



# PROGRAMMING AND OPTIMIZATION FOR INTEL<sup>®</sup> ARCHITECTURE

The Hands-On Workshop (HOW) Series  
Session 6

*Colfax International* — [colfaxresearch.com](http://colfaxresearch.com)

September 2016

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- ▶ **HOW to Program Intel Architecture**
  - 01. Parallelism, specialization, guided tour – Sep 26
  - 02. Programming Intel Xeon Phi (KNC, KNL) – Sep 27
- ▶ **HOW to Express Parallelism**
  - 03. Automatic vectorization – Sep 28
  - 04. Multi-threading with OpenMP – Sep 29
- ▶ **HOW to Get Performance**
  - 05. Comprehensive demo – Sep 30
  - 06. Scalar & vectorization tuning – Oct 3
  - 07. Multi-threading: common issues – Oct 4
  - 08. Multi-threading: memory aspect – Oct 5
  - 09. Memory traffic – Oct 6
- ▶ **HOW to Scale**
  - 10. Distributed Computing: MPI – Oct 7

September 2016						
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30	31					
■ — Webinar+remote access						

Course page: [colfaxresearch.com/how-16-09](http://colfaxresearch.com/how-16-09)

- ▶ Slides (including this one), code downloads
- ▶ Video of recorded sessions
- ▶ Chat (during webinars or offline)



Additional resources:

- ▶ More workshops like this one: [colfaxresearch.com/training](http://colfaxresearch.com/training)
- ▶ Video courses: [colfaxresearch.com/video-courses](http://colfaxresearch.com/video-courses)

# GET YOUR QUESTIONS ANSWERED

## Chat (current):

[colfaxresearch.com/how-16-09](http://colfaxresearch.com/how-16-09)



## Forums (technical):

[colfaxresearch.com/discussion](http://colfaxresearch.com/discussion)

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Tap our experts and your peers to help meet the challenge of optimizing applications on modern hardware. This is the place to browse or post questions (and get answers) related to computational science, parallel programming and code modernization on Intel® Architecture.

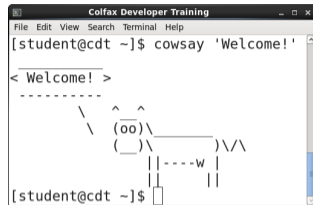
Welcome aboard. Post questions today!

## Email (organizational):

[training@colfax-intl.com](mailto:training@colfax-intl.com)

# HANDS-ON EXERCISES AND REMOTE ACCESS

- ▶ 96 people receive a remote access token
- ▶ Virtualized Intel Xeon CPU, real Intel Xeon Phi coprocessor (1st gen, KNC), SW tools
- ▶ Can access the system the entire 2 weeks of the workshop



```
Colfax Developer Training
File Edit View Search Terminal Help
[student@cdt ~]$ cowsay 'Welcome!'
< Welcome! >
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            (_____)
                )\/)
                ||----w |
                ||     ||

[student@cdt ~]$
```

- ▶ Not among the 96? Stay tuned: follow along with instructor, use own system, or wait for a seat
- ▶ Use it or lose it: if you do not log in for a while, remote access token goes to next student on the list



## **§2. PERFORMANCE OPTIMIZATION**

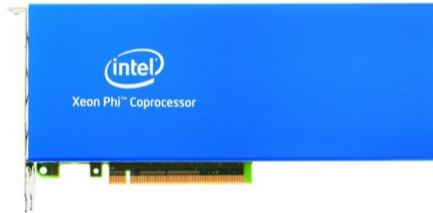
## Intel Xeon Processor



Current: Broadwell  
Upcoming: Skylake

Multi-Core Architecture

## Intel Xeon Phi Coprocessor, 1st generation



Knights Corner (KNC)

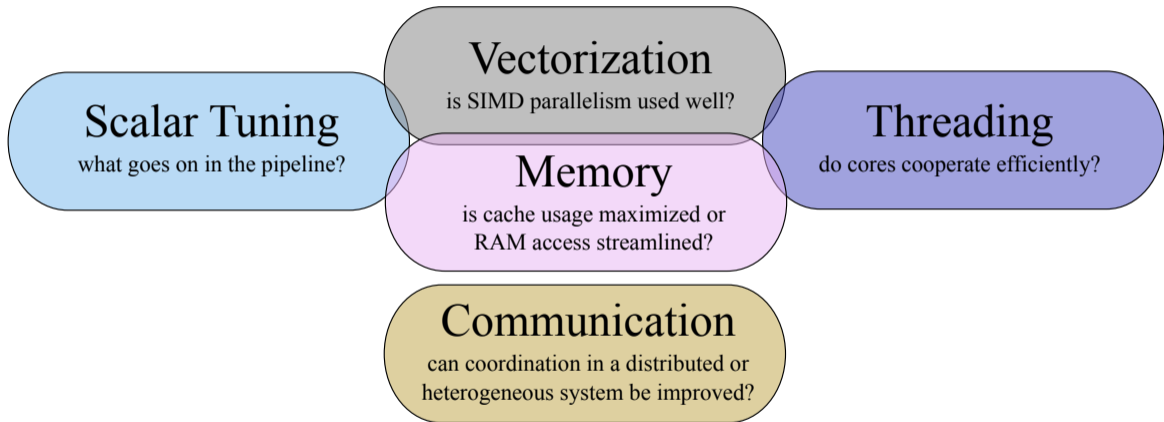
## Intel Xeon Phi Processor, 2nd generation\*



\* socket and coprocessor versions

Knights Landing (KNL)

Intel Many Integrated Core (MIC) Architecture





## **§3. SCALAR TUNING**



# COMPILER ARGUMENTS

# OPTIMIZATION LEVEL

## Default optimization level -O2

- ▶ optimization for speed
- ▶ automatic vectorization
- ▶ inlining
- ▶ constant propagation
- ▶ dead-code elimination
- ▶ loop unrolling

## Optimization level -O3

- ▶ aggressive optimization
- ▶ loop fusion
- ▶ block-unroll-and-jam
- ▶ if-statement collapse
- ▶ *may or may not be better than -O2*

For the entire file:

```
vega@lyra% icpc -o mycode -O3 source.cc
```

For a specific function:

```
1 #pragma intel optimization_level 3
2 void my_function() {
3     //...
4 }
```

# FLOATING-POINT SEMANTICS

The Intel C++ Compiler may represent floating-point expressions in executable code differently, depending on the *floating-point semantics*.

<code>-fp-model strict</code>	Only value-safe optimizations
<code>-fp-model precise</code>	calculations are reproducible from run to run exceptions controlled using <code>-fp-model except</code> (default)
<code>-fp-model fast=1</code>	Value-unsafe optimizations are allowed
<code>-fp-model fast=2</code>	better performance at the cost of lower accuracy
<code>-fp-model source</code>	Intermediate arithmetic results are rounded to the precision defined in the source code.
<code>-fp-model double</code>	Intermediate arithmetic results are rounded to 53-bit (double) precision.
<code>-fp-model extended</code>	Intermediate arithmetic results are rounded to 64-bit (extended) precision.
<code>-fp-model [no-]except</code>	controls floating-point exception semantics.

## PRECISION CONTROL FOR TRANSCENDENTAL FUNCTIONS

- `-fimf-precision=value[:funclist]` Defines the precision for math functions. `value` is one of: `high`, `medium` or `low`
- `-fimf-max-error=ulps[:funclist]` The maximum allowable error expressed in ulps (*units in last place*)
- `-fimf-accuracy-bits=n[:funclist]` The number of correct bits required for mathematical function accuracy.
- `-fimf-domain-exclusion=n[:funclist]` Defines a list of special-value numbers that do not need to be handled.  
`int` `n` derived by the bitwise OR of types:  
extremes: 1, NaNs: 2, infinities: 4, denormals<sup>1</sup>: 8, zeroes: 16.

---

<sup>1</sup>by default, on Intel Xeon Phi, denormals are flushed to zero in hardware, but supported in SVMML



# **PROGRAMMING PRACTICES**

# STRENGTH REDUCTION

## Common Subexpression Elimination.

```

1  for (int i = 0; i < n; i++) {
2      A[i] /= B;
3  }
```

```

1  const float Br = 1.0f/B;
2  for (int i = 0; i < n; i++)
3      A[i] *= Br;
```

## Replace division with multiplication.

```

1  for (int i = 0; i < n; i++) {
2      P[i] = (Q[i]/R[i])/S[i];
3  }
```

```

1  for (int i = 0; i < n; i++) {
2      P[i] = Q[i]/(R[i]*S[i]);
3  }
```

## Use functions with Hardware support.

```

1  double r = pow(r2, -0.5);
2  double v = exp(x);
3  double y = y0*exp(log(x/x0)*
4              log(y1/y0)/log(x1/x0));
```

```

1  double r = 1.0/sqrt(r2);
2  double v = exp2(x*1.44269504089);
3  double y = y0*exp2(log2(x/x0)*
4              log2(y1/y0)/log2(x1/x0));
```

# CONSISTENCY OF PRECISION: CONSTANTS

```
1 // Bad: 2 is "int"
2 long b=a*2;
3
4 // Bad: overflow
5 long n=100000*100000;
6
7 // Bad: excessive
8 float p=6.283185307179586;
9
10 // Bad: 2 is "int"
11 float q=2*p;
12
13 // Bad: 1e9 is "double"
14 float r=1e9*p;
15
16 // Bad: 1 is "int"
17 double t=s+1;
```

```
1 // Good: 2L is "long"
2 long b=a*2L;
3
4 // Good: correct
5 long n=100000L*100000L;
6
7 // Good: accurate
8 float p=6.283185f;
9
10 // Good: 2.0f is "float"
11 float q=2.0f*p;
12
13 // Good: 1e9f is "float"
14 float r=1e9f*p;
15
16 // Good: 1.0 is "double"
17 double t=s+1.0;
```

# CONSISTENCY OF PRECISION: FUNCTIONS

```
1 // Bad: 3.14 is a double
2 float x = 3.14;
3
4 // Bad: sin() is a
5 // double precision function
6 float s = sin(x);
7
8 // Bad: round() takes double
9 // and returns double
10 long v = round(x);
11
12 // Bad: abs() is not from IML
13 // it takes int and returns int
14 int v = abs(x);
```

```
1 // Good: 3.14f is a float
2 float x = 3.14f;
3
4 // Good: sin() is a
5 // single precision function
6 float s = sinf(x);
7
8 // Good: lroundf() takes float
9 // and returns long
10 long v = lroundf(x);
11
12 // Good: fabsf() is from IML
13 // It takes and returns a float
14 float v = fabsf(x);
```

# CONSISTENCY OF PRECISION: FUNCTIONS

Transcendental functions are *not* overloaded (unless in namespace `std` in C++).

```
vega@lyra% ./Scalar-TestF0verload
Proof that exp() is not overloaded:
exp (1.0f)=2.7182818284590451
exp (1.0 )=2.7182818284590451
Exact:    e=2.71828182845904523536...

Proof that expf() gives lower precision:
expf(1.0f)=2.7182817459106445
expf(1.0 )=2.7182817459106445
Exact:    e=2.71828182845904523536...

Overloading in namespace std:
std::exp(1.0f)=2.7182817459106445
std::exp(1.0 )=2.7182818284590451
Exact:    e=2.71828182845904523536...
```

# MOVE BRANCHES OUTSIDE OF LOOPS

```
1 // Elegant, but bad for performance
2 for (i = 0; i < n; i++) {
3     if (i == 0) {
4         // Absorbing boundary
5         B[i] = 0.0;
6     } else if (i == n - 1) {
7         // Injection at boundary
8         B[i] = B[i] + 1.0;
9     } else {
10        // Diffusion between boundaries
11        B[i] = 0.25*(A[i-1] +
12                    2.0*A[i] + A[i+1]);
13    }
14 }
```

```
1 // Moving branches out of loops
2
3
4 // Absorbing boundary
5 B[i] = 0.0;
6
7 for (i = 1; i < n - 1; i++) {
8     // Diffusion between boundaries
9     B[i] = 0.25*(A[i-1] + 2.0*A[i] +
10                A[i+1]);
11 }
12
13 // Injection at boundary
14 B[n-1] = B[n-1] + 1.0;
```

# REDUNDANT CODE IS OK

```
1 // Elegant, but bad for performance
2 for (ii = 0; ii < n; ii+=16) {
3     for (i = ii; i < ii+16; i++)
4         // Branch causes unnecessary
5         // masking of vector iterations
6         if (i < n) {
7             A[k*n + i] = ...
8         }
9 }
```

```
1 // Redundant code, but faster
2 const int nTrunc = n - 16;
3 for (ii = 0; ii < nTrunc; ii+=16) {
4     for (i = ii; i < ii+16; i++)
5         A[k*n + i] = ...
6
7     for (i = nTrunc; i < n; i++)
8         A[k*n + i] = ...
9 }
```



## **§4. VECTORIZATION**

# SHORT VECTOR SUPPORT

Vector instructions – one of the implementations of SIMD (Single Instruction Multiple Data) parallelism.

Scalar Instructions

$$\begin{array}{r} 4 + 1 = 5 \\ 0 + 3 = 3 \\ -2 + 8 = 6 \\ 9 + -7 = 2 \end{array}$$

Vector Instructions

$$\begin{array}{r} 4 \\ 0 \\ -2 \\ 9 \end{array} + \begin{array}{r} 1 \\ 3 \\ 8 \\ -7 \end{array} = \begin{array}{r} 5 \\ 3 \\ 6 \\ 2 \end{array}$$

↑ Vector Length ↓



# **DATA STRUCTURES AND MEMORY ACCESS**

# UNIT-STRIDE ACCESS

Unit-stride access is optimal:

```
1 for (int i = 0; i < n; i++)
2   A[i] += B[i];
```

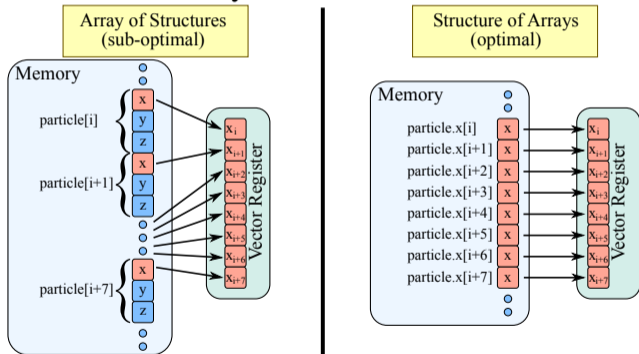
Non-unit stride is slower:

```
1 for (int i = 0; i < n; i++)
2   A[i*stride] += B[i];
```

Stochastic access may be vectorized (but not efficient):

```
1 for (int i = 0; i < n; i++)
2   A[offset[i]] += B[i];
```

It may be a question of changing the order of loop nesting, but sometimes you need to modify data structures:



## SUGGESTED EXERCISE

Review lab 4.01 (N-body simulation) or perform lab 4.02 (Coulomb's law calculation) to re-visit the AoS to SoA conversion.



## **ALIGNMENT AND PADDING**

# DATA ALIGNMENT REQUIREMENTS

Array `char* p` is `n`-byte aligned if  $((\text{size\_t})p \% n == 0)$ .

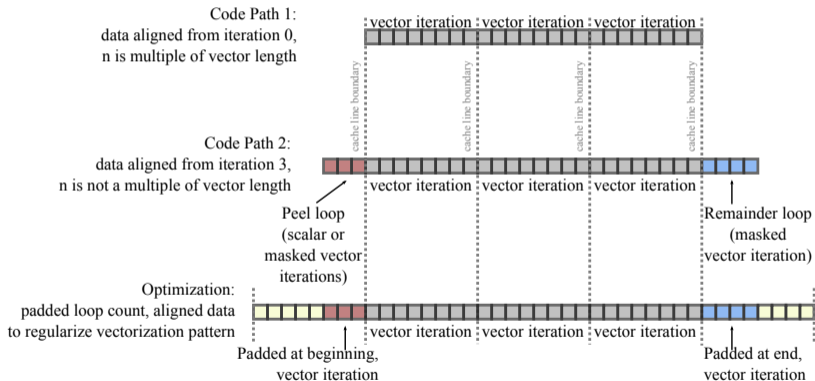
Processor	Operation	Alignment
Xeon (Westmere and earlier)	SSE load, store	16-byte
Xeon (Sandy Bridge and later)	AVX load, store	32-byte (relaxed)
Xeon Phi (1st gen)	IMCI load, store	64-byte (strict)
Xeon Phi (1st gen)	DMA transfer in offload	4096-byte (preferred)
Xeon Phi (2nd gen)	AVX-512 load, store	64-byte (relaxed)

Why align: speed up vector load/stores, avoid false sharing (see Session 7), accelerate RDMA.

# WHAT HAPPENS WITHOUT ALIGNMENT

Compiler may implement peel and remainder loops:

```
for (i = 0; i < n; i++) A[i] = ...
```



# CREATING ALIGNED DATA CONTAINERS

## ▷ Data alignment on the stack

```
1 float A[n] __attribute__((aligned(64))); // 64-byte alignment applied
```

## ▷ Data alignment on the heap

```
1 float *A = (float*) _mm_malloc(sizeof(float)*n, 64);
```

- ▷ A[0] is aligned on a 64-byte boundary.
- ▷ Very high alignment value may lead to wasted virtual memory.
- ▷ Fortran: directive or compiler argument `-align array64byte`

# PADDING MULTI-DIMENSIONAL CONTAINERS FOR ALIGNMENT

To use aligned instructions, you may need to pad inner dimension of multi-dimensional arrays to a multiple of 16 (in SP) or 8 (DP) elements.

Incorrect:

```
1 // A - matrix of size (n x n)
2 // n is not a multiple of 16
3 float* A =
4   _mm_malloc(sizeof(float)*n*n, 64);
5
6 for (int i = 0; i < n; i++)
7     // A[i*n + 0] may be unaligned
8     for (int j = 0; j < n; j++)
9         A[i*n + j] = ...
```

Correct:

```
1 // ... Padding inner dimension
2 int lda=n + (16-n%16); // lda%16==0
3 float* A =
4   _mm_malloc(sizeof(float)*n*lda, 64);
5
6 for (int i = 0; i < n; i++)
7     // A[i*lda + 0] aligned for any i
8     for (int j = 0; j < n; j++)
9         A[i*lda + j] = ...
```

# DATA ALIGNMENT HINTS

Programmer may promise to the compiler (under penalty of segmentation fault) that alignment has been taken care of:

```
1 // Promising that A[i*lda + 0] is aligned for every i
2 // and the same for every other array in this loop
3 #pragma vector aligned
4     for (int j = 0; j < n; j++)
5         A[i*lda + j] -= ...
```

This can lead to significant speedups, because compiler will not implement runtime checks for alignment situation and *peel loops*.



## **EXAMPLE: LU DECOMPOSITION**

# EXAMPLE: LU DECOMPOSITION

```

1 void LU_decomp(const int n, float* const A) {
2     // LU decomposition (Doolittle algorithm)
3     // In-place decomposition of form A=LU
4     // L is returned below main diagonal of A
5     // U is returned at and above main diagonal
6     for (int b = 0; b < n; b++) {
7         // Strength reduction:
8         const float recAbb = 1.0f/A[b*n + b];
9         for (int i = b+1; i < n; i++) {
10            A[i*n + b] = A[i*n + b]*recAbb;
11        #pragma simd
12            for (int j = b+1; j < n; j++)
13                A[i*n + j] -= A[i*n + b]*A[b*n + j];
14        }
15    }
16 }

```

LU decomposition for small matrices. ( $n \approx 128$ )

Based on publication:

<http://xeonphi.com/papers/>

Non-optimal  
Vectorization Pattern.

- ▶ Unaligned
- ▶ Irregular loop count

# LU DECOMPOSITION: REGULARIZING VECTORIZATION

Before:

```

1  for (int b = 0; b < n; b++) {
2      // ...
3      // ...
4      for (int i = b+1; i < n; i++) {
5          // ...
6          for (int j = b+1; j < n; j++)
7              A[i*n+j] -= A[i*n+b]*A[b*n+j];
8      }
9  }
```

After:

```

1  for (int b = 0; b < n; b++) {
2      // ...
3      const int jMin = (b+1) - (b+1)%16;
4      for (int i = b+1; i < n; i++) {
5          // ...
6          for (int j = jMin; j < n; j++)
7              A[i*n+j] -= L[i*n+b]*A[b*n+j];
8      }
9  }
```

Loop in j always starts on a multiple of 64 →  
aligned access to A and L

# LU DECOMPOSITION: COMPILER HINTS

- ▶ Data alignment hint: `#pragma vector aligned`

Before:

```

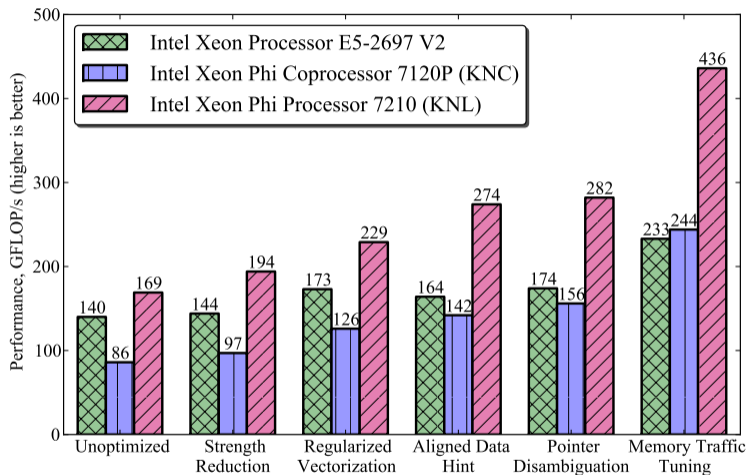
1  for (int b = 0; b < n; b++) {
2      const int jMin = (b+1)-(b+1)%tile;
3      const float recAbb = 1.0f/A[b*n+b];
4      for (int i = b+1; i < n; i++) {
5          L[i*n + b] = A[i*n + b]*recAbb;
6
7
8      #pragma simd
9          for (int j = jMin; j < n; j++)
10             A[i*n+j] -= L[i*n+b]*A[b*n+j];
11     }
12 }
```

After:

```

1  for (int b = 0; b < n; b++) {
2      const int jMin = (b+1)-(b+1)%tile;
3      const float recAbb = 1.0f/A[b*n+b];
4      for (int i = b+1; i < n; i++) {
5          L[i*n + b] = A[i*n + b]*recAbb;
6
7          #pragma vector aligned
8          #pragma ivdep
9          #pragma simd
10             for (int j = jMin; j < n; j++)
11                 A[i*n+j] -= L[i*n+b]*A[b*n+j];
12     }
13 }
```

# LU DECOMPOSITION: PERFORMANCE



Paper: <http://xeonphi.com/papers/lu>

## LOOP WAS VECTORIZED, NOW WHAT?

1. Ensure unit stride access
2. Align data
3. Pad multi-dimensional containers
4. Eliminate peel loops
5. Eliminate multiversioning
6. **Optimize data re-use in caches**

### Good to Know

Vector FLOPs are cheap compared to memory access.

If your data is served by RAM and not caches, it does not matter if you have vectorization: you will be bottlenecked by memory access.



## **STRIP-MINING FOR VECTORIZATION**

# STRIP-MINING: METHOD

- ▶ Strip-mining is a programming technique that turns one loop into two nested loops.
- ▶ used to expose vectorization opportunities in the inner loop.

Original code:

```
1 for (int i = 0; i < n; i++) {  
2     // ... do work  
3 }
```

Strip-mined implementation:

```
1 const int STRIP=1024;  
2 for (int ii = 0; ii < n; ii += STRIP)  
3     for (int i = ii; i < ii+STRIP; i++) {  
4         // ... do work  
5     }
```

## **EXAMPLE: BINNING**

# EXAMPLE: BINNING PROBLEM

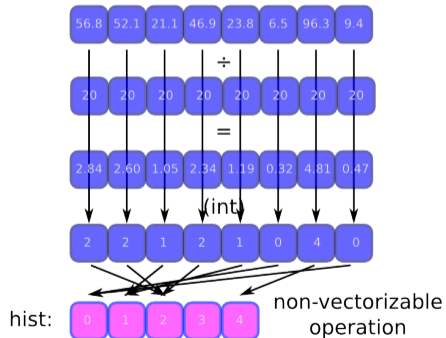
Computing a histogram ( $m \ll n$ ):

```

1 void Histogram(
2     // Ages, values from 0.0f to 100.0f:
3     const float* age,
4     // Size of array age, n=100000000:
5     const int n,
6     // Output: counts in groups:
7     int* const hist,
8     // Size of array hist, m=5:
9     const int m,
10    const float group_width) {
11    for (int i = 0; i < n; i++) {
12        const int j = int(age[i]/group_width);
13        hist[j]++;
14    }
15 }

```

- ▶ Vector dependence in `hist[j]++`
- ▶ Strip-mine or use conflict detection

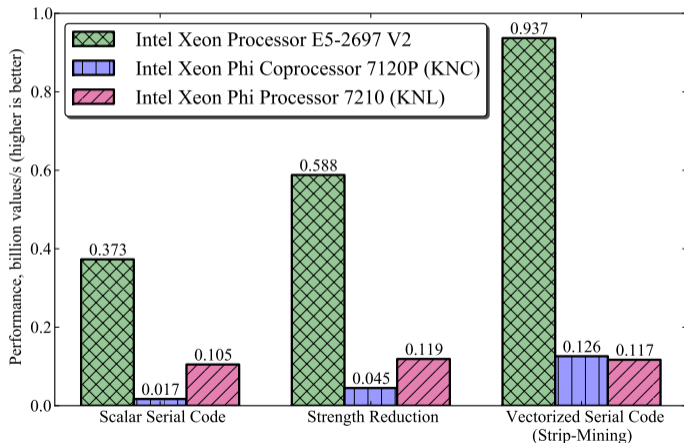


# THE SAME CALCULATION, STRIP-MINED, VECTORIZED

```
1 void Histogram(const float* age, int* const hist, const int n,  
2 const float group_width, const int m) {  
3     const int vecLen = 16; // Length of vectorized loop  
4     const float invGroupWidth = 1.0f/group_width; // Pre-compute the reciprocal  
5     // Strip-mining the loop in order to vectorize the inner short loop  
6     // Note: this algorithm assumes n%vecLen == 0.  
7     for (int ii = 0; ii < n; ii += vecLen) { //Temporary store vecLen indices  
8         int index[vecLen] __attribute__((aligned(64)));  
9         // Vectorize the multiplication and rounding  
10    #pragma vector aligned  
11        for (int i = ii; i < ii + vecLen; i++)  
12            index[i-ii] = (int) ( age[i] * invGroupWidth );  
13        // Scattered memory access, does not get vectorized  
14        for (int c = 0; c < vecLen; c++)  
15            hist[index[c]]++;  
16    }  
17 }
```

# STRIP-MINING FOR VECTORIZATION

Vectorization improves performance on both platforms. However, more work is needed to take advantage of the MIC architecture. See materials on multi-threading.





## **§5. REVIEW AND WHAT'S NEXT**

# SUMMARY

1. Vector-Friendly Data Structures
  - Use data structures that allow for unit-stride vector load.
2. Regularization of Vectorization Pattern
  - Align data to 64-byte boundaries
  - Pad data containers and loop bounds
3. Remove Run-time Checks
  - Disable run-time checks for alignment and aliasing with compiler hints
4. Strip-Mining for Vectorization
  - Use strip-mining expose vectorization opportunities.

## NEXT SESSION

Next class: optimization of thread parallelism, part I.

1. Controlling synchronization in parallel reduction
2. Dealing with insufficient parallelism



**LEARN MORE**

# HOW SERIES: KNIGHTS LANDING

HOW SERIES "KNIGHTS LANDING":

PROGRAMMING AND OPTIMIZATION FOR  
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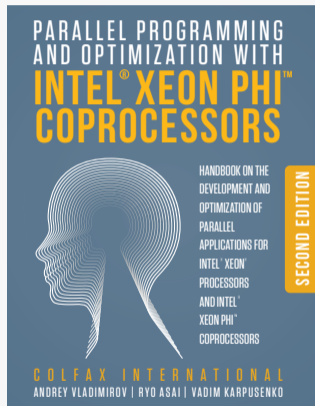
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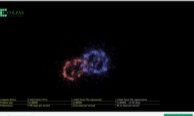
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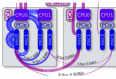
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