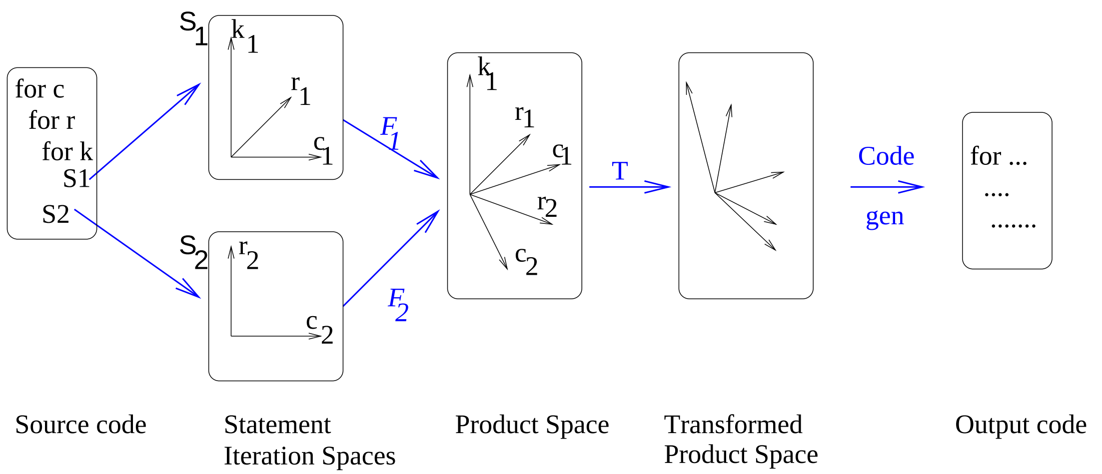
Locality Enhancement for Imperfectly-nested Loops

General approach



- Each statement has a statement iteration space.
- Product space: Cartesian product of individual statement interation spaces.
- Each statement iteration space is embedded into product space using affine embedding functions F_i.
- Product space is transformed using linear loop transformations to enhance locality.
- Code is produced to scan points in final space.

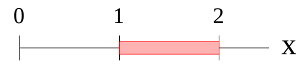
Key result required to compute embeddings:

Farkas's Lemma: Any affine function $f(x)$ which is non-negative everywhere in a polyhedron $Ax + b \geq 0$ can be represented as follows:

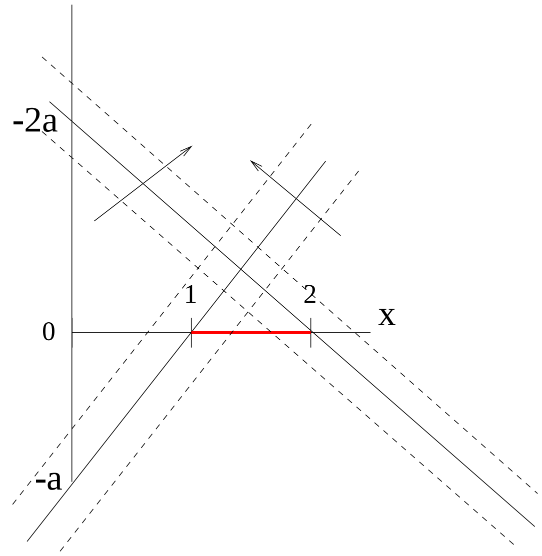
$$f(x) = \lambda_0 + \Lambda^T(Ax + b) \text{ where } \lambda_0 \geq 0, \Lambda \geq 0$$

In words: any function that is positive everywhere in a polyhedron $Ax + b \geq 0$ can be expressed as a positive linear combination of the rows of the vector $Ax + b$.

Example for Farkas's Lemma: Let $f(x) = ax + b$ be non-negative in domain



What are constraints on a and b?



It is easy to see geometrically that

if a is +ve, then $b \geq -a$ if a is -ve, then $b \geq -2a$

How do we deduce this algebraically?

Domain:

$x - 1 \geq 0$

$2 - x \geq 0$

Function: $f(x) = ax + b$

From Farkas's lemma, we can write

$f(x) = \lambda_0 + \lambda_1(x - 1) + \lambda_2(2 - x)$

Equating coefficients for the two expressions for f, we see that

$\lambda_0 - \lambda_1 + 2\lambda_2 = b$

$\lambda_1 - \lambda_2 = a$

$\lambda_0 \geq 0$

$\lambda_1 \geq 0$

$\lambda_2 \geq 0$

Use Fourier-Motzkin elimination to eliminate λ's from system:

$$\lambda_0 - \lambda_1 + 2\lambda_2 = b$$

$$\lambda_1 - \lambda_2 = a$$

$$\lambda_0 \geq 0$$

$$\lambda_1 \geq 0$$

$$\lambda_2 \geq 0$$

to get

$$(b + a) \geq max(-a, 0)$$

which is equivalent to what we determined geometrically.

Determining embeddings for legality

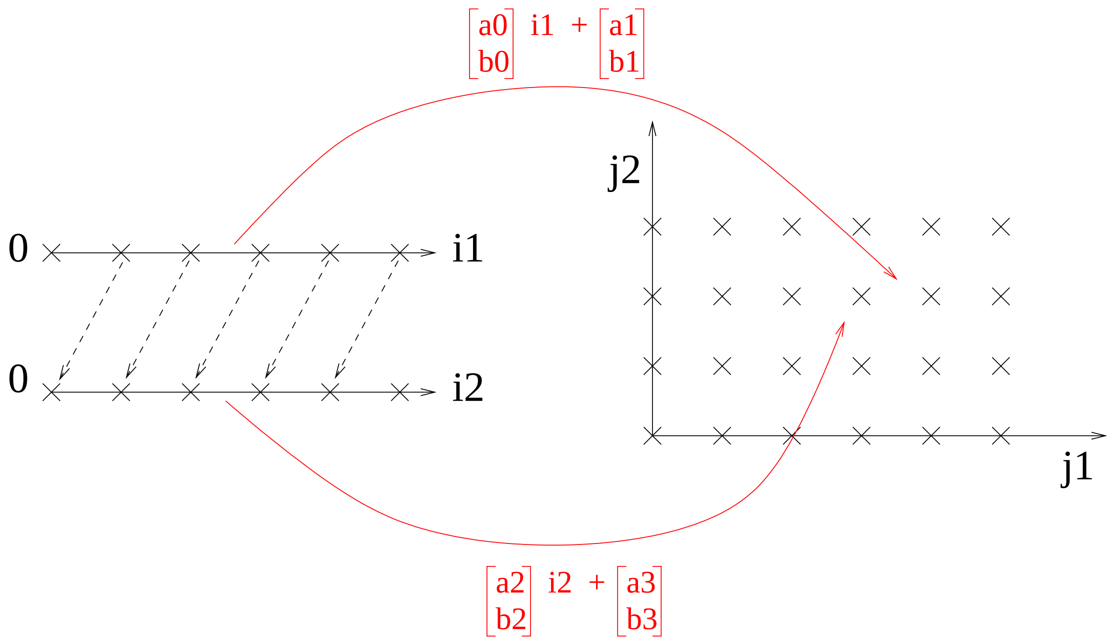
Let us consider a simpler problem than locality enhancement:

Given an imperfectly nested loop,

find embeddings into product space to generate a legal program (lexicographic order of execution in product space is legal).

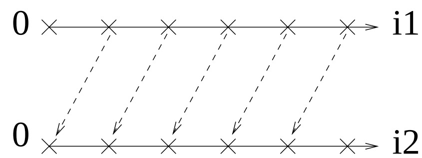
Example for embeddings:

```
S1: for i1 = 0, N-1                for j1 = -inf, inf
          A(i1) = ....               for j2 = -inf, inf
                              =>      if (S1(m) is mapped to (j1,j2))
S2: for i2 = 0, N-1                       execute S1(m);
          sum = sum + A(i2+1)         if (S2(n) is mapped to (j1,j2))
                                          execute S2(n);
```



Dependence polyhedron:

```
S1: for i1 = 0, N-1
      A(i1) = ....
S2: for i2 = 0, N-1
      sum = sum + A(i2+1)
```



$i1 = i2 + 1$

$0 \leq i1 \leq N - 1$

$0 \leq i2 \leq N - 1$

which can be written as follows:

$$\begin{pmatrix} -1 & 1 & 0 \\ 1 & -1 & 0 \\ 1 & 0 & 0 \\ -1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & -1 & 1 \end{pmatrix} \begin{pmatrix} i1 \\ i2 \\ N \end{pmatrix} + \begin{pmatrix} 1 \\ -1 \\ 0 \\ -1 \\ 0 \\ -1 \end{pmatrix} \geq 0$$

Let us write this as:

$$D \begin{pmatrix} i1 \\ i2 \\ N \end{pmatrix} + \underline{d} \geq 0$$

Constraint on embeddings:

$$\begin{pmatrix} a0 \\ b0 \end{pmatrix} i1 + \begin{pmatrix} a1 \\ b1 \end{pmatrix} \preceq \begin{pmatrix} a2 \\ b2 \end{pmatrix} i2 + \begin{pmatrix} a3 \\ b3 \end{pmatrix}$$

Let us first determine embeddings that make the first dimension of difference vector between dependent iterations +ve.

We want $f(x) = a2 * i2 + a3 - a0 * i1 - a1 > 0$

which can be written as $f(x) = a2 * i2 + a3 - a0 * i1 - a1 - 1 \geq 0$

Using Farkas's lemma, we can write this as follows:

$f(x) = a2 * i2 + a3 - a0 * i1 - a1 - 1 \geq 0 - - - - - -(1)$

$$f(x) = \lambda_0 + \Lambda^T(D * \begin{pmatrix} i1 \\ i2 \\ N \end{pmatrix} + \underline{d}) - - - - - -(2)$$

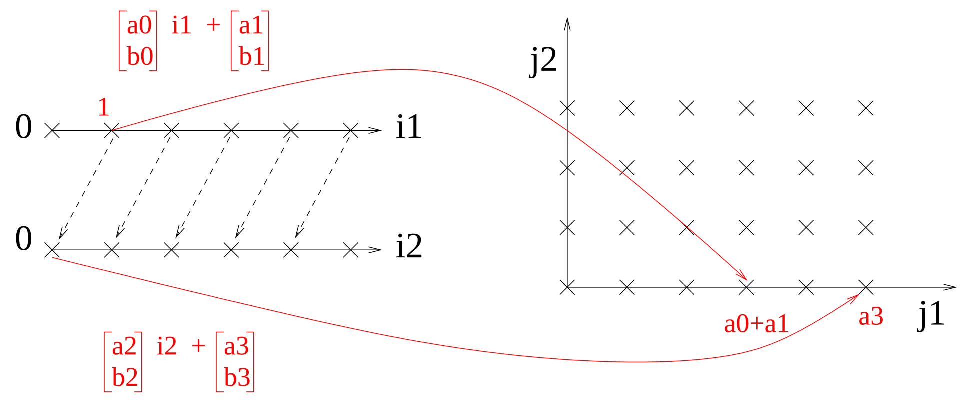
Equating coefficients, we get:

$$\begin{aligned} -a0 &= -\lambda_1 + \lambda_2 + \lambda_3 - \lambda_4 \\ a2 &= \lambda_1 - \lambda_2 + \lambda_5 - \lambda_6 \\ \lambda_4 + \lambda_6 &= 0 \\ a3 - a1 &= \lambda_0 + \lambda_1 - \lambda_2 - \lambda_4 - \lambda_6 \end{aligned}$$

Using Fourier-Motzkin elimination to eliminate the λ's, we get the following constraints on the coefficients of the embedding functions:

$$
\begin{aligned}
a0 + a1 &< a3 \\
a0 &\leq a2
\end{aligned}
$$

Let us see geometrically why this makes sense!



$$a0 + a1 < a3$$

$$a0 \leq a2$$

First constraint ensures that first two dependent points are in correct order.

Second constraint ensures that "jumps" to successive points are always larger for S2 than S1.

Other choices for embedding functions:

$$\begin{pmatrix} a0 \\ b0 \end{pmatrix} i1 + \begin{pmatrix} a1 \\ b1 \end{pmatrix} \preceq \begin{pmatrix} a2 \\ b2 \end{pmatrix} i2 + \begin{pmatrix} a3 \\ b3 \end{pmatrix}$$

- Make first dimension of difference vector = 0 within dependence polyhedron
  $a0 * i1 + a1 = a2 * i2 + a3$
  This can be expressed as two inequalities, and two applications of Farkas's lemma gives $a0 + a1 = a3, a0 = a2$.
- Make second dimension of difference vector positive within dependence polyhedron
  $g(x) = (b2 * i2 + b3) - (b0 * i1 + b1) > 0$
  This gives $b0 + b1 < b3, b0 \leq b2$.

Complete solution for legal embeddings:

- Dependence vector of form $(+, *)^{\mathrm{T}}$

$$a0 + a1 < a3$$

$$a0 \leq a2$$

- Dependence vector of form $(0, +)^{\mathrm{T}}$

$$a0 + a1 = a3$$

$$a0 = a2$$

$$b0 + b1 < b3$$

$$b0 \leq b2$$

- We can also get a dependence vector of form $(0, 0)^{\mathrm{T}}$

General picture for determining embeddings into product space:

Statement iteration spaces: $I_1, I_2, ..., I_n$

Product space: $I_1 \times I_2 ... \times I_n$

Embeddings: $F_1, F_2, ..., F_n$

Dependence polyhedra: $(D_1, d_1), (D_2, d_2), ..., (D_k, d_k)$

Legality:

$\forall (D_m, d_m) \forall (i_j \rightarrow i_k) \in (D_m, d_m) . F_k(i_k) - F_j(i_j) \succeq 0$

Solving for embeddings: solve for each dimension of P

1. first dimension: all difference vector entries must be positive or zero
2. remaining dimensions: satisfied dependences can be dropped

Small caveat: we want to avoid a solution in which all statement instances get mapped to a single point in product space!!

This is a trivial solution and is not very useful.

Our solution:

Restrict F_i to act like the identity in the subspace I_i of the product space.

There may be other ways to solve this problem, but this seems to work fine in practice.

Determining embeddings that promote locality:

Reuse polyhedra: formulate similar to dependence polyhedra

One strategy:

- find legal embeddings F_i
- for each legal embedding, find best transformation T
- pick best one

Too many possibilities....

One approach: starting with first dimension, determine embeddings dimension by dimension, choosing embeddings for a dimension before going on to next one.

Seems to work fine in practice, but in principle, it may fail to find legal embeddings....

Sketch of greedy algorithm: [Ahmed,Mateev,Pingali (ICS'00)]

Go dimension by dimension trying to

- height reduce reuse classes
- make entries of dependence vectors positive to enable tiling

To avoid combinatorial explosion, pick embeddings for each dimension before looking at succeeding dimensions.

```
DU = set of all unsatisfied dependence classes;
DS = set of all satisfied dependence classes;
RS = ordered set of all reuse classes sorted by priority;
for each dimension p of product space P do
  { L = Legality Constraints(p,DU,DS);
    if system L has solutions
     {Embedding coefficients for dimension p =
        PromoteReuse(p,L,RS);
      Update DS and DU;
     }
    else abort;
  }
```

```
ALGORITHM LegalityConstraints(q, DU, DS ) {
 /*
   q is dimension being processed.
   DU is set of unsatisfied dependence classes.
   DS is set of satisfied dependence classes.
 */

  Construct system Temp constraining the qth dimension
    of every embedding function as follows:

  for each unsatisfied dependence class u ∈ DU
     Add constraints so that each entry in dimension q
       of all difference vectors of u is non-negative;
  //enable tiling by considering satisfied dependence classes as well
  for each satisfied dependence class s ∈ DS
     Add constraints so that each entry in dimension q
       of all difference vectors of s is non-negative;

  Use Farkas' lemma to convert system Temp into
    a system L constraining unknown embedding
    coefficients;

  Return L; }
```

```
ALGORITHM PromoteReuse(q,L,RS) {
 /*
   q is dimension being processed.
   L is a system constraining unknown embedding coefficients.
   RS is set of prioritized reuse classes.
 */


L':= L
for every reuse class R in RS in priority order
 {
    Z := System constraining unknown embedding function
         coefficients so qth dimension entries of
         all reuse vectors of class R is zero

    if (L' ∩ Z ≠ ∅)
     {
         L' := L' ∩ Z
     }
 }
 return any set of coefficients satisfying L';
}
```

Limitation of this algorithm: does not consider T, so we do not consider illegal embeddings that can be "fixed" by choosing T appropriately.

Solution: determine T and embeddings simultaneously.

See paper for details.

Next slide shows the kind of modifications that need to be made.

Modification to permit skewing T:

```
ALGORITHM LegalityConstraints(q, DU, DS ) {
 /*
   q is dimension being processed.
   DU is set of unsatisfied dependence classes.
   DS is set of satisfied dependence classes.
 */
  Construct system Temp constraining the qth dimension
    of every embedding function as follows:

  for each unsatisfied dependence class u ∈ DU
     Add constraints so that each entry in dimension q
       of all difference vectors of u is non-negative;
  //enable tiling by considering satisfied dependence classes as well
  //permit skewing to enable tiling
  for each satisfied dependence class s ∈ DS
     Add constraints so that each entry in dimension q
       of all difference vectors of s + positive α
       is non-negative; //skewing later will eliminate -ve entries

  Use Farkas' lemma to convert system Temp into
    a system L constraining unknown embedding
    coefficients;
  Return L; }
```

```
ALGORITHM LocalityEnhancement {
Q  := Set of dimensions of product space;
DU := Set of unsatisfied dependence classes
            (initialized to all dependence classes);
DS := Set of satisfied dependence classes
            (initialized to empty set);
RS := Set of reuse classes of the program
            (sorted by priority);
j  := Current dimension in transformed product space
            (initialized to 1);
while (Q is non-empty)
 {for each q in Q
    {L = LegalityConstraints(q, DU, DS);
       if system L has solutions
        {   Embedding coefficients for dimension j =
               PromoteReuse(q,L,RS);
            Update DS and DU;
            Delete q from Q;
            j = j + 1;
        }
     }
   // No more dimensions q can be added to current band.
   // Start a new band of fully permutable loops.
   DS := empty set;  }
```

```
Apply Algorithm  DimensionOrdering to the dimensions;
Eliminate redundant dimensions;
Tile permutable dimensions with non-zero ReusePenalty;
}
```

```
ALGORITHM DimensionOrdering

RPO  =  {i1, i2, ... ip}  // ReusePenalty order
NRPO =  ∅                 // nearby permutation

m = p  // number of dimensions left to process
k = 0   // number of dimensions processed
while  RPO ≠ ∅
 {
    for dimension j = 1,m
     {
        l = ij  ∈  RPO
        Let NRPO = {i1′, i2′, ... ik′}
        if {i1′, i2′, ... ik′, l} is legal
         {  NRPO = {i1′, i2′, ... ik′, l}
            RPO  = RPO  −  {l}
            m = m − 1
            k = k + 1
            continue while loop
         }
     }
 }
```

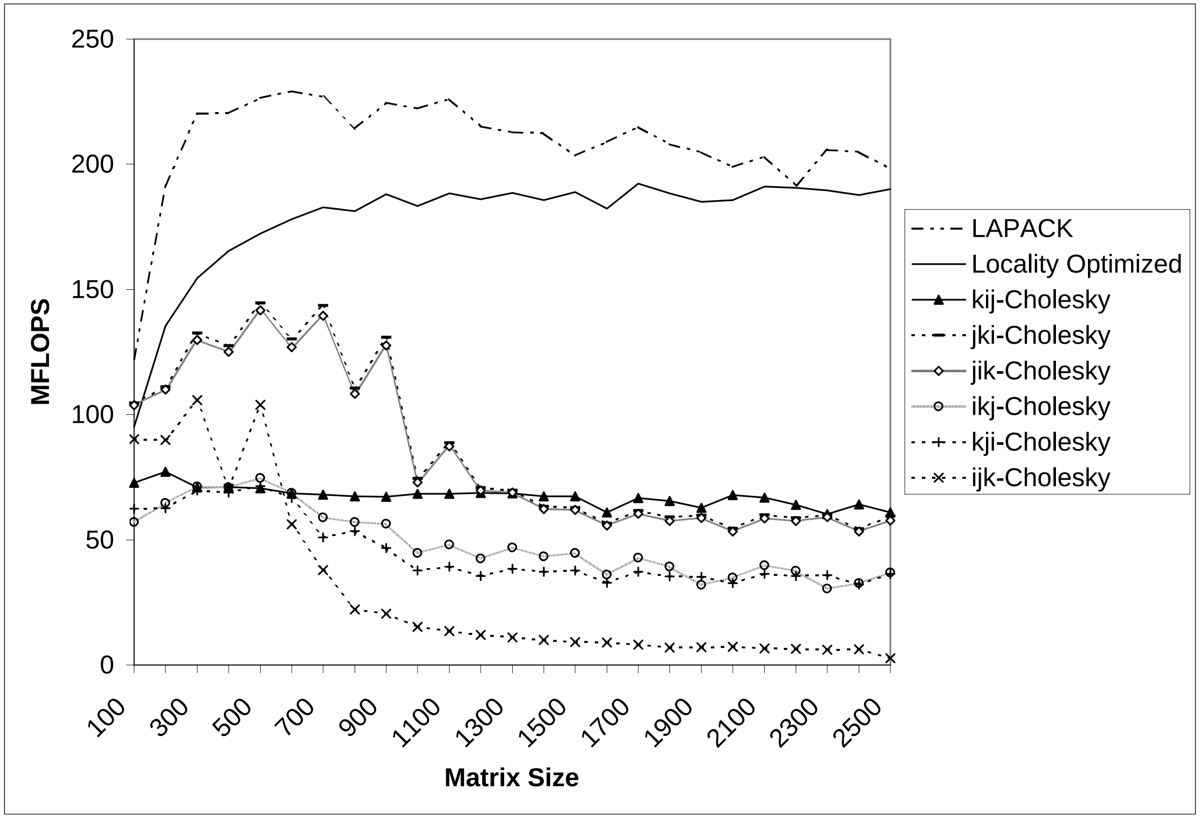
Eliminating redundant dimensions:

$\mathcal{P}$: a Cartesian space

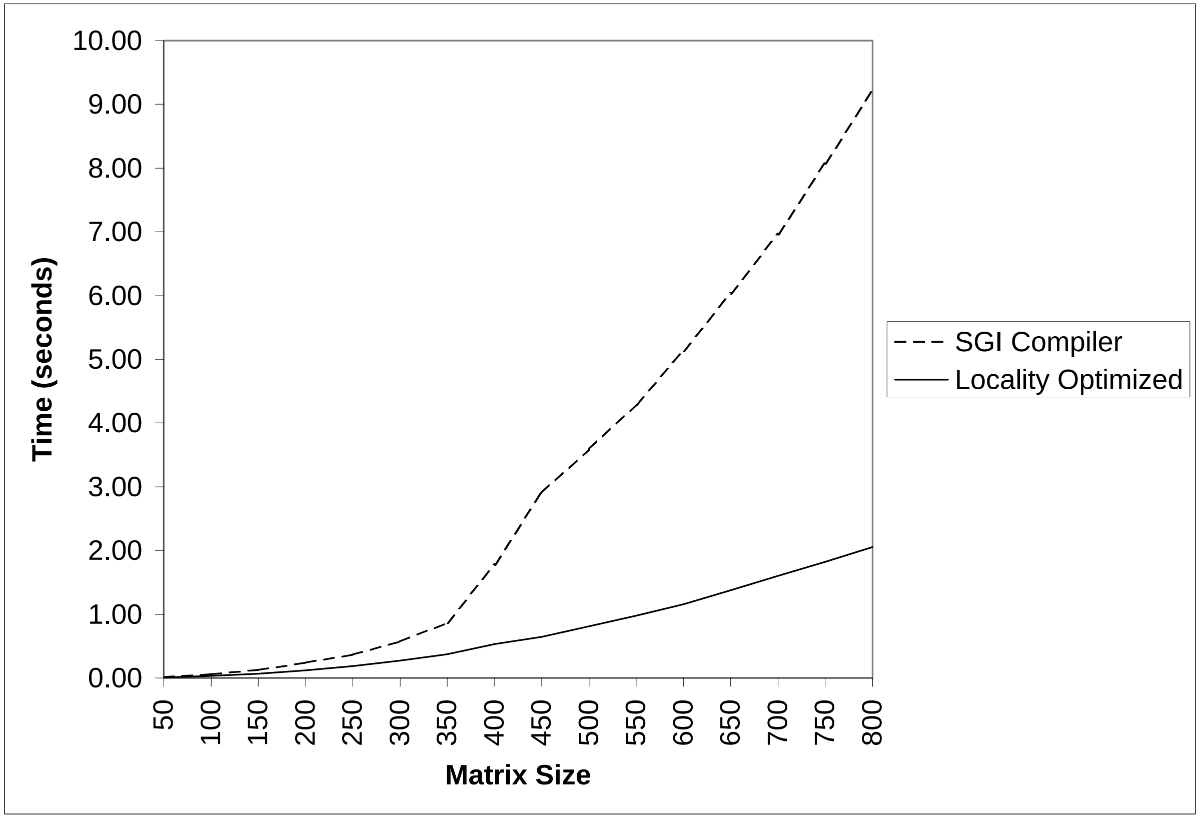
$\mathcal{F} = \{F_1, F_2, \ldots, F_n\}$: a set of affine embedding functions where $F_k(\vec{\imath}_k) = G_k \vec{\imath}_k + g_k$.

Number of independent dimensions of $\mathcal{P}$ =
number of independent rows of matrix $G = [G_1 G_2 \ldots G_n]$.

Experimental results:



Cholesky factorization on SGI Octane



Jacobi on SGI Octane

Summary

- We have seen a polyhedral framework for imperfectly-nested loop transformations.
- We can do a reasonable job of locality enhancement in
  - BLAS: inner product, MVM, MMM, triangular solve
  - Cholesky factorization
  - Relaxation codes like Jacobi and Gauss-Seidel
- Accurate tile size determination is a problem.
  Empirical optimization might be one solution.
- Block-recursive codes: we can generate block-recursive codes from iterative codes using this approach.
- Is product space tractable for large programs?
  Perhaps we can treat basic blocks as single statement.
- LU factorization with pivoting: requires fractal symbolic analysis
- QR factorization: not clear what a compiler can do