Programming OpenMP

Vectorization (SIMD)

Christian Terboven

RWTH AACHEN UNIVERSITY

Vectorization

- **SIMD = S**ingle **I**nstruction **M**ultiple **D**ata
  - → Special hardware instructions to operate on multiple data points at once
  - → Instructions work on vector registers
  - → Vector length is hardware dependent

```
double a[4],b[4],c[4];
…

for(i=0 ; i < 4 ; i++)
{
        a[i]=b[i]+c[i];
}
```

Sequential

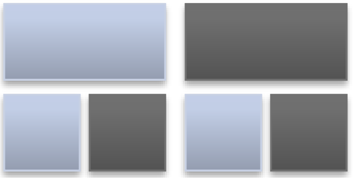
Step 1	Step 2	Step 3	Step 4
b[0]	b[1]	b[2]	b[3]
+	+	+	+
c[0]	c[1]	c[2]	c[3]
=	=	=	=
a[0]	a[1]	a[2]	a[3]

Vectorized

Step 1	Step 2
b[0],b[1]	b[2],b[3]
+	+
c[0],c[1]	c[2],c[3]
=	=
a[0],a[1]	a[2],a[3]

Vectorization

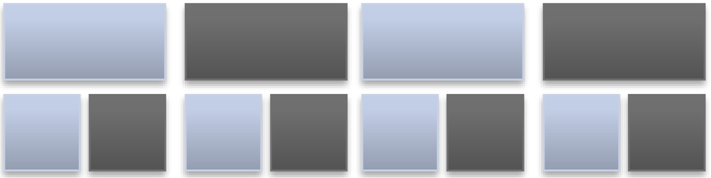
- **Vector lengths on Intel architectures**
  - → 128 bit: SSE = Streaming SIMD Extensions



2 x double

4 x float

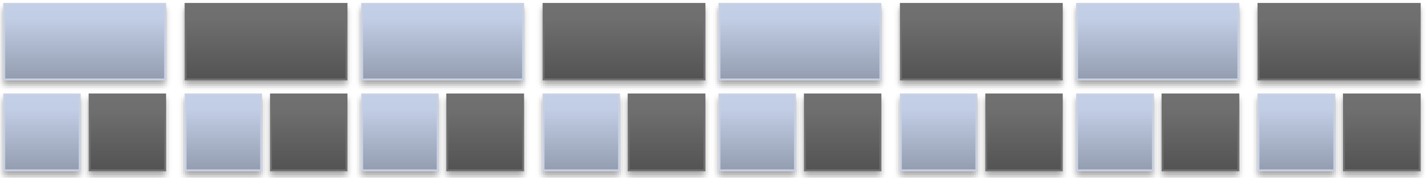
  - → 256 bit: AVX = Advanced Vector Extensions



4 x double

8 x float

  - → 512 bit: AVX-512

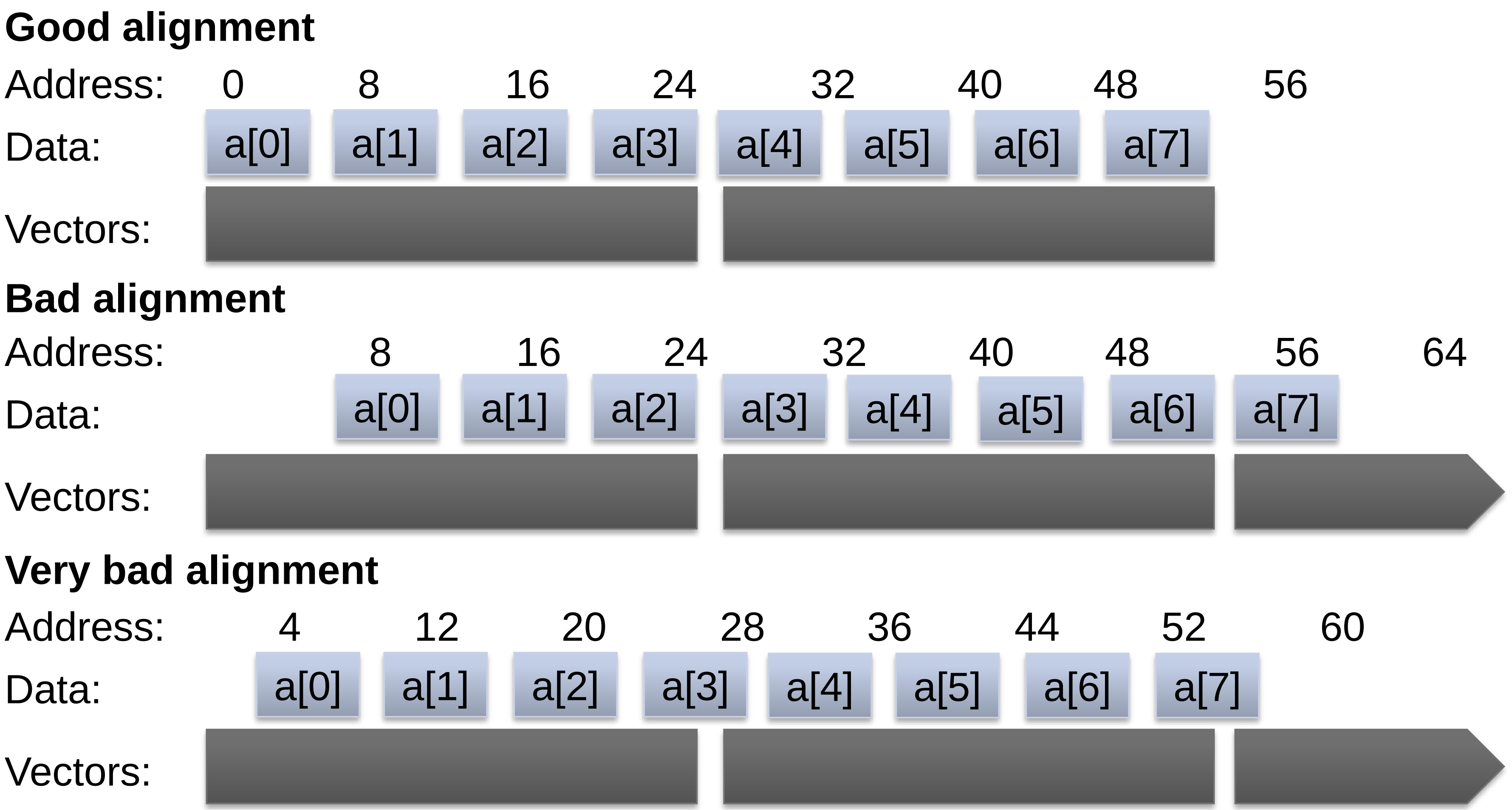


8 x double

16 x float

Data Alignment

- **Vectorization works best on aligned data structures.**



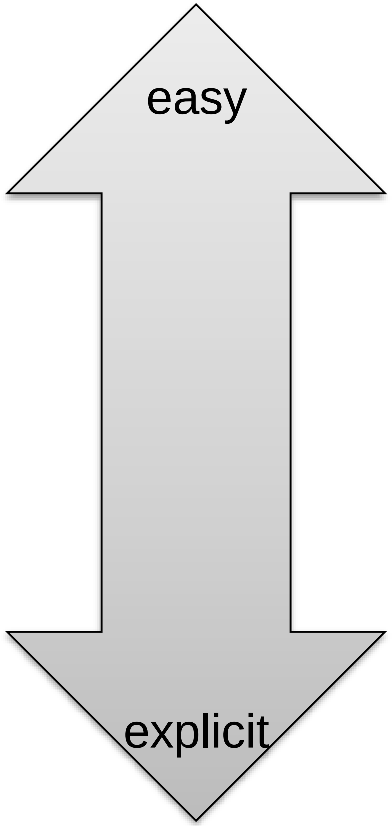
Approaches to Vectorization

Compiler
auto-vectorization

Explicit Vector Programming
(e.g. with OpenMP)

Inline Assembly
(e.g.)

Assembler Code
(e.g. addps, mulpd, …)



Data Dependencies

Data Dependencies

- Suppose two statements S1 and S2
- S2 depends on S1, iff S1 must execute before S2
  - →Control-flow dependence
  - →Data dependence
  - →Dependencies can be carried over between loop iterations
- Important flavors of data dependencies

FLOW

```
s1: a = 40

    b = 21
s2: c = a + 2
```

ANTI

```
    b = 40

s1: a = b + 1
s2: b = 21
```

Loop-Carried Dependencies

- Dependencies may occur across loop iterations
  - →Loop-carried dependency
- The following code contains such a dependency:

```
void lcd_ex(float* a, float* b, size_t n, float c1, float c2)
{
    size_t i;
    for (i = 0; i < n; i++) {
        a[i] = c1 * a[i + 17] + c2 * b[i];
    }
}
```

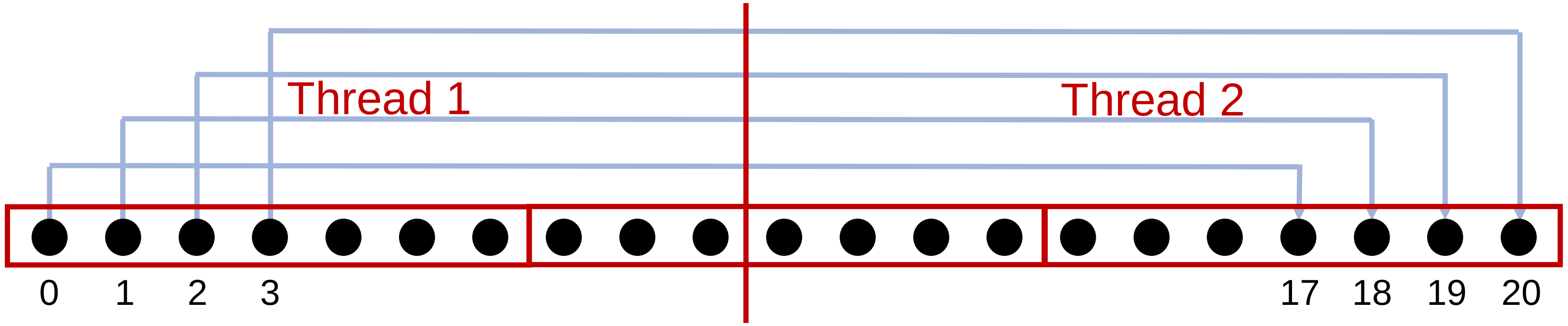
Loop-carried dependency for a[i] and a[i+17]; distance is 17.

- Some iterations of the loop have to complete before the next iteration can run
  - →Simple trick: Can you reverse the loop w/o getting wrong results?

Loop-carried Dependencies

- Can we parallelize or vectorize the loop?

```
void lcd_ex(float* a, float* b, size_t n, float c1, float c2) {
    for (int i = 0; i < n; i++) {
        a[i] = c1 * a[i + 17] + c2 * b[i];
}   }
```



→ Parallelization: no
(except for very specific loop schedules)

→ Vectorization: yes
(iff vector length is shorter than any distance of any dependency)

Example: Loop not Countable

- “Loop not Countable” plus “Assumed Dependencies”

```
typedef struct {
    float* data;
    size_t size;
} vec_t;

void vec_eltwise_product(vec_t* a, vec_t* b, vec_t* c) {
    size_t i;
    for (i = 0; i < a->size; i++) {
        c->data[i] = a->data[i] * b->data[i];
    }
}
```

The OpenMP SIMD constructs

The SIMD construct

- **The SIMD construct enables the execution of multiple iterations of the associated loops concurrently by means of SIMD instructions.**

```
C/C++:
#pragma omp simd [clause(s)]
   for-loops
```

```
Fortran:
!$omp simd [clause(s)]
   do-loops
[!$omp end simd]
```

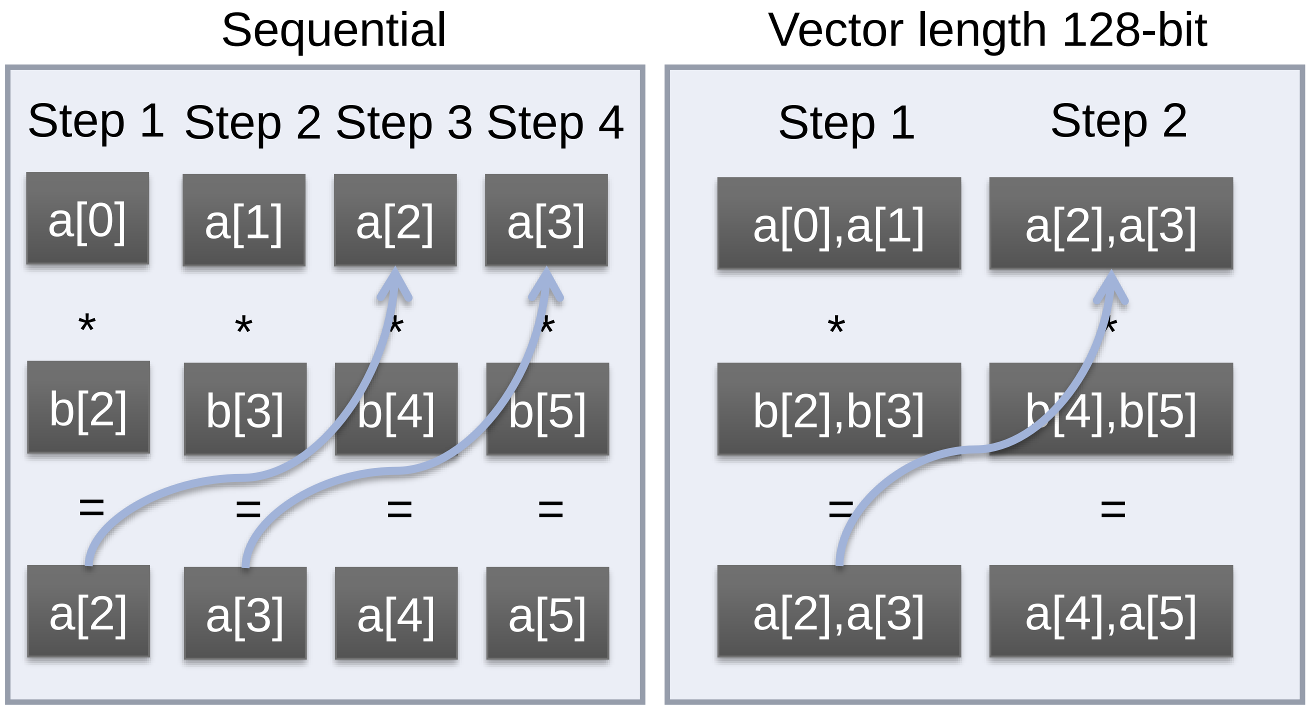
- **where clauses are:**
  - → linear(*list[:linear-step]*), a variable increases linearly in every loop iteration
  - → aligned(*list[:alignment]*), specifies that data is aligned
  - → private(*list*), as usual
  - → lastprivate(*list*) , as usual
  - → reduction(*reduction-identifier:list*) , as usual
  - → collapse(*n*), collapse loops first, and than apply SIMD instructions

The SIMD construct

- **The safelen clause allows to specify a distance of loop iterations where no dependencies occur.**

```
double a[6],b[6];
…

for(i=2 ; i < 6 ; i++)
{
        a[i]=a[i-2]*b[i];
}
```

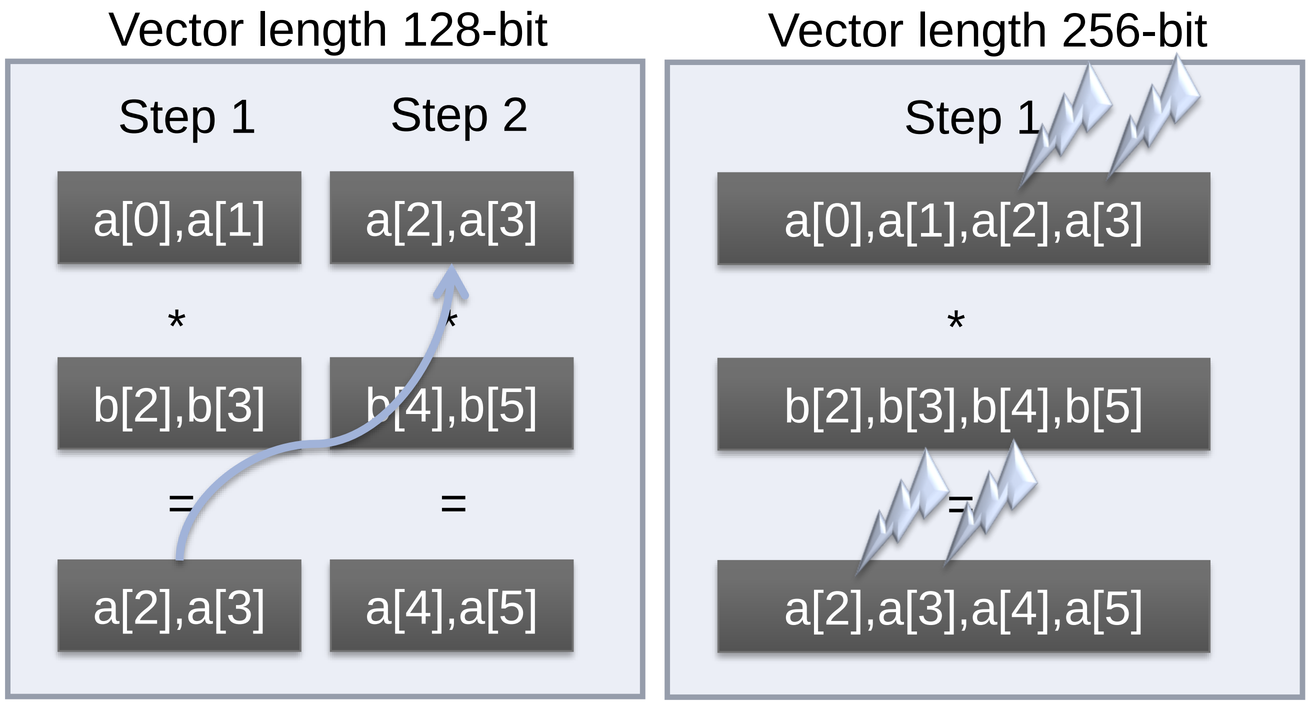


The SIMD construct

- **The safelen clause allows to specify a distance of loop iterations where no dependencies occur.**

```
double a[6],b[6];
…

for(i=2 ; i < 6 ; i++)
{
        a[i]=a[i-2]*b[i];
}
```



- **Any vector length smaller than or equal to the length specified by safelen can be chosen for vectorizaion.**
- **In contrast to parallel for/do loops the iterations are executed in a specified order.**

The loop SIMD construct

- **The loop SIMD construct specifies a loop that can be executed in parallel by all threads and in SIMD fashion on each thread.**

C/C++:
```
#pragma omp for simd [clause(s)]
   for-loops
```

Fortran:
```
!$omp do simd [clause(s)]
   do-loops
[!$omp end do simd [nowait]]
```

- **Loop iterations are first distributed across threads, then each chunk is handled as a SIMD loop.**
- **Clauses:**
  - → All clauses from the *loop*- or SIMD-construct are allowed
  - → Clauses which are allowed for both constructs are applied twice, once for the threads and once for the SIMDization.

The declare SIMD construct

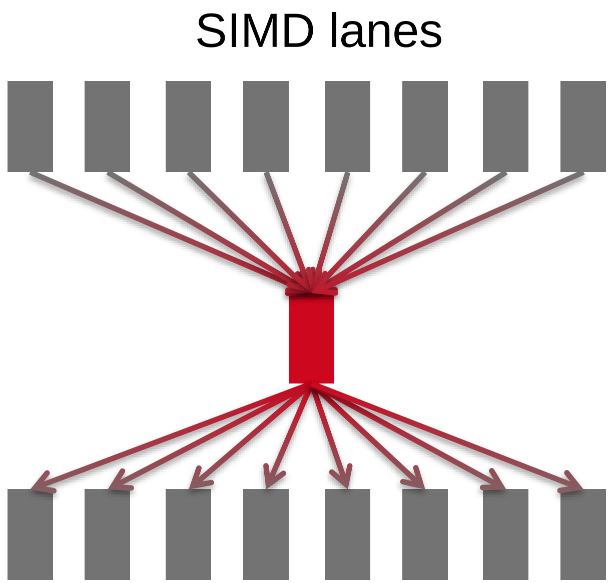
- **Function calls in SIMD-loops can lead to bottlenecks, because functions need to be executed serially.**

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

        d[i]=sin(a[i]);

        e[i]=5*d[i];

}
```



Solutions:

- avoid or inline functions
- create functions which work on vectors instead of scalars

The declare SIMD construct

- **Enables the creation of multiple versions of a function or subroutine where one or more versions can process multiple arguments using SIMD instructions.**

C/C++:

```
#pragma omp declare simd [clause(s)]
[#pragma omp declare simd [clause(s)]]
   function definition / declaration
```

Fortran:

```
!$omp declare simd (proc_name)[clause(s)]
```

- **where clauses are:**
  - → simdlen(*length*), the number of arguments to process simultanously
  - → linear(*list[:linear-step]*), a variable increases linearly in every loop iteration
  - → aligned(*argument-list[:alignment]*), specifies that data is aligned
  - → uniform(*argument-list*), arguments have an invariant value
  - → inbranch / notinbranch, function is always/never called from within a conditional statement

File: f.c

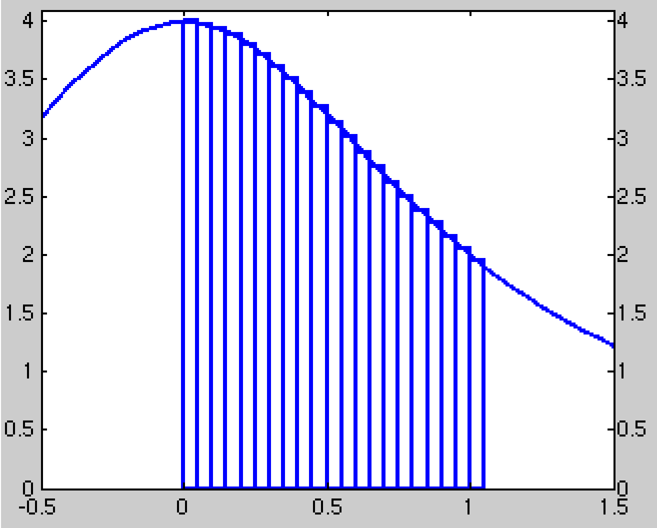
```c
#pragma omp declare simd
double f(double x)
{
    return (4.0 / (1.0 + x*x));
}
```

File: pi.c

```c
#pragma omp declare simd
double f(double x);
…
#pragma omp simd linear(i) private(fX)
reduction(+:fSum)
for (i = 0; i < n; i++)
{
    fX = fH * ((double)i + 0.5);
    fSum += f(fX);
}
return fH * fSum;
```

Calculating Pi with numerical integration of:

$$\pi = \int_0^1 \frac{4}{1 + x^2}$$



Example: Pi

- **Runtime of the benchmark on:**
  - → Westmere CPU with SSE (128-bit vectors)
  - → Intel Xeon Phi with AVX-512 (512-bit vectors)

	Runtime Westmere	Speedup Westmere	Runtime Xeon Phi	Speedup Xeon Phi
non vectorized	1.44 sec	1	16.25 sec	1
vectorized	0.72 sec	2	1.82 sec	8.9

Note: Speedup for memory bound applications might be lower on both systems.