



Programming and Optimization for Intel[®] Architecture

The Hands-On Workshop (HOW) Series

Colfax International — @colfaxintl


June 2016 , Rev. 02d

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 – June 20
 - ▶ Programming model continuity – June 20
- ② Programming models for Xeon Phi coprocessors
 - ▶ Native programming – June 20
 - ▶ Offload programming – June 21
- ③ Expressing Parallelism
 - ▶ Introduction to vectorization – June 22
 - ▶ Crash-course on OpenMP – June 23
- ④ Optimization – intro on June 24
 - ▶ Vectorization tuning – June 27
 - ▶ Multi-threading – June 28, 29
 - ▶ Memory traffic – June 30
- ⑤ Distributed Computing: MPI – July 1

June 2016						
S	M	T	W	H	F	S
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5	6	7	8	9	10	11
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July 2016						
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24	25	26	27	28	29	30
31						

 — 3:00pm UTC
 Lecture+remote access

HOW Online

Course page: colfaxresearch.com/how-16-06

- 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

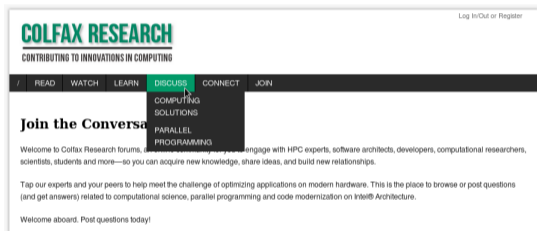
Chat (current):

colfaxresearch.com/how-16-06



Forums (technical):

colfaxresearch.com/discussion

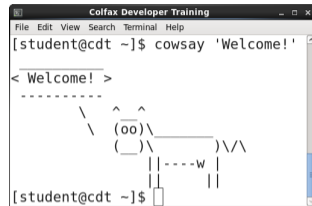


Email (organizational):

training@colfax-intl.com

Hands-On Exercises and Remote Access

- 96 people receive a remote access token
- Can access the system the entire 3 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. Programming Coprocessors

Offload and Native Models

Computing Platforms

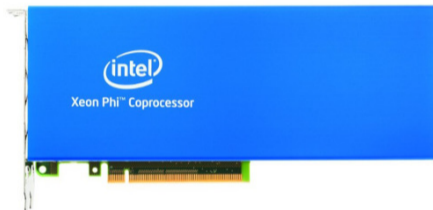
Intel Xeon Processor



Current: Broadwell
Upcoming: Skylake

Multi-Core Architecture

Intel Xeon Phi Coprocessor, 1st generation



Knights Corner (KNC)

Intel Xeon Phi Processor, 2nd generation*



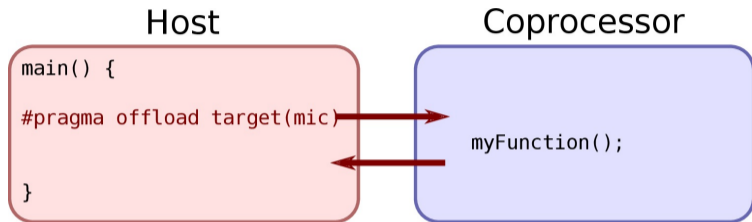
* socket and coprocessor versions

Knights Landing (KNL)

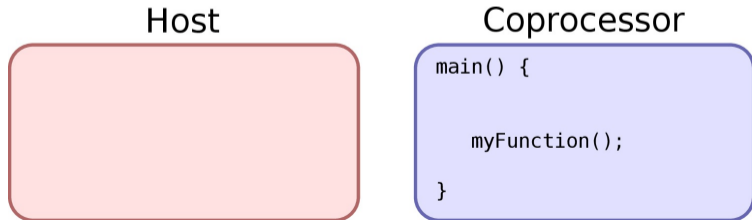
Intel Many Integrated Core (MIC) Architecture

Offload and Native Models

- Offload model (explicit/virtual-shared memory/OpenMP 4.0):



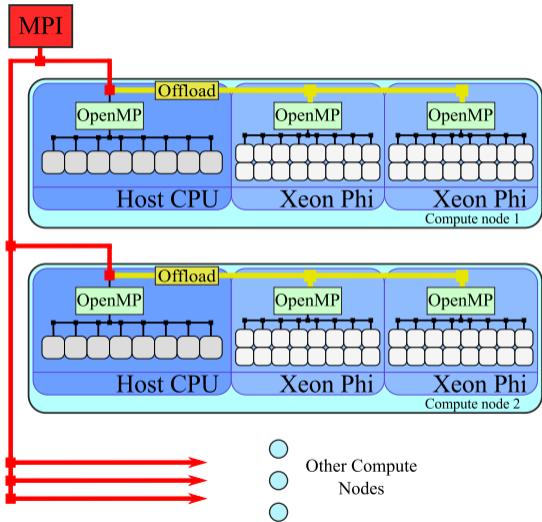
- Native model (standalone application/MPI process):



Heterogeneous Distributed Computing with Xeon Phi

Option 1: MPI+OpenMP with Offload.

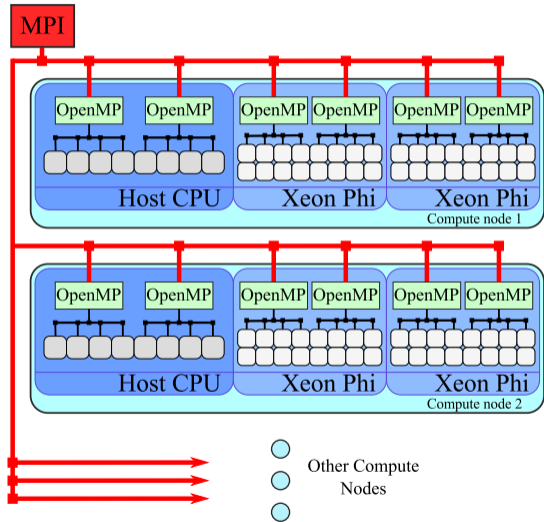
- MPI processes are multi-threaded with OpenMP.
- MPI runs only on CPUs.
- MPI processes offload to coprocessor(s).
- OpenMP in offload regions.



Heterogeneous Distributed Computing with Xeon Phi

Option 2: Symmetric hybrid MPI+OpenMP.

- MPI processes on hosts
- Native MPI processes on the coprocessor.
- Multi-threading with OpenMP.



Explicit Offload (LEO)

Explicit Offload: Pragma-based approach

“Hello World” in the explicit offload model:

```
1 #include <stdio.h>
2 int main(int argc, char * argv[]) {
3     printf("Hello World from host!\n");
4     #pragma offload target(mic)
5     {
6         printf("Hello World from coprocessor!\n"); fflush(stdout);
7     }
8     printf("Bye\n");
9 }
```

Application runs on the host, but some parts of code and data are moved (“offloaded”) to the coprocessor.

Detailed syntax in the [Intel C++ Compiler Reference](#).

Compiling and Running an Offload Application

```
vega@lyra% icpc hello_offload.cpp -o hello_offload
vega@lyra% ./hello_offload
Hello World from host!
Bye
Hello World from coprocessor!
```

- No additional arguments if compiled with an Intel compiler
- Run application on host as a regular application
- Code inside of `#pragma offload` is offloaded automatically
- Console output on Intel Xeon Phi coprocessor is buffered and mirrored to the host console
- If coprocessor is not installed, code inside `#pragma offload` runs on the host system

Offloading Functions and Data

Offloading Functions

```
1  __attribute__((target(mic))) void MyFunction() {
2      // ... implement function as usual
3  }
4
5  int main(int argc, char * argv[] ) {
6      #pragma offload target(mic)
7          {
8              MyFunction();
9          }
10 }
```

- Functions used on coprocessor must be marked with the specifier `__attribute__((target(mic)))`
- Compiler produces a host version and a coprocessor version of such functions (to enable fall-back to host)

Offloading Multiple Functions

```
1 #pragma offload_attribute(push, target(mic))
2 void MyFunctionOne() {
3 // ... implement function as usual
4 }
5
6 void MyFunctionTwo() {
7 // ... implement function as usual
8 }
9 #pragma offload_attribute(pop)
```

- To mark a long block of code with the offload attribute, use `#pragma offload_attribute(push/pop)`

Offloading Data: Local Scalars and Arrays

```
1 void MyFunction() {  
2     const int N = 1000;  
3     int data[N];  
4     #pragma offload target(mic)  
5     {  
6         for (int i = 0; i < N; i++)  
7             data[i] = 0;  
8     }
```

- Scope-local scalars and known-size arrays offloaded automatically
- Data is copied from host to coprocessor at the start of offload
- Data is copied back from coprocessor to host at the end of offload
- Bitwise-copyable data only (arrays of basic types and scalars)
C++ classes, etc. should use virtual-shared memory model

Offloading Data: Global and Static Variables

```
1 int* __attribute__((target(mic))) data;  
2  
3 void MyFunction() {  
4     static int __attribute__((target(mic))) N;  
5     // ...  
6 }  
7  
8 int main() {  
9     // ...  
10 }
```

- Global and static variables must be marked with the offload attribute
- `#pragma offload_attribute(push/pop)` may be used as well

Data Marshalling for Dynamically Allocated Data

```
1 double *p1=(double*)malloc(sizeof(double)*N);  
2 double *p2=(double*)malloc(sizeof(double)*N);  
3  
4 #pragma offload target(mic) in(p1 : length(N)) out(p2 : length(N))  
5 {  
6     // ... perform operations on p1[] and p2[]  
7 }
```

- #pragma offload recognizes clauses in, out, inout and nocopy
- Data size (length), alignment, redirection, and other properties may be specified
- Marshalling is required for pointer-based data

Optional Offload, Fall-Back to Host

```
1 #pragma offload target(mic) optional
2 {
3     printf("Hello World! I have %d logical processors.\n",
4         sysconf(_SC_NPROCESSORS_ONLN )); fflush(stdout);
5 }
```

```
vega@lyra% icpc Offload-Fallback.cc -o Offload-Fallback
vega@lyra% ./Offload-Fallback
Hello World! I have 244 logical processors.
vega@lyra% sudo systemctl stop mpss # Disabling coprocessors
vega@lyra% ./Offload-Fallback
Hello World! I have 48 logical processors.
```

Multiple Coprocessors with Explicit Offload

Multiple Coprocessors with Explicit Offload

- Querying the number of coprocessors:

```
1 const int numDevices = _Offload_number_of_devices();  
2 printf("Number of available coprocessors: %d\n" , numDevices);
```

- Specifying offload target:

```
1 #pragma offload target(mic: 0)  
2 { /* ... */ }
```

- Query the device number from within Offload:

```
1 #pragma offload target(mic)  
2 {  
3     const int deviceNum = _Offload_get_device_number();  
4     printf("Hello from coprocessor %d!\n" , deviceNum);  
5 }
```

Multiple Blocking Offloads Using Host Threads (Explicit Offload)

```
1  const int nDevices = _Offload_number_of_devices();  
2  #pragma omp parallel num_threads(nDevices)  
3  {  
4      const int i = omp_get_thread_num();  
5      #pragma offload target(mic: i)  
6          {  
7              MyFunction(/*...*/);  
8          }  
9  }  
10 }
```

- Up to 8 coprocessors, up to 56 host threads
- All offloads start simultaneously and block the respective thread

Blocking Explicit Offloads Using Threads: Dynamic Work Distribution Across Coprocessors

```
1  const int nDevices = _Offload_number_of_devices();  
2  omp_set_num_threads(nDevices);  
3  #pragma omp parallel for schedule(dynamic, 1)  
4      for (int i = 0; i < nWorkItems; i++) {  
5          const int iDevice = omp_get_thread_num();  
6          #pragma offload target(mic: iDevice)  
7              {  
8                  MyFunction(i);  
9              }  
10     }
```

- Up to 8 coprocessors, up to 32 host threads
- nWorkItems are dynamically scheduled on nDevices

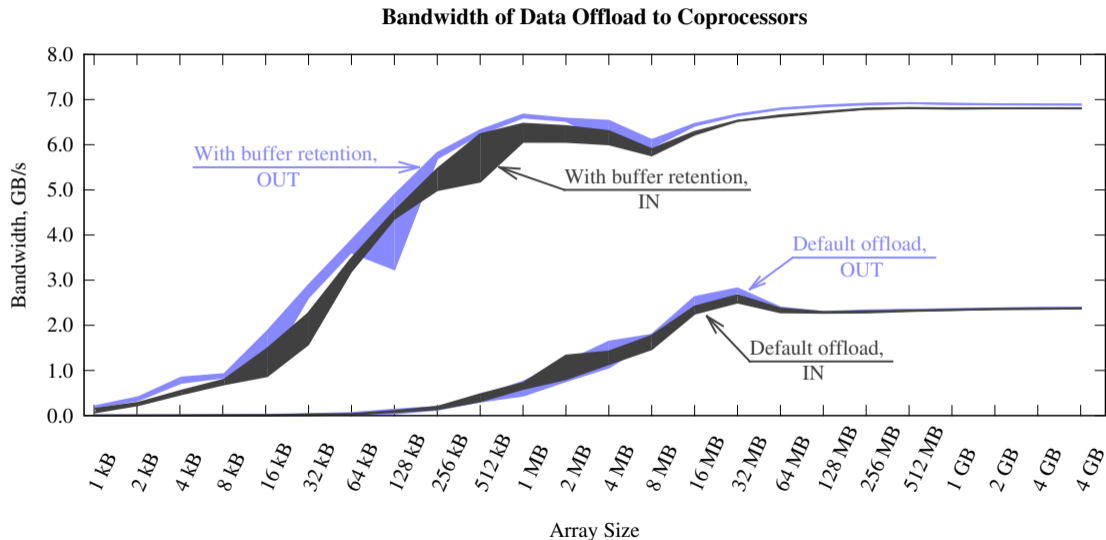
Memory Allocation Control

Memory retention and data persistence on coprocessor

- By default, memory on coprocessor is allocated before, deallocated after offload
- Specifiers `alloc_if` and `free_if` allow to avoid allocation/deallocation
- Data transfer across the PCIe bus rate is ≈ 7 GB/s
- To allocate memory on the coprocessor – 0.5-2.0 GB/s

```
1 #pragma offload target(mic:0) in(p : length(N) alloc_if(1) free_if(0) )
2 { /* allocate memory for array p on coprocessor, do not deallocate */ }
3
4 #pragma offload target(mic:0) in(p : length(N) alloc_if(0) free_if(0) )
5 { /* re-use previously allocated memory buffer on coprocessor */ }
6
7 #pragma offload target(mic:0) in(p : length(0) alloc_if(0) free_if(0) )
8 { /* re-use previously transferred data on coprocessor */ }
9
10 #pragma offload target(mic:0) out(p : length(N) alloc_if(0) free_if(1) )
11 { /* re-use memory and deallocate at the end of offload */ }
```

Offload Latency With and Without Memory/Data Retention



Precautions with persistent data

- Use explicit zero-based coprocessor number (e.g., `mic:0` as shown below)
- With multiple coprocessors, if target number is unspecified, any coprocessor can be used, which will result in runtime errors if persistent data cannot be found.

```
1 #pragma offload target(mic:0) in(p : length(N) alloc_if(1) free_if(0) )  
2 { /* allocate memory for array p on coprocessor, do not deallocate */ }
```

- Do not change the value of the host pointer to a persistent array: the runtime system finds the data on coprocessor using the host pointer value, not variable name.

Overlapping Communication and Computation

Asynchronous Offload

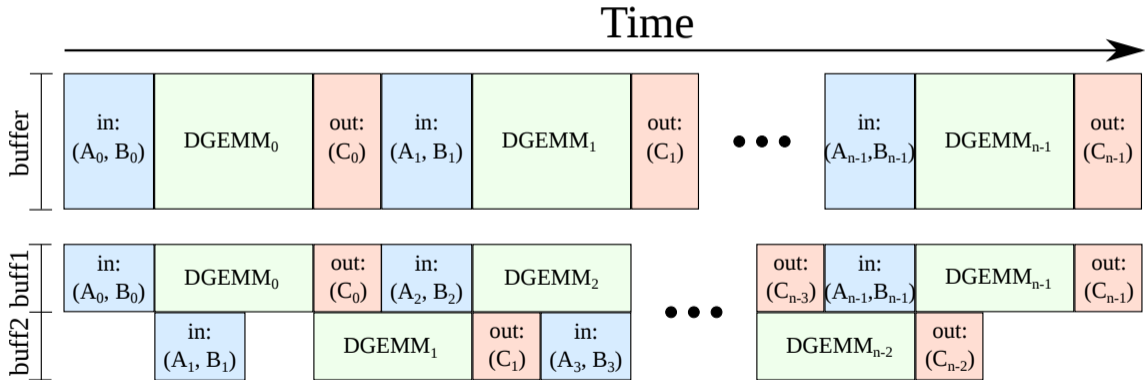
- By default, `#pragma offload` blocks until offload completes
- Use clause “signal” with any pointer to avoid blocking
- Use `#pragma offload_wait` to block where needed

```
1 float* offload0 = &data[0]; // Any unique pointer value as signal
2 #pragma offload target(mic:0) signal(offload0) in(data : length(N))
3 { /* ... will not block code execution because of clause "signal" */ }
4
5 DoSomethingElse();
6
7 /* Now block until offload signalled by pointer "offload0" completes */
8 #pragma offload_wait target(mic:0) wait(offload0)
```

- Use the target number to avoid hanging

Overlapping Communication and Computation

Usage example: double buffering to mask communication latency



Double Buffering with Asynchronous Offload

```

1 for(int i = 1; i < nMatrices-1; i++) {
2     double* A_T = MatrixA[i]; // Dataset to send next; ...same for B and C
3
4     #pragma offload target(mic:0) signal(A_buff_C) \
5         in(A_buff_C: length(0) alloc_if(0) free_if(0)) ...(same for B and C)
6         { cblas_dgemm(..., A_buff_C, ...); } // Asynchronous offload (COMPUTATION)
7
8     // Send next data set, retrieve previous results (COMMUNICATION):
9     #pragma offload_transfer target(mic:0) in(A_T[0:n*n]: into (A_buff_T[0:n*n]))...
10    #pragma offload_transfer target(mic:0) out(C_buff_T[0:n*n]: into (C_T[0:n*n]))
11    // Wait for asynchronous offload (SYNCHRONIZATION):
12    #pragma offload_wait target(mic:0) wait(A_buff_C)
13
14    if(i%2==1) // Swap Buffers
15        { A_buff_T=A_buff2; A_buff_C =A_buff1; /* ...same for B and C */ }
16    else
17        { A_buff_T=A_buff1; A_buff_C =A_buff2; /* ...same for B and C */ }

```

Additional Offload Controls

Target-Specific Code

- During MIC architecture compilation, preprocessor macro `__MIC__` is defined.
- Allows to fine-tune application performance or output where necessary

```
1 __attribute__((target(mic))) void MyFunction() {  
2 #ifdef __MIC__  
3     printf("I am running on a coprocessor.\n");  
4     const int tuningParameter = 16;  
5 #else  
6     printf("I am running on the host.\n");  
7     const int tuningParameter = 8;  
8 #endif  
9     // ... Proceed, using the variable tuningParameter  
10 }
```

Offload diagnostics

```
vega@lyra% export OFFLOAD_REPORT=2
vega@lyra% ./offload-application
Transferring some data to and from coprocessor...
Done. Bye!
[Offload] [MIC 0] [File]                offload-application.cpp
[Offload] [MIC 0] [Line]                6
[Offload] [MIC 0] [CPU Time]            0.505982 (seconds)
[Offload] [MIC 0] [CPU->MIC Data]      1024 (bytes)
[Offload] [MIC 0] [MIC Time]           0.000409 (seconds)
[Offload] [MIC 0] [MIC->CPU Data]      1024 (bytes)
vega@lyra%
```

- Set environment variable `OFFLOAD_REPORT` to 1 or 2 for automatic collection and output of offload information.
- Unset or set `OFFLOAD_REPORT=0` to disable offload diagnostics

Offload Devices, Specifying Available Coprocessors

- Specify coprocessors to use; For example (using 0 and 1),

```
vega@lyra% export OFFLOAD_DEVICES=0,1
```

- Disable Offloading

```
vega@lyra% export OFFLOAD_DEVICES=none
```

Disabling Offload is useful for debugging. For example;

```
vega@lyra% icpc Offload-Fallback.cc -o Offload-Fallback
vega@lyra% ./Offload-Fallback
Hello from offload on MIC with 244 logical processors.
vega@lyra% export OFFLOAD_DEVICES=none # Coprocessors disabled
vega@lyra% ./Offload-Fallback
Hello from offload on CPU with 48 logical processors.
```

Environment variable forwarding with offload

- By default, all host environment variables on the host will be copied to the coprocessor when offload starts.
- In order to have different values for an environment variable on host and coprocessor, set MIC_ENV_PREFIX
- The prefix is dropped when variables are copied to coprocessor

```
vega@lyra% # This sets the value of OMP_NUM_THREADS on the host:
vega@lyra% export OMP_NUM_THREADS=48
vega@lyra%
vega@lyra% # This enables special rules for variable copying:
vega@lyra% export MIC_ENV_PREFIX=XEONPHI
vega@lyra%
vega@lyra% # This sets the value of OMP_NUM_THREADS on the coprocessor:
vega@lyra% export XEONPHI_OMP_NUM_THREADS=240
```

Offload in OpenMP 4.0

OpenMP 4.0 Target Offload

- Another API for offload: `#pragma omp target`
- Part of the OpenMP 4.0 standard
- Designed as portable solution (coprocessors, GPGPUs)
- On Xeon Phi, uses the same back-end as `#pragma offload`

```
1 #pragma omp target
2 {
3 #pragma omp parallel for
4     for(int i=0; i<size; i++)
5         data[i] = 0;
6 }
```

runs on the host, but some parts of code and data are moved (“offloaded”) the coprocessor. Scope-local scalars and stack arrays offloaded automatically.

Clauses of pragma omp target

```
1 #pragma omp target [clause[, clause[, ...]]
```

- `device(int)` – offload to a specific device (coprocessor)
- `map([type:] variables)` – create data environment. `type` is `to`, `from`, `tofrom` or `alloc`
- `if(expr)` – optional offload

Link to [reference manual](#).

OpenMP 4.0 Target Data Mapping

Use `#pragma omp target data` to create a device data environment. This allows to keep persistent data on coprocessor. Example:

```
1 #pragma omp target data map(from:data)
2 {
3 #pragma omp target
4 #pragma omp parallel for
5     for(int i=0; i<size; i++) data[i] = 0;
6
7 #pragma omp target
8 #pragma omp parallel for
9     for(int i=0; i<size; i++) data[i] += 1;
10 }
```

array copied back from coprocessor only once at the end.
Link to [reference manual](#).

Movement of Persistent Data

Use `#pragma omp target update` to force data movement within the data environment. Example:

```
1  #pragma omp target data map(from:data)  
2  {  
3  #pragma omp target  
4    { ... }  
5  
6  #pragma omp target update from(data)  
7  
8  #pragma omp target  
9    { ... }  
10 }
```

data array copied from coprocessor between offloads, and at the end.

Link to [reference manual](#).

Offloading functions with #pragma omp target

Use #pragma omp declare target on functions that may be offloaded (similar to __attribute__((target(mic)))). Example:

```
1 #pragma omp declare target
2 void myinit(int* data, int size){
3 #pragma omp parallel for
4   for(int i=0; i<size; i++) data[i] = 0;
5 }
6 #pragma omp end declare target
7
8 int main(int argv, char** argc){
9   ...
10 #pragma omp target map(tofrom:data) map(to:size)
11   myinit(data, size);
12 }
```

Link to [reference manual](#).

#pragma offload target vs. #pragma omp target

- 1 Different interfaces to the same offload library back-end
- 2 #pragma offload target is Intel-specific, #pragma omp target is part of a cross-platform standard (although, as today, cross-platform support is not widespread).
- 3 #pragma offload target allows data/memory persistence outside of the scope of a pragma, #pragma omp target – only within the lexically structured scope (correct us if we're wrong).
- 4 #pragma offload is a more flexible model and will continue to be supported (see Intel's [communication](#)).

Additional information: [webinar](#).

Shared Virtual Memory Offload Model

Shared Virtual Memory Model

```
1  _Cilk_shared int arr[N]; // This is a virtual-shared array
2
3  _Cilk_shared void Compute() { // This function may be offloaded
4      // ... function uses array arr[]
5  }
6
7  int main() {
8      // arr[] can be initialized on the host
9      _Cilk_offload Compute(); // and used on coprocessor
10     // and the values are returned to the host
11 }
```

- Alternative to Explicit Offload
- Data synced from host to coprocessor before the start of offload
- Data synced from coprocessor to host at the end of offload

Shared Virtual Memory Model

```
1 int* _Cilk_shared data; // Pointer to a virtual-shared array
2
3 int main() {
4     // Working with pointer-based data is illustrated below:
5     data = (_Cilk_shared int*)_Offload_shared_malloc(N*sizeof(float));
6     _Offload_shared_free(data);
7 }
```

- Addresses of virtual-shared pointers identical on host and coprocessors
- Synchronized before and after offload, with page granularity

Review and What's Next

- Explicit offload – `#pragma offload` or `#pragma omp target` – allows data marshalling; for bitwise-copyable data
- Shared virtual memory – `_Cilk_shared/_Cilk_offload` – automatic coherence; for complex objects
- Offload = application is launched on host, some functions run on coprocessor

Next session: expressing data parallelism, vectorization.

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GOT THE TOOLS - NOW WHAT?

Learn workflows and methodology with the “HOW” tools* training and hands-on demos

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PARALLEL STUDIO XE

The graphic features a blue header with the text 'GOT THE TOOLS - NOW WHAT?'. Below this is a light-colored wood-grain background. On the left is a book cover for 'PARALLEL STUDIO XE' with the Intel logo. To the right of the book is the text 'Learn workflows and methodology with the “HOW” tools* training and hands-on demos' and a list of tools: '* Intel MKL | Intel Advisor | Intel VTune Amplifier'. At the bottom right, three silver wrenches are arranged vertically.

colfaxresearch.com/how-tools-16-06

Developer's Guide to Knights Landing



colfaxresearch.com/knl-webinar/

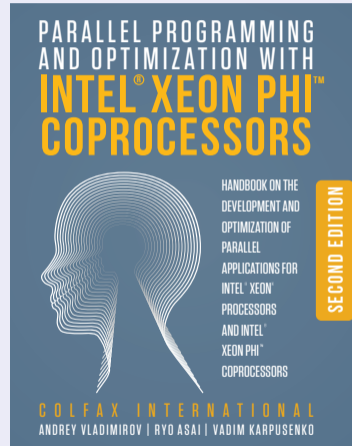
Textbook

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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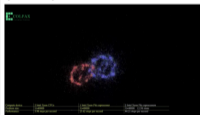


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