Compiling Fortran 90D/HPF for Distributed Memory MIMD Computers

ZEKI BOZKUS, ALOK CHOUHARY, GEOFFREY FOX, TOMASZ HAUPT, SANJAY RANKA, AND MIN-YOU WU
Syracuse University, Northeast Parallel Architectures Center, 3-201, Center for Science and Technology,
Syracuse University, Syracuse, New York 13244-4100

Reprinted from JOURNAL OF PARALLEL AND DISTRIBUTED COMPUTING, Volume 21, No. 1, April 1994
Copyright © 1994 by Academic Press, Inc. Printed in U.S.A.
Compiling Fortran 90D/HPF for Distributed Memory MIMD Computers

ZEKI BOZKUS, ALOK CHOUDHARY, * GEOFFREY FOX, TOMASZ HAUPT, SANJAY RANKA, † AND MIN-YOU WU ‡

Syracuse University, Northeast Parallel Architectures Center, 3-201, Center for Science and Technology,
Syracuse University, Syracuse, New York 13244-4100

This paper describes the design of the Fortran90D/HPF compiler, a source-to-source parallel compiler for distributed memory systems being developed at Syracuse University. Fortran 90D/HPF is a data parallel language with special directives to specify data alignment and distributions. A systematic methodology to process distribution directives of Fortran 90D/HPF is presented. Furthermore, techniques for data and computation partitioning, communication detection and generation, and the run-time support for the compiler are discussed. Finally, initial performance results for the compiler are presented. We believe that the methodology to process data distribution, computation partitioning, communication system design, and the overall compiler design can be used by the implementors of compilers for HPF. © 1994 Academic Press, Inc.

1. INTRODUCTION

Distributed memory multiprocessors are increasingly being used for providing high performance for scientific applications. Distributed memory machines offer significant advantages over their shared memory counterparts in terms of cost and scalability, though it is widely accepted that they are difficult to program, given the current state of the software technology. Currently, distributed memory machines are programmed using a node language and a message-passing library. This process is tedious and error prone because the user must perform the task of data distribution and communication for non-local data accesses.

There has been significant research in developing parallelizing compilers. In this approach, the compiler takes a sequential program as input, applies a set of transformation rules, and produces a parallelized code for the target machine. However, a sequential language, such as Fortran 77, obscures the parallelism of a problem in sequential loops and other sequential constructs. This makes the potential parallelism of a program difficult to detect by a parallelizing compiler. Thus, in our opinion, compiling a sequential program into a parallel program is not a natural approach. An alternative approach is to use a programming language that can naturally represent an application without losing the application’s original parallelism. Fortran 90 [2] (with some extensions) is such a language. The extensions include parallel loop, such as a forall statement and compiler directives for data partitioning, such as decomposition, alignment, and distribution. Fortran 90 with these extensions is what we call “Fortran 90D”, a Fortran 90 version of the Fortran D language [10]. We developed the Fortran D language with our colleagues at Rice University. There is an analogous version of Fortran 77, with compiler directives and other constructs, called Fortran 77D. Fortran D allows a user to advise the compiler on the allocation of data to processor memories. Recently, the High Performance Fortran Forum, an informal group of people from academia, industry, and national labs, led by Ken Kennedy, developed a language called HPF (High Performance Fortran) [15] based on a number of languages such as Fortran D, CM Fortran [24], and Vienna Fortran [25]. HPF essentially adds extensions to Fortran 90 similar to the Fortran D directives. Hence, Fortran 90D and HPF are very similar except for a few syntactic differences. For this reason, we call our compiler the Fortran 90D/HPF compiler.

From our point of view, Fortran 90 is not only a language for SIMD computers [24, 19], but it is also a natural language for specifying parallelism in a class of problems called loosely synchronous problems. In Fortran 90D/HPF, parallelism is represented with parallel constructs such as array operations, where statements, forall statements, and intrinsic functions. This gives the programmer a powerful tool to express the data parallelism natural to a problem.

This paper presents the design of a prototype compiler for Fortran 90D/HPF. The compiler takes as input a program written in Fortran 90D/HPF. Output is a SPMD (Single Program Multiple Data) program with appropriate data and computation partitioning and communication calls for distributed memory MIMD machines. Therefore, the user can still program using a data parallel lan-
guage but is relieved of the responsibility to perform data
distribution and communication.

The rest of this paper is organized as follows. The com-
piler system overview is described in Section 2. Data
partitioning and computation partitioning are discussed
in Sections 3 and 4. Section 5 presents the communica-
tion primitives and communication generation for For-
tran 90D/HPF programs. In Section 6, we present the
runtime support system including the intrinsic functions.
Section 7 summarizes our initial experience using the
current version of the compiler. It also presents a com-
parison of the performance with hand-written parallel
code. Section 8 presents a summary of related work. Fi-
nally, a summary and conclusions are presented in Sec-
tion 9.

2. COMPILER SYSTEM OVERVIEW

Our Fortran 90D/HPF compiler exploits only the par-
allelism expressed in the data parallel constructs. We do
not attempt to parallelize other constructs such as do
loops and while loops, since they are used only as natu-
rally sequential control constructs in this language. The
foundation of our design lies in recognizing commonly
occurring computation and communication patterns.
These patterns are then replaced by calls to optimized
run-time support system routines. The run-time support
system includes parallel intrinsic functions, data distribu-
tion functions, communication primitives, and several
other miscellaneous routines.

The basic structure of our Fortran 90D/HPF compiler
is organized around four major modules: parsing, parti-
tioning, communication detection and insertion, and
code generation. Given a syntactically correct Fortran
90D/HPF program, the first step of the compilation is to
generate a parse tree. The front-end to parse Fortran 90
for the compiler was obtained from ParaSoft Corp. This
module parses the input program into an abstract syntax
tree, performs semantic analysis to annotate the tree with
type information, and builds up a symbol table; it also
performs error checking. Our compiler transforms each
array assignment statement and where statement into an
equivalent forall statement with no loss of information
[3]. In this way, subsequent steps need only deal with
forall statements.

Currently, our compiler does not handle module,
pointer, and allocatable array statements of Fortran 90.
And also it can not provide some of HPF distributions,
subprogram interfaces for distributed arrays, INHERIT,
INDEPENDENT directives, and some of the new HPF
intrinsic.

The partitioning module processes data distribution di-
rectives, namely, decomposition, distribute and align.
Using these directives, it partitions data and computation
among processors.

Dependence analysis is carried out to obtain depend-
ce information for use in sequentialization of the data
parallel constructs and insertion of communication primit-
ives. Standard techniques of data dependence analysis
for Fortran programs can be applied here.

After partitioning, the parallel constructs of the node
program are sequentialized, since they will be executed
on a single processor. This is performed by the sequen-
tialization module. Array operations and forall state-
ments in the original program are transferred into loops
or nested loops. The communication module detects
communication requirements and inserts appropriate
communication primitives.

Finally, the code generator produces a loosely syn-
chronous SPMD code. The generated code is structured
as alternating phases of local computation and global
communication. Local computations consist of opera-
tions by each processor on the data in its own memory.
Collective communication includes any transfer of data
among processors, possibly with arithmetic or logical
computation on the data as it is transferred (e.g., reduc-
tion functions). In such a model, processes do not need to
synchronize during local computation. But, if two or
more nodes interact, they are implicitly synchronized by
global communication.

3. DATA PARTITIONING

Distributed memory systems solve the memory bottle-
neck of vector supercomputers by having separate mem-
ory for each processor. However, distributed memory
systems require high locality for good performance.
Therefore, the distribution of data across processors is of
critical importance to the efficiency of a parallel program
in a distributed memory system.

Fortran D provides users with explicit control over
data partitioning with data alignment and distribution
specifications. It has three main compiler directives.

- DECOMPOSITION
- ALIGN
- DISTRIBUTE

The DECOMPOSITION directive is used to declare
the name, dimensionality, and the size of each problem
domain. A decomposition is simply an abstract represen-
tation of a problem or index domain. We call it "tem-
plate" (a name chosen to describe DECOMPOSITION in
HPF [15]).

The ALIGN directive specifies fine-grain parallelism,
mapping each array element onto one or more elements
of the template. There may be multiple templates rep-
local accesses will be reduced. The \texttt{DECOMPOSITION} directive defines the shape and rank of a given template. Let $A$ be an $m$-dimensional array and \texttt{TEMPL} be an $n$-dimensional template. The general form of the alignment directive is

\begin{verbatim}
C$ ALIGN A(i[*], ..., i_m[*]) WITH TEMPL( f_1(i_1[*]), ..., f_n( i_n[*]) )
\end{verbatim}

The specified elements of $A$ are aligned to those of \texttt{TEMPL}. The template is eventually distributed on a set of processors and the compiler guarantees that the array elements aligned to the same element of the template will be mapped to the same processor.

An alignment function, $f_k$, is required to be an affine function. That is, $f_k = s_k * i_k + o_k$ or $f_k = o_k$. The parameters $i_k$, $s_k$, and $o_k$ correspond to the three components of the alignment: \texttt{axis}, \texttt{stride}, and \texttt{offset}. Misalignment in the stride components causes \texttt{unstructured communication}, and misalignment in the offset component causes nearest-neighbor communication [7].

The Fortran 90D/HPF compiler requires that each of $A$'s subscripts $i_1$, ..., $i_m$ appear exactly once on the \texttt{TEMPL}’s subscripts, so that a one-to-one correspondence with a section of \texttt{TEMPL} is established. This restriction does not permit skew alignments such as aligning $A(I)$ with \texttt{TEMPL}(I, I) or $A(I, J)$ with \texttt{TEMPL}(I + J). The order of axes in the array may be different from the order of axes in the template. This permits transpose style alignments such as aligning $A(I, J)$ with \texttt{TEMPL}(J, I).

The symbol \texttt{***} indicates that the corresponding dimension is replicated or collapsed. It may appear in both the array and the template subscripts. The array rank (number of dimensions) $m$ may be different from the rank of the template, $n$. For example, the directive

\begin{verbatim}
C$ ALIGN A(i, *) WITH TEMPL(i + 1)
\end{verbatim}

requires the second dimension of the array $A$ be collapsed (not distributed), while the directive

\begin{verbatim}
C$ ALIGN A(i) WITH TEMPL(*, i + 1)
\end{verbatim}

forces replication of array $A$ along the first dimension of the template \texttt{TEMPL}.

Algorithm 1 gives the steps in the algorithm used by our Fortran 90D/HPF compiler to process the align directives. The following example illustrates the steps and all the transformations performed to transform array indices from the \texttt{array index domain} to \texttt{template index domain} and vice versa.

Consider the Fortran 90D/HPF code fragment shown in Fig. 2. There are three arrays \texttt{ODD(N/2)}, \texttt{EVEN(N/2)} and \texttt{NUM(N)}. Elements of the array \texttt{ODD} are aligned
Algorithm 1 (Compiling Align directives)

Input: Fortran 90D/HPF syntax tree with some alignment functions to template
Output: Fortran 90D/HPF syntax tree with identical alignment functions to template
Method: For each aligned array, and for each dimension of that array, carry out the following steps:

1. Extend aligned arrays to match template size.
2. Determine local shape of arrays.
3. Apply alignment functions to the aligned arrays.
4. Transform into canonical form.
5. Compute $f^{\text{id}}(I)$.

with odd elements of TEMPL. Similarly, elements of the array EVEN are aligned with the even elements of TEMPL. NUM is aligned identically with TEMPL. Hence, ODD and EVEN are aligned with odd and even indices of NUM respectively, because they are aligned to the same template.

Step 1. Extend aligned arrays to match template size.
Note that we assume that the array size is equal to or smaller than the template size in the distributed dimension(s). If an array size is smaller than the template size in the distributed dimension, the compiler extends the array size to match the template size. For example, ODD and EVEN arrays are extended to size N to match the template TEMPL's size, which is N. Note that an array is only extended in the distributed dimension of the array. An alternative approach such as proposed by Chatterjee et al. [8] is to compute and store the local index in a table. However, this introduces a level of indirection for each access. Furthermore, storing an index table also requires memory space that can be potentially as large as the distributed array itself. Many of the commercial compilers (e.g., Dec MPP Fortran [19], CM-Fortran [24], and Cray MPP Fortran [21]) extend arrays to the nearest power of two, whereas we extend in the distributed dimension to match the template size.

Step 2. Determine local shape of arrays. In this step, the compiler determines the local shape and size of the distributed arrays based on the processor grid information associated with the corresponding template. In the above example, the template TEMPL is distributed on P processors. P is a compile-time parameter for each dimension of DISTRIBUTION directive. Hence, the compiler determines the size of the distributed dimension of arrays as ODD(N/P), EVEN(N/P), and NUM(N/P). Since our compiler produces SPMD code, array declarations are the same in every processor.

Step 3. Apply alignment functions to the aligned arrays. In this step, all indices of each occurrence of an array (all the statements) in the input program are transformed into the template index domain using the alignment function $f(I)$. Arrays ODD, EVEN, and NUM are associated with $f_\text{od}(I) = 2 * I + 1$, $f_\text{ev}(I) = 2 * I$, $f_\text{nu}(I) = I$ functions, respectively. Figure 3 illustrates this transformation on the array ODD. For example, the first forall assignment statement in Fig. 2

\[
\text{NUM}(I) = \text{ODD}(I + 1)/2
\]

is transformed into

\[
\text{NUM}(I) = \text{ODD}(2*(I + 1)/2 - 1) (1)
\]

by applying the functions $f_\text{od}(I) = I$ (identify function) and $f_\text{ev}(I) = 2 * I - 1$ to the lhs and the rhs respectively.

Step 4. Transform into canonical form. In this step, the compiler simplifies all functions applied in Step 3 by performing symbolic manipulation and partial evaluation of constants. For example, statement (1) becomes

\[
\text{NUM}(I) = \text{ODD}(I)
\]

The above simplification of indices helps the compiler to choose efficient collective communication routines. Our communication detection algorithm is based on sym-

1. PARAMETER(WPROC=10, N=100)
2. REAL NUM(N), ODD(N/2), EVEN(N/2)
3. CS DECOMPOSITION TEMPL(N)
4. CS DISTRIBUTE TEMPL(BLOCK)
5. CS ALIGN NUM(I) WITH TEMPL(I)
6. CS ALIGN ODD(I) WITH TEMPL(2*I-1)
7. CS ALIGN EVEN(I) WITH TEMPL(2*I)
8. FORALL(I=1:N-2) NUM(I) = ODD((I+1)/2)
9. FORALL(I=2:N-2) NUM(I) = EVEN(I/2)
10. LOC=MAXLOC(ODD)

FIG. 2. Example 1: A Fortran 90D/HPF program fragment involving directives, forall's and an intrinsic function.

FIG. 3. Transforming array ODD of the example from array index domain to template index domain.
bolically comparing the lhs and rhs reference patterns and determining if the pattern is associated with one of the collective communication routines. In the above statement the compiler compares lhs and rhs indexes and determines that no communication is required, because both of the array reference patterns are given by \( i \) and are aligned to the same template. However, if the rhs are ODD(\( i+2 \)), it will be recognized as a shift communication.

**Step 5.** Compute \( f^{-1}(i) \). For each array, we compute the inverse alignment function \( f^{-1}(i) \) corresponding to each \( f(i); f^{-1}(i) \) is stored in the Distributed Array Descriptor (DAD) \([1] \). In DAD, for each alignment function (affine) we store constants \( a \) and \( b \), where \( f(i) = ai + b \). This function is needed when any computation needs to be performed using the original index of an array. For example, the last statement in Fig. 2 calls the intrinsic function MAXLOC to find the location of the maximum element in the array ODD. This function must be evaluated using the original array indices. The inverse function for array ODD is \( f^{-1}(i) = (i + 1)/2 \). MAXLOC will return the location of the maximum value in the original array index domain by applying the \( f^{-1} \) function.

### 4. Computation Partitioning

Once the data is distributed, there are several alternatives for assigning computations to processing elements (PEs) for each instance of a forall statement. Note that we internally transform all array statements into equivalent forall representations. One of the most common methods for computation assignment is to use the owner computes rule. In the owner computes rule, the computation is assigned to the PE owning the lhs data element. This rule is simple to implement and performs well in many cases. Most of the current implementations of parallelizing compilers use the owner computes rule \([25, 6] \). However, it may not be possible to apply the owner computes rule for every case. The following examples describe how our compiler performs computation partitioning.

**Example 1 (Canonical Form).** Consider the following statement, taken from the Jacobi relaxation program

```fortran
forall (i=1:N, j=1:N)
&   B(i,j) = 0.25*(A(i-1,j)+A(i+1,j)+A(i,j-1)+A(i,j+1))
```

In the above example, as in a large number of scientific computations, the forall statement can be written in the canonical form. In this form, the subscript value in the lhs is identical to the forall iteration variable. In such cases, the iterations can be easily distributed using the owner computes rule.

Figure 4 shows the possible data and iteration distributions for the \( lhs = rhs \) assignment caused by iteration instance \( I \). Cases 1 and 2 illustrate the order of communication and computation arising from the owner computes rule. Essentially, all the communications to fetch off-processor data required to execute an iteration instance are performed before the computation is performed.

**Example 2 (Non-canonical Form).** Consider the following statement, taken from an FFT program

```fortran
forall (i=1:incrm, j=1:nx/2)
&   x(i+j*incrm*2+incrm) = x(i+j*incrm*2)
&   term2(i+j*incrm*2+incrm)
```

The lhs array index is not in the canonical form. In this case, the compiler equally distributes the iteration space on the number of processors on which the lhs array is distributed. Hence, the total number of iterations will still be the same as the number of lhs array elements being assigned. However, this type of forall statement will result in either Case 3 or Case 4 in Fig. 2. The generated code will be in the following order.

```
Communications ! some global communication primitives to read off-processor values
Computation   ! local computation
Communication ! a communication primitive to write the calculated values to off-processors
```

### 5. Communication

Our Fortran 90D/HPF compiler produces calls to collective communication routines instead of generating individual processor send and receive calls inside the compiler code. The idea of using collective communication routines came from researchers involved in developing scientific application programs \([11] \). There are three main
5.1. Communication Primitives

In order to perform a collective communication on array elements, the communication primitive needs the following information: send processors list, receive processors list, local index list of the source array, and local index list of the destination array.

There are two ways of determining the above information. (1) Using a preprocessing loop to compute the above values or, (2) based on the type of communication the above information may be implicitly available, and therefore, not require preprocessing. We classify our communication primitives into unstructured and structured communication, respectively.

Our structured communication primitives are based on a logical grid configuration of the processors. Hence, they use grid-based communications such as shift along dimensions, broadcast along dimensions, etc. The following summarizes some of the structured communication primitives implemented in our compiler.

- **transfer**: Single source to single destination message.
- **multicast**: Broadcast along a dimension of the logical grid.
- **overlap_shift**: Shifting data into overlap areas in one or more grid dimensions. This is particularly useful when the shift amount is known at compile time. This primitive uses that fact to avoid intra-processor copying of data and directly stores data in the overlap areas [12].
- **temporary_shift**: This is similar to overlap shift except that the data is shifted into a temporary array. This is useful when the shift amount is not a compile time constant. This shift may require intra-processor copying of data.
- **concatenation**: This primitive concatenates a distributed array and the resultant array ends up in all the processors participating in this primitive.

We have implemented two sets of unstructured communication primitives: (1) where the communicating processors can determine the send and receive lists based only on local information, and hence, only require preprocessing that involves local computations, [17] and (2) where to determine the send and receive lists preprocessing itself requires communication among the processors [23].

- **precomp_read**: This primitive is used to bring all non-local data to the place it is needed before the computation is performed.
- **postcomp_write**: This primitive is used to store remote data by sending it to the processors that own the data after the computation is performed. Note that these two primitives require only local computation in the preprocessing loop.
- **gather**: This is similar to **precomp_read** except that preprocessing loop itself may require communication.
* scatter: This is similar to postcomp_write except that preprocessing loop itself may require communication.

The compiler must recognize the presence of collective communication patterns in the computations in order to generate the appropriate communication calls. Specifically, this involves a number of tests on the relationships among the subscripts of various arrays in a forall statement. These tests should also include information about array alignments and distributions. We use pattern matching techniques similar to those proposed by Li and Chen [18]. Further, we extend the above tests to include unstructured communication. Table I shows the patterns of communication primitives used in our compiler. The details of our communication detection algorithm can be found in [3].

```plaintext
1. call set_BOUND (lb, ub, st, i, N, i) ! compute local lb, ub, and st
2. call set_BOUND (lb1, ub1, st1, i, M, i) ! compute local lb, ub, and st
3. call set_DAD (B_DAD, ...) ! put information for B into B_DAD
4. call multicast (B, B_DAD, TMP, source_proc=global_to_proc(3), dim=2)
5. DO I=1b, ub, st
6. DO J=lb1, ub1, st1
7. A(I, J) = TMP(I)
8. END DO
```

In the above code, the set_BOUND primitive (line 1) computes the local bounds for computation assignment based on the iteration distribution (Section 4). In line 2, the primitive set_DAD is used to fill the distributed array descriptor (DAD) associated with array B so that it can be passed to the multicast structured communication primitive at run-time. The DAD has sufficient information for the communication primitives to compute all the necessary information including local bounds, distributions, global shape, etc. Line 4 shows a broadcast along dimension 2 of the logical processor grid by the processors owning elements B(I, 3), 1 ≤ I ≤ N.

In distributed memory MIMD architectures, there is typically a non-trivial communication latency or startup cost. Hence, it is attractive to vectorize messages to reduce the number of startups. For unstructured communication, this optimization can be achieved by performing the entire preprocessing loop before communication so that the schedule routine can combine messages. The preprocessing loop is also called the “inspector” loop [9, 17].

**EXAMPLE 2 (Gather).** Consider the statement

```plaintext
FORALL (I=1:N) A(I) = B(V(I))
```

The array B is marked as requiring gather communication since the subscript can only be known at runtime. The receiving processors can know what non-local data they need from other processors, but a processor may not know what local data it needs to send to other processors. For simplicity, in this example we assume that the indirection array V is replicated. If it is not replicated, the indirection array must also be communicated to compute the receive list on each processor.

![TABLE I](https://example.com/table1.png)

<table>
<thead>
<tr>
<th>Steps</th>
<th>(lhs, rhs)</th>
<th>Comm. primitives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(i, s)</td>
<td>multicast</td>
</tr>
<tr>
<td>2</td>
<td>(i, i+c)</td>
<td>overlap_shift</td>
</tr>
<tr>
<td>3</td>
<td>(i, i-c)</td>
<td>overlap_shift</td>
</tr>
<tr>
<td>4</td>
<td>(i, i+s)</td>
<td>temporary_shift</td>
</tr>
<tr>
<td>5</td>
<td>(i, i-s)</td>
<td>temporary_shift</td>
</tr>
<tr>
<td>6</td>
<td>(d, s)</td>
<td>transfer</td>
</tr>
<tr>
<td>7</td>
<td>(i, d)</td>
<td>no_communication</td>
</tr>
<tr>
<td>8</td>
<td>(i, f0)</td>
<td>precomp_read</td>
</tr>
<tr>
<td>9</td>
<td>(f0, i)</td>
<td>postcomp_write</td>
</tr>
<tr>
<td>10</td>
<td>(i, V(i))</td>
<td>gather</td>
</tr>
<tr>
<td>11</td>
<td>(V(i), i)</td>
<td>scatter</td>
</tr>
<tr>
<td>12</td>
<td>(i, unknown)</td>
<td>gather</td>
</tr>
<tr>
<td>13</td>
<td>(unknown, i)</td>
<td>scatter</td>
</tr>
</tbody>
</table>

*Note: (c: compile time constant, s, d: scalar, f: invertible function, V: an indirection array.)*
1 count=1
2 call set_BOUND(lb, ub, st, 1, N, 1)
3 DO I=lb, ub, st
4 receive_list(count)=global_to_proc(V(i))
5 local_list(count) = global_to_local(V(i))
6 count=count+1
7 END DO
8 isch = schedule2(receive_list, local_list, count)
9 call gather(isch, temp, B)
10 count=1
11 DO I=lb, ub, st
12 A(I) = temp(count)
13 count= count+1
14 END DO

Once the scheduling is completed, every processor knows exactly which non-local data elements it needs to send to (and receive from) other processors. The task of schedule2 is to determine exactly which send and receive communications must be carried out by each processor. The scheduler first figures out how many messages each processor will have to send and receive during the data exchange. Each processor computes the number of elements (receive_list) and the location index of each element it needs from all other processors. In schedule2 routine, processors communicate to combine these lists (a fan-in type of communication). At the end of this processing, each processor contains the send and receive list. After this point, each processor transmits to the appropriate processors a list of required array elements (local_list). Each processor now has the information required to set up the communication schedule.

The schedule isch can also be used to carry out identical patterns of data exchanges on several different, but identically distributed arrays or array sections. The same schedule can be reused repeatedly to carry out a particular pattern of data exchange on a single distributed array. In these cases, the cost of generating the schedules can be amortized by executing it only once. This analysis can be performed at compile time. Hence, if the compiler recognizes that the same schedule can be reused, it does not generate code for scheduling but passes a pointer to the already existing schedule.

The gather and scatter operations are powerful enough to provide the ability to read and write distributed arrays with vectorized communication facility. These two primitives are available in PARTI (Parallel Automatic Runtime Toolkit at ICASE) [9] designed to efficiently support irregular patterns of distributed array accesses. PARTI and other communication primitives and intrinsic functions form the run-time support system of our Fortran 90D compiler.

6. RUN-TIME SUPPORT SYSTEM

The Fortran 90D/HPF compiler relies on a very powerful run-time support system. The run-time support system consists of functions that can be called from the node programs of a distributed memory machine. Intrinsic functions support many of the basic data parallel operations in Fortran 90. They not only provide a concise means of expressing operations on arrays, but also identify parallel computation patterns that may be difficult to detect automatically. Fortran 90 provides intrinsic functions for operations such as shift, reduction, transpose, reshape, and matrix multiplication. The intrinsic functions that may induce communication can be divided into five categories as shown in Table II.

The first category requires data to be transferred using fewer overhead structured shift communications operations. The second category of intrinsic functions require computations based on local data followed by the use of a reduction tree on the processors involved in the execution of the intrinsic function. The third category uses multiple broadcast trees to spread data. The fourth category is implemented using unstructured communication patterns. The fifth category is implemented using existing research on parallel matrix algorithms [11]. Some intrinsic functions can be further optimized for the underlying hardware architecture.

Table III presents a sample of performance numbers for a subset of the intrinsic functions on iPSC/860. A detailed performance study is presented in [1]. The times in the table include both the computation and communi-
TABLE III
Performance of Some Fortran 90D Intrinsic Functions (Time is in Milliseconds)

<table>
<thead>
<tr>
<th>Nproc</th>
<th>ALL (1K × 1K)</th>
<th>ANY (1K × 1K)</th>
<th>MAXVAL (1K × 1K)</th>
<th>PRODUCT (256K)</th>
<th>DOT PRODUCT (256K)</th>
<th>TRANSPOSE (512 × 512)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>580.6</td>
<td>606.2</td>
<td>658.8</td>
<td>90.1</td>
<td>164.8</td>
<td>299.0</td>
</tr>
<tr>
<td>2</td>
<td>291.0</td>
<td>303.7</td>
<td>330.4</td>
<td>50.0</td>
<td>83.0</td>
<td>575.0</td>
</tr>
<tr>
<td>4</td>
<td>146.2</td>
<td>152.6</td>
<td>166.1</td>
<td>25.1</td>
<td>42.2</td>
<td>395.0</td>
</tr>
<tr>
<td>8</td>
<td>73.84</td>
<td>77.1</td>
<td>34.1</td>
<td>13.1</td>
<td>22.0</td>
<td>213.0</td>
</tr>
<tr>
<td>16</td>
<td>37.9</td>
<td>39.4</td>
<td>43.4</td>
<td>7.2</td>
<td>12.1</td>
<td>121.0</td>
</tr>
<tr>
<td>32</td>
<td>19.9</td>
<td>20.7</td>
<td>23.2</td>
<td>4.2</td>
<td>7.4</td>
<td>69.0</td>
</tr>
</tbody>
</table>

cation times for each function. For most of the functions we were able to obtain almost linear speedups. In the case of the TRANSPOSE function, going from one processor to two or four actually results in an increase in the time due to communication requirements. However, for larger size multiprocessors the times decrease, as expected.

Arrays may be redistributed across subroutine boundaries. A dummy argument that is distributed differently from its actual argument in the calling routine is automatically redistributed upon entry to the subroutine by the compiler, and is automatically redistributed back to its original distribution at subroutine exit. These operations are performed by the redistribution primitives which transform from block to cyclic or vice versa.

When a distributed array is passed as an argument to some of the run-time support primitives, it is also necessary to provide information such as its size, distribution among the nodes of the distributed memory machine, etc. All this information is stored into a structure called distributed array descriptor (DAD) [1].

7. EXPERIMENTAL RESULTS

To illustrate the performance of our compiler, we present benchmark results from four programs and the first 10 Livermore loop kernels. Gauss solves a system of linear equations with partial pivoting. Nbody program simulates the universe using the algorithm in [11]. Optip program predicts the stock option pricing using stochastic volatility European model. Pi program calculates the value of \( \pi \), using numerical integration. The Livermore kernels are 24 loops abstracted from actual production codes that have been widely used to evaluate the performance of various computer systems. Data for all programs were block distributed and were written outside of the compiler group at NPAC by experienced message passing programmers.

Tables IV and V show the performance of compiler generated codes (F90D/HPF) and hand-written if77 + MP code. The tables contain data from running these programs with a varying number of processors on Intel iPSC/860. The compiler generated codes and hand-written codes use the Express message passing library. Timings were taken using extime() function having an accuracy of one microsecond. The programs were compiled by using Parasoft Express Fortran compiler, which calls Portland Group if77 release 4.0 compiler with all optimizations turned on (-04).

We observe that the performance of the compiler generated codes are usually within a factor of 2 of the handwritten codes. This is due to the fact that an experienced

TABLE IV
Comparison of the Execution Times of the Hand-Written Code and Fortran 90D Compiler Generated Code for Several Applications

<table>
<thead>
<tr>
<th>Program</th>
<th>Problem Size</th>
<th>Number of PEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauss Hand</td>
<td>1024 × 1024</td>
<td>1</td>
</tr>
<tr>
<td>Gauss F90D</td>
<td>1024 × 1024</td>
<td>1</td>
</tr>
<tr>
<td>Nbody Hand</td>
<td>1024 × 1024</td>
<td>1</td>
</tr>
<tr>
<td>Nbody F90D</td>
<td>1024 × 1024</td>
<td>1</td>
</tr>
<tr>
<td>Option Hand</td>
<td>8192</td>
<td>4</td>
</tr>
<tr>
<td>Option F90D</td>
<td>8192</td>
<td>4</td>
</tr>
<tr>
<td>Pi Hand</td>
<td>65536</td>
<td>1</td>
</tr>
<tr>
<td>Pi F90D</td>
<td>65536</td>
<td>1</td>
</tr>
</tbody>
</table>

Note. (Intel iPSC/860, time is in seconds.)

TABLE V
Comparison of the Execution Times of the Hand-Written Code and Fortran 90D Compiler Generated Code for the First 10 Livermore Loop Kernels

<table>
<thead>
<tr>
<th>Loop number</th>
<th>Type of Application</th>
<th>F90D/HPF</th>
<th>Hand</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Hydrodynamics</td>
<td>2.545</td>
<td>2.550</td>
<td>0.9980</td>
</tr>
<tr>
<td>2.</td>
<td>Incomplete Cholesky</td>
<td>11.783</td>
<td>10.440</td>
<td>1.1286</td>
</tr>
<tr>
<td>3.</td>
<td>Inner product</td>
<td>3.253</td>
<td>3.249</td>
<td>1.0012</td>
</tr>
<tr>
<td>4.</td>
<td>Banded linear equations</td>
<td>5.139</td>
<td>5.212</td>
<td>1.0000</td>
</tr>
<tr>
<td>5.</td>
<td>Tridiagonal elimination</td>
<td>30928.6</td>
<td>30897.7</td>
<td>1.0011</td>
</tr>
<tr>
<td>6.</td>
<td>Linear recurrence relations</td>
<td>1849.1</td>
<td>1886.5</td>
<td>0.9901</td>
</tr>
<tr>
<td>8.</td>
<td>A.D.I</td>
<td>38.656</td>
<td>20.038</td>
<td>1.9291</td>
</tr>
<tr>
<td>9.</td>
<td>Numerical Integration</td>
<td>2.255</td>
<td>2.441</td>
<td>0.9238</td>
</tr>
</tbody>
</table>

Note. Data size is 16K real. (A 16 node Intel iPSC/860, time is in milliseconds.)
programmer can incorporate more optimizations than our compiler currently does. For example, a programmer can combine or eliminate some of the communication or some of the intra-processor temporary copying. The compiler uses a more generic packing routine, whereas a programmer can combine communication for the same source and destination for different arrays. Another observation is that our run-time system shift routine is slower than the programmer’s shift routines.

8. SUMMARY OF RELATED WORK

Callahan and Kennedy [6] proposed distributed-memory compilation techniques based on data-dependence driven program transformations. These techniques were implemented in a prototype compiler in the ParaScope programming environment. Currently, a Fortran 77D compiler is being developed at Rice [16]. The Fortran 77D compiler introduces and classifies a number of advanced optimizations needed to achieve acceptable performance; they are analyzed and empirically evaluated for stencil computations. SUPERB [25] is a semi-automatic parallelization tool designed for MIMD distributed-memory machines. It supports arbitrary user-specified contiguous rectangular distributions, and performs dependence analysis to guide interactive program transformations. KALI [17] is the first compiler system that supports both regular and irregular computations on MIMD machines. KALI requires that the programmer explicitly partition loop iterations onto the processor grid. An inspector/executor strategy is used for run-time preprocessing of the communication for irregularly distributed arrays. Dataparallel C [14] is a variant of the original C* programming language, designed by Thinking Machines Corporation for its Connection Machines processor array. Data parallel C extends C to provide the programmer access to a parallel virtual machine. ARF is a compiler for irregular computations [23]. Saltz et al. describe and experimentally characterize ARF compiler and runtime support procedures that embody methods capable of handling a wide range of irregular problems in scientific computing. Many techniques, especially the unstructured communication of the Fortran 90D/HPF compiler are adapted from the ARF compiler. The ADAPT system [20] compiles Fortran 90 for execution on MIMD distributed memory architectures. The ADAPTOR [5] is a tool that transforms data parallel programs written in Fortran with array extensions and layout directives to explicit message passing. Li and Chen [18] describe general compiler optimization techniques that reduce communication overhead for Fortran-90 implementation on massively parallel machines. Our compiler uses pattern matching techniques to detect communication similar to Li and Chen’s. Sabot [22] describes the techniques used by the CM compiler to map the fine-grained array parallelism of languages such as Fortran 90 and C* onto the Connection Machine architectures.

9. SUMMARY AND CONCLUSIONS

Fortran 90D/HPF is a language that incorporates parallel constructs and allows users to specify data distributions. In this paper, we have presented a design for a Fortran 90D/HPF compiler for distributed memory machines. Specifically, techniques for the processing of distribution directives, computation partitioning, communication detection, and generation were presented. Our design is both efficient and portable. We presented preliminary performance results from our compiler.

We believe that the methodology presented in this paper to compile Fortran 90D/HPF can be used by the designers and implementors of the HPF compiler.

ACKNOWLEDGMENTS

We are grateful to Parasoft for providing the Fortran 90 parser and Express, without which the prototype compiler could have been delayed. We thank the other members of our compiler research group: R. Bordawekar, R. Ponnumay, R. Thakur, and J. C. Wang for their contribution to the project including the development of the run-time library functions, testing, and help with programming. We also thank K. Kennedy, C. Koelbel, C. Tseng, and S. Hiranantam of Rice University. Finally, special thanks to S. Saltz and his group at Maryland University for many inspiring discussions and inputs that have greatly influenced this work as well as for providing us with PARTI runtime system.

This work was supported by ARPA under Contract DABT63-91-C-0028. The content of the information does not necessarily reflect the position or the policy of the government and no official endorsement should be inferred. Alok Choudhary is also supported by an NSF Young Investigator Award, CCR-9357840.

REFERENCES

Alok Choudhary received his Ph.D. from University of Illinois, Urbana-Champaign, in electrical and computer engineering, in 1989. M.S. from University of Massachusetts, Amherst, in 1986, and B.E.(Hons.) in electrical and electronics engineering from Birla Institute of Technology and Science, Pilani, India, in 1982. He joined the Department of Electrical and Computer Engineering at Syracuse University in 1989, where he is currently an associate professor. He was a visiting scientist at IBM, T. J. Watson Research Center during the summers of 1987 and 1988. He worked as a system analyst and designer for 1982–1984. His main research interests are in parallel and distributed processing, software development environments for parallel computers including compilers and runtime support, parallel computer architectures, parallel I/O, and computer vision. He has published over 50 journal and conference papers in the above areas. He has also authored a book Parallel Architectures and Parallel Algorithms for Integrated Vision Systems published by Kluwer Academic, 1990. He was a program co-chair for International Conference on Parallel Processing, 1993. He served as a guest editor for IEEE Computer and Journal of Parallel and Distributed Computing. He is currently a subject-area editor of Journal of Parallel and Distributed Computing. He is a member of IEEE Computer Society and the Association for Computing Machinery. He received an IEEE Engineering Foundation award in 1990. Alok Choudhary received the NSF Young Investigator Award in 1993.

Geoffrey Fox is an internationally recognized expert in the use of parallel architectures and the development of concurrent algorithms. He leads a major project to develop prototype high-performance Fortran (Fortran90D) compilers. He is also a leading proponent for the development of computational science as an academic discipline and a scientific method. His research on parallel computing has focused on development and use of this technology to solve large scale computational problems. Fox directs ACTION-NYS which is focused on accelerating the introduction of parallel computing into New York state industry. He co-authored Solving Problems on Concurrent Processors and edits Concurrency: Practice and Experience and the International Journal of Modern Physics: C. Fox earned his Ph.D. in theoretical physics from Cambridge University in 1967. His research experience includes work at the Institute for Advanced Study at Princeton; Lawrence Berkeley Laboratory; Cavendish Laboratory at Cambridge; Brookhaven National Laboratory; and Argonne National Laboratory. He has served as Dean for Educational Computing and Assistant Provost for Computing at Caltech. Fox is currently professor of Computer Science and Physics at Syracuse University and Director of the Northeast Parallel Architectures Center.

Tomasz Haupt received the masters degree in Physics from Jagiellonian University, Krakow, Poland, in 1981, and a Ph.D. in Physics from Institute of Nuclear Physics in Krakow, 1985. After several years of research in experimental high-energy physics, he changed his research interest toward computer science. He is currently a research scientist at NPAC, Syracuse University, where he is playing a leading role in the project for developing a Fortran 90D compiler and benchmarking HPF compilers.

Sanjay Ranka is an associate professor in the School of Computer Science at Syracuse University, where he has been on the faculty since 1988. He received his B.Tech. in computer science and engineering from Indian Institute of Technology, Kanpur in 1985 and Ph.D. in computer and information science from the University of Minnesota, Minneapolis in 1988. He is a co-author of the book Hypercube Algorithms with Applications to Image Processing and Pattern Recognition (Springer Verlag, 1990). He is one of the project leaders on Fortran 90D/HPF compiler development at Syracuse. His main research areas include the design and analysis of parallel algorithms, models of parallel computation, compilers and software environments for parallel machines, high performance computing and neural networks.
MIN-YOU WU received the M.S. degree from the graduate school of Academia Sinica, Beijing, China, and the Ph.D. degree from Santa Clara University, California. Before he joined the Department of Computer Science, State University of New York, Buffalo where he is currently an assistant professor, he has held various positions at University of Illinois at Urbana-Champaign, University of California at Irvine, Yale University, and Syracuse University. His research interests include parallel operating systems, compilers for parallel computers, programming tools, and application of parallel systems. He has published papers in the area of parallel computing and VLSI design. He is a member of IEEE.

Received April 1, 1993; revised August 24, 1993; accepted October 26, 1993