Department of Electrical and Computer Engineering
University of Colorado
Boulder, Colorado

by
Harry F. Jordan
Muhammad S. Benten
Norbert S. Arenstorf
and
Aruna V. Ramanan

Computer Systems Design Group
Department of Electrical and Computer Engineering
University of Colorado
Boulder, Colorado 80309-0425

Revised
June 1987

This work was supported in part by Encore Computer Corporation, by NASA Langley Research Center under NAG-1-540, and by the Office of Naval Research under N00014-86-K-0204.
TABLE OF CONTENTS

I. Introduction 1

II. Description of the Force Macros: 4
   A. Macros Specifying Program Structure 5
   B. Variable Declarations 9
   C. Parallel Execution 12
   D. Synchronization 18

III. Restrictions on the Force Macros 22

IV. How to Invoke the Force 23
   A. Flex/32 (Flexible Computer Corp.) 23
   B. Multimax (Encore Computer Corp.) 24
   C. Balance (Sequent Computer Corp.) 25

V. Sample Program Listing 26

References 29
I. Introduction

The principle of global parallelism in parallel programming was introduced by Jordan[1], through a set of FORTRAN macros called the Force macros. These macros support the construction of programs to be executed in parallel by a Force of processes. The number of processes is left unspecified at compile time, but is potentially quite large. The Force provides a FORTRAN style parallel programming language utilizing an extensive set of parallel constructs. The programmer, insulated from process management, is left free to concentrate on the synchronization issues of parallel programming.

A Force module, i.e., a main program or subroutine, consists of regular FORTRAN 77 statements that will be executed by all processes from the first line of the program listing, unless limited by a process synchronization construct. Macros in the Force support parallel execution of DO loops using pre-scheduled and self-scheduled algorithms. The Force includes constructs to allow for mutual exclusion, synchronization, and/or sequential execution when necessary, and constructs for data based control of execution.

A key feature of the Force is its management of variables in an MIMD environment. The Force maintains six classes of variables. Each class in turn supports all the standard FORTRAN variable types: INTEGER, REAL, COMPLEX, etc. The parallelism class of a Force variable determines how it is accessed by different processes and may be Private, Shared, or Async. Each of these three classes will also inherit from FORTRAN the storage class of COMMON among program modules or local to one module, yielding six classes. Private variables have separate instantiations for each component process of the Force. Shared variables have only a single instantiation and are accessible by all processes of the Force. Async, or "asynchronous," variables have a "full/empty" state associated with them, and are shared between processes as well. Interprocess communication is achieved through use of Shared or Async variables. The FORTRAN COMMON mechanism is used to implement Force COMMON. The Force variable declarations are meant to supersede FORTRAN variable declarations. However, ordinary FORTRAN declarations will normally be treated as Private, so that sequential FORTRAN modules may be called from Force modules.

This manual will describe the Force constructs in detail. Force constructs are divided into four categories: program structure, declaration of variables, parallel execution, and synchronization. The programmer using the Force writes a program that is to be executed simultaneously by an arbitrary number of processes. This number is a run-time parameter. The program may consist of many Force modules. A Force module is analogous to a Fortran main program or subroutine, except that a Force module is called and executed by all of the processes. The Force constructs are summarized in TABLE-I. Triangular brackets, < >, are used to indicate required parameters; square brackets, [], are used to indicate optional parameters. An example of a complete Force program is shown later in this manual.
TABLE-I Force Program Constructs

Program Structure:

Force <name> of <# of procs> ident <proc id>
< declaration of variables>
[Externf <Force module name>]
End declarations
<Force program>
Join
END

......

Forcecall <name>([parameters])

......

Forcesub <name>([parameters]) of <# of procs> ident <proc id>
< declarations>
[Externf <Force module name>]
End declarations
<subroutine body>
RETURN
END

Declaration of Variables:

Private <FORTRAN type> <variable list>
Private Common /<label>/ <FORTRAN type> <variable list>

Shared <FORTRAN type> <variable list>
Shared Common /<label>/ <FORTRAN type> <variable list>

Async <FORTRAN type> <variable list>
Async Common /<label>/ <FORTRAN type> <variable list>
### TABLE-I Force Program Constructs (continued)

**Parallel Execution:**
- **Pcase on** `<variable>`
  ```
  [Usect]
  [Csect (<condition>)]
  End pcase
  ```
- **Scase**
  ```
  [Csect (<condition>)]
  <code block>
  [Usect]
  End scase
  ```

- **Presched Do** `<n> <var> = <i1>,<i2>,<i3>`
  ```
  <loop body>
  ```
- **Selfsched Do** `<n> <var> = <i1>,<i2>,<i3>`
  ```
  <loop body>
  ```

- **Pre2do** `<n> <var1> = <i1>,<i2>,<i3>; <var2> = <j1>,<j2>,<j3>`
  ```
  <doubly indexed loop body>
  ```
- **Self2do** `<n> <var1> = <i1>,<i2>,<i3>; <var2> = <j1>,<j2>,<j3>`
  ```
  <doubly indexed loop body>
  ```

**Synchronization:**
- **Barrier**
  ```
  <code block>
  End barrier
  ```
- **Critical** `<lock-var>`
  ```
  <code block>
  ```
- **Void** `<async variable>`
  ```
  Produce <async variable> = <expression>
  ```
- **Consume** `<async variable> into <variable>`
- **Copy** `<async variable> into <variable>`
  ```
  ... Isfull(<async variable>) ...
  ```
II. Description of the Force Macros

The macros are divided into four groups: program structure, variable declaration, parallel execution, and synchronization. The user of the Force macros writes a single parallel main program, zero or more parallel Force subroutines, and zero or more single stream subroutines to be executed by a single process. When writing the parallel main program and parallel subroutines, the macros given in the previous Table and described below may be used. The single stream subroutines and all of the code except the macros in the parallel routines are in FORTRAN 77 and familiarity with that language is assumed.

The number of processes executing a Force program is a parameter that the user will supply at run time. What actually happens is that execution of a Force program begins with a "driver" routine. The driver will determine the number of processes, create these processes, and then transfer control to the user main program. This procedure is invisible to the user and programmer.

Two terms are used when referring to the parallel execution macros. These terms are "pre-scheduling" and "self-scheduling." Pre-scheduling refers to a division of labor (usually based on the local process index) that is fixed at compile time and independent of the actual work being done. Self-scheduling refers to a dynamic, run time allocation of work to processes. Self-scheduling is more sophisticated, and regulates the work load better; but it requires greater overhead.

We have adopted the following convention: the first Force keyword to appear on a line must have the first letter capitalized with the remaining letters in lower case. Additional keywords on the same line are case insensitive. For example, Barrier would be recognized by the Force preprocessor, but barrier or BARRIER would not. A pattern matching preprocessor is used, and this convention makes confusion between Force keywords and FORTRAN variable names less likely.

Syntactically, the Force macros adhere to FORTRAN standards. A few differences between the Force macros and standard FORTRAN syntax exist; these will be given later in the restrictions section.
II A. Macros Specifying Program Structure

**Force**

The **Force** macro declares the start of a parallel main program and has the following syntax:

```
Force <name> of <nproc> ident <me>
```

The **Force** statement sets up the parallel environment. All processes begin execution from this point on, until they are terminated by the **Join** statement. `<nproc>` and `<me>` are both user named integer variables, with `<nproc>` containing the number of processes in the Force, and `<me>` containing a unique identifier for each process (between 1 and `<nproc>`). `<nproc>` and `<me>` will be declared automatically. Values are assigned automatically to `<nproc>` and `<me>`, but these values must not be changed by the user program.

The **Force** main program ends with a **Join** statement usually followed by the FORTRAN END statement. The **Join** statement terminates all but one of the Force of processes. This last process will return control to the Force driver program. An example:

```
Force MYFORCE of COUNT ident MYINDEX
    <declarations>
End declarations

C Force body with

C COUNT - is a user named shared integer
C variable containing the number
C of processes executing the program.

C MYINDEX- is a user named private integer
C variable that contains a unique
C index for each process, numbered
C between 1 and count.

Join
END
```

**End declarations**

This macro call terminates the declarations section of a Force module and begins its executable code. It marks the place to insert declarations generated automatically by the macros and may generate some executable code. **End declarations** must follow the last declaration statement and precede the first executable statement of a Force module.

Some examples using the **End declarations** macro are given on the pages describing the **Force** and **Forcesub** macros. Please note, every **Force** or
Forcesub statement must have exactly one End declarations statement following it at some point in the program listing for that module.

Join

Join terminates execution of the parallel main program. It is an executable statement, but is listed with the macros determining program structure because it is, in some sense, the inverse of the Force statement. Instead of creating a Force of processes, Join will terminate all processes except the last one to reach it. This last process returns to the Force driver program, where it too will be terminated. Note, the non-executable FORTRAN END statement is still necessary.

Forcesub

The Forcesub statement declares the start of a parallel subroutine and has the general form:

```
Forcesub <name>(<parameter list>) of <nproc> ident <me>
```

This statement is roughly analogous to the Force statement. Each process will maintain its local copy of its process index, <me>, from the calling module; however, this index may be renamed in the Forcesub header. Declarations including Private, Private Common, Shared, Shared Common, Async, or Async Common statements may come between a Forcesub statement and the following End declarations. There is no special Force keyword to terminate a parallel subroutine. The Fortran RETURN statement is used to return control to the calling module. The arguments passed to a Forcesub via the parameter list should be declared using only normal FORTRAN declarations. Such arguments retain the parallelism class, Private or Shared, with which they were defined in the calling module. Current implementations do not support Asynchronous variables passed as parameters. The following is an example of a Forcesub:
MATRIX MULTIPLICATION SUBROUTINE:  \( C = A \times B \) --

Forcesub \( \text{MULT}(A,B,C,N1,N2,M1) \) of NPROCS ident ME

INTEGER  \( N1,N2,M1 \)
REAL  \( A(N1,N2), B(N2,M1), C(N1,M1) \)
Private INTEGER  \( I,J,K \)
End declarations

C Initialize \( C \) ...

Pre2do 100  \( I=1,N1 \);  \( J=1,M1 \)
\( C(I,J) = 0.0 \)
100 End presched do

C The multiplication process ...

Presched DO 300  \( I=1,N1 \)
  DO 200  \( J=1,M1 \)
    DO 200  \( K=1,N2 \)
    C\( (I,J) = C(I,J) + A(I,K) \times B(K,J) \)
200 End presched DO
300 End RETURN
END

This parallel subroutine can be called with call statement as follows:

Shared REAL  \( A(100,50), B(50,100), C(100,100) \)
Private N1, N2, M1
End declarations

Forcecall \( \text{MULT}(A,B,C,N1,N2,M1) \)

\textbf{Externf}

The syntax of this macro is as follows:

\textbf{Externf} <Force module name list>

\textbf{Externf} is used to inform the Force compiler/preprocessor about external \textbf{Forcesub} modules that are called using \textbf{Forcecall}. "External modules" refer only to Force modules that are not included in the same file as the Force main program. Modules defined below the main Force program (within the same file) are not required to be declared \textbf{Externf}. This feature preserves the "separate compilation" feature of the FORTRAN language. When a list of external module names is specified using \textbf{Externf}, names in the list should be separated by commas. Some examples:
The \textit{Externf} statement is placed in the declarations section of a \textit{Force} program. \textit{Externf} may appear in any \textit{Force} module that has itself been declared \textit{Externf}. Consider the following example. \textit{Force} modules A, B, and C each appear in separate files which are perhaps to be compiled separately. If the \textit{Force} main program, A, calls \textit{Forcesub} B, which in turn calls \textit{Forcesub} C, then A must declare B using \textit{Externf}, and B would declare C as \textit{Externf}. The point is that as long as C is declared \textit{Externf} in B, which is declared in A, then A need not declare C as \textit{Externf}. Multiple declarations, while not required, are allowed.

\textit{Forcecall}

The \textit{Forcecall} executable statement is used to invoke parallel subroutines that have been declared as named \textit{Forcesub} modules.

\textit{Forcecall} (<parameter list>)

The entire \textit{Force} of processes will jump to and execute the parallel subroutine. However, \textit{Forcecall} does not cause synchronization. \textit{Forcecall} differs from the regular FORTRAN \textsc{call} only in that provisions are made to automatically pass the local process identifier \texttt{<me>}. Normal Fortran scope rules apply to \textit{Force} variables. Note, Async variables may not be included in the parameter list, but may be passed through an \textit{Async Common} block instead.
II B. Variable Declarations

The implementation of the Force as a preprocessor, which does not construct a symbol table, requires that all type information be included in the Private or Shared declarations, so that it is available during the preprocessing of that statement. It should be noted that FORTRAN IMPLICIT typing of variables is allowed under the Force, and that all implicitly typed variables will be of Force variable class Private.

**Private**

*Private <type> <variable list>*

When a variable is declared Private, then each process of the Force maintains its own storage space for that variable, even though the variable is named only once in the main program listing.

For example:

```
Private DOUBLE PRECISION X (100,100)
Private INTEGER  I, J, K
Private CHARACTER*80 STRING1
```

Such variables are normally used for arithmetic temporaries or index values which have distinct values for each process of the Force.

**Private Common**

A Private Common variable is Private in the sense defined above, but it may be Common between Force modules. This declaration would appear, with the variables specified in the same order, in each of the modules that wished to include the Common variables. The syntax is as follows:

*Private Common /<label>/ <type> <variable list>*

Unlike FORTRAN 77, Force Common variables are typed within the same statement that declares them to be Common. For example:

```
Private Common /MYCOPY /REAL TIME(15)
Private Common /MYCOPY /INTEGER POS, SPEED
Private Common /GRID /COMPLEX X, Y
```

From the example, we can see that variables of different type may be combined within the same Common block, but this requires different declaration statements. **As in FORTRAN 77, it is the programmers responsibility, to insure that all Force modules that use a given COMMON block, specify the variables of that COMMON block in the proper order.** Also note that arrays are dimensioned on this line. FORTRAN "blank COMMON" is not allowed.
**Shared**

When a variable is declared `Shared`, then only one copy of that variable is maintained by all of the processes in the Force. In this manner, multiple processes may operate on and communicate through shared memory locations. Care must be taken when multiple processes try to modify a `Shared` variable all at once. Normally, one would modify a `Shared` variable only within a critical section of the program. Regular FORTRAN declarations follow the `Shared` keyword. The syntax is as follows:

```
Shared <type> <variable list>
```

For example,

```
Shared INTEGER I, J
Shared REAL A(800), B(800)
```

This example declares I and J to be shared integers and declares A and B to be real vectors of the specified dimension.

**Shared Common**

This statement has the following syntax:

```
Shared Common /<label>/ <type> <variable list>
```

A `Shared Common` variable is `Shared` between processes as defined above. In addition, `Shared Common` variables may be common between Force modules. That is to say, different processes in different Force modules (subroutines) all have access to the same variable. Again, as in `Private Common`, the type of a variable is declared on the same line with the `Common` declaration. Variables of different type may be combined within the same `Shared Common` block, but this will require the use of several declaration statements. Once again, as in FORTRAN 77, it is the programmer's responsibility to preserve the ordering of variables in a Common block. An example:

```
Shared Common /PENPOS/ DOUBLE PRECISION X,Y
Shared Common /PENCOL/ INTEGER COLOR(8)
```

**Async**

This statement has the general form:

```
Async <type> <variable list>
```

Asynchronous variables are shared between processes; that is, they have only one instantiation for all processes. The distinguishing feature of an `Async` variable is its "full/empty" state. The use of these variables is governed by the `Produce`, `Consume`, `Copy`, `Void`, and `Isfull` macros which are described later. Briefly, an asynchronous variable may be `Consumed` or `Copied` only if it is "full," and `Produced` only if it is "empty." Thus, `Async` variables may be used to implement data based synchronization.
For example, the following Force program fragment illustrates the use of this macro:

```
Async INTEGER I
Async REAL  X, Y, Z
.
End Declarations
.
Barrier
Void X
End barrier
.
Produce X = local_stuff
.
```

**Async Common**

This statement has the general form:

```
Async Common /<label>/ <type> <variable list>
```

Async Common variables have all the properties of Async variables described above. In addition, they may be Common between Force modules that include this designation.
II C. Parallel Execution

Parallel execution is specified using macros related to the DOALL and parallel case constructs. The two constructs are similar in the extent that both involve segments of code that can be executed in any order. DOALL applies to independent instances of the loop body for different loop index values. The parallel case construct applies to different single stream code blocks which are mutually independent. The distribution of work may either be pre-scheduled or self-scheduled.

Pcase

This statement establishes a pre-scheduled parallel case construct which starts with either of the following constructs:

Pcase

or

Pcase on <var>

The construct consists of a series of independent sections of code, each of which is to be executed by a single process. The sections are delimited by a Pcase, zero or more Usect, zero or more Csect and an End pcase statements.

The construct assigns its own private integer variable unless the variable <var> is used explicitly in the second form of the construct. In such cases it the programmer's responsibility to declare <var> as a Private Integer variable. In either case the execution of multiple cases is pre-scheduled using this variable which will be assigned the value i during the execution of the ith_case. The jth_case of a Pcase will be executed by the process with local_id equal to ((j-1) mod np)+1, where np is the number of processes.

If there are more processes in the Force than there are code sections then all code sections will be executed simultaneously. Otherwise some of the sections will be executed sequentially by the same process. For this reason care must be taken while using asynchronous variables (producer/consumer) within a Pcase. A parallel case with only one code section is similar to a barrier in that the code is executed by a single process, but differs in that no synchronization of other processes occurs.

There are slight variations in the implementation of the parallel case construct. An example of the simplest implementation is given below. Here each task represents a group of regular (single stream) FORTRAN 77 instructions.

Pcase

<task A>

Usect

<task B>

Usect

<task C>

End pcase
If any of the single stream code sections are conditional, the Csect statement can be used. The condition is built into the Csect construct. An example when all code sections are conditional is given below.

```
Pcase
  Csect (<condition>)
  <task A>
  Csect (<condition>)
  <task B>
  Csect (<condition>)
  <task C>
End pcase
```

Csect and Usect can both appear in a parallel case construct. The sections on Csect and Usect outline the variation in implementation of parallel case construct.

**Usect**

This statement separates multiple single stream code sections of a parallel case. When Csect is used to start a conditional case section then Usect is not used to separate it from the previous code section. Also, Usect is not used if there is only one code section.

**Csect**

This statement begins a conditional single stream code section of a parallel case and has the following form:

```
Csect (<condition>)
```

where, <condition> is a FORTRAN condition of the same form allowed in a FORTRAN IF statement.

**End pcase**

The pre-scheduled parallel case construct is terminated by this statement. Note that some processes may proceed past this point while portions of the parallel case are still being executed.

**Scase**

The Scase statement is an alternative to the Pcase statement of a parallel case construct. When a parallel case is initialized by the statement Scase, the allocation of the work is done at the execution time rather than being pre-scheduled. A process receives the next available case section when it finishes the previously assigned section. The other aspects of a self-
scheduled parallel case construct are the same as the pre-scheduled parallel case construct, except that it is terminated by an *End scase* statement instead of *End pcase*.

In contrast to the *Pcase* construct, process synchronization is included to ensure that two instances of a self-scheduled construct, either a parallel case or a parallel DO loop, are not being executed simultaneously.

*End scase*

The self-scheduled parallel case construct is terminated by this statement. Although processes may proceed past this point while portions of the self-scheduled parallel case are still being executed, no process may enter another self-scheduled construct (parallel case or loop) or re-enter this one a second time before all processes have exited.

*Presched DO*

A pre-scheduled parallel loop is introduced by the *Presched DO*, which has the following form:

```
Presched DO <n> <i> = <i1>,<i2>[,<i3>]
```

This statement must have a body such that instances of the body for different values of the local variable <i> are independent and can thus be executed in parallel. Pre-scheduling partitions different values of <i> evenly over processes in a manner fixed at compile time. Pre-scheduled loops are useful when the execution time of the loop body is fairly constant. The step size <i3> is optional and is taken as one if missing.

The parameters <i1>, <i2> and <i3> must be constants or expressions yielding an integer value. These values must be identical for all processes of the Force (i.e., if *Private* variables are in the expressions), and they must remain fixed during execution of the loop. The parallel DO constructs do not nest with each other, however they may be nested (internally or externally) with normal FORTRAN DO loops.

An example:

```
Presched DO 99 J= 1,M1
C(J) = 0.0
99   End presched DO
```

would initialize the the first M1 elements of the vector c to zeros. Note that M1 and the vector c are assumed to have been declared *Shared* or *Shared Common*. Also note that no process synchronization occurs - processes may enter and leave the loop asynchronously.
<n>  End presched DO
This statement terminates the body of a pre-scheduled DO loop. The
statement number <n> must match that on the Presched DO state-
ment.

Selfsched DO
The Selfsched DO statement is an alternative for introducing a parallel
loop and it has the following general form:
Selfsched DO <n>  <i>=<i1>,<i2>,<i3>

The behavior of the Selfsched DO loop is the same as that of a Presched
DO except that the allocation of the work is done at execution time. A
process receives the next unassigned value of <i> when it finishes its
previous iteration. This tends to even the workload over processes when
the execution time of the loop varies significantly for different values of
<i>. The parameters <i1>, <i2> and <i3> must be constants or
expressions yielding an integer value, and this value should remain fixed
during execution of the loop. The implementation generates a Shared
temporary variable to handle the shared loop index. Synchronization is
provided to ensure that the execution of different instances of self-
scheduled loops or cases is not overlapped. This means that the over-
head is higher for self-scheduled loops versus pre-scheduled loops.
As was the case with pre-scheduled loops, the parameters <i1>, <i2>
and <i3> must be constants or expressions yielding an integer value.
These values must be identical for all processes of the Force, and remain
fixed while the loop is executing. The parallel DO constructs do not nest
with each other, however they may be nested (internally or externally)
with normal FORTRAN DO loops.
For example:

Selfsched DO 99 J= 1,M1
  C(J) = 0.0
  IF (J/7 .EQ. J/7.0) CALL HARDWORK(C(J))
99  End selfsched DO

would initialize the the first M1 elements of the vector C to zeros, and
call hardwork if J is a multiple of seven. Note that M1 and the vector C
are assumed to have been declared Shared or Shared Common. Also note
that processes may enter the loop before all have arrived and may leave
the loop before all have finished, but no process may enter another self-
scheduled loop, or re-enter this one a second time, until all have exited.
Processes may also not enter a subsequent self-scheduled case construct
until this self-scheduled construct is complete.
End selfsched DO

This statement ends the body of the self-scheduled DO loop with statement number \(<n>\).

Pre2do

Doubly indexed DO loops are supported as separate constructs within the Force. Semantic considerations dictate that these be implemented with separate constructs rather than to allow nesting of the parallel DO loops.

\[\text{Pre2do } \{n\} \ <i> = <i1>, <i2>, <i3> ; \ <j> = <j1>, <j2>, <j3> \]

Like single-index parallel DO loops, this statement must have a body where instances of the body for different values of the local indices \(<i>\) and \(<j>\) are independent. Pre-scheduling partitions different pairs of values of \(<i>\) and \(<j>\) evenly over processes in a manner fixed at compile time. Step sizes \(<i3>\) and \(<j3>\) are optional, and they are taken as one if missing. For example:

\[
\text{Pre2do 99 J = 1.LIM ; K = 10,1,-1} \\
\text{C(J,K) = A(J,K) + B(J,K)} \\
\text{99 End Presched DO}
\]

Note that LIM and the vectors A, B, and C are assumed to have been declared \textit{Shared} or \textit{Shared Common}, and I and K are \textit{Private}. Again, note that no process synchronization occurs - processes may enter and leave the loop asynchronously.

End presched DO

This statement ends the body of the doubly indexed pre-scheduled DO loop as well. \(<n>\) must match the \(<n>\) given in the \textit{Pre2do} statement.

Self2do

The \textit{Self2do} statement is a self-scheduled version of the doubly indexed DO loop. It has the following form:

\[\text{Self2do } \{n\} \ <i> = <i1>, <i2>, <i3> ; \ <j> = <j1>, <j2>, <j3> \]

Scheduling of the indices is done at execution time; processes receive the “next” pair of indices available when they are ready to perform an iteration of the doubly indexed loop. Self-scheduling regulates the workload among processes at a cost of higher synchronization overhead. When loop iterations require approximately the same amount of execution time, then it is more efficient to use a pre-scheduled DO loop. Once again, there must be no data dependencies between loop bodies for different
<i>, <j> pairs; this is the programmers responsibility.
The parameters <i1> through <i3> and <j1> through <j3> must be integer constants or expressions, which remain fixed during a given execution of the Self2do loop. Overlapping executions are prevented for different instances of doubly indexed, as well as singly indexed, self-scheduled loops.

An example:

```
Self2do 100 I= 1,M1 ; J= 1,M1
  IF (I .NE. J) THEN
    C(I,J) = 0.0
  ELSE
    C(I,J) = DTAN(DOUBLE(J*PI/M1))
  END IF
  100 End selfsched DO
```

Processes may enter the loop before all have arrived and leave before all have finished, but no process may enter a second instance of a self-scheduled loop before all have exited.

<n> End selfsched DO

This statement terminates the body of a doubly indexed self-scheduled DO loop as well. The statement number <n> must match that on the Self2do statement.
II D. Synchronization

Barrier

This statement must be executed by all processes of the Force. When all have reached the Barrier statement, a single process will execute the "body" of the Barrier; the body is defined as the block of code between the Barrier and the End barrier statements. After the body has been executed by a single process, all the processes of the Force will resume execution after the End barrier statement, and they will have been synchronized. Note, it is not necessary for the Barrier to have a body at all, but End barrier is always required.

Example:

Barrier
X = X + 1
End barrier

Barrier synchronization will cause all the processes to wait at the first Barrier statement until the last one arrives. A single process will then execute the body of the Barrier construct, in this case incrementing X by one. After the body has been executed, then all processes continue at once with statements following the End barrier statement.

It is the programmer's responsibility to place Barriers where they make sense. To place a Barrier inside a Pcase causes a deadlock, since not all processes will reach the Barrier, and those that did would hang. Likewise, Barriers within Self or Pre-scheduled DO loops should be avoided. They would also deadlock, unless the number of processes divides evenly into the number of loop iterations.

End barrier

Paired with the previous statement, this one delimits a section of code executed by a single instruction stream. Synchronized parallel execution begins after this statement.

Critical

Mutual exclusion can be accomplished by named critical sections using the Critical construct, which has the following form:

Critical <lock-var>

The critical section is ended by the End critical statement. Use of a Critical section guarantees that only one process will be executing any block of code nested between the Critical and End Critical statements of critical sections with the same <lock-var>.
The user must declare <lock-var> as a Shared variable, preferably of type LOGICAL. This variable is used as a lock and should contain no other value. Two or more critical sections may share the same <lock-var>. Two critical sections on the same <lock-var> cannot execute simultaneously. If one wishes to coordinate activities between Force modules, then the <lock-var> may be a Shared Common variable, declared in those Force modules that wish to use it. For example:

```
Shared Common /IO/ LOGICAL WRITER
End Declarations

Critical WRITER
  WRITE(6,10) ME
  FORMAT(1X,"Me = ",I3)
End critical
```

End critical

This statement is paired with the nearest unmatched preceding Critical statement to delimit a critical section. Nested critical sections are allowed; however there is no automatic deadlock prevention employed if critical sections are improperly nested.

Produce

Produce <async var> = <expr>

If the asynchronous variable <async var> is "empty," Produce will assign the value of the expression <expr> to <async var> and mark <async var> as "full." If <async var> is not "empty," the process currently executing Produce will wait until <async var> becomes "empty" and then make the assignment and mark <async var> as "full." These actions occur atomically. The variable <async var> must have been declared as an asynchronous variable using the Async statement.
Example:

```plaintext
Private REAL YY
Async REAL XX

End Declarations

Barrier
Void XX
End Barrier

YY = 7.0*COS(A+B)
Produce XX = YY + 3

Consume
Consume <async var> into <var2>
If the asynchronous variable is "full," then this macro routine will assign the value of <async var> to <var2> and mark <async var> as "empty." If it is not "full," Consume will wait until <async var> becomes "full," store its value, and mark it as "empty." If multiple processes are executing a Consume statement on the same <async var>, and if the <async var> is "full," then only one consumer process will succeed. The others will have to wait until <async var> is set "full" again (by a Produce) before they will have a chance to succeed. The variable <async var> must have been declared as an asynchronous variable. In most applications, <var2> will be Private. For example:
    Consume XX into YY
```

```plaintext
Copy
Copy <async var> into <var2>
This macro routine will store the value of the asynchronous variable <async var> into <var2> if <async var> is "full," without changing the variable's status. If the variable is "empty," then Copy will wait until <async var> becomes "full," and then return its value, and leave it "full." The variable <async var> must have been declared as an asynchronous variable. For example:
    Copy XX into YY
```
Void

Void <async var>

This macro routine will unconditionally mark the asynchronous variable <async var> as "empty." The variable <async var> must have been declared as an asynchronous variable by the Async statement. Note, asynchronous variables are not necessarily "empty" when declared; normally one would first Void an asynchronous variable before using it in a producer/consumer macro. For example:

```
Void XX
```

Isfull

Isfull( <async var> )

This macro "function" will return the logical state of the asynchronous variable <var>, with TRUE corresponding to "full" and FALSE indicating that the asynchronous variable is "empty." It may be used anywhere that a FORTRAN logical function would be used. The variable <async var> must have been declared as an asynchronous variable by the Async statement. For example:

```
Async REAL XX
Private REAL MYCOPY
End declarations

IF( Isfull(XX) ) THEN
  Consume XX into MYCOPY
ELSE
  <do something else>
END IF
```
III. Restrictions on the Force Macros

The Force macro implementations on the Flex/32, the Encore Multimax and the Sequent Balance adhere to almost all of the FORTRAN standards and elements of style except for the following points:

1. *Barrier, Forcecall,* and *Join,* and all of the macros that specify parallel execution must be executed by all the processes executing the parallel program. Skipping over these constructs by a fraction of the processes may cause an indefinite hang up and unexpected results may be obtained.

2. Branching into or out of a body of a Force construct is not allowed and may not be detected by either the Force preprocessor or the FORTRAN compiler and will lead to unexpected results.

3. Except for the statements closing parallel DO loops, Force statements should not be numbered, and numbered Force statements will not be recognized by the preprocessor and will produce FORTRAN syntax errors. Also, Force statements may not be continued on two or more lines.

4. The Force preprocessor may generate subroutine names using a variation on the name of a given Force module. For this reason, the first five characters of the name of a Force module must uniquely identify that module.

5. Asynchronous variables cannot be passed as parameters to other modules or subroutines and be expected to behave asynchronously. *Async common* must be used for this purpose.

6. FORTRAN BLOCK DATA is currently not supported and thus *Shared* and *Shared Common* variables cannot be initialized statically at compile time.

7. The FORTRAN DATA statement can only be used to initialize *Private* variables.

8. Finally, it should be noted that the line numbers which are referenced by the error messages resulting from using the "force" command refer to the .f files and not to the .src files.
IV. How to Invoke the Force

This section will discuss the UNIX shell scripts, force, forcerun, and preforce, used to invoke the Force. Implementations on three machines will be considered: the Flex/32 (Flexible Computer Corp.), the Multimax (Encore Computer Corp.) and the Balance (Sequent Computer Corp.).

force is the shell command that is used to preprocess, compile and link Force source programs. The force command takes an argument list of files and flags and produces a parallel executable output program. We will adopt the convention that Force source files have a filename ending with a .frc extension. Files in the argument list with a .frc extension will first be preprocessed to expand the Force macros. The resulting files along with the Force driver program and any other files specified will then be compiled and linked.

forcerun is the shell command that is used to execute a Force program. forcerun also specifies the number of component processes to be used by the Force program during that run. forcerun takes two arguments: the first is the name of the Force executable file, and the second is an integer number representing the number of processes (processors on Flex/32) to be used for that run.

preforce command performs only the preprocessing steps, producing FORTRAN .f files from Force .frc files specified in the argument list. The preforce shell script is intended as a debugging convenience, as the f77 compiler used by the force command will give line numbers referring to the .f file when referencing errors.

The force, forcerun, and preforce commands are executable from any directory, and we recommend that frequent users of the Force include aliases for these shell scripts in their .cshrc files or links to them in their own bins. All three commands, when invoked with no arguments, will print a help message illustrating their use. The sections below will describe features and options of the commands that are specific to the Flex/32, the Multimax or the Balance.

IV A. Flex/32 (Flexible Computer Corp.)

The shell scripts, force, forcerun, and preforce, may be found in the /usr/local/force directory on NASA/Langley's Flex/32.

On the Flex/32, the force command uses Flexible's cf77 compiling command, and the Force preprocessor will generate .cf files from .frc files in the argument list. force will accept all options associated with cf77. The Greenhills compiler is automatically selected by force, and cfg.18 is used as a default if no other configuration file is specified. The syntax is as follows.

force [cf77 options] <filename list>

Some examples:

force matmul.frc init.frc subs.f
force -o test.exe -h cfg.8 test1.frc test2.frc
The **forcerun** command is used to execute a Force program. It has the following syntax:

```
forcerun <executable file> <number of processors>
```

For example:

```
forcerun test.exe 18
```

On the Flex/32, **preforce** invokes both the Flexible and Force preprocessors. **preforce** accepts files ending with an `.frc` or `.cf` extension and creates the `.f FORTRAN` equivalents. There are two options. The `-cf` option invokes only the Force preprocessor, creating `.cf` files from `.frc` source files. The `-a` option creates "all files": `.cf`, `.f`, `.su.f`, `.sh.f`, and `.CF.I`. When used without options, **preforce** will create only `.f` files. The syntax is as follows:

```
preforce <filename> [filename,...]
```

An example:

```
preforce thisfile.frc
```

### IV B. Multimax (Encore Computer Corp.)

The shell scripts, **force**, **forcerun**, and **preforce**, may be found in the `/usr/local/unsupp/force` directory on the University of Colorado at Boulder’s Multimax (max). For the Multimax, **force** preprocesses `.frc` files in the argument list producing `.f` files, and then uses the standard `f77` compiler. **force** will accept all options associated with `f77`. The syntax is as follows.

```
force [f77 options] <filename list>
```

An example:

```
force -o matmul.exe matmul.frc x.f
```

The **forcerun** command is used to execute a Force program. It has the following syntax:

```
forcerun <executable file> <number of processes>
```

For example:

```
forcerun matmul.exe 8
```

The **preforce** command performs only the preprocessing steps, producing FORTRAN `.f` files from Force `.frc` input files. The syntax is as follows:

```
preforce <filename> [filename,...]
```

An example:

```
preforce matmul.frc
```
IV C. Balance (Sequent Computer Corp.)

The shell scripts, force, forcerun and preforce, may be found in the /usr/local/unsupp/force directory on the University of Colorado at Boulder's Sequent (tramp). For the Sequent, force preprocesses .frc files in the argument list producing .f files, and then uses the standard FORTRAN (Silicon Valley) compiler. force will accept all options associated with the (NS32000 series Silicon Valley) FORTRAN compiler. The syntax is as follows.

force [fortran options] <filename list>

An example:
force -o matmul.exe matmul.frc x.f

The forcerun command is used to execute a Force program. It has the following syntax:
forcerun <executable file> <number of processes>

For example:
forcerun matmul.exe 8

The prefonce command performs only the preprocessing steps, producing FORTRAN .f files from Force .frc input files. The syntax is as follows:
preforce <filename> [filename...]

An example:
preforce matmul.frc
V. Sample Program Listing

******************************************************************************
* Force demo program
* This program normalizes a square matrix by its largest element.
* An external Force module, INTMAT, is called to initialize the
* matrix. Another Force module, OUTMAT, is called to print the
* final matrix.
******************************************************************************

Force DEMO of NP ident ME
Private REAL PMAX, TEM
Private INTEGER INDEX
Shared REAL X(100,100)
Async REAL ALLMAX
External INTMAT
End declarations

C INTMAT is an external subroutine that will initialize the matrix.
Forcecall INTMAT(X,100)

C Now we must search the matrix for its greatest element...
C ALLMAX holds the current maximum value
C Initialize ALLMAX
Barrier
Void ALLMAX
Produce ALLMAX = 0
End barrier

PMAX = 0

C Preschedule rows of X among processors...
C Each processor finds the maximum of its row in the inner loop.
Presched do 100 I=1,100
DO 200 j=1,100
   TEM = ABS(X(I,J))
   IF (TEM .GT. PMAX) PMAX = TEM
CONTINUE
200
100 End presched do

C The processors communicate to find the overall max of their local max vals.
Consume ALLMAX into TEM
IF (PMAX .GT. TEM) TEM = PMAX
Produce ALLMAX = TEM
C Synchronize ...
Barrier
End Barrier

Copy ALLMAX into PMAX

IF (PMAX .GT. 0) THEN

C Normalize the matrix, dividing the labor on the outer loop.
Presched do 300 I= 1,100
DO 400 J= 1,100
   X(I,J)=X(I,J) / PMAX
400    CONTINUE
300    End presched do

Barrier
End barrier

END IF

C OUTMAT will perform sequential i/o...
Pcase on INDEX
   Call OUTMAT(X,100)
End pcase

Join
END

SUBROUTINE OUTMAT(X,N)
INTEGER N, INDEX
REAL X(N,N)

   DO 10 I= 1,N
      DO 10 J= 1,N
10         write(6,*), I, J, X(I,J)

RETURN
END

**************************************************************************************************************
* Assume that the next program listing is in a separate file.
**************************************************************************************************************

Forcesub INTMAT(MAT,N) of NP ident ME

C This parallel subroutine will initialize the matrix MAT
C to a "test" value.
INTEGER N
REAL MAT(N,N), GEN
End declarations

Presched do 20 I=1,N
   DO 30 J=1,N
   C The sequential function GEN is used to generate values.
      MAT(I,J) = GEN(I,J)
   30 CONTINUE
20 End presched do

RETURN
END

REAL FUNCTION GEN(I,J)
C 0.0 < GEN <= 1000.0
INTEGER I,J
IF ((I+J) .GE. 1) THEN
   GEN = 1000.0 / (I+J)
ELSE
   GEN = 1000.0
END IF
RETURN
END

*******************************************************************************
*******************************************************************************
REFERENCES


A methodology for writing parallel programs for shared memory multiprocessors has been formalized as an extension to the Fortran language and implemented as a macro preprocessor. The extended language is known as the Force, and this manual describes how to write Force programs and execute them on the Flexible Computer Corporation Flex/32, the Encore Multimax and the Sequent Balance computers. The parallel extension macros are described in detail, but knowledge of Fortran is assumed.