ver DJ2013-05
as 1 Dec 2013

PowerPoint original
available on request

Intel Xeon Phi MIC
Offload Programming Models

Doug James
Dec 2013

Key References

- Jeffers and Reinders, Intel Xeon Phi...
  - but some material is no longer current
- Intel Developer Zone
  - http://software.intel.com/en-us/mic-developer
  - http://software.intel.com/en-us/articles/effective-use-of-the-intel-compilers-offload-features
- Stampede User Guide and related TACC resources
  - Search User Guide for "Advanced Offload" and follow link

Other specific recommendations throughout this presentation

Overview

Basic Concepts

Three Offload Models

Issues and Recommendations

Source code available on Stampede:

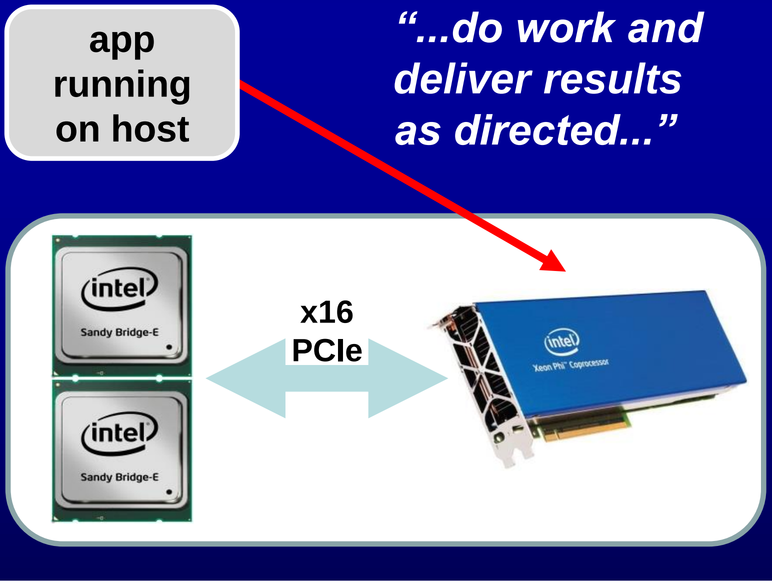
```
tar xvf ~train00/offload_demos.tar
```

Project code: `20131204MIC` (TACC Portal)

Offloading:
MIC as assistant processor

A program running on the host “offloads” work by directing the MIC to execute a specified block of code. The host also directs the exchange of data between host and MIC.

Ideally, the host stays active while the MIC coprocessor does its assigned work.



app running on host

“...do work and deliver results as directed...”

x16 PCIe

Offload Models

- Compiler Assisted Offload (CAO)
  - Explicit
    - Programmer explicitly directs data movement and code execution
  - Implicit
    - Programmer marks some data as “shared” in the virtual sense
    - Runtime automatically synchronizes values between host and MIC
- Automatic Offload (AO)
  - Computationally intensive calls to Intel Math Kernel Library (MKL)
  - MKL automatically manages details
  - More than offload: work division across host and MIC!

Explicit Model:
Direct Control of Data Movement

- aka Copyin/Copyout, Non-Shared, COI*
- Available for C/C++ and Fortran
- Supports simple ("bitwise copyable") data structures (think 1d arrays of scalars)

*Coprocessor Offload Infrastructure

Explicit Offload

F90

```
program main

  use omp_lib

  integer :: nprocs


  nprocs = omp_get_num_procs()

  print*, "procs: ", nprocs

end program
```

```
ifort -openmp off00host.f90

 icc -openmp off00host.c
```

C/C++

```
#include <stdio.h>
#include <omp.h>

int main( void )  {

    int totalProcs;


    totalProcs = omp_get_num_procs();

    printf( "procs: %d\n", totalProcs );
    return 0;

}
```

Simple Fortran and C codes that each return "procs: 16" on Sandy Bridge host…

Explicit Offload

F90

```
program main

  use omp_lib

  integer :: nprocs

  !dir$ offload target(mic)
  nprocs = omp_get_num_procs()

  print*, "procs: ", nprocs

end program
```

offload directive

runs on MIC

runs on host

```
ifort -openmp off01simple.f90
```

```
icc -openmp off01simple.c
```

C/C++

```
#include <stdio.h>
#include <omp.h>

int main( void )  {

  int totalProcs;

  #pragma offload target(mic)
  totalProcs = omp_get_num_procs();

  printf( "procs: %d\n", totalProcs );
  return 0;

}
```

offload pragma

runs on MIC

runs on host

Add a one-line directive/pragma that offloads to the MIC the <u>one</u> line of executable code that occurs below it…

…codes now return "procs: 240"…

Explicit Offload

F90

```
program main

  use omp_lib

  integer :: nprocs

  !dir$ offload target(mic)
  nprocs = omp_get_num_procs()

  print*, "procs: ", nprocs

end program
```

don't use "-mmic"

```
ifort -openmp off01simple.f90

icc -openmp off01simple.c
```

C/C++

```
#include <stdio.h>
#include <omp.h>

int main( void )  {

  int totalProcs;

  #pragma offload target(mic)
  totalProcs = omp_get_num_procs();

  printf( "procs: %d\n", totalProcs );
  return 0;

}
```

Don't even need to change the compile line…

Explicit Offload

F90

```
program main

  use omp_lib

  integer :: nprocs

  !dir$ offload target(mic)
  nprocs = omp_get_num_procs()

  print*, "procs: ", nprocs

end program
```

off01simple

C/C++

```
#include <stdio.h>
#include <omp.h>

int main( void )  {

  int totalProcs;

  #pragma offload target(mic)
  totalProcs = omp_get_num_procs();

  printf( "procs: %d\n", totalProcs );
  return 0;

}
```

Not asynchronous (yet):
the host pauses until
MIC is finished.

Explicit Offload

F90

```
!dir$ offload begin target(mic)
   nprocs     = omp_get_num_procs()
   maxthreads = omp_get_max_threads()
!dir$ end offload
```

off02block

Can offload a block of code
(generally safer than
the one-line approach)…

C/C++

```
#pragma offload target(mic)
   {
     totalProcs = omp_get_num_procs();
     maxThreads = omp_get_max_threads();
   }
```

Explicit Offload

F90

```
program main

  integer, parameter :: N = 500000   ! constant
  real               :: a(N)         ! on stack

  !dir$ offload target(mic)
    !$omp parallel do
      do i=1,N
        a(i) = real(i)
      end do
    !$omp end parallel do
  ...
```

`off03omp`

…or an OpenMP region defined by an omp directive…

C/C++

```
int main( void ) {

  double a[500000];
    // on the stack; literal here is important
  int i;

  #pragma offload target(mic)
    #pragma omp parallel for
      for ( i=0; i<500000; i++ )  {
        a[i] = (double)i;
      }
  ...
```

Explicit Offload

```
[redacted]
integer function successor( m )
  ...

program main
  ...
  integer :: successor
 [redacted]
  ...

  !dir$ offload target(mic)
    n = successor( m )
```

F90

off04proc

```
[redacted] int  successor( int   m );
           void increment( int* pm );

int main( void ) {

    int i;

    #pragma offload target(mic)
      {
        i = successor( 123 );
        increment( &i );
      }
```

C/C++

…or procedure(s) defined by the programmer

(though now there's another step)…

Explicit Offload

```
!dir$ attributes offload:mic :: successor
integer function successor( m )
  ...

program main
  ...
  integer :: successor
  !dir$ attributes offload:mic :: successor
  ...

  !dir$ offload target(mic)
    n = successor( m )
```

F90

off04proc

```
__declspec( target(mic) ) int  successor( int   m );
__declspec( target(mic) ) void increment( int* pm );

int main( void ) {

    int i;

    #pragma offload target(mic)
      {
        i = successor( 123 );
        increment( &i );
      }
```

C/C++

…mark prototypes to tell compiler to build executable code on both sides...

Explicit Offload

```
module mymodvars
  !dir$ attributes offload:mic :: mymoduleint
  integer                      :: mymoduleint
end module mymodvars

program main

  use mymodvars
  implicit  none

  integer       :: mylocalint = 123
  integer, save :: mysaveint !no decoration required
```

F90

off05global

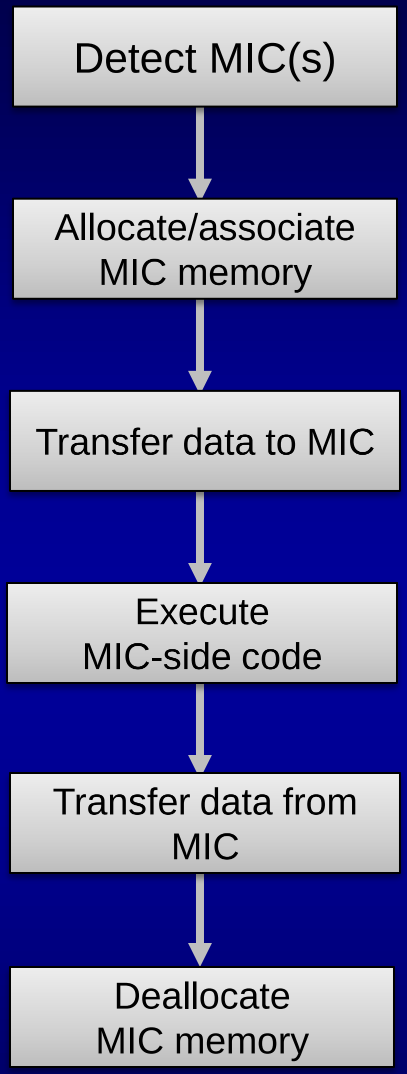
…and mark all global and static identifiers…

```
__declspec( target(mic) ) int myGlobalInt;

int main( void ) {

  int myLocalInt = 123;
  __declspec( target(mic) ) static int myStaticInt;
```

C/C++

Controlling the Offload

Additional decorations (clauses, attributes, specifiers, keywords) give the programmer a high degree of control over all steps in the process.



Detect MIC(s)

Allocate/associate MIC memory

Transfer data to MIC

Execute MIC-side code

Transfer data from MIC

Deallocate MIC memory

Explicit Offload

```
!dir$ offload target(mic)
  !$omp parallel do
    do i=1,N
      a(i) = real(i)
    end do
  !$omp end parallel do
```

F90

`off03omp`

```
#pragma offload target(mic)
  #pragma omp parallel for
    for ( i=0; i<500000; i++ )  {
      a[i] = (double)i;
    }
```

C/C++

…"target(mic)"
means
"find a MIC,
any ol' MIC"…

Explicit Offload

```
!dir$ offload target(mic:0)
  !$omp parallel do
    do i=1,N
      a(i) = real(i)
    end do
  !$omp end parallel do
```

F90

off03omp

…"target(mic:0)"
or "target(mic:i)"
means
"find a specific MIC"…

```
#pragma offload target(mic:0)
  #pragma omp parallel for
    for ( i=0; i<500000; i++ )  {
      a[i] = (double)i;
    }
```

C/C++

Explicit Offload

```
 integer, parameter :: N = 100000              ! constant
 real               :: a(N), b(N), c(N), d(N)  ! on stack
  ...
!dir$ offload target(mic)          &
 in( a ), out( c, d ), inout( b )
    !$omp parallel do
      do i=1,N
        c(i) =  a(i) + b(i)
        d(i) =  a(i) - b(i)
        b(i) = -b(i)
      end do
    !$omp end parallel do
```

F90

off06stack

…control data transfer
between host and MIC…

```
double a[100000], b[100000], c[100000], d[100000];
  // on the stack; literal is necessary for now

...

#pragma offload target(mic)         \
  in( a ), out( c, d ), inout( b )
    #pragma omp parallel for
      for ( i=0; i<100000; i++ )   {
        c[i] =  a[i] + b[i];
        d[i] =  a[i] - b[i];
        b[i] = -b[i];
      }
```

C/C++

Explicit Offload

```
real, allocatable  :: a(:), b(:)
integer, parameter :: N = 5000000
allocate(  a(N), b(N)   )
...

!
!dir$ offload target(mic)                            &
 in(  a : alloc_if(.true.) free_if(.true.)   ),  &
 out( b : alloc_if(.true.) free_if(.false.) )
  !$omp parallel do
    do i=1,N
      b(i) = 2.0 * a(i)
    end do
  !$omp end parallel do
```

(see source file for alignment directives)

F90

off07heap

```
int N = 5000000;
double *a, *b;

a = ( double* ) memalign( 64, N*sizeof(double) );
b = ( double* ) memalign( 64, N*sizeof(double) );
...
#pragma offload target(mic)                        \
 in(  a :            alloc_if(1) free_if(1) ), \
 out( b :            alloc_if(1) free_if(0) )
  #pragma omp parallel for
    for ( i=0; i<N; i++ )  {
      b[i] = 2.0 * a[i];
    }
```

C/C++

…manage MIC memory and its association with dynamically allocated memory on the host…

Explicit Offload

```
real, allocatable  :: a(:), b(:)
integer, parameter :: N = 5000000
allocate(  a(N), b(N)  )
...

! Fortran allocatable arrays don't need length attribute...
!dir$ offload target(mic)                              &
 in(  a : alloc_if(.true.) free_if(.true.)  ),  &
 out( b : alloc_if(.true.) free_if(.false.) )
  !$omp parallel do
    do i=1,N
      b(i) = 2.0 * a(i)
    end do
  !$omp end parallel do
```

(see source file for alignment directives)

F90

off07heap

…Dynamically allocated arrays in C/C++ require an additional "length" attribute...

```
int N = 5000000;
double *a, *b;

a = ( double* ) memalign( 64, N*sizeof(double) );
b = ( double* ) memalign( 64, N*sizeof(double) );
...
#pragma offload target(mic)                          \
 in(  a : length(N) alloc_if(1) free_if(1) ), \
 out( b : length(N) alloc_if(1) free_if(0) )
  #pragma omp parallel for
    for ( i=0; i<N; i++ )  {
      b[i] = 2.0 * a[i];
    }
```

C/C++

Explicit Offload

```
integer  :: n = 123

!dir$ offload begin target(mic:0)  signal( n )
  call incrementslowly( n )
!dir$ end offload

...

print *, "  n: ", n
```

for now, any initialized 4 or 8 byte integer

F90

off08asynch

```
int n = 123;

#pragma offload target(mic:0)  signal( &n )
  incrementSlowly( &n );

...

printf( "\n\tn = %d \n", n );
```

pointer to any initialized variable

C/C++

…Asynchronous offload with "signal": work on host continues while offload proceeds...

Explicit Offload

```
integer  :: n = 123

!dir$ offload begin target(mic:0)  signal( n )
  call incrementslowly( n )
!dir$ end offload


...
!dir$ offload_wait target(mic:0)  wait( n )





print *, "  n: ", n
```

F90

off09transfer

```
int n = 123;

#pragma offload target(mic:0)  signal( &n )
  incrementSlowly( &n );


...
#pragma offload_wait target(mic:0)  wait( &n )





printf( "\n\tn = %d \n", n );
```

device number required

C/C++

…offload_wait pauses the host but initiates no new work on MIC…

Explicit Offload

```
integer  :: n = 123

!dir$ offload begin target(mic:0)  signal( n )
  call incrementslowly( n )
!dir$ end offload


...
!dir$ offload begin target(mic:0) wait( n )
  print *, "  procs: ", omp_get_num_procs()
  call flush(0)
!dir$ end offload

print *, "  n: ", n
```

F90

off09transfer

```
int n = 123;

#pragma offload target(mic:0)  signal( &n )
  incrementSlowly( &n );

...
#pragma offload target(mic:0)  wait( &n )
  {
  printf( "\n\tprocs: %d\n", omp_get_num_procs() );
  fflush(0);
  }

printf( "\n\tn = %d \n", n );
```

C/C++

…classical offload
(as opposed to
offload_wait)
will offload the next
line/block of code...

...both constructs need a
wait() clause with tag

Explicit Offload

```
!dir$ offload_transfer target(mic:0)                     &
  in(     a : alloc_if(.true.) free_if(.false.) ), &
  nocopy( b : alloc_if(.true.) free_if(.false.) )  &
  signal( tag1 )
```

F90

`off09transfer`

…offload_transfer is
a data-only offload
(no executable code
sent to MIC)…

...use it to move data
and manage memory
(alloc and free)...

```
#pragma offload_transfer target(mic:0)             \
  in(     a : length(N) alloc_if(1) free_if(0) ), \
  nocopy( b : length(N) alloc_if(1) free_if(0) )  \
  signal( tag1 )
```

these examples are
asynchronous

C/C++

Detecting/Monitoring Offload

- `export OFFLOAD_REPORT=2  # or 1, 3`
- Compile time info: `-opt-report-phase=offload`
- `__MIC__` macro defined on device
  - can be used for conditional compilation
  - use only within offloaded procedure
  - use capitalized “F90” suffix to pre-process during compilation
- `ssh mic0` (not mic:0) and run top
  - offload processes owned by “micuser”

Other Key Environment Variables

`OMP_NUM_THREADS`

- default is 1; that's probably not what you want!

`MIC_OMP_NUM_THREADS`

- default behavior is 244 (var undefined); you definitely don't want that

`MIC_STACKSIZE`

- default is only 12MB

`MIC_KMP_AFFINITY` and other performance-related settings

Offload: making it worthwhile

- Enough computation to justify data movement
- High degree of parallelism
  - threading, vectorization
- Work division: keep host and MIC active
  - asynchronous directives
  - offloads from OpenMP regions
- Intelligent data management and alignment
  - persistent data on MIC when possible

http://software.intel.com/en-us/articles/effective-use-of-the-intel-compilers-offload-features

Automatic Offload (AO)

- Feature of Intel Math Kernel Library (MKL)
  - growing list of computationally intensive functions
  - xGEMM and variants; also LU, QR, Cholesky
  - kicks in at appropriate size thresholds
    - (e.g. SGEMM: (M,N,K) = (2048, 2048, 256)
  - http://software.intel.com/en-us/articles/intel-mkl-automatic-offload-enabled-functions-for-intel-xeon-phi-coprocessors
- Essentially no programmer action required
  - more than offload: work division across host and MIC
  - http://software.intel.com/en-us/articles/performance-tips-of-using-intel-mkl-on-intel-xeon-phi-coprocessor

Automatic Offload

```
...

M =   8000
P =   9000
N = 10000

...

CALL DGEMM( 'N','N',M,N,P,ALPHA,A,M,B,P,BETA,C,M )
```

Fortran

`ao_intel`

```
#include "mkl.h"

...
m = 8000;
p = 9000;
n = 10000;

...

cblas_dgemm(
  CblasRowMajor, CblasNoTrans, CblasNoTrans,
  m, n, p, alpha, A, p, B, n, beta, C, n );
```

C/C++

…call one of the supported MKL functions for sufficiently large matrices...

Automatic Offload

```
                     ifort -openmp -mkl main.f
...

M =   8000
P =   9000
N = 10000

...

CALL DGEMM( 'N','N',M,N,P,ALPHA,A,M,B,P,BETA,C,M )
```

Fortran

ao_intel

```
#include "mkl.h"
                     icc -openmp -mkl main.c

...
m = 8000;
p = 9000;
n = 10000;

...

cblas_dgemm(
  CblasRowMajor, CblasNoTrans, CblasNoTrans,
  m, n, p, alpha, A, p, B, n, beta, C, n );
```

C/C++

…use Intel compiler
and link to MKL…

…ldd should show
libmkl_intel_thread…

Automatic Offload

- Set at least three environment variables before launching your code:

```
export MKL_MIC_ENABLE=1
export OMP_NUM_THREADS=16
export MIC_OMP_NUM_THREADS=240
```

- Other environment variables provide additional fine-grained control over host-MIC work division et al.

http://software.intel.com/sites/products/documentation/doclib/mkl_sa/11/mkl_userguide_lnx/GUID-3DC4FC7D-A1E4-423D-9C0C-06AB265FFA86.htm

MKL Offload: Other Opportunities

- Apps that call MKL “under the hood” can exploit AO
  - Need to build with Intel and link to threaded MKL
    - In other words, use **`-mkl`** or **`-mkl=parallel`**; do not use **`-mkl=sequential`**
  - Matlab on Stampede:

```
export BLAS_VERSION=$TACC_MKL_LIB/libmkl_rt.so
```

  - AO for R temporarily available with "module load R_mkl"
    - New AO-enabled parallel R coming soon
  - AO for Python: coming soon to Stampede
- Can also explicitly offload MKL functions

Implicit Offload: Virtual Shared Memory

- aka Shared Memory, MYO*
- Programmer marks data as shared between host and MIC; runtime manages synchronization
- Supports "arbitrarily complex" data structures, including objects and their methods
- Available only for C/C++

*"Mine-Yours-Ours"

Implicit Offload

_Cilk_shared marks global data as usable and synchronized between host and MIC. Runtime handles the details.

C/C++ only

```
int          _Cilk_shared mySharedInt;
COrderedPair _Cilk_shared mySharedP1;
```

Implicit Offload

_Cilk_shared also marks functions as suitable for offload. Signatures in prototypes and definitions determine how shared and unshared functions operate on shared data.

C/C++ only

```
int          _Cilk_shared mySharedInt;
COrderedPair _Cilk_shared mySharedP1;

int  _Cilk_shared incrementByReturn( int n );
void _Cilk_shared incrementByRef( _Cilk_shared int& n );
void _Cilk_shared modObjBySharedPtr(
  COrderedPair _Cilk_shared *ptrToShared );
```

Implicit Offload

C/C++ only

```
int          _Cilk_shared mySharedInt;
COrderedPair _Cilk_shared mySharedP1;

int  _Cilk_shared incrementByReturn( int n );
void _Cilk_shared incrementByRef( _Cilk_shared int& n );
void _Cilk_shared modObjBySharedPtr(
  COrderedPair _Cilk_shared *ptrToShared );


...
mySharedInt
  = _Cilk_offload incrementByReturn( mySharedInt );

_Cilk_offload modObjBySharedPtr( &mySharedP1 );
```

_Cilk_offload executes a shared function on MIC (does not operate on a block of code)

Implicit Offload

C/C++ only

```
int          _Cilk_shared mySharedInt;
COrderedPair _Cilk_shared mySharedP1;

int  _Cilk_shared incrementByReturn( int n );
void _Cilk_shared incrementByRef( _Cilk_shared int& n );
void _Cilk_shared modObjBySharedPtr(
  COrderedPair _Cilk_shared *ptrToShared );

...
mySharedInt
  = _Cilk_offload incrementByReturn( mySharedInt );

_Cilk_offload modObjBySharedPtr( &mySharedP1 );
```

But the devil’s
in the details...

Implicit Offload: Issues

- Shared data must be global
- Shared vs unshared datatypes
  - need for casting and overloading (equality, copy constructors)
- Special memory managers
  - “placement new” to share STL classes
- Infrastructure less stable and mature
  - Intel sample code available, but other resources are sparse
  - we all have a lot to learn about this
- By its nature a little slower than explicit offload

Offload: Issues and Gotchas

- Fast moving target
  - Functionality/syntax varies across compiler versions
  - Documentation often lags behind ground truth
- First offload takes longer
  - Consider an untimed initMIC offload
- Memory limits
  - ~6.7GB available for heap; 12MB default stack
- File I/O essentially impossible from offload region
  - console output ok; flush buffer
- Optional offload in transition
  - -no-offload compiler flag works on Stampede

Summary

- Offload may be for you if your app is...
  - computationally intensive
  - highly parallel (threading, vectorization)
- Best practices revolve around...
  - asynchronous operations
  - intelligent data movement (persistence)
- Three models currently supported
  - explicit: simple data structures
  - automatic: computationally-intensive MKL calls
  - implicit: complex data structures (objects and their methods)

Exercise Options
(pick and choose)

- Option A: `tar xvf ~train00/offload_lab.tar`
  - Exercise 1: Simple Offload Examples
  - Exercise 2: Data Transfer Optimization
  - Exercise 3: Concurrent and Asynchronous Offloads
- Option B: `tar xvf ~train00/offload_demos.tar`
  - Explicit offload: exercises based on TACC examples from presentation
  - Automatic offload: exercises based on Intel examples from presentation

Project code: `20131204MIC`

Doug James

djames@tacc.utexas.edu

(512) 471-0696

For more information:

www.tacc.utexas.edu

License