COMP 515: Advanced Compilation for Vector and Parallel Processors

Prof. Vivek Sarkar
Department of Computer Science
Rice University
vsarkar@rice.edu

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Enhancing Fine-Grained Parallelism

(contd)

Chapter 5 of Allen and Kennedy

Scalar Expansion and its use in Removing Anti and Output Dependences (Recap)

```
     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 Renaming (Recap)

```
   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 (Recap)

- **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)
```

Scalar Renaming: Profitability

- **Scalar renaming will break recurrences in which a loop-independent output dependence or anti-dependence is a critical element of a cycle**
- **Relatively cheap to use scalar renaming**
- **Usually done by compilers when calculating live ranges for register allocation**

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Array Renaming

```
     DO I = 1, N
S1        A(I) = A(I-1) + X
S2        Y(I) = A(I) + Z
S3        A(I) = B(I) + C
     ENDDO
```

- $S_1\ \delta_\infty\ S_2$ $\quad$ $S_2\ \delta_\infty^{-1}\ S_3$ $\quad$ $S_3\ \delta_1\ S_1$ $\quad$ $S_1\ \delta_\infty^{0}\ S_3$

- **Rename A(I) to A'(I):**

```
     DO I = 1, N
S1        A'(I) = A(I-1) + X
S2        Y(I) = A'(I) + Z
S3        A(I) = B(I) + C
     ENDDO
```

- **Dependences remaining:** $S_1\ \delta_\infty\ S_2$ **and** $S_3\ \delta_1\ S_1$

Array Renaming: Profitability

- Examining dependence graph and determining minimum set of critical edges to break a recurrence is NP-complete!
- Solution: determine edges that are removed by array renaming and analyze effects on dependence graph
- procedure array_partition:
  - Assumes no control flow in loop body
  - Identifies collections of references to arrays which refer to the same value
  - Identifies deletable output dependences and antidependences
- Use this procedure to generate code
  - Minimize amount of copying back to the “original” array at the beginning and the end

Seen So Far...

- Uncovering potential vectorization in loops by
  - Loop Interchange
  - Scalar Expansion
  - Scalar and Array Renaming
- Safety and Profitability of these transformations

What's next ...

- More transformations to expose more fine-grained parallelism
  - Node Splitting
  - Recognition of Reductions
  - Index-Set Splitting
  - Run-time Symbolic Resolution
  - Loop Skewing

Today's lecture

Next lecture

- Unified framework to generate vector code
- Note: these transformations are useful for generating other forms of parallel and locality-optimized code as well (beyond vectorization)

Node Splitting

- Sometimes Renaming fails

```
DO I = 1, N
  S1:       A(I) = X(I+1) + X(I)
  S2:       X(I+1) = B(I) + 32
ENDDO
```

- Recurrence kept intact by renaming algorithm

```
DO I = 1, N
  S0:       X'(I) = X(I)
  S1:       A(I) = X(I+1) + X'(I)
  S2:       X'(I+1) = B(I) + 32
ENDDO
```

- NOTE: renaming X(I) and X(I+1) to Z(I) and Z(I+1) can help!

Node Splitting

```
DO I = 1, N
S1:  A(I) = X(I+1) + X(I)
S2:  X(I+1) = B(I) + 32
ENDDO
```

- Break critical antidependence
- Make copy of read from which antidependence emanates

```
DO I = 1, N
S1': X$ = X(I+1)
S1: A(I) = X$ + X(I)
S2: X(I+1) = B(I) + 32
ENDDO
```

```
DO I = 1, N
S1': X$(I) = X(I+1)
S1: A(I) = X$(I) + X(I)
S2: X(I+1) = B(I) + 32
ENDDO
```

- Recurrence broken
- Vectorized to

```
S1':  X$(1:N) = X(2:N+1)
S2:   X(2:N+1) = B(1:N) + 32
S1:   A(1:N) = X$(1:N) + X(1:N)
```

Node Splitting Algorithm

- Takes a constant loop independent antidependence D
- Add new assignment x: T$=source(D)
- Insert x before source(D)
- Replace source(D) with T$
- Make changes in the dependence graph

Node Splitting: Profitability

- Not always profitable
- For example

```
DO I = 1, N
S1: A(I) = X(I+1) + X(I)
S2: X(I+1) = A(I) + 32
ENDDO
```

- Node Splitting gives

```
DO I = 1, N
S1':X$(I) = X(I+1)
S1:     A(I) = X$(I) + X(I)
S2:     X(I+1) = A(I) + 32
ENDDO
```

- Recurrence still not broken
- Antidependence was not critical

Node Splitting

- **Determining minimal set of critical antidependences is NP-hard**
- **Perfect job of Node Splitting difficult**
- **Heuristic:**
  - Select antidependences
  - Delete it to see if acyclic
  - If acyclic, apply Node Splitting

Recognition of Reductions

- Sum Reduction, Min/Max Reduction, Count Reduction
- Vector ---> Single Element

```
S = 0.0
DO I = 1, N
    S = S + A(I)
ENDDO
```

- Not directly vectorizable

Recognition of Reductions

- Assuming commutativity and associativity

```
S = 0.0
DO k = 1, 4
   SUM(k) = 0.0
   DO I = k, N, 4
     SUM(k) = SUM(k) + A(I)
   ENDDO
   S = S + SUM(k)
ENDDO
```

- Distribute `k` loop

```
S = 0.0
DO k = 1, 4
    SUM(k) = 0.0
ENDDO
DO k = 1, 4
    DO I = k, N, 4
        SUM(k) = SUM(k) + A(I)
    ENDDO
ENDDO
DO k = 1, 4
    S = S + SUM(k)
ENDDO
```

Recognition of Reductions

- **After Loop Interchange**

```
DO I = 1, N, 4
  DO k = I, min(I+3,N)
    SUM(k-I+1) = SUM(k-I+1) + A(I)
  ENDDO
ENDDO
```

- **Vectorize**

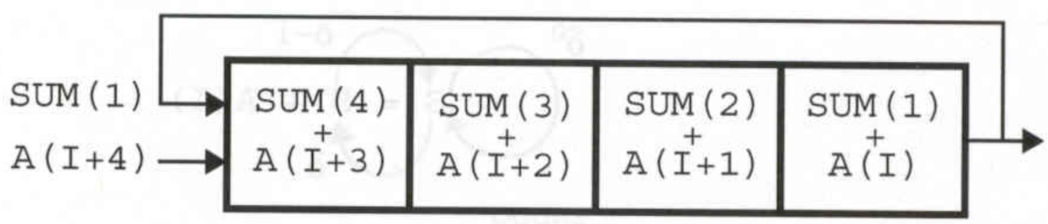
```
DO I = 1, N, 4
  SUM(1:4) = SUM(1:4) + A(I:I+3)
ENDDO
```

Recognition of Reductions

- Useful for vector machines with 4 stage pipeline, and fine-grain SIMD parallelism on modern processors (MMX, Altivec)

- Recognize Reduction and Replace by the efficient version

Pipeline for Sum Reduction.



Recognition of Reductions

- Properties of Reductions
  - Reduce Vector/Array to one element
  - No use of Intermediate values
  - Reduction operates on vector and nothing else
- Reduction recognized by
  - Presence of self true, output and anti dependences
  - Absence of other true dependences

Index-set Splitting

- Subdivide loop into different iteration ranges to achieve partial parallelization
  - Threshold Analysis [Strong SIV, Weak Crossing SIV]
  - Loop Peeling [Weak Zero SIV]
  - Section Based Splitting [Variation of loop peeling]

Threshold Analysis

```
DO I = 1, 20
     A(I+20) = A(I) + B
ENDDO
Vectorize to..
A(21:40) = A(1:20) + B
```

```
DO I = 1, 100
     A(I+20) = A(I) + B
ENDDO
Strip mine to..
DO I = 1, 100, 20
   DO ii = I, I+19
     A(ii+20) = A(ii) + B
   ENDDO
ENDDO
```

Vectorize this

Threshold Analysis

- **Crossing thresholds**

```
DO I = 1, 100
     A(100-I) = A(I) + B
ENDDO
```

Strip mine to…

```
DO I = 1, 100, 50
   DO ii = I, I+49
     A(101-ii) = A(ii) + B
   ENDDO
ENDDO
```

Vectorize to…

```
DO I = 1, 100, 50
     A(101-I:51-I) = A(I:I+49) + B
ENDDO
```

Loop Peeling

- **Source of dependence is a single iteration**

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

Loop peeled to..

```
A(1) = A(1) + A(1)
DO I = 2, N
    A(I) = A(I) + A(1)
ENDDO
```

Vectorize to..

```
A(1) = A(1) + A(1)
A(2:N)= A(2:N) + A(1)
```

Section-based Splitting

```
DO I = 1, N
   DO J = 1, N/2
S1:  B(J,I) = A(J,I) + C
   ENDDO
   DO J = 1, N
S2:  A(J,I+1) = B(J,I) + D
   ENDDO
ENDDO
```

- J Loop bound by recurrence due to B
- Only a portion of B is responsible for it

- Partition second loop into loop that uses result of S1 and loop that does not

```
DO I = 1, N
    DO J = 1, N/2
S1: B(J,I) = A(J,I) + C
    ENDDO
    DO J = 1, N/2
S2: A(J,I+1) = B(J,I) + D
    ENDDO
    DO J = N/2+1, N
S3: A(J,I+1) = B(J,I) + D
    ENDDO
ENDDO
```

Section-based Splitting

```
DO I = 1, N
   DO J = 1, N/2
S1:  B(J,I) = A(J,I) + C
   ENDDO
   DO J = 1, N/2
S2:  A(J,I+1) = B(J,I) + D
   ENDDO
   DO J = N/2+1, N
S3:  A(J,I+1) = B(J,I) + D
   ENDDO
ENDDO
```

- S3 now independent of S1 and S2

- Loop distribute to

```
DO I = 1, N
    DO J = N/2+1, N
S3: A(J,I+1) = B(J,I) + D
    ENDDO
ENDDO
DO I = 1, N
    DO J = 1, N/2
S1: B(J,I) = A(J,I) + C
    ENDDO
    DO J = 1, N/2
S2: A(J,I+1) = B(J,I) + D
    ENDDO
ENDDO
```

Section-based Splitting

```
DO I = 1, N
   DO J = N/2+1, N
S3:   A(J,I+1) = B(J,I) + D
   ENDDO
ENDDO
```

- **Vectorized to**

```
A(N/2+1:N,2:N+1) = B(N/2+1:N,1:N) + D
```

```
DO I = 1, N
   DO J = 1, N/2
S1:   B(J,I) = A(J,I) + C
   ENDDO
   DO J = 1, N/2
S2:   A(J,I+1) = B(J,I) + D
   ENDDO
ENDDO
```

```
DO I = 1, N
 B(1:N/2,I) = A(1:N/2,I) + C
 A(1:N/2,I+1) = B(1:N/2,I) + D
ENDDO
```

Homework #3 (REMINDER)

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**