



Programming and Optimization for Intel[®] Architecture

The Hands-On Workshop (HOW) Series

Colfax International — @colfaxintl

August 2016 , Rev. 03b

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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Parallel Programming Boot Camp (1-Day) / Workshop (4-Days)



Instructor-led 1-day or 4-days training, at your office or at Colfax facility in Sunnyvale, CA

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1-Day Parallel Programming Boot Camp
 For software engineers and architects, providing an overview of parallel programming frameworks and optimization guidelines for multi-core CPUs (Intel® Xeon®) and many-core coprocessors (Intel® Xeon Phi™):

- Discussions about three layers of parallelism: SIMD, Threads, Cluster environment
- Tips for quick porting/development of HPC software applications
- Real-life examples of code and optimization techniques
- Hardware solution and corresponding software implementations, APIs, and frameworks

4-Days Parallel Programming Workshop
 For the developer who wants to hit the ground running with the modern multi-core CPUs (Intel® Xeon®), many-core coprocessors (Intel® Xeon Phi™) and leading software development tools:

- Hardware installation
- MPSS tools and the Linux environment on the Intel® Xeon Phi™ coprocessor
- Exploring differences in serial vs. parallel programming / processing / hardware usage
- Accelerated clusters
- Optimizations of vector arithmetics, memory traffic, thread parallelism and communication
- Using the Intel® Math Kernel Library

Register Now!

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Course Roadmap

- HOW to Program Intel Architecture
 - ▶ 01. Parallelism, specialization, guided tour – Aug 29
 - ▶ 02. Programming Intel Xeon Phi (KNC, KNL) – Aug 30
- HOW to Express Parallelism
 - ▶ 03. Automatic vectorization – Aug 31
 - ▶ 04. Multi-threading with OpenMP – Sep 1
- HOW to Get Performance
 - ▶ 05. Comprehensive demo – Sep 2
 - ▶ 06. Scalar & vectorization tuning – Sep 5
 - ▶ 07. Multi-threading I – Sep 6
 - ▶ 08. Multi-threading II – Sep 7
 - ▶ 09. Memory traffic – Sep 8
- HOW to Scale
 - ▶ 10. Distributed Computing: MPI – Sep 9

August 2016						
S	M	T	W	H	F	S
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

September 2016						
S	M	T	W	H	F	S
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11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	

 — Webinar+remote access

HOW Online

Course page: colfaxresearch.com/how-16-08

- 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
- Video courses: colfaxresearch.com/video-courses

Get Your Questions Answered

Chat (current):

colfaxresearch.com/how-16-08



Forums (technical):

colfaxresearch.com/discussion

Log In/Register

COLFAX RESEARCH

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Join the Conversation

Welcome to Colfax Research forums, an online community for you to engage with HPC experts, software architects, developers, computational researchers, scientists, students and more—so you can acquire new knowledge, share ideas, and build new relationships.

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.

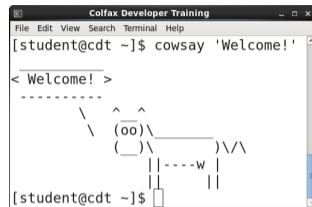
Welcome aboard. Post questions today!

Email (organizational):

training@colfax-intl.com

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
-
- 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



```
Colfax Developer Training
File Edit View Search Terminal Help
[student@cdt ~]$ cowsay 'Welcome!'
< Welcome! >
-----
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[student@cdt ~]$
```

§2. Expressing Task Parallelism

Handling Multiple Cores

Computing Platforms

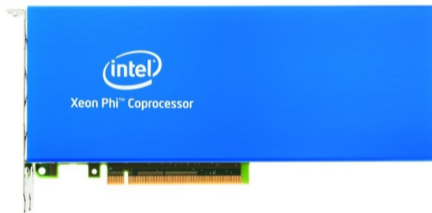
Intel Xeon Processor



Current: Broadwell
Upcoming: Skylake

Multi-Core Architecture

Intel Xeon Phi Coprocessor, 1st generation



Knights Corner (KNC)

Intel Xeon Phi Processor, 2nd generation*

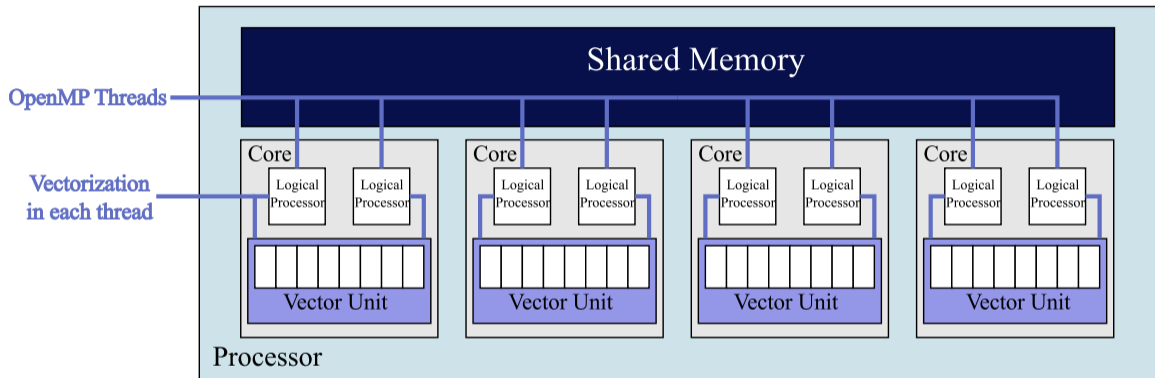


* socket and coprocessor versions

Knights Landing (KNL)

Intel Many Integrated Core (MIC) Architecture

Co-Existence with Vectors



Utilize cores: run multiple threads/processes (MIMD)

Utilize vectors: each thread (process) issues vector instructions (SIMD)

Simultaneous Threading and Vectorization

This approach often works:

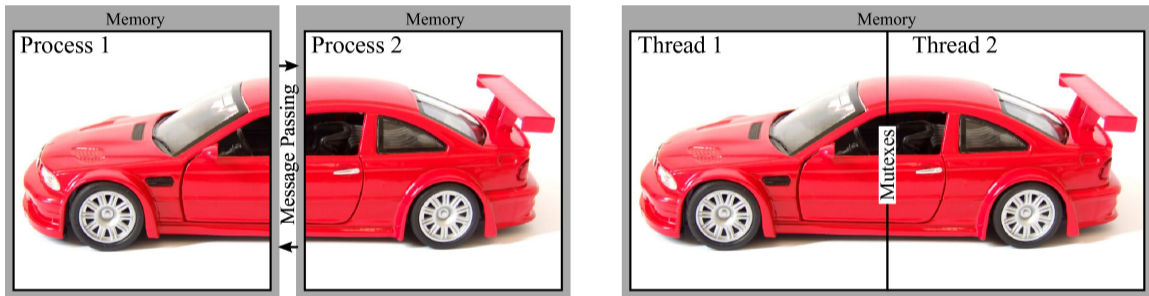
```
1 #pragma omp parallel for
2 for (int i = 0; i < n; i++) // Thread parallelism in outer loop
3 #pragma simd
4   for (int j = 0; j < m; j++) // Vectorization in inner loop
5     DoSomeWork(A[i][j]);
```

That works as well:

```
1 #pragma omp parallel for simd
2 for (int i = 0; i < n; i++) // If the problem is all data-parallel
3   DoSomeWork(A[i]);
```

Threads versus Processes

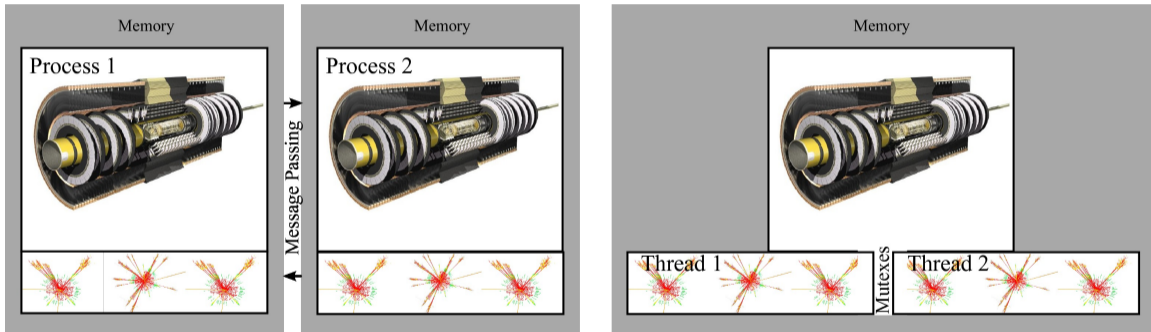
Option 1: Partitioning data set between threads/processes



Examples: computational fluid dynamics (CFD), image processing.

Threads versus Processes

Option 2: Sharing data set between threads/processes



Examples: particle transport simulation, machine learning (inference).

Scalability Expectations (CPU)

T = number of threads

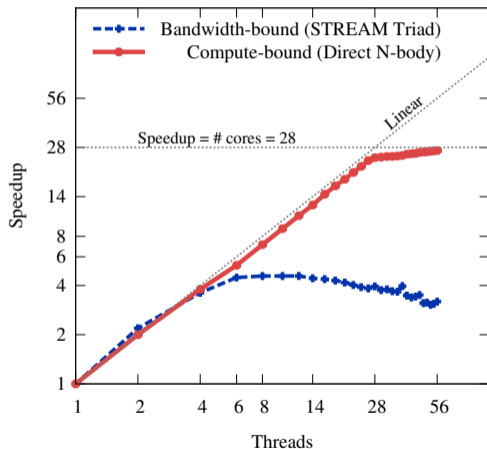
$$\text{Speedup}(T) = \frac{\text{Performance}(T)}{\text{Performance}(1)}$$

$$\text{Efficiency}(T) = \frac{\text{Speedup}(T)}{T}$$

Linear scaling (ideal case, 100% parallel efficiency):

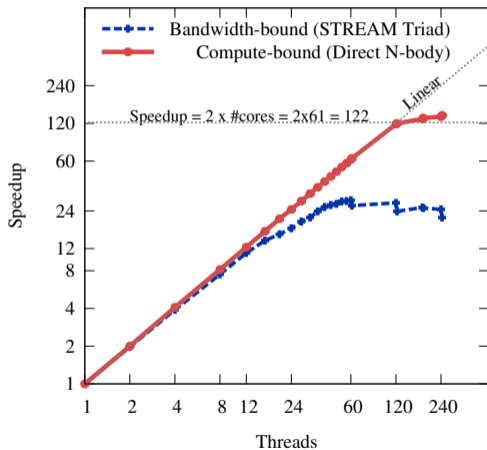
$$\text{Speedup}(T) = T$$

Performance on the CPU architecture

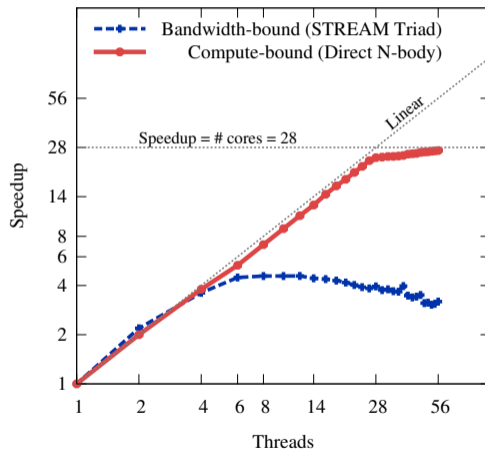


Scalability Expectations: MIC versus CPU

Performance on the MIC architecture



Performance on the CPU architecture



Threading Frameworks

Framework	Implementation	Complexity	Functionality
POSIX Threads	Various	Simple	Manually control everything
Cilk Plus	Intel, Public	Very simple	Automatic loops and tasks, no user control
TBB	Intel, Public	Complex	Automatic trees of tasks, au- tomatic scheduler
OpenMP	Various	Simple to Complex	HPC-specific functional- ity, automatic and manual control possible

OpenMP Basics

“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 }
```

“Hello World” OpenMP Programs

```
vega@lyra% icpc -qopenmp hello_omp.cc
vega@lyra% export OMP_NUM_THREADS=5
vega@lyra% ./a.out
OpenMP with 5 threads
Hello World from thread 0
Hello World from thread 3
Hello World from thread 1
Hello World from thread 2
Hello World from thread 4
```

`OMP_NUM_THREADS` controls number of OpenMP threads (default: logical CPU count)

Control of Variable Sharing

Method 1: using clauses in pragma omp parallel (C, C++, Fortran):

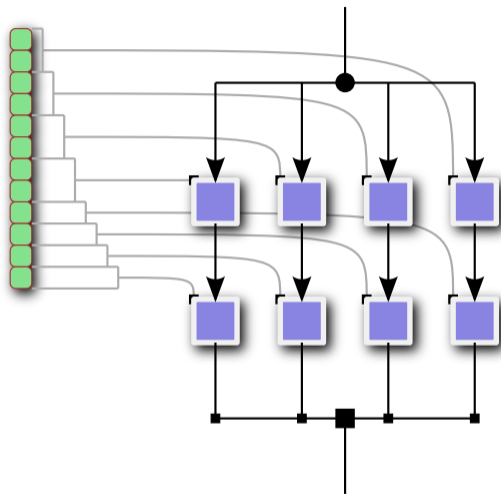
```
1 int A, B; // Variables declared at the beginning of a function
2 #pragma omp parallel private(A) shared(B)
3 {
4     // Each thread has its own copy of A, but B is shared
5 }
```

Method 2: using scoping (only C and C++):

```
1 int B; // Variable declared outside of parallel scope - shared by default
2 #pragma omp parallel
3 {
4     int A; // Variable declared inside the parallel scope - always private
5     // Each thread has its own copy of A, but B is shared
6 }
```

Loop-Centric Parallelism: For-Loops in OpenMP

- Simultaneously launch multiple threads
- Scheduler assigns loop iterations to threads
- Each thread processes one iteration at a time



Parallelizing a for-loop.

Loop-Centric Parallelism: For-Loops in OpenMP

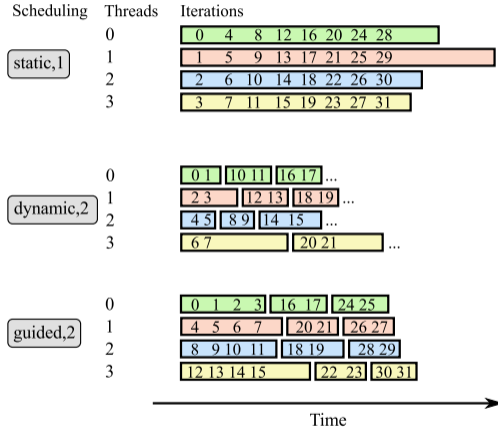
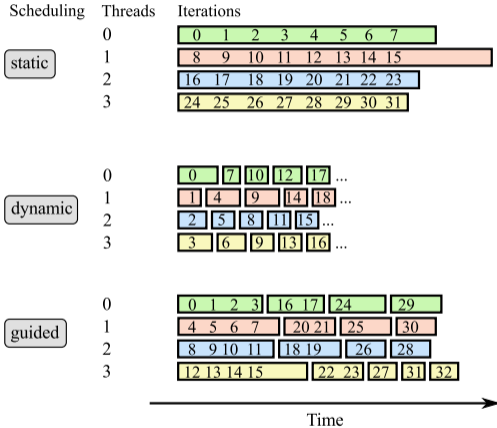
The OpenMP library will distribute the iterations of the loop following the `#pragma omp parallel for` across threads.

```
1  #pragma omp parallel for  
2  for (int i = 0; i < n; i++) {  
3      printf("Iteration %d is processed by thread %d\n",  
4          i, omp_get_thread_num());  
5      // ... iterations will be distributed across available threads...  
6  }
```

Loop-Centric Parallelism: For-Loops in OpenMP

```
1  #pragma omp parallel
2  {
3      // Code placed here will be executed by all threads.
4
5      // Alternative way to specify private variables:
6      // declare them in the scope of pragma omp parallel
7      int private_number=0;
8
9      #pragma omp for
10     for (int i = 0; i < n; i++) {
11         // ... iterations will be distributed across available threads...
12     }
13     // ... code placed here will be executed by all threads
14 }
```

Loop Scheduling Modes in OpenMP



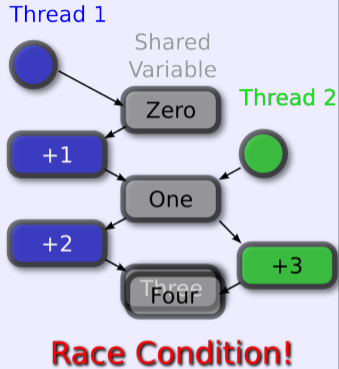
Thread Synchronization

Race Conditions and Unpredictable Program Behavior

```

1 #include <omp.h>
2 #include <stdio.h>
3 int main() {
4     const int n = 1000;
5     int total = 0;
6     #pragma omp parallel for
7     for (int i = 0; i < n; i++) {
8         // Race condition
9         total = total + i;
10    }
11    printf("total=%d (must be %d)\n", total, ((n-1)*n)/2);
12 }

```



```

vega@lyra% icpc -o omp-race omp-race.cc -qopenmp
vega@lyra% ./omp-race
total=208112 (must be 499500)

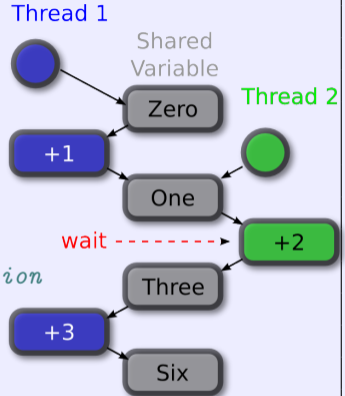
```

Protecting Race Conditions with a Critical Section

```

1 #include <omp.h>
2 #include <stdio.h>
3 int main() {
4     const int n = 1000;
5     int total = 0;
6     #pragma omp parallel for
7     for (int i = 0; i < n; i++) {
8     #pragma omp critical
9         { // Only one thread at a time can execute this section
10         total = total + i;
11         }
12 } }

```



```

vega@lyra% icpc -o omp-critical omp-critical.cc -qopenmp
vega@lyra% ./omp-critical
total=499500 (must be 499500)

```

Avoiding Races with Atomic Operations

This parallel fragment of code has predictable behavior, because the race condition was eliminated with *an atomic operation*:

```
1  #pragma omp parallel for
2  for (int i = 0; i < n; i++)
3  { // Lightweight synchronization
4  #pragma omp atomic
5     total += i;
6  }
```

Limitations of Atomic Operations

Read : operations in the form $v = x$

Write : operations in the form $x = v$

Update : operations in the form $x++$, $x--$, $--x$, $++x$, $x \text{ binop} = \text{expr}$
and $x = x \text{ binop} \text{ expr}$

Capture : operations in the form $v = x++$, $v = x--$, $v = -x$, $v = ++x$,
 $v = x \text{ binop} \text{ expr}$

- Here x and v are scalar variables
- *binop* is one of $+$, $*$, $-$, $- /$, $\&$, \wedge , $|$, \ll , \gg .
- No “trickery” is allowed for atomic operations:
 - ▶ no operator overload,
 - ▶ no non-scalar types,
 - ▶ no complex expressions.

Parallel Reduction

Reduction Clause in Parallel Region

```
1 #include <omp.h>
2 #include <stdio>
3
4 int main() {
5     const int n = 1000;
6     int total = 0;
7     #pragma omp parallel for reduction(+: total)
8     for (int i = 0; i < n; i++) {
9         total = total + i;
10    }
11    printf("total=%d (must be %d)\n", total, ((n-1)*n)/2);
12 }
```

```
vega@lyra% icpc -o omp-reduction omp-reduction.cc -qopenmp
vega@lyra% ./omp-reduction
total=499500 (must be 499500)
```

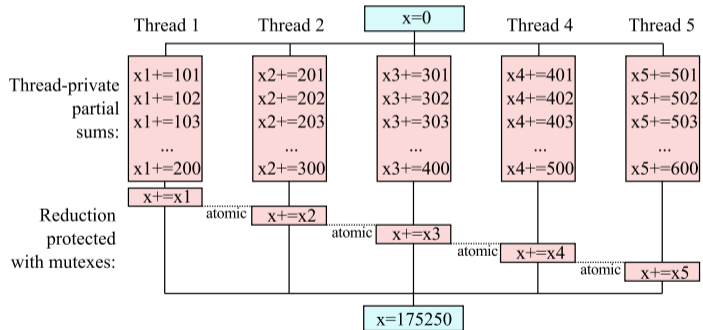
Avoiding Races with Thread-Private Storage

Correct and efficient code:

```

1  int total = 0;
2  #pragma omp parallel
3  {
4      int total_thr = 0;
5      #pragma omp for
6      for (int i=0; i<n; i++)
7          total_thr += i;
8
9      #pragma omp atomic
10     total += total_thr;
11 }
12

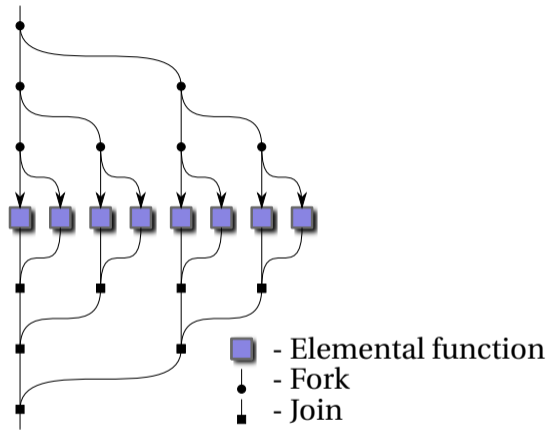
```



Tasks in OpenMP

Fork-Join Model of Parallel Execution

- Each thread can spawn daughter threads
- Available threads pick up queued tasks
- Expresses algorithms that cannot be expressed in the loop model (e.g., parallel recursion)



Fork-join model of parallel execution.

(#pragma omp task functionality)

Tasks in OpenMP: Example

```
1 // Starting the first task:  
2 #pragma omp parallel  
3 { // Enter a parallel region  
4 #pragma omp single  
5   { // Start the first task  
6     // from only one thread  
7     RecursiveWorkload(args);  
8   }  
9 }
```

```
1 // Recursive task spawning:  
2 void RecursiveWorkload(Arg* args) {  
3   if (args->size > threshold) {  
4     // Split work  
5     Arg* args1=args->FirstHalf();  
6     Arg* args2=args->SecondHalf();  
7  
8     // Parallel divide-and-conquer  
9     #pragma omp task firstprivate(args1)  
10    { RecursiveWorkload(args1); }  
11    #pragma omp task firstprivate(args2)  
12    { RecursiveWorkload(args2); }  
13  } else {  
14    // End of recursion  
15    args->ProcessSmallestSubTask();  
16  }  
17 }
```

Recipes for Success

Recipe for Success: “Take a Deep Breath”

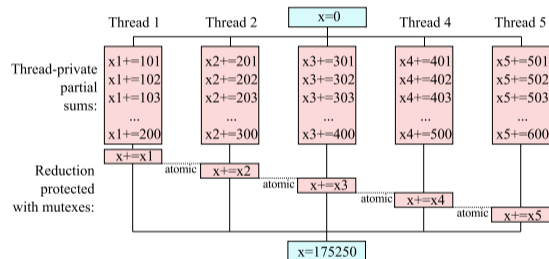
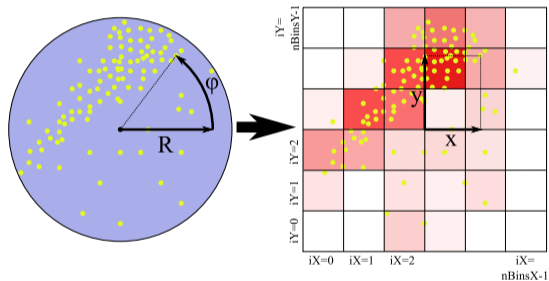
Where is parallelism in your application?



See also full interview with James Reinders at [Colfax Research](#)

Suggested Additional Reading

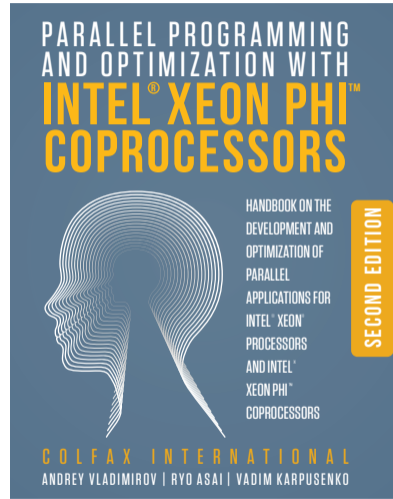
Colfax Research tutorial on multi-threading in a binning code



<http://colfaxresearch.com/?p=6>

Additional Materials on OpenMP

- 1 OpenMP Specifications
- 2 Intel's OpenMP Video Course
- 3 LLNL tutorial: OpenMP
- 4 Book: “Parallel Programming and Optimization with Intel Xeon Phi Coprocessors” by Colfax.



Summary

Discussed today:

- Cores can run independent programs
- Use threads to scale across cores
- OpenMP – well-established parallel framework for HPC
- Data races lead to incorrect, unpredictable results
- Mutexes control data races at cost of performance
- Co-exist with have vectorization in each thread

Next session: introduction into optimization for Xeon and Xeon Phi.

[Learn More](#)

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OPTIMIZATION FOR INTEL® XEON PHI™ PROCESSOR DEVELOPER'S GUIDE TO KNIGHTS LANDING

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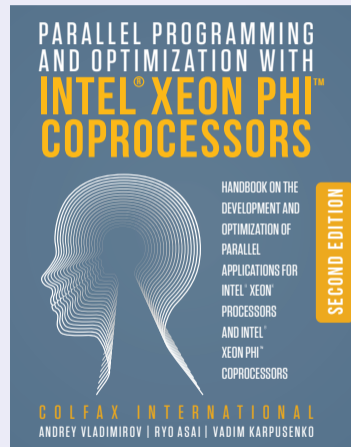
Textbook

ISBN: 978-0-9885234-0-1 (508 pages, Electronic or Print)

Parallel Programming and Optimization with Intel® Xeon Phi™ Coproprocessors

Handbook on the Development and
Optimization of Parallel Applications
for Intel® Xeon® Processors
and Intel® Xeon Phi™ Coprocessors

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