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Code Parallelization with CAPO — A User Manual

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USING CAPO

Contents

1. General Information

1.1. What is CAPO

CAPO (Captools-based Automatic Parallelizer using OpenMP) automates the insertion of compiler directives to facilitate parallel processing on shared memory parallel (SMP) machines. While CAPO is currently integrated seamlessly into CAPTools (developed at the University of Greenwich), CAPO is independently developed at NASA Ames Research Center as one of the components for Legacy Code Modernization (LCM) project. Utilizing the data dependence information produced by CAPTools, CAPO produces either OpenMP or SGI multiprocessing directives for sequential FORTRAN programs with nominal user interaction. Due to the broad support of the OpenMP standard, the generated OpenMP codes can potentially run on a wide range of SMP machines. Generation of a mixed message-passing (e.g. MPI) and OpenMP code is possible because of the integration of CAPO and CAPTools.

The success of CAPO relies on accurate interprocedual data dependence information which is provided by CAPTools. CAPO generates compiler directives in three stages:

1) identification of parallel loops in the outer-most level,
2) construction and optimization of parallel regions around parallel loops, and
3) insertion of directives with a proper list of private, reduction, and shared variables.

Attempts have also been made to identify potential pipeline parallelism (implemented with point-to-point synchronization). Although the user is still expected to inspect the generated code before actual execution, the task has been simplified tremendously by the automation process and the built-in graphic user interface, known as the Directives Browser. The Directives Browser provides tools for user to interact with the parallelization process. It presents information in such a way that the user can easily isolate problematic code sections from the rest of the code and find a solution quickly.

1.2. Distribution and Contact Information

CAPO is currently integrated in CAPTools and distributed directly from NASA Ames Research Center. It is released in a similar way as the standard CAPTools distribution. The distributed executable of CAPO includes all the functionality of CAPTools for generating message-passing programs as well as the capability of producing OpenMP codes. So the user needs only to maintain one copy that is distributed with CAPO to access the functionality of both CAPTools and CAPO.

To require a copy of CAPO, send a request to *capo@nas.nasa.gov*. You will need a license to run CAPTools/CAPO. A test license may be obtained from the CAPTools web site (see below) or by sending email to *captools@gre.ac.uk*. For NASA users, please contact *capo@nas.nasa.gov* directly.

For any feedback and bug report on CAPO, please send to:

CAPO Development Team at *capo@nas.nasa.gov*

For any feedback and user support on CAPTools, please contact:

captools-support@gre.ac.uk or check the web site at *http://captools.gre.ac.uk/*.

For more information on the LCM project, check:

http://www.nas.nasa.gov/Groups/Tools/Projects/LCM.

1.3. Installation and Execution

Once the user has obtained a copy of CAPO in a compressed tar file, extract files by

```
% gunzip -c capo-sgi-1.1.tar.gz | tar xvf -
```

The CAPO distribution is maintained in a similar directory structure as the CAPTools distribution does. For example the executable of CAPO is in

```
captool/bin/{machine}/capo
```

where `{machine}` is `sgi` for SGI machine running IRIX, sun for SUN workstation running Solaris, and `linux_x86` for Intel machine running Linux.

The user should follow the same installation procedure to CAPTools to set up CAPO. For the installation and use of CAPTools, please refer to the web site at *http://captools.gre.ac.uk/*. In summary, the user needs to set up the following environment variables:

`CAPHOME`	– home directory for the CAPTools/CAPO installation
`OPENWINHOME`	– home directory for the XVIEW library
`CAPLIBHOME`	– home directory for CAPLib (not necessary for OpenMP codes).

and add "`$CAPHOME/bin/{machine}`" to the searching path, e.g. in `csh`:

```
setenv CAPHOME /usr/local/captool
setenv OPENWINHOME $CAPHOME/openwin
set path = ($CAPHOME/bin/sgi $path)
```

CAPO is then ready for use.

1.4. How to Use This Manual

The manual is organized into three parts around the use of CAPO:

1) **Using CAPO** – discusses the fundamentals of using CAPO to parallelize codes,
2) **Appendix** – lists detailed references of parameters and the graphic user interface, and
3) **Tutorials** – gives more hands-on experiences.

For major changes in different versions of CAPO, see *WhatsNew* included in the CAPO distribution.

Convention generally followed in this manual:

Italic	address (including email), URL, remarks, emphasis
`Courier`	code list, syntax description, program outputs
Bold	window name, menu name, list name
Bold italic	summary head, menu item
Box	button, setting selection

Throughout this document, we refer *CAPO* to OpenMP generation and the relevant components and *CAPTools* to the rest, but sometimes these two terms are used interchangeably for shared components.

2. Computer-Aided Parallelization Process

The shared memory and distributed memory programming paradigms are two of the most popular models used to transform existing serial codes to a parallel form. For a distributed memory parallelization it is necessary to consider the whole program when using an SPMD paradigm. Data placement is an essential consideration to efficiently use the available distributed memory, while the placement of explicit communication calls requires careful consideration. Nowadays, scalability and high performance are mostly involving hand-written parallel programs using message-passing libraries (e.g. MPI). However, this process is very difficult.

The parallelization on a shared memory system is only relatively easier because of the globally addressable space. The data placement appears to be less crucial than for a distributed memory parallelization. Historically, the lack of a programming standard for using directives and the rather limited performance due to scalability have affected the take-up of the shared memory programming model approach. Significant progress has been made in hardware and software technologies, as a result the performance of parallel programs with compiler directives has also made improvements. The introduction of an industrial standard for shared-memory programming with directives, OpenMP [8], has also addressed the issue of portability.

In general the parallelization process in any case is error-prone, time-consuming and requires a detailed level of expertise. Programming with directives may not necessarily produce a result that enhances performance. In the worst case, the inserted directives can create erroneous results when used incorrectly. While vendors may have provided tools to perform error-checking and profiling, automation in directive insertion is very limited and often failed on large programs, primarily due to the lack of a thorough enough data dependence analysis. Presence of these deficiencies motivated the development of the parallelization tool, CAPO. The tool automatically inserts OpenMP directives in Fortran programs and applies a degree of optimization with nominal user interaction. CAPO is aimed at taking advantage of the detailed interprocedural data dependence analysis provided by Computer-Aided Parallelization Tools (CAPTools) [3], developed by the University of Greenwich, to reduce potential errors made by users and, with nominal help from user, achieve performance close to that obtained when directives are inserted by hand. Our approach is differed from other tools and compilers in two respects: 1) emphasizing the quality of dependence analysis and relaxing much of the time constraint on the analysis; 2) performing directive insertion and preserving the original code structure for maintainability. Translation of OpenMP codes to executables is left to proper OpenMP compilers.

In this section, we outline the OpenMP programming model, give an overview of CAPTools, and then its extension, CAPO, for generating OpenMP programs.

2.1. The OpenMP Programming Model

OpenMP [8] was designed to facilitate portable implementation of shared memory parallel programs. It includes a set of compiler directives and callable runtime library routines that extend Fortran, C and C++ to support shared memory parallelism. It promises an incremental path for parallelizing sequential software, as well as targeting at scalability and performance for any complete rewrites or new construction of applications.

OpenMP follows the *fork-and-join* execution model. A fork-and-join program initializes as a single lightweight process, called the *master thread*. The master thread executes sequentially until the first parallel construct (OMP PARALLEL) is encountered. At that point, the master thread creates a team of threads, including itself as a member of the team, to concurrently execute the statements in the parallel construct. When a work-sharing construct such as a parallel do (OMP DO) is encountered, the workload is distributed among the members of the team. An implied synchronization occurs at the end of the DO loop unless a "NOWAIT" is specified. Data sharing of variables is specified at the start of parallel or work-sharing constructs using the SHARED and PRIVATE clauses. In addition, reduction operations (such as summation) can be specified by the REDUCTION clause. Upon completion of the parallel construct, the threads in the team synchronize and only the master thread continues execution. The fork-and-join process can be repeated many times in the course of program execution.

Beyond the inclusion of parallel constructs to distribute work to multiple threads, OpenMP introduces a powerful concept of *orphan directives* that greatly simplifies the task of implementing coarse grain parallel algorithms. Orphan directives are directives outside the lexical extent of a parallel region. This allows the user to specify control or synchronization from anywhere inside the parallel region, not just from the lexically contained region.

2.2. CAPTools

The Computer-Aided Parallelization Tools (CAPTools) [3] is a software toolkit that was designed to automate the generation of message-passing parallel code. CAPTools accepts FORTRAN-77 serial code as input, performs extensive dependence analysis, and uses domain decomposition to exploit parallelism. The tool employs sophisticated algorithms to calculate execution control masks and minimize communication. The generated parallel codes contain portable interface to message passing standards, such as MPI and PVM, through a low-overhead library (CAPLib).

There are two important strengths that make CAPTools stands out. Firstly, an extensive set of extensions to the conventional dependence analysis techniques has allowed CAPTools to obtain much more accurate dependence information and, thus, produce more efficient parallel code. Secondly, the tool contains a set of browsers that allow user to inspect and assist parallelization at different stages.

2.3. Generating OpenMP Directives

The goal of developing computer-aided tools to help parallelize applications is to let the tools do as much as possible and minimize the amount of tedious and error-prone work performed by the user. The key to automatic detection of parallelism in a program and, thus parallelization is to obtain accurate data dependences in the program. Generating OpenMP directives is simplified somehow because we are now working in a globally addressed space without explicitly concerning data distribution. However, we still have to realize that there are always cases in which certain conditions could prevent tools from detecting possible parallelization, thus, an interactive user environment is also important.

The design of the CAPTools-based automatic parallelizer with OpenMP, CAPO, had kept the above tactics in mind. CAPO uses the data dependence analysis engine in CAPTools, exploits loop level parallelism in a program, and inserts OpenMP directives automatically. The schematic structure of CAPO is illustrated in Figure 1. CAPO takes a serial code as input and first performs the data dependence analysis. User knowledge on certain input parameters in the source code may be entered to assist this analysis for more accurate results. The process of generating OpenMP directives is summarized in the following three stages.

1) *Identify parallel loops and parallel regions.* The loop-level analysis is carried out to classify loops as parallel (including reduction), serial or potential pipeline based on the data dependence information. Parallel loops to be distributed with work-sharing directives for parallel execution are identified by traversing the call graph of the program from top to down. Only outer-most parallel loops are considered, partly due to the very limited support of multi-level parallelization in available OpenMP compilers. Parallel regions are then formed around the distributed parallel loops. Attempt is also made to identify and create parallel pipelines.

2) *Optimize loops and regions*. This stage is mainly for reducing overhead caused by fork-and-join and synchronization. A parallel region is first expanded as far as possible and may include calls to subroutines that contain additional (*orphaned*) parallel loops. Regions are then merged together if there is no violation of data usage in doing so. Region expansion is currently limited to within a subroutine. Synchronization optimization between loops in a parallel region is performed by checking if the loops can be executed asynchronously.

3) *Transform codes and insert directives*. Variables in common blocks are analyzed for their usage in all parallel regions in order to identify threadprivate common blocks. If a private variable is used in a non-threadprivate common block, the variable is treated with a special code transformation. A routine needs to be duplicated if its usage conflicts at different calling points.

By traversing the call graph one more time OpenMP directives are lastly added for parallel regions and parallel loops with variables properly listed. The variable usage analysis is performed at several points to identify how variables are used (e.g. private, shared, reduction, etc.) in a loop or region. Such analysis is required for the identification of loop types, the construction of parallel regions, the treatment of private variables in common blocks, and the insertion of directives.

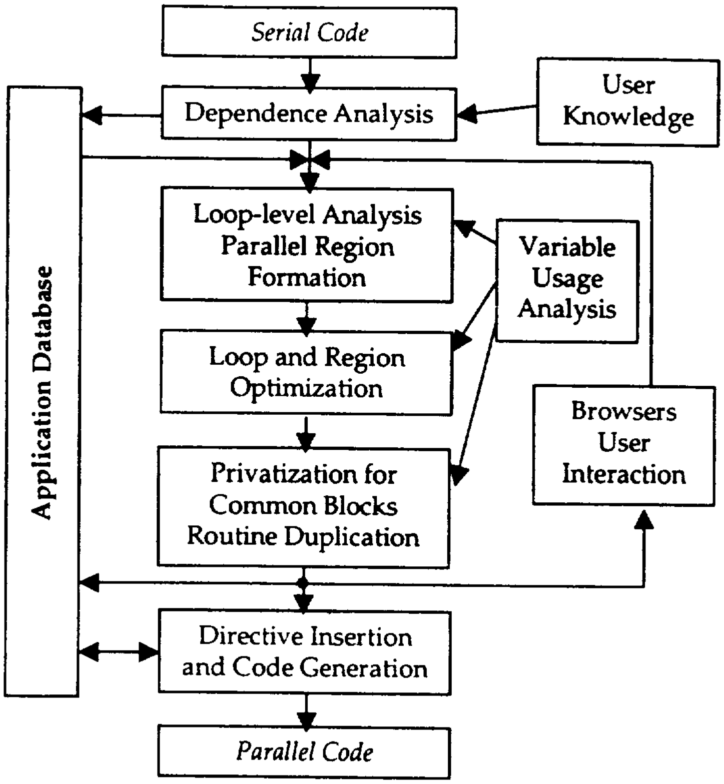

Serial Code
Dependence Analysis
User Knowledge
Application Database
Loop-level Analysis Parallel Region Formation
Variable Usage Analysis
Loop and Region Optimization
Browsers User Interaction
Privatization for Common Blocks Routine Duplication
Directive Insertion and Code Generation
Parallel Code

Figure 1: Schematic flow chart of the CAPO architecture.

Intermediate results can be stored into or retrieved from a database. User assistance to the parallelization process is possible through browsers implemented in CAPO (Directives Browser) and in CAPTools. The Directives Browser is designed to provide more interactive information from the parallelization process, such as reasons why loops are parallel or serial, distributed or not distributed. User can concentrate on areas where potential improvements could be made, for example, by removing false data dependences. It is part of the iterative process of parallelization.

3. Producing Parallel Code with CAPO

This section describes the usual steps a user will take to produce parallel code with CAPO. The procedure follows the outline given in Figure 1. One can refer to the Tutorials and Appendix for more information. It is also important to keep in mind that in order to get an efficiency parallel code user interaction with tools is almost always needed. The optimization process with CAPO Directive Browser is given in Section 4.

3.1. Prepare Serial FORTRAN Codes

CAPO currently works on FORTRAN 77 codes. A user can either create a single file that contains all the subroutines or provide a `.list` file that lists all the FORTRAN files in the program. Figure 2 shows an example of an "`All.list`" file. The source directory structure is preserved. The file names can be used later in the code generation.

Any unresolved symbols can be provided with dummy routines. For example, if the FORTRAN program calls C subroutines, dummy FORTRAN routines could be supplied to emulate the C functions even through these dummy routines may be deleted later on from the generated parallel code. This was a requirement of CAPTools prior to Version 2.1. The latest CAPTools provides interfaces to the dummy routines automatically.

CAPTools does not accept source codes that contain pre-processing directives. It is necessary to preprocess these files before used in CAPTools. Although the tool tries to preserve the original source form, these preprocessing directives will be lost.

```
lu.f
blts.f
buts.f
domain.f
erhs.f
error.f
exact.f
jacld.f
jacu.f
l2norm.f
pintgr.f
read_input.f
rhs.f
setbv.f
setcoeff.f
setiv.f
ssor.f
verify.f
../common/print_results.f
../common/timers.f
../common/wtime.f
```

Figure 2: An example of "All.list".

3.2. Make Dependence Analysis

Data dependence analysis is performed on the whole program, which is one of the key steps for directives generation. After source files are loaded into CAPTools, user knowledge, for instance the range of variables from the READ statements, may be entered. User supplied information can help obtain more accurate data dependences and, thus, more efficient parallel code. An example is illustrated in the following code:

```
      read(*,*) isize
      do 10 j=1,jm
      do 10 i=1,im
        ix = i + (j-1)*isize
        A(ix) = A(ix) + B(i,j)
   10 continue
```

The value of the parameter `isize` affects the loop parallelization. For the `j` loop, if `isize` > 0, no loop-carried data dependence exists for variable A; if `isize` = 0, there are loop-carried data dependences for variable A. The ambiguity in the `isize` value will prevent the `j` loop from being parallelized, i.e. a data dependence on variable A will be assumed. User could supply the "`isize` > 0" information to improve the analysis accuracy.

Depending on the program size and the thoroughness of the analysis specified, the dependence analysis process can take minutes, hours or days to complete. Once the analysis is finished, the user should save the result to a database before proceeding further. The dependence analysis is the most CPU intensive part of the parallelization process. Table 1 lists CPU time spent on analyzing the NPB BT benchmark on several machines. The analysis uses a single CPU. As one can see, the analysis time is roughly proportional to the clock speed of a processor.

Table 1: CPU time spent by CAPTools on analyzing the NPB BT benchmark on several machines.

Machine Type	OS Type	CPU Time
Intel PIII, 500MHz 512MB RAM, 512KB Cache	Linux	10.5 mins
Intel PII, 300MHz 512MB RAM, 512KB Cache	Linux	16.4 mins
Sun UltraSparcII, 360 MHz 1GB RAM, 16KB L1, 4MB L2	Solaris	15.0 mins
Sun UltraSparcII, 300 MHz 2GB RAM, 16KB L1, 4MB L2	Solaris	17.6 mins
SGI R5K, 150 MHz 128MB RAM, 32KB L1	IRIX	71.4 mins
SGI R10K, 195MHz 512MB RAM, 32KB L1, 1MB L2	IRIX	26.4 mins
SGI R12K, 300MHz 1GB RAM, 32KB L1, 2MB L2	IRIX	17.8 mins

3.3. Inspect Loops and Optimize Directive Generation

The parallelization strategy in CAPO is loop-based. Thus, an important next step is to inspect loops after the dependence analysis is performed, which may involve inspecting the dependences produced by CAPTools. Quite often a dependence causing a loop to be serialized is due to insufficient knowledge of value limits for some variables, as indicated in the previous section. The user can use the dependence browser (DepGraph) to remove unnecessary dependences. However, the information in the DepGraph window could be overwhelming.

A better approach for inspecting the loops is to use the Directives Browser implemented in CAPO (see Section 4 for details). The browser can be activated from the **View→Directives** menu and is designed to display information that are directly related to directives insertion and are gathered from the directives analysis. For instance, the browser provides more interactive information on the reasons for loops to be parallel or serial and the relevant variables. The user can concentrate on loops that are indicated as serial and optimize the dependence graph if needed. It is also possible to enforce a user-defined loop type. After changes are made, the directive analysis is reapplied to take into account these changes. This is an iterative process (see Figure 1). It is always a good idea to save the result to a database whenever a change is made before directives are actually inserted.

One should keep in mind that CAPO/CAPTools parallelization relies on the static analysis of the serial code. The dynamic information cannot be detected and applied by the tool. Thus, in most cases user-guided parallelization process is the only way to achieve a good quality parallel code. Tools offer resources to simplify this process.

3.4. Generate Parallel Code with Directives

Once the dependence analysis is completed and the loop information is inspected, directives can automatically be inserted by selecting the "*Save OpenMP Directive Code*" option under the File menu. The type of directives is controlled by the CAPO parameters (as described in Appendix 1), which are also selectable from the Setting box in the Directives Browser. One can elect to use the default setup, which is to produce OpenMP directives with a full range of analysis. Steps in the generation of directives are logged to a log file, by default to "code-output.log". Contents of the log file are described in Appendix 2.

3.5. Inspect the Generated Codes and the Log Information

It is very important to inspect the generated parallel code, together with the log information in the log file. In particular, one should look into any shared variables, private variables and I/O statements that are potentially incorrectly listed. Warnings in the last section (PASS 3) of the log file can indicate places where potential problems might exist. Of course, one can use other tools (such as ASSURE from Kuck & Associate) to check for problems in the parallel code.

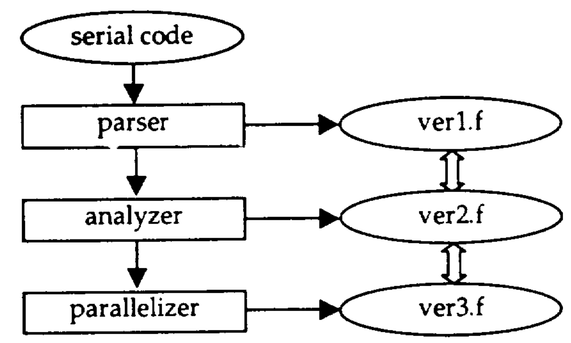


Figure 3: Compare source codes at different stages.

Sometimes it is useful to find out what have been changed at different stages of code parallelization. In the framework of CAPO, one can compare codes created at three stages as shown in Figure 3: parsing, analyzing and parallelizing. The codes can be compared with for example the Unix 'diff' command. Comparison of ver1.f and ver2.f will review code sections that were deemed to be redundant and were removed by the CAPTools' dependence analysis process. Comparison of ver2.f and ver3.f will review the change from parallelization, such as directives inserted and code transformation.

3.6. Compile and Run the Parallel Code

Once the parallel code is generated, use an OpenMP compiler to compile the code. Typically a compiler option is required to enable the directives. For example on the SGI Origin2000, the "-mp" option is needed for the SGI MIPSpro compiler to compile OpenMP codes

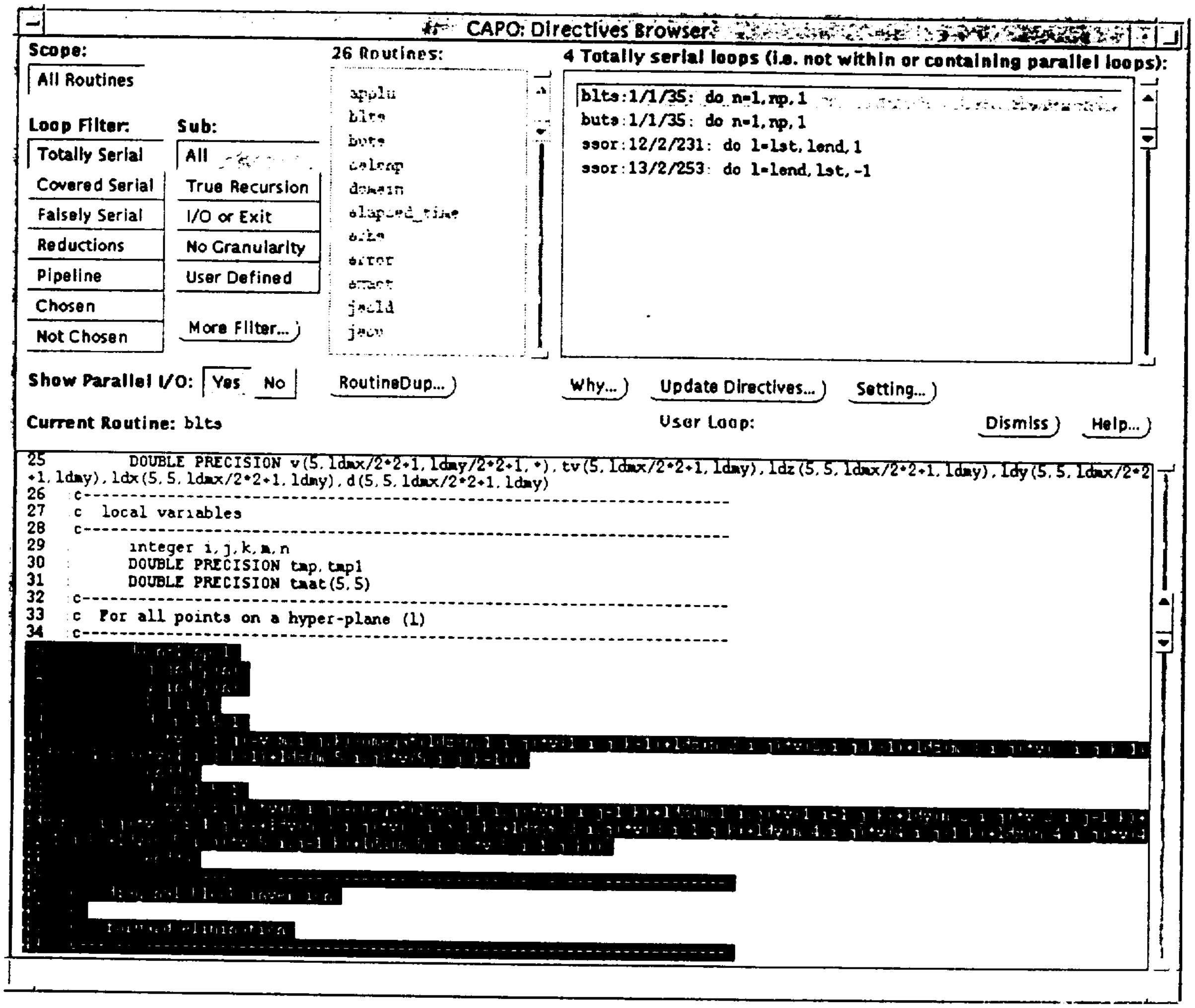
```
% f77 -o a.out -mp -O parallelcode.f
```

To run the code with 8 CPUs, do

```
% setenv OMP_NUM_THREADS 8
% ./a.out
```

4. Interacting with the Directives Browser

As mentioned before although the dependence analysis carried out is very detailed, it can often contain dependencies that had to be assumed to exist. In these cases, user assistance can be used to improve the quality of the generated OpenMP code. This is done by classifying the different types of loops that generally exist in application codes and using the Directives Browser to inspect and interrogate all the loops in turn. The Directives Browser is activated from the *View* menu of CAPO after CAPO finishes the directive analysis (see Figure 4 for the main window of the browser). The browser displays loops according to their types and provides more interactive information on the reasons why loops are parallel or serial. The user can concentrate on loops that are indicated as serial (fully or covered, as given below). The user can also enforce the classification of a selected loop by re-defining the loop type or define the granularity threshold for a loop so that any loop below this level is not considered for parallelization. Another feature of the browser is to provide the access for the user to manipulate the dependence graph (in conjunction with the DepGraph Browser) and improve the parallelization efficiency.



4 Totally serial loops (i.e. not within or containing parallel loops):

```
blts:1/1/35: do n=1,np,1
buts:1/1/35: do n=1,np,1
ssor:12/2/231: do l=lst,lend,1
ssor:13/2/253: do l=lend,lst,-1
```

Current Routine: blts

User Loop:

```
      DOUBLE PRECISION v(5,ldmx/2*2+1,ldmy/2*2+1,*),tv(5,ldmx/2*2+1,ldmy),ldz(5,5,ldmx/2*2+1,ldmy),ldy(5,5,ldmx/2*2
+1,ldmy),ldx(5,5,ldmx/2*2+1,ldmy),d(5,5,ldmx/2*2+1,ldmy)
c-----------------------------------------------------------------
c  local variables
c-----------------------------------------------------------------
      integer i,j,k,m,n
      DOUBLE PRECISION tmp,tmp1
      DOUBLE PRECISION tmat(5,5)
c-----------------------------------------------------------------
c  For all points on a hyper-plane (l)
c-----------------------------------------------------------------
```

Figure 4: The Directives Broswer main window.

4.1. Loop Classification

The loops are identified in the browser for the following types:

i. *Totally serial loops* – These loops contain a loop-carried true data dependence that causes the serialization of the loop i.e. data assigned in an iteration of the loop is used in a later iteration. (Other possible reasons for a loop to be defined as serial include the presence of I/O or loop exiting statements within the loop body). In addition, this loop type does not contain any nested parallel loops and also is not contained within a parallel loop. The directive browser shows a list of the variables and a textual explanation of why the loop is serial. However, the data dependence may have been assumed to exist and the user may be able to supplement the dependence analyzer with additional information to prove that the data dependence does not exist. Alternatively, the user may wish to enforce the removal of a serializing data dependence using the dependence browser.

ii. *Covered serial loops* – These are also serial loops containing a loop-carried true data dependence, so they can be treated in a similar way to totally serial loops. However, this type of serial loop is either nested within a parallel loop or contains parallel loops within it. In the latter case, if the serial loop can be made parallel (see *totally serial loops*) then the parallelism can be defined at a higher level and may therefore enhance the performance of the execution.

iii. *Falsely serial loops* – These loops are not serial due to a loop-carried true dependence. Instead, they will need to execute in serial due to the existence of pseudo dependencies that represent memory re-use as this needs to be considered when working within a globally addressable memory. The directive and dependence browsers can be used together with any additional information the user may wish to offer to re-examine if the variable(s) concerned can be privatized. In the process, dependencies into or out of the loop are examined to test if the variable could be made `PRIVATE`, or to re-examine if the loop carried pseudo dependencies are needed, in an attempt to allow the loop to execute in parallel.

iv. *Reduction loops* – The analysis is used to determine if the loop body computations represent a global reduction operation such as a `MAX` or summation. These loops provide a partial update of the results by each thread followed by a global update to give the final reduction value.

v. *Pipeline loops* – This is a special class of serial loops with loop-carried true dependencies. Directive-based software pipelines can be used to good effect in parallel. Figure 5 shows an example where OpenMP function calls are used to define the pipeline start-up before the `J`-loop and the pipeline shutdown after the loop. The example is taken from a version of the NAS LU benchmark. This is a similar strategy to that adopted for a software pipeline used in a distributed memory parallelization with message passing. For comparison a software pipeline implementation using a high level message passing library (CAPLib) is shown in the lower panel of Figure 5. CAPLib is a thin layer that covers a choice of message passing libraries such as PVM, MPI, Cray Shmem etc.

vi. *Chosen parallel loops* – These are the parallel loops at which the `OMP DO` construct is defined. These loops may contain serial or parallel loops within their nesting but are not surrounded by other parallel loops.

vii. *Not chosen parallel loops* - Also parallel loops, but these have not been selected for application to the `OMP DO` directive. This is because these loops are surrounded by other parallel loops at a higher nesting level. In general, the OpenMP compiler suppliers do not currently support nested parallelism, therefore, even though parallelism exists at these lower levels, it is not currently exploited.

The sub filter can be used together with the loop filter to control the finer selection of loop types. Detailed explanation of these filters can be found in Appendix 3.2 and examples of using the loop filters are in Tutorials.

```
(a)    lloop = jend-jst
       if (lloop .gt. mthnum) lloop = mthnum
       iam = omp_get_thread_num()
       if (iam .gt. 0 .and. iam .le. lloop) then
         neigh = iam - 1
         do while (isync(neigh) .eq. 0)
!$OMP FLUSH(isync)
         end do
         isync(neigh) = 0
!$OMP FLUSH(isync)
       endif
!$OMP DO SCHEDULE(STATIC)
       do j=jst,jend,1
         do i=ist,iend,1
c forward elimination and back substitution for diag. block inversion
         enddo
       enddo
!$OMP END DO nowait
       if (iam .lt. lloop) then
         do while (isync(iam) .eq. 1)
!$OMP FLUSH(isync)
         end do
         isync(iam) = 1
!$OMP FLUSH(isync)
       endif
```

```
(b)    CALL CAP_RECEIVE(v(1,2,LOW-1,k),nx0*5-10,3,CAP_LEFT)
       do j=MAX(jst,jst+LOW-2),MIN(jend,jst+HIGH-2),1
         do i=ist,iend,1
c forward elimination and back substitution for diag. block inversion
         enddo
       enddo
       CALL CAP_SEND(v(1,2,HIGH,k),nx0*5-10,3,CAP_RIGHT)
```

Figure 5: Implementation of a software pipeline for routine BLTS using (a) OpenMP (b) message passing.

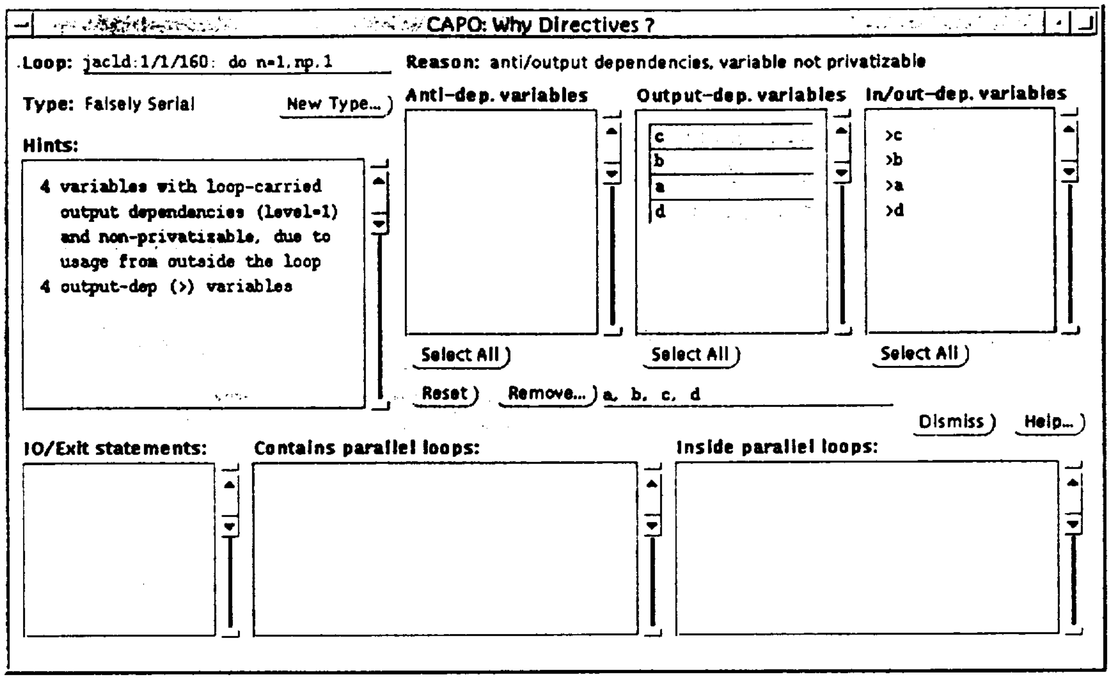
4.2. Browsing Different Types of Loops

The accurate dependence analysis allows the algorithm to automatically generate efficient OpenMP code in many cases. Experience has shown that this typically leaves a small proportion of cases that require user interaction. For example, the use of workspace arrays is very common in application codes, but the value-based nature of the dependence analysis will often prove that no data is passed between iterations of a loop. The memory re-use (pseudo) dependencies must however be set. This correctly does not classify such loops as serial, however, the legal privatization of these arrays to allow parallel execution requires that no data is passed into or out of these arrays from or to outside the loop. The value-based analysis, again greatly aids in proving that no such dependencies into or out of the loop exist.

Normally the user wants to go through the following loop types and use the **WhyDirectives** window to find out the reason for a particular loop type:

- `Totally Serial->True Recursion`
- `Covered Serial->True Recursion`

- Falsely Serial->Privatization
- Chosen->CopyIn/Out



Loop: jacld:1/1/160: do n=1,np,1

Reason: anti/output dependencies, variable not privatizable

Type: Falsely Serial

Hints:

```
4 variables with loop-carried
  output dependencies (level=1)
  and non-privatizable, due to
  usage from outside the loop
4 output-dep (>) variables
```

Output-dep. variables: c, b, a, d

In/out-dep. variables: >c, >b, >a, >d

a, b, c, d

Figure 6: The WhyDirectives window for a falsely serial loop.

The **WhyDirectives** window (as shown in Figure 6) can be activated by clicking on the Why... button in the **Directives Browser** window once a loop is selected. The window displays information on variables that cause a loop to be so classified. The cause for a loop not to be parallel can come from several sources, for example, loop-carried TRUE/ANTI/OUTPUT dependence, non-privatizable variables (re-use of memory). If one is sure that some of these dependences are false (mostly due to lack of input information for the dependence analysis) and can be removed, the Dep-Graph browser can be used to modify the dependence graph. A shortcut is provided in the **WhyDirectives** window where variables can be selected from the variable-list boxes and the relevant dependences can be removed by clicking the Remove button. The following relevant dependences will be removed, based on the loop type and variable list type:

Loop Type	Variable List	Dependence Type
Totally Serial	True-dep.	Loop-carried TRUE dependence
	Anti-dep.	Loop-carried ANTI dependence
	Output-dep.	Loop-carried OUTPUT dependence
Covered Serial	True-dep.	Loop-carried TRUE dependence
	Anti-dep.	Loop-carried ANTI dependence
	Output-dep.	Loop-carried OUTPUT dependence
Falsely Serial	Anti-dep.	Loop-carried ANTI dependence
	Output-dep.	Loop-carried OUTPUT dependence
	In/Out-dep.	TRUE dependence from outside of the loop
Chosen Parallel	Copyin/Out	TRUE dependence from outside of the loop

Once a change to the dependence graph (either via the Dep-Graph browser or via the WhyDirectives browser) is made, be sure to save the change to the database (*File→Save Database*) and re-perform the directive analysis (Update Directives... button).

4.3. Enforcing New Loop Type

A loop type as described in the previous section and defined by CAPO can be overridden by the user with the **LoopType** dialog box which is activated from the New Type button (see Figure 6). Typically this may occur when a loop is chosen for parallelization by CAPO but does not have proper granularity. The user may want to force it to be serial and let the tool choose another loop that is nested inside this loop. Another possibility is when the user wants to enable parallelization for a loop that contains I/O statements.

Currently the following four types are selectable:

`Parallel`	- from parallel without granularity or with I/O statements
`Serial`	- from parallel loop, including reduction
`Reduction`	- from serial loop with loop-carried true dependence
`Break`	- from any other types.

Only the conversions as indicated are possible from the dialog box. Although loop types can be redefined from the user-defined loop file (see Appendix 1.3), use of the **LoopType** dialog box is safer. However, one should keep in mind that changing the loop type manually could potential lead to incorrect results if the above rule is not carefully followed.

4.4. Routine Duplication

Routine duplication is performed after all the loop-level analyses and optimization are done but before directives are inserted. A routine may be duplicated if it causes usage conflicts at different calling points. For example, if a routine contains parallel regions and is called both inside a parallel loop and outside another parallel loop but still inside a parallel region, the routine is duplicated so that the copy of the routine without directives is used inside the parallel loop and the second copy containing only orphaned directives without "`OMP PARALLEL`" is used inside parallel regions but outside parallel loops. Routine duplication is often used in a message-passing program to handle different data distributions in the same routine.

There are two selectable types of routine duplication (see the Settings in Appendix 3) for a routine that contains parallel regions in the dynamic extent of this routine:

- '`Loop`' as the type for routine duplication if the routine is called both inside and outside parallel loop(s).
- '`Region`' as the default type for routine duplication if the routine is called inside parallel loop(s) and inside parallel region(s) but outside parallel loop(s).

This first option removes any nested parallelization. The second option confirms the OpenMP standard that a parallel region can be nested inside a work-sharing construct (parallel loop) but not inside a parallel region.

The **RoutineDup** browser (from *View→Directives→RoutDup*) is used for browsing routines that will be duplicated. The browser will indicate those calls that are inside parallel loops and those that are outside parallel loops. One may inspect the calls that are outside parallel loops for possible improvements, for example, de-serializing any potential outside loop nests.

5. Other Features

5.1. CAPO Parameters and Log Information

Parameters are referring to inputs that user can supply to control the behavior of directive generation in CAPO. A list of all the parameters is given in Appendix 1. These parameters can be defined from a file, environment variables, the Setting window in the Directives Browser, or the CAPO command interface. All the parameters have their default values. The Setting window from the Directives Browser is the most straightforward way to change parameters. It allows a user to select the log information type, define the directive type, set the loop granularity for parallelization, enable/disable the generation of the `THREADPRIVATE` directive, etc. For example, if the **Directive Type** is set to *No Directive*, the generated code will not contain directives and any associated transformations as indicated in the next section.

By default, the process of automatic insertion of directives is logged to the log-file "`code-output.log`". Information in this file may be examined after directives are added. There are three main sections in the log file, as outlined in Appendix 2. Depending on the log-info type, different levels of information details may be logged. In general, the log-info type controls:

1) `min` — only minimum amount of information, such as WARNING and INFO messages,

2) `std` — information from `min`, plus summary for each routine and each region,

3) `more` — information from `std`, plus more detailed results for each loop and each region,

4) `debug` — information from `more`, plus additional debug information that are probably too much for an ordinary user.

Warning messages in the log file should be paid enough attention since they indicate potential problems in the generated parallel code, which may be caused by user's interaction or bug in the tool.

5.2. Automatic Code Transformation and Optimization

CAPO performs the following code transformation and optimization automatically and logs the actions into the log file.

- Removal of the end-of-loop synchronization (using the `NOWAIT` construct) if it is proved valid. The function can be switched off from the parameter setting.

- Loop nest interchange to improve cache performance. The array usage is analyzed against the loop nesting order for possible misalignment. Loop transformation is performed to reduce misalignment. The module is activated only when the O3 optimization is chosen.

- The ability to treat private variables with unknown size. A variable with unknown size is usually declared as "`(*)`" (sometime as "`(1)`") for its last dimension in a subroutine. Use of such a variable as `PRIVATE` in a parallel region would cause ambiguity in size declaration and likely run-time error. In the current implementation, variable size is automatically detected (back tracing and usage checking) and dimension adjustment is then performed.

- Reduction of an array is transformed into local array updates plus a global update in a critical section at the end.

- Detection of reduction via an IF statement. The reduction is automatically transformed to local updates and a global update in a critical section at the end. This type of reduction is indicated as `IMIN` or `IMAX` in the Directives Browser.

5.3. Command Interface and the Batch Mode

The command interface for CAPO is available in Version 1.1 and works closely with the CAPTools' command interface. It provides a way to access the functionality of GUI components without starting the components. It serves as a mean to record actions (to a log file) as a result of any user GUI activities so that these actions can be played back later. The commands in the command interface are usually recorded to a log file or a command file with

```
capo -logfile capo_run.cmd
```

and played back with

```
capo [-batch] capo_run.cmd.
```

The second line with the [-batch] option can be used to start a CAPO session in a batch mode. This is especially useful for the data dependence analysis since it is the most CPU intensive part and very little use interaction is required once the analysis is started. Refer to Appendix 4 for a list of CAPO commands and several useful CAPTools commands for the command interface.

5.4. Parallel I/O

Strictly speaking parallel I/O is not supported in CAPO. I/O is serialized by default, i.e., it is handled by the master thread only. If any I/O is in the dynamic extent of a loop nest, the loop will be executed sequentially. However, in some cases, one may want to exploit parallel I/Os. For example in the following code:

```
DO K=1,NZ
  ...
  IF (V(K).LT.0.0) THEN
    WRITE(*,*) 'Warning: Negative value at K=', K
  ENDIF
END DO
```

The WRITE statement prints a warning message only when a condition is reached. The order of the write statement is not important, thus, one may seek for parallelizing the loop nest.

Another commonly encountered case is that warning messages are printed inside subroutine calls while data are read/written in the current scope of a loop nest. One may want to ignore the warning messages inside subroutine calls but serialize loops containing I/O in the current scope.

The level of parallel I/O in CAPO is controlled by the parameter "CAPO_PIO". If a value of "incall" is given, CAPO will ignore any I/Os inside subroutine calls when parallel loops are considered. Another possible value is "write", which allows any WRITE to stdout (UNIT=* or 6) inside parallel loops. This can be used for the above example. Of course, one can always enforce a user-defined loop type. During the code generation warnings will be printed in the log file if I/O is encountered inside a parallel region. One can examine these warnings for potential problems.

5.5. Mix of Message Passing and OpenMP

As pointed out in Section 2, CAPTools is designed to generate message-passing codes while CAPO is used to create OpenMP codes. Mixing message passing (such as MPI) and OpenMP is possibie in the framework of CAPTools/CAPO since the two tools are integrated together. A commonly used *hybrid* model is to have MPI for the coarse-grained parallelization and OpenMP for the fine-grained parallelization. Such a parallelization model is very effective if an application can be divided into domains and different domains are only loosely coupled. MPI is used for inter-domain parallelism and OpenMP for intra-domain parallelism.

Tutorial 5 gives an example of producing a mixed parallel code for the NAS BT benchmark. Although in general there is no particular good reason that you want to mix MPI and OpenMP within the same domain because of poor performance, the tutorial simply illustrates the capability of the tools to generate mixed codes.

6. Case Studies

For completeness in this section we present case studies of using CAPO to parallelize the NAS parallel benchmarks and two computational fluid dynamics (CFD) codes well known in the aerospace field: ARC3D and OVERFLOW. The parallelization process described in Section 3 was followed. We mainly present the results and discuss issues encountered in the parallelization. Most of the results have been reported in Ref. [6].

In the case studies, we used an SGI workstation (R5K, 150MHz) and a Sun E10000 node to run CAPO. The resulting OpenMP codes were tested on an SGI Origin2000 system, which consisted of 64 CPUs and 16 GB globally addressable memory. Each CPU in the system is a R10K 195 MHz processor with 32KB primary data cache and 4MB secondary data cache. The SGI's MIPSpro Fortran 77 compiler (7.2.1) was used for compilation with the "-O3 -mp" flag.

6.1. The NAS Parallel Benchmarks

The NAS Parallel Benchmarks (NPBs) were designed to compare the performance of parallel computers and are widely recognized as a standard indicator of computer performance. The NPB suite consists of five kernels and three simulated CFD applications derived from important classes of aerophysics applications. The five kernels mimic the computational core of five numerical methods used by CFD applications. The simulated CFD applications reproduce much of the data movement and computation found in full CFD codes. Details of the benchmark specifications can be found in Refs. [1] and [2].

In this study we used six benchmarks (LU, SP, BT, FT, MG and CG) from the sequential version of NPB2.3 [2] with additional optimization described in [5]. Parallelization of the benchmarks with CAPO is straightforward except for FT where additional user interaction was needed. User knowledge on the grid size (≥ 6) was entered for the data dependence analysis of BT, SP and LU. In all cases, the parallelization process for each benchmark took from tens of minutes up to one hour, most of the time being spent in the data dependence analysis. The performance of CAPO generated codes is summarized in Figure 7 together with comparison to other parallel versions of NPB: MPI from NPB2.3, hand-coded OpenMP [5], and versions generated with the commercial tool SGI-PFA [10].

CAPO was able to locate effective parallelization at the outer-most loop level for the three application benchmarks and automatically pipelined the SSOR algorithm in LU. As shown in Figure 7, the performance of CAPO-BT, SP and LU is within 10% to the hand-coded OpenMP version and much better than the results from SGI-PFA. The SGI-PFA curves represent results from the parallel version generated by SGI-PFA without any change for SP and with user optimization for BT (see [10] for details). The worse performance of SGI-PFA simply indicates the importance of accurate interprocedural dependence analysis that usually cannot be emphasized in a compiler. It should be pointed out that the sequential version used in the SGI-PFA study was not optimized, thus, the sequential performance needs to be counted for the comparison. The hand-coded MPI versions scaled better, especially for LU. We attribute the performance degradation in the directive implementation of LU to less data locality and larger synchronization overhead in the 1-D pipeline used in the OpenMP version as compared to the 2-D pipeline used in the MPI version.

The directive code generated by CAPO for MG performs 36% worse on 32 processors than the hand-coded version, primarily due to an unparallelized loop in routine norm2u3. The loop contains two reduction operations of different types. One of the reductions was expressed in an IF statement, which was not detected by CAPO Version 1.0 (the IF reduction will automatically be detected by Version 1.1), thus, the routine was ran in serial. Although this routine takes only about 2% of the total execution time on a single node, it translates into a large portion of the parallel execution on large number of processors, for example, 40% on 32 processors. All the parallel versions achieved similar results for CG.

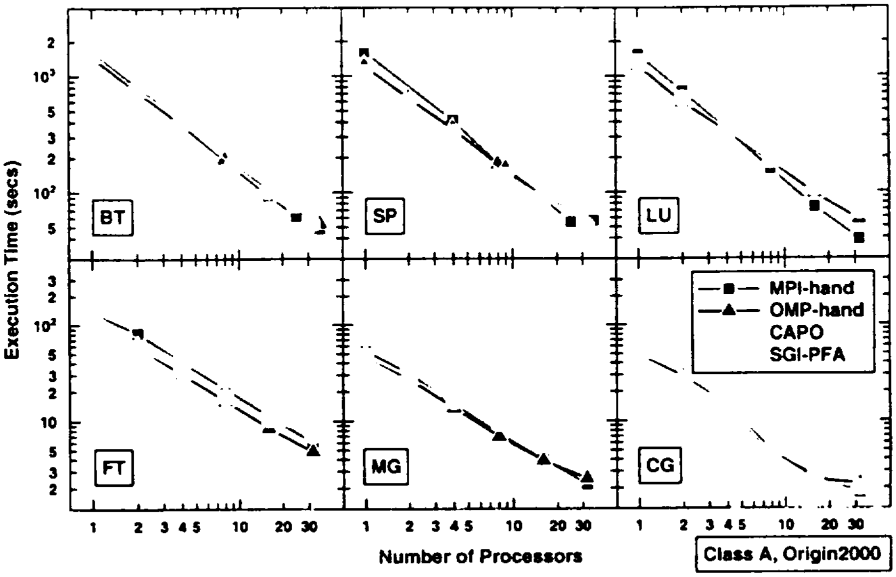


Figure 7: Comparison of the OpenMP NPB generated by CAPO with other parallel versions: MPI from NPB2.3, OpenMP by hand, and SGI-PFA.

The basic loop structure for the Fast Fourier Transform (FFT) in one dimension in FT is as follows.

```
DO K=1,D3
  DO J=1,D2
    DO I=1,D1
      Y(I) = X(I,J,K)
    END DO
    CALL CFFTZ(...,Y)
    DO I=1,D1
      X(I,J,K) = Y(I)
    END DO
  END DO
END DO
```

A slice of the 3-D data (X) is first copied to a 1-D work array (Y). The 1-D FFT routine CFFTZ is called to work on Y. The returned result in Y is then copied back to the 3-D array (X). Due to the complicated pattern of loop limits inside CFFTZ, CAPTools could not disprove the loop-carried true dependences by the working array Y for loop K. These dependences were deleted by hand in CAPO to identify the K loop as a parallel loop.

The resulted parallel FT code gave a reasonable performance as indicated by the curve with filled circles in Figure 7. It does not scale as well as the hand-coded versions (both in MPI and OpenMP), mainly due to the unparallelized code section for the matrix creation which was artificially done with random number generators. Restructuring the code section was done in the hand-coded version to parallelize the matrix creation. Again, the SGI-PFA generated code performed worse.

6.2. ARC3D

ARC3D is a moderate-size CFD application. It solves Euler and Navier-Stokes equations in three dimensions using a single rectilinear grid. ARC3D has a structure similar to NPB-SP but contains curve linear coordinates, turbulent models and more realistic boundary conditions. The Beam-Warming algorithm is used to approximately factorize an implicit scheme of finite difference equations, which is then solved in three directions alternatively.

For generating the OpenMP parallel version of ARC3D, we used a serial code that was already optimized for cache performance by hand [9]. The parallelization process with CAPO was straightforward and OpenMP directives were inserted without further user interaction. The parallel version was tested on the Origin2000.and the result for a 194x194x194-size problem is shown in the left panel of Figure 8. The results from a hand-parallelized version with SGI multi-tasking directives (*MT by hand*) [9] and a message-passing version generated by CAPTools (*CAP MPI*) [6] from the same serial version are also included in the figure for comparison.

As one can see from the figure, the OpenMP version generated by CAPO is essentially the same as the hand-coded version in performance. This is indicative of the accurate data dependence analysis and sufficient parallelism that was exploited in the outer-most loop level. The MPI version is about 10% worse than the directive-based versions. The MPI version uses extra buffers for communication and this could contribute to the increase of execution time.

6.3. OVERFLOW

OVERFLOW is widely used for airflow simulation in the aerospace community. It solves compressible Navier-Stokes equations with first-order implicit time scheme, complicated turbulence model and Chimera boundary condition in multiple zones. The code has been parallelized by hand [4] with several approaches: PVM for zone-level parallelization only, MPI for both inter- and intra-zone parallelization, multi-tasking directives, and multi-level parallelization. This code offers a good test case for our tool not only because of its complexity but also its size (about 100K lines of FORTRAN 77).

In this study, we used the sequential version (1.8f) of OVERFLOW. CAPO took 25 hours on a Sun E10K node to complete the data dependence analysis. A fair amount of effort was spent on pruning data dependences that were placed due to lack of necessary knowledge during the analysis. An example of false dependence is illustrated in the following code segment:

```
      NTMP2 = JD*KD*31
      DO 100 L=LS,LE
         CALL GETARX(NTMP2,TMP2,ITMP2)
         CALL WORK(L,TMP2(ITMP2,1),TMP2(ITMP2,7),...)
         CALL FREARX(NTMP2,TMP2,ITMP2)
  100 CONTINUE
```

Inside the loop nest, the memory space for an array TMP2 is first allocated by GETARX. The working array is then used in WORK and freed afterwards. However, the data analysis has reviewed that the loop contains loop-carried true dependences caused by variable TMP2, thus, the loop can only be executed in serial. The memory allocation and de-allocation are performed dynamically and cannot be handled by CAPO. This kind of false dependence can safely be removed with Dependence Browser included in the tool. Even so, CAPO provides an easy way for user to

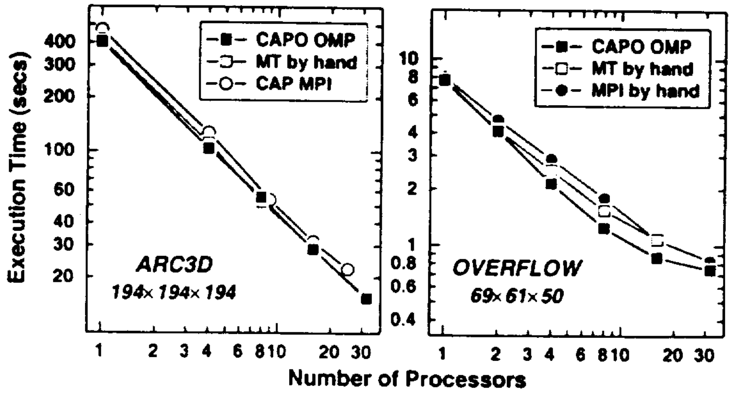


Figure 8: Comparison of execution times of CAPO generated parallel codes with hand-coded parallel versions for two CFD applications: ARC3D on the left and OVERFLOW on the right.

interact with the parallelization process. The OpenMP version was generated within a day after the analysis was completed and an additional few days were used to test the code.

The right panel of Figure 8 shows the execution time per time-iteration of the CAPO-OMP version compared with the hand-coded MPI version and hand-coded directive (MT) version. All three versions were running with a test case of size 69×61×50, 210K grid points in single zone. Although the scaling is not quite linear (when comparing to ARC3D), especially for more than 16 processors, the CAPO version out-performed both hand-coded versions. The MPI version contains sizable extra codes [4] to handle intra-zone data distributions and communications. It is not surprising that the overhead is unavoidably large. However, the MPI version is catching up with the CAPO-OMP version on large number of processors. On the other hand, further review has indicated that the multi-tasking version used a fairly similar parallelization strategy as CAPO did, but in quite a few small routines the MT version did not place any directives for the hope that the compiler (SGI-PFA in this case) would automatically parallelize loops inside these routines. The performance number seemed to have indicated otherwise.

We also tested with a large problem of 1.5M grid points. The result was not included in the figure but CAPO's version has achieved 18-fold speedup on 32 processors of the Origin2000 (10 out of 32 for the small test case). It is not surprising that the problem with large grid size has achieved better parallel performance.

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APPENDIX

Contents

1. Parameters for CAPO

The following describes parameters available in Version 1.1.

1.1. General

Parameters are referring to inputs that user can supply to control the behavior of directive generation in CAPO. There are default settings for all the parameters (see Section 1.3). Parameters can be defined from a file, environment variables, or the Setting box in the Directives Browser. Values from the parameter file or environment variables supersede any defaults. Values from the parameter file supersede environment variables. Changes from the Setting box (Section 3.5) in the Directives Browser are applied at last. Parameter setting can also be done from the CAPO command interface. See Section 4 for details.

1.2. The Parameter File

The parameter filename can be defined via the environment variable CAPO_PAR. The default filename is "capo-inp.par" in the current directory. An example of this file is given in Section 1.5.

Format of the parameter file:

'#'	the sign starts a comment
'key value'	the pair defines an entry

1.3. Parameter Keys and Possible Values

ENV_VARIABLE	*KEY*	*DEFAULT*	*POSSIBLE VALUES*
CAPO_PAR		capo-inp.par	
CAPO_LOG	log-file	on	(off on stdout)
CAPO_LOGNAME	log-file-name	codeoutput.log	
CAPO_LOGINFO	log-info	std	(min std more debug)
CAPO_PLOOP	loop-granularity	6	(0 1 2 ...)
CAPO_TYPE	directive-type	omp	(omp sgi sgix no)
CAPO_REGION	region-type	default	(loop bloop one join full)
CAPO_OPTIMIZE	optimize-type	o2	(off on o2 o3)
CAPO_USERLOOP	user-loop-file	user-loop.par	
CAPO_DIRCLEAR	directive-clear	default-list	(off on filename)
CAPO_TPRIV	tpriv-directive	on	(off on)
CAPO_COMMENT	comment-type	f90	(f77 f90)
CAPO_USEPARTI	use-parti-loop	no	(no yes)
CAPO_RDUPTYPE	rdup-type	region	(loop region)
CAPO_UNKSIZE	allow-unksize	false	(false true)
CAPO_PIO	allow-pio	no	(no incall write noread any)

Description of the parameters:

- "`log-file`" type is one of

  `off` — Logging to file is off, only minimum messages are printed on screen
  `on` — Information are logged to the log-file
  `stdout` — Information are printed to stdout (screen)

- "`log-file-name`" defines the name for a log file. If no name is defined, CAPO will use the output filename from the code generation to form a log filename. Contents of the log file are described in Section 2.

- "`log-info`" type is one of

  `min` — Only minimum information are logged or printed
  `std` — Print standard set of log information
  `more` — Print more detailed log information, including region and loop numbers in the final Fortran file
  `debug` — Print debugging information, probably more than you want, including region and loop numbers in the final Fortran file

- The loop granularity is based only on the loop iterations at this point. Future extension to include profile information can easily be added.

- Currently supported directive types are

  `omp` — Produce OpenMP directives (default)
  `sgi` — Produce SGI native directives
  `sgix` — Produce OpenMP directives with SGI extensions. Currently, only the '`NEST`' directive is supported
  `no` — Do not insert directives in code generation (useful for comparison).

- Different region types

  `loop` — consider only one loop for one region (no pipeline)
  `bloop` — consider one block + one loop for one region (no pipeline)
  `one` — consider one region (region not joined, no pipeline)
  `join` — consider joined region (outer loop nesting, no pipeline)
  `full` — consider full region (region joined and possible pipeline)

  For SGI directives, only "loop" is allowed for the region type (region-type). The default region-type is "loop" for SGI and "full" for OMP.

- Optimization type is intended for possible improvements to be applied, such as loop granularity check, synchronization overhead reduction, and loop transformation. Currently an attempt to reduce synchronization at end-of-loop is implemented. Other optimizations are less defined and/or tested.

  `off` — Do not do any optimization
  `on` — Try to reduce synchronization at end-of-loop
  `o2` — Use logical disprove (slow sometime) for affinity comparison
  `o3` — Perform additional optimization (such as loop transformation) before loop analysis and directive insertion.

- User-defined loop types are read from a file that can be defined via environment variable `CAPO_USERLOOP` or "`user-loop-file`" entry in the parameter file. If a "`userloop.par`" file exists in the current working directory, this file will be taken if the other two methods are not used. The format of this file is:

```
# starts comment
#RoutineName LoopNumber NewType
routine_name loop_count S|P|R|B[options]
```

Entries are specified line-by-line. "Routine_name" is case insensitive. For a program without the main-routine name defined, "MAIN" can be used to indicate the main routine.

"loop_count" is the loop number counted from the beginning of a given routine. A negative "loop_count" indicates the loop (defined by -loop_count) will not be considered for automatic loop transformation.

Currently the following new loop types are supported:

"S" for serial
"P" for parallel
"R" for reduction
"B" for break-type (e.g. so that a parallel region won't be formed around this loop).

The "R" type can optionally be attached with

"[OPR:VAR]" or "[OPR:VAR()]" list

to indicate the reduction operator and the reduction variable, no space in-between. The second form indicates an array reduction.

- List of directives to be cleared can be read from a file or taken from the default list. The default list contains the following:

```
"cdir$",                 /* Cray vector directive */
"cmic$",                 /* Cray autotasking directive */
"c$par",                 /* PCF (Parallel Computing Forum) directive */
"c$doacross", "c$&",     /* SGI multiprocessing directive */
"c$ ", "c$\t",
"c$omp",                 /* OMP directive */
"c$sgi"                  /* SGI OMP extension */
```

The default setting is to use the above list. The 'clearing' action may be turned off by setting CAPO_DIRCLEAR to 'off'. Additional directives may be added to the default list by prefixing a '+' in front of the filename for CAPO_DIRCLEAR.

A dirclear-list file contains simply a list of directives (keywords) to be considered. A keyword should lead with one of ['C', '!', '*']. A '-' sign can be added to the front of a keyword to indicate the corresponding directive should not be cleared (i.e. keep its original form), otherwise, the directive will be commented out (cleared).

- The THREADPRIVATE directive will be generated by default. If the option is turned off via CAPO_TPRIV (=off), CAPO will use an alternative method to treat private variables used in a common block.

off — Use an alternative method to handle private variables
on — Try to create THREADPRIVATE directives

- The comment type refers to the leading character to be used for directives. The 'C' character is for the f77 type and the '!' character is for the f90 type. Default is '!'.

- By default, if a loop is partitioned in a message-passing program, the loop will not be considered for directives (CAPO_USEPARTI=no). This is equivalent to a two-level parallelization. If a partitioned loop is intended for directives as well, CAPO_USEPARTI can be set to 'yes'. This would be a one-level parallelization with mixed type. The option is only meaningful when CAPTools is first used to generate message-passing program and CAPO is then applied to insert directives.

- Two types of routine duplication (RDUP) can be selected:

  loop — as the type for RDUP if a routine is used both inside and outside parallel loop(s).
  region — as the (default) type for RDUP if a routine is used inside a parallel loop and inside parallel region but outside parallel loop.

  The second option allows nested parallel regions and confirms the OpenMP standard that a parallel region can be nested inside a parallel loop but not inside a parallel region.

- The environment variable CAPO_UNKSIZE controls how unknown-size private variable (USPV) is treated. A unknown-size variable has its last dimension declared as "*" or "1" in a subroutine and is in the routine argument list. By default, if an USPV is encountered, CAPO will take effort to adjust the size of the unknown dimension. If the size cannot be adjusted, the corresponding loop will be made serial. If CAPO_UNKSIZE is set to "true", the loop with USPV will not be made serial, instead, a warning will be printed so that the user can make manual change later on.

- By default I/O statements are not allowed in the dynamic extent of parallel loops. However, one can exploit certain degrees of parallel I/O with CAPO_PIO.

  no — no I/O statements in the dynamic extent of a loop (default).
  incall — no I/O in the current scope of a loop, but allowed inside subroutine calls.
  write — allow "WRITE(*,*)", i.e. write to standard output.
  noread — no READ, but allow any WRITE.
  any — allow any type of I/O statements.

1.4. Parameters for Debugging Purpose

The following parameters are only available from the Setting box (Section 3.5) in the Directives browser. By default, all these parameters are enabled. The Setting box can be used to disable them for debugging purpose.

Generate-NOWAIT — enable/disable the NOWAIT directive
Transform-Induction-Loop — enable/disable induction loop treatment
Handle-Array-Reduction — enable/disable array reduction
Remove-Old-Directives — enable/disable removing old directives
Apply-UserLoop-Type — enable/disable applying userloop types
Setup-Pipeline-Loop — enable/disable pipeline loop

1.5. Sample Parameter File

```
# env: CAPO_PAR
# Parameters for CAPTools-based Parallelizer with OpenMP (CAPO)
# They apply to version 1.1

# env: CAPO_LOG
# defines if log-information is wanted
log-file                on      (off on stdout)

# env: CAPO_LOGNAME
# defines log-file name when log-file = on
log-file-name                   (default: codeoutput.log)

# env: CAPO_LOGINFO
# defines type of information to be logged
log-info                std     (min std more debug)

# env: CAPO_PLOOP
# defines granularity (min. no. of iters.) for parallel loops
loop-granularity        6       (0 1 2 ...)

# env: CAPO_TYPE
# defines type of directives to be produced
directive-type          omp     (omp sgi sgix no)

# env: CAPO_REGION
# defines type of parallel regions to be considered
region-type             full    (loop bloop one join full)

# env: CAPO_OPTIMIZE
# defines optimization type for parallel regions
optimize-type           o2      (off on o2 o3)

# env: CAPO_USERLOOP
# defines the file name for user-defined loop types
user-loop-file                  (default: user-loop.par)

# env: CAPO_DIRCLEAR
# defines the file name for directives to be cleared
directive-clear         Default (off on filename)

# env: CAPO_TPRIV
# switches on/off the generation of THREADPRIVATE
tpriv-directive         on      (off on)

# env: CAPO_COMMENT
# chooses a comment type for directives
comment-type            f90     (f77 f90)

# env: CAPO_USEPARTI
# uses partitioned loops for directives
use-parti-loop          no      (no yes)

# env: CAPO_RDUPTYPE
# defines routine duplication type
rdup-type               region  (loop region)

# env: CAPO_UNKSIZE
# allows unknown-size variables
allow-unksize           false   (false true)

# env: CAPO_PIO
# allows parallel I/O
allow-pio               no      (no incall write noread any)
```

2. Messages and Symbols in the Log File

By default, the process of automatic insertion of directives is logged to the log-file "code-output.log". Information in this file may be examined after directives are added. There are three main sections in the log file, as outlined in the following subsections. Depending on the log-info type as described in Section 1, different levels of information details may be logged. In general, the log-info type controls:

1) min — only minimum amount of information, such as WARNING and INFO messages,

2) std — information from min, plus summary for each routine and each region,

3) more — information from std, plus more detailed results for each loop and each region,

4) debug — information from more, plus additional debug information that are probably too much for an ordinary user.

In the case of "more" and "debug", additional labels (region# and loop#) are added as comments for parallel loops in the generated parallel code. Regions and loops are labeled within a given routine, sequentially.

2.1. Classification of Loops

The first section lists the analysis of loops in all routines from the dependence information. For a given routine a loop is labeled with its sequence number, the group number and the loop-nesting level. The group number is defined as a sequence number for a loop-nest group at a given nesting level. Loops are classified as parallel, serial, or possible pipeline. For a parallel loop, it is further tested for granularity and is indicated if a parallel directive is to be added, provided the loop is not nested inside another parallel loop. For a serial loop, the reason of serialization as well as the first variable that causes the loop to be serialized is given. The causes of loop serialization include loop-carried dependences (true, anti and output), I/O statement inside, and breaking out of the loop. A pipeline loop is a serial loop with only loop-carried true dependences and determinable dependence vectors. The basic information for loops is as the following:

```
Routine: ROUTINE_NAME
  Loop # (loop_variable), group #, level #: parallel/serial
       TYPE? Reason for serial...
```

"TYPE?" is one of types from the loop type list:

```
   "REDU", "NPAR", "PAR", "IO", "LVAR", "SER", "ANTI", "PIPE",
   "BRK", "UPIPE", "PAREG", "INDU", "INPLP", "RDINP", "GRAN", "PARTI"
```

As an example, part of the analysis for three routines in NPB-LU is given here (with log_info set to MORE).

```
Routine: BUTS
 Loop 1 (J), group 1, level 1: parallel, granularity - ok
        PAR-> directives to be added for the loop <1,1>
 Loop 2 (I), group 1, level 2: parallel, granularity - ok
        INPLP? no directive, loop inside a parallel loop
 Loop 3 (M), group 1, level 3: parallel, granularity - no
 Loop 4 (J), group 2, level 1: serial
```

```
          PIPE? true dependence, pipeline loop? dvector: V[0,0,-1,0]
  Loop 5 (I), group 2, level 2: serial
          PIPE? true dependence, pipeline loop? dvector: V[0,-1,0,0]
  Loop 6 (M), group 2, level 3: parallel, granularity - no
  Loop 7 (M), group 2, level 3: parallel, granularity - no
  *** Total number of loops: 7, parallel: 5, serial: 2, directive: 1
Routine: JACU
  Loop 1 (J), group 1, level 1: parallel, granularity - ok
          PAR-> directives to be added for the loop <1,1>
  Loop 2 (I), group 1, level 2: parallel, granularity - ok
          INPLP? no directive, loop inside a parallel loop
  *** Total number of loops: 2, parallel: 2, serial: 0, directive: 1
...
Routine: SSOR
  Loop 1 (I), group 1, level 1: serial
          ANTI? loop carried output or non-exact anti dependence: ELAPSED
  Loop 2 (I), group 2, level 1: serial
          ANTI? loop carried output or non-exact anti dependence: ELAPSED
  Loop 3 (ISTEP), group 3, level 1: serial
          BRK? break out of the loop or comm-call inside the loop
  Loop 4 (K), group 3, level 2: parallel, granularity - ok
          PAR-> directives to be added for the loop <2,1>
  Loop 5 (J), group 3, level 3: parallel, granularity - ok
          INPLP? no directive, loop inside a parallel loop
  Loop 6 (I), group 3, level 4: parallel, granularity - ok
          INPLP? no directive, loop inside a parallel loop
  Loop 7 (M), group 3, level 5: parallel, granularity - no
  Loop 8 (K), group 3, level 2: serial
          SER? loop carried true dependence: ELAPSED
  Loop 9 (K), group 3, level 2: serial
          SER? loop carried true dependence: ELAPSED
  Loop 10 (K), group 3, level 2: parallel, granularity - ok
          PAR-> directives to be added for the loop <2,2>
  Loop 11 (J), group 3, level 3: parallel, granularity - ok
          INPLP? no directive, loop inside a parallel loop
  Loop 12 (I), group 3, level 4: parallel, granularity - ok
          INPLP? no directive, loop inside a parallel loop
  Loop 13 (M), group 3, level 5: parallel, granularity - no
  *** Total number of loops: 13, parallel: 8, serial: 5, directive: 2

>>>> Grand total: num_routines 25, num_loops 157
            loops: parallel 145, serial 12, directive 30
```

The label for a parallel loop with directive to be added (PAR->) is given as <level,group> pairs. In the case of a serial loop only one variable is listed for the cause of serialization. For a potential pipeline loop, the dependence vector for the first related variable is given, as the case of V[0,0,-1,0] for loop 4 (J) in routine BUTS.

The user-defined loop types are applied after the loop classification. Therefore, it is user's responsibility to ensure the correctness of user-supplied loop types.

2.2. Construction of Parallel Regions

This section contains first the summary from the pass-two analysis of all the routines in the outer-most loop level to decide if directives need to be added in a routine. Routines are traversed on their call sequences. A <yes> or <no> flag is marked for each analyzed routine to indicate the addition of directives in the routine. A routine may need to be duplicated if it is called both inside and outside a parallel loop and will contain directives in itself.

```
Routine: ROUTINE_NAME <yes/no/inploop/noploop>
```

<yes> — routine is added with directives for parallel loops
<no> — routine has no directives
<inploop> — routine is called inside a parallel loop
<noploop> — routine has no parallel loop, but may contain potential pipeline loops

A sample result from the analysis of NPB-LU looks like the following.

```
Routine: APPLU <yes>
Routine: READ_INPUT <no>
Routine: DOMAIN <no>
Routine: SETCOEFF <no>
Routine: SETBV <yes>
Routine: SETIV <yes>
Routine: ERHS <yes>
Routine: SSOR <yes>
Routine: TIMER_CLEAR <no>
Routine: JACLD <yes>
Routine: BLTS <yes>
Routine: JACU <yes>
Routine: BUTS <yes>
Routine: RHS <yes>
Routine: TIMER_START <no>
Routine: L2NORM <yes>
Routine: TIMER_STOP <no>
Routine: ELAPSED_TIME <no>
Routine: WTIME <no>
Routine: ERROR <yes>
Routine: EXACT <no>
Routine: PINTGR <yes>
Routine: VERIFY <no>
Routine: PRINT_RESULTS <no>
Routine: TIMER_READ <no>
>>> Total routines: 25, checked: 24, with directives: 13
    in/outside ploop: 0, in/with ploop: 0, no ploop: 12
    Total directive loops: 30, effective: 30, in ploop: 0
```

The last line of the statistics indicates how many loops can be put with directives, how many of them are really added with directives, and how many of them are nested inside other loops with directives.

Next is to construct parallel regions based on the loop information. A parallel region includes at least one parallel loop or pipeline loop with possible basic blocks in the beginning of the loop. No nested parallel loops are considered at this point. Two neighboring regions can be joined together if no codes other than comments or nops (such as continue) exist between the two regions. Individual regions are labeled sequentially within a routine. For each region a number is included in () to indicate the end (or last) region of a joined area of regions. For disjointed regions, the end region is the same as the region itself. Additional information included for a region are: loops in the region and type of the region. Regions are also summarized for a routine as "region-type-summary".

Region-type:

one ploop — containing exactly one parallel loop (no pipeline)
+prev-block — one parallel loop plus any preceded basic blocks
sub ploop — one or more parallel loops nested at different levels
pipeline — potential pipeline
<default> — region with joined neighbors

Region-type-summary:

DEFAULT — routine contains normal parallel regions
PIPE — routine is part of a pipeline region
UPIPE — routine contains potential pipeline regions

Sample outputs from the analysis of NPB-LU:

```
Region-in-Routine: BUTS
 region-type-summary: UPIPE
 Parallel region 1 (2): loops [1-3]
 Parallel region 2 (2): loops [4-7]
 *** Total number of regions: 2, joined regions: 1
Region-in-Routine: JACU
 region-type-summary: DEFAULT
 Parallel region 1 (1): loops [1-2] one ploop
 *** Total number of regions: 1, joined regions: 1
Region-in-Routine: SSOR
 region-type-summary: DEFAULT
 Parallel region 1 (1): loops [4-7] one ploop
 Parallel region 2 (2): loops [10-13] one ploop
 *** Total number of regions: 2, joined regions: 2
```

Once the initial regions are determined, routines are then checked for possible pipeline regions across routines. If such a region is identified, the pipeline-loop limit is checked against all other parallel loops in the same pipeline region for alignment. If a discrepancy is found, a message will be printed out as either "not the same limit" or "low-high limit swapped!". In the first case, the suggested pipeline operation may produce incorrect run-time result and further check of this generated code is needed. In the second case CAPO automatically swaps the loop limit to ensure the consistence. If pipeline loops are not desirable, set the environment variable CAPO_REGION to "join".

For LU, routines BUTS and JACU were identified to be part of a pipeline region in routine SSOR and information was generated as follows.

```
Region-in-Routine: BUTS
 region-type-summary: PIPE
 pipeloop: DO J=JEND,JST,-1 (BUTS)
 thisloop: DO J=JEND,JST,-1 (BUTS)
   same limit
Region-in-Routine: JACU
 region-type-summary: PIPE
 pipeloop: DO J=JEND,JST,-1 (BUTS)
 thisloop: DO J=JST,JEND,1 (JACU)
   low-high limit swapped!
Region-in-Routine: SSOR
 region-type-summary: DEFAULT
 Parallel region 1 (1): loops [4-7] one ploop
 Parallel region 2 (2): loops [8-8] pipeline
 Parallel region 3 (3): loops [9-9] pipeline
 Parallel region 4 (4): loops [10-13] one ploop
 *** Total number of regions: 4, joined regions: 4

>>>> Grand total: routines 25, regions 34, joined regions 26
```

Parallel regions are further optimized for removal of end-of-loop synchronization (use the 'NOWAIT' construct). Although more conservative approach is taken, careful examination of NOWAIT is still needed. For example, one should pay attention to the WARNING messages on 'EndLoop-Sync required/re-enforced'. If any problem occurs, one can always switch the optimization off (setenv CAPO_OPTIMIZE off).

For LU, this is the summary after region optimization:

>>>> Total number of syncs removed: 7, in 4 routines (13 checked)

2.3. Insertion of Directives in Routines

There are four functions performed in this stage:

- clearing any old directives if CAPO_DIRCLEAR is not off (Section 1.3),
- searching for threadprivate common blocks and inserting the THREADPRIVATE directive if CAPO_TPRIV is not off,
- duplicating routines if needed, and
- inserting region/loop-level directives.

Information resulted from these four actions are not fed back to the Directives Browser except for presented as directives in the source code. Thus, once directives are inserted, the Directives Browser should not be used to do further changes.

A threadprivate common block is the one that have all its variables used as private (including copyin) for all the parallel regions in the whole program. It means even a single instance of a non-private usage of a variable can prevent the common block from becoming threadprivate. In the debug mode, causes of a common block being determined as threadprivate or shared can be examined. See Section 2.4 for details. Normally messages are printed for identified threadprivate common blocks and routines that contain them. An example is given here.

```
T_PRIV common blocks:
 -/WORK_1D/-18: SP SET_CONSTANTS EXACT_RHS INITIALIZE ADI TXINVR X_SOLVE
       NINVR Y_SOLVE PINVR Z_SOLVE LHSINIT TZETAR ADD VERIFY ERROR_NORM
       COMPUTE_RHS RHS_NORM
 -/WORK_LHS/-18: SP SET_CONSTANTS EXACT_RHS INITIALIZE ADI TXINVR X_SOLVE
       NINVR Y_SOLVE PINVR Z_SOLVE LHSINIT TZETAR ADD VERIFY ERROR_NORM
       COMPUTE_RHS RHS_NORM

>>> THREADPRIVATE directive added for 2 common blocks in 18 routines
```

Warnings may be printed for those common blocks that potentially be threadprivate:

```
WARNING! SSOR... region 4, loop 8
```

```
    /CJAC/ Type conflict: old SHARED, new PRIV - use SHARED
```

It indicates that in routine SSOR all variables in common block /CJAC/ are used as private in region 4, but the common block is shared in other places. One can trace further for where the common block is shared in the debug mode.

Directives are added by annotating the call graph and using the parallel region information obtained in 2.2. The call paths are printed as the insertion is progressing. Any routine is only visited one time.

```
Routine: APPLU
Routine: APPLU->SETCOEFF
Routine: APPLU
Routine: APPLU->SETBV
Routine: APPLU
Routine: APPLU->SETIV
Routine: APPLU
Routine: APPLU->ERHS
Routine: APPLU
Routine: APPLU->SSOR
Routine: APPLU->SSOR->RHS
Routine: APPLU->SSOR->RHS->TIMER_START
Routine: APPLU->SSOR->RHS->TIMER_START->ELAPSED_TIME
Routine: APPLU->SSOR->RHS->TIMER_START->ELAPSED_TIME->WTIME
Routine: APPLU->SSOR->RHS->TIMER_START->ELAPSED_TIME
Routine: APPLU->SSOR->RHS->TIMER_START
Routine: APPLU->SSOR->RHS
Routine: APPLU->SSOR->RHS->TIMER_STOP
Routine: APPLU->SSOR->RHS
Routine: APPLU->SSOR
Routine: APPLU->SSOR->L2NORM
INFO! Array reduction variable replaced with local critical in region 1 -
        SUM() --> SUM_CAP1()
Routine: APPLU->SSOR
Routine: APPLU->SSOR->JACLD
Routine: APPLU->SSOR
Routine: APPLU->SSOR->BLTS
Routine: APPLU->SSOR
WARNING! Potential memory conflict for shared variable in region <2,1> -
ELAPSED
Routine: APPLU->SSOR->JACU
Routine: APPLU->SSOR
Routine: APPLU->SSOR->BUTS
Routine: APPLU->SSOR
WARNING! Potential memory conflict for shared variable in region <3,1> -
ELAPSED
Routine: APPLU
Routine: APPLU->ERROR
INFO! Array reduction variable replaced with local critical in region 1 -
        ERRNM() --> ERRNM_CAP1()
Routine: APPLU
Routine: APPLU->PINTGR
Routine: APPLU
Routine: APPLU->VERIFY
Routine: APPLU
```

WARNINGs for "...variable used after a parallel region", "potential memory conflict", and INFOs on the changes made to routine arguments should be examined carefully. These are just warnings, may or may not cause any programming errors. The warnings are the cases where CAPO are uncertain of decision making and user needs to inspect the generated code at the pointed places for verification. The parallel region is labeled as `<region_number, parallel_loop_number>` pairs in the call path right preceding the warning message.

Meanings of keywords in the WARNING message:

"variable" — a variable used in the current routine scope
"common-variable" — a variable used outside the current scope, e.g. through COMMON blocks or SAVE statements in a subroutine
"Shared" — variable shared in the current region
"Plocal" — potential private variable in the current region
"Control" — variable with multiple control paths, i.e. variable could be updated either inside or outside the current region
"I/O statement" — routine called inside a parallel region contains i/o (OPEN,READ,WRITE,CLOSE) statements
"STOP statement" — routine called inside a parallel region contains STOP/PAUSE statements
"Potential memory conflict" — for shared variable that can cause memory conflict in a parallel region

If a private variable in a parallel region is updated via a COMMON block in a subroutine, CAPO tries to privatize such a variable by adding it to the subroutine's argument list and renaming the original variable in the COMMON block of the subroutine. CAPO will generate the following INFO messages in this process:

```
New argument () added to CALL OTHER_ROUTINE():# in ROUTINE_NAME
New symbol () added to the argument list of ROUTINE_NAME
Common block /cblk/ duplicated for ROUTINE_NAME
```

CAPO performs a code transformation automatically for a reduction variable that is an array element. The corresponding message is like:

```
Array reduction variable replaced with scalar in region # -
      OLD_ARRAY_ELEMENT --> NEW_SCALAR_VARIABLE
```

2.4. Debug Information

More information will be logged if `CAPO_LOGINFO` is set to "debug". These are useful for debugging CAPO. Some of the information are included here for reference only.

- UserLoop information for user-defined loop types

  ```
  Userloop: Defined loop # in routine ROUTINENAME - newtype
  ```

  "newtype" is one of (S, P, R, B) as mentioned in Section 1.3.

- List of old directives to be cleared

- Summary of loop type with list of all dependence vector deltas for pipeline loops

- Three tests during region formation

```
Mem-Conflict check for region #R, loops #L-#L...
   Conflict variables: <var,var...>
Shared-Array check for region #R, loops #L-#L...Assigned <Symbol>
IO-Statement check for region #R, loops #L-#L...
   I/O or Reduction in routine <RoutineName>
```

- List of symbols and types in each region

TYPE

`Private`	— Local (privatizable) variable
`Reduction`	— Scalar reduction variable
`ArrayReduction`	— Array reduction variable
`Shared`	— Shared variable
`LastPrivate`	— Usage in and after the region
`FirstPrivate`	— Usage in and before the region
`CopyInOut`	— Shared but no or no proof of loop-variable dependence
`ThreadPrivate`	— Used in a threadprivate common block
`UnknownType`	— Type not defined yet

CONTROL

`No-Control`	— Symbol not in a control dependence
`Control-Dep`	— Symbol in a control dependence

SCOPE

`In-Scope`	— Symbol defined in the current routine
`Not-in-Scope`	— Symbol not defined in the current routine (defined via common block or save statement)
`Not-in-Use`	— Symbol passed into a subroutine but not used in the subroutine

`DTYPE:DEPTH` (printed in `[.:.]`)

IO	-1,	Input/Output
NT	0,	Non-exact True
NA	1,	Non-exact Anti
NO	2,	Non-exact Output
ET	3,	Exact True
EA	4,	Exact Anti
EO	5,	Exact Output
CT	6,	Control
UN	7,	Unknown type

`Depth = 0` for loop-independent dependence

- List of routine call types, indicating the usage of a routine inside/outside parallel regions/loops. Five bits are used:

`bit1`	`[0x01]`	called outside parallel region
`bit2`	`[0x02]`	called inside paregion but outside parallel loop
`bit3`	`[0x04]`	called inside parallel loop
`bit4`	`[0x08]`	called outside parallel loop (= bit1 | bit2)
`bit5`	`[0x10]`	called inside parallel region

- Information on updating duplicated routines

```
Replace call to DROUTINE with CAP_DROUTINE in ROUTINE
Removed ROUTINE from the calledby list of DROUTINE
Added   ROUTINE to the calledby list of CAP_DROUTINE
```

- List of symbols and affine expressions for testing loop limits (such as in the removal of end-of-loop synchronizations)

```
HOME (LOOP-VAR-EXPR, #hits) Low <EXPR> High <EXPR> [A1:INDX,A2:INDX..]
     (LOOP-VAR-EXPR, #hits) Low <EXPR> High <EXPR> [B1:INDX,B2:INDX..]
OTHER (NONLOOP-EXPR, #hits) [C1:INDX,C2:INDX..]
      (NONLOOP-EXPR, #hits) [D1:INDX,D2:INDX..]
```

Here <EXPR> is a symbolic expression, A,B,C,D are array names, INDX is the relevant array index. The lists are for both source and sink.

- Summary of fields associated with the ploopinfo data struct, mainly for development purpose.

```
 Loop   Lvar   D/L    Type    G WP IP Nest Flag
Routine: ROUTINE_NAME
    #   var    ?/?    TYPE?   ?  ?  ? n/cn [321]
```

'Loop' — the loop number in a routine
'Lvar' — the loop variable name
'D' — the 'dlevel' value
'L' — the 'level' value of the loop
'Type' — one of type strings given in Section 2.1
'G' — the loop granularity flag (internal info only)
'WP' — '1' containing parallel loop, '0' without parallel loop
'IP' — '1' inside parallel loop, '0' not inside parallel loop
'n' — this loop nest flag (containing nested parallel loop)
'cn' — child loop nest flag (part of nested parallel loops)
'Flag' — three bits for internal usage only

- Symbols and their types in common blocks (for testing threadprivate). Meanings of symbol types:

[U] — Unset
[P] — Private
[R] — Reduction
[A] — ArrayReduction
[S] — Shared (RW)
[s] — Shared (Readonly)
[L] — LastPrivate
[F] — FirstPrivate
[C] — CopyInOut

- Methods used in determining the declaration size of unknown-size variables

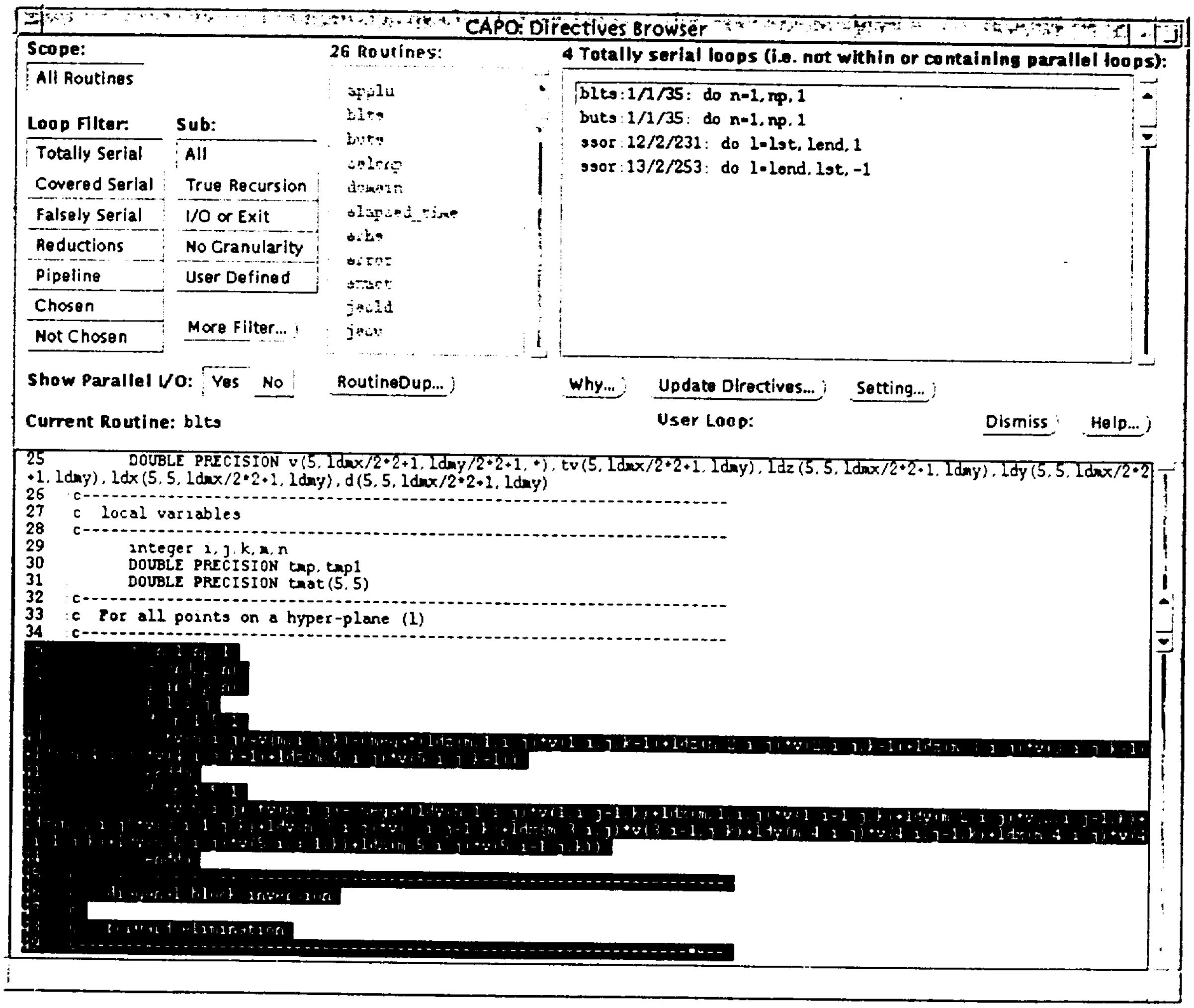
```
[NOT ]IDENTICAL SIZE, method 1 (caller declaration) used
MAX(e1,...), MIN(e1,...), method 2|3 (access range in routine) used
NO method - variable NOT safe - <var>
```

3. CAPO Graphic User Interface

CAPO is currently integrated into CAPTools as a component to generate OpenMP directives. For CAPO-enabled CAPTools, additional items have been added to the **File**, **View** and **Edit** menus (see Section 3.10) to access the CAPO graphic user interface (GUI).

The CAPO GUI is also referred to as the *Directives Browser*. It provides an easy way for user to access information generated during the directives analysis and insertion. The browser consists of several information windows and dialog boxes as given in the following sections. It also provides hookups to the CAPTools' GUI tools, such as DepGraph, Variable Browser, etc., so that one can easily navigate and interact with the parallelization process.

3.1. Directives Browser Main Window



```
blts:1/1/35: do n=1,np,1
buts:1/1/35: do n=1,np,1
ssor:12/2/231: do l=lst,lend,1
ssor:13/2/253: do l=lend,lst,-1
```

```
         DOUBLE PRECISION v(5,ldmx/2*2+1,ldmy/2*2+1,*),tv(5,ldmx/2*2+1,ldmy),ldz(5,5,ldmx/2*2+1,ldmy),ldy(5,5,ldmx/2*2
+1,ldmy),ldx(5,5,ldmx/2*2+1,ldmy),d(5,5,ldmx/2*2+1,ldmy)
   c---------------------------------------------------------------
   c  local variables
   c---------------------------------------------------------------
         integer i,j,k,m,n
         DOUBLE PRECISION tmp,tmp1
         DOUBLE PRECISION tmat(5,5)
   c---------------------------------------------------------------
   c  For all points on a hyper-plane (l)
   c---------------------------------------------------------------
[illegible]
   c  diagonal block inversion
   c
   c  forward elimination
   c---------------------------------------------------------------
```

The main window of the Directives browser is activated by **View->*Directives...*** from the CAPTools main window (see Section 3.9) after a source or database is loaded in. It presents information from the first two phases of the directives analysis (before directives are added). It is organized around loop types and is an entry point for other browser windows, such as **WhyDirectives** and **RoutineDuplication**.

Once directives are generated (via ***Save OpenMP Directives Code***), the Directives browser should not be used to do further changes.

Scope [setting]: selects one routine or all routines for loop listing.

Routines [list]: a list of routines that can be selected for loop listing.

Loops [list]: a list of loops under the selected routine/loop filters. To activate the **WhyDirectives** window through the Why... button, a loop needs to be selected.

Loop Filter [list]: provides a way to focus on a particular type of loops, mainly serial or parallel, as described in details in Section 3.2.

Sub [list]: sub-loop filter to be combined with the loop filter to provide finer control of loop selection.

More Filter [button]: activates the **Loop Variable Filter** window to perform even finer loop selection (Section 3.2.1).

Show Parallel I/O [setting]: controls the way that a loop with I/O statements inside is displayed. By default (*Yes*), loops with potential parallel I/O are classified as parallel although parallel I/O with directives is not supported at this point.

RoutDup [button]: activates the **RoutineDuplication** window (Section 3.4).

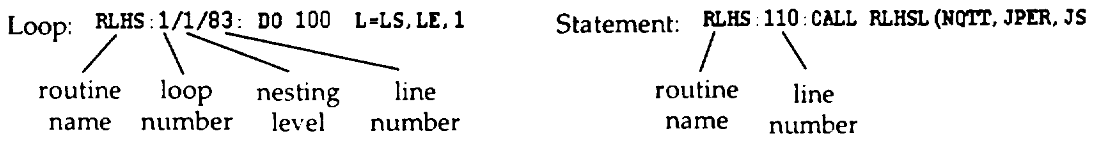
Why [button]: activates the **WhyDirectives window** (Section 3.3) after a loop is selected.

Update Directives [button]: activates the **Update** dialog box (Section 3.5) to re-perform the directives analysis, usually after settings are changed.

Setting [button]: activates the **Setting** window (Section 3.6) to reset parameters for CAPO. The window may also be launched from **Edit->*Directives Setting...*** in the CAPTools main window.

Current Routine [textpane]: displays the source of a selected routine or a routine in which a selected loop is located. The selected loop nest is highlighted.

How a loop or a statement is labeled:



Loop: `RLHS:1/1/83: DO 100 L=LS,LE,1`

Statement: `RLHS:110:CALL RLHSL(NQTT,JPER,JS`

3.2. Loop Filters and Sub-filters

Definitions of basic loop types:

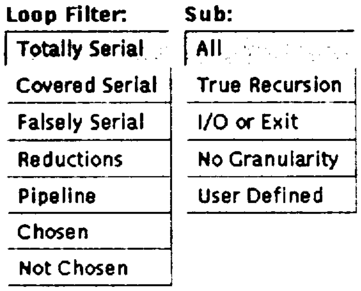
Serial loop — a loop *with* loop-carried TRUE dependence from data flow, ANTI/OUTPUT dependence from non-privatizable variables, I/O statements, and/or exit statements.

Parallel loop — a loop *without* loop-carried TRUE dependence from data flow, ANTI/OUTPUT dependence from non-privatizable variables, I/O statements, and exit statements. Such a loop can be executed in parallel.

Reduction loop — a loop, other than one or more reduction operations, that can be executed in parallel.

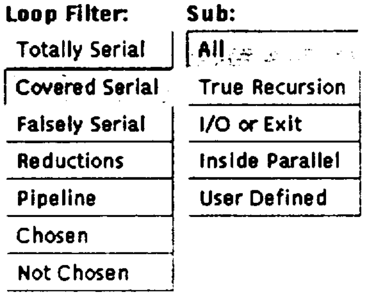
Pipeline loop — a loop that contains loop-carried TRUE dependences with determinable, non-negative dependence vectors. The loop can potentially be used to set up a parallel pipeline with an outer loop.

Distributed loop — one of Parallel loop, Reduction loop or Pipeline loop.



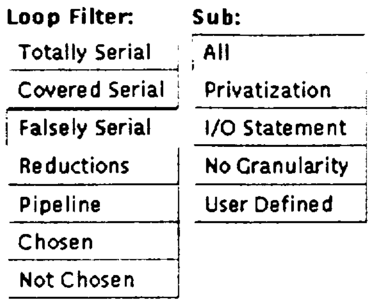
Loop Filter: ***Totally Serial*** —
serial loop with loop-carried TRUE dependence, containing no distributed loop and not nested inside other distributed loop. The code section in the loop will be executed sequentially.

Sub-filter: ***True Recursion*** — no I/O or exit statements
I/O or Exit — with I/O and/or exit statements
No Granularity — one or no iteration
User Defined — user-defined serial loop "S"



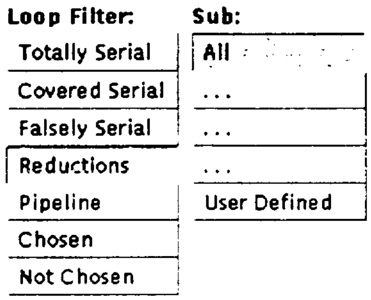
Loop Filter: ***Covered Serial*** —
serial loop with loop-carried TRUE dependence, containing distributed loop or nested inside other distributed loop. The code section in the loop will partially or completely be executed in parallel.

Sub-filter: ***True Recursion*** — no I/O or exit statements
I/O or Exit — with I/O and/or exit statements
Inside Parallel — inside other parallel loops
User Defined — user-defined serial loop "S"



Loop Filter: *Falsely Serial* —
serial loop without loop-carried TRUE dependence, but containing ANTI/OUTPUT dependence from non-privatizable variables. Loop may contain distributed loops for parallel execution.

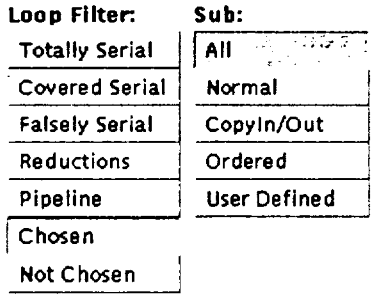
Sub-filter: ***Privatization*** — due to non-privatizable variables
I/O Statement — with I/O statements but no nested parallel loops
No Granularity — no granularity and no nested parallel loops
User Defined — user-defined serial loop "S"



Loop Filter: *Reductions* —
loop with one or more reduction operations which can be executed as parallel reductions.

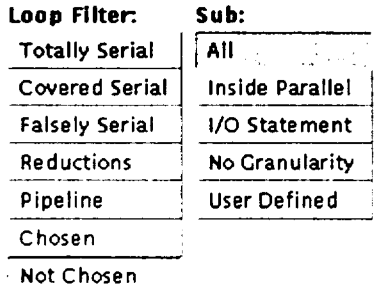
Loop Filter: *Pipeline* —
A pipeline loop as part of a parallel pipeline working with an outer loop.

Sub-filter: ***All*** — all loops with reductions/pipeline
User Defined — user-defined reduction loop "R"



Loop Filter: *Chosen (Parallel)* —
parallel loop chosen for distribution with directives. The code section in the loop will be executed in parallel.

Sub-filter: ***Normal*** — regular parallel loop
CopyIn/Out — with copyin/copyout variables
Ordered — with ordered code section
User Defined — user-defined parallel loop "P"



Loop Filter: *Not Chosen (Parallel)* —
parallel loop not chosen due to other parallel loop(s) already been chosen. The loop is either inside other distributed loop or contains distributed loops.

Sub-filter: ***Inside Parallel*** — inside other parallel loops
I/O Statement — with I/O statements
No Granularity — parallel but no granularity
User Defined — user-defined parallel loop "P"

3.2.1. Loop Variable Filter Window

The Loop Variable Filter Window controls even finer selection of loops in conjunction with the main loop filter and sub filter. The filter applys to variables used in loop heads.

Routine [label]: indicates the currently selected routine.

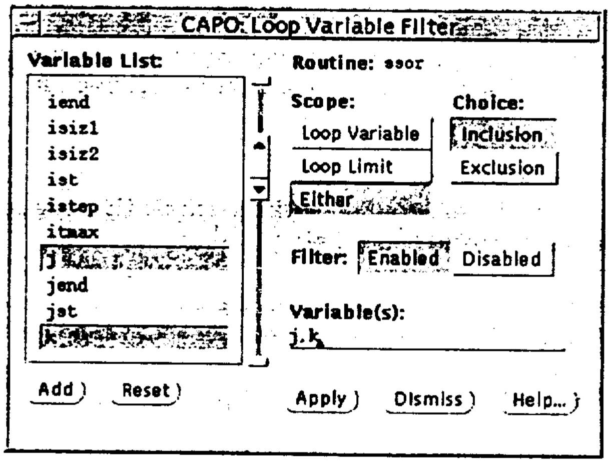
Variable List [list]: contains a list of variables used in the loop heads of the current routine.

Scope [setting]: controls the scope of variables.

Loop Variable	— variables from loop iteration
Loop Limit	— variables from loop high-low limit
Either	— either of the above two cases

Choice [setting]: controls the filtering effect.

Inclusion	— show loops when variables appear
Exclusion	— show loops when variables do not appear



CAPO: Loop Variable Filter

Variable List:

iend
isiz1
isiz2
ist
istep
itmax
j
jend
jst
k

Routine: ssor

Scope: [✓ Either]

Choice: [✓ Inclusion]

Filter: [✓ Enabled]

Variable(s): j.k

Filter [setting]: disables or enables the loop variable filter.

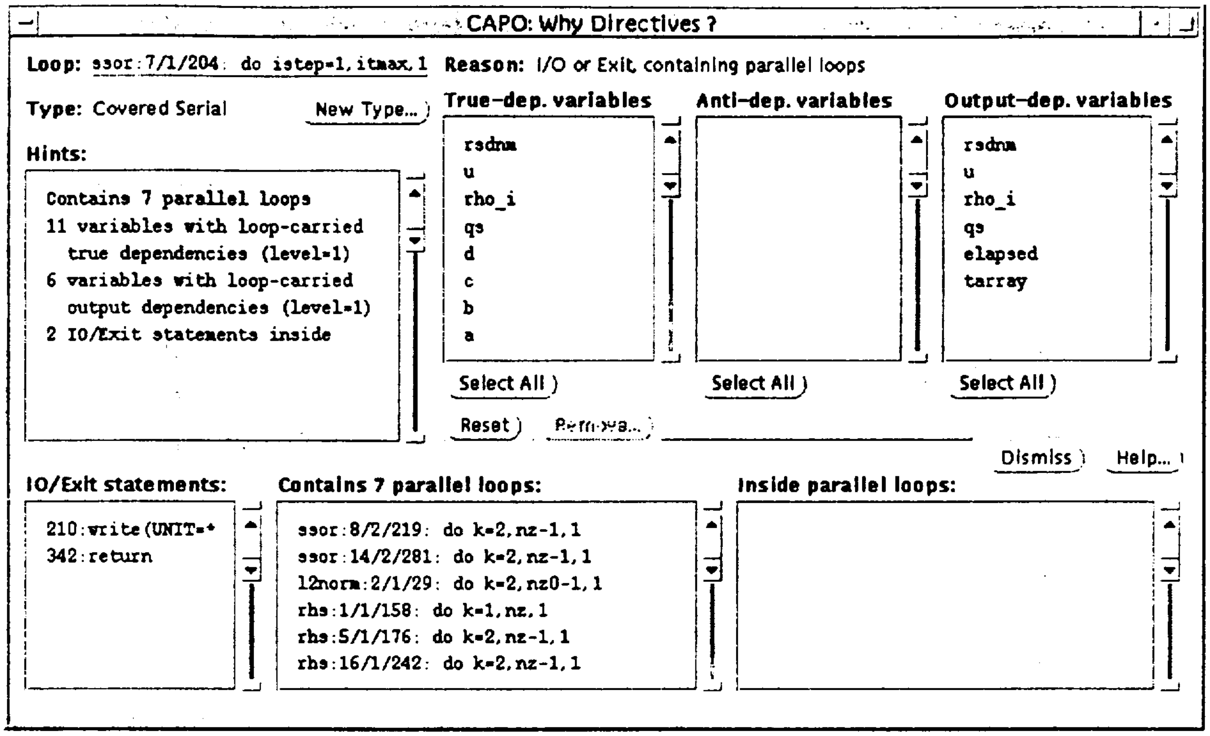
Variable(s) [textfield]: contains a list of the currently filtered variables.

Add [button]: adds the selected variables in the *Variable List* to the filtered variable list.

Reset [button]: resets variable selection.

Apply [button]: applies the current filter to the display.

3.3. WhyDirectives Window



CAPO: Why Directives ?

Loop: ssor:7/1/204: do istep=1,itmax,1 **Reason:** I/O or Exit containing parallel loops

Type: Covered Serial

Hints:

```
Contains 7 parallel loops
11 variables with loop-carried
  true dependencies (level=1)
6 variables with loop-carried
  output dependencies (level=1)
2 IO/Exit statements inside
```

True-dep. variables

```
rsdnm
u
rho_i
qs
d
c
b
a
```

Anti-dep. variables

Output-dep. variables

```
rsdnm
u
rho_i
qs
elapsed
tarray
```

IO/Exit statements:

```
210:write(UNIT=*
342:return
```

Contains 7 parallel loops:

```
ssor:8/2/219: do k=2,nz-1,1
ssor:14/2/281: do k=2,nz-1,1
l2norm:2/1/29: do k=2,nz0-1,1
rhs:1/1/158: do k=1,nz,1
rhs:5/1/176: do k=2,nz-1,1
rhs:16/1/242: do k=2,nz-1,1
```

Inside parallel loops:

The **WhyDirectives** window is displayed for a selected loop after the Why... button is clicked in the **Directives** main window. It presents detailed information for the selected loop, in particular, reasons and hints on why the loop was classified as serial or parallel. The window can be used to remove false dependences identified by the user and to redefine the loop type. Depending on the current loop type, the three variable lists may show different types of variables and the two loop lists may present different information. The displayed window is for *Covered Serial*.

<u>The following items are common for **All Loop Types.**</u>

Loop [textfield]: currently selected loop with routine name and loop labels (see the end of Section 3.2).

Type [textfield]: loop type as described in Section 3.1.

Reason [textfield]: one sentence summarizing why the loop was classified to its type.

Hints [textarea]: more detailed summary of the usage of the relevant variables in the loop and whether the loop contains I/O statements, exit statements, etc.

New Type [button]: activates the **New Loop Type** dialog box (Section 3.6).

Select All [button]: selects all variables in the corresponding variable list.

Reset [button]: deselects all variables in the variable lists.

Remove [button]: activates the **Variable Removal** dialog box (Section 3.8) for the selected variables.

IO/Exit statements [list]: list of I/O and exit statements in the selected loop nest.

<u>The following list is common for **Totally Serial and Covered Serial.**</u>

True-dep. variables [list]: list of variables causing loop-carried TRUE dependences, *removable*. An "[x]" followed a variable indicates the dependence vector length for this variable.

<u>The following lists are common for **Totally Serial, Covered Serial and Falsely Serial.**</u>

Anti-dep. variables [list]: list of variables causing loop-carried ANTI dependences and the variables cannot be privatized, *removable*.

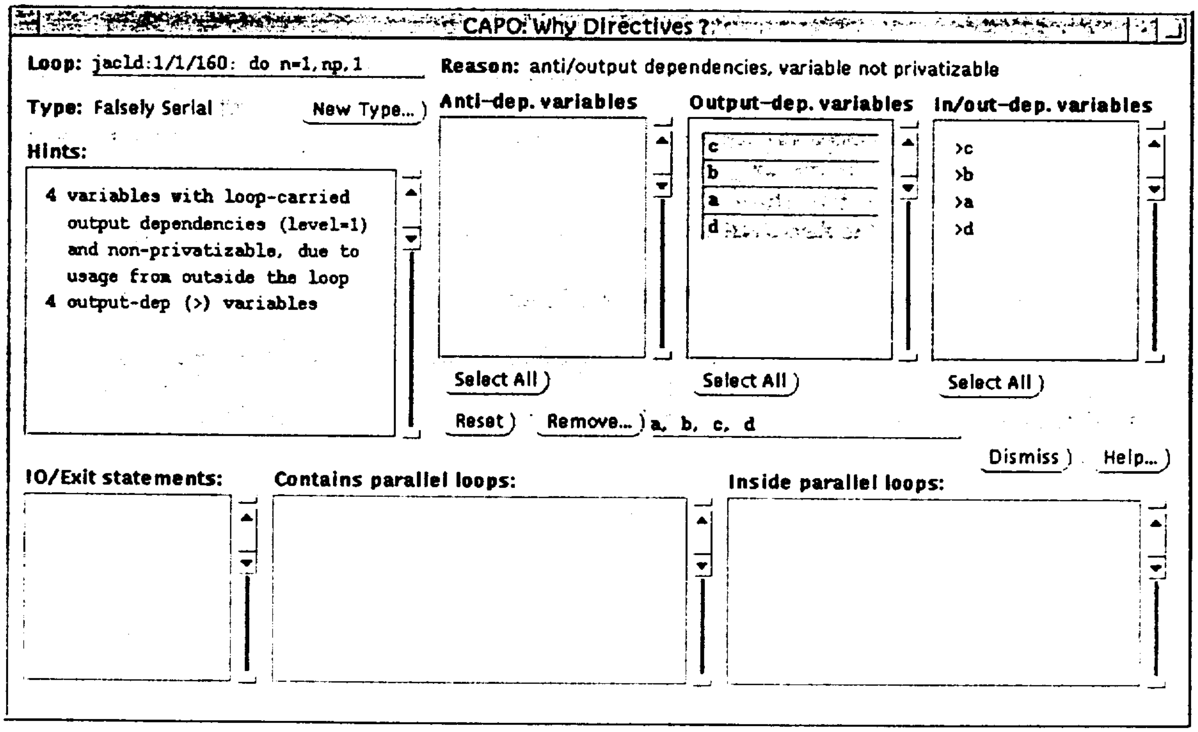
Output-dep. variables [list]: list of variables causing loop-carried OUTPUT dependences and the variables cannot be privatized, *removable*.

Contains parallel loops [list]: list of parallel loops that are nested inside the current loop.

Inside parallel loops [list]: list of parallel loops that contain the current loop.

<u>The following list is for **Falsely Serial.**</u>

In/out-dep. variables [list]: list of variables that have data (TRUE) dependences from the outside of the loop, *removable*.



CAPO: Why Directives ?

Loop: jacld:1/1/160: do n=1,np,1

Reason: anti/output dependencies, variable not privatizable

Type: Falsely Serial

Hints:

```
4 variables with loop-carried
  output dependencies (level=1)
  and non-privatizable, due to
  usage from outside the loop
4 output-dep (>) variables
```

Anti-dep. variables:

Output-dep. variables: c, b, a, d

In/out-dep. variables: >c, >b, >a, >d

Remove... a, b, c, d

IO/Exit statements:

Contains parallel loops:

Inside parallel loops:

The above window is for a *Falsely Serial* loop.

The following lists are common for **Reductions, Pipeline, Chosen, and Not Chosen.**

Private variables [list]: list of privatizable variables in the loop nest, *not removable.*

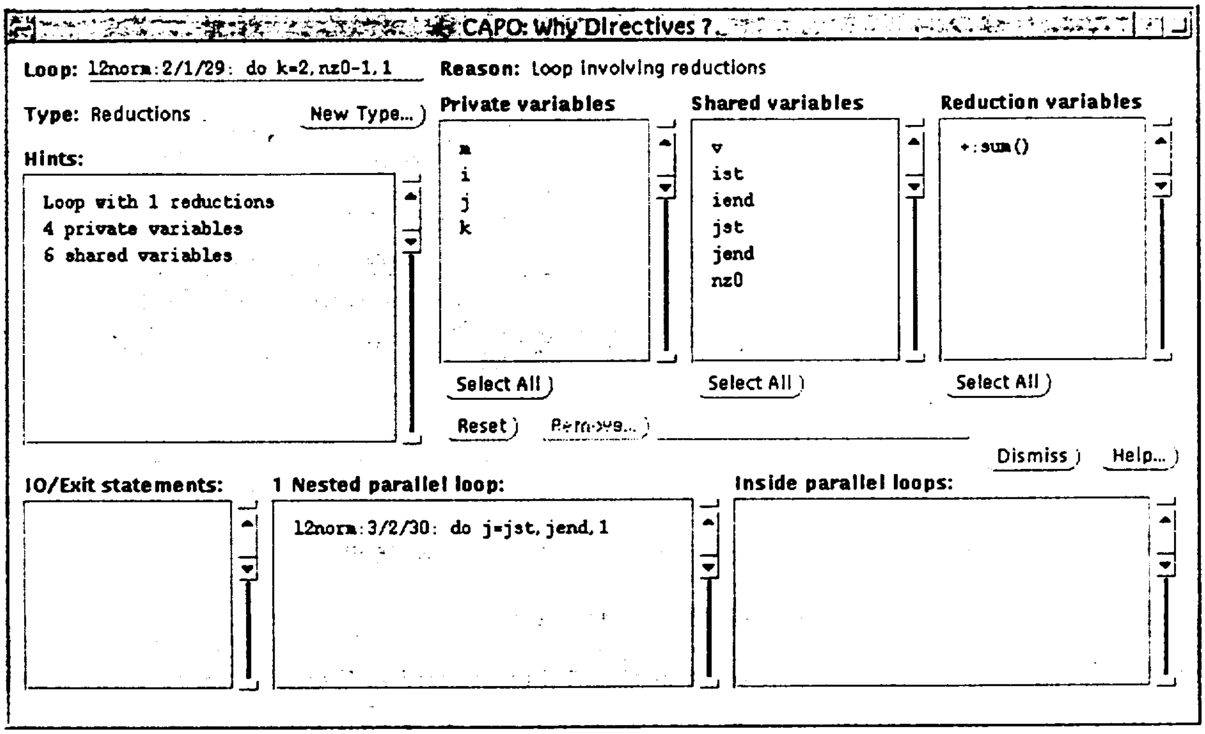
Shared variables [list]: list of shared variables in the loop nest, *not removable.*

Nested parallel loops [list]: list of secondary parallel loops that are nested inside the current loop.

Inside parallel loops [list]: list of parallel loops that contain the current loop (except for Pipeline).

The following list is only for **Reduction Loop.**

Reduction variables [list]: list of variables for reductions in the loop nest, *not removable.* Reduction variables are preceded with labels indicating reduction operators or intrinsic functions. A "()" after a variable indicates an array reduction.



CAPO: Why Directives ?

Loop: 12norm:2/1/29: do k=2,nz0-1,1

Reason: Loop involving reductions

Type: Reductions

Hints:

```
Loop with 1 reductions
4 private variables
6 shared variables
```

Private variables:

```
m
i
j
k
```

Shared variables:

```
v
ist
iend
jst
jend
nz0
```

Reduction variables:

```
+:sum()
```

IO/Exit statements:

1 Nested parallel loop:

```
12norm:3/2/30: do j=jst,jend,1
```

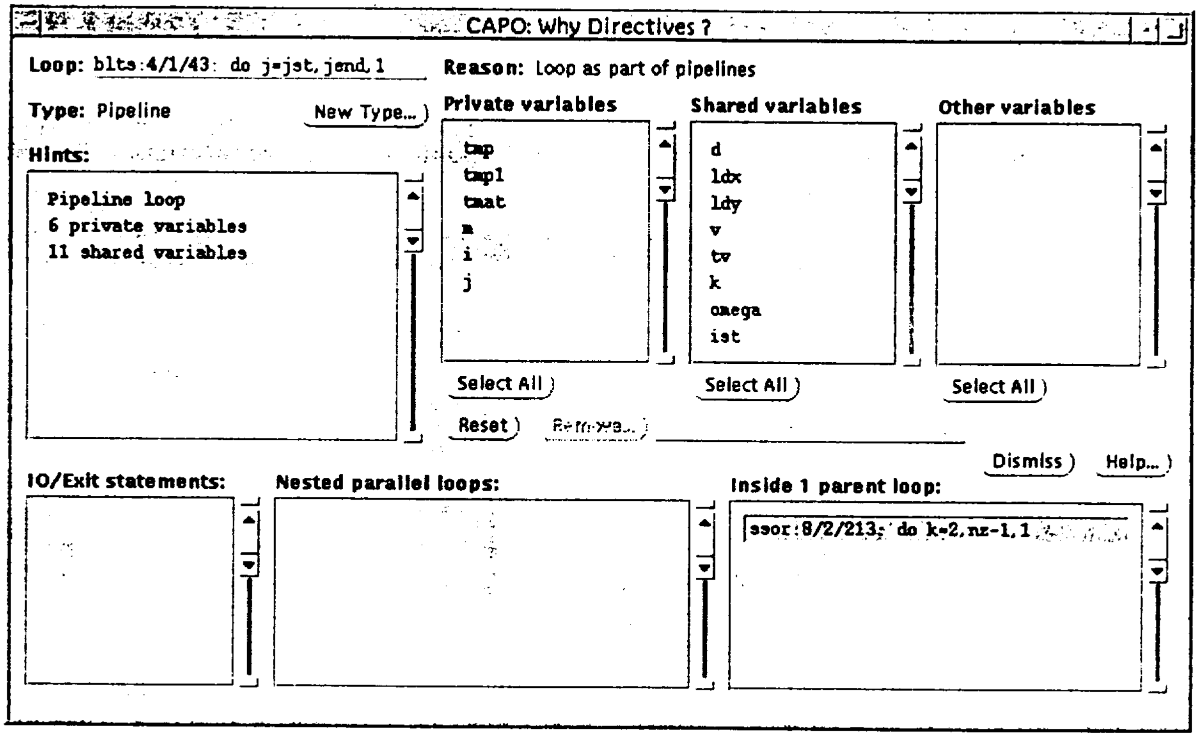
Inside parallel loops:

The above window is for a *Reduction* loop with reduction array variable "sum()".

The following lists are only for **Pipeline Loop.**

Inside parent loops [list]: list of loops that are nested above the current pipeline loop to form parallel pipelines. Appropriate synchronization directives and statements will be inserted at the code generation. A parent loop is usually a serial loop without I/O and exit statement inside.

Other variables [list]: list of variables other than private and shared, such as **CopyIn/CopyOut** variables, *not removeable*.



CAPO: Why Directives ?

Loop: blts:4/1/43: do j=jst,jend,1

Reason: Loop as part of pipelines

Type: Pipeline

Hints:

```
Pipeline loop
6 private variables
11 shared variables
```

Private variables

```
tmp
tmp1
tmat
m
i
j
```

Shared variables

```
d
ldx
ldy
v
tv
k
omega
ist
```

Other variables

IO/Exit statements:

Nested parallel loops:

Inside 1 parent loop:

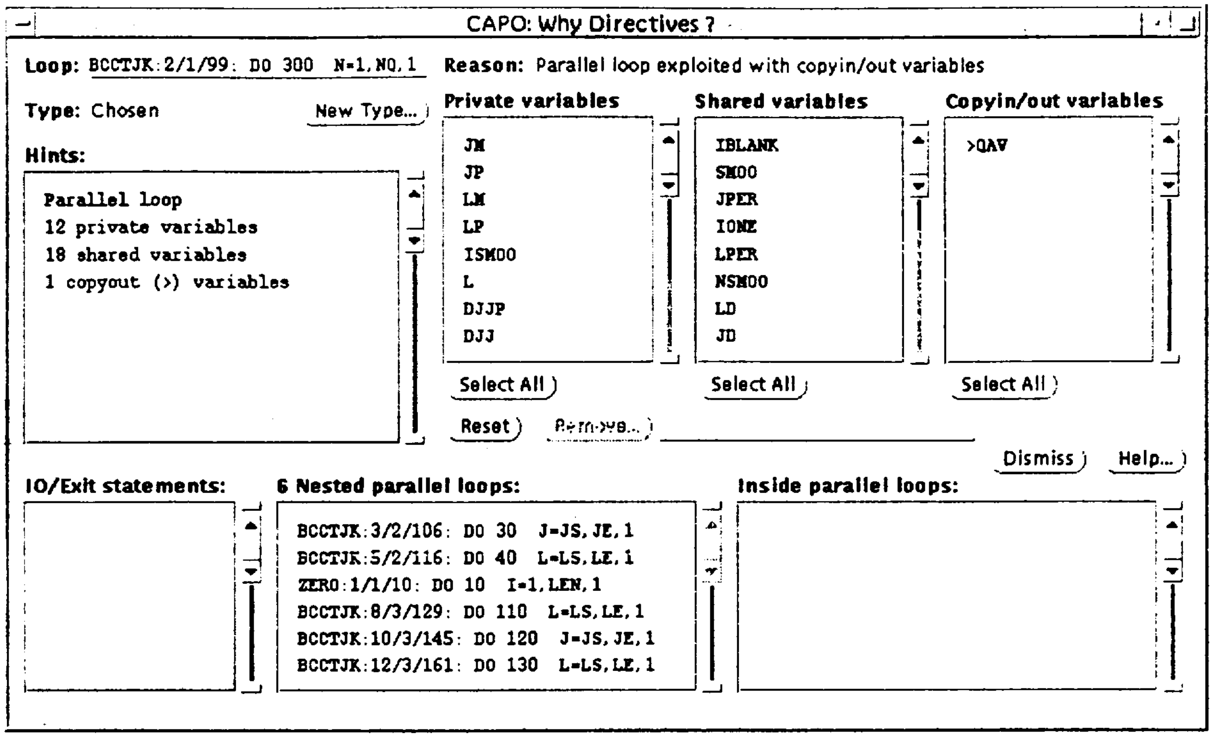
```
ssor:8/2/213: do k=2,nz-1,1
```

The above window is for a *Pipeline* loop with the parent loop highlighted.

The following lists are only for **Chosen Parallel Loop.**

Copyin/out variables [list]: list of variables that will be declared as **CopyIn** (FIRSTPRIVATE) and/or **CopyOut** (LASTPRIVATE) due to potential conflict in updating the same memory location and the variable(s) having usage outside of the loop. It might arise, for example, from an induction variable that is assigned before the loop and used after the loop. It could also indicate a programming bug.

Controlled variables [list]: list of variables that will be placed inside an "ORDERED" code section. These variables are usually inside IF conditional statements and the corresponding assignments need to be executed in a designated order as is in sequential.



CAPO: Why Directives ?

Loop: BCCTJK:2/1/99: DO 300 N=1,NQ,1

Reason: Parallel loop exploited with copyin/out variables

Type: Chosen

Hints:

Parallel loop
12 private variables
18 shared variables
1 copyout (>) variables

Private variables

JM
JP
LM
LP
ISMOO
L
DJJP
DJJ

Shared variables

IBLANK
SMOO
JPER
IONE
LPER
NSMOO
LD
JD

Copyin/out variables

>QAV

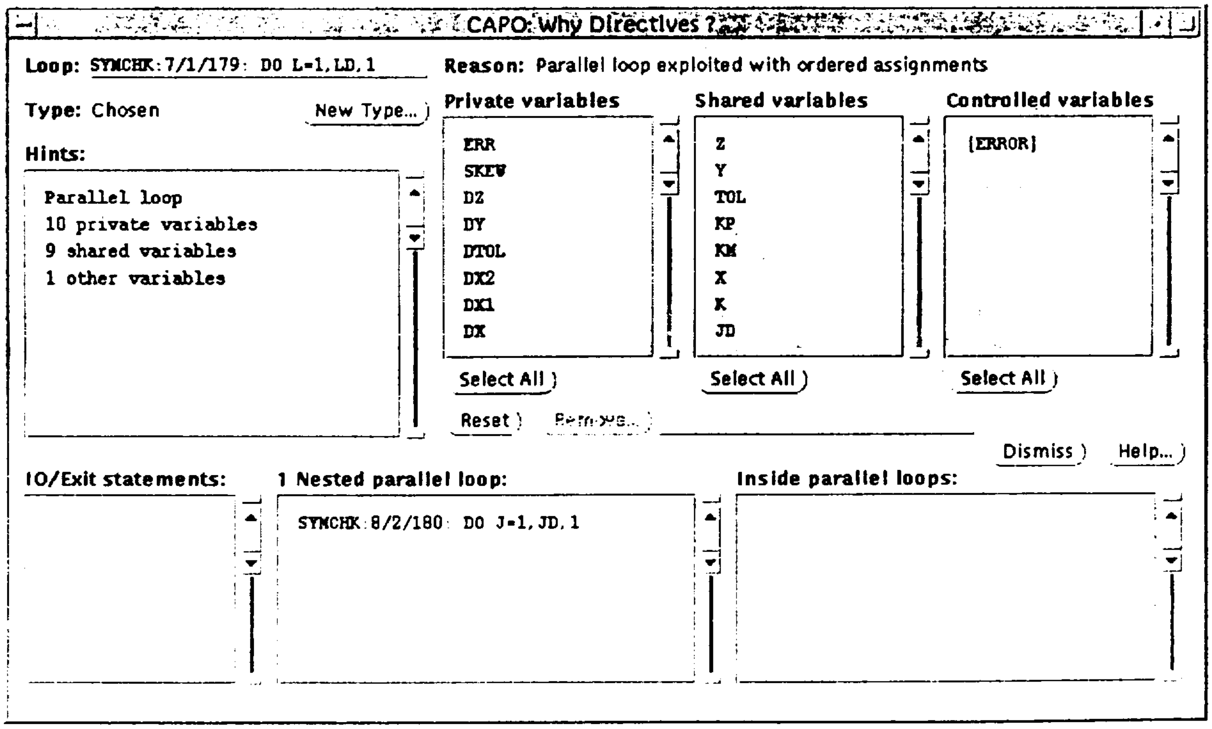
IO/Exit statements:

6 Nested parallel loops:

```
BCCTJK:3/2/106: DO 30  J=JS,JE,1
BCCTJK:5/2/116: DO 40  L=LS,LE,1
ZERO:1/1/10: DO 10  I=1,LEN,1
BCCTJK:8/3/129: DO 110  L=LS,LE,1
BCCTJK:10/3/145: DO 120  J=JS,JE,1
BCCTJK:12/3/161: DO 130  L=LS,LE,1
```

Inside parallel loops:

The above windows is for Chosen parallel loop with Copyin/out variables.



CAPO: Why Directives ?

Loop: SYMCHK:7/1/179: DO L=1,LD,1

Reason: Parallel loop exploited with ordered assignments

Type: Chosen

Hints:

Parallel loop
10 private variables
9 shared variables
1 other variables

Private variables

ERR
SKEW
DZ
DY
DTOL
DX2
DX1
DX

Shared variables

Z
Y
TOL
KP
KM
X
K
JD

Controlled variables

{ERROR}

IO/Exit statements:

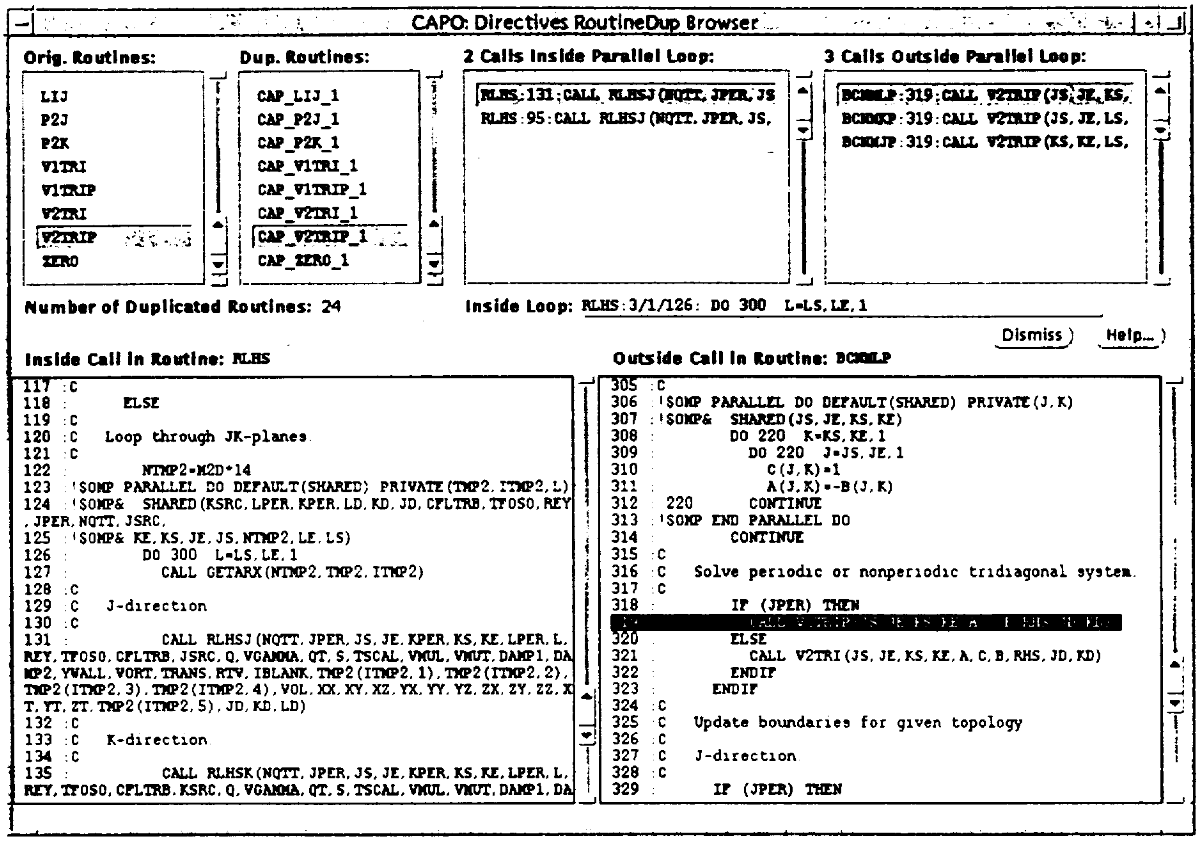
1 Nested parallel loop:

```
SYMCHK:8/2/180: DO J=1,JD,1
```

Inside parallel loops:

The above window is for Chosen parallel loop with Controlled variables.

3.4. Routine Duplication Browser



Orig. Routines:

```
LIJ
P2J
P2K
V1TRI
V1TRIP
V2TRI
V2TRIP
ZERO
```

Dup. Routines:

```
CAP_LIJ_1
CAP_P2J_1
CAP_P2K_1
CAP_V1TRI_1
CAP_V1TRIP_1
CAP_V2TRI_1
CAP_V2TRIP_1
CAP_ZERO_1
```

2 Calls Inside Parallel Loop:

```
RLHS:131:CALL RLHSJ(NQTT,JPER,JS
RLHS:95:CALL RLHSJ(NQTT,JPER,JS,
```

3 Calls Outside Parallel Loop:

```
BCOMLP:319:CALL V2TRIP(JS,JE,KS,
BCOMKP:319:CALL V2TRIP(JS,JE,LS,
BCOMJP:319:CALL V2TRIP(KS,KE,LS,
```

Number of Duplicated Routines: 24

Inside Loop: RLHS:3/1/126: DO 300 L=LS,LE,1

Inside Call in Routine: RLHS

```
117 :C
118 :       ELSE
119 :C
120 :C   Loop through JK-planes.
121 :C
122 :          NTMP2=M2D*14
123 :!$OMP PARALLEL DO DEFAULT(SHARED) PRIVATE(TMP2,ITMP2,L)
124 :!$OMP&  SHARED(KSRC,LPER,KPER,LD,KD,JD,CFLTRB,TFOSO,REY
,JPER,NQTT,JSRC,
125 :!$OMP& KE,KS,JE,JS,NTMP2,LE,LS)
126 :          DO 300  L=LS,LE,1
127 :             CALL GETARX(NTMP2,TMP2,ITMP2)
128 :C
129 :C   J-direction
130 :C
131 :             CALL RLHSJ(NQTT,JPER,JS,JE,KPER,KS,KE,LPER,L,
REY,TFOSO,CFLTRB,JSRC,Q,VGAMMA,QT,S,TSCAL,VMUL,VMUT,DAMP1,DA
MP2,YWALL,VORT,TRANS,RTV,IBLANK,TMP2(ITMP2,1),TMP2(ITMP2,2),
TMP2(ITMP2,3),TMP2(ITMP2,4),VOL,XX,XY,XZ,YX,YY,YZ,ZX,ZY,ZZ,X
T,YT,ZT,TMP2(ITMP2,5),JD,KD,LD)
132 :C
133 :C   K-direction
134 :C
135 :             CALL RLHSK(NQTT,JPER,JS,JE,KPER,KS,KE,LPER,L,
REY,TFOSO,CFLTRB,KSRC,Q,VGAMMA,QT,S,TSCAL,VMUL,VMUT,DAMP1,DA
```

Outside Call in Routine: BCOMLP

```
305 :C
306 :!$OMP PARALLEL DO DEFAULT(SHARED) PRIVATE(J,K)
307 :!$OMP&  SHARED(JS,JE,KS,KE)
308 :         DO 220  K=KS,KE,1
309 :            DO 220  J=JS,JE,1
310 :               C(J,K)=1
311 :               A(J,K)=-B(J,K)
312 : 220        CONTINUE
313 :!$OMP END PARALLEL DO
314 :         CONTINUE
315 :C
316 :C   Solve periodic or nonperiodic tridiagonal system.
317 :C
318 :         IF (JPER) THEN
319 :            CALL V2TRIP(JS,JE,KS,KE,A,C,B,RHS,JD,KD)
320 :         ELSE
321 :            CALL V2TRI(JS,JE,KS,KE,A,C,B,RHS,JD,KD)
322 :         ENDIF
323 :      ENDIF
324 :C
325 :C   Update boundaries for given topology
326 :C
327 :C   J-direction
328 :C
329 :      IF (JPER) THEN
```

The RoutineDuplication window is used for browsing routines that are to be or were duplicated to avoid usage conflict of directives. The window is activated from the RoutDup... button in the Directives browser main window.

Orig. Routines [list]: list of original routines to be duplicated.

Dup. Routines [list]: list of duplicated routines. Before code generation, this list will be empty. After code generation, the list is filled with new routines that have one-to-one correspondence to the original routines. The matched (original, duplicated) routine pairs are selected in concert.

Number of Duplicated Routines [numeric]: as it says.

Calls Inside Parallel Loop [list]: list of call statements (to a selected original routine) that are inside parallel loop(s).

Calls Outside Parallel Loop [list]: list of call statements (to a selected duplicated routine) that are outside any parallel loop.

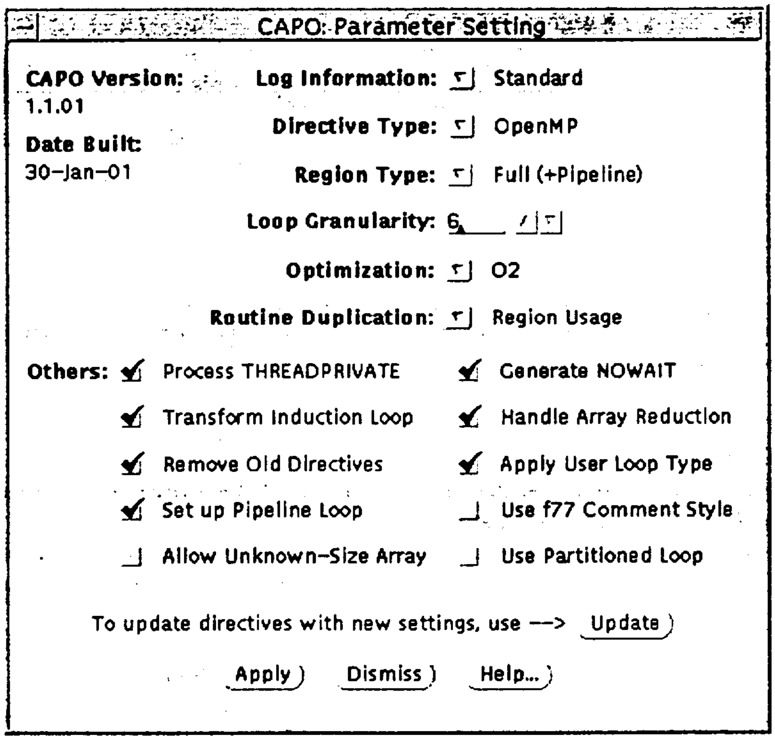
Inside Loop [textfield]: the loop that contains the selected call statement to an original routine.

Inside Call in Routine [textpane]: the source for the corresponding loop for **Inside Loop**. The textpane is also used for displaying source code for the selected original routine.

Outside Call in Routine [textpane]: the source around the selected call statement from the **Call Outside Parallel Loop** list. The textpane is also used for displaying source code for the selected duplicated routine.

3.5. Parameter Setting Window

A default setup for the **Parameter Setting** window is displayed on the left. It is launched from either the Setting... button in the Directives main window or the **Edit** → *Directives Setting...* in CAPTools main window. The window is used to reset parameters for CAPO to control the directives analysis and generation. The available parameters and their values are described in Section 1.



CAPO:Parameter Setting

CAPO Version: 1.1.01

Date Built: 30-Jan-01

Log Information: Standard

Directive Type: OpenMP

Region Type: Full (+Pipeline)

Loop Granularity: 6

Optimization: O2

Routine Duplication: Region Usage

Others:
- ☑ Process THREADPRIVATE
- ☑ Generate NOWAIT
- ☑ Transform Induction Loop
- ☑ Handle Array Reduction
- ☑ Remove Old Directives
- ☑ Apply User Loop Type
- ☑ Set up Pipeline Loop
- □ Use f77 Comment Style
- □ Allow Unknown-Size Array
- □ Use Partitioned Loop

To update directives with new settings, use —> Update

CAPO Version: the current version number of CAPO.

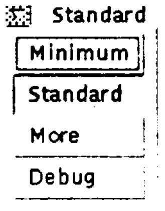
Date Built: date on which the current version of CAPO was built.

Update [button]: re-performs directives analysis with the current parameters.

Apply [button]: applies the current parameter setting without performing the directives analysis.

For detailed information on settings and checks, see Sections 1.3 and 2. The following briefly describes each setting and check box in the window.

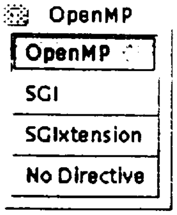
Loop Granularity [numeric]: the minimum number of iterations in a loop for the consideration as a distributed loop. If the number is 0 or if the number of iterations cannot be evaluated, there will be no check on the granularity for the loop.



Log Information [setting]:

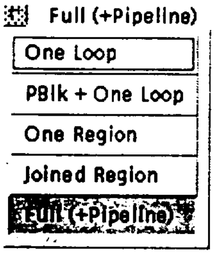
Minimum — minimum log information, such as warning and info messages,
Standard — "Minimum" information plus statistics for loops and regions,
More — "Standard" information plus more detailed loop and region information,
Debug — "More" information plus much more for debugging purpose.

For both *More* and *Debug*, loop and region labels are inserted in the generated source code.



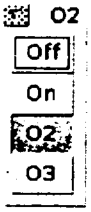
Directive Type [setting]:

OpenMP — generate OpenMP directives (default),
SGI — generate SGI native directives,
SGIxtension— generate OpenMP directives with SGI extensions,
No Directive— create source file without directives.



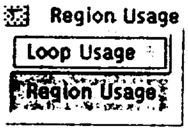
Region Type [setting]:

One Loop — only one loop for one region,
Pblk + One Loop — one pre-block plus one loop for one region,
One Region — regions are not joined,
Joined Region — regions are joined, no pipeline consideration,
Full Region — consider joined region and possible pipeline (default).



Optimization [setting]:

Off — do not do any optimization,
On — try to reduce synchronization at end-of-loop,
O2 — use logical disprove (slow sometime) for affinity comparison,
O3 — enable additional optimization (such as automatic loop transformation) before directive insertion.



Routine Duplication [setting]:

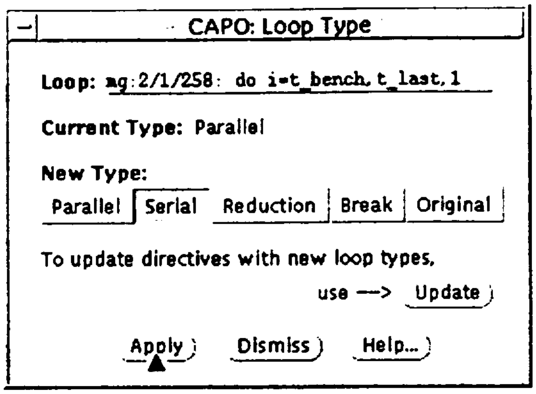
Loop Usage — routine duplicated if it is used both inside and outside parallel Loops (no nested parallel region),
Region Usage — routine duplicated if it is used inside a parallel loop and inside parallel region but outside parallel loop (allow nested parallel region).

Others [checkbox]:

Process THREADPRIVATE — enable/disable the THREADPRIVATE directive
Generate NOWAIT — enable/disable the NOWAIT directive
Transform Induction Loop — enable/disable induction loop treatment
Handle Array Reduction — enable/disable array reduction
Remove Old Directives — enable/disable removing old directives
Apply UserLoop Type — enable/disable applying userloop types
Setup Pipeline Loop — enable/disable pipeline loop
Use f77 Comment Style — use f77 (not checked) or f90 (checked) comment style
Allow Unknown-Size Array — enable/disable the use unknown-size array in PRIVATE
Use Partitioned Loop — enable/disable partitioned loop for directives

3.6. User Loop Type Window

The loop type window is used to redefine a loop type manually. It is displayed for a selected loop by clicking on the New Type button in the **WhyDirectives** window.



Loop: mg:2/1/258: do i=t_bench,t_last,1

Current Type: Parallel

To update directives with new loop types,
use —> Update

Loop [textfield]: print of the selected loop.

Current Type [textfield]: the current loop type.

New Type [setting]: one of the selectable types.

Parallel – a parallel loop
Serial – a serial loop
Reduction – a parallel loop with reduction. The Reduction setting may activate an additional dialog box: **Reduction Operator** (See Section 3.7).
Break – a serial loop excluded from any parallel region
Original – the type originally set by CAPO.

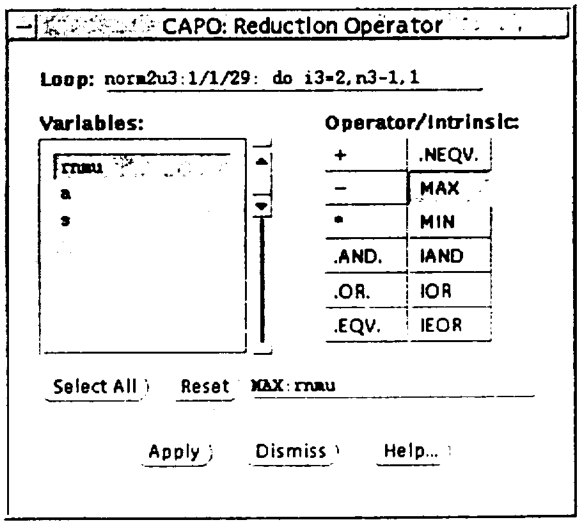
An un-selectable type indicates a type that cannot be converted to from the current type.

Update [button]: saves the newly defined loop type to the `userloop.par` file and re-performs the directives analysis with the new setting.

Apply [button]: saves the newly defined loop type to the `userloop.par` file but does not re-perform the directives analysis.

3.7. Reduction Operator Dialog

This is a dialog box to select an option (or options) for user-defined reduction loop type. The option specifies reduction operators/intrinsics and variables as part of the entry in the userloop.par file. See Section 1.3 for the description of the userloop.par file. The dialog box is activated only if the *Reduction* setting in the LoopType window is selected and there exist potential reducible variables detected in the loop by CAPO.



Loop: norm2u3:1/1/29: do i3=2,n3-1,1

MAX:rnmu

Loop [textfield]: print of the selected loop.

Variables [list]: list of variables that can potentially be selected as reduction variables, *selectable*.

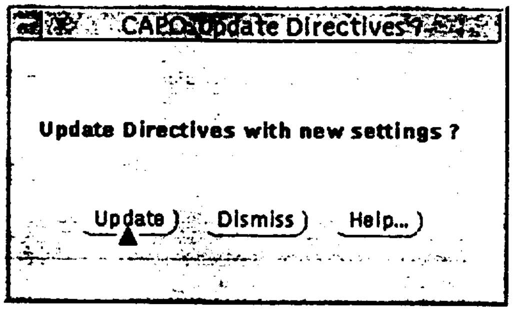
Operator/Intrinsic [setting]: one of the defined reduction operators or intrinsic functions.

Select All [button]: selects all the variables in the variable list.

Reset [setting]: resets any previous selection. The textfield on the right lists the selected Operator/ Intrinsic and variables.

Apply [button]: creates an [operator/intrinsic:variables] combination and add to the option list for the currently selected loop. The option and user-loop type are only stored to the userloop.par file when the Apply or Update button in the **LoopType** window is pushed.

3.8. Updating Directives Dialog

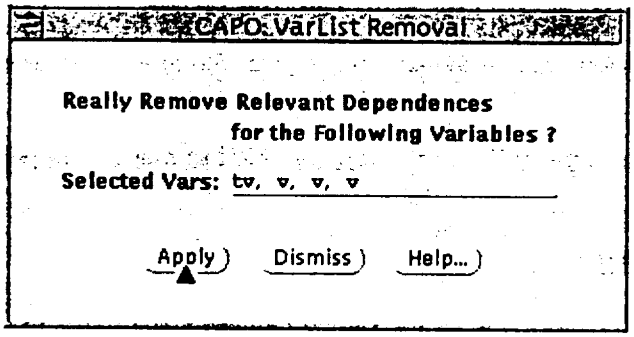


Update Directives with new settings ?

This is a dialog box for confirming the analysis of directives with new settings. It is popped up after the Update button in the **Directives browser** main window is pushed.

Update [button]: performs the directives analysis, including loop and region level analysis, without generating directives. The dialog will be disabled after the OpenMP directives code is generated.

3.9. Variable Removal Confirmation Dialog



Really Remove Relevant Dependences for the Following Variables ?

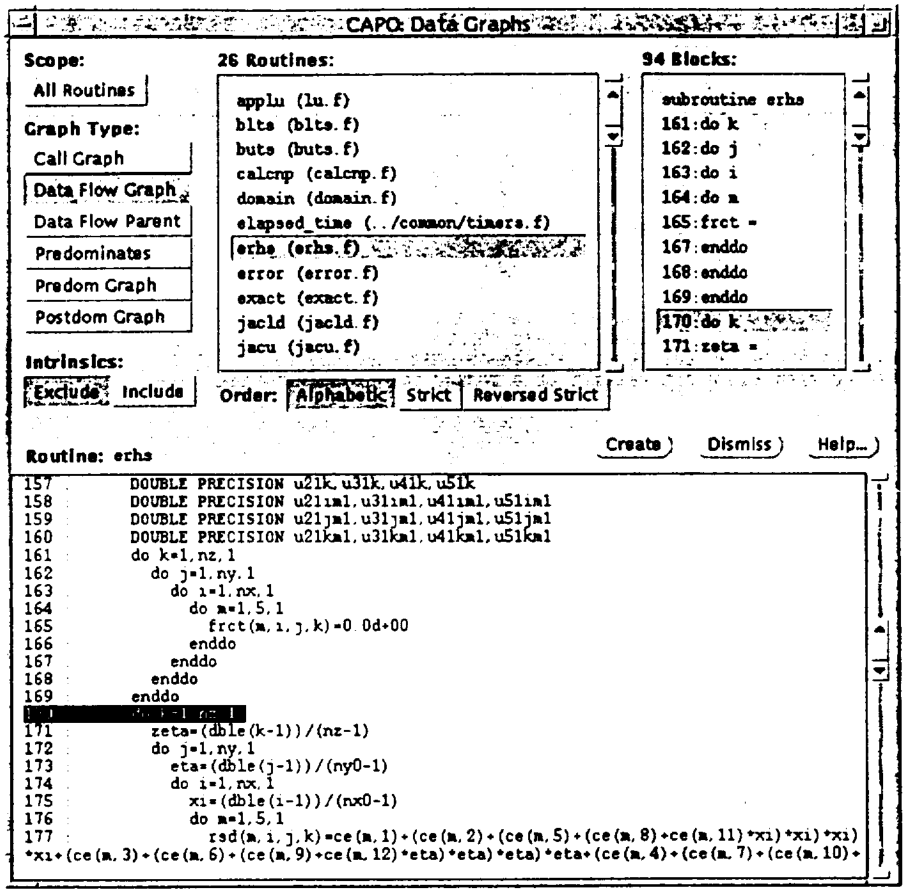
Selected Vars: tv, v, v, v

The dialog is used for confirming the removal of dependences for selected variables and types. The variables and types are determined in the **WhyDirectives** window and the dialog box is activated by pushing the Remove button. This box provides a shortcut to the **DepGraph** for quickly deleting false dependences.

Selected Vars [textfield]: list of selected variables from the **WhyDirectives** window.

Apply [button]: applies the removal action.

3.10. Data Graph Window



Scope: All Routines

Graph Type: Data Flow Graph

Intrinsics: Exclude

Order: Alphabetic

26 Routines:

```
applu (lu.f)
blts (blts.f)
buts (buts.f)
calcnp (calcnp.f)
domain (domain.f)
elapsed_time (../common/timers.f)
erhs (erhs.f)
error (error.f)
exact (exact.f)
jacld (jacld.f)
jacu (jacu.f)
```

94 Blocks:

```
subroutine erhs
161:do k
162:do j
163:do i
164:do m
165:frct =
167:enddo
168:enddo
169:enddo
170:do k
171:zeta =
```

Routine: erhs

```
      DOUBLE PRECISION u21k,u31k,u41k,u51k
      DOUBLE PRECISION u21im1,u31im1,u41im1,u51im1
      DOUBLE PRECISION u21jm1,u31jm1,u41jm1,u51jm1
      DOUBLE PRECISION u21km1,u31km1,u41km1,u51km1
      do k=1,nz,1
        do j=1,ny,1
          do i=1,nx,1
            do m=1,5,1
              frct(m,i,j,k)=0.0d+00
            enddo
          enddo
        enddo
      enddo
      do k=1,nz,1
        zeta=(dble(k-1))/(nz-1)
        do j=1,ny,1
          eta=(dble(j-1))/(ny0-1)
          do i=1,nx,1
            xi=(dble(i-1))/(nx0-1)
            do m=1,5,1
              rsd(m,i,j,k)=ce(m,1)+(ce(m,2)+(ce(m,5)+(ce(m,8)+ce(m,11)*xi)*xi)*xi)
*xi+(ce(m,3)+(ce(m,6)+(ce(m,9)+ce(m,12)*eta)*eta)*eta)*eta+(ce(m,4)+(ce(m,7)+(ce(m,10)+
```

The Data Graph window is used to create graphs for development purpose. It may have little use to a typical user, but is included for reference. The window is activated from *View→Data Graph* in the CAPTools main window. If the "Data Graph" menu item is not present, try to start CAPO with the [-capodg] option.

Scope [setting]: defines the scope of the routine list.

Graph Type [setting]: chooses from one of the predefined graph types.

Intrinsics [setting]: excludes or includes intrinsic functions in the routine list and in the graph.

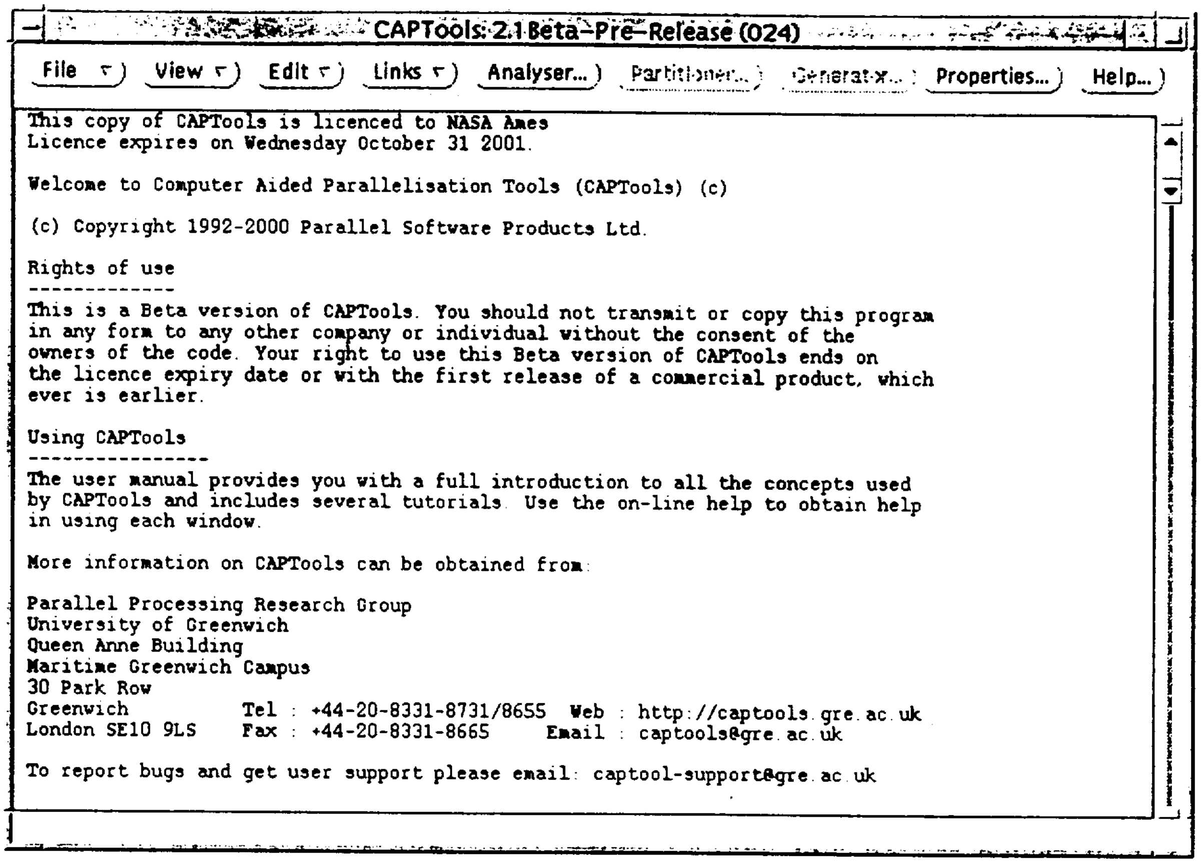
Routines [list]: list of routines (name of the file containing a routine).

Order [setting]: defines the way routines are listed (Alphabetic, Strict, Reversed Strict).

Blocks [list]: list of basic program blocks in the selected routine.

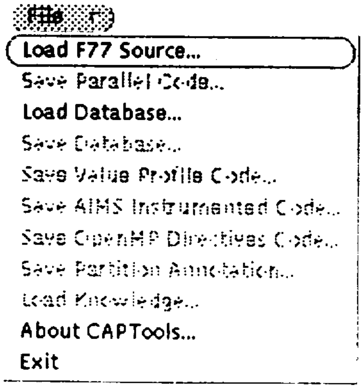
Create [button]: creates a graph for the selected routine and/or block (currently *xvcg* is used to display the graph).

3.11. Hookups to CAPTools

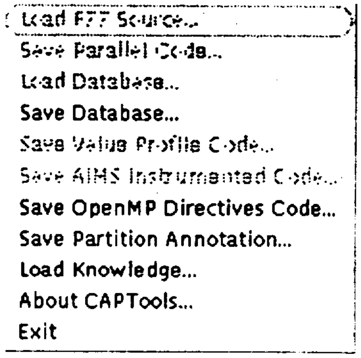


```
This copy of CAPTools is licenced to NASA Ames
Licence expires on Wednesday October 31 2001.

Welcome to Computer Aided Parallelisation Tools (CAPTools) (c)

(c) Copyright 1992-2000 Parallel Software Products Ltd.

Rights of use
-------------
This is a Beta version of CAPTools. You should not transmit or copy this program
in any form to any other company or individual without the consent of the
owners of the code. Your right to use this Beta version of CAPTools ends on
the licence expiry date or with the first release of a commercial product, which
ever is earlier.

Using CAPTools
----------------
The user manual provides you with a full introduction to all the concepts used
by CAPTools and includes several tutorials. Use the on-line help to obtain help
in using each window.

More information on CAPTools can be obtained from:

Parallel Processing Research Group
University of Greenwich
Queen Anne Building
Maritime Greenwich Campus
30 Park Row
Greenwich          Tel : +44-20-8331-8731/8655  Web : http://captools.gre.ac.uk
London SE10 9LS    Fax : +44-20-8331-8665     Email : captools@gre.ac.uk

To report bugs and get user support please email: captool-support@gre.ac.uk
```

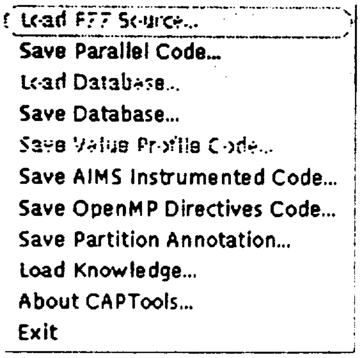
This is the main GUI window when CAPTools is started. CAPO is integrated into CAPTools as a component to generate OpenMP directives. For CAPO-enabled CAPTools, additional items are added to the File (*Save OpenMP Directives Code*), View (*Directives*) and Edit (*Directives Setting*) menus. Those menu items that are relevant to directives generation are summarized here.


File
Load F77 Source...
Save Parallel Code...
Load Database...
Save Database...
Save Value Profile Code...
Save AIMS Instrumented Code...
Save OpenMP Directives Code...
Save Partition Annotation...
Load Knowledge...
About CAPTools...
Exit

Before source is loaded


Load F77 Source...
Save Parallel Code...
Load Database...
Save Database...
Save Value Profile Code...
Save AIMS Instrumented Code...
Save OpenMP Directives Code...
Save Partition Annotation...
Load Knowledge...
About CAPTools...
Exit

After source is loaded


Load F77 Source...
Save Parallel Code...
Load Database...
Save Database...
Save Value Profile Code...
Save AIMS Instrumented Code...
Save OpenMP Directives Code...
Save Partition Annotation...
Load Knowledge...
About CAPTools...
Exit

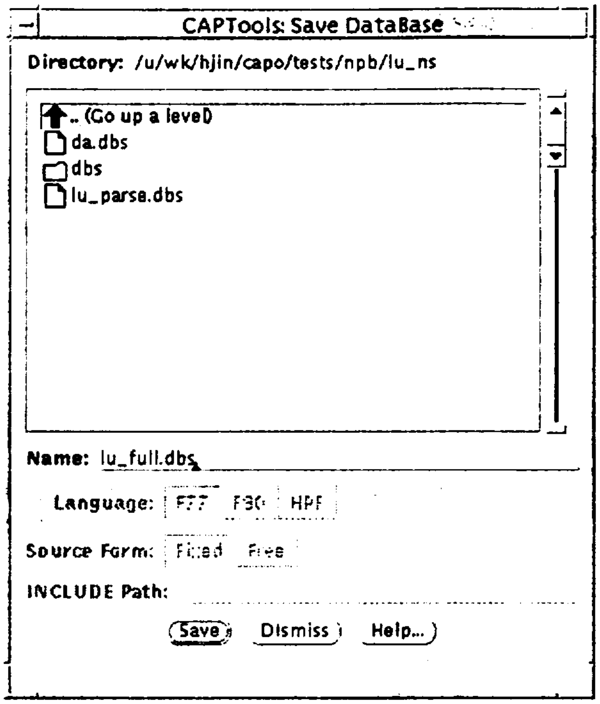
After communication is generated

The File menu:

Load F77 Source [entry]: loads Fortran 77 source (.f or .list file).

Load Database [entry]: loads a previously saved database (.dbs file).

Save Database [entry]: saves the current analysis result to a database. As of CAPO version 1.1, the directives analysis result is not yet saved to the database. But the inserted directives are saved.



CAPTools: Save DataBase

Directory: /u/wk/hjin/capo/tests/npb/lu_ns

.. (Go up a level)
da.dbs
dbs
lu_parse.dbs

Name: lu_full.dbs

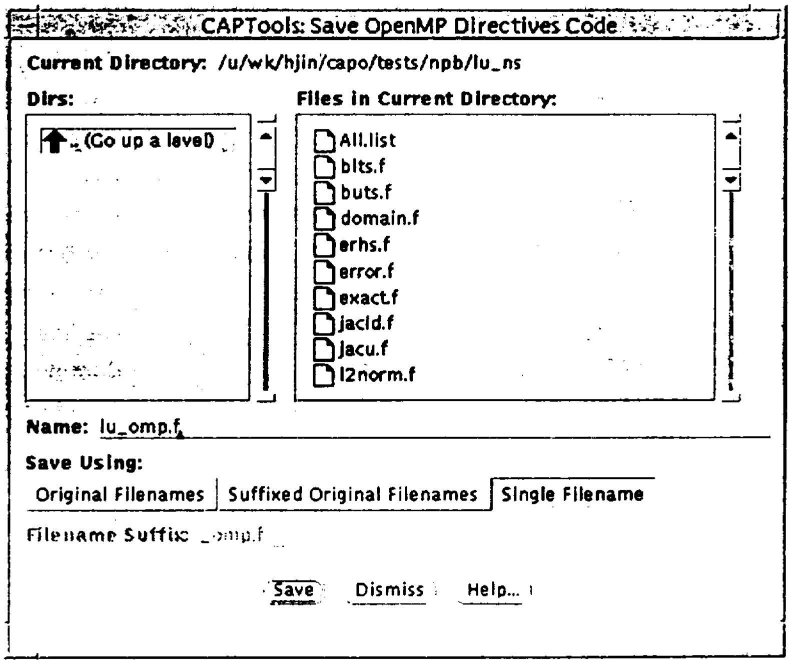
Language: F77 F90 HPF

Source Form: Fixed Free

INCLUDE Path:

The **Save Database** dialog box.

Save OpenMP Directives Code [entry]: performs the directives analysis if it has not been done and generates OpenMP directives.



CAPTools: Save OpenMP Directives Code

Current Directory: /u/wk/hjin/capo/tests/npb/lu_ns

Dirs:
.. (Go up a level)

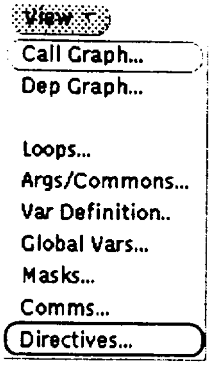
Files in Current Directory:
All.list
blts.f
buts.f
domain.f
erhs.f
error.f
exact.f
jacld.f
jacu.f
l2norm.f

Name: lu_omp.f

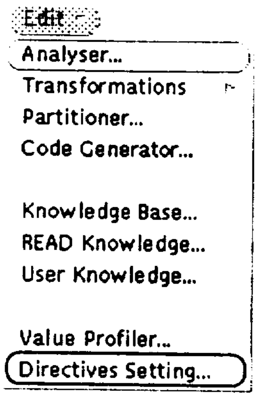
Save Using: Original Filenames | Suffixed Original Filenames | Single Filename

Filename Suffix: _omp.f

The Save OpenMP Directives Code dialog box.

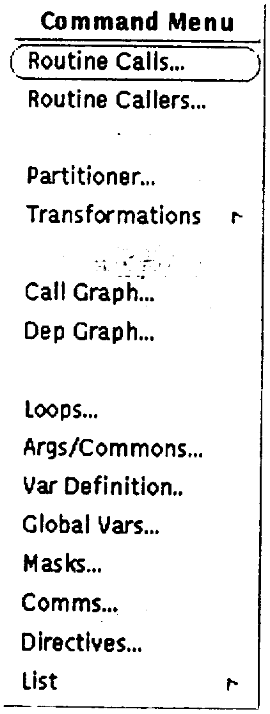


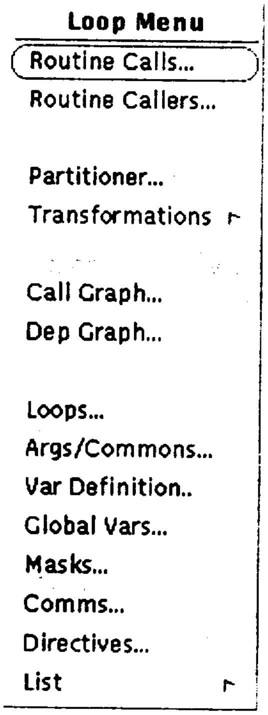
The View menu:
Directives [entry]: activates the Directives browser, which performs the directives analysis (if not yet done) and presents information on directives.

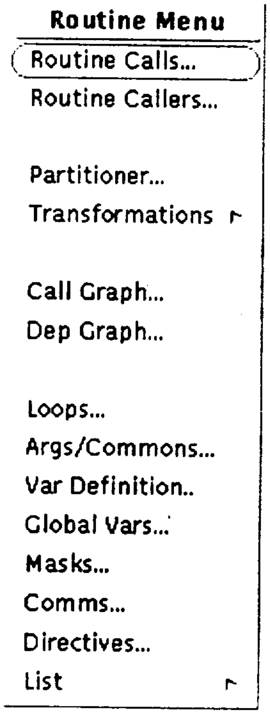


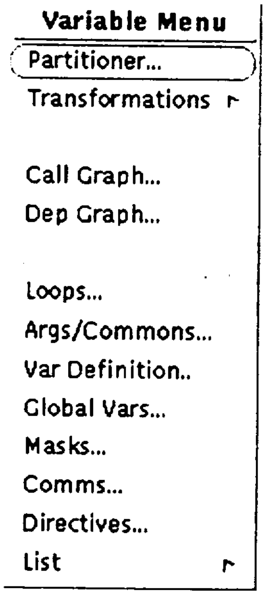
The Edit menu:
Directives Setting [entry]: activates the Setting dialog box as given in Section 3.5. It can be used to set up parameters for CAPO before the the directives analysis is performed.

The following popup menus are hookups to various tools from selected lists or items in a GUI window, usually activated with a right-mouse-button click.









Command Menu [popup]: for a selected statement.

Loop Menu [popup]: for a selected loop.

Routine Menu [popup]: for a selected routine.

Variable Menu [popup]: for a selected variable.

4. CAPO Command Interface

The command interface for CAPO is available in Version 1.1 and works closely with the CAPTools' command interface. It provides a way to access the functionality of GUI components without starting the components. It serves as a mean to record actions (to a log file) as a result of any user GUI activities so that these actions can be played back later. The commands in the command interface are usually recorded to a log file or a command file with

```
capo -logfile capo_run.cmd
```

and played back with

```
capo [-batch] capo_run.cmd.
```

The command interface for CAPO is different from the command-line version of CAPO, which takes simply the database as input and creates the Fortran output:

```
capo -capoc [-options] database.dbs output.f.
```

This stand-alone version is mostly for testing purpose. The command interface is the preferred method.

4.1. Commands for the Command Interface

CAPO commands start with the keyword "capo" to distinguish them from CAPTools commands.

Main commands:

`load <file.dbs>`
- Load database file

`capo version 1`
- Define CAPO command version

`capo removedep <routine> <variable> <loop_number> <dtype> <fc> [<drout>]`
- Remove loop-related data dependences
  * `routine` - routine name
  * `variable` - relevant variable in the routine
  * `loop_number` - loop to be considered
  * `dtype` - dependence type: 1 for loop-carried TRUE dependences
    2 for TRUE dependences from outside loop
    3 for loop-carried ANTI dependences
    4 for loop-carried OUTPUT dependences
  * `fc` - `1` father list, `2` child list, `0` both lists
  * `[drout]` - optional field to define routine in which the variable is actually declared (if it is different from `<routine>`)

`capo update [0/1]`
- Perform directives analysis with the new setting
  `'0'` for initial analysis, `'1'` for new update

`capo passtwo`
- Re-perform the pass-two analysis

`capo generate [<file.f>]`

- Generate OpenMP directives. <file.f> is used to define the logfile name, i.e. <file.log>. If <file.f> is not given, "capo-info.log" is assumed for the logfile name.

```
save source <file.f> 3 0
```

- Save source code to <file.f>
  '3' indicates a single file

("load" and "save" are two CAPTools commands. See 4.2 for details.)

Parameter setting commands:

```
capo set log-file on/off/stdout
```

- Turn on/off information logging, default is on

```
capo set log-file-name <filename>
```

- Define log filename, default is "capo-info.log"

```
capo set log-info minl/std/more/debug
```

- Select log information type, default is std

```
capo set loop-granularity <value>
```

- Set loop granularity threshold, default value = 6

```
capo set directive-type omp/sgi/sgix/no
```

- Select directive type, default is omp

```
capo set optimize-type off/o1/o2/o3
```

- Set the optimization type, default is o2

```
capo set user-loop-file <filename>
```

- Define user loop file, default is "userloop.par"

```
capo set directive-clear off/on/<filename>
```

- Turn on/off old directive clearing, default is on
  A <filename> is used to define a new set of directives

```
capo set comment-type f77/f90
```

- Set the comment type for directive, default is f90

```
capo set use-parti-loop yes/no
```

- Allow the partitioned loop for directive, default is no

```
capo set rdup-type loop/region
```

- Select the routine duplication type, default is region

```
capo set allow-pio no/incall/write/noread/any
```

- Allow parallel I/O type, default is no

Setting commands for debugging purpose:

```
capo set mflag <mflag_value>
```

- Define the module flag
  <mflag_value> can be <number>/<m1:m2..> with [+-] sign

```
capo set region-type default/loop/bloop/one/join/full
```

- Set a region type, default is full

```
capo set tpriv-directive on/off
```

- Turn on/off the generation of THREADPRIVATE, default is on

```
capo set allow-unksize true/false
```

- Allow the use of unknown-size private variables, default is false

```
capo set have-pipeloop true/false
    - Generate pipeline loop, default is  true
capo set have-induc true/false
    - Treat parallel induction loop, default is  true
capo set have-arreduc true/false
    - Treat array reduction, default is  true
capo set have-nowait true/false
    - Generate the NOWAIT directive, default is true
capo set apply-userloop yes/no
    - Apply user defined loop types, default is  yes
capo set apply-dirclear yes/no
    - Apply old directive clearing, default is  yes
```

4.2. Other CAPTools Commands Useful for CAPO

```
version 2
    - Define CAPTools command version
load <file.f/file.list/file.dbs>
    - Load source/database file
save database <file.dbs>
    - Save to database
save source <dir/suffix/file.f> <1/2/3> 0
    - Save source with type  1, 2 or 3
      Type 1 :  Save to original files,  <dir> is required for directory name
      Type 2 :  Save to original files with  <suffix>,<dir/suffix> required
      Type 3 :  Save to a single file with file name  <file.f>
set exact on
set scaler on
set knowledge on
set disproofs on
set interprocedural on
set logic on
    - Settings for the analysis power
add read knowledge applu:76:((nx-5 .GT. 0))
    - Define read user knowledge
analyse
    - Perform dependence analysis
```

4.3. An Example of "capo_run.cmd"

```
version 2
load applu_full.dbs
capo version 1
capo set log-file-name applu_omp.log
capo update 0
capo removedep setbv u 1 4 0
capo removedep setbv u 3 4 0
capo removedep setbv u 5 4 0
capo update 1
capo generate
save source applu_omp.f 3 0
```

To use the command file, do "capo -batch capo_run.cmd".

TUTORIALS

Source codes for all the tutorials described in this manual are included in the CAPO distribution and can also be obtained from site http://www.nas.nasa.gov/Tools/CAPO/. Refer to "`Examples.txt`" included in the `examples` directory for additional information.

Contents

Tutorial 1. A Simple Jacobi Code

This tutorial demonstrates the very basic operations you would follow to generate an OpenMP code without little user intervention. The code (jacobi.f) has an initialization loop and an iteration loop. The iteration loop computes new solutions by averaging two neighboring points and checks the maximum residual.

Steps of parallelization:

1. **Perform the data dependence analysis**. In CAPO, click ***Load F77 Source*** in the **File** menu. Select jacobi.f and click Load. In the **Analyser** window, select the Full option and click Analyse. This will just take a few seconds.

2. **Save to database**. In the **File** menu, click ***Save database***. Enter a filename for the database or take the default name (jacobi_full.dbs) and click Save. It is always a good idea to save the results from different stages of the code analysis.

3. **Browse directives**. In the **View** menu, click ***Directives*** to perform the directives analysis. The Directives browser will be popped up quickly. Select the All Routines scope and browse through all loop filters. You will notice that the Jacobi code contains one *Reduction* loop (`DO 30 I=1,N`), two *Chosen* (parallel) loops (`DO 10 I=1,N` and `DO 20 I=2,N-1`), and one *Falsely Serial* loop (`DO 50 I=1,N`containing an I/O statement).

4. **Produce OpenMP code**. In the **File** menu, click ***Save OpenMP Directives Code***. Enter a filename (or take the default name, jacobi_omp.f) and click Save. If the directives analysis has not been performed (via Step 3), it will automatically be performed before the parallel code is generated. The log file, jacobi_omp.log, contains additional information for the parallelization process.

To compile the OpenMP code on the SGI Origin2000, do

```
% f77 -o jacobi_omp -O3 -r8 -mp jacobi_omp.f
```

To execute the parallel code with 2 threads, do

```
% setenv OMP_NUM_THREADS 2
% ./jacobi_omp
Enter the values of N and TOL ...
1000 1.0e-6
```

The output looks like

```
...
49.99968169151887
  1166848  9.9999888192314756E-07
```

You can compare the result with a single thread run or a serial version run. You will notice the program does not scale well, primarily due to little work inside each distributed loop.

Tutorial 2. NPB LU-hp Removing False Dependences

This tutorial demonstrates the basic user interaction with CAPO: removing false dependences to improve the quality of data dependence and directives analyses. False dependences usually arise from insufficient knowledge of certain parameters (such as from READ statements or calculated at runtime) during CAPTools data dependence analysis. With the Directives browser, the user can inspect the results and remove these false dependences if needed.

The example is one of the benchmarks from the NAS Parallel Benchmark (NPB) suite. The benchmark, LU-hp, uses an SSOR algorithm to solve the Navier-Stokes equations in three dimensions. A hyper-plane implementation of the SSOR algorithm is used in LU-hp. The code is split into many .f files. In order to load the code to CAPO, we first create a list file "All.list" that contains names of all the .f files.

Steps of parallelization:

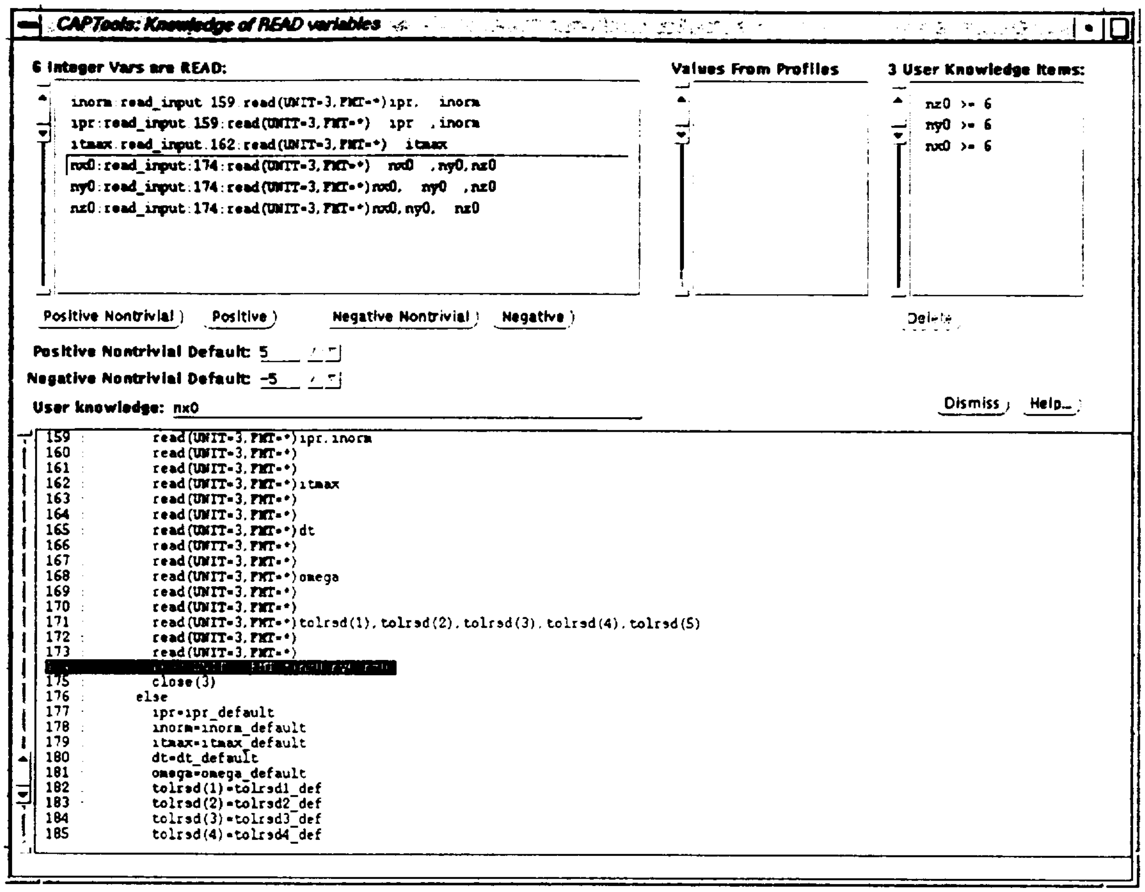
1. **Load file and enter user knowledge**. Click ***Load F77 Source*** in the **File** menu. Select All.list and click the Load button. Select ***READ Knowledge*** from the **Edit** menu. In the **READ Knowledge** window, select variable nx0 and click Positive Nontrivial, see Figure T2-1 on next page. Apply the same steps to variables ny0 and nz0. These three variables define the number of grid points in each dimension. Making them positive nontrivial (> 5 in the current case) improves the quality of data dependence analysis.

2. **Perform the data dependence analysis**. After the user knowledge is entered, in the **Analyser** window select the Full option and click Analyse. On an Indy R5000 workstation, the analysis process takes about 18 minutes.

3. **Save to database**. In the **File** menu, click ***Save Database***. Enter a filename for the database (lu_hp_full.dbs) and click Save.

4. **Browse directives**. In the **View** menu, click ***Directives*** to perform the directives analysis. The Directives browser will be popped up shortly. Select the All Routines scope and browse through all loop filters. Pay attention to the serial loops (*Totally*, *Covered* and *Falsely*. For meanings of these loop types, refer to Section 3.2 in Appendix).

5. **Remove false dependences**. In the Directives browser window, select the Totally Serial loop filter and the All Routines scope. There are four loops listed under this category. Choose the first loop: `blts:1/1/35: do n=1,np,1` and click the Why button. The **WhyDirectives** window as shown in Figure T2-2 will be popped up. As indicated in the window, the serialization of this loop is caused by loop-carried data dependences from two variables: v and tv. After inspecting the loop, the user realizes that this loop performs calculation for all points on a given hyper-plane. Each point on one hyper-plane could be calculated independently, thus in parallel. However, indirect indexing was used to access data elements on the plane and these indices were calculated dynamically and not available at the data dependence analysis stage. Conservative decisions were made to keep these data dependences during the analysis. So, the user can safely remove these *false* dependences to enforce a parallel loop: using either the **DepGraph** window (in CAPTools) or the WhyDirectives window here (simpler). With the second method, select variable v and tv in the three lists (**True**, **Anti** and **Output**), click the Remove button and click the Apply button to confirm the action. Apply the same procedure to the second loop: `buts:1/1/35: do n=1,np,1`.



CAPTools: Knowledge of READ variables

6 Integer Vars are READ:

```
inorm read_input 159 read(UNIT=3,FMT=*)ipr,  inorm
ipr:read_input 159:read(UNIT=3,FMT=*)  ipr  ,inorm
itmax read_input 162:read(UNIT=3,FMT=*)  itmax
nx0:read_input:174:read(UNIT=3,FMT=*)  nx0  ,ny0,nz0
ny0:read_input:174:read(UNIT=3,FMT=*)nx0,  ny0  ,nz0
nz0:read_input:174:read(UNIT=3,FMT=*)nx0,ny0,  nz0
```

Values From Profiles

3 User Knowledge Items:

```
nz0 >= 6
ny0 >= 6
nx0 >= 6
```

Positive Nontrivial Default: 5

Negative Nontrivial Default: -5

User knowledge: nx0

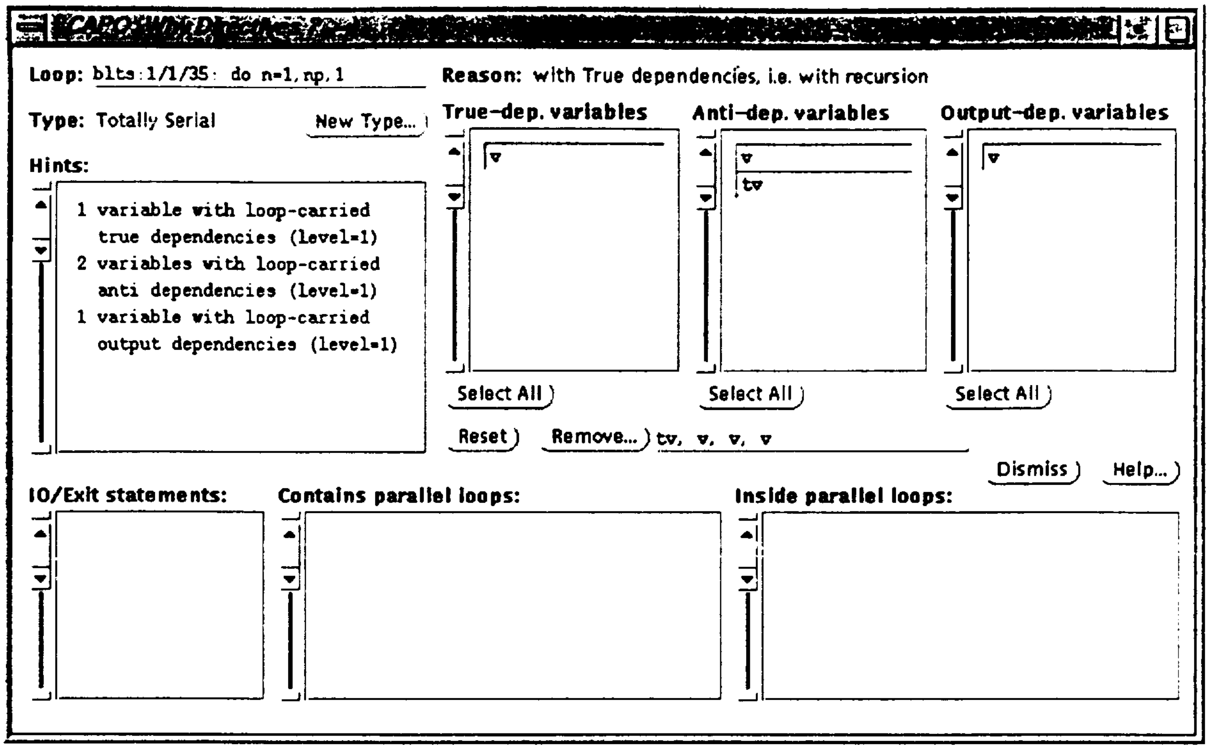
```
159 :         read(UNIT=3,FMT=*)ipr,inorm
160 :         read(UNIT=3,FMT=*)
161 :         read(UNIT=3,FMT=*)
162 :         read(UNIT=3,FMT=*)itmax
163 :         read(UNIT=3,FMT=*)
164 :         read(UNIT=3,FMT=*)
165 :         read(UNIT=3,FMT=*)dt
166 :         read(UNIT=3,FMT=*)
167 :         read(UNIT=3,FMT=*)
168 :         read(UNIT=3,FMT=*)omega
169 :         read(UNIT=3,FMT=*)
170 :         read(UNIT=3,FMT=*)
171 :         read(UNIT=3,FMT=*)tolrsd(1),tolrsd(2),tolrsd(3),tolrsd(4),tolrsd(5)
172 :         read(UNIT=3,FMT=*)
173 :         read(UNIT=3,FMT=*)
174 :         read(UNIT=3,FMT=*)nx0,ny0,nz0
175 :         close(3)
176 :       else
177 :         ipr=ipr_default
178 :         inorm=inorm_default
179 :         itmax=itmax_default
180 :         dt=dt_default
181 :         omega=omega_default
182 :         tolrsd(1)=tolrsd1_def
183 :         tolrsd(2)=tolrsd2_def
184 :         tolrsd(3)=tolrsd3_def
185 :         tolrsd(4)=tolrsd4_def
```

Figure T2-1: The READ Knowledge window for entering initial user knowledge.

In the Directives browser window, select loop filter Falsely Serial and sub-filter Privatization. Two loops are listed in this category. Choose the first loop: `jacld:1/1/160: do n=1,np,1` and click the Why button if the **WhyDirectives** window is not visible. A new set of variables is shown in the window, Figure T2-3. By the same token as above, the user selects those variables listed in the **Output-dep** list and applies Remove to delete the relevant loop-carried *Output* dependences. The variables in the **In/Out-dep** list were not selected because they are indeed used outside the current loop. If a variable is removed from the **In/Out-dep** list and kept in the **Output-dep** list, the variable would be *privatized*, which is not what we want here. Use the same procedure on the second loop: `jacu:1/1/160: do n=1,np,1`.

6. **Save new database and re-perform the directives analysis**. Once data dependences are modified, it is wise to save the results to a new database. In the **File** menu, click *Save database*. Enter a filename for the database (lu_full_prune.dbs) and click Save. To re-perform the directives analysis with changes taking into account, click the Update Directives button in the **Directives** main window and Update to confirm the action. After the update, you will notice the four loops treated above are now listed in *Chosen* (parallel). CAPO automatically recognizes five reduction loops, two of them being array reductions.

7. **Produce OpenMP code**. In the **File** menu, click *Save OpenMP Directives Code*. Choose the *Single Filename* setting, enter a filename (lu_hp_omp.f) and click Save. The log file, lu_hp_omp.log, contains additional information and statistics for the parallelization process.



Loop: blts:1/1/35: do n=1,np,1

Reason: with True dependencies, i.e. with recursion

Type: Totally Serial

Hints:

```
1 variable with loop-carried
  true dependencies (level=1)
2 variables with loop-carried
  anti dependencies (level=1)
1 variable with loop-carried
  output dependencies (level=1)
```

True-dep. variables: v

Anti-dep. variables: v, tv

Output-dep. variables: v

Remove... tv, v, v, v

Figure T2-2: The WhyDirectives window for a *Totally Serial* loop. It can be used to remove false dependences for the selected variables.

To compile the OpenMP code on the SGI Origin2000, do

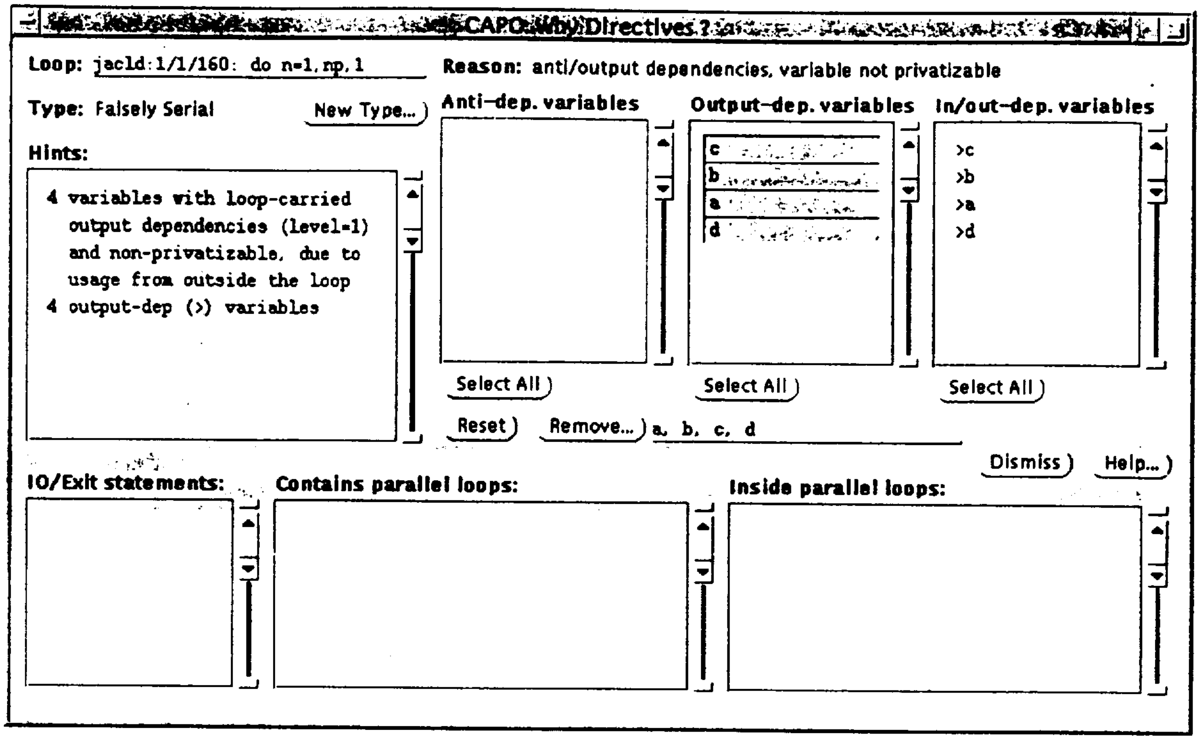
```
% f77 -o lu_hp_omp -O3 -mp lu_hp_omp.f
```

To execute the parallel code with 4 threads, do

```
% setenv OMP_NUM_THREADS 4
% ./lu_hp_omp
```

The output (for a class-W problem on 195MHz O2K) looks like:

```
Programming Baseline for NPB - LU Benchmark

Size:  33x 33x 33
Iterations: 300
Time step    1
...
     0.1161399311023E+02 0.1161399311023E+02 0.3074289103934E-13
Verification Successful

LU Benchmark Completed.
Class           =                   W
Size            =         33x 33x 33
Iterations      =                 300
Time in seconds =               52.74
Mop/s total     =              342.43
```



Loop: jacld:1/1/160: do n=1,np,1

Reason: anti/output dependencies, variable not privatizable

Type: Falsely Serial

Hints:

4 variables with loop-carried output dependencies (level=1) and non-privatizable, due to usage from outside the Loop
4 output-dep (>) variables

Output-dep. variables: c, b, a, d

In/out-dep. variables: >c, >b, >a, >d

a, b, c, d

Figure T2-3: The WhyDirectives window for a *Falsely Serial* loop. The loop-carried output dependences for variables a,b,c,d are selected for removal.

The output from a single process execution looks like:

```
Programming Baseline for NPB - LU Benchmark

Size:  33x 33x 33
Iterations: 300
Time step    1
...
     0.1161399311023E+02 0.1161399311023E+02 0.3227238810597E-13
Verification Successful

LU Benchmark Completed.
Class           =                        W
Size            =               33x 33x 33
Iterations      =                      300
Time in seconds =                   155.97
Mop/s total     =                   115.80
```

We have a speedup of 2.96 on 4 CPUs for this particular problem. If the pipelined LU were used, the performance would be better (speedup of 3.32 on 4 CPUs). A version of the LU benchmark using the pipeline algorithm is included in directory LU. Parallelizing LU with CAPO is straightforward and similar steps as for parallelizing the hyper-plane LU can be followed. The difference is that the user does not even need to remove any false dependences when generating the OpenMP code (skip Steps 5 and 6). CAPO is able to automatically set up the parallel pipeline.

Tutorial 3. NPB MG User-Defined Loop Type

This tutorial was included in Version 1.0 of CAPO to demonstrate how the user enforces loop type to improve the performance. This kind of interaction is not very often and can be done either within or outside CAPO. The outside interaction is often involved with direct change to the source code. In the following we first show the steps of parallelization without any change and then illustrate two ways of user manipulation to the source code.

The example is one of the benchmarks from the NAS Parallel Benchmark (NPB) suite. The benchmark, MG, uses the V-cycle multigrid algorithm to obtain an approximate solution to a discrete Poisson problem in three dimensions. The norm of the solution is calculated in each iteration to check for convergence. As was done in Tutorial 2, all the .f files are first listed in a single file: `All.list`.

Parallelization of the original code.

1. **Perform the data dependence analysis**. Click *Load F77 Source* in the **File** menu. Select All.list and click the Load button. In the **Analyser** window select the Full option and click Analyse. On a Sun workstation, the analysis process takes about 20 minutes.

2. **Save to database**. In the **File** menu, click *Save database*. Enter a filename for the database (mg_full.dbs) and click Save.

3. **Browse directives**. In the **View** menu, click *Directives* to perform the directives analysis. The Directives browser will be popped up shortly. Choose scope All Routines and loop filter Totally Serial and sub-filter True Recursion. Select loop: `norm2u3:1/1/27: do i3=2,n3-1` and click the Why button. Figure T3-1 is what you will see afterwards. The loop nest (and two others inside) contains an `IF` statement which prevents the loop being recognized as a reduction loop over variable `rnmu`[1]. In order to be a valid reduction statement for OpenMP, the code needs to be modified (see Step 5). Without any change, this piece of code will be run in sequential.

4. **Produce OpenMP code**. In the **File** menu, click *Save OpenMP Directives Code*. Enter a filename (mg_omp.f) and click Save. The log file, mg_omp.log, contains additional information and statistics for the parallelization process.

To compile the OpenMP code on the SGI Origin2000, do

```
% f77 -o mg_omp -O3 -mp mg_omp.f
```

To execute the parallel code with 8 threads, do

```
% setenv OMP_NUM_THREADS 8
% ./mg_omp
```

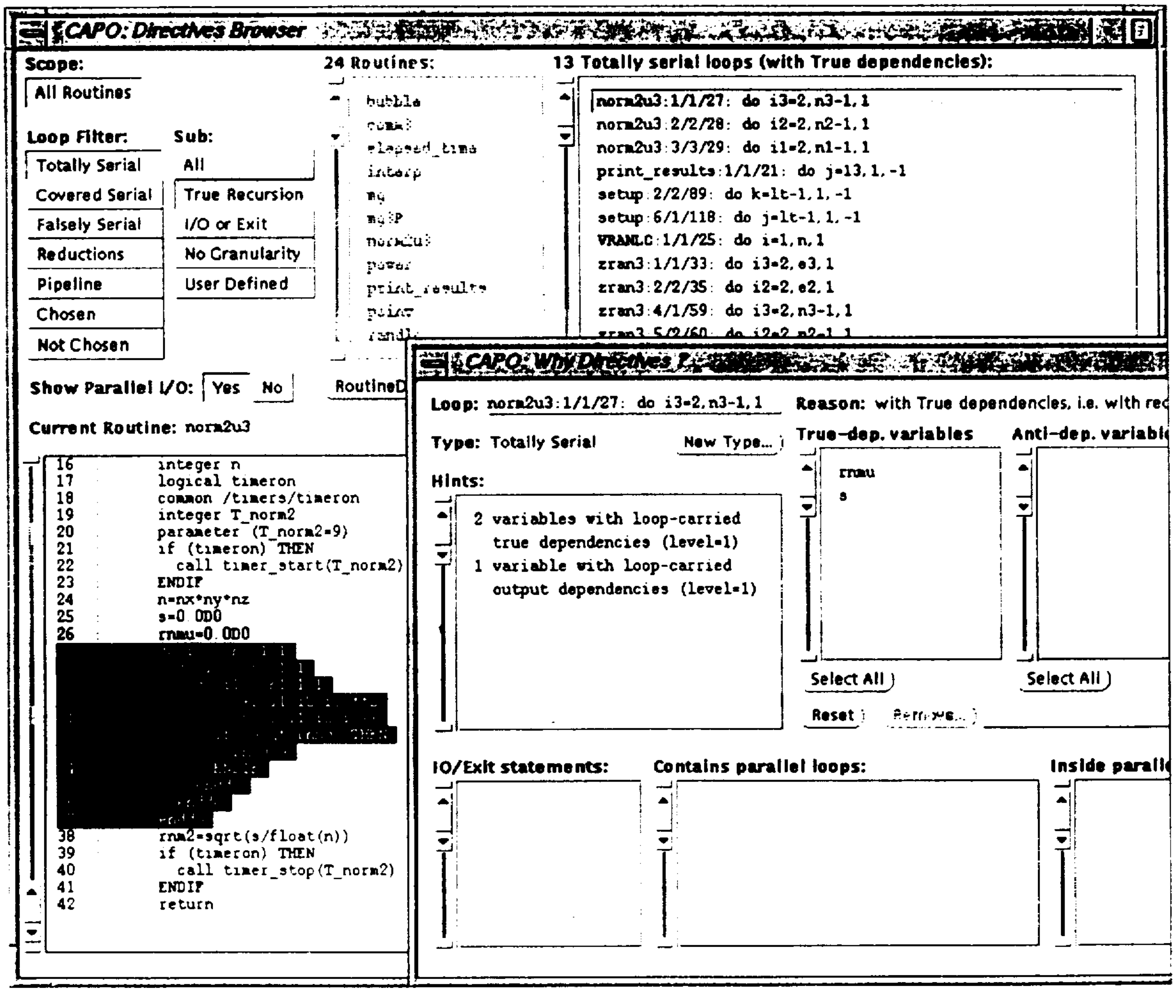
The output (for a class-A problem on 250MHz O2K) looks like:

```
 Programming Baseline for NPB - MG Benchmark
```

[1] Due to the improvement in Version 1.1 of CAPO, the IF-type reduction is now automatically recognized. The described serial loops will no longer exist. But the concept of user interaction from this Tutorial is still valid.

```
...
VERIFICATION SUCCESSFUL
L2 Norm is    0.243336530907E-05
Error is      0.692805188218E-16

MG Benchmark Completed.
Class          =                   A
Size           =         256x256x256
Iterations     =                   4
Time in seconds =               6.65
Mop/s total    =              585.42
```

A single-CPU run of this code took 39.29 seconds. We have a speedup of 5.91 on 8 CPUs for this particular problem.



13 Totally serial loops (with True dependencies):

```
norm2u3:1/1/27: do i3=2,n3-1,1
norm2u3:2/2/28: do i2=2,n2-1,1
norm2u3:3/3/29: do i1=2,n1-1,1
print_results:1/1/21: do j=13,1,-1
setup:2/2/89: do k=lt-1,1,-1
setup:6/1/118: do j=lt-1,1,-1
VRANLC:1/1/25: do i=1,n,1
zran3:1/1/33: do i3=2,e3,1
zran3:2/2/35: do i2=2,e2,1
zran3:4/1/59: do i3=2,n3-1,1
zran3:5/2/60: do i2=2,n2-1,1
```

Current Routine: norm2u3

```
      integer n
      logical timeron
      common /timers/timeron
      integer T_norm2
      parameter (T_norm2=9)
      if (timeron) THEN
        call timer_start(T_norm2)
      ENDIF
      n=nx*ny*nz
      s=0.0D0
      rnmu=0.0D0
[illegible]
      rnm2=sqrt(s/float(n))
      if (timeron) THEN
        call timer_stop(T_norm2)
      ENDIF
      return
```

Loop: norm2u3:1/1/27: do i3=2,n3-1,1

Reason: with True dependencies, i.e. with rec

Type: Totally Serial

Hints:

```
2 variables with loop-carried
  true dependencies (level=1)
1 variable with loop-carried
  output dependencies (level=1)
```

True-dep. variables

```
rnmu
s
```

Figure T3-1: The window shows a serial loop in norm2u3, MG.

Further improvement to the code can be made by parallelizing the loop in routine norm2u3 (the highlighted area in Figure T3-1). The operations inside the loop nest can be expressed as reductions with slight code modification. There are two ways to achieve the goal: modifying the serial code and re-performing the dependence analysis (Steps 5-7) or user enforcing loop type in the tool without re-analysis (Steps 8-9).

Modification of the serial code.

5. **Modify the serial code**. The step involves directly modifying the serial code (mg.f) with an editor before the analysis. In routine norm2u3, change the IF statement

   ```
   if (a.gt.rnmu) rnmu = a
   ```

   to a form that can be expressed with reduction

   ```
   rnmu = dmax1(rnmu, a)
   ```

   Save the new version to mg2.f and create a new list file 'All2.list' to include mg2.f.

6. **Perform the data dependence analysis.** Click ***Load F77 Source*** in the **File** menu. Select All2.list and click the Load button. In the **Analyser** window select the Full option and click Analyse. Save the result to a database (mg2_full.dbs). Browse directives if you like (**View →** ***Directives***). You will notice the loop in routine norm2u3 is now recognized as reduction.

7. **Produce OpenMP code**. In the **File** menu, click ***Save OpenMP Directives Code***. Enter a filename (mg2_omp.f) and click Save. The log file, mg2_omp.log, contains additional information and statistics for the parallelization process.

   Now you can compile and run the parallel code as described after Step 9.

User enforced loop type.

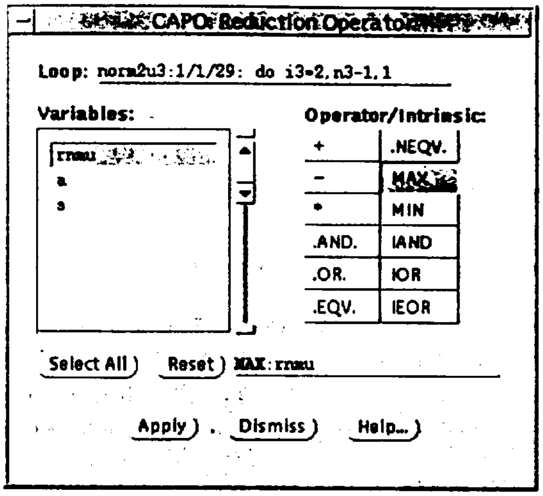
8. **Define a new loop type**. From the **File** menu, load in the database "mg_full.dbs" from the previous analysis. Perform Step 3. In the **WhyDirectives** window, click the New Type button. Right after the Reduction setting is selected the **Reduction Operator** dialog box is shown up (see Figure T3-2). Select variable "rnmu" and intrinsic function "max", and push Apply in the **Reduction Operator** dialog and in the **Loop Type** dialog. A new entry "`R[max:rnmu]`" is added to file "userloop.par" in the current working directoy. This is to inform CAPO to treat variable "rnmu" as a reduction variable besides other variables (such as "s"). Now in CAPO click Update Directives to re-perform the directives analysis, which will take into account the user-defined loop types from file "userloop.par."

9. **Save and change OpenMP code.** In the **File** menu, click ***Save OpenMP Directives Code***. Enter a filename (mg2_omp.f) and click Save. We need to do one last change in the generated OpenMP code: Use an editor, change in routine norm2u3

   ```
   if (a.gt.rnmu) THEN
     rnmu=a
   ENDIF
   ```

   to an "OpenMP-compliant" form

   ```
   rnmu = dmax1(rnmu, a)
   ```



Loop: norm2u3:1/1/29: do i3=2,n3-1,1

MAX: rnmu

Figure T3-2: The **Reduction Operator** dialog after the Reduction setting is selected.

From either method, we should produce the same new parallel code (mg2_omp.f). Use the same process after Step 4 to compile and run the new code. The output from a run with 8 CPUs (for a class-A problem on 250MHz O2K) looks like:

```
Programming Baseline for NPB - MG Benchmark
...
VERIFICATION SUCCESSFUL
L2 Norm is    0.243336530907E-05
Error is      0.694753363997E-16

MG Benchmark Completed.
Class          =                A
Size           =      256x256x256
Iterations     =                4
Time in seconds =            5.67
Mop/s total    =           686.60
```

The new code took 39.12 seconds on 1 CPU and 5.67 seconds on 8 CPUs, a speedup of 6.90 and 14% improvement over the first version.

Tutorial 4. A More Realistic CFD Application

The sample code, teamkel, in this tutorial has been taken from one of the CAPTools' tutorials with a slight modification. This is a more realistic application. It includes structures that may be encountered in many scientific applications. The example illustrates an incremental approach to achieve good performance with assistant from CAPO and other tools like SpeedShop (available on the Origin 2000 machine). These tools are used to pinpoint problematic code sections quickly so that the user can apply necessary changes.

Parallelization of the original code: teamkel.f

1. **Perform the data dependence analysis**. Start CAPO, click ***Load F77 Source*** in the **File** menu. Select teamkel.f and click the Load button. In the **Analyser** window select the Full option and click Analyse. The analysis process takes only a few minutes.

2. **Save to database**. In the **File** menu, click ***Save Database***. Enter a filename for the database (teamkel_full.dbs) and click Save.

3. **Perform the directives analysis**. In the **View** menu, click ***Directives*** to perform the directives analysis. The Directives browser will be popped up shortly. Choose the All Routines scope and browse through different loop filters. You will notice there are a quite number of *Totally Serial* loops (see Figure T4-1), which will limit the performance of this code. At this point, we only look into more details of the loop nest in routine CALCP1. The rest of the loops will be discussed in Step 5 and after.

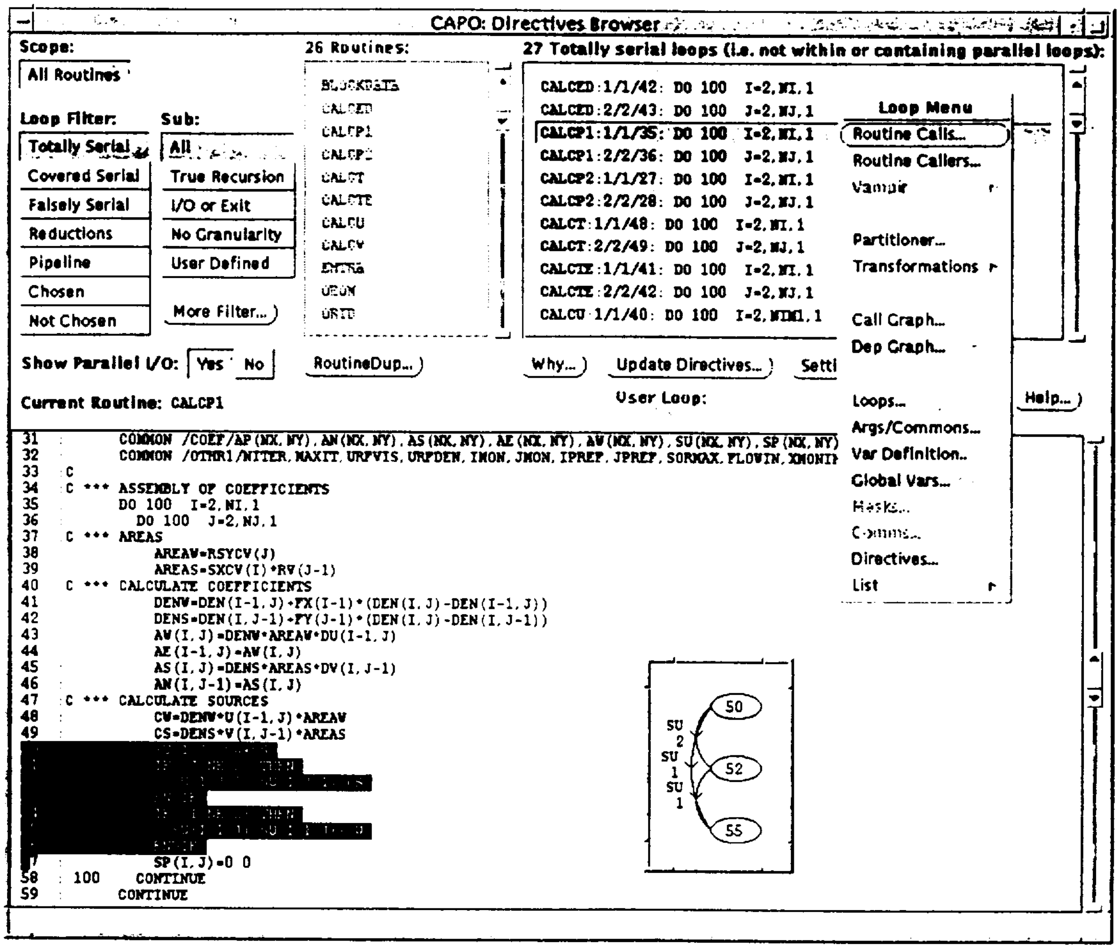
   Choose the loop "`CALCP1:1/1/35: DO 100 I=2,NI,1`" and click Why. The ***WhyDirectives*** window indicates the loop was serialized due to loop-carried dependences for variable SU. The ***DepGraph*** (activated from the right-mouse button **Loop Menu** over the selected loop) shows level-1 and level-2 dependences from statement 50 to 52 to 55 (see Figure T4-1). In particular the 52 → 55 dependence prevents even a pipeline being formed within the loop nests. In fact, we realize the add operation for variable SU in statements 52 and 55 is associative, thus, the execution order of the two statements can be switched and the 52 → 55 dependence can be removed.

   In the DepGraph window, click the 52 → 55 dependence edge with the right-mouse button and load the "***Why Dependence?***" window (see Figure T4-2). Apply the Remove This Dependence button and confirm the action. Save to a new database if you like. Click Update Directives to re-perform the directives analysis and a pipeline is automatically recognized in routine CALCP1.

   Loop types are summarized here:

25	*Totally Serial* loops
10	*Reduction* loops
1	*Pipeline* loop in routine CALCP1
45	*Chosen* (parallel) loops

4. **Produce OpenMP code**. Without additional change, in the **File** menu, click ***Save OpenMP Directives Code***. Enter a filename (teamkel_omp.f) and click Save.



27 Totally serial loops (i.e. not within or containing parallel loops):

```
CALCED:1/1/42: DO 100  I=2,NI,1
CALCED:2/2/43: DO 100  J=2,NJ,1
CALCP1:1/1/35: DO 100  I=2,NI,1
CALCP1:2/2/36: DO 100  J=2,NJ,1
CALCP2:1/1/27: DO 100  I=2,NI,1
CALCP2:2/2/28: DO 100  J=2,NJ,1
CALCT:1/1/48: DO 100  I=2,NI,1
CALCT:2/2/49: DO 100  J=2,NJ,1
CALCTE:1/1/41: DO 100  I=2,NI,1
CALCTE:2/2/42: DO 100  J=2,NJ,1
CALCU 1/1/40: DO 100  I=2,NIM1,1
```

Current Routine: CALCP1

```
      COMMON /COEF/AP(NX,NY),AN(NX,NY),AS(NX,NY),AE(NX,NY),AW(NX,NY),SU(NX,NY),SP(NX,NY)
      COMMON /OTHR1/NITER,MAXIT,URFVIS,URFDEN,IMON,JMON,IPREF,JPREF,SORMAX,FLOWIN,XMONIT
C
C *** ASSEMBLY OF COEFFICIENTS
      DO 100  I=2,NI,1
        DO 100  J=2,NJ,1
C *** AREAS
          AREAW=RSYCV(J)
          AREAS=SXCV(I)*RV(J-1)
C *** CALCULATE COEFFICIENTS
          DENW=DEN(I-1,J)+FX(I-1)*(DEN(I,J)-DEN(I-1,J))
          DENS=DEN(I,J-1)+FY(J-1)*(DEN(I,J)-DEN(I,J-1))
          AW(I,J)=DENW*AREAW*DU(I-1,J)
          AE(I-1,J)=AW(I,J)
          AS(I,J)=DENS*AREAS*DV(I,J-1)
          AN(I,J-1)=AS(I,J)
C *** CALCULATE SOURCES
          CW=DENW*U(I-1,J)*AREAW
          CS=DENS*V(I,J-1)*AREAS
[illegible]
          SP(I,J)=0 0
  100   CONTINUE
      CONTINUE
```

Figure T4-1: The Directives Browser window displaying *Totally Serial* loops in teamkel. The **Loop Menu** is used to activate the DepGraph (shown as inset) for the selected loop.

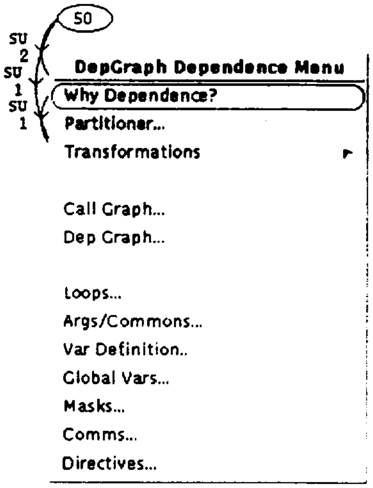


Figure T4-2: The DepGraph Dependence Menu after clicking on a dependence edge.

To compile the OpenMP code on the SGI Origin2000, do

```
% f77 -o teamkel_omp -O2 -mp teamkel_omp.f
```

or use the supplied Makefile

```
% make VERNO=1
```

To execute the parallel code with 4 threads, do

```
% setenv OMP_NUM_THREADS 4
% ./teamkel_omp < inp.dat > teamkel_omp.out.4
```

Use the SpeedShop tool available on the Origin 2000 to profile the code. For 1 CPU:

```
% setenv OMP_NUM_THREADS 1
% ssrun -pcsamp ./teamkel_omp < inp.dat > teamkel_omp.out.1
```

A sampling file named as "teamkel_omp.pcsamp.m(pid)" will be created. Here "(pid)" is a proper process id. Use the "prof" command to create the profile output:

```
% prof teamkel_omp teamkel_omp.pcsamp.m(pid) > teamkel_omp.prof.1
```

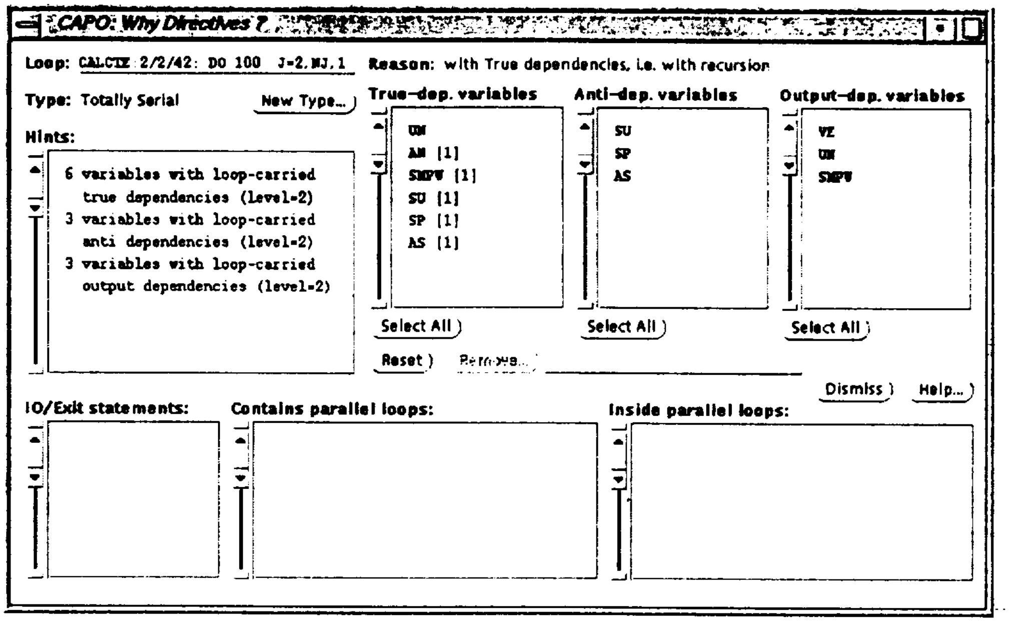
Follow the same procedure to obtain profile on 4 CPUs. The profile outputs for the key routines on 1 and 4 CPUs are compared in Table T4-1. "ratio" is 1-CPU time over 4-CPU time, or the speedup on 4 CPUs. The error of ratio is calculated from the statistical sampling error reported in the profile data. As we can see, except for two routines (calcp1 and props), the major routines do not scale. The poor performance correlates with the ***Totally Serial*** loops indicated in Figure T4-1. These loops were executed sequentially. In order to improve the performance, we need to investigate and find a way to parallelize these loops.

Table T4-1: Comparison of profile results for the first parallel version of teamkel. Time is given in seconds.

Function	1CPU	4CPUs	ratio	error
LISOLV	16.18	16.89	0.958	0.033
CALCTE	9.53	9.06	1.052	0.049
CALCV	8.95	7.86	1.139	0.056
CALCU	8.58	7.58	1.132	0.056
CALCED	8.10	7.71	1.051	0.053
CALCT	7.10	6.47	1.097	0.060
calcp1	4.78	1.59	3.006	0.275
CALCP2	4.11	4.03	1.020	0.071
props	0.48	0.16	3.000	0.866
init	0.25	0.15	1.667	0.544
PRINT	0.06	0.20	0.300	0.140
Total	**80.83**	**74.21**	**1.089**	**0.018**

Version 2 – Code modification without change to the basic algorithm:

5. **Inspect code sections**. Restart CAPO and load back teamkel_full.dbs (*Load Database* in the File menu). In the View menu, click *Directives* to perform the directives analysis. In the **Directives browser** window, choose scope All Routines, loop filter Totally Serial and loop "CALCTE:2/12/42: DO 100 J=2,NJ". Click the Why button and the **WhyDirectives** window as shown in Figure T4-2 will be displayed. There are six variables with loop-carried true dependences, five of which have a determinable dependence vector length as indicated by "[1]". This is an indication of a potential pipeline loop if changes can be made to variable UN and two other variables VE and SMPW presented in the **Output-dep.** variable list.



Loop: CALCTE 2/2/42: DO 100 J=2,NJ,1

Reason: with True dependencies, i.e. with recursion

Type: Totally Serial

Hints:

```
6 variables with loop-carried
  true dependencies (level=2)
3 variables with loop-carried
  anti dependencies (level=2)
3 variables with loop-carried
  output dependencies (level=2)
```

True-dep. variables	Anti-dep. variables	Output-dep. variables
UN	SU	VE
AM [1]	SP	UN
SMPW [1]	AS	SMPW
SU [1]		
SP [1]		
AS [1]		

IO/Exit statements:

Contains parallel loops:

Inside parallel loops:

Figure T4-3: The WhyDirectives window for a *Totally Serial* loop in teamkel.

6. **Change scalar assignments**. Checking the code section in loop nests I and J, we realize that the dependences on scalar variables UN and VE were caused by the reuse of the assigned values from the previous J or I iteration in an IF statement. The dependences can be removed if we recalculate both variables at each J or I iteration.

Start a text editor and load in teamkel.f. In subroutine CALCTE modify the assignment for UN from

```
      IF(J.NE.NJ)UN=0.5*(U(I,J)+U(I-1,J)+FY(J)*(U(I,J+1)+U(I-1,J+1)-
     >             U(I,J)-U(I-1,J)
```

to

```
      IF(J.NE.NJ)THEN
        UN=0.5*(U(I,J)+U(I-1,J)+FY(J)*(U(I,J+1)+U(I-1,J+1)-
           U(I,J)-U(I-1,J)
      ELSE
        UN=0.5*(U(I,J-1)+U(I-1,J-1)+FY(J-1)*(U(I,J)+U(I-1,J)-
     >     U(I,J-1)-U(I-1,J-1)))
      ENDIF
```

and for VE from

```
      IF(I.NE.NI)VE=0.5*(V(I,J)+V(I,J-1)+FX(I)*(V(I+1,J)+V(I+1,J-1)-
     >             V(I,J)-V(I,J-1)
```

```
to
     IF(I.NE.NI)THEN
       VE=0.5*(V(I,J)+V(I,J-1)+FX(I)*(V(I+1,J)+V(I+1,J-1)-
          V(I,J)-V(I,J-1)
     ELSE
       VE=0.5*(V(I-1,J)+V(I-1,J-1)+FX(I-1)*(V(I,J)+V(I,J-1)-
    >     V(I-1,J)-V(I-1,J-1)))
     ENDIF
```

Apply a similar modification to variables in three other routines. The changes are summarized:

Routine	*Loop*	*Variable*	*Description*
CALCP2	DO 100 J=2,NJ	SUS, SUW	Recalculate at each iteration
CALCTE	DO 100 J=2,NJ	VE, UN	
CALCU	DO 100 J=2,NJ	GAMN, DVDXN	
CALCV	DO 100 J=2,NJM1	GAME	

7. **Expand 1-D array to 2-D**. Variable SMPW is a 1-D working array throughout the program. In order to set up a pipeline of the J loop with the outer I loop, this array needs to be expanded to two dimensional. As an example, in routine CALCTE, change the declaration of SMPW from 1-D to 2-D, i.e. SMPW(NX) → SMPW(NX,NY). Then modify the following code section from

```
     CP=AMAX1(0.0,(SMPW(J)+CW))
     SMPW(J)=-CW-CS
     SMPW(J-1)=SMPW(J-1)+CS
```

to

```
     CP=AMAX1(0.0,(SMPW(I-1,J)+CW))
     SMPW(I,J)=-CW-CS
     SMPW(I,J-1)=SMPW(I,J-1)+CS
```

The initialization of SMPW is done in subroutine (entry) INIT. In this routine modify the declaration from SMPW(NX) to SMPW(NX,NY) and the assignment from SMPW(J)=0.0 to SMPW(I,J)=0.0.

Similar changes are made in several other places. The modifications on SMPW are summarized here:

Routine	*Loop*	*Description*
CALCED	DO 100 J=2,NJ	Expand SMPW from 1-D to 2-D
CALCT	DO 100 J=2,NJ	Change declaration in the whole program
CALCTE	DO 100 J=2,NJ	
CALCU	DO 100 J=2,NJ	
CALCV	DO 100 J=2,NJM1	
INIT	DO 951 J=1,NJ	

All the modifications do not alter the basic algorithm, so the same run-time results should be expected. Save the modified code to a new file: teamke2.f.

8. **Perform code analysis**. Restart CAPO and load teamke2.f. Perform the Full data dependence analysis and save to teamke2_full.dbs. Start the Directives browser from the **View** menu and the ***Directives*** menu item. With the All Routines scope browse through different loop filters. You will notice that the number of *Totally Serial* loops has been reduced from 25 to 13 with increase in the number of pipeline loops. Loop types are summarized here:

13	*Totally Serial* loops (mainly in routine LISOLV)
10	*Reduction* loops
7	*Pipeline* loops
45	*Chosen* (parallel) loops

9. **Produce OpenMP code**. In the File menu, click *Save OpenMP Directives Code* and save to file teamke2_omp.f.

Compile and run the parallel code as before. The SpeedShop profile results for the new parallel code are summarized in Table T4-2. As one can see, the parallel performance of Version 2 has been improved in almost all routines except in routine LISOLV. LISOLV still executes serially and affects overall performance. The single CPU execution time increased slightly in comparison with the original version. This is because the recalculation of scalar variables in the new code costs slightly more time.

Table T4-2: Comparison of profile results for the second parallel version. Time is given in seconds.

Function	1CPU	4CPUs	ratio	error
LISOLV	16.14	18.00	0. 897	0.031
calcte	9.89	3.19	3.100	0.200
calcv	9.28	2.92	3.178	0.213
calcu	8.82	2.83	3.117	0.213
calced	8.76	2.87	3.052	0.208
calct	7.79	2.39	3.259	0.241
calcp1	5.04	1.75	2.880	0.253
calcp2	4.06	1.11	3.658	0.392
props	0.53	0.20	2.650	0.695
init	0.28	0.13	2.154	0.723
PRINT	0.14	0.26	0.538	0.178
Total	**83.77**	**46.67**	**1.795**	**0.033**

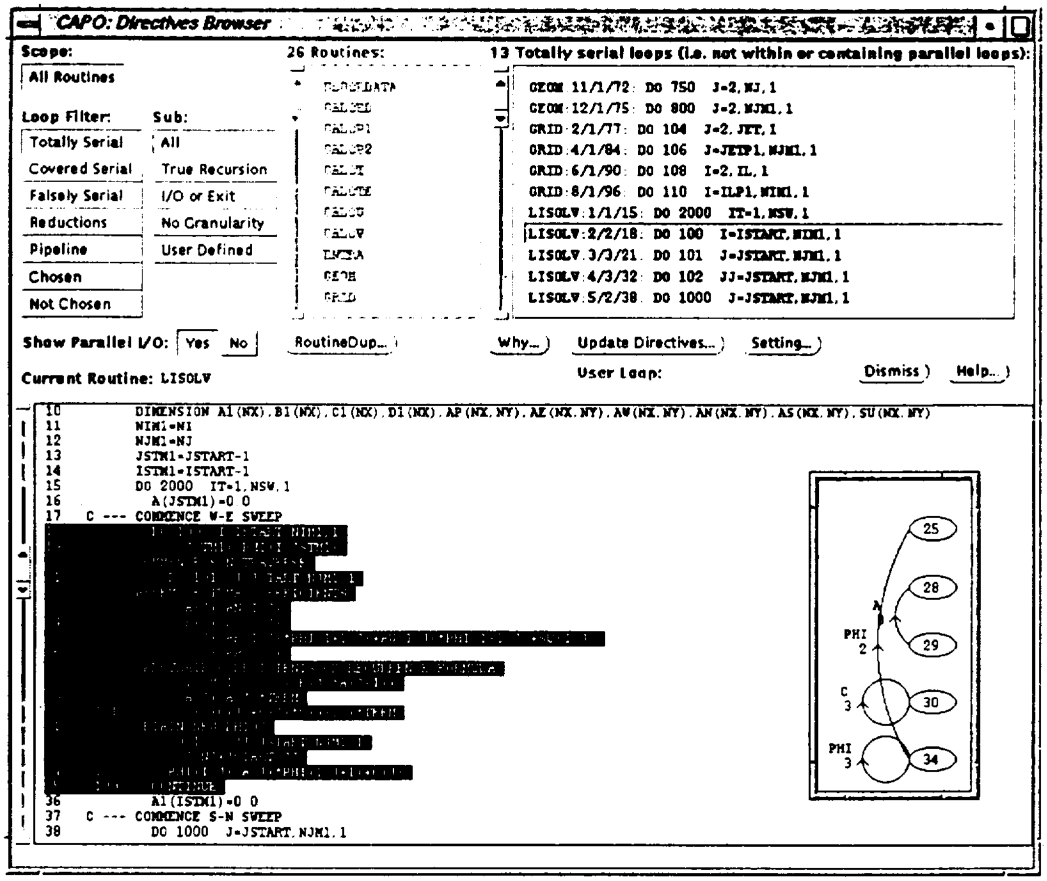
Version 3 – Change of algorithm in LISOLV:

10. **Inspect code sections**. Restart CAPO and load back teamke2_full.dbs (***Load Database*** in the **File** menu). In the **View** menu, click ***Directives*** to perform the directives analysis. In the **Directives browser** window, choose scope All Routines, loop filter Totally Serial and loop "LISOLV:2/2/18: DO 100 I=ISTART,NIM1". **Click the right mouse button to activate the Loop Menu.** In the menu choose ***Dep Graph*** and the **DepGraph** window will show data dependences that serialize the loop (see Figure T4-4 and the inset): variable PHI at level 2 (loop I) and 3 (loop J) and variable A,C at level 3 (loop J). In loop I, variable PHI is used to calculate A and C and gets updated at each I iteration.

11. **Modify the algorithm**. We can use a more explicit algorithm in the I loop: Variables A and C are calculated for all the values of I before variable PHI is updated. The I loop then becomes parallel. The impact of such a change is mainly on the convergence speed of the underline algorithm. One may have to balance convergence rate and parallelization. In this case parallelization seems to be more important.

    The modifications to the code involve expanding the dimensionality of A and C from 1-D to 2-D and splitting the I loop into two parts: the first part calculates A and C from PHI and the second part updates PHI. The modified code section is shown in Figure T4-4. Apply the same change to loop "DO 1000 J=JSTART, NJM1".

Save the final code to teamke3.f



13 Totally serial loops (i.e. not within or containing parallel loops):

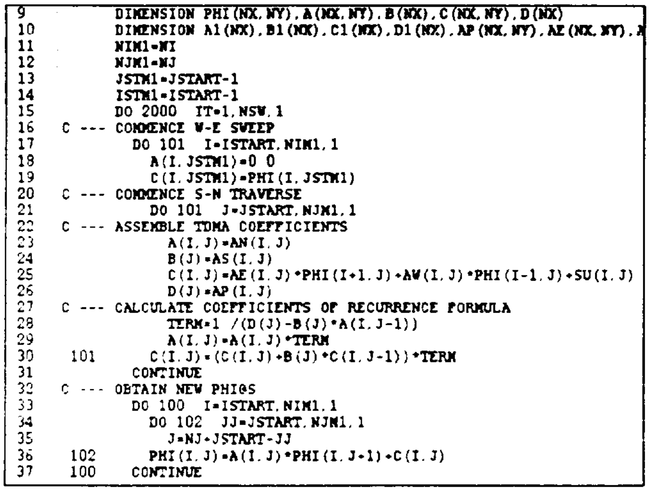
```
GEOM:11/1/72:  DO 750   J=2,NJ,1
GEOM:12/1/75:  DO 800   J=2,NJM1,1
GRID:2/1/77:  DO 104   J=2,JET,1
GRID:4/1/84:  DO 106   J=JETP1,NJM1,1
GRID:6/1/90:  DO 108   I=2,IL,1
GRID:8/1/96:  DO 110   I=ILP1,NIM1,1
LISOLV:1/1/15:  DO 2000   IT=1,NSW,1
LISOLV:2/2/18:  DO 100   I=ISTART,NIM1,1
LISOLV:3/3/21:  DO 101   J=JSTART,NJM1,1
LISOLV:4/3/32:  DO 102   JJ=JSTART,NJM1,1
LISOLV:5/2/38:  DO 1000   J=JSTART,NJM1,1
```

Current Routine: LISOLV

User Loop:

```
      DIMENSION A1(NX),B1(NX),C1(NX),D1(NX),AP(NX,NY),AE(NX,NY),AW(NX,NY),AN(NX,NY),AS(NX,NY),SU(NX,NY)
      NIM1=NI
      NJM1=NJ
      JSTM1=JSTART-1
      ISTM1=ISTART-1
      DO 2000  IT=1,NSW,1
        A(JSTM1)=0.0
C --- COMMENCE W-E SWEEP
[illegible]
        A1(ISTM1)=0.0
C --- COMMENCE S-N SWEEP
        DO 1000  J=JSTART,NJM1,1
```

Figure T4-4: The Directive Browser window for *Totally Serial* loops in teamke2. The highlighted code section in routine LISOLV is to be modified to a more explicit form.



```
      DIMENSION PHI(NX,NY),A(NX,NY),B(NX),C(NX,NY),D(NX)
      DIMENSION A1(NX),B1(NX),C1(NX),D1(NX),AP(NX,NY),AE(NX,NY),A
      NIM1=NI
      NJM1=NJ
      JSTM1=JSTART-1
      ISTM1=ISTART-1
      DO 2000  IT=1,NSW,1
C --- COMMENCE W-E SWEEP
        DO 101  I=ISTART,NIM1,1
          A(I,JSTM1)=0.0
          C(I,JSTM1)=PHI(I,JSTM1)
C --- COMMENCE S-N TRAVERSE
          DO 101  J=JSTART,NJM1,1
C --- ASSEMBLE TDMA COEFFICIENTS
            A(I,J)=AN(I,J)
            B(J)=AS(I,J)
            C(I,J)=AE(I,J)*PHI(I+1,J)+AW(I,J)*PHI(I-1,J)+SU(I,J)
            D(J)=AP(I,J)
C --- CALCULATE COEFFICIENTS OF RECURRENCE FORMULA
            TERM=1./(D(J)-B(J)*A(I,J-1))
            A(I,J)=A(I,J)*TERM
 101      C(I,J)=(C(I,J)+B(J)*C(I,J-1))*TERM
        CONTINUE
C --- OBTAIN NEW PHI@S
        DO 100  I=ISTART,NIM1,1
          DO 102  JJ=JSTART,NJM1,1
            J=NJ+JSTART-JJ
 102      PHI(I,J)=A(I,J)*PHI(I,J+1)+C(I,J)
 100    CONTINUE
```

Figure T4-5: The modified code section after loop I is split into two parts.

12. **Perform code analysis**. Restart CAPO and load teamke3.f. Perform the **Full** data dependence analysis and save to teamke3_full.dbs. Start the Directives browser from the **View** menu and the ***Directives*** menu item. With the All Routines scope browse through different loop filters. You will notice that the number of *Totally Serial* loops has been reduced from 13 to 6 and these loops are in routines GEOM and GRID. Loop types are summarized here:

6	*Totally Serial* loops
10	*Reduction* loops
7	*Pipeline* loops
49	*Chosen* (parallel) loops

13. **Produce OpenMP code**. In the **File** menu, click ***Save OpenMP Directives Code*** and save to file teamke3_omp.f.

Compile and run the parallel code as before. The SpeedShop profile results for the final parallel code are summarized in Table T4-3. As one can see, the parallel performance of Version 3 has been improved over Version 2 and a reasonable speedup has been obtained. The single CPU execution time of routine LISOLV increased about 40% in comparison with the previous version but the parallel execution time decreased quite a bit.

Table T4-3: Comparison of profile results for the third parallel version. Time is given in seconds.

Function	1CPU	4CPUs	ratio	error
lisolv	22.71	7.47	3.040	0.128
calcte	9.74	2.95	3.302	0.219
calcv	9.11	2.78	3.277	0.225
calced	8.89	2.55	3.486	0.248
calcu	8.74	2.64	3.311	0.232
calct	7.83	2.34	3.346	0.249
calcp1	4.87	1.80	2.706	0.236
calcp2	4.01	1.07	3.748	0.408
props	0.52	0.24	2.167	0.535
init	0.27	0.12	2.250	0.781
PRINT	0.05	0.37	0.135	0.064
Total	**89.92**	**36.23**	**2.482**	**0.049**

Tutorial 5. Mix of Message-Passing and OpenMP

This tutorial demonstrates one way to generate a *hybrid* parallel code with CAPTools/CAPO. The parallelization is done at two levels: message-passing (MP) at one level and OpenMP at another. The example relies on the thread-safe feature introduced in MPI-2 and the success of execution depends on the implementation of a thread-safe MPI-2 library. We need to emphasize that the hybrid parallelization here is not the best way to achieve good performance for the currently selected code. We mainly like to illustrate that it is possible to produce a hybrid parallel code with the tools.

The example is one of the benchmarks from the NAS Parallel Benchmark (NPB) suite. The benchmark, BT, uses an implicit scheme to solve the Navier-Stokes equations in three dimensions. Within one time iteration the solver sweeps through each dimension successively. Each step has strong data dependences in the swept direction, but is completely parallel in the other two directions. The multi-level parallelization is achieved by first distributing the data in the `J` dimension for message passing and then applying directives on loops working on the `K` dimension. Small modification to the generated parallel code by hand is needed in order to work around an incompletion due to that the hybrid code generation is not really supported by the current tools.

The sequential version of the source code is in directory `BT-mix`. In order to load the code to CAPO, we list all the .f files in one file: `All.list`.

Parallelization with message-passing at the first level:

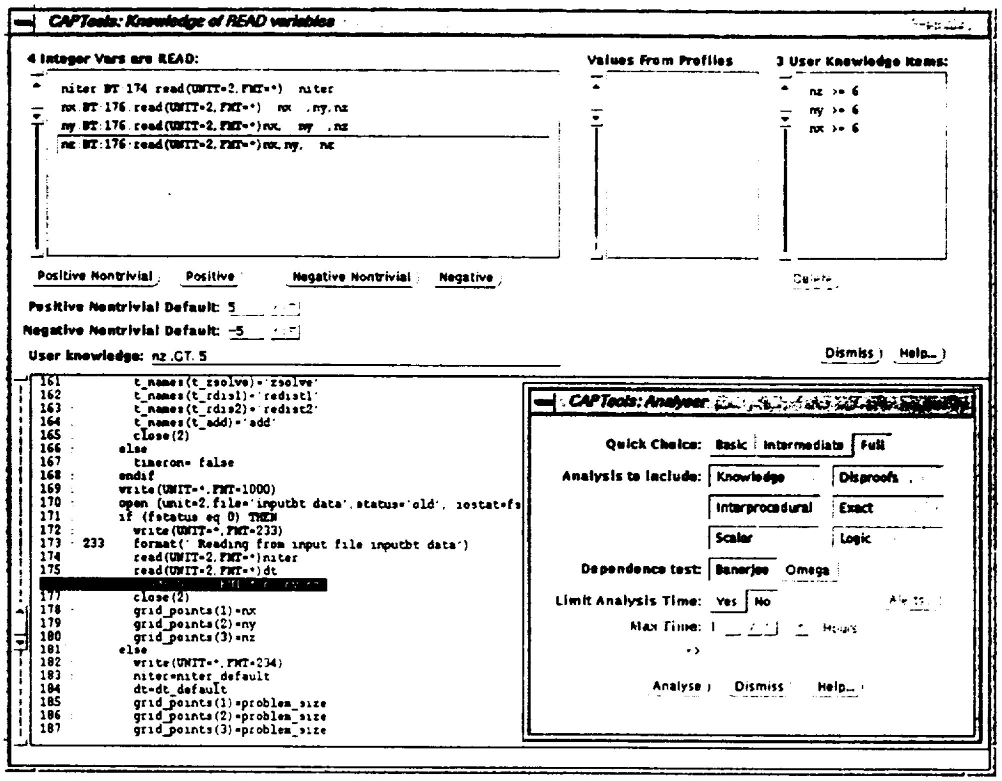
1. **Load source and enter user knowledge**. Click ***Load F77 Source*** in the **File** menu. Select All.list and click the Load button. Select ***READ Knowledge*** from the **Edit** menu. In the **READ Knowledge** window, select variable nx and click Positive Nontrivial, see Figure T5-1 on next page. Apply the same steps to variables ny and `nz`. These three variables define the number of grid points in each dimension. Making them positive nontrivial improves the quality of data dependence analysis in Step 2.

2. **Perform the data dependence analysis**. After the user knowledge is entered, in the **Analyser** window select the Full option and click Analyse. On a Sun Sparc (Ultra-4) workstation, the analysis process took 12 minutes.

3. **Save to database**. In the **File** menu, click ***Save Database***. Enter a filename for the database (bt_full.dbs) and click Save.

4. **Partition data**. Launch the **Partitioner** from the CAPTools main window. Choose routine "add", array "u" and index "3" (see Figure T5-2) and click Generate Partition. This step creates a data distribution for array "u" on the 3rd index (the `J` dimension) and CAPTools also partitions automatically the relevant arrays throughout the program. Figure T5-3 shows the partitioning window after the process is finished. You will notice that array "`lhsb`" was left untouched. The next thing to do is to select this array, index 4 and perform another partitioning.

5. **Save to database**. Use the ***Save Database*** menu to save the partitioned data to bt_part_j.dbs.



CAPTools: Knowledge of READ variables

4 Integer Vars are READ:

```
niter BT 174 read(UNIT=2,FMT=*)  niter
nx BT 176 read(UNIT=2,FMT=*)  nx  ,ny,nz
ny BT 176 read(UNIT=2,FMT=*)nx,  ny  ,nz
nz BT 176 read(UNIT=2,FMT=*)nx,ny,  nz
```

Values From Profiles

3 User Knowledge Items:

```
nz >= 6
ny >= 6
nx >= 6
```

Positive Nontrivial Default: 5

Negative Nontrivial Default: -5

User knowledge: nz .GT. 5

```
161            t_names(t_zsolve)='zsolve'
162            t_names(t_rdis1)='redist1'
163            t_names(t_rdis2)='redist2'
164            t_names(t_add)='add'
165            close(2)
166          else
167            timeron= false
168          endif
169          write(UNIT=*,FMT=1000)
170          open (unit=2,file='inputbt data',status='old', iostat=fs
171          if (fstatus eq 0) THEN
172            write(UNIT=*,FMT=233)
173   233      format(' Reading from input file inputbt data')
174            read(UNIT=2,FMT=*)niter
175            read(UNIT=2,FMT=*)dt
[illegible]
177            close(2)
178            grid_points(1)=nx
179            grid_points(2)=ny
180            grid_points(3)=nz
181          else
182            write(UNIT=*,FMT=234)
183            niter=niter_default
184            dt=dt_default
185            grid_points(1)=problem_size
186            grid_points(2)=problem_size
187            grid_points(3)=problem_size
```

CAPTools: Analyser

Quick Choice: Basic | Intermediate | [✓ Full]

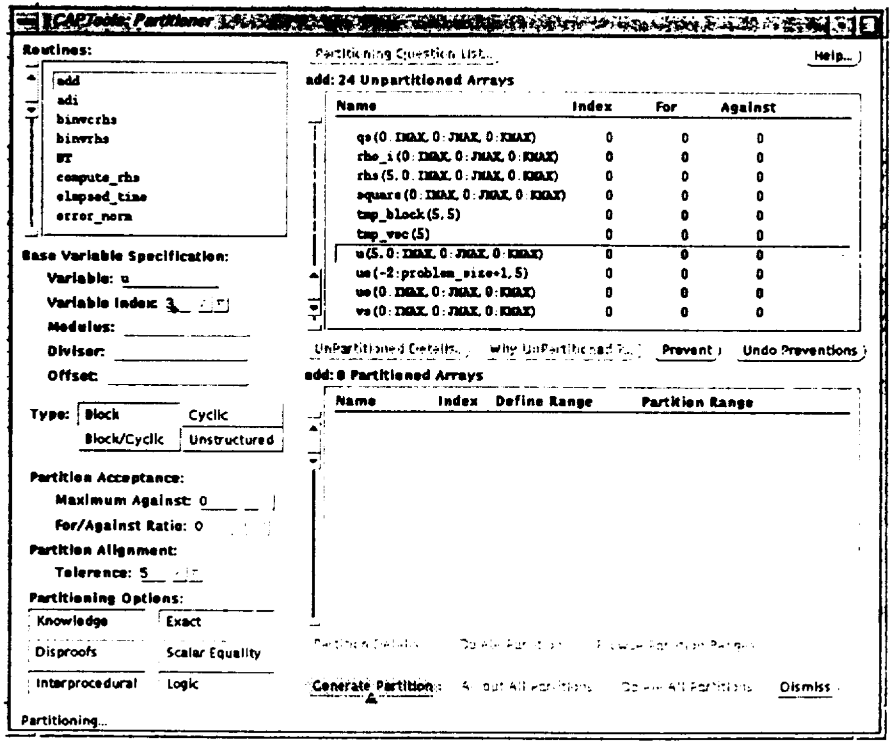
Analysis to include: [✓ Knowledge] [✓ Disproofs] [✓ Interprocedural] [✓ Exact] [✓ Scalar] [✓ Logic]

Dependence test: [✓ Banerjee] Omega

Limit Analysis Time: Yes [✓ No]

Max Time: 1 Hours

Figure T5-1: The READ Knowledge window for entering user knowledge and the Analyser window.



CAPTools: Partitioner

Routines:

```
add
adi
binvcrhs
binvrhs
BT
compute_rhs
elapsed_time
error_norm
```

add: 24 Unpartitioned Arrays

Name	Index	For	Against
qs(0:IMAX,0:JMAX,0:KMAX)	0	0	0
rho_i(0:IMAX,0:JMAX,0:KMAX)	0	0	0
rhs(5,0:IMAX,0:JMAX,0:KMAX)	0	0	0
square(0:IMAX,0:JMAX,0:KMAX)	0	0	0
tmp_block(5,5)	0	0	0
tmp_vec(5)	0	0	0
u(5,0:IMAX,0:JMAX,0:KMAX)	0	0	0
ue(-2:problem_size+1,5)	0	0	0
us(0:IMAX,0:JMAX,0:KMAX)	0	0	0
vs(0:IMAX,0:JMAX,0:KMAX)	0	0	0

Base Variable Specification:

Variable: u

Variable Index: 3

Modulus:

Divisor:

Offset:

Type: [✓ Block] Cyclic Block/Cyclic Unstructured

add: 0 Partitioned Arrays

Name	Index	Define Range	Partition Range

Partition Acceptance:

Maximum Against: 0

For/Against Ratio: 0

Partition Alignment:

Tolerence: 5

Partitioning Options:

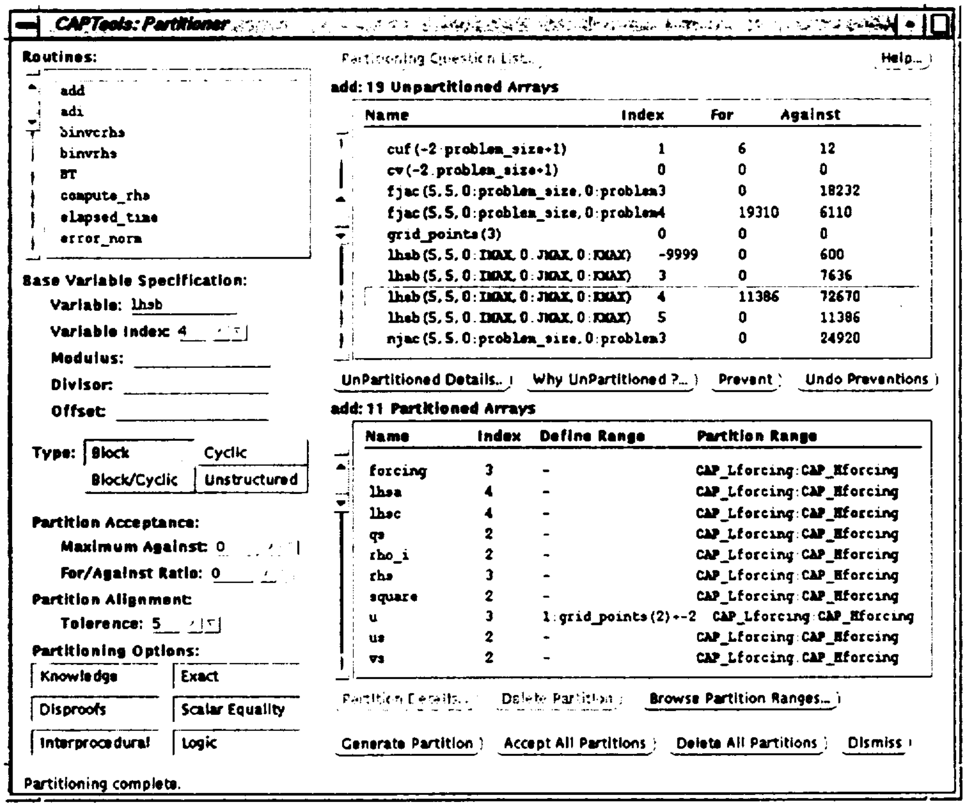
Knowledge Exact

Disproofs Scalar Equality

Interprocedural Logic

Partitioning...

Figure T5-2: The Partitioner window for array partitioning: routine add, array u, index 3.



Routines:

- add
- adi
- binvcrhs
- binvrhs
- BT
- compute_rhs
- elapsed_time
- error_norm

Base Variable Specification:

Variable: lhsb

Variable Index: 4

Modulus:

Divisor:

Offset:

Type: Block | Cyclic | Block/Cyclic | Unstructured

Partition Acceptance:

Maximum Against: 0

For/Against Ratio: 0

Partition Alignment:

Tolerence: 5

Partitioning Options: Knowledge | Exact | Disproofs | Scalar Equality | Interprocedural | Logic

Partitioning complete.

add: 19 Unpartitioned Arrays

Name	Index	For	Against
cuf(-2:problem_size+1)	1	6	12
cv(-2.problem_size+1)	0	0	0
fjac(5,5,0:problem_size,0:problem	3	0	18232
fjac(5,5,0:problem_size,0:problem	4	19310	6110
grid_points(3)	0	0	0
lhsb(5,5,0:IMAX,0:JMAX,0:KMAX)	-9999	0	600
lhsb(5,5,0:IMAX,0:JMAX,0:KMAX)	3	0	7636
lhsb(5,5,0:IMAX,0:JMAX,0:KMAX)	4	11386	72670
lhsb(5,5,0.IMAX,0.JMAX,0:KMAX)	5	0	11386
njac(5,5,0:problem_size,0:problem	3	0	24920

add: 11 Partitioned Arrays

Name	Index	Define Range	Partition Range
forcing	3	-	CAP_Lforcing:CAP_Hforcing
lhsa	4	-	CAP_Lforcing:CAP_Hforcing
lhsc	4	-	CAP_Lforcing:CAP_Hforcing
qs	2	-	CAP_Lforcing:CAP_Hforcing
rho_i	2	-	CAP_Lforcing:CAP_Hforcing
rhs	3	-	CAP_Lforcing:CAP_Hforcing
square	2	-	CAP_Lforcing:CAP_Hforcing
u	3	1:grid_points(2)+-2	CAP_Lforcing:CAP_Hforcing
us	2	-	CAP_Lforcing:CAP_Hforcing
vs	2	-	CAP_Lforcing.CAP_Hforcing

Figure T5-3: Apply array partitioning on the second array: lhsb, index 4.

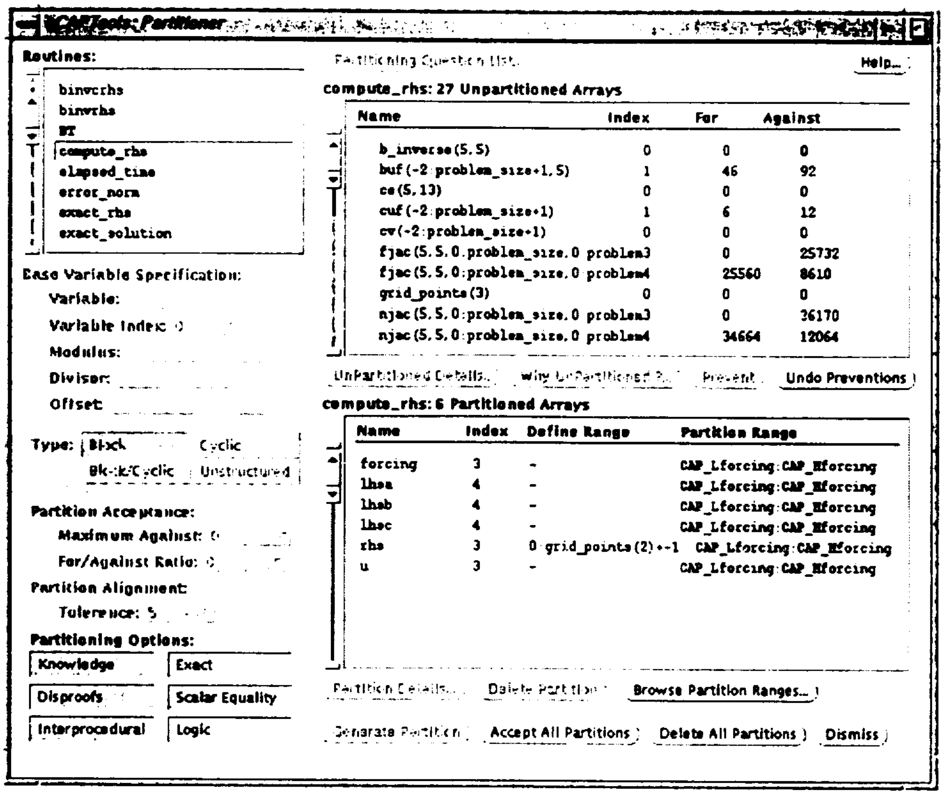
6. **Remove unwanted partitions**. If you use the result produced from Step 4 to generate message-passing code, you would notice that CAPTools place quite a few communication calls inside routine COMPUTE_RHS, which exchange boundary values of some of the working arrays (such as qs, rho_i...) for the partitioned dimension. These boundary values, in fact, can be calculated in the routine instead of being communicated from neighbors to improve the performance. This kind of improvement can be achieved within CAPTools by removing partitions on the relevant arrays (although it is not very obvious and intuitive). In the **Partitioner** window, select routine "compute_rhs". Select "qs" in the **Partitioned Array** list and click the Delete Partition button. Apply the same procedure to arrays: rho_i, square, us, vs, and ws. Figure T5-4 is what you will see after this process from which partitions on six arrays have been removed.

   Click the Accept All Partitions button.

7. **Generate masks and communications**. Start the **Code Generator** from the CAPTools main window. Choose 2 for **Min Slabs Per Processor**, which indicates at least 2 slabs in the partitioned direction to be used for the execution and reduces number of communications calls placed. Select Gather/Scatter for **Communication Type**. Click Generate Masks to start the mask generation and Calc & Gen Comms to generate communications. See Figure T5-5.

   At this point you could produce a pure message-passing program if you wish (the Generate & Save Final Code button). But we move onto next step.

8. **Save to database**. Use the *Save Database* menu to save the communication data to bt_comm_j.dbs.



CAPTools: Partitioner

Routines:

- binvcrhs
- binvrhs
- BT
- compute_rhs
- elapsed_time
- error_norm
- exact_rhs
- exact_solution

compute_rhs: 27 Unpartitioned Arrays

Name	Index	For	Against
b_inverse(5,5)	0	0	0
buf(-2:problem_size+1,5)	1	46	92
ce(5,13)	0	0	0
cuf(-2:problem_size+1)	1	6	12
cv(-2:problem_size+1)	0	0	0
fjac(5,5,0:problem_size,0 problem3	0		25732
fjac(5,5,0:problem_size,0 problem4		25560	8610
grid_points(3)	0	0	0
njac(5,5,0:problem_size,0 problem3		0	36170
njac(5,5,0:problem_size,0 problem4		34664	12064

compute_rhs: 6 Partitioned Arrays

Name	Index	Define Range	Partition Range
forcing	3	-	CAP_Lforcing:CAP_Hforcing
lhsa	4	-	CAP_Lforcing:CAP_Hforcing
lhsb	4	-	CAP_Lforcing:CAP_Hforcing
lhsc	4	-	CAP_Lforcing:CAP_Hforcing
rhs	3	0:grid_points(2)+-1	CAP_Lforcing:CAP_Hforcing
u	3	-	CAP_Lforcing:CAP_Hforcing

Base Variable Specification:

Variable:

Variable Index: 0

Modulus:

Divisor:

Offset:

Type: Block | Cyclic | Blk-k/Cyclic | Unstructured

Partition Acceptance:

Maximum Against: 0

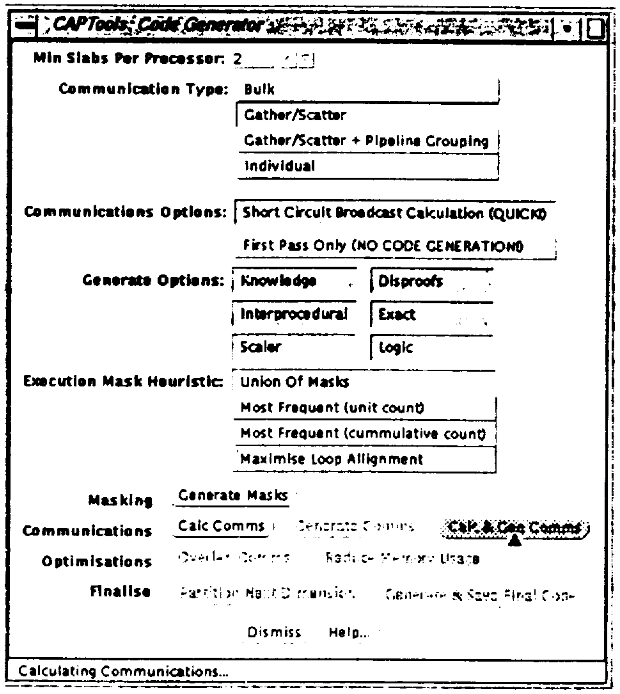
For/Against Ratio: 0

Partition Alignment:

Tolerence: 5

Partitioning Options:

Figure T5-4: The Partitioner window after partitions on six arrays were deleted.



CAPTools: Code Generator

Min Slabs Per Processor: 2

Communication Type:

Communications Options:

Generate Options:

Execution Mask Heuristic:

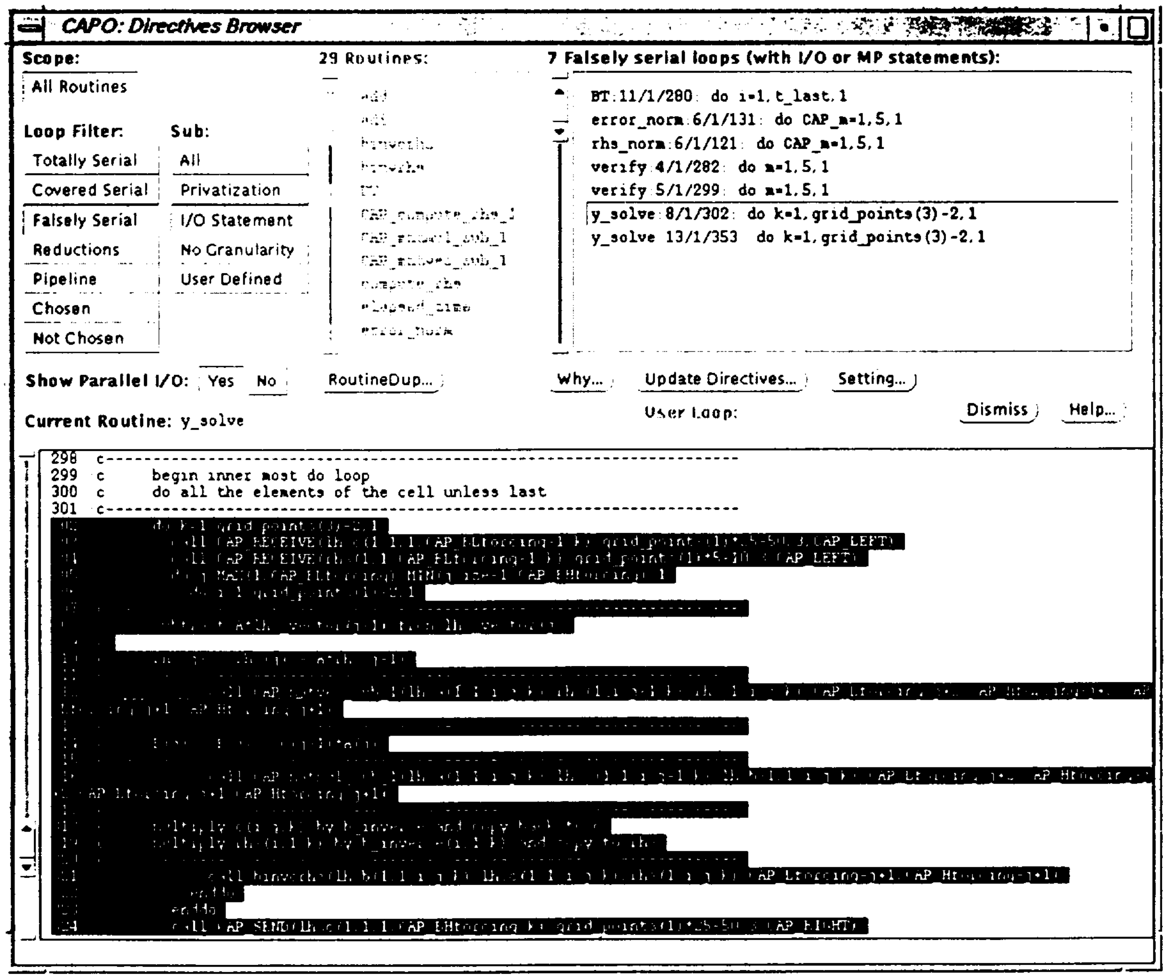
Calculating Communications...

Figure T5-5: The Code Generator window for the final generation of message-passing code.

Insertion of OpenMP directives at the second level:

9. **Browse directives**. In the View menu, click *Directives* to perform the directives analysis. The Directives browser will be popped up shortly. Select the All Routines scope and browse through all loop filters. Pay attention to the serial loops (*Totally, Covered* and *Falsely*).

10. **Re-enforce new loop types**. In the Directives browser window, select the All Routines scope, the Falsely Serial loop filter and I/O Statement sub filter (Figure T5-6). There are two K loops listed under this category. Choose the first loop: `y_solve:8/1/302: do k=1,grid..` and click the Why button. The **WhyDirectives** window (see Figure T5-7) indicates that there are four MP (Message-Passing) calls (as part of the parallel pipelines) inside the K loop, which serialize the K loop. If nothing is done here, the inside I loop will be chosen for the second level parallelization with directives, which will not give a good performance.



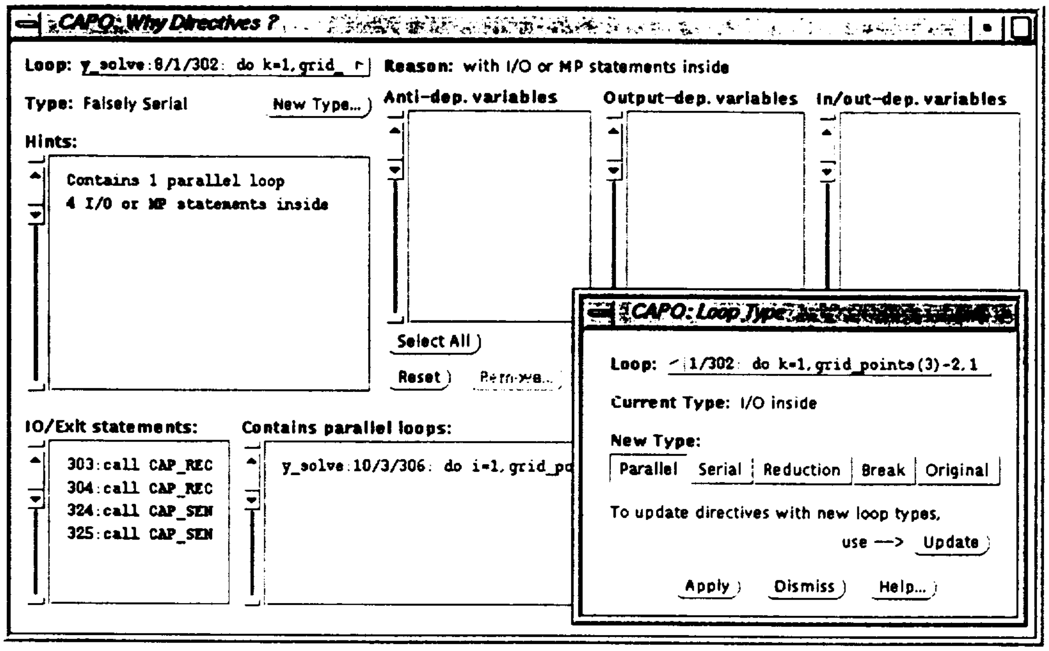
```
BT:11/1/280: do i=1,t_last,1
error_norm:6/1/131: do CAP_m=1,5,1
rhs_norm:6/1/121: do CAP_m=1,5,1
verify:4/1/282: do m=1,5,1
verify:5/1/299: do m=1,5,1
y_solve:8/1/302: do k=1,grid_points(3)-2,1
y_solve:13/1/353: do k=1,grid_points(3)-2,1
```

```
298  c-----------------------------------------------------------------
299  c      begin inner most do loop
300  c      do all the elements of the cell unless last
301  c-----------------------------------------------------------------
302        do k=1,grid_points(3)-2,1
             call CAP_RECEIVE(lhs(1,1,1,CAP_BLforcing-1,k),grid_points(1)*5-50,3,CAP_LEFT)
             call CAP_RECEIVE(rhs(1,1,CAP_BLforcing-1,k),grid_points(1)*5-10,3,CAP_LEFT)
             do j=MAX(1,CAP_BLforcing),MIN(j_size-1,CAP_BHforcing),1
               do i=1,grid_points(1)-2,1
[illegible]
        call CAP_SEND(lhs(1,1,1,CAP_BHforcing,k),grid_points(1)*5-50,3,CAP_RIGHT)
```

Figure T5-6: The Directives Browser window for the *Falsely Serial* and *I/O Statement* type.

In order to improve the performance, we can enforce a parallel type for the two K loops with an assumption that the MP calls are thread-safe. This is possible within the context of MPI-2. To define a new loop type, click the New Type button in the **WhyDirectives** window (Figure T5-7). Select new type Parallel and push Apply. A new entry is now added to file `userloop.par`.

Select the second K loop. `y_solve:13/1/353: do k=1,grid..` and click the New Type button. Again in the **LoopType** window choose new type Parallel and push Update. CAPO will save the new entry to file `userloop.par` and re-perform the directives analysis with the new loop types.



CAPO: Why Directives ?

Loop: y_solve:8/1/302: do k=1,grid_

Reason: with I/O or MP statements inside

Type: Falsely Serial

Hints:

```
Contains 1 parallel loop
4 I/O or MP statements inside
```

IO/Exit statements:

```
303:call CAP_REC
304:call CAP_REC
324:call CAP_SEN
325:call CAP_SEN
```

Contains parallel loops:

```
y_solve:10/3/306: do i=1,grid_pc
```

CAPO: Loop Type

Loop: 1/302: do k=1,grid_points(3)-2,1

Current Type: I/O inside

New Type: Parallel

To update directives with new loop types, use ---> Update

Figure T5-7: The WhyDirectives window for the selected loop and the LoopType window for defining a new loop type.

11. **Insert OpenMP directives**. In the File menu, click *Save OpenMP Directives Code*. Enter a filename (bt_cap_j_omp.f) and click Save. By now you will have the first version of a hybrid BT code. The log file, bt_cap_j_omp.log, contains additional information and statistics for the parallelization process. You will see warnings on "*I/O or MP statements inside parallel region*". This is what we need to fix next.

Modification to the generated hybrid code:

12. **Replace MP calls with thread-safe version**. As mentioned before, the current tool does not really support the generation of hybrid codes, but is merely used to assist such a process. The message-passing (MP) calls (CAP_SEND, CAP_RECEIVE...) placed inside the generated code by the tool are assumed to be used in a single-threaded environment. The supporting library, CAPLIB, is designed to run under a single-threaded environment as well. So in order to have the hybrid code working properly, we need to modify the message-passing calls inside parallel regions so that they can work safely under a multi-threaded environment. To achieve the goal, we will create a subset of the routines in CAPLIB to support multi-threading. These routines contain an additional field "*TAG*" in the argument for use with a specific thread. A sample implementation of the *thread-safe* MP routines used in this tutorial is included in file `caplib_thread.F`.

So we want to make a final touch to the generated code: replace several message-passing calls with the thread-safe version. Edit file bt_cap_j_omp.f with a text editor:

1) In subroutine Y_SOLVE, include the following two lines in the declaration

```
      integer omp_get_thread_num, myid
      external omp_get_thread_num
```

2) In subroutine Y_SOLVE, the third parallel region, change

```
!$OMP PARALLEL DO DEFAULT(SHARED) PRIVATE(i,j,k)
```

to

```
!$OMP PARALLEL DEFAULT(SHARED) PRIVATE(i,j,k,myid)
```

and add the following lines before "do k=1,grid_points(3)-2,1"

```
      myid = omp_get_thread_num()
!$OMP DO
```

Now add a message tag to the four MP statements in the K loop by replacing

```
      CALL CAP_RECEIVE(...)
```

with

```
      CALL CAP_RECEIVE_TAG(...,2000+myid)
```

and

```
      CALL CAP_SEND(...)
```

with

```
      CALL CAP_SEND_TAG(...,2000+myid)
```

The tagged SEND and RECEIVE calls are from caplib_thread.F and the tag "2000+myid" is added to ensure the point-to-point communication between two threads with the same thread number. The offset "2000" in the tag is to avoid potential conflict with message tags internally used by CAPLIB, but the choice of the value is a bit of arbitrary.

Lastly, change

```
!$OMP END PARALLEL DO
```

to

```
!$OMP END DO NOWAIT
!$OMP END PARALLEL
```

3) Apply the same changes as in 2) to the fifth parallel region in subroutine Y_SOLVE and save the modification.

Compile and run the hybrid code.

In order to compile and run the hybrid code successfully, the following additions or installations are required:

1) The CAPLIB library from the CAPTools distribution. CAPLIB can be downloaded from http://captools.gre.ac.uk/.

2) A thread-safe extension to some of the routines in CAPLIB, which are supplied here in caplib_thread.F for MPI. One of the main things in the file is a dummy MPI_INIT() routine which just passes the call to MPI_INIT_THREAD(). The CAP_*_TAG routines are also in this file.

3) A thread-safe implementation of MPI-2 library that supports MPI_INIT_THREAD in level MPI_THREAD_MULTIPLE. Such an implementation is available from SGI's MIPSpro 7.3 compilers and MPT 1.4 toolkit.

We will use the supplied Makefile to compile the hybrid code on the SGI Origin2000. Modify the content of Makefile, in particular the value for CAPLIB. Then do

```
% make
```

which will create an executable "bt_cap_j_omp.1". To execute the parallel code with 3 MPI processes and 3 threads per MPI process, do

```
% setenv OMP_NUM_THREADS 3
% mpirun -np 3 ./bt_cap_j_omp.1 -top pipe3
```

The output (for a class-W problem on 195MHz O2K) looks like:

```
Thread support on Rank    0 =  3, number of threads =  3
Thread support on Rank    1 =  3, number of threads =  3
Thread support on Rank    2 =  3, number of threads =  3
PID      HOSTNAME     MPI_PROCNAME   UNIX_PID      BIN_NAME
  1      turing          turing      35973         bt_cap_j_omp.1
  2      turing          turing      35974         bt_cap_j_omp.1
  3      turing          turing      35979         bt_cap_j_omp.1

Programming Baseline for NPB - BT Benchmark

 Size:  24x 24x 24
 Iterations: 200    dt:    0.000800
 Time step    1
 ...
      5 0.1018045837718E+02 0.1018045837718E+02 0.4575047075825E-12
 Verification Successful

 BT Benchmark Completed.
 Class           =                     W
 Size            =             24x 24x 24
 Iterations      =                   200
 Time in seconds =                 11.66
 Mop/s total     =                662.12
```

The execution time from a single process run is 84.69 seconds, so we have a speedup of 7.3 on 9 CPUs. You can run the code with different combinations of MPI processes and OpenMP threads, for example, to run with 2 MPI processes and 8 threads per MPI (2x8 = 16 CPUs):

```
% setenv OMP_NUM_THREADS 8
% mpirun -np 2 ./bt_cap_j_omp.1 -top pipe2
```

Table T5-1 on next page contains a collection of results from runs on two SGI Origin2000s: 195 (CPU type 195 MHz, 32Kb L1 and 4Mb L2 cache) and 300 (CPU type 300 MHz, 32Kb L1 and 8Mb L2 cache). NP stands for number of MPI processes and NT is the number of threads per MPI process. For a given number of CPUs, the hybrid code has a better performance when NP is close to NT. However, you also notice that "8x2" performs better than "4x4" or to say MPI is more preferable in this case.

Table T5-1: Execution time (in seconds) and Mop/s (million floating point operations per second) of the hybrid BT code, obtained for the Class W (24x24x24) and with 1, 9 or 16 CPUs.

195 MHz Origin2000, 1 or 9 CPUs					
NPxNT	1x9	3x3	9x1	1x1	
Time	14.26	11.66	12.26	84.69	
Mop/s	541.46	662.12	629.47	91.14	
300 MHz Origin2000, 16 CPUs					
NPxNT	1x16	2x8	4x4	8x2	16x1
Time	8.21	6.38	5.76	5.38	6.88
Mop/s	940.61	1210.05	1339.76	1433.53	1122.38