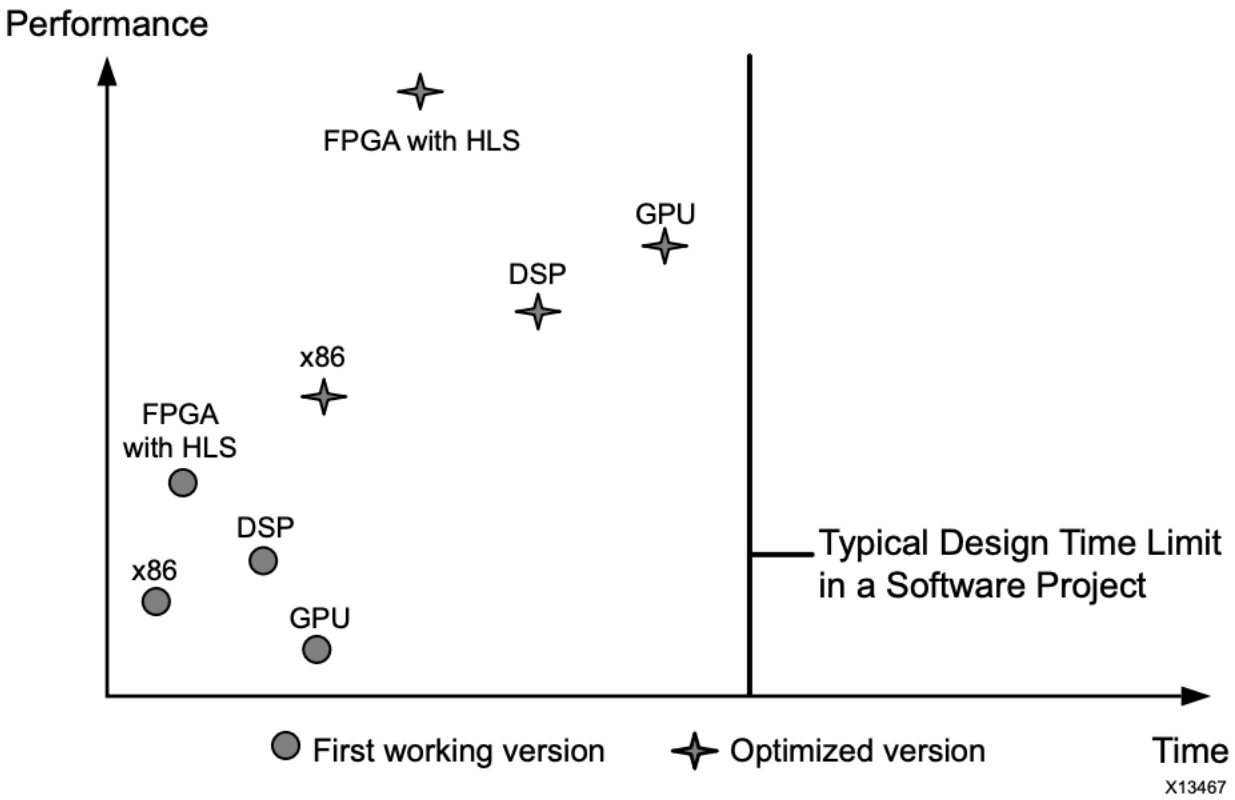
An FPGA Block Diagram



4x4 Array Multiplier (Logic gates and adders)

FPGA Programming Model

- The FPGA programming model is centered on register-transfer level description instead of C/C++ (or other high-level languages).
  - Time required to develop RTL or design for FPGA is high compared to CPU/GPU.
  - The design philosophy is like regular IC than a CPU/GPU.
  - Advances in HLS compiler provides the ability to port C/C++ code to FPGAs.

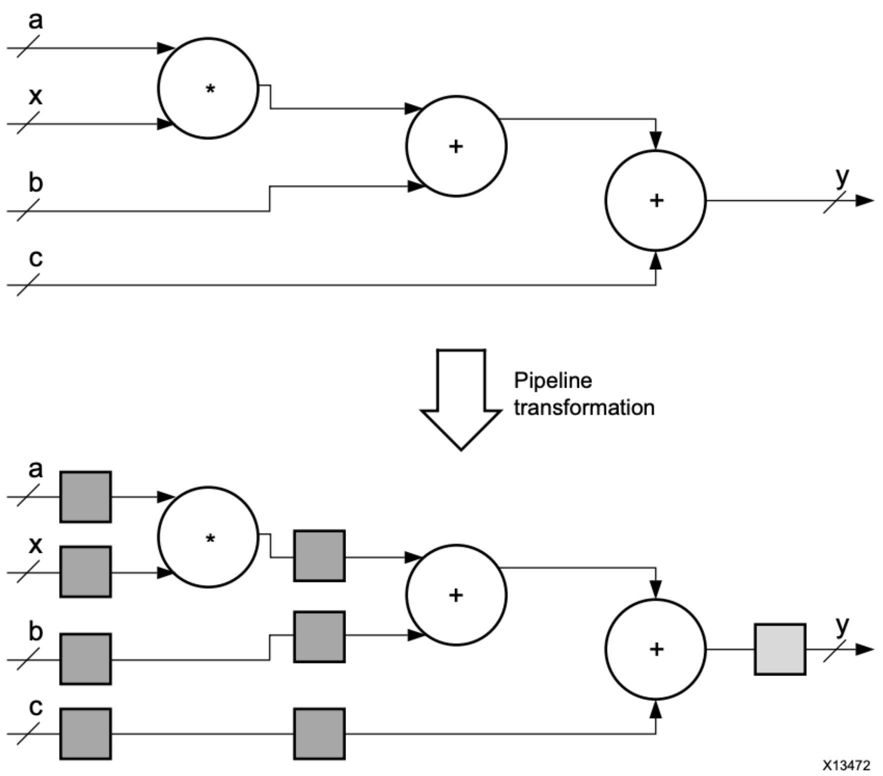


Xilinx Doc: UG998 (v1.1)

FPGA Parallelism

- FPGA is an inherently parallel processing fabric capable of implementing any logical and arithmetic function that can run on a CPU.
  - Scheduling: group operations in same clock cycle.
  - Pipelining: stages run in parallel.
  - Dataflow: parallel execution of functions in a single program.

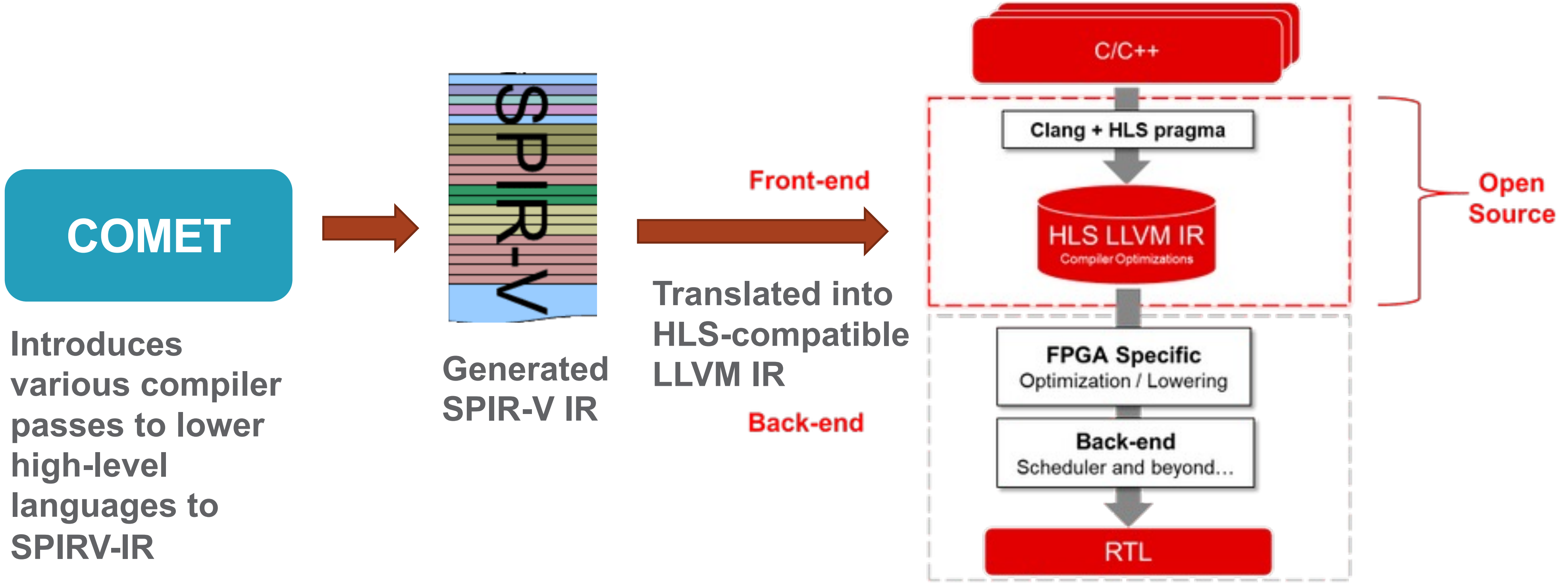
FPGA implementation of
y = (a * x) + b + c



Xilinx Doc: UG998 (v1.1)

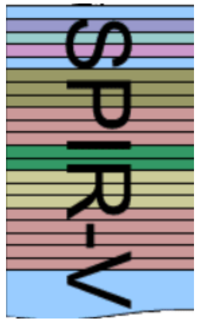
Agile Development of FPGA Accelerators for HPC

- The methodology is based on automated generation of novel hardware concepts starting from a high-level description of the algorithm.



Heterogeneous Devices

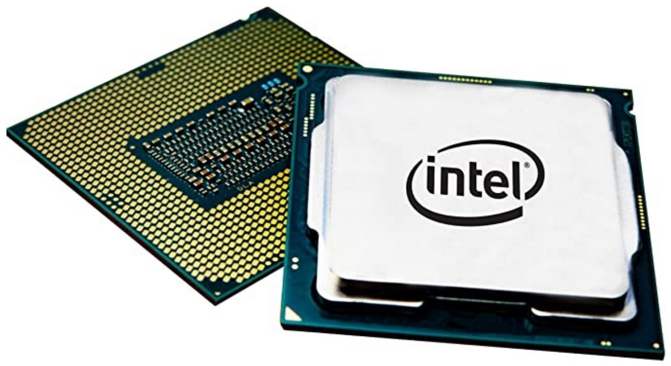
- SPIR-V generated by COMET can be used to program FPGAs, GPUs, and CPUs.



Generated SPIR-V IR

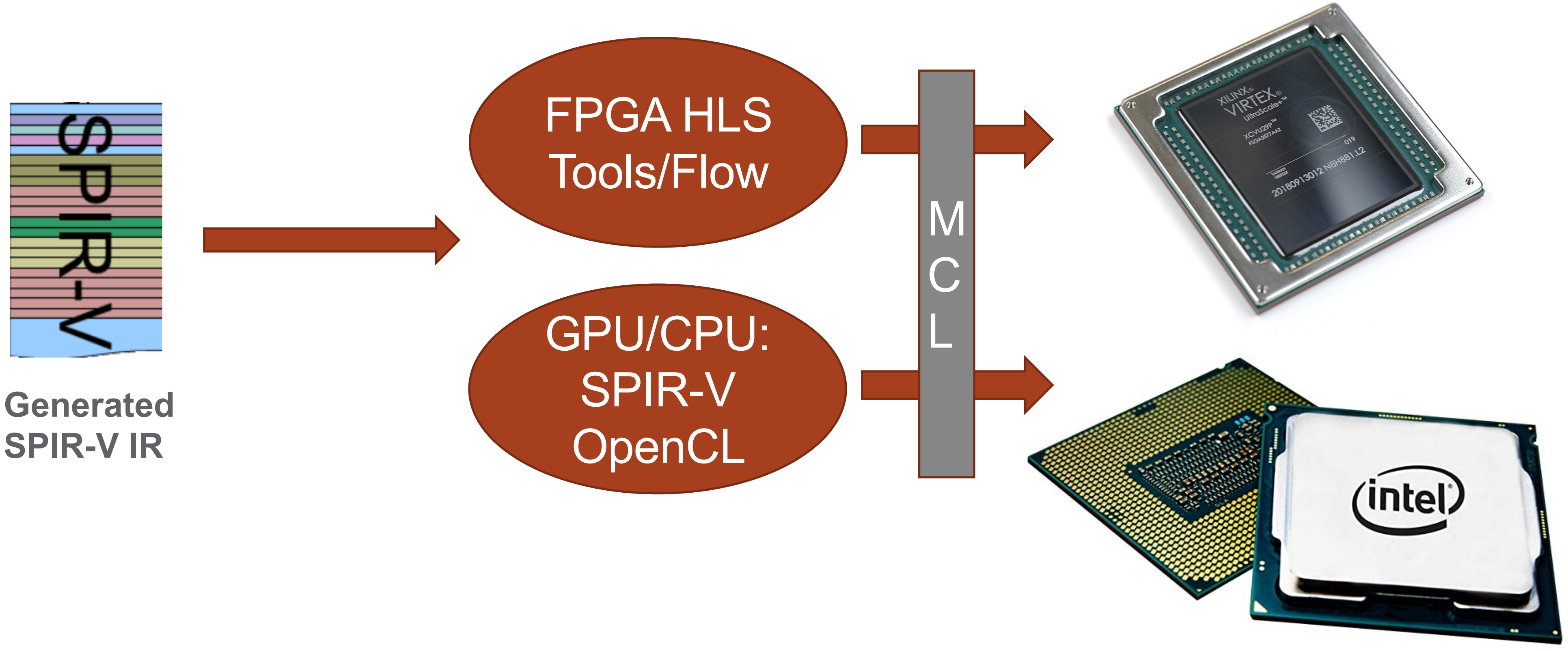
FPGA HLS Tools/Flow

GPU/CPU: SPIR-V OpenCL



Heterogeneous Devices: Minos Computing Lib.

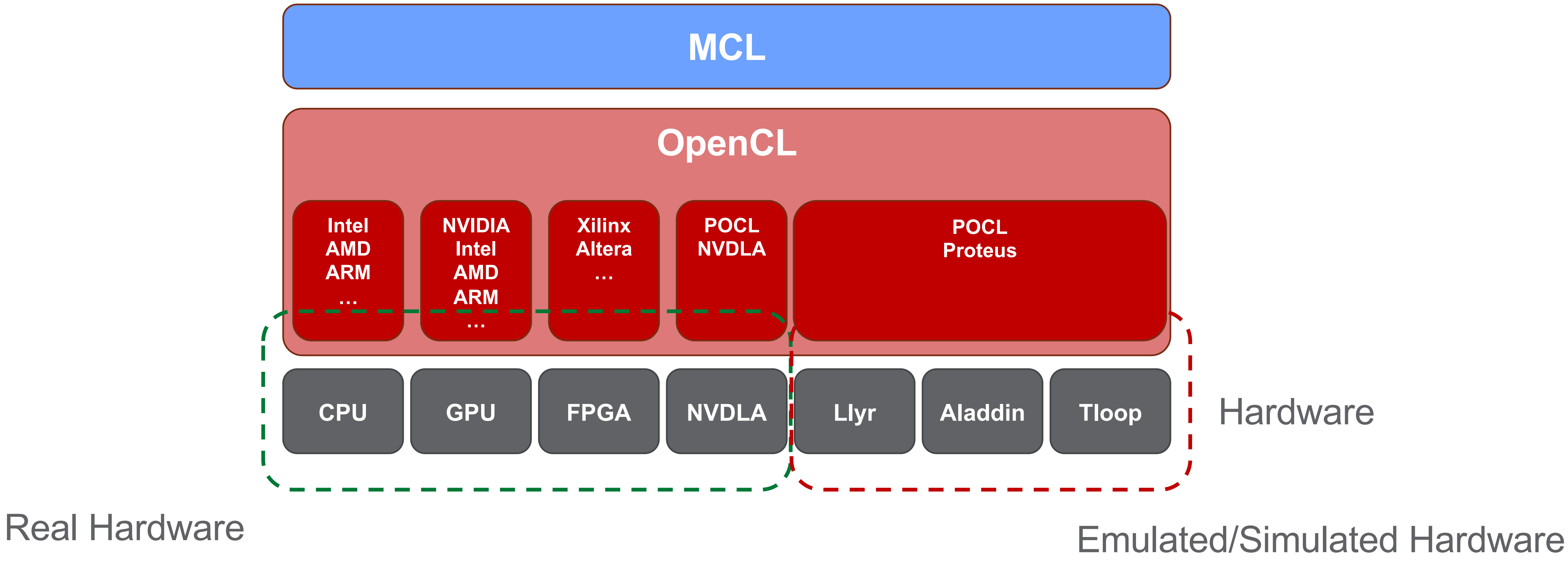
- MCL[1] is an asynchronous task-based programming model and runtime.
  - Orchestrates compute and data among available devices (checks for resources, runtime compilation of kernel code, data locality, power constraints)



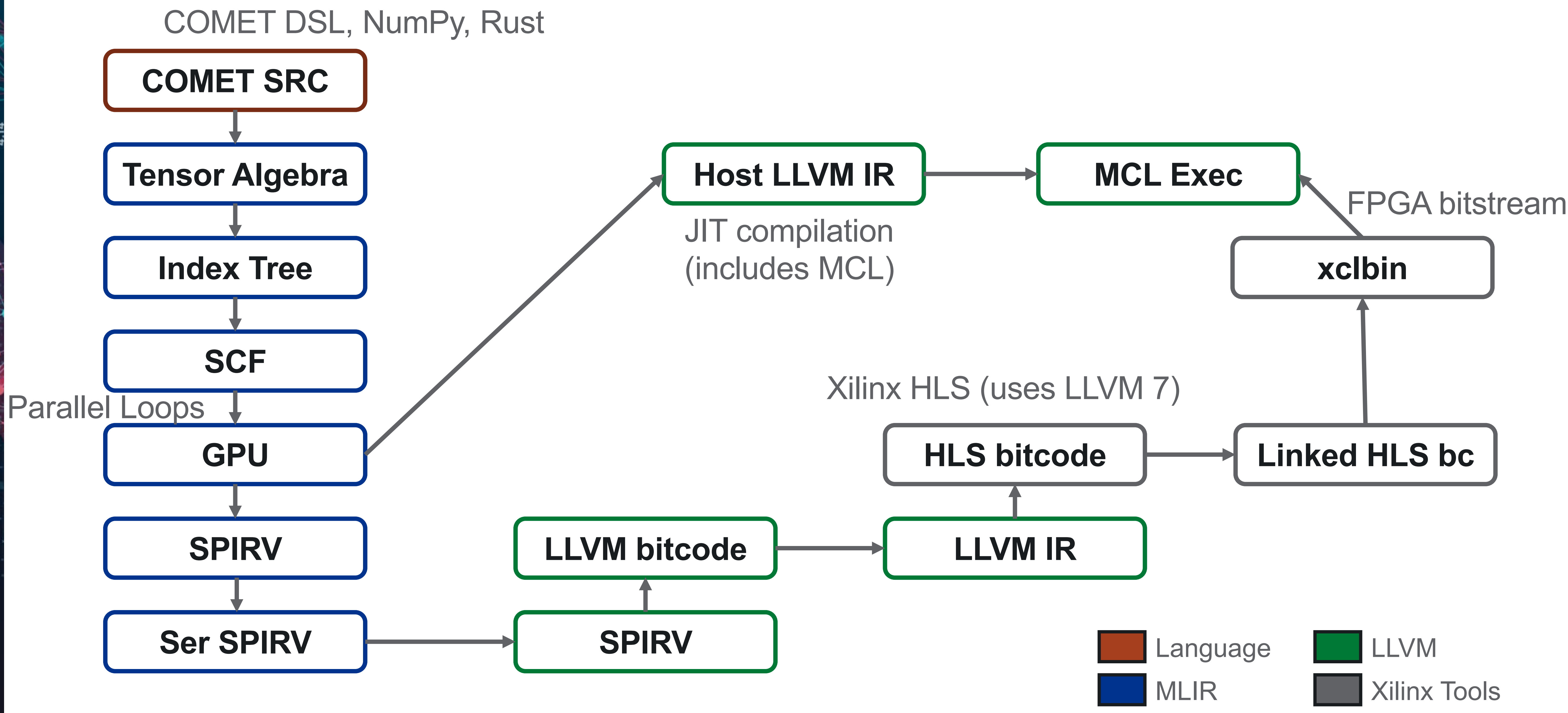
[1] Roberto Gioiosa, Burcu O. Mutlu, Seyong Lee, Jeffrey S. Vetter, Giulio Picierro, and Marco Cesati. 2020. The Minos Computing Library: efficient parallel programming for extremely heterogeneous systems. In Proceedings of the 13th Annual Workshop on General Purpose Processing using Graphics Processing Unit (GPGPU '20)

Minos Computing Library (MCL)

- MCL is based on the OpenCL programming paradigm.
  - Compute-intensive kernels are off-loaded onto accelerators driven from the host.
  - Available as open-source: https://github.com/pnnl/mcl



Workflow for Programming FPGAs Using COMET



COMET Hands-on Session

April 4th, 2022

Case_spgemm: SpGEMM

```
def main() {
    #IndexLabel Declarations
    IndexLabel [a] = [?];
    IndexLabel [b] = [?];
    IndexLabel [c] = [?];

    #Tensor Declarations
    Tensor<double> A([a, b], {CSR});
    Tensor<double> B([b, c], {CSR});
    Tensor<double> C([a, c], {CSR});

    #Tensor Data Initialization
    A[a, b] = read_from_file(0);
    B[b, c] = read_from_file(1);

    #Tensor Contraction
    C[a, c] = A[a, b] * B[b, c];
}
```

- Sparse matrix-sparse matrix multiplication, the output matrix is **sparse**
- Apply workspace transformations

```
$COMET_OPT                  \
    --convert-ta-to-it  \
    --opt-comp-workspace \
    --convert-to-loops  \
    ../benchs/$fname &> ../IRs/$fname-loop.mlir
```

Execution time: 1.083105

Demo: Case_spgemm

```
ops — kest268@bluesky:~/projects/DuoMO/COMET/tutorial/pact22/testcases — ssh bluesky — 102×28
...ps — kest268@bluesky:~/projects/DuoMO/COMET/tutorial/pact22/testcases — ssh bluesky    ~/projects/duomo/COMET/tutorial/pact22/testcases — -zsh
(base) [kest268@bluesky testcases]$
```

Case_spgemm_dense: SpGEMM

```
def main() {
    #IndexLabel Declarations
    IndexLabel [a] = [?];
    IndexLabel [b] = [?];
    IndexLabel [c] = [?];

    #Tensor Declarations
    Tensor<double> A([a, b], {CSR});
    Tensor<double> B([b, c], {CSR});
    Tensor<double> C([a, c], {Dense});

    #Tensor Data Initialization
    A[a, b] = read_from_file(0);
    B[b, c] = read_from_file(1);
    C[a, c] = 0.0;

    #Tensor Contraction
    C[a, c] = A[a, b] * B[b, c];
}
```

- Sparse matrix-sparse matrix multiplication, the output matrix is **dense**
- No need to apply workspace transformations

```
$COMET_OPT                  \
    --convert-ta-to-it      \
    --convert-to-loops      \
    ../benchs/$fname &> ../IRs/$fname-loop.mlir
```

Execution time: 0.506258

Demo: Case_spgemm_dense

```
ops — kest268@bluesky:~/projects/DuoMO/COMET/tutorial/pact22/testcases — ssh bluesky — 102×28
...ps — kest268@bluesky:~/projects/DuoMO/COMET/tutorial/pact22/testcases — ssh bluesky    ~/projects/duomo/COMET/tutorial/pact22/testcases — -zsh
(base) [kest268@bluesky testcases]$
```

Case_f1: GNN without fusion

```
def main() {
    #IndexLabel Declarations
    IndexLabel [i] = [?];
    IndexLabel [k] = [?];
    IndexLabel [j] = [16];
    IndexLabel [h] = [16];

    Tensor<double> B([i, k], {CSR});
    Tensor<double> C([k, h], {Dense});
    Tensor<double> D([h, j], {Dense});
    Tensor<double> A([i, j], {Dense});
    Tensor<double> T([i, h], {Dense});

    #Tensor Data Initialization
    B[i, k] = read_from_file(0);
    C[k, h] = 1.2;
    D[h, j] = 3.4;
    A[i, j] = 0.0;
    T[i, h] = 0.0;


    #GNN
    T[i, h] = B[i, k] * C[k, h];
    A[i, j] = T[i, h] * D[h, j];

}
```

GNN code generation **without fusion**

```
$COMET_OPT                  \
    --convert-ta-to-it      \
    --convert-to-loops      \
    ../benchs/$fname &> ../IRs/$fname-loop.mlir
```

Execution time: 0.056588

Demo: Case_f1


kest268 — kest268@bluesky:~/projects/DuoMO/COMET/tutorial/pact22 — ssh bluesky — 105×29
(base) [kest268@bluesky pact22]$

Case_f2: GNN with fusion

```
def main() {
    #IndexLabel Declarations
    IndexLabel [i] = [?];
    IndexLabel [k] = [?];
    IndexLabel [j] = [16];
    IndexLabel [h] = [16];

    Tensor<double> B([i, k], {CSR});
    Tensor<double> C([k, h], {Dense});
    Tensor<double> D([h, j], {Dense});
    Tensor<double> A([i, j], {Dense});
    Tensor<double> T([i, h], {Dense});

    #Tensor Data Initialization
    B[i, k] = read_from_file(0);
    C[k, h] = 1.2;
    D[h, j] = 3.4;
    A[i, j] = 0.0;
    T[i, h] = 0.0;


    #GNN
    T[i, h] = B[i, k] * C[k, h];
    A[i, j] = T[i, h] * D[h, j];

}
```

GNN code generation **with fusion**

```
$COMET_OPT                   \
     --convert-ta-to-it      \
     --opt-partial-fusion    \
     --convert-to-loops      \
     ../benchs/$fname &> ../IRs/$fname-loop.mlir
```

Execution time: 0.040478

1.39x Speedup

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Demo: Case_f2

```
kest268 — kest268@bluesky:~/projects/DuoMO/COMET/tutorial/pact22/testcases — ssh bluesky — 105×29
(base) [kest268@bluesky testcases]$
```

Case_plustimes: Semiring

```
def main() {
    #IndexLabel Declarations
    IndexLabel [a] = [?];
    IndexLabel [b] = [?];
    IndexLabel [c] = [?];

    #Tensor Declarations
    Tensor<double> A([a, b], {CSR});
    Tensor<double> B([b, c], {CSR});
    Tensor<double> C([a, c], {CSR});

    #Tensor Data Initialization
    A[a, b] = read_from_file(0);
    B[b, c] = read_from_file(1);

    #PlusTimes semiring
    C[a, c] = A[a, b] @(+,*) B[b, c];
}
```

- Plus-times semiring
- Since the output is sparse, need to apply workspace transformations

```
$COMET_OPT                  \
    --convert-ta-to-it  \
    --opt-comp-workspace \
    --convert-to-loops  \
    ../benchs/$fname &> ../IRs/$fname-loop.mlir
```

Case_minfirst: Semiring

```
def main() {
    #IndexLabel Declarations
    IndexLabel [a] = [?];
    IndexLabel [b] = [?];
    IndexLabel [c] = [?];

    #Tensor Declarations
    Tensor<double> A([a, b], {CSR});
    Tensor<double> B([b, c], {CSR});
    Tensor<double> C([a, c], {CSR});

    #Tensor Data Initialization
    A[a, b] = read_from_file(0);
    B[b, c] = read_from_file(1);

    #MinFirst semiring
    C[a, c] = A[a, b] @(min,first) B[b, c];
}
```

- Min-first semiring, used in BFS algorithm
- Since the output is sparse, need to apply workspace transformations

```
$COMET_OPT                  \
    --convert-ta-to-it   \
    --opt-comp-workspace \
    --convert-to-loops   \
    ../benchs/$fname &> ../IRs/$fname-loop.mlir
```

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Thank you