COMP 515: Advanced Compilation for Vector and Parallel Processors

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

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Acknowledgments

- Slides from previous offerings of COMP 515 by Prof. Ken Kennedy
  - http://www.cs.rice.edu/~ken/comp515/

Compiler Improvement of Register Usage

Chapter 8 (contd)

Scalar Replacement

- Example: Scalar Replacement in case of loop carried dependence spanning multiple iterations

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

```
t1 = B(0)
t2 = B(1)
DO I = 1, N
    t3 = B(I+1)
    A(I) = t1 + t3
    t1 = t2
    t2 = t3
ENDDO
```

- One fewer load for each iteration for reference to B which had a loop carried input dependence spanning 2 iterations
- Invariants maintained were

  t1=B(I-1);t2=B(I);t3=B(I+1)

Eliminate Scalar Copies

```
t1 = B(0)
t2 = B(1)
DO I = 1, N
     t3 = B(I+1)
     A(I) = t1 + t3
     t1 = t2
     t2 = t3
ENDDO
```

- Unnecessary register-register copies
- Unroll loop 3 times

Preloop

```
t1 = B(0)
t2 = B(1)
mN3 = MOD(N,3)
DO I = 1, mN3
     t3 = B(I+1)
     A(I) = t1 + t3
     t1 = t2
     t2 = t3
ENDDO
```

Main Loop

```
DO I = mN3 + 1, N, 3
     t3 = B(I+1)
     A(I) = t1 + t3
     t1 = B(I+2)
     A(I+1) = t2 + t1
     t2 = B(I+3)
     A(I+2) = t3 + t2
ENDDO
```

Pruning the dependence graph

```
DO I = 1, N

      A(I+1) = A(I-1) + B(I-1)

      A(I) = A(I) + B(I) + B(I+1)

ENDDO
```

- Dependence pattern before pruning (including input dependences)
- Not all edges suggest memory access savings

Pruning the dependence graph

```
DO I = 1, N

    A(I+1) = A(I-1) + B(I-1)

    A(I) = A(I) + B(I) + B(I+1)

ENDDO
```

- Dependence pattern before pruning (including input dependences)
- Not all edges suggest memory access savings

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

- Dashed edges are pruned
- Each reference has at most one predecessor in the pruned graph
- Generator = source of edge in pruned graph

Pruning the dependence graph

```
DO I = 1, N

      A(I+1) = A(I-1) + B(I-1)

      A(I) = A(I) + B(I) + B(I+1)

ENDDO
```

- Apply scalar replacement after pruning the dependence graph

```
t0A = A(0); t1A0 = A(1);
tB1 = B(0); tB2 = B(1);
DO I = 1, N
      t1A1 = t0A + tB1
      tB3 = B(I+1)
      t0A = t1A0 + tB2 + tB3
      A(I) = t0A
      t1A0 = t1A1
      tB1 = tB2
      tB2 = tB3
ENDDO
A(N+1) = t1A1
```

- Only one load and one store per iteration

Pruning the dependence graph

- Prune all anti dependence edges
- Prune flow and input dependence edges that do not represent a potential reuse
- Prune redundant input dependence edges
- Prune output dependence edges after rest of the pruning is done

Pruning the dependence graph

- Phase 1: Eliminate killed dependences
  - When killed dependence is a flow dependence

```
S1: A(I+1) = ...
S2: A(I)   = ...
S3: ...   = A(I)
```

  - Store in S2 is a killing store. Flow dependence from S1 to S3 is pruned
  - When killed dependence is an input dependence

```
S1: ... = A(I+1)
S2: A(I)   = ...
S3: ...   = A(I-1)
```

  - Store in S2 is a killing store. Input dependence from S1 to S3 is pruned

Pruning the dependence graph

- Phase 2: Identify generators

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

- Any assignment reference with at least one flow dependence emanating from it to another statement in the loop
- Any use reference with at least one input dependence emanating from it and no input or flow dependence into it

Pruning the dependence graph

- Phase 3: Find name partitions and eliminate input dependences
  - Use Typed Fusion
    - References as vertices
    - An edge joins two references
    - Output and anti- dependences are bad edges
    - Name of array as type
- Eliminate input dependences between two elements of same name partition unless source is a generator

Pruning the dependence graph

- Special cases
  - Reference is in a dependence cycle in the loop

```
DO I = 1, N

    A(J) = B(I) + C(I,J)

    C(I,J) = A(J) + D(I)

ENDDO
```

- Assign single scalar to the reference in the cycle
- Replace A(J) by a scalar tA and insert A(J)=tA before or after the loop depending on upward/downward exposed occurrence

Pruning the dependence graph

- Special cases: Inconsistent dependences

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

- Store to A(J) kills A(I)

- Only one scalar replacement possible

```
DO I = 1, N
     tAI = A(I-1) + B(I)
     A(I) = tAI
     A(J) = A(J) + tAI
ENDDO
```

- This code can be improved substantially by index set splitting

Pruning the dependence graph

```
DO I = 1, N
   tAI = A(I-1) + B(I)
   A(I) = tAI
   A(J) = A(J) + tAI
ENDDO
```

- Split this loop into three separate parts
  - A loop up to J
  - Iteration J
  - A loop after iteration J to N

```
tAI = A(0); tAJ = A(J)
JU = MAX(J-1,0)
DO I = 1, JU
   tAI = tAI + B(I); A(I) = tAI
   tAJ = tAJ + tAI
ENDDO
IF(J.GT.0.AND.J.LE.N) THEN
   tAI = tAI + B(I); A(I) = tAI
   tAJ = tAJ + tAI
   tAI = tAJ
ENDIF
DO I = JU+2, N
   tAI = tAI + B(I); A(I) = tAI
   tAJ = tAJ + tAI
ENDDO
A(J) = tAJ
```

Scalar Replacement: Putting it together

1. Prune dependence graph; Apply typed fusion
2. Select a set of name partitions using register pressure moderation
3. For each selected partition
   A) If non-cyclic, replace using set of temporaries
   B) If cyclic replace reference with single temporary
   C) For each inconsistent dependence
      Use index set splitting or insert loads and stores
4. Unroll loop to eliminate scalar copies

Scalar Replacement: Case A

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

```
t0A = A(0); t1A0 = A(1);
tB1 = B(0); tB2 = B(1)
DO I = 1, N
      t1A1 = t0A + tB1
      tB3 = B(I+1)
      t0A = t1A0 + tB3 + tB2
      A(I) = t0A
      t1A0 = t1A1
      tB1 = tB2
      tB2 = tB3
ENDDO
A(N+1) = t1A1
```

Scalar Replacement: Case B

```
DO I = 1, N

      A(J) = B(I) + C(I,J)

      C(I,J) = A(J) + D(I)

ENDDO
```

replace with single temporary...

```
DO I = 1, N
      tA = B(I) + C(I,J)
      C(I,J) = tA + D(I)
ENDDO
A(J) = tA
```

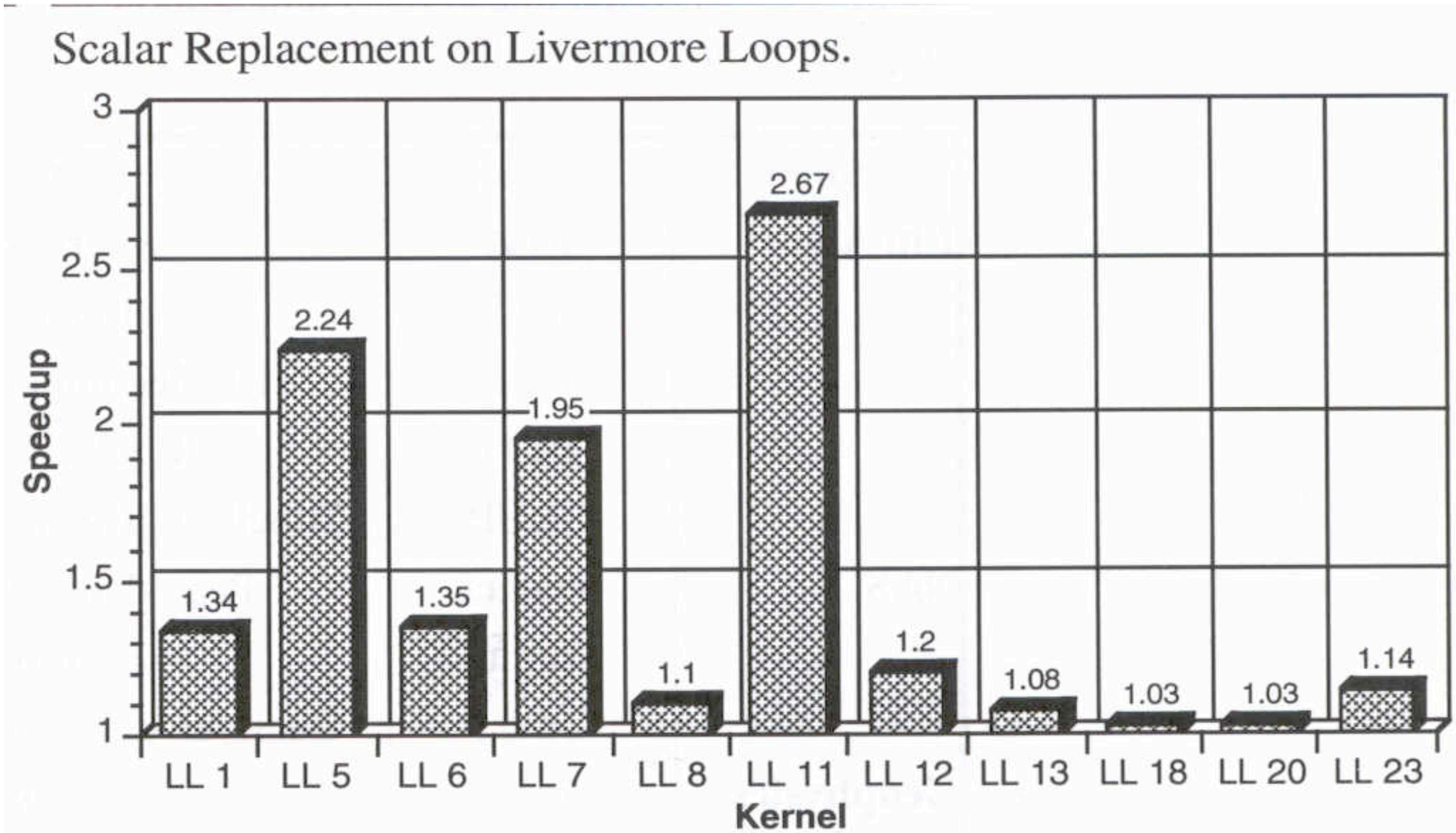
Scalar Replacement: Case C

```
DO I = 1, N
   tAI = A(I-1) + B(I)
   A(I) = tAI
   A(J) = A(J) + tAI
ENDDO
```

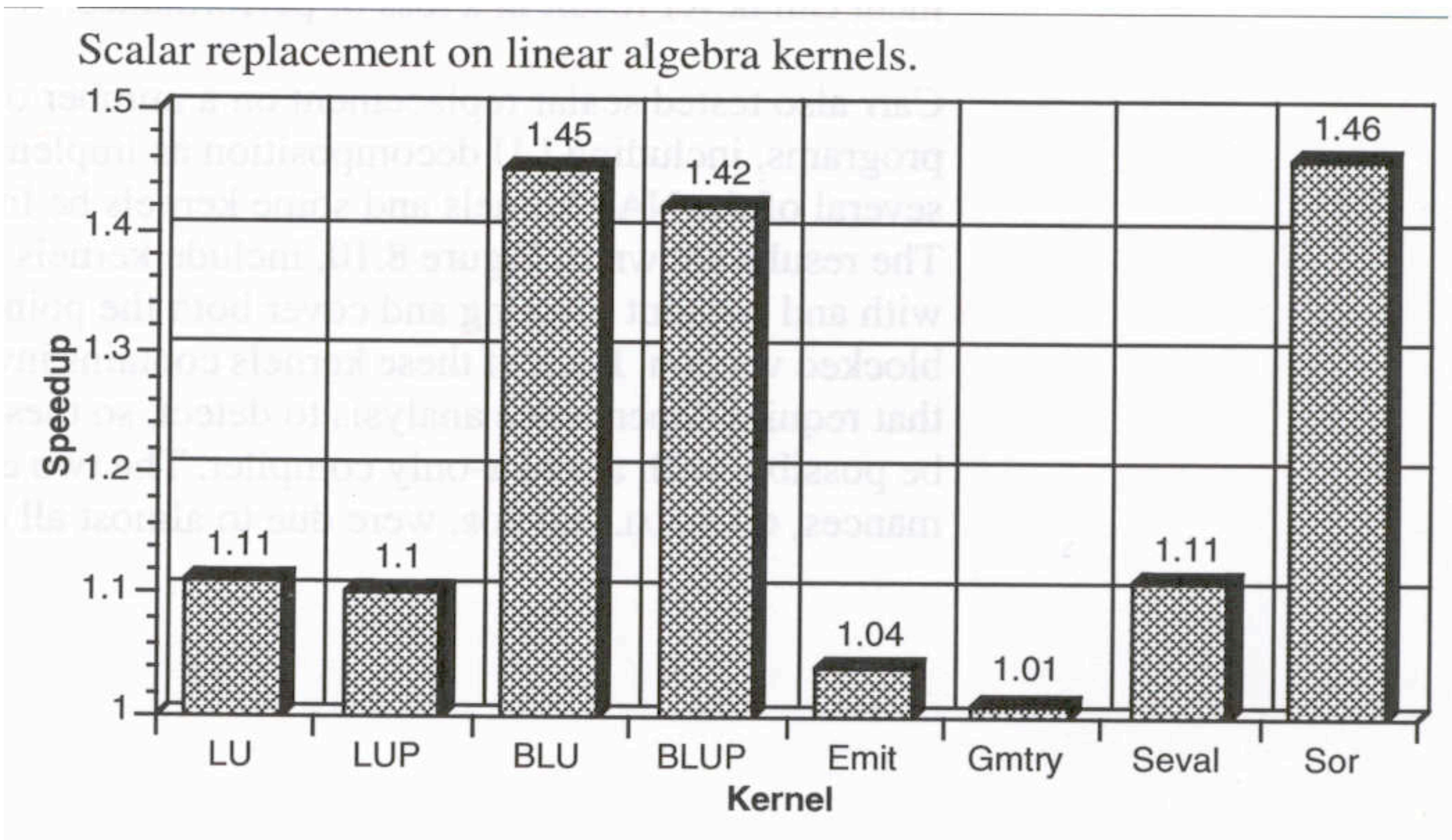
- Split this loop into three separate parts
  - A loop up to J
  - Iteration J
  - A loop after iteration J to N

```
tAI = A(0); tAJ = A(J)
JU = MAX(J-1,0)
DO I = 1, JU
   tAI = tAI + B(I); A(I) = tAI
   tAJ = tAJ + tAI
ENDDO
IF(J.GT.0.AND.J.LE.N) THEN
   tAI = tAI + B(I); A(I) = tAI
   tAJ = tAJ + tAI
   tAI = tAJ
ENDIF
DO I = JU+2, N
   tAI = tAI + B(I); A(I) = tAI
   tAJ = tAJ + tAI
ENDDO
A(J) = tAJ
```

Experiments on Scalar Replacement



Experiments on Scalar Replacement



Unroll-and-Jam

```
DO I = 1, N*2
   DO J = 1, M
        A(I) = A(I) + B(J)
   ENDDO
ENDDO
```

- Can we achieve reuse of references to B ?
- Use transformation called Unroll-and-Jam

```
DO I = 1, N*2, 2
   DO J = 1, M
        A(I) = A(I) + B(J)
        A(I+1) = A(I+1) + B(J)
   ENDDO
ENDDO
```

- Unroll outer loop twice and then fuse the copies of the inner loop
- Brought two uses of B(J) together

Unroll-and-Jam

```
DO I = 1, N*2, 2
   DO J = 1, M
        A(I) = A(I) + B(J)
        A(I+1) = A(I+1) + B(J)
   ENDDO
ENDDO
```

- Apply scalar replacement on this code

```
DO I = 1, N*2, 2
   s0 = A(I)
   s1 = A(I+1)
   DO J = 1, M
        t = B(J)
        s0 = s0 + t
        s1 = s1 + t
   ENDDO
   A(I) = s0
   A(I+1) = s1
ENDDO
```

- Half the number of loads as the original program

Legality of Unroll-and-Jam

- Is unroll-and-jam always legal?

```
DO I = 1, N*2
   DO J = 1, M
        A(I+1,J-1) = A(I,J) + B(I,J)
   ENDDO
ENDDO
```

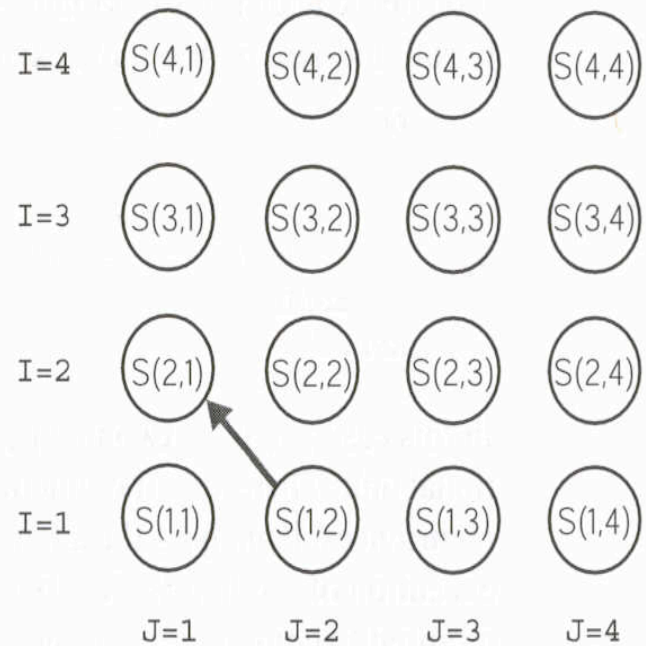
- Apply unroll-and-jam

```
DO I = 1, N*2, 2
   DO J = 1, M
        A(I+1,J-1) = A(I,J) + B(I,J)
        A(I+2,J-1) = A(I+1,J) + B(I
   +1,J)
   ENDDO
ENDDO
```

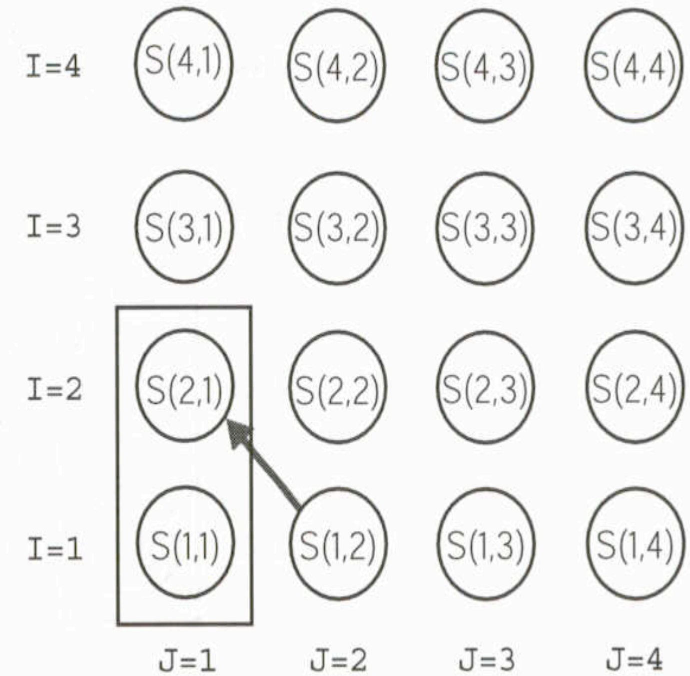
- This is wrong!!!

Legality of Unroll-and-Jam

Legality of unroll-and-jam



Legality of unroll-and-jam.



Legality of Unroll-and-Jam

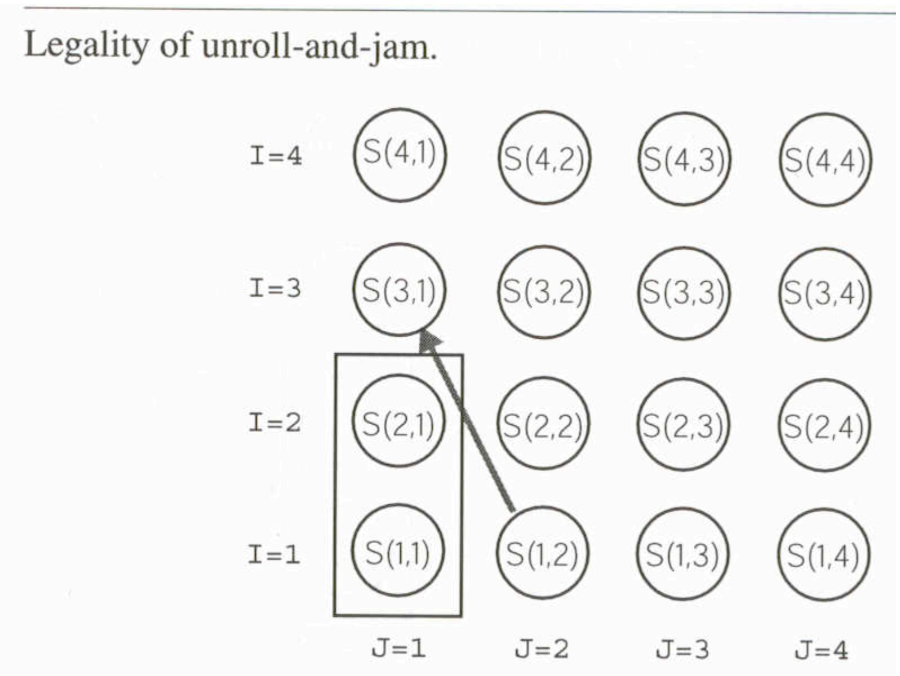
- Direction vector in this example was (<,>)
  - This makes loop interchange illegal
  - Unroll-and-Jam is loop interchange followed by unrolling inner loop followed by another loop interchange
- But does loop interchange illegal imply unroll-and-jam illegal ? NO

Legality of Unroll-and-Jam

- Consider this example

```
DO I = 1, N*2
   DO J = 1, M
   A(I+2,J-1) = A(I,J) + B(I,J)
   ENDDO
ENDDO
```

- Direction vector is (<,>); still unroll-and-jam possible because of distances involved



Conditions for legality of unroll-and-jam

- **Definition:** Unroll-and-jam to factor n consists of unrolling the outer loop n-1 times and fusing those copies together.
- **Theorem:** An unroll-and-jam to a factor of n is legal iff there exists no dependence with direction vector (<,>) such that the distance for the outer loop is less than n.

Unroll-and-jam Algorithm

1. Create preloop
2. Unroll main loop m(the unroll-and-jam factor) times
3. Apply typed fusion to loops within the body of the unrolled loop
4. Apply unroll-and-jam recursively to the inner nested loop

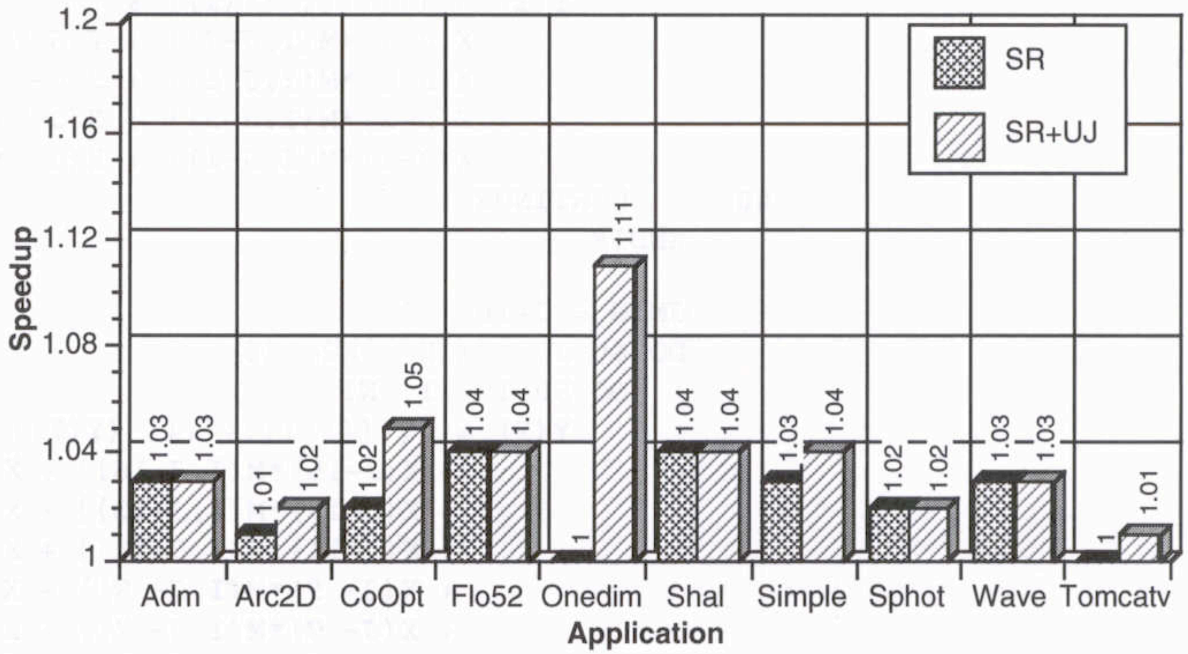
Unroll-and-jam example

```
DO I = 1, N
 DO K = 1, N
  A(I) = A(I) + X(I,K)
 ENDDO
 DO J = 1, M
   DO K = 1, N
        B(J,K) = B(J,K) + A(I)
   ENDDO
 ENDDO
 DO J = 1, M
  C(J,I) = B(J,N)/A(I)
 ENDDO
ENDDO
```

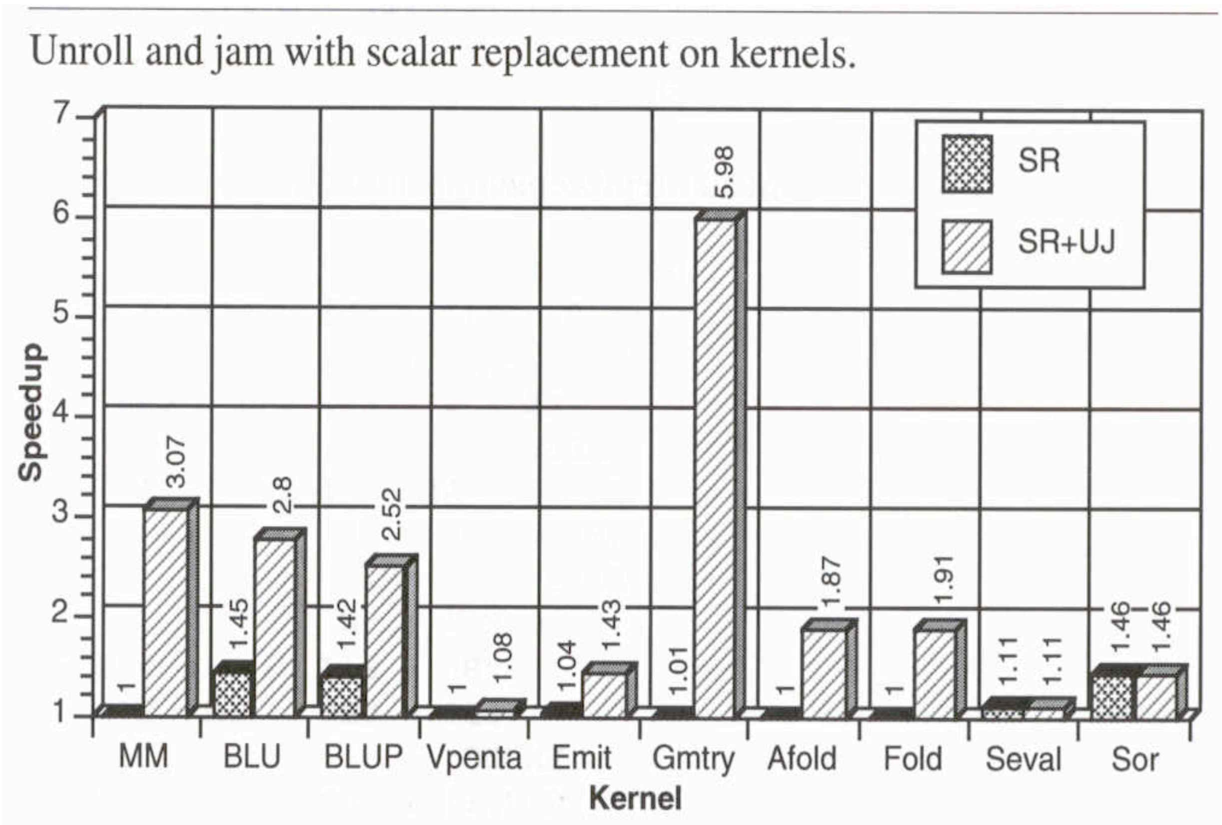
```
DO I = mN2+1, N, 2
 DO K = 1, N
  A(I) = A(I) + X(I,K)
  A(I+1) = A(I+1) + X(I+1,K)
 ENDDO
 DO J = 1, M
   DO K = 1, N
     B(J,K) = B(J,K) + A(I)
     B(J,K) = B(J,K) + A(I+1)
   ENDDO
   C(J,I) = B(J,N)/A(I)
   C(J,I+1) = B(J,N)/A(I+1)
 ENDDO
ENDDO
```

Unroll-and-jam: Experiments

Unroll-and-jam with scalar replacement on applications.



Unroll-and-jam: Experiments



Conclusion

- **We have learned two memory hierarchy transformations:**
  - **scalar replacement**
  - **unroll-and-jam**
- **They reduce the number of memory accesses by maximum use of processor registers**

Homework #5 (Written Assignment)

1. **Solve exercise 8.2 in book**

- **Due by 5pm on Monday, Oct 31st**
- Homework should be turned into Amanda Nokleby, Duncan Hall 3137
- Honor Code Policy: All submitted homeworks are expected to be the result of your individual effort. You are free to discuss course material and approaches to problems with your other classmates, the teaching assistants and the professor, but you should never misrepresent someone else's work as your own. If you use any material from external sources, you must provide proper attribution.