OpenMP: Vectorization and `#pragma omp simd`

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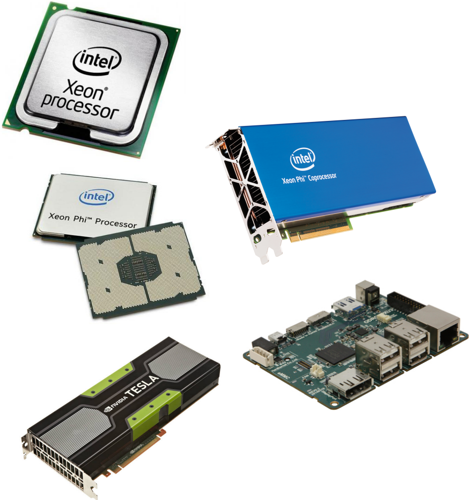
Where does it come from?

$$c_i = a_i + b_i \quad \forall i$$

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
$+$	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
$=$	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8


intel
Xeon processor
intel
Xeon Phi™ Processor
intel
Xeon Phi™ Coprocessor
NVIDIA TESLA

Why would I care?

Why would I care?

Everywhere...

x86	SSE AVX(2) AVX-512 (IMCI)	128 bit 256 bit 512 bit
ARM	NEON	128 bit
POWER	AltiVec/VMX/VSX QPX	128 bit 256 bit
SPARC	HPC-ACE HPC-ACE2	128 bit 256 bit

Vectorization on Intel CPUs

```
[v]mova[p/s]s reg1, reg2/mem

reg: xmm0-xmm15 (128bit)
     ymm0-ymm15 (256bit)
     zmm0-zmm15 (512bit)

vaddps: Vectorized
vaddss: Scalar
```

How to see assembly: add `-S` to command line.

Vectorization: Indication

Profiling! Worth it on the hot path!

- Increases available memory bandwidth to cache
- **Increases throughput of compute operations**
- More power efficient
- Reduce frontend pressure (fewer instructions to decode)

Keep in mind Ahmdahl's law!

Cool! How can I use that?

- Libraries
  (MKL, OpenBLAS, BLIS, fftw, numpy, OpenCV)
- Hoping for a good compiler: Autovectorization
- Assisting compiler through annotations: OpenMP SIMD pragma
- Writing intrinsics/assembly code (not covered here)

Autovectorization

- The compiler needs to prove that the optimization is legal
- And the compiler needs to prove that the optimization is beneficial (under almost all circumstances)

- What could possibly go wrong?
- Conditionals (different vector lanes executing different code)
- Inner loops (might have different trip counts)
- Function calls (the functions might not be vectorized)
- Cross-iteration dependencies

- OpenMP addresses the last two points in particular

The OpenMP simd pragma

- Unifies the enforcement of vectorization for `for` loop
- Introduced in OpenMP 4.0
- Explicit vectorization of for loops
- Same restrictions as `omp for`, and then some
- Executions in chunks of simdlength, concurrently executed
- Only directive allowed inside: `omp ordered simd` (OpenMP 4.5)
- Can be combined with `omp for`
- No exceptions

Clauses

- `safelen(len)`: Maximum number of iterations per chunk
- `simdlen(len)`: Recommended number of iterations per chunk
- `linear(stride: var, ...)`: with respect to iteration variable
- `aligned(alignment: var)`: alignment of variable
- `private`, `lastprivate`, `reduction`, `collapse`: As with `omp for`

Issues with your code

- Aliasing
- Alignment
- Floating point issues
- Correctness
- Function calls
- Ordering

Aliasing

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

Compiler does not know that a and b do not overlap.
Has to be conservative.

Aliasing

```
float * a = ...;
float * b = ...;
float aa[N];
memcpy(aa, a, N * sizeof(float));
float bb[N];
memcpy(bb, b, N * sizeof(float));
float s;
...
for (int i = 0; i < N; i++) {
  aa[i] += s * bb[i];
}
memcpy(a, aa, N * sizeof(float));
```

Aliasing

```
float * __restrict__ a = ...;
float * __restrict__ b = ...;
float s;
...
for (int i = 0; i < N; i++) {
  a[i] += s * b[i];
}
```

Aliasing

```
float * a = ...;
float * b = ...;
float s;
...
#pragma omp simd
for (int i = 0; i < N; i++) {
  a[i] += s * b[i];
}
```

Alignment

- Loading a chunk of data is cheaper if the address is aligned.
- Allows for faster hardware instructions to load a vector.
- Avoid cache line splits.
- Ex: Recent Intel CPUs have 64 byte cache lines, and 32 byte vectors, best alignment is 32 bytes.

```
Cache lines A,B,...:
AAAABBBBCCCCDDDDEEEEFFFFGGGGHHHHIIII
   ####  <- Want to load this data? Unaligned.
    #### <- Want to load this data? Aligned.
```

Alignment

```
float * a;
posix_memalign(&a, ...);
float * b;
posix_memalign(&b, ...);
float s;
...
__assume_aligned(a, 32); // Intel
__assume_aligned(b, 32); // Intel
#pragma omp simd
for (int i = 0; i < N; i++) {
  a[i] += s * b[i];
}
```

Alignment

```
float * a;
posix_memalign(&a, ...);
float * b;
posix_memalign(&b, ...);
float s;
...
#pragma omp simd aligned(a, b: 32)
for (int i = 0; i < N; i++) {
  a[i] += s * b[i];
}
```

Floating Point Models

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

`-ffast-math /fp:fast -fp-model fast=2`

```
#pragma omp simd reduction(+: sum)
for (int i = 0; i < n; i++) {
  sum += a[i];
}
```

https://msdn.microsoft.com/en-us/library/aa289157.aspx

Correctness

```
for (int i = 0; i < N; i++) {
  int j = d[i];
  a[j] += s * b[i];
}
```

Vectorization is only legal is the elements in `d` are distinct.
This case occurs in applications!

```
#pragma omp simd
for (int i = 0; i < N; i++) {
  int j = d[i];
  a[j] += s * b[i];
}
```

Functions

```
// This won't vectorize unless foo inlined.
foo(float a, float * b, float c);

float s;
#pragma omp simd
for (int i = 0; i < N; i++) {
  int j = d[i];
  a[j] += foo(s, &b[i], a[j]);
}
```

The OpenMP declare simd directive

- asks compiler to generate veectorized version of a function
- allows vectorization of loops with function calls
- notinbranch, inbranch: Generate masking code, non-masking code
- everything from the simd pragma + uniform
- uniform: does not change
- linear: increases with index

Functions

```
#pragma omp declare simd uniform(a) linear(1: b)
foo(float a, float * b, float c);

float s;
#pragma omp simd
for (int i = 0; i < N; i++) {
  int j = d[i];
  a[j] += foo(s, &b[i], a[j]);
}
```

Masks

```
#pragma omp simd
for (int i = 0; i < n; i++) {
  if (a[i] < 1.0) continue;
  // ..
  int j = d[i];
  a[j] = ...;
}
```

Ordering

```
#pragma omp simd
for (int i = 0; i < n; i++) {
  if (a[i] < 1.0) continue;
  // ..
  int j = d[i];
  #pragma omp ordered simd
  a[j] = ...;
}
```

If `d` is not containing distinct elements.