OpenMP* SIMD Programming

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# Levels of Parallelism

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SIMD on Intel® Architecture

**SSE**
- 128 bit: 2 x DP, 4 x SP

**AVX**
- 256 bit: 4 x DP, 8 x SP

**MIC**
- 512 bit: 8 x DP

**AVX-512**
- 512 bit: 16 x SP
More Powerful SIMD Units

- SIMD instructions become more powerful on the Intel® Xeon Phi™ Processor

```
vaddpd dest, source1, source2
```

512 bit

```
\[
\begin{array}{cccccccc}
a_7 & a_6 & a_5 & a_4 & a_3 & a_2 & a_1 & a_0 \\
b_7 & b_6 & b_5 & b_4 & b_3 & b_2 & b_1 & b_0 \\
\end{array}
\]
```

+ 

```
\[
\begin{array}{cccccccc}
a_7+b_7 & a_6+b_6 & a_5+b_5 & a_4+b_4 & a_3+b_3 & a_2+b_2 & a_1+b_1 & a_0+b_0 \\
\end{array}
\]
```
More Powerful SIMD Units

- SIMD instructions become more powerful on the Intel® Xeon Phi™ Processor

\[
vfmadd213pd \text{ source1, source2, source3}
\]

\[
\begin{array}{cccccccc}
\text{a7} & \text{a6} & \text{a5} & \text{a4} & \text{a3} & \text{a2} & \text{a1} & \text{a0} \\
\text{b7} & \text{b6} & \text{b5} & \text{b4} & \text{b3} & \text{b2} & \text{b1} & \text{b0} \\
\text{c7} & \text{c6} & \text{c5} & \text{c4} & \text{c3} & \text{c2} & \text{c1} & \text{c0} \\
\end{array}
\]

\[
\begin{array}{cccccccc}
\text{a7*b7} & \text{a6*b6} & \text{a5*b5} & \text{a4*b4} & \text{a3*b3} & \text{a2*b2} & \text{a1*b1} & \text{a0*b0} \\
+ & + & + & + & + & + & + & + \\
\text{c7} & \text{c6} & \text{c5} & \text{c4} & \text{c3} & \text{c2} & \text{c1} & \text{c0} \\
\end{array}
\]

\[
\begin{array}{cccccccc}
\text{dest} \\
\end{array}
\]
More Powerful SIMD Units

- SIMD instructions become more powerful on the Intel® Xeon Phi™ Processor

\[
\begin{align*}
vaddpd \text{ dest}\{k1\}, \text{ source2, source3} \\
\begin{array}{cccccccc}
\text{a7} & \text{a6} & \text{a5} & \text{a4} & \text{a3} & \text{a2} & \text{a1} & \text{a0} \\
\text{b7} & \text{b6} & \text{b5} & \text{b4} & \text{b3} & \text{b2} & \text{b1} & \text{b0} \\
\text{1} & \text{0} & \text{1} & \text{0} & \text{0} & \text{1} & \text{0} & \text{1}
\end{array}
\end{align*}
\]

\[
\begin{align*}
\text{a7+b7} & \text{ d6} & \text{a5+b5} & \text{d4} & \text{d3} & \text{a2+b2} & \text{d1} & \text{a0+b0} \\
\end{align*}
\]
More Powerful SIMD Units

- SIMD instructions become more powerful on the Intel® Xeon Phi™ Processor

```
vmovapd dest, source{dacb}
```

```c
swizzle

move
```

source

“tmp”

dest
• Auto vectorization only helps in some cases
  • Increased complexity of instructions makes it hard for the compiler to select proper instructions
  • Code pattern needs to be recognized by the compiler
  • Precision requirements often inhibit SIMD code gen

• Example: Intel® Composer XE
  • -vec (automatically enabled with –O2)
  • -qopt-report
Why Auto-vectorizers Fail

• Data dependencies
• Other potential reasons
  • Alignment
  • Function calls in loop block
  • Complex control flow / conditional branches
  • Loop not “countable”
    • E.g. upper bound not a runtime constant
  • Mixed data types
  • Non-unit stride between elements
  • Loop body too complex (register pressure)
  • Vectorization seems inefficient
• Many more ... but less likely to occur
Example: Loop not Countable

- “Loop not Countable” plus “Assumed Dependencies”

```c
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];
    }
}
```
In a Time before OpenMP 4.0

- Programmers had to rely on auto-vectorization...
- ... or to use vendor-specific extensions
  - Programming models (e.g., Intel® Cilk™ Plus)
  - Compiler pragmas (e.g., #pragma vector)
  - Low-level constructs (e.g., _mm_add_pd())

```c
#pragma omp parallel for
#pragma vector always
#pragma ivdep
for (int i = 0; i < N; i++) {
    a[i] = b[i] + ...;
}
```

You need to trust the compiler to do the “right” thing.
OpenMP SIMD Loop Construct

• Vectorize a loop nest
  • Cut loop into chunks that fit a SIMD vector register
  • No parallelization of the loop body

• Syntax (C/C++)
  #pragma omp simd [clause[,...]]
  for-loops

• Syntax (Fortran)
  !$omp simd [clause[,...]]
  do-loops
Example

```c
void sprod(float *a, float *b, int n) {
    float sum = 0.0f;
    #pragma omp simd reduction(+:sum)
    for (int k=0; k<n; k++)
        sum += a[k] * b[k];
    return sum;
}
```

vectorize
Data Sharing Clauses

• `private(var-list)`:
  Uninitialized vectors for variables in `var-list`

  ![Image](x: 42 → ? ? ? ?)

• `firstprivate(var-list)`:
  Initialized vectors for variables in `var-list`

  ![Image](x: 42 → 42 42 42 42)

• `reduction(op: var-list)`:
  Create private variables for `var-list` and apply reduction operator `op` at the end of the construct

  ![Image](12 5 8 17 → x: 42)
SIMD Loop Clauses

• **safelen** (*length*)
  • Maximum number of iterations that can run concurrently without breaking a dependence
  • in practice, maximum vector length

• **linear** (*list[::linear-step]*)
  • The variable’s value is in relationship with the iteration number
  \[ x_i = x_{\text{orig}} + i \times \text{linear-step} \]

• **aligned** (*list[::alignment]*)
  • Specifies that the list items have a given alignment
  • Default is alignment for the architecture

• **collapse** (*n*)
Loop-Carried Dependencies

• Dependencies may occur across loop iterations
  • Loop-carried dependency

• The following code contains such a dependency:

```c
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];
    }
}
```

• 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?
  • Parallelization: no
    (except for very specific loop schedules)
  • Vectorization: yes
    (if vector length is shorter than any distance of any dependency)
SIMD Worksharing Construct

- Parallelize and vectorize a loop nest
  - Distribute a loop’s iteration space across a thread team
  - Subdivide loop chunks to fit a SIMD vector register

- Syntax (C/C++)
  ```cpp
  #pragma omp for simd [clause[[], clause],...]
  for-loops
  ```

- Syntax (Fortran)
  ```fortran
  !$omp do simd [clause[[], clause],...]
  do-loops
  ```
Example

```c
void sprod(float *a, float *b, int n) {
    float sum = 0.0f;
#pragma omp for simd reduction(+:sum)
    for (int k=0; k<n; k++)
        sum += a[k] * b[k];
    return sum;
}
```

**parallelize**

Thread 0 | Thread 1 | Thread 2

**vectorize**

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Be Careful What You Wish For...

void sprod(float *a, float *b, int n) {
    float sum = 0.0f;
    #pragma omp for simd reduction(+:sum) \
    schedule(static, 5)
    for (int k=0; k<n; k++)
        sum += a[k] * b[k];
    return sum;
}

- You should choose chunk sizes that are multiples of the SIMD length
  - Remainder loops are not triggered
  - Likely better performance
- In the above example ...
  - and AVX2, the code will only execute the remainder loop!
  - and SSE, the code will have one iteration in the SIMD loop plus one in the remainder loop!
Schedule Modifiers

```c
void sprod(float *a, float *b, int n) {
    float sum = 0.0f;
#pragma omp for simd reduction(+:sum) \  
      schedule(simd:static, 5)
    for (int k=0; k<n; k++)
        sum += a[k] * b[k];
    return sum;
}
```

- The new simd modifier automatically adjusts the chunk size to match it with the length of the SIMD register.
  - New chunk size becomes \[\frac{\text{chunksz}}{\text{simdlen}} \times \text{simdlen}\]
  - AVX2: new chunk size will be 8
  - SSE: new chunk size will be 8
SIMD Function Vectorization

float min(float a, float b) {
    return a < b ? a : b;
}

float distsq(float x, float y) {
    return (x - y) * (x - y);
}

void example() {
    #pragma omp parallel for simd
    for (i=0; i<N; i++) {
        d[i] = min(distsq(a[i], b[i]), c[i]);
    }
}
SIMD Function Vectorization

- Declare one or more functions to be compiled for calls from a SIMD-parallel loop

- Syntax (C/C++):
  
  ```
  #pragma omp declare simd [clause[,[,] clause],...]
  [#pragma omp declare simd [clause[,[,] clause],...]]
  [...] 
  function-definition-or-declaration
  ```

- Syntax (Fortran):
  
  ```
  !$omp declare simd (proc-name-list)
  ```
# SIMD Function Vectorization

```c
#pragma omp declare simd
float min(float a, float b) {
    return a < b ? a : b;
}
```

```c
#pragma omp declare simd
float distsq(float x, float y) {
    return (x - y) * (x - y);
}
```

```c
void example() {
    #pragma omp parallel for simd
    for (i=0; i<N; i++) {
        d[i] = min(distsq(a[i], b[i]), c[i]);
    }
}
```

```c
vec8 min_v(vec8 a, vec8 b) {
    return a < b ? a : b;
}
```

```c
vec8 distsq_v(vec8 x, vec8 y) {
    return (x - y) * (x - y);
}
```

```c
vd = min_v(distsq_v(va, vb, vc))
```
SIMD Function Vectorization

• simdlen \((length)\)
  • generate function to support a given vector length
• uniform \((argument-list)\)
  • argument has a constant value between the iterations of a given loop
• inbranch
  • function always called from inside an if statement
• notinbranch
  • function never called from inside an if statement
• linear \((argument-list[::linear-step])\)
• aligned \((argument-list[::alignment])\)
• reduction \((operator:list)\)
```c
#pragma omp declare simd inbranch

float do_stuff(float x) {
    /* do something */
    return x * 2.0;
}

void example() {
    #pragma omp simd
    for (int i = 0; i < N; i++)
        if (a[i] < 0.0)
            b[i] = do_stuff(a[i]);
}

vec8 do_stuff_v(vec8 x, mask m) {
    /* do something */
    vmulpd x{m}, 2.0, tmp
    return tmp;
}

for (int i = 0; i < N; i+=8) {
    vcmp_lt &a[i], 0.0, mask
    b[i] = do_stuff_v(&a[i], mask);
}
```

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