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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
adilla.susungi@mines-paristech.fr
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norman.rink@tu-dresden.de
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
\[ t_{ijk} = \sum_{l,m,n} A^T_{kl} \cdot A^T_{jm} \cdot A^T_{il} \cdot u_{lmn} \]
\[ p_{ijk} = D_{ijk} \cdot t_{ijk} \]
\[ v_{ijk} = \sum_{l,m,n} A_{kn} \cdot A_{jm} \cdot A_{il} \cdot p_{lmn} \]

Tensor Optimization Frameworks
Domain-specific expressivity
Flexible/Adaptive optimization heuristics
Hidden and/or rigid optimization heuristics
Generic expressivity

Related Work
Different levels of expressiveness and control on optimizations
Flexible/adaptive
Hidden/rigid
Specific
Generic

Optimizing CFD Kernels with Existing Tools
Several limitations
- Few opportunities for adaptations
Limited expressivity
Limited optimizations
Unadapted heuristics
Unadapted constructs

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

Inverse 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])

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

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

# Tensor contractions
tmp5 = contract(A, tmp4, [2, 1])
tmp6 = contract(A, tmp5, [2, 2])
v = contract(A, tmp6, [2, 3])

# Loop interchanges
interchange(i1, i3)
interchange(i4, i1)
interchange(j2, j1)
interchange(j1, j4)

# Transpositions
tmp2t = vtranspose(tmp2, 1, 2)
replace_array(j3, tmp2, tmp2t)
replace_array(k4, tmp3, tmp3t)
replace_array(k4, tmp3, tmp3t)

# Association of iterators to computations
build(D, [i1, i2, i3, i4])
build(v, [k12, k22, k33, k42])

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

Future Work
- Applications to other domains
- Syntax refinement
- Formal semantics

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