Vectorization

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Exploiting the parallel universe

Instruction Level Parallelism

- Single thread (ST) performance
- Automatically exposed by HW/tools
- Effectively limited to a few instructions

Data Level Parallelism

- Single thread (ST) performance
- Exposed by tools and programming models
- Operate on 4/8/16 elements at a time

Task Level Parallelism

- Multi thread/task (MT) performance
- Exposed by programming models
- Execute tens/hundreds/thousands task concurrently

Process Level Parallelism

- Multi Process (MP) performance
- Exposed by programming models
- Execute tens/hundreds/thousands of process concurrently across several nodes

Agenda

- Vector Processing Units
- Profiling
- Optimizing Memory Access
- Auto Vectorization
- Guided Vectorization
- Examples

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- **Vector Processing Units**
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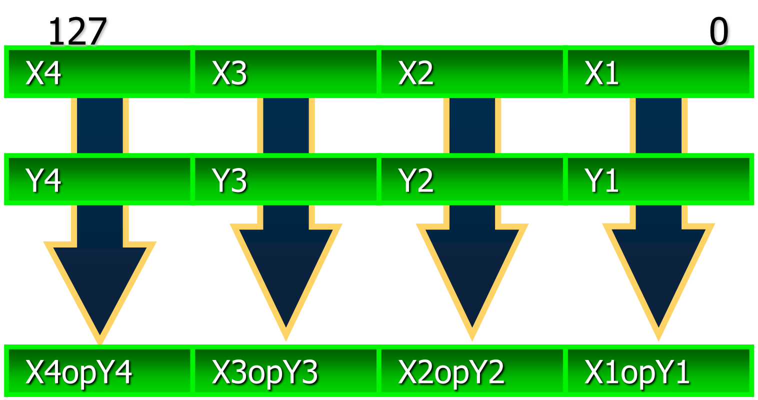
Vectorial processing Intel® Architecture

MMX	Intel® SSE	Intel® AVX / AVX2	Intel® MIC / AVX-512
Vector size: 64bit Data types: 8, 16 and 32 bit integers VL: 2,4,8	Vector size: 128bit Data types: 8,16,32,64 bit integers 32 and 64bit float VL: 2,4,8,16	Vector size: 256bit Data types: 32 and 64 bit floats VL: 4, 8, 16 Sample: Xi, Yi 32 bit int or float	Vector size: 512bit Data types: 32 and 64 bit integers 32 and 64bit float VL: 8,16



Exponential & Reciprocal Instructions (ERI)
Prefetch Instructions (PFI)
Foundation instructions (FI)
Conflict Detection Instructions (CDI)
Byte & Word Instructions (BWI)
Double-/Quad-word Instructions (DQI)
Vector Length Extensions (VLE)

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- Examples

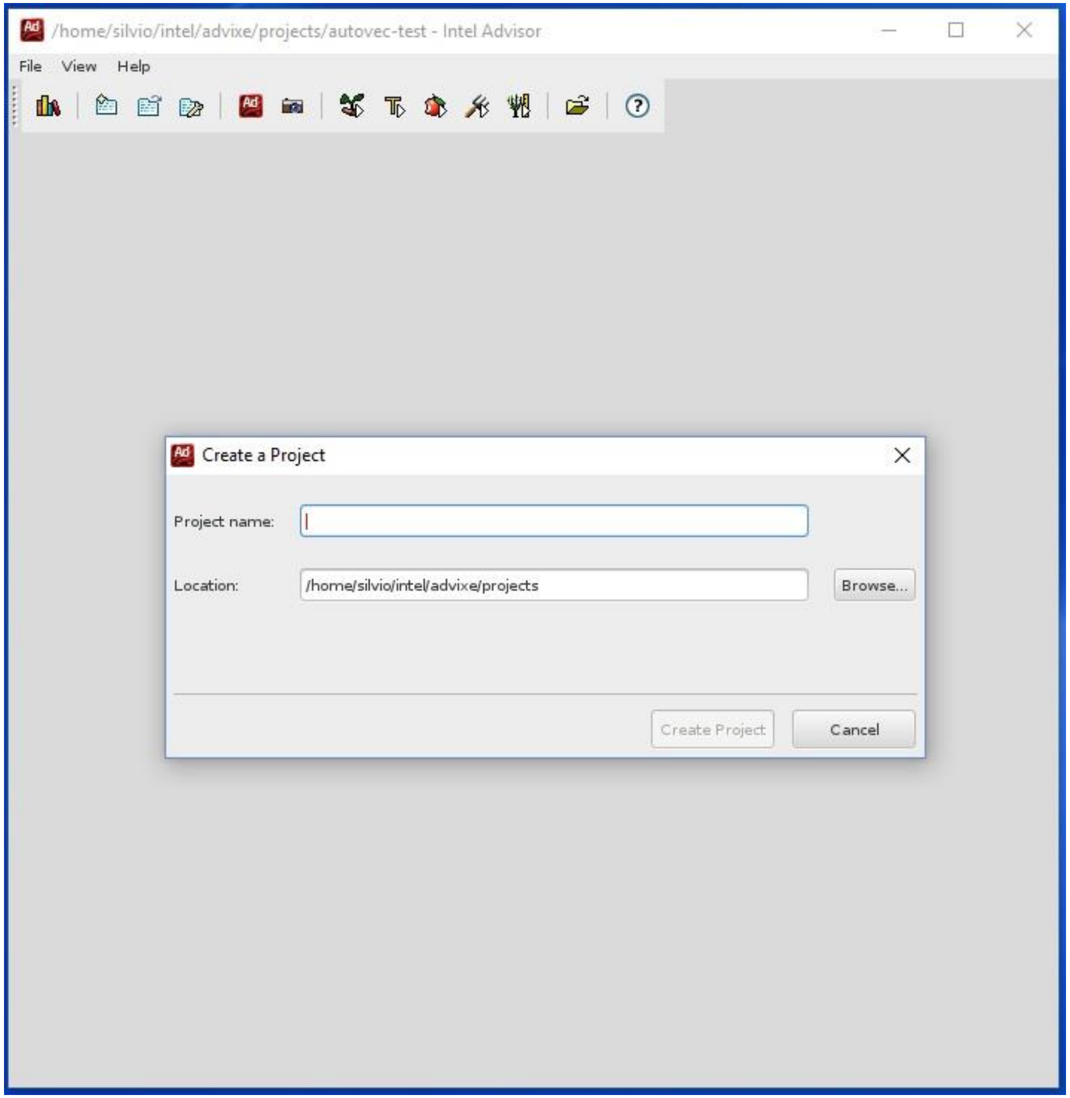
Intel Advisor

- Evaluate multi-threading parallelization
- Intel® Advisor XE
  - ❑ Performance modeling using several frameworks for multi-threading in processors and co-processors:
    - OpenMP, Intel® Cilk ™ Plus, Intel® Threading Bulding Blocks
    - C, C++, Fortran (OpenMP only) and C# (Microsoft TPL)
  - ❑ Identify parallel opportunities
    - Detailed information about vectorization;
    - Check loop dependencies;
  - ❑ Scalability prediction: amount of threads/performance gains
  - ❑ Correctness (deadlocks, race conditions)

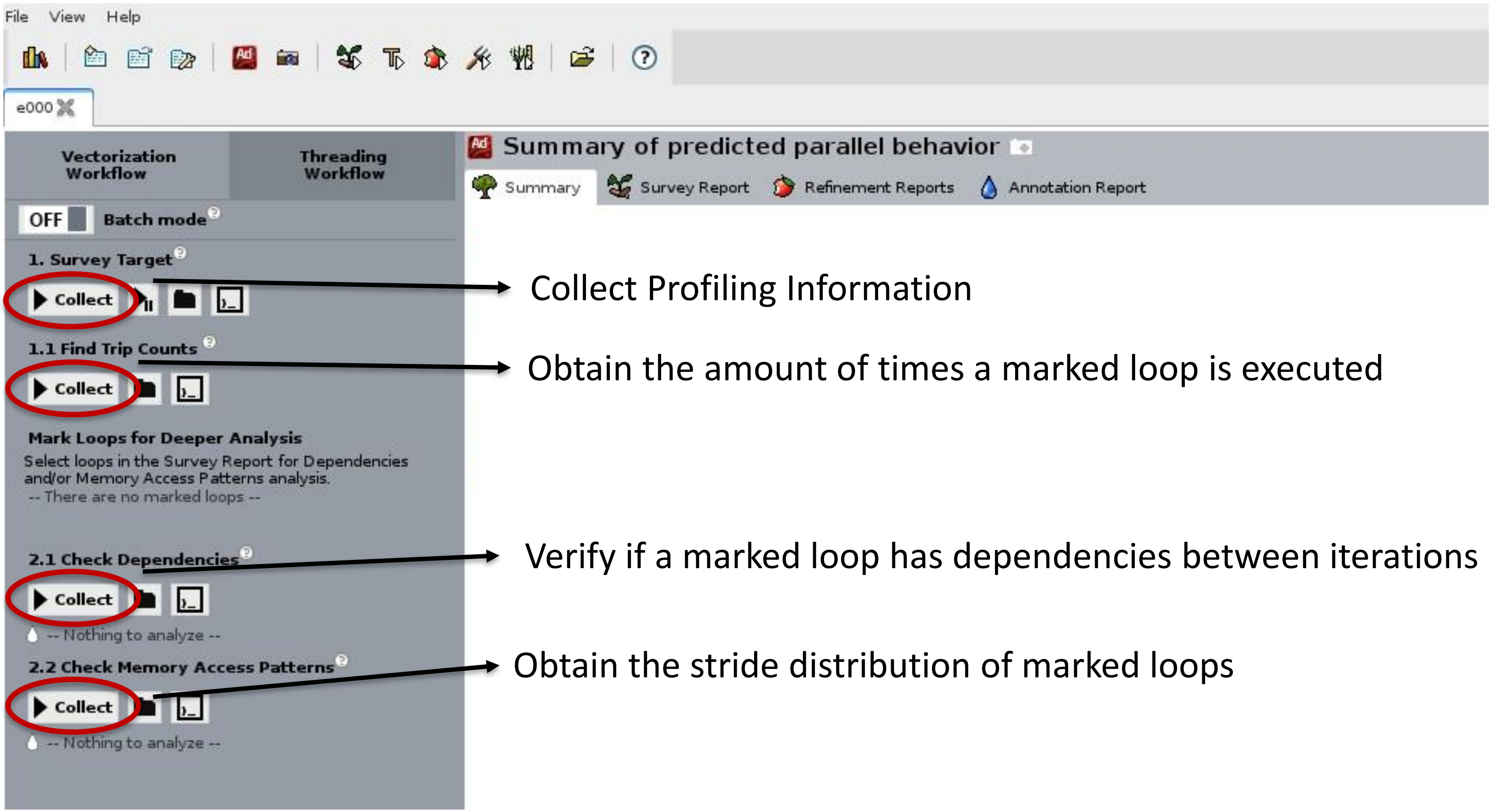
Intel Advisor

- Survey Target;
  - Vectorization of loops: detailed information about vectorization;
  - Total Time: elapsed time on each loop considering the time involved in internal loops;
  - Self Time: elapsed time on each loop not considering the time involved in internal loops;
- Find Trip Counts;
  - Analysis to identify how many time particular loops run;
- Check Dependencies;
  - Analysis it there are many loop-carried dependencies;
- Check Memory Access Patterns.
  - Analysis to identify how your code is iterating with memory.

Advisor – New Project



Advisor - Analysis



Collect Profiling Information

Obtain the amount of times a marked loop is executed

Verify if a marked loop has dependencies between iterations

Obtain the stride distribution of marked loops

Advisor – Survey Target

Summary | Survey Report | Refinement Reports | Annotation Report

Function Call Sites and Loops		Vector Issues	Self Time	Total Time	Type	Vectorized Loops: Vec...	Efficiency	Gai...	VL (Vector Length)	Compiler Estimated Gain	Instruction Set Analysis: Traits
[loop in main at vec.c:50]		2 Inefficient memory access patterns present	0.730s	0.730s	Vectorized (Body)	AVX2		2.20x	16	2.20x	Extracts; Type Conversions
[loop in main at vec.c:63]		2 Data type conversions present	0.680s	0.680s	Vectorized Versions	AVX	~71%	5.71x	2; 8	<5.71x	Extracts; Inserts; Type Conversions
[loop in main at vec.c:55]		1 Data type conversions present	0.490s	0.490s	Vectorized (Body)	AVX2	~72%	5.79x	8	5.79x	Extracts; Inserts; Type Conversions

Source | Top Down | Loop Analytics | Loop Assembly | Recommendations | Compiler Diagnostic Details

File: vec.c:50 main

Line	Source	Total Time	%	Loop Time	%	Tra
36	`randV=0;`					
37						
38	`a = (double*) mm malloc(msize * msize *sizeof(double),64);`					
39	`b = (double*) mm malloc(msize * msize *sizeof(double),64);`					
40	`c = (double*) mm malloc(msize * msize * sizeof(double),64);`					
41						
42	`srand(time(NULL));`					
43	`randV=rand();`					
44	`randV=randV*0.11;`					
45	`printf("randV %f\n", randV);`					
46						
47						
48	`for(j=0; j<10000; j++) {`			1,899.980m		
49						
50	`for(i=0; i<40000; i++) {`			729.970ms		
51	`aosobj[i].x=i + randV;`	229.961ms				Extracts; Type Conversions
52	`aosobj[i].y=i*i+ randV;`	290.000ms				Extracts; Type Conversions
53	`aosobj[i].z=i+i+ randV;`	210.009ms				Extracts; Type Conversions
54	`}`					
55	`for(i=0; i<40000; i++) {`	30.003ms		490.029ms		
56	`soaobj.x[i]=i+i+ randV;`	129.997ms				Extracts; Inserts; Type Conversions
57	`soaobj.y[i]=i-i+ randV;`	40.001ms				Type Conversions
58	`soaobj.z[i]=i*i+ randV;`	290.027ms				Extracts; Inserts; Type Conversions
59	`}`					
60	`randV=rand();`					Type Conversions
61	`randV=randV*0.11;`					
62						
63	`for(i=0; i<40000; i++) {`	9.999ms		679.985ms		
64	`aosobj[i].x= aosobj[i].y+ aosobj[i].z + randV;`	489.987ms				Extracts; Inserts; Type Conversions
65	`}`					
66						
67	`for(i=0; i<40000; i++) {`					
68						
69	`soaobj.x[i]= soaobj.y[i]+ soaobj.z[i] + randV;`	179.999ms				Extracts; Inserts; Type Conversions
70	`}`					
71	`}`					

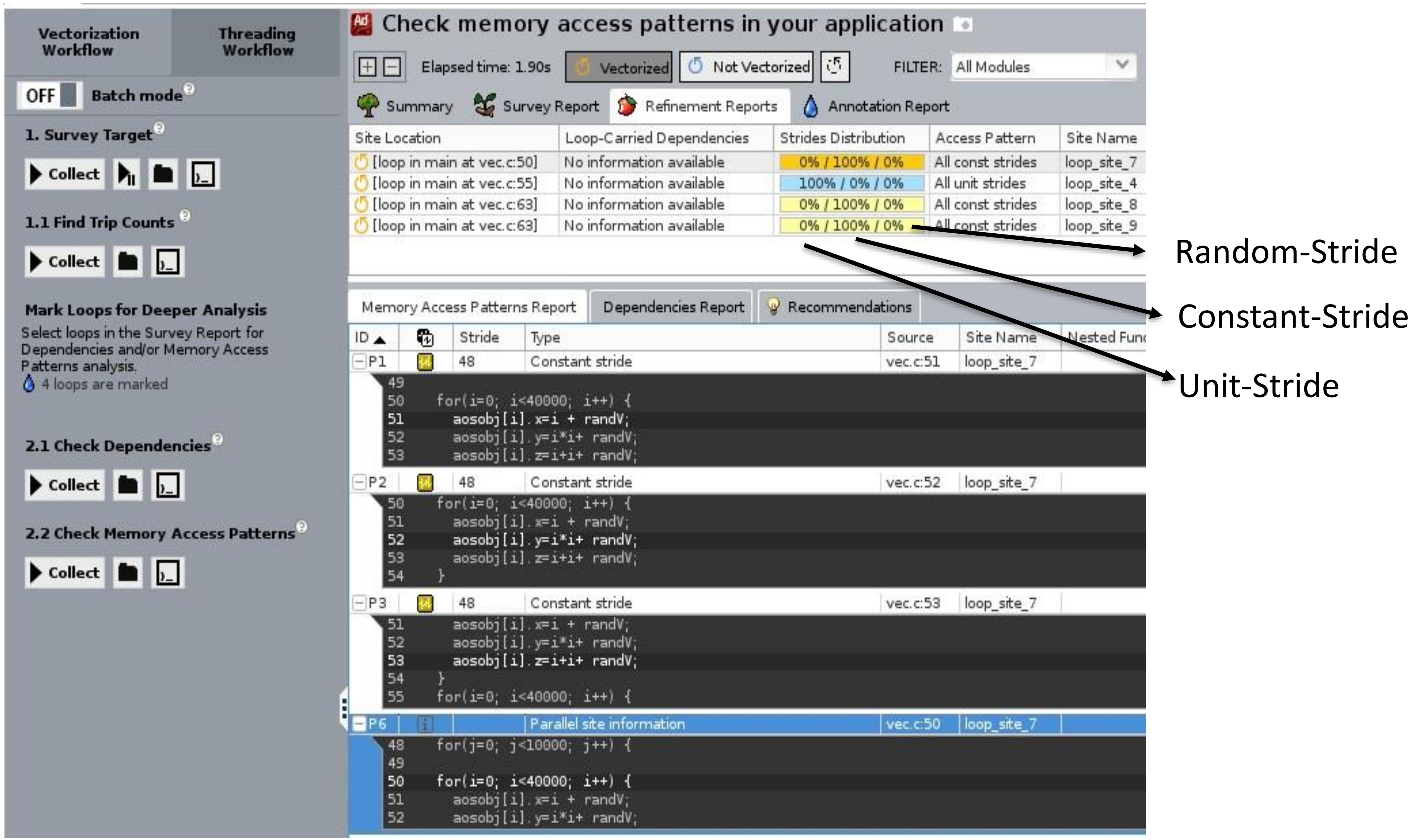
Advisor – Survey Target

Instruction Set Analysis

Traits	Data Types	Number of Vector Registers	Vector Widths	Instruction Sets
Extracts; Type Conversions	Float32; Float64; Int32; UIn...	15	128/256	AVX; AVX2
Extracts; Inserts; Type Conversions	Float32; Float64	14; 15	128; 256	AVX
Extracts; Inserts; Type Conversions	Float32; Float64; Int32; UIn...	16	256	AVX; AVX2

Advanced				
Transformations	Unroll Factor	Vectorization Details	Optimization Details	Location
				vec.c:50
Fused; Unrolled	4		LOOP WAS DISTRIBUTED, CHUNK 1; LOOP WAS DISTRIBUTED, C...	vec.c:63
				vec.c:55

Advisor – Memory Access Patterns



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Stride (array elements)

- Stride:
  - Step size between consecutive access of array elements;

- Strided access with stride k means touching every kth memory element
  - Unit Stride :
    - ❑ Sequential access (0, 1, 2, 3, 4, 5, 6, ...)
  - Non-unit stride
    - ❑ Constant Stride =
      - 2 is (0, 2, 4, 6, 8, ...)
    - ❑ k is (0, k, 2k, 3k, 4k, ...)
    - ❑ Random Access;

- Strides > 1 commonly found in multidimensional data
  - Row accesses (stride=N) & diagonal accesses (stride=N+1)
  - Scientific computing (e.g., matrix multiplication)

- Vectorization more efficient with unit strides
  - Non-unit strides will generate gather/scatter
  - Unit strides also better for data locality

Data layout - Padding

- Data structures may have members with different sizes.
- To maintain proper alignment the translator normally inserts additional unnamed data members so that each member is properly aligned.
- Example:

```
struct stu_a {
   int i;
   char c;
};
```

- Actual size 4+1 (5)

i	i	i	i	c	i	i	i	c	i	i	i	c

8 bytes	8 bytes

- After Padding size 4+4 (5)

i	i	i	i	c	c	c	c	i	i	i	i	c

8 bytes	8 bytes

- …

Data layout - Array of Structures vs Structure of Arrays

- AoS vs SoA (Array of Structures vs Structure of Arrays)

```
// Array of Structures (AoS)
struct coordinate {
    float x, y, z;
} crd[N];
    …
for (int i = 0; i < N; i++)
    … = … f(crd[i].x, crd[i],y,
crd[i].z);
```

Consecutive elements in memory →

x0	y0	z0	x1	y1	z1	…	x(n-1)	y(n-1)	z(n-1)

```
// Structure of Arrays (SoA)
struct coordinate {
    float x[N], y[N], z[N];
} crd;
    …
for (int i = 0; i < N; i++)
    … = … f(crd.x[i], crd.y[i],
crd.z[i]);
```

Consecutive elements in memory →

x0 x1 … x(n-1)	y0 y1 … y(n-1)	z0 z1 … z(n-1)

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Vectorization on Intel® compilers

Easy of use

Auto Vectorization

- Compiler knobs

Guided Vectorization

- Compiler hints/pragmas
- Array notation
- Elemental Functions

Low level Vectorization

- C/C++ vector classes
- Intrinsics/Assembly

Fine control

Auto vectorization

- Relies on the compiler for vectorization
  - No source code changes
  - Enabled with `-vec` compiler knob (default in `-O2` and `-O3` modes)
- Compiler smart enough to apply loop transformations
  - It will allow to vectorize more loops

Option	Description
`-O0`	Disables all optimizations.
`-O1`	Enables optimizations for speed which are know to not cause code size increase.
`-O2/-O` (default)	Enables intra-file interprocedural optimizations for speed, including: • **Vectorization** • **Loop unrolling**
`-O3`	**Performs O2 optimizations and enables more aggressive loop transformations such as:** • **Loop fusion** • **Block unroll-and-jam** • **Collapsing IF statements** This option is recommended for applications that have loops that heavily use floating-point calculations and process large data sets. However, it might incur in slower code, numerical stability issues, and compilation time increase.

Vectorization: target architecture options

Option	Description
`-mmic`	Builds an application that runs natively on Intel® MIC Architecture.
`-xfeature` `-xHost`	Tells the compiler which processor features it may target, referring to which instruction sets and optimizations it may generate (not available for Intel® Xeon Phi™ architecture). Values for *feature* are: • `COMMON-AVX512` (includes AVX512 FI and CDI instructions) • **`MIC-AVX512` (includes AVX512 FI, CDI, PFI, and ERI instructions)** • **`CORE-AVX512` (includes AVX512 FI, CDI, BWI, DQI, and VLE instructions)** • **`CORE-AVX2`** • `CORE-AVX-I` (including RDRND instruction) • `AVX` • `SSE4.2, SSE4.1` • `ATOM_SSE4.2, ATOM_SSSE3` (including MOVBE instruction) • `SSSE3, SSE3, SSE2` **When using `-xHost`, the compiler will generate instructions for the highest instruction set available on the compilation host processor.**
`-axfeature`	Tells the compiler to generate multiple, feature-specific auto-dispatch code paths for Intel® processors if there is a performance benefit. Values for *feature* are the same described for `-xfeature` option. Multiple features/paths possible, e.g.: `-axSSE2,AVX`. It also generates a baseline code path for the default case.

Auto vectorization: not all loops will vectorize

- Data dependencies between iterations
  - Proven Read-after-Write data (i.e., loop carried) dependencies
  - Assumed data dependencies
    - Aggressive optimizations

RaW dependency

```
for (int i = 0; i < N; i++)
    a[i] = a[i-1] + b[i];
```

- Vectorization won't be efficient
  - Compiler estimates how better the vectorized version will be
  - Affected by data alignment, data layout, etc.

Inefficient vectorization

```
for (int i = 0; i < N; i++)
    a[c[i]] = b[d[i]];
```

- Unsupported loop structure
  - While-loop, for-loop with unknown number of iterations
  - Complex loops, unsupported data types, etc.
  - (Some) function calls within loop bodies

Function call within loop body

```
for (int i = 0; i < N; i++)
    a[i] = foo(b[i]);
```

Validating vectorization

- Generate compiler report about optimizations

`-qopt-report[=n]` Generate report (level [1..6], default 2)

```
LOOP BEGIN at gas_dyn2.f90(193,11) inlined into gas_dyn2.f90(4326,31)
   remark #15300: LOOP WAS VECTORIZED
   remark #15448: unmasked aligned unit stride loads: 1
   remark #15450: unmasked unaligned unit stride loads: 1
   remark #15475: --- begin vector loop cost summary ---
   remark #15476: scalar loop cost: 53
   remark #15477: vector loop cost: 14.870
   remark #15478: estimated potential speedup: 2.520
   remark #15479: lightweight vector operations: 19
   remark #15481: heavy-overhead vector operations: 1
   remark #15488: --- end vector loop cost summary ---
   remark #25456: Number of Array Refs Scalar Replaced In Loop: 1
   remark #25015: Estimate of max trip count of loop=4
LOOP END
```

Vectorized loop

```
LOOP BEGIN at gas_dyn2.f90(2346,15)
   remark #15344: loop was not vectorized: vector dependence prevents vectorization
   remark #15346: vector dependence: assumed OUTPUT dependence between IOLD line 376 and IOLD line 354
   remark #25015: Estimate of max trip count of loop=3000001
LOOP END
```

Non-vectorized loop

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Intel® compiler directives for vectorization

Directive	Clause	Description
`ivdep`		Instructs the compiler to ignore assumed vector dependencies.
`vector`	`always`	Force vectorization even when it might be not efficient.
	`[un]aligned`	Use [un]aligned data movement instructions for all array vector references.
	`[non]temporal(`*`var1`*`[,…])`	Do or do not generate non-temporal (streaming) stores for the given array variables. On Intel® MIC architecture, generates a cache-line-evict instruction when the store is known to be aligned.
	`[no]vecreminder`	Do (not) vectorize the remainder loop when the main loop is vectorized.
	`[no]mask_readwrite`	Enables/disables memory speculation causing the generation of [non-]masked loads and stores within conditions.
`simd`	`vectorlength(`*`n1`*`[,…])` `vectorlengthfor(`*`dtype`*`)`	Assume safe vectorization for the given vector length values or data type.

	`private(`*`var1`*`[,…])`
	`firstprivate(`*`var1`*`[,…])`
	`lastprivate(`*`var1`*`[,…])`
		Which variables are private to each iteration; *firstprivate*, initial value is broadcasted to all private instances; *lastprivate*, last value is copied out from the last instance.

	`linear(`*`var1`*`:`*`step1`*`[,…])`	Letting know the compiler that *var1* is incremented by *step1* on every iteration of the original loop.
	`reduction(`*`oper`*`:`*`var1`*`[,…])`	Which variables are reduction variables with a given operator.
	`[no]assert`	Warning or error when vectorization fails.
	`[no]vecremainder`	Do (not) vectorize the remainder loop when the mail loop is vectorized.

Guided vectorization: disambiguation hints

- Assume function arguments won't be aliased
  - C/C++: Compile with `-fargument-noalias`
- C99 "restrict" keyword for pointers
  - Compile with `-restrict` otherwise

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

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

Guided vectorization:

- `#pragma simd or #pragma ivdep`
  - Force loop vectorization ignoring **all** dependencies
    - Additional clauses for specify reductions, etc.

```
void v_add(float *c, float *a, float *b)
{
#pragma simd
    for (int i = 0; i < N; i++)
        c[i] = a[i] + b[i];
}
```

SIMD loop

```
__declspec(vector)
void v_add(float c, float a, float b)
{
    c = a + b;
}
    …
for (int i = 0; i < N; i++)
    v_add(C[i], A[i], B[i]);
```

SIMD function

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- **Examples**

Matrix Multiplication - Serial

```
void multiply(int msize, int tidx, int numt, TYPE a[][NUM], TYPE
b[][NUM], TYPE c[][NUM], TYPE t[][NUM])
{


int i,j,k;
	for(i=0; i<msize; i++) {
		for(k=0; k<msize; k++) {
			for(j=0; j<msize; j++) {
				c[i][j] = c[i][j] + a[i][k] * b[k][j];
			}
		}
	}
}
```

Matrix Multiplication

Function Call Sites and Loops		Vector Issues	Self Time	Total Time	Type	Why No Vectorization?
[loop in multiply3 at multiply.c:228]		2 Assume ...	0.170s	0.170s	Scalar	vector dependence prevents vectorization
[loop in __libc_csu_init]			0.000s	0.000s	Scalar	
[loop in _INTERNAL_16_offload_host_cpp_ad92 ...			0.000s	0.000s	Scalar	
[loop in func@0x5b810]		2 Data typ..	0.000s	0.000s	Scalar	
[loop in main at matrix.c:144]		2 Data typ..	0.000s	0.000s	Scalar	inner loop was already vectorized
[loop in multiply3 at multiply.c:227]		2 Assume ...	0.000s	0.170s	Scalar	vector dependence prevents vectorization
[loop in multiply3 at multiply.c:226]		2 Assume ...	0.000s	0.170s	Scalar	vector dependence prevents vectorization
[loop in main at matrix.c:144]		1 Data typ..	0.000s	0.000s	Vectorized (B ...	

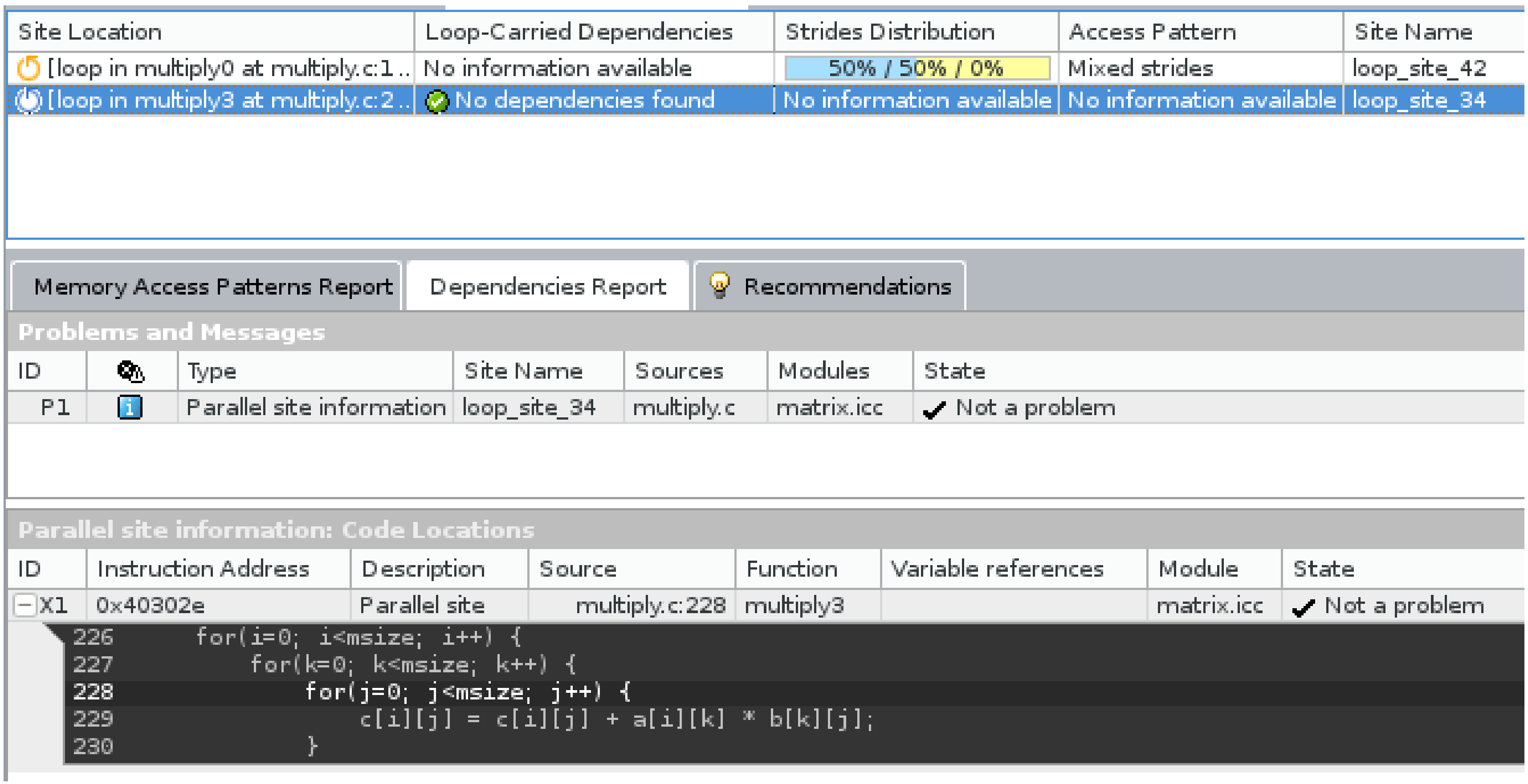
Source | Top Down | Loop Analytics | Loop Assembly | Recommendations | Compiler Diagnostic Details

File: multiply.c:228 multiply3

```
Line  Source
218   void multiply3(int msize, int tidx, int numt, TYPE a[][NUM], TYPE b[][NUM], TYPE c[][NUM], TYPE t[][NUM])
219   {
220
221   //#pragma omp target device(0) map(a[0:NUM][0:NUM]) \
222     //map(b[0:NUM][0:NUM]) map(c[0:NUM][0:NUM])
223     //{
224       int i,j,k;
225   //    #pragma omp parallel for collapse (2) //num threads(60)
226       for(i=0; i<msize; i++) {
          [loop in multiply3 at multiply.c:226]
            Scalar loop. Not vectorized: vector dependence prevents vectorization
            No loop transformations applied
227           for(k=0; k<msize; k++) {
          [loop in multiply3 at multiply.c:227]
            Scalar loop. Not vectorized: vector dependence prevents vectorization
            Remainder loop
228               for(j=0; j<msize; j++) {
          [loop in multiply3 at multiply.c:228]
            Scalar loop. Not vectorized: vector dependence prevents vectorization
            Loop was unrolled by 2
229                   c[i][j] = c[i][j] + a[i][k] * b[k][j];
230               }
231           }
232       }
233     //}
234   }
235
```

Matrix Multiplication

- Check dependency analysis shows that it is safe to enforce the vectorization of this loop



Matrix Multiplication - vectorized

```
void multiply(int msize, int tidx, int numt, TYPE a[][NUM], TYPE
b[][NUM], TYPE c[][NUM], TYPE t[][NUM])
{

int i,j,k;
    for(i=0; i<msize; i++) {
        for(k=0; k<msize; k++) {
            #pragma simd
            for(j=0; j<msize; j++) {
                c[i][j] = c[i][j] + a[i][k] * b[k][j];
            }
        }
    }
}
```

Matrix Multiplication

Function Call Sites and Loops		Vector Issues	Self Time	Total Time	Type	Why No Vectorization?	Vectorized Loops Vec...	Efficiency	Gain E...
[loop in multiply4 at multiply.c:245]			0.460s	0.460s	Vectorized (B...		AVX2	~100%	4.24x
[loop in multiply4 at multiply.c:243]			0.010s	0.470s	Scalar				
[loop in __libc_csu_init]			0.000s	0.000s	Scalar				
[loop in _INTERNAL_16_offload_host_cpp_ad92...			0.000s	0.000s	Scalar				
[loop in func@0x5b810]		3 Data typ...	0.000s	0.000s	Scalar				
[loop in func@0x54bf0]		1 System ...	0.000s	0.000s	Scalar				

Source | Top Down | Loop Analytics | Loop Assembly | Recommendations | Compiler Diagnostic Details

File: multiply.c:245 multiply4

Line | Source

```
            }
        }
    }
  //}
}

void multiply4(int msize, int tidx, int numt, TYPE a[][NUM], TYPE b[][NUM], TYPE c[][NUM], TYPE t[][NUM])
{
  //loop vectorization with pragma omp simd

  int i,j,k;
//  #pragma omp parallel for collapse (2) //num_threads(60)
  for(i=0; i<msize; i++) {
      [loop in multiply4 at multiply.c:242]
        Scalar loop. Not vectorized: inner loop was already vectorized
        No loop transformations applied
    for(k=0; k<msize; k++) {
      [loop in multiply4 at multiply.c:243]
        Scalar loop
        No loop transformations applied
      #pragma omp simd
      for(j=0; j<msize; j++) {
      [loop in multiply4 at multiply.c:245]
        Vectorized AVX; FMA loop processes Float64 data type(s) and includes FMA
        Loop was unrolled by 4
      [loop in multiply4 at multiply.c:245]
        Scalar peeled loop [not executed]
        Loop was unrolled by 4
      [loop in multiply4 at multiply.c:245]
        Vectorized AVX; FMA remainder loop [not executed] processes Float64 data type(s) and includes FMA
        No loop transformations applied
      [loop in multiply4 at multiply.c:245]
        Scalar remainder loop [not executed]
```

Example

- Particle Binning Problem**[1]**

- Optimizations:
  – Automatic Vectorization
  – Data Alignment

[1] http://colfaxresearch.com/optimization-techniques-for-the-intel-mic-architecture-part-2-of-3-strip-mining-for-vectorization/

Particle Binning - Serial

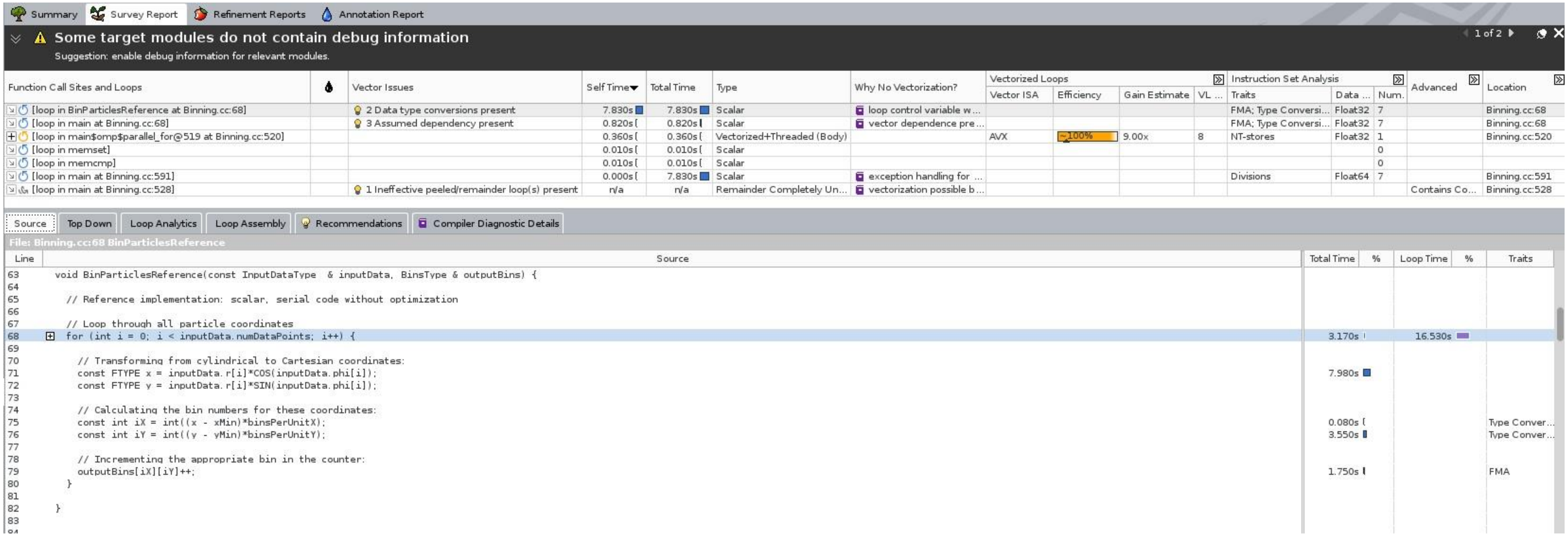
```
for (int i = 0; i < inputData.numDataPoints; i++) {

    // Transforming from cylindrical to Cartesian coordinates:
    const FTYPE x = inputData.r[i]*COS(inputData.phi[i]);
    const FTYPE y = inputData.r[i]*SIN(inputData.phi[i]);

    // Calculating the bin numbers for these coordinates:
    const int iX = int((x - xMin)*binsPerUnitX);
    const int iY = int((y - yMin)*binsPerUnitY);

}
```

Particle Binning - Serial



Particle Binning - Vectorized

```
for (int ii = 0; ii < inputData.numDataPoints; ii += STRIP_WIDTH) {

    int iX[STRIP_WIDTH];
    int iY[STRIP_WIDTH];

    const FTYPE* r   = &(inputData.r[ii]);
    const FTYPE* phi = &(inputData.phi[ii]);

    // Vector loop

    for (int c = 0; c < STRIP_WIDTH; c++) {
        // Transforming from cylindrical to Cartesian coordinates:
        const FTYPE x = r[c]*COS(phi[c]);
       const FTYPE y = r[c]*SIN(phi[c]);

        // Calculating the bin numbers for these coordinates:
        iX[c] = int((x - xMin)*binsPerUnitX);
        iY[c] = int((y - yMin)*binsPerUnitY);
    }

}
```

Particle Binning - Vectorized

Function Call Sites and Loops		Vector Issues	Self Time	Total Time	Type	Why No Vectorization?	Vectorized Loops				Instruction Set Analysis			Advanced	Location
							Vector ISA	Efficiency	Gain Estimate	VL ...	Traits	Data ...	Num.		
[loop in main at Binning.cc:68]		3 Assumed dependency present	0.880s	0.880s	Scalar	vector dependence pre...					FMA; Type Conversi...	Float32	7		Binning.cc:68
[loop in BinParticles_3 at Binning.cc:173]		1 Potential underutilization of FMA instructions	0.850s	1.420s	Scalar	inner loop was already ...							9		Binning.cc:173
[loop in BinParticles_3 at Binning.cc:182]		1 Data type conversions present	0.570s	0.570s	Vectorized (Body)		AVX2	~100%	17.64x	8	FMA; Type Conversi...	Float3...	9		Binning.cc:182
[loop in mainompparallel_for@519 at Binning.cc:520]			0.359s	0.359s	Vectorized+Threaded (Body)		AVX	~100%	9.00x	8	NT-stores	Float32	1		Binning.cc:520
[loop in operator new]			0.010s	0.010s	Scalar								0		
[loop in memcmp]			0.010s	0.010s	Scalar								0		
[loop in main at Binning.cc:591]			0.000s	1.420s	Scalar	exception handling for ...					Divisions	Float64	8		Binning.cc:591
[loop in main at Binning.cc:528]		1 Ineffective peeled/remainder loop(s) present	n/a	n/a	Remainder Completely Un...	vectorization possible b...								Contains Co...	Binning.cc:528

Source | Top Down | Loop Analytics | Loop Assembly | Recommendations | Compiler Diagnostic Details

File: Binning.cc:68 main

Line	Source	Total Time	%	Loop Time	%	Traits
169	`threadPrivateBins[i][j] = 0;`					
170						
171	`// Loop through all bunches of particles`					
172	`//#pragma omp for`					
173	`for (int ii = 0; ii < inputData.numDataPoints; ii += STRIP WIDTH) {`	0.050s		4.250s		
174						
175	`int iX[STRIP WIDTH];`					
176	`int iY[STRIP WIDTH];`					
177						
178	`const FTYPE* r   = &(inputData.r[ii]);`					
179	`const FTYPE* phi = &(inputData.phi[ii]);`	0.010s				
180						
181	`// Vector loop`					
182	`for (int c = 0; c < STRIP_WIDTH; c++) {` [loop in BinParticles_3 at Binning.cc:182] Vectorized AVX; FMA loop processes Float32; Int32 data type(s) and includes FMA; Type Conversions Loop stmts were reordered	0.060s		3.400s		
183	`// Transforming from cylindrical to Cartesian coordinates:`					
184	`const FTYPE x = r[c]*COS(phi[c]);`					
185	`const FTYPE y = r[c]*SIN(phi[c]);`	3.040s				

Particle Binning - Data Alignment

```
for (int ii = 0; ii < inputData.numDataPoints; ii += STRIP_WIDTH) {

    int iX[STRIP_WIDTH] __attribute__((aligned(64)));
    int iY[STRIP_WIDTH] __attribute__((aligned(64)));

    const FTYPE* r   = &(inputData.r[ii]);
    const FTYPE* phi = &(inputData.phi[ii]);

    // Vector loop
#pragma vector aligned
    for (int c = 0; c < STRIP_WIDTH; c++) {
        // Transforming from cylindrical to Cartesian coordinates:
        const FTYPE x = r[c]*COS(phi[c]);
        const FTYPE y = r[c]*SIN(phi[c]);

        // Calculating the bin numbers for these coordinates:
        iX[c] = int((x - xMin)*binsPerUnitX);
        iY[c] = int((y - yMin)*binsPerUnitY);
    }

}
```

Particle Binning - Data Alignment

Function Call Sites and Loops		Vector Issues	Self Time	Total Time	Type	Why No Vectorization?	Vectorized Loops				Instruction Set Analysis			Advanced	Location
							Vector ISA	Efficiency	Gain Estimate	VL ...	Traits	Data ...	Num.		
[loop in BinParticles_4 at Binning.cc:226]		1 Potential underutilization of FMA instructions	0.940s	1.470s	Scalar	inner loop was already ...							9		Binning.cc:226
[loop in main at Binning.cc:68]		3 Assumed dependency present	0.900s	0.900s	Scalar	vector dependence pre ...					FMA; Type Conversi...	Float32	7		Binning.cc:68
[loop in BinParticles_4 at Binning.cc:236]		1 Data type conversions present	0.530s	0.530s	Vectorized (Body)		AVX2	~100%	18.50x	8	FMA; Type Conversi...	Float3...	9		Binning.cc:236
[loop in mainompparallel_for@519 at Binning.cc:520]			0.370s	0.370s	Vectorized+Threaded (Body)		AVX	~100%	9.00x	8	NT-stores	Float32	1		Binning.cc:520
[loop in memcmp]			0.010s	0.010s	Scalar								0		
[loop in main at Binning.cc:591]			0.000s	1.470s	Scalar	exception handling for ...					Divisions	Float64	8		Binning.cc:591
[loop in main at Binning.cc:528]		1 Ineffective peeled/remainder loop(s) present	n/a	n/a	Remainder Completely Un...	vectorization possible b ...								Contains Co...	Binning.cc:528

Source | Top Down | Loop Analytics | Loop Assembly | Recommendations | Compiler Diagnostic Details

File: Binning.cc:226 BinParticles_4

Line	Source	Total Time	%	Loop Time	%	Traits
232	`const FTYPE* phi = &(inputData.phi[ii]);`	0.010s				
233						
234	`// Vector loop`					
235	`#pragma vector aligned`					
236	`for (int c = 0; c < STRIP_WIDTH; c++) {`			3.250s		
	[loop in BinParticles_4 at Binning.cc:236] Vectorized AVX; FMA loop processes Float32; Int32 data type(s) and includes FMA; Type Conversions No loop transformations applied					
237	`// Transforming from cylindrical to Cartesian coordinates:`					
238	`const FTYPE x = r[c]*COS(phi[c]);`	0.090s				
239	`const FTYPE y = r[c]*SIN(phi[c]);`	2.740s				
240						
241	`// Calculating the bin numbers for these coordinates:`					
242	`iX[c] = int((x - xMin)*binsPerUnitX);`	0.110s				FMA; Type C...
243	`iY[c] = int((y - yMin)*binsPerUnitY);`	0.310s				FMA; Type C...
244	`}`					
245						
246	`// Scalar loop`					
247	`for (int c = 0; c < STRIP_WIDTH; c++)`					
248	`threadPrivateBins[iX[c]][iY[c]]++;`	0.890s				

Diffusion - Serial

Function Call Sites and Loops▲		Vector Issues	Self Time	Total Time	Type	Why No Vectorization?
[loop in diffusion_baseline at diffusion_base.c:103]		1 Potential ..	0.000s	10.530s	Scalar	outer loop was not auto-vectorized: consider using SIMD ...
[loop in diffusion_baseline at diffusion_base.c:104]		1 Potential ..	0.010s	10.450s	Scalar	outer loop was not auto-vectorized: consider using SIMD ...
[loop in diffusion_baseline at diffusion_base.c:105]		2 Assume ...	0.130s	10.370s	Scalar	vector dependence: assumed dependence between lines
[loop in diffusion_baseline at diffusion_base.c:105]		2 Assume ...	0.000s	0.080s	Scalar Versions	1 vector dependence: assumed dependence between lines
[loop in diffusion_baseline at diffusion_base.c:107]		2 Assume ...	10.240s	10.240s	Scalar	vector dependence: assumed dependence between lines
[loop in diffusion_baseline at diffusion_base.c:107]		2 Assume ...	0.070s	0.070s	Scalar Versions	1 vector dependence: assumed dependence between lines
[loop in diffusion_baseline at diffusion_base.c:107]		2 Assume ...	0.060s	0.060s	Scalar	vector dependence: assumed dependence between lines

Source | Top Down | Loop Analytics | Loop Assembly | Recommendations | Compiler Diagnostic Details

File: diffusion_base.c:107 diffusion_baseline

Line | Source

```
97      void
98      diffusion_baseline(REAL *f1, REAL *f2, int nx, int ny, int nz,
99                         REAL ce, REAL cw, REAL cn, REAL cs, REAL ct,
100                        REAL cb, REAL cc, REAL dt,
101                        int count) {
102       int i;
103       for (i = 0; i < count; ++i) {
104         for (int z = 0; z < nz; z++) {
105           for (int y = 0; y < ny; y++) {
106             //#pragma simd
107             for (int x = 0; x < nx; x++) {
          [loop in diffusion_baseline at diffusion_base.c:107]
             Scalar loop. Vector dependence: assumed dependence between lines
             No loop transformations applied
          [loop in diffusion_baseline at diffusion_base.c:107]
             Scalar loop. Vector dependence: assumed dependence between lines
             No loop transformations applied
          [loop in diffusion_baseline at diffusion_base.c:107]
             Scalar loop. Vector dependence: assumed dependence between lines
             No loop transformations applied
          [loop in diffusion_baseline at diffusion_base.c:107]
             Scalar loop. Vector dependence: assumed dependence between lines
             No loop transformations applied
          [loop in diffusion_baseline at diffusion_base.c:107]
             Scalar loop. Vector dependence: assumed dependence between lines
             No loop transformations applied
```

Diffusion - Vectorized

Potential inefficient memory access;

Function Call Sites and Loops		Vector Issues	Self Time	Total Time	Type	Why No Vectorization?	Vectorized Loops		
							Vec...	Efficiency	Gai...
[loop in diffusion_openmpv at diffusion_ompvect.c:106]		1 Potential ..	0.640s	5.050s	Scalar	inner loop was already vectorized			
[loop in diffusion_openmpv at diffusion_ompvect.c:106]		1 Potential ..	0.000s	0.060s	Scalar Versions	1 inner loop was already vectorized			
[loop in diffusion_openmpv at diffusion_ompvect.c:108]			4.410s	4.410s	Vectorized (B...		AVX2	~62%	4.93x
[loop in diffusion_openmpv at diffusion_ompvect.c:108]		1 Possible i..	0.060s	0.060s	Vectorized Ve...		AVX2	~50%	4.00x
[loop in diffusion_openmpv at diffusion_ompvect.c:108]		1 Possible i..	0.030s	0.030s	Vectorized (B...		AVX2	~50%	4.00x
[loop in diffusion_openmpv at diffusion_ompvect.c:108]		1 Possible i..	0.030s	0.030s	Vectorized (B...		AVX2	~50%	4.00x
[loop in init at diffusion_ompvect.c:71]		1 Data typ..	0.000s	0.060s	Scalar	inner loop was already vectorized			

Source | Top Down | Loop Analytics | Loop Assembly | Recommendations | Compiler Diagnostic Details

File: diffusion_ompvect.c:108 diffusion_openmpv

```
Line   Source
97     void
98     diffusion_openmpv(REAL *restrict f1, REAL *restrict f2, int nx, int ny, int nz,
99                       REAL ce, REAL cw, REAL cn, REAL cs, REAL ct,
100                      REAL cb, REAL cc, REAL dt, int count) {
101      REAL *f1_t = f1;
102      REAL *f2_t = f2;
103
104      for (int i = 0; i < count; ++i) {
105        for (int z = 0; z < nz; z++) {
106          for (int y = 0; y < ny; y++) {
107        #pragma simd
108            for (int x = 0; x < nx; x++) {
         [loop in diffusion_openmpv at diffusion_ompvect.c:108]
            Vectorized AVX; FMA loop processes Float32 data type(s) and includes FMA
            No loop transformations applied
         [loop in diffusion_openmpv at diffusion_ompvect.c:108]
            Vectorized AVX; AVX2; AVX2GATHER; FMA loop processes Float32; Int32 data type(s) and includes FMA; Gathers
            No loop transformations applied
         [loop in diffusion_openmpv at diffusion_ompvect.c:108]
            Vectorized AVX; AVX2; AVX2GATHER; FMA loop processes Float32; Int32 data type(s) and includes FMA; Gathers
            No loop transformations applied
         [loop in diffusion_openmpv at diffusion_ompvect.c:108]
            Vectorized AVX; AVX2; AVX2GATHER; FMA loop processes Float32; Int32 data type(s) and includes FMA; Gathers
            No loop transformations applied
         [loop in diffusion_openmpv at diffusion_ompvect.c:108]
            Vectorized AVX; AVX2; AVX2GATHER; FMA loop processes Float32; Int32 data type(s) and includes FMA; Gathers
            No loop transformations applied
```

Diffusion - alignment

Function Call Sites and Loops		Vector Issues	Self Time	Total Time	Type	Why No Vectorization?	Vectorized Loops: Vec...	Efficiency	Gai...
[loop in accuracy at diffusion_peel.c:91]			0.010s	0.010s	Vectorized (B...		AVX2	~100%	12. ...
[loop in diffusion_peel at diffusion_peel.c:106]		1 Potential underutilization of FMA instructions	0.000s	5.240s	Scalar	inner loop was already vectorized			
[loop in diffusion_peel at diffusion_peel.c:108]		1 Potential underutilization of FMA instructions	0.000s	5.240s	Scalar	inner loop was already vectorized			
[loop in diffusion_peel at diffusion_peel.c:109]		1 Potential underutilization of FMA instructions	0.580s	5.240s	Scalar	inner loop was already vectorized			
[loop in diffusion_peel at diffusion_peel.c:120]			**4.660s**	**4.660s**	**Vectorized ...**		**AVX.**	~99%	**7.8..**

Source | Top Down | Loop Analytics | Loop Assembly | Recommendations | Compiler Diagnostic Details

File: diffusion_peel.c:120 diffusion_peel

Line	Source	Total Time	%	Loop Time	%
96					
97	`void`				
98	`diffusion_peel(REAL *restrict f1, REAL *restrict f2, int nx, int ny, int nz,`				
99	`REAL ce, REAL cw, REAL cn, REAL cs, REAL ct,`				
100	`REAL cb, REAL cc, REAL dt, int count) {`				
101	`//#pragma omp parallel`				
102	`// {`				
103	`REAL *f1_t = f1;`				
104	`REAL *f2_t = f2;`				
105					
106	`for (int i = 0; i < count; ++i) {`			5.240s	
107	`//#pragma omp for collapse(2)`				
108	`for (int z = 0; z < nz; z++) {`			5.240s	
109	`for (int y = 0; y < ny; y++) {`			5.240s	
110	`int x, c, n, s, b, t;`				
111	`x = 0;`				
112	`c = x + y * NXP + z * NXP * ny;`				
113	`n = (y == 0) ? c : c - NXP;`				
114	`s = (y == ny-1) ? c : c + NXP;`	0.020s			
115	`b = (z == 0) ? c : c - NXP * ny;`				
116	`t = (z == nz-1) ? c : c + NXP * ny;`				
117	`f2_t[c] = cc * f1_t[c] + cw * f1_t[c] + ce * f1_t[c+1]`	0.010s			
118	`+ cs * f1_t[s] + cn * f1_t[n] + cb * f1_t[b] + ct * f1_t[t];`	0.030s			
119	`#pragma simd`				
120	`for (x = 1; x < nx-1; x++) {`	0.140s		4.660s	
	[loop in diffusion_peel at diffusion_peel.c:120] Vectorized AVX; FMA loop processes Float32 data type(s) and includes FMA No loop transformations applied				
121	`++c;`				
122	`++n;`	0.010s			
123	`++s;`				
124	`++b;`				
125	`++t;`				
126	`f2_t[c] = cc * f1_t[c] + cw * f1_t[c-1] + ce * f1_t[c+1]`	0.760s			
127	`+ cs * f1_t[s] + cn * f1_t[n] + cb * f1_t[b] + ct * f1_t[t];`	4.240s			
128	`}`				
129	`++c;`				
130	`++n;`				
131	`++s;`				
132	`++b;`				
133	`++t;`				
134	`f2_t[c] = cc * f1_t[c] + cw * f1_t[c-1] + ce * f1_t[c]`				
135	`+ cs * f1_t[s] + cn * f1_t[n] + cb * f1_t[b] + ct * f1_t[t];`	0.030s			
136	`}`				
137	`}`				
138	`REAL *t = f1_t;`				
139	`f1_t = f2_t;`				

Pragma omp simd - Interpolation

```
__declspec(vector)
int FindPosition(double x) {
   return (int)(log(exp(x*steps)));
}

__declspec(vector)
double Interpolate(double x, const point*
vals)
{
   int ind = FindPosition(x);
   ...

   return res;
}
```

```
int main ( int argc , char argv [] )
{
   . . .
  for ( i=0; i <ARRAY_SIZE;++ i ) {
      dst[i] = Interpolate( src[i], vals ) ;
   }
   . . .
}
```

George M. Raskulinec, Evgeny Fiksman “Chapter 22 - **SIMD functions via OpenMP**”, In High Performance Parallelism Pearls, edited by James Reinders and Jim Jeffers, Morgan Kaufmann, Boston, 2015, Pages 171-190, ISBN 9780128038192

Vectorization report - Interpolate

Begin optimization report for: Interpolate.._simdsimd3__H2n_v1_s1.P(double, const point *)

Report from: Vector optimizations [vec]

remark #15301: FUNCTION WAS VECTORIZED [main.c(74,48)]
===

Begin optimization report for: Interpolate.._simdsimd3__H2m_v1_s1.P(double, const point *)

Report from: Vector optimizations [vec]

remark #15301: FUNCTION WAS VECTORIZED [main.c(74,48)]
===

Begin optimization report for: Interpolate.._simdsimd3__L4n_v1_s1.V(double, const point *)

Report from: Vector optimizations [vec]

remark #15301: FUNCTION WAS VECTORIZED [main.c(74,48)]
remark #15415: vectorization support: gather was generated for the variable pnt: indirect access, 64bit indexed [main.c(78,26)]
remark #15415: vectorization support: gather was generated for the variable pnt: indirect access, 64bit indexed [main.c(78,36)]
===

Begin optimization report for: Interpolate.._simdsimd3__L4m_v1_s1.V(double, const point *)

Report from: Vector optimizations [vec]

remark #15301: FUNCTION WAS VECTORIZED [main.c(74,48)]
remark #15415: vectorization support: gather was generated for the variable pnt: masked, indirect access, 64bit indexed [main.c(78,26)]
remark #15415: vectorization support: gather was generated for the variable pnt: masked, indirect access, 64bit indexed [main.c(78,36)]

Vectorization report - FindPosition

egin optimization report for: FindPosition.._simdsimd3__H2n_v1.P(double)

Report from: Vector optimizations [vec]

remark #15301: FUNCTION WAS VECTORIZED [main.c(70,28)]
===

Begin optimization report for: FindPosition.._simdsimd3__H2m_v1.P(double)

Report from: Vector optimizations [vec]

remark #15301: FUNCTION WAS VECTORIZED [main.c(70,28)]
===

Begin optimization report for: FindPosition.._simdsimd3__L4n_v1.V(double)

Report from: Vector optimizations [vec]

remark #15301: FUNCTION WAS VECTORIZED [main.c(70,28)]
===

Begin optimization report for: FindPosition.._simdsimd3__L4m_v1.V(double)

Report from: Vector optimizations [vec]

remark #15301: FUNCTION WAS VECTORIZED [main.c(70,28)]
===

Lattice Boltzmann

Function Call Sites and Loops		Vector Issues	Self Time	Total Time	Type	Why No Vectorization?	Vectorized Loops Vec...	Efficiency	Gai...	VL ...
[loop in fCalcInteraction_ShanChen_Boundary at lbpFORCE.c...		2 Assume ...	0.130s	0.210s	Scalar	vector depende...				
[loop in fCalcInteraction_ShanChen_Boundary at lbpFORCE.c...		2 Assume ...	0.080s	0.080s	Scalar	vector depende...				
[loop in fCalcPotential_ShanChen at lbpFORCE.cpp:36]			0.000s	5.742s	Scalar	loop control vari...				
[loop in fCalcPotential_ShanChen at lbpFORCE.cpp:49]		1 Potential..	0.000s	5.742s	Threaded (OpenMP)	inner loop was al...				
[loop in fCollisionBGKompparallel@338 at lbpBGK.cpp:351]		1 Ineffecti...	0.160s	0.160s	Vectorized (Remainder)		AVX2	~67%	2.69x	4
[loop in fGetEquilibriumF at lbpSUB.cpp:615]		**2 Data t...**	**3.910s**	**3.910s**	**Vectorized (Body; ...**		**AVX.**	~91%	**3.6..**	**4**
[loop in fGetEquilibriumF at lbpSUB.cpp:615]		1 Data typ..	3.120s	3.120s	Vectorized (Body)		AVX2			4
[loop in fGetEquilibriumF at lbpSUB.cpp:615]		1 Data typ..	0.790s	0.790s	Remainder					

Source | Top Down | Loop Analytics | Loop Assembly | Recommendations | Compiler Diagnostic Details

File: lbpSUB.cpp:615 fGetEquilibriumF

Line | Source

```
int fGetEquilibriumF(double *feq, double *v, double rho)
{

  // calculate equilibrium distribution function for compressible fluid:
  // only suitable for square lattices, not suitable for incompressible fluid

  double modv = v[0]*v[0] + v[1]*v[1] + v[2]*v[2];
  double uv;

    //#pragma loop count(20)
    //for(int i=0; i<lbsy.nq +1; i++)
    for(int i=0; i<lbsy.nq; i++)
      [loop in fGetEquilibriumF at lbpSUB.cpp:615]
        Scalar loop. Not vectorized: vector dependence prevents vectorization
        No loop transformations applied
      [loop in fGetEquilibriumF at lbpSUB.cpp:615]
        Vectorized AVX; FMA loop processes Float64; Int32; UInt32 data type(s) and includes FMA; Type Conversions; Unpacks
        No loop transformations applied
      [loop in fGetEquilibriumF at lbpSUB.cpp:615]
        Scalar remainder loop
        No loop transformations applied
```

Lattice Boltzmann

Function Call Sites and Loops		Vector Issues	Self Time	Total Time	Type	Why No Vectorization?	Vectorized Loops Vec…	Efficiency	Gai…	VL …
[loop in fCalcPotential_ShanChen at lbpFORCE.cpp:49]		1 Potential…	0.000s	5.871s	Threaded (OpenMP)	inner loop was al…				
[loop in fCollisionBGKompparallel@338 at lbpBGK.cpp:351]		1 Ineffecti…	0.290s	0.290s	Vectorized (Remainder)		AVX2	~67%	2.69x	4
[loop in fGetEquilibriumF at lbpSUB.cpp:614]		**1 Data t…**	**4.000s**	**4.000s**	**Vectorized (Body)**		**AVX.**	~88%	**3.5..**	**4**
[loop in fGetEquilibriumF at lbpSUB.cpp:614]		1 Data typ…	4.000s	4.000s	Vectorized (Body)		AVX2			4
[loop in fGetEquilibriumF at lbpSUB.cpp:614]		3 Assume…	0.030s	0.030s	Scalar	vector depende…				
[loop in fGetEquilibriumF at lbpSUB.cpp:614]		3 Assume…	0.010s	0.010s	Scalar	vector depende…				
[loop in fGetFracSite at lbpGET.cpp:121]		2 Ineffecti…	0.210s	0.210s	Vectorized Versions		AVX…	~31%	2.50x	4; 8
[loop in fGetOneDirecSpeedSite at lbpGET.cpp:241]			0.030s	0.140s	Scalar					

Source | Top Down | Loop Analytics | Loop Assembly | Recommendations | Compiler Diagnostic Details

File: lbpSUB.cpp:614 fGetEquilibriumF

```
Line  Source
603
604   int fGetEquilibriumF(double *feq, double *v, double rho)
605   {
606
607     // calculate equilibrium distribution function for compressible fluid:
608     // only suitable for square lattices, not suitable for incompressible fluid
609
610     double modv = v[0]*v[0] + v[1]*v[1] + v[2]*v[2];
611     double uv;
612
613       #pragma loop count(20)
614       for(int i=0; i<lbsy.nq +1; i++)
          [loop in fGetEquilibriumF at lbpSUB.cpp:614]
            Scalar loop. Not vectorized: vector dependence prevents vectorization
            No loop transformations applied
          [loop in fGetEquilibriumF at lbpSUB.cpp:614]
            Scalar loop. Not vectorized: vector dependence prevents vectorization
            No loop transformations applied
          [loop in fGetEquilibriumF at lbpSUB.cpp:614]
            Vectorized AVX; FMA loop processes Float64; Int32; UInt32 data type(s) and includes FMA; Type Conversions; Unpacks
            No loop transformations applied
          [loop in fGetEquilibriumF at lbpSUB.cpp:614]
            Scalar remainder loop [not executed]
            No loop transformations applied
```