MPI in Practice

William Gropp

Mathematics and Computer Science Division
Argonne National Laboratory
Argonne, IL 60439
gropp@mcs.anl.gov

Course Outline

- MPI basics
- Running MPI programs
- Intermediate MPI
- Understanding buffering
- Tools for writing libraries
- Performance tuning MPI programs

These books on MPI supplement this tutorial:

- *Using MPI: Portable Parallel Programming with the Message-Passing Interface*, by Gropp, Lusk, and Skjellum, MIT Press, 1994
- *MPI: The Complete Reference*, by Snir et al., MIT Press, 1995.
- *Parallel Programming with MPI*, by Pacheco, Morgan Kaufmann, 1996.

Material that begins with this symbol is 'advanced' and may be skipped on a first reading.

MPI2: This material indicates MPI-2 features that are expected.

What is MPI?

- A *message-passing library specification*
  - message-passing model
  - not a compiler specification
  - not a specific product
- For parallel computers, clusters, and heterogeneous networks
- Full-featured
- Designed to permit (unleash?) the development of parallel software libraries
- Designed to provide access to advanced parallel hardware for
  - end users
  - library writers
  - tool developers

Motivation for a New Design

- Message Passing now mature as programming paradigm
  - well understood
  - efficient match to hardware
  - many applications
- Vendor systems not portable
- Portable systems are mostly research projects
  - incomplete
  - lack vendor support
  - not at most efficient level

Motivation (cont.)

Few systems offer the full range of desired features.

- modularity (for libraries)
- access to peak performance
- portability
- heterogeneity
- subgroups
- topologies
- performance measurement tools

The MPI Process and Schedule

- Began at Williamsburg Workshop in April 1992
- MPI Forum organized at Supercomputing '92
- Followed HPF format and process
- Met for two days every six weeks
- Extensive, open e-mail discussions, drafts, readings, votes
- Pre-final draft distributed at Supercomputing '93
- Two-month public comment period
- MPI-1.0 released in May 1994
- Widely available now on the Web, ftp sites, netlib (http://www.mcs.anl.gov/mpi)
- Forum resumes meeting in March 1995, for MPI-2
- MPI-1.1 released in May 1995
- MPI-2.0 draft released at Supercomputing '96
- MPI-2.0 (and MPI-1.2) expected May '97

Who Designed MPI?

- Broad participation
- Vendors
  - IBM, Intel, TMC, Meiko, Cray, Convex, Ncube
- Library writers
  - PVM, p4, Zipcode, TCGMSG, Chameleon, Express, Linda
- Application specialists and consultants

Companies	Laboratories	Universities
ARCO	ANL	UC Santa Barbara
Convex	GMD	Syracuse U
Cray Res	LANL	Michigan State U
IBM	LLNL	Oregon Grad Inst
Intel	NOAA	U of New Mexico
KAI	NSF	Miss. State U.
Meiko	ORNL	U of Southampton
NAG	PNL	U of Colorado
nCUBE	Sandia	Yale U
ParaSoft	SDSC	U of Tennessee
Shell	SRC	U of Maryland
TMC		Western Mich U
		U of Edinburgh
		Cornell U.
		Rice U.
		U of San Francisco

Features of MPI

- General
  - Communicators combine context and group for message security
  - Thread safety
  - Supports heterogeneous environments
  - Supports SPMD and MPMD (MIMD) programming models
- Point-to-point communication
  - Structured buffers and derived datatypes, heterogeneity
  - Modes: normal (blocking and non-blocking), synchronous, ready (to allow access to fast protocols), buffered
- Collective
  - Both built-in and user-defined collective operations
  - Large number of data movement routines
  - Subgroups defined directly or by topology

Features of MPI (cont.)

- Application-oriented process topologies
  - Built-in support for grids and graphs (uses groups)
- Profiling
  - Hooks allow users to intercept MPI calls to install their own tools
- Environmental
  - inquiry
  - error control

Features not in MPI

- Non-message-passing concepts not included:
  - process management
  - remote memory transfers
  - active messages
  - threads
  - virtual shared memory
- MPI does not address these issues, but has tried to remain compatible with these ideas (e.g. thread safety as a goal, intercommunicators)
- MPI does not provide C++ or Fortran 90 language bindings—Use C and Fortran77 instead.

MPI2: Many of these are under consideration for MPI 2. See http://www.mcs.anl.gov/mpi/mpi2/mpi2.html for more information.

Is MPI Large or Small?

- MPI is large (125 functions)
  - MPI's extensive functionality requires many functions
  - Number of functions not necessarily a measure of complexity
- MPI is small (6 functions)
  - Many parallel programs can be written with just 6 basic functions.
- MPI is just right
  - One can access flexibility when it is required.
  - One need not master all parts of MPI to use it.

Where to use MPI?

- You need a portable parallel program
- You are writing a parallel library
- You have irregular or dynamic data relationships that do not fit a data parallel model

Where *not* to use MPI:

- You can use HPF or a parallel Fortran 90
- You don't need parallelism at all
- You can use libraries (which may be written in MPI)

Why learn MPI?

- Portable
- Expressive
- Good way to learn about subtle issues in parallel computing

Getting started

- Writing MPI programs
- Compiling and linking
- Running MPI programs
- More information
  - *Using MPI* by William Gropp, Ewing Lusk, and Anthony Skjellum,
  - *MPI: The Complete Reference*, by Snir et al.
  - *Parallel Programming with MPI*, by Peter Pacheco
  - The LAM companion to "Using MPI..." by Zdzislaw Meglicki
  - *Designing and Building Parallel Programs* by Ian Foster.
  - The MPI standard and other information is available at http://www.mcs.anl.gov/mpi. Also the source for several implementations.

Writing MPI programs

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

int main( argc, argv )
int argc;
char **argv;
{
    MPI_Init( &argc, &argv );
    printf( "Hello world\n" );
    MPI_Finalize();
    return 0;
}
```

Commentary

- `#include "mpi.h"` provides basic MPI definitions and types
- `MPI_Init` starts MPI
- `MPI_Finalize` exits MPI
- Note that all non-MPI routines are local; thus the `printf` run on each process

Compiling and linking

For simple programs, special compiler commands can be used. For large projects, it is best to use a standard Makefile.

The MPICH implementation provides the commands `mpicc` and `mpif77` as well as '`Makefile`' examples in '`/usr/local/mpi/examples/Makefile.in`'

Just like Fortran and C, MPI is specified by a document, not a particular implementation. You will need to consult site-specific documentation on how to compile, link, and run MPI programs.

Special compilation commands

The commands

```
mpicc -o first first.c
mpif77 -o firstf firstf.f
```

may be used to build simple programs when using MPICH.

These provide special options that exploit the profiling features of MPI

-mpilog Generate log files of MPI calls

-mpitrace Trace execution of MPI calls

-mpianim Real-time animation of MPI (not available on all systems)

There are specific to the MPICH implementation; other implementations may provide similar commands (e.g., `mpcc` and `mpxlf` on IBM SP). Others only require you to link with a special library (e.g., `-lmpi` on SGI).

Running MPI programs

```
mpirun -np 2 hello
```

'`mpirun`' is not part of the standard, but some version of it is common with several MPI implementations. The version shown here is for the MPICH implementation of MPI.

Just as Fortran does not specify how Fortran programs are started, MPI does not specify how MPI programs are started.

The option `-t` *shows the commands that* `mpirun` *would execute; you can use this to find out how* `mpirun` *starts programs on yor system. The option* `-help` *shows all options to* `mpirun`.

MPI2: An `mpiexec` command may be defined to run MPI programs.

Finding out about the environment

Two of the first questions asked in a parallel program are: How many processes are there? and Who am I?

How many is answered with `MPI_Comm_size` and who am I is answered with `MPI_Comm_rank`.

The rank is a number between zero and `size-1`.

A simple program

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

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

Caveats

These sample programs have been kept as simple as possible by assuming that all processes can do output. Not all parallel systems provide this feature, and MPI provides a way to handle this case.

Exercise - Getting Started

Objective: Learn how to login, write, compile, and run a simple MPI program.

Run the "Hello world" programs. Try two different parallel computers. What does the output look like?

The MPIEXMPL Web Site

A collection of exercises is available online at http://www.mcs.anl.gov/mpi/tutorial/mpiexmpl/index.html

Each exercise contains a brief description of the assignment, sample output and hints, active links to man pages for the MPI routines that you'll need, and a complete solution. Some exercises also have "related exercises" that present variations of the exercise.

The first exercise is available at http://www.mcs.anl.gov/mpi/tutorial/mpiexmpl/src/hellow/C/main.html

What are messages?

When one process gives data to another process, two events must occur:

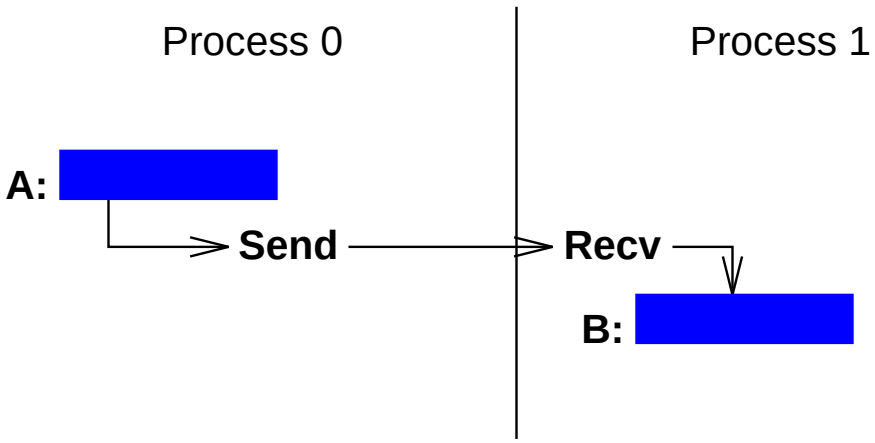
1. The data must be transferred (or a way to access it in shared memory)

2. The two processes must agree that the data has been transferred. This is a *synchronization* step.

Message-passing accomplishes these two events by combining them: A message is sent from one process to another; when the message is received both the data transfer and synchronization have occurred.

MPI2: So-called one-sided or remote memory operations separate that transfer and synchronization, though some method for ensuring that the data are available is still necessary

Sending and Receiving messages



Questions:

- To whom is data sent?
- What is sent?
- How does the receiver identify it?

Message-Passing

- A typical blocking send looks like

```
send( dest, type, address, length )
```

  where

  - `dest` is an integer identifier representing the process to receive the message.
  - `type` is a nonnegative integer that the destination can use to selectively screen messages.
  - (`address, length`) describes a contiguous area in memory containing the message to be sent.

  and

- A typical global operation looks like:

```
broadcast( type, address, length )
```

- All of these specifications are a good match to hardware, easy to understand, but too inflexible.

The Buffer

Sending and receiving only a contiguous array of bytes:

- hides the real data structure from hardware which might be able to handle it directly
- requires pre-packing dispersed data
  - rows of a matrix stored columnwise
  - general collections of structures
- prevents communications between machines with different representations (even lengths) for same data type

Generalizing the Buffer Description

- Specified in MPI by *starting address*, *datatype*, and *count*, where datatype is:
  - elementary (all C and Fortran datatypes)
  - contiguous array of datatypes
  - strided blocks of datatypes
  - indexed array of blocks of datatypes
  - general structure
- Datatypes are constructed recursively.
- Specifications of elementary datatypes allows heterogeneous communication.
- Elimination of length in favor of count is clearer.
- Specifying application-oriented layout of data allows maximal use of special hardware.

Generalizing the Type

- A single type field is too constraining. Often overloaded to provide needed flexibility.
- Problems:
  - under user control
  - wild cards allowed (`MPI_ANY_TAG`)
  - library use conflicts with user and with other libraries

Sample Program using Library Calls

What can go wrong when "wild card" matches are allowed?

Consider two libraries provided by different groups (or one library and "user" code).

`Sub1` and `Sub2` are from different libraries.

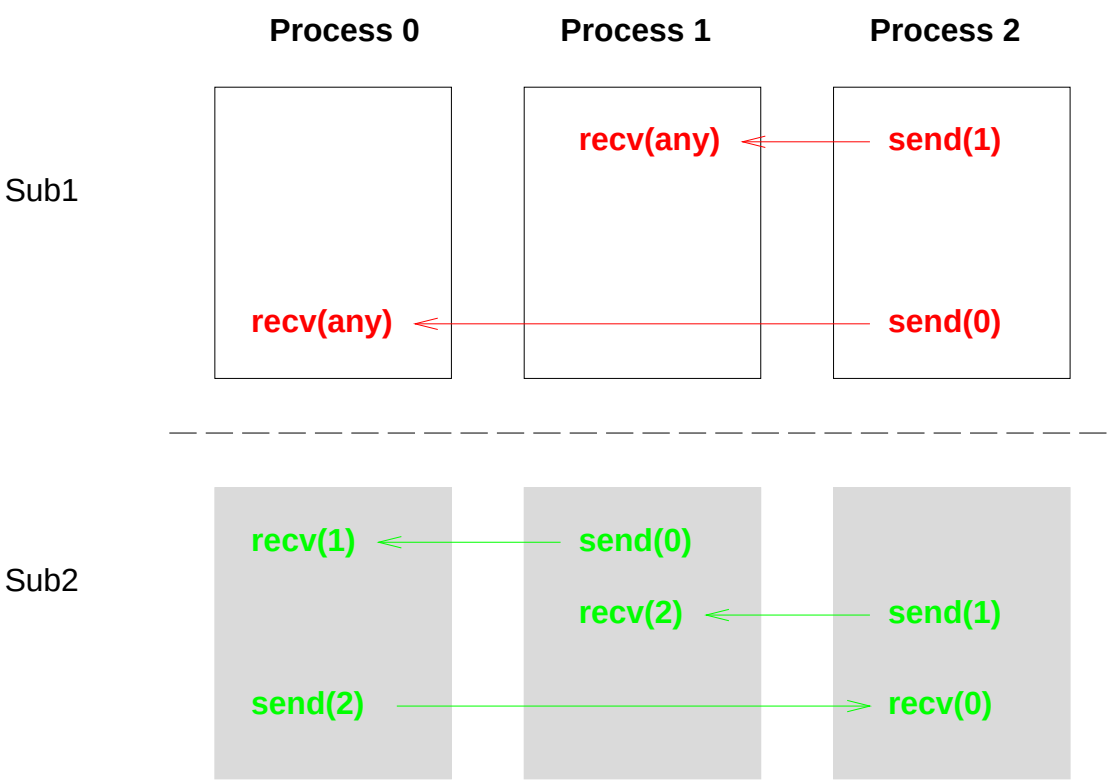
```
Sub1();
Sub2();
```

`Sub1a` and `Sub1b` are from the same library

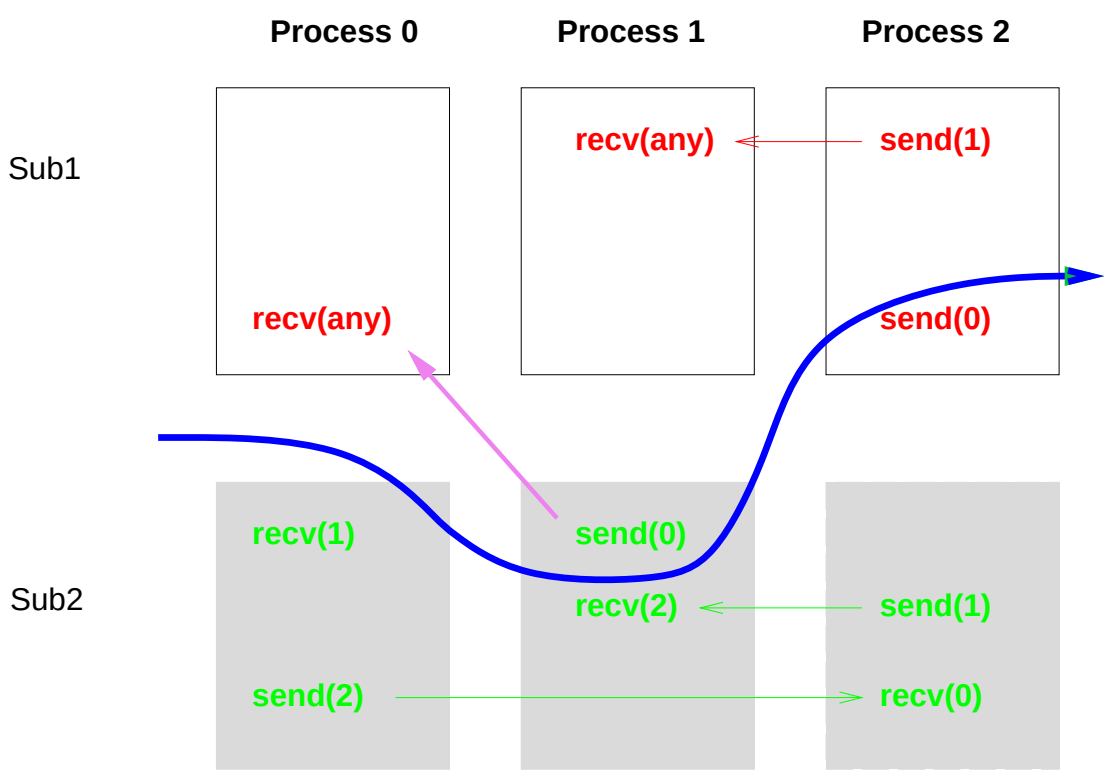
```
Sub1a();
Sub2();
Sub1b();
```

Thanks to Marc Snir for the following four examples

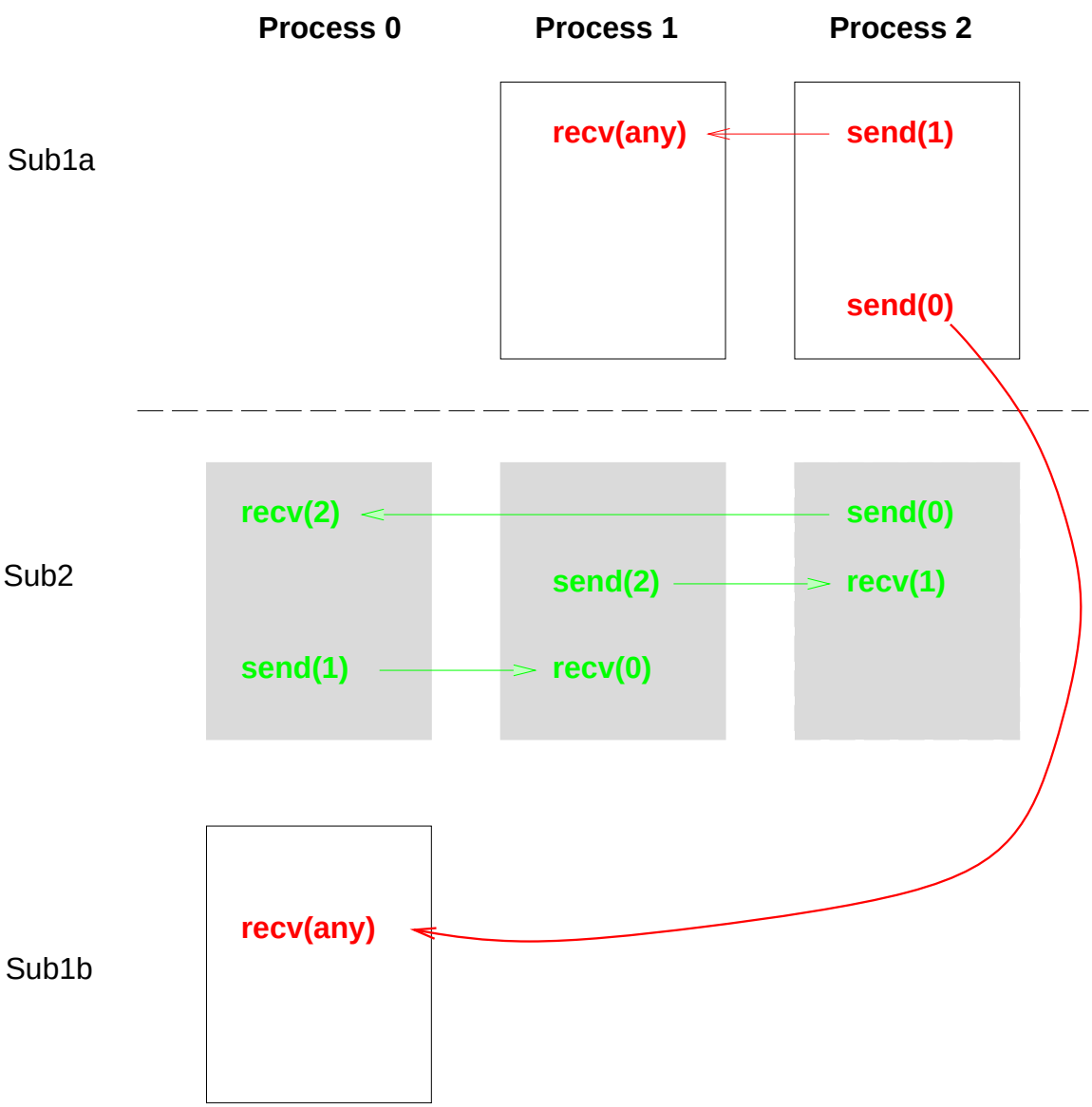
Correct Execution of Library Calls



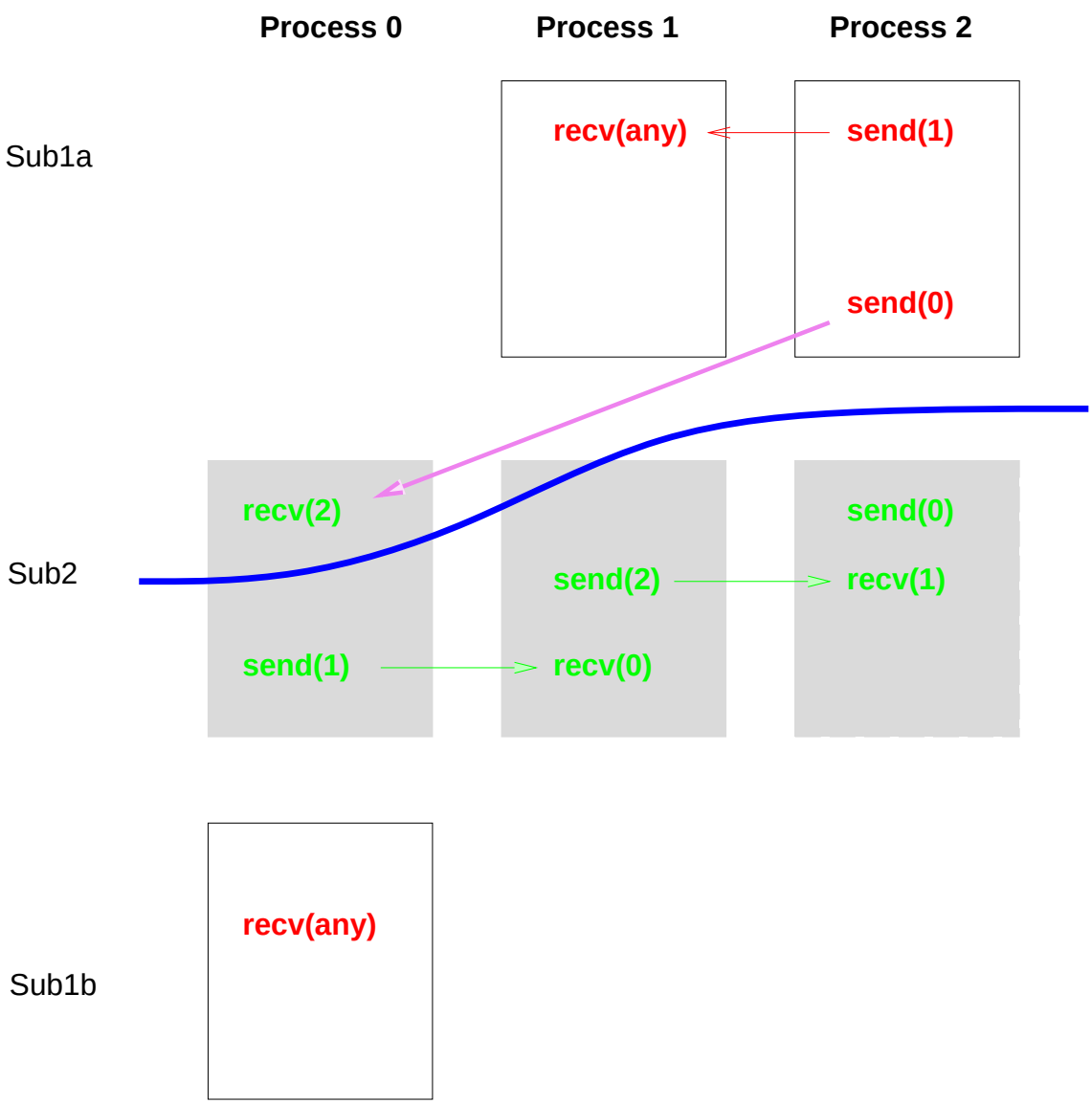
Incorrect Execution of Library Calls



Correct Execution of Library Calls with Pending Communcication



Incorrect Execution of Library Calls with Pending Communication



Solution to the type problem

- A separate communication *context* for each family of messages, used for queueing and matching. (This has often been simulated in the past by overloading the tag field.)
- No wild cards allowed, for security
- Allocated by the system, for security
- Types (*tags*, in MPI) retained for normal use (wild cards OK)

Delimiting Scope of Communication

- Separate groups of processes working on subproblems
  - Merging of process name space interferes with modularity
  - "Local" process identifiers desirable
- Parallel invocation of parallel libraries
  - Messages from application must be kept separate from messages internal to library.
  - Knowledge of library message types interferes with modularity.
  - Synchronizing before and after library calls is undesirable.

Generalizing the Process Identifier

- Collective operations typically operated on all processes (although some systems provide subgroups).
- This is too restrictive (e.g., need minimum over a column or a sum across a row, of processes)
- MPI provides *groups* of processes
  - initial "all" group
  - group management routines (build, delete groups)
- All communication (not just collective operations) takes place in groups.
- A group and a context are combined in a *communicator*.
- Source/destination in send/receive operations refer to *rank* in group associated with a given communicator. `MPI_ANY_SOURCE` permitted in a receive.

MPI Basic Send/Receive

Thus the basic (blocking) send has become:

```
MPI_Send( start, count, datatype, dest, tag,
          comm )
```

and the receive:

```
MPI_Recv(start, count, datatype, source, tag,
         comm, status)
```

The source, tag, and count of the message actually received can be retrieved from `status`.

Two simple collective operations:

```
MPI_Bcast(start, count, datatype, root, comm)
MPI_Reduce(start, result, count, datatype,
           operation, root, comm)
```

Getting information about a message

```
MPI_Status status;
MPI_Recv( ..., &status );
... status.MPI_TAG;
... status.MPI_SOURCE;
MPI_Get_count( &status, datatype, &count );
```

MPI_TAG and MPI_SOURCE primarily of use when MPI_ANY_TAG and/or MPI_ANY_SOURCE in the receive.

MPI_Get_count may be used to determine how much data of a particular type was received.

status.MPI_ERROR *may contain information about failed messages in certain cases, but should not normally be used.*

Simple Fortran example

```
      program main
      include 'mpif.h'

      integer rank, size, to, from, tag, count, i, ierr
      integer src, dest
      integer st_source, st_tag, st_count
      integer status(MPI_STATUS_SIZE)
      double precision data(100)

      call MPI_INIT( ierr )
      call MPI_COMM_RANK( MPI_COMM_WORLD, rank, ierr )
      call MPI_COMM_SIZE( MPI_COMM_WORLD, size, ierr )
      print *, 'Process ', rank, ' of ', size, ' is alive'
      dest = size - 1
      src = 0
C
      if (rank .eq. src) then
         to     = dest
         count  = 10
         tag    = 2001
         do 10 i=1, 10
 10         data(i) = i
         call MPI_SEND( data, count, MPI_DOUBLE_PRECISION, to,
     +                  tag, MPI_COMM_WORLD, ierr )
      else if (rank .eq. dest) then
         tag   = MPI_ANY_TAG
         count = 10
         from  = MPI_ANY_SOURCE
         call MPI_RECV(data, count, MPI_DOUBLE_PRECISION, from,
     +                 tag, MPI_COMM_WORLD, status, ierr )
```

Simple Fortran example (cont.)

```
          call MPI_GET_COUNT( status, MPI_DOUBLE_PRECISION,
     +                        st_count, ierr )
          st_source = status(MPI_SOURCE)
          st_tag    = status(MPI_TAG)
C
          print *, 'Status info: source = ', st_source,
     +             ' tag = ', st_tag, ' count = ', st_count
          print *, rank, ' received', (data(i),i=1,10)
        endif

        call MPI_FINALIZE( ierr )
        end
```

Six Function MPI

MPI is very simple. These six functions allow you to write many programs:

MPI_Init

MPI_Finalize

MPI_Comm_size

MPI_Comm_rank

MPI_Send

MPI_Recv

Two More Functions

There are two more functions that are very useful in building even the simplest MPI programs:

MPI_Wtime Returns, as a double (`DOUBLE PRECISION` in Fortran), the number of seconds (wall clock) since some fixed but unspecified time in the past.

MPI_Abort Aborts an MPI program. Use this instead of `exit` (in C) or `STOP` (in Fortran).

A taste of things to come

The following examples show a C and Fortran version of the same program.

This program computes PI (with a very simple method) but does not use `MPI_Send` and `MPI_Recv`. Instead, it uses *collective* operations to send data to and from all of the running processes. This gives a *different* six-function MPI set:

MPI_Init

MPI_Finalize

MPI_Comm_size

MPI_Comm_rank

MPI_Bcast

MPI_Reduce

Broadcast and Reduction

The routine `MPI_Bcast` sends data from one process to all others.

The routine `MPI_Reduce` combines data from all processes (`MPI_SUM` says to add them in this case), and returning the result to a single process.

Fortran example: PI

```
      program main

      include "mpif.h"

      double precision  PI25DT
      parameter        (PI25DT = 3.14159265358979323846264338d0)

      double precision  mypi, pi, h, sum, x, f, a
      integer n, myid, numprocs, i, rc
c                                  function to integrate
      f(a) = 4.d0 / (1.d0 + a*a)

      call MPI_INIT( ierr )
      call MPI_COMM_RANK( MPI_COMM_WORLD, myid, ierr )
      call MPI_COMM_SIZE( MPI_COMM_WORLD, numprocs, ierr )

 10   if ( myid .eq. 0 ) then
         write(6,98)
 98      format('Enter the number of intervals: (0 quits)')
         read(5,99) n
 99      format(i10)
      endif

      call MPI_BCAST(n,1,MPI_INTEGER,0,MPI_COMM_WORLD,ierr)
```

Fortran example (cont.)

```
c                                     check for quit signal
      if ( n .le. 0 ) goto 30

c                                     calculate the interval size
      h = 1.0d0/n

      sum  = 0.0d0
      do 20 i = myid+1, n, numprocs
         x    = h * (dble(i) - 0.5d0)
         sum = sum + f(x)
 20   continue
      mypi = h * sum

c                                     collect all the partial sums
      call MPI_REDUCE(mypi,pi,1,MPI_DOUBLE_PRECISION,MPI_SUM,0,
     $     MPI_COMM_WORLD,ierr)

c                                     node 0 prints the answer.
      if (myid .eq. 0) then
         write(6, 97) pi, abs(pi - PI25DT)
 97      format('  pi is approximately: ', F18.16,
     +          '  Error is: ', F18.16)
      endif

      goto 10

 30   call MPI_FINALIZE(rc)
      stop
      end
```

C example: PI

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

int main(argc,argv)
int argc;
char *argv[];
{
  int done = 0, n, myid, numprocs, i, rc;
  double PI25DT = 3.141592653589793238462643;
  double mypi, pi, h, sum, x, a;

  MPI_Init(&argc,&argv);
  MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
  MPI_Comm_rank(MPI_COMM_WORLD,&myid);
```

C example (cont.)

```
  while (!done)
  {
    if (myid == 0) {
        printf("Enter the number of intervals: (0 quits) ");
        scanf("%d",&n);
    }
    MPI_Bcast(&n, 1, MPI_INT, 0, MPI_COMM_WORLD);
    if (n == 0) break;

    h   = 1.0 / (double) n;
    sum = 0.0;
    for (i = myid + 1; i <= n; i += numprocs) {
        x = h * ((double)i - 0.5);
        sum += 4.0 / (1.0 + x*x);
    }
    mypi = h * sum;

    MPI_Reduce(&mypi, &pi, 1, MPI_DOUBLE, MPI_SUM, 0,
               MPI_COMM_WORLD);

    if (myid == 0)
        printf("pi is approximately %.16f, Error is %.16f\n",
               pi, fabs(pi - PI25DT));
  }
  MPI_Finalize();
  return 0;
}
```

Exercise - PI

Objective: Experiment with send/receive

Run either program for PI. Write new versions that replace the calls to `MPI_Bcast` and `MPI_Reduce` with `MPI_Send` and `MPI_Recv`.

The MPI broadcast and reduce operations use at most $\log p$ *send and receive operations on each process where* p *is the size of* `MPI_COMM_WORLD`*. How many operations do your versions use? You can use* `MPI_Wtime` *to time your programs.*

Exercise - Ring

Objective: Experiment with send/receive

Write a program to send a message around a ring of processors. That is, processor 0 sends to processor 1, who sends to processor 2, etc. The last processor returns the message to processor 0.

A related version of this exercise is available at http://www.mcs.anl.gov/mpi/tutorial/mpiexmpl/src/ring/C/main.html

You can use the routine MPI_Wtime *to time code in MPI.*

Common Problems

- `mpicc`, `mpirun`, or `mpif77` not in `PATH`
- The "wrong" command is in PATH (e.g., mixing two different MPI implementations)
- On workstations, unguarded `stty` or `tset` commands

For Fortran users:

- Missing `ierr` argument at end of MPI call
- `status` not declared as an array of `MPI_STATUS_SIZE`

Topologies

MPI provides routines to provide structure to collections of processes

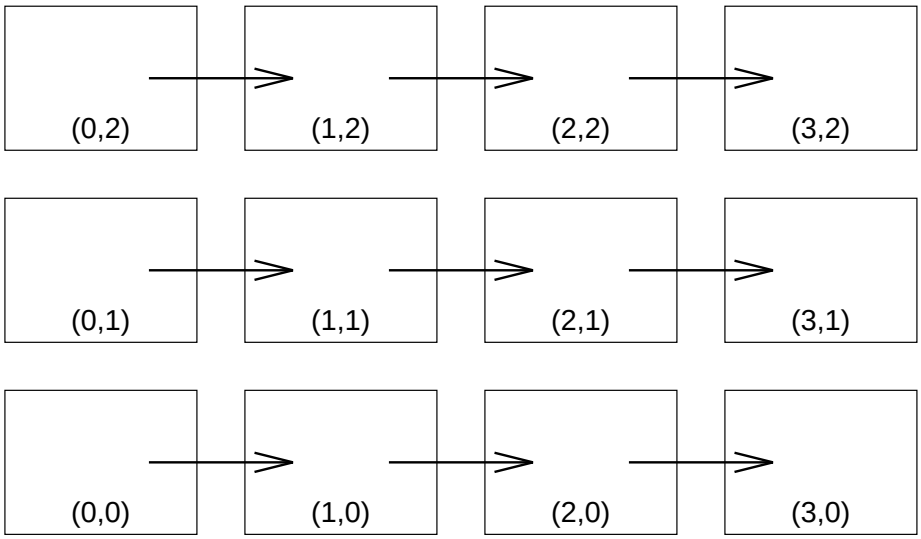
This helps to answer the question:

Who are my neighbors?

Cartesian Topologies

A Cartesian topology is a mesh

Example of 3×4 Cartesian mesh with arrows pointing at the *right* neighbors:



Defining a Cartesian Topology

The routine MPI_Cart_create creates a Cartesian decomposition of the processes, with the number of dimensions given by the ndim argument.

```
dims(1)    = 4
dims(2)    = 3
periods(1) = .false.
periods(2) = .false.
reorder    = .true.
ndim       = 2
call MPI_CART_CREATE( MPI_COMM_WORLD, ndim, dims,
$                     periods, reorder, comm2d, ierr )
```

Finding neighbors

MPI_Cart_create creates a new *communicator* with the same processes as the input communicator, but with the specified topology.

The question, Who are my neighbors, can now be answered with MPI_Cart_shift:

```
call MPI_CART_SHIFT( comm2d, 0,  1,
                     nbrleft, nbrright, ierr )
call MPI_CART_SHIFT( comm2d, 1,  1,
                     nbrbottom, nbrtop, ierr )
```

The values returned are the ranks, in the communicator comm2d, of the neighbors shifted by ± 1 in the two dimensions.

Who am I?

Can be answered with

```
  integer coords(2)
  call MPI_COMM_RANK( comm1d, myrank, ierr )
  call MPI_CART_COORDS( comm1d, myrank, 2,
 $                      coords, ierr )
```

Returns the Cartesian coordinates of the calling process in `coords`.

Partitioning

When creating a Cartesian topology, one question is "What is a good choice for the decomposition of the processors?"

This question can be answered with MPI_Dims_create:

```
integer dims(2)
dims(1) = 0
dims(2) = 0
call MPI_COMM_SIZE( MPI_COMM_WORLD, size, ierr )
call MPI_DIMS_CREATE( size, 2, dims, ierr )
```

Other Topology Routines

MPI contains routines to translate between Cartesian coordinates and ranks in a communicator, and to access the properties of a Cartesian topology.

The routine `MPI_Graph_create` allows the creation of a general graph topology.

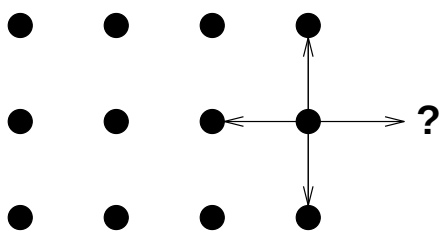
Why are these routines in MPI?

In many parallel computer interconnects, some processors are closer to than others. These routines allow the MPI implementation to provide an ordering of processes in a topology that makes logical neighbors close in the physical interconnect.

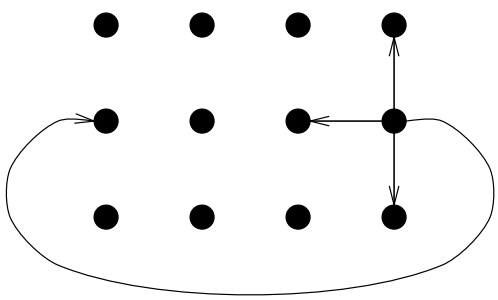
Some parallel programmers may remember hypercubes and the effort that went into assigning nodes in a mesh to processors in a hypercube through the use of Grey codes. Many new systems have different interconnects; ones with multiple paths may have notions of near neighbors that changes with time. These routines free the programmer from many of these considerations. The `reorder` *argument is used to request the best ordering.*

The periods argument

Who are my neighbors if I am at the edge of a Cartesian Mesh?



Periodic Grids



Specify this in MPI_Cart_create with

```
   dims(1)    = 4
   dims(2)    = 3
   periods(1) = .TRUE.
   periods(2) = .TRUE.
   reorder    = .true.
   ndim       = 2
   call MPI_CART_CREATE( MPI_COMM_WORLD, ndim, dims,
  $                periods, reorder, comm2d, ierr )
```

Nonperiodic Grids

In the nonperiodic case, a neighbor may not exist. This is indicated by a rank of `MPI_PROC_NULL`.

This rank *may be used* in send and receive calls in MPI. The action in both cases is as if the call was not made.

Collective Communications in MPI

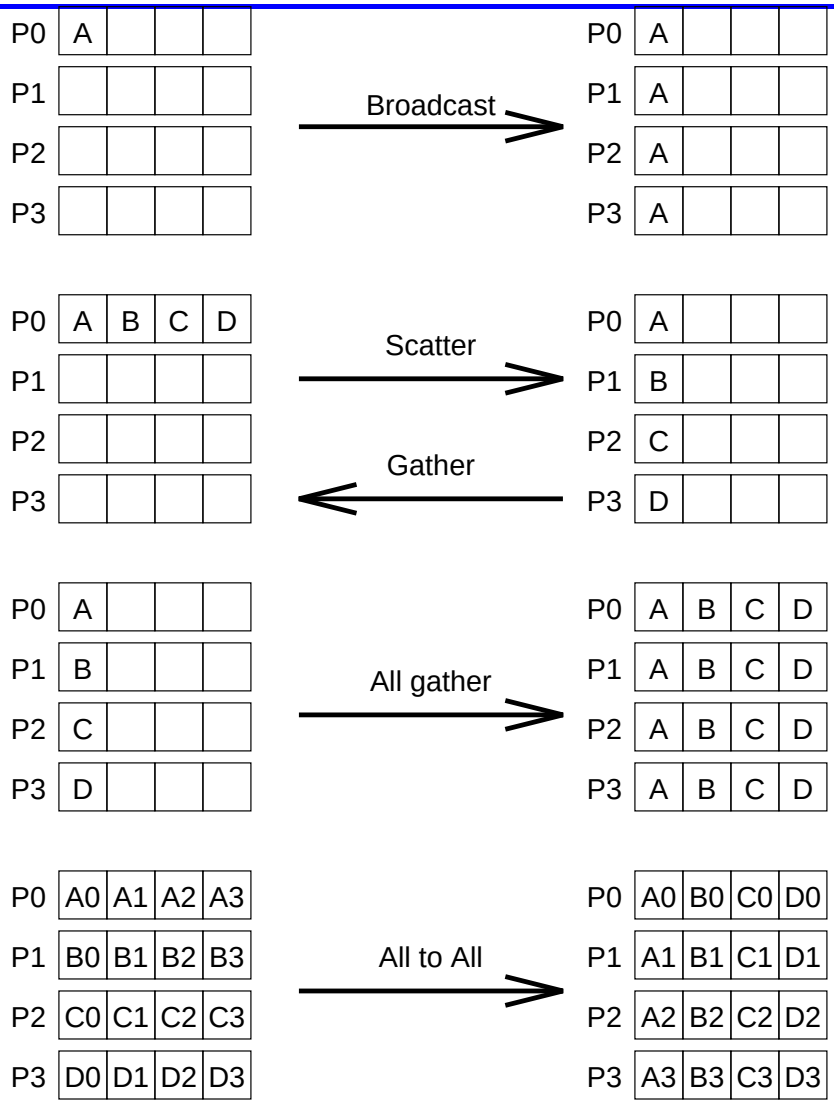
- Communication is coordinated among a group of processes.
- Groups can be constructed "by hand" with MPI group-manipulation routines or by using MPI topology-definition routines.
- Message tags are not used. Different communicators are used instead.
- No non-blocking collective operations.
- Three classes of collective operations:
  - synchronization
  - data movement
  - collective computation

Synchronization

- `MPI_Barrier(comm)`
- Function blocks untill all processes in `comm` call it.

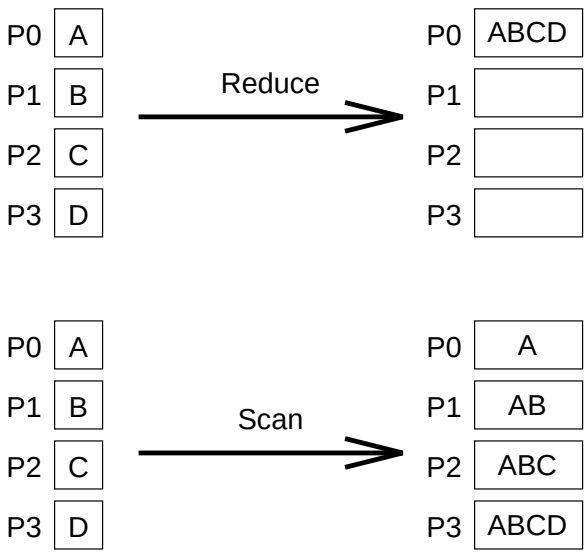
`MPI_Barrier` *does not synchronize processes in time; it simply guarentees that no process exits the barrier until all processes have entered.*

Available Collective Patterns



Schematic representation of collective data movement in MPI. (AlltoAll is a kind of "Allscatter")

Available Collective Computation Patterns



Schematic representation of collective data movement in MPI

MPI Collective Routines

- Many routines:

Allgather	Allgatherv	Allreduce
Alltoall	Alltoallv	Bcast
Gather	Gatherv	Reduce
ReduceScatter	Scan	Scatter
Scatterv		

- `All` versions deliver results to all participating processes.

- `V` versions allow the chunks to have different sizes.

- Allreduce, Reduce, ReduceScatter, and Scan take both built-in and user-defined combination functions.

Built-in Collective Computation Operations

MPI Name	Operation
MPI_MAX	Maximum
MPI_MIN	Minimum
MPI_PROD	Product
MPI_SUM	Sum
MPI_LAND	Logical and
MPI_LOR	Logical or
MPI_LXOR	Logical exclusive or (xor)
MPI_BAND	Bitwise and
MPI_BOR	Bitwise or
MPI_BXOR	Bitwise xor
MPI_MAXLOC	Maximum value and location
MPI_MINLOC	Minimum value and location

Defining Your Own Collective Operations

```
MPI_Op_create(user_function, commute, op)
MPI_Op_free(op)

user_function(invec, inoutvec, len, datatype)
```

The user function should perform

```
inoutvec[i] = invec[i] op inoutvec[i];
```

for `i` from `0` to `len-1`.

`user_function` can be non-commutative (e.g., matrix multiply).

Sample user function

For example, to create an operation that has the same effect as MPI_SUM on Fortran double precision values, use

```
subroutine myfunc( invec, inoutvec, len, datatype )
   integer len, datatype
   double precision invec(len), inoutvec(len)
   integer i
   do 10 i=1,len
10   inoutvec(i) = invec(i) + inoutvec(i)
   return
   end
```

To use, just

```
integer myop
call MPI_Op_create( myfunc, .true., myop, ierr )
call MPI_Reduce( a, b, 1, MPI_DOUBLE_PRECISON, myop,
                 comm, ierr )
```

The routine MPI_Op_free destroys user-functions when they are no longer needed.

Defining groups and communicators

All MPI communication is relative to a *communicator* which contains a *context* and a *group*. The group is just a set of processes.

When an MPI job starts, all processes are in `MPI_COMM_WORLD`, numbered from `0` to `n-1`.

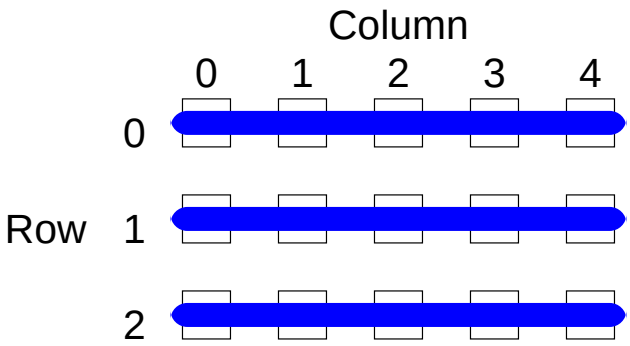
All groups (and communicators) are formed relative to an existing group (or communicator). `MPI_COMM_WORLD` is the starting point.

Since most MPI routines require communicators, there are several routines to build a communicator and its group together.

Subdividing a communicator

The easiest way to create communicators with new groups is with MPI_COMM_SPLIT.

For example, to form groups represeting rows of processes



use

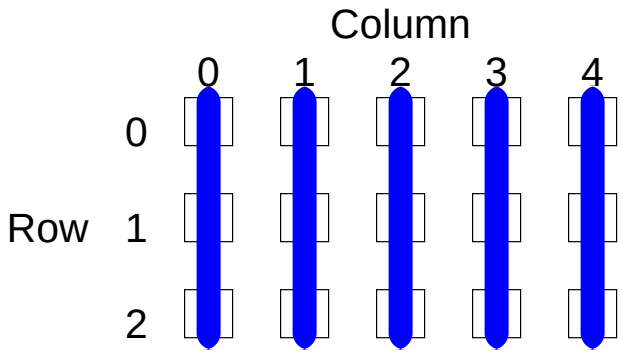
```
MPI_Comm_size( oldcomm, &size );
row = size / 3;
MPI_Comm_split( oldcomm, row, 0, &newcomm );
```

To maintain the order by rank, use

```
MPI_Comm_rank( oldcomm, &rank );
MPI_Comm_split( oldcomm, row, rank, &newcomm );
```

Subdividing (con't)

Similarly, to form groups of columns,



use

```
MPI_Comm_size( oldcomm, &size );
column = size % 5;
MPI_Comm_split( oldcomm, column, 0, &newcomm2 );
```

To maintain the order by rank, use

```
MPI_Comm_rank( oldcomm, &rank );
MPI_Comm_split( oldcomm, column, rank, &newcomm2 );
```

Exercise: what does

```
MPI_Comm_rank( oldcomm, &rank );
MPI_Comm_size( oldcomm, &size );
MPI_Comm_split( oldcomm, 0, size - rank, &newcomm3 );
```

do?

Destroying communicators

When a communicator is no longer needed, it should be removed with

```
MPI_Comm_free( &oldcomm );
```

The number of available communicators is implementation defined; most provide at least a few thousand.

Exercise: Collective operations

Write a program to divide the processes into groups of rows and columns. In each communicator, form

1. The sum of the ranks in `MPI_COMM_WORLD` of the members of the communicator
2. The partial sum of the ranks
3. The rank of the process with the largest rank in the new communicator, using the `MPI_MAXLOC` operator

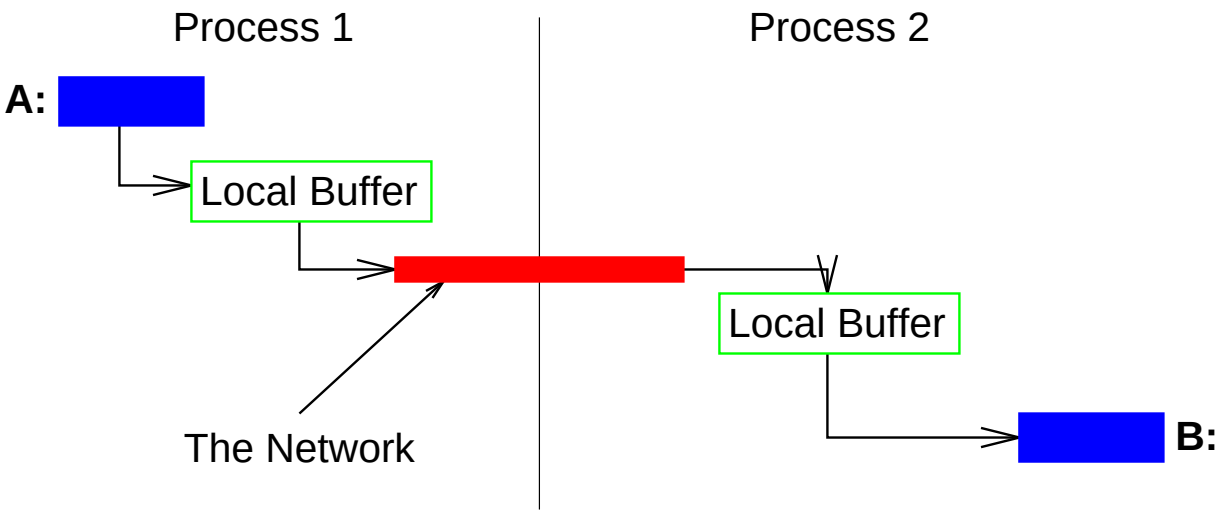
Correctness and Performance in Message Passing

The simple message passing model ignores some of the real-world limitations of any computing system, particularly those of processor memory. MPI makes it possible to understand and program in a way that recognizes these limitations.

Since understanding (and limiting) memory operations are critical to performance of any application, the same concepts that provide correctness on systems with finite memory also can be used for better performance.

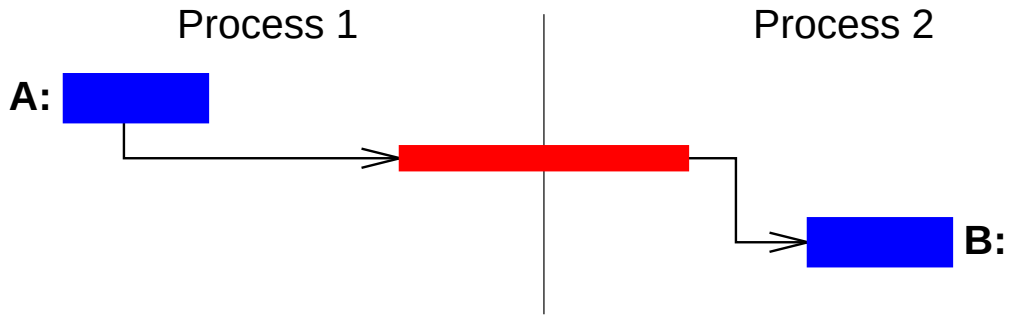
Buffering issues

Where does data go when you send it? One possibility is:



Better buffering

This is not very efficient. There are three copies in addition to the exchange of data between processes. We prefer



But this requires that either that `MPI_Send` not return until the data has been delivered *or* that we allow a send operation to return before completing the transfer. In this case, we need to test for completion later.

Blocking and Non-Blocking communication

- So far we have used **blocking** communication:
  - `MPI_Send` does not complete until buffer is empty (available for reuse).
  - `MPI_Recv` does not complete until buffer is full (available for use).

- This is simple, but can be "unsafe":

Process 0	Process 1
Send(1)	Send(0)
Recv(1)	Recv(0)

  Completion depends in general on size of message and amount of system buffering.

Send works for small enough messages but fails when messages get too large. Too large ranges from zero bytes to 100's of Megabytes, depending on the MPI implementation. Further, even if it does work, it (usually) copies, thus robbing performance.

Some Solutions to the "Unsafe" Problem

- Order the operations more carefully:

Process 0	Process 1
Send(1)	Recv(0)
Recv(1)	Send(0)

  This is hard to do in general. MPI offers 2.5 alternatives:

- Supply receive buffer at same time as send, with `MPI_Sendrecv`:

Process 0	Process 1
Sendrecv(1)	Sendrecv(0)

  Only useful in (important) special cases.

- Use non-blocking operations:

Process 0	Process 1
Isend(1)	Isend(0)
Irecv(1)	Irecv(0)
Waitall	Waitall

  This is the general solution.

- Use `MPI_Bsend`

  This is the solution of last resort.

MPI's Non-Blocking Operations

Non-blocking operations return (immediately) "request handles" that can be waited on and queried:

- `MPI_Isend(start, count, datatype, dest, tag, comm, &request)`
- `MPI_Irecv(start, count, datatype, dest, tag, comm, &request)`
- `MPI_Wait(&request, status)`

One can also test without waiting:
`MPI_Test( &request, flag, status)`

Nonblocking operations are important for *correctness*, not just for performance.

Multiple completions

It is often desirable to wait on multiple requests. An example is a master/slave program, where the master waits for one or more slaves to send it a message.

- `MPI_Waitall(count, array_of_requests, array_of_statuses)`
- `MPI_Waitany(count, array_of_requests, index, status)`
- `MPI_Waitsome(incount, array_of_requests, outcount, array_of_indices, array_of_statuses)`

There are corresponding versions of test for each of these.

The `MPI_WAITSOME` *and* `MPI_TESTSOME` *may be used to implement master/slave algorithms that provide fair access to the master by the slaves.*

Performance Issues

What are the performance issues?

To get the best performance, memory copies must be avoided. The nonblocking operations give the system the best opportunity to minimize memory copies. On a shared-memory system, in principle, a single copy from user send buffer to user receive buffer is all that is required. Often, shared memory applications would do this anyway to place data in local cache.

The nonblocking operations also all communication with computation to *overlap*, but few systems can provide this (they are often already memory-bandwidth limited).

Fairness

What happens with this program:

```
#include "mpi.h"
#include <stdio.h>
int main(argc, argv)
int argc;
char **argv;
{
int rank, size, i, buf[1];
MPI_Status status;

MPI_Init( &argc, &argv );
MPI_Comm_rank( MPI_COMM_WORLD, &rank );
MPI_Comm_size( MPI_COMM_WORLD, &size );
if (rank == 0) {
    for (i=0; i<100*(size-1); i++) {
        MPI_Recv( buf, 1, MPI_INT, MPI_ANY_SOURCE,
                  MPI_ANY_TAG, MPI_COMM_WORLD, &status );
        printf( "Msg from %d with tag %d\n",
                status.MPI_SOURCE, status.MPI_TAG );
        }
    }
else {
    for (i=0; i<100; i++)
        MPI_Send( buf, 1, MPI_INT, 0, i, MPI_COMM_WORLD );
    }
MPI_Finalize();
return 0;
}
```

Fairness in message-passing

A parallel algorithm is *fair* if no process is effectively ignored. In the preceeding program, processes with low rank (like process zero) may be the only one whose messages are received.

MPI makes no guarentees about fairness. However, MPI makes it possible to write efficient, fair programs.

Providing Fairness

One alternative is

```
#define large 128
MPI_Request requests[large];
MPI_Status  statuses[large];
int         indices[large];
int         buf[large];
for (i=1; i<size; i++)
    MPI_Irecv( buf+i, 1, MPI_INT, i,
               MPI_ANY_TAG, MPI_COMM_WORLD, &requests[i-1] );
while(not done) {
    MPI_Waitsome( size-1, requests, &ndone, indices, statuses );
    for (i=0; i<ndone; i++) {
        j = indices[i];
        printf( "Msg from %d with tag %d\n",
                statuses[i].MPI_SOURCE,
                statuses[i].MPI_TAG );
        MPI_Irecv( buf+j, 1, MPI_INT, j,
                   MPI_ANY_TAG, MPI_COMM_WORLD, &requests[j] );
        }
    }
```

Providing Fairness (Fortran)

One alternative is

```
   parameter( large = 128 )
   integer requests(large);
   integer statuses(MPI_STATUS_SIZE,large);
   integer indices(large);
   integer buf(large);
   logical done
   do 10 i = 1,size-1
10 call MPI_Irecv( buf(i), 1, MPI_INTEGER, i,
  *            MPI_ANY_TAG, MPI_COMM_WORLD, requests(i), ierr )
20 if (.not. done) then
    call MPI_Waitsome( size-1, requests, ndone,
                       indices, statuses, ierr )
    do 30 i=1, ndone
        j = indices(i)
        print *, 'Msg from ', statuses(MPI_SOURCE,i), ' with tag',
     *               statuses(MPI_TAG,i)
        call MPI_Irecv( buf(j), 1, MPI_INTEGER, j,
                    MPI_ANY_TAG, MPI_COMM_WORLD, requests(j), ierr )
        done = ...
30  continue
    goto 20
    endif
```

Exercise - Fairness

Objective: Use nonblocking communications

Complete the program fragment on "providing fairness". Make sure that you leave no uncompleted requests. How would you test your program?

More on nonblocking communication

In applications where the time to send data between processes is large, it is often helpful to cause communication and computation to overlap. This can easily be done with MPI's non-blocking routines. More importantly, these routines allow the system to separate data transfer from synchronization, permitting data to be delivered in an optimal order.

For example, in a 2-D finite difference mesh, moving data needed for the boundaries can be done at the same time as computation on the interior.

```
MPI_Irecv( ... each ghost edge ... );
MPI_Isend( ... data for each ghost edge ... );
... compute on interior
while (still some uncompleted requests) {
    MPI_Waitany( ... requests ... )
    if (request is a receive)
        ... compute on that edge ...
    }
```

Note that we call MPI_Waitany several times. This exploits the fact that after a request is satisfied, it is set to MPI_REQUEST_NULL, and that this is a valid request object to the wait and test routines.

Communication Modes

MPI provides mulitple *modes* for sending messages:

- Synchronous mode (`MPI_Ssend`): the send does not complete until a matching receive has begun. (Unsafe programs become incorrect and usually deadlock within an `MPI_Ssend`.)
- Buffered mode (`MPI_Bsend`): the user supplies the buffer to system for its use. (User supplies enough memory to make unsafe program safe).
- Ready mode (`MPI_Rsend`): user guarantees that matching receive has been posted.
  - allows access to fast protocols
  - undefined behavior if the matching receive is not posted

Non-blocking versions:
`MPI_Issend`, `MPI_Irsend`, `MPI_Ibsend`

Note that an `MPI_Recv` may receive messages sent with *any* send mode.

Buffered Send

MPI provides a send routine that may be used when MPI_Isend is awkward to use (e.g., lots of small messages).

MPI_Bsend makes use of a *user-provided* buffer to save any messages that can not be immediately sent.

```
int  bufsize;
char *buf = malloc(bufsize);
MPI_Buffer_attach( buf, bufsize );
...
MPI_Bsend( ... same as MPI_Send ... );
...
MPI_Buffer_detach( &buf, &bufsize );
```

The MPI_Buffer_detach call does not complete until all messages are sent (e.g., buf may be reused).

The performance of MPI_Bsend depends on the implementation of MPI and may also depend on the size of the message. For example, making a message one byte longer may cause a significant drop in performance.

Reusing the same buffer

Consider a loop

```
MPI_Buffer_attach( buf, bufsize );
while (!done) {
    ...
    MPI_Bsend( ... );
    }
```

where the `buf` is large enough to hold the message in the `MPI_Bsend`. This code may *fail* because the buffer may not have been sent by the first `MPI_Bsend` when the second is called. To flush the `MPI_Bsend` buffer (force all messages to be delivered), you can do this:

```
{
void *buf; int bufsize;
MPI_Buffer_detach( &buf, &bufsize );
MPI_Buffer_attach( buf, bufsize );
}
```

This isn't possible in Fortran 77 because there are no pointers.

Message Passing and Shared Memory

The shared memory programming model is often described as easier to use that message passing. While this is true in some cases, there are some subtle issues with shared memory that are often overlooked. These include

- Is the memory coherent?
- Is the memory/CPU sequentially consistent?
- What are the performance issues of "nearby" data (i.e., false sharing on cache lines)?
- Are reads/write atomic?
- How general are synchronization mechanisms?

MPI2: Remote memory operations (put and get) are expected. Special commands that address the issues described above are included.

Datatypes and Heterogenity

MPI datatypes have two main purposes

- Heterogenity — parallel programs between different processors
- Noncontiguous data — structures, vectors with non-unit stride, etc.

Basic datatypes, corresponding to the underlying language, are predefined.

The user can construct new datatypes at run time; these are called *derived datatypes*.

Datatypes in MPI

Elementary: Language-defined types (e.g., `MPI_INT` or `MPI_DOUBLE_PRECISION`)

Vector: Separated by constant "stride"

Contiguous: Vector with stride of one

Hvector: Vector, with stride in bytes

Indexed: Array of indices (for scatter/gather)

Hindexed: Indexed, with indices in bytes

Struct: General mixed types (for C structs etc.)

Basic Datatypes (Fortran)

MPI datatype	Fortran datatype
MPI_INTEGER	INTEGER
MPI_REAL	REAL
MPI_DOUBLE_PRECISION	DOUBLE PRECISION
MPI_COMPLEX	COMPLEX
MPI_LOGICAL	LOGICAL
MPI_CHARACTER	CHARACTER(1)
MPI_BYTE	
MPI_PACKED	

Basic Datatypes (C)

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

Vectors

Consider the block of memory

29	30	31	32	33	34	35
22	23	24	25	26	27	28
15	16	17	18	19	20	21
8	9	10	11	12	13	14
1	2	3	4	5	6	7

To specify this column (in C order), we can use

```
MPI_Type_vector( count, blocklen, stride, oldtype,
                 &newtype );
MPI_Type_commit( &newtype );
```

The exact code for this is

```
MPI_Type_vector( 5, 1, 7, MPI_DOUBLE, &newtype );
MPI_Type_commit( &newtype );
```

Read this as "newtype is a vector that contains 5 blocks, each of 1 `double`, with a stride of 7 doubles between blocks."

Structures

Structures are described by arrays of

- number of elements (`array_of_len`)
- displacement or location (`array_of_displs`)
- datatype (`array_of_types`)

```
MPI_Type_structure( count, array_of_len,
                           array_of_displs,
                           array_of_types, &newtype );
```

Example: Structures

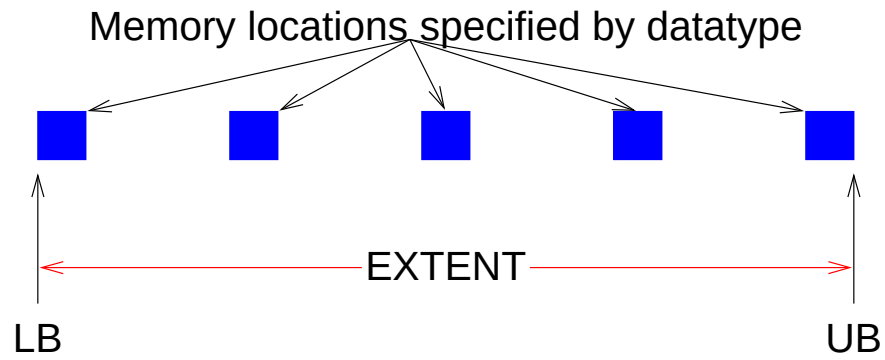
```
struct {
    char      display[50];   /* Name of display */
    int       maxiter;       /* max # of iterations */
    double    xmin, ymin;    /* lower left corner of rectangle */
    double    xmax, ymax;    /* upper right corner */
    int       width;         /* of display in pixels */
    int       height;        /* of display in pixels */
} cmdline;

/* set up 4 blocks */
int           blockcounts[4] = {50,1,4,2};
MPI_Datatype  types[4];
MPI_Aint      displs[4];
MPI_Datatype  cmdtype;

/* initialize types and displs with addresses of items */
MPI_Address( &cmdline.display, &displs[0] );
MPI_Address( &cmdline.maxiter, &displs[1] );
MPI_Address( &cmdline.xmin,    &displs[2] );
MPI_Address( &cmdline.width,   &displs[3] );
types[0] = MPI_CHAR;
types[1] = MPI_INT;
types[2] = MPI_DOUBLE;
types[3] = MPI_INT;
for (i = 3; i >= 0; i--)
    displs[i] -= displs[0];
MPI_Type_struct( 4, blockcounts, displs, types, &cmdtype );
MPI_Type_commit( &cmdtype );
```

Strides

The extent of a datatype is (normally) the distance between the first and last member.



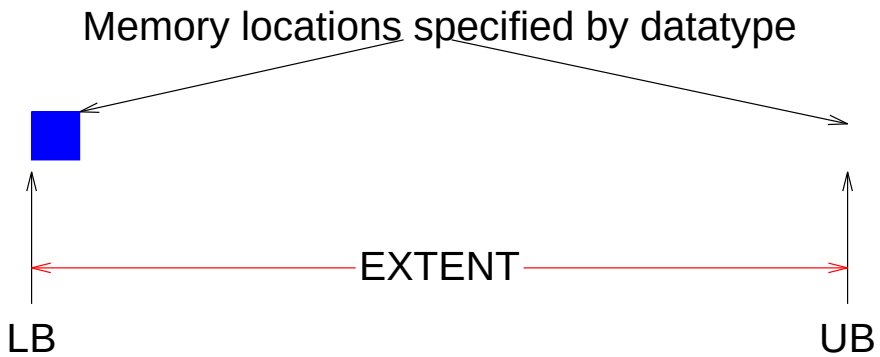
You can set an artificial extent by using `MPI_UB` (for Upper Bound) and `MPI_LB` (Lower Bound) in `MPI_Type_struct`.

Using MPI_LB: Vectors revisited

This code creates a datatype for an arbitrary number of element in a row of an array stored in Fortran order (column first).

```
int blens[2], displs[2];
MPI_Datatype types[2], rowtype;
blens[0]  = 1;
blens[1]  = 1;
displs[0] = 0;
displs[1] = number_in_column * sizeof(double);
types[0]  = MPI_DOUBLE;
types[1]  = MPI_UB;
MPI_Type_struct( 2, blens, displs, types, &rowtype );
MPI_Type_commit( &rowtype );
```

This datatype looks like



To send n elements, you can use

```
MPI_Send( buf, n, rowtype, ... );
```

Structures revisited

When sending an array of a structure, it is important to ensure that MPI and the C compiler have the same value for the size of each structure. The most portable way to do this is to add an MPI_UB to the structure definition for the end of the structure. In the previous example, this is

```
/* initialize types and displs with addresses of items */
MPI_Address( &cmdline.display, &displs[0] );
MPI_Address( &cmdline.maxiter, &displs[1] );
MPI_Address( &cmdline.xmin,    &displs[2] );
MPI_Address( &cmdline.width,   &displs[3] );
MPI_Address( &cmdline+1,       &displs[4] );
types[0] = MPI_CHAR;
types[1] = MPI_INT;
types[2] = MPI_DOUBLE;
types[3] = MPI_INT;
types[4] = MPI_UB;
for (i = 4; i >= 0; i--)
    displs[i] -= displs[0];
MPI_Type_struct( 5, blockcounts, displs, types, &cmdtype );
MPI_Type_commit( &cmdtype );
```

Interleaving data

By moving the UB inside the data, you can interleave data.

Consider the matrix (# indicates memory locations)

0	8	16	24	32
1	9	17	25	33
2	10	18	26	34
3	11	19	27	35
4	12	20	28	36
5	13	21	29	37
6	14	22	30	38
7	15	23	31	39

We wish to send 0-3,8-11,16-19, and 24-27 to process 0, 4-7,12-15,20-23, and 28-31 to process 1, etc. How can we do this?

This is a scatter operation; we'll use `MPI_Scatterv` (`MPI_Scatter` with more general arguments).

An interleaved datatype

```
MPI_Type_vector( 4, 4, 8, MPI_DOUBLE, &vec );
```

defines a block of this matrix.

Execise: Write a sentance like that used to describe the vector type on the slide introducing vectors for this call.

```
blens[0]  = 1;   blens[1] = 1;
types[0]  = vec; types[1] = MPI_UB;
displs[0] = 0;   displs[1] = sizeof(double);
MPI_Type_struct( 2, blens, displs, types, &block );
```

defines a block whose extent is just 1 double.

Scattering a Matrix

We set the displacements for each block as the location of the first element in the block. This works because MPI_Scatterv uses the extents to determine the start of each piece to send.

```
scdispls[0] = 0;   sendcounts[0] = 1;
scdispls[1] = 4;   sendcounts[1] = 1;
scdispls[2] = 32;  sendcounts[2] = 1;
scdispls[3] = 36;  sendcounts[3] = 1;
MPI_Scatterv( sendbuf, sendcounts, scdispls, block,
              recvbuf, 4 * 4, MPI_DOUBLE, 0,
               MPI_COMM_WORLD );
```

The scdispls[i] are just the number of doubles from the first block to the beginning of the i^{th} block.

Exercise: Can you do this by putting the UB after the first four doubles? What are the values of scdispls then?

How would use use the topology routines to make this more general?

Exercises on datatypes

Objective: Learn about datatypes

1. Write a program to send rows of a matrix (stored in column-major form) to the other processors.

   Let processor 0 have the entire matrix, which has as many rows as processors.

   Processor 0 sends row i to processor i. Processor i reads that row into a local array that holds only that row. That is, processor 0 has a matrix $A(N, M)$ while the other processors have a row $B(M)$.

   (a) Write the program to handle the case where the matrix is square.

   (b) Write the program to handle a number of columns read from the terminal.

   C programmers may send columns of a matrix stored in row-major form if they prefer.

Exercises on datatypes - 2

If you have time, try one of the following. If you don't have time, think about how you would program these.

1. Write a program to transpose a matrix, where each processor has a part of the matrix. Use topologies to define a 2-Dimensional partitioning of the matrix across the processors, and assume that all processors have the same size submatrix.

   (a) Use `MPI_Send` and `MPI_Recv` to send the block, the transpose the block.

   (b) Use `MPI_Sendrecv` instead.

   (c) Create a datatype that allows you to receive the block already transposed.

2. Transpose a matrix, but in this case, each processor has all of the columns for a block of rows. For example, for four processes and a 16×16 matrix, let process i have rows $i * 4 + 1$ to $(i + 1) * 4$. Use `MPI_Alltoallv` to perform the communications.

Exercises on datatypes - 3

1. Write a program to send the "ghostpoints" of a 2-Dimensional mesh to the neighboring processors. Assume that each processor has the same size subblock.

   (a) Use topologies to find the neighbors

   (b) Define a datatype for the "rows"

   (c) Use `MPI_Sendrecv` or `MPI_IRecv` and `MPI_Send` with `MPI_Waitall`.

   (d) Use `MPI_Isend` and `MPI_Irecv` to start the communication, do some computation on the interior, and then use `MPI_Waitany` to process the boundaries as they arrive

   The same approach works for general datastructures, such as unstructured meshes.

2. Do 3, but for 3-Dimensional meshes. You will need `MPI_Type_Hvector`.

Tools for writing libraries

MPI is specifically designed to make it easier to write message-passing libraries

- Communicators solve tag/source wild-card problem
- Attributes provide a way to attach information to a communicator

Private communicators

One of the first thing that a library should normally do is create private communicator. This allows the library to send and receive messages that are known only to the library.

The call

```
MPI_Comm_dup( old_comm, &new_comm );
```

creates a new communicator `new_comm` that contains all the processes in `old_comm`. Messages sent in `new_comm` may only be received by routines that use `new_comm` as their communicator.

Attributes

Attributes are data that can be attached to one or more communicators.

Attributes are referenced by *keyval*. Keyvals are created with `MPI_KEYVAL_CREATE`.

Attributes are attached to a communicator with `MPI_Attr_put` and their values accessed by `MPI_Attr_get`.

Operations are defined for what happens to an attribute when it is copied (by creating one communicator from another) or deleted (by deleting a communicator) when the keyval *is created.*

What is an attribute?

In C, an attribute is a pointer of type `void *`. You must allocate storage for the attribute to point to (make sure that you don't use the address of a local variable).

In Fortran, it is a single `INTEGER`.

MPI defines four attributes

MPI_TAG_UB Largest allowed tag. Must be at least 32767.

MPI_HOST Rank in `MPI_COMM_WORLD` of "host" process, or `MPI_PROC_NULL`

MPI_IO Rank of process that can perform I/O. `MPI_ANY_SOURCE` if all can; `MPI_PROC_NULL` if none can.

MPI_WTIME_IS_GLOBAL `1` if `MPI_Wtime` values are synchronized across `MPI_COMM_WORLD`, `0` otherwise.

Getting the basic attributes

For example, to determine if MPI_Wtime is synchronized, use

```
int flag;
int *v;
MPI_Attr_get( MPI_COMM_WORLD,
              MPI_WTIME_IS_GLOBAL,
              &v, &flag );
if (flag && *v) {
    printf( "Wtime is global\n" );
}
```

Note that the value returned is a *pointer*, not the value. This makes it easy to attach structures (by their address) to an attribute.

In Fortran, the value itself is returned (no pointers).

Examples of using attributes

- Forcing sequential operation
- Managing tags

Sequential Sections

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

static int MPE_Seq_keyval = MPI_KEYVAL_INVALID;

/*@
   MPE_Seq_begin - Begins a sequential section of code.

   Input Parameters:
.  comm - Communicator to sequentialize.
.  ng   - Number in group.  This many processes are allowed
   to execute at the same time.  Usually one.

@*/
void MPE_Seq_begin( comm, ng )
MPI_Comm comm;
int      ng;
{
int        lidx, np;
int        flag;
MPI_Comm   local_comm;
MPI_Status status;

/* Get the private communicator for the
   sequential operations */
if (MPE_Seq_keyval == MPI_KEYVAL_INVALID) {
    MPI_Keyval_create( MPI_NULL_COPY_FN,
                       MPI_NULL_DELETE_FN,
                       &MPE_Seq_keyval, NULL );
    }
```

Sequential Sections II

```
MPI_Attr_get( comm, MPE_Seq_keyval, (void *)&local_comm,
              &flag );
if (!flag) {
    /* This expects a communicator to be a pointer */
    MPI_Comm_dup( comm, &local_comm );
    MPI_Attr_put( comm, MPE_Seq_keyval,
                  (void *)local_comm );
    }
MPI_Comm_rank( comm, &lidx );
MPI_Comm_size( comm, &np );
if (lidx != 0) {
    MPI_Recv( NULL, 0, MPI_INT, lidx-1, 0, local_comm,
              &status );
    }
/* Send to the next process in the group unless we
   are the last process in the processor set */
if ( (lidx % ng) < ng - 1 && lidx != np - 1) {
    MPI_Send( NULL, 0, MPI_INT, lidx + 1, 0, local_comm );
    }
}
```

Sequential Sections III

```
/*@
   MPE_Seq_end - Ends a sequential section of code.
   Input Parameters:
.  comm - Communicator to sequentialize.
.  ng   - Number in group.
@*/
void MPE_Seq_end( comm, ng )
MPI_Comm comm;
int      ng;
{
int        lidx, np, flag;
MPI_Status status;
MPI_Comm   local_comm;

MPI_Comm_rank( comm, &lidx );
MPI_Comm_size( comm, &np );
MPI_Attr_get( comm, MPE_Seq_keyval, (void *)&local_comm,
              &flag );
if (!flag)
    MPI_Abort( comm, MPI_ERR_UNKNOWN );
/* Send to the first process in the next group OR to the
   first process in the processor set */
if ( (lidx % ng) == ng - 1 || lidx == np - 1) {
    MPI_Send( NULL, 0, MPI_INT, (lidx + 1) % np, 0,
              local_comm );
    }
if (lidx == 0) {
    MPI_Recv( NULL, 0, MPI_INT, np-1, 0, local_comm,
              &status );
    }
}
```

Comments on sequential sections

- Note use of `MPI_KEYVAL_INVALID` to determine to create a keyval
- Note use of flag on `MPI_Attr_get` to discover that a communicator has no attribute for the keyval

Example: Managing tags

Problem: A library contains many objects that need to communicate in ways that are not known until runtime.

Messages between objects are kept separate by using different message tags. How are these tags chosen?

- Unsafe to use compile time values
- Must allocate tag values at runtime

Solution:
Use a private communicator and use an attribute to keep track of available tags in that communicator.

Caching tags on communicator

```
#include "mpi.h"

static int MPE_Tag_keyval = MPI_KEYVAL_INVALID;

/*
   Private routine to delete internal storage when a
   communicator is freed.

   MPI 1.0 required int *keyval.
 */
int MPE_DelTag( comm, keyval, attr_val, extra_state )
MPI_Comm *comm;
int      keyval;
void     *attr_val, *extra_state;
{
free( attr_val );
return MPI_SUCCESS;
}
```

Caching tags on communicator II

```
/*@
  MPE_GetTags - Returns tags that can be used in
communication with a
  communicator

  Input Parameters:
. comm_in - Input communicator
. ntags   - Number of tags

  Output Parameters:
. comm_out - Output communicator.  May be 'comm_in'.
. first_tag - First tag available
@*/
int MPE_GetTags( comm_in, ntags, comm_out, first_tag )
MPI_Comm comm_in, *comm_out;
int      ntags, *first_tag;
{
int mpe_errno = MPI_SUCCESS;
int tagval, *tagvalp, *maxval, flag;

if (MPE_Tag_keyval == MPI_KEYVAL_INVALID) {
    MPI_Keyval_create( MPI_NULL_COPY_FN, MPE_DelTag,
                       &MPE_Tag_keyval, (void *)0 );
    }
```

Caching tags on communicator III

```
if (mpe_errno = MPI_Attr_get( comm_in, MPE_Tag_keyval,
&tagvalp, &flag ))
    return mpe_errno;

if (!flag) {
    /* This communicator is not yet known to this system,
       so we dup it and setup the first value */
    MPI_Comm_dup( comm_in, comm_out );
    comm_in = *comm_out;
    MPI_Attr_get( MPI_COMM_WORLD, MPI_TAG_UB, &maxval,
                  &flag );
    tagvalp = (int *)malloc( 2 * sizeof(int) );
    printf( "Mallocing address %x\n", tagvalp );
    if (!tagvalp) return MPI_ERR_EXHAUSTED;
    tagvalp = *maxval;
    MPI_Attr_put( comm_in, MPE_Tag_keyval, tagvalp );
    return MPI_SUCCESS;
    }
```

Caching tags on communicator IV

```
*comm_out = comm_in;
if (*tagvalp < ntags) {
    /* Error, out of tags.  Another solution would be to do
       an MPI_Comm_dup. */
    return MPI_ERR_INTERN;
    }
*first_tag = *tagvalp - ntags;
*tagvalp   = *first_tag;

return MPI_SUCCESS;
}
```

Caching tags on communicator V

```
/*@
  MPE_ReturnTags - Returns tags allocated with MPE_GetTags.

  Input Parameters:
. comm - Communicator to return tags to
. first_tag - First of the tags to return
. ntags - Number of tags to return.
@*/
int MPE_ReturnTags( comm, first_tag, ntags )
MPI_Comm comm;
int      first_tag, ntags;
{
int *tagvalp, flag, mpe_errno;

if (mpe_errno = MPI_Attr_get( comm, MPE_Tag_keyval,
                              &tagvalp, &flag ))
    return mpe_errno;

if (!flag) {
    /* Error, attribute does not exist in
       this communicator */
    return MPI_ERR_OTHER;
    }
if (*tagvalp == first_tag)
    *tagvalp = first_tag + ntags;

return MPI_SUCCESS;
}
```

Caching tags on communicator VI

```
/*@
  MPE_TagsEnd - Returns the private keyval.
@*/
int MPE_TagsEnd()
{
MPI_Keyval_free( &MPE_Tag_keyval );
MPE_Tag_keyval = MPI_KEYVAL_INVALID;
}
```

Commentary

- Use `MPI_KEYVAL_INVALID` to detect when keyval must be created
- Use `flag` return from `MPI_ATTR_GET` to detect when a communicator needs to be initialized

Exercise - Writing libraries

Objective: Use private communicators and attributes

Write a routine to circulate data to the next process, using a nonblocking send and receive operation.

```
void Init_pipe( comm )
void ISend_pipe( comm, bufin, len, datatype, bufout )
void Wait_pipe( comm )
```

A typical use is

```
Init_pipe( MPI_COMM_WORLD )
for (i=0; i<n; i++) {
    ISend_pipe( comm, bufin, len, datatype, bufout );
    Do_Work( bufin, len );
    Wait_pipe( comm );
    t = bufin; bufin = bufout; bufout = t;
    }
```

What happens if `Do_Work` calls MPI routines?

What do you need to do to clean up `Init_pipe`*?*

How can you use a user-defined topology to determine the next process? (Hint: see `MPI_Topo_test` *and* `MPI_Cartdim_get`*.)*

MPI Objects

MPI has a variety of objects (communicators, groups, datatypes, etc.) that can be created and destroyed. This section discusses the types of these data and how MPI manages them.

This entire chapter may be skipped by beginners.

The MPI Objects

`MPI_Request` Handle for nonblocking communication, normally freed by MPI in a test or wait, but can be freed with `MPI_Request_free`.

`MPI_Datatype` MPI datatype. Free with `MPI_Type_free`.

`MPI_Op` User-defined operation. Free with `MPI_Op_free`.

`MPI_Comm` Communicator. Free with `MPI_Comm_free`.

`MPI_Group` Group of processes. Free with `MPI_Group_free`.

`MPI_Errhandler` MPI errorhandler. Free with `MPI_Errhandler_free`.

When should objects be freed?

Consider this code

```
MPI_Type_vector( ly, 1, nx, MPI_DOUBLE, &newx1 );
MPI_Type_hvector( lz, 1, nx*ny*sizeof(double), newx1,
                  &newx );
MPI_Type_commit( &newx );
```

(This creates a datatype for one face of a 3-D decomposition.) When should `newx1` be freed?

Reference counting

MPI keeps track of the use of an MPI object, and only truely destroys it when no-one is using it. `newx1` is being used by the user (the `MPI_Type_vector` that created it) and by the `MPI_Datatype newx` that uses it.

If `newx1` is not needed after `newx` is defined, it should be freed:

```
MPI_Type_vector( ly, 1, nx, MPI_DOUBLE, &newx1 );
MPI_Type_hvector( lz, 1, nx*ny*sizeof(double), newx1,
                  &newx );
MPI_Type_free( &newx1 );
MPI_Type_commit( &newx );
```

MPI keeps track of how many active *references* there are to an MPI object.

Why reference counts

Why not just free the object?

Consider this library routine:

```
void MakeDatatype( nx, ny, ly, lz, MPI_Datatype *new )
{
MPI_Datatype newx1;
MPI_Type_vector( ly, 1, nx, MPI_DOUBLE, &newx1 );
MPI_Type_hvector( lz, 1, nx*ny*sizeof(double), newx1,
                  new );
MPI_Type_free( &newx1 );
MPI_Type_commit( new );
}
```

Without the `MPI_Type_free( &newx1 )`, it would be very awkward to later free `newx1` when `new` was freed.

Tools for evaluating programs

MPI provides some tools for evaluating the performance of parallel programs.

These are

- Timer (mentioned earlier)
- Profiling interface

The performance of any MPI implementation changes as vendors improve their product; the code starting at http://www.mcs.anl.gov/mpi/tutorial/mpiexmpl/src3/memcpy/C/main.html can be used to measure the performance of your MPI implementation.

The MPI Timer

The elapsed (wall-clock) time between two points in an MPI program can be computed using MPI_Wtime:

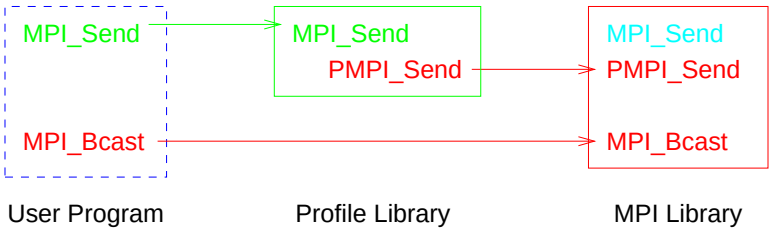
```
double t1, t2;
t1 = MPI_Wtime();
...
t2 = MPI_Wtime();
printf( "Elapsed time is %f\n", t2 - t1 );
```

The value returned by a single call to MPI_Wtime has little value.

The times are local; the attribute MPI_WTIME_IS_GLOBAL *may be used to determine if the times are* also *synchronized with each other for all processes in* MPI_COMM_WORLD.

Profiling

- All routines have two entry points: `MPI_...` and `PMPI_...`.
- This makes it easy to provide a single level of low-overhead routines to intercept MPI calls without any source code modifications.
- Used to provide "automatic" generation of trace files.




```
static int nsend = 0;
int MPI_Send( start, count, datatype, dest, tag, comm )
{
 nsend++;
 return PMPI_Send( start, count, datatype, dest, tag, comm );
}
```

Using the profiling interface

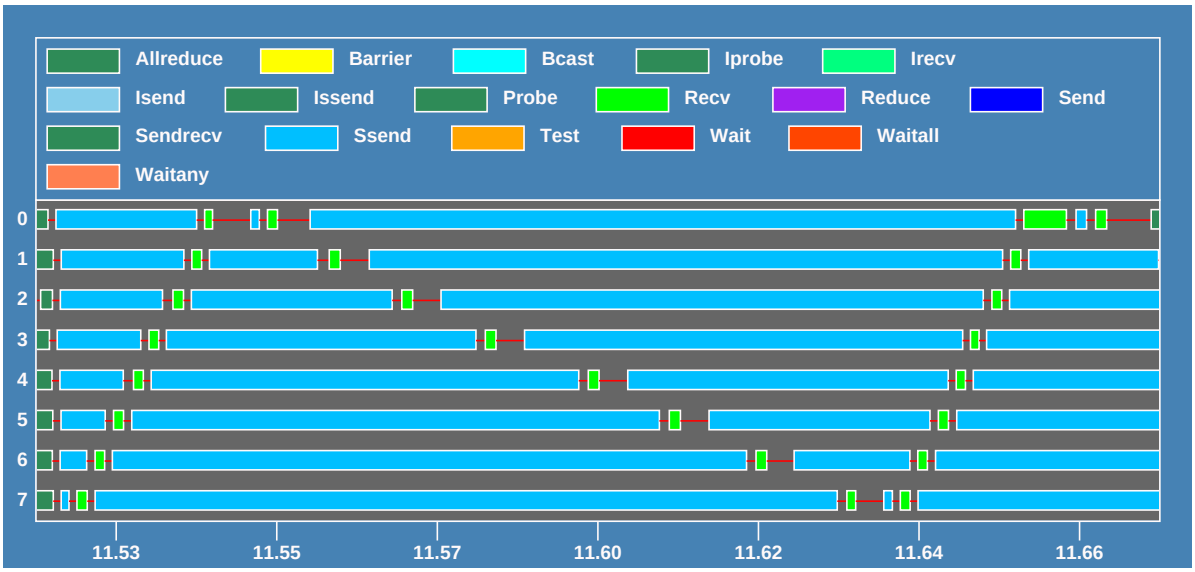
Programs that use MPI_Send can fail if they are depending on some finite buffering. A correct MPI program should run even if every use of MPI_Send is replaced by MPI_Ssend (synchronous send). How can we test a program to make sure that the uses of MPI_Send are correct?

Very easily: use the profiling interface to replace MPI_Send with PMPI_Ssend. Note that we can do this without recompiling the program!

```
int MPI_Send( start, count, datatype, dest,
              tag, comm )
{
 return PMPI_Ssend( start, count, datatype,
                    dest, tag, comm );
}
```

Generating and viewing log files

Log files that contain a history of a parallel computation can be very valuable in understanding a parallel program. The upshot and nupshot programs, provided in the MPICH implementation, may be used to view log files



Generating a log file

This is very easy with the MPICH implementation of MPI. Simply replace `-lmpi` with `-llmpi -lpmpi -lm` in the link line for your program, and relink your program. You do not need to recompile.

On some systems, you can get a real-time animation by using the libraries `-lampi -lmpe -lm -lX11 -lpmpi`.

Alternately, you can use the `-mpilog` or `-mpianim` options to the `mpicc` or `mpif77` commands.

Other MPI implementations have their own profiling tools.

Final Comments

Additional features of MPI not covered in this tutorial

- Intercommunicators
- Persistent Communication
- Error handling

MPI2: Intercommunicators become important for dynamic processes.

Sharable MPI Resources

- The Standard itself:
  - As postscript for ftp: at ftp.mcs.anl.gov in **pub/mpi/mpi-report.ps**.
  - As hypertext on the World Wide Web: http://www.mcs.anl.gov/mpi
  - As a journal article: Journal of Supercomputing Applications, Volume 8, 34 pp. 165–416.
- MPI Forum discussions
  - The MPI Forum email discussions and both current and earlier versions of the Standard are available from **netlib**.
- Books:
  - *Using MPI: Portable Parallel Programming with the Message-Passing Interface*, by Gropp, Lusk, and Skjellum, MIT Press, 1994
  - *MPI: The Complete Reference*, by Snir et al., MIT Press, 1995.
  - *Parallel Programming with MPI*, by Pacheco, Morgan Kaufmann, 1996.

Sharable MPI Resources, continued

- Newsgroup:
  - `comp.parallel.mpi`
- Mailing lists:
  - `mpi-comm@mcs.anl.gov`: the MPI Forum discussion list.
  - `mpi-impl@mcs.anl.gov`: the implementors' discussion list.
- Implementations available by `ftp`:
  - MPICH is available by anonymous `ftp` from `ftp.mcs.anl.gov` in the directory `pub/mpi/mpich`, file `mpich.tar.Z`.
  - LAM is available by anonymous `ftp` from `tbag.osc.edu` in the directory `pub/lam`.
  - Other implementations are listed at http://www.osc.edu/mpi/
- Test code repository:
  - ftp://ftp.mcs.anl.gov/pub/mpi/mpi-test

Software that uses MPI

- Parallel libraries are now available that use MPI:
  - PETSc http://www.mcs.anl.gov/petsc/petsc.html
  - ScaLAPACK http://www.netlib.org/scalapack/index.html
  - Aztec http://www.cs.sandia.gov/HPCCIT/aztec.html
  - Others listed at http://www.mcs.anl.gov/Projects/mpi/libraries.html
- Some commercial libraries, including IBM Parallel ESSL.
- Programs in structural analysis, computational biology, and weather modeling

MPI-2

- The MPI Forum (with old and new participants) has begun a follow-on series of meetings.
- Goals
  - clarify existing draft
  - provide features users have requested
  - make extensions, not changes
- Major Topics being considered
  - dynamic process management
  - client/server
  - real-time extensions
  - "one-sided" communication (put/get, active messages)
  - portable access to MPI system state (for debuggers)
  - language bindings for C++ and Fortran-90
  - Parallel I/O recently added
- Schedule
  - MPI-2 complete by May 1997

Summary

- The parallel computing community has cooperated to develop a full-featured standard message-passing library interface.
- Implementations abound
- Applications beginning to be developed or ported
- MPI-2 process beginning
- Lots of MPI material available