SIMD Vectorization with OpenMP

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Credits

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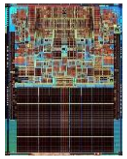
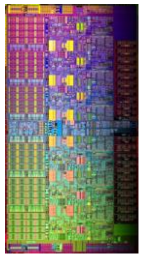
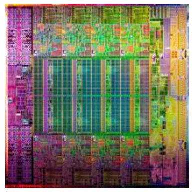
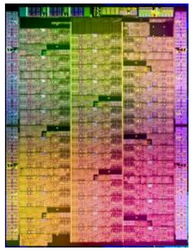
Disclaimer & Optimization Notice

Optimization Notice

Evolution of Hardware (Intel)



Images not intended to reflect actual die sizes

	64-bit Intel® Xeon® processor	Intel® Xeon® processor 5100 series	Intel® Xeon® processor 5500 series	Intel® Xeon® processor 5600 series	Intel® Xeon® processor E5-2600v2 series	Intel® Xeon Phi™ Co-processor 7120P
Frequency	3.6 GHz	3.0 GHz	3.2 GHz	3.3 GHz	2.7 GHz	1.238 MHz
Core(s)	1	2	4	6	12	61
Thread(s)	2	2	8	12	24	244
SIMD width	128 (2 clock)	128 (1 clock)	128 (1 clock)	128 (1 clock)	256 (1 clock)	512 (1 clock)

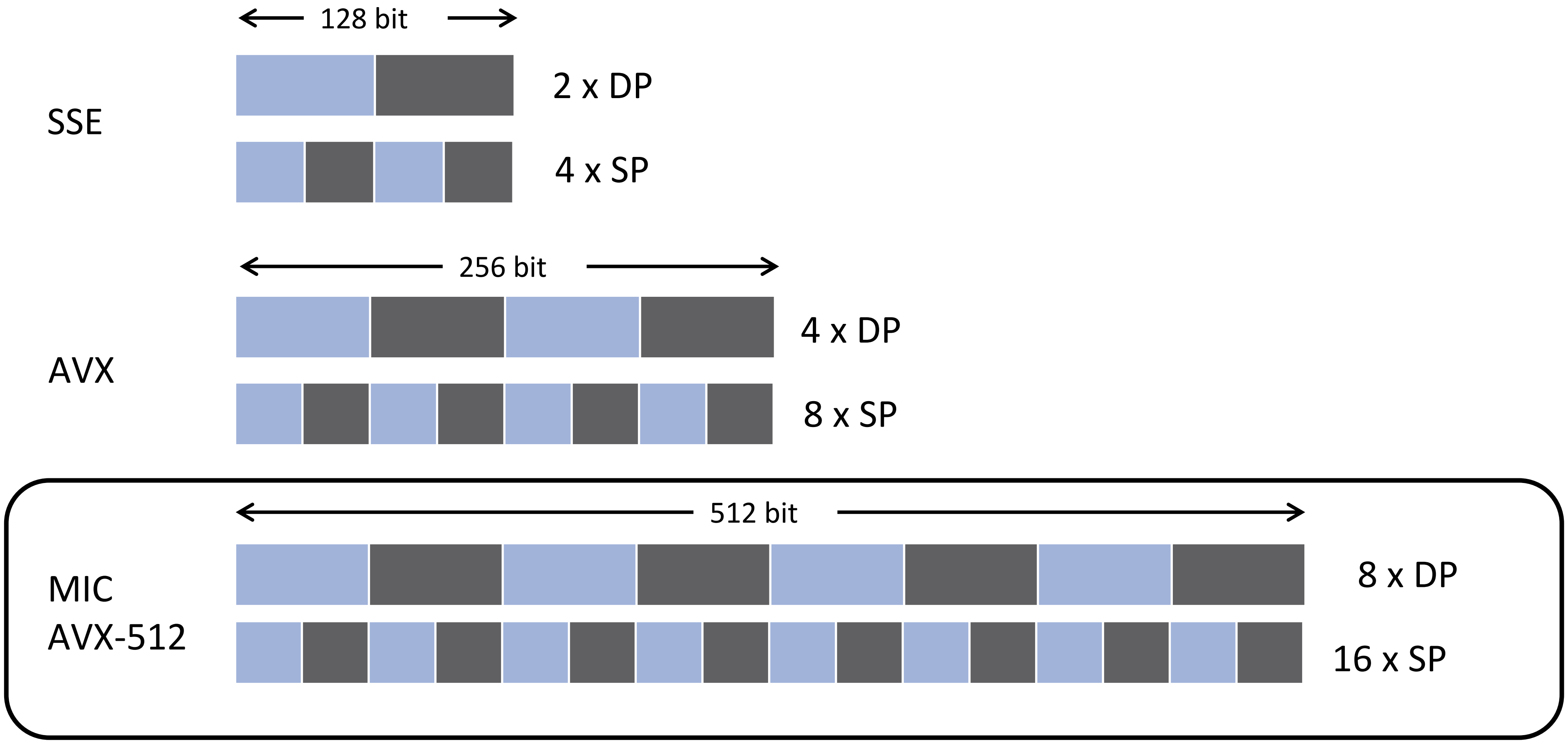
Levels of Parallelism

- OpenMP already supports several levels of parallelism in today's hardware

Cluster	🟥	Group of computers communicating through fast interconnect
Coprocessors/Accelerators	🟩	Special compute devices attached to the local node through special interconnect
Node	🟩	Group of processors communicating through shared memory
Socket	🟩	Group of cores communicating through shared cache
Core	🟩	Group of functional units communicating through registers
Hyper-Threads	🟩	Group of thread contexts sharing functional units
Superscalar	🟨	Group of instructions sharing functional units
Pipeline	🟨	Sequence of instructions sharing functional units
Vector	🟩	Single instruction using multiple functional units

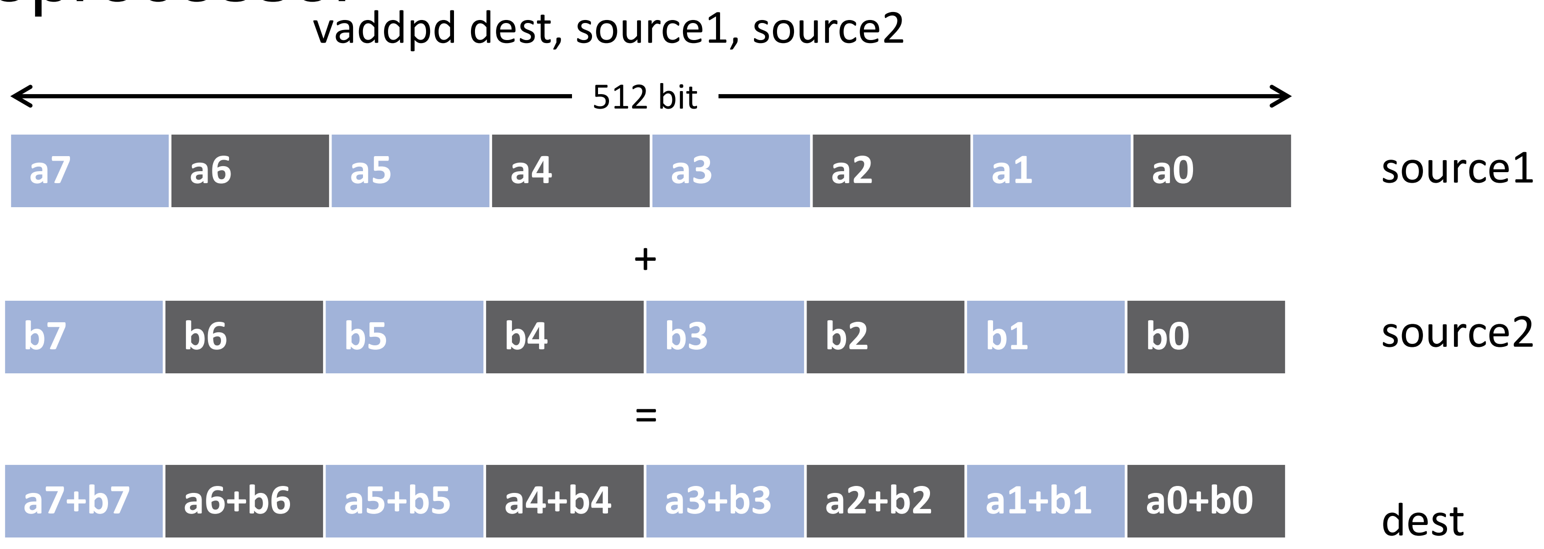
SIMD on Intel® Architecture

- Width of SIMD registers has been growing:



More Powerful SIMD Units

- SIMD instructions become more powerful
- One example is the Intel® Xeon Phi™ Coprocessor



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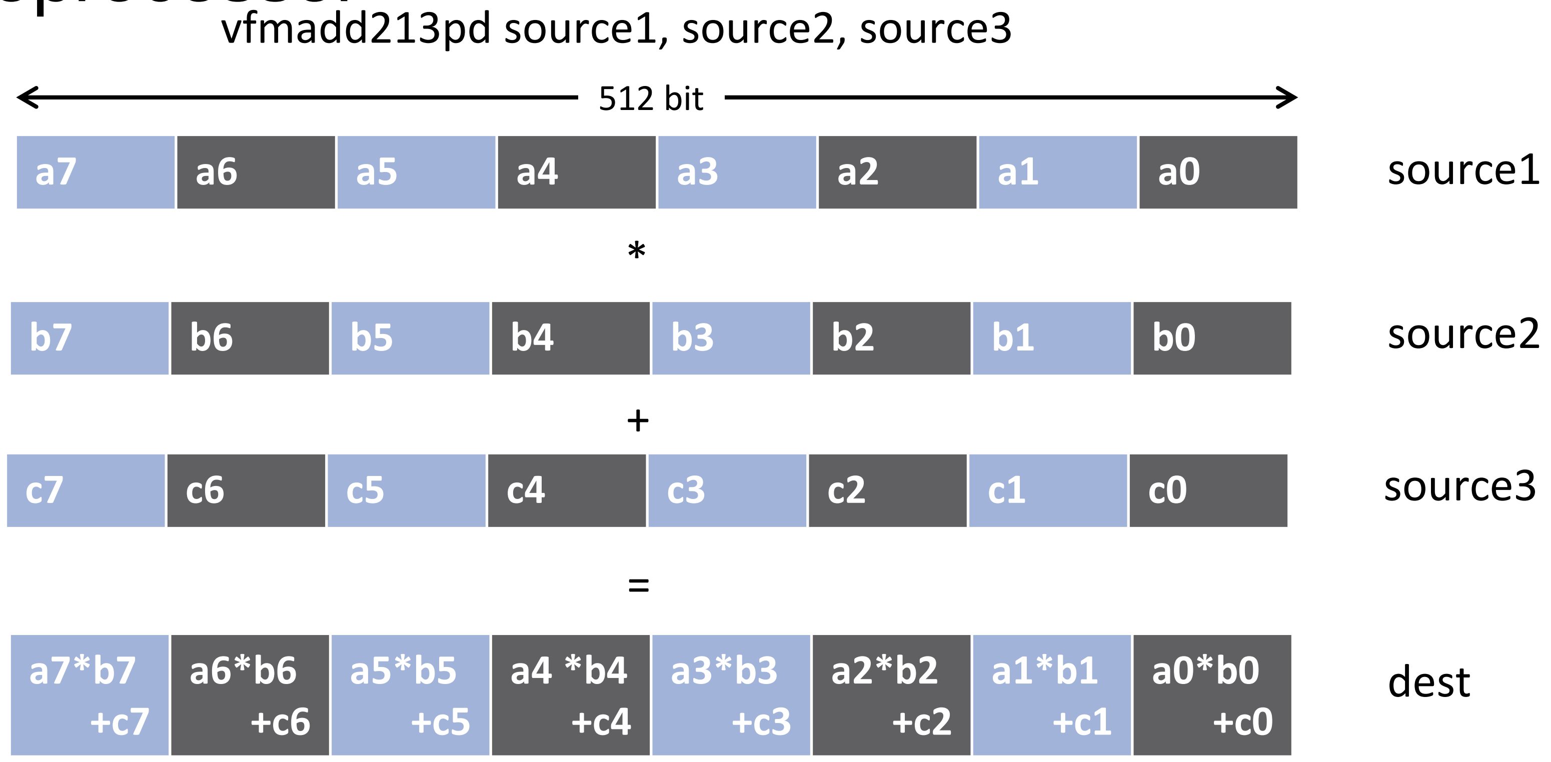

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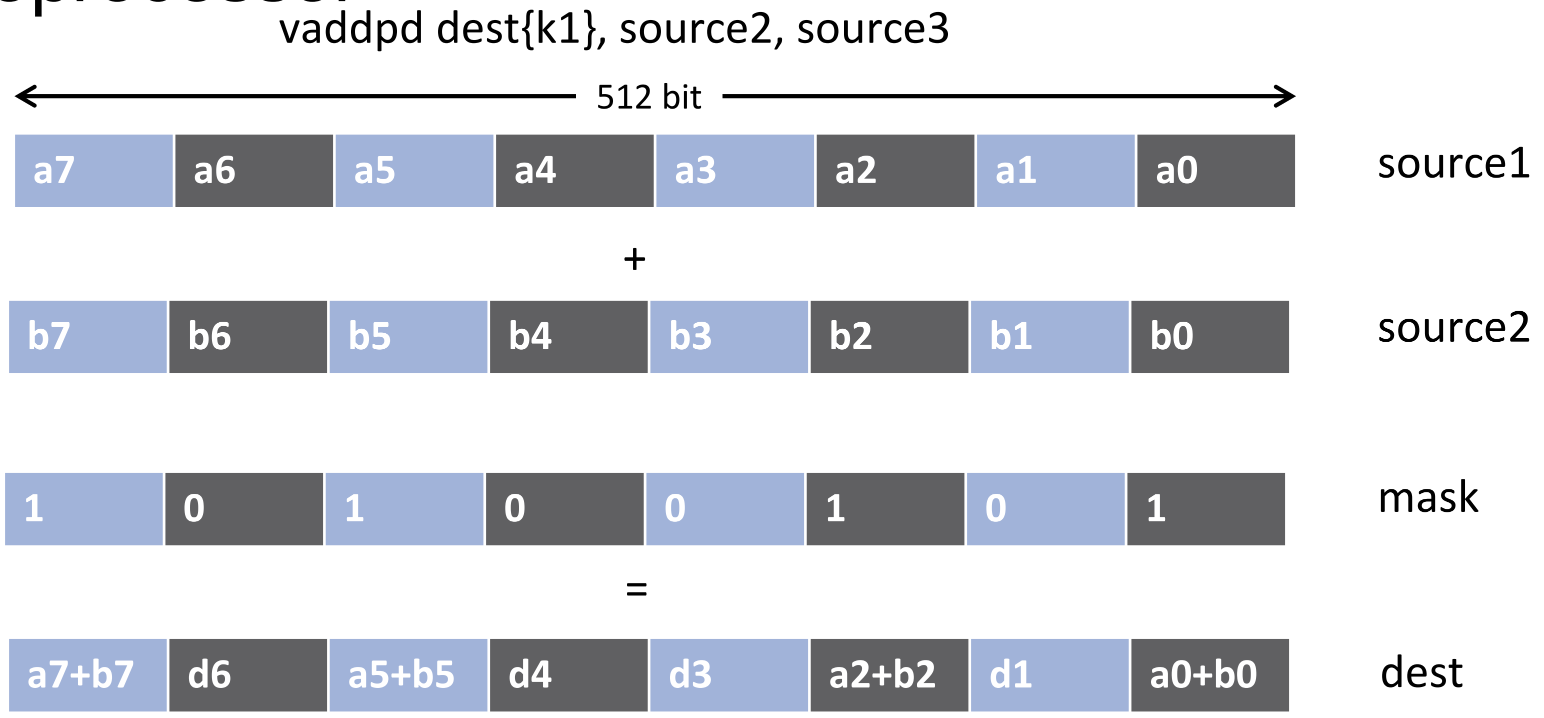

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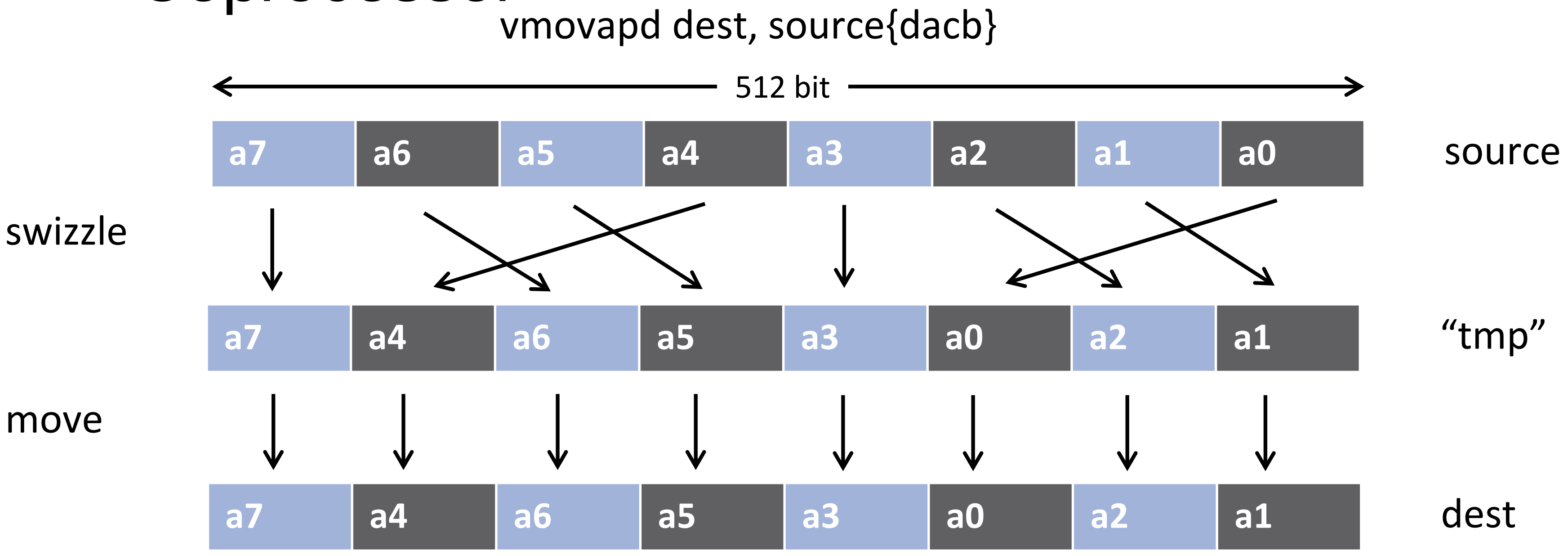


Auto-vectorization

- 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 **`–O3`**)

`-vec-report`

`-opt-report`

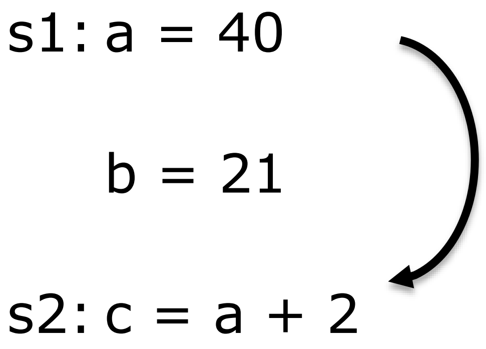
Why Auto-vectorizers Fail

- 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

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 across loop iterations
- Important flavors of data dependencies

FLOW

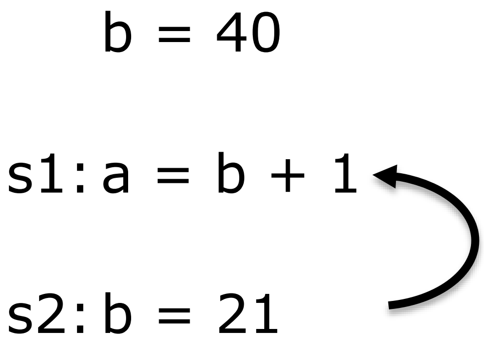


```
s1: a = 40

    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:

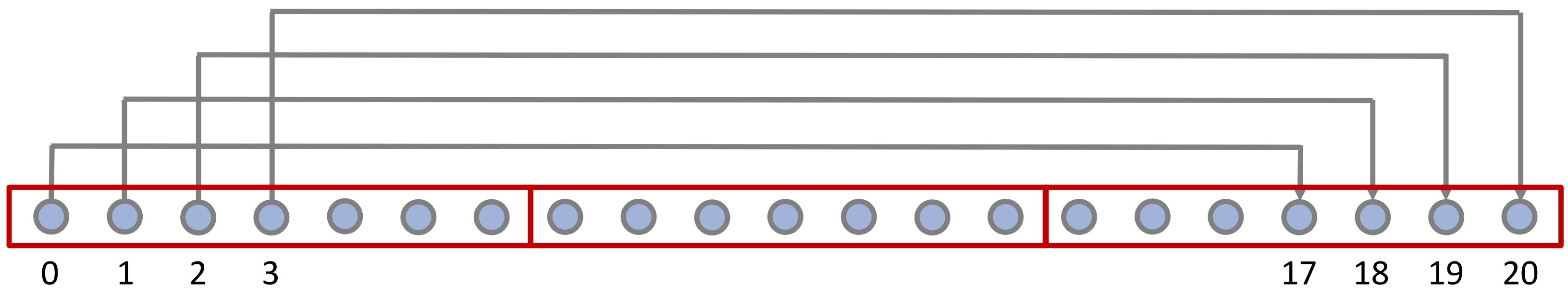
```
void lcd_ex(float* a, float* b, size_t n, float c1, float c2) {
    size_t i;
    for (i = 0; i < n; i++) {
        a[i] = c1 * a[i + 17] + c2 * b[i];
    }
}
```

- 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)



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];
    }
}
```

In a Time Before OpenMP 4.0

- Support required vendor-specific extensions
  - → Programming models (e.g., Intel® Cilk Plus)
  - → Compiler pragmas (e.g., `#pragma vector`)
  - → Low-level constructs (e.g., `_mm_add_pd()`)

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

You need to trust your compiler to do the "right" thing.

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++)

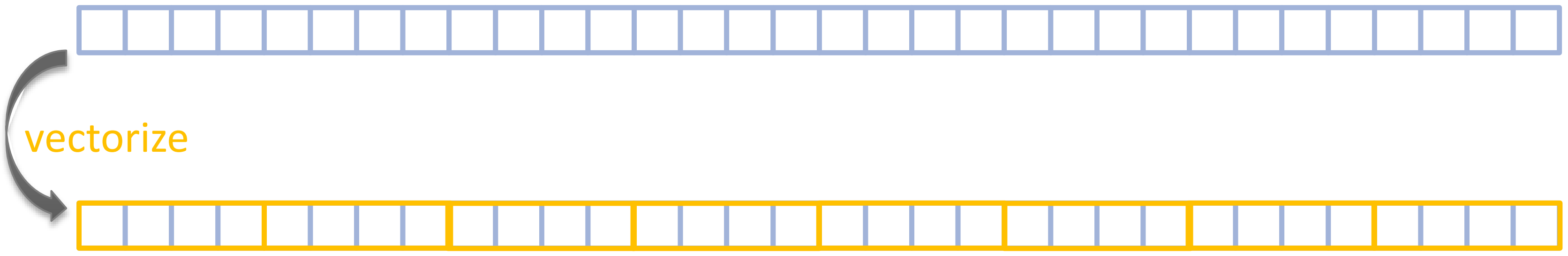
```
#pragma omp simd [clause[[,] clause],…]
for-loops
```

- Syntax (Fortran)

```
!$omp simd [clause[[,] clause],…]
do-loops
[!$omp end simd]
```

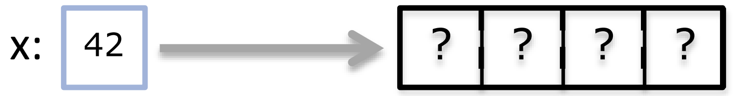
Example

```
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;
}
```

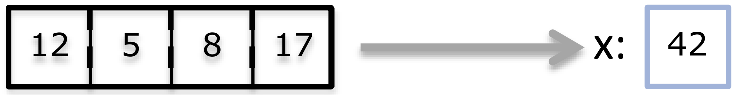


Data Sharing Clauses

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



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



SIMD Loop Clauses

- `safelen (`*`length`*`)`
  - → Maximum number of iterations that can run concurrently without breaking a dependence
  - → in practice, maximum vector length
- `simdlen (length)`
  - → Specify preferred length of SIMD registers used
  - → Must be less or equal to `safelen` if also present
- `linear (`*`list`*`[:`*`linear-step`*`])`
  - → The variable's value is in relationship with the iteration number
    - → $x_i = x_{orig}$ + i * linear-step
- `aligned (`*`list`*`[:`*`alignment`*`])`
  - → Specifies that the list items have a given alignment
  - → Default is alignment for the architecture
- `collapse (`*`n`*`)`

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++)

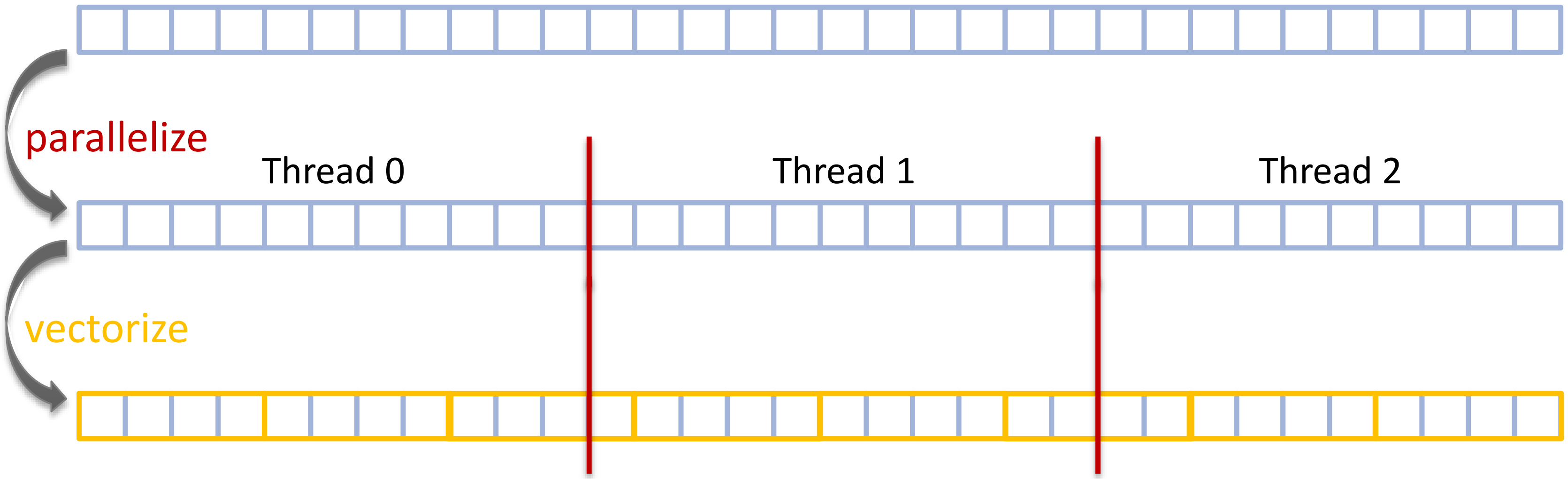
```
#pragma omp for simd [clause[[,] clause],…]
for-loops
```

- Syntax (Fortran)

```
!$omp do simd [clause[[,] clause],…]
do-loops
[!$omp end do simd [nowait]]
```

Example

```
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;
}
```



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

```
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 $\lceil chunksz/simdlen \rceil * simdlen$
  - → 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

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

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

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

```
vec8 distsq_v(vec8 x, vec8 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]);
}   }
```

```
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)`

Same as before

inbranch & notinbranch

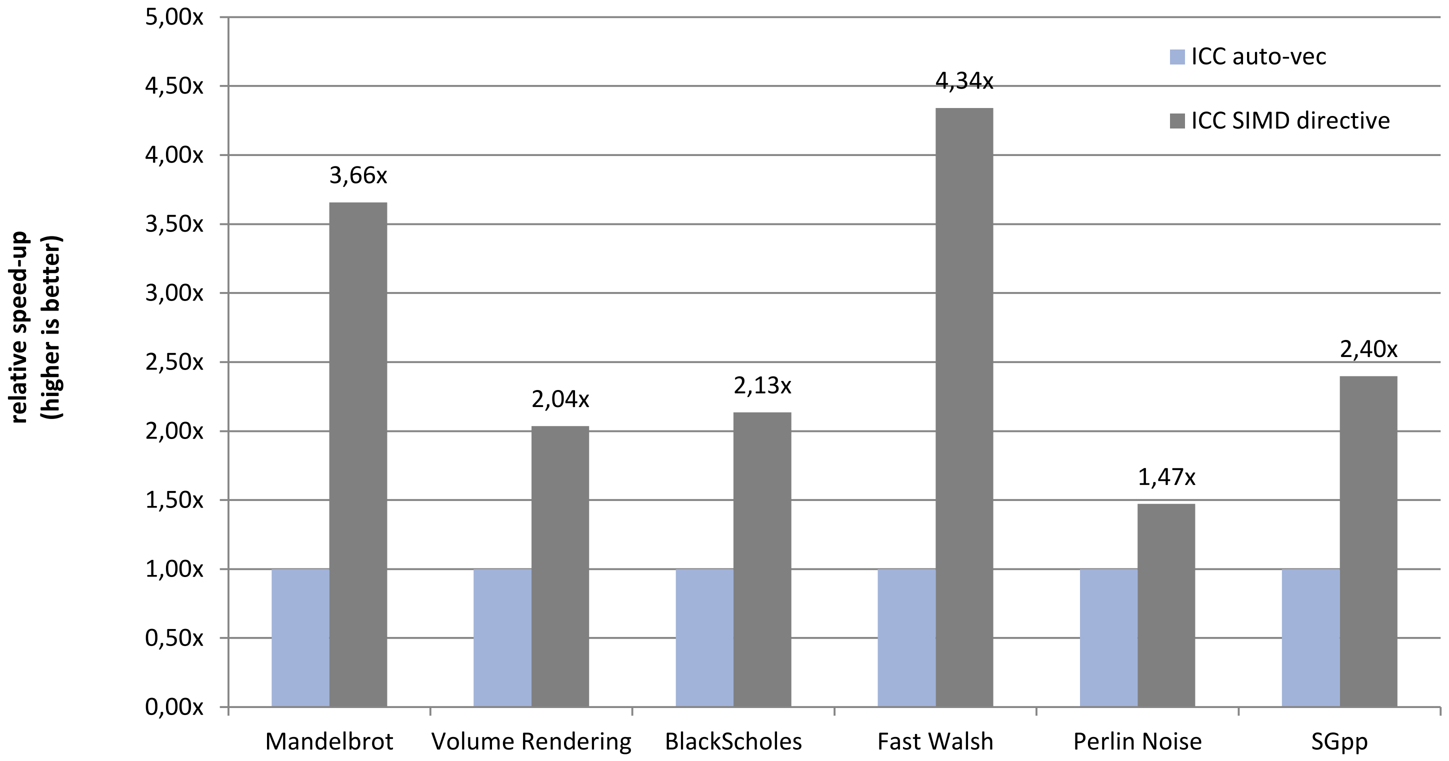
```
#pragma omp declare simd inbranch
float do_stuff(float x) {
    /* do something */
    return x * 2.0;
}

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);
}
```

SIMD Constructs & Performance



M.Klemm, A.Duran, X.Tian, H.Saito, D.Caballero, and X.Martorell. Extending OpenMP with Vector Constructs for Modern Multicore SIMD Architectures. In Proc. of the Intl. Workshop on OpenMP, pages 59-72, Rome, Italy, June 2012. LNCS 7312.