COMP 515: Advanced Compilation for Vector and Parallel Processors

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https://wiki.rice.edu/confluence/display/PARPROG/COMP515

COMP 515 Projects

- Yuhan Peng, Maggie Tang
  - DFGL transformations and OpenCL generation
- Prasanth Chatarasi
  - Polyhedral extensions for data race detection
- Lucas Martinelli, Jonathan Sharman,
  - Exploration of dependences and transformations in higher level OO languages, with a focus on C++ language and libraries (RAJA, Kokkos)
- Jack Feser
  - Exploration of ILP solvers for dependence analysis
- Pete Curry, Lung Li
  - OpenCL transformations for Digital Signal Processors
- Zhipeng Wang
  - Memory Hierarchy Management for iterative graph structures.

Simple Vectorization Algorithm (Recap)

procedure vectorize (L, D)
// L is the maximal loop nest containing the statement.
// D is the dependence graph for statements in L.

1. find the set $\{S_1, S_2, \ldots, S_m\}$ of maximal strongly-connected regions in the dependence graph D restricted to L (Tarjan);

2. construct L_p from L by reducing each S_i to a single node and compute D_p, the dependence graph naturally induced on L_p by D;

3. let $\{p_1, p_2, \ldots, p_m\}$ be the m nodes of L_p numbered in an order consistent with D_p (use topological sort);

4. for i = 1 to m do begin
    if p_i is a dependence cycle then
      generate a DO-loop nest around the statements in p_i;
    else
      directly rewrite p_i in Fortran 90, vectorizing it with respect to every loop containing it;
  end

end vectorize

Problems With Simple Vectorization

```
    DO I = 1, N
            DO J = 1, M
S1                  A(I+1,J) = A(I,J) + B
            ENDDO
    ENDDO
```

- **Dependence from S_1 to itself with d(i, j) = (1,0)**
- **Key observation: Since dependence is at level 1, we can vectorize the inner loop!**
- **Can be converted to:**

```
    DO I = 1, N
S1    A(I+1,1:M) = A(I,1:M) + B
    ENDDO
```

- **The simple algorithm does not capitalize on such opportunities**

Advanced Vectorization Algorithm (Recursive "codegen" procedure)

procedure codegen(R, k, D);
// R is the region for which we must generate code.
// k is the minimum nesting level of possible parallel loops.
// D is the dependence graph among statements in R..

1. find the set $\{S_1, S_2, \ldots, S_m\}$ of maximal strongly-connected regions in the dependence graph D restricted to R;
2. construct R_p from R by reducing each S_i to a single node and compute D_p, the dependence graph naturally induced on R_p by D;
3. let $\{p_1, p_2, \ldots, p_m\}$ be the m nodes of R_p numbered in an order consistent with D_p (topological sort);
4. for i = 1 to m do begin

   if p_i is cyclic then begin

      generate a level-k DO statement;

      let D_i be the dependence graph consisting of all dependence edges in D that are at level k+1 or greater and are internal to p_i;

      codegen (p_i, k+1, D_i);

      generate the level-k ENDDO statement;

   end

   else

      generate a vector statement for p_i in $r(p_i)$-k+1 dimensions, where r (p_i) is the number of loops containing p_i;

end

codegen(L, 1, D); // Root call for recursive "codegen" procedure

Advanced Vectorization Algorithm

```
DO I = 1, 100
S1        X(I) = Y(I) + 10
 DO J = 1, 100
S2           B(J) = A(J,N)
          DO K = 1, 100
S3             A(J+1,K)=B(J)+C(J,K)
          ENDDO
S4           Y(I+J) = A(J+1, N)
 ENDDO
ENDDO
```

- **codegen called at the outermost level**
- **S_1 will be vectorized, and moved later due to topological sort**

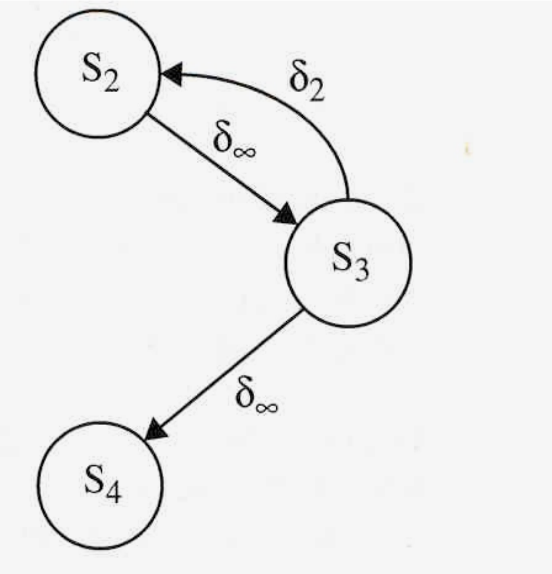
```
DO I = 1, 100
   codegen({S2, S3, S4}, 2, D)
ENDDO
X(1:100) = Y(1:100) + 10
```

Advanced Vectorization Algorithm

- codegen ({S_2, S_3, S_4}, 2, D)
- level-1 dependences are stripped off

```
DO I = 1, 100
  DO J = 1, 100
     codegen({S2, S3}, 3, D)
  ENDDO
S4  Y(I+1:I+100) = A(2:101,N)
ENDDO

X(1:100) = Y(1:100) + 10
```

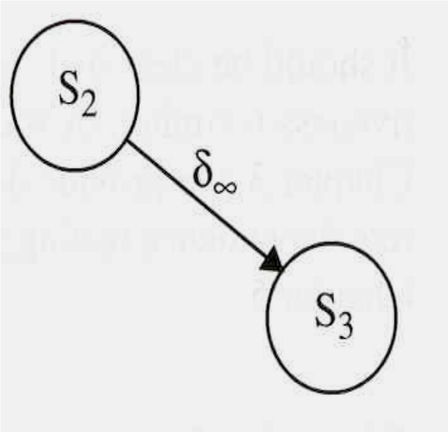


Advanced Vectorization Algorithm

- codegen ({S_2, S_3}, 3, D)
- level-2 dependences are stripped off

```
DO I = 1, 100
S1          X(I) = Y(I) + 10
 DO J = 1, 100
S2              B(J) = A(J,N)
              DO K = 1, 100
S3                A(J+1,K)=B(J)
+C(J,K)
              ENDDO
S4              Y(I+J) = A(J+1, N)
 ENDDO
ENDDO
```

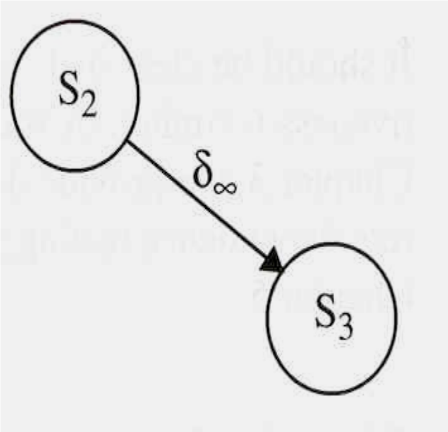
```
DO I = 1, 100
  DO J = 1, 100
    B(J) = A(J,N)
    A(J+1,1:100)=B(J)+C(J,1:100)
  ENDDO
  Y(I+1:I+100) = A(2:101,N)
ENDDO
X(1:100) = Y(1:100) + 10
```



Advanced Vectorization Algorithm (shown as distributed parallel loops)

```
DO I = 1, 100
  DO J = 1, 100
S2:     B(J) = A(J,N)
    DOALL K = 1, 100
S3:      A(J+1,K)=B(J)+C(J,K)
    ENDDO
  ENDDO
  DOALL J = 1, 100
S4:    Y(I+J) = A(J+1,N)
  END DO
ENDDO
DOALL I = 1, 100
S1:  X(I) = Y(I) + 10
END DO
```

```
DO I = 1, 100
S1          X(I) = Y(I) + 10
 DO J = 1, 100
S2              B(J) = A(J,N)
            DO K = 1, 100
S3                  A(J+1,K)=B(J)
+C(J,K)
            ENDDO
S4              Y(I+J) = A(J+1, N)
 ENDDO
ENDDO
```



Enhancing Fine-Grained Parallelism

Chapter 5 of Allen and Kennedy

Fine-Grained Parallelism

Techniques to enhance fine-grained (vector) parallelism:

- Loop Interchange
- Scalar Expansion
- Scalar Renaming
- Array Renaming

Loop Shifting (Permutation)

- **Motivation: Identify loops which can be moved and interchange them to "optimal" nesting levels**

- Theorem 5.3 **In a perfect loop nest, if loops at level** `i, i+1,...,i+n` **carry no dependence, it is always legal to shift these loops inside of loop** `i+n+1`**. Furthermore, these loops will not carry any dependences in their new position.**

Loop Shifting

```
 DO I = 1, N
   DO J = 1, N
      DO K = 1, N
S           A(I,J) = A(I,J) + B(I,K)*C(K,J)
       ENDDO
   ENDDO
 ENDDO
```

I J K
(=, =, <)

- S has true, anti and output dependences on itself, hence codegen will fail as recurrence exists at innermost level
- Use loop shifting to shift loops I and J inside loop K:

```
 DO K = 1, N
    DO I = 1, N
      DO J = 1, N
S          A(I,J) = A(I,J) + B(I,K)*C(K,J)
      ENDDO
    ENDDO
 ENDDO
```

Loop Shifting

```
 DO K= 1, N
    DO I = 1, N
      DO J = 1, N
S         A(I,J) = A(I,J) + B(I,K)*C(K,J)
      ENDDO
    ENDDO
 ENDDO
```

K I J
(<, =, =)

codegen vectorizes to:

```
 DO K = 1, N

     A(1:N,1:N) = A(1:N,1:N) + SPREAD(B(1:N,K),2)*SPREAD(C(K,1:N),1)

 ENDDO
```

Loop Selection

- Loop Shifting doesn't always find the best loop to move. Consider:

```
   DO I = 1, N
      DO J = 1, M
S        A(I+1,J+1) = A(I,J) + A(I+1,J)
      ENDDO
   ENDDO
```

- Direction matrix: $\begin{pmatrix} < & < \\ = & < \end{pmatrix}$

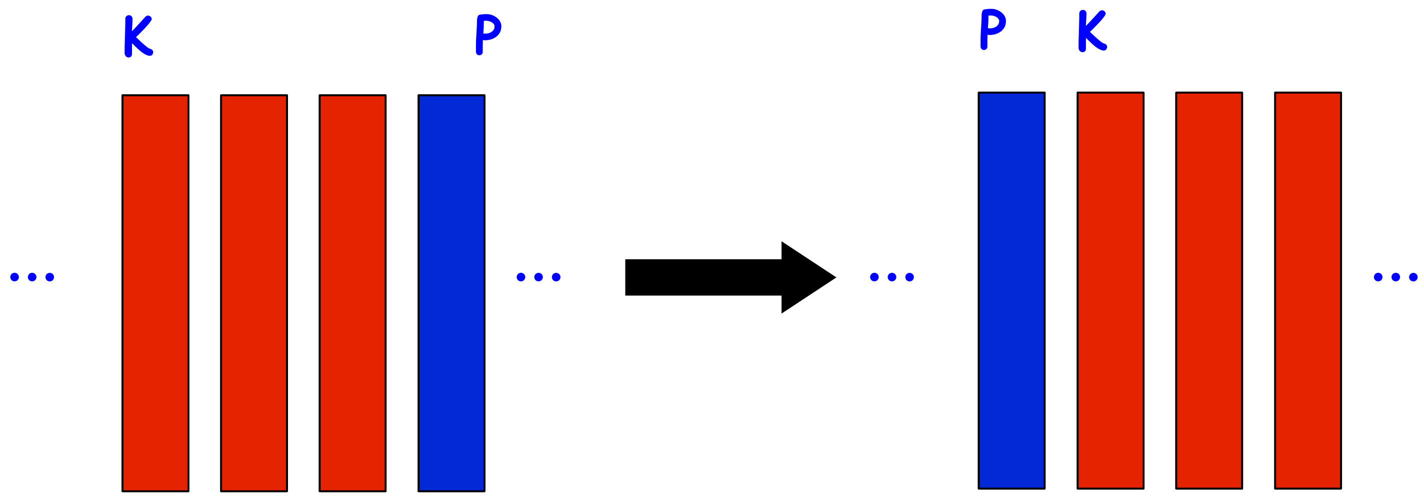
- Loop shifting algorithm will fail to uncover vector loops; however, interchanging the loops can lead to:

```
DO J = 1, M
   A(2:N+1,J+1) = A(1:N,J) + A(2:N+1,J)
ENDDO
```

- Need a more general algorithm $\begin{pmatrix} < & < \\ < & = \end{pmatrix}$

Loop Selection

- **Loop selection:**
  - Select a loop at nesting level p ≥ k that can be safely moved outward to level k and shift the loops at level k, k+1, …, p-1 inside it



Fully Permutable Loop Nest

- A contiguous set of k ≥ 1 loops, $i_j,\ldots,i_{j+k-1}$ is fully permutable if all permutations of $i_j,\ldots,i_{j+k-1}$ are legal

- Data dependence test: Loops $i_j,\ldots,i_{j+k-1}$ are fully permutable if for each dependence vector $(d_1,\ldots,d_n)$ carried at levels j … j +k-1, each of $d_j,\ldots,d_{j+k-1}$ is non-negative

- Fundamental result (to be discussed later in course): a set of k fully permutable loops can be transformed using only Interchange, Reversal and Skewing transformations into an equivalent set of k loops where k-1 of the loops are parallel

Scalar Expansion and its use in Removing Anti and Output Dependences

```
     DO I = 1, N
S1      T = A(I)
S2      A(I) = B(I)
S3      B(I) = T
     ENDDO
```

- **Scalar Expansion:**

```
     DO I = 1, N
S1      T$(I) = A(I)
S2      A(I) = B(I)
S3      B(I) = T$(I)
     ENDDO
     T = T$(N)
```

- **leads to:**

```
S1      T$(1:N) = A(1:N)
S2      A(1:N) = B(1:N)
S3      B(1:N) = T$(1:N)
        T = T$(N)
```

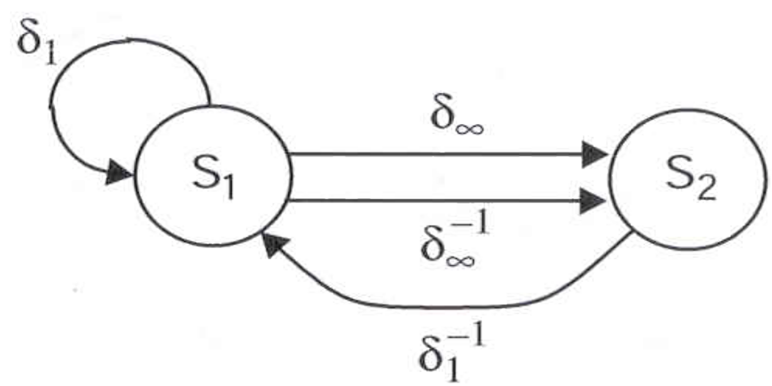
Scalar Expansion

- **However, scalar expansion (or any other form of storage duplication) is not useful in removing true dependences. Consider:**

```
 DO I = 1, N
    T = T + A(I) + A(I+1)
    A(I) = T
ENDDO
```

- **Scalar expansion gives us:**

```
    T$(0) = T
    DO I = 1, N
S1      T$(I) = T$(I-1) + A(I) + A(I+1)
S2      A(I) = T$(I)
    ENDDO
    T = T$(N)
```



Scalar Expansion: Safety

- Scalar expansion is always safe
- When is it useful?
  - Brute force approach: Expand all scalars, vectorize, shrink all unnecessary expansions.
  - However, we want to predict when expansion is useful i.e., when scalar expansion can enable a dependence edge to be deleted
- Dependences due to reuse of memory location vs. reuse of values
  - Dependences due to reuse of values must be preserved (true dependences)
  - Dependences due to reuse of memory location can be deleted by expansion (anti & output dependences)
    - This is also why functional languages are easier to parallelize, at the cost of increased memory overhead

Scalar Renaming

```
    DO I = 1, 100
S1      T = A(I) + B(I)
S2      C(I) = T + T
S3      T = D(I) - B(I)
S4      A(I+1) = T * T
   ENDDO
```

- **Renaming scalar T:**

```
DO I = 1, 100
S1      T1 = A(I) + B(I)
S2      C(I) = T1 + T1
S3      T2 = D(I) - B(I)
S4      A(I+1) = T2 * T2
   ENDDO
```

Scalar Renaming

- **will lead to:**

```
S3      T2$(1:100) = D(1:100) - B(1:100)
S4      A(2:101) = T2$(1:100) * T2$(1:100)
S1      T1$(1:100) = A(1:100) + B(1:100)
S2      C(1:100) = T1$(1:100) + T1$(1:100)
        T = T2$(100)
```

Homework #3 (Written Assignment)

1. **Solve exercise 5.6 in book**
   - Your solution should be legal for all values of K (note that the value of K is invariant in loop I)

Exercise 5.6: What vector code should be generated for the following loop?

```
DO I = 1, 100
    A(I) = B(K) + C(I)
    B(I+1) = A(I) + D(I)
END DO
```

- **Due in class on Thursday, Oct 8th**