TECHNICAL PAPER
Parallel Computing, Vol. 20, No. 4, pp. 657-673, April 1994.

THE DESIGN OF A STANDARD MESSAGE PASSING INTERFACE FOR DISTRIBUTED MEMORY CONCURRENT COMPUTERS[1]

David W. Walker
Mathematical Sciences Section
Oak Ridge National Laboratory
P. O. Box 2008, Bldg. 6012
Oak Ridge, TN 37831-6367

[1] This work was supported in part by ARPA under contract number DAAL03-91-C-0047 administered by ARO

THE DESIGN OF A STANDARD MESSAGE PASSING INTERFACE FOR DISTRIBUTED MEMORY CONCURRENT COMPUTERS

David W. Walker

This paper presents an overview of MPI, a proposed standard message passing interface for MIMD distributed memory concurrent computers. The design of MPI has been a collective effort involving researchers in the United States and Europe from many organizations and institutions. MPI includes point-to-point and collective communication routines, as well as support for process groups, communication contexts, and application topologies. While making use of new ideas where appropriate, the MPI standard is based largely on current practice.

Key words: *Message passing, distributed memory computers, standards, point-to-point communication, collective communication, process groups, communication contexts, application topologies.*

1 Introduction

This paper gives an overview of MPI, a proposed standard message passing interface for distributed memory concurrent computers. The main advantages of establishing a message passing interface for such machines are portability and ease-of-use, and a standard message passing interface is a key component in building a concurrent computing environment in which applications, software libraries, and tools can be transparently ported between different machines. Furthermore, the definition of a message passing standard provides vendors with a clearly defined set of routines that they can implement efficiently, or in some cases provide hardware or low-level system support for, thereby enhancing scalability.

The functionality that MPI is designed to provide is based on current common practice, and is similar to that provided by widely-used message passing systems such as Express [12], NX/2 [13], Vertex, [11], PARMACS [8, 9], and P4 [10]. In addition, the flexibility and usefulness of MPI has been broadened by incorporating ideas from more recent and innovative message passing systems such as CHIMP [4, 5], Zipcode [14, 15], and the IBM External User Interface [7]. The general design philosophy followed by MPI is that while it would be imprudent to include new and untested features in the standard, concepts that have been tested in a research environment should be considered for inclusion. Many of the features in MPI related to process groups and communication contexts have been investigated within research groups for several years, but not in commercial or production environments. However, their incorporation into MPI is justified by the expressive power they bring to the standard.

The MPI standardization effort involves about 60 people from 40 organizations mainly from the United States and Europe. Most of the major vendors of concurrent computers are involved in MPI, along with researchers from universities, government laboratories, and industry. The standardization process began with the Workshop on Standards for Message Passing in a Distributed Memory Environment, sponsored by the Center for Research on Parallel Computing, held April 29-30, 1992, in Williamsburg, Virginia [16]. At this workshop the basic features essential to a standard message passing interface were discussed, and a working group established to continue the standardization process.

A preliminary draft proposal, known as MPI1, was put forward by Dongarra, Hempel, Hey, and Walker in November 1992, and a revised version was completed in February 1993 [3]. MPI1 embodies the main features that were identified at the Williamsburg workshop as being necessary in a message passing standard. This proposal was intended to initiate discussion of standardization issues within the distributed memory concurrent computing community, and has served as a basis for the subsequent MPI standardization process. Since MPI1 was primarily intended to promote discussion and "get the ball rolling," it focuses mainly on point-to-point communications. MPI1 does not include any collective communication routines. MPI1 brought to the forefront a number of important standardization issues, and has served as a catalyst for subsequent progress, however, its major deficiency is that the management of resources is not thread-safe. Although MPI1 and the MPI draft standard described in this paper have many features in common, they are distinct proposals, with MPI1 now being largely superseded by the MPI draft standard.

In November 1992, a meeting of the MPI working group was held in Minneapolis, at which it was decided to place the standardization process on a more formal footing, and to generally adopt the procedures and organization of the High Performance Fortran forum. Subcommittees were formed for the major component areas of the standard, and an email discussion service established for each. In addition, the goal of producing a draft MPI standard by the Fall of 1993 was set. To achieve this goal the MPI working group has met every 6 weeks for two days throughout the first 9 months of 1993, and it is intended to present the draft MPI standard at the Supercomputing 93 conference in November 1993. These meetings and the email discussion together constitute the MPI forum, membership of which has been open to all members of the high performance computing community.

This paper is being written at a time when MPI is still in the process of being defined, but when the main features have been agreed upon. The only major exception concerns communication between processes in different groups. Some syntactical details, and the language bindings for Fortran-77 and C, have not yet been considered in depth, and so will not be discussed here. This paper is not intended to give a definitive, or even a complete, description of MPI. While the main design features of MPI will be described, limitations on space prevent detailed justifications for why these features were adopted. For these details the reader is referred to the MPI specification document, and the archived email discussions, which are available electronically as described in Section 4.

2 An Overview of MPI

MPI is intended to be a standard message passing interface for applications running on MIMD distributed memory concurrent computers. We expect MPI also to be useful in building libraries of mathematical software for such machines. MPI is not specifically designed for use by parallelizing compilers. MPI does not contain any support for fault tolerance, and assumes reliable communications. MPI is a message passing interface, not a complete parallel computing programming environment. Thus, issues such as parallel I/O, parallel program composition, and debugging are not addressed by MPI. In addition, MPI does not provide explicit support for active messages or virtual communication channels, although extensions for such features are not precluded, and may be made in the future. Finally, MPI provides no explicit support for multithreading, although one of the design goals of MPI was to ensure that it can be implemented efficiently in a multithreaded environment.

The MPI standard does not mandate that an implementation should be interoperable with other MPI implementations. However, MPI does provide all the datatype information needed to allow a single MPI implementation to operate in a heterogeneous environment.

A set of routines that support point-to-point communication between pairs of processes forms the core of MPI. Routines for sending and receiving blocking and nonblocking messages are provided. A blocking send does not return until it is safe for the application to alter the message buffer on the sending process without corrupting or changing the message sent. A nonblocking send may return while the message buffer on the sending process is still volatile, and it should not be changed until it is guaranteed that this will not corrupt the message. This may be done by either calling a routine that blocks until the message buffer may be safely reused, or by calling a routine that performs a nonblocking check on the message status. A blocking receive suspends execution on the receiving process until the incoming message has been placed in the specified application buffer. A nonblocking receive may return before

SEND	Blocking	Nonblocking
Standard	`mpi_send`	`mpi_isend`
Ready	`mpi_rsend`	`mpi_irsend`
Synchronous	`mpi_ssend`	`mpi_issend`

RECEIVE	Blocking	Nonblocking
Standard	`mpi_recv`	`mpi_irecv`

Figure 1: Classification and names of the point-to-point send and receive routines.

the message has been received into the specified application buffer, and a subsequent call must be made to ensure that this has occurred before the application uses the data in the message.

In MPI a message may be sent in one of three communication modes. The communication mode specifies the conditions under which the sending of a message may be initiated, or when it completes. In *ready* mode a message may be sent only if a corresponding receive has been initiated. In *standard* mode a message may be sent regardless of whether a corresponding receive has been initiated. Finally, MPI includes a *synchronous* mode which is the same as the standard mode, except that the send operation will not complete until a corresponding receive has been initiated on the destination process.

There are, therefore, 6 types of send operation and 2 types of receive, as shown in Figure 1. In addition, routines are provided that send to one process while receiving from another. Different versions are provided for when the send and receive buffers are distinct, and for when they are the same. The send/receive operation is blocking, so does not return until the send buffer is ready for reuse, and the incoming message has been received. The two send/receive routines bring the total number of point-to-point message passing routines up to 10.

3 Details of MPI

In this section we discuss the MPI routines in more detail. Since the point-to-point and collective communication routines depend heavily on the approach taken to groups and contexts, and to a lesser extent on process topologies, we shall discuss groups, contexts, and topologies first. These three related areas have generated much discussion within the MPI forum, and a consensus has emerged only in the last few weeks. To some extent this difficulty in arriving at a consensus arises because different commonly-used message passing interfaces generally handle groups, contexts, and topologies differently, and offer varying levels of support. The differing requirements in these three areas within the parallel computing community have also contributed to the diversity of views.

3.1 Groups, Contexts, and Communicators

Although it is now agreed within the MPI forum that groups and contexts should be bound together into abstract communicator objects, as described in Section 3.1.3, the precise details have yet to be worked out, particularly in the case of communicators for communication between groups. Thus, in this subsection we will give an overview of groups, contexts, and communicators, without going into specific details that may subsequently change. In particular, we will not discuss communication between processes in different groups as at the time of writing the precise details are still under discussion.

3.1.1 Process Groups

The prevailing view within the MPI forum is that a process group is an ordered collection of processes, and each process is uniquely identified by its rank within the ordering. For a group of n processes the ranks run from 0 to $n-1$. This definition of groups closely conforms to current practice.

Process groups can be used in two important ways. First, they can be used to specify which processes are involved in a collective communication operation, such as a broadcast. Second, they can be used to introduce task parallelism into an application, so that different groups perform different tasks. If this is done by loading different executable codes into each group, then we refer to this as MIMD task parallelism. Alternatively, if each group executes a different conditional branch within the same executable code, then we refer to this as SPMD task parallelism (also known as control parallelism). Although MPI does not provide mechanisms for loading executable codes onto processors, nor for creating processes and assigning them to processors, each process may execute its own distinct code. However, it is expected that many initial MPI implementations will adopt a static process model, so that, as far as the application is concerned, a fixed number of processes exist from program initiation to completion, each running the same SPMD code.

Although the MPI process model is static, process groups are dynamic in the sense that they can be created and destroyed, and each process can belong to several groups simultaneously. However, the membership of a group cannot be changed asynchronously. For one or more processes to join or leave a group, a new group must be created which requires the synchronization of all processes in the group so formed. In MPI a group is an opaque object referenced by means of a handle. MPI provides routines for creating new groups by listing the ranks (within a specified parent group) of the processes making up the new group, or by partitioning an existing group using a key. The group partitioning routine is also passed an index, the size of which determines the rank of the process in the new group. This also provides a way of permuting the ranks within a group, if all processes in the group use the same value for the key, and set the index equal to the desired new rank. Additional routines give the rank of the calling process within a given group, test whether the calling process is in a given group, perform a barrier synchronization with a group, and inquire about the size and membership of a group. Other routines concerned with groups may be included in the final MPI draft.

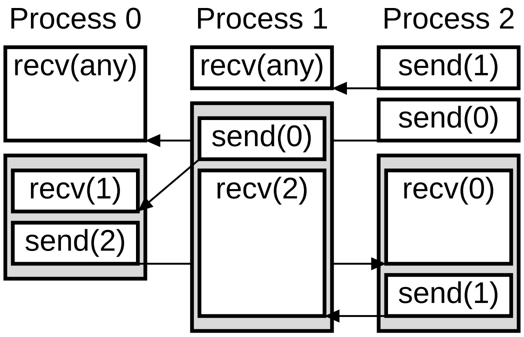


Figure 2: Use of contexts. Time increases down the page. Numbers in parentheses indicate the process to which data are being sent or received. The gray shaded area represents the library routine call. In this case the program behaves as intended. Note that the second message sent by process 2 is received by process 0, and that the message sent by process 0 is received by process 2.

3.1.2 Communication Contexts

Communication contexts, first used in the Zipcode communication system [14, 15], promote software modularity by allowing the construction of independent communication streams between processes, thereby ensuring that messages sent in one phase of an application are not incorrectly intercepted by another phase. Communication contexts are particularly important in allowing libraries that make message passing calls to be used safely within an application. The point here is that the application developer has no way of knowing if the tag, group, and rank completely disambiguate the message traffic of different libraries and the rest of the application. Context provides an additional criterion for message selection, and hence permits the construction of independent tag spaces.

If communication contexts are not used there are two ways in which a call to a library routine can lead to unintended behavior. In the first case the processes enter a library routine synchronously when a send has been initiated for which the matching receive is not posted until after the library call. In this case the message may be incorrectly received in the library routine. The second possibility arises when different processes enter a library routine asynchronously, as shown in the example in Figure 2, resulting in nondeterministic behavior. If the program behaves correctly processes 0 and 1 each receive a message from process 2, using a wildcarded selection criterion to indicate that they are prepared to receive a message from any process. The three processes then pass data around in a ring within the library routine. If communication contexts are not used this program may intermittently fail. Suppose we delay the sending of the second message sent by process 2, for example, by inserting some computation, as shown in Figure 3. In this case the wildcarded receive in process 0 is satisfied by a message sent from process 1, rather than from process 2, and deadlock results. By supplying a different communication context to the library routine we can ensure that the program is executed correctly, regardless of when the processes enter the library routine.

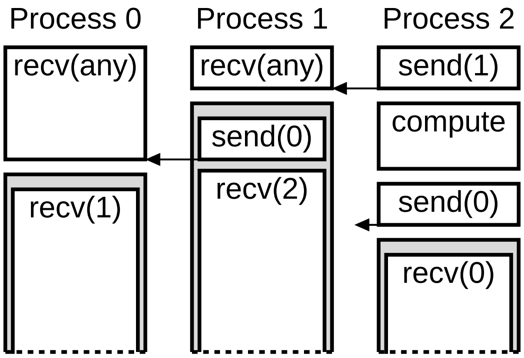


Figure 3: Unintended behavior of program. In this case the message from process 2 to process 0 is never received, and deadlock results.

3.1.3 Communicator Objects

The "scope" of a communication operation is specified by the communication context used, and the group, or groups, involved. In a collective communication, or in a point-to-point communication between members of the same group, only one group needs to be specified, and the source and destination processes are given by their rank within this group. In a point-to-point communication between processes in different groups, two groups must be specified to define the scope. In this case the source and destination processes are given by their ranks within their respective groups. In MPI abstract opaque objects called "communicators" are used to define the scope of a communication operation. In intragroup communication involving members of the same group a communicator can be regarded as binding together a context and a group. The creation of intergroup communicators for communicating between processes in different groups is still under discussion within the MPI Forum, and so will not be discussed here.

3.2 Application Topologies

In many applications the processes are arranged with a particular topology, such as a two- or three-dimensional grid. MPI provides support for general application topologies that are specified by a graph in which processes that communicate a significant amount are connected by an arc. If the application topology is an n-dimensional Cartesian grid then this generality is not needed, so as a convenience MPI provides explicit support for such topologies. For a Cartesian grid periodic or nonperiodic boundary conditions may apply in any specified grid dimension. In MPI a group either has a Cartesian or graph topology, or no topology.

In MPI, application topologies are supported by an initialization routine, MPI_GRAPH_CREATE or MPI_CART_CREATE, that specifies the topology of a given group, a function MPI_CART_RANK that determines the rank given a location in the topology associated with a group, and the inverse function MPI_CART_COORDS that determines where a process is in the topology. In addition, the routine MPI_TOPO_TEST returns the topology associated with a given group, and for a group with a Cartesian topology, the routine MPI_CARTDIM_GET gives the size and periodicity of the topology.

In addition to removing from the user the burden of having to write code to translate between process identifier, as specified by group and rank, and location in the topology, MPI also:

1. allows knowledge of the application topology to be exploited in order to efficiently assign processes to physical processors,

2. provides a routine MPI_CART_SUB for partitioning a Cartesian grid into hyperplane groups by removing a specified set of dimensions,

3. provides support for shifting data along a specified dimension of a Cartesian grid, and

By dividing a Cartesian grid into hyperplane groups it is possible to perform collective communication operations within these groups. In particular, if all but one dimension is removed a set of one-dimensional subgroups is formed, and it is possible, for example, to perform a multicast in the corresponding direction.

Support for shift operations is provided by a routine, MPI_CART_SHIFT, that returns the ranks of the processes that a process must send data to, and receive data from, when participating in the shift. Once the source and destination process are known for each process, the shift is performed by calling the routine MPI_SENDRECV that allows each process to send to one process while receiving from another. In a circular shift each process sends data to the process whose location in the given dimension is obtained by adding a specified integer (which may be negative) to its own location, modulo the number of processes in that dimension. In an end-off shift each process determines the rank of its destination process by adding a specified integer to its own rank, but if this exceeds the number of processes in the given dimension, or is less than zero, then no data are sent. If the Cartesian grid is periodic in the dimension in which the shift is done, then MPI_CART_SHIFT returns source and destination processes appropriate for a circular shift. Otherwise MPI_CART_SHIFT returns source and destination processes appropriate for an end-off shift.

3.3 Point-to-Point Communication

3.3.1 Message Selectivity

In MPI a process involved in a communication operation is identified by group and rank with that group. Thus,

$$\text{Process ID} \equiv (\text{group, rank})$$

In point-to-point communication, messages may be considered labeled by communication context and message tag within that context. Thus,

$$\text{Message ID} \equiv (\text{context, tag})$$

When sending or receiving a message the process and message identifiers must be specified. The group and context, which define the scope of the communication operation, are specified by means of a communicator object in the argument list of the send and receive routines. The rank and tag also appear in the argument list. A message sent in one scope cannot be received in a different scope, so the communicator objects specified by the send and receive routines must match. The group and context components of a communicator may not be

```
MPI_SEND (
    IN start_of_buffer
    IN number_of_items
    IN datatype_of_items
    IN destination_rank
    IN tag
    IN communicator)
```

```
MPI_RECV (
    OUT start_of_buffer
    IN max_number_of_items
    IN datatype_of_items
    IN source_rank
    IN tag
    IN communicator
    OUT return_status_object)
```

Figure 4: Argument lists for the blocking send and receive routines.

wildcarded. Within a given scope, message selectivity is by rank and tag. Either, or both, of these may be wildcarded by a receiving process to indicate that the corresponding selection criterion is to be ignored. The argument lists for the block send and receive routines are shown in Figure 4.

In Figure 4, the last argument to MPI_RECV is a handle to a return status object. This object may passed to an inquiry routine to determine the length of the message, or the actual source rank and/or message tag if wildcards have been used. The argument lists for the nonblocking send and receives are very similar, except that each returns a handle to an object that identifies the communication operation. This object is used subsequently to check for completion of the operation. In addition, the nonblocking receive does not return a return status object. Instead the return status object is returned by the routine that confirms completion of the receive operation.

3.3.2 General Datatypes

All point-to-point message passing routines in MPI take as an argument the datatype of the data communicated. In the simplest case this will be a primitive datatype, such as an integer or floating point number. However, MPI also supports more general datatypes, and thereby supports the communication of array sections and structures involving combinations of primitive datatypes.

A general datatype is a sequence of pairs of primitive datatypes and integer byte displacements. Thus,

$$\text{Datatype} = \Big\{ (\text{type}_0, \text{disp}_0),\ (\text{type}_1, \text{disp}_1), \ldots,\ (\text{type}_{n-1}, \text{disp}_{n-1}) \Big\}$$

Together with a base address, a datatype specifies a communication buffer. General datatypes are built up hierarchically from simpler components. There are four basic constructors for datatypes, namely the contiguous, vector, indexed, and structure constructors. We will now discuss each of these in turn.

The *contiguous* constructor creates a new datatype from repetitions of a specified old datatype. This requires us to specify the old datatype and the number of repetitions, n. For example, if the old datatype is `oldtype` $= \{\, (\texttt{double}, 0),\ (\texttt{char}, 8) \,\}$ and $n = 3$, then the new datatype would be,

$$\{\, (\texttt{double}, 0),\ (\texttt{char}, 8),\ (\texttt{double}, 16),\ (\texttt{char}, 24),\ (\texttt{double}, 32),\ (\texttt{char}, 40) \,\}$$

It should be noted how each repeated unit in the new datatype is aligned with a double word boundary. This alignment is dictated by the appearance of a `double` in the old datatype, so that the extent of the old datatype is taken as 16 bytes, rather than 9 bytes.

The *vector* constructor builds a new datatype by replicating an old datatype in blocks at fixed offsets. The new datatype consists of `count` blocks, each of which is a repetition of `blocklen` items of some specified old datatype. The starts of successive blocks are offset by `stride` items of the old datatype. Thus, if `count` $= 2$, `blocklen` $= 3$, and `stride` $= 4$ then the new datatype would be,

$$\begin{aligned}\{\, &(\texttt{double}, 0),\ (\texttt{char}, 8),\ (\texttt{double}, 16),\ (\texttt{char}, 24),\ (\texttt{double}, 32),\ (\texttt{char}, 40),\\ &(\texttt{double}, 64),\ (\texttt{char}, 72),\ (\texttt{double}, 80),\ (\texttt{char}, 88),\ (\texttt{double}, 96),\ (\texttt{char}, 104)\}\end{aligned}$$

Here the offset between the two blocks is 64 bytes, which is the stride multiplied by the extent of the old datatype.

The *indexed* constructor is a generalization of the vector constructor in which each block has a different size and offset. The sizes and offsets are given by the entries in two integer arrays, `B` and `I`. The new datatype consists of `count` blocks, and the ith block is of length `B[i]` items of the specified old datatype. The offset of the start of the ith block is `I[i]` items of the old datatype. Thus, if `count` $= 2$, `B` $= \{3, 1\}$, and `I` $= \{64, 0\}$, then the new datatype would be,

$$\begin{aligned}\{\, &(\texttt{double}, 64),\ (\texttt{char}, 72),\ (\texttt{double}, 80),\ (\texttt{char}, 88),\ (\texttt{double}, 96),\ (\texttt{char}, 104),\\ &(\texttt{double}, 0),\ (\texttt{char}, 8) \,\}\end{aligned}$$

The *structure* constructor is the most general of the datatype constructors. This constructor generalizes the indexed constructor by allowing each block to be of a different datatype. Thus, in addition to specifying the number of blocks, `count`, and the block length and offset arrays, `B` and `I`, we must also give the datatype of the replicated unit in each block. Let us assume this is specified in an array `T`. The length of the ith block is `B[i]`

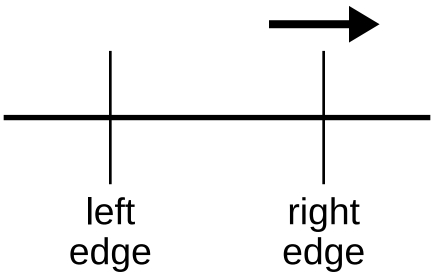


Figure 5: Particle migration in a one-dimensional code. The left and right edges of a process domain are shown. We shall consider just the migration of particles across the righthand boundary.

items of type `T[i]`, and the offset of the start of the ith block is `I[i]` bytes. Thus, if `count=3`, `T` = {`MPI_FLOAT`, `oldtype`, `MPI_CHAR`}, `I` = $\{0, 16, 26\}$, and `B` = $\{2, 1, 3\}$, then the new datatype would be,

{ (`float`, 0), (`float`, 4), (`double`, 16), (`char`, 24), (`char`, 26) (`char`, 27) (`char`, 28) }

In addition to the constructors described above, there is a variant of the vector constructor in which the stride is given in bytes instead of the number of items. There is also a variant of the indexed constructor in which the block offsets are given in bytes.

To better understand the use of general data structures consider the example of an application in which particles move on a one-dimensional domain. We assume that each process is responsible for a different section of this domain. In each time step particles may move from the subdomain of one process to that of another, and so the data for such particles must be communicated between processes. We shall just consider here the task of migrating particles across the righthand boundary of a process, as shown in Figure 5. The particle data are stored in an array of structures, with each entry in this structure consisting of the particle position, `x`, velocity, `v`, and type, `k`:

```
struct Pstruct { double x; double v; int k; };
```

The C code for migrating particles across the righthand boundary is shown in Figure 6.

In Figure 6 the code in the first box creates a datatype, `Ptype`, that represents the `Pstruct` structure for a single particle. This datatype is,

```
Ptype = {(double,0), (double,8), (int,16)}
```

In the second code box the particles that have crossed the righthand boundary are identified, and their index in the `particle` array is stored in `Pindex`. It is assumed that no more than 100 particles cross the boundary. The call to `MPI_type_indexed` uses an indexed constructor to create a new datatype, `Ztype`, that references all the migrating particles. Before sending the data, the `Ztype` datatype must be committed. This is done to allow the system to use a different internal representation for `Ztype`, and to optimize the communication operation. Committing a datatype is most likely to be advantageous when reusing a datatype many times, which is not the case in this example. Finally, the migrating particles are sent to their destination process, `dest`, by a call to `MPI_send`. The offsets in the `Ztype` datatype are interpreted relative to the address of the start of the `particle` array.

```
struct Pstruct particle[1000];
MPI_datatype Ptype, Ztype;
MPI_datatype Stype[3]={MPI_double, MPI_double, MPI_int};
int Sblock[3]={1, 1, 1};
int Sindex[3];
int Pindex[100];
int Pblock[100];

Sindex[0] = 0;
Sindex[1] = sizeof(double);
Sindex[2] = 2*sizeof(double);
MPI_type_struct (3, Stype, Sindex, Sblock, &Ptype);

j=0;
for (i=0;i<1000;i++)
  if (x[i] > right_edge) {
    Pindex[j] = i;
    Pblock[j] = 1;
    j++;}
MPI_type_indexed (j, Ptype, Pindex, Pblock, &Ztype);

MPI_type_commit (Ztype);
MPI_send (particle, 1, Ztype, dest, tag, comm);
```

Figure 6: Fragment of C code for migrating particles across the righthand process boundary

3.3.3 Communication Completion

Following a call to a nonblocking send or receive routine there are a number of ways in which the handle returned by the call can be used to check the completion status of the communication operation, or to suspend further execution until the operation is complete. MPI_WAIT does not return until the communication operation referred to by the input handle is complete. MPI_TEST does not wait until the operation identified by the input handle is complete, but instead returns a logical variable that is TRUE if the operation is complete, and FALSE otherwise. If the input handle refers to a receive operation, then MPI_WAIT and MPI_TEST both return a handle to a return status object. This handle can subsequently be passed to a query routine to determine the actual source, tag, and length of the message received.

An additional two routines exist for waiting for the completion of any or all of the handles in a list of handles. Similarly, there are variants of the test routine that check if all, or at least one, of the communication operations identified by a list of handles is complete.

3.3.4 Persistent Communication Objects

MPI also provides a set of routines for creating communication objects that completely describe a send or receive operation by binding together all the parameters of the operation. A handle to the communication object so formed is returned, and may subsequently be passed to the routine MPI_START to actually initiate the communication. The MPI_WAIT routine, or a similar completion routine, must be called to ensure completion of the operation, as discussed in Section 3.3.3.

Persistent communication objects may be used to optimize communication performance, particularly when the same communication pattern is repeated many times in an application. For example, if a send routine is called within a loop, performance may be improved by creating a communication object that describes the parameters of the send prior to entering the loop, and then calling MPI_START inside the loop to send the data on each pass through the loop.

There are four routines for creating communication objects: three for send operations, corresponding to the standard, ready, and synchronous modes, and one for receive operations. A persistent communication object must be deallocated when no longer needed.

3.4 Collective Communication

Collective communication routines provide for coordinated communication among a group of processes [1, 2]. The process group is given by the communicator object that is input to the routine. The MPI collective communication routines have been designed so that their syntax and semantics are consistent with those of the point-to-point routines. The collective communication routines may, but do not have to be, implemented using the MPI point-to-point routines. Collective communication routines do not have message tag arguments, though an implementation in terms of the point-to-point routines may need to make use of tags. A collective communication routine must be called by all members of the group with consistent arguments. As soon as a process has completed its role in the collective communication it may continue with other tasks. Thus, a collective communication is not necessarily a barrier synchronization for the group. MPI does not include nonblocking forms of the collective communication routines. MPI collective communication routines are divided into two broad classes: data movement routines, and global computation routines.

3.4.1 Collective Data Movement Routines

There are 3 basic types of collective data movement routine: broadcast, scatter, and gather. There are two versions of each of these three routines: in the one-all case data are communicated between one process and all others; in the all-all case data are communicated between each process and all others. Figure 7 shows the one-all and all-all versions of the broadcast, scatter, and gather routines for a group of six processors.

The all-all broadcast, and both varieties of the scatter and gather routines, involve each process sending distinct data to each process, and/or receiving distinct data from each process. In these routines each process may send to and/or receive from each other process a different number of data items, but the send and receive datatypes must be consistent. To illustrate this point consider the following example in which process 0 gathers data from processes 1 and 2. Suppose the receive datatype in process 0, and the send datatypes in processes 1 and 2 are as follows,

In process 0: `recvtype`={(`int`, 0), (`float`, 4)}

In process 1: `sendtype`={(`int`, 0), (`float`, 4), (`int`, 96), (`float`, 100), (`int`, 32), (`float`, 36)}

In process 2: `sendtype`={(`int`, 16), (`float`, 20), (`int`, 48), (`float`, 52)}

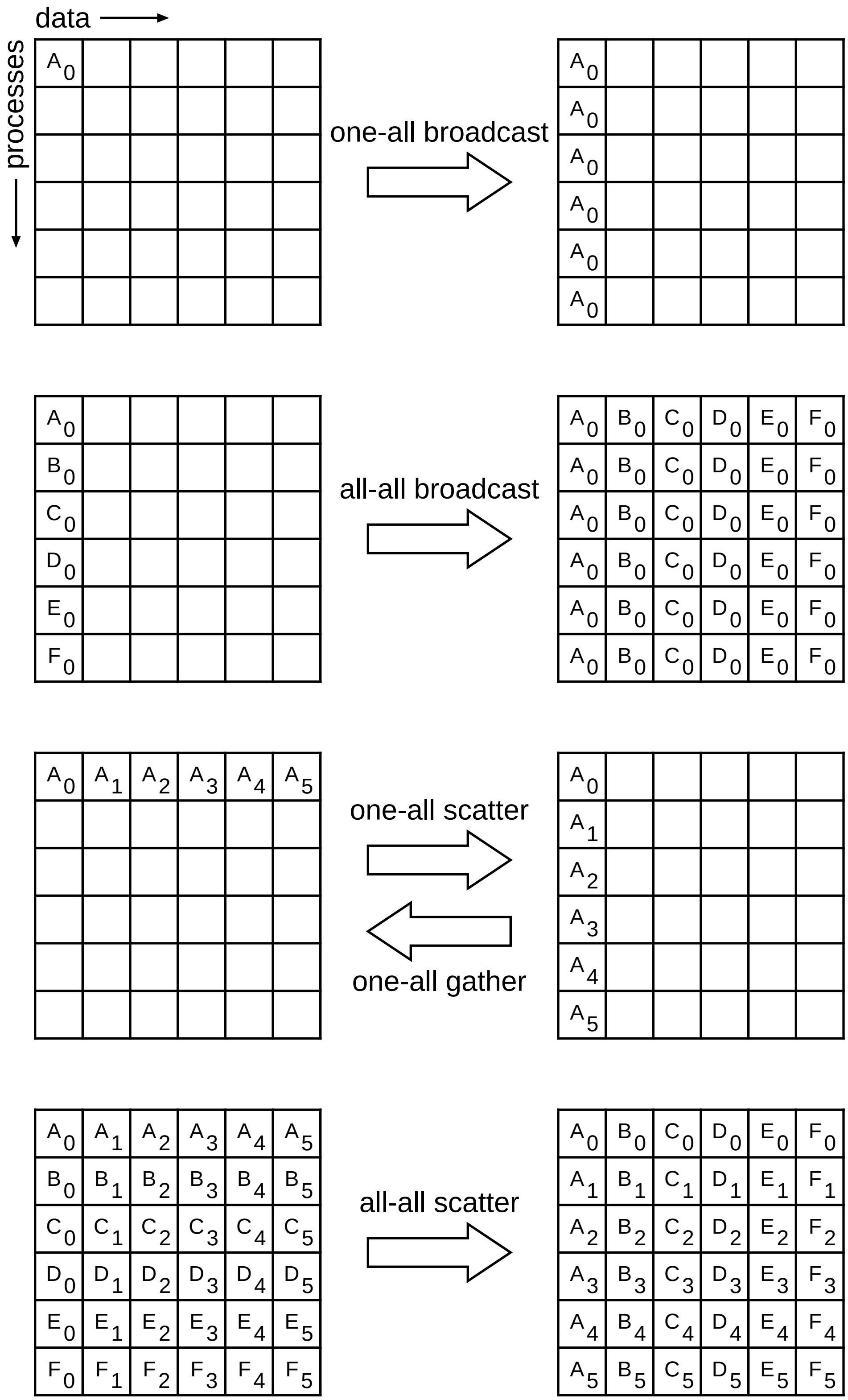
Such a situation could arise in a C program in which an indexed datatype constructor has been applied to an array of structures, each element of which consists of an integer and a floating-point number. Although the datatypes are different in each process, they are *type consistent*, since each consists of repetitions of an integer followed by a float.

The one-all broadcast routine broadcasts data from one process to all other processes in the group. The all-all broadcast broadcasts data from each process to all others, and on completion each has received the same data. Thus, for the all-all broadcast each process ends up with the same output data, which is the concatenation of the input data of all processes, in rank order.

The one-all scatter routine sends distinct data from one process to all processes in the group. This is also known as "one-to-all personalized communication". In the all-all scatter routine each process scatters distinct data to all processes in the group, so the processes receive different data from each process. This is also known as "all-to-all personalized communication".

The communication patterns in the gather routines are the same as in the scatter routines, except that the direction of flow of data is reversed. In the one-all gather routine one process (the root) receives data from every process in the group. The root process receives the concatenation of the input buffers of all processes, in rank order. There is no separate all-all gather routine since this would just be identical to the all-all scatter routine, so there are 5 basic data movement routines.

In addition, MPI provides versions of all these 5 routines, except the one-all broadcast, in which the send and receive datatypes are type consistent as discussed above, but in which



A_0					

A_0					
A_0					
A_0					
A_0					
A_0					
A_0					

A_0					
B_0					
C_0					
D_0					
E_0					
F_0					

A_0	B_0	C_0	D_0	E_0	F_0
A_0	B_0	C_0	D_0	E_0	F_0
A_0	B_0	C_0	D_0	E_0	F_0
A_0	B_0	C_0	D_0	E_0	F_0
A_0	B_0	C_0	D_0	E_0	F_0
A_0	B_0	C_0	D_0	E_0	F_0

A_0	A_1	A_2	A_3	A_4	A_5

A_0					
A_1					
A_2					
A_3					
A_4					
A_5					

A_0	A_1	A_2	A_3	A_4	A_5
B_0	B_1	B_2	B_3	B_4	B_5
C_0	C_1	C_2	C_3	C_4	C_5
D_0	D_1	D_2	D_3	D_4	D_5
E_0	E_1	E_2	E_3	E_4	E_5
F_0	F_1	F_2	F_3	F_4	F_5

A_0	B_0	C_0	D_0	E_0	F_0
A_1	B_1	C_1	D_1	E_1	F_1
A_2	B_2	C_2	D_2	E_2	F_2
A_3	B_3	C_3	D_3	E_3	F_3
A_4	B_4	C_4	D_4	E_4	F_4
A_5	B_5	C_5	D_5	E_5	F_5

Figure 7: One-all and all-all versions of the broadcast, scatter, and gather routines for a group of six processes. In each case, each row of boxes represents data locations in one process. Thus, in the one-all broadcast, initially just the first process contains the data A_0, but after the broadcast all processes contain it.

each process is allocated a *fixed* size portion of the communication buffer. These bring the total number of data movement routines to 9.

3.4.2 Global Computation Routines

There are two basic global computation routines in MPI: reduce and scan. The reduce and scan routines both require the specification of an input function. One version is provided in which the user selects the function from a predefined list; in the second version the user supplies (a pointer to) a function that is associative and commutative; in the third version the user supplies (a pointer to) a function that is associative, but not necessarily commutative. In addition, there are three variants of the reduction routines. In one variant the reduced results are returned to a single specified process; in the second variant the reduced results are returned to all processes involved; and, in the third variant the reduced results are scattered across the processes involved. This latter variant is a generalization of the `fold` routine described in Chapter 21 of [6]. Thus, there are 12 global computation routines, and a total of 21 collective communication routines (or 22 if we include the routine for performing a barrier synchronization over a process group).

The reduce routines combine the values provided in the input buffer of each process using a specified function. Thus, if D_i is the data in the process with rank i in the group, and $\oplus$ is the combining function, then the following quantity is evaluated,

$$\mathcal{D} = D_0 \oplus D_1 \oplus D_2 \oplus \cdots \oplus D_{n-1} \tag{1}$$

where n is the size of the group. Common reduction operations are the evaluation of the maximum, minimum, or sum of a set of values distributed across a group of processes.

The scan routines perform a parallel prefix with respect to an associative reduction operation on data distributed across a specified group. On completion the output buffer of the process with rank i contains the result of combining the values from the processes with rank $0, 1, \ldots, i-1$, i. e.,

$$\mathcal{D}_i = D_0 \oplus D_1 \oplus D_2 \oplus \cdots \oplus D_{i-1} \tag{2}$$

It should be noted that segmented scans can be performed by first creating distinct subgroups for each segment.

4 Summary

This paper has given an overview of the main features of MPI, but has not described the detailed syntax of the MPI routines, or discussed language binding issues. These will be fully discussed in the MPI specification document, a draft of which is expected to be available by the Supercomputing 93 conference in November 1993.

The design of MPI has been a cooperative effort involving about 60 people. Much of the discussion has been by electronic mail, and has been archived, along with copies of the MPI draft and other key documents. Copies of the archives and documents may be obtained by netlib. For details of what is available, and how to get it, please send the message "send index from mpi" to `netlib@ornl.gov`.

Acknowledgments

Many people have contributed to MPI , so it is not possible to acknowledge them all individually. However, many of the ideas presented in this paper are due to the MPI subcommittee chairs: Scott Berryman, James Cownie, Jack Dongarra, Al Geist, William Gropp, Rolf Hempel, Steve Huss-Lederman, Anthony Skjellum, Marc Snir, and Steven Zenith. Lyndon Clarke, Bob Knighten, Rik Littlefield, and Rusty Lusk have also made important contributions, as has also Steve Otto, the editor of the MPI specification document.

References

[1] V. Bala, J. Bruck, R. Cypher, P. Elustondo, A. Ho, C.-T. Ho, S. Kipnis, and Marc Snir. Ccl: A portable and tunable collective communication library for scalable parallel computers. Technical report, IBM T. J. Watson Research Center, 1993. Preprint.

[2] J. Bruck, R. Cypher, P. Elustondo, A. Ho, C.-T. Ho, S. Kipnis, and Marc Snir. Ccl: A portable and tunable collective communication library for scalable parallel computers. Technical report, IBM Almaden Research Center, 1993. Preprint.

[3] J. J. Dongarra, R. Hempel, A. J. G. Hey, and D. W. Walker. A proposal for a user-level, message passing interface in a distributed memory environment. Technical Report TM-12231, Oak Ridge National Laboratory, February 1993.

[4] Edinburgh Parallel Computing Centre, University of Edinburgh. *CHIMP Concepts*, June 1991.

[5] Edinburgh Parallel Computing Centre, University of Edinburgh. *CHIMP Version 1.0 Interface*, May 1992.

[6] G. C. Fox, M. A. Johnson, G. A. Lyzenga, S. W. Otto, J. K. Salmon, and D. W. Walker. *Solving Problems on Concurrent Processors*, volume 1. Prentice Hall, Englewood Cliffs, N.J., 1988.

[7] D. Frye, R. Bryant, H. Ho, R. Lawrence, and M. Snir. An external user interface for scalable parallel systems. Technical report, IBM, May 1992.

[8] R. Hempel. The ANL/GMD macros (PARMACS) in fortran for portable parallel programming using the message passing programming model – users' guide and reference manual. Technical report, GMD, Postfach 1316, D-5205 Sankt Augustin 1, Germany, November 1991.

[9] R. Hempel, H.-C. Hoppe, and A. Supalov. A proposal for a PARMACS library interface. Technical report, GMD, Postfach 1316, D-5205 Sankt Augustin 1, Germany, October 1992.

[10] Ewing Lusk, Ross Overbeek, et al. *Portable Programs for Parallel Processors.* Holt, Rinehart and Winston, Inc., 1987.

[11] nCUBE Corporation. *nCUBE 2 Programmers Guide, r2.0*, December 1990.

[12] Parasoft Corporation. *Express Version 1.0: A Communication Environment for Parallel Computers*, 1988.

[13] Paul Pierce. The NX/2 operating system. In *Proceedings of the Third Conference on Hypercube Concurrent Computers and Applications*, pages 384–390. ACM Press, 1988.

[14] A. Skjellum and A. Leung. Zipcode: a portable multicomputer communication library atop the reactive kernel. In D. W. Walker and Q. F. Stout, editors, *Proceedings of the Fifth Distributed Memory Concurrent Computing Conference*, pages 767–776. IEEE Press, 1990.

[15] A. Skjellum, S. Smith, C. Still, A. Leung, and M. Morari. The Zipcode message passing system. Technical report, Lawrence Livermore National Laboratory, September 1992.

[16] D. Walker. Standards for message passing in a distributed memory environment. Technical Report TM-12147, Oak Ridge National Laboratory, August 1992.