The Message Passing Interface (MPI) is a portable message-passing standard that facilitates development of parallel applications and libraries. MPI defines the syntax and semantics of a core of library routines useful to a wide range of users writing portable message-passing programs in Fortran 77 or C. The standard also forms a possible target for such language compilers as High Performance Fortran [7]. Commercial and free, public-domain implementations of MPI have been available since 1994 (see the sidebar, “MPI Implementations”), running on both tightly coupled, massively parallel processing (MPP) machines and on networks of workstations (NOWs).

The MPI standard was developed over a 12-month period in 1993-1994 of intensive meetings involving more than 80 people from approximately 40 organizations, mainly from the U.S. and Europe. The meetings were announced on various bulletin boards and mailing lists and were open to the technical community. The MPI meetings operated on a tight budget (actually no budget when the first meeting was announced). DARPA provided partial travel support for U.S. academic participants through the National Science Foundation. Support for several European participants was provided by the European Commission through its Esprit program. Formal voting at the meetings was by a single vote per organization; in order to vote, an organization needed to have had at least one representative at two of the last three meetings. To provide guidance for preparing formal proposals, frequent informal votes including all those present were held. Many vendors of concurrent computers were involved, as were researchers from universities, government laboratories, and industry.

This effort culminated in the 1994 publication of the MPI specification [8]. Other sources of information on MPI are available [10] or are under development (see the sidebar, “More MPI Assistance”).

Researchers incorporated into MPI the

Jack J. Dongarra, Steve W. Otto, Marc Snir, and David Walker
The MPI standard defines a core of communication library routines for the processes forming concurrent programs on MPP machines and on networks of workstations.

most useful features of several systems, rather than choosing a single system as the standard. MPI has roots in PVM [4, 5], Express [9], P4 [1], Zipcode [10], and PARMACS [2], and in systems sold by IBM, Intel, Meiko Scientific, Cray Research, and nCube.

MPI is used to specify the communication among a set of processes forming a concurrent program. The message-passing paradigm is attractive because of its wide portability and scalability. It is easily compatible with both distributed-memory multicomputers and shared-memory multiprocessors, with NOWs, and with combinations of these elements. Message passing will not be made obsolete by increased network speeds or by architectures combining shared and distributed-memory components.

Though much of MPI standardizes the common practice of existing message-passing systems, MPI goes further to define such advanced features as user-defined datatypes, persistent communication ports, powerful collective communication operations, and scoping mechanisms for communication. No previous system incorporated all these features.

In considering MPI, it is important to understand the constraints implied by such an endeavor and the practical constraints under which the committee operated, as well as the following goals:

- Design an application programming interface (not necessarily for compilers or a system implementation library).
- Allow efficient communication, avoiding memory-to-memory copying and supporting overlap of computation and communication and offload to communication coprocessors where available.
- Allow implementations in heterogeneous environments.
- Allow convenient C and Fortran 77 bindings for the interface.
- Assume a reliable communication interface so the user need not cope with communication failures dealt with by the underlying communication subsystem.
- Define an interface not too different from current practice, such as Express, Intel’s NX, PVM, and P4, while providing extensions allowing greater flexibility.
- Define an interface that can be implemented on many vendors’ platforms with no significant changes in the underlying communication and system software.
- Design interface semantics to be language independent.
- Design the interface to allow for thread safety.

What MPI Does and Does Not Specify

The standard specifies the form of the following:

- **Point-to-point communications.** Messages between pairs of processes.
- **Collective communications.** Communication or synchronization operations involving entire groups of processes.
- **Process groups.** How process groups are used and manipulated.
- **Communicators.** A mechanism for providing separate communication scopes for modules or libraries. Each communicator specifies a distinct name space for processes and a distinct communication context for mes-

**MPI Implementations**

MPI is available on parallel computers from Convex Computer, Cray Research, IBM, Intel, Meiko Scientific, nCube, NEC, and Silicon Graphics. A number of public-domain MPI implementations are available and can be found at the following locations:

- Argonne National Laboratory/Mississippi State University implementation. Available by anonymous ftp at info.mcs.anl.gov/pub/mpi.
- Edinburgh Parallel Computing Centre CHIMP implementation. Available by anonymous ftp at ftp.epcc.ed.ac.uk/pub/chimp/release/chimp.tar.Z.
- Mississippi State University UNIFY implementation. The UNIFY system provides a subset of MPI within the PVM environment without sacrificing the PVM calls already available. Available by anonymous ftp at ftp.erc.msstate.edu/unify.
- Ohio Supercomputer Center LAM implementation. A full MPI standard implementation for LAM, a Unix cluster computing environment. Available by anonymous ftp: tbag.osc.edu/pub/lam.
sages; it may also carry additional scope-specific information.

- **Process topologies**. Functions that allow convenient manipulation of process labels when the processes are regarded as forming a particular topology, such as a Cartesian grid.

- **Bindings for Fortran 77 and ANSI C**. MPI was designed so that versions of it in both C and Fortran had straightforward syntax. In fact, the detailed form of the interface in these two languages is specified and is part of the standard.

- **Profiling interface**. The interface is designed so that run-time profiling or performance-monitoring tools can be joined to the message-passing system. It is not necessary to have access to the MPI source to do performance monitoring and instrumentation; hence portable profiling systems are easily constructed.

- **Environmental management and inquiry functions**. These functions provide a portable timer, some system-querying capabilities, and the ability to influence error behavior and error-handling functions.

However, many relevant issues of parallel programming are not covered by the standard, including:

- Shared-memory operations
- Interrupt-driven messages, remote execution, and active messages
- Program construction tools
- Debugging support
- Thread support
- Process or task management
- Input and output functions

The main reasons for not addressing these issues were the committee’s self-imposed time constraint and by the view that many of them are system dependent. Meetings focusing on extending MPI began in 1995 and will end in 1997. The rest of this article discusses some of MPI’s more interesting features, including point-to-point communication, user-defined datatypes, collective communications, and groups, contexts, and communicators.

### Point-to-Point Communication

MPI provides a set of send and receive functions that allow the communication of typed data with an associated tag. Typing of the message contents is necessary for the heterogeneous support needed for the performance of correct data representation conversions as data is sent from one architecture to another architecture. The tag allows selectivity of messages at the receiving end; a user’s program can receive on a particular tag, or the program can wildcard, or self-define, this quantity, allowing reception of messages with any tag. Also provided is message selectivity on the source process of the message.

The fragment of code in Figure 1 for the example of process 0 sending a message to process 1 executes on both process 0 and process 1, sending a character string. MPI_COMM_WORLD is a default communicator provided upon startup. Among other things, a communicator defines the allowed set of processes involved in a communication operation. Process ranks are integers, serving to label processes and are discovered through inquiry to a communicator (see the call to MPI_Comm_rank () in Figure 1). The typing of the communication is evident by the specification of MPI_CHAR. The receiving process specified that the incoming data was to be placed in msg and that it had a maximum size of 20 elements of type MPI_CHAR. The variable status, set by MPI_Recv (), gives information on the source and tag of the message and the number of elements actually received. For example, the receiver can examine this variable to find out the actual length of the character string received.

This example employs blocking send and receive functions. The send call blocks until the send buffer can be reclaimed; that is, after the send, process 0 can safely overwrite the contents of msg. Similarly, the receive function blocks until the receive buffer actually contains the contents of the message.
MPI also provides nonblocking send and receive functions that allow the overlap of message transmit-
tal with computation or the overlap of multiple mes-
sage transmittals with one another. Nonblocking
functions always come in two parts: the posting func-
tions, which begin the requested operation, and the
test-for-completion functions, which allow the appli-
cation program to discover whether the requested
operation has been completed.

While this description may already seem like
rather a lot to say about a simple transmittal of data
from one process to another, there is more. To
understand why, we examine two aspects of the com-
munication: the semantics of the communication
primitives and the underlying protocols that imple-
ment them. Consider the earlier example on process
0 after the blocking send has completed. If the send
has completed, does this tell us anything about the
receiving process? Can we know that the receive has
finished, or even that it has begun?

Such questions of semantics are related to the
nature of the underlying protocol implementing the
operations. If a user wishes to implement a protocol
minimizing the copying and buffering of data, the
most natural semantics might be the rendezvous ver-

minimizing the copying and buffering of data, the
operations. If a user wishes to implement a protocol
minimizing the copying and buffering of data, the
most natural semantics might be the rendezvous version,
in which completion of the send implies the receive has been initiated (at least). On the other
hand, a protocol that attempts to block processes for
the minimal amount of time necessarily ends up doing more buffering and copying of data.

The trouble is that one choice of semantics is not
best for all applications, nor is it best for all architec-
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ture for the transfer of data.

In standard mode, the completion of the send does not necessarily mean that the matching
receive has started, and no assumption should be made in the application program
about whether the outgoing data is buffered by
MPI. In buffered mode, the user can guarantee
that a certain amount of buffering space is
available. The catch is that the space must be
explicitly provided by the application program.

In synchronous mode, a rendezvous semantics
between sender and receiver is used. Finally,
ready mode allows the user to exploit extra
knowledge to simplify the protocol and poten-
tially achieve higher performance. In a ready-
mode send, the user asserts that the matching
receive is already posted.

User-Defined Datatypes
All MPI communication functions take a
datatype argument. In the simplest case, the
datatype is a primitive type, such as an integer
or floating-point number. An important and
powerful generalization results from allowing
user-defined types wherever the primitive types
can occur. These are not "types" as far as the
programming language is concerned. They are
types only in that MPI is made aware of them
through type-constructor functions describing
the layout in memory of sets of primitive types.

Through user-defined types, MPI supports
communication of complex data structures,
such as array sections and structures contain-
ing combinations of primitive datatypes. Fig-

Figure 1. C code. Process 0 sends a message to process 1.

/* static variable used as "key" for library */
/* Only one per process is necessary, even if multiple */
extern int lib_key;
/* library invocations can be concurrently active. */
void lib_init ()
{

/* allocate a process-unique key */
MPI_Keyval_create(MPI_NULL_FN, MPI_NULL_FN, &lib_key, (void *)NULL);
}

/* retrieve private communicator */
MPI_Comm_rank( MPI_COMM_WORLD, &myrank ); /* find my rank */
MPI_Comm create( MPI_COMM_WORLD, &myrank, 99, MPI_COMM_WORLD);
MPI_Status status;
char msg[20];
int myrank, tag = 99,
MPI_Status status;
...
ure 2 gives an example of using a user-defined type to send the upper-triangular part of a matrix.

Collective Communications
Collective communications transmit data among all the processes specified by a communicator object. One function, the barrier, serves to synchronize processes without passing data. MPI provides the following collective communication functions:

- Barrier synchronization across all processes
- Broadcast from one process to all
- Gathering data from all processes to one
- Scattering data from one to all
- Allgather, like a gather followed by a broadcast of the gather output
- Alloall, like a set of gathers in which each process receives a distinct result
- Global reduction operations, such as sum, max, min, and user-defined functions
- Scan (or prefix) across processes

Figure 3 shows broadcast, scatter, gather, allgather, and alloall. Many of the collective functions also have “vector” variants, whereby different amounts of data can be sent to or received from different processes. For these vector variants, the simple grids in Figure 3 become more complex.

The syntax and semantics of the MPI collective functions were designed to be consistent with point-to-point communications. However, to keep the number of functions and their argument lists at a reasonable level of complexity, the MPI committee made collective functions more restrictive than the point-to-point functions in several ways. One restriction is that, in contrast to point-to-point communication, the amount of data sent must exactly match the amount of data specified by the receiver. This restriction was imposed to avoid the need for an array of status variables as an argument to the functions that would otherwise be necessary for the receiver to discover the amount of data actually received.

A major simplification is that collective functions come only in blocking versions. Though a standing joke at committee meetings concerned the nonblocking barrier, such functions can be quite useful and may be included in a future version of MPI.

A final simplification of collective functions concerns modes, which come in only one type that may be regarded as analogous to the standard mode of point-to-point. Specifically, the semantics are: A call collective function (on a given process) can return to the user’s program as soon as its participation in the overall communication is complete. As usual, the completion indicates that the caller is now free to access and modify locations in the communication buffer. The completion does not indicate that other processes have completed—or even started—the operation.

Thus, a collective communication may or may not have the effect of synchronizing all calling processes. The barrier, of course, is the exception to this statement.

These semantics were chosen to allow a variety of implementations. And the MPI user must keep these issues in mind. For example, even though a particular implementation of MPI may provide a broadcast with the side effect of synchronization (the standard allows this side effect), the standard does not require it, and hence, any program that relies on synchronization is nonportable. On the other hand, a correct and portable program must allow a collective function to be synchronizing. Though one should not rely on synchronization side effects, one must program to allow for them.

Though these issues and statements may seem unusually obscure, they are merely a consequence of the desire of MPI to do two things:

- Allow efficient implementations on a variety of architectures
- Be clear about exactly what is and what is not guaranteed by the standard

Groups, Contexts, and Communicators
A key feature needed to support robust, parallel libraries is a guarantee that communication within a library routine does not conflict with communication extraneous to the routine. The concepts encapsulated by an MPI communicator provide this support.

A communicator is a data object that specifies the scope of a communication operation, that is, the group of processes involved and the communication context. Contexts partition the communication space. A message sent in one context cannot be received in another context. Process ranks are interpreted with respect to the process group associated with a communicator. MPI applications begin with a default communicator, MPI_COMM_WORLD, which has as its process group the entire set of processes (of

1The nonblocking barrier would, of course, block at the test-for-completion call.
Communicators are created from existing communicators; creation of a communicator is a collective operation. New communicators are especially important for the design of parallel software libraries. Suppose we have a parallel matrix-multiplication routine as a member of a library. We would like to allow distinct subgroups of processes to concurrently perform different matrix multiplications. A communicator provides a convenient mechanism for passing into the library routine the appropriate group of processes, and within the routine, process ranks are interpreted relative to this group. The grouping and labeling mechanisms provided by communicators are useful, and communicators are typically passed into library routines that perform internal communications.

Such library routines can also create their own unique communicators for internal use. For example, consider an application in which process 0 posts a wildcarded, nonblocking receive just before entry to a library routine. Such “promiscuous” posting of receives is a common technique for increasing performance. If an internal communicator is not created, incorrect behavior may result, since the receive may be satisfied by a message sent by process 1 from within the library routine—if process 1 invokes the library ahead of process 0. Another example is a case in which a process sends a message before entry into a library routine, but the destination process does not post the matching receive until after it exits the library routine. In this case, the message may be received incorrectly within the library routine.

These problems are avoided by proper design and use of parallel libraries. One workable design is for the application program to pass communicators into the library routine specifying the group and ensuring a safe context. Another design has the library create a “hidden” and unique communicator in a library initialization call, again leading to correct partitioning of the message space between application and library.

The sidebar, “Library Communicator and Caching,” reveals how one might implement the second type of design. Some thought reveals that as one creates separate communicators for libraries, it is convenient to associate these new communicators with the old communicators from which they were derived. The MPI caching mechanism provides a way to set up such an association. Though one can associate arbitrary objects with communicators using caching, the ability to perform such associations for library internal communicators is one of the most important uses of caching.

Conclusions
A pleasant surprise for participants in the MPI effort was the interesting intellectual issues that kept coming up. This article has concentrated on some of them, but for most cases, programming in MPI is straightforward and similar to programming with other message-passing interfaces.

MPI does not claim to be the definitive answer to all message-passing needs. Indeed, our insistence on simplicity and timeliness of the standard precludes MPI being the definitive passing system. The MPI interface provides a useful basis for developing software for message-passing environments. Besides promoting the

**Figure 3.** Collective move functions for a group of six processes. For each process, each row of boxes represents data locations in one process. Thus, in the broadcast, initially only the first process contains the data $A_0$, but after the broadcast all processes contain the data.
emergence of parallel software, a message-passing standard gives vendors a clearly defined base set of routines they can implement efficiently. Hardware support for parts of the system is also possible and may greatly enhance parallel scalability.

The final MPI 1 Forum meeting in February 1994 decided that plans for extending MPI should wait for more experience with the current version. The MPI 2 Forum now under way is moving in the following directions:

- Parallel input/output
- Remote store/access
- Active messages
- Process startup
- Dynamic process control
- Nonblocking collective operations
- Fortran 90 and C++ language bindings
- Graphics
- Real-time support

For more information, see the MPI-specific news-group at comp.parallel.mpi. The official version of the specification document can be obtained from netlib [3] by sending an email message to netlib@www.netlib.org with the message: “send mpi-report.ps from mpi”. A postscript file will be mailed back to you by the netlib server. The document may also be obtained via anonymous ftp from www.netlib.org/mpi/mpi-report.ps. A hypertext version is available on the World-Wide Web at http://www.mcs.anl.gov/mpi/mpi-report/mpi-report.html.

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Standard system decides whether message is buffered. Buffered user explicitly controls buffering. Synchronous send waits for matching receive. Message Passing MPP Problems. All data layout must be handled by software. cannot retrieve remote data except with message request/reply. Message passing has high software overhead. Early machines had to invoke OS on each message (100Ps-1ms/message). Dedicated interprocessor networks for message passing MPPs T3E shell circuitry large backplane for Starfire directory storage and routers in SGI Origin. Large machines cost more per processor than small machines! Page 10. Clusters. Connect multiple complete machines together using standard fast interconnects. Little or no hardware development cost Each node can boot separately and operate. independently Interconnect can be attached at I/O bus (most common).