TC-CIM: Empowering Tensor Comprehensions for Computing In Memory

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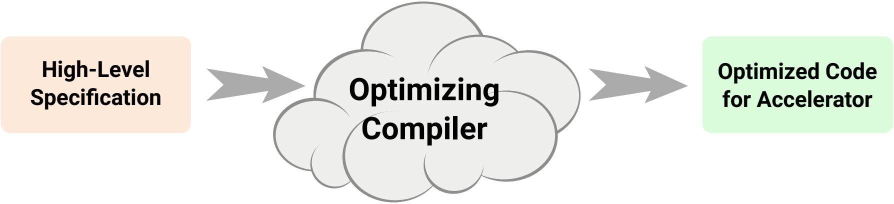
Detecting Operations for Accelerators



- Goal: Reliably detect operations for efficient offloading

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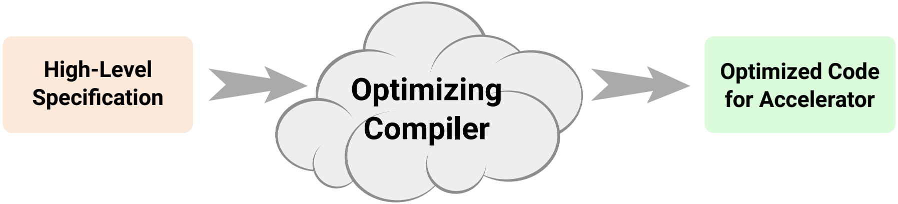
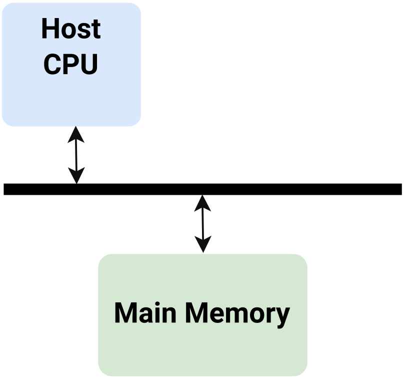


- Goal: Reliably detect operations for efficient offloading
- At which stage?
- On which representation?
- Create reusable infrastructure

Von-Neumann Bottleneck



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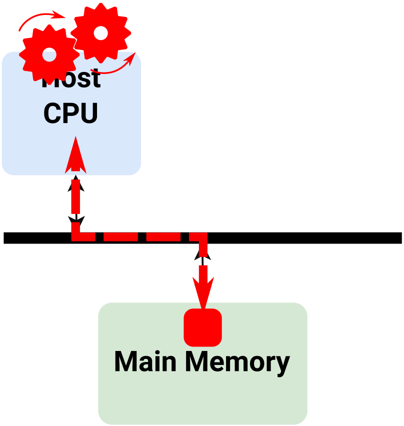

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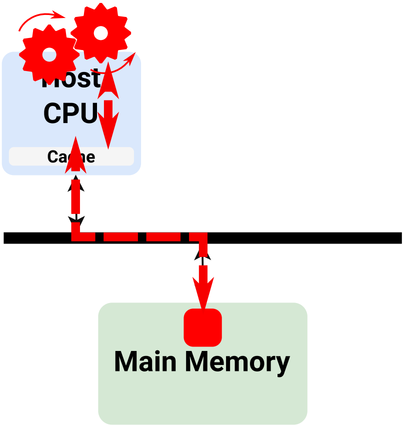

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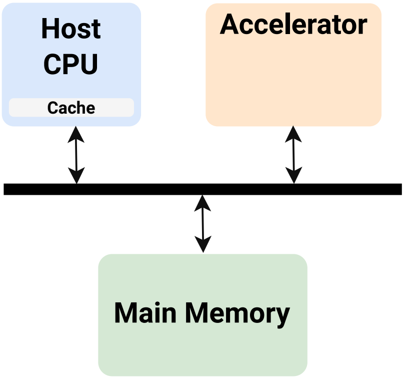

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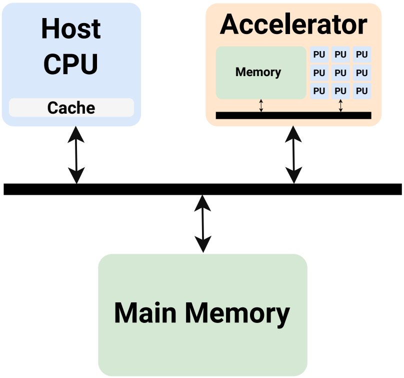
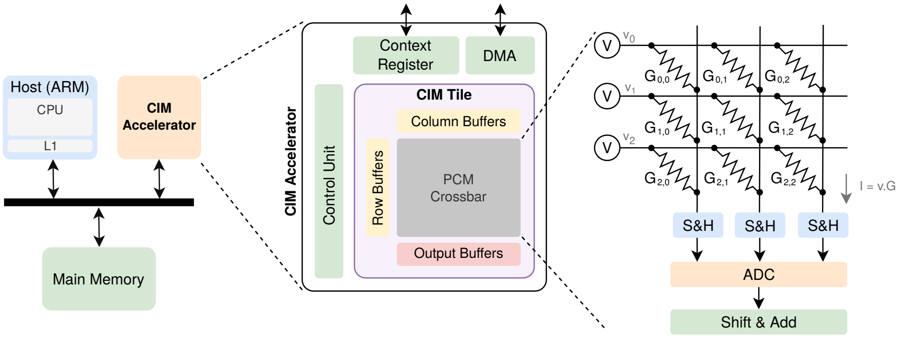


Compute In Memory (CIM)



- Interweave Computation and Storage
- Example: Memristor-based Architecture from MNEMOSENE project (`https://www.mnemosene.eu`)

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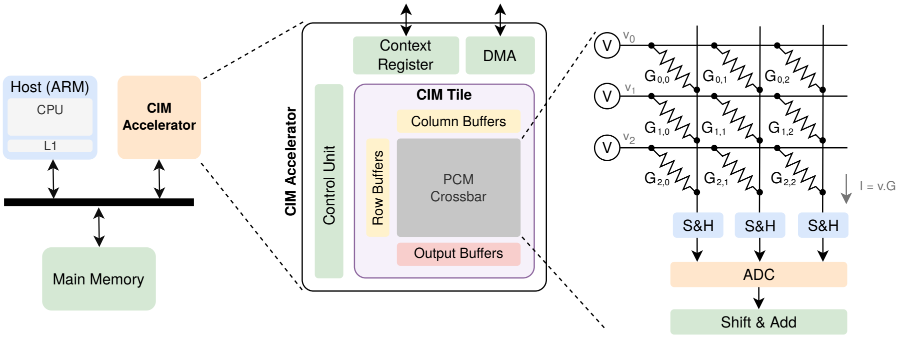
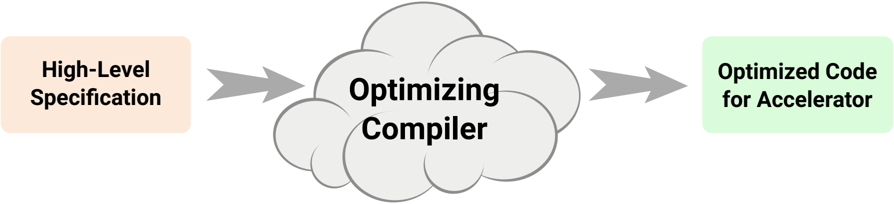


- Interweave Computation and Storage
- Example: Memristor-based Architecture from MNEMOSENE project (`https://www.mnemosene.eu`)
- High energy efficiency and throughput with fixed functions (e.g., matrix multiplication)

Detecting Accelerated Operations for CIM



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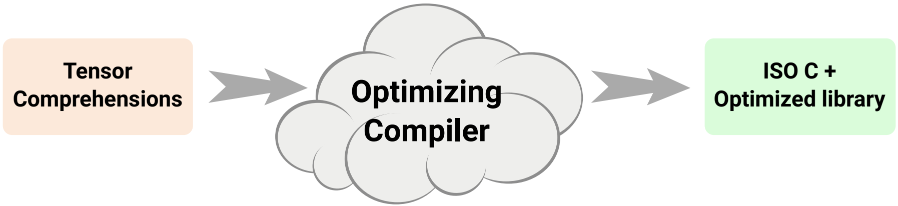

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Tensor Comprehensions

Math-like notation

- Expresses operations on tensors
- Only information needed to define operation unambiguously
- Compiler infers shapes and iteration domains

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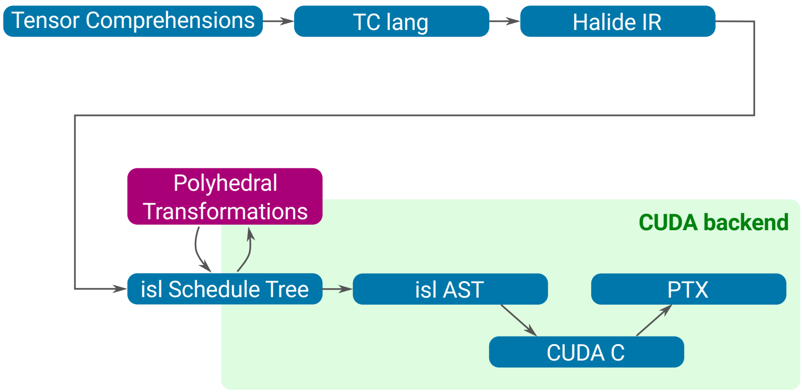
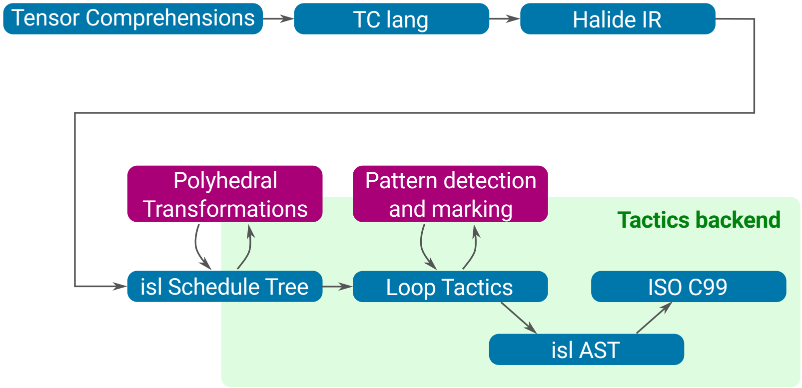
Example:

```
def mv(float(M,K) A, float(K) x) -> (C)
{
  C(i) +=! A(i,k) * x(k)
}
```

Tensor Comprehensions: Compilation



Integration of Loop Tactics



Matching Example: Matrix Multiplications

```
def kernel(
     float(M,N) A,
     float(N,K) B) -> (C)
{
   ...
   C(i,k) +=!
     A(i, n) * B(n, k)
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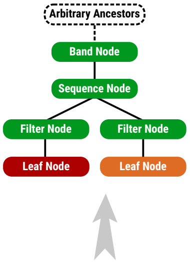


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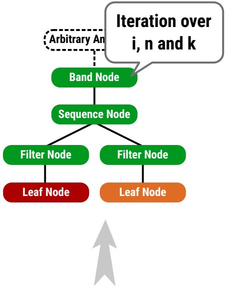


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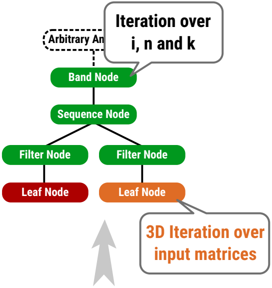


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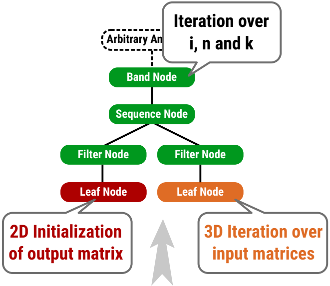


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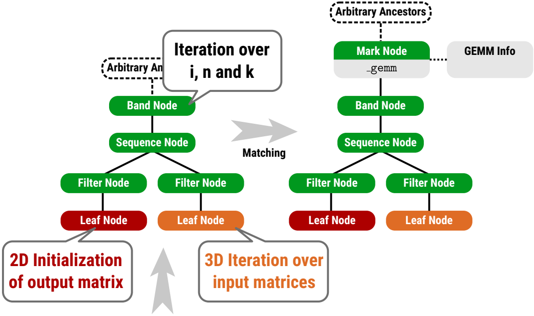


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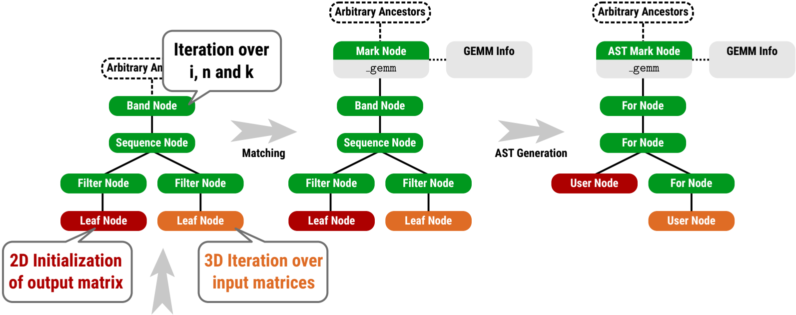


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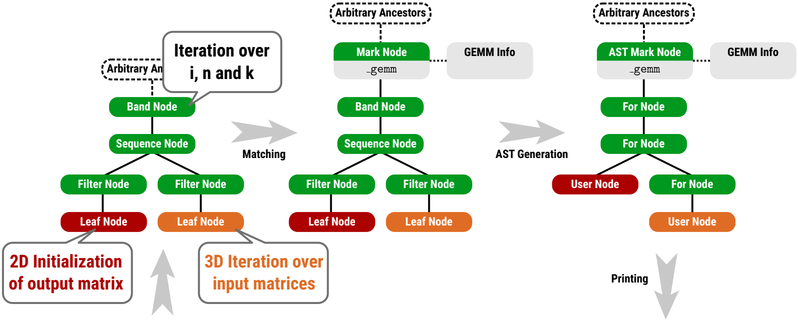


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   ...
}
```

```
void kernel(int K, int M, int N,
            float* C,
            float* A,
            float* B)
{
   ...
   cimblas_gemm(K, M, N,
                C, A, B,
                ...);
   ...
}
```

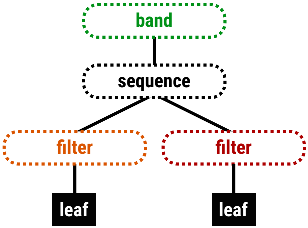
Loop Tactics: Tree Matchers

Tree Matcher defines pattern for subtree and captures nodes

```
schedule_node body;
schedule_node initBody;
schedule_node schedule;

auto matcher =
    band(schedule,
        sequence(
            filter(initBody,
                hasGemmInitPattern,
                leaf()),

            filter(body,
                hasGemmPattern,
                leaf())));
```



Loop Tactics Access Relation Matchers

Access Relation Matcher: Matches tensor accesses

```
auto hasGemmPattern = [&](schedule_node node) {
  auto _i = placeholder();
  auto _j = placeholder();
  auto _k = placeholder();
  auto _A = arrayPlaceholder();
  auto _B = arrayPlaceholder();
  auto _C = arrayPlaceholder();

  auto reads = /* get read accesses */;
  auto writes = /* get write accesses */;
  auto mRead = allOf(
      access(_C, _i, _j),
      access(_A, _i, _k),
      access(_B, _k, _j));

  auto mWrite = allOf(access(_C, _i, _j));
  return match(reads, mRead).size() == 1 &&
         match(writes, mWrite).size() == 1;
};
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Additionally match leaf expressions

Loop Tactics: Tree Builders

Tree Builder generates Subtree after Transformation

```
auto builder =
  mark ([&]() { return marker() },
    band([&]() { return schedule.getSchedule() },
      sequence(
        filter([&]() { return initBody.getFilter() }),
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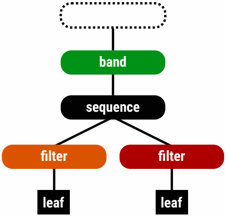

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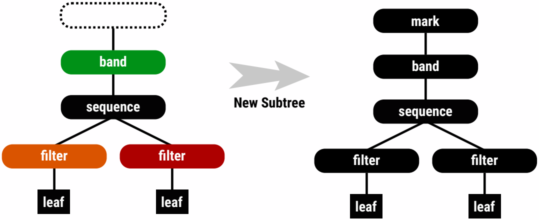

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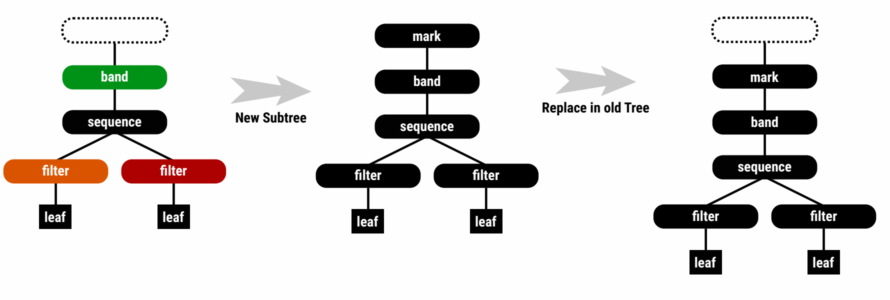

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- Test robustness against prior Transposition / Tiling

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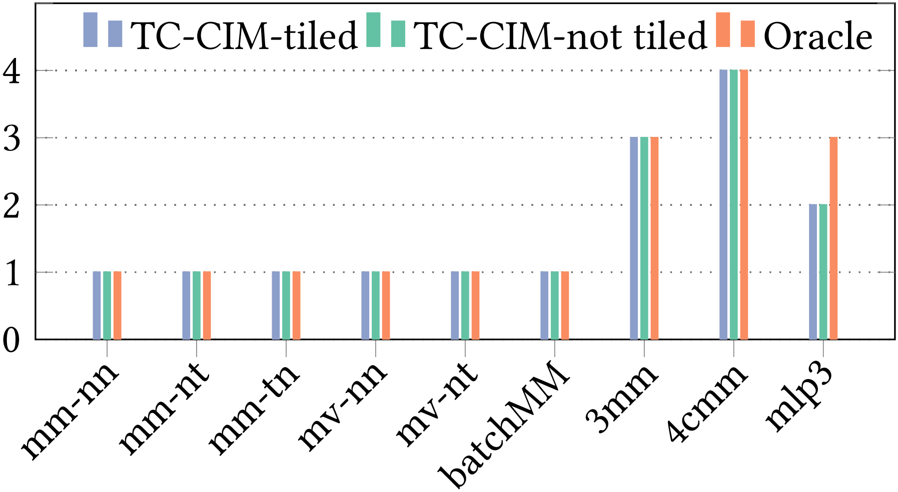
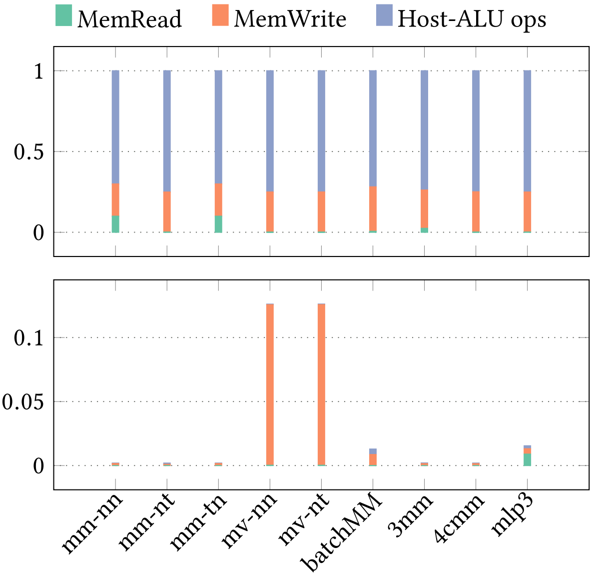
Dynamic Impact

- Dynamic instruction count unoptimized vs. optimized version

Detected Patterns in the Code



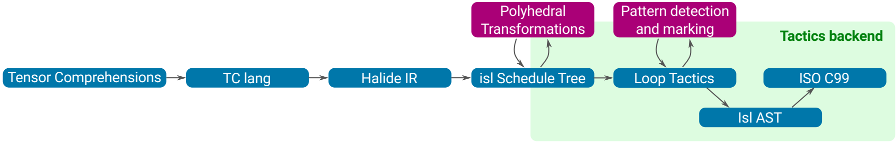
Breakdown of Dynamic Host CPU Instructions



No offloading (host CPU only)

With offloading Normalized to #instructions without offloading

Positioning in the Pipeline



Matching after Affine Scheduling without Rescheduling:

- Leverages enabling transformations (e.g., fusion, tiling)
- Initial schedule as canonical form (e.g., permutability, band coalescing)
- No feedback for transformations (e.g., no architecture-specific tiling, fusion decisions, etc.)
- Complexity of matchers rises with prior transformations

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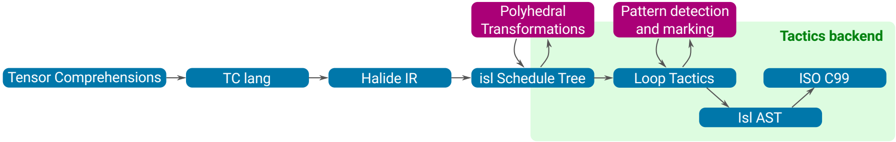

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- Complexity of matchers rises with prior transformations

Matching earlier (at higher level of abstraction)

- More high-level information for matchers
- Simpler matchers & builders
- Less / no benefits from affine transformations

Summary and Future Work

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- TC-CIM: Compilation flow for (CIM) accelerators
- Integration of Loop Tactics into Tensor Comprehensions
- Reliable detection + significant dynamic impact

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Future Work

- Explore positioning in the pipeline
- More complex matchers: fusion / minimizing data transfers
- Matching in MLIR (e.g., raise from lower-level dialects to high-level dialects)