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Towards Compositional and Generative Tensor Optimizations
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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
\[ t_{ijk} = \sum_{l,m,n} A^T_{kn} \cdot A^T_{jm} \cdot A^T_{il} \cdot w_{lmn} \]
\[ p_{ijk} = D_{ijk} \cdot t_{ijk} \]
\[ v_{ijk} = \sum_{l,m,n} A_{kn} \cdot A_{jm} \cdot A_{il} \cdot p_{lmn} \]

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

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

Tensor Optimization Frameworks
- 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
- Interpreting/compiling
- Meta-programming
- Iterative search

Search Space Exploration
- Evaluation order of tensor contractions
- Fusions
- Permutations
- Vectorization
- Collapsing
- Unrolling

Inverse Helmholtz by Example

# Basic array declaration
\[ A = \text{array}(2, \text{double}, [N, N]) \]
\[ u = \text{array}(3, \text{double}, [N, N, N]) \]
\[ D = \text{array}(3, \text{double}, [N, N, N]) \]

# Transposition
\[ At = \text{vtranspose}(A, 1, 2) \]

# Tensor contractions
\[ tmp1 = \text{contract}(At, u, [2, 1]) \]
\[ tmp2 = \text{contract}(At, tmp1, [2, 2]) \]
\[ v = \text{contract}(A, tmp6, [2, 3]) \]

# Iterator declaration
\[ i1 = \text{iterator}(0, N, 1) \]
\[ i2 = \text{iterator}(0, N, 1) \]

# Association of iterators to computations
build(D, [td1, td2, td3])
build(tmp4, [i1, i2, i3, i4])
build(v, [k12, k22, k32, k42])

Search Space Exploration
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Future Work
- Applications to other domains
- Syntax refinement
- Formal semantics

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