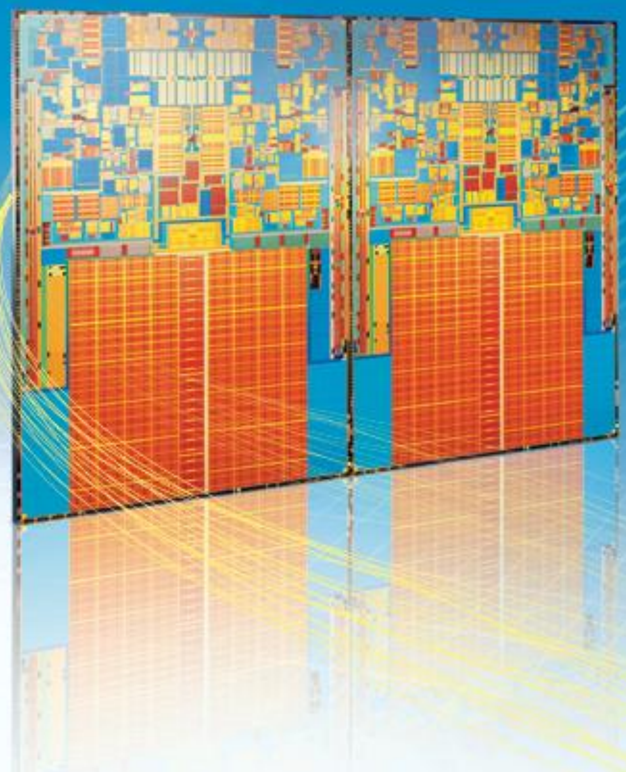
Vector Programming
A proposal for WG21

(presented to CPLEX within WG14)



N3734

2013-09-02

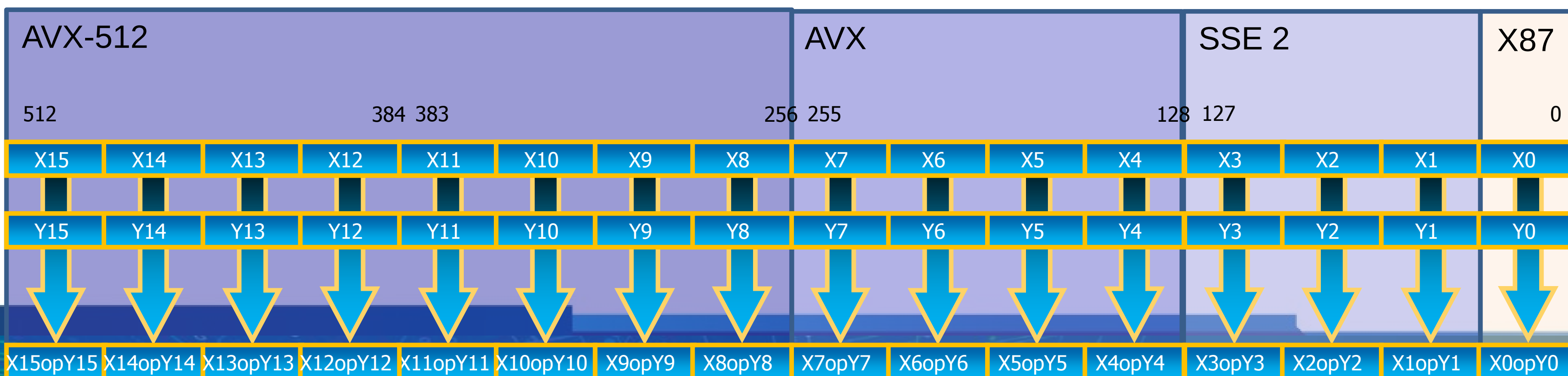
Robert Geva

Context

- Posing a presentation rather than a document
  - Multiple documents with the syntax and semantics shows in SG1 to date
- In Bristol, semantics were presented w/o a way for the programmer to actualize them
- This is the next step, presenting syntax
- The presentation covers vector loops, elemental functions and array notation.
  - Array notations may not be presented in the Chicago meeting.
- A comment on the dual syntax:
  - The syntax that is actually implemented and shipping is the #pragma based syntax.
  - The syntax being proposed is the keyword based syntax
  - The expectation is that capabilities, semantics and performance are the same
  - Some examples and illustrations here use #pragma, some use keywords.

SIMD / Vector Hardware Resources

- XMM (128 bit)
  - 16x chars
  - 8X shorts
  - 4x dwords / floats
  - 2X qwords / doubles / float complex
  - Double complex
- YMM (256 bit)
  - 32X chars
  - 16X short
  - 8X dowrd / float
  - 4X qword / double
  - 2X double complex
- AVX- 512
  - 16x chars/shorts (converted to int)
  - 16x dwords/floats
  - 8x qwords/doubles/float complex
  - 4x double complex



3

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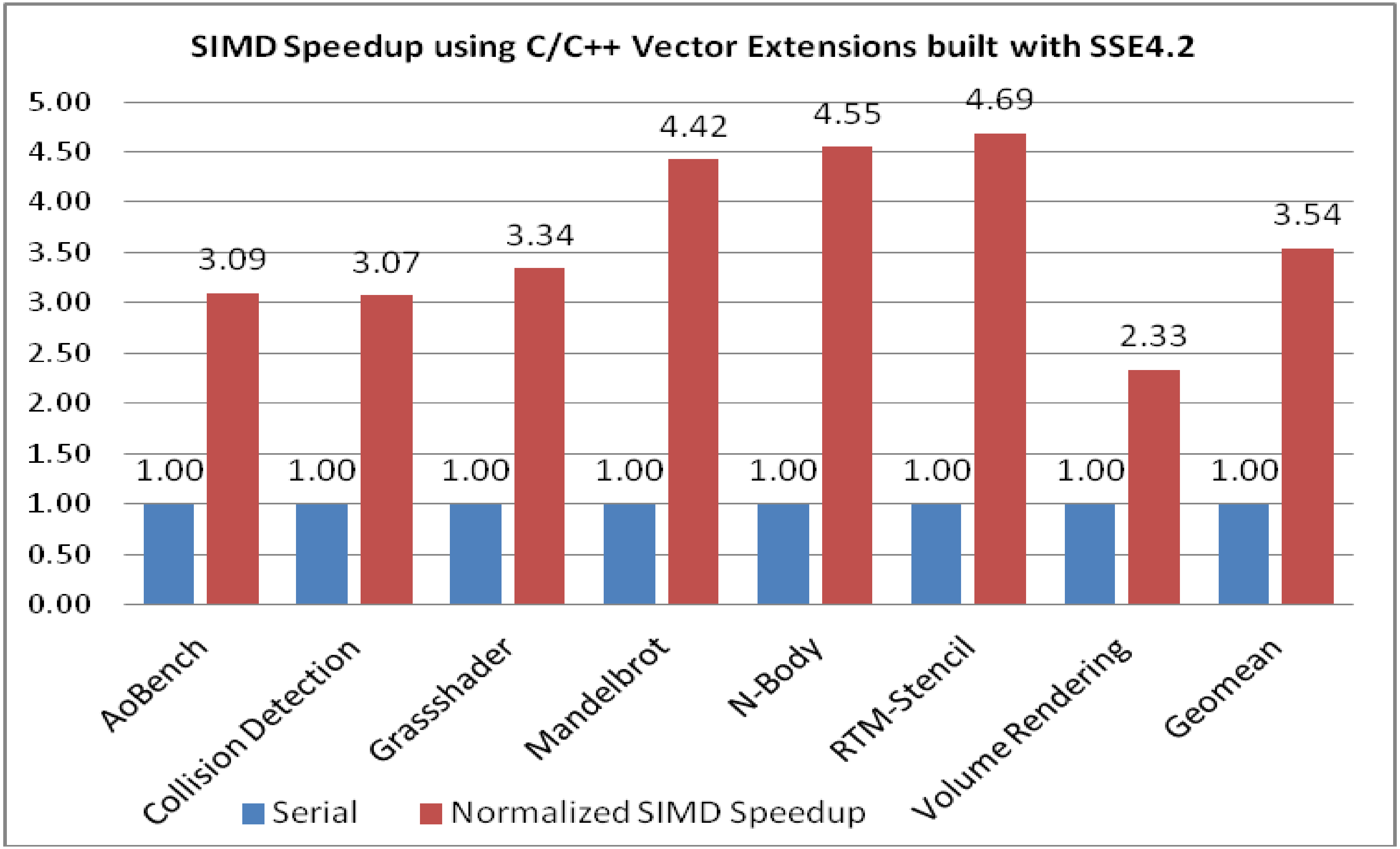
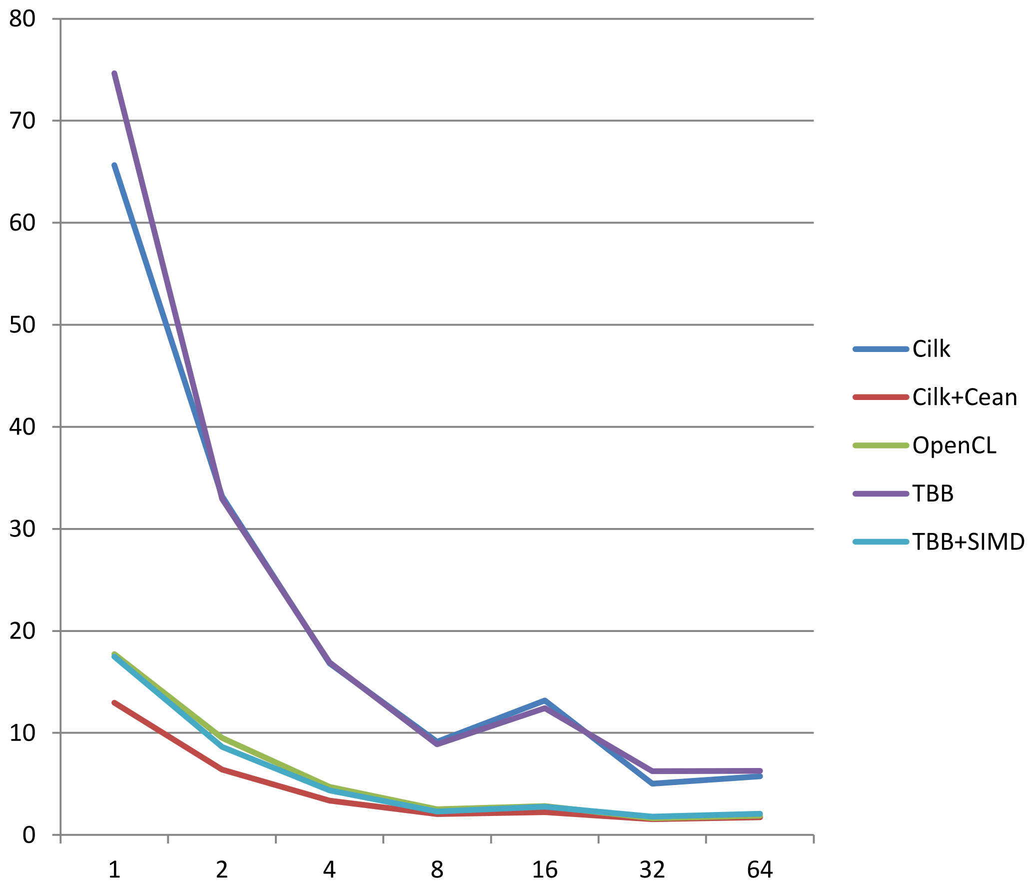
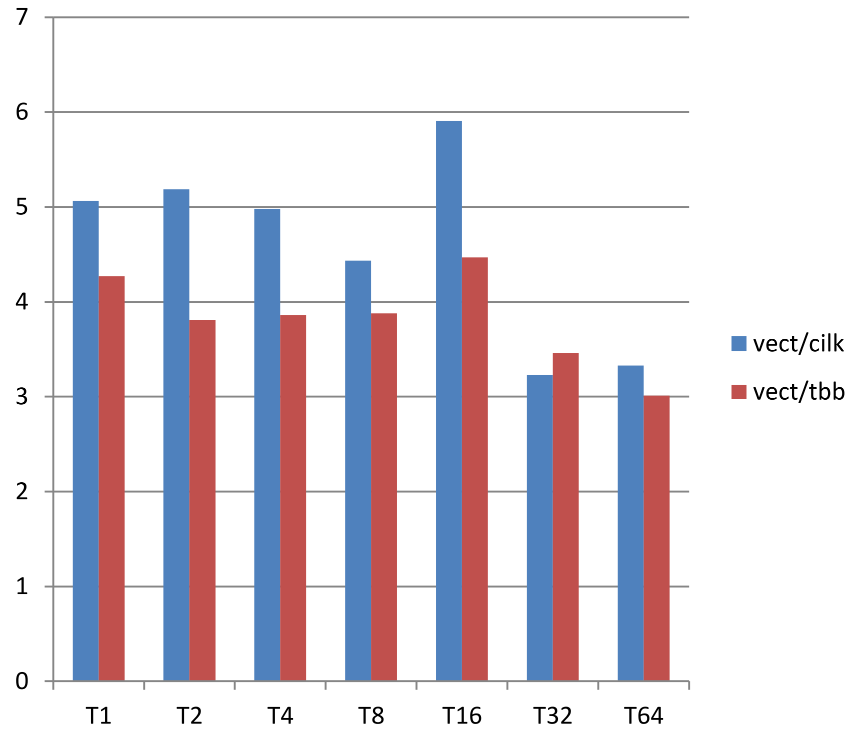
Performance with Vector Parallelism



Measurements by Xinmin Tian for paper in IPDPS, PLC'12

Vectorization performance with 64 threads (a stencil benchmark)





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Write Vector Code Only Once and Just Recompile for multiple Targets

```
#define ABS(X) \
   ((X) >= 0? (X) : -(X))
int A[1000]; double B[1000];
void foo(int n){
  int i;
  for (i=0; i<n; i++){
    B[i] += ABS(A[i]);
  }
}
```

-O2

```
movq      xmm1, [A+r9+rax*4]
pxor      xmm0, xmm0
pcmpgtd   xmm0, xmm1
pxor      xmm1, xmm0
psubd     xmm1, xmm0
cvtdq2pd  xmm2, xmm1
addpd     xmm2, [B+r9+rax*8]
movaps    [B+r9+rax*8], xmm2
add       rax, 2
cmp       rax, rcx
jb        .B1.4
```

ABS sequence

2 elements

-O2 -QxAVX

```
vpabsd    xmm0, [A+r9+rax*4]
vcvtdq2pd ymm1, xmm0
vaddpd    ymm2, ymm1, [B+r9+rax*8]
vmovupd   [B+r9+rax*8], ymm2
add       rax, 4
cmp       rax, rcx
jb        .B1.4
```

4 elements

-QxSSSE3

```
movq      xmm0, [A+r9+rax*4]
pabsd     xmm1, xmm0
cvtdq2pd  xmm2, xmm1
addpd     xmm2, [B+r9+rax*8]
movaps    [B+r9+rax*8], xmm
add       rax, 2
cmp       rax, rcx
jb        .B1.4
```

ABS instruction

2 elements

Vector Programming

Vector Loops

- Loop iterations execute in "vector order" and use vector instructions

Elemental functions

- Compiled as if part of a vector loop

Array Notations

- Element-wise operations on arrays with vector order semantics

Language extensions to express vector parallelism

Programming vs. Hinting

- Vector programming is a part of parallel programming
- Language syntax provided for “go ahead and generate vector code” model
  - If the results $\neq$ scalar code then it may be a programmers bug, rather than a compiler bug
- Additional constructs include private, reduction, linear, etc

	directive	hint
vector	SIMD	IVDEP
thread	OpenMP	PARALLEL

Not all pragmas are hints

Capabilities in vector loops

Capability	Syntax	Meaning
Vector loop	simd_for (; ;)	Vector order of evaluation
Limit the chunk size	simd_for_chunk(N) (; ;)	Limit the number of iterations that can be grouped together and execute in a chunk
A uniform variable		A single object common for all iterations in a chunk. If iters assign diff values the behavior is undefined
A private variable		Each iteration has a separate object
induction	simd_for (; ; x+=s, p+=4)	A single object across all iteration, and they are allowed to all increment (exception to uniform).
Reduction	TBD, consistent with proposal for reduction in tasking	A single object for all vector lanes, allowed to be modified differently by different iterations, value undefined during the loop, available after the loop.
Turn vector ordering off	simd_off { }	Turn off the relaxed order of evaluaiton within the scope and re-impose C11 order of evaluation.
Elemental Functions	T f (args) simd (qualified args)	Consecutive iterations of the function are chunked and execute together, as if they were in the body of a vector loop

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Capabilities in Elemental Functions

Capability	Syntax	Meaning
Elemental function	T f (args) simd(args, chunk(N)) { body }	N Consecutive invocations of f are chunked and execute in vector order
A varying parameter	default	Values of the arg within the chunk are unrelated to each other
A uniform parameter	uniform arg	All N values of the arg are the same
A Linear parameter	linear arg:s	N values of args are linear increments by S
Chunk size	chunk(N)	Determines the numbers of consecutive invocations to be grouped together
Multiple versions	T f (args) simd(args, chunk(N1)) simd(args, chunk(N2)) { body }	Multiple versions of f are generated, differ by argument qualifiers and /or chunk size

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Vector Loops Semantics

- The loops has to be “countable”
- The loop has *logical iterations* numbered 0, 1, … ,N-1
- Order of evaluation:
  - If X is sequenced before Y in the body of the loop, then for each iteration i, X_i is sequenced before Y_i
  - For every X and Y evaluated as part of the vector loop, if X is sequenced before Y and i<j then X_i is sequenced before Y_j
- If the chunk c≥1 is specified then in addition:
  - For every expression X and every iteration i, X_i is sequenced before X_{i+c}
- Note:
  - The above allows order of evaluation that facilitates generation of vector code,
  - it also allows the regular, “scalar” order
  - i.e. vector order of evaluation is not mandated

Different order of evaluation from sequential and from parallel loops

Illustration: Vector Order of Evaluation

```
simd_for (int n = 0; n < N; ++n) {
    a[n] += b[n];
    c[n] += d[n];
}
```

(Remainder loop is left as an exercise for the reader)

```
for (int n = 0; n < N; n+=2) {
    t1 = a[n]; t2 = a[n+1]; // a[n+1] can be written
                            // before c[n] and d[n] are read
    t5 = b[n]; t6 = b[n+1];
    t1 += t5; t2 += t6;
    a[n] = t1; a[n+1] = t2;
    t3 = c[n]; t4 = c[n+1]; // c[n+1] can only be accessed
                            // after a[n]
    t5 = d[n]; t6 = d[n+1];
    t3 += t5; t4 += t6
    c[n] = t3; d[n] = t4;
}
```

Uniform vs. Private variables

```
float m = 3.6f;
float *p = a;
int s = 4;

simd_for (int i = 0; i < N; ++i, p+=s) {
    float tmp = 0.0;
    tmp = *p * m;
    b[i] += tmp;
}
```

- In this example m is uniform: a single object shared between all iterations within a chunk.
- tmp is private: each iteration has a distinct object.
- Different iterations within a chunk cannot assign different values to a uniform variable.

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Data in Vector Loops

```
float sum = 0.0f;
float *p = a;
int step = 4;
#pragma omp simd

for (int i = 0; i < N; ++i) {
        sum += *p;
        p += step;
}
```

- The two statements with the += operations have different meaning from each other
- The programmer should be able to express those differently
- The compiler has to generate different code
- The variables *i*, *p* and *step* have different “meaning” from each other

Data in Vector Loops

```
float sum = 0.0f;
float *p = a;
int step = 4;
#pragma omp simd reduction(+:sum) \
Linear (p:step)
for (int i = 0; i < N; ++i) {
        sum += *p;
        p += step;
}
```

- The two statements with the += operations have different meaning from each other
- The programmer should be able to express those differently
- The compiler has to generate different code
- The variables *i*, *p* and *step* have different "meaning" from each other

Outer Loop Vectorization

```
simd_for (i=0; i<n; i++) {
    complex<float> c = a[i];
    complex<float> z = c;
    int k = 0;
    while ((k < max_cnt)
          && (abs(z)< limit)) {
          z = z*z + c;
          k++;
    };
    color[i] = k;
}
```

- Each iteration of the(outer) vector loop executes its own version of the (inner) while loop.
- The trip counts of the inner loops are unrelated to each other.
- Each has its own instance of “k”.
- Masking may be required for inactive vector lanes

Outer Loop Vectorization as a motivating example for a uniform qualifier

(*not implemented yet)

```
simd_for (int i=0; i<N; ++i) {
    for (int j = 0; j < M; ++j) {
        a[i][j] = (a[i][j-1] + a[i][j+1])/2;
    }
    b[i] += a[i][N/2];
}
```

- All iterations of the inner loop are the same
- If each iteration has its own instance of “j” then this is not expressed.
- Allow the programmer to express that the inner loop have the same trip count by allowing the declaration of “j” as <u>uniform</u>

In-order Blocks

```
simd_for (int n = 0; n < N; ++n) {
    a[n] += b[n];
    simd_off {
        g1+=a[n];
        g2+=b[n];
    }
}
```

Turn off the vector order of evaluation within the scope of the {}
Enforce scalar order of evaluation
Useful when a portion of the loop is semantically non vectorizeable
For example append noted to a linked list

In-order blocks of code are useful for non-vectorizeable code within loops, where the rest of the loop vectorizeable.

Elemental Functions

- Write a function to describe an operation for one element
- Add __declspec(vector) to get vector code for it

- Then deploy the function across a collection of elements, e.g. arrays
- Each invocation will produce a vector of results instead of a single result

```
float foo(float a, float b, float c, float d) simd()
{
    return a * b + c * d;
}
------------------------------
     vmulps ymm0, ymm0, ymm1
     vmulps ymm2, ymm2, ymm3
     vaddps ymm0, ymm0, ymm2 // vector of results
     ret
```


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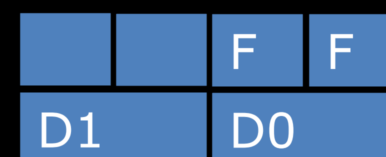
Chunk Size

- How many vectorized copies of the function should execute together per function call?
- As many as you can fit into the hardware vector register
- Constraints: this ratio must be determined consistently yet independently for the function declaration and its callers → cannot rely on the code inside the function, only return type and parameters
- The cases of v_add_f and v_add_d are handled as expected
- In “oops”, most of the time is being spent in single precision, but the compiler cannot automatically use it as the “characteristic type” of the function
- The clause chunk is provided for override
- Another motivation is for correctness
- The use of the chunk clauses changes the linkage of the function

```
float v_add_f(float b, float c) simd()
{
   return b+c;
}
```


```
double v_add_d(double b, double c) simd()
{
         return b+c;
}
```


```
double oops(double e, double f) simd()
{
         return
         sinf(float(e)*sinf(float(f))
}
```



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Uniform/Linear clauses

- One motivating use case is in address computation
- Can make the difference between vector ld / st (efficient) vs. gather / scatter (less efficient) or multiple scalar loads and merge

```
__declspec(vector)
void foo(float *a, int i);
```

a is a vector of pointers

i is a vector of integers

a[i] becomes gather/scatter

The slow version may defeat the purpose of vector programming altogether

```
__declspec(vector( uniform (a)))
void foo(float *a, int i);
```

a is a pointer

i is a vector of integers

a[i] becomes gather/scatter

```
__declspec(vector( linear(i)))
void foo(float *a, int i);
```

a is a vector of pointers

i is a sequence of integers [i, i+1, i+2…]

a[i] becomes gather/scatter

```
__declspec(vector(uniform(a),linear(i)))
void foo(float *a, int i);
```

a is a pointer

i is a sequence of integers [i, i+1, i+2…]

a[i] is a unit-stride load/store ([v]movups)

BEST PERFORMING OPTION

Multiple versions: Illustration

```
void
vec_add ( float *r, float *op1, float *op2, int i)
    simd (chunk(N))
    simd (uniform (r,op1, op2) , linear (i), chunk(N))
{
    r[i] = op1[i] + op2[i];
}
```

Two vector versions and one scalar

```
simd_for (int i = 0; i<N; ++i) {
    vec_add(a,b,c,i);
}
```

Call matches the version with the uniforms

```
simd_for (int i = 0; i<N; ++i) {
    vec_add(a[x1[[i]],b[x2[[i]],c[x3[[i]],i);
}
```

Call matches the version w/o the uniforms

Invoking Elemental Functions

Construct	Example	Semantics

Sequential for loop	`for (j = 0; j < N; j++) {`
	`    a[j] = my_ef(b[j]);`
	`}`
		Single thread,
		auto vectorization

Vector loop	`simd_for (j = 0; j < N; j++) {`
	`    a[j] = my_ef(b[j]);`
	`}`
		Single thread,
		vectorized, use the vector version if matched

parallel loop	`cilk_for (j = 0; j < N; j++) {`
	`    a[j] = my_ef(b[j]);`
	`}`
		Both vectorization and concurrent execution

Array notation	`a[:] = my_ef(b[:]);`	Vectorization

The rest may not be covered in the Chicago meeting, depending on time.

Array notations for C/C++

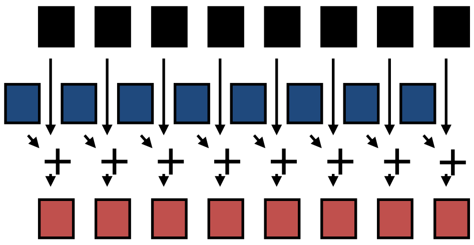
data parallel operations on array sections → vectorization is always semantically correct

```
<array base> [<lower bound>:<length>[:<stride>]]+
```

```
A[:]       // All of vector A
B[2:6]     // Elements 2 to 7 of vector B
C[:][5]    // Column 5 of matrix C
D[0:3:2]   // Elements 0,2,4 of vector D
```

```
A[:]  = B[:] + C[:]
```

All language standard arithmetic and logical operations.



C /C++ syntax with guaranteed vector implementation

Array Section

```
float a[10];
..
  = a[:];
..
```

a:

0	1	2	3	4	5	6	7	8	9

Array Section

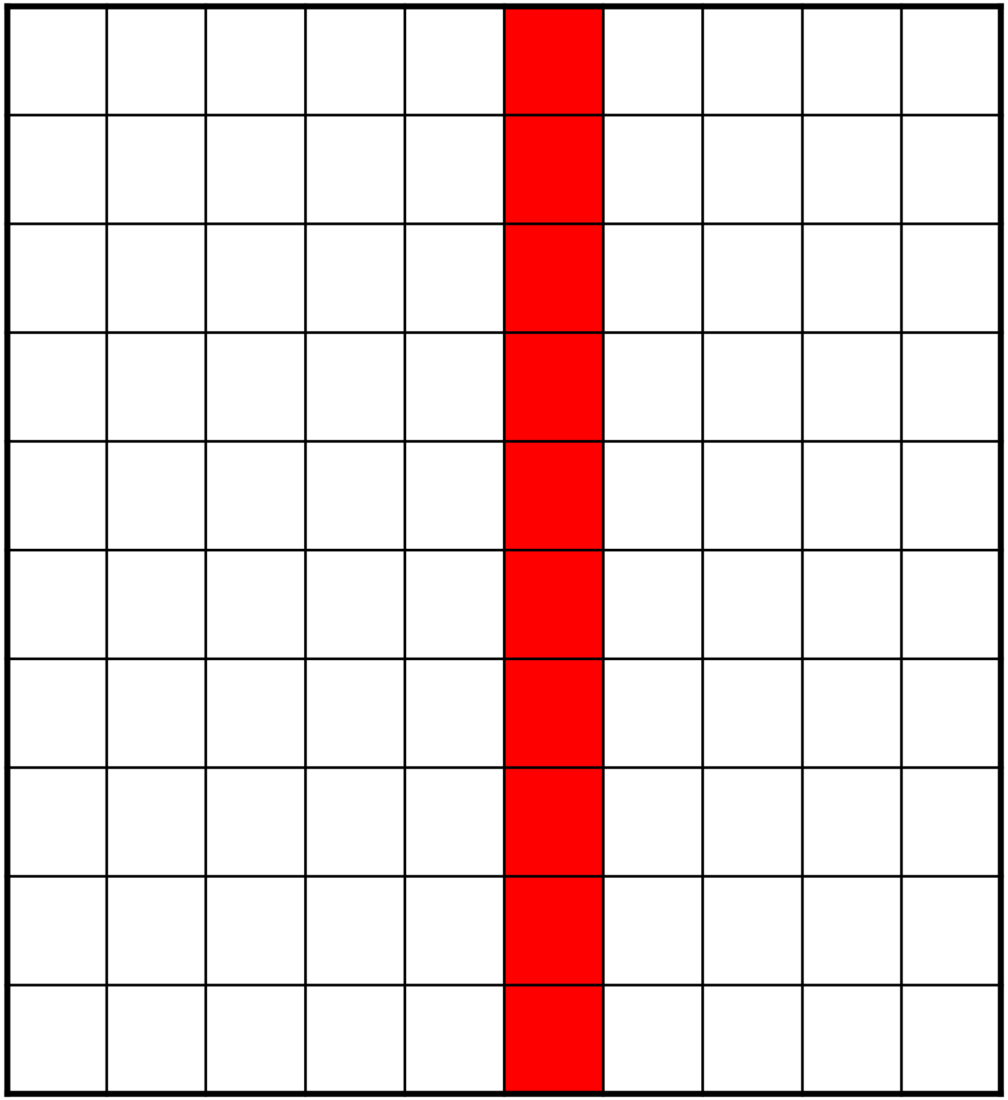
```
float b[10];
..
  = b[2:6];
..
```

b:

Array Section

```
float c[10][10];
..
  = c[:][5];
..
```

c:



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Array Section

```
float d[10];
..
  = d[0:3:2];
..
```

d:	0	1	2	3	4	5	6	7	8	9

Operator Maps

- Most arithmetic and logic operators for C/C++ basic data types are available for array sections:

```
+, -, *, /, %, <,==,!=,>,|,&,^,&&,||,!,-(unary),
+(unary),++,--, +=, -=, *=, /=, *(p)
```

- An operator is implicitly mapped to all the elements of the array section operands:

```
a[0:s]+b[2:s] => {a[i]+b[i+2], forall
(i=0;i<s;i++)}
```

  - Operations are parallel among all the elements
  - Array operands must have the same *rank* and *extent*
  - Scalar operand is automatically expanded to fill the whole section

```
a[0:s]*c => {a[i]*c, forall (i=0;i<s;i++)}
```


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Assignment

- Assignment maps to all elements of the LHS array section in parallel:

```
a[:][:] = b[:][2][:] + c;
e[:] = d;
e[:] = b[:][1][:];        // error
a[:][:] = e[:];    // error
```

- LHS of an assignment defines an array context where RHS is evaluated.
  - The rank of the RHS array section must be the same as the LHS
  - The length of each rank must match the corresponding LHS rank
  - Scalar is expanded automatically
- In case of partial overlap between RHS and LHS, results are undefined.
  - Save the temp arrays, deliver higher performance

```
a[1:s] = a[0:s] + 1  // Undefined behavior
```


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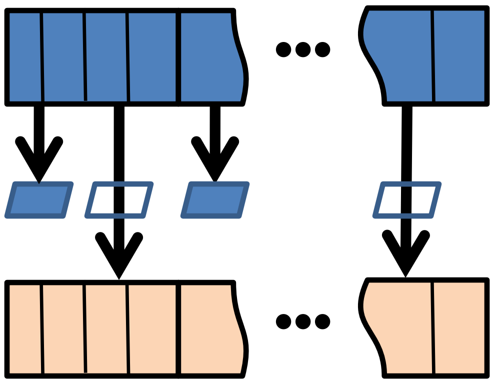
Conditional Statements

"If statement" creates a masked vector operation

```
if (a[:] > 0) {
  b[:] = 1;
} else {
  b[:] *= d[:];
}
```

Statements from both "then" and "else" may execute



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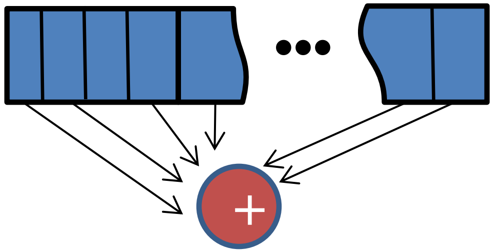
Reductions

- Reduction combines array section elements to generate a scalar result

```
int a[] = {1,2,3,4};
sum = __sec_reduce_add(a[:]); // sum
                              // is 10
```



- Nine built-in reduction functions supporting basic C data-types:
  - add, mul, max, max_ind, min, min_ind, all_zero, all_non_zero, any_nonzero

- Supports user-defined reduction function

```
type fn(type in1, type in2); // scalar reduction function
out = __sec_reduce(fn, identity_value, in[x:y:z]);
```

  - Built-in reductions provide best performance

Gather/Scatter

- Take non-consecutive array elements and “gather” them into consecutive locations, or vice-versa.
- The indices of interest are in an *index array*

Gather

```
c[:] = a[b[:]];      // gather elements of a into c,
                     // according to index array b
```

Scatter

```
a[b[:]] = c[:];      // scatter elements of c into a,
                     // according to index array b
```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Shift/Rotate

```
b[:] = __sec_shift_right(a[:],  shift_val, fill_val)
b[:] = __sec_shift_left(a[:],   shift_val, fill_val)
b[:] = __sec_rotate_right(a[:], rotate_val)
b[:] = __sec_rotate_left(a[:],  rotate_val)
```

- Shift elements in a[:] to the right/left by *shift_val*
- The leftmost/rightmost element will get *fill_val* assigned
- Rotate will circular-shift elements in a[:] to the right/left by *rotate_val*
- Result is assigned to b[:]
- Argument a[:] is not modified

Shuffle

```
b[:] = __sec_shuffle(a[:], perm)
```

- Permute elements in the array section a[:] and copy the result into b[:].
- The parameter perm is a const array of integer values, which contains the permutation indices to apply to the source.

```
const int perm[] = {3, 2, 1, 0};
…
for (i = 0; i < MAX-4; i+=4) {
   b[i:4] = __sec_shuffle(a[i:4], perm)
}
Resulting in:
…
b[i+0] = a[i + 3];
b[i+1] = a[i + 2];
b[i+2] = a[i + 1];
b[i+3] = a[i + 0];
```

Rank and Shape

- An array section doesn't have a new kind of type
  - the type of an array section is exactly that of the analogous subscript expression.
  - Additionally, an array section has rank and shape.
- A section implicitly iterates over some elements of an array.
  - Rank is the number of levels of loop nesting (i.e. dimensions) in the iteration space.
  - Shape is a (mathematical) vector of lengths. (The rank is the same as the length of the shape vector.)

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Rank and Shape (continued)

- The rank of an expression is determined statically. In general the shape of a section is determined dynamically.

Expression	Rank	Shape
`a[0]`	0	
`a[0:n]`	1	n
`a[0][i:10]`	1	10
`a[i:n][j:m]`	2	n×m

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Shapes have to match

- If array size is not known, both lower-bound and length must be specified
- Section ranks and lengths ("shapes") must match.
  - Scalars are OK.

```
a[0:5] = b[0:6]; // No. Size mismatch.
a[0:5][0:4] = b[0:5]; // No. Rank mismatch.
a[0:5] = b[0:5][0:5]; // No. No 2D->1D
a[0:4] = 5; // OK. 4 elements of A filled w/ 5.
a[0:4] = b[i]; // OK. Fill with scalar b[i].
a[10][0:4] = b[1:4]; // OK. Both are 1D sections.
b[i] = a[0:4]; // No. 1D → 0 D
```


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Array Notation Example

Serial Example

```
float dot_product(unsigned int sz,float A[], float B[])
{
    float dp=0.0f;
    for (int i=0; i<size; i++)
         dp += A[i] * B[i];
    return dp;
}
```

Array Notation Version

```
float dot_product(unsigned int sz,float A[], float B[])
{
    return __sec_reduce_add(A[0:sz] * B[0:sz]);
}
```

Intrinsic reduction

Array Section

Element-wise multiplication

N3734

Vector Programming Summary

- Vector programming is part of parallel programming
- New syntax provided to express vector semantics
- Source code is independent of target architecture
- Currently provided by the Intel compilers, expecting soon in additional compilers
- Standardized as part of OpenMP® 4.0
- Being proposed to the C and C++ committees

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Vector Instructions are Sometimes Smarter (not just wider)

```
#define MAX(x,y) ((x)>(y)?(x):(y))
#define MIN(x,y) ((x)<(y)?(x):(y))
#define SAT2SI16(x) \
  MAX(MIN((x),32767),-32768)
short A[N];

for (i=0; i<n; i++) {
    A[i] = SAT2SI16(A[i]+B[i]);
}
```

Saturating Add

```
movsx     r11d, [rdx+r9*2]
movsx     ebx, [r8+r9*2]
add       r11d, ebx
cmp       r11d, 327
cmovge    r11d, eax
cmp       r11d, -327
cmovl     r11d, ecx
mov       [rdx+r9*2], r11w
inc       r9
cmp       r9, r10
jb        .B1.8
```

11 insts / 1 elem

```
movdqa    xmm0, [rdx+rax*2]
paddsw    xmm0,  [r8+rax*2]
movdqa    [rdx+rax*2], xmm0
add       rax, 8
cmp       rax, r9
jb        .B1.4
```

6 insts / 8 elems

Auto-Vectorization – Limited by Serial Semantics

```
for(i=0;i<*p;i++) {
  a[i] = b[i]*c[i];
  sum = sum + a[i];
}
```

Compiler checks for

- Is "*p" loop invariant?
- Are a, b, and c loop invariant?
- Does a[] overlap with b[], c[], and/or sum?
- Is "+" operator associative? (Does the order of "add"s matter?)
- Vector computation on the target expected to be faster than scalar code?

- Also:
  - How do you vectorize an outer loop
  - How do you allow function calls in vector loop?
  - What if "idiom recognition" fails?

Auto vectorization is limited by the language rules: you can't say what you mean!

Multiple versions

- Multiple declspec(vector) lines are allowed for a single function
- Each will result in another compiled version of the function
- Example: the same function may be called with uniform / non uniform arguments
- Avoiding the second line will deliver correct results but lose performance
- If only the line with uniform is given, then for call sites where the actual arguments are not uniform, the compiler will call the scalar, not vector, version of the function!

```
__declspec(vector)
__declspec(vector(uniform(b,c))
float vmul(float a, float b, float c)
{
   return sqrt(a)*sqrt(b) +
          sqrt(a)*sqrt(c) +
          sqrt(b)*sqrt(c);
}
```