The Message Passing Interface (MPI): Parallelism on Distributed CPUs

http://mpi-forum.org
https://www.open-mpi.org/

Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License

Why Two URLs?

http://mpi-forum.org
This is the definitive reference for the MPI standard. Go here if you want to read the official specification, which, BTW, continues to evolve.

https://www.open-mpi.org/
This consortium formed later. This is the open source version of MPI. If you want to start using MPI, I recommend you look here. This is the MPI that the COE systems use

https://www.open-mpi.org/doc/v4.0/
This URL is also really good – it is a link to all of the MPI man pages
Programs on different CPUs coordinate computations by passing messages between each other.

**Note:** Each CPU in the MPI “cluster” must be prepared ahead of time by having the MPI server code installed on it. It must then have that server code running and listening on its socket connection.

Each MPI CPU must also have an integer ID assigned to it (called its *rank*).
This paradigm is how modern supercomputers work!

The Texas Advanced Computing Center’s Frontera supercomputer

How to SSH to the COE MPI Cluster

`flip3 151% ssh submit-c hpc.engr.oregonstate.edu`

`submit-c 142% module load slurm`

`submit-c 143% module load openmpi`

Type these right away to set your path correctly

ssh over to an MPI submission machine -- submit-a and submit-b will also work

BTW, you can find out more about the COE cluster here: [https://it.engineering.oregonstate.edu/hpc](https://it.engineering.oregonstate.edu/hpc)

“The College of Engineering HPC cluster is a heterogeneous mix of about 130 servers providing nearly 4000 CPU cores, over 200 GPUs, and over 43 TB total RAM. The systems are connected via gigabit ethernet and Infiniband. Most of the latest servers utilize Mellanox EDR or HDR InfiniBand network connection. The cluster also has access to 150TB global scratch from the College of Engineering's Dell/EMC Isilon enterprise storage. The CoE HPC Cluster is rated at over 1700 peak TFLOPS (double-precision)."
Compiling and Running

- C
  \[\text{mpicc} \ -o \ \text{program} \ \text{program.c} \ldots\]
  or
  \[\text{mpic++} \ -o \ \text{program} \ \text{program.cpp} \ldots\]

- C++

\[\text{mpiexec} \ -mca\ \text{btl}\ \text{self,}\text{tcp} \ -np\ \text{4} \ \text{program}\]

All distributed processors execute the same program at the same time

# of processors to use

Warning – use \texttt{mpic++} and \texttt{mpiexec}!

Don’t use g++.

Don’t run by just typing the name of the executable!

Running with a \textit{bash} Batch Script

\begin{verbatim}
#!/bin/bash
#SBATCH -J AutoCorr
#SBATCH -A cs475-575
#SBATCH -p classmpitest
#SBATCH -N 8 # number of nodes
#SBATCH -n 8 # number of tasks
#SBATCH -o mpiproject.out
#SBATCH -e mpiproject.err
#SBATCH --mail-type=END,FAIL
#SBATCH --mail-user=joeparallel@oregonstate.edu
module load openmpi
mpic++ mpiproject.cpp -o mpiproject -lm
mpiexec -mca btl self,tcp -np 4 ./mpiproject
\end{verbatim}

This is the partition name that we use for our class when debugging and testing your program. Use \texttt{classmpifinal} for taking your final performance numbers.

submit-c 143% sbatch submit.bash
Submitted batch job 258759
What is the Difference Between the Partitions `classmpitest` and `classmpifinal`?

`classmpitest` lets your program get into the system sooner, but it might be running alongside other jobs, so its performance might suffer. But, you don't care because you are just compiling and debugging, not taking performance numbers for your report.

`classmpifinal` makes your program wait in line until it can get dedicated resources so that you get performance results that are much more representative of what the machines can do, and thus are worthy to be listed in your report.

Auto-Notifications via Email

#SBATCH --mail-user=joeparallel@oregonstate.edu

You don’t have to ask the system to email information to you, but if you do, please be sure you get your own email address right!

Our IT people are getting really tired of fielding the bounced emails when people misspell their own email address.
Use slurm’s `scancel` if your Job Needs to Be Killed

```
submit-c 143% sbatch_submit.bash
Submitted batch job 258759

submit-c 144% scancel 258759
```

Setting Up and Finishing MPI

```
#include <mpi.h>

int main( int argc, char *argv[ ] )
{
    ...
    MPI_Init( &argc, &argv );
    ...
    MPI_Finalize( );
    return 0;
}
```

You don’t need to process command line arguments if you don’t want to. You can just call MPI_Init( ) as:

```
MPI_Init( NULL, NULL );
```
MPI Follows a Single-Program-Multiple-Data (SPMD) Model

A communicator is a collection of CPUs that are capable of sending messages to each other. This requires MPI server code getting installed on all those CPUs. That code then needs to be running and listening on a socket connection. Only an administrator can do this.

Getting information about our place in the communicator:

```c
int numCPUs;       // total # of cpus involved
int me;            // which one I am

MPI_Comm_size( MPI_COMM_WORLD, &numCPUs );
MPI_Comm_rank( MPI_COMM_WORLD, &me );
```

It is then each CPU's job to figure out what piece of the overall problem it is responsible for and then go do it.

A First Test of MPI

```c
#include <stdio.h>
#include <math.h>
#include <mpi.h>

#define THEBOSS 0

int main( int argc, char *argv[] )
{
    MPI_Init( &argc, &argv );

    int numCPUs;       // total # of cpus involved
    int me;            // which one I am

    MPI_Comm_size( MPI_COMM_WORLD, &numCPUs );
    MPI_Comm_rank( MPI_COMM_WORLD, &me );

    if( me == THEBOSS )
        fprintf( stderr, "Rank %d says that we have a Communicator of size %d
        THEBOSS, numCPUs );
    else
        fprintf( stderr, "Welcome from Rank %d
        me );

    MPI_Finalize( );
    return 0;
}
```
So, we have a group (a “communicator”) of distributed processors. How do they communicate about what work they are supposed to do?

Who am I? Where am I? What am I supposed to be doing? Hello? Is anyone listening?

Example: You could coordinate the units of our DGX system using MPI
A Good Place to Start: MPI Broadcasting

MPI_Bcast( array, count, type, src, MPI_COMM_WORLD );

Address of the data to send from if you are the src node;

Address of the data to receive into if you are not

# elements

MPI_CHAR
MPI_INT
MPI_LONG
MPI_FLOAT
MPI_DOUBLE

rank of the CPU doing the sending

Both the sender and receivers need to execute MPI_Bcast -- there is no separate receive function

MPI Broadcast Example

This is our heat transfer equation from before. Clearly, every CPU will need to know this value.

\[
\Delta T = \frac{k}{\rho C} \left( \frac{T_{i+1} - 2T_i + T_{i-1}}{(\Delta x)^2} \right) \Delta t
\]

int numCPUs;
int me;
float k_over_rho_c; // the THEBOSS node will know this value, the others won’t (yet)

#define THEBOSS 0

MPI_Comm_size( MPI_COMM_WORLD, &numCPUs ); // how many are in this communicator
MPI_Comm_rank( MPI_COMM_WORLD, &me ); // which one am I?

if( me == THEBOSS )
{
    << read k_over_rho_c from the data file >>
}

MPI_Bcast( &k_over_rho_c, 1, MPI_FLOAT, THEBOSS, MPI_COMM_WORLD ); // send if I am THEBOSS, and receive if not
How Does this Work?  
Think Star Trek Wormholes!

Sending Data from One Source CPU to Just One Destination CPU

MPI_Send( array, numToSend, type, dst, tag, MPI_COMM_WORLD );

- address of data to send from
- # elements (note: this is the number of \textit{elements}, not the number of \textit{bytes}!)
- MPI_CHAR
- MPI_INT
- MPI_LONG
- MPI_FLOAT
- MPI_DOUBLE
- ...  
- rank of the CPU to send to
- An integer or character to differentiate this transmission from any other transmission.  I like to use chars.

Rules:

- One message from a specific src to a specific dst cannot overtake a previous message from the same src to the same dst.
- MPI_Send( ) blocks until the transfer is far enough along that array can be destroyed or re-used.
- There are no guarantees on order from different src’s.
Receiving Data in a Destination CPU from a Source CPU

```c
MPI_Recv( array, maxCanReceive, type, src, tag, MPI_COMM_WORLD, &status );
```

**Rules:**
- The receiver blocks waiting for data that matches what it declares to be looking for.
- One message from a specific `src` to a specific `dst` cannot overtake a previous message from the same `src` to the same `dst`.
- There are no guarantees on the order from different `src`'s.
- The order from different `src`'s could be implied in the `tag`.
- `status` is type `MPI_Status` – the "&status" can be replaced with `MPI_STATUS_IGNORE`.

**Example**

Remember, this identical code runs on all CPUs:

```c
int numCPUs;
int me;
#define MYDATA_SIZE 128
char mydata[ MYDATA_SIZE ];
#define THEBOSS 0
MPI_Comm_size( MPI_COMM_WORLD, &numCPUs );
MPI_Comm_rank( MPI_COMM_WORLD, &me );

if( me == THEBOSS ) // the primary
{
for( int dst = 0; dst < numCPUs; dst++ )
{
    if( dst != THEBOSS )
    {
        char *InputData = "Hello, Beavers!";
        MPI_Send( InputData, strlen(InputData)+1, MPI_CHAR, dst, 'B', MPI_COMM_WORLD );
    }
}
}
else // a secondary
{
    MPI_Recv( myData, MYDATA_SIZE, MPI_CHAR, THEBOSS, 'B', MPI_COMM_WORLD, MPI_STATUS_IGNORE );
    printf( " '%s' from rank # %d
", in, me );
}
```

You are highly discouraged from sending to yourself. Because both the send and receive are capable of blocking, the result could be deadlock.
How does MPI let the Sender perform an MPI_Send( ) even if the Receivers are not ready to MPI_Recv( )?

MPI_Send( ) blocks until the transfer is far enough along that the array can be destroyed or re-used.

Another Example

You typically don't send the entire workload to each dst – you just send part of it, like this:

```c
#define NUMELEMENTS ????
int numCPUs;
int me;
#define THEBOSS 0

MPI_Comm_size( MPI_COMM_WORLD, &numCPUs );
MPI_Comm_rank( MPI_COMM_WORLD, &me );

int PPSIZE = NUMELEMENTS / numCPUs; // per-processor data size -- assuming it comes out evenly
float *myData = new float [ PPSIZE ];

if( me == THEBOSS ) // the sender
{
    float *InputData = new float [ NUMELEMENTS ];
    << read the full input data into InputData from disk >>
    for( int dst = 0; dst < numCPUs; dst++ )
    {
        if( dst != THEBOSS )
        {
            MPI_Send( &InputData[dst*PPSize], PPSIZE, MPI_FLOAT, dst, 0, MPI_COMM_WORLD );
        }
    }
}
else // a receiver
{
    MPI_Recv( myData, PPSIZE, MPI_FLOAT, THEBOSS, 0, MPI_COMM_WORLD, MPI_STATUS_IGNORE );
    // do something with this subset of the data
}
```
In Distributed Computing, You Often Hear About These Design Patterns

Broadcast

This sends the same data to each processor

Scatter

This sends pieces of the data to each processor

Gather

This brings back pieces of the results from each processor

Scatter and Gather Usually Go Together

This sends pieces of the data to each processor

Scatter

Gather

This brings back pieces of the results from each processor

Note surprisingly, this is referred to by the combined term Scatter/Gather
**MPI Scatter**

Take a data array, break it into ~equal portions, and send it to each CPU

\[
\text{MPI Scatter}( \text{snd\_array}, \text{snd\_count}, \text{snd\_type}, \text{rcv\_array}, \text{rcv\_count}, \text{rcv\_type}, \text{src}, \text{MPI\_COMM\_WORLD} );
\]

- The total large array to split up
- # elements to send per-processor
- Local array to store this processor's piece in
- # elements to receive per-processor
- This is who is doing the sending – everyone else is receiving

Both the sender and receivers need to execute **MPI Scatter**.
There is no separate receive function

**MPI Gather**

The total large array to put the pieces back into

\[
\text{MPI Gather}( \text{snd\_array}, \text{snd\_count}, \text{snd\_type}, \text{rcv\_array}, \text{rcv\_count}, \text{rcv\_type}, \text{dst}, \text{MPI\_COMM\_WORLD} );
\]

- The total large array to put the pieces back into
- # elements to return per-processor
- Local array that this processor is sending back
- # elements to send back per-processor
- This is who is doing the receiving – everyone else is sending

Both the sender and receivers need to execute **MPI Gather**.
There is no separate transmit function
Remember This? It's Baaaaaack as a complete Scatter/Gather Example

The Compute : Communicate Ratio still applies, except that it is even more important now because there is much more overhead in the Communicate portion.

This pattern of breaking a big problem up into pieces, sending them to different CPUs, computing on the pieces, and getting the results back is very common. That's why MPI has its own scatter and gather functions.

---

heat.cpp, I

```c
#include <stdio.h>
#include <math.h>
#include <mpi.h>

const float RHO = 8050.;
const float C   = 0.466;
const float K   = 20.;
float k_over_rho_c = K / (RHO*C); // units of m²/sec  NOTE: this cannot be a const!
// K / (RHO*C) = 5.33x10^-6 m²/sec
const float DX    = 1.0;
const float DT    = 1.0;

#define THEBOSS 0
#define NUMELEMENTS (8*1024*1024)
#define NUM_TIME_STEPS 4
#define DEBUG false

float * NextTemps; // per-processor array to hold computer next-values
int   NumCpus;    // total # of cpus involved
int   PPSize;     // per-processor local array size
float * PPTemps;  // per-processor local array temperature data
float * TempData; // the overall NUMELEMENTS-big temperature data

void DoOneTimeStep( int );

```
int main( int argc, char *argv[] )
{
    MPI_Init( &argc, &argv );

    int me; // which one I am
    MPI_Comm_size( MPI_COMM_WORLD, &NumCpus );
    MPI_Comm_rank( MPI_COMM_WORLD, &me );

    // decide how much data to send to each processor:
    PPSize = NUMELEMENTS / NumCpus; // assuming it comes out evenly
    PPTemps = new float [PPSize]; // all processors now have this uninitialized Local array
    NextTemps = new float [PPSize]; // all processors now have this uninitialized local array too

    // broadcast the constant:
    MPI_Bcast( (void *)&k_over_rho_c, 1, MPI_FLOAT, THEBOSS, MPI_COMM_WORLD );

    if( me == THEBOSS ) // this is the data-creator
    {
        TempData = new float[NUMELEMENTS];
        for( int i = 0; i < NUMELEMENTS; i++ )
        {
            TempData[i] = 0.;
        }
        TempData[NUMELEMENTS/2] = 100.;
    }

    MPI_Scatter( TempData, PPSize, MPI_FLOAT, PPTemps, PPSize, MPI_FLOAT,
                 THEBOSS, MPI_COMM_WORLD );
// all the PPTemps arrays have now been filled
// do the time steps:

    double time0 = MPI_Wtime();

    for( int steps = 0; steps < NUM_TIME_STEPS; steps++ )
    {
        // do the computation for one time step:
        DoOneTimeStep( me );

        // ask for all the data:
        #ifdef WANT_EACH_TIME_STEPS_DATA_BACK
            MPI_Gather( PPTemps, PPSize, MPI_FLOAT, TempData, PPSize, MPI_FLOAT,
                        THEBOSS, MPI_COMM_WORLD );
        #endif
    }

    #ifndef WANT_EACH_TIME_STEPS_DATA_BACK
        MPI_Gather( PPTemps, PPSize, MPI_FLOAT, TempData, PPSize, MPI_FLOAT,
                    THEBOSS, MPI_COMM_WORLD );
    #endif

    double time1 = MPI_Wtime();

    if( me == THEBOSS )
    {
        double seconds = time1 - time0;
        double performance =
            (double)NUM_TIME_STEPS * (double)NUMELEMENTS / seconds / 1000000.;
        // mega-elements computed per second
        fprintf( stderr, "%3d, %10d, %8.2lf
", NumCpus, NUMELEMENTS, performance );
    }

    MPI_Finalize();
    return 0;
void DoOneTimeStep( int me )
{
    MPI_Status status;

    // send out the left and right end values:
    // (the tag is from the point of view of the sender)
    if( me != 0 ) // i.e., if I'm not the first group on the left
    {
        // send my PPTemps[0] to me-1 using tag 'L'
        MPI_Send( &PPTemps[0], 1, MPI_FLOAT, me-1, 'L', MPI_COMM_WORLD );
        if( DEBUG )   fprintf( stderr, "%3d sent 'L' to %3d
        if( DEBUG )   fprintf( stderr, "%3d received 'R' from %3d
    }
    if( me != NumCpus-1 ) // i.e., not the last group on the right
    {
        // send my PPTemps[PPSize-1] to me+1 using tag 'R'
        MPI_Send( &PPTemps[PPSize-1], 1, MPI_FLOAT, me+1, 'R', MPI_COMM_WORLD );
        if( DEBUG ) fprintf( stderr, "%3d received 'L' from %3d
    }
}

float left = 0.;
float right = 0.;

if( me != 0 ) // i.e., if I'm not the first group on the left
{
    // receive my "left" from me-1 using tag 'R'
    MPI_Recv( &left, 1, MPI_FLOAT, me-1, 'R', MPI_COMM_WORLD, &status );
    if( DEBUG ) fprintf( stderr, "%3d received 'R' from %3d
}

if( me != NumCpus-1 ) // i.e., not the last group on the right
{
    // receive my "right" from me+1 using tag 'L'
    MPI_Recv( &right, 1, MPI_FLOAT, me+1, 'L', MPI_COMM_WORLD, &status );
    if( DEBUG ) fprintf( stderr, "%3d received 'L' from %3d
}
Sharing Values Across the Boundaries

1D Compute-to-Communicate Ratio

Compute : Communicate ratio = N : 2

where N is the number of compute cells per processor

In the above drawing, Compute : Communicate is 4 : 2
DoOneTimeStep, III

// first element on the left (0):
{
    float dtemp = ( k_over_rho_c * 
        ( left - 2.*PPTemps[0] + PPTemps[1] ) / ( DX*DX ) ) * DT;
    NextTemps[0] = PPTemps[0] + dtemp;
}

// all the nodes in the middle:
for( int i = 1; i < PPSize-1; i++ )
{
    float dtemp = ( k_over_rho_c * 
        ( PPTemps[i-1] - 2.*PPTemps[i] + PPTemps[i+1] ) / ( DX*DX ) ) * DT;
    NextTemps[i] = PPTemps[i] + dtemp;
}

// last element on the right (PPSize-1):
{
    float dtemp = ( k_over_rho_c * 
        ( PPTemps[PPSize-2] - 2.*PPTemps[PPSize-1] + right ) / ( DX*DX ) ) * DT;
    NextTemps[PPSize-1] = PPTemps[PPSize-1] + dtemp;
}

DoOneTimeStep, IV

// update the local dataset:
for( int i = 0; i < PPSize; i++ )
{
    PPTemps[ i ] = NextTemps[ i ];
}
### MPI Performance

Mega-Elements Computed Per Second vs. Number of Elements

- Number of Elements vs. Number of Processors
- Lines represent different numbers of processors (1, 2, 4, 8, 16, 32)

### Low Dataset-Size MPI Performance

Mega-Elements Computed Per Second vs. Number of Elements

- Number of Elements vs. Number of Processors
- Lines represent different numbers of processors (1, 2, 4, 8, 16, 32)
From: Peter Johnsen, Mark Straka, Melvyn Shapiro, Alan Norton, Thomas Galameau, Petascale WRF Simulation of Hurricane Sandy.
MPI Reduction

\[ \text{MPI\_Reduce}( \text{partialResult, globalResult, count, type, operator, dst, MPI\_COMM\_WORLD} ); \]

- Where the partial result is stored on each CPU
- Place to store the full result on the dst CPU
- Number of elements in the partial result
- Who is given the final answer
- MPI\_CHAR
- MPI\_INT
- MPI\_LONG
- MPI\_FLOAT
- MPI\_DOUBLE
- \ldots

This really should be called Scatter/Gather/Reduction

Both the sender and receivers need to execute MPI\_Reduce.
There is no separate receive function

MPI Reduction Example

```c
// gratuitous use of a reduce -- average all the temperatures:
float partialSum = 0.;
for( int i = 0; i < PPSize; i++ )
    partialSum += PPTemps[ i ];
float globalSum = 0.;
MPI\_Reduce( &partialSum, &globalSum, 1, MPI\_FLOAT, MPI\_SUM, THEBOSS, MPI\_COMM\_WORLD );
if( me == THEBOSS )
    fprintf( stderr, "Average temperature = %f\n", globalSum/(float)NUMELEMENTS );
```
**MPI Barriers**

```c
MPI_Barrier( MPI_COMM_WORLD );
```

**Distributed Processors:**

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
</table>

All CPUs must execute the call to `MPI_Barrier()` before any of the CPUs can move past it. That is, each CPU’s `MPI_Barrier()` blocks until all CPUs execute a call to `MPI_Barrier()`.

---

**MPI Derived Types**

**Idea:** In addition to types `MPI_INT`, `MPI_FLOAT`, etc., allow the creation of new MPI types so that you can transmit an “array of structures”.

**Reason:** There is significant overhead with each transmission. Better to send one entire array of structures instead of sending several arrays separately.

```c
MPI_Type_create_struct( count, blocklengths, displacements, types, datatype );
```

```c
struct point
{
  int pointSize;
  float x, y, z;
};
```

```c
MPI_Datatype MPI_POINT;
int blocklengths[ ] = { 1, 1, 1, 1 };
int displacements[ ] = { 0, 6, 12 };
MPI_type types[ ] = { MPI_INT, MPI_FLOAT, MPI_FLOAT, MPI_FLOAT };
MPI_Type_create_struct( 4, blocklengths, displacements, types, &MPI_POINT );
```

You can now use `MPI_POINT` everywhere you could have used `MPI_INT`, `MPI_FLOAT`, etc.
**MPI Timing**

```c
double MPI_Wtick();
```

Returns the resolution of the clock, in seconds.

```c
double MPI_Wtime();
```

Returns the time, in seconds, since "some time in the past".

*Warning: the clocks on the different CPUs are not guaranteed to be synchronized!*

---

**MPI Status-Checking**

Some MPI calls have a `&status` in their argument list.

The `status` argument is declared to be of type `MPI_Status`, which is actually a struct:

```c
typedef struct _MPI_Status
{
    int MPI_SOURCE;
    int MPI_TAG;
    int MPI_ERROR;
} MPI_Status;
```

- `MPI_SOURCE` is the rank of the node who sent this
- `MPI_TAG` is the tag used during the send
- `MPI_ERROR` is the error number that occurred

**Example:**

```c
MPI_Status status;
MPI_Recv( myData, MYDATA_SIZE, MPI_CHAR, THEBOSS, MPI_ANY_TAG, MPI_COMM_WORLD, &status );

fprintf( stderr, "Rank = %d, Tag = %d, Error Code = %d\n",
        status.MPI_SOURCE, status.MPI_TAG, status.MPI_ERROR );
```
<table>
<thead>
<tr>
<th>MPI Error Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPI_SUCCESS</td>
<td>No error</td>
</tr>
<tr>
<td>MPI.ERR_Buffer</td>
<td>Invalid buffer pointer</td>
</tr>
<tr>
<td>MPI.ERR_Count</td>
<td>Invalid count argument</td>
</tr>
<tr>
<td>MPI.ERR_Type</td>
<td>Invalid data type argument</td>
</tr>
<tr>
<td>MPI.ERR_Tag</td>
<td>Invalid tag argument</td>
</tr>
<tr>
<td>MPI.ERR_Comm</td>
<td>Invalid communicator</td>
</tr>
<tr>
<td>MPI.ERR_RANK</td>
<td>Invalid rank</td>
</tr>
<tr>
<td>MPI.ERR_REQUEST</td>
<td>Invalid request (send)</td>
</tr>
<tr>
<td>MPI.ERR_ROOT</td>
<td>Invalid root</td>
</tr>
<tr>
<td>MPI.ERR_GROUP</td>
<td>Invalid group</td>
</tr>
<tr>
<td>MPI.ERR_OPERATION</td>
<td>Invalid operation</td>
</tr>
<tr>
<td>MPI.ERR_LAPACK</td>
<td>Invalid LAPACK</td>
</tr>
<tr>
<td>MPI.ERR_DIMENSION</td>
<td>Invalid dimension argument</td>
</tr>
<tr>
<td>MPI.ERR_UNKNOWN</td>
<td>Invalid argument of some other kind</td>
</tr>
<tr>
<td>MPI.ERR_TRUNCATE</td>
<td>Unknown error</td>
</tr>
<tr>
<td>MPI.ERR_Other</td>
<td>Message translated on receive</td>
</tr>
<tr>
<td>MPI.ERR_INTRA</td>
<td>Known error not in list</td>
</tr>
<tr>
<td>MPI.ERR_INTERN</td>
<td>Unknown error in operation</td>
</tr>
<tr>
<td>MPI.ERR_PENDING</td>
<td>Internal MPI (implementation) error</td>
</tr>
<tr>
<td>MPI.ERR같은</td>
<td>Pending request</td>
</tr>
<tr>
<td>MPI.ERR_FILE</td>
<td>Invalid file handle</td>
</tr>
<tr>
<td>MPI.ERR_NOT_SAME</td>
<td>Collective argument not identical on all processes, or collective operation issued in a different order by different processes</td>
</tr>
<tr>
<td>MPI.ERR_AMODE</td>
<td>Error related to the amode passed to MPI_FILE_OPEN</td>
</tr>
<tr>
<td>MPI.ERR_UNSUPPORTED_DATAREP</td>
<td>Unsupported operation, such as seeking on a file which supports sequential access only</td>
</tr>
<tr>
<td>MPI.ERR_NO_SUCH_FILE</td>
<td>Unspecified file does not exist</td>
</tr>
<tr>
<td>MPI.ERR_FILE_OPEN</td>
<td>File does not exist</td>
</tr>
<tr>
<td>MPI.ERR_BAD_FILE</td>
<td>File does not exist</td>
</tr>
<tr>
<td>MPI.ERR_ACCESS</td>
<td>File does not exist</td>
</tr>
<tr>
<td>MPI.ERR_QUOTA</td>
<td>File exists</td>
</tr>
<tr>
<td>MPI.ERR_READ_ONLY</td>
<td>Invalid file name (e.g., path name too long)</td>
</tr>
<tr>
<td>MPI.ERR_PERMISSION_DENIED</td>
<td>Permission denied</td>
</tr>
<tr>
<td>MPI.ERR_NOT_ENOUGH_SPACE</td>
<td>Not enough space</td>
</tr>
<tr>
<td>MPI.ERR_QUOTA_EXCEEDED</td>
<td>Quota exceeded</td>
</tr>
<tr>
<td>MPI.ERR aluno</td>
<td>Read only file on file system</td>
</tr>
<tr>
<td>MPI.ERR_FILE_IN_USE</td>
<td>File operation could not be completed, as the file is currently open by some process</td>
</tr>
<tr>
<td>MPI.ERR_REGISTER_DATAREP</td>
<td>Conversion functions could not be registered because a data representation identifier that was already defined was passed to MPI_REGISTER_DATAREP</td>
</tr>
<tr>
<td>MPI.ERR_CONV</td>
<td>An error occurred in user supplied data conversion function</td>
</tr>
<tr>
<td>MPI.ERR_CONV_FAIL</td>
<td>Other I/O error</td>
</tr>
<tr>
<td>MPI.ERR_CONV_FAIL</td>
<td>Last error code</td>
</tr>
</tbody>
</table>
Example: Autocorrelation

The Original Signal

```plaintext
NUMELEMENTS
```

Divide NUMELEMENTS into pieces for the NumCpus
(this is what MPI_Scatter does)

But, in the Autocorrelation case, we need MAXSHIFTS more
data values for each CPU

```
NUMELEMENTS
```

Autocorrelation – More than Just a Scatter
Autocorrelation – How the Shifting Works

Shift = 0

Shift = 1

Shift = 2

Shift = 3

Shift = MAXSHIFTS-1

NUMELEMENTS
NumCpus
MAXSHIFTS

NUMELEMENTS
NumCpus
MAXSHIFTS

NUMELEMENTS
NumCpus
MAXSHIFTS

NUMELEMENTS
NumCpus
MAXSHIFTS