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# Force User's Manual

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## 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,  $\langle \rangle$ , 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>
    <code block>
[Usect]
:
[Csect (<condition>)]
:
End pcase

Scase
[Csect (<condition>)]
    <code block>
:
[Usect]
:
End scase

Presched Do <n> <var> = <i1>,<i2>[,<i3>]
    <loop body>
<n> End Presched Do

Selfsched Do <n> <var> = <i1>,<i2>[,<i3>]
    <loop body>
<n> End Selfsched Do

Pre2do <n> <var1> = <i1>,<i2>[,<i3>]; <var2> = <j1>,<j2>[,<j3>]
    <doubly indexed loop body>
<n> End Presched Do

Self2do <n> <var1> = <i1>,<i2>[,<i3>]; <var2> = <j1>,<j2>[,<j3>]
    <doubly indexed loop body>
<n> End Selfsched Do

```

### Synchronization:

```

Barrier
    < code block >
End barrier

Critical <lock-var>
    < code block >
End critical

Void <async variable>
Produce <async variable> = <expression>
Consume <async variable> into <variable>
Copy <async variable> into <variable>
... !sfull( <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*:

C----- MATRIX MULTIPLICATION SUBROUTINE: C=A\*B ---

```
Forcesub 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
200    C(I,J) = C(I,J) + A(I,K)*B(K,J)
300    End presched DO
      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 MULT(A,B,C,N1,N2,M1)
```

### *Externf*

The syntax of this macro is as follows:

*Externf* <Force module name list>

*Externf* is used to inform the Force compiler/preprocessor about external *Forcesub* modules that are called using *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 *Externf*. This feature preserves the "separate compilation" feature of the FORTRAN language. When a list of external module names is specified using *Externf*, names in the list should be separated by commas. Some examples:

Externf INTMAT  
Externf INTMAT, OUTMAT

The *Externf* statement is placed in the declarations section of a Force program. *Externf* may appear in any Force module that has itself been declared *Externf*. Consider the following example. Force modules A, B, and C each appear in separate files which are perhaps to be compiled separately. If the *Force* main program, A, calls *Forcesub* B, which in turn calls *Forcesub* C, then A must declare B using *Externf*, and B would declare C as *Externf*. The point is that as long as C is declared *Externf* in B, which is declared in A, then A need not declare C as *Externf*. Multiple declarations, while not required, are allowed.

*Forcecall*

The *Forcecall* executable statement is used to invoke parallel subroutines that have been declared as named *Forcesub* modules.

*Forcecall* (<parameter list>)

The entire Force of processes will jump to and execute the parallel subroutine. However, *Forcecall* does not cause synchronization. *Forcecall* differs from the regular FORTRAN CALL only in that provisions are made to automatically pass the local process identifier <me>. Normal Fortran scope rules apply to Force variables. Note, Async variables may not be included in the parameter list, but may be passed through an *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 to 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 is 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 *i*th\_case. The *j*th\_case of a *Pcase* will be executed by the process with *local\_id* equal to  $((j-1) \bmod np)+1$ , 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* statement.

*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 overhead 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.

**<n> 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.

**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:

```
Pre2do 99 J= 1,LIM ; K= 10,1,-1
      C(J,K) = A(J,K) + B(J,K)
99      End Presched DO
```

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

**<n> 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 *Pre2do* statement.

**Self2do**

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

**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 programmers 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
10             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:

```
.
.
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

### *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 **.frc** 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.

The **forcerun** command 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.

The **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 **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
```

## 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
Externf 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 currunt 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
200 CONTINUE
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...
      Pease on INDEX
      Call OUTMAT(X,100)
      End pease

      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

*****
*****

```

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