Native Computing and Optimization on Intel Xeon Phi

IEEE Cluster 2013
September 23, 2013

Lucas A. Wilson
lwilson@tacc.utexas.edu
Overview

• Why run native?
• What is a native application?
• Building a native application
• Running a native application

• Setting affinity and pinning tasks
• Optimization
  – Vectorization
  – Alignment
  – Parallelization
What is a native application?

• It is an application built to run exclusively on the MIC coprocessor.
• MIC is not binary compatible with the host processor
  – Instruction set is *similar* to Pentium, but not all 64 bit scalar extensions are included.
  – MIC has 512 bit vector extensions, but does NOT have MMX, SSE, or AVX extensions.
• Native applications can’t be used on the host CPU, and vice versa.
Why run a native application?

• It is possible to login and run applications on the MIC without any host intervention

• Easy way to get acquainted with the properties of the MIC
  – Performance studies
  – Single card scaling tests (OMP/MPI)
  – No issues with data exchange with host

• The native code probably performs quite well on the host CPU once you build a host version
  – Good path for symmetric runs (afternoon talk)
Will My Code Run on Xeon Phi?

• Yes
• … but that’s the wrong question
  – Will your code run *best* on Phi?, or
  – Will you get great Phi performance without additional work?
Building a native application

- Cross-compile on the host (login or compute nodes)
  - No compilers installed on coprocessors
- MIC is fully supported by the Intel C/C++ and Fortran compilers (v13+):
  
  ```
  icc -openmp -mmic mysource.c -o myapp.mic
  ifort -openmp -mmic mysource.f90 -o myapp.mic
  ```
- The `-mmic` flag causes the compiler to generate a native mic executable
- It is convenient to use a `.mic` extension to differentiate MIC executables
Running a native application

- Options to run from **mic0** from a compute node:
  1. Traditional ssh remote command execution
     - `c422-703% ssh mic0 ls`
     - Clumsy if environment variables or directory changes needed
  2. Interactively login to **mic**:
     - `c422-703% ssh mic0`
     - Then use as a normal server
  3. Explicit launcher:
     - `c422-703% micrun ./a.out.mic`
  4. Implicit launcher:
     - `c422-703% ./a.out.mic`
Native Application Launcher

• The micrun launcher has three nice features:
  – It propagates the current working directory
  – It propagates the shell environment (with translation)
    • Environment variables that need to be different on host and coprocessor need to be defined using the MIC_ prefix on the host. E.g.,
      – c422-703% export MIC_OMP_NUMTHREADS=183
      – c422-703% export MIC_KMP_AFFINITY="verbose,balanced"
  – It propagates the command return code back to the host shell

• These features work whether the launcher is used explicitly or implicitly
Environmental Variables on the MIC

• If you ssh to mic0 and run directly from the card use the regular names:
  – OMP_NUM_THREADS
  – KMP_AFFINITY
  – I_MPI_PIN_PROCESSOR_LIST
  – ...

• If you use the launcher, use the MIC_ prefix to define them on the host:
  – MIC_OMP_NUM_THREADS
  – MIC_KMP_AFFINITY
  – MIC_I_MPI_PIN_PROCESSOR_LIST
  – ...

• You can also define a different prefix:
  – export MIC_ENV_PREFIX=MYMIC
  – MYMIC_OMP_NUM_THREADS
  – ...

Native Execution Quirks

• The mic runs a lightweight version of Linux, based on BusyBox
  – Some tools are missing: \textit{w, numaclt}
  – Some tools have reduced functionality: \textit{ps}

• Relatively few libraries have been ported to the coprocessor environment

• These issues make the implicit or explicit launcher approach even more convenient
Best Practices For Running Native Apps

- Always bind processes to cores
  - For MPI tasks (more on next presentation)
    - `I_MPI_PIN`
    - `I_MPI_PIN_MODE`
    - `I_MPI_PIN_PROCESSOR_LIST`
  - For threads
    - `KMP_AFFINITY={compact, scatter, balanced}`
    - `KMP_AFFINITY=explicit, proclist=[0,1,2,3,4]`
    - Adding `verbose` will dump the full affinity information when the run starts
    - Adding `granularity=fine` binds to specific thread contexts and may help in codes with heavy L1 cache reuse
- The MIC is a single chip, so there is no need for `numactl`
- If other affinity options can’t be used the command `taskset` is available.
KMP_AFFINITY Example

compact

balanced

scatter
Logical to Physical Processor Mapping

- **Hardware:**
  - Physical Cores are 0..60
  - Logical Cores are 0..243

- **Mapping is not what you are used to!**
  - Logical Core 0 maps to Physical core 60, thread context 0
  - Logical Core 1 maps to Physical core 0, thread context 0
  - Logical Core 2 maps to Physical core 0, thread context 1
  - Logical Core 3 maps to Physical core 0, thread context 2
  - Logical Core 4 maps to Physical core 0, thread context 3
  - Logical Core 5 maps to Physical core 1, thread context 0
  - ...
  - Logical Core 240 maps to Physical core 59, thread context 3
  - Logical Core 241 maps to Physical core 60, thread context 1
  - Logical Core 242 maps to Physical core 60, thread context 2
  - Logical Core 243 maps to Physical core 60, thread context 3

- **OpenMP threads start binding to logical core 1, not logical core 0**
  - For *compact* mapping 240 OpenMP threads are mapped to the first 60 cores
    - No contention for the core containing logical core 0 – the core that the O/S uses most
  - But for *scatter* and *balanced* mappings, contention for logical core 0 begins at 61 threads
    - Not much performance impact unless O/S is very busy
    - Best to avoid core 60 for offload jobs & MPI jobs with compute/communication overlap
How Do I Tune Native Applications?

- Vectorization and Parallelization are critical!
  - Single-thread scalar performance: ~1 GHz Pentium

- Vector width is 512 bits
  - 8 double precision values / 16 single precision values
  - You don’t want to lose factors of 8-16 in performance

- Compiler reports provide important information about effectiveness of compiler at vectorization
  - Start with a simple code – the compiler reports can be very long & hard to follow
  - There are lots of options & reports! Details at:
Vectorization Compiler reports

• Option `-vec-report3` gives diagnostic information about every loop, including
  – Loops successfully vectorized (also at `-vec-report1`)
  – Loops not vectorized & reasons (also at `-vec-report2`)
  – Specific dependency info for failures to vectorize
  – Option `-vec-report6` provides additional info:
    • Array alignment for each loop
    • Unrolling depth for each loop

• Quirks
  – Functions typically have most/all of the vectorization messages repeated with the line number of the call site – ignore these and look at the messages with the line number of the actual loop
  – Reported reasons for not vectorizing are not very helpful – look at specific dependency info & remember about C aliasing rules
vec-report Example

- Code: STREAM Copy kernel

```c
#pragma omp parallel for
for (j=0; j<STREAM_ARRAY_SIZE; j++)
c[j] = a[j];
```

- **vec-report** messages
  - `stream_5-10.c(354)`: (col. 6) remark: vectorization support: reference c has aligned access.
  - `stream_5-10.c(354)`: (col. 6) remark: vectorization support: reference a has aligned access.
  - `stream_5-10.c(354)`: (col. 6) remark: vectorization support: streaming store was generated for c.
  - `stream_5-10.c(353)`: (col. 2) remark: LOOP WAS VECTORIZED.
  - `stream_5-10.c(354)`: (col. 6) remark: vectorization support: reference c has unaligned access.
  - `stream_5-10.c(354)`: (col. 6) remark: vectorization support: reference a has unaligned access.
  - `stream_5-10.c(354)`: (col. 6) remark: vectorization support: unaligned access used inside loop body.
  - `stream_5-10.c(353)`: (col. 2) remark: loop was not vectorized: vectorization possible but seems inefficient.

- Many other combinations of messages are possible
  - Remember that OpenMP will split loops in ways that can break 64-Byte alignment – alignment depends on thread count
Additional Compiler Reports

- Option `--opt-report-phase hpo` provides good info on OpenMP parallelization
- Option `--opt-report-phase hlo` provides info on software prefetching
- Option `--opt-report 1` gives a medium level of detail from all compiler phases, split up by routine
- Option `--opt-report-file=filename` saves the lengthy optimization report output to a file
Tuning Limitations

• Currently there is no support for gprof when compiling native applications

• Profiling is supported by Intel’s Vtune product
  – But this is not currently enabled on Stampede
  – Vtune is a complex profiling software that deserves its own training session
Performance Tuning Notes (1)

• Xeon Phi always has HyperThreading enabled
  – Four thread contexts per physical core
  – Registers are replicated
  – L1D, L1I, and (private, unified) L2 caches are shared

• Vector Unit instruction issue limitation:
  – The vector unit can issue one instruction per cycle
  – L1D Cache can deliver 64 Bytes (1 vector register) every cycle
  – But a thread can issue a vector instruction every other cycle
  – Need at least two threads to fully utilize the vector unit
  – Using 3-4 threads does not increase maximum issue rate, but often helps tolerate latency
Knights Corner Core

George Chrysos, Intel, Hot Chips 24 (2012):

X86 specific logic < 2% of core + L2 area
Vector Processing Unit

George Chrysos, Intel, Hot Chips 24 (2012):
Performance Tuning Notes (2)

• Cache Hierarchy:
  – L1I and L1D are 32kB, 8-way associative, 64-Byte cache lines
    • Same sizes & associativity as Xeon E5 (“Sandy Bridge”), but shared when using multiple threads/core
    • 1 cycle latency for scalar loads, 3 cycles for vector loads
  – L2 (unified, private) is 512kB, 8-way associative, 64-Byte lines
    • Latency ~25 cycles (idle), increases under load
    • Bandwidth is 1 cache line every other cycle
  – All 60 of the other L2 caches are snooped on an L2 cache miss
    • Clean or Dirty data will be transferred to requestor’s L1D
    • This eliminates load from DRAM on shared data accesses
    • Cache-to-Cache transfers are about 275ns, independent of relative core numbers
Performance Tuning Notes (3)

• Idle Memory Latency is ~275-280 ns
• Required Concurrency:
  – 277 ns * 352 GB/s = 97,504 Bytes = 1524 cache lines
    • This is ~25 concurrent cache misses per core
    • Theoretically supported by the HW, but not attainable in practice
    • The actual number increases under load as the latency increases
• Hardware Prefetch
  – No L1 prefetchers
  – Simplified L2 prefetcher
    • Only identifies strides up to 2 cache lines
    • Prefetches up to 4 cache-line-pairs per stream
    • Monitors up to 16 streams (on different 4kB pages)
      – These are *shared* by the hardware threads on a core
• Software prefetch is often required to obtain good bandwidth
Prefetch and Bandwidth

Effect of HW & SW Prefetch on STREAM Triad Bandwidth on Xeon Phi

- 61 threads
- 122 threads
- 183 threads
- 244 threads

STREAM Triad BW (MB/s)
Software Prefetch vs Data Location

• Xeon Phi can only issue one vector instruction every other cycle from a single thread context, so:
  – If data is already in the L1 Cache, Vector Prefetch instructions use up valuable instruction issue bandwidth
  – But, if data is in the L2 cache or memory, Vector Prefetch instructions provide significant increases in sustained performance.

• The next slide shows the effect of including vector prefetch instructions (default with “-O3”) vs excluding them (with “-no-opt-prefetch”)
  – Data is L1 contained for array sizes of 2k elements or less
  – Data is L2-contained for array sizes of ~32k elements or less
Effect of SW Prefetch with Data on Cache

Stream2 DAXPY on Xeon Phi SE10P: Effect of Software Prefetch on Performance with Data in Cache

- DAXPY w/ SW PF
- DAXPY w/o SW PF

Sustained Bandwidth (MB/s)

Number of 64-bit elements per array
Tuning Memory Bandwidth on the MIC

- STREAM Benchmark performance varies considerably with compilation options
  - "-O3" flags, small pages, malloc: 63 GB/s to 98 GB/s
  - "-O3" flags, small pages, -fno-alias: 125 GB/s to 140 GB/s
  - "tuned" flags, small pages: 142 GB/s to 162 GB/s
  - "tuned" flags, large pages: up to 175 GB/s
- Best Performance can be obtained with 1, 2, 3, or 4 threads per core
  - Aggressive SW prefetch or >4 memory access streams per thread gives best results with 1 thread per core
  - Less aggressive SW prefetch or 1-4 memory access streams per thread give better results with more threads
- Details:
  - "-O3" compiler flags:
    -O3 -openmp -mcmodel=medium -fno-alias
  - "tuned" compiler flags use "-O3" flags plus:
    -mP2OPT_hlo_use_const_pref_dist=64 \[-mP2OPT_hlo_use_const_second_pref_dist=32 \]
    -mGLOB_default_function_attrs="knc_stream_store_controls=2"

Intel reference material

• Main Software Developers web page:

• A list of links to very good training material at:

• Many answers can also be found in the Intel forums:

• Specific information about building and running “native” applications:

• Debugging:
More Intel reference Material

• Search for these at www.intel.com by document number
  – This is more likely to get the most recent version than searching for the document number via Google.

• Primary Reference:
  – “Intel Xeon Phi Coprocessor System Software Developers Guide” (document 488596 or 328207)

• Advanced Topics:
  – “Intel Xeon Phi Coprocessor (codename: Knights Corner) Performance Monitoring Units” (document 327357)

• WARNING:
  – Intel sometimes describes the number of vector registers as 16 in this documents. The actual number is 32.
Questions?

For more information:
www.tacc.utexas.edu
Native Computing Lab

Lab instructions at:
www.tacc.utexas.edu/user-services/training/course-materials

• **Exercise 1: Compiler Reports**
  – In this exercise you will apply the knowledge learned during the presentation to interpret and use the information in the compiler optimization reports.

• **Exercise 2: Affinity**
  – In this exercise you will apply different affinity settings to a native code and analyze the affinity report to correlate it with the hardware layout in the MIC.