

# Message Passing Interface (MPI)

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## Abstract

The Message Passing Interface Standard (MPI) is a message passing library standard based on the consensus of the MPI Forum, which has over 40 participating organizations, including vendors, researchers, software library developers, and users. The goal of the Message Passing Interface is to establish a portable, efficient, and flexible standard for message passing that will be widely used for writing message passing programs. As such, MPI is the first standardized, vendor independent, message passing library. The advantages of developing message passing software using MPI closely match the design goals of portability, efficiency, and flexibility. MPI is not an IEEE or ISO standard, but has in fact, become the "industry standard" for writing message passing programs on HPC platforms.

The goal of this tutorial is to teach those unfamiliar with MPI how to develop and run parallel programs according to the MPI standard. The primary topics that are presented focus on those which are the most useful for new MPI programmers. The tutorial begins with an introduction, background, and basic information for getting started with MPI. This is followed by a detailed look at the MPI routines that are most useful for new MPI programmers, including MPI Environment Management, Point-to-Point Communications, and Collective Communications routines. Numerous examples in both C and Fortran are provided, as well as a lab exercise.

The tutorial materials also include more advanced topics such as Derived Data Types, Group and Communicator Management Routines, and Virtual Topologies. However, these are not actually presented during the lecture, but are meant to serve as "further reading" for those who are interested.

**Level/Prerequisites:** This tutorial is ideal for those who are new to parallel programming with MPI. A basic understanding of parallel programming in C or Fortran is required. For those who are unfamiliar with Parallel Programming in general, the material covered in [EC3500: Introduction To Parallel Computing](#) would be helpful.

## What is MPI?

### ► An Interface Specification:

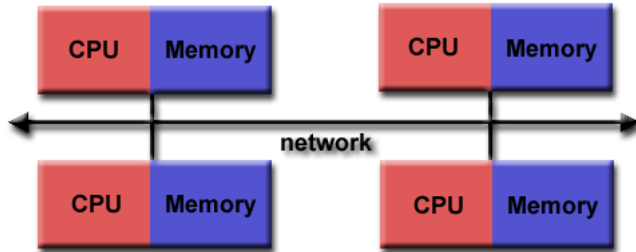
- **M P I = Message Passing Interface**
- MPI is a **specification** for the developers and users of message passing libraries. By itself, it is NOT a library - but rather the specification of what such a library should be.
- MPI primarily addresses the **message-passing parallel programming model**: data is moved from the address space of one process to that of another process through cooperative operations on each process.
- Simply stated, the goal of the Message Passing Interface is to provide a widely used standard for writing message passing programs. The interface attempts to be:
  - Practical
  - Portable
  - Efficient
  - Flexible



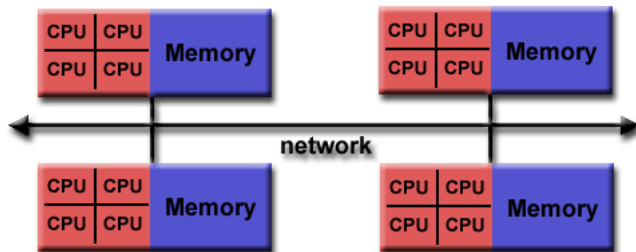
- The MPI standard has gone through a number of revisions, with the most recent version being MPI-3.x
- Interface specifications have been defined for C and Fortran90 language bindings:
  - C++ bindings from MPI-1 are removed in MPI-3
  - MPI-3 also provides support for Fortran 2003 and 2008 features
- Actual MPI library implementations differ in which version and features of the MPI standard they support. Developers/users will need to be aware of this.

#### ► Programming Model:

- Originally, MPI was designed for distributed memory architectures, which were becoming increasingly popular at that time (1980s - early 1990s).



- As architecture trends changed, shared memory SMPs were combined over networks creating hybrid distributed memory / shared memory systems.
- MPI implementors adapted their libraries to handle both types of underlying memory architectures seamlessly. They also adapted/developed ways of handling different interconnects and protocols.



- Today, MPI runs on virtually any hardware platform:
  - Distributed Memory
  - Shared Memory
  - Hybrid
- The programming model clearly remains a distributed memory model however, regardless of the underlying physical architecture of the machine.
- All parallelism is explicit: the programmer is responsible for correctly identifying parallelism and implementing parallel algorithms using MPI constructs.

#### ► Reasons for Using MPI:

- **Standardization** - MPI is the only message passing library that can be considered a standard. It is supported on virtually all HPC platforms. Practically, it has replaced all previous message passing libraries.
- **Portability** - There is little or no need to modify your source code when you port your application to a different platform that supports (and is compliant with) the MPI standard.
- **Performance Opportunities** - Vendor implementations should be able to exploit native hardware features to optimize performance. Any implementation is free to develop optimized algorithms.
- **Functionality** - There are **over 430** routines defined in MPI-3, which includes the majority of those in MPI-2 and MPI-1.

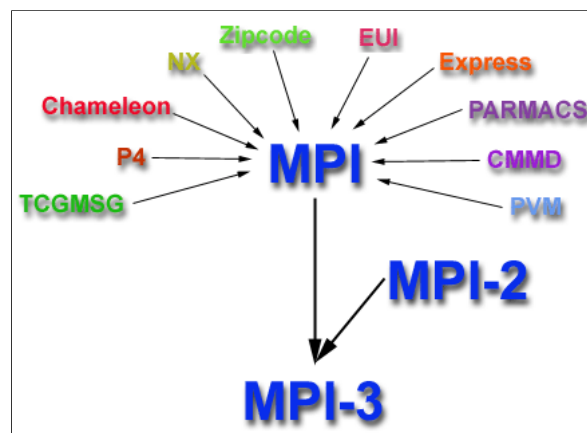
**Note:** Most MPI programs can be written using a dozen or less routines

- **Availability** - A variety of implementations are available, both vendor and public domain.

#### ► History and Evolution: (for those interested)

- MPI has resulted from the efforts of numerous individuals and groups that began in 1992. Some history:
- **1980s - early 1990s:** Distributed memory, parallel computing develops, as do a number of incompatible software tools for writing such programs - usually with tradeoffs between portability, performance, functionality and price. Recognition of the need for a standard arose.
- **Apr 1992:** Workshop on Standards for Message Passing in a Distributed Memory Environment, sponsored by the Center for Research on Parallel Computing, Williamsburg, Virginia. The basic features essential to a standard message passing interface were discussed, and a working group established to continue the standardization process. Preliminary draft proposal developed subsequently.
- **Nov 1992:** Working group meets in Minneapolis. MPI draft proposal (MPI1) from ORNL presented. Group adopts procedures and organization to form the [MPI Forum](https://computing.llnl.gov/tutorials/mpl/). It eventually comprised of about 175 individuals from 40 organizations including parallel computer vendors, software writers, academia and application scientists.

- **Nov 1993:** Supercomputing 93 conference - draft MPI standard presented.
- **May 1994:** Final version of MPI-1.0 released
  - MPI-1.1 (Jun 1995)
  - MPI-1.2 (Jul 1997)
  - MPI-1.3 (May 2008).
- **1998:** MPI-2 picked up where the first MPI specification left off, and addressed topics which went far beyond the MPI-1 specification.
  - MPI-2.1 (Sep 2008)
  - MPI-2.2 (Sep 2009)
- **Sep 2012:** The MPI-3.0 standard was approved.
  - MPI-3.1 (Jun 2015)
- **Current:** The MPI-4.0 standard is under development.



#### Documentation:

- Documentation for all versions of the MPI standard is available at: <http://www.mpi-forum.org/docs/>.

## LLNL MPI Implementations and Compilers

### Multiple Implementations:

- Although the MPI programming interface has been standardized, actual library implementations will differ.
- For example, just a few considerations of many:
  - Which version of the MPI standard is supported?
  - Are all of the features in a particular MPI version supported?
  - Have any new features been added?
  - What network interfaces are supported?
  - How are MPI applications compiled?
  - How are MPI jobs launched?
  - Runtime environment variable controls?
- MPI library implementations on LC systems vary, as do the compilers they are built for. These are summarized in the table below:

MPI Library	Where?	Compilers
MVAPICH	Linux clusters	GNU, Intel, PGI, Clang
Open MPI	Linux clusters	GNU, Intel, PGI, Clang
Intel MPI	Linux clusters	Intel, GNU
IBM Spectrum MPI	Coral Early Access and Sierra clusters	IBM, GNU, PGI, Clang

- Each MPI library is briefly discussed in the following sections, including links to additional detailed information.

### Selecting Your MPI Library and Compiler:

- LC provides a default MPI library for each cluster.
- LC also provides default compilers for each cluster.
- Typically, there are multiple versions of MPI libraries and compilers on each cluster.
- Modules are used to select a specific MPI library or compiler: More info [HERE](#).
- For example, using modules:
  - List which modules are currently loaded
  - Show all available modules
  - Load a different MPI module
  - Load a different compiler module
  - Confirm newly loaded modules

```
### List currently loaded modules
% module list

Currently Loaded Modules:
  1) intel/18.0.1   2) mvapich2/2.2   3) texlive/2016   4) StdEnv

### Show all available modules
% module avail

----- /usr/tce/modulefiles/MPI/mvapich2/2.2 -----
  openss/2.3
```

```

----- /usr/tce/modulefiles/MPI/intel/18.0.1/mvapich2/2.2 -----
MUST/1.5      fftw/3.3.7      mpip/3.4.1
boost/1.66.0  hdf5-parallel/1.8.18    pnetcdf/1.9.0

----- /usr/tce/modulefiles/Compiler/intel/18.0.1 -----
hdf5-serial/1.8.18  impi/2018.0 (D)  netcdf-fortran/4.4.4
hpctoolkit/10102016 mvapich2/2.2 (L,D) openmpi/2.0.0 (D)
impi/5.1.3          mvapich2/2.3      openmpi/2.1.0
impi/2017.0         ncl_ncarg/6.3.0   openmpi/3.0.1
impi/2017.1         netcdf/4.4.1.1

----- /usr/tce/modulefiles/Core -----
StdEnv (L)      inspector/2018.0 (D)  pgi/16.3
advisor/2016.4 intel/14.0.3      pgi/16.7
advisor/2017.1 intel/15.0.6      pgi/16.9
advisor/2017.2 intel/16.0.2      pgi/17.10
advisor/2018.0 intel/16.0.3      pgi/18.1 (D)
advisor/2018.1 (D) intel/16.0.4      python/2.7.11
allineaforge/6.0.5 intel/17.0.0      python/2.7.13
allineaforge/6.1.1 intel/17.0.2      python/2.7.14 (D)
allineaforge/7.0.3 (D) intel/18.0-beta  python/3.5.1
atom/1.13.1      intel/18.0.0      python/3.6.0
cbflib/0.9.2     intel/18.0.1 (L,D) python/3.6.4
clang/3.9.0      intel/18.0.2      rasmol/2.7.5.2
clang/3.9.1      intel/19.0-beta   spindle/0.10
clang/4.0.0 (D)   iorun             sqlcipher/3.7.9
cmake/3.5.2 (D)   itac/2017.1       stat/2.2.0
cmake/3.8.2      itac/2018.0 (D)   stat/3.0.0 (D)
cmake/3.9.2      launchmon/1.0.2   sublime_text/3.1.1
cqrllib/1.0.5    ld-auto-rpath     svn/1.6.23
cvector/1.0.3    license-llnl-ocf  svn/1.7.14 (D)
dyninst/9.1.0    make/4.2.1        tcclap/1.2.0
dyninst/9.3.1 (D)  mathematica/10.3.1 tecplot/2016.1
emacs/24.3-redhat matlab/8.1         texlive/2016 (L)
emacs/25.3 (D)    memcheckview/3.11.0 totalview/2016.01.06
ensight/10.1.6   memcheckview/3.12.0 totalview/2016.04.08
fgfs/1.1         memcheckview/3.13.0 (D) totalview/2016.06.21
gcc/4.8-redhat   mesa3d/17.0.5     totalview/2016.07.22
gcc/4.9.3 (D)    mkl/11.3.3        totalview/2017X.01.07
gcc/6.1.0        mkl/2017.1        totalview/2017.1.21
gcc/7.1.0 (D)    mkl/2018.0 (D)    totalview/2017.3.8 (D)
gdal/1.9.0       mpa/1.1           valgrind/3.11.0
git/1.8.3.1      mpifileutils/0.6   valgrind/3.12.0
git/2.8.3 (D)    mpifileutils/0.7 (D) valgrind/3.13.0 (D)
git-lfs/1.4.1    mrnet/5.0.1        vampir/9.1.0
glxgears/1.2     neartree/5.1.1     vampir/9.2 (D)
gmt/5.1.2        nvidia/375         vmd/1.9.3
gnuplot/5.0.0    opt               vtune/2016.3
grace/5.1.25     papi/5.4.3         vtune/2017.1
graphlib/2.0.0   paraview/5.0        vtune/2018.0 (D)
graphlib/3.0.0 (D) paraview/5.4-server xalt
idl/8.5          paraview/5.4 (D)   xforms/1.0.91
inspector/2016.3 patchelf/0.8       xsu
inspector/2017.0 perfreports/7.0.3

----- /usr/apps/modulefiles -----
Spheral/exp      Spheral/old      pact/current      pact/new
Spheral/new (D)  pact/current_s    pact/new_s (D)

----- /usr/share/lmod/lmod/modulefiles/Core -----
lmod/6.5.1  settarg/6.5.1

Where:
L: Module is loaded
D: Default Module

Use "module spider" to find all possible modules.
Use "module keyword key1 key2 ..." to search for all possible modules matching any of
the "keys".

### Load a different MPI module
% module load openmpi/3.0.1

Lmod is automatically replacing "mvapich2/2.2" with "openmpi/3.0.1"

### Load a different compiler module
% module load pgi/18.1

Lmod is automatically replacing "intel/18.0.1" with "pgi/18.1"

Due to MODULEPATH changes the following have been reloaded:

```

```
1) openmpi/3.0.1
```

```
### Confirm newly loaded modules
% module list
```

```
Currently Loaded Modules:
```

```
1) texlive/2016 2) StdEnv 3) pgi/18.1 4) openmpi/3.0.1
```

## MVAPICH

### General Info:

- MVAPICH MPI is developed and supported by the [Network-Based Computing Lab](#) at Ohio State University.
- Available on all of LC's Linux clusters.
- MVAPICH2
  - Default MPI implementation
  - Multiple versions available
  - MPI-2 and MPI-3 implementations based on MPICH MPI library from Argonne National Laboratory. Versions 1.9 and later implement MPI-3 according to the developer's documentation.
  - Thread-safe
- To see what versions are available, and/or to select an alternate version, use [Modules](#) commands. For example:

```
module avail mvapich      (list available modules)
module load mvapich2/2.3  (use the module of interest)
```

### Compiling:

- See the [MPI Build Scripts](#) table below.

### Running:

- MPI executables are launched using the SLURM **srun** command with the appropriate options. For example, to launch an 8-process MPI job split across two different nodes in the **pdebug** pool:

```
srun -N2 -n8 -ppdebug a.out
```

- The **srun** command is discussed in detail in the [Running Jobs](#) section of the Linux Clusters Overview tutorial.

### Documentation:

- MVAPICH home page: [mvapich.cse.ohio-state.edu/](http://mvapich.cse.ohio-state.edu/)
- MVAPICH2 User Guides: <http://mvapich.cse.ohio-state.edu/userguide/>



## Open MPI

### General Information:

- Open MPI is a thread-safe, open source MPI implementation developed and supported by a consortium of academic, research, and industry partners.
- Available on all LC Linux clusters. However, you'll need to load the desired [module](#) first. For example:

```
module avail      (list available modules)
module load openmpi/3.0.1 (use the module of interest)
```

This ensures that LC's MPI wrapper scripts point to the desired version of Open MPI.

### Compiling:

- See the [MPI Build Scripts](#) table below.

### Running:

- Be sure to load the same Open MPI module that you used to build your executable. If you are running a batch job, you will need to load the module in your batch script.
- Launching an Open MPI job can be done using the following commands. For example, to run a 48 process MPI job:

```
mpirun -np 48 a.out
mpiexec -np 48 a.out
srun -n 48 a.out
```

### Documentation:



- Open MPI home page: <http://www.open-mpi.org/>

### Intel MPI:

- Available on LC's Linux clusters.
- Based on MPICH3. Supports MPI-3 functionality.
- Thread-safe
- Compiling and running Intel MPI programs: see the LC documentation at: <https://lc.llnl.gov/confluence/pages/viewpage.action?pageId=137725526>

### CORAL Early Access and Sierra Clusters:

- The IBM Spectrum MPI library is the only supported implementation on these clusters.
- Based on Open MPI. Includes MPI-3 functionality.
- Thread-safe
- NVIDIA GPU support
- Compiling and running IBM Spectrum MPI programs: see the Sierra Tutorial at <https://hpc.llnl.gov/training/tutorials/using-lcs-sierra-system>

### MPI Build Scripts

- LC developed MPI compiler wrapper scripts are used to compile MPI programs on all LC systems.
- Automatically perform some error checks, include the appropriate MPI #include files, link to the necessary MPI libraries, and pass options to the underlying compiler.



**Note:** you may need to load a [module](#) for the desired MPI implementation, as discussed previously. Failing to do this will result in getting the default implementation.

- The table below lists the primary MPI compiler wrapper scripts for LC's Linux clusters. For CORAL EA / Sierra systems, see the links provided above.

MPI Build Scripts - Linux Clusters			
Implementation	Language	Script Name	Underlying Compiler
MVAPCH2	C	mpicc	C compiler for loaded compiler package
	C++	mpicxx mpic++	C++ compiler for loaded compiler package
	Fortran	mpif77	Fortran77 compiler for loaded compiler package. Points to mpifort.
		mpif90	Fortran90 compiler for loaded compiler package. Points to mpifort.
		mpifort	Fortran 77/90 compiler for loaded compiler package.
Open MPI	C	mpicc	C compiler for loaded compiler package
	C++	mpicc mpic++ mpicxx	C++ compiler for loaded compiler package
	Fortran	mpif77	Fortran77 compiler for loaded compiler package. Points to mpifort.
		mpif90	Fortran90 compiler for loaded compiler package. Points to mpifort.
		mpifort	Fortran 77/90 compiler for loaded compiler package.

- For additional information:
  - See the man page (if it exists)
  - Issue the script name with the **-help** option
  - View the script yourself directly

### Level of Thread Support

- MPI libraries vary in their level of thread support:
  - **MPI\_THREAD\_SINGLE** - Level 0: Only one thread will execute.

- **MPI\_THREAD\_FUNNELED** - Level 1: The process may be multi-threaded, but only the main thread will make MPI calls - all MPI calls are funneled to the main thread.
  - **MPI\_THREAD\_SERIALIZED** - Level 2: The process may be multi-threaded, and multiple threads may make MPI calls, but only one at a time. That is, calls are not made concurrently from two distinct threads as all MPI calls are serialized.
  - **MPI\_THREAD\_MULTIPLE** - Level 3: Multiple threads may call MPI with no restrictions.
- Consult the [MPI\\_Init\\_thread\(.\) man page](#) for details.
  - A simple C language example for determining thread level support is shown below.

```
#include "mpi.h"
#include <stdio.h>

int main( int argc, char *argv[] )
{
    int provided, claimed;

    /** Select one of the following
    MPI_Init_thread( 0, 0, MPI_THREAD_SINGLE, &provided );
    MPI_Init_thread( 0, 0, MPI_THREAD_FUNNELED, &provided );
    MPI_Init_thread( 0, 0, MPI_THREAD_SERIALIZED, &provided );
    MPI_Init_thread( 0, 0, MPI_THREAD_MULTIPLE, &provided );
    ***/

    MPI_Init_thread(0, 0, MPI_THREAD_MULTIPLE, &provided );
    MPI_Query_thread( &claimed );
    printf( "Query thread level= %d Init_thread level= %d\n", claimed, provided );

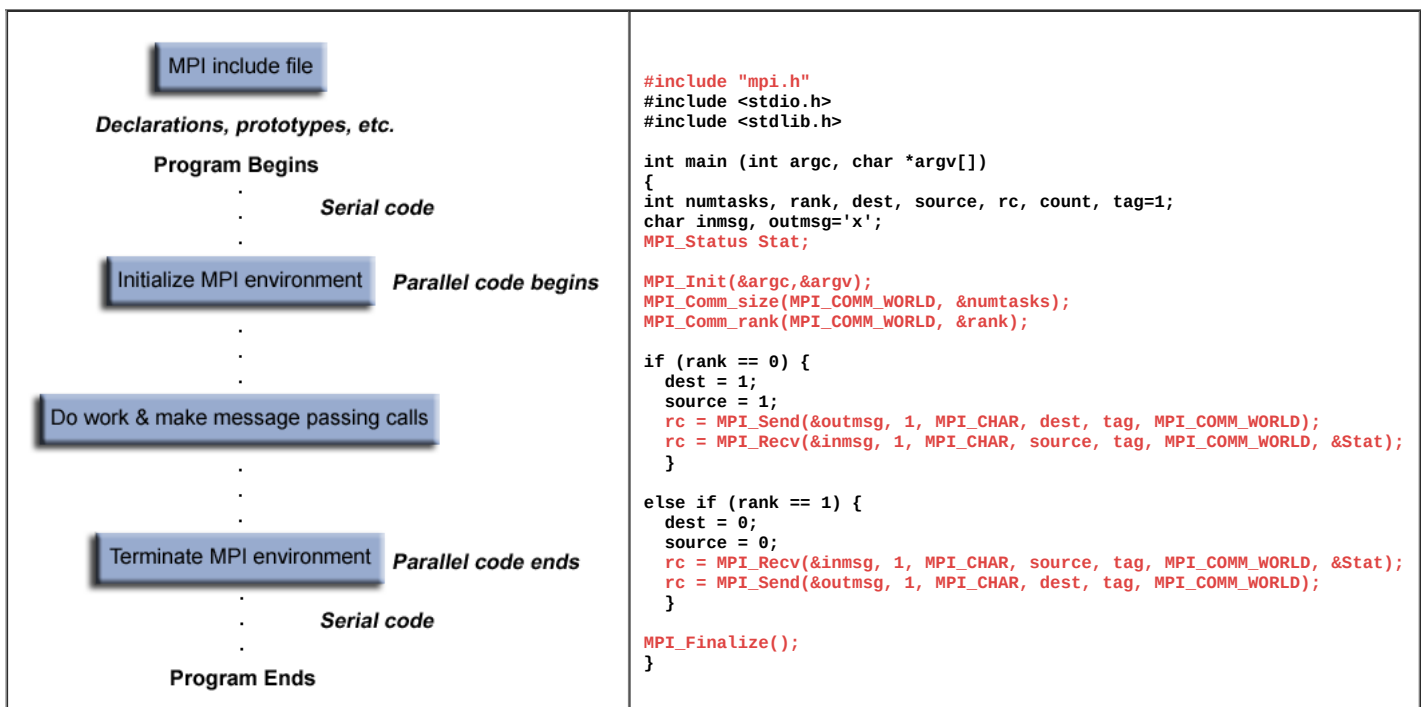
    MPI_Finalize();
}
```

Sample output:

Query thread level= 3 Init\_thread level= 3

## Getting Started

### ► General MPI Program Structure:



### ► Header File:

- Required for all programs that make MPI library calls.



C include file	Fortran include file
<code>#include "mpi.h"</code>	<code>include 'mpif.h'</code>

- With MPI-3 Fortran, the **USE mpi\_f08** module is preferred over using the include file shown above.

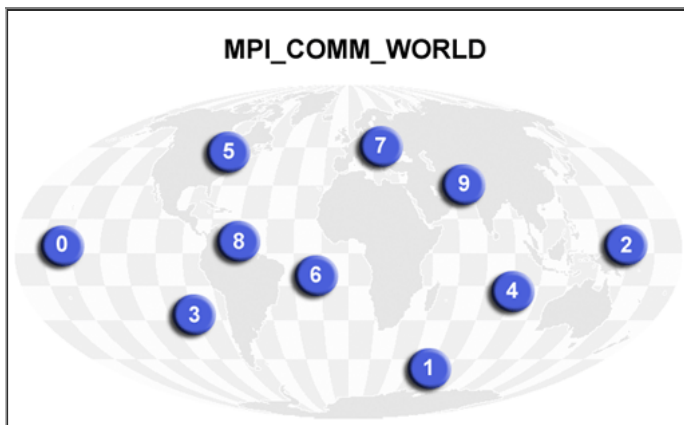
#### ► Format of MPI Calls:

- C names are case sensitive; Fortran names are not.
- Programs must not declare variables or functions with names beginning with the prefix MPI\_ or PMPI\_ (profiling interface).

C Binding	
Format:	<code>rc = MPI_Xxxx(parameter, ... )</code>
Example:	<code>rc = MPI_Bsend(&amp;buf, count, type, dest, tag, comm)</code>
Error code:	Returned as "rc". MPI_SUCCESS if successful
Fortran Binding	
Format:	<code>CALL MPI_XXXX(parameter, ..., ierr)</code> <code>call mpi_xxxx(parameter, ..., ierr)</code>
Example:	<code>CALL MPI_BSEND(buf, count, type, dest, tag, comm, ierr)</code>
Error code:	Returned as "ierr" parameter. MPI_SUCCESS if successful

#### ► Communicators and Groups:

- MPI uses objects called communicators and groups to define which collection of processes may communicate with each other.
- Most MPI routines require you to specify a communicator as an argument.
- Communicators and groups will be covered in more detail later. For now, simply use **MPI\_COMM\_WORLD** whenever a communicator is required - it is the predefined communicator that includes all of your MPI processes.



#### ► Rank:

- Within a communicator, every process has its own unique, integer identifier assigned by the system when the process initializes. A rank is sometimes also called a "task ID". Ranks are contiguous and begin at zero.
- Used by the programmer to specify the source and destination of messages. Often used conditionally by the application to control program execution (if rank=0 do this / if rank=1 do that).

#### ► Error Handling:

- Most MPI routines include a return/error code parameter, as described in the "Format of MPI Calls" section above.
- However, according to the MPI standard, the default behavior of an MPI call is to abort if there is an error. This means you will probably not be able to capture a return/error code other than MPI\_SUCCESS (zero).
- The standard does provide a means to override this default error handler. A discussion on how to do this is available [HERE](http://www.mpi-forum.org/docs/). You can also consult the error handling section of the relevant MPI Standard documentation located at <http://www.mpi-forum.org/docs/>.
- The types of errors displayed to the user are implementation dependent.

### Environment Management Routines

This group of routines is used for interrogating and setting the MPI execution environment, and covers an assortment of purposes, such as initializing and terminating the MPI environment, querying a rank's identity, querying the MPI library's version, etc. Most of the commonly used ones are described below.



### [MPI\\_Init](#)

Initializes the MPI execution environment. This function must be called in every MPI program, must be called before any other MPI functions and must be called only once in an MPI program. For C programs, MPI\_Init may be used to pass the command line arguments to all processes, although this is not required by the standard and is implementation dependent.

```
MPI_Init (&argc,&argv)
MPI_INIT (ierr)
```

### [MPI\\_Comm\\_size](#)

Returns the total number of MPI processes in the specified communicator, such as MPI\_COMM\_WORLD. If the communicator is MPI\_COMM\_WORLD, then it represents the number of MPI tasks available to your application.

```
MPI_Comm_size (comm,&size)
MPI_COMM_SIZE (comm,size,ierr)
```

### [MPI\\_Comm\\_rank](#)

Returns the rank of the calling MPI process within the specified communicator. Initially, each process will be assigned a unique integer rank between 0 and number of tasks - 1 within the communicator MPI\_COMM\_WORLD. This rank is often referred to as a task ID. If a process becomes associated with other communicators, it will have a unique rank within each of these as well.

```
MPI_Comm_rank (comm,&rank)
MPI_COMM_RANK (comm,rank,ierr)
```

### [MPI\\_Abort](#)

Terminates all MPI processes associated with the communicator. In most MPI implementations it terminates ALL processes regardless of the communicator specified.

```
MPI_Abort (comm,errorcode)
MPI_ABORT (comm,errorcode,ierr)
```

### [MPI\\_Get\\_processor\\_name](#)

Returns the processor name. Also returns the length of the name. The buffer for "name" must be at least MPI\_MAX\_PROCESSOR\_NAME characters in size. What is returned into "name" is implementation dependent - may not be the same as the output of the "hostname" or "host" shell commands.

```
MPI_Get_processor_name (&name,&resultlength)
MPI_GET_PROCESSOR_NAME (name,resultlength,ierr)
```

### [MPI\\_Get\\_version](#)

Returns the version and subversion of the MPI standard that's implemented by the library.

```
MPI_Get_version (&version,&subversion)
MPI_GET_VERSION (version,subversion,ierr)
```

### [MPI\\_Initialized](#)

Indicates whether MPI\_Init has been called - returns flag as either logical true (1) or false(0). MPI requires that MPI\_Init be called once and only once by each process. This may pose a problem for modules that want to use MPI and are prepared to call MPI\_Init if necessary. MPI\_Initialized solves this problem.

```
MPI_Initialized (&flag)
MPI_INITIALIZED (flag,ierr)
```

### [MPI\\_Wtime](#)

Returns an elapsed wall clock time in seconds (double precision) on the calling processor.

```
MPI_Wtime ()
MPI_WTIME ()
```

### [MPI\\_Wtick](#)

Returns the resolution in seconds (double precision) of MPI\_Wtime.

```
MPI_Wtick ()
MPI_WTICK ()
```

### [MPI Finalize](#)

Terminates the MPI execution environment. This function should be the last MPI routine called in every MPI program - no other MPI routines may be called after it.

```
MPI_Finalize ()
MPI_FINALIZE (ierr)
```

## Examples: Environment Management Routines



### C Language - Environment Management Routines

```
1 // required MPI include file
2 #include "mpi.h"
3 #include <stdio.h>
4
5 int main(int argc, char *argv[]) {
6     int numtasks, rank, len, rc;
7     char hostname[MPI_MAX_PROCESSOR_NAME];
8
9     // initialize MPI
10    MPI_Init(&argc,&argv);
11
12    // get number of tasks
13    MPI_Comm_size(MPI_COMM_WORLD,&numtasks);
14
15    // get my rank
16    MPI_Comm_rank(MPI_COMM_WORLD,&rank);
17
18    // this one is obvious
19    MPI_Get_processor_name(hostname, &len);
20    printf ("Number of tasks= %d My rank= %d Running on %s\n", numtasks,rank,hostname);
21
22
23    // do some work with message passing
24
25
26    // done with MPI
27    MPI_Finalize();
28 }
```



### Fortran - Environment Management Routines

```
1 program simple
2
3 ! required MPI include file
4 include 'mpif.h'
5
6 integer numtasks, rank, len, ierr
7 character(MPI_MAX_PROCESSOR_NAME) hostname
8
9 ! initialize MPI
10 call MPI_INIT(ierr)
11
12 ! get number of tasks
13 call MPI_COMM_SIZE(MPI_COMM_WORLD, numtasks, ierr)
14
15 ! get my rank
16 call MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierr)
17
18 ! this one is obvious
19 call MPI_GET_PROCESSOR_NAME(hostname, len, ierr)
20 print *, 'Number of tasks=',numtasks,' My rank=',rank,' Running on=',hostname
21
```

```

22
23      ! do some work with message passing
24
25
26      ! done with MPI
27      call MPI_FINALIZE(ierr)
28
29      end

```

## MPI Exercise 1

### Getting Started

#### Overview:

- Login to an LC cluster using your workshop username and OTP token
- Copy the exercise files to your home directory
- Familiarize yourself with LC's MPI compilers
- Write a simple "Hello World" MPI program using several MPI Environment Management routines
- Successfully compile your program
- Successfully run your program - several different ways



[GO TO THE EXERCISE HERE](#)

Approx. 20 minutes

## Point to Point Communication Routines

### General Concepts

#### ► First, a Simple Example:

- The value of PI can be calculated in various ways. Consider the Monte Carlo method of approximating PI:
  - Inscribe a circle with radius  $r$  in a square with side length of  $2r$
  - The area of the circle is  $\pi r^2$  and the area of the square is  $4r^2$
  - The ratio of the area of the circle to the area of the square is:
 
$$\pi r^2 / 4r^2 = \pi / 4$$
  - If you randomly generate  $N$  points inside the square, approximately  $N * \pi / 4$  of those points ( $M$ ) should fall inside the circle.
  - $\pi$  is then approximated as:
 
$$N * \pi / 4 = M$$

$$\pi / 4 = M / N$$

$$\pi = 4 * M / N$$
  - Note that increasing the number of points generated improves the approximation.

- Serial pseudo code for this procedure:

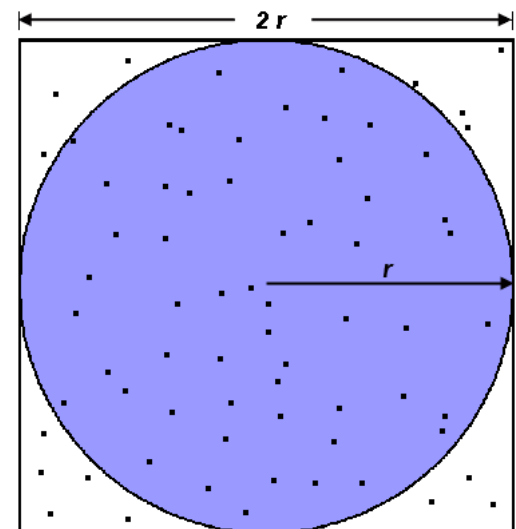
```

npoints = 10000
circle_count = 0

do j = 1,npoints
  generate 2 random numbers between 0 and 1
  xcoordinate = random1
  ycoordinate = random2
  if (xcoordinate, ycoordinate) inside circle
    then circle_count = circle_count + 1
  end do

PI = 4.0*circle_count/npoints

```



$$A_S = (2r)^2 = 4r^2$$

$$A_C = \pi r^2$$

$$\pi = 4 \times \frac{A_C}{A_S}$$

- Leads to an "embarrassingly parallel" solution:

- Break the loop iterations into chunks that can be executed by different tasks simultaneously.
- Each task executes its portion of the loop a number of times.
- Each task can do its work without requiring any information from the other tasks (there are no data dependencies).
- Master task receives results from other tasks **using send/receive point-to-point operations**.

- Pseudo code solution: **red** highlights changes for parallelism.

```

npoints = 10000
circle_count = 0

p = number of tasks
num = npoints/p

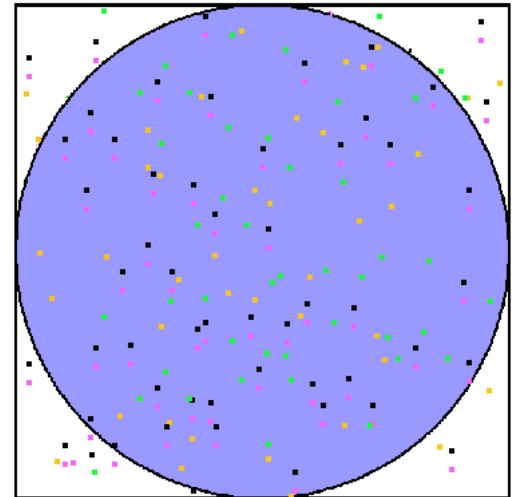
find out if I am MASTER or WORKER

do j = 1,num
  generate 2 random numbers between 0 and 1
  xcoordinate = random1
  ycoordinate = random2
  if (xcoordinate, ycoordinate) inside circle
    then circle_count = circle_count + 1
  end do

  if I am MASTER
    receive from WORKERS their circle_counts
    compute PI (use MASTER and WORKER calculations)
  else if I am WORKER
    send to MASTER circle_count
  endif

```

Example MPI Program in C: [mpi\\_pi\\_reduce.c](#)  
 Example MPI Program in Fortran: [mpi\\_pi\\_reduce.f](#)



■ task 1  
 ■ task 2  
 ■ task 3  
 ■ task 4

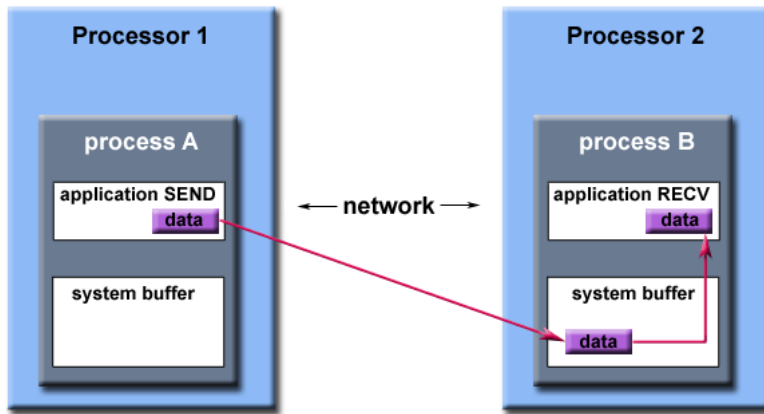
- **Key Concept:** Divide work between available tasks which communicate data via point-to-point message passing calls.

#### ► Types of Point-to-Point Operations:

- MPI point-to-point operations typically involve message passing between two, and only two, different MPI tasks. One task is performing a send operation and the other task is performing a matching receive operation.
- There are different types of send and receive routines used for different purposes. For example:
  - Synchronous send
  - Blocking send / blocking receive
  - Non-blocking send / non-blocking receive
  - Buffered send
  - Combined send/receive
  - "Ready" send
- Any type of send routine can be paired with any type of receive routine.
- MPI also provides several routines associated with send - receive operations, such as those used to wait for a message's arrival or probe to find out if a message has arrived.

#### ► Buffering:

- In a perfect world, every send operation would be perfectly synchronized with its matching receive. This is rarely the case. Somehow or other, the MPI implementation must be able to deal with storing data when the two tasks are out of sync.
- Consider the following two cases:
  - A send operation occurs 5 seconds before the receive is ready - where is the message while the receive is pending?
  - Multiple sends arrive at the same receiving task which can only accept one send at a time - what happens to the messages that are "backing up"?
- The MPI implementation (not the MPI standard) decides what happens to data in these types of cases. Typically, a **system buffer** area is reserved to hold data in transit. For example:



**Path of a message buffered at the receiving process**

- System buffer space is:
  - Opaque to the programmer and managed entirely by the MPI library
  - A finite resource that can be easy to exhaust
  - Often mysterious and not well documented
  - Able to exist on the sending side, the receiving side, or both
  - Something that may improve program performance because it allows send - receive operations to be asynchronous.
- User managed address space (i.e. your program variables) is called the **application buffer**. MPI also provides for a user managed send buffer.

#### ► Blocking vs. Non-blocking:

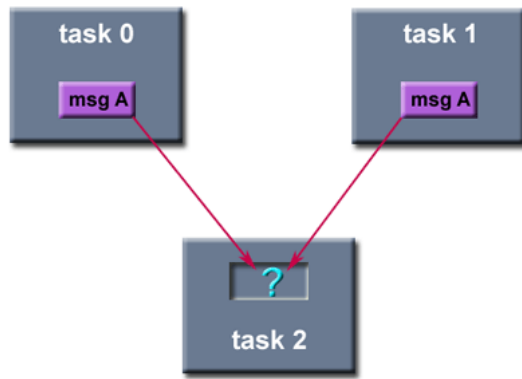
- Most of the MPI point-to-point routines can be used in either blocking or non-blocking mode.
- Blocking:**
  - A blocking send routine will only "return" after it is safe to modify the application buffer (your send data) for reuse. Safe means that modifications will not affect the data intended for the receive task. Safe does not imply that the data was actually received - it may very well be sitting in a system buffer.
  - A blocking send can be synchronous which means there is handshaking occurring with the receive task to confirm a safe send.
  - A blocking send can be asynchronous if a system buffer is used to hold the data for eventual delivery to the receive.
  - A blocking receive only "returns" after the data has arrived and is ready for use by the program.
- Non-blocking:**
  - Non-blocking send and receive routines behave similarly - they will return almost immediately. They do not wait for any communication events to complete, such as message copying from user memory to system buffer space or the actual arrival of message.
  - Non-blocking operations simply "request" the MPI library to perform the operation when it is able. The user can not predict when that will happen.
  - It is unsafe to modify the application buffer (your variable space) until you know for a fact the requested non-blocking operation was actually performed by the library. There are "wait" routines used to do this.
  - Non-blocking communications are primarily used to overlap computation with communication and exploit possible performance gains.

Blocking Send	Non-blocking Send
<pre> myvar = 0;  for (i=1; i&lt;ntasks; i++) {   task = i;   MPI_Send (&amp;myvar ... .. task ...);   myvar = myvar + 2;    /* do some work */ }</pre>	<pre> myvar = 0;  for (i=1; i&lt;ntasks; i++) {   task = i;   MPI_Isend (&amp;myvar ... .. task ...);   myvar = myvar + 2;    /* do some work */    MPI_Wait (...); }</pre>
Safe. Why?	Unsafe. Why?

#### ► Order and Fairness:

- Order:**
  - MPI guarantees that messages will not overtake each other.
  - If a sender sends two messages (Message 1 and Message 2) in succession to the same destination, and both match the same receive, the receive operation will receive Message 1 before Message 2.
  - If a receiver posts two receives (Receive 1 and Receive 2), in succession, and both are looking for the same message, Receive 1 will receive the message before Receive 2.
  - Order rules do not apply if there are multiple threads participating in the communication operations.
- Fairness:**
  - MPI does not guarantee fairness - it's up to the programmer to prevent "operation starvation".

- Example: task 0 sends a message to task 2. However, task 1 sends a competing message that matches task 2's receive. Only one of the sends will complete.



## Point to Point Communication Routines

### MPI Message Passing Routine Arguments

MPI point-to-point communication routines generally have an argument list that takes one of the following formats:

Blocking sends	<code>MPI_Send(buffer, count, type, dest, tag, comm)</code>
Non-blocking sends	<code>MPI_Isend(buffer, count, type, dest, tag, comm, request)</code>
Blocking receive	<code>MPI_Recv(buffer, count, type, source, tag, comm, status)</code>
Non-blocking receive	<code>MPI_Irecv(buffer, count, type, source, tag, comm, request)</code>

### Buffer

Program (application) address space that references the data that is to be sent or received. In most cases, this is simply the variable name that is sent/received. For C programs, this argument is passed by reference and usually must be prepended with an ampersand: **&var1**

### Data Count

Indicates the number of data elements of a particular type to be sent.

### Data Type

For reasons of portability, MPI predefines its elementary data types. The table below lists those required by the standard.

C Data Types		Fortran Data Types	
<b>MPI_CHAR</b>	char	<b>MPI_CHARACTER</b>	character(1)
<b>MPI_WCHAR</b>	wchar_t - wide character		
<b>MPI_SHORT</b>	signed short int		
<b>MPI_INT</b>	signed int	<b>MPI_INTEGER</b> <b>MPI_INTEGER1</b> <b>MPI_INTEGER2</b> <b>MPI_INTEGER4</b>	integer integer*1 integer*2 integer*4
<b>MPI_LONG</b>	signed long int		
<b>MPI_LONG_LONG_INT</b> <b>MPI_LONG_LONG</b>	signed long long int		
<b>MPI_SIGNED_CHAR</b>	signed char		
<b>MPI_UNSIGNED_CHAR</b>	unsigned char		
<b>MPI_UNSIGNED_SHORT</b>	unsigned short int		
<b>MPI_UNSIGNED</b>	unsigned int		
<b>MPI_UNSIGNED_LONG</b>	unsigned long int		
<b>MPI_UNSIGNED_LONG_LONG</b>	unsigned long long int		
<b>MPI_FLOAT</b>	float	<b>MPI_REAL</b> <b>MPI_REAL2</b> <b>MPI_REAL4</b> <b>MPI_REAL8</b>	real real*2 real*4 real*8
<b>MPI_DOUBLE</b>	double	<b>MPI_DOUBLE_PRECISION</b>	double precision

<b>MPI_LONG_DOUBLE</b>	long double		
<b>MPI_C_COMPLEX</b> <b>MPI_C_FLOAT_COMPLEX</b>	float _Complex	<b>MPI_COMPLEX</b>	complex
<b>MPI_C_DOUBLE_COMPLEX</b>	double _Complex	<b>MPI_DOUBLE_COMPLEX</b>	double complex
<b>MPI_C_LONG_DOUBLE_COMPLEX</b>	long double _Complex		
<b>MPI_C_BOOL</b>	_Bool	<b>MPI_LOGICAL</b>	logical
<b>MPI_INT8_T</b> <b>MPI_INT16_T</b> <b>MPI_INT32_T</b> <b>MPI_INT64_T</b>	int8_t int16_t int32_t int64_t		
<b>MPI_UINT8_T</b> <b>MPI_UINT16_T</b> <b>MPI_UINT32_T</b> <b>MPI_UINT64_T</b>	uint8_t uint16_t uint32_t uint64_t		
<b>MPI_BYTE</b>	8 binary digits	<b>MPI_BYTE</b>	8 binary digits
<b>MPI_PACKED</b>	data packed or unpacked with MPI_Pack()/ MPI_Unpack	<b>MPI_PACKED</b>	data packed or unpacked with MPI_Pack()/ MPI_Unpack

**Notes:**

- Programmers may also create their own data types (see [Derived Data Types](#)).
- MPI\_BYTE and MPI\_PACKED do not correspond to standard C or Fortran types.
- Types shown in **GRAY FONT** are recommended if possible.
- Some implementations may include additional elementary data types (MPI\_LOGICAL2, MPI\_COMPLEX32, etc.). Check the MPI header file.

**Destination**

An argument to send routines that indicates the process where a message should be delivered. Specified as the rank of the receiving process.

**Source**

An argument to receive routines that indicates the originating process of the message. Specified as the rank of the sending process. This may be set to the wild card MPI\_ANY\_SOURCE to receive a message from any task.

**Tag**

Arbitrary non-negative integer assigned by the programmer to uniquely identify a message. Send and receive operations should match message tags. For a receive operation, the wild card MPI\_ANY\_TAG can be used to receive any message regardless of its tag. The MPI standard guarantees that integers 0-32767 can be used as tags, but most implementations allow a much larger range than this.

**Communicator**

Indicates the communication context, or set of processes for which the source or destination fields are valid. Unless the programmer is explicitly creating new communicators, the predefined communicator MPI\_COMM\_WORLD is usually used.

**Status**

For a receive operation, indicates the source of the message and the tag of the message. In C, this argument is a pointer to a predefined structure MPI\_Status (ex. **stat.MPI\_SOURCE stat.MPI\_TAG**). In Fortran, it is an integer array of size MPI\_STATUS\_SIZE (ex. **stat(MPI\_SOURCE) stat(MPI\_TAG)**). Additionally, the actual number of bytes received is obtainable from Status via the MPI\_Get\_count routine. The constants MPI\_STATUS\_IGNORE and MPI\_STATUSES\_IGNORE can be substituted if a message's source, tag or size will be queried later.

**Request**

Used by non-blocking send and receive operations. Since non-blocking operations may return before the requested system buffer space is obtained, the system issues a unique "request number". The programmer uses this system assigned "handle" later (in a WAIT type routine) to determine completion of the non-blocking operation. In C, this argument is a pointer to a predefined structure MPI\_Request. In Fortran, it is an integer.

**Point to Point Communication Routines****Blocking Message Passing Routines**

The more commonly used MPI blocking message passing routines are described below.

**MPI\_Send**

Basic blocking send operation. Routine returns only after the application buffer in the sending task is free for reuse. Note that this routine may be implemented differently on different systems. The MPI standard permits the use of a system buffer but does not require it. Some implementations may actually use a synchronous send (discussed below) to implement the basic blocking send.

```
MPI_Send (&buf, count, datatype, dest, tag, comm)
MPI_SEND (buf, count, datatype, dest, tag, comm, ierr)
```



### [MPI Recv](#)

Receive a message and block until the requested data is available in the application buffer in the receiving task.

```
MPI_Recv (&buf, count, datatype, source, tag, comm, &status)
MPI_RECV (buf, count, datatype, source, tag, comm, status, ierr)
```

### [MPI Ssend](#)

Synchronous blocking send: Send a message and block until the application buffer in the sending task is free for reuse and the destination process has started to receive the message.

```
MPI_Ssend (&buf, count, datatype, dest, tag, comm)
MPI_SSEND (buf, count, datatype, dest, tag, comm, ierr)
```

### [MPI Sendrecv](#)

Send a message and post a receive before blocking. Will block until the sending application buffer is free for reuse and until the receiving application buffer contains the received message.

```
MPI_Sendrecv (&sendbuf, sendcount, sendtype, dest, sendtag,
..... &recvbuf, recvcount, recvtype, source, recvtag,
..... comm, &status)
MPI_SENDRECV (sendbuf, sendcount, sendtype, dest, sendtag,
..... recvbuf, recvcount, recvtype, source, recvtag,
..... comm, status, ierr)
```

### [MPI Wait](#)

### [MPI Waitany](#)

### [MPI Waitall](#)

### [MPI Waitsome](#)

MPI\_Wait blocks until a specified non-blocking send or receive operation has completed. For multiple non-blocking operations, the programmer can specify any, all or some completions.

```
MPI_Wait (&request, &status)
MPI_Waitany (count, &array_of_requests, &index, &status)
MPI_Waitall (count, &array_of_requests, &array_of_statuses)
MPI_Waitsome (incount, &array_of_requests, &outcount,
..... &array_of_offsets, &array_of_statuses)
MPI_WAIT (request, status, ierr)
MPI_WAITANY (count, array_of_requests, index, status, ierr)
MPI_WAITALL (count, array_of_requests, array_of_statuses,
..... ierr)
MPI_WAITSOME (incount, array_of_requests, outcount,
..... array_of_offsets, array_of_statuses, ierr)
```

### [MPI Probe](#)

Performs a blocking test for a message. The "wildcards" MPI\_ANY\_SOURCE and MPI\_ANY\_TAG may be used to test for a message from any source or with any tag. For the C routine, the actual source and tag will be returned in the status structure as **status.MPI\_SOURCE** and **status.MPI\_TAG**. For the Fortran routine, they will be returned in the integer array **status(MPI\_SOURCE)** and **status(MPI\_TAG)**.

Example Use

```
MPI_Probe (source, tag, comm, &status)
MPI_PROBE (source, tag, comm, status, ierr)
```

### [MPI Get count](#)

Returns the source, tag and number of elements of datatype received. Can be used with both blocking and non-blocking receive operations. For the C routine, the actual source and tag will be returned in the status structure as **status.MPI\_SOURCE** and **status.MPI\_TAG**. For the Fortran routine, they will be returned in the integer array **status(MPI\_SOURCE)** and **status(MPI\_TAG)**.

```
MPI_Get_count (&status, datatype, &count)
MPI_GET_COUNT (status, datatype, count, ierr)
```

## Examples: Blocking Message Passing Routines

Task 0 pings task 1 and awaits return ping

**C Language - Blocking Message Passing Example**

```

1  #include "mpi.h"
2  #include <stdio.h>
3
4  main(int argc, char *argv[]) {
5      int numtasks, rank, dest, source, rc, count, tag=1;
6      char inmsg, outmsg='x';
7      MPI_Status Stat; // required variable for receive routines
8
9      MPI_Init(&argc,&argv);
10     MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
11     MPI_Comm_rank(MPI_COMM_WORLD, &rank);
12
13     // task 0 sends to task 1 and waits to receive a return message
14     if (rank == 0) {
15         dest = 1;
16         source = 1;
17         MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
18         MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD, &Stat);
19     }
20
21     // task 1 waits for task 0 message then returns a message
22     else if (rank == 1) {
23         dest = 0;
24         source = 0;
25         MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD, &Stat);
26         MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
27     }
28
29     // query receive Stat variable and print message details
30     MPI_Get_count(&Stat, MPI_CHAR, &count);
31     printf("Task %d: Received %d char(s) from task %d with tag %d \n",
32           rank, count, Stat.MPI_SOURCE, Stat.MPI_TAG);
33
34     MPI_Finalize();
35 }

```

**Fortran - Blocking Message Passing Example**

```

1  program ping
2  include 'mpif.h'
3
4  integer numtasks, rank, dest, source, count, tag, ierr
5  integer stat(MPI_STATUS_SIZE) ! required variable for receive routines
6  character inmsg, outmsg
7  outmsg = 'x'
8  tag = 1
9
10 call MPI_INIT(ierr)
11 call MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierr)
12 call MPI_COMM_SIZE(MPI_COMM_WORLD, numtasks, ierr)
13
14 ! task 0 sends to task 1 and waits to receive a return message
15 if (rank .eq. 0) then
16     dest = 1
17     source = 1
18     call MPI_SEND(outmsg, 1, MPI_CHARACTER, dest, tag, MPI_COMM_WORLD, ierr)
19     call MPI_RECV(inmsg, 1, MPI_CHARACTER, source, tag, MPI_COMM_WORLD, stat, ierr)
20
21 ! task 1 waits for task 0 message then returns a message
22 else if (rank .eq. 1) then
23     dest = 0
24     source = 0
25     call MPI_RECV(inmsg, 1, MPI_CHARACTER, source, tag, MPI_COMM_WORLD, stat, err)
26     call MPI_SEND(outmsg, 1, MPI_CHARACTER, dest, tag, MPI_COMM_WORLD, err)
27 endif
28
29 ! query receive Stat variable and print message details
30 call MPI_GET_COUNT(stat, MPI_CHARACTER, count, ierr)

```

```

31  print *, 'Task ',rank,': Received', count, 'char(s) from task', &
32      stat(MPI_SOURCE), 'with tag',stat(MPI_TAG)
33
34  call MPI_FINALIZE(ierr)
35
36  end

```

## Point to Point Communication Routines

### Non-blocking Message Passing Routines

The more commonly used MPI non-blocking message passing routines are described below.

#### [MPI\\_Isend](#)

Identifies an area in memory to serve as a send buffer. Processing continues immediately without waiting for the message to be copied out from the application buffer. A communication request handle is returned for handling the pending message status. The program should not modify the application buffer until subsequent calls to MPI\_Wait or MPI\_Test indicate that the non-blocking send has completed.

```

MPI_Isend (&buf, count, datatype, dest, tag, comm, &request)
MPI_ISEND (buf, count, datatype, dest, tag, comm, request, ierr)

```

#### [MPI\\_Irecv](#)

Identifies an area in memory to serve as a receive buffer. Processing continues immediately without actually waiting for the message to be received and copied into the application buffer. A communication request handle is returned for handling the pending message status. The program must use calls to MPI\_Wait or MPI\_Test to determine when the non-blocking receive operation completes and the requested message is available in the application buffer.

```

MPI_Irecv (&buf, count, datatype, source, tag, comm, &request)
MPI_IRecv (buf, count, datatype, source, tag, comm, request, ierr)

```

#### [MPI\\_Issend](#)

Non-blocking synchronous send. Similar to MPI\_Isend(), except MPI\_Wait() or MPI\_Test() indicates when the destination process has received the message.

```

MPI_Issend (&buf, count, datatype, dest, tag, comm, &request)
MPI_ISSEND (buf, count, datatype, dest, tag, comm, request, ierr)

```

#### [MPI\\_Test](#)

#### [MPI\\_Testany](#)

#### [MPI\\_Testall](#)

#### [MPI\\_Testsome](#)

MPI\_Test checks the status of a specified non-blocking send or receive operation. The "flag" parameter is returned logical true (1) if the operation has completed, and logical false (0) if not. For multiple non-blocking operations, the programmer can specify any, all or some completions.

```

MPI_Test (&request, &flag, &status)
MPI_Testany (count, &array_of_requests, &index, &flag, &status)
MPI_Testall (count, &array_of_requests, &flag, &array_of_statuses)
MPI_Testsome (incount, &array_of_requests, &outcount,
..... &array_of_offsets, &array_of_statuses)
MPI_TEST (request, flag, status, ierr)
MPI_TESTANY (count, array_of_requests, index, flag, status, ierr)
MPI_TESTALL (count, array_of_requests, flag, array_of_statuses, ierr)
MPI_TESTSOME (incount, array_of_requests, outcount,
..... array_of_offsets, array_of_statuses, ierr)

```

#### [MPI\\_Iprobe](#)

Performs a non-blocking test for a message. The "wildcards" MPI\_ANY\_SOURCE and MPI\_ANY\_TAG may be used to test for a message from any source or with any tag. The integer "flag" parameter is returned logical true (1) if a message has arrived, and logical false (0) if not. For the C routine, the actual source and tag will be returned in the status structure as **status.MPI\_SOURCE** and **status.MPI\_TAG**. For the Fortran routine, they will be returned in the integer array **status(MPI\_SOURCE)** and **status(MPI\_TAG)**.

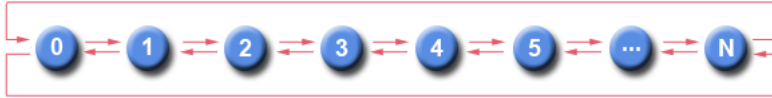
```

MPI_Iprobe (source, tag, comm, &flag, &status)
MPI_IPROBE (source, tag, comm, flag, status, ierr)

```

## Examples: Non-blocking Message Passing Routines

Nearest neighbor exchange in a ring topology



### C Language - Non-blocking Message Passing Example

```

1  #include "mpi.h"
2  #include <stdio.h>
3
4  main(int argc, char *argv[]) {
5      int numtasks, rank, next, prev, buf[2], tag1=1, tag2=2;
6      MPI_Request reqs[4]; // required variable for non-blocking calls
7      MPI_Status stats[4]; // required variable for Waitall routine
8
9      MPI_Init(&argc,&argv);
10     MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
11     MPI_Comm_rank(MPI_COMM_WORLD, &rank);
12
13     // determine left and right neighbors
14     prev = rank-1;
15     next = rank+1;
16     if (rank == 0) prev = numtasks - 1;
17     if (rank == (numtasks - 1)) next = 0;
18
19     // post non-blocking receives and sends for neighbors
20     MPI_Irecv(&buf[0], 1, MPI_INT, prev, tag1, MPI_COMM_WORLD, &reqs[0]);
21     MPI_Irecv(&buf[1], 1, MPI_INT, next, tag2, MPI_COMM_WORLD, &reqs[1]);
22
23     MPI_Isend(&rank, 1, MPI_INT, prev, tag2, MPI_COMM_WORLD, &reqs[2]);
24     MPI_Isend(&rank, 1, MPI_INT, next, tag1, MPI_COMM_WORLD, &reqs[3]);
25
26     // do some work while sends/receives progress in background
27
28     // wait for all non-blocking operations to complete
29     MPI_Waitall(4, reqs, stats);
30
31     // continue - do more work
32
33     MPI_Finalize();
34 }

```



### Fortran - Non-blocking Message Passing Example

```

1  program ringtopo
2  include 'mpif.h'
3
4  integer numtasks, rank, next, prev, buf(2), tag1, tag2, ierr
5  integer reqs(4) ! required variable for non-blocking calls
6  integer stats(MPI_STATUS_SIZE,4) ! required variable for WAITALL routine
7  tag1 = 1
8  tag2 = 2
9
10 call MPI_INIT(ierr)
11 call MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierr)
12 call MPI_COMM_SIZE(MPI_COMM_WORLD, numtasks, ierr)
13
14 ! determine left and right neighbors
15 prev = rank - 1
16 next = rank + 1
17 if (rank .eq. 0) then
18     prev = numtasks - 1
19 endif
20 if (rank .eq. numtasks - 1) then
21     next = 0

```

```

22  endif
23
24  ! post non-blocking receives and sends for neighbors
25  call MPI_Irecv(buf(1), 1, MPI_INTEGER, prev, tag1, MPI_COMM_WORLD, reqs(1), ierr)
26  call MPI_Irecv(buf(2), 1, MPI_INTEGER, next, tag2, MPI_COMM_WORLD, reqs(2), ierr)
27
28  call MPI_Isend(rank, 1, MPI_INTEGER, prev, tag2, MPI_COMM_WORLD, reqs(3), ierr)
29  call MPI_Isend(rank, 1, MPI_INTEGER, next, tag1, MPI_COMM_WORLD, reqs(4), ierr)
30
31  ! do some work while sends/receives progress in background
32
33  ! wait for all non-blocking operations to complete
34  call MPI_WAITALL(4, reqs, stats, ierr);
35
36  ! continue - do more work
37
38  call MPI_FINALIZE(ierr)
39
40  end

```

## MPI Exercise 2

### Point-to-Point Message Passing

#### Overview:

- Login to the LC workshop cluster, if you are not already logged in
- Using your "Hello World" MPI program from Exercise 1, add MPI blocking point-to-point routines to send and receive messages
- Successfully compile your program
- Successfully run your program - several different ways
- Try the same thing with nonblocking send/receive routines



[GO TO THE EXERCISE HERE](#)

Approx. 20 minutes

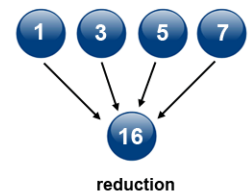
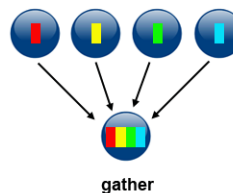
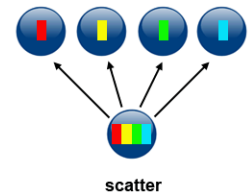
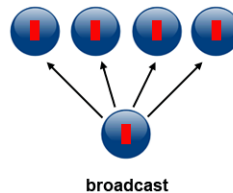
## Collective Communication Routines

### Types of Collective Operations:

- **Synchronization** - processes wait until all members of the group have reached the synchronization point.
- **Data Movement** - broadcast, scatter/gather, all to all.
- **Collective Computation** (reductions) - one member of the group collects data from the other members and performs an operation (min, max, add, multiply, etc.) on that data.

### Scope:

- Collective communication routines must involve **all** processes within the scope of a communicator.
  - All processes are by default, members in the communicator MPI\_COMM\_WORLD.
  - Additional communicators can be defined by the programmer. See the [Group and Communicator Management Routines](#) section for details.



- Unexpected behavior, including program failure, can occur if even one task in the communicator doesn't participate.
- It is the programmer's responsibility to ensure that all processes within a communicator participate in any collective operations.

**► Programming Considerations and Restrictions:**

- Collective communication routines do not take message tag arguments.
- Collective operations within subsets of processes are accomplished by first partitioning the subsets into new groups and then attaching the new groups to new communicators (discussed in the [Group and Communicator Management Routines](#) section).
- Can only be used with MPI predefined datatypes - not with MPI [Derived Data Types](#).
- MPI-2 extended most collective operations to allow data movement between intercommunicators (not covered here).
- With MPI-3, collective operations can be blocking or non-blocking. Only blocking operations are covered in this tutorial.

**Collective Communication Routines****[MPI Barrier](#)**

Synchronization operation. Creates a barrier synchronization in a group. Each task, when reaching the MPI\_Barrier call, blocks until all tasks in the group reach the same MPI\_Barrier call. Then all tasks are free to proceed.

```
MPI_Barrier (comm)
MPI_BARRIER (comm,ierr)
```

**[MPI Bcast](#)**

Data movement operation. Broadcasts (sends) a message from the process with rank "root" to all other processes in the group.

[Diagram Here](#)

```
MPI_Bcast (&buffer,count,datatype,root,comm)
MPI_BCAST (buffer,count,datatype,root,comm,ierr)
```

**[MPI Scatter](#)**

Data movement operation. Distributes distinct messages from a single source task to each task in the group.

[Diagram Here](#)

```
MPI_Scatter (&sendbuf,sendcnt,sendtype,&recvbuf,
..... recvcnt,recvtype,root,comm)
MPI_SCATTER (sendbuf,sendcnt,sendtype,recvbuf,
..... recvcnt,recvtype,root,comm,ierr)
```

**[MPI Gather](#)**

Data movement operation. Gathers distinct messages from each task in the group to a single destination task. This routine is the reverse operation of MPI\_Scatter.

[Diagram Here](#)

```
MPI_Gather (&sendbuf,sendcnt,sendtype,&recvbuf,
..... recvcount,recvtype,root,comm)
MPI_GATHER (sendbuf,sendcnt,sendtype,recvbuf,
..... recvcount,recvtype,root,comm,ierr)
```

**[MPI Allgather](#)**

Data movement operation. Concatenation of data to all tasks in a group. Each task in the group, in effect, performs a one-to-all broadcasting operation within the group.

[Diagram Here](#)

```
MPI_Allgather (&sendbuf,sendcount,sendtype,&recvbuf,
..... recvcount,recvtype,comm)
MPI_ALLGATHER (sendbuf,sendcount,sendtype,recvbuf,
..... recvcount,recvtype,comm,info)
```

**[MPI Reduce](#)**

Collective computation operation. Applies a reduction operation on all tasks in the group and places the result in one task.

[Diagram Here](#)

```
MPI_Reduce (&sendbuf,&recvbuf,count,datatype,op,root,comm)
MPI_REDUCE (sendbuf,recvbuf,count,datatype,op,root,comm,ierr)
```

The predefined MPI reduction operations appear below. Users can also define their own reduction functions by using the [MPI\\_Op\\_create](#) routine.

MPI Reduction Operation		C Data Types	Fortran Data Type
<b>MPI_MAX</b>	maximum	integer, float	integer, real, complex
<b>MPI_MIN</b>	minimum	integer, float	integer, real, complex
<b>MPI_SUM</b>	sum	integer, float	integer, real, complex
<b>MPI_PROD</b>	product	integer, float	integer, real, complex
<b>MPI LAND</b>	logical AND	integer	logical
<b>MPI_BAND</b>	bit-wise AND	integer, MPI_BYTE	integer, MPI_BYTE
<b>MPI_LOR</b>	logical OR	integer	logical
<b>MPI BOR</b>	bit-wise OR	integer, MPI_BYTE	integer, MPI_BYTE
<b>MPI_LXOR</b>	logical XOR	integer	logical
<b>MPI_BXOR</b>	bit-wise XOR	integer, MPI_BYTE	integer, MPI_BYTE
<b>MPI_MAXLOC</b>	max value and location	float, double and long double	real, complex, double precision
<b>MPI_MINLOC</b>	min value and location	float, double and long double	real, complex, double precision

- Note from the MPI\_Reduce man page: The operation is always assumed to be associative. All predefined operations are also assumed to be commutative. Users may define operations that are assumed to be associative, but not commutative. The "canonical" evaluation order of a reduction is determined by the ranks of the processes in the group. However, the implementation can take advantage of associativity, or associativity and commutativity in order to change the order of evaluation. This may change the result of the reduction for operations that are not strictly associative and commutative, such as floating point addition. [Advice to implementors] It is strongly recommended that MPI\_REDUCE be implemented so that the same result be obtained whenever the function is applied on the same arguments, appearing in the same order. Note that this may prevent optimizations that take advantage of the physical location of processors. [End of advice to implementors]

### [MPI Allreduce](#)

Collective computation operation + data movement. Applies a reduction operation and places the result in all tasks in the group. This is equivalent to an MPI\_Reduce followed by an MPI\_Bcast.

[Diagram Here](#)

```
MPI_Allreduce (&sendbuf,&recvbuf,count,datatype,op,comm)
MPI_ALLREDUCE (sendbuf,recvbuf,count,datatype,op,comm,ierr)
```

### [MPI Reduce\\_scatter](#)

Collective computation operation + data movement. First does an element-wise reduction on a vector across all tasks in the group. Next, the result vector is split into disjoint segments and distributed across the tasks. This is equivalent to an MPI\_Reduce followed by an MPI\_Scatter operation.

[Diagram Here](#)

```
MPI_Reduce_scatter (&sendbuf,&recvbuf,recvcount,datatype,
..... op,comm)
MPI_REDUCE_SCATTER (sendbuf,recvbuf,recvcount,datatype,
..... op,comm,ierr)
```

### [MPI Alltoall](#)

Data movement operation. Each task in a group performs a scatter operation, sending a distinct message to all the tasks in the group in order by index.

[Diagram Here](#)

```
MPI_Alltoall (&sendbuf,sendcount,sendtype,&recvbuf,
..... recvcnt,recvtype,comm)
MPI_ALLTOALL (sendbuf,sendcount,sendtype,recvbuf,
..... recvcnt,recvtype,comm,ierr)
```

### [MPI Scan](#)

Performs a scan operation with respect to a reduction operation across a task group.

[Diagram Here](#)

```
MPI_Scan (&sendbuf,&recvbuf,count,datatype,op,comm)
MPI_SCAN (sendbuf,recvbuf,count,datatype,op,comm,ierr)
```



**Examples: Collective Communications**

Perform a scatter operation on the rows of an array

**C Language - Collective Communications Example**

```

1  #include "mpi.h"
2  #include <stdio.h>
3  #define SIZE 4
4
5  main(int argc, char *argv[]) {
6      int numtasks, rank, sendcount, recvcnt, source;
7      float sendbuf[SIZE][SIZE] = {
8          {1.0, 2.0, 3.0, 4.0},
9          {5.0, 6.0, 7.0, 8.0},
10         {9.0, 10.0, 11.0, 12.0},
11         {13.0, 14.0, 15.0, 16.0} };
12     float recvbuf[SIZE];
13
14     MPI_Init(&argc,&argv);
15     MPI_Comm_rank(MPI_COMM_WORLD, &rank);
16     MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
17
18     if (numtasks == SIZE) {
19         // define source task and elements to send/receive, then perform collective scatter
20         source = 1;
21         sendcount = SIZE;
22         recvcnt = SIZE;
23         MPI_Scatter(sendbuf, sendcount, MPI_FLOAT, recvbuf, recvcnt,
24                     MPI_FLOAT, source, MPI_COMM_WORLD);
25
26         printf("rank= %d Results: %f %f %f %f\n", rank, recvbuf[0],
27                recvbuf[1], recvbuf[2], recvbuf[3]);
28     }
29     else
30         printf("Must specify %d processors. Terminating.\n", SIZE);
31
32     MPI_Finalize();
33 }

```

**Fortran - Collective Communications Example**

```

1  program scatter
2  include 'mpif.h'
3
4  integer SIZE
5  parameter(SIZE=4)
6  integer numtasks, rank, sendcount, recvcnt, source, ierr
7  real*4 sendbuf(SIZE,SIZE), recvbuf(SIZE)
8
9  ! Fortran stores this array in column major order, so the
10 ! scatter will actually scatter columns, not rows.
11 data sendbuf /1.0, 2.0, 3.0, 4.0, &
12              5.0, 6.0, 7.0, 8.0, &
13              9.0, 10.0, 11.0, 12.0, &
14              13.0, 14.0, 15.0, 16.0 /
15
16 call MPI_INIT(ierr)
17 call MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierr)
18 call MPI_COMM_SIZE(MPI_COMM_WORLD, numtasks, ierr)
19
20 if (numtasks .eq. SIZE) then
21     ! define source task and elements to send/receive, then perform collective scatter
22     source = 1
23     sendcount = SIZE
24     recvcnt = SIZE
25     call MPI_SCATTER(sendbuf, sendcount, MPI_REAL, recvbuf, recvcnt, MPI_REAL, &
26                     source, MPI_COMM_WORLD, ierr)
27
28     print *, 'rank= ', rank, ' Results: ', recvbuf
29
30 else

```

```

31     print *, 'Must specify',SIZE,' processors.  Terminating.'
32 endif
33
34 call MPI_FINALIZE(ierr)
35
36 end

```

Sample program output:

```

rank= 0 Results: 1.000000 2.000000 3.000000 4.000000
rank= 1 Results: 5.000000 6.000000 7.000000 8.000000
rank= 2 Results: 9.000000 10.000000 11.000000 12.000000
rank= 3 Results: 13.000000 14.000000 15.000000 16.000000

```

## Derived Data Types

- As [previously mentioned](#), MPI predefines its primitive data types:

C Data Types		Fortran Data Types
MPI_CHAR	MPI_C_COMPLEX	MPI_CHARACTER
MPI_WCHAR	MPI_C_FLOAT_COMPLEX	MPI_INTEGER
MPI_SHORT	MPI_C_DOUBLE_COMPLEX	MPI_INTEGER1
MPI_INT	MPI_C_LONG_DOUBLE_COMPLEX	MPI_INTEGER2
MPI_LONG	MPI_C_BOOL	MPI_INTEGER4
MPI_LONG_LONG_INT	MPI_LOGICAL	MPI_REAL
MPI_LONG_LONG	MPI_C_LONG_DOUBLE_COMPLEX	MPI_REAL2
MPI_SIGNED_CHAR	MPI_INT8_T	MPI_REAL4
MPI_UNSIGNED_CHAR	MPI_INT16_T	MPI_REAL8
MPI_UNSIGNED_SHORT	MPI_INT32_T	MPI_DOUBLE_PRECISION
MPI_UNSIGNED_LONG	MPI_INT64_T	MPI_COMPLEX
MPI_UNSIGNED	MPI_UINT8_T	MPI_DOUBLE_COMPLEX
MPI_FLOAT	MPI_UINT16_T	MPI_LOGICAL
MPI_DOUBLE	MPI_UINT32_T	MPI_BYTE
MPI_LONG_DOUBLE	MPI_UINT64_T	MPI_PACKED
	MPI_BYTE	
	MPI_PACKED	

- MPI also provides facilities for you to define your own data structures based upon sequences of the MPI primitive data types. Such user defined structures are called derived data types.
- Primitive data types are contiguous. Derived data types allow you to specify non-contiguous data in a convenient manner and to treat it as though it was contiguous.
- MPI provides several methods for constructing derived data types:
  - Contiguous
  - Vector
  - Indexed
  - Struct

## Derived Data Type Routines

### [MPI Type contiguous](#)

The simplest constructor. Produces a new data type by making count copies of an existing data type.

```

MPI_Type_contiguous (count,oldtype,&newtype)
MPI_TYPE_CONTIGUOUS (count,oldtype,newtype,ierr)

```

### [MPI Type vector](#)

### [MPI Type hvector](#)

Similar to contiguous, but allows for regular gaps (stride) in the displacements. MPI\_Type\_hvector is identical to MPI\_Type\_vector except that stride is specified in bytes.

```

MPI_Type_vector (count,blocklength,stride,oldtype,&newtype)
MPI_TYPE_VECTOR (count,blocklength,stride,oldtype,newtype,ierr)

```

### [MPI Type indexed](#)

### [MPI Type hindexed](#)

An array of displacements of the input data type is provided as the map for the new data type. `MPI_Type_hindexed` is identical to `MPI_Type_indexed` except that offsets are specified in bytes.

```
MPI_Type_indexed (count,blocklens[],offsets[],old_type,&newtype)
MPI_Type_INDEXED (count,blocklens(),offsets(),old_type,newtype,ierr)
```

### [MPI\\_Type\\_struct](#)

The new data type is formed according to completely defined map of the component data types.

**NOTE:** This function is deprecated in MPI-2.0 and replaced by `MPI_Type_create_struct` in MPI-3.0

```
MPI_Type_struct (count,blocklens[],offsets[],old_types,&newtype)
MPI_Type_STRUCT (count,blocklens(),offsets(),old_types,newtype,ierr)
```

### [MPI\\_Type\\_extent](#)

Returns the size in bytes of the specified data type. Useful for the MPI subroutines that require specification of offsets in bytes.

**NOTE:** This function is deprecated in MPI-2.0 and replaced by `MPI_Type_get_extent` in MPI-3.0

```
MPI_Type_extent (datatype,&extent)
MPI_Type_EXTENT (datatype,extent,ierr)
```

### [MPI\\_Type\\_commit](#)

Commits new datatype to the system. Required for all user constructed (derived) datatypes.

```
MPI_Type_commit (&datatype)
MPI_Type_COMMIT (datatype,ierr)
```

### [MPI\\_Type\\_free](#)

Deallocates the specified datatype object. Use of this routine is especially important to prevent memory exhaustion if many datatype objects are created, as in a loop.

```
MPI_Type_free (&datatype)
MPI_Type_FREE (datatype,ierr)
```

## Examples: Contiguous Derived Data Type

Create a data type representing a row of an array and distribute a different row to all processes.

[Diagram Here](#)



### C Language - Contiguous Derived Data Type Example

```
1  #include "mpi.h"
2  #include <stdio.h>
3  #define SIZE 4
4
5  main(int argc, char *argv[]) {
6  int numtasks, rank, source=0, dest, tag=1, i;
7  float a[SIZE][SIZE] =
8      {1.0, 2.0, 3.0, 4.0,
9        5.0, 6.0, 7.0, 8.0,
10       9.0, 10.0, 11.0, 12.0,
11       13.0, 14.0, 15.0, 16.0};
12  float b[SIZE];
13
14  MPI_Status stat;
15  MPI_Datatype rowtype; // required variable
16
17  MPI_Init(&argc,&argv);
18  MPI_Comm_rank(MPI_COMM_WORLD, &rank);
19  MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
20
21  // create contiguous derived data type
22  MPI_Type_contiguous(SIZE, MPI_FLOAT, &rowtype);
23  MPI_Type_commit(&rowtype);
24
```

```

25  if (numtasks == SIZE) {
26      // task 0 sends one element of rowtype to all tasks
27      if (rank == 0) {
28          for (i=0; i<numtasks; i++)
29              MPI_Send(&a[i][0], 1, rowtype, i, tag, MPI_COMM_WORLD);
30      }
31
32      // all tasks receive rowtype data from task 0
33      MPI_Recv(b, SIZE, MPI_FLOAT, source, tag, MPI_COMM_WORLD, &stat);
34      printf("rank= %d  b= %3.1f %3.1f %3.1f %3.1f\n",
35             rank, b[0], b[1], b[2], b[3]);
36  }
37  else
38      printf("Must specify %d processors. Terminating.\n", SIZE);
39
40  // free datatype when done using it
41  MPI_Type_free(&rowtype);
42  MPI_Finalize();
43  }

```



#### Fortran - Contiguous Derived Data Type Example

```

1  program contiguous
2  include 'mpif.h'
3
4  integer SIZE
5  parameter(SIZE=4)
6  integer numtasks, rank, source, dest, tag, i, ierr
7  real*4 a(0:SIZE-1,0:SIZE-1), b(0:SIZE-1)
8  integer stat(MPI_STATUS_SIZE)
9  integer columntype ! required variable
10 tag = 1
11
12 ! Fortran stores this array in column major order
13 data a /1.0, 2.0, 3.0, 4.0, &
14         5.0, 6.0, 7.0, 8.0, &
15         9.0, 10.0, 11.0, 12.0, &
16         13.0, 14.0, 15.0, 16.0 /
17
18 call MPI_INIT(ierr)
19 call MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierr)
20 call MPI_COMM_SIZE(MPI_COMM_WORLD, numtasks, ierr)
21
22 ! create contiguous derived data type
23 call MPI_TYPE_CONTIGUOUS(SIZE, MPI_REAL, columntype, ierr)
24 call MPI_TYPE_COMMIT(columntype, ierr)
25
26 if (numtasks .eq. SIZE) then
27     ! task 0 sends one element of columntype to all tasks
28     if (rank .eq. 0) then
29         do i=0, numtasks-1
30             call MPI_SEND(a(0,i), 1, columntype, i, tag, MPI_COMM_WORLD, ierr)
31         end do
32     endif
33
34     ! all tasks receive columntype data from task 0
35     source = 0
36     call MPI_RECV(b, SIZE, MPI_REAL, source, tag, MPI_COMM_WORLD, stat, ierr)
37     print *, 'rank= ', rank, ' b= ', b
38 else
39     print *, 'Must specify', SIZE, ' processors. Terminating.'
40 endif
41
42 ! free datatype when done using it
43 call MPI_TYPE_FREE(columntype, ierr)
44 call MPI_FINALIZE(ierr)
45
46 end

```

Sample program output:

```
rank= 0  b= 1.0 2.0 3.0 4.0
rank= 1  b= 5.0 6.0 7.0 8.0
rank= 2  b= 9.0 10.0 11.0 12.0
rank= 3  b= 13.0 14.0 15.0 16.0
```

## Examples: Vector Derived Data Type

Create a data type representing a column of an array and distribute different columns to all processes.

[Diagram Here](#)



### C Language - Vector Derived Data Type Example

```
1  #include "mpi.h"
2  #include <stdio.h>
3  #define SIZE 4
4
5  main(int argc, char *argv[]) {
6      int numtasks, rank, source=0, dest, tag=1, i;
7      float a[SIZE][SIZE] =
8          {1.0, 2.0, 3.0, 4.0,
9           5.0, 6.0, 7.0, 8.0,
10          9.0, 10.0, 11.0, 12.0,
11          13.0, 14.0, 15.0, 16.0};
12     float b[SIZE];
13
14     MPI_Status stat;
15     MPI_Datatype columntype; // required variable
16
17
18     MPI_Init(&argc,&argv);
19     MPI_Comm_rank(MPI_COMM_WORLD, &rank);
20     MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
21
22     // create vector derived data type
23     MPI_Type_vector(SIZE, 1, SIZE, MPI_FLOAT, &columntype);
24     MPI_Type_commit(&columntype);
25
26     if (numtasks == SIZE) {
27         // task 0 sends one element of columntype to all tasks
28         if (rank == 0) {
29             for (i=0; i<numtasks; i++)
30                 MPI_Send(&a[0][i], 1, columntype, i, tag, MPI_COMM_WORLD);
31         }
32
33         // all tasks receive columntype data from task 0
34         MPI_Recv(b, SIZE, MPI_FLOAT, source, tag, MPI_COMM_WORLD, &stat);
35         printf("rank= %d  b= %3.1f %3.1f %3.1f %3.1f\n",
36              rank, b[0], b[1], b[2], b[3]);
37     }
38     else
39         printf("Must specify %d processors. Terminating.\n", SIZE);
40
41     // free datatype when done using it
42     MPI_Type_free(&columntype);
43     MPI_Finalize();
44 }
```



### Fortran - Vector Derived Data Type Example

```
1  program vector
2  include 'mpif.h'
3
4  integer SIZE
5  parameter(SIZE=4)
6  integer numtasks, rank, source, dest, tag, i, ierr
7  real*4 a(0:SIZE-1,0:SIZE-1), b(0:SIZE-1)
```

```

 8  integer stat(MPI_STATUS_SIZE)
 9  integer rowtype    ! required variable
10  tag = 1
11
12  ! Fortran stores this array in column major order
13  data a  /1.0, 2.0, 3.0, 4.0, &
14          5.0, 6.0, 7.0, 8.0, &
15          9.0, 10.0, 11.0, 12.0, &
16          13.0, 14.0, 15.0, 16.0 /
17
18  call MPI_INIT(ierr)
19  call MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierr)
20  call MPI_COMM_SIZE(MPI_COMM_WORLD, numtasks, ierr)
21
22  ! create vector derived data type
23  call MPI_TYPE_VECTOR(SIZE, 1, SIZE, MPI_REAL, rowtype, ierr)
24  call MPI_TYPE_COMMIT(rowtype, ierr)
25
26  if (numtasks .eq. SIZE) then
27    ! task 0 sends one element of rowtype to all tasks
28    if (rank .eq. 0) then
29      do i=0, numtasks-1
30        call MPI_SEND(a(i,0), 1, rowtype, i, tag, MPI_COMM_WORLD, ierr)
31      end do
32    endif
33
34    ! all tasks receive rowtype data from task 0
35    source = 0
36    call MPI_RECV(b, SIZE, MPI_REAL, source, tag, MPI_COMM_WORLD, stat, ierr)
37    print *, 'rank= ',rank,' b= ',b
38  else
39    print *, 'Must specify',SIZE,' processors. Terminating.'
40  endif
41
42  ! free datatype when done using it
43  call MPI_TYPE_FREE(rowtype, ierr)
44  call MPI_FINALIZE(ierr)
45
46  end

```

Sample program output:

```

rank= 0  b= 1.0 5.0 9.0 13.0
rank= 1  b= 2.0 6.0 10.0 14.0
rank= 2  b= 3.0 7.0 11.0 15.0
rank= 3  b= 4.0 8.0 12.0 16.0

```

## Examples: Indexed Derived Data Type

Create a datatype by extracting variable portions of an array and distribute to all tasks.

[Diagram Here](#)



### C Language - Indexed Derived Data Type Example

```

1  #include "mpi.h"
2  #include <stdio.h>
3  #define NELEMENTS 6
4
5  main(int argc, char *argv[]) {
6    int numtasks, rank, source=0, dest, tag=1, i;
7    int blocklengths[2], displacements[2];
8    float a[16] =
9      {1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0,
10     9.0, 10.0, 11.0, 12.0, 13.0, 14.0, 15.0, 16.0};
11    float b[NELEMENTS];
12
13    MPI_Status stat;
14    MPI_Datatype indextype;    // required variable
15
16    MPI_Init(&argc,&argv);
17    MPI_Comm_rank(MPI_COMM_WORLD, &rank);

```

```

18 MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
19
20 blocklengths[0] = 4;
21 blocklengths[1] = 2;
22 displacements[0] = 5;
23 displacements[1] = 12;
24
25 // create indexed derived data type
26 MPI_Type_indexed(2, blocklengths, displacements, MPI_FLOAT, &indextype);
27 MPI_Type_commit(&indextype);
28
29 if (rank == 0) {
30     for (i=0; i<numtasks; i++)
31         // task 0 sends one element of indextype to all tasks
32         MPI_Send(a, 1, indextype, i, tag, MPI_COMM_WORLD);
33     }
34
35 // all tasks receive indextype data from task 0
36 MPI_Recv(b, NELEMENTS, MPI_FLOAT, source, tag, MPI_COMM_WORLD, &stat);
37 printf("rank= %d  b= %3.1f %3.1f %3.1f %3.1f %3.1f %3.1f\n",
38        rank, b[0], b[1], b[2], b[3], b[4], b[5]);
39
40 // free datatype when done using it
41 MPI_Type_free(&indextype);
42 MPI_Finalize();
43 }

```



#### Fortran - Indexed Derived Data Type Example

```

1  program indexed
2  include 'mpif.h'
3
4  integer NELEMENTS
5  parameter(NELEMENTS=6)
6  integer numtasks, rank, source, dest, tag, i, ierr
7  integer blocklengths(0:1), displacements(0:1)
8  real*4 a(0:15), b(0:NELEMENTS-1)
9  integer stat(MPI_STATUS_SIZE)
10 integer indextype ! required variable
11 tag = 1
12
13 data a /1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, &
14        9.0, 10.0, 11.0, 12.0, 13.0, 14.0, 15.0, 16.0 /
15
16 call MPI_INIT(ierr)
17 call MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierr)
18 call MPI_COMM_SIZE(MPI_COMM_WORLD, numtasks, ierr)
19
20 blocklengths(0) = 4
21 blocklengths(1) = 2
22 displacements(0) = 5
23 displacements(1) = 12
24
25 ! create indexed derived data type
26 call MPI_TYPE_INDEXED(2, blocklengths, displacements, MPI_REAL, &
27                      indextype, ierr)
28 call MPI_TYPE_COMMIT(indextype, ierr)
29
30 if (rank .eq. 0) then
31     ! task 0 sends one element of indextype to all tasks
32     do i=0, numtasks-1
33         call MPI_SEND(a, 1, indextype, i, tag, MPI_COMM_WORLD, ierr)
34     end do
35 endif
36
37 ! all tasks receive indextype data from task 0
38 source = 0
39 call MPI_RECV(b, NELEMENTS, MPI_REAL, source, tag, MPI_COMM_WORLD, &
40             stat, ierr)
41 print *, 'rank= ', rank, ' b= ', b
42
43 ! free datatype when done using it
44 call MPI_TYPE_FREE(indextype, ierr)
45 call MPI_FINALIZE(ierr)

```



```

46
47     end

```

Sample program output:

```

rank= 0  b= 6.0 7.0 8.0 9.0 13.0 14.0
rank= 1  b= 6.0 7.0 8.0 9.0 13.0 14.0
rank= 2  b= 6.0 7.0 8.0 9.0 13.0 14.0
rank= 3  b= 6.0 7.0 8.0 9.0 13.0 14.0

```

## Examples: Struct Derived Data Type

Create a data type that represents a particle and distribute an array of such particles to all processes.

[Diagram Here](#)



### C Language - Struct Derived Data Type Example

```

1  #include "mpi.h"
2  #include <stdio.h>
3  #define NELEM 25
4
5  main(int argc, char *argv[]) {
6      int numtasks, rank, source=0, dest, tag=1, i;
7
8      typedef struct {
9          float x, y, z;
10         float velocity;
11         int n, type;
12     } Particle;
13     Particle p[NELEM], particles[NELEM];
14     MPI_Datatype particletype, oldtypes[2]; // required variables
15     int blockcounts[2];
16
17     // MPI_Aint type used to be consistent with syntax of
18     // MPI_Type_extent routine
19     MPI_Aint offsets[2], extent;
20
21     MPI_Status stat;
22
23     MPI_Init(&argc,&argv);
24     MPI_Comm_rank(MPI_COMM_WORLD, &rank);
25     MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
26
27     // setup description of the 4 MPI_FLOAT fields x, y, z, velocity
28     offsets[0] = 0;
29     oldtypes[0] = MPI_FLOAT;
30     blockcounts[0] = 4;
31
32     // setup description of the 2 MPI_INT fields n, type
33     // need to first figure offset by getting size of MPI_FLOAT
34     MPI_Type_extent(MPI_FLOAT, &extent);
35     offsets[1] = 4 * extent;
36     oldtypes[1] = MPI_INT;
37     blockcounts[1] = 2;
38
39     // define structured type and commit it
40     MPI_Type_struct(2, blockcounts, offsets, oldtypes, &particletype);
41     MPI_Type_commit(&particletype);
42
43     // task 0 initializes the particle array and then sends it to each task
44     if (rank == 0) {
45         for (i=0; i<NELEM; i++) {
46             particles[i].x = i * 1.0;
47             particles[i].y = i * -1.0;
48             particles[i].z = i * 1.0;
49             particles[i].velocity = 0.25;
50             particles[i].n = i;
51             particles[i].type = i % 2;
52         }
53         for (i=0; i<numtasks; i++)
54             MPI_Send(particles, NELEM, particletype, i, tag, MPI_COMM_WORLD);

```

```

55     }
56
57     // all tasks receive particletype data
58     MPI_Recv(p, NELEM, particletype, source, tag, MPI_COMM_WORLD, &stat);
59
60     printf("rank= %d    %3.2f %3.2f %3.2f %3.2f %d %d\n", rank, p[3].x,
61           p[3].y, p[3].z, p[3].velocity, p[3].n, p[3].type);
62
63     // free datatype when done using it
64     MPI_Type_free(&particletype);
65     MPI_Finalize();
66 }

```



## Fortran - Struct Derived Data Type Example

```

1  program struct
2  include 'mpif.h'
3
4  integer NELEM
5  parameter(NELEM=25)
6  integer numtasks, rank, source, dest, tag, i, ierr
7  integer stat(MPI_STATUS_SIZE)
8
9  type Particle
10 sequence
11 real*4 x, y, z, velocity
12 integer n, type
13 end type Particle
14
15 type (Particle) p(NELEM), particles(NELEM)
16 integer particletype, oldtypes(0:1) ! required variables
17 integer blockcounts(0:1), offsets(0:1), extent
18 tag = 1
19
20 call MPI_INIT(ierr)
21 call MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierr)
22 call MPI_COMM_SIZE(MPI_COMM_WORLD, numtasks, ierr)
23
24 ! setup description of the 4 MPI_REAL fields x, y, z, velocity
25 offsets(0) = 0
26 oldtypes(0) = MPI_REAL
27 blockcounts(0) = 4
28
29 ! setup description of the 2 MPI_INTEGER fields n, type
30 ! need to first figure offset by getting size of MPI_REAL
31 call MPI_TYPE_EXTENT(MPI_REAL, extent, ierr)
32 offsets(1) = 4 * extent
33 oldtypes(1) = MPI_INTEGER
34 blockcounts(1) = 2
35
36 ! define structured type and commit it
37 call MPI_TYPE_STRUCT(2, blockcounts, offsets, oldtypes, &
38                    particletype, ierr)
39 call MPI_TYPE_COMMIT(particletype, ierr)
40
41 ! task 0 initializes the particle array and then sends it to each task
42 if (rank .eq. 0) then
43   do i=0, NELEM-1
44     particles(i) = Particle ( 1.0*i, -1.0*i, 1.0*i, 0.25, i, mod(i,2) )
45   end do
46
47   do i=0, numtasks-1
48     call MPI_SEND(particles, NELEM, particletype, i, tag, &
49                  MPI_COMM_WORLD, ierr)
50   end do
51 endif
52
53 ! all tasks receive particletype data
54 source = 0
55 call MPI_RECV(p, NELEM, particletype, source, tag, &
56              MPI_COMM_WORLD, stat, ierr)
57
58 print *, 'rank= ', rank, ' p(3)= ', p(3)
59

```

```

60  ! free datatype when done using it
61  call MPI_TYPE_FREE(particletype, ierr)
62  call MPI_FINALIZE(ierr)
63  end

```

Sample program output:

```

rank= 0   3.00 -3.00 3.00 0.25 3 1
rank= 2   3.00 -3.00 3.00 0.25 3 1
rank= 1   3.00 -3.00 3.00 0.25 3 1
rank= 3   3.00 -3.00 3.00 0.25 3 1

```

## Group and Communicator Management Routines

### ► Groups vs. Communicators:

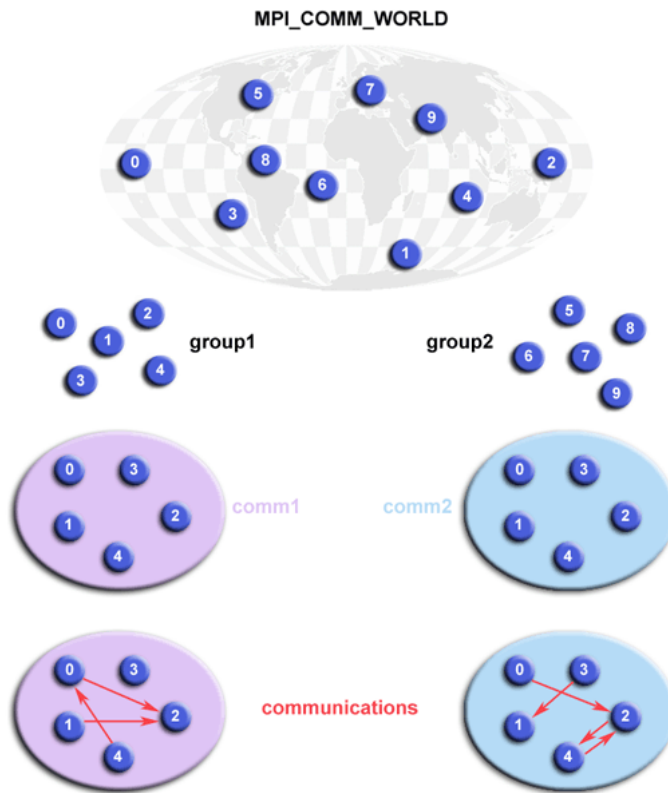
- A group is an ordered set of processes. Each process in a group is associated with a unique integer rank. Rank values start at zero and go to N-1, where N is the number of processes in the group. In MPI, a group is represented within system memory as an object. It is accessible to the programmer only by a "handle". A group is always associated with a communicator object.
- A communicator encompasses a group of processes that may communicate with each other. All MPI messages must specify a communicator. In the simplest sense, the communicator is an extra "tag" that must be included with MPI calls. Like groups, communicators are represented within system memory as objects and are accessible to the programmer only by "handles". For example, the handle for the communicator that comprises all tasks is MPI\_COMM\_WORLD.
- From the programmer's perspective, a group and a communicator are one. The group routines are primarily used to specify which processes should be used to construct a communicator.

### ► Primary Purposes of Group and Communicator Objects:

1. Allow you to organize tasks, based upon function, into task groups.
2. Enable Collective Communications operations across a subset of related tasks.
3. Provide basis for implementing user defined virtual topologies
4. Provide for safe communications

### ► Programming Considerations and Restrictions:

- Groups/communicators are dynamic - they can be created and destroyed during program execution.
- Processes may be in more than one group/communicator. They will have a unique rank within each group/communicator.
- MPI provides over 40 routines related to groups, communicators, and virtual topologies.
- Typical usage:
  1. Extract handle of global group from MPI\_COMM\_WORLD using MPI\_Comm\_group
  2. Form new group as a subset of global group using MPI\_Group\_incl
  3. Create new communicator for new group using MPI\_Comm\_create
  4. Determine new rank in new communicator using MPI\_Comm\_rank
  5. Conduct communications using any MPI message passing routine
  6. When finished, free up new communicator and group (optional) using MPI\_Comm\_free and MPI\_Group\_free



## Group and Communicator Management Routines

Create two different process groups for separate collective communications exchange. Requires creating new communicators also.



### C Language - Group and Communicator Example

```

1  #include "mpi.h"
2  #include <stdio.h>
3  #define NPROCS 8
4
5  main(int argc, char *argv[]) {
6      int rank, new_rank, sendbuf, recvbuf, numtasks,
7          ranks1[4]={0,1,2,3}, ranks2[4]={4,5,6,7};
8      MPI_Group orig_group, new_group; // required variables
9      MPI_Comm new_comm; // required variable
10
11     MPI_Init(&argc,&argv);
12     MPI_Comm_rank(MPI_COMM_WORLD, &rank);
13     MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
14
15     if (numtasks != NPROCS) {
16         printf("Must specify MP_PROCS= %d. Terminating.\n",NPROCS);
17         MPI_Finalize();
18         exit(0);
19     }
20
21     sendbuf = rank;
22
23     // extract the original group handle
24     MPI_Comm_group(MPI_COMM_WORLD, &orig_group);
25
26     // divide tasks into two distinct groups based upon rank
27     if (rank < NPROCS/2) {
28         MPI_Group_incl(orig_group, NPROCS/2, ranks1, &new_group);
29     }
30     else {
31         MPI_Group_incl(orig_group, NPROCS/2, ranks2, &new_group);
32     }
33
34     // create new new communicator and then perform collective communications
35     MPI_Comm_create(MPI_COMM_WORLD, new_group, &new_comm);
36     MPI_Allreduce(&sendbuf, &recvbuf, 1, MPI_INT, MPI_SUM, new_comm);
37

```

```

38 // get rank in new group
39 MPI_Group_rank (new_group, &new_rank);
40 printf("rank= %d newrank= %d recvbuf= %d\n", rank, new_rank, recvbuf);
41
42 MPI_Finalize();
43 }

```



#### Fortran - Group and Communicator Example

```

1  program group
2  include 'mpif.h'
3
4  integer NPROCS
5  parameter(NPROCS=8)
6  integer rank, new_rank, sendbuf, recvbuf, numtasks
7  integer ranks1(4), ranks2(4), ierr
8  integer orig_group, new_group, new_comm ! required variables
9  data ranks1 /0, 1, 2, 3/, ranks2 /4, 5, 6, 7/
10
11 call MPI_INIT(ierr)
12 call MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierr)
13 call MPI_COMM_SIZE(MPI_COMM_WORLD, numtasks, ierr)
14
15 if (numtasks .ne. NPROCS) then
16   print *, 'Must specify NPROCS= ', NPROCS, ' Terminating.'
17   call MPI_FINALIZE(ierr)
18   stop
19 endif
20
21 sendbuf = rank
22
23 ! extract the original group handle
24 call MPI_COMM_GROUP(MPI_COMM_WORLD, orig_group, ierr)
25
26 ! divide tasks into two distinct groups based upon rank
27 if (rank .lt. NPROCS/2) then
28   call MPI_GROUP_INCL(orig_group, NPROCS/2, ranks1, new_group, ierr)
29 else
30   call MPI_GROUP_INCL(orig_group, NPROCS/2, ranks2, new_group, ierr)
31 endif
32
33 ! create new new communicator and then perform collective communications
34 call MPI_COMM_CREATE(MPI_COMM_WORLD, new_group, new_comm, ierr)
35 call MPI_ALLREDUCE(sendbuf, recvbuf, 1, MPI_INTEGER, MPI_SUM, new_comm, ierr)
36
37 ! get rank in new group
38 call MPI_GROUP_RANK(new_group, new_rank, ierr)
39 print *, 'rank= ', rank, ' newrank= ', new_rank, ' recvbuf= ', recvbuf
40
41 call MPI_FINALIZE(ierr)
42 end

```

Sample program output:

```

rank= 7 newrank= 3 recvbuf= 22
rank= 0 newrank= 0 recvbuf= 6
rank= 1 newrank= 1 recvbuf= 6
rank= 2 newrank= 2 recvbuf= 6
rank= 6 newrank= 2 recvbuf= 22
rank= 3 newrank= 3 recvbuf= 6
rank= 4 newrank= 0 recvbuf= 22
rank= 5 newrank= 1 recvbuf= 22

```

## Virtual Topologies

### ► What Are They?

- In terms of MPI, a virtual topology describes a mapping/ordering of MPI processes into a geometric "shape".

- The two main types of topologies supported by MPI are Cartesian (grid) and Graph.
- MPI topologies are virtual - there may be no relation between the physical structure of the parallel machine and the process topology.
- Virtual topologies are built upon MPI communicators and groups.
- Must be "programmed" by the application developer.

#### ► Why Use Them?

- Convenience
  - Virtual topologies may be useful for applications with specific communication patterns - patterns that match an MPI topology structure.
  - For example, a Cartesian topology might prove convenient for an application that requires 4-way nearest neighbor communications for grid based data.
- Communication Efficiency
  - Some hardware architectures may impose penalties for communications between successively distant "nodes".
  - A particular implementation may optimize process mapping based upon the physical characteristics of a given parallel machine.
  - The mapping of processes into an MPI virtual topology is dependent upon the MPI implementation, and may be totally ignored.

#### ► Example:

A simplified mapping of processes into a Cartesian virtual topology appears below:

0 (0,0)	1 (0,1)	2 (0,2)	3 (0,3)
4 (1,0)	5 (1,1)	6 (1,2)	7 (1,3)
8 (2,0)	9 (2,1)	10 (2,2)	11 (2,3)
12 (3,0)	13 (3,1)	14 (3,2)	15 (3,3)

### Virtual Topology Routines

Create a 4 x 4 Cartesian topology from 16 processors and have each process exchange its rank with four neighbors.



#### C Language - Cartesian Virtual Topology Example

```

1  #include "mpi.h"
2  #include <stdio.h>
3  #define SIZE 16
4  #define UP 0
5  #define DOWN 1
6  #define LEFT 2
7  #define RIGHT 3
8
9  main(int argc, char *argv[]) {
10     int numtasks, rank, source, dest, outbuf, i, tag=1,
11         inbuf[4]={MPI_PROC_NULL,MPI_PROC_NULL,MPI_PROC_NULL,MPI_PROC_NULL},
12         nbrs[4], dims[2]={4,4},
13         periods[2]={0,0}, reorder=0, coords[2];
14
15     MPI_Request reqs[8];
16     MPI_Status stats[8];
17     MPI_Comm cartcomm; // required variable
18
19     MPI_Init(&argc,&argv);
20     MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
21
22     if (numtasks == SIZE) {
23         // create cartesian virtual topology, get rank, coordinates, neighbor ranks
24         MPI_Cart_create(MPI_COMM_WORLD, 2, dims, periods, reorder, &cartcomm);
25         MPI_Comm_rank(cartcomm, &rank);
26         MPI_Cart_coords(cartcomm, rank, 2, coords);
27         MPI_Cart_shift(cartcomm, 0, 1, &nbrs[UP], &nbrs[DOWN]);
28         MPI_Cart_shift(cartcomm, 1, 1, &nbrs[LEFT], &nbrs[RIGHT]);
29
30         printf("rank= %d coords= %d %d neighbors(u,d,l,r)= %d %d %d %d\n",
31             rank, coords[0], coords[1], nbrs[UP], nbrs[DOWN], nbrs[LEFT],

```

```

32         nbrs[RIGHT]);
33
34     outbuf = rank;
35
36     // exchange data (rank) with 4 neighbors
37     for (i=0; i<4; i++) {
38         dest = nbrs[i];
39         source = nbrs[i];
40         MPI_Isend(&outbuf, 1, MPI_INT, dest, tag,
41                 MPI_COMM_WORLD, &reqs[i]);
42         MPI_Irecv(&inbuf[i], 1, MPI_INT, source, tag,
43                 MPI_COMM_WORLD, &reqs[i+4]);
44     }
45
46     MPI_Waitall(8, reqs, stats);
47
48     printf("rank= %d                inbuf(u,d,l,r)= %d %d %d %d\n",
49           rank,inbuf[UP],inbuf[DOWN],inbuf[LEFT],inbuf[RIGHT]); }
50 else
51     printf("Must specify %d processors. Terminating.\n",SIZE);
52
53 MPI_Finalize();
54 }

```



#### Fortran - Cartesian Virtual Topology Example

```

1  program cartesian
2  include 'mpif.h'
3
4  integer SIZE, UP, DOWN, LEFT, RIGHT
5  parameter(SIZE=16)
6  parameter(UP=1)
7  parameter(DOWN=2)
8  parameter(LEFT=3)
9  parameter(RIGHT=4)
10 integer numtasks, rank, source, dest, outbuf, i, tag, ierr, &
11     inbuf(4), nbrs(4), dims(2), coords(2), periods(2), reorder
12 integer stats(MPI_STATUS_SIZE, 8), reqs(8)
13 integer cartcomm ! required variable
14 data inbuf /MPI_PROC_NULL,MPI_PROC_NULL,MPI_PROC_NULL,MPI_PROC_NULL/, &
15     dims /4,4/, tag /1/, periods /0,0/, reorder /0/
16
17 call MPI_INIT(ierr)
18 call MPI_COMM_SIZE(MPI_COMM_WORLD, numtasks, ierr)
19
20 if (numtasks .eq. SIZE) then
21     ! create cartesian virtual topology, get rank, coordinates, neighbor ranks
22     call MPI_CART_CREATE(MPI_COMM_WORLD, 2, dims, periods, reorder, &
23         cartcomm, ierr)
24     call MPI_COMM_RANK(cartcomm, rank, ierr)
25     call MPI_CART_COORDS(cartcomm, rank, 2, coords, ierr)
26     call MPI_CART_SHIFT(cartcomm, 0, 1, nbrs(UP), nbrs(DOWN), ierr)
27     call MPI_CART_SHIFT(cartcomm, 1, 1, nbrs(LEFT), nbrs(RIGHT), ierr)
28
29     write(*,20) rank,coords(1),coords(2),nbrs(UP),nbrs(DOWN), &
30         nbrs(LEFT),nbrs(RIGHT)
31
32     ! exchange data (rank) with 4 neighbors
33     outbuf = rank
34     do i=1,4
35         dest = nbrs(i)
36         source = nbrs(i)
37         call MPI_ISEND(outbuf, 1, MPI_INTEGER, dest, tag, &
38             MPI_COMM_WORLD, reqs(i), ierr)
39         call MPI_IRECV(inbuf(i), 1, MPI_INTEGER, source, tag, &
40             MPI_COMM_WORLD, reqs(i+4), ierr)
41     enddo
42
43     call MPI_WAITALL(8, reqs, stats, ierr)
44
45     write(*,30) rank,inbuf
46
47 else
48     print *, 'Must specify',SIZE,' processors. Terminating.'

```



```

49  endif
50
51  call MPI_FINALIZE(ierr)
52
53  20 format('rank= ',I3,' coords= ',I2,I2, &
54         ' neighbors(u,d,l,r)= ',I3,I3,I3,I3 )
55  30 format('rank= ',I3,'
56         ' inbuf(u,d,l,r)= ',I3,I3,I3,I3 )
57
58  end

```

Sample program output: (partial)

```

rank=   0 coords=   0 0 neighbors(u,d,l,r)=  -1  4 -1  1
rank=   0                      inbuf(u,d,l,r)=  -1  4 -1  1
rank=   8 coords=   2 0 neighbors(u,d,l,r)=   4 12 -1  9
rank=   8                      inbuf(u,d,l,r)=   4 12 -1  9
rank=   1 coords=   0 1 neighbors(u,d,l,r)=  -1  5  0  2
rank=   1                      inbuf(u,d,l,r)=  -1  5  0  2
rank=  13 coords=   3 1 neighbors(u,d,l,r)=   9 -1 12 14
rank=  13                      inbuf(u,d,l,r)=   9 -1 12 14
...
...
rank=   3 coords=   0 3 neighbors(u,d,l,r)=  -1  7  2 -1
rank=   3                      inbuf(u,d,l,r)=  -1  7  2 -1
rank=  11 coords=   2 3 neighbors(u,d,l,r)=   7 15 10 -1
rank=  11                      inbuf(u,d,l,r)=   7 15 10 -1
rank=  10 coords=   2 2 neighbors(u,d,l,r)=   6 14  9 11
rank=  10                      inbuf(u,d,l,r)=   6 14  9 11
rank=   9 coords=   2 1 neighbors(u,d,l,r)=   5 13  8 10
rank=   9                      inbuf(u,d,l,r)=   5 13  8 10

```

## A Brief Word on MPI-2 and MPI-3

### ► MPI-2:

- Intentionally, the MPI-1 specification did not address several "difficult" issues. For reasons of expediency, these issues were deferred to a second specification, called MPI-2 in 1998.
- MPI-2 was a major revision to MPI-1 adding new functionality and corrections.
- Key areas of new functionality in MPI-2:
  - **Dynamic Processes** - extensions that remove the static process model of MPI. Provides routines to create new processes after job startup.
  - **One-Sided Communications** - provides routines for one directional communications. Include shared memory operations (put/get) and remote accumulate operations.
  - **Extended Collective Operations** - allows for the application of collective operations to inter-communicators
  - **External Interfaces** - defines routines that allow developers to layer on top of MPI, such as for debuggers and profilers.
  - **Additional Language Bindings** - describes C++ bindings and discusses Fortran-90 issues.
  - **Parallel I/O** - describes MPI support for parallel I/O.

### ► MPI-3:

- The MPI-3 standard was adopted in 2012, and contains significant extensions to MPI-1 and MPI-2 functionality including:
  - **Nonblocking Collective Operations** - permits tasks in a collective to perform operations without blocking, possibly offering performance improvements.
  - **New One-sided Communication Operations** - to better handle different memory models.
  - **Neighborhood Collectives** - extends the distributed graph and Cartesian process topologies with additional communication power.
  - **Fortran 2008 Bindings** - expanded from Fortran90 bindings
  - **MPIT Tool Interface** - allows the MPI implementation to expose certain internal variables, counters, and other states to the user (most likely performance tools).
  - **Matched Probe** - fixes an old bug in MPI-2 where one could not probe for messages in a multi-threaded environment.

### ► More Information on MPI-2 and MPI-3:

- MPI Standard documents: <http://www.mpi-forum.org/docs/>

## MPI Exercise 3

### Your Choice

#### Overview:

- Login to the LC workshop cluster, if you are not already logged in
- Following the Exercise 3 instructions will take you through all sorts of MPI programs - pick any/all that are of interest.
- The intention is review the codes and see what's happening - not just compile and run.
- Several codes provide serial examples for a comparison with the parallel MPI versions.
- Check out the "bug" programs.



[GO TO THE EXERCISE HERE](#)

This completes the tutorial.

**Evaluation  
Form**

Please complete the online evaluation form - unless you are doing the exercise, in which case please complete it at the end of the exercises.

Where would you like to go now?

- [Exercise 3](#)
- [Agenda](#)
- [Back to the top](#)

## References and More Information

- Original Author: Blaise Barney; Contact: [hpc-tutorials@llnl.gov](mailto:hpc-tutorials@llnl.gov), Livermore Computing.
- MPI Standard documents:  
<http://www.mpi-forum.org/docs/>
- "Using MPI", Gropp, Lusk and Skjellum. MIT Press, 1994.
- MPI Tutorials:  
[www.mcs.anl.gov/research/projects/mpi/tutorial](http://www.mcs.anl.gov/research/projects/mpi/tutorial)
- Livermore Computing specific information:
  - Linux Clusters Overview tutorial  
[computing.llnl.gov/tutorials/linux\\_clusters](http://computing.llnl.gov/tutorials/linux_clusters)
- "A User's Guide to MPI", Peter S. Pacheco. Department of Mathematics, University of San Francisco.

## Appendix A: MPI-1 Routine Index

- These man pages were derived from the MVAPICH 0.9 implementation of MPI and may differ from the man pages of other implementations.
- Not all MPI routines are shown
- \* = deprecated in MPI-2.0, replaced in MPI-3.0
- The complete MPI-3 standard (2012) defines over 430 routines.

Environment Management Routines			
<a href="#">MPI_Abort</a>	<a href="#">MPI_Errhandler_create*</a>	<a href="#">MPI_Errhandler_free</a>	<a href="#">MPI_Errhandler_get*</a>
<a href="#">MPI_Errhandler_set*</a>	<a href="#">MPI_Error_class</a>	<a href="#">MPI_Error_string</a>	<a href="#">MPI_Finalize</a>
<a href="#">MPI_Get_processor_name</a>	<a href="#">MPI_Get_version</a>	<a href="#">MPI_Init</a>	<a href="#">MPI_Initialized</a>
<a href="#">MPI_Wtick</a>	<a href="#">MPI_Wtime</a>		
Point-to-Point Communication Routines			
<a href="#">MPI_Bsend</a>	<a href="#">MPI_Bsend_init</a>	<a href="#">MPI_Buffer_attach</a>	<a href="#">MPI_Buffer_detach</a>
<a href="#">MPI_Cancel</a>	<a href="#">MPI_Get_count</a>	<a href="#">MPI_Get_elements</a>	<a href="#">MPI_Ibsend</a>
<a href="#">MPI_Iprobe</a>	<a href="#">MPI_Irecv</a>	<a href="#">MPI_Irsend</a>	<a href="#">MPI_Isend</a>
<a href="#">MPI_Issend</a>	<a href="#">MPI_Probe</a>	<a href="#">MPI_Recv</a>	<a href="#">MPI_Recv_init</a>
<a href="#">MPI_Request_free</a>	<a href="#">MPI_Rsend</a>	<a href="#">MPI_Rsend_init</a>	<a href="#">MPI_Send</a>
<a href="#">MPI_Send_init</a>	<a href="#">MPI_Sendrecv</a>	<a href="#">MPI_Sendrecv_replace</a>	<a href="#">MPI_Ssend</a>
<a href="#">MPI_Ssend_init</a>	<a href="#">MPI_Start</a>	<a href="#">MPI_Startall</a>	<a href="#">MPI_Test</a>
<a href="#">MPI_Test_cancelled</a>	<a href="#">MPI_Testall</a>	<a href="#">MPI_Testany</a>	<a href="#">MPI_Testsome</a>
<a href="#">MPI_Wait</a>	<a href="#">MPI_Waitall</a>	<a href="#">MPI_Waitany</a>	<a href="#">MPI_Waitsome</a>
Collective Communication Routines			
<a href="#">MPI_Allgather</a>	<a href="#">MPI_Allgatherv</a>	<a href="#">MPI_Allreduce</a>	<a href="#">MPI_Alltoall</a>
<a href="#">MPI_Alltoallv</a>	<a href="#">MPI_Barrier</a>	<a href="#">MPI_Bcast</a>	<a href="#">MPI_Gather</a>
<a href="#">MPI_Gatherv</a>	<a href="#">MPI_Op_create</a>	<a href="#">MPI_Op_free</a>	<a href="#">MPI_Reduce</a>
<a href="#">MPI_Reduce_scatter</a>	<a href="#">MPI_Scan</a>	<a href="#">MPI_Scatter</a>	<a href="#">MPI_Scatterv</a>
Process Group Routines			
<a href="#">MPI_Group_compare</a>	<a href="#">MPI_Group_difference</a>	<a href="#">MPI_Group_excl</a>	<a href="#">MPI_Group_free</a>
<a href="#">MPI_Group_incl</a>	<a href="#">MPI_Group_intersection</a>	<a href="#">MPI_Group_range_excl</a>	<a href="#">MPI_Group_range_incl</a>
<a href="#">MPI_Group_rank</a>	<a href="#">MPI_Group_size</a>	<a href="#">MPI_Group_translate_ranks</a>	<a href="#">MPI_Group_union</a>
Communicators Routines			
<a href="#">MPI_Comm_compare</a>	<a href="#">MPI_Comm_create</a>	<a href="#">MPI_Comm_dup</a>	<a href="#">MPI_Comm_free</a>
<a href="#">MPI_Comm_group</a>	<a href="#">MPI_Comm_rank</a>	<a href="#">MPI_Comm_remote_group</a>	<a href="#">MPI_Comm_remote_size</a>
<a href="#">MPI_Comm_size</a>	<a href="#">MPI_Comm_split</a>	<a href="#">MPI_Comm_test_inter</a>	<a href="#">MPI_Intercomm_create</a>
<a href="#">MPI_Intercomm_merge</a>			
Derived Types Routines			
<a href="#">MPI_Type_commit</a>	<a href="#">MPI_Type_contiguous</a>	<a href="#">MPI_Type_extent*</a>	<a href="#">MPI_Type_free</a>
<a href="#">MPI_Type_hindexed*</a>	<a href="#">MPI_Type_hvector*</a>	<a href="#">MPI_Type_indexed</a>	<a href="#">MPI_Type_lb</a>
<a href="#">MPI_Type_size</a>	<a href="#">MPI_Type_struct*</a>	<a href="#">MPI_Type_ub*</a>	<a href="#">MPI_Type_vector</a>
Virtual Topology Routines			
<a href="#">MPI_Cart_coords</a>	<a href="#">MPI_Cart_create</a>	<a href="#">MPI_Cart_get</a>	<a href="#">MPI_Cart_map</a>
<a href="#">MPI_Cart_rank</a>	<a href="#">MPI_Cart_shift</a>	<a href="#">MPI_Cart_sub</a>	<a href="#">MPI_Cartdim_get</a>
<a href="#">MPI_Dims_create</a>	<a href="#">MPI_Graph_create</a>	<a href="#">MPI_Graph_get</a>	<a href="#">MPI_Graph_map</a>
<a href="#">MPI_Graph_neighbors</a>	<a href="#">MPI_Graph_neighbors_count</a>	<a href="#">MPI_Graphdims_get</a>	<a href="#">MPI_Topo_test</a>
Miscellaneous Routines			
<a href="#">MPI_Address*</a>	<a href="#">MPI_Attr_delete*</a>	<a href="#">MPI_Attr_get*</a>	<a href="#">MPI_Attr_put*</a>
<a href="#">MPI_Keyval_create*</a>	<a href="#">MPI_Keyval_free*</a>	<a href="#">MPI_Pack</a>	<a href="#">MPI_Pack_size</a>
<a href="#">MPI_Pcontrol</a>	<a href="#">MPI_Unpack</a>		

<https://computing.llnl.gov/tutorials/mpi/>  
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