PROGRAMMING AND OPTIMIZATION FOR INTEL® ARCHITECTURE

Hands-On Workshop (HOW) Series "Deep Dive"

Session 9

Colfax International — colfaxresearch.com

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COURSE ROADMAP

- Module I. Programming Models
  - 01. Intel Architecture and Modern Code
  - 02. Xeon Phi, Coprocessors, Omni-Path
- Module II. Expressing Parallelism
  - 03. Automatic vectorization
  - 04. Multi-threading with OpenMP
  - 05. Distributed Computing, MPI
- Module III. Performance Optimization
  - 06. Optimization Overview: N-body
  - 07. Scalar tuning, Vectorization
  - 08. Common Multi-threading Problems
  - 09. Multi-threading, Memory Aspect
  - 10. Access to Caches and Memory

HOW SERIES ONLINE

Course page:
colfaxresearch.com/how-series

- Slides
- Code
- Video
- Chat

More workshops:
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Forum

Colfax Cluster

Discussion of Colfax Cluster usage policies, troubleshooting.

Developer Training, HOW Series

Questions about any of the Colfax trainings? Usage of training servers, experience with specific exercises, inquiries on what's inside, suggestions for future trainings - post them here.

Performance Optimization and Parallelism

Discuss with Colfax Research and colleagues any topics related to computational science, parallel programming, performance optimization and code modernization.

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HANDS-ON EXERCISES AND REMOTE ACCESS

- All registrants receive an invitation from cluster@colfaxresearch.com
- Queue-based access to Intel Xeon E5, Intel Xeon Phi (KNC and KNL)
- Can access the cluster the entire 2 weeks of the workshop

§2. REFRESH

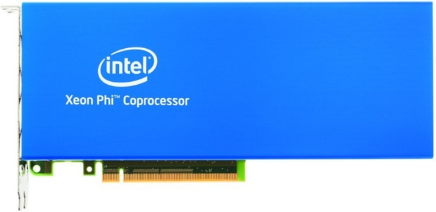
PERFORMANCE OPTIMIZATION

COMPUTING PLATFORMS

Intel Xeon Processor

Current: Broadwell
Upcoming: Skylake

Intel Xeon Phi Coprocessor, 1st generation



Knights Corner (KNC)

Intel Xeon Phi Processor, 2nd generation*

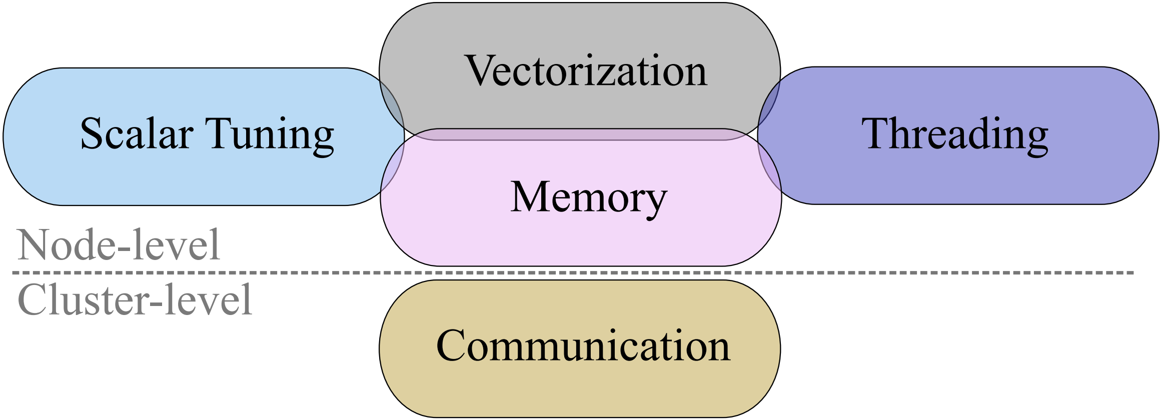
* socket and coprocessor versions

Knights Landing (KNL)

Multi-Core Architecture

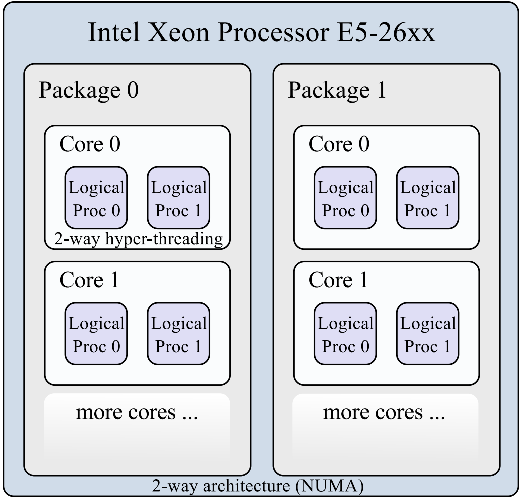
Intel Many Integrated Core (MIC) Architecture

OPTIMIZATION AREAS



CORES, THREADS AND OPENMP

PROCESSOR HIERARCHY

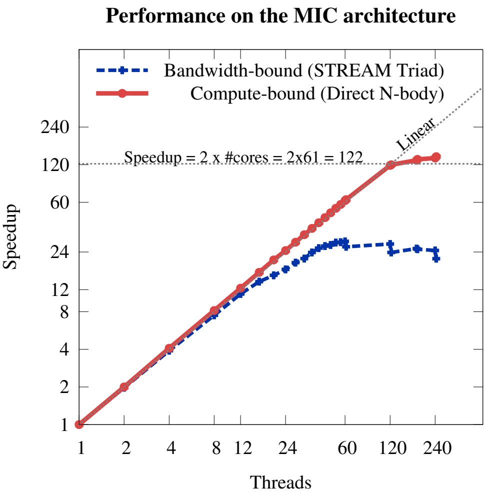


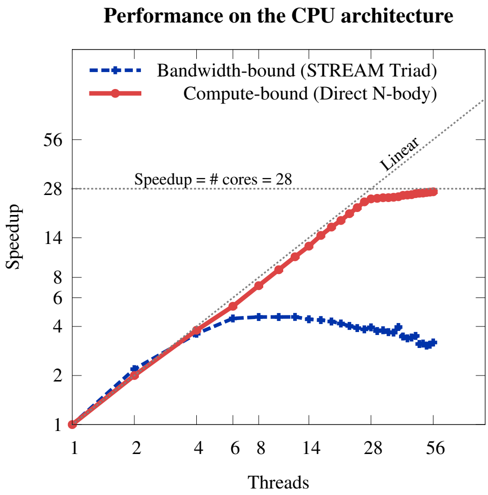
Hierarchy:
Packages ->
Cores ->
Logical processors

OS Proc = numerical ID of logical processor

Jargon:
"socket" = **package**
"logical core" =
"hyper-thread" =
"hardware thread" =
logical processor

SCALABILITY EXPECTATIONS: MIC VERSUS CPU



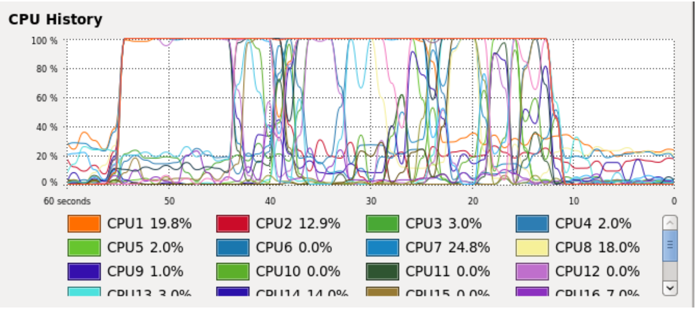


§3. MULTI-THREADING II: MEMORY ASPECT

THREAD AFFINITY

WHAT IS THREAD AFFINITY

- OpenMP threads may migrate between cores
- Forbid migration — improve locality — increase performance
- Affinity patterns “scatter” and “compact” may improve cache sharing, relieve thread contention



THE KMP_HW_SUBSET ENVIRONMENT VARIABLE

Control the # of cores and # of threads per core:

```
KMP_HW_SUBSET=[<cores>c,]<threads-per-core>t
```

```
vega@lyra-mic0% export KMP_HW_SUBSET=3t # 3 threads per core
vega@lyra-mic0% ./my-native-app
```

or

```
vega@lyra% export MIC_ENV_PREFIX=XEONPHI
vega@lyra% export KMP_HW_SUBSET=1t # 1 thread per core on host
vega@lyra% export XEONPHI_KMP_HW_SUBSET=2t # 2 threads per core on Xeon Phi
vega@lyra% ./my-offload-app
```

THE KMP_AFFINITY ENVIRONMENT VARIABLE

```
KMP_AFFINITY=[<modifier>,...]<type>[,<permute>][,<offset>]
```

`modifier`:

- `verbose/nonverbose`
- `respect/norespect`
- `warnings/nowarnings`
- `granularity=core` or `thread`

- `type=compact`, `scatter` or `balanced`
- `type=explicit, proclist=[<proc_list>]`
- `type=disabled` or `none`.

The most important argument is `type`:

- `compact`: place threads as *close to each* other as possible
- `scatter`: place threads as *far from each* other as possible

OMP_PROC_BIND and OMP_PLACES Variables

Control the binding pattern, including nested parallelism:

```
OMP_PROC_BIND=type[,type[,...]]
```

Here type=true, false, spread, close or master.
Comma separates settings for different levels of nesting (OMP_NESTED must be enabled).

Control the granularity of binding:

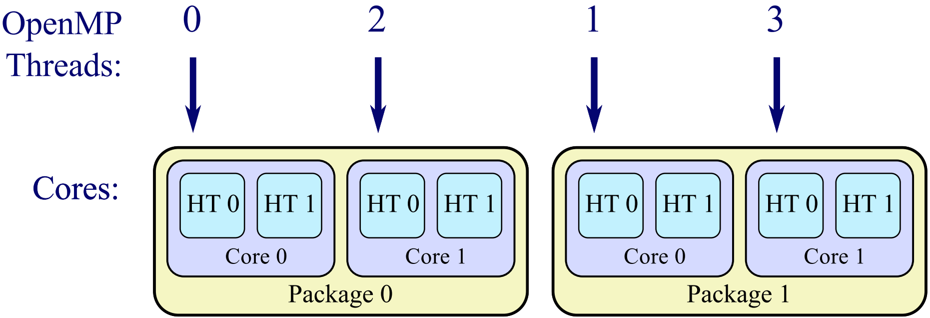
```
OMP_PLACES=<threads|cores|sockets|(explicit)>
```

THREAD AFFINITY: SCATTER PATTERN

Generally beneficial for bandwidth-bound applications.

`OMP_NUM_THREADS={1 thread/core}` or `KMP_HW_SUBSET=1t`

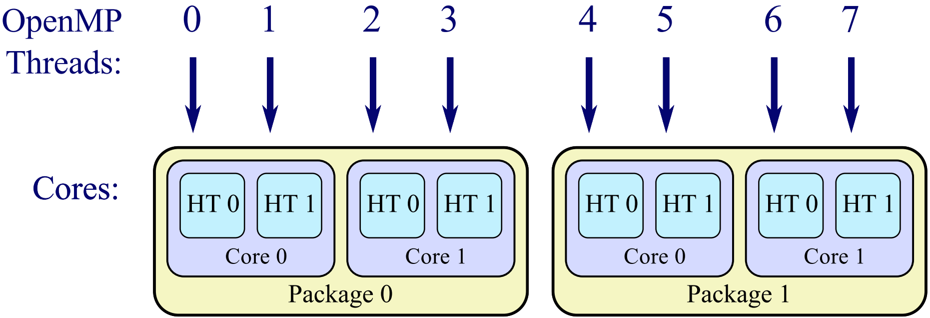
`KMP_AFFINITY=scatter,granularity=fine`



Thread Affinity: Compact Pattern

Generally beneficial for compute-bound applications.

```
OMP_NUM_THREADS={2(4) threads/core on Xeon (Xeon Phi)}
KMP_AFFINITY=compact,granularity=fine
```



PARALLELISM AND AFFINITY INTERFACES

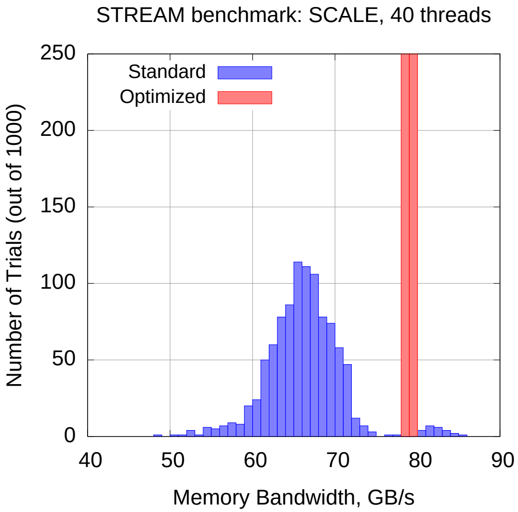
Intel-specific (in order of priority):

- Functions (e.g., `kmp_set_affinity()`)
- Compiler arguments (e.g., `-par-affinity`)
- Environment variables (e.g., `KMP_AFFINITY`)

Defined by the OpenMP standard (in order of priority):

- Clauses in pragmas (e.g., `proc_bind`)
- Functions (e.g., `omp_set_num_threads()`)
- Environment variables (e.g., `OMP_PROC_BIND`)

IMPACT OF AFFINITY ON BANDWIDTH



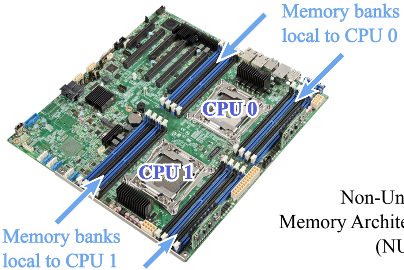
- Without affinity: "fortunate" and "unfortunate" runs
- With affinity "scatter": consistently good performance

Plot from this paper

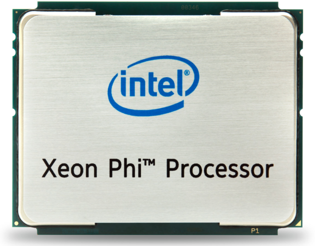
NUMA LOCALITY

NUMA ARCHITECTURES

NUMA = Non-Uniform Memory Access. Cores have fast access to local memory, slow access to remote memory.



Non-Uniform
Memory Architecture
(NUMA)



Examples:

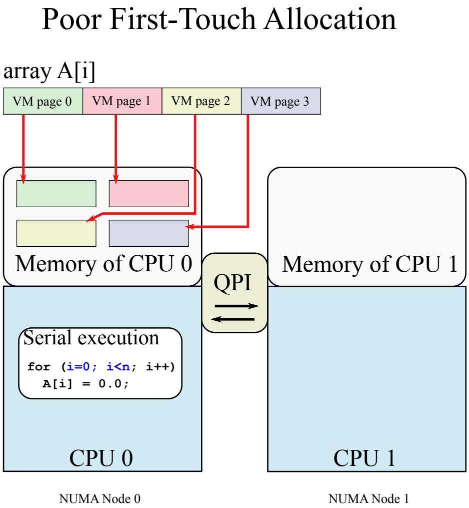
- Multi-socket Intel Xeon processors
- Second generation Intel Xeon Phi in sub-NUMA clustering mode

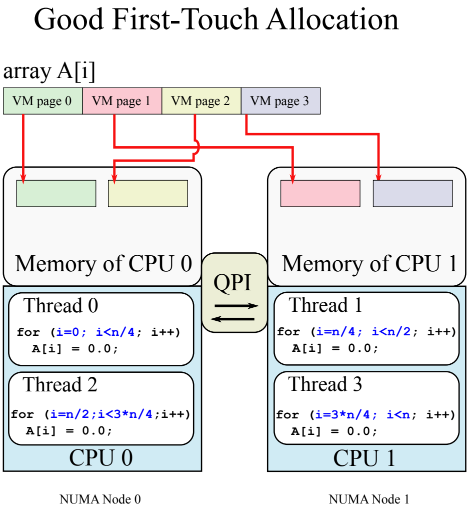
ALLOCATION ON FIRST TOUCH

- Memory allocation occurs not during `_mm_malloc()`, but upon the first write to the buffer ("first touch")
- Default NUMA allocation policy is "on first touch"
- For better performance in NUMA systems, initialize data with the same parallel pattern as during data usage

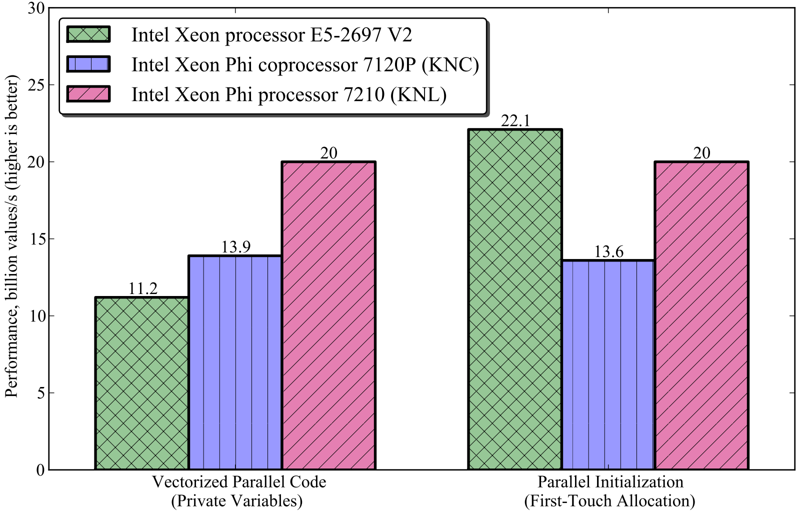
```
float* A = (float*)_mm_malloc(n*m*sizeof(float), 64);

// Initializing from parallel region for better performance
#pragma omp parallel for
for (int i = 0; i < n; i++)
  for (int j = 0; j < m; j++)
    A[i*m + j] = 0.0f;
```

FIRST-TOUCH ALLOCATION POLICY





IMPACT OF FIRST-TOUCH ALLOCATION



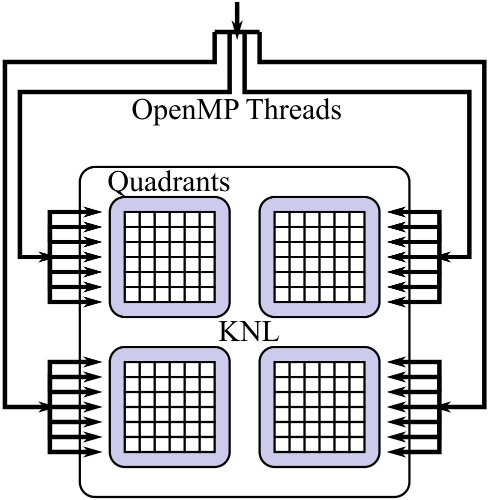
BINDING TO NUMA NODES WITH `numactl`

- `libnuma` – a Linux library for fine-grained control over NUMA policy
- `numactl` – a tool for global NUMA policy control

```
vega@lyra% numactl --hardware
available: 2 nodes (0-1)
node 0 cpus: 0 1 2 3 4 5 12 13 14 15 16 17
node 0 size: 65457 MB
node 0 free: 24426 MB
node 1 cpus: 6 7 8 9 10 11 18 19 20 21 22 23
node 1 size: 65536 MB
node 1 free: 53725 MB
node distances:
node   0   1
  0:  10  21
  1:  21  10
vega@lyra% numactl --membind=<nodes> --cpunodebind=<nodes> ./myApplication
```

NESTED PARALLELISM

NESTED PARALLELISM WITH OPENMP

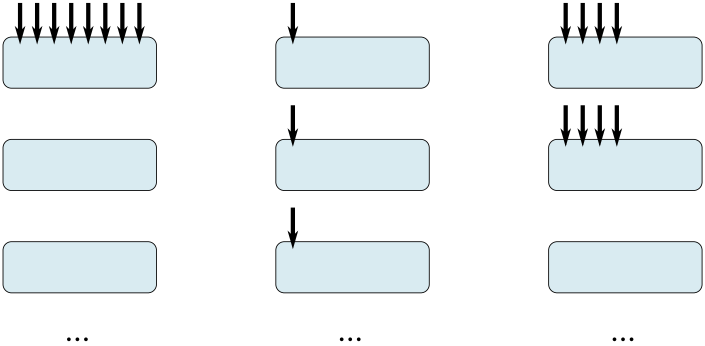



```
#pragma omp parallel
{
#pragma omp parallel
  {
    // ...
  }
}
```

- Tune granularity of parallelism
- Improve resource sharing in NUMA systems

MOTIVATION FOR NESTED PARALLELISM

Fine-grained parallelism | Coarse-grained parallelism | Nested parallelism



throwing all threads on one work-item

using one thread per work-item

putting teams of threads on several work-items

OPENMP HOT TEAMS

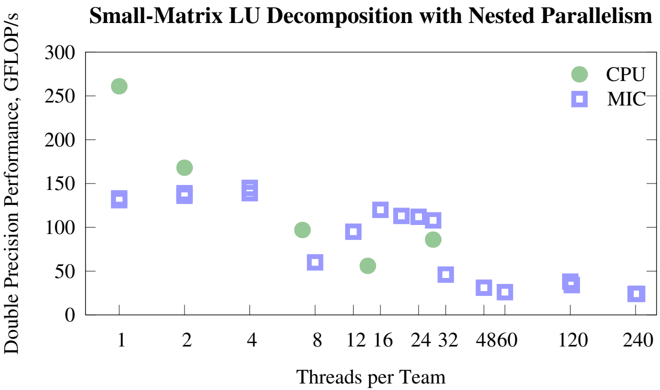
Xeon	Xeon Phi
▷ `OMP_NUM_THREADS=2,14`	▷ `OMP_NUM_THREADS=60,4`

▷ `OMP_NESTED=1`
`OMP_PROC_BIND=spread,close`
`OMP_PLACES=cores`
	▷ `OMP_NESTED=1`
	`OMP_PROC_BIND=spread,close`
	`OMP_PLACES=threads`

▷ `KMP_HOT_TEAMS_MODE=1`
`KMP_HOT_TEAMS_MAX_LEVEL=2`
`OMP_MAX_ACTIVE_LEVELS=2`
	▷ `KMP_HOT_TEAMS_MODE=1`
	`KMP_HOT_TEAMS_MAX_LEVEL=2`
	`OMP_MAX_ACTIVE_LEVELS=2`

SMALL MATRIX LU DECOMPOSITION WITH NESTED PARALLELISM

Decomposing 10^3 small square matrices of size 1024×1024.



See HOW Series “Tools” (MKL webinar).

§4. REVIEW AND WHAT'S NEXT

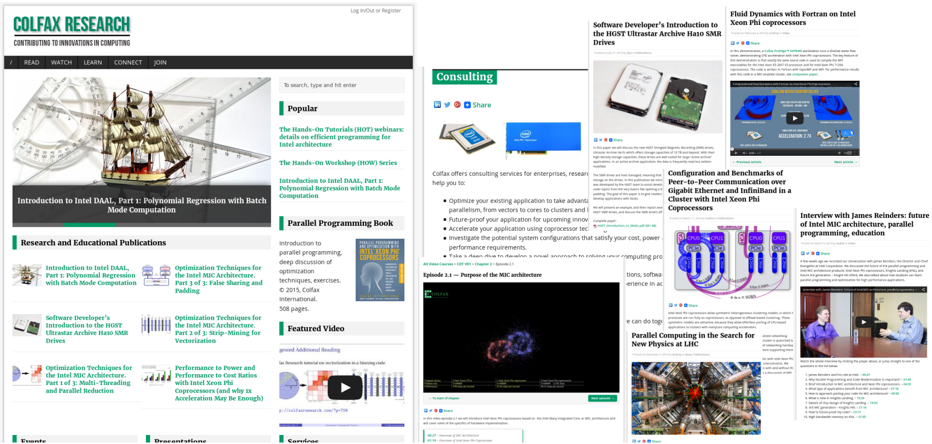
SUMMARY

This session:

1. Setting affinity prevents thread migration
2. Affinity pattern “scatter” for bandwidth-bound
3. Affinity pattern “compact” for compute-bound
4. NUMA locality: use parallel first touch
5. Nested parallelism: reduce memory overhead/expose more work-items

Next session: optimization of memory traffic.

COLFAX RESEARCH



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