

CS 610: Parallelizing Loops

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Enhancing Program Performance

- Loops are one of most **commonly used** constructs in HPC programs
- Compilers perform many loop optimizations automatically to
 - ▶ Exploit fine-grained parallelism
 - ▶ Multiple pipelined functional units in each core
 - ▶ Vector instruction sets (SSE, AVX, AVX-512)
 - ▶ Exploit coarse-grained parallelism for SMP systems
 - ▶ Keep multiple asynchronous processors busy with work
 - ▶ Minimize cost of memory accesses
- In some cases, source code modifications can enhance the optimizer's ability to transform code

Different Levels of Parallelization in Hardware

Instruction-level Parallelism

Microarchitectural techniques like pipelining, OOO execution, and superscalar instruction issue

Data-level Parallelism

Use Single Instruction Multiple Data (SIMD) vector processing instructions and units

Thread-level Parallelism

Simultaneous multithreading or hyperthreading

Vectorization

Vectorization

- Vectorization is the process of transforming a scalar operation on single data elements at a time (SISD) to an operation on multiple data elements at once (SIMD)
- Helps transform a loop nest so that the same operation is performed on several vector elements at the same time

Don't use a single Vector lane/thread!

Un-vectorized and un-threaded software will under perform



Permission to Design for All Lanes

Threading and Vectorization needed to fully utilize modern hardware

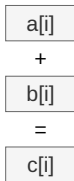


Vectorization

```
double *a, *b, *c;  
for (int i = 0; i < N; i++)  
    c[i] = a[i] + b[i];
```

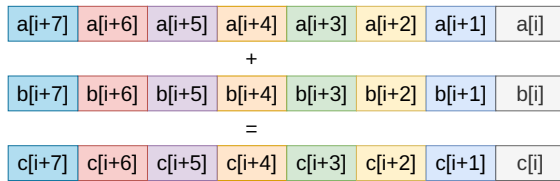
Scalar mode

One instruction (e.g., vaddsd/vaddss) produces one result



Vector mode

One instruction (e.g., vaddpd/vaddps) can produce multiple results



Vectorization

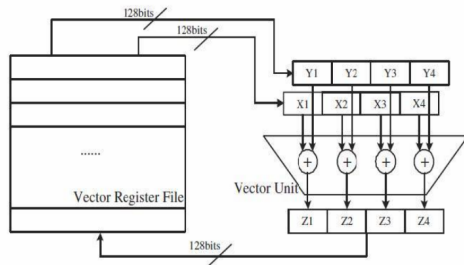
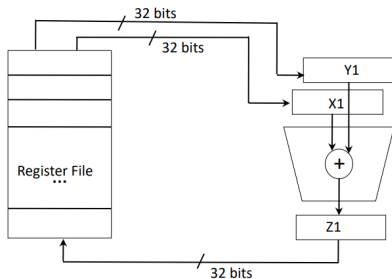
n times {

```
ld r1, addr1
ld r2, addr2
add r3, r1, r2
st r3, addr3
```

```
for (i=0; i<n; i++) {
    c[i] = a[i] + b[i];
}
```

$\frac{n}{4}$ times {

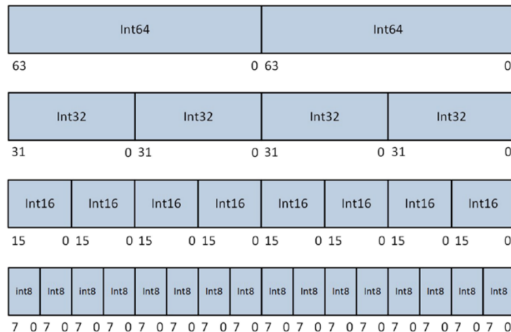
```
ldv vr1, addr1
ldv vr2, addr2
addv vr3, vr1, vr2
stv vr3, addr3
```



SIMD Vectorization

- Use of SIMD units can speed up the program
- Intel SSE has 128-bit vector registers and functional units
- Assuming a single ALU, these SIMD units can execute 4 single precision floating point number or 2 double precision operations in the time it takes to do only one of these operations by a scalar unit

128-bit wide operands using integer types

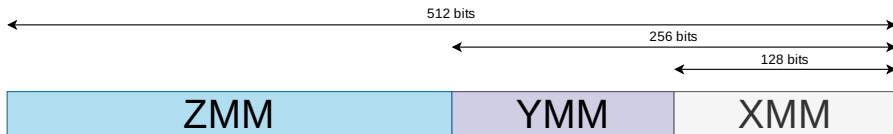


Intel-Supported SIMD Extensions

SIMD Extensions	Width (bits)	SP calculations	DP calculations	Introduced
SSE2/SSE3/SSE4	128	4	2	~2001–2007
AVX/AVX2	256	8	4	~2011–2015
AVX-512	512	16	8	~2017

Other platforms that support SIMD have different extensions (e.g., ARM Neon and Power Altivec)

Intel-Supported SIMD Extensions



64-bit architecture

SSE	XMM ₀ –XMM ₁₅	Low-order 128 bits of each YMM register is aliased to a corresponding XMM register
AVX	YMM ₀ –YMM ₁₅	
AVX-512	ZMM ₀ –ZMM ₃₁	
		Low-order 256 and 128 bits are aliased to registers YMM ₀ –YMM ₃₁ and XMM ₀ –XMM ₃₁ respectively

x86_64 Vector Operations

[] required
() optional

Example instructions

Move (V)MOV[A/U][P/S][D/S]

Comparison (V)CMP[P/S][D/S]

Arithmetic (V)[ADD/SUB/MUL/DIV][P/S][D/S]

Instruction decoding

V AVX

P,S packed, scalar

A,U aligned, unaligned

D,S double-, single-precision

B,W,D,Q byte, word, doubleword, quadword integers

x86_64 Vector Operations

`movss xmm1, xmm2` Copy scalar single-precision floating-point value (low 32 bits) from xmm2 to xmm1

`vmovapd xmm1, xmm2` Move aligned packed double-precision floating-point values from xmm2 to xmm1

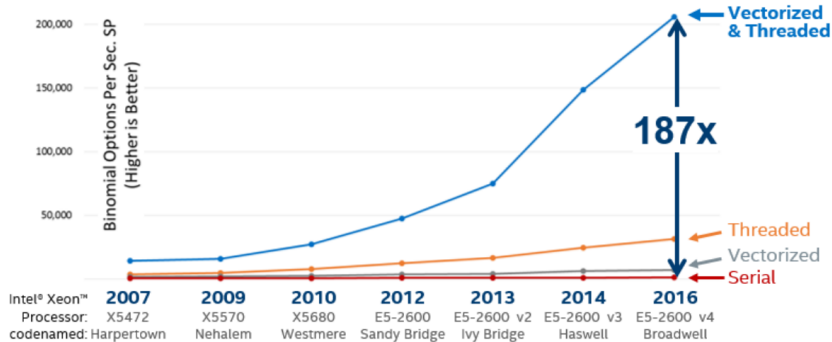
`vaddss xmm0, xmm1, xmm2`

$\text{xmm0}[31:0] = \text{xmm1}[31:0] + \text{xmm2}[31:0]$
 $\text{xmm0}[127:32] = \text{xmm1}[127:32]$

`vaddsd xmm0, xmm1, xmm2`

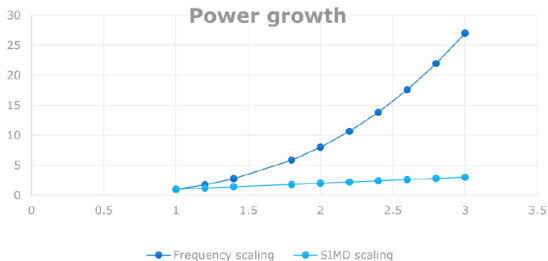
$\text{xmm0}[63:0] = \text{xmm1}[63:0] + \text{xmm2}[63:0]$
 $\text{xmm0}[127:64] = \text{xmm1}[127:64]$

The combined effect of vectorization and threading



The Difference Is Growing With Each New Generation of Hardware

Why SIMD vector parallelism?



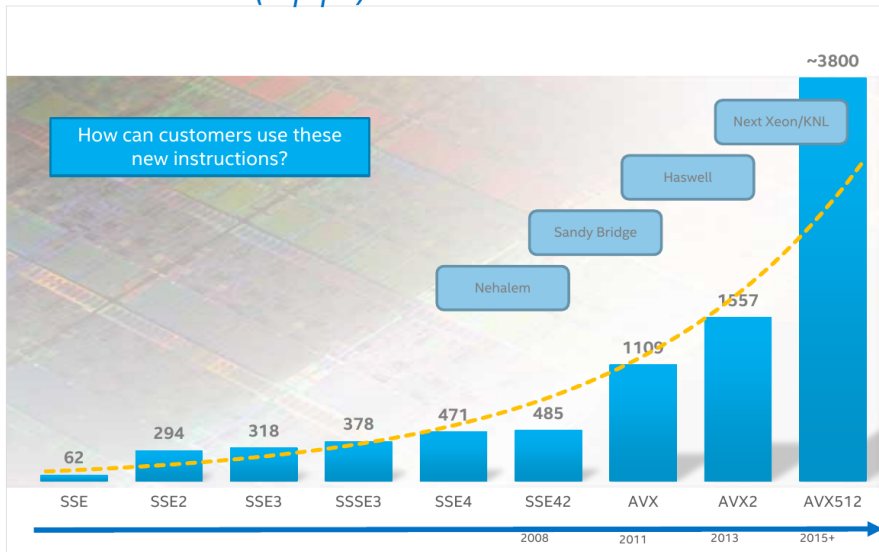
Wider SIMD -- Linear increase in area and power

Wider superscalar – Quadratic increase in area and power

Higher frequency – Cubic increase in power

With SIMD we can go faster with less power

Cumulative (app.) # of Vector Instructions



Vectorization Examples

- Vectorization output can vary across compiler versions and architecture generations
- Correlate the assembly code with the high-level C++ statements
- Check CPU features 
- Vectorize a loop nest with increasing control 

Enhancing Fine-Grained Parallelism

Focus is on vectorization of inner loops

Relevance of Data Dependence Graph in Vectorization

- Loop dependences guide vectorization
 - ▶ Statements not data dependent on each other can be reordered, executed in parallel, or coalesced into a vector operation
- If the Data Dependence Graph (DDG) is acyclic, then vectorizing the program is straightforward

```
    for (i=1; i<=n; i++) {  
S1      a[i] = b[i] + 1;  
S2      c[i] = a[i-1] + 2;  
    }
```

⇒

```
a[1:n] = b[1:n] + 1;  
c[1:n] = a[0:n-1] + 2;
```

Loop Interchange (Loop Permutation)

- Switch the nesting order of loops in a perfect loop nest
- Can increase parallelism, can improve spatial locality
- Dependence is now carried by the outer loop, inner loop can be vectorized

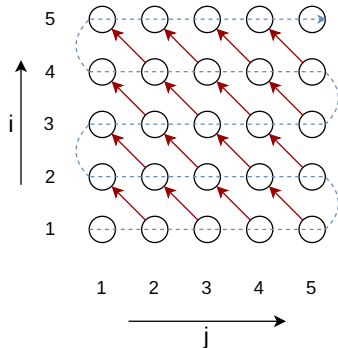
```
DO J = 1, M  
  DO I = 1, N  
S    A(I+1,J) = A(I,J) + B
```



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

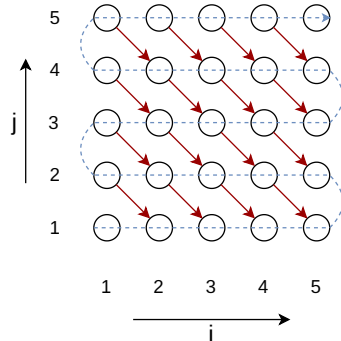
Example of Loop Interchange

```
DO i = 1, n
  DO j = 1, n
    C(i, j) = C(i-1, j+1)
```



valid?

```
DO j = 1, n
  DO i = 1, n
    C(i, j) = C(i-1, j+1)
```



Validity of Loop Permutation

- (i) Construct direction vectors for all possible dependences in the loop to form a direction matrix
 - ▶ Identical direction vectors are represented by a single row in the matrix
- (ii) Compute direction vectors based on the intended loop permutation
- (iii) Permutation is illegal if any permuted vector is lexicographically negative

A loop nest is **fully** permutable if any permutation transformation to the loop nest is legal

Example: $d_1 = (1, -1, 1)$ and $d_2 = (0, 2, -1)$

$ijk \rightarrow jik?$ $(1, -1, 1) \rightarrow (-1, 1, 1)$: illegal

$ijk \rightarrow kij?$ $(0, 2, -1) \rightarrow (-1, 0, 2)$: illegal

$ijk \rightarrow ikj?$ $(0, 2, -1) \rightarrow (0, -1, 2)$: illegal

Does Loop Interchange/Permutation Always Help?

```
DO i = 1, 10000  
  DO j = 1, 1000  
    a(i) = a(i) + b(j,i) * c(i)
```

```
DO i = 1, N  
  DO j = 1, M  
    DO k = 1, L  
      a(i+1,j+1,k) = a(i,j,k) + b
```

- Benefits from loop interchange depends on the target machine, the data structures accessed, memory layout, and stride patterns
- Optimization choices for the snippet on the right
 - ▶ Vectorize J and K
 - ▶ Move K outermost and parallelize K with threads
 - ▶ Move I innermost and vectorize assuming column-major layout

Loop Shifting

- In a perfect loop nest, if loops at level $i, i+1, \dots, i+n$ carry no dependence, i.e., all dependences are carried by loops at level smaller than i or greater than $i+n$, then it is always legal to shift these loops inside of loop $i+n+1$
- These loops will not carry any dependences in their new position

Loops i to $i+n$

Dependence carried by outer loops	+	0	+	0	0	0	Dependence carried by inner loops
	0	+	-	+	+	0	
	0	0	0	0	+	+	
	0	0	0	0	0	+	

Loop Shift for Matrix Multiply

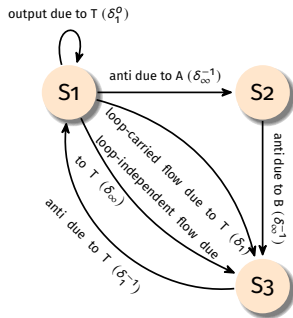
```
DO I = 1, N
  DO J = 1, N
    DO K = 1, N
S      A(I,J) = A(I,J) + B(I,K)*C(K,J)
```

Is the loop nest
vectorizable as is?

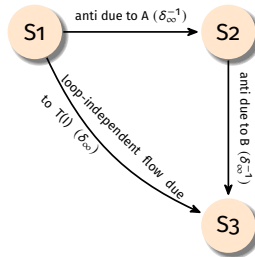
Scalar Expansion

Eliminates dependences that arise from reuse of memory locations at the cost of extra memory

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



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



Understanding Scalar Expansion

Pros

- + Eliminates dependences due to reuse of memory locations, helps with parallelism

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

can also try forward substitution

⇒

```
DO I = 1, N, 64
  DO i = 0, 63
    T = A(I+i) + A(I+1+i)
    A(I+i) = T + B(I+i)
```

strip mining

⇒

```
DO I = 1, N, 64
  DO i = 0, 63
    $T(i) = A(I+i) + A(I+1+i)
    A(I+i) = $T(i) + B(I+i)
```

strip loop

Cons

- Increases memory and addressing overhead

Strip mining (also known as sectioning) is a special case of 1-D loop tiling

Limits of Scalar Expansion

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

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

Can we parallelize
the I loop?

```
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
```

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

Can we vectorize the
loop nest?

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
```

```
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
    T = T2
```

Can we vectorize the loop nest?

Allows Vectorization with Statement Interchange

```
      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
      T = T2
```

⇒

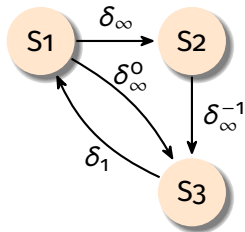
```
      DO I = 1, 100
S3      T2 = D(I) - B(I)
S4      A(I+1) = T2 * T2
S1      T1 = A(I) + B(I)
S2      C(I) = T1 + T1
      T = T2
```

⇒

```
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)
```

Array Renaming

	DO I = 1, 100
S1	$\underline{A(I)} = A(I-1) + X$
S2	$\underline{Y(I)} = A(I) + Z$
S3	$\underline{A(I)} = B(I) + C$

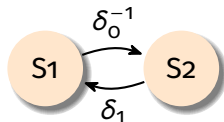


	DO I = 1, 100
S1	$\$A(I) = A(I-1) + X$
S2	$Y(I) = \$A(I) + Z$
S3	$A(I) = B(I) + C$

Array renaming requires sophisticated analysis

Node Splitting

	DO I = 1, 100
S1	$A(I) = \frac{X(I+1)}{B(I)} + \frac{X(I)}{10}$
S2	$X(I+1) = B(I) + 10$



	DO I = 1, 100
S0	$\$X(I) = X(I+1)$
S1	$A(I) = \$X(I) + X(I)$
S2	$X(I+1) = B(I) + 10$

Can we vectorize the loop nest?

Index-Set Splitting

```
DO I = 1, 100  
  A(I+20) = A(I) + B
```

strip mining

```
DO I = 1, 100, 20  
  DO i = I, I+19  
    A(i+20) = A(i) + B
```

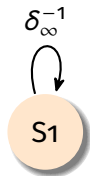
An index-set splitting transformation subdivides the loop into different iteration ranges

Loop Splitting

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

assume N is
divisible by 2

```
M = N/2  
DO I = 1, M-1  
  A(I) = A(N/2) + B(I)  
A(M) = A(N/2) + B(I)  
DO I = M+1, N  
  A(I) = A(N/2) + B(I)
```



Loop Peeling

- Splits any problematic iterations (could be first, middle, or last few) from the loop body
- Change a loop-carried dependence to a loop-independent dependence
- Transformed loop carries no dependence, can be parallelized
- Peeled iterations execute in the original order, transformation is always legal to perform

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

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

Section-Based Splitting

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

⇒

S3 is
independent

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

⇒

cannot
vectorize I

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

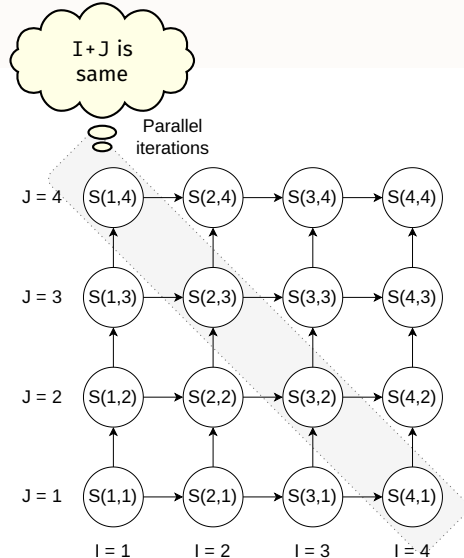
⇒

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

Loop Skewing

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

Which loops carry dependences?

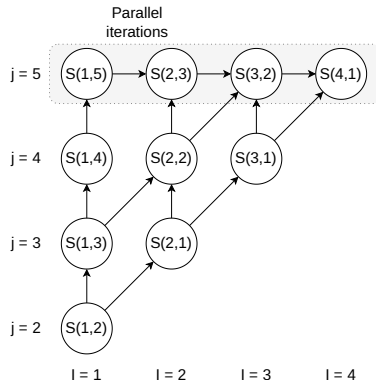


Loop Skewing

$j = I + J$

```
DO I = 1, N
  DO j = I+1, I+N
S    A(I, j-I) = A(I-1, j-I) + A(I, j-I-1)
```

What are the dependences now? Which loop carries the dependence?



Loop skewing skews the inner loop relative to the outer loop by adding the index of the outer loop times a skewing factor f to the bounds of the inner loop and subtracting the same value from all the uses of the inner loop index

Perform Loop Interchange

Given a dependency vector (a, b) , skewing transforms it to $(a, fa + b)$

```
DO I = 1, N
  DO j = I+1, I+N
S    A(I, j-I) = A(I-1, j-I) + A(I, j-I-1)
```



can use Fourier-
Motzkin elimination

```
DO j = 2, N+N
  DO I = max(1, j-N), min(N, j-1)
S    A(I, j-I) = A(I-1, j-I) + A(I, j-I-1)
```

Understanding Loop Skewing

Pros

- + Reshapes the iteration space to find possible parallelism
- + Preserves lexicographic order of the dependences, is always legal
- + Allows for loop interchange in future

Cons

- Resulting iteration space can be trapezoidal
- Irregular loops are not very amenable for vectorization
- Need to be careful about load imbalance

Loop Unrolling (Loop Unwinding)

- Reduce number of iterations of loops
- Add statement(s) to do work of missing iterations
- JIT compilers try to perform unrolling at run-time

```
for (i=0; i<n; i++) {  
    for (j=0; j<n; j++) {  
        y[i] = y[i] + a[i][j]*x[j];  
    }  
}
```

4-way inner loop unrolling

```
for (i=0; i<n; i++) {  
    for (j=0; j<n; j+=4) {  
        y[i] = y[i] + a[i][j]*x[j]  
            + a[i][j+1]*x[j+1]  
            + a[i][j+2]*x[j+2]  
            + a[i][j+3]*x[j+3];  
    }  
}
```

Outer Loop Unrolling + Inner Loop Jamming

```
for (i=0; i<2*n; i++) {  
    for (j=0; j<m; j++) {  
        loop-body(i,j);  
    }  
}
```

```
for (i=0; i<2*n; i+=2) {  
    for (j=0; j<m; j++) {  
        loop-body(i,j);  
    }  
    for (j=0; j<m; j++) {  
        loop-body(i+1,j);  
    }  
}
```

```
for (i=0; i<2*n; i+=2) {  
    for (j=0; j<m; j++) {  
        loop-body(i,j);  
        loop-body(i+1,j);  
    }  
}
```

2-way outer unroll does not increase operation-level parallelism in the inner loop

Is Loop Unroll and Jam Legal?

```
DO I = 1, N  
  DO J = 1, M  
    A(I,J) = A(I-1,J+1)+C
```

```
DO I = 1, N, 2  
  DO J = 1, M  
    A(I,J) = A(I-1,J+1)+C  
    A(I+1,J) = A(I,J+1)+C
```

Validity Condition for Loop Unroll and Jam

- Complete unroll and jam of a loop is equivalent to a loop permutation that moves that loop innermost, without changing order of other loops
- If such a loop permutation is valid, unroll and jam of the loop is valid
- Example: 4D loop $ijkl$; $d_1 = (1, -1, 0, 2)$, $d_2 = (1, 1, -2, -1)$
 - i $d_1 \rightarrow (-1, 0, 2, 1)$, $\implies$ invalid to unroll and jam
 - j $d_1 \rightarrow (1, 0, 2, -1)$; $d_2 \rightarrow (1, -2, -1, 1)$, $\implies$ valid to unroll and jam
 - k $d_1 \rightarrow (1, -1, 2, 0)$; $d_2 \rightarrow (1, 1, -1, -2)$, $\implies$ valid to unroll and jam
 - l d_1 and d_2 are unchanged; innermost loop can always be unrolled

Understanding Loop Unrolling

Pros

- + Small loop bodies are problematic, reduces control overhead of loops
- + Increases operation-level parallelism in loop body
- + Allows other optimizations like reuse of temporaries across iterations

Cons

- Increases the executable size
- Increases register usage
- May prevent function inlining

Loop Tiling (Loop Blocking)

- Improve data reuse by chunking the data in to smaller tiles (blocks)
 - ▶ All the required blocks are supposed to fit in the cache
- Performs strip mining in multiple array dimensions
- Tries to exploit spatial and temporal locality of data
- Determining the tile size
 - ▶ Requires accurate estimate of array accesses and the cache size of the target machine
 - ▶ Loop nest order also influences performance
 - ▶ Difficult theoretical problem, usually heuristics are applied
 - ▶ Cache-oblivious algorithms make efficient use of cache without explicit blocking

```
for (i = 0; i < N; i++) {  
    ...  
}
```

```
for (ii = 0; ii < N; ii+=B) {  
    for (i = ii; i < min(N,ii+B), i++) {  
        ...  
    }  
}
```

Validity Condition for Loop Tiling

- A band of loops is fully permutable if all permutations of the loops in that band are legal
- A contiguous band of loops can be tiled if they are fully permutable
- Example: $d = (1, 2, -3)$
 - ▶ Tiling all three loops ijk is not valid, since the permutation kij is invalid
 - ▶ 2D tiling of band ij is valid
 - ▶ 2D tiling of band jk is valid

```
for (i = 0; i < n; i++)  
  for (j = 0; j < n; j++)  
    for (k = 0; k < n; k++)  
      loop_body(i, j, k)
```

```
for (it = 0; it < n; it+=T)  
  for (jt = 0; jt < n; jt+=T)  
    for (i = it; i < it+T; i++)  
      for (j = jt; j < jt+T; j++)  
        for (k = 0; k < n; k++)  
          loop_body(i, j, k)
```

Ways to Vectorize Code

Ways to Vectorize Code

- Auto-vectorizing compiler
- Vector intrinsics
- Assembly programming
- Use SIMD-capable libraries like Intel Math Kernel Library (MKL)

easier, but less control

```
for (i=0; i<LEN; i++)  
    c[i] = a[i] + b[i];
```

```
void example() {  
    __m128 rA, rB, rC;  
    for (int i = 0; i < LEN; i+=4) {  
        rA = _mm_load_ps(&a[i]);  
        rB = _mm_load_ps(&b[i]);  
        rC = _mm_add_ps(rA, rB);  
        _mm_store_ps(&c[i], rC);  
    }  
}
```

```
..B8.5  
movaps a(,%rdx,4), %xmm0  
addps b(,%rdx,4), %xmm0  
movaps %xmm0, c(,%rdx,4)  
addq $4, %rdx  
cmpq $rdi, %rdx  
jl ..B8.5
```

harder, but more control

Auto-Vectorization

Compiler vectorizes automatically No code changes

Semi auto-vectorization Use pragmas as hints to guide compiler

Explicit vector programming OpenMP SIMD pragmas

Advantages

- + Transparent to programmers
- + Compilers can apply other transformations
- + Code is portable across architectures
 - ▶ Vectorization instructions may differ, but compilers take care of it

Compilers may fail to vectorize

- Programmers may give hints to help the compiler
- Programmers may have to manually vectorize their code

Steps in Loop Vectorization

- Compiler computes the dependences
 - (i) The compiler figures out dependences by
 - ▶ Solving a system of (integer) equations (with constraints)
 - ▶ Demonstrating that there is no solution to the system of equations
 - (ii) Tries to remove cycles in the dependence graph
 - (iii) Determines data alignment
 - (iv) Determines if vectorization is profitable
 - ▶ Loop vectorization is not always a legal and profitable transformation

Vectorizing a loop with several statements is equivalent to strip-mining the loop and then applying loop distribution

```
for (i=0; i<LEN; i++) {  
    a[i] = b[i] + 1;  
    c[i] = b[i] + 2;  
}
```

```
for (i=0; i<LEN; i+=strip_size){  
    for (j=i; j<i+strip_size; j++)  
        a[j] = b[j] + 1;  
    for (j=i; j<i+strip_size; j++)  
        c[j] = b[j] + 2;  
}
```

Acyclic Dependences

Forward dependences are vectorized

```
for (i=0; i<LEN; i++) {  
    a[i] = b[i] + c[i];  
    d[i] = a[i] + 1;  
}
```

```
a[0:LEN-1] = b[0:LEN-1] + c[0:LEN-1];  
d[0:LEN-1] = a[0:LEN-1] + 1;
```

Backward dependences can sometimes be vectorized

```
for (i=0; i<LEN; i++) {  
S1    a[i] = b[i] + c[i]  
S2    d[i] = a[i+1] + 1;  
}
```

```
S2 d[0:LEN-1] = a[1:LEN] + 1;  
S1 a[0:LEN-1] = b[0:LEN-1] + c[0:LEN-1];
```

```
for (int i = 1; i<LEN; i++) {  
S1    a[i] = d[i-1] + c[i];  
S2    d[i] = b[i] + e[i];  
}
```

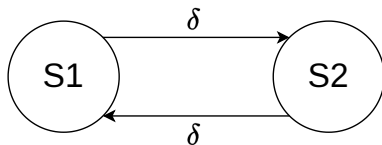
```
S2 d[1:LEN-1] = b[1:LEN-1] + e[1:LEN-1];  
S1 a[1:LEN-1] = d[0:LEN-2] + c[1:LEN-1];
```

Data Dependence Graph and Vectorization

- If the DDG is cyclic, then try to transform the DDG to an acyclic graph
 - ▶ When cycles are present, vectorization can be achieved by
 - ▶ Freezing loops
 - ▶ Separating (distributing) the statements not in a cycle
 - ▶ Removing dependences
 - ▶ Changing the algorithm

Freezing Loops

```
    FOR I=1, N
      FOR J=1, M
S1      A(I,J) = B(I-1,J+1) + C
S2      B(I,J) = A(I-1,J-1) + K
```



Cycles in the DDG

```
S1  for (int i=0; i<LEN-1; i++) {  
    a[i]=a[i+1]+b[i];  
}
```

Self anti-dependence can be vectorized

```
S1  for (int i=1; i<LEN; i++) {  
    a[i]=a[i-1]+b[i];  
}
```

Self true dependence cannot be vectorized

```
S1  for (int i=1; i<LEN; i++) {  
    a[i]=a[i-4]+b[i];  
}
```

Self true dependence with larger distance vectors can be vectorized

Vectorization in Presence of Cycles

Loop Distribution (or Fission)

```
    for (i=1; i<n; i++) {  
S1      b[i] = b[i] + c[i];  
S2      a[i] = a[i-1]*a[i-2]+b[i];  
S3      c[i] = a[i] + 1;  
    }
```

```
S1  b[1:n-1] = b[1:n-1] + c[1:n-1];  
    for (i=1; i<n; i++){  
S2      a[i] = a[i-1]*a[i-2]+b[i];  
    }  
S3  c[1:n-1] = a[1:n-1] + 1;
```

Scalar Expansion

```
    for (i=0; i<n; i++) {  
S1      a = b[i] + 1;  
S2      c[i] = a + 2;  
    }
```

```
    for (i=0; i<n; i++) {  
S1      $a[i] = b[i] + 1;  
S2      c[i] = $a[i] + 2;  
    }  
    a = $a[n-1]
```

```
$a[0:n-1] = b[0:n-1] + 1;  
c[0:n-1] = $a[0:n-1] + 2;  
a = $a[n-1]
```

Vectorization in Presence of Cycles

Are there transformations which allow vectorizing the following loop?

```
    for (int i=1; i<LEN; i++) {  
S1      a[i] = b[i] + c[i];  
S2      d[i] = a[i] + e[i-1];  
S3      e[i] = d[i] + c[i];  
    }
```

Cycles in the DDG

```
S1  for (int i=0; i<LEN; i++) {  
      a[r[i]] = a[r[i]] * 2;  
  }
```

Are there i and i' such that $r[i] == r[i']$ and $i \neq i'$?

Cycles can appear in the DDG because the compiler cannot prove that there cannot be dependences

Change the Algorithm

- When there is a recurrence, it is necessary to change the algorithm in order to vectorize
- Compilers use pattern matching to identify the recurrence and then replace it with a parallel version
- Examples of recurrences include

Reductions `sum += A[i]`

Linear recurrences `A[i] = B[i]*A[i-1]+C[i]`

Boolean recurrences `if (A[i]>max) { max = A[i] }`

Reductions

Reduction is an operation, such as addition, which is applied to the elements of an array to produce a result of a lesser rank

```
sum = 0;
for (int i=0; i<LEN; ++i) {
    sum += a[i];
}
```

```
x = a[0];
index = 0;
for (int i=0; i<LEN; ++i) {
    if (a[i] > x) {
        x = a[i];
        index = i;
    }
}
```

Challenges in Vectorization

Loop Transformations using Compiler Directives

When the compiler does not vectorize automatically due to dependences, the programmer can inform the compiler that it is safe to vectorize

```
for (int i = val; i < LEN-k; i++)  
    a[i] = a[i+k]+b[i];
```

- Assume vector width is 4 elements
- This loop can be vectorized when $k < -3$ and $k \geq 0$

Suppose programmers know that $k > 0$. How can the programmer tell the compiler that $k \geq 0$?

Compiler Directives

Compiler vectorizes many loops, but many more can be vectorized if appropriate directives are used

Intel ICC

<code>#pragma ivdep</code>	Ignore data dependences
<code>#pragma vector always</code>	Override efficiency heuristics
<code>#pragma novector</code>	Disable vectorization

GCC

<code>#pragma GCC ivdep</code>	Asserts absence of loop-carried dependences
<code>#pragma GCC novector</code>	Disable vectorization

Aliasing

```
void test(float* A, float* B, float* C) {  
    for (int i = 0; i < LEN; i++) {  
        C[i] = A[i] + B[i];  
    }  
}
```

```
float *C = &A[1];  
...  
void test(float* A, float* B, float* C) {  
    for (int i = 0; i < LEN; i++) {  
        C[i] = A[i] + B[i];  
    }  
}
```

Aliasing

- To vectorize, the compiler needs to guarantee that the pointers are not aliased
- When the compiler does not know if two pointers are aliases, it can still vectorize but needs to add up to $O(n^2)$ run-time checks, where n is the number of pointers
 - ▶ When the number of pointers is large, the compiler may decide to not vectorize
- Two possible workarounds
 - (i) Static and globally defined arrays
 - (ii) Use the `__restrict__` keyword

Resolving Aliases Using Static and Global Arrays

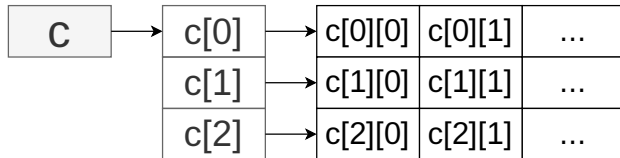
```
float A[LEN] __attribute__((aligned(16)));
float B[LEN] __attribute__((aligned(16)));
float C[LEN] __attribute__((aligned(16)));
void func1() {
    for (int i=0; i<LEN; i++)
        A[i] = B[i] + C[i];
}
int main() {
    ...
    func1();
}
```

Resolving Aliases Using `__restrict__` Keyword

```
...  
float *A = &B[i];  
void test(float* __restrict__ A, float* __restrict__ B,  
          float* __restrict__ C) {  
    __assume_aligned(A, 16);  
    __assume_aligned(B, 16);  
    __assume_aligned(C, 16);  
    for (int i = 0; i < LEN; i++) {  
        A[i]=B[i]+C[i];  
    }  
}  
int main() {  
    float* A=(float*) memalign(16,LEN*sizeof(float));  
    float* B=(float*) memalign(16,LEN*sizeof(float));  
    float* C=(float*) memalign(16,LEN*sizeof(float));  
    ...  
    func1(A,B,C);  
}
```

Aliasing in Multidimensional Arrays

```
void func1(float** __restrict__ a, float** __restrict__ b,  
           float** __restrict__ c) {  
    for (int i=0; i<LEN; i++)  
        for (int j=1; j<LEN; j++)  
            a[i][j] = b[i][j-1] * c[i][j];  
}
```



Aliasing in Multidimensional Arrays

Three solutions to try when `__restrict__` does not enable vectorization

- (i) Static and global arrays
- (ii) Linearize the arrays and then use `__restrict__` keyword
- (iii) Use compiler directives

Static and global declaration

```
float a[N][N] __attribute__((aligned(16)));
void t() {
    a[i][j] ...
}
int main() {
    ...
    t();
    ...
}
```

Aliasing in Multidimensional Arrays

Linearize the array

```
void t(float* __restrict__ a){  
    // Access to a[i][j] is now a[i*128+j]  
    ...  
}  
int main() {  
    float* a = (float*) memalign(16,128*128*sizeof(float));  
    ...  
    t(a);  
}
```

Use compiler
directives

```
void func1(float **a, float **b, float **c) {  
#pragma ivdep  
    for (int i=0; i<m; i++) {  
        for (int j=0; j<LEN; j++)  
            c[i][j] = b[i][j] * a[i][j];  
    }  
}
```

Induction Variables

Induction variables can be expressed as a function of the loop iteration variable

```
float s = 0.0;
for (int i=0; i<LEN; i++) {
    s += 2.0;
    a[i] = s * b[i];
}
```

```
for (int i=0; i<LEN; i++) {
    a[i] = 2.0*(i+1)*b[i];
}
```

Coding style may influence a compiler's ability to vectorize

```
for (int i=0; i<LEN; i++) {
    *a = *b + *c;
    a++; b++; c++;
}
```

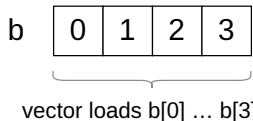
```
for (int i=0; i<LEN; i++) {
    a[i] = b[i] + c[i];
}
```

Data Alignment

- Suppose vector loads (stores) load (store) 128 consecutive bits to a vector register
- Data addresses need to be 16-byte (128 bits) aligned to be loaded/stored
 - ▶ Intel platforms support aligned and unaligned load/stores
 - ▶ IBM platforms do not support unaligned load/stores

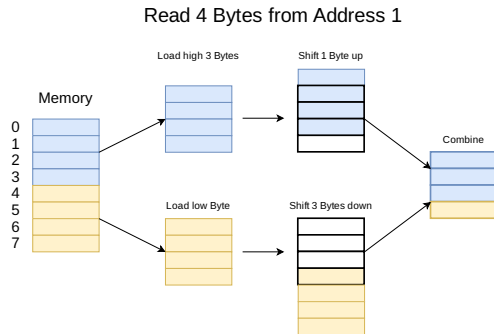
```
void test1(float *a, float *b, float *c) {  
    for (int i=0; i<LEN; i++) {  
        a[i] = b[i] + c[i];  
    }  
}
```

Is &b[0] 16-byte aligned?



Why Data Alignment May Improve Efficiency?

- Vector load/store from aligned data requires one memory access
- Vector load/store from unaligned data requires multiple memory accesses and some shift operations
- A pointer is 16-byte aligned if the address is divisible by 16
 - ▶ That is, the last digit of the pointer address in hex must be 0



```
float B[1024] __attribute__((aligned(16)));  
int main() {  
    printf("%p, %p\n", &B[0], &B[4]);  
}  
// Output: 0x7fff1e9d8580, 0x7fff1e9d8590
```

Data Alignment

Manual 16-byte alignment can be achieved by forcing the base address to be a multiple of 16

```
// Static allocation  
float b[N] __attribute__((aligned(16))) ;  
// Dynamic allocation  
float* a = (float*) memalign(16,N*sizeof(float));
```

When a pointer is passed to a function, the compiler can be made aware of alignment

```
void func1(float *a, float *b, float *c) {  
    __assume_aligned(a, 16);  
    __assume_aligned(b, 16);  
    __assume_aligned(c, 16);  
    for int (i=0; i<LEN; i++)  
        a[i] = b[i] + c[i];  
}
```

Alignment in a struct

```
struct st {
    char A;
    int B[64];
    float C;
    int D[64];
};

int main() {
    st s1;
    printf("%p\n", &s1.A); // 0x7fffe6765f00
    printf("%p\n", &s1.B); // 0x7fffe6765f04
    printf("%p\n", &s1.C); // 0x7fffe6766004
    printf("%p\n", &s1.D); // 0x7fffe6766008
}
```

```
struct st {
    char A;
    int B[64] __attribute__((aligned(16)));
    float C;
    int D[64] __attribute__((aligned(16)));
};

int main() {
    st s1;
    printf("%p\n", &s1.A); // 0x7fffe6765f00
    printf("%p\n", &s1.B); // 0x7fff1e9d8590
    printf("%p\n", &s1.C); // 0x7fffe6766004
    printf("%p\n", &s1.D); // 0x7fff1e9d86a0
}
```

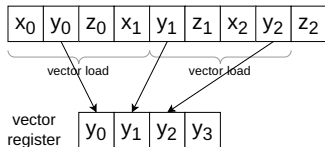
Arrays B and D are not 16-bytes aligned

Non-unit Stride

Array of structures

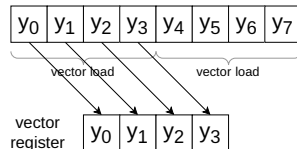
```
typedef struct {int x, y, z} point;  
point pt[LEN];  
for (int i=0; i<LEN; i++) {  
    pt[i].y *= scale;  
}
```

point pt[N];



Structure of arrays

```
int ptx[LEN], pty[LEN], ptz[LEN];  
for (int i=0; i<LEN; i++) {  
    pty[i] *= scale;  
}
```



Conditional Statements

- A compiler may not vectorize a loop with a conditional if it is unsure about the profitability
 - ▶ Furthermore, removing the condition may lead to exceptions
- You may need to introduce hints like `#pragma vector always`
- Compiler may create multiple versions of the code (e.g., scalar and vector)
 - ▶ Compiler may remove the conditions when generating the vector version

```
#pragma vector always
for (int i = 0; i < LEN; i++) {
    if (c[i] < 0.0)
        a[i] = a[i] * b[i] + d[i];
}
```

Vectorization Examples

- Vectorization output can vary across compiler versions and architecture generations
- Correlate the assembly code with the high-level C++ statements
- Understanding alignment
 - ▶ `struct.cpp` 
 - ▶ `unaligned-cost-gcc.cpp` 
- Makefile 
 - ▶ Check the Makefile for relevant options passed to GCC

Vectorization with Intrinsics

Vector Intrinsics

- Intrinsics are useful when
 - ▶ the compiler fails to vectorize, or
 - ▶ when the programmer thinks it is possible to generate better code than what is produced by the compiler
- Intrinsics are architecture specific

Intel Intrinsics Header Files

- We will focus on the Intel vector intrinsics
- You have to include one of the following header files for using intrinsics

```
SSE #include <xmmintrin.h>
SSE2 #include <emmintrin.h>
SSE3 #include <pmmintrin.h>
SSSE3 #include <tmmintrin.h>
SSE4.1 #include <smmintrin.h>
SSE4.2 #include <nmmintrin.h>
AVX #include <immintrin.h>
AVX2 #include <immintrin.h>
AVX512 #include <immintrin.h>
```

- Alternatively, use `#include <x86intrin.h>`, it includes all relevant headers

Format of Intel Intrinsic APIs

```
_mm_instruction_suffix(...)  
_mm256_instruction_suffix(...)
```

Suffix can take many forms

- ss** scalar single precision
- ps** packed (vector) single precision
- sd** scalar double precision
- pd** packed double precision
- si#** scalar integer (8, 16, 32, 64, or 128 bits)
- su#** scalar unsigned integer (8, 16, 32, 64, or 128 bits)

Data Types

Few examples

`__m128` packed single precision (vector XMM register)

`__m128d` packed double precision (vector XMM register)

`__m128i` packed integer (vector XMM register)

Load four 16-byte aligned single precision values in a vector

```
float a[4]={1.0,2.0,3.0,4.0}; // a must be 16-byte aligned
__m128 x = _mm_load_ps(a);
```

Add two vectors containing four single precision values

```
__m128 a, b;
__m128 c = _mm_add_ps(a, b);
```

Examples with Intrinsics

- Understanding alignment cost with intrinsics 
- Inclusive prefix sum with SSE 
- Makefile 

Summary

- Relevance of vectorization to improve program performance is likely to increase in the future as vector lengths grow
- Compilers are often only partially successful at vectorizing code
- When the compiler fails, programmers can
 - ▶ add compiler directives, or
 - ▶ apply loop transformations
- If after transforming the code, the compiler still fails to vectorize (or the performance of the generated code is poor), use vector extensions (e.g., intrinsics or assembly) directly

Enhancing Coarse-Grained Parallelism

Focus is on parallelization of outer loops

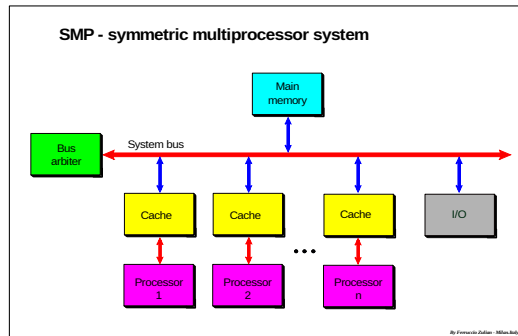
Find Work for Threads

Setup

- Symmetric multiprocessors with shared memory
- Threads are running on each core and are coordinating execution with occasional synchronization

Challenge

Balance the granularity of parallelism with communication overheads



Challenges in Coarse-Grained Parallelism

Minimize communication and synchronization overhead while evenly load balancing across the processors

Running everything on one processor achieves minimal communication and synchronization overhead

Very fine-grained parallelism achieves good load balance, but benefits may be outweighed by frequent communication and synchronization

Privatization

Temporaries can be made local to each iteration

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

```
      PARALLEL DO I = 1,N  
          PRIVATE t  
S1      t = A(I)  
S2      A(I) = B(I)  
S3      B(I) = t
```

Privatization

A scalar variable x in a loop L is privatizable if every path from the entry of L to a use of x in the loop passes through a definition of x

- No use of the variable is upward exposed, i.e., the use never reads a value that was assigned outside the loop
- No use of the variable is from an assignment in an earlier iteration

Computing upward-exposed variables from a block BB

$$up(BB) = use(BB) \cup \left(\neg def(BB) \cap \bigcup_{y \in succ(BB)} up(y) \right)$$

Computing privatizable variables for a loop body B where BB_0 is the entry block

$$private(B) = \neg up(BB_0) \cap \left(\bigcup_{y \in B} def(y) \right)$$

Comparing Privatization and Scalar Expansion

- Privatization is preferred compared to scalar expansion
 - ▶ Less memory requirement
 - ▶ Scalar expansion may suffer from false sharing
- There are examples where scalar expansion works but privatization does not

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

Scalar
expansion

```
PARALLEL DO I = 1, N  
  T$(I) = A(I) + B(I)  
  A(I-1) = T$(I)
```

⇓ Privatization

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

⇓

```
PARALLEL DO I = 1, N  
  T$(I) = A(I) + B(I)  
PARALLEL DO I = 1, N  
  A(I-1) = T$(I)
```

Loop Distribution (Loop Fission)

```
      DO I = 1, 100
        DO J = 1, 100
S1      A(I,J) = B(I,J) + C(I,J)
S2      D(I,J) = A(I,J-1) * 2.0
```

```
      DO I = 1, 100
        DO J = 1, 100
S1      A(I,J) = B(I,J) + C(I,J)

        DO J = 1, 100
S2      D(I,J) = A(I,J-1) * 2.0
```

Eliminates loop-carried
dependences

Validity Condition for Loop Distribution

A loop with two statements can be distributed if there are no dependences from any instance of the **later** statement to any instance of the **earlier** one

- Sufficient (but not necessary) condition
- Generalizes to more statements

	DO I = 1, N
S1	A(I) = B(I) + C(I)
S2	E(I) = A(I+1) * D(I)

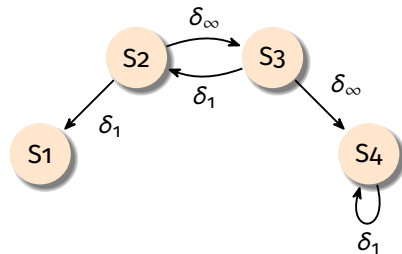
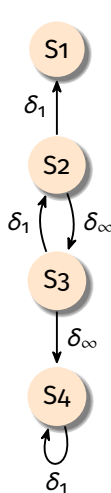
	DO I = 1, N
S1	A(I) = B(I) + C(I)
S2	E(I) = A(I-1) * D(I)

Performing Loop Distribution

Steps

- (i) Build the DDG
- (ii) Identify strongly-connected components (SCCs) in the DDG
- (iii) Make each SCC a separate loop
- (iv) Arrange the new loops in a topological order of the DDG

```
DO I = 1, N
S1  A[I] = A[I] + B[I-1]
S2  B[I] = C[I-1] + X
S3  C[I] = B[I] + Y
S4  D[I] = C[I] + D[I-1]
```



```
DO I = 1, N
S2  B[I] = C[I-1] + X
S3  C[I] = B[I] + Y
DO I = 1, N
S1  A[I] = A[I] + B[I-1]
DO I = 1, N
S4  D[I] = C[I] + D[I-1]
```

Understanding Loop Distribution

Pros

- + Execute source of a dependence before the sink
- + Reduces the memory footprint of the original loop for both data and code
- + Improves opportunities for vectorization

Cons

- Can increase the synchronization required between dependence points

Loop Alignment

Unlike loop distribution, realign the loop to compute and use the values in the same iteration

```
DO I = 2, N
S1  A(I) = B(I) + C(I)
S2  D(I) = A(I-1) * 2.0
```

cannot be parallelized

```
DO i = 1, N+1
    if i > 1 && i < N+1
S1    A(i) = B(i) + C(i)
    if i < N
S2    D(i+1) = A(i) * 2.0
```

carried dependence becomes
loop independent

Can Loop Alignment Eliminate All Carried Dependences?

```
DO I = 1, N
S1  A(I) = B(I) + C
S2  B(I+1) = A(I) + D
```

A is aligned, B
is misaligned



```
DO i = 1, N+1
  if i > 1
S2    B(i) = A(i-1) + D
  if i < N+1
S1    A(i) = B(i) + C
```

```
DO I = 1, N
S1  A(I+1) = B(I) + C
S2  X(I) = A(I+1) + A(I)
```



```
DO i = 0, N
  if i > 0
S1    A(i+1) = B(i) + C
  if i < N
S2    X(i+1) = A(i+2) + A(i+1)
```

Loop Fusion (Loop Jamming)

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

$\Rightarrow$

```
L1  DO I = 1, N
      A(I) = B(I) + 1
L2  DO I = 1, N
      C(I) = A(I) + C(I-1)
L3  DO I = 1, N
      D(I) = A(I) + X
```

$\Rightarrow$

```
L13 DO I = 1, N
      A(I) = B(I) + 1
      D(I) = A(I) + X
L2  DO I = 1, N
      C(I) = A(I) + C(I-1)
```

Validity Condition for Loop Fusion

- Consider a loop-independent dependence between statements in two different loops (i.e., from S1 to S2)
- A dependence is fusion-preventing if fusing the two loops causes the dependence to be carried by the combined loop in the reverse direction (from S2 to S1)

	DO I = 1, N
S1	A(I) = B(I) + C
	DO I = 1, N
S2	D(I) = A(I+1) + E

loop-independent
flow dependence

	DO I = 1, N
S1	A(I) = B(I) + C
S2	D(I) = A(I+1) + E

backward loop-carried
anti dependence

Understanding Loop Fusion

Pros

- + Reduce overhead of loops
- + May improve temporal locality

	DO I = 1, N
S1	A(I) = B(I) + C
	DO I = 1, N
S2	D(I) = A(I-1) + E

Cons

- May decrease data locality in the fused loop

	DO I = 1, N
S1	A(I) = B(I) + C
S2	D(I) = A(I-1) + E

Loop Interchange

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

Parallelizing J is good for vectorization,
but not for coarse-grained parallelism

⇒

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

Dependence-free loops should
move to the outermost level

⇓

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

Condition for Loop Interchange

In a perfect loop nest, a loop can be parallelized at the outermost level iff that column of the direction matrix contains only “o” entries

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

Parallel Code Generation Strategy

- (i) Continue till there are no more columns to move
 - ▶ Choose a loop from the direction matrix that has all “o” entries in the column
 - ▶ Move it to the outermost position
 - ▶ Eliminate the column from the direction matrix
- (ii) Pick loop with most “+” entries, move to the next outermost position
 - ▶ Generate a sequential loop
 - ▶ Eliminate the column
 - ▶ Eliminate any rows that represent dependences carried by this loop
- (iii) Repeat from Step (i)

Code Generation Example

```
DO I = 1, N
  DO J = 1, M
    DO K = 1, L
      A(I+1,J,K) = A(I,J,K) + X1
      B(I,J,K+1) = B(I,J,K) + X2
      C(I+1,J+1,K+1) = C(I,J,K) + X3
```

What is the direction matrix? Can we permute the loops?

```
DO I = 1, N
  PARALLEL DO J = 1, M
    DO K = 1, L
      A(I+1,J,K) = A(I,J,K) + X1
      B(I,J,K+1) = B(I,J,K) + X2
      C(I+1,J+1,K+1) = C(I,J,K) + X3
```

How did we pick loop J for parallelization?

How can we parallelize this loop?

```
DO I = 2, N+1  
  DO J = 2, M+1  
    DO K = 1, L  
      A(I,J,K) = A(I,J-1,K+1) + A(I-1,J,K+1)
```

No single loop carries all the dependences,
so we can only parallelize loop K

Loop Reversal

```
DO I = 2, N+1
  DO J = 2, M+1
    DO K = 1, L
      A(I,J,K) = A(I,J-1,K+1) + A(I-1,J,K+1)
```



```
DO I = 2, N+1
  DO J = 2, M+1
    DO K = L, 1, -1
      A(I,J,K) = A(I,J-1,K+1) + A(I-1,J,K+1)
```

When the iteration space of a loop is reversed, the direction of dependences within that reversed iteration space are also reversed

- A “+” dependence becomes a “-” dependence, and vice versa
- We cannot perform loop reversal if the loop carries a dependence

Perform Interchange after Loop Reversal

```
DO I = 2, N+1
  DO J = 2, M+1
    DO K = L, 1, -1
      A(I,J,K) = A(I,J-1,K+1) + A(I-1,J,K+1)
```



```
DO K = L, 1, -1
  DO I = 2, N+1
    DO J = 2, M+1
      A(I,J,K) = A(I,J-1,K+1) + A(I-1,J,K+1)
```

increases options for performing other optimizations

Unimodular Transformations

Loop Transformations

```
for (int i = 0; i < N; i++)  
    for (int j = 0; j < M; j++)  
        S(i, j);
```

The iteration space IS is given by

$$IS = \{(i, j) \mid 0 \leq i < N, 0 \leq j < M\}$$

An affine loop transformation maps I to $I' = TI + t'$, where I, I' are iteration vectors.

- T has to be an integer matrix and t is a translation vector.

Unimodular Transformations

- A **unimodular** matrix is a square integer matrix having determinant 1 or -1 (e.g., $\begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}$)
- Few loop transformations can be modeled as matrix transformations involving unimodular matrices

- ▶ Loop interchange maps iteration (i, j) to iteration (j, i)

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i \\ j \end{bmatrix} = \begin{bmatrix} j \\ i \end{bmatrix}$$

- ▶ Given transformation T is linear, the transformed dependence is given by Td where d is the dependence vector in the original iteration space

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} d_2 \\ d_1 \end{bmatrix}$$

- ▶ The transformation matrix for loop reversal of the outer loop i in a 2D loop nest is $\begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$
- ▶ The transformation matrix for loop skewing of a 2D loop nest (i, j) is the identity matrix T with $T_{j,i}$ equal to f , where we skew loop j with respect to loop i by a factor f

Example of Loop Skewing

Original

```
FOR I=1,5  
  FOR J=1,5  
    A(I,J) = A(I-1,J) + A(I,J-1)
```

Dependences $D = \{(1, 0), (0, 1)\}$

Skewed

```
FOR I=1,5  
  FOR j=I+1,I+5  
    A(I,j-I) = A(I-1,j-I) + A(I,j-I-1)
```

Transformation matrix = $\begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$

Dependences $D' = TD = \{(1, 1), (0, 1)\}$

Representing Compound Transformations

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

Loop interchange is illegal because

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ -1 \end{bmatrix} = \begin{bmatrix} -1 \\ 1 \end{bmatrix}$$

Let us try loop interchange followed by loop reversal. The transformation matrix T is

$$\begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

Applying T to the loop nest is legal because

$$\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ -1 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

```
DO J = N, 1, -1  
  DO I = 1, N  
    A[I,J] = A[I-1,J+1] + C
```

Challenges in Applying Transformations

Challenges in Applying Transformations

- We have discussed transformations (legality and benefits) in isolation
- Compilers need to apply compound transformations (e.g., loop interchange followed by reversal)
- It is challenging to decide on the desired transformations and their order of application
 - ▶ Choice and order is sensitive to the program input, a priori order does not work
- Other considerations: conditional execution, symbolic loop bounds, and indirect memory accesses

Which Transformations are Most Important?

- Selecting the best loops for parallelization is a NP-complete problem
- Flow dependences are difficult to remove
 - ▶ Try to reorder statements as in loop peeling, loop distribution
 - ▶ Loops often use scalars for temporary values
 - ▶ Techniques like scalar expansion and privatization can be useful

+	+	O	O
+	O	+	O
+	O	O	+
O	+	O	O
O	O	+	O
O	O	O	+

carries the most dependences

Code Examples

-  check-cpu-capability.cpp
-  diff-variants-v1.cpp
-  diff-variants-v2.cpp
-  struct.cpp
-  unaligned-cost-gcc.cpp
-  inclusive-prefix-sum-gcc-sse4.cpp
-  unaligned-cost-intrinsics.cpp
-  Makefile

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