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Case Study:
MPI: Message Passing Interface.

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Outline

- The MPI library: functions, types;
- MPI programming concepts: processes, communicators, etc.;
- Basic MPI functions, blocking/non-blocking send/receive;
- Collective operations: barriers, broadcast, gather/scatter, reduce, etc.;
- Communicators.

References

- Chapter 4.6 Case Study: MPI, in "*Distributed Systems – Concepts and Design*", Coulouris et al, Addison Wesley
- Tutorial: Message Passing Interface (MPI) https://computing.llnl.gov/tutorials/mpi/
- MPICH - A Portable Implementation of MPI http://www.mpich.org/
- MPI Tutorials and Other documents http://www.mpich.org/documentation/guides/ http://www.mcs.anl.gov/research/projects/mpi/learning.html

MPI: Message Passing Interface

- MPI is a message-passing library specification for multiprocessor, clusters, and heterogeneous networks
  - Not a compiler specification, not a specific product.
  - Message-passing model and API
  - Designed
    - To allow the development of parallel software libraries
    - To provide access to advanced parallel hardware for end users, library writers, and tool developers.
  - MPI is a de facto standard for message passing systems
  - Language bindings: Fortran and C

- MPICH and LAM – the two most popular implementations of MPI today
  - MPICH is more generally usable on various platforms
  - LAM – for TCP/IP networks

- Other message-passing programming environment: PVM (Parallel Virtual Machine)

The MPI Library (API)

The MPI library is large: about 130 functions

- extensive functionality and flexibility
- message passing (point-to-point, collective)
- process groups and topologies

The MPI library is “small”: only 6 functions allow writing many programs

- `MPI_Init, MPI_Finalize,`
  `MPI_Comm_size, MPI_Comm_rank,`
  `MPI_Send, MPI_Recv`

All MPI functions, constants and data types have prefix `MPI_`

C Data Types Mapping in MPI

mpi.h

MPI datatype	C datatype
MPI_CHAR	signed char
MPI_SHORT	signed short int
MPI_INT	signed int
MPI_LONG	signed long int
MPI_UNSIGNED_CHAR	unsigned char
MPI_UNSIGNED_SHORT	unsigned short int
MPI_UNSIGNED	unsigned int
MPI_UNSIGNED_LONG	unsigned long int
MPI_FLOAT	float
MPI_DOUBLE	double
MPI_LONG_DOUBLE	long double
MPI_BYTE	
MPI_PACKED	

MPI Programming Concepts: Processes

MPI process

- A smallest unit of computation, e.g. a Unix process.
- Uniquely identified by its rank in a process group (communicator).
- Processes communicate with tagged messages within process groups identified by communicators (communication contexts)
- A proc can send messages either synchronously or asynchronously.
- The proc is responsible for receiving messages directed to it.
- The proc uses either blocking or non-blocking receive/send.
- The proc can participate in a collective operation such as broadcast, gather, barrier, that involves all processes in a group.

MPI application

- a static set of processes that interact to solve a problem.
- `mpiexec -np 2 hello` – starts two `hello` processes.

Communicators. Process groups. Ranks

Communicator

- An opaque object that defines a process group and a communication context for the group. Delimits scope of communication.
  - Separate groups of processes working on sub-problems each with specific communication context identified by a communicator.

Process group

- A virtual set of processes identified by a communicator.
  - Grouped for collective and point-to-point communications.
  - All communication (not just collective operations) takes place in groups.
  - Each process has a unique index (rank) in a given group.

Rank

- A unique identifier (index) of a process within a communicator (in a proc group)
- Ranks are in the range 0, … , size-1 (where size is the size of the group)

Developing, Building and Running an MPI Application

- **Install** one of the MPI implementations, e.g. MPICH-2
- **Develop** your application in an SPMD-style – one program for all processes
  - The number of processes is specified at run time (could be 1)
  - Use the number of proc and proc ranks to determine process tasks
  - In C: `#include <mpi.h>`
- **Compile and buld:**
  `mpicc -o myprog myprog.c`
  - For large projects, develop a `Makefile`
  - To compile C++: `mpicc –cc=g++ -o myprog myprog.cpp`
  - The option -`help` shows all options to `mpicc`.
- **Run:**
  `mpiexec -np 2 myprog`
  - The option -`help` shows all options to `mpiexec`.
  - Alternatively, you can call `mpirun` (which is a link to `mpiexec`)

Process Managers (1/2)

Process managers (e.g. Hydra, MPD) are external distributed agents that spawn and manage parallel jobs.

- A process manager communicates with MPICH processes using a predefined interface called PMI (process management interface).
- You can use any process managers as long as they follow the same wire protocol.
- Three known implementations of the PMI wire protocol: "simple", "smpd" and "slurm“ (default: simple)

MPICH provides several different process managers, e.g.

- Hydra, MPD, Gforker and Remshell which follow the "simple" PMI wire protocol.

Process Managers (2/2)

MPD has been the traditional default process manager for MPICH till the 1.2.x release series.

Starting the 1.3.x series, **Hydra is the default process manager**.

See "*Using the Hydra Process Manager*" at

https://wiki.mpich.org/mpich/index.php/Using_the_Hydra_Process_Manager

Basic MPI Functions

`int MPI_Init( int *argc, char **argv[] )`

- Start MPI, enroll the process in the MPI application

`int MPI_Finalize()`

- Stop (exit) MPI

`int MPI_Comm_size(MPI_Comm comm, int *size)`

- Determine the number of processes in the group `comm`.
  - `comm` – communicator, e.g. `MPI_COMM_WORLD`
  - `size` – number of processes in group (returned)

`int MPI_Comm_rank(MPI_Comm comm, int *rank)`

- Determine the rank of the calling process in the group `comm`.
  - `comm` – communicator, e.g. `MPI_COMM_WORLD`
  - `rank` – the rank (returned) is a number between zero and `size-1`

Example: “Hello World”

```
#include "mpi.h"
#include <stdio.h>
int main( argc, argv )
    int argc;
    char **argv;
    {
        int rank, size;
        MPI_Init( &argc, &argv );
        MPI_Comm_rank( MPI_COMM_WORLD, &rank );
        MPI_Comm_size( MPI_COMM_WORLD, &size );
        printf( "Hello world! I'm %d of %d\n", rank, size );
        MPI_Finalize();
        return 0;
    }
```

Basic (Blocking) Send

```
int MPI_Send(void *buf, int count, MPI_datatype dt,
             int dest, int tag, MPI_Comm comm)
```

- Send a message with the given tag to the given destination in the given communicator

`buf`	send buffer
`count`	number of items in buffer
`dt`	data type of items
`dest`	destination process rank
`tag`	message tag
`comm`	communicator

- Returns integer result code as for all MPI functions, normally `MPI_SUCCESS`
- *`datatype`* can be elementary, continues array of data types, stridden blocks of data types, indexed array of blocks of data types, general structure.

Basic (Blocking) Receive

```
int MPI_Recv( void *buf, int count, MPI_datatype dt,
              int source, int tag, MPI_Comm comm,
              MPI_Status *status)
```

- Receive a message with the given tag from the given source in the given communicator

`buf`	receive buffer (loaded)
`count`	max number of entries in buffer
`dt`	data type of entries
`source`	source process rank
`tag`	message tag
`comm`	communicator
`status`	status (returned).

- “Wildcard” values are provided for tag (`MPI_ANY_TAG`) and source (`MPI_ANY_SOURCE`).

Inspecting Received Message

- If wildcard values are used for tag and/or sources, the received message can be inspected via a **MPI_Status** structure that has three components **MPI_SOURCE**, **MPI_TAG**, **MPI_ERROR**

```
MPI_Status status;
MPI_Recv( ..., &status );
int tag_received = status.MPI_TAG;
int rank_of_source = status.MPI_SOURCE;
MPI_Get_count( &status, datatype, &count );
```

- **MPI_Get_count** is used to determine how much data of a particular type has been received.

Communication Modes of Blocking Send

Standard blocking send (non-local) **`MPI_Send`**

- Implementation defined buffering: If the message is buffered, the send may complete before a matching receive is invoked.

Buffered blocking send (local) **`MPI_Bsend`**

- Can be started whether or not a matching receive has been posted;
- May complete before a matching receive is posted.

Synchronous blocking send (non-local) **`MPI_Ssend`**

- Can be started whether or not a matching receive has been posted;
- Completes when a matching receive is posted and has started to receive.

Ready blocking send (non-local) **`MPI_Rsend`**

- May be started only if the matching receive is already posted;
- Otherwise outcome is undefined.

Example 1: Exchange of Messages (Always Succeeds)

```
MPI_Comm_rank(comm, &rank);
if (rank == 0) {
    MPI_Send(sendbuf, count, MPI_REAL, 1, tag, comm);
    MPI_Recv(recvbuf, count, MPI_REAL, 1, tag, comm, &status);
}
if (rank == 1) {
    MPI_Recv(recvbuf, count, MPI_REAL, 0, tag, comm, &status);
    MPI_Send(sendbuf, count, MPI_REAL, 0, tag, comm);
}
```

- This program will succeed even if no buffer space for data is available.
- The standard send operation can be replaced, in this example, with asynchronous send.

Example 2: Exchange of Messages (Always Deadlocks)

```
MPI_Comm_rank(comm, &rank);
if (rank == 0) {
    MPI_Recv(recvbuf, count, MPI_REAL, 1, tag, comm, &status);
    MPI_Send(sendbuf, count, MPI_REAL, 1, tag, comm);
}
if (rank == 1) {
    MPI_Recv(recvbuf, count, MPI_REAL, 0, tag, comm, &status);
    MPI_Send(sendbuf, count, MPI_REAL, 0, tag, comm);
  }
```

- This program will always deadlock!
- The same holds for any other send mode.

Example 3: Exchange of Messages (Relies on Buffering)

```
MPI_Comm_rank(comm, &rank);
if (rank == 0)
  {
    MPI_Send(sendbuf, count, MPI_REAL, 1, tag, comm);
    MPI_Recv(recvbuf, count, MPI_REAL, 1, tag, comm, &status);
  }
if (rank == 1)
  {
    MPI_Send(sendbuf, count, MPI_REAL, 0, tag, comm);
    MPI_Recv(recvbuf, count, MPI_REAL, 0, tag, comm, &status);
  }
```

- For the program to complete, it is necessary that at least one of the two messages sent has been buffered.
- The program can succeed only if the communication system can buffer at least count words of data.

Non-Blocking Communication Operations

Non-blocking send initiates sending:

```
int MPI_Isend(void* buf, int count, MPI_Datatype type,
              int dest, int tag, MPI_Comm comm,
              MPI_Request *request)
```

Non-blocking receive initiates receiving:

```
int MPI_Irecv(void* buf, int count, MPI_Datatype type,
              int source, int tag, MPI_Comm comm,
              MPI_Request *request)
```

- A request object is returned in `request` to identify the operation.

Non-Blocking Operations (cont'd)

To query the status of communication or to wait for its completion:

```
int MPI_Test( MPI_Request *request, int *flag,
              MPI_Status *status)
```

– Returns immediately with `flag = true` if the operation identified by `request` has completed,
otherwise returns immediately with `flag = false`.

```
int MPI_Wait(MPI_Request *request, MPI_Status *status)
```

– Returns when the operation identified by `request` completes.

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Example: Non-Blocking Send/Receive

```
MPI_Comm_rank(comm, &rank);
if (rank = 0)
  {
    MPI_Isend(a, 10, MPI_REAL, 1, tag, comm, request);
    /**** do some computation to mask latency ****/
    MPI_Wait(request, &status);
  }
if (rank = 1)
  {
    MPI_Irecv(a, 10, MPI_REAL, 0, tag, comm, request);
    /**** do some computation to mask latency ****/
    MPI_Wait(request, &status);
  }
}
```

Probing for Pending Messages

Non-blocking/blocking check for an incoming message without receiving it

```
MPI_Iprobe(source, tag, comm, flag, status)
```

– polls for pending messages

```
MPI_Probe(source, tag, comm, status)
```

– returns when a message is pending

Collective Operations

A ***collective operation*** is executed by having all processes in the communicator call the same communication routine with matching arguments.

- Several collective routines have a single originating or receiving process – the ***root***.
- Some arguments in the collective functions are specified as “significant only at root”, and are ignored for all participants except the root.

Collective Communication

Collective synchronization (barrier):

```
int MPI_Barrier( MPI_Comm comm )
```

Broadcast from `buf` of `root` to all processes:

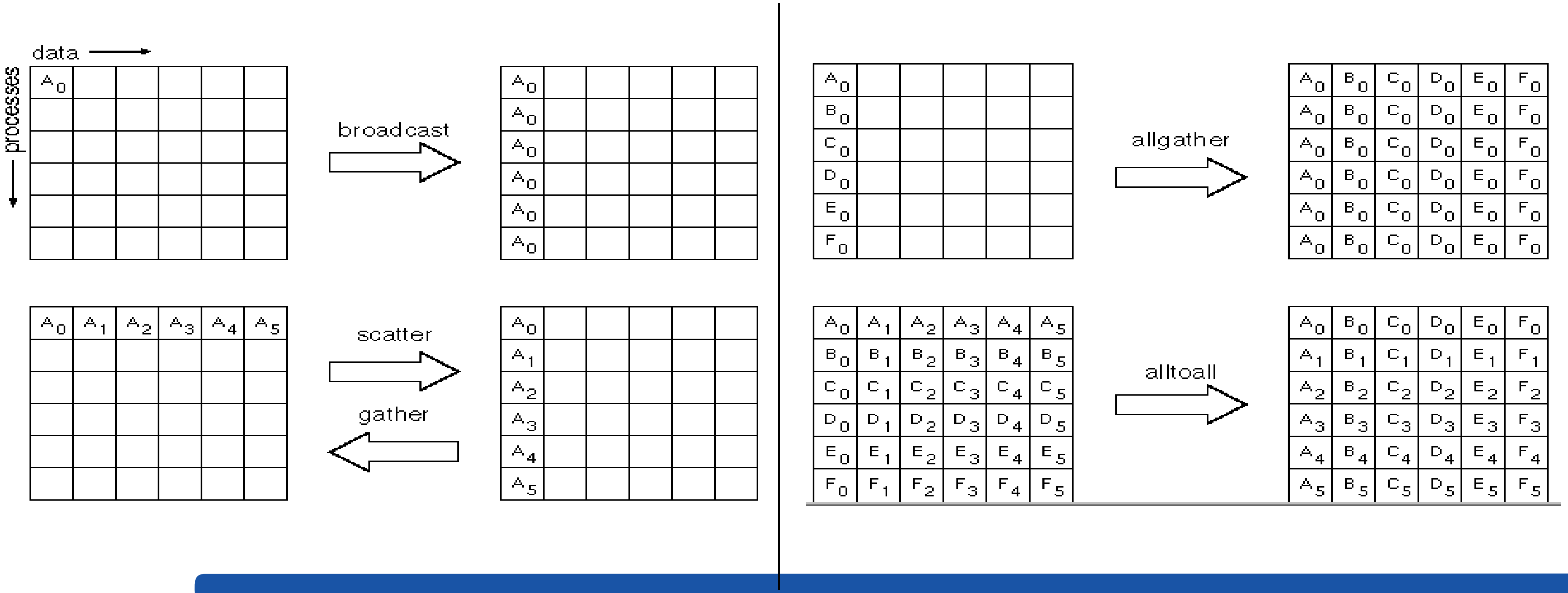
```
int MPI_Bcast( void *buf, int count, MPI_datatype dt, int root, MPI_Comm comm )
```

Collective data transfer:

```
int MPI_Gather( void *sendbuf, int sendcount, MPI_datatype sendtype,
                void *recvbuf, int recvcount, MPI_datatype recvtype,
                int root, MPI_Comm comm )

int MPI_Scatter( void *sendbuf, int sendcount, MPI_datatype sendtype,
                 void *recvbuf, int recvcount, MPI_datatype recvtype,
                 int root, MPI_Comm comm )
```

Collective Data Transfer Operations



Example 1: Broadcast

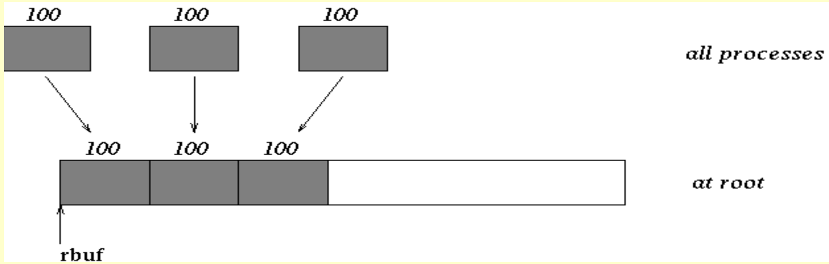
Broadcast 100 integers from process 0 (root) to every process in the group.

```
MPI_Comm comm;
    int array[100];
    int root=0;
    ...
    MPI_Bcast( array, 100, MPI_INT, root, comm);
}
```

Example 2: Gather

Gather 100 integers from every process in group to root.

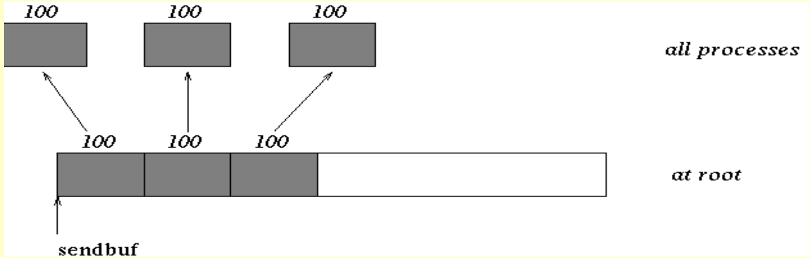
```
MPI_Comm comm;
int gsize, sendarray[100];
int root, myrank, *rbuf;
...
MPI_Comm_rank(comm, myrank);
MPI_Comm_size(comm, &gsize);
...
if (myrank == root) rbuf = (int *)malloc(gsize*100*sizeof(int));
MPI_Gather(sendarray, 100, MPI_INT, rbuf, 100, MPI_INT, root, comm);
```



Example 3: Scatter

The reverse of Example 2 (previous slide): Scatter sets of 100 integers from the root to each process in the group.

```
MPI_Comm comm;
int gsize,*sendbuf;
int root, rbuf[100];
...
MPI_Comm_rank(comm, myrank);
MPI_Comm_size(comm, &gsize);
if ( myrank == root) {
    sendbuf = (int *)malloc(gsize*100*sizeof(int));
    ... // fill the send buffer with data to be scattered
}
MPI_Scatter(sendbuf, 100, MPI_INT, rbuf, 100, MPI_INT, root, comm);
```



Global Reduction Operations

Reduce data from send buffers of all participating processes into a receive buffer of the `root` proc using operation `op`

```
int MPI_Reduce( void *sendbuf, void *recvbuf, int count,
                MPI_datatype dt, MPI_Op op, int root, MPI_Comm comm)
```

Reduce data from send buffers of all participating processes into receive buffers of all the processes using operation `op`

```
int MPI_Allreduce( void * sendbuf, void * recvbuf, int count,
                   MPI_datatype dt, MPI_Op op, MPI_Comm comm )
```

Available operations (`MPI_Op op`): `MPI_MAX`, `MPI_MIN`, `MPI_SUM`, `MPI_LAND`, `MPI_BOR`, ...

Timing Functions

`double MPI_Wtime(void)`

– Returns a floating-point number of seconds, representing elapsed wall-clock time since some time in the past. The time is “local” on the host.

`double MPI_Wtick(void)`

– Returns the resolution of `MPI_WTIME` in seconds, the number of seconds between successive clock ticks.

Example:

```
{
   double starttime, endtime;
   starttime = double MPI_Wtime();
    ....  stuff to be timed  ...
   endtime   = double MPI_Wtime();
   printf("That took %f seconds\n", endtime - starttime);
}
```

Modularity: Communicators

A **communicator** identifies a process group and provides a context for all communication within the group

- Communicator acts as an extra tag on messages

The communicator **`MPI_COMM_WORLD`** identifies all running processes of the MPI application

Create/Destroy Communicators

- Create new communicator: same group, new context:

```
int MPI_Comm_dup(MPI_Comm comm, MPI_Comm *newcomm)
```

- Create new communicators based on colors, ordered by keys:

```
int MPI_Comm_split( MPI_Comm comm, int color, int key, MPI_Comm *newcomm )
```

  `color` identifies a group, `key` – rank in the group

- Create an inter-communicator from two intra-communicators

```
int MPI_Intercomm_create( MPI_Comm local_comm, int local_leader,
                          MPI_Comm peer_comm, int remoteleader,
                          int tag, MPI_Comm *inter_comm)
```

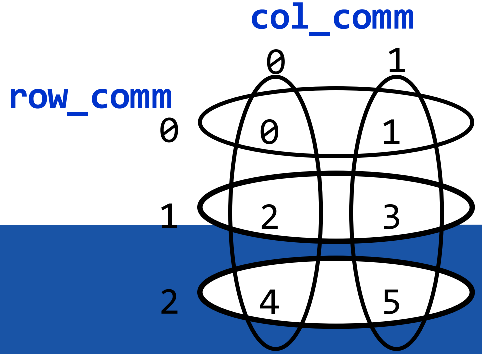
- Destroy a communicator

```
int MPI_Comm_free(MPI_Comm *comm)
```

Example MPI_Comm_split

```
// 2D topology with nrow rows and mcol (2) columns
// Split 3x2 grid into 2 communicators
// one (row_comm) corresponds to 3 rows;
// another (col_comm) – to 2 columns
irow = myID / mcol;        // logical row number
jcol = myID % mcol;                // logical column number
int row_comm, col_comm;
MPI_Comm_split(MPI_COMM_WORLD, irow, jcol, &row_comm);
MPI_Comm_split(MPI_COMM_WORLD, jcol, irow, &col_comm);
```

myID	0	1	2	3	4	5
irow	0	0	1	1	2	2
jcol	0	1	0	1	0	1



Communicators (cont'd)

One use of communicators is for calling parallel library routines in different context:

```
MPI_Comm *newcomm;
...
MPI_Comm_dup(comm, newcomm);
transpose(newcomm, matrix);  /* call library function */
MPI_Comm_free(newcomm);
```

Example: Compute PI

```
#include "mpi.h"
#include <math.h>
int main(int argc, char *argv[]) {
    int done = 0, n, myid, numprocs, i, rc;
    double PI25DT = 3.141592653589793238462643, mypi, pi, h, sum, x, a;
    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);
    while (!done) {
       if (myid == 0) {
          printf("Enter the number of intervals: (0 quits) "); scanf("%d",&n);
       }
       MPI_Bcast(&n, 1, MPI_INT, 0, MPI_COMM_WORLD);
       if (n == 0) break;
       h  = 1.0 / (double) n;
       sum = 0.0;
       for (i = myid + 1; i <= n; i += numprocs) {
          x = h * ((double)i - 0.5);
          sum += 4.0 / (1.0 + x*x);
       }
       mypi = h * sum;
       MPI_Reduce(&mypi, &pi, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_WORLD);
       if (myid == 0) printf("pi is approximately %.16f, Error is %.16f\n",  pi, fabs(pi - PI25DT));
     }
  MPI_Finalize();
}
```