

How to Write Fast Code

SIMD Vectorization

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13th and 14th Lecture

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Organization

■ Overview

- Idea, benefits, reasons, restrictions
- History and state-of-the-art floating-point SIMD extensions
- How to use it: compiler vectorization, class library, intrinsics, inline assembly

■ Writing code for Intel's SSE

- Compiler vectorization
- Intrinsics: instructions
- Intrinsics: common building blocks

■ Selected topics

- SSE integer instructions
- Other SIMD extensions: AltiVec/VMX, Cell SPU

■ Conclusion: How to write good vector code

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SIMD (Signal Instruction Multiple Data) vector instructions in a nutshell

■ What are these instructions?

- Extension of the ISA. Data types and instructions for parallel computation on short (2-16) vectors of integers and floats



■ Why are they here?

- **Useful:** Many applications (e.g., multi media) feature the required fine grain parallelism – code potentially faster
- **Doable:** Chip designers have enough transistors available, easy to implement

Evolution of Intel Vector Instructions

- **MMX (1996, Pentium)**
 - *CPU-based MPEG decoding*
 - Integers only, 64-bit divided into 2 x 32 to 8 x 8
 - Phased out with SSE4
- **SSE (1999, Pentium III)**
 - *CPU-based 3D graphics*
 - 4-way float operations, single precision
 - 8 new 128 bit Register, 100+ instructions
- **SSE2 (2001, Pentium 4)**
 - *High-performance computing*
 - Adds 2-way float ops, double-precision; same registers as 4-way single-precision
 - Integer SSE instructions make MMX obsolete
- **SSE3 (2004, Pentium 4E Prescott)**
 - *Scientific computing*
 - New 2-way and 4-way vector instructions for complex arithmetic
- **SSSE3 (2006, Core Duo)**
 - Minor advancement over SSE3
- **SSE4 (2007, Core2 Duo Penryn)**
 - *Modern codecs, cryptography*
 - New integer instructions
 - Better support for unaligned data, super shuffle engine

More details at http://en.wikipedia.org/wiki/Streaming_SIMD_Extensions

Overview Floating-Point Vector ISAs

Vendor	Name		ν -way	Precision	Introduced with
Intel	SSE		4-way	single	Pentium III
	SSE2	+	2-way	double	Pentium 4
	SSE3				Pentium 4 (Prescott)
	SSSE3				Core Duo
	SSE4				Core2 Extreme (Penryn)
Intel	IPF		2-way	single	Itanium
AMD	3DNow!		2-way	single	K6
	Enhanced 3DNow!				K7
	3DNow! Professional	+	4-way	single	Athlon XP
	AMD64	+	2-way	double	Opteron
Motorola	AltiVec		4-way	single	MPC 7400 G4
IBM	VMX		4-way	single	PowerPC 970 G5
	SPU	+	2-way	double	Cell BE
IBM	Double FPU		2-way	double	PowerPC 440 FP2

Within a extension family, newer generations add features to older ones

Convergence: 3DNow! Professional = 3DNow! + SSE; VMX = AltiVec; SPU³/₄VMX

Related Technologies

- **Original SIMD machines (CM-2,...)**
 - Don't really have anything in common with SIMD vector extension
- **Vector Computers (NEC SX6, Earth simulator)**
 - Vector lengths of up to 128
 - High bandwidth memory, no memory hierarchy
 - Pipelined vector operations
 - Support strided memory access
- **Very long instruction word (VLIW) architectures (Itanium,...)**
 - Explicit parallelism
 - More flexible
 - No data reorganization necessary
- **Superscalar processors (x86, ...)**
 - No explicit parallelism
 - Memory hierarchy

SIMD vector extensions borrow multiple concepts

How to use SIMD Vector Extensions?

- **Prerequisite: fine grain parallelism**
- **Helpful: regular algorithm structure**
- **Easiest way: use existing libraries**
Intel MKL and IPP, Apple vDSP, AMD ACML,
Atlas, FFTW, Spiral
- **Do it yourself:**
 - **Use compiler vectorization: write vectorizable code**
 - **Use language extensions to explicitly issue the instructions**
Vector data types and intrinsic/builtin functions
Intel C++ compiler, GNU C compiler, IBM VisualAge for BG/L,...
 - **Implement kernels using assembly (inline or coding of full modules)**

Characterization of Available Methods

■ Interface used

- Portable high-level language (possibly with pragmas)
- Proprietary language extension (builtin functions and data types)
- C++ Class interface
- Assembly language

■ Who vectorizes

- Programmer or code generator expresses parallelism
- Vectorizing compiler extracts parallelism

■ Structures vectorized

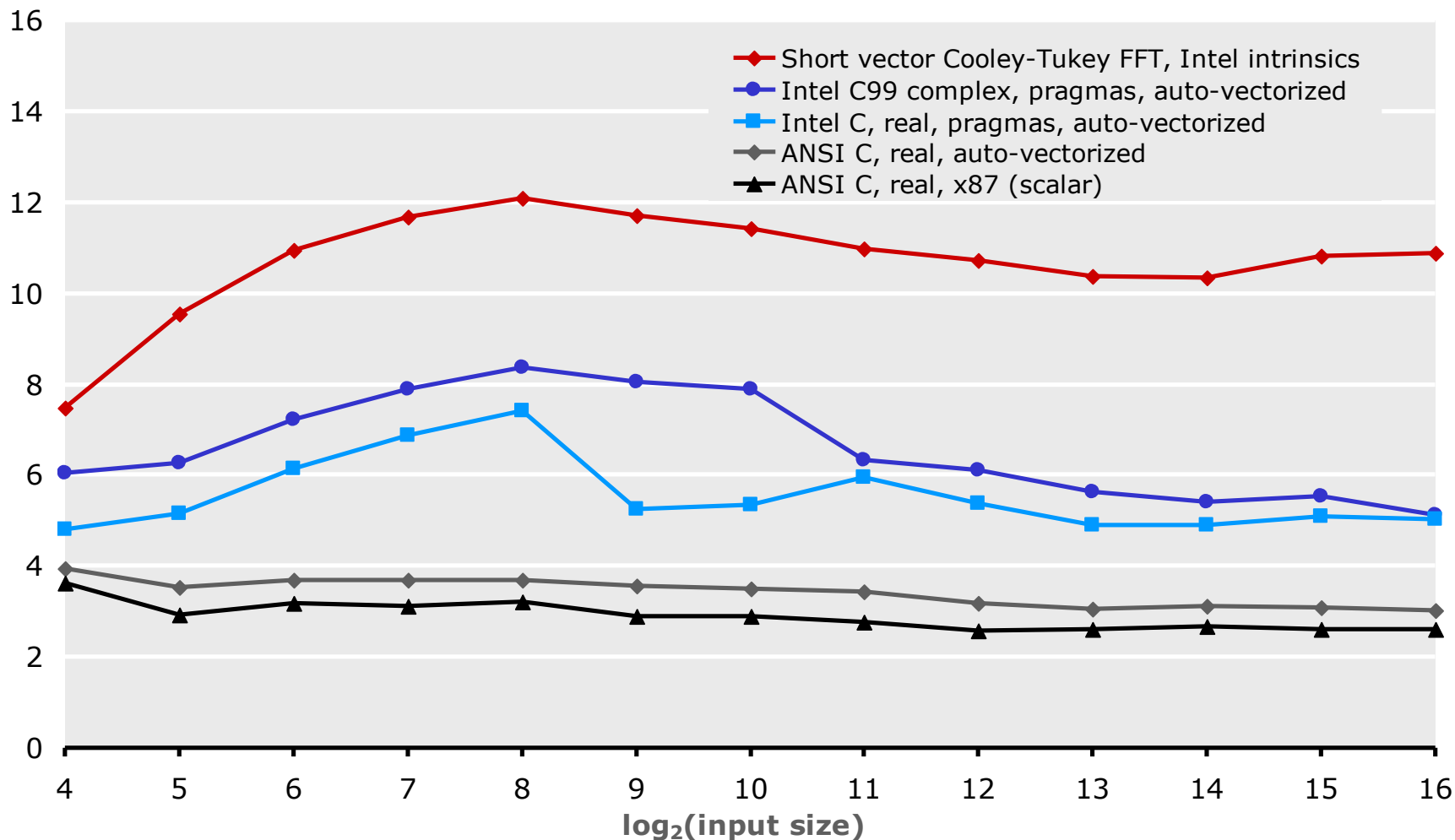
- Vectorization of independent loops
- Instruction-level parallelism extraction

■ Generality of approach

- General purpose (e.g., for complex code or for loops)
- Problem specific (for FFTs or for matrix products)

Spiral-generated FFT on 2.66 GHz Core2 (4-way SSE)

performance [Gflop/s], single-precision, Intel C++ 9.1, SSSE, Windows XP 32-bit



- limitations of compiler vectorization
- `C99_complex` and `#pragma` help, but still slower than hand-vectorized code

Problems

- Correct data alignment paramount
- Reordering data kills runtime
- Algorithms must be adapted to suit machine needs
- Adaptation and optimization is machine/extension dependent
- Thorough understanding of ISA + Micro architecture required

One can easily slow down a program by vectorizing it

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Intel Streaming SIMD Extension (SSE)

■ Instruction classes

- Memory access (explicit and implicit)
- Basic arithmetic (+, -, *)
- Expensive arithmetic (1/x, sqrt(x), min, max, /, 1/sqrt)
- Logic (and, or, xor, nand)
- Comparison (+, <, >, ...)
- Data reorder (shuffling)

■ Data types

- float: `__m128` (SSE)
- double: `__m128d` (SSE2)
- Integer: `__m128i` (8 bit – 128 bit)

■ Intel C++ Compiler Manual

<http://www.intel.com/cd/software/products/asm-na/eng/347618.htm>

<http://www.intel.com/cd/software/products/asm-na/eng/346158.htm>

<http://msdn2.microsoft.com/en-us/library/26td21ds.aspx>

Intel C++ Compiler: Automatic Vectorization

■ Example program: pointwise vector multiplication

```
void func(float *c, float *a, float *b, int n) {  
    for (int i=0; i<n; i++)  
        c[i] = a[i] * b[i];  
}
```

■ Compiler invocation

```
C:\>iclvars > NUL
```

```
C:\>C>icl /Qc99 /Qrestrict /O3 /QxW /Qvec-report3 /FAs /c  
test.c
```

```
Intel(R) C++ Compiler for 32-bit applications, Version 9.1  
Copyright (C) 1985-2006 Intel Corporation. All rights  
reserved.
```

```
test.c
```

```
test.c(2) : (col. 5) remark: LOOP WAS VECTORIZED.
```

Intel C++ Compiler: Auto Vectorizer Manual

The screenshot shows the Intel(R) C++ Compiler Documentation window. The left pane displays a tree view of the documentation structure, with 'Language Support and Directives' selected under the 'Auto-vectorization' section. The right pane displays the content of this section, including a paragraph of text and a table of features.

Language Support and Directives

This topic addresses language features that better help to vectorize code. The `__declspec (align (n))` declaration enables you to overcome hardware alignment constraints. The restrict qualifier and the pragmas address the stylistic issues due to lexical scope, data dependency, and ambiguity resolution.

Language Support

Feature	Description
<code>__declspec (align (n))</code>	Directs the compiler to align the variable to an <i>n</i> -byte boundary. Address of the variable is <i>address mod n=0</i> .
<code>__declspec (align (n, off))</code>	Directs the compiler to align the variable to an <i>n</i> -byte boundary with offset <i>off</i> within each <i>n</i> -byte boundary. Address of the variable is <i>address mod n=off</i> .
<code>restrict</code>	Permits the disambiguator flexibility in alias assumptions, which enables more vectorization.
<code>__assume_aligned (a, n)</code>	Instructs the compiler to assume that array <i>a</i> is aligned on an <i>n</i> -byte boundary; used in cases where the compiler has failed to obtain alignment information.
<code>#pragma ivdep</code>	Instructs the compiler to ignore assumed vector dependencies.
<code>#pragma vector {aligned unaligned always}</code>	Specifies how to vectorize the loop and indicates that efficiency heuristics should be ignored.
<code>#pragmanovector</code>	Specifies that the loop should never be vectorized,

Multi-version Code

Intel C++ Compiler: Options and Output

- On Windows Intel C++ compiler requires VisualStudio
- On command line `iclvars.cmd` initializes the environment
- **Compiler Options**
 - C99 syntax: `/Qc99 /Qrestrict`
 - Full optimization: `/O3`
 - Vectorization target: SSE2 `/QxW`
other targets: `/QxK` (SSE) , `/QxP` (SSE3), `/QxT` (SSSE), `/QxS` (SSE4)
 - Vectorization report: `/Qvec-report3`
 - Assembly output (source + assembly): `/FAs`
- **Check vectorization quality: Checking output assembly**

```

$B1$17:                                ; Preds $B1$17 $B1$16
  movups  xmm0, XMMWORD PTR [ecx+edi*4]    ;3.16
  mulps   xmm0, XMMWORD PTR [edx+edi*4]    ;3.23
  movaps  XMMWORD PTR [esi+edi*4], xmm0    ;3.9
  movups  xmm1, XMMWORD PTR [ecx+edi*4+16] ;3.16
  mulps   xmm1, XMMWORD PTR [edx+edi*4+16] ;3.23
  movaps  XMMWORD PTR [esi+edi*4+16], xmm1 ;3.9
  add     edi, 8                            ;2.5

```


Intel C++ Compiler: Language Extension

■ Language extension

- C99 “restrict” keyword
- Aligned C library functions: `_mm_malloc()`, `_mm_free()`
- `_assume_aligned()`
- `__declspec(__align())`
- Pragmas
 - `#pragma vector aligned | unaligned | always`
 - `#pragma ivdep`
 - `#pragma novector`

■ Example using language extension

```
void func(float *restrict c, float *restrict a,  
         float *restrict b, int n) {  
#pragma vector always  
    for (int i=0; i<n; i++)  
        c[i] = a[i] * b[i];  
}
```

Intel SSE Intrinsics Interface

■ Data types

- `__m128 f; // ={float f3, f2, f1, f0}`
- `__m128d d; // ={double d1, d0}`

■ Intrinsics

- Native instructions: `_mm_add_ps()`, `_mm_mul_ps()`, ...
- Multi-instruction: `_mm_setr_ps()`, `_mm_set1_ps`, ...

■ Macros

- Transpose: `_MM_TRANSPOSE4_PS()`, ...
- Helper: `_MM_SHUFFLE()`

Intel SSE: Load Instructions

Intel(R) C++ Compiler Documentation

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Load Operations for Streaming SIMD Extensions

The prototypes for Streaming SIMD Extensions (SSE) intrinsic are in the `xmmintrin.h` header file.

To see detailed information about an intrinsic, click on that intrinsic name in the following table.

The results of each intrinsic operation are placed in a register. This register is illustrated for each intrinsic with R0-R3. R0, R1, R2 and R3 each represent one of the 4 32-bit pieces of the result register.

Intrinsic Name	Operation	Corresponding SSE Instruction
_mm_loadh_pi	Load high	MOVHPS reg, mem
_mm_loadl_pi	Load low	MOVLPS reg, mem
_mm_load_ss	Load the low value and clear the three high values	MOVSS
_mm_load1_ps	Load one value into all four words	MOVSS + Shuffling
_mm_load_ps	Load four values, address aligned	MOVAPS
_mm_loadu_ps	Load four values, address unaligned	MOVUPS
_mm_loadr_ps	Load four values in reverse	MOVAPS + Shuffling

```
_m128 _mm_loadh_pi(_m128 a, __m64 const *p)
Sets the upper two SP FP values with 64 bits of data loaded from the address p.
```

R0	R1	R2	R3
a0	a1	*p0	*p1

Intel SSE: Vector Arithmetic

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Arithmetic Operations for Streaming SIMD Extensions

The prototypes for Streaming SIMD Extensions (SSE) intrinsics are in the `xmmintrin.h` header file.

The results of each intrinsic operation are placed in a register. This register is illustrated for each intrinsic with R0-R3. R0, R1, R2 and R3 each represent one of the 4 32-bit pieces of the result register.

To see detailed information about an intrinsic, click on that intrinsic name in the following table.

Intrinsic	Operation	Corresponding SSE Instruction
_mm_add_ss	Addition	ADDSS
_mm_add_ps	Addition	ADDPS
_mm_sub_ss	Subtraction	SUBSS
_mm_sub_ps	Subtraction	SUBPS
_mm_mul_ss	Multiplication	MULSS
_mm_mul_ps	Multiplication	MULPS
_mm_div_ss	Division	DIVSS
_mm_div_ps	Division	DIVPS
_mm_sqrt_ss	Squared Root	SQRTSS
_mm_sqrt_ps	Squared Root	SQRTPS
_mm_rcp_ss	Reciprocal	RCPSS
_mm_rcp_ps	Reciprocal	RCPPS
_mm_rsqrt_ss	Reciprocal Squared Root	RSQRTSS
_mm_rsqrt_ps	Reciprocal Squared Root	RSQRTPS
_mm_min_ss	Computes Minimum	MINSS

Intel SSE: SSE3 Horizontal Add and SUB

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Single-precision Floating-point Vector Intrinsic for Streaming SIMD Extensions 3

The single-precision floating-point vector intrinsic listed here are designed for the Intel® Pentium® 4 processor with Streaming SIMD Extensions 3 (SSE3).

The results of each intrinsic operation are placed in the registers R0, R1, R2, and R3.

To see detailed information about an intrinsic, click on that intrinsic name in the following table.

The prototypes for these intrinsics are in the `pmmintrin.h` header file.

Intrinsic Name	Operation	Corresponding SSE3 Instruction
_mm_addsub_ps	Subtract and add	ADDSSUBPS
_mm_hadd_ps	Add	HADDPS
_mm_hsub_ps	Subtracts	HSSUBPS
_mm_movehdup_ps	Duplicates	MOVSHDUP
_mm_movedup_ps	Duplicates	MOVSLDUP

```
extern __m128 _mm_addsub_ps(__m128 a, __m128 b);
```

Subtracts even vector elements while adding odd vector elements.

R0	R1	R2	R3
a0 - b0;	a1 + b1;	a2 - b2;	a3 + b3;

```
extern __m128 _mm_hadd_ps(__m128 a, __m128 b);
```

Adds adjacent vector elements.

R0	R1	R2	R3
a0 + a1;	a2 + a3;	b0 + b1;	b2 + b3;

Intel SSE: Reorder Instructions

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Miscellaneous Intrinsic Using Streaming SIMD Extensions

The prototypes for Streaming SIMD Extensions (SSE) intrinsic are in the `xmmintrin.h` header file.

The results of each intrinsic operation are placed in registers. The information about what is placed in each register appears in the tables below, in the detailed explanation of each intrinsic. R, R0, R1, R2 and R3 represent the registers in which results are placed.

To see detailed information about an intrinsic, click on that intrinsic name in the following table.

Intrinsic Name	Operation	Corresponding SSE Instruction
_mm_shuffle_ps	Shuffle	SHUFFPS
_mm_unpackhi_ps	Unpack High	UNPCKHPS
_mm_unpacklo_ps	Unpack Low	UNPCKLPS
_mm_move_ss	Set low word, pass in three high values	MOVSS
_mm_movehl_ps	Move High to Low	MOVHLPS
_mm_movelh_ps	Move Low to High	MOVLHPS
_mm_movemask_ps	Create four-bit mask	MOVMSKPS

`__m128 _mm_shuffle_ps(__m128 a, __m128 b, unsigned int imm8)`

Selects four specific SP FP values from a and b, based on the mask `imm8`. The mask must be an immediate. See [Macro Function for Shuffle Using Streaming SIMD Extensions](#) for a description of the shuffle semantics.

`__m128 _mm_unpackhi_ps(__m128 a, __m128 b)`

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Intel SSE: Transpose Macro

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Macro Function for Matrix Transposition

The Streaming SIMD Extensions (SSE) provide the following macro function to transpose a 4 by 4 matrix of single precision floating point values.

```
__MM_TRANSPOSE4_PS(row0, row1, row2, row3)
```

The arguments `row0`, `row1`, `row2`, and `row3` are `__m128` values whose elements form the corresponding rows of a 4 by 4 matrix. The matrix transposition is returned in arguments `row0`, `row1`, `row2`, and `row3` where `row0` now holds column 0 of the original matrix, `row1` now holds column 1 of the original matrix, and so on.

The transposition function of this macro is illustrated in the "Matrix Transposition Using the `__MM_TRANSPOSE4_PS`" figure.

Matrix Transposition Using `__MM_TRANSPOSE4_PS` Macro

row0	X ₀	Y ₀	Z ₀	W ₀
row1	X ₁	Y ₁	Z ₁	W ₁
row2	X ₂	Y ₂	Z ₂	W ₂
row3	X ₃	Y ₃	Z ₃	W ₃

least significant element				most significant element
---------------------------	--	--	--	--------------------------

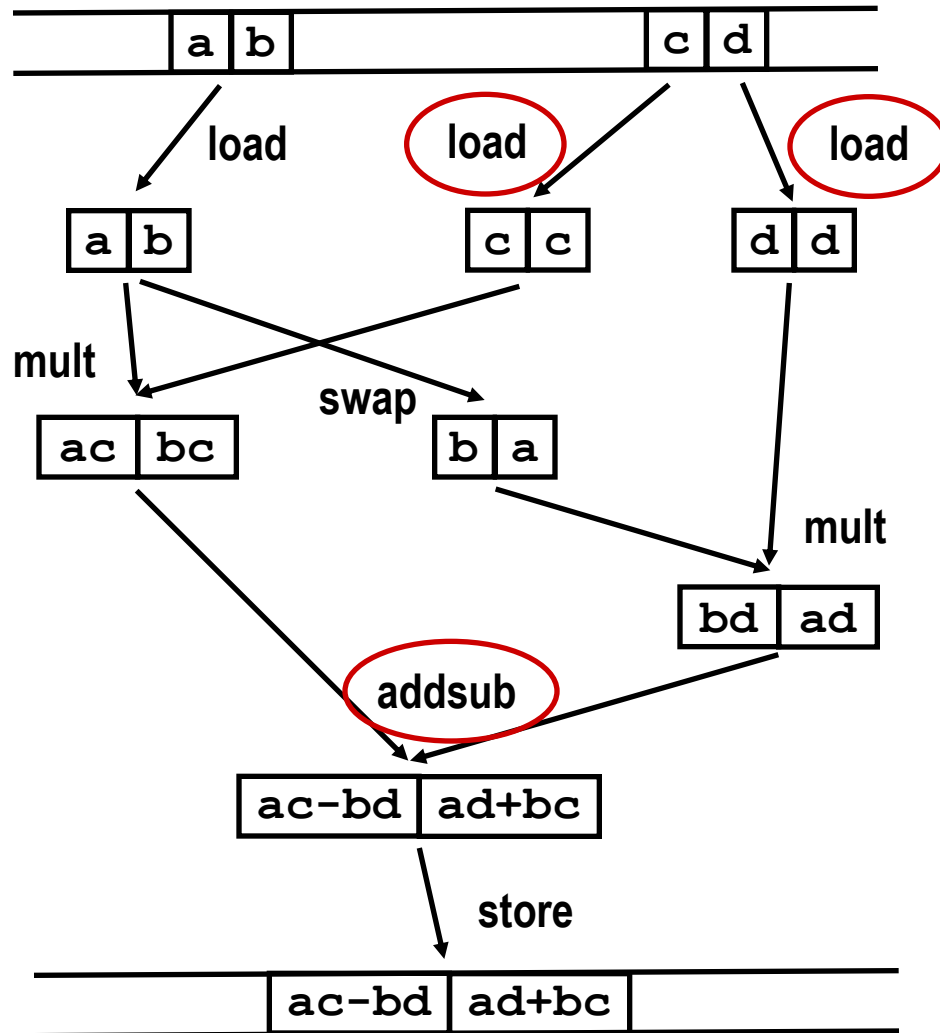
row0	X ₀	X ₁	X ₂	X ₃
row1	Y ₀	Y ₁	Y ₂	Y ₃
row2	Z ₀	Z ₁	Z ₂	Z ₃
row3	W ₀	W ₁	W ₂	W ₃

least significant element				most significant element
---------------------------	--	--	--	--------------------------

OQ48831

Example: Complex Multiplication SSE3

$$(a + ib)(c + id) = (ac - bd) + i(ad + bc)$$



Memory

Result:
4 load/stores
3 arithm. ops.
1 reorder op

**Not available
in SSE2**

Memory

Looking at the Assembly

SSE3:

```
movapd    xmm0, XMMWORD PTR A
movddup   xmm2, QWORD PTR B
mulpd     xmm2, xmm0
movddup   xmm1, QWORD PTR B+8
shufpd    xmm0, xmm0, 1
mulpd     xmm1, xmm0
addsubpd  xmm2, xmm1
movapd    XMMWORD PTR C, xmm2
```

SSE2:

```
movsd     xmm3, QWORD PTR A
movapd    xmm4, xmm3
movsd     xmm5, QWORD PTR A+8
movapd    xmm0, xmm5
movsd     xmm1, QWORD PTR B
mulsd     xmm4, xmm1
mulsd     xmm5, xmm1
movsd     xmm2, QWORD PTR B+8
mulsd     xmm0, xmm2
mulsd     xmm3, xmm2
subsd     xmm4, xmm0
movsd     QWORD PTR C, xmm4
addsd     xmm5, xmm3
movsd     QWORD PTR C, xmm5
```

In SSE2 Intel C++ generates
scalar code (better?)

Organization

■ Overview

- Idea, benefits, reasons, restrictions
- History and state-of-the-art floating-point SIMD extensions
- How to use it: compiler vectorization, class library, intrinsics, inline assembly

■ Writing code for Intel's SSE

- Compiler vectorization
- Intrinsics: instructions
- Intrinsics: common building blocks

■ Selected topics

- SSE integer instructions
- Other SIMD extensions: AltiVec/VMX, Cell SPU

■ Conclusion: How to write good vector code

Intel SSE: Integer Modes

Register Insertion/Extraction Intrinsics for Streaming SIMD Extensions 4

These intrinsics enable data insertion and extraction between general purpose registers and XMM registers.

Intrinsic Name	Operation	Corresponding SSE4 Instruction
<code>_mm_insert_ps</code>	Insert single precision float into packed single precision array element selected by index	INSERTPS
<code>_mm_extract_ps</code>	Extract single precision float from packed single precision array element selected by index	EXTRACTPS
<code>_mm_extract_epi8</code>	Extract integer byte from packed integer array element selected by index	PEXTRB
<code>_mm_extract_epi32</code>	Extract integer double word from packed integer array element selected by index	PEXTRD
<code>_mm_extract_epi64</code>	Extract integer quad word from packed integer array element selected by index	PEXTRQ
<code>_mm_extract_epi16</code>	Extract integer word from packed integer array element selected by index	PEXTRW
<code>_mm_insert_epi8</code>	Insert integer byte into packed integer array element selected by index	PINSRB
<code>_mm_insert_epi32</code>	Insert integer double word into packed integer array element selected by index	PINSRD
<code>_mm_insert_epi64</code>	Insert integer quad word into packed integer array element selected by index	PINSRQ

SSE Integer Modes (1)

■ SSE generations

- Introduced with SSE2
- Functionality extended drastically with SSSE3 and SSE4

■ Modes

- 1x128 bit, 2x64 bit, 4x32 bit 8x 16 bit, 16x8 bit
- Signed and unsigned
- Saturating and non-saturating

■ Operations

- Arithmetic, logic, and shift, mullo/hi
- Compare, test; min, max, and average
- Conversion from/to floating-point, across precisions
- Load/store/set
- Shuffle, insert, extract, blend

SSE Integer Modes (2)

■ Interoperability

- Integer operations can be used with floating-point data
- Typecast support

■ Problems

- Only subset of operations available in each mode
- Sometimes need to “build” operation yourself
- Gathers and scatters even more expensive (8- and 16-way)

```
// right-shift for signed __int8 16-way
__forceinline __m128i _mm_srli_epi8(__m128i x, int sh) {
    __m128i signs = _mm_and_si128(x, _mm_set1_epi32(0x80808080));
    __m128i z = _mm_srli_epi16(x, 1);
    z = _mm_and_si128(z, _mm_set1_epi32(0x7f7f7f7f));
    return _mm_or_si128(z, signs);
}
```

Extending Floating-Point Functionality

■ Sign change

- No sign-change instruction for vector elements exist
- Integer exclusive-or helps

```
// sign-change of second vector element
__forceinline __m128 mm_chsgn2_ps(__m128 f) {
    return _castsi128_ps(_mm_xor_si128(
        _mm_castps_si128(f),
        _mm_castps_si128(_mm_set_ps(0.0,0.0,-0.0,0.0))));
}
```

■ Align instruction

- `alignr` only exists for signed 8-bit integer

```
// alignr 4-way float variant
__forceinline __m128 mm_alignr_ps(__m128 f1, __m128 f2, int sh) {
    return _castsi128_ps(_mm_alignr_epi8(
        _mm_castps_si128(f1), _mm_castps_si128(f2), sh));
}
```

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Altivec, VMX, Cell BE PPU and SPU,...

■ Altivec: 4-way float, 4-, 8-, and 16-way integer

- Introduced with Motorola MPC 7400 G4 (direct competitor to Intel SSE and Pentium III)
- Gave big boost to Apple multi media applications
- Still available in Freescale PowerPC processors
- Supported by GNU C builtin functions (2.95, 3.X)

■ Altivec became IBM VMX

- PowerPC 970 G5 (G4 successor) and POWER6
- Cell BE PPU (PowerPC)
- VMX128 version for Xbox 360 (Xenon processor)

■ Cell SPU: closely aligned with VMX

- Double-precision instructions (very slow at this point)

Altivec vs. SSE

- **Altivec: PowerPC is 3-operand RISC**
 - Fused multiply-add
 - Powerful general shuffle instruction
 - More registers (32 – 128)
- **Problem: non-vector memory access**
 - Unaligned load/store
 - Subvector load/store
- **Altivec/VMX is not changing as quickly as SSE**
 - Variants: Altivec/VMX, VMX128, SPU
 - Altivec important in embedded computing
 - SSE is closer to the consumer market, permanently updated

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How to Write Good Vector Code?

- **Take the “right” algorithm and the “right” data structures**
 - Fine grain parallelism
 - Correct alignment in memory
 - Contiguous arrays
- **Use a good compiler (e. g., vendor compiler)**
- **First: Try compiler vectorization**
 - Right options, pragmas and dynamic memory functions
(Inform compiler about data alignment, loop independence,...)
 - Check generated assembly code *and* runtime
- **If necessary: Write vector code yourself**
 - Most expensive subroutine first
 - Use intrinsics, no (inline) assembly
 - Important: Understand the ISA

Remaining time: Discussion