Programming and Optimization for Intel® Architecture

The Hands-On Workshop (HOW) Series

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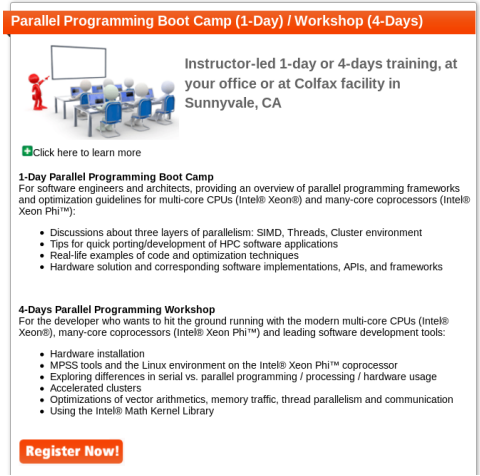
About This Document

This document represents the materials of a Web-based training “Programming and Optimization with Intel Architecture“ developed and run by Colfax International.



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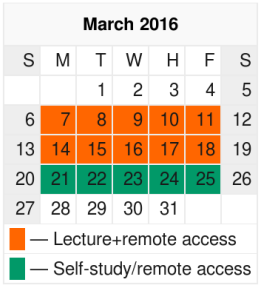
Course Roadmap

1. Why Intel Parallel Architectures?
   - Parallelism and specialization – March 7
   - Programming model continuity – March 7
2. Programming models for Xeon Phi coprocessors
   - Native programming – March 7
   - Offload programming – March 8
3. Expressing Parallelism
   - Introduction to vectorization – March 9
   - Crash-course on OpenMP – March 10
4. Optimization – intro on March 11
   - Vectorization tuning – March 14
   - Multi-threading – March 15, 16
   - Memory traffic – March 17
5. ~~Tools: MKL and VTune~~ MPI – March 18



HOW Online

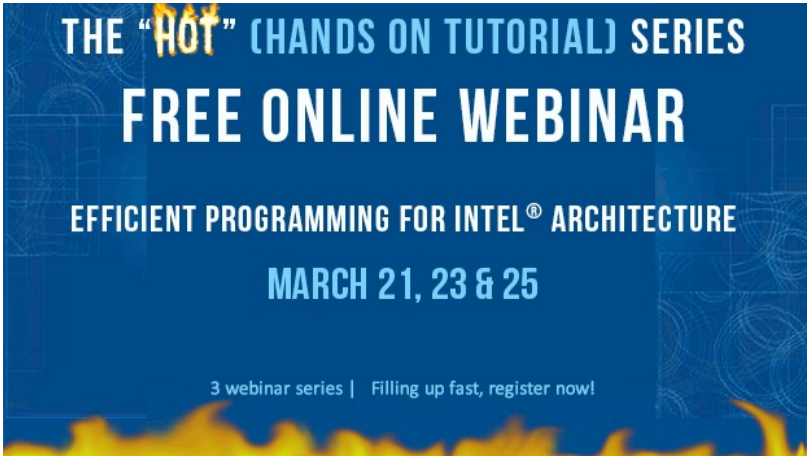
Course page: colfaxresearch.com/how-16-03

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

Additional resources:

- More workshops like this one: colfaxresearch.com/how-series
- Video courses: colfaxresearch.com/video-courses
- Intel Many Integrated Core Architecture Forum

HOT Series



colfaxresearch.com/hot-16-03/

HOW Series, April 2016

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§2. Refresh

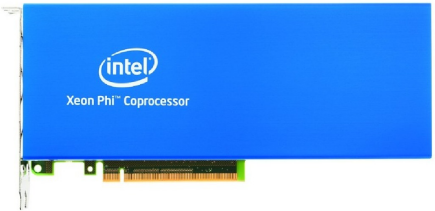
Performance Optimization

Computing Platforms

Intel Xeon Processor

Current: Haswell
Upcoming: Broadwell

Intel Xeon Phi Corocessor, 1st generation



Current: Knights Corner (KNC)

Intel Xeon Phi Processor, 2nd generation*

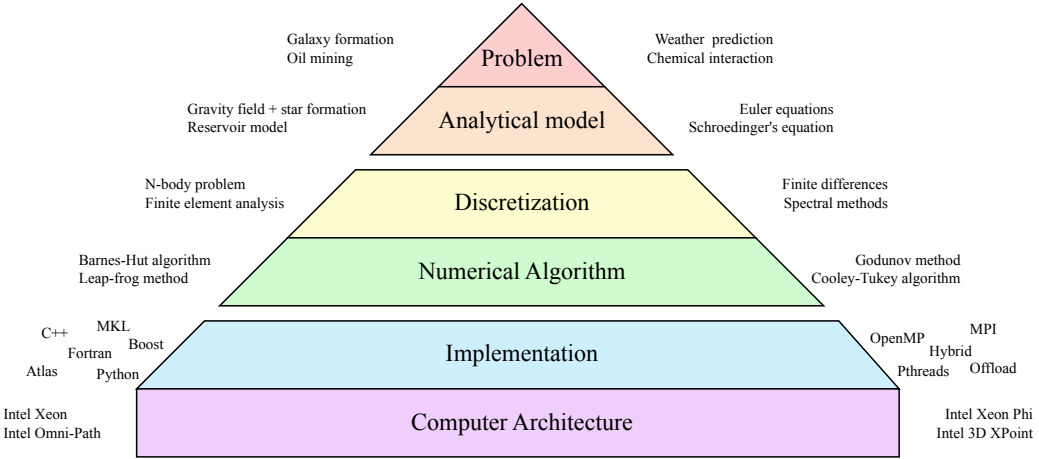
* socket and coprocessor versions

Upcoming: Knights Landing (KNL)

Multi-Core Architecture

Intel Many Integrated Core (MIC) Architecture

Computing in Science and Engineering

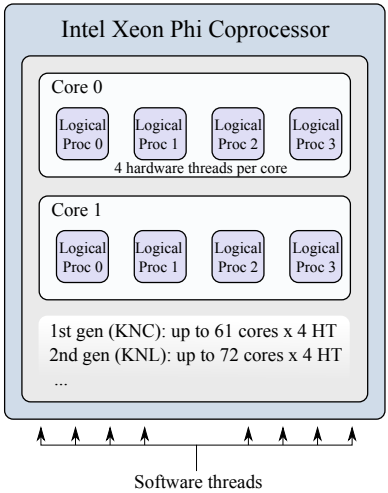


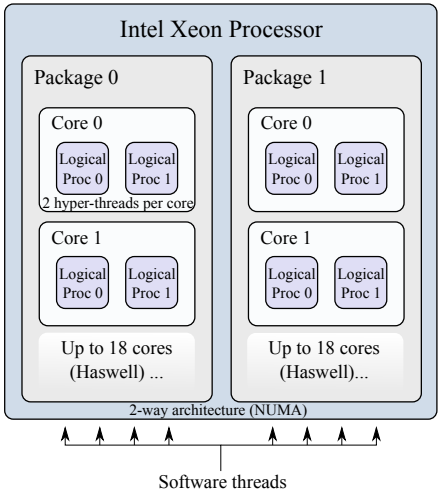
Optimization Areas

1. **Scalar optimization** (compiler-friendly practices)
2. **Vectorization** (must use 16- or 8-wide vectors)
3. **Multi-threading** (must scale to 100+ threads)
4. **Memory access** (streaming access or tiling)
5. **Communication** (offload, MPI traffic control)

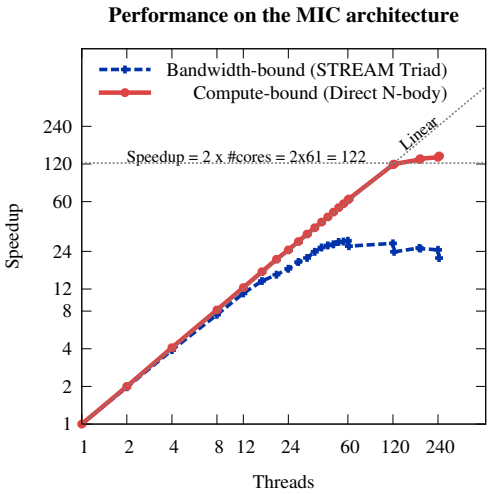
Cores, Threads and OpenMP

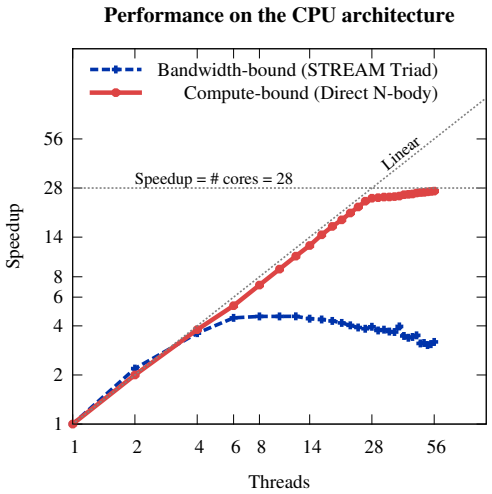
Processor Hierarchy





Scalability Expectations: MIC versus CPU





“Hello World” OpenMP Programs

```
1  #include <omp.h>
2  #include <stdio.h>
3
4  int main(){
5    const int nt=omp_get_max_threads();
6    printf("OpenMP with %d threads\n", nt);
7
8  #pragma omp parallel
9    {
10     printf("Hello World from thread %d\n", omp_get_thread_num());
11   }
12 }
```


§3. Optimization of Multi-Threading I

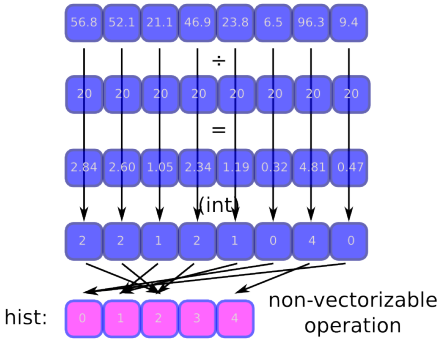
Too Much Synchronization

Example: Strip-Mining for Vectorization

Computing a histogram ($m << n$):

```
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   // group_width=20.0f
11   const float group_width) {
12     for (int i = 0; i < n; i++) {
13       const int j = int(age[i]/group_width);
14       hist[j]++;
15     }
16 }
```

- Code cannot be auto-vectorized
- True vector dependence

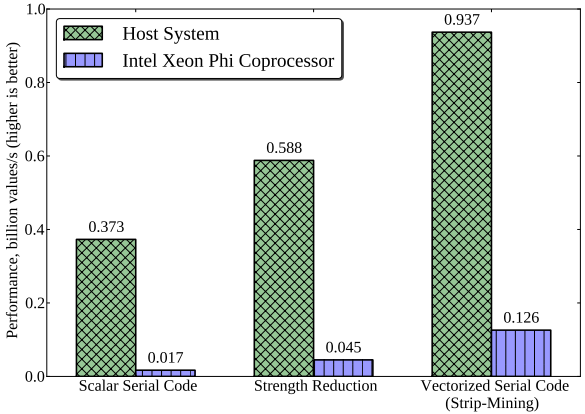


The Same Calculation, Strip-Mined, Vectorized

```
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.



Histogram Calculation Example: Adding Thread Parallelism

Incorrect solution: unprotected data races

```
1  #pragma omp parallel for schedule(guided)
2  for (int ii = 0; ii < n; ii += vecLen) {
3    int index[vecLen] __attribute__((aligned(64)));
4  #pragma vector aligned
5    for (int i = ii; i < ii + vecLen; i++)
6      index[i-ii] = (int) ( age[i] * invGroupWidth );
7    for (int c = 0; c < vecLen; c++)
8      // Multiple threads will write into a single shared container
9      // These data races lead to incorrect results!
10     hist[index[c]]++;
11 }
```


Histogram Calculation Example: Adding Thread Parallelism

Correct, but inefficient solution:

```
#pragma omp parallel for schedule(guided)
for (int ii = 0; ii < n; ii += vecLen) {
  int index[vecLen] __attribute__((aligned(64)));
#pragma vector aligned
  for (int i = ii; i < ii + vecLen; i++)
    index[i-ii] = (int) ( age[i] * invGroupWidth );
  for (int c = 0; c < vecLen; c++)
    // Protect the ++ operation with the atomic mutex (inefficient!)
#pragma omp critical
    { hist[index[c]]++; }
}
```


Histogram Calculation Example: Adding Thread Parallelism

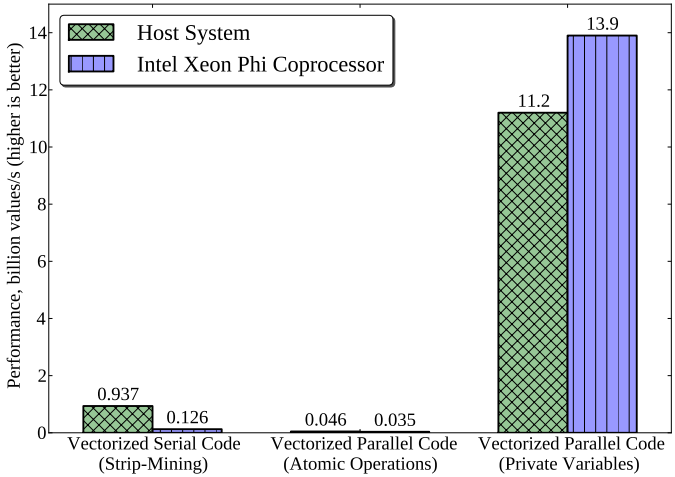
Correct, but inefficient solution:

```
#pragma omp parallel for schedule(guided)
for (int ii = 0; ii < n; ii += vecLen) {
  int index[vecLen] __attribute__((aligned(64)));
#pragma vector aligned
  for (int i = ii; i < ii + vecLen; i++)
    index[i-ii] = (int) ( age[i] * invGroupWidth );
  for (int c = 0; c < vecLen; c++)
    // Protect the ++ operation with the atomic mutex (inefficient!)
#pragma omp atomic
    hist[index[c]]++;
}
```


Correct and Efficient Solution with Reduction

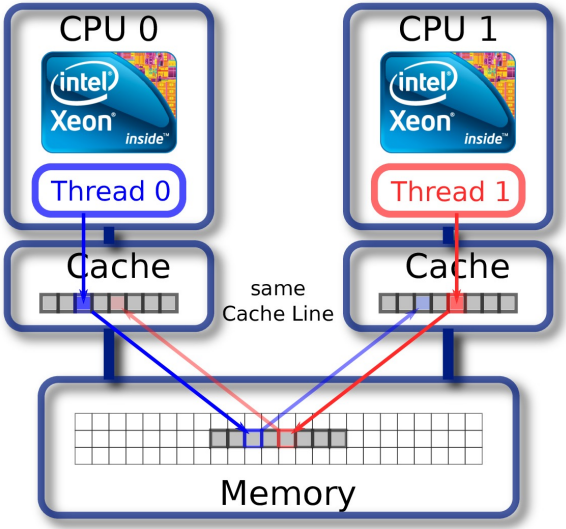
```
#pragma omp parallel
{
  int hist_priv[m]; // Better idea: thread-private storage
  hist_priv[:] = 0;
  int index[vecLen] __attribute__((aligned(64)));
#pragma omp for schedule(guided)
  for (int ii = 0; ii < n; ii += vecLen) {
#pragma vector aligned
    for (int i = ii; i < ii + vecLen; i++)
      index[i-ii] = (int) ( age[i] * invGroupWidth );
    for (int c = 0; c < vecLen; c++)
      hist_priv[index[c]]++;
  }
  for (int c = 0; c < m; c++) {
#pragma omp atomic
    hist[c] += hist_priv[c];
} }
```


Using Reduction instead of Synchronization



False Sharing

False Sharing. Data Padding and Private Variables



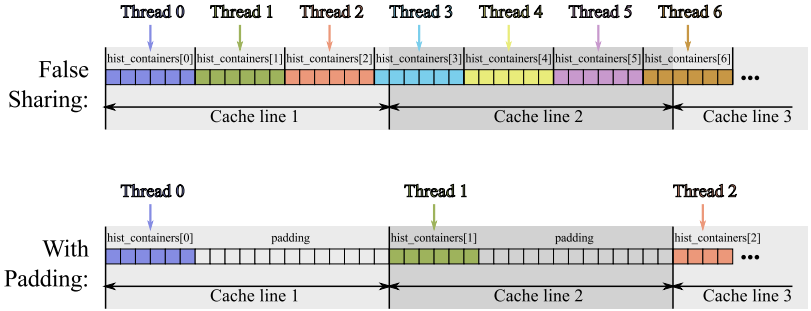
- False sharing is similar to race condition
- Threads accessing the same cache line
- Caused by coherent caches
- Cache line is 64-byte wide (in modern Intel architectures)

False Sharing. Data Padding and Private Variables

```
1  const int m = 5;
2  int hist_thr[nThreads][m];
3  #pragma omp parallel for
4  for (int ii = 0; ii < n; ii += vecLen) {
5    // ...
6    // False sharing occurs here
7    for (int c = 0; c < vecLen; c++)
8      hist_thr[iThread][index[c]]++;
9  }
10 // Reducing results from all threads to the common histogram hist
11 for (int iThread = 0; iThread < nThreads; iThread++)
12   hist[0:m] += hist_thr[iThread][0:m];
```

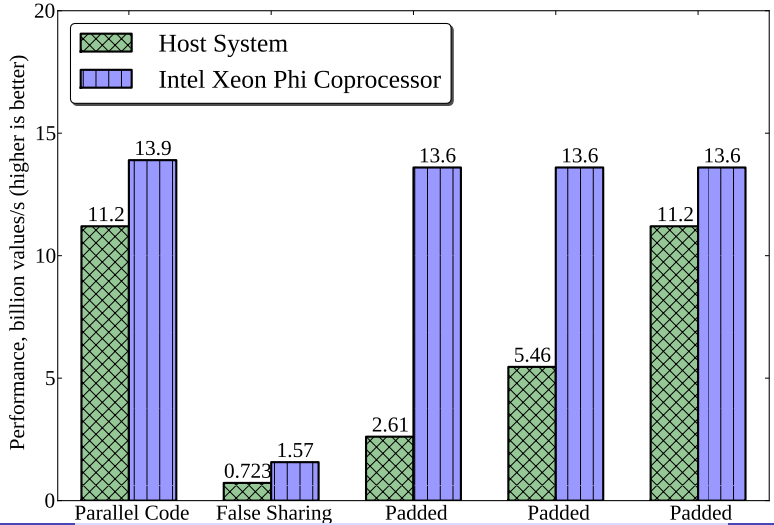
- The value of `m=5` is small
- Array elements `hist_thr[0][:]` are within `m*sizeof(int)=20` bytes of array elements `hist_thr[1][:]`

Padding to Avoid False Sharing




```
1 // Padding to avoid sharing a cache line between threads
2 const int paddingBytes = 64;
3 const int paddingElements = paddingBytes / sizeof(int);
4 const int mPadded = m + (paddingElements-m%paddingElements);
5 int hist_containers[nThreads][mPadded]; // New container
```


Padding to Avoid False Sharing



Insufficient Parallelism

Example: Dealing with Insufficient Parallelism

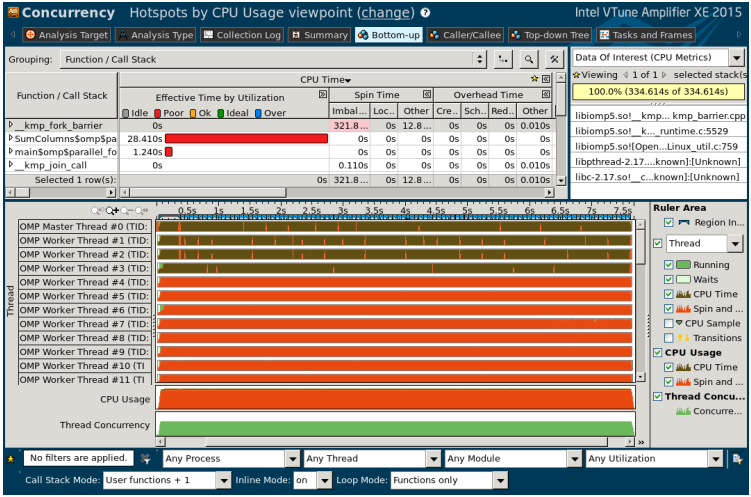
$$S_i = \sum_{j=0}^{n} M_{ij},\ i = 0 \ldots m. \tag{1}$$

- `m=4` is small, smaller than the number of threads in the system
- `n` $\approx 10^8$ is large enough so that matrix does not fit into cache

```
1 void sum_unoptimized(const int m, const int n, long* M, long* s){
2 #pragma omp parallel for
3   for (int i=0; i<m; i++) { // m=4
4     long sum=0;
5 #pragma vector aligned
6     for (int j=0; j<n; j++) // n=100000000
7       sum+=M[i*n+j];
8   s[i]=sum; }}
```


Dealing with Insufficient Parallelism

VTune Analysis: Row-Wise Reduction of a Short, Wide Matrix



Does not Work: Parallelizing Inner Loop

Inner loop has more iterations, parallelize there?

```
1  void SumParallelInnerLoop(const int m, const int n, long* M, long* s){
2    for (int i = 0; i < m; i++) { // m=4
3      long sumOfColumns = 0;
4  #pragma omp parallel for reduction(+: sumOfColumns)
5      for (int j = 0; j < n; j++) { // n=100000000
6        sumOfColumns += M[i*n + j];
7      }
8      s[i] = sumOfColumns;
9    }
10 }
```

Does not work well: code must spawn and stop threads many times; OpenMP does not see the entire parallel region.

Loop Collapse: Principle

Idea: combine iterations spaces of the inner loop and the outer loop.

```
1 #pragma omp parallel for collapse(2)
2   for (int i = 0; i < m; i++)
3     for (int j = 0; j < n; j++) {
4       // ...
5       // ...
6     }
```

```
1 #pragma omp parallel for
2   for (int c = 0; c < m*n; c++)  {
3     i = c / n;
4     j = c % n;
5     // ...
6   }
```

Does not Work, but Correct Direction: Loop Collapse

Loop collapse applied to the wide short matrix example:

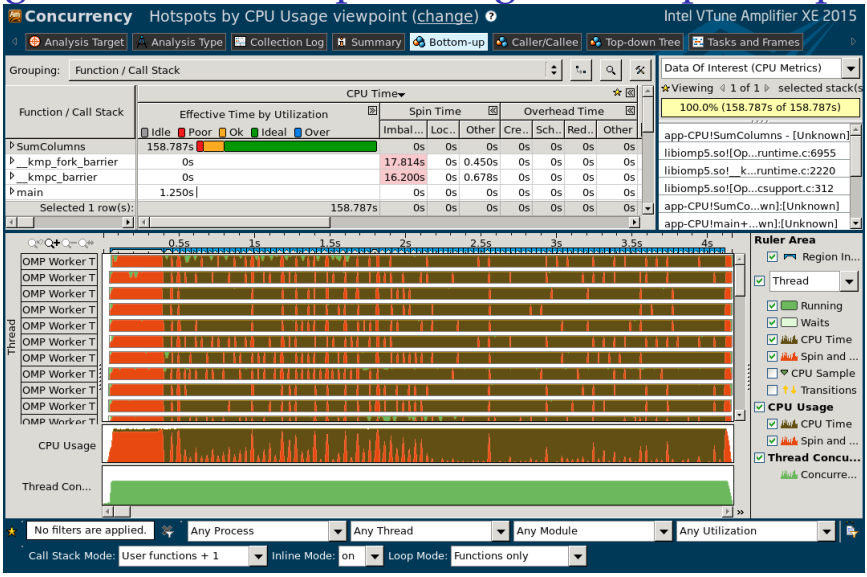
```
1  void SumCollapse(const int m, const int n, long* M, long* s){
2    s[:]=0;
3  #pragma omp parallel
4    { // Each thread will have a private container
5      long sumOfColumns[m];  sumOfColumns[:] = 0;
6  #pragma omp for collapse(2)
7      for (int i = 0; i < m; i++) // m=4
8        for (int j = 0; j < n; j++) // n=100000000
9          sumOfColumns[i] += M[i*n + j];
10     for (int i = 0; i < m; i++)
11 #pragma omp atomic
12       s[i]=sumOfColumns[i];
13 } }
```

Does not work: automatic vectorization fails.

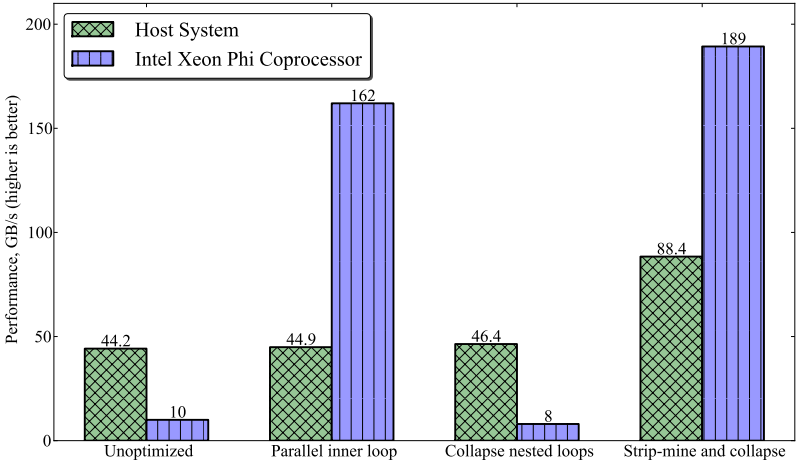
Exposing Parallelism: Strip-Mining and Loop Collapse

```
1  void sum_stripmine(const int m, const int n, long* M, long* s){
2    const int STRIP=1024;
3    assert(n%STRIP==0);
4    s[0:m]=0;
5  #pragma omp parallel
6    {
7      long sum[m];   sum[0:m]=0;
8  #pragma omp for collapse(2) schedule(guided)
9      for (int i=0; i<m; i++)
10       for (int jj=0; jj<n; jj+=STRIP)
11 #pragma vector aligned
12         for (int j=jj; j<jj+STRIP; j++)
13           sum[i]+=M[i*n+j];
14     for (int i=0; i<m; i++)          // Reduction
15 #pragma omp atomic
16       s[i]+=sum[i];
17 }   }
```


Exposing Parallelism: Strip-Mining and Loop Collapse



Dealing with Insufficient Parallelism



Techniques that did not work well are discussed in the book.

§4. Review and What's Next

Summary

This session:

1. Synchronization is necessary to resolve data races, but mutexes must be moved out of innermost loops
2. False sharing can be resolved with padding
3. Strip-mining can help to expose parallelism

Next session: optimization of thread affinity, NUMA locality, nested parallelism and loop scheduling.

