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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

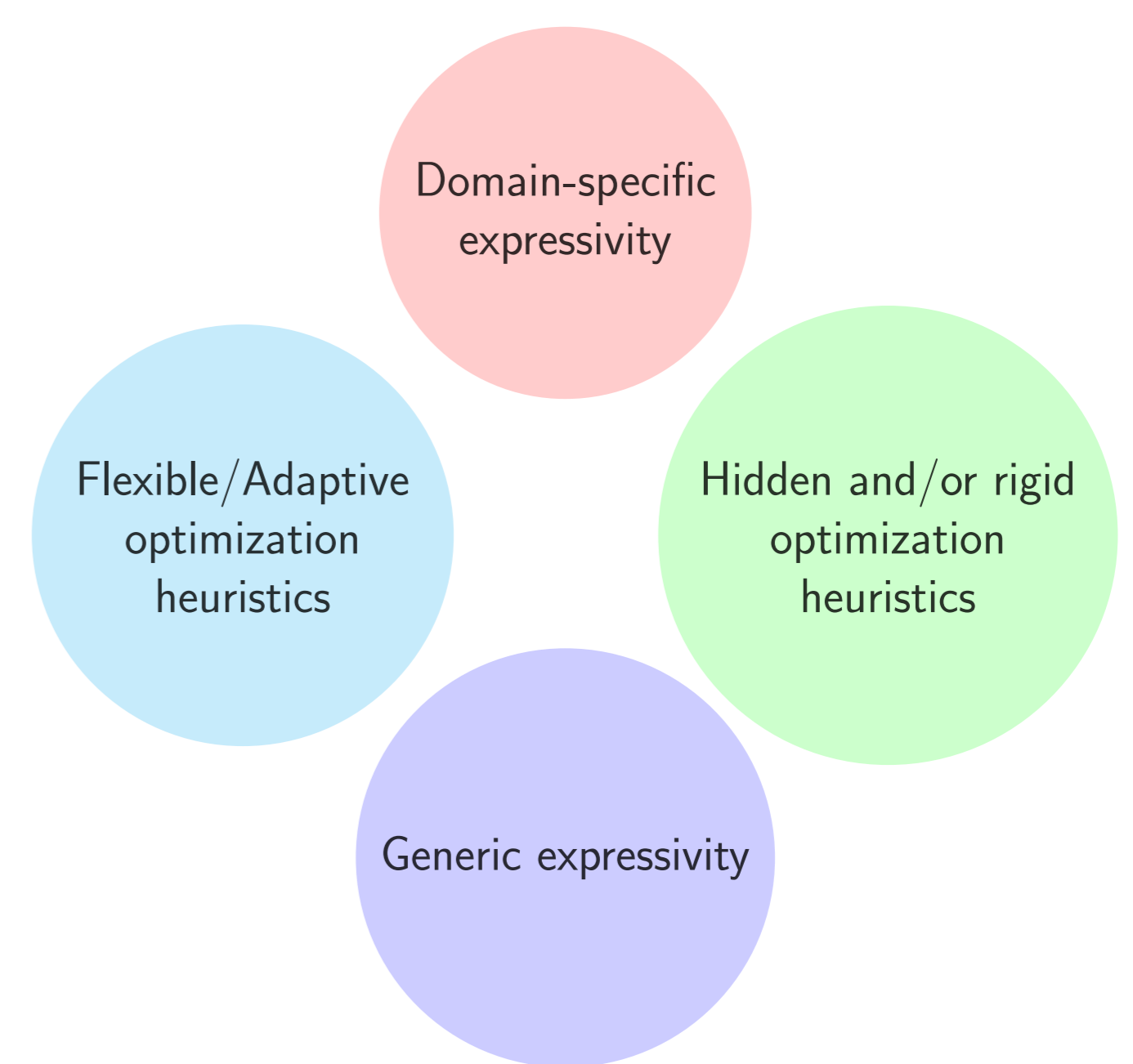
Inverse Helmholtz

$$t_{ijk} = \sum_{l,m,n} A_{kn}^T \cdot A_{jm}^T \cdot A_{il}^T \cdot u_{lmn}$$

$$p_{ijk} = D_{ijk} \cdot t_{ijk}$$

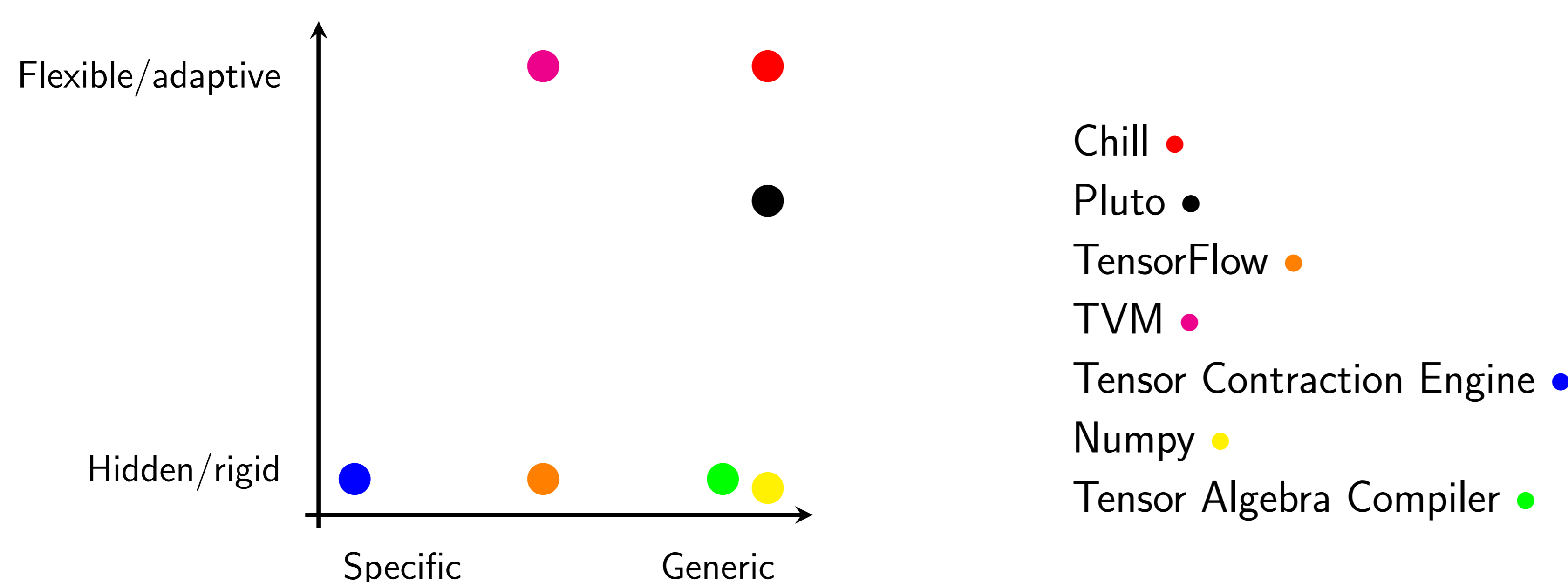
$$v_{ijk} = \sum_{l,m,n} A_{kn} \cdot A_{jm} \cdot A_{il} \cdot p_{lmn}$$

Tensor Optimization Frameworks



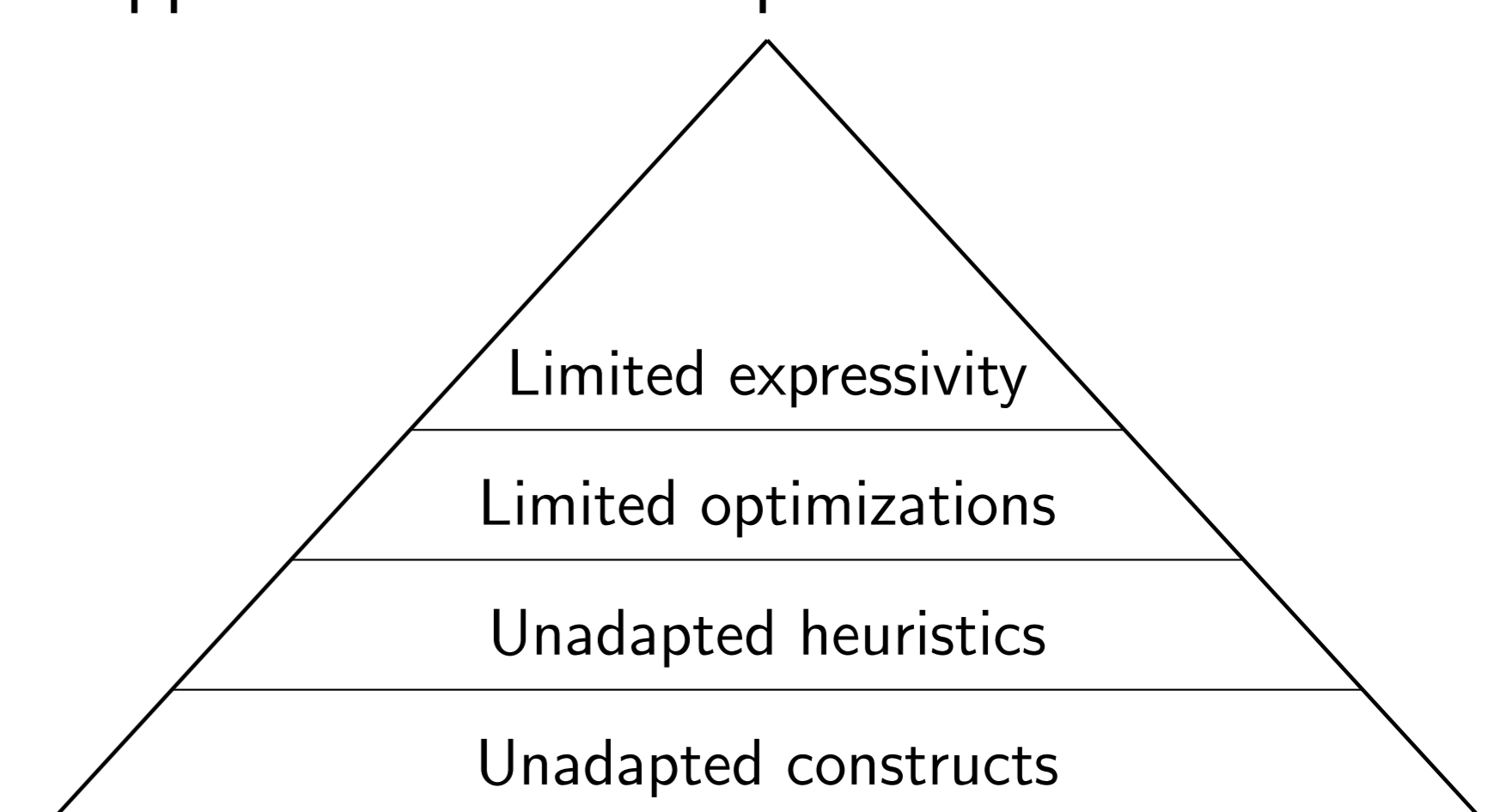
Related Work

- Different levels of expressiveness and control on optimizations



Optimizing CFD Kernels with Existing Tools

- Several limitations
- Few opportunities for adaptations



Should we create yet another domain-specific solution?

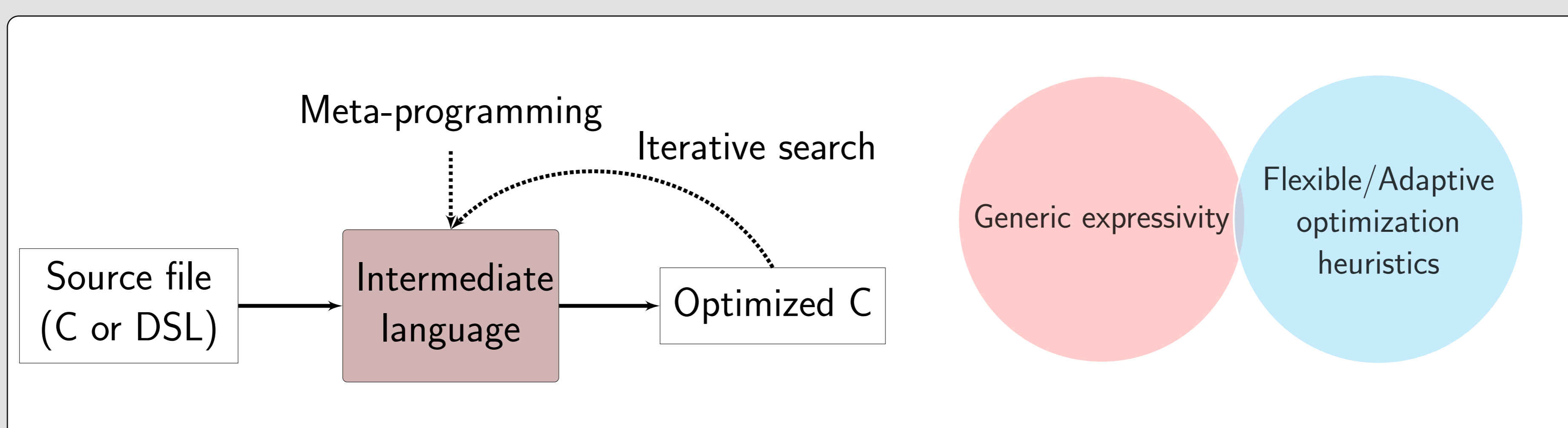
Goal

A cross-domain intermediate language for tensor optimizations

Intermediate Language

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

Envisioned Tool



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])

# 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])

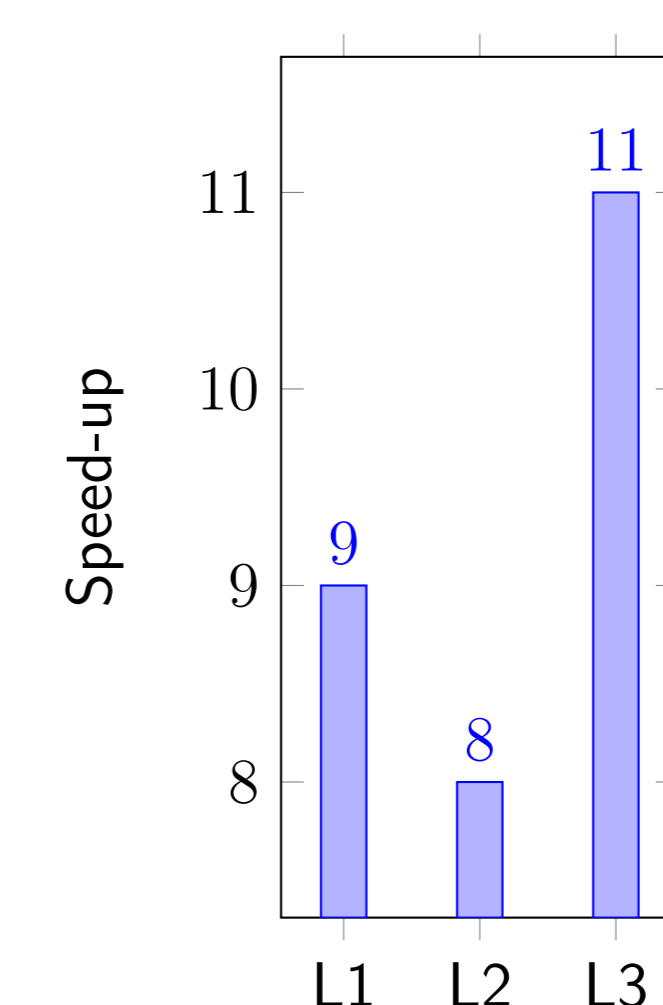
# Iterator declaration
i1 = iterator(0, N, 1)
i2 = iterator(0, N, 1)
# ... other iterator declarations

# Association of iterators
# to computations
build(D, [td1, td2, td3])
build(tmp1, [i1, i2, i3, i4])
# Also applies to tmp2, ..., tmp6
build(v, [k12, k22, k32, k42])

# 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)
tmp3t = vtranspose(tmp3, 1, 3)
replace_array(k4, tmp3, tmp3t)
interchange(k3, k2)
# ... other optimizations
```

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



- Variant L1: Loop interchanges only;
- Variant L2: Loop interchanges + data transpositions with copying;
- Variant L3: Loop interchanges + data transpositions without copying.

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

