Program Optimization Through Loop Vectorization

SIMD

Single Instruction

multiple Data

Topics covered

- What are the microprocessor vector extensions or SIMD (Single Instruction Multiple Data Units)
- Overcoming limitations to SIMD-Vectorization
  - Data Dependences
  - Data Alignment
  - Aliasing
  - Non-unit strides
  - Conditional Statements
- Vectorization with intrinsics

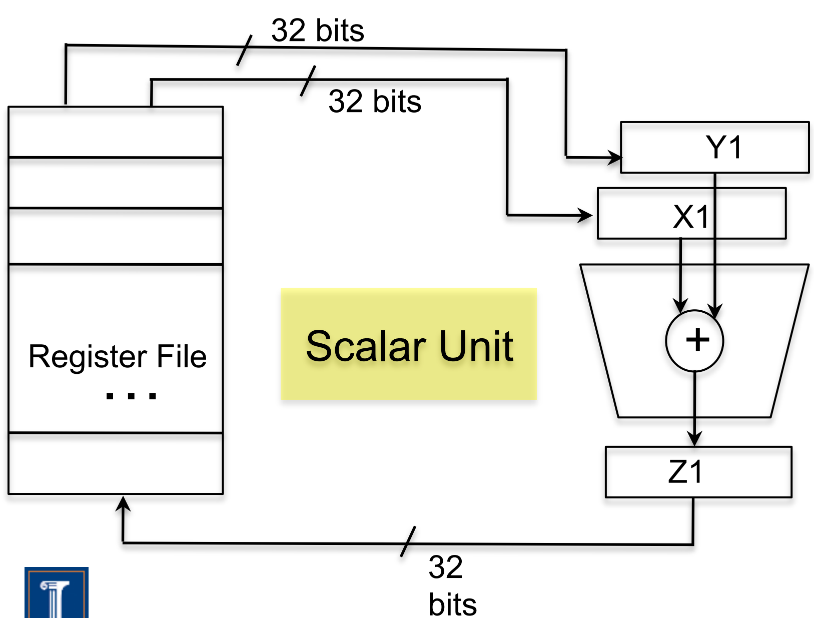
Simple Example

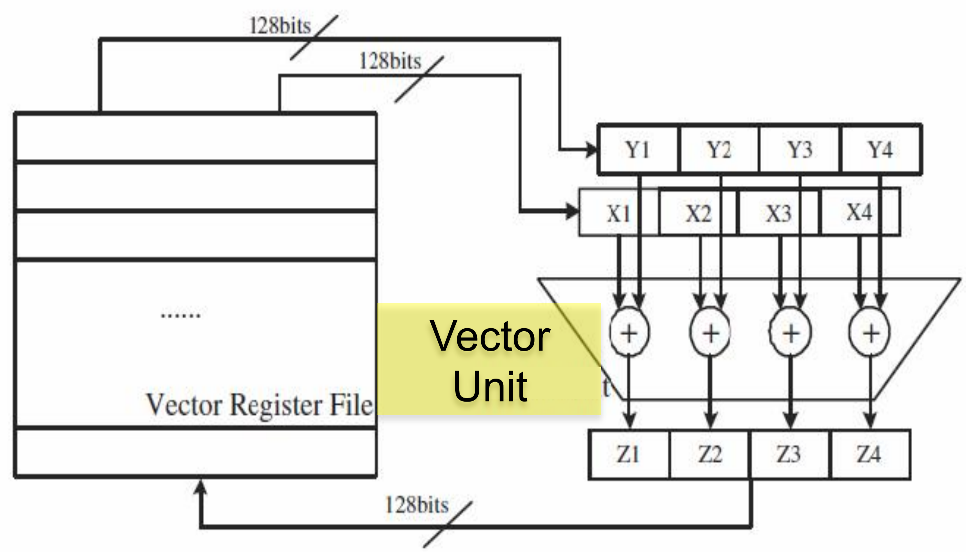
- Loop vectorization transforms a program so that the same operation is performed at the same time on several vector elements

```
lw $t0, 0($a0)
lw  $t1, 0($a1)
add $t3, $t0, $t1
sw $t3, 0($a3)
```

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

```
lwv $vt0, 0($a0)
lwv $vt1, 0($a1)
addv $vt3, $vt0, $vt1
swv %vt3, $0($a3)
```





SIMD Vectorization

- The use of SIMD units can speed up the program.
- Intel SSE and IBM Altivec have 128-bit vector registers and functional units
  - 4 32-bit single precision floating point numbers
  - 2 64-bit double precision floating point numbers
  - 4 32-bit integer numbers
  - 2 64 bit integer
  - 8 16-bit integer or shorts
  - 16 8-bit bytes or chars
- 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.
- Newer processors, such as Sandy or Ivy Bridge have AVX that support 256-bit vector registers.

Experimental results

- Results are shown for different platforms with their compilers:
  - Report generated by the compiler
  - Execution Time for each platform

Platform 1: Intel Nehalem
Intel Core i7 CPU 920@2.67GHz
Intel ICC compiler, version 11.1
OS Ubuntu Linux 9.04

Platform 2: IBM Power 7
IBM Power 7, 3.55 GHz
IBM xlc compiler, version 11.0
OS Red Hat Linux Enterprise 5.4

The examples use single precision floating point numbers

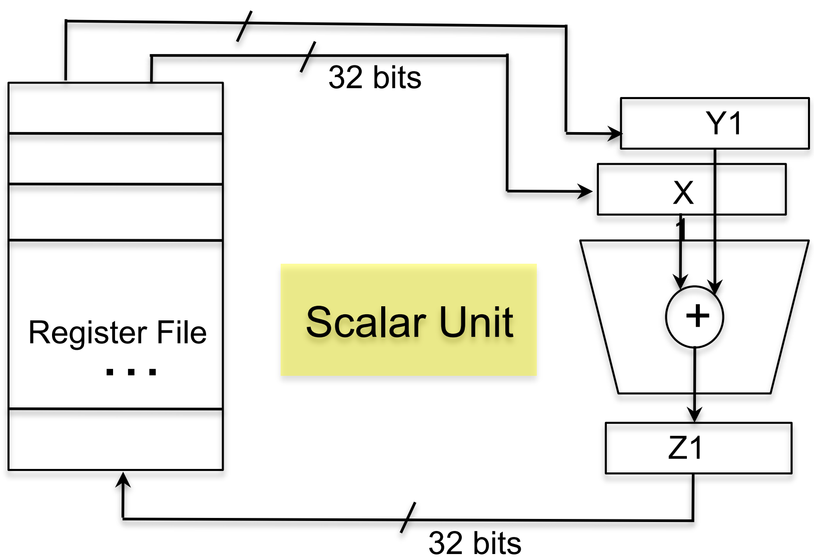
4

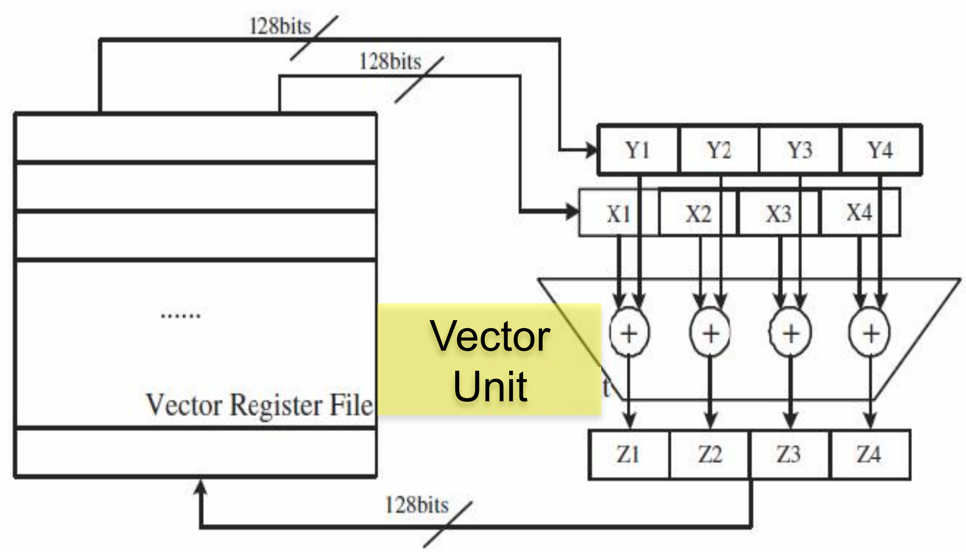
Executing Our Simple Example

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

Intel Nehalem
Exec. Time scalar code: 6.1
Exec. Time vector code: 3.2
Speedup: 1.8

IBM Power 7
Exec. Time scalar code: 2.1
Exec. Time vector code: 1.0
Speedup: 2.1





How do we access the SIMD units?

- Three choices
  1. Assembly Language

```
..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
```

  2. Macros or Vector Intrinsics

```
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);
}}
```

  3. C code and a vectorizing compiler

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

Why use compiler vectorization?

1. Easier
2. Portable across vendors and machines
   – Although compiler directives differ across compilers
3. Better performance of the compiler generated code
   – Compiler applies other transformations

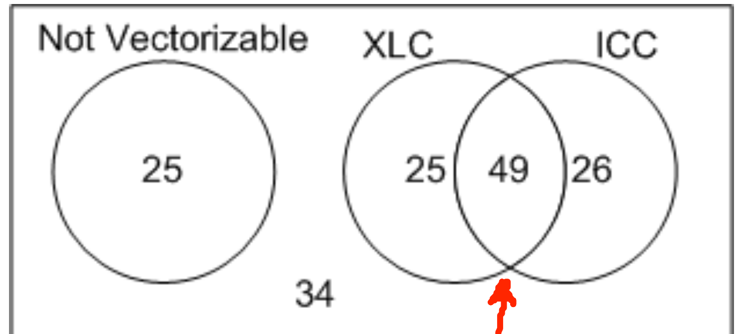
Compilers make your codes (almost) machine independent

How well do compilers vectorize?

IBM INTEL

Loops \ Compiler	XLC	ICC	GCC
Total	159		
Vectorized	74	75	32
Not vectorized	85	84	127
Average Speed Up	1.73	1.85	1.30

Loops \ Compiler	XLC but not ICC	ICC but not XLC
Vectorized	25	26



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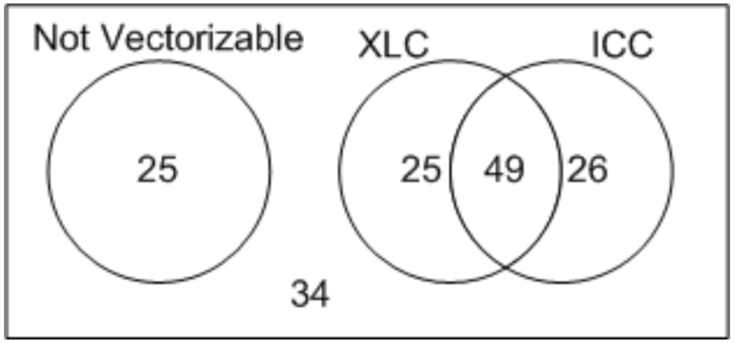


By adding manual vectorization the average speedup was 3.78 (versus 1.73 obtained by the XLC compiler)

Compiler Vectorization

- Compilers can vectorize for us, but they may fail:

    1. Code cannot be vectorized due to data dependences: vectorization will produce incorrect results.

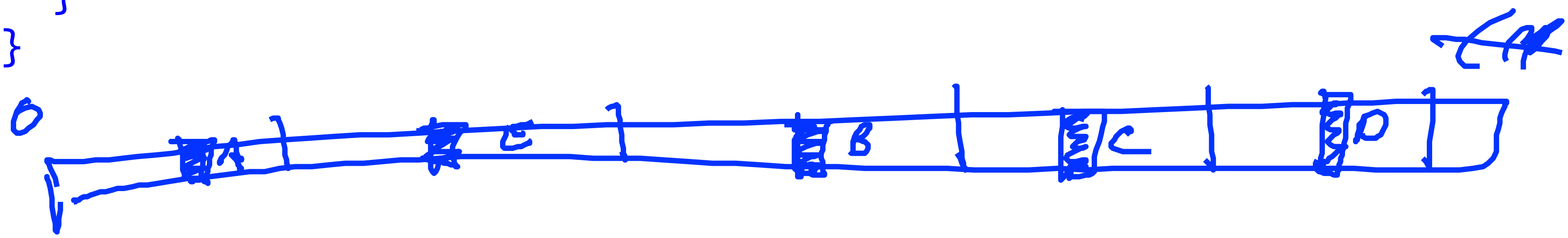
    2. Code can be vectorized, but the compiler fail to vectorize the code in its current form

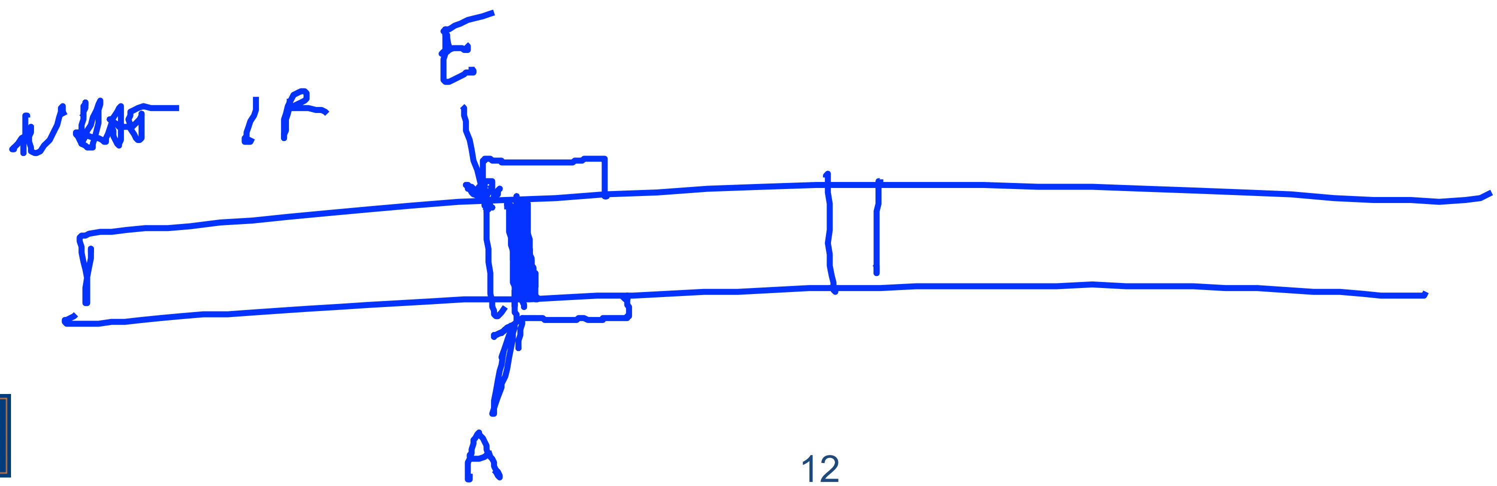
        1. Programmer can use compiler directives to give the compiler the necessary information

        2. Programmer can transform the code

Example

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





Compiler directives

directive

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

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

Intel Nehalem
Compiler report: Loop was not vectorized.
Exec. Time scalar code: 5.6
Exec. Time vector code: --
Speedup: --

Intel Nehalem
Compiler report: Loop was vectorized.
Exec. Time scalar code: 5.6
Exec. Time vector code: 2.2
Speedup: 2.5

Compiler directives

float A[128], B[128];
float *C = &A[1]

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

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

Power 7
Compiler report: Loop was not vectorized.
Exec. Time scalar code: 2.3
Exec. Time vector code: --
Speedup: --

Power 7
Compiler report: Loop was vectorized.
Exec. Time scalar code: 1.6
Exec. Time vector code: 0.6
Speedup: 2.7

Vectorization is not always legal

- Vectorization of some codes could produce incorrect results

- Compilers (and programmers) can compute data dependences to determine if a program can be vectorized

Definition of Dependence

T

S

- A statement S is said to be data dependent on statement T if
  - T executes before S in the original sequential/scalar program
  - S and T access the same data item
  - At least one of the accesses is a write.

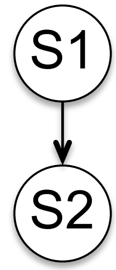
Tour on Data Dependences

C = X + A
X = A + B

Flow dependence (True dependence)

S1: X = A+B
S2: C= X+A

RAW
read-after-write

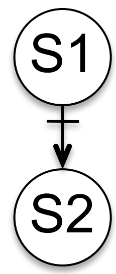


producer
consumer

Anti dependence

S1: A = X + B
S2: X= C + D

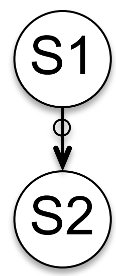
WAR



Output dependence

S1: X = A+B
S2: X= C + D

name dependence



Data Dependence

- Dependences indicate an execution order that must be honored.
- Executing statements in the order of the dependences guarantee correct results.
- Statements not dependent on each other can be reordered, executed in parallel, or coalesced into a vector operation.

Data Dependences

S1: A = B + D

S2: C = A + T

S3: Z = P + T

Data Dependences

ORIG

S1: A = B + D

S2: C = A + T

S3: Z = P + T

S1

S2

S3

S1: A = B + D

S3: Z = P + T

S2: C = A + T

S2: C = A + T

S1: A = B + D

S3: Z = P + T

A) yes b) NO

Dependences in Loops (I)

- Dependences in loops are easy to understand if the loops are unrolled. Now the dependences are between statement "executions".

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

a[i+1] c

Dependences in Loops (I)

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

i=0	i=1	i=2
S1: a[0] = b[0] + 1	S1: a[1] = b[1] + 1	S1: a[2] = b[2] + 1
S2: c[0] = a[0] + 2	S2: c[1] = a[1] + 2	S2: c[2] = a[2] + 2

A) Yes   B) No

SAFE to vectorize

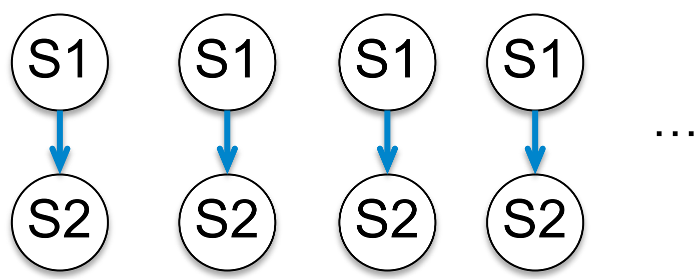
Dependences in Loops (I)

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

iteration: 0 1 2 3 …

instances of S1:

instances of S2:



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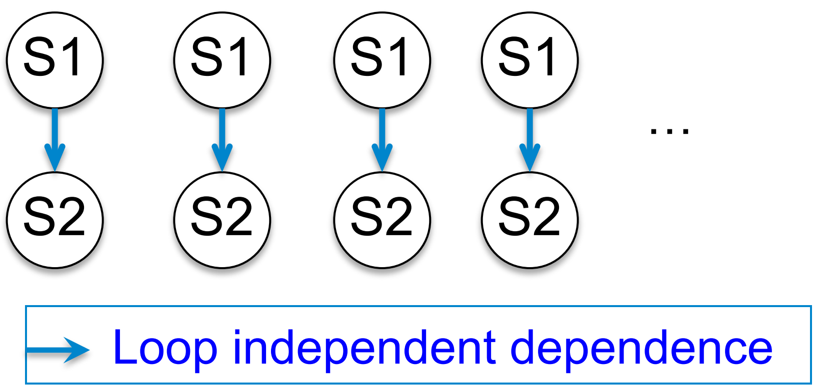

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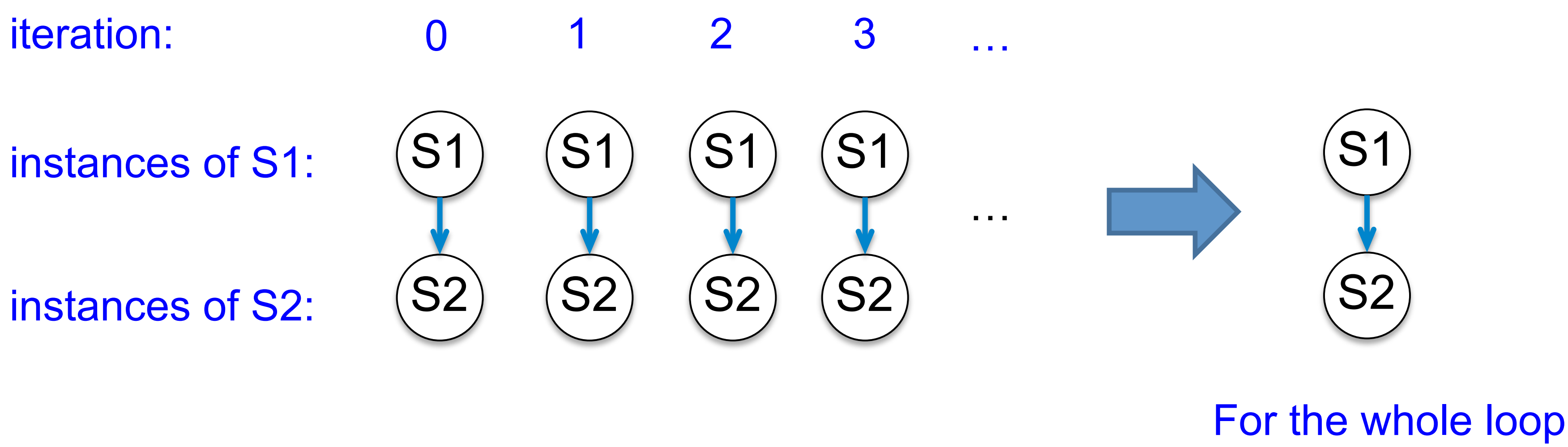

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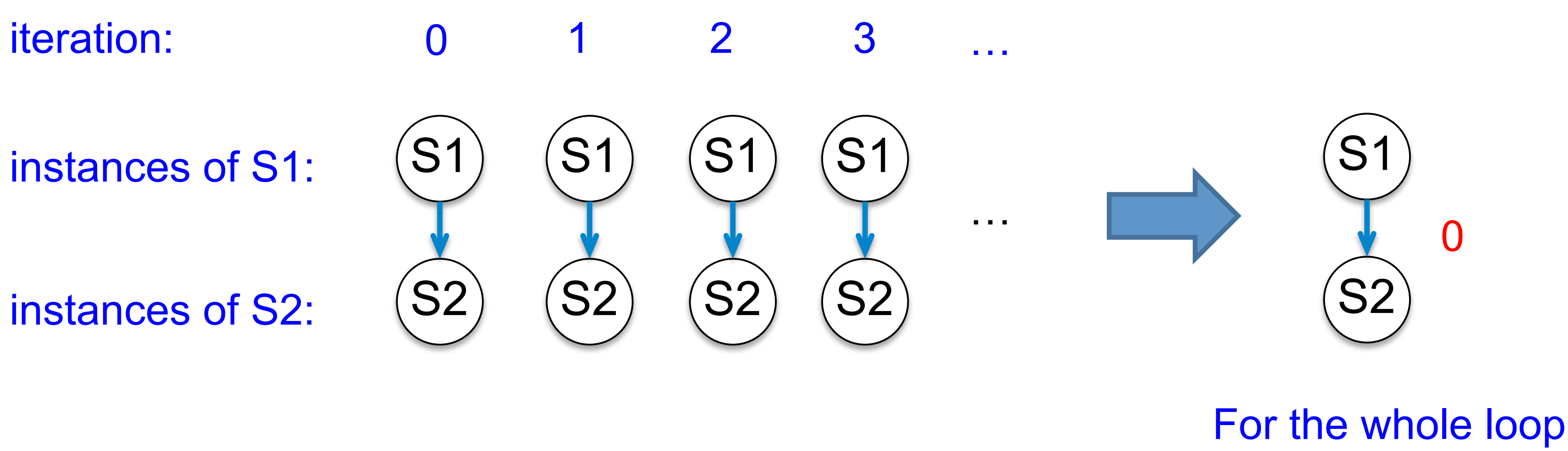

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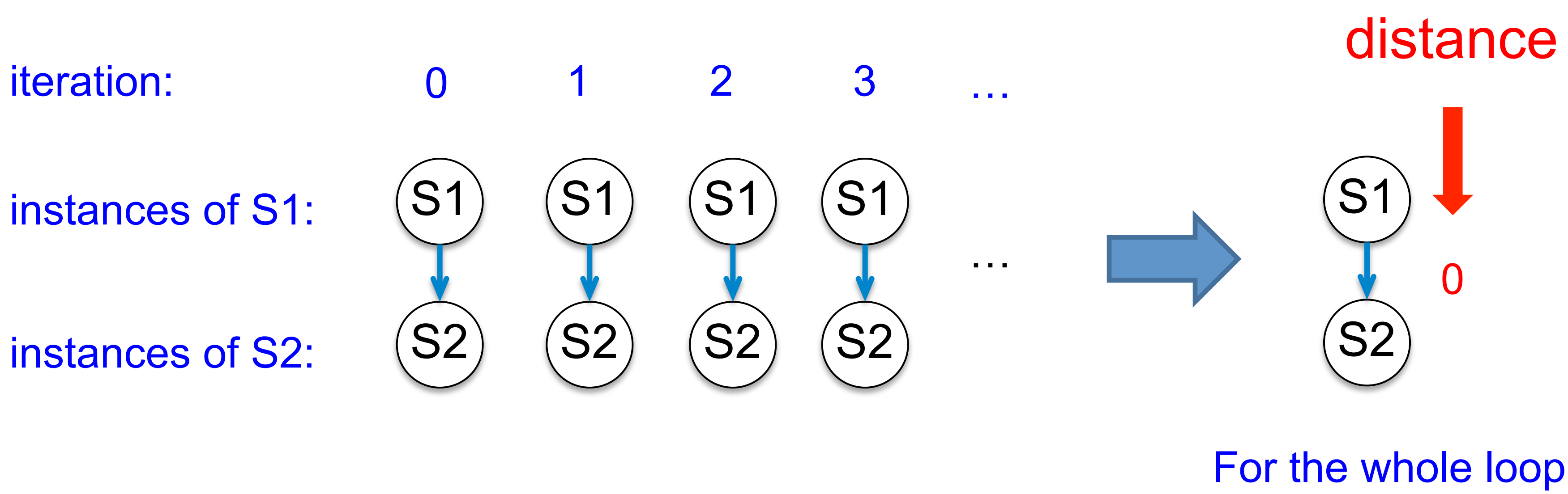


Dependences in Loops (I)

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

For the dependences shown here, we assume that arrays do not overlap in memory (no aliasing). Compilers must know that there is no aliasing in order to vectorize.

Dependences in Loops (II)

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

Dependences in Loops (II)

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

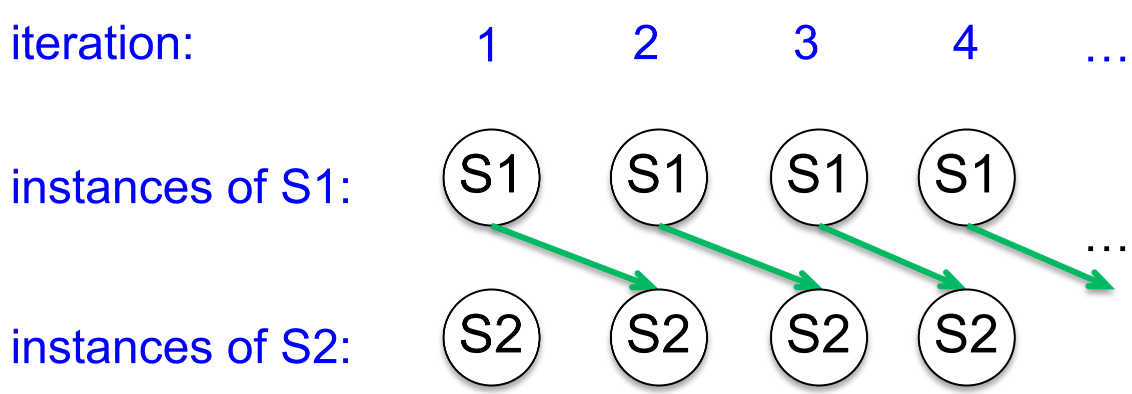
i=1 i=2 i=3

i=1	i=2	i=3
1 S1: a[1] = b[1] + 1	3 S1: a[2] = b[2] + 1	5 S1: a[3] = b[3] + 1
2 S2: c[1] = a[0] + 2	4 S2: c[2] = a[1] + 2	6 S2: c[3] = a[2] + 2

A) yes B) no

Dependences in Loops (II)

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



Dependences in Loops (II)

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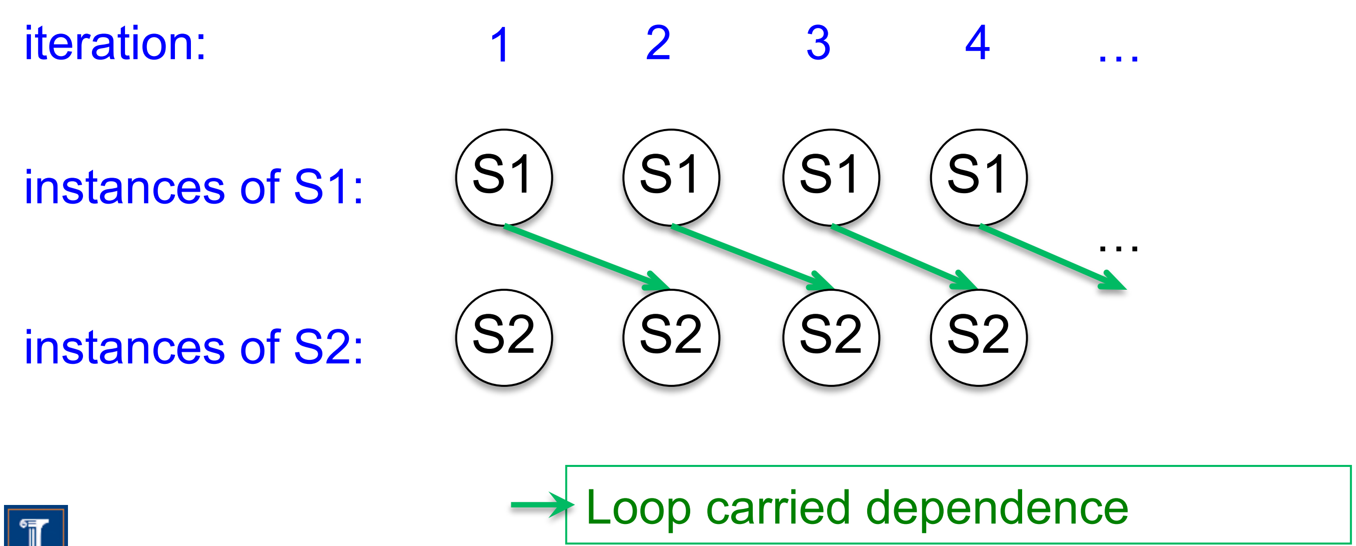

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```
    for (i=1; i<n; i++){
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```
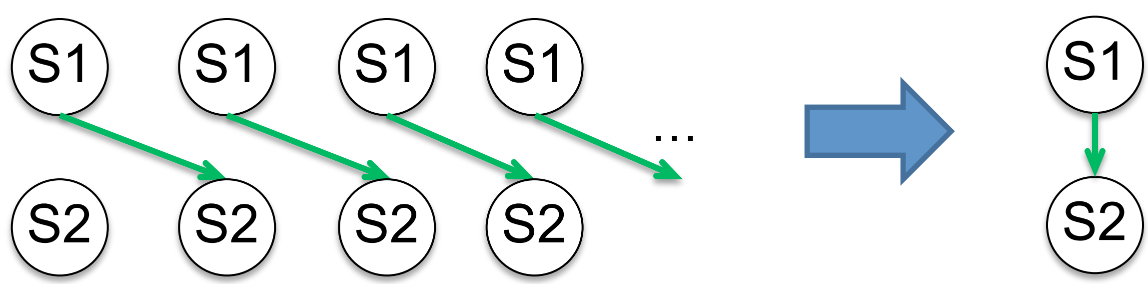

iteration: 1 2 3 4 …

instances of S1:

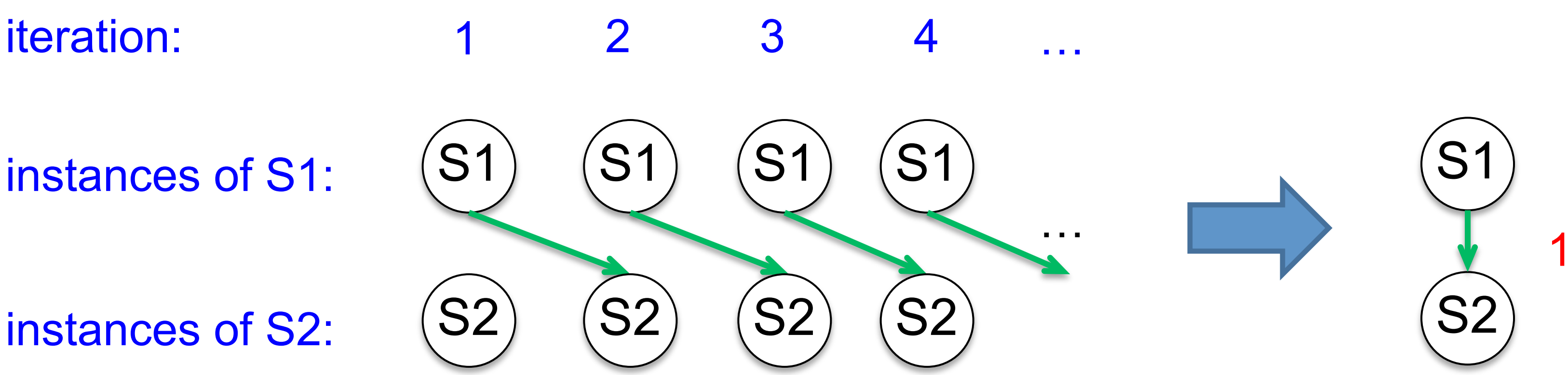
instances of S2:



For the whole loop

Dependences in Loops (II)

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

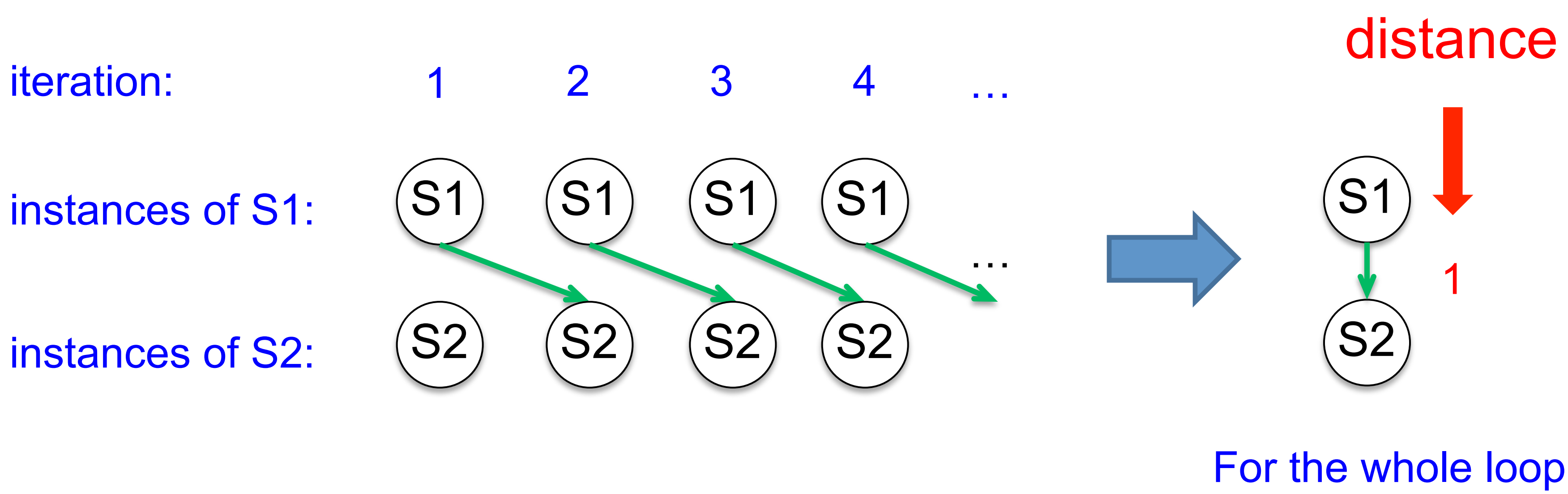


For the whole loop

Dependences in Loops (II)

- Dependences in loops are easy to understand if loops are unrolled. Now the dependences are between statement “executions”

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



Dependences in Loops (III)

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

Dependences in Loops (III)

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

i=0

S1: a= b[0] + 1
S2: c[0] = a + 2

i=1

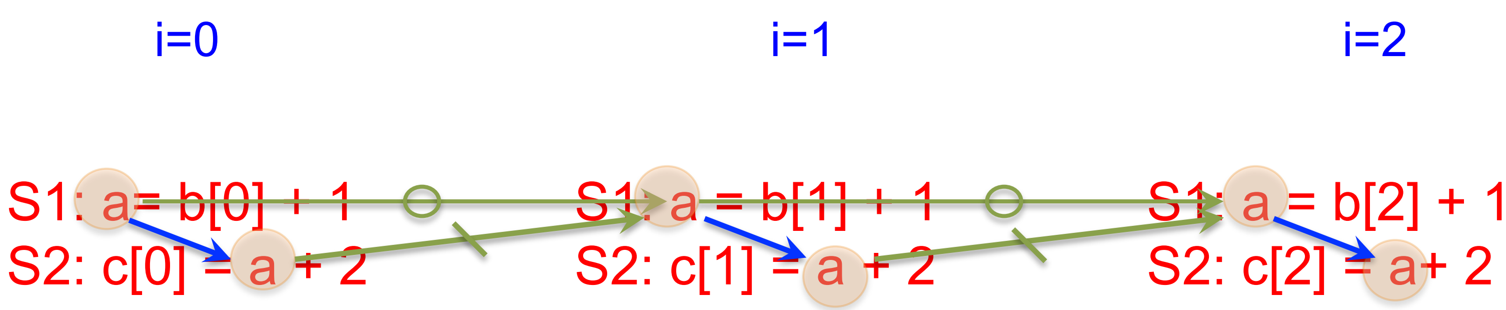
S1: a = b[1] + 1
S2: c[1] = a + 2

i=2

S1: a = b[2] + 1
S2: c[2] = a+ 2

Dependences in Loops (III)

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



Loop independent dependence

Loop carried dependence

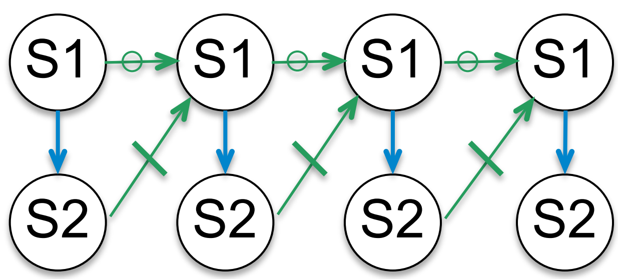
Dependences in Loops (III)

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

iteration: 0 1 2 3 …

instances of S1:

instances of S2:



Dependences in Loops (III)

A[i]

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

A[i]

iteration: 0 1 2 3 …

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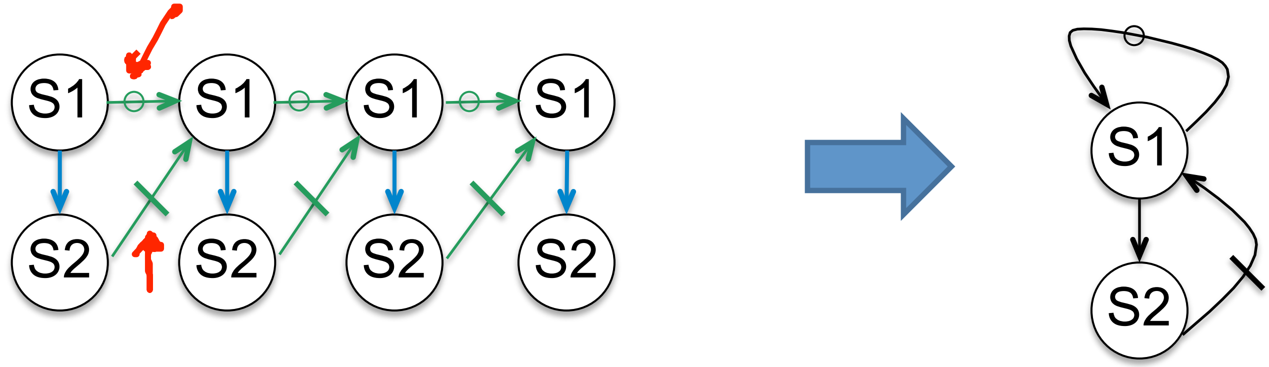
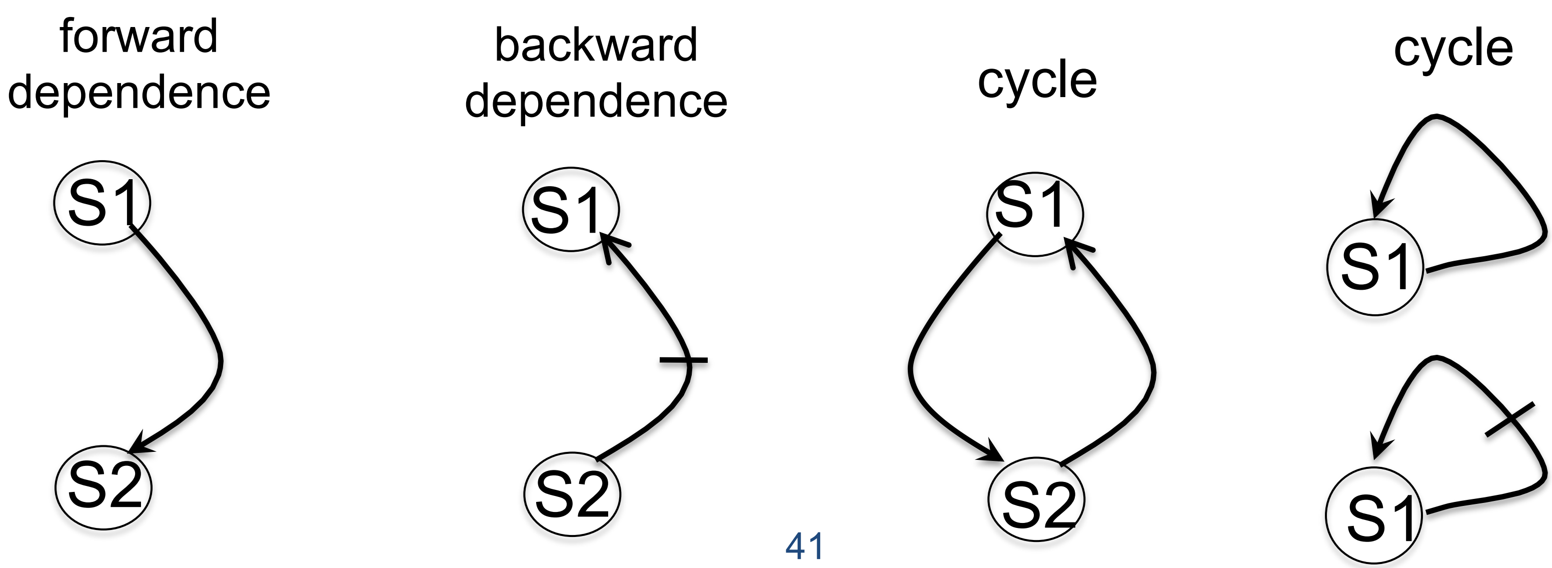


Loop Vectorization

- Loop Vectorization is not always a legal transformation.
  - Compilers can vectorize when there are only forward dependences
  - Compilers cannot vectorize when there is a cycle in the data dependences (with the exception of self-antidependence), unless a transformation is applied to remove the cycle
  - Codes with only backward dependences can be vectorized, but need to be transformed



Simple Example

- Loop vectorization transforms a program so that the same operation is performed at the same time on several vector elements

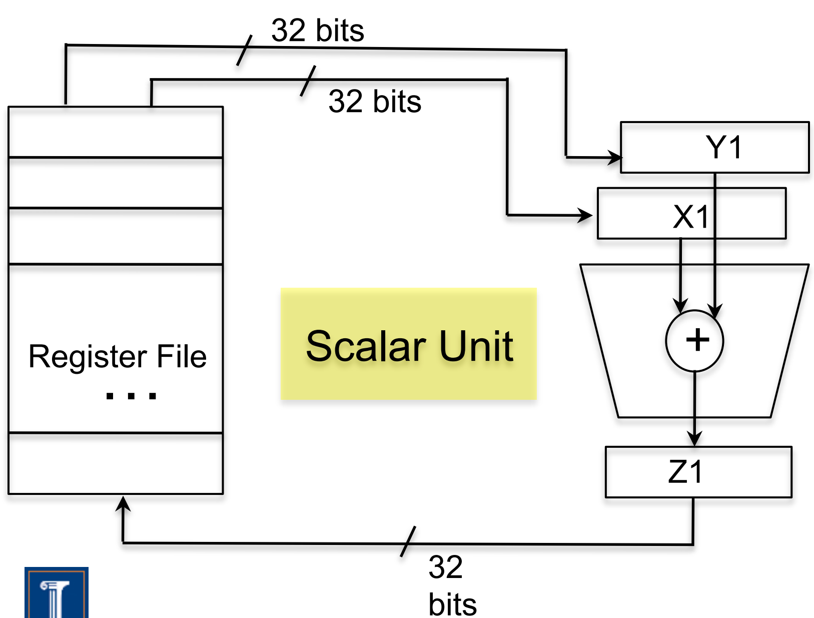
n times

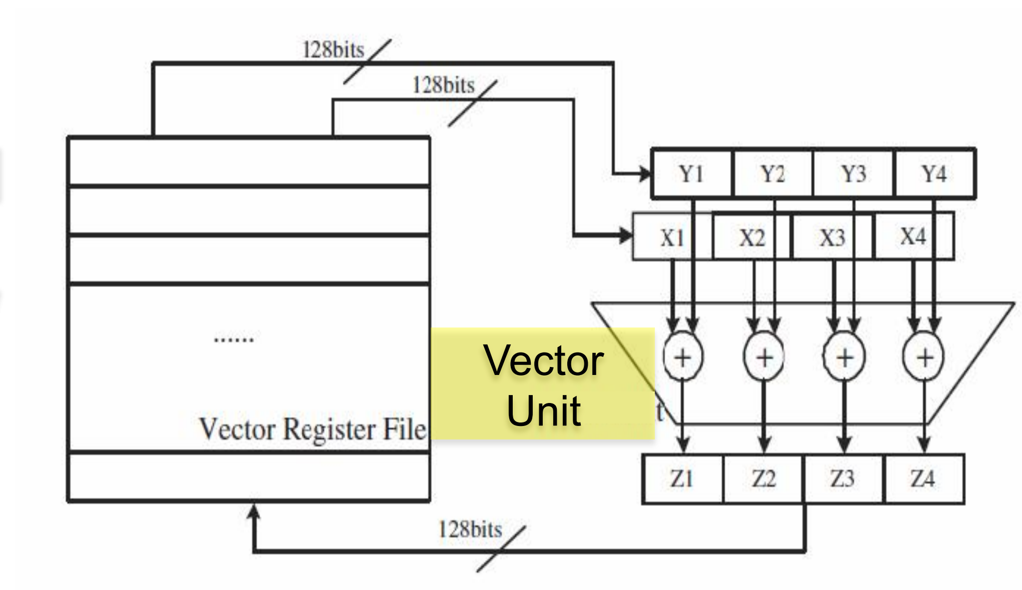
```
lw $t0, 0($a0)
lw  $t1, 0($a1)
add $t3, $t0, $t1
sw $t3, 0($a3)
```

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

n/4 times

```
lwv $vt0, 0($a0)
lwv $vt1, 0($a1)
addv $vt3, $vt0, $vt1
swv %vt3, $0($a3)
```





Loop Vectorization

- When vectorizing a loop with several statements the compiler need to strip-mine the loop and then apply loop distribution

```
 for (i=0; i<LEN; i++){
S1 a[i]=b[i]+(float)1.0;
S2 c[i]=b[i]+(float)2.0;
 }
```

```
for (i=0; i<LEN; i+=strip_size){
 for (j=i; j<i+strip_size; j++)
   a[j]=b[j]+(float)1.0;
   c[j]=b[j]+(float)2.0;
}
```

```
for (i=0; i<LEN; i+=strip_size){
 for (j=i; j<i+strip_size; j++)
   a[j]=b[j]+(float)1.0;
 for (j=i; j<i+strip_size; j++)
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 for (i=0; i<LEN; i++){
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```
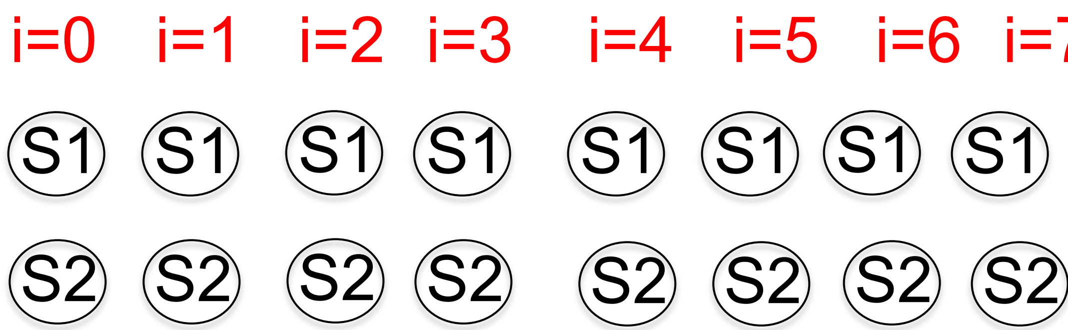

→

```
for (i=0; i<LEN; i+=strip_size){
 for (j=i; j<i+strip_size; j++)
   a[j]=b[j]+(float)1.0;
 for (j=i; j<i+strip_size; j++)
   c[j]=b[j]+(float)2.0;
}
```



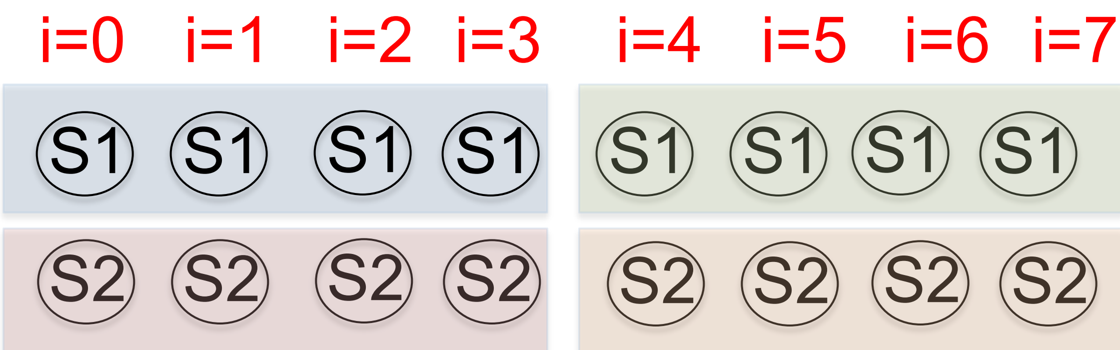
Loop Vectorization

- When vectorizing a loop with several statements the compiler needs to strip-mine the loop and then apply loop distribution

```
   for (i=0; i<LEN; i++){
S1   a[i]=b[i]+(float)1.0;
S2   c[i]=b[i]+(float)2.0;
   }
```

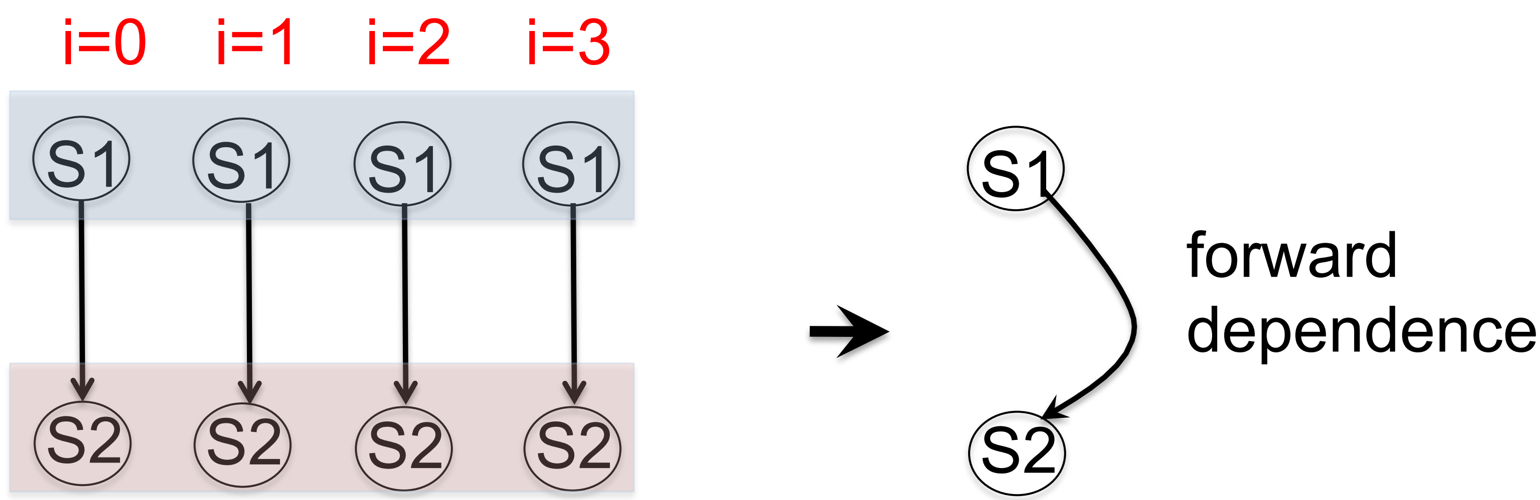
→

```
for (i=0; i<LEN; i+=strip_size){
  for (j=i; j<i+strip_size; j++)
    a[j]=b[j]+(float)1.0;
  for (j=i; j<i+strip_size; j++)
    c[j]=b[j]+(float)2.0;
}
```



Acyclic Dependence Graphs: Forward Dependences

```
 for (i=0; i<LEN; i++) {
S1 a[i]= b[i] + c[i]
S2 d[i] = a[i] + (float) 1.0;
 }
```



Acyclic Dependence Graphs: Forward Dependences

```
for (i=0; i<LEN; i++) {
  a[i]= b[i] + c[i]
  d[i] = a[i] + (float) 1.0;
}
```

Intel Nehalem
Compiler report: Loop was vectorized
Exec. Time scalar code: 10.2
Exec. Time vector code: 6.3
Speedup: 1.6

IBM Power 7
Compiler report: Loop was SIMD vectorized
Exec. Time scalar code: 3.1
Exec. Time vector code: 1.5
Speedup: 2.0

Acyclic Dependenden Graphs Backward Dependences (I)

```
   for (i=0; i<LEN; i++) {
S1   a[i]= b[i] + c[i]
S2   d[i] = a[i+1] + (float) 1.0;
   }
```

$\text{i=0}\left\{\begin{array}{l}\text{S1: a[0] = b[0] + c[0]}\\ \text{S2: d[0] = a[1] + 1}\end{array}\right.$

$\text{i=1}\left\{\begin{array}{l}\text{S1: a[1] = b[0] + c[0]}\\ \text{S2: d[1] = a[2] + 1}\end{array}\right.$

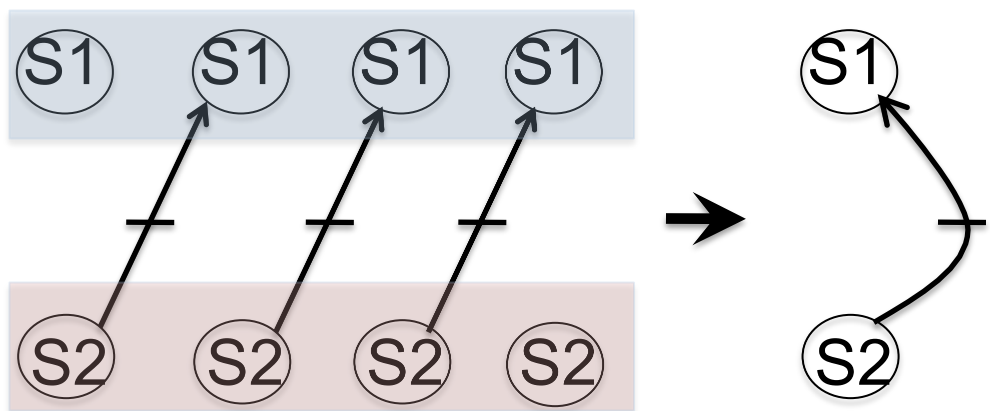
Acyclic Dependenden Graphs Backward Dependences (I)

```
   for (i=0; i<LEN; i++) {
S1  a[i]= b[i] + c[i]
S2  d[i] = a[i+1] + (float) 1.0;
   }
```

backward dependence

i=0
- S1: a[0] = b[0] + c[0]
- S2: d[0] = a[1] + 1

i=1
- S1: a[1] = b[0] + c[0]
- S2: d[1] = a[2] + 1



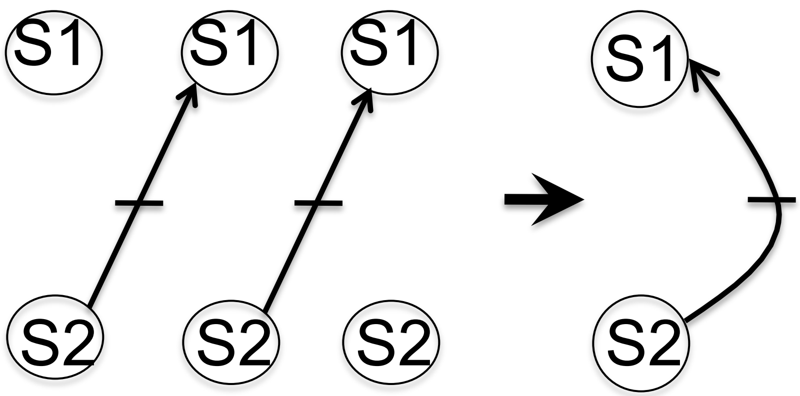
This loop cannot be vectorized as it is

Acyclic Dependenden Graphs
Backward Dependences (I)

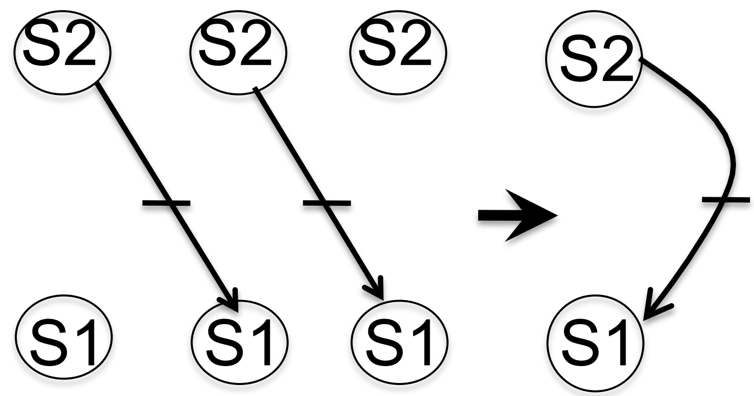
Reorder of statements

```
   for (i=0; i<LEN; i++) {
S1   a[i]= b[i] + c[i]
S2   d[i] = a[i+1] + (float) 1.0;
   }
```

```
   for (i=0; i<LEN; i++) {
S2   d[i] = a[i+1]+(float)1.0;
S1   a[i]= b[i] + c[i];
   }
```



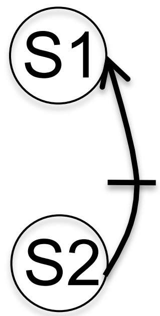
backward
depedence



forward
depedence

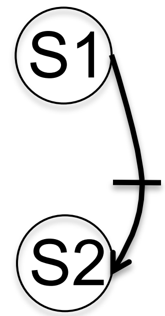
Acyclic Dependenden Graphs Backward Dependences (I)

```
for (i=0; i<LEN; i++) {
  a[i]= b[i] + c[i];
  d[i] = a[i+1]+(float)1.0;
}
```



Intel Nehalem
Compiler report: Loop was not vectorized. Existence of vector dependence
Exec. Time scalar code: 12.6
Exec. Time vector code: --
Speedup: --

```
for (i=0; i<LEN; i++) {
  d[i] = a[i+1]+(float)1.0;
  a[i]= b[i] + c[i];
}
```

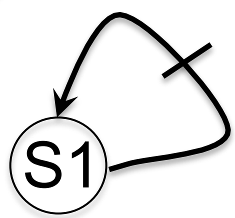


Intel Nehalem
Compiler report: Loop was vectorized
Exec. Time scalar code: 10.7
Exec. Time vector code: 6.2
Speedup: 1.72
Speedup vs non-reordered code:2.03

Cycles in the DG (III)

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

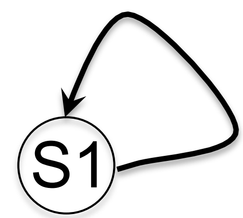
a[0]=a[1]+b[0]
a[1]=a[2]+b[1]
a[2]=a[3]+b[2]
a[3]=a[4]+b[3]



Self-antidependence
can be vectorized

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

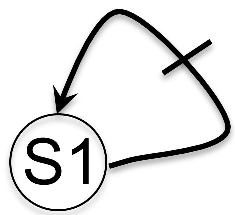
a[1]=a[0]+b[1]
a[2]=a[1]+b[2]
a[3]=a[2]+b[3]
a[4]=a[3]+b[4]



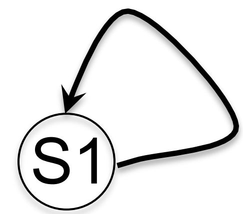
Self true-dependence
can not vectorized
(as it is)

Cycles in the DG (III)

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




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



Intel Nehalem
Compiler report: Loop was vectorized
Exec. Time scalar code: 6.0
Exec. Time vector code: 2.7
Speedup: 2.2

Intel Nehalem
Compiler report: Loop was not vectorized. Existence of vector dependence
Exec. Time scalar code: 7.2
Exec. Time vector code: --
Speedup: --