Advanced Systems Lab

Spring 2022

Lecture: SIMD extensions, AVX, compiler vectorization

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Flynn's Taxonomy

	Single instruction	**Multiple instruction**
Single data	***SISD*** Uniprocessor	***MISD***
Multiple data	***SIMD*** Vector computer Short vector extensions	***MIMD*** Multiprocessors VLIW

SIMD Extensions and AVX

AVX intrinsics

Compiler vectorization

The first version of this lecture (for SSE) was created together with Franz Franchetti (ECE, Carnegie Mellon) in 2008

Joao Rivera helped with the update to AVX in 2019

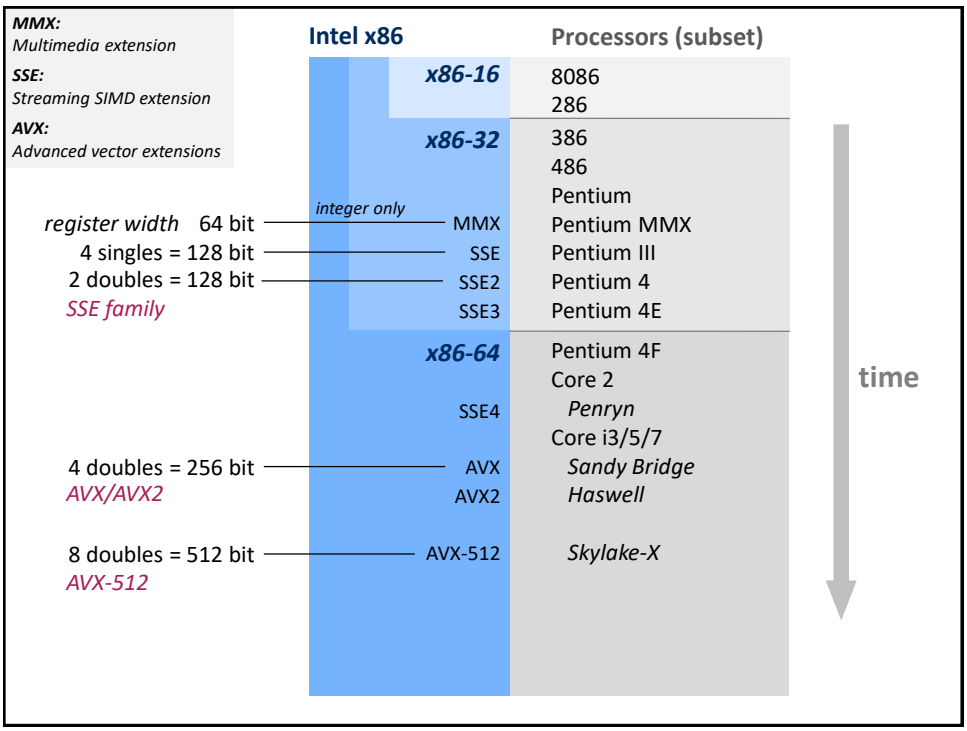
SIMD Vector Extensions

What is it?

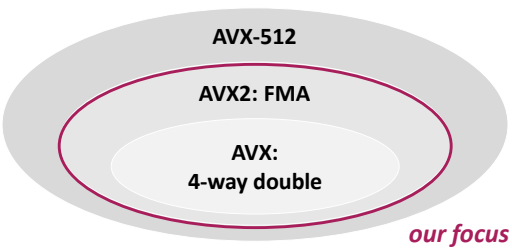
- *Extension of the ISA*
- *Data types and instructions for the parallel computation on short (length 2, 4, 8, …) vectors of integers or floats*
- *Names: SSE, SSE2, AVX, AVX2 …*

Why do they exist?

- ***Useful:** Many applications have the necessary fine-grain parallelism Then: speedup by a factor close to vector length*
- ***Doable:** Relatively easy to design by replicating functional units*



Example AVX Family: Floating Point



Not drawn to scale

AVX: introduces three-operand instructions (c = a + b vs. a = a + b)

AVX2: Introduces fused multiply-add (FMA: c = c + a*b)

Sandy Bridge and later has (at least) AVX

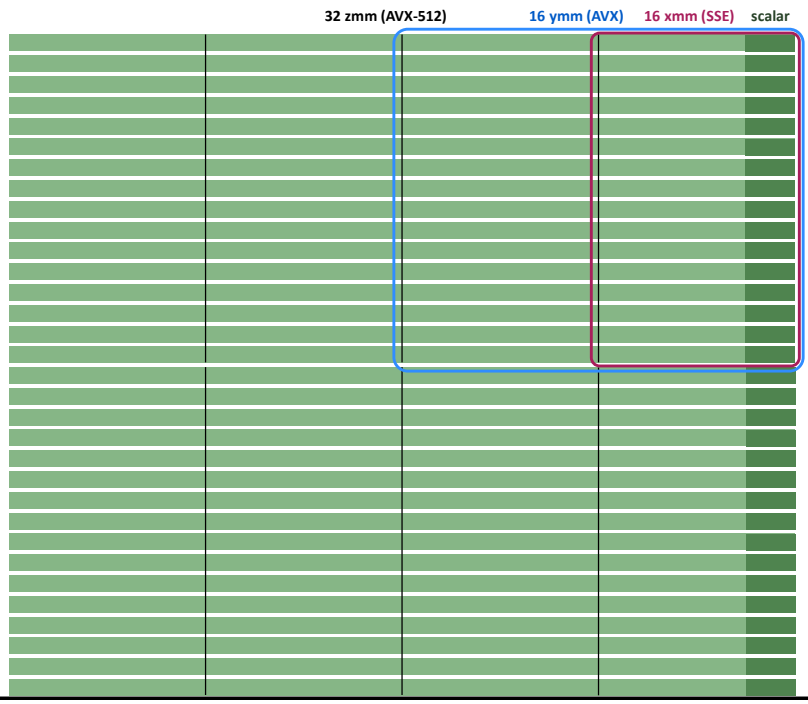
Haswell/Skylake/ …

Have AVX2

16 AVX registers

256 bit = 4 doubles = 8 singles

%ymm0	%ymm8
%ymm1	%ymm9
%ymm2	%ymm10
%ymm3	%ymm11
%ymm4	%ymm12
%ymm5	%ymm13
%ymm6	%ymm14
%ymm7	%ymm15

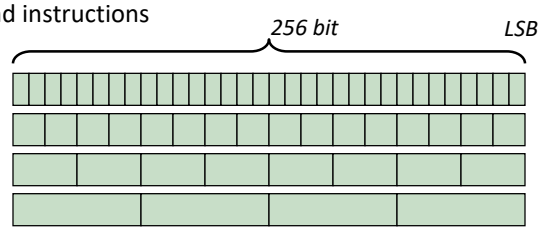


AVX Registers

Used for different data types and instructions

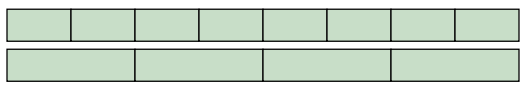
Integer vectors:

- *32-way byte*
- *16-way 2 bytes*
- *8-way 4 bytes*
- *4-way 8 bytes*



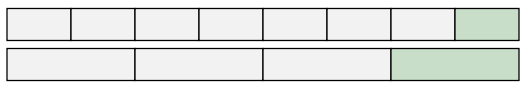
Floating point vectors:

- *8-way single*
- *4-way double*



Floating point scalars:

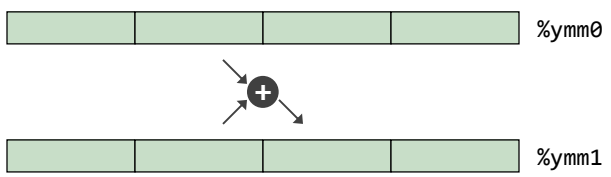
- *single*
- *double*



AVX Instructions: Examples

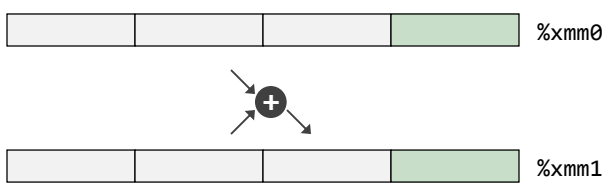
(three-operand!)

Double precision *4-way vector add:* `vaddpd %ymm1 %ymm0 %ymm1`

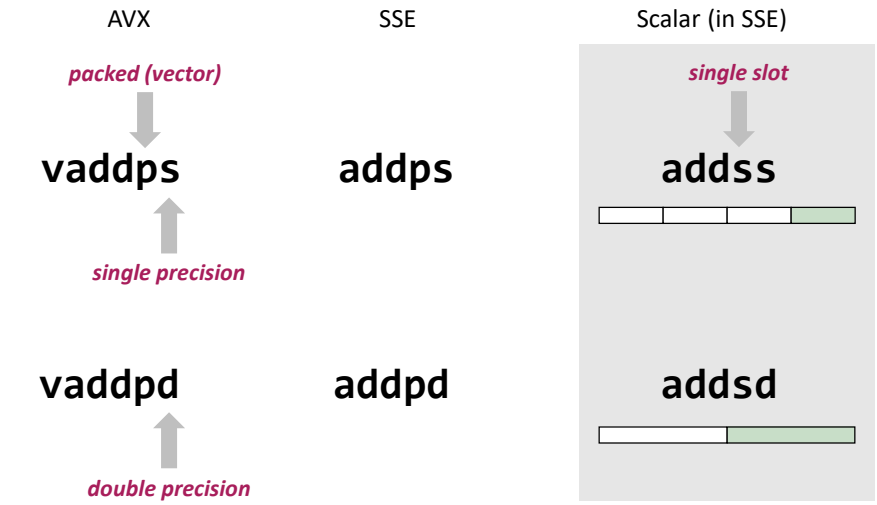


(two-operand!)

Double precision *scalar add (in SSE2):* `addsd %xmm0 %xmm1`



Instruction Names (Assembly)



Compiler will use this for floating point

x86-64 FP Code Example

Inner product of two vectors

- *Double precision arithmetic*
- *Compiled: **not vectorized**, uses (single-slot) SSE instructions*

```
double ipf (double x[],
            double y[],
            int n) {
 int i;
 double result = 0.0;

 for (i = 0; i < n; i++)
   result += x[i]*y[i];
 return result;
}
```

```
ipf:
   xorpd   %xmm1, %xmm1           # result = 0.0
   xorl    %ecx, %ecx             # i = 0
   jmp     .L8                    # goto middle
.L10:                             # loop:
   movslq  %ecx,%rax              # icpy = i
   incl    %ecx                   # i++
   movsd   (%rsi,%rax,4), %xmm0   # t =  y[icpy]
   mulsd   (%rdi,%rax,4), %xmm0   # t *= x[icpy]
   addsd   %xmm0, %xmm1           # result += t
.L8:                              # middle:
   cmpl    %edx, %ecx             # i:n
   jl      .L10                   # if < goto loop
   movapd  %xmm1, %xmm0           # return result
   ret
```

AVX: How to Take Advantage?

Necessary: fine grain parallelism

Options (ordered by effort):

- *Use vectorized libraries (easy, not always available)*
- *Compiler vectorization (this lecture)*
- *Use intrinsics (this lecture)*
- *Write assembly*

We will focus on floating point and double precision (4-way)

SIMD Extensions and AVX

Overview: AVX family

AVX intrinsics

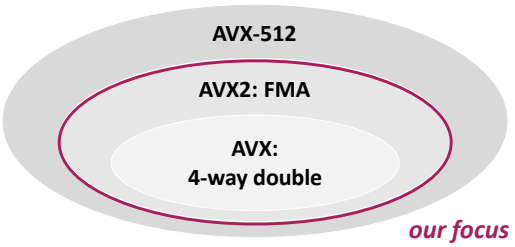
Compiler vectorization

References:
Intel Intrinsics Guide
(easy access to all instructions, nicely done!)

Intel icc compiler manual

Visual Studio manual

Example AVX Family: Floating Point



Not drawn to scale

AVX: introduces three-operand instructions (c = a + b vs. a = a + b)

AVX2: Introduces fused multiply-add (FMA)

Sandy Bridge and later has (at least) AVX

Intrinsics

Enable explicit use of vector instructions in C/C++

Assembly coded C functions

Expanded inline upon compilation: no overhead

Like writing assembly inside C

Floating point:

- *Intrinsics for basic operations (add, mult, …)*
- *Intrinsics for math functions: log, sin, …*

Our introduction is based on icc

- *Almost all intrinsics work with gcc and Visual Studio (VS)*
- *Some language extensions are icc (or even VS) specific*

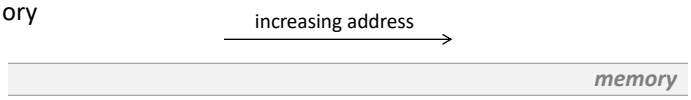
Number of intrinsics

ISA	Count
MMX	124
SSE	154
SSE2	236
SSE3	11
SSSE3	32
SSE41	61
SSE42	19
AVX	188
AVX2	191
AVX-512	3857
FMA	32
KNC	601
SVML	406

2019

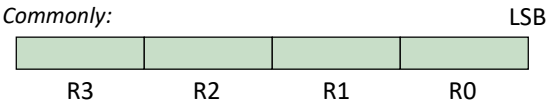
Visual Conventions We Will Use

Memory

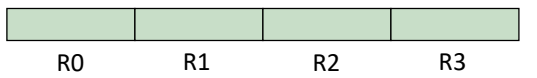


Registers

- *Commonly:*



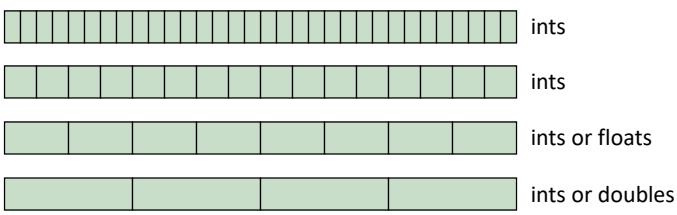
- *We will use*
  LSB



AVX Intrinsics (Focus Floating Point)

Data types

```
__m256  f;   // = {float f0, f1, f2, f3, f4, f5, f6, f7}
__m256d d;   // = {double d0, d1, d3, d4}
__m256i i;   // 32 8-bit, 16 16-bit, 8 32-bit, or 4 64-bit
```



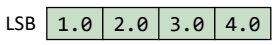
AVX Intrinsics (Focus Floating Point)

Instructions

- *Naming convention: _mm256_<intrin_op>_<suffix>*
- *Example:*

```
// a is 32-byte aligned
double a[4] = {1.0, 2.0, 3.0, 4.0};
__m256d t = _mm256_load_pd(a);
```

p: packed
d: double precision



- *Same result as*

```
__m256d t = _mm256_set_pd(4.0, 3.0, 2.0, 1.0)
```


AVX Intrinsics

Native instructions (one-to-one with assembly)

```
_mm256_load_pd() ↔ vmovapd
_mm256_add_pd()  ↔ vaddpd
_mm256_mul_pd()  ↔ vmulpd
…
```

Multi instructions (map to several assembly instructions)

```
_mm256_set_pd()
_mm256_set1_pd()
…
```

Macros and helpers

```
_MM_SHUFFLE()
…
```

Intel Intrinsics Guide

Intel Intrinsics Guide

Great resource to quickly find the right intrinsics

Has latency and throughput information for many instructions

Note: Intel measures throughput in cycles, i.e., really shows 1/throughput.
Example: Intel throughput 0.33 means throughput is 3 ops/cycle.

What Are the Main Issues?

Alignment is important (256 bit = 32 byte)

You need to code explicit loads and stores

Overhead through shuffles

Not all instructions in SSE (AVX) have a counterpart in AVX (or AVX-512)

Reason: building in hardware an AVX unit by pasting together 2 SSE units is easy (e.g., vaddpd is just 2 parallel addpd); if SSE "lanes" need to be crossed it is expensive

SSE vs. AVX vs. AVX-512

	SSE	AVX	AVX-512
float, double	4-way, 2-way	8-way, 4-way	16-way, 8-way
register	16 x 128 bits: %xmm0 - %xmm15	16 x 256 bits: %ymm0 - %ymm15 *The lower halves are the %xmms*	32 x 512 bits: %zmm0 - %zmm31 *The lower halves are the %ymms*
assembly ops	addps, mulpd, …	vaddps, vmulpd	vaddps, vmulpd
intrinsics data type	__m128, __m128d	__m256, __m256d	__m512, __m512d
intrinsics instructions	_mm_load_ps, _mm_add_pd, …	_mm256_load_ps, _mm256_add_pd	_mm512_load_ps, _mm512_add_pd

Mixing SSE and AVX may incur penalties

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AVX Intrinsics

Load and store

Constants

Arithmetic

Comparison

Conversion

Shuffles

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Loads and Stores

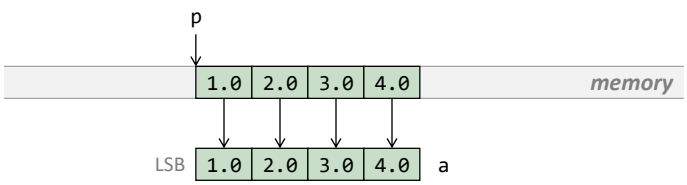
Intrinsic Name	Operation	Corresponding AVX Instructions
_mm256_load_pd	Load four double values, address aligned	VMOVAPD ymm, mem
_mm256_loadu_pd	Load four double values, address unaligned	VMOVUPD ymm, mem
_mm256_maskload_pd	Load four double values using mask	VMASKMOVPD ymm, mem
_mm256_broadcast_sd	Load one double value into all four words	VBROADCASTSD ymm, mem
_mm256_broadcast_pd	Load a pair of double values into the lower and higher part of vector.	VBROADCASTSD ymm, mem
_mm256_i64gather_pd	Load double values from memory using indices.	VGATHERPD ymm, mem, ymm

Intrinsic Name	Operation	Corresponding AVX Instruction
_mm256_set1_pd	Set all four words with the same value	Composite
_mm256_set_pd	Set four values	Composite
_mm256_setr_pd	Set four values, in reverse order	Composite
_mm256_setzero_pd	Clear all four values	VXORPD
_mm256_set_m128d	Set lower and higher 128-bit parts	VINSERTF128

Tables show only most important instructions in category

Loads and Stores

Skylake:
Lat = 7
Tp = 2




```
a = _mm256_load_pd(p);  // p 32-byte aligned
a = _mm256_loadu_pd(p); // p not aligned
```

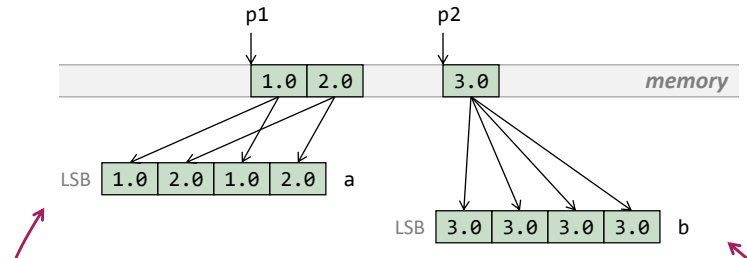
May incur a significant performance penalty

`load_pd` on unaligned pointer: seg fault

→ blackboard

Loads and Stores

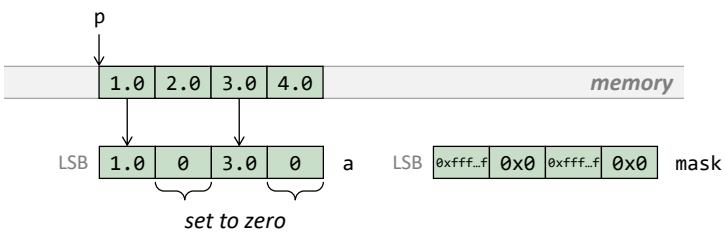
Skylake:
Lat = -
Tp = -




```
a = _mm256_broadcast_pd(p1); // p1 any alignment
b = _mm256_broadcast_sd(p2); // p2 any alignment
```


Loads and Stores

Skylake:
Lat = -
Tp = -

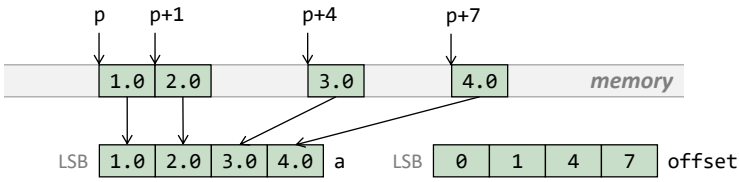



```
a = _mm256_maskload_pd(p, mask); // p any alignment
```

__m256i

Loads and Stores

Skylake:
Lat = -
Tp = -




```
a = _mm256_i64gather_pd(p, offset, 8); // p any alignment
```

scale = {1,2,4,8}
above: scale = 8 = size of double

Stores Analogous to Loads

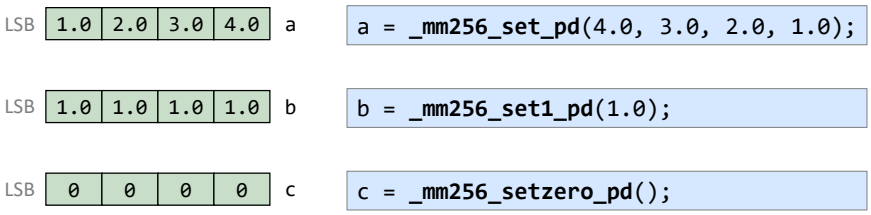
Intrinsic Name	Operation	Corresponding AVX Instruction
_mm256_store_pd	Store four values, address aligned	VMOVAPD
_mm256_storeu_pd	Store four values, address unaligned	VMOVUPD
_mm256_maskstore_pd	Store four values using mask	VMASKMOVPD
_mm256_storeu2_m128d	Store lower and higher 128-bit parts into different memory locations	Composite
_mm256_stream_pd	Store values without caching, address aligned	VMOVNTPD

Tables show only most important instructions in category

Setzero only

Skylake:
Lat = 1
Tp = 3

Constants



→ blackboard

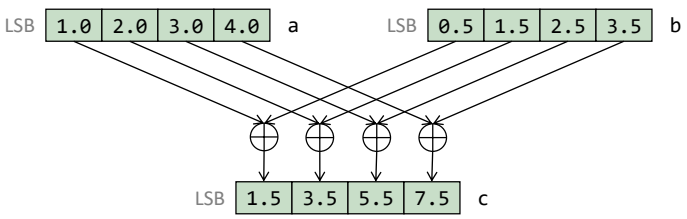
Arithmetic

Intrinsic Name	Operation	Corresponding AVX Instruction
_mm256_add_pd	Addition	VADDPD
_mm256_sub_pd	Subtraction	VSUBPD
_mm256_addsub_pd	Alternatively add and subtract	VADDSUBPD
_mm256_hadd_pd	Half addition	VHADDPD
_mm256_hsub_pd	Half subtraction	VHSUBPD
_mm256_mul_pd	Multiplication	VMULPD
_mm256_div_pd	Division	VDIVPD
_mm256_sqrt_pd	Squared Root	VSQRTPD
_mm256_max_pd	Computes Maximum	VMAXPD
_mm256_min_pd	Computes Minimum	VMINPD
_mm256_ceil_pd	Computes Ceil	VROUNDPD
_mm256_floor_pd	Computes Floor	VROUNDPD
_mm256_round_pd	Round	VROUNDPD
_mm256_dp_ps	Single precision dot product	VDPPS
_mm256_fmadd_pd	Fused multiply-add	VFMADD132pd
_mm256_fmsub_pd	Fused multiply-subtract	VFMSUB132pd
_mm256_fmaddsub_pd	Alternatively fmadd, fmsub	VFMADDSUB132pd

Tables show only most important instructions in category

Arithmetic

Skylake:
Lat = 4
Tp = 2




```
c = _mm256_add_pd(a, b);
```

analogous:

```
c = _mm256_sub_pd(a, b);
```

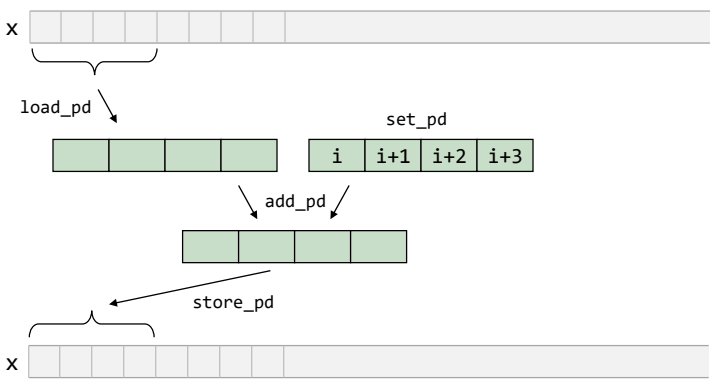
```
c = _mm256_mul_pd(a, b);
```

→ blackboard

Example

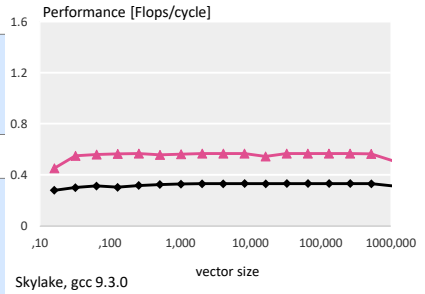
```
void addindex(double *x, int n) {
  for (int i = 0; i < n; i++)
    x[i] = x[i] + i;
}
```

Vectorization by drawing:



Example

```
void addindex(double *x, int n) {
  for (int i = 0; i < n; i++)
    x[i] = x[i] + i;
}
```



Skylake, gcc 9.3.0
-O3 –march=native -fno-tree-vectorize

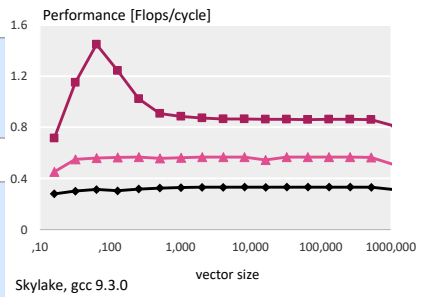
```
#include <immintrin.h>

// n a multiple of 4, x is 32-byte aligned
void addindex_vec1(double *x, int n) {
  __m256d index, x_vec;

  for (int i = 0; i < n; i+=4) {
    x_vec = _mm256_load_pd(x+i);                  // load 4 doubles
    index = _mm256_set_pd(i+3, i+2, i+1, i);      // create vector with indexes
    x_vec = _mm256_add_pd(x_vec, index);          // add the two
    _mm256_store_pd(x+i, x_vec);                  // store back
  }
}
```

Is this the best solution?

No! _mm256_set_pd may be too expensive

Example

```
void addindex(double *x, int n) {
  for (int i = 0; i < n; i++)
    x[i] = x[i] + i;
}
```



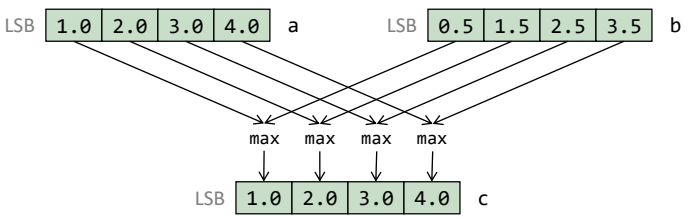
Skylake, gcc 9.3.0
-O3 –march=native -fno-tree-vectorize

```
#include <immintrin.h>

// n a multiple of 4, x is 32-byte aligned
void addindex_vec2(double *x, int n) {
  __m256d x_vec, init, incr, ind;

  ind  = _mm256_set_pd(3, 2, 1, 0);
  incr = _mm256_set1_pd(4);
  for (int i = 0; i < n; i+=4) {
    x_vec = _mm256_load_pd(x+i);                  // load 4 doubles
    x_vec = _mm256_add_pd(x_vec, ind);            // add the two
    ind   = _mm256_add_pd(ind, incr);             // update ind
    _mm256_store_pd(x+i, x_vec);                  // store back
  }
}
```

Code style helps with performance! ***Why?***

Arithmetic

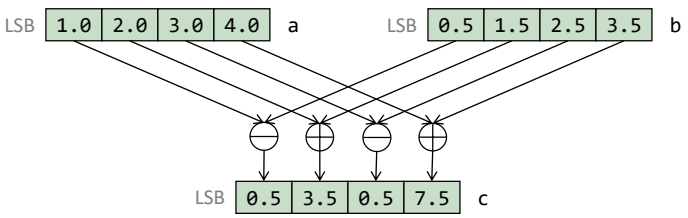
Skylake:
Lat = 4
Tp = 2




```
c = _mm256_max_pd(a, b);
```


Arithmetic

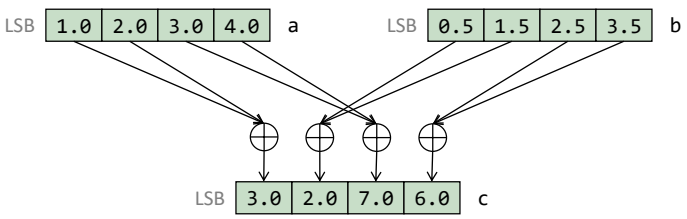
Skylake:
Lat = 4
Tp = 2




```
c = _mm256_addsub_pd(a, b);
```

Arithmetic

Skylake:
Lat = -
Tp = -




```
c = _mm256_hadd_pd(a, b);
```

analogous:

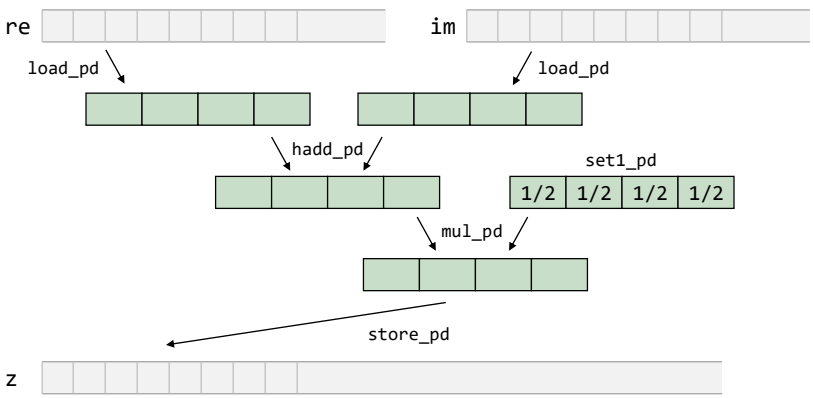
```
c = _mm256_hsub_pd(a, b);
```

Does not cross between 128-bit lanes

→ blackboard

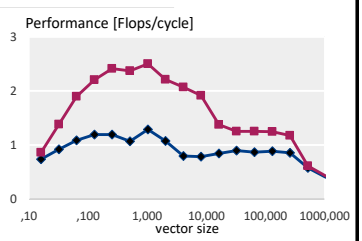
Example

```
// n is even, low pass filter on complex numbers
// output z is in interleaved format
void clp(double *re, double *im, double *z, int n) {
  for (int i = 0; i < n; i+=2) {
    z[i]   = (re[i] + re[i+1])/2;
    z[i+1] = (im[i] + im[i+1])/2;
  }
}
```



Example

```
// n is even, low pass filter on complex numbers
// output z is in interleaved format
void clp(double *re, double *im, double *z, int n) {
  for (int i = 0; i < n; i+=2) {
    z[i]   = (re[i] + re[i+1])/2;
    z[i+1] = (im[i] + im[i+1])/2;
  }
}
```

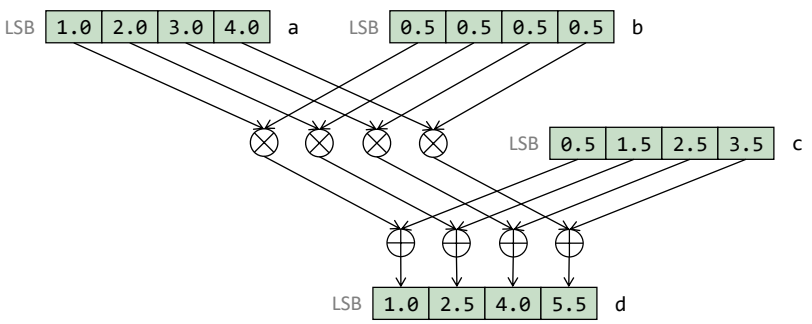


Skylake, gcc 9.3.0
-O3 –march=native -fno-tree-vectorize

```
#include <immintrin.h>

// n a multiple of 4, re, im, z are 32-byte aligned
void clp_vec(double *re, double *im, double *z, int n) {
  __m256d half, v1, v2, avg;

  half = _mm256_set1_pd(0.5);          // set vector to all 0.5
  for(int i = 0; i < n; i+=4) {
    v1  = _mm256_load_pd(re+i);        // load 4 doubles of re
    v2  = _mm256_load_pd(im+i);        // load 4 doubles of im
    avg = _mm256_hadd_pd(v1, v2);      // add pairs of doubles
    avg = _mm256_mul_pd(avg, half);    // multiply with 0.5
    _mm256_store_pd(z+i, avg);         // save result
  }
}
```


Arithmetic (FMA)

Skylake:
Lat = 4
Tp = 2




```
d = _mm256_fmadd_pd(a, b, c);
```

analogous:

```
d = _mm256_fmsub_pd(a, b, c);
```

scalar FMA (128 bit):

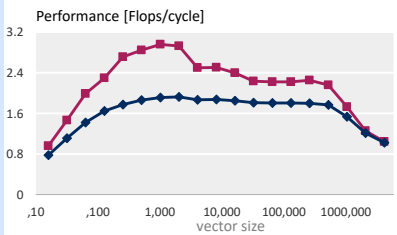
```
d = _mm_fmadd_sd(a, b, c);
```

Example

```
// y = a + x^2 on complex numbers, a is constant
void complex_square(double *a, double *x, double *y, int n) {
  for (int i = 0; i < n; i+=2) {
    y[i]   = a[0] + x[i]*x[i] - x[i+1]*x[i+1];
    y[i+1] = a[1] + 2.0*x[i]*x[i+1];
  }}
```

```
#include <immintrin.h>

void complex_square_fma(double *a, double *x, double *y, int n) {
  __m128d re, im, a_re, a_im, two;

  two  = _mm_set_sd(2.0);
  a_re = _mm_set_sd(a[0]);
  a_im = _mm_set_sd(a[1]);
  for (int i = 0; i < n; i+=2) {
    x_re = _mm_load_sd(x+i);
    x_im = _mm_load_sd(x+i+1);
    re   = _mm_fmadd_sd(x_re, x_re, a_re);
    re   = _mm_fnmadd_sd(x_im, x_im, re);
    im   = _mm_mul_sd(two, x_re);
    im   = _mm_fmadd_sd(im, x_im, a_im);
    _mm_store_sd(y+i, re);
    _mm_store_sd(y+i+1, im);
  }}
```

not vectorized!



Coffee Lake, clang 9.0.0
-O3 -mavx2 -mfma -fno-tree-vectorize

Arithmetic

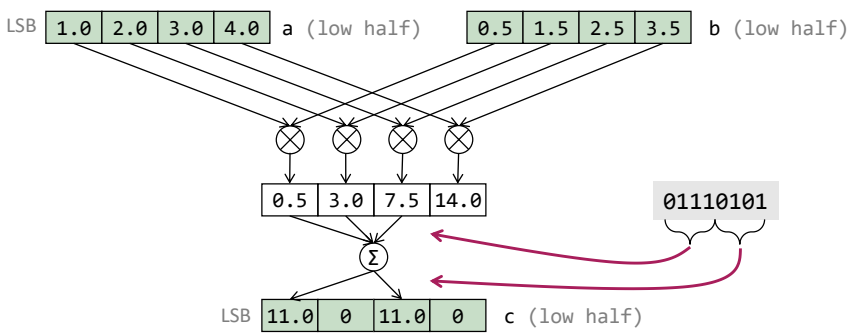
Skylake:
Lat = 13
Tp = 2/3

```
__m256 _mm256_dp_ps(__m256 a, __m256 b, const int mask)
```

_mm256_dp_pd does not exist

Computes the pointwise product of a and b and writes a selected sum of the resulting numbers into selected elements of c; the others are set to zero. The selections are encoded in the mask. (Only for floats)

Example: `mask = 117 = 01110101`



Same is done for the upper half

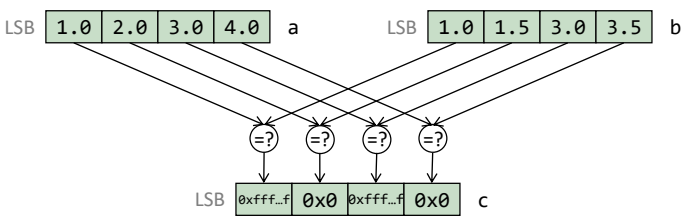
Comparisons

Intrinsic Name	Macro for operation	Operation
_mm256_cmp_pd (VCMPPD)	_CMP_EQ_OQ	Equal
	_CMP_EQ_UQ	Equal (unordered)
	_CMP_GE_OQ	Greater Than or Equal
	_CMP_GT_OQ	Greater Than
	_CMP_LE_OQ	Less Than or Equal
	_CMP_LT_OQ	Less Than
	_CMP_NEQ_OQ	Not Equal
	_CMP_NEQ_UQ	Not Equal (unordered)
	_CMP_NGE_UQ	Not Greater Than or Equal (unordered)
	_CMP_NGT_UQ	Not Greater Than (unordered)
	_CMP_NLE_UQ	Not Less Than or Equal (unordered)
	_CMP_NLT_UQ	Not Less Than (unordered)
	_CMP_TRUE_UQ	True (unordered)
	_CMP_FALSE_OQ	False
	_CMP_ORD_Q	Ordered
	_CMP_UNORD_Q	Unordered

Tables show only most important instructions in category

Comparisons

Skylake:
Lat = 4
Tp = 2




```
c = _mm256_cmp_pd(a, b, _CMP_EQ_OQ);
```

Each field:
`0xffff…f` if true
`0x0` if false

Return type: __m256d

analogous:

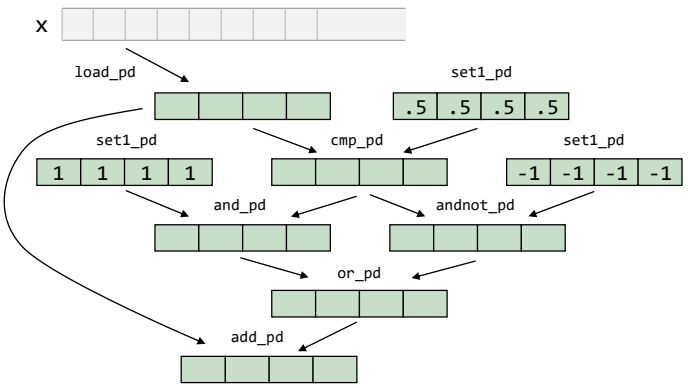
```
c = _mm256_cmp_pd(a, b, _CMP_GE_OQ);
c = _mm256_cmp_pd(a, b, _CMP_LT_OQ);
```

etc.

→ blackboard

Example

```
void fcond(double *x, size_t n) {
  int i;

  for(i = 0; i < n; i++) {
    if(x[i] > 0.5)
      x[i] += 1.;
    else x[i] -= 1.;
  }
}
```



Example

```
void fcond(double *x, size_t n) {
  int i;

  for(i = 0; i < n; i++) {
    if(x[i] > 0.5)
      x[i] += 1.;
    else x[i] -= 1.;
  }
}
```

```
#include <xmmintrin.h>

void fcond_vec1(double *x, size_t n) {
  int i;
  __m256d vt, vmask, vp, vm, vr, ones, mones, thresholds;

  ones       = _mm256_set1_pd(1.);
  mones      = _mm256_set1_pd(-1.);
  thresholds = _mm256_set1_pd(0.5);
  for(i = 0; i < n; i+=4) {
    vt    = _mm256_load_pd(x+i);
    vmask = _mm256_cmp_pd(vt, thresholds, _CMP_GT_OQ);
    vp    = _mm256_and_pd(vmask, ones);
    vm    = _mm256_andnot_pd(vmask, mones);
    vr    = _mm256_add_pd(vt, _mm256_or_pd(vp, vm));
    _mm256_store_pd(x+i, vr);
  }
}
```

Vectorization

=

Picture: www.druckundbestell.de

Conversion

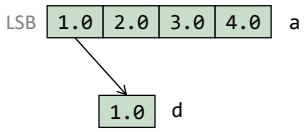
Intrinsic Name	Operation	Corresponding AVX Instruction
_mm256_cvtepi32_pd	Convert from 32-bit integer	VCVTDQ2PD
_mm256_cvtepi32_ps	Convert from 32-bit integer	VCVTDQ2PS
_mm256_cvtpd_epi32	Convert to 32-bit integer	VCVTPD2DQ
_mm256_cvtps_epi32	Convert to 32-bit integer	VCVTPS2DQ
_mm256_cvtps_pd	Convert from floats	VCVTPS2PD
_mm256_cvtpd_ps	Convert to floats	VCVTPD2PS
_mm256_cvttpd_epi32	Convert to 32-bit integer with truncation	VCVTPD2DQ
_mm256_cvtsd_f64	Extract	MOVSD
_mm256_cvtss_f32	Extract	MOVSS

Tables show only most important instructions in category

Conversion

Skylake:
Lat = -
Tp = -

```
double _mm256_cvtsd_f64(__m256d a)
```

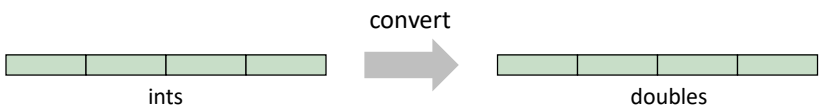



```
double d;

d = _mm_cvtsd_f64(a);
```


Conversion

Skylake:
Lat = 7
Tp = 1

```
__m256d _mm256_cvtepi32_pd(__m128i a)
```



See also:

```
__m256d _mm256_cvtepi64_pd(__m256i a)
```

```
__m256d _mm256_cvtepu32_pd(__m256i a)
```

```
__m256d _mm256_cvtepu64_pd(__m256i a)
```

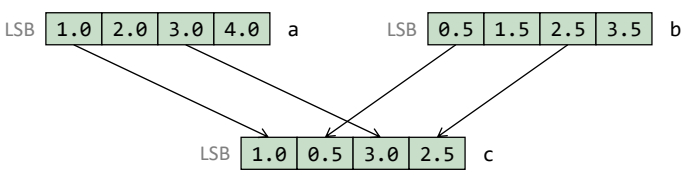
Shuffles

Intrinsic Name	Operation	Corresponding AVX Instruction
_mm256_unpackhi_pd	Unpack High	VUNPCKHPD
_mm256_unpacklo_pd	Unpack Low	VUNPCKLPD
_mm256_movemask_pd	Create four-bit mask	VMOVMSKPD
_mm256_movedup_pd	Duplicates	VMOVDDUP
_mm256_blend_pd	Selects data from 2 sources using constant mask	VBLENDPD
_mm256_blendv_pd	Selects data from 2 sources using variable mask	VBLENDVPD
_mm256_insertf128_pd	Insert 128-bit value into packed array elements selected by index.	VINSERTF128
_mm256_extractf128_pd	Extract 128-bits selected by index.	VEXTRACTF128
_mm256_shuffle_pd	Shuffle	VSHUFPD
_mm256_permute_pd	Permute	VPERMILPD
_mm256_permute4x64_pd	Permute 64-bits elements	VPERMPD
_mm256_permute2f128_pd	Permute 128-bits elements	VPERM2F128

Tables show only most important instructions in category

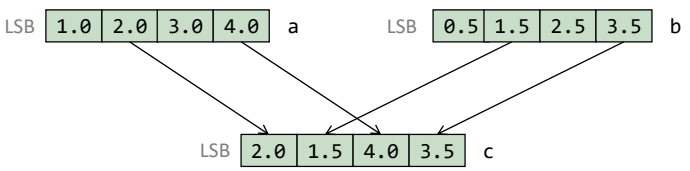
Shuffles

Skylake:
Lat = 1
Tp = 1




```
c = _mm256_unpacklo_pd(a, b);
```

Does not cross between 128-bit lanes




```
c = _mm256_unpackhi_pd(a, b);
```

→ blackboard

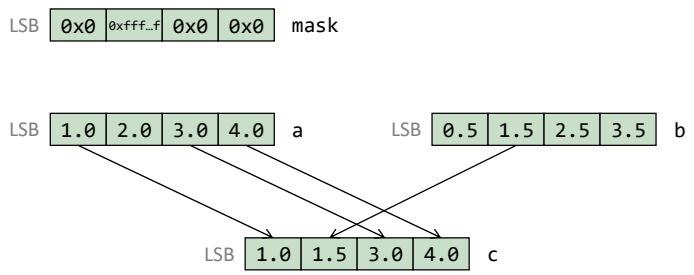
Shuffles

Skylake:
Lat = 2
Tp = 3/2

```
__m256d _mm256_blendv_pd(__m256d a, __m256d b, __m256d mask)
```

Result is filled in each position by an element of a or b in the same position as specified by mask

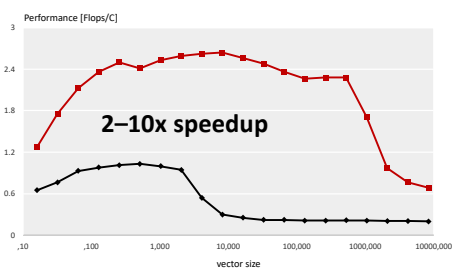
Example:



see also `_mm256_blend_pd`:
same with integer mask, Tp = 3!

Example (Continued From Before)

```
void fcond(double *x, size_t n) {
  int i;

  for(i = 0; i < n; i++) {
    if(x[i] > 0.5)
      x[i] += 1.;
    else x[i] -= 1.;
  }
}
```

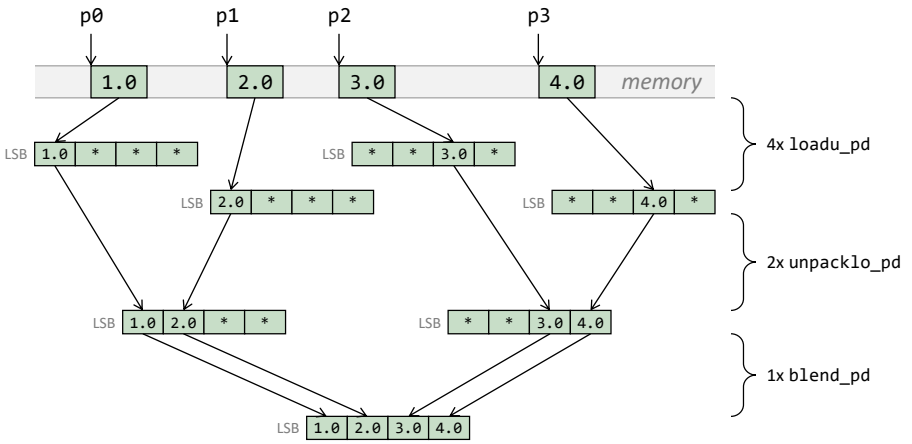


Skylake, gcc 9.3.0
-O3 -march=native -fno-tree-vectorize

```
#include <immintrin.h>

void fcond_vec2(double *x, size_t n) {
  int i;
  __m256d vt, vmask, vp, vm, vr, ones, mones, thresholds;

  ones       = _mm256_set1_pd(1.);
  mones      = _mm256_set1_pd(-1.);
  thresholds = _mm256_set1_pd(0.5);
  for(i = 0; i < n; i+=4) {
    vt    = _mm256_load_pd(x+i);
    vmask = _mm256_cmp_pd(vt, thresholds, _CMP_GT_OQ);
    vb    = _mm256_blendv_pd(mones, ones, vmask);
    vr    = _mm256_add_pd(vt, vb);
    _mm256_store_pd(x+i, vr);
  }
}
```

Example: Loading 4 Real Numbers from Arbitrary Memory Locations

Assumes all values are within one array



7 instructions, this is one way of doing it

Code For Previous Slide

```
#include <immintrin.h>

__m256d LoadArbitrary(double *p0, double *p1, double *p2, double *p3) {
  __m256d a, b, c, d, e, f;

  a = _mm256_loadu_pd(p0);
  b = _mm256_loadu_pd(p1);
  c = _mm256_loadu_pd(p2-2);
  d = _mm256_loadu_pd(p3-2);
  e = _mm256_unpacklo_pd(a, b);
  f = _mm256_unpacklo_pd(c, d);
  return _mm256_blend_pd(e, f, 0b1100);
}
```

Example compilation:

```
vmovupd   ymm0, [rdi]
vmovupd   ymm1, [-16+rdx]
vunpcklpd ymm2, ymm0, [rsi]
vunpcklpd ymm3, ymm1, [-16+rcx]
vblendpd  ymm0, ymm2, ymm3, 12
```

no intrinsic for this instruction (Nov 2019)

Example: Loading 4 Real Numbers from Arbitrary Memory Locations (cont'd)

Whenever possible avoid the previous situation

Restructure algorithm and use the aligned `_mm256_load_pd()`

Example: Loading 4 Real Numbers from Arbitrary Memory Locations (cont'd)

Other possibility

```
__m256 vf;

vf = _mm256_set_pd(*p3, *p2, *p1, *p0);
```

Example compilation:

```
vmovsd   xmm0, [rdi]
vmovsd   xmm1, [rdx]
vmovhpd  xmm2, xmm0, [rsi] // SSE register xmm2 written
vmovhpd  xmm3, xmm1, [rcx]
vinsertf128 ymm0, ymm2, xmm3, 1 // accessed as ymm2
```

vmovhpd cannot be expressed as intrinsic (Nov 2019) but movpd can (`_mm_loadh_pd`)

Example: Loading 4 Real Numbers from Arbitrary Memory Locations (cont'd)

Example compilation:

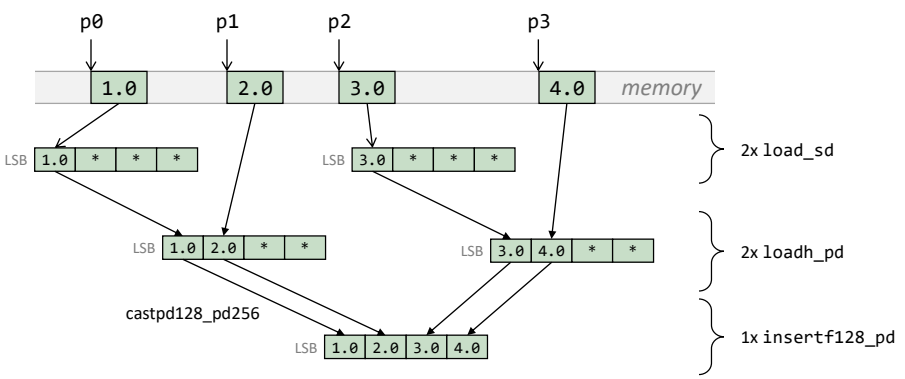
```
vmovsd  xmm0 [rdi]
vmovsd  xmm1, [rdx]
vmovhpd xmm2, xmm0, [rsi] // SSE register xmm2 written
vmovhpd xmm3, xmm1, [rcx]
vinsertf128 ymm0, ymm2, xmm3, 1 // accessed as ymm2
```

Written in intrinsics (reverse-engineered):

```
#include <immintrin.h>

__m256d myArbitraryLoad2(double *a, double *b, double *c, double *d) {
  __m128d t1, t2, t3, t4;
  __m256d t5;

  t1 = _mm_load_sd(a);      // SSE
  t2 = _mm_loadh_pd(t1, b); // SSE
  t3 = _mm_load_sd(c);      // SSE
  t4 = _mm_loadh_pd(t3, d); // SSE
  t5 = _mm256_castpd128_pd256(t2); // cast __m128d -> __m256d
  return _mm256_insertf128_pd(t5, t4, 1);
}
```


Example: Loading 4 Real Numbers from Arbitrary Memory Locations

Picture for previous slide (this solution always works):



Example: Loading 4 Real Numbers from Arbitrary Memory Locations (cont'd)

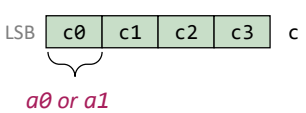
Do not do this (why?):

```
__declspec(align(32)) double g[4];
__m256d vf;

g[0] = *p0;
g[1] = *p1;
g[2] = *p2;
g[3] = *p3;
vf = _mm256_load_pd(g);
```


Shuffles

Skylake:
Lat = 1
Tp = 1

```
__m256d _mm256_shuffle_pd(__m256d a, __m256d b, const int mask)
```




```
c0 = mask.bit0 ? a1 : a0
c1 = mask.bit1 ? b1 : b0
c2 = mask.bit2 ? a3 : a2
c3 = mask.bit3 ? b3 : b2
```

Does not cross between 128-bit lanes

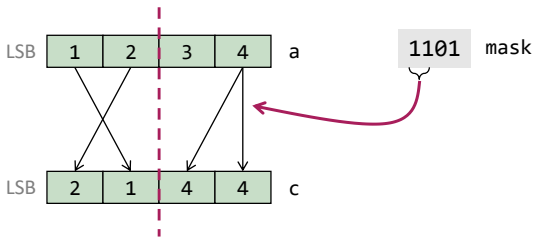
Shuffles

Skylake:
Lat = 1
Tp = 1

```
__m256d _mm256_permute_pd(__m256d a, int mask)
```

Shuffle elements within 128-bits lanes.

Example:



Does not cross between 128-bit lanes

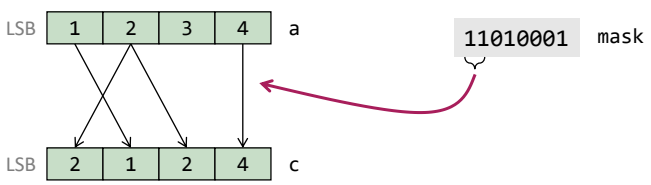
Shuffles

Skylake:
Lat = 3
Tp = 1

```
__m256d _mm256_permute4x64_pd(__m256d a, int mask)
```

Result is filled in each position by any element of a, as specified by mask

Example:



Somewhat more expensive due to shuffle between 128-bits lanes

Apple M1 Processor

ISA: ARMv8.4 with 128-bit Neon vector instructions

2-way double (`float64x2_t`), 4-way single (`float32x4_t`),
8-way half (`float16x8_t`)

Some common intrinsics: (see intrinsics website)

- `vaddq_f64`
- `vmulq_f64`
- `vld1q_f64` *(load vector of 2 doubles)*
- `vst1q_f64`

Example code:

```
#include <arm_neon.h>
float64x2_t a, b, c;
……
c = vaddq_f64(a, b);
```


SIMDe Library for M1

Easy to use library. Provides header file (e.g., x86/avx) to make Intel's SIMD intrinsics available on M1.

Define SIMDE_ENABLE_NATIVE_ALIASES before the header to use the same names as intel's intrinsics, e.g., _mm256_add_pd, (otherwise it must be prefixed with "simde_").

Define SIMDE_ARM_NEON_A64V8_NATIVE to specify that the native platform supports NEON and the library uses those intrinsics.

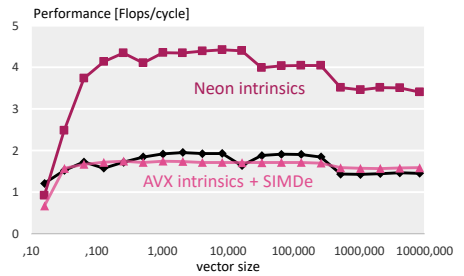
Example of internal _mm256_add_pd implementation provided by library (simplified for readability):

```
__m256d _mm256_add_pd (__m256d a, __m256d b) {
  …
  r_.m128d[0] = _mm_add_pd(a_.m128d[0], b_.m128d[0]);
  r_.m128d[1] = _mm_add_pd(a_.m128d[1], b_.m128d[1]);
  return __m256d_from_private(r_);
}

__m128d _mm_add_pd (__m128d a, __m128d b) {
  …
  r_.neon_f64 = vaddq_f64(a_.neon_f64, b_.neon_f64); // NEON intrinsic
  return __m256d_from_private(r_);
}
```

SIMDe Library vs. Neon Intrinsics

```
void fcond(double *x, size_t n) {
  int i;

  for(i = 0; i < n; i++) {
    if(x[i] > 0.5)
      x[i] += 1.;
    else x[i] -= 1.;
  }
}
```

```
#include <arm_neon.h>
void fcond_neon(double* x, int n) {
  float64x2_t vt1, vb1, vr1, vmask1;
  float64x2_t vt2, vb2, vr2, vmask2;
  float64x2_t ones       = vdupq_n_f64(1.);
  float64x2_t mones      = vdupq_n_f64(-1.);
  float64x2_t thresholds = vdupq_n_f64(0.5);

  for(int i = 0; i < n; i+=4) {
    vt1    = vld1q_f64(x+i);
    vt2    = vld1q_f64(x+i+2);
    vmask1 = vcgtq_f64(vt1, thresholds);
    vmask2 = vcgtq_f64(vt2, thresholds);
    vb1    = vbslq_f64(vmask1, ones, mones);
    vb2    = vbslq_f64(vmask2, ones, mones);
    vr1    = vaddq_f64(vt1, vb1);
    vr2    = vaddq_f64(vt2, vb2);
    vst1q_f64(x+i,   vr1);
    vst1q_f64(x+i+2, vr2); } }
```



Apple M1 Pro, Clang 13.0.0
-O3 -mcpu=apple-m1 -fno-tree-vectorize

No guarantee that translation with SIMDe is close to optimal in more complicated cases

Vectorization With Intrinsics: Key Points

Use aligned loads and stores as much as possible

Minimize shuffle instructions

Minimize use of suboptimal arithmetic instructions.
E.g., add_pd has higher throughput than hadd_pd

Be aware of available instructions (intrinsics guide!) and their performance

SIMD Extensions and AVX

AVX intrinsics

Compiler vectorization

References:
Intel icc manual (look for auto vectorization)

Compiler Vectorization

Compiler flags

Aliasing

Proper code style

Alignment

How Do I Know the Compiler Vectorized?

`vec-report`

Look at assembly: `vmulpd, vaddpd, xxxpd`

Generate assembly with source code annotation:

- *Visual Studio + icc: /Fas*
- *icc on Linux/Mac: -S*

Example

```
void myadd(double *a, double *b, const int n) {
  for (int i = 0; i < n; i++)
    a[i] = a[i] + b[i];
}
```

unvectorized: `/Qvec-`

```
<more>
;;;    a[i] = a[i] + b[i];
vmovsd      xmm0, DWORD PTR [rcx+rax*4]
vaddsd      xmm0, DWORD PTR [rdx+rax*4]
vmovsd      DWORD PTR [rcx+rax*4], xmm0
<more>
```

vectorized:

```
<more>
;;;    a[i] = a[i] + b[i];
vmovsd      xmm0, DWORD PTR [rcx+r11*4]
vaddsd      xmm0, DWORD PTR [rdx+r11*4]
vmovsd      DWORD PTR [rcx+r11*4], xmm0
…
vmovupd     ymm0, YMMWORD PTR [rdx+r10*4]
vmovupd     ymm1, YMMWORD PTR [16+rdx+r10*4]
vaddpd      ymm0, ymm0, YMMWORD PTR [rcx+r10*4]
vaddpd      ymm1, ymm1, YMMWORD PTR [16+rcx+r10*4]
vmovupd     YMMWORD PTR [rcx+r10*4], ymm0
vmovupd     YMMWORD PTR [16+rcx+r10*4], ymm1
<more>
```

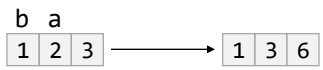
why this?

why everything twice?

Are These Programs Equivalent?

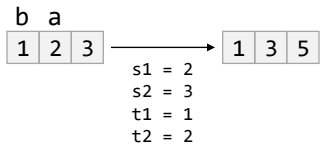
P1:

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



P2:

```
for (i = 0; i < n; i+=2) // n even
{
  s1 = a[i];
  s2 = a[i+1];
  t1 = b[i];
  t2 = b[i+1];
  s1 = s1 + t1;
  s2 = s2 + t2;
  a[i] = s1;
  a[i+1] = s2;
}
```



No! Possible aliasing

Aliasing

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

Cannot be vectorized in a straightforward way due to potential aliasing.

However, in this case compiler can insert runtime check:

```
if (a + n < b || b + n < a)
  /* vectorized loop */
  ...
else
  /* serial loop */
  ...
```

Removing Aliasing

Globally with compiler flag:

- *-fno-alias, /Oa*
- *-fargument-noalias, /Qalias-args-* *(function arguments only)*

For one loop: pragma

```
void add(double *a, double *b, int n) {
  #pragma ivdep
  for (i = 0; i < n; i++)
    a[i] = a[i] + b[i];
}
```

For specific arrays: restrict (needs compiler flag –restrict, /Qrestrict)

```
void add(double *restrict a, double *restrict b, int n) {
for (i = 0; i < n; i++)
    a[i] = a[i] + b[i];
}
```


Proper Code Style

Use countable loops = number of iterations known at runtime

- *Number of iterations is a:*
  constant
  loop invariant term
  linear function of outermost loop indices

Countable or not?

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

```
void vsum(double *a, double *b, double *c) {
  int i = 0;

  while (a[i] > 0.0) {
    a[i] = b[i] * c[i];
    i++;
  }
}
```

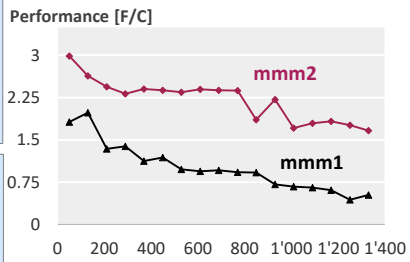
Proper Code Style

Use arrays, structs of arrays, not arrays of structs

Ideally: unit stride access in innermost loop

```
void mmm1(double *a, double *b, double *c) {
  int N = 100;
  int i, j, k;

  for (i = 0; i < N; i++)
    for (j = 0; j < N; j++)
      for (k = 0; k < N; k++)
        c[i*n + j] += a[i*n + k] * b[k*n + j];
}
```

```
void mmm2(double *a, double *b, double *c) {
  int N = 100;
  int i, j, k;

  for (i = 0; i < N; i++)
    for (k = 0; k < N; k++)
      for (j = 0; j < N; j++)
        c[i*n + j] += a[i*n + k] * b[k*n + j];
}
```



Coffee Lake
GCC 7.3.1
Flags: -O3 -ffast-math -march=skylake

Alignment

```
double *x = (double *) malloc(1024*sizeof(double));
int i;

for (i = 0; i < 1024; i++)
   x[i] = 1;
```

Without alignment information would require unaligned loads if vectorized.
However, the compiler can peel the loop to start it at an aligned address:
the generated assembly would mimic the below C code:

```
double *x = (double *) malloc(1024*sizeof(double));
int i;

peel = (unsigned long) x & 0x1f; /* x mod 32 */
if (peel != 0) {
  peel = (32 - peel)/sizeof(double);
  /* initial segment */
  for (i = 0; i < peel; i++)
    x[i] = 1;
}
/* 32-byte aligned access */
for (i = peel; i < 1024; i++)
  x[i] = 1;
```

Ensuring Alignment

Align arrays to 32-byte boundaries (see earlier discussion)

If compiler cannot analyze:

- *Use pragma for loops*

```
double *x = (double *) malloc(1024*sizeof(double));
int i;

#pragma vector aligned
for (i = 0; i < 1024; i++)
   x[i] = 1;
```

- *For specific arrays:*
  __assume_aligned(a, 32);

More Tips (icc 19.1)

https://software.intel.com/en-us/cpp-compiler-developer-guide-and-reference-programming-guidelines-for-vectorization

Use simple for loops. Avoid complex loop termination conditions – the upper iteration limit must be invariant within the loop. For the innermost loop in a nest of loops, you could set the upper limit iteration to be a function of the outer loop indices.

Write straight-line code. Avoid branches such as switch, goto, or return statements, most function calls, or if constructs that can not be treated as masked assignments.

Avoid dependencies between loop iterations or at the least, avoid read-after-write dependencies.

Try to use array notations instead of the use of pointers. C programs in particular impose very few restrictions on the use of pointers; aliased pointers may lead to unexpected dependencies. Without help, the compiler often cannot tell whether it is safe to vectorize code containing pointers.

Wherever possible, use the loop index directly in array subscripts instead of incrementing a separate counter for use as an array address.

Access memory efficiently:

- ***Favor inner loops with unit stride.***
- ***Minimize indirect addressing.***
- ***Align your data to 32 byte boundaries (for AVX instructions).***

Choose a suitable data layout with care. Most multimedia extension instruction sets are rather sensitive to alignment.

Read the above website

Compiler Vectorization

Understand the limitations

Carefully read the manual