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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

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
\[ t_{ijk} = \sum_{l,m,n} A_{kn}^T \cdot A_{jm}^T \cdot A_{il}^T \cdot w_{lmn} \]
\[ p_{ijk} = D_{ijk} \cdot t_{ijk} \]
\[ v_{ijk} = \sum_{l,m,n} A_{kn} \cdot A_{jm} \cdot A_{il} \cdot p_{lmn} \]

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

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

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

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, 2])

# Tensor operators
A_Tkn = transpose(A, n, k)

# 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(i4, i3)
interchange(i4, i2)
interchange(j2, j1)
interchange(j1, j4)

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

# Association of iterators
build(D, [td1, td2, td3])
build(tmp1, [i1, i2, i3, i4])

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

Optimizing CFD Kernels with Existing Tools
- Several limitations
- Few opportunities for adaptations

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

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

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