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Towards Compositional and Generative Tensor Optimizations

Adilla Susungi, Norman A. Rink, Jerónimo Castrillón, Immo Huismann, Albert Cohen, Claude Tadonki, Jörg Stiller and Jochen Fröhlich

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Tensors in Computational Fluid Dynamics (CFD)

- Loop characteristics:
  - 3 to 4 dimensions nesting
  - Few iterations per dimension (e.g., 17 or 33 iterations)
- Type of computations:
  - Tensor contractions
  - Outer products
  - Element-wise multiplications
- Computations on each element of a structured mesh

Inverse Helmholtz

\[
\begin{align*}
t_{ijk} &= \sum_{l,m,n} A_{kln}^T \cdot A_{jm}^T \cdot A_{il}^T \cdot w_{lmn} \\
p_{ijk} &= D_{ijk} \cdot t_{ijk} \\
v_{ijk} &= \sum_{l,m,n} A_{kln} \cdot A_{jm} \cdot A_{il} \cdot p_{lmn}
\end{align*}
\]

Tensor Optimization Frameworks

- Domain-specific expressivity
- Flexible/Adaptive optimization heuristics
- Hidden and/or rigid optimization heuristics

Related Work

- Different levels of expressiveness and control on optimizations
  - Flexible/adaptive
  - Hidden/rigid

- Specific
- Generic

- Chill
- Pluto
- TensorFlow
- TVM
- Tensor Contraction Engine
- Numpy
- Tensor Algebra Compiler

Optimizing CFD Kernels with Existing Tools

- Several limitations
- Few opportunities for adaptations

Goal

A cross-domain intermediate language for tensor optimizations

Intermediate Language

- Modular constructs
- First-class citizens:
  - Arrays
  - Tensor operators
  - Loop iterators
  - Transformations

Envisioned Tool

- Meta-programming
- Iterative search

Search Space Exploration

- Evaluation order of tensor contractions
- Fusions
- Permutations
- Vectorization
- Collapsing
- Unrolling

In reverse Helmholtz by Example

```
# Basic array declaration
A = array(2, double, [N, N])
u = array(3, double, [N, N, N])
D = array(3, double, [N, N, N])

# Transposition
At = vtranspose(A, 1, 2)

# Tensor contractions
tmp1 = contract(At, u, [2, 1])
tmp2 = contract(At, tmp1, [2, 2])
tmp3 = contract(At, tmp2, [2, 3])

# Element-wise multiplication
tmp4 = entrywise(D, tmp3)

# Tensor contractions
tmp5 = contract(A, tmp4, [2, 1])
tmp6 = contract(A, tmp5, [2, 2])

# Iterator declaration
i1 = iterator(0, N, 1)
i2 = iterator(0, N, 1)

# Association of iterators
build(D, [td1, td2, td3])
build(tmp1, [i1, 12, 13, i4])
build(tmp2, [k12, k22, k32, k42])

# Optimize
build(v, [k12, k22, k32, k42])
```

Example of assessment: Different heuristics of loop interchanges (+ parallelization)

```
L1
L2
L3
Baseline: sequential execution (3.32s). Machine: 24-core Intel(R) Xeon(R) CPU E5-2680 v3 @ 2.50GHz (Haswell)
```

Future Work

- Applications to other domains
- Syntax refinement
- Formal semantics

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