Hybrid MPI/OpenMP programming

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Overview

• Single and multilevel parallelism.
• Example of MPI-OpenMP buildup.
• Compilation and running.
• Performance suggestions.
• Code examples.
• Survey

https://www.surveymonkey.com/r/8P5YVK8
Single level parallelism

• Shared memory computers
  ▪ N processors, single system image
  ▪ thread-based parallelism - OpenMP, shmem
  ▪ message-based parallelism - MPI

• Distributed memory computers
  ▪ nodes with local memory, coupled via network
  ▪ message-based parallelism – MPI
  ▪ partitioned global space – UPC, Coarray Fortran
Shared-Distributed memory

- Each node has $N$ processors that share memory
- Nodes loosely connected (network)
- CHPC:
  - 8, 12, 16, 20, 24, 28 core cluster nodes
Multilevel parallelism

- Coarse and fine grain level
  - coarse – nodes, processors (sockets)
    fine – CPU cores
  - MPI - nodes, CPU sockets
  - OpenMP, pthreads, shmem – CPU cores
  - OpenMP works best with processing intensive loops

- Multilevel advantages
  - memory limitations – extra memory for each copy of executable on the node
  - process vs. thread overhead
  - message overhead
  - portability, ease to maintain (can disable OpenMP)
• MPI (Message Passing Interface)
  ▪ standardized library (not a language)
  ▪ collection of processes communicating via messages
  ▪ available for most architectures

• OpenMP
  ▪ API for shared memory programming
  ▪ available on most architectures as a compiler extension (C/C++, Fortran)
  ▪ includes compiler directives, library routines and environment variables
  ▪ [www.openmp.org](http://www.openmp.org)
Processes vs. threads

- **Process**
  - have own address space
  - can have multiple threads

- **MPI**
  - many processes
  - shared-nothing architecture
  - explicit messaging
  - implicit synchronization
  - all or nothing parallelization

- **Thread**
  - executes within process
  - same address space
  - share process’s stack
  - thread specific data

- **OpenMP**
  - 1 process, many threads
  - shared-everything architecture
  - implicit messaging
  - explicit synchronization
  - incremental parallelism
• Calculation of value of π using integral:

\[
\int_0^1 \frac{dx}{x^2 + 1} = \frac{\pi}{4}
\]

• trapezoidal rule

• simple loop easy to parallelize both with MPI and OpenMP
```
#include <stdio.h>
#include <math.h>
#include "timer.h"

int main(int argc, char *argv[]){
    const int N = 10000000000;
    const double h = 1.0/N;
    const double PI = 3.141592653589793238462643;
    double x, sum, pi, error, time; int i;

    time = ctimer();
    sum = 0.0;
    for (i=0; i<=N; i++) {
        x = h * (double)i;
        sum += 4.0/(1.0+x*x);
    }
    pi = h*sum;
    time += ctimer();

    error = pi - PI;
    error = error<0 ? -error: error;
    printf("pi = %18.16f +/- %18.16f\n", pi, error);
    printf("time = %18.16f sec\n", time);
    return 0;
}
```

- User-defined timer
- Calculation loop
- Print out result
#include <stdio.h>
#include <math.h>
#include "timer.h"

int main(int argc, char *argv[]){
  const int N = 10000000000;
  const double h = 1.0/N;
  const double PI = 3.141592653589793238462643;
  double x,sum,pi,error,time; int i;

  time = -ctimer();
  sum = 0.0;

  #pragma omp parallel for shared(N,h),private(i,x),reduction(+:sum)
  for (i=0;i<=N;i++){
    x = h * (double)i;
    sum += 4.0/(1.0+x*x);
  }

  pi = h*sum;
  time += ctimer();

  .......

  return 0;}

• OpenMP directive
```c
#include <stdio.h>
#include <math.h>
#include "timer.h"

int main(int argc, char *argv[])
{
    const int N = 10000000000;
    const double h = 1.0/N;
    const double PI = 3.141592653589793238462643;
    double x, sum, pi, error, time, mypi; int i;
    int myrank, nproc;

    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
    MPI_Comm_size(MPI_COMM_WORLD, &nproc);

    time = -ctimer();
    sum = 0.0;
    for (i = myrank; i <= N; i = i + nproc)
    {
        x = h * (double)i;
        sum += 4.0/(1.0 + x*x);
    }
    mypi = h*sum;
    MPI_Reduce(&mypi, &pi, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_WORLD);
    time += ctimer();
    ....
    return 0;
}
```

• **MPI initialization**

• **Distributed loop**
OK here, inefficient for vectors due to strided memory access

• **Global reduction**
```c
#include <stdio.h>
#include <math.h>
#include "timer.h"
int main(int argc, char *argv[]){
    const int N = 10000000000;
    const double h = 1.0/N;
    const double PI = 3.141592653589793238462643;
    double x,sum,pi,error,time,mypi; int i;
    int myrank,nproc;

    MPI_Init(&argc,&argv);
    MPI_Comm_rank(MPI_COMM_WORLD,&myrank);
    MPI_Comm_size(MPI_COMM_WORLD,&nproc);
    time = -ctimer();
    sum = 0.0;

    #pragma omp parallel for shared(N,h,myrank,nproc),private(i,x),reduction(+:sum
    for (i=myrank;i<=N;i=i+nproc){
        x = h * (double)i;
        sum += 4.0/(1.0+x*x);
    }
    mypi = h*sum;
    MPI_Reduce(&mypi,&pi,1,MPI_DOUBLE,MPI_SUM,0,MPI_COMM_WORLD);
    time += ctimer();
    ......
    return 0;}
```

- **OpenMP directive to parallelize each MPI task loop using threads**
- **Sum MPI task local values of π**
- GNU, PGI, Intel compilers, OpenMP with `-fopenmp`, `-mp`, `-qopenmp` switch

- MPICH, MVAPICH2, OpenMPI or Intel MPI

  module load mpich MPICH
  module load mvapich2 MVAPICH2
  module load openmpi OpenMPI
  module load impi Intel MPI

  mpicc -mp=numa source.c -o program.exe (PGI)
  mpif90 -qopenmp source.f -o program.exe (Intel)
  mpif90 -fopenmp source.f -o program.exe (GNU)
• BLASes and FFTW are threaded
• Intel compilers:
  -I/uufs/chpc.utah.edu/sys/pkg/fftw/std_intel/include
  -lfftw3 -lfftw3_omp
  -L/uufs/chpc.utah.edu/sys/pkg/fftw/std_intel/lib
  -Wl,-rpath=/uufs/chpc.utah.edu/sys/installdir/intel/mkl/lib/intel64
  -L/uufs/chpc.utah.edu/sys/installdir/intel/mkl/lib/intel64
  -lmkl_intel_lp64 -lmkl_intel_thread -lmkl_core -liomp5 -lpthread
• PGI compilers:
  -I/uufs/chpc.utah.edu/sys/pkg/fftw/std_pgi/include
  -lfftw3 -lfftw3_omp
  -L/uufs/chpc.utah.edu/sys/pkg/fftw/std_pgi/lib -lacml_mp
• MKL ScaLAPACK w/ Intel
  -Wl,-rpath=/uufs/chpc.utah.edu/sys/installdir/intel/mkl/lib/intel64
  -L/uufs/chpc.utah.edu/sys/installdir/intel/mkl/lib/intel64
  -lmkl_scalapack_ilp64 -lmkl_intel_ilp64 -lmkl_core
  -lmkl_intel_thread -lmkl_blacs_intelmpi_ilp64 -liomp5 -lpthread -lm
• Ask for #MPI processes
• Use SLURM environment variables to get OpenMP thread count
• Interactive batch (asking for 2 nodes, 2 tasks/node)

\[
\text{\texttt{srun -n 4 -N 2 -t 1:00:00 -p kingspeak -A chpc -pty}} \\
/\text{bin/tcsh -l} \\
\ldots \text{wait for prompt} \ldots
\]

\[
\text{\texttt{set TPN=`echo \$SLURM_TASKS_PER_NODE | cut -f 1 -d \(}} \\
\text{\texttt{set PPN=`echo \$SLURM_JOB_CPUS_PER_NODE | cut -f 1 -d \(}} \\
\text{\texttt{@ THREADS = ( \$PPN / \$TPN )}} \\
\text{\texttt{mpirun -genv OMP_NUM_THREADS=\$THREADS -np \$SLURM_NTASKS}} \\
\text{\texttt{./program.exe}}
\]

• Non-interactive batch
  • same thing, except in a Slurm script
• Current NUMA architectures penalize memory access on neighboring CPU sockets
• Distribute and bind processes to CPU sockets

• Intel compilers can also pin threads to cores
```
module load intel mvapich2
mpirun -genv KMP_AFFINITY granularity=fine,compact,1,0 -genv MV2_BINDING_POLICY scatter -genv MV2_BINDING_LEVEL socket -genv OMP_NUM_THREADS 8 -np 4
```

• Intel MPI binds processes to sockets by default
```
module load intel impi
mpirun -x KMP_AFFINITY granularity=fine,compact,1,0 -genv OMP_NUM_THREADS 8 -np 4
```

or use `I_MPI_PIN_DOMAIN=socket`
Default pinning policies for compilers and MPI distributions vary


Some applications can gain up to 30% performance with pinning processes AND threads

Use pinthreads.sh script from the article with common compilers (Intel, PGI, GNU) and MPIS (MPICH, MVAPICH2, IMPI, OpenMPI)

```bash
mpirun -np 8 -genv OMP_NUM_THREADS 3 -bind-to socket -map-by socket ./pinthreads.sh ./myprogram
```

Check the pinning by this bash one-liner:

```bash
for i in $(pgrep myprogram); do for tid in $(ps --no-headers -mo tid -p $i |grep -v -); do taskset -cp "$\{tid\}"; done;
```
General multilevel approach

- Parallelize main problem using MPI
  - task decomposition
    - frequencies in wave solvers
  - domain decomposition
    - distribute atoms in molecular dynamics
    - distribute mesh in ODE/PDE solvers
- Exploit internal parallelism with OpenMP
  - use profiler to find most computationally intense areas
    - internal frequency loop in wave solvers
    - local force loop in MD
    - local element update loop in ODE/PDE solvers
  - measure the efficiency to determine optimal number of threads to use
  - Intel AdvisorXE can be helpful (module load advisorxe)
Things to be aware of

- Not every MPI program will benefit from adding threads
  - not worth with loosely parallel codes (too little communication)
  - overhead with thread creation about $10^4$ flops
  - time with different node/thread count to get the best performing combination
- MPI communication within OpenMP
  - can be tricky if each thread communicates
  - be aware of thread safety in MPI when using MPI_THREAD_MULTIPLE
Four MPI threading models

- **MPI_THREAD_SINGLE**
  - only non-threaded section communicates

- **MPI_THREAD_FUNNELLED**
  - process may be multithreaded but only master thread communicates

- **MPI_THREAD_SERIALIZED**
  - multiple threads may communicate but only one at time

- **MPI_THREAD_MULTIPLE**
  - all threads communicate
• Complex norm routine

```c
int main(int argc, char **argv){
    ........
    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);
    ........

double _Complex stabWmnorm(double *Wm, double _Complex *stab, int size)
{
    double _Complex norm, vec, norml;
    int i;

    norml = 0 + I*0;
    #pragma omp parallel for private(i,vec) reduction(+:norml)
    for (i=0;i<size;i++)
    {
        vec = stab[i]*Wm[i];
        norml = norml + vec*conj(vec);
    }
    MPI_Allreduce(&norml,&norm,1,MPI_DOUBLE_COMPLEX,MPI_SUM,MPI_COMM_WORLD);

    return sqrt(norm);
}

MPI_Finalize();
```
Multiple threads comm.
- initialization

- Special MPI_Init
  - Returns variable thread_status which indicates what level of threading is supported

```c
int thread_status;

MPI_Init_thread(&argc, &argv, MPI_THREAD_MULTIPLE, &thread_status);
if (thread_status!=MPI_THREAD_MULTIPLE)
{
    printf("Failed to initialize MPI_THREAD_MULTIPLE\n");
    exit(-1);
}
...

MPI_Finalize();
```
Multiple threads point-to-point communication

```c
#pragma omp parallel private(iis,niip,iip,iisf)
{
  double _Complex *ne, *nh; int comlab, mythread, nthreads;
  MPI_Status statx[fwdd->Nz];
  MPI_Request reqx[fwdd->Nz];

#ifdef _OPENMP
  mythread = omp_get_thread_num(); nthreads = omp_get_num_threads();
#endif
  ne = (double _Complex *)malloc(sizeof(double _Complex)*3*Nxy);
  comlab = mythread*10000; // different tag for each proc/thread

  for (iis=mythread; iis < Ncp[0]; iis+=nthreads)
  {
    ... do a lot of calculation
    if (cpuinfo[0] == iip)
    {
      MPI_Isend( &ne[0], Nxy, MPI_DOUBLE_COMPLEX, Dp[0], comlab, MPI_COMM_WORLD, reqx[Nreqi[0]]);
      Nreqi[0]++; comlab++;
    }
    else if (cpuinfo[0] == Dp[0])
    {
      MPI_Irecv(&Ebb[ie[0]*Nxy], Nxy, MPI_DOUBLE_COMPLEX, iip, comlab, MPI_COMM_WORLD, reqx[Nreqi[0]]);
      Nreqi[0]++; comlab++;
    }
    MPI_Waitall(Nreqi[0], &reqx[0], &statx[0]);
  }

  free(ne);
}
```

- Start parallel OpenMP section
- Data structures for non-blocking communication
- Find thread # and # of threads
- Allocate local thread arrays
- Each thread does different iteration of this loop
- Each communication pair has unique tag
- Finalize non-blocking communication
- Free local thread arrays
- End OpenMP parallel section

-> use message tag to differentiate between threads
Multiple threads collective communication

```c
MPI_Comm comm_thread[NOMPUPUS];

#pragma omp parallel private(iis,niip,iip,iisf)
{
    double _Complex *ne; int mythread, nthreads

#ifdef _OPENMP
    mythread = omp_get_thread_num(); nthreads = omp_get_num_threads();
#endif

    ne = (double _Complex *)malloc(sizeof(double _Complex)*3*Nxy);

    for(ithr=0;ithr<nthreads;ithr++)
    {
        #pragma omp barrier // synchronize so that each process gets the right thread
        if (ithr==mythread) MPI_Comm_dup(comm_domain, &comm_thread[mythread]);
    }

    for (iis=mythread; iis < Ncp[0]; iis+=nthreads)
    {
        ... calculate ne ...
        MPI_Gatherv( &ne[indgbp[iic]],Nxy_loc,MPI_DOUBLE_COMPLEX, &Gb[ie[ic]*Nxy2 + iit2], Nxy_rec, Nxy_disp, MPI_DOUBLE_COMPLEX, Dp[ic],comm_thread[mythread]);
    }

    for(ithr=0;ithr<nthreads;ithr++)
    {
        if (ithr==mythread) MPI_Comm_free(&comm_thread[mythread]);
    }

    free(ne);
}
```

- Use communicators to differentiate between threads
- Start parallel OpenMP section
- Find thread # and # of threads
- Allocate local thread arrays
- Per thread communicator
  - Each thread does different iteration of this loop
- Thread communicator
- Free thread communicators
- Free local thread arrays
- End OpenMP parallel section
- Slide 24
• Mixed MPI-OpenMP has become commonplace
  ▪ reduces memory footprint per core
  ▪ better locality of memory access per core
  ▪ faster inter-node communication – larger messages, smaller overhead
• Single and multilevel parallelism
• Simple MPI-OpenMP example
• Compilation, running
• A few advices

http://www.chpc.utah.edu/short_courses/mpi_omp
• MPI
  http://www.mpi-forum.org/
  Pacheco - Parallel Programming with MPI
  Gropp, Lusk, Skjellum – Using MPI 1, 2

• OpenMP
  http://www.openmp.org/
  Chandra, Dagum, Kohr,… - Parallel Programming in 
  OpenMP

• MPI+OpenMP
  Pacheco – Introduction to Parallel Programming

Survey
  https://www.surveymonkey.com/r/8P5YVK8