A Software Tool For Building Supercomputer Applications

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ABSTRACT

We describe a software tool that consists of an interactive environment for helping users restructure programs to optimize execution on parallel/vector multiprocessors. The system is used to help programmers fine tune codes that have already been passed through an automatic parallelizing system or codes have been designed from the start from new parallel algorithms. In particular, programs optimized for one machine can be easily reoptimized for another using this system. To accomplish this task, the tool provides mechanisms to give the programmer feedback concerning the potential performance of his code on the chosen target machine and allows the user an interactive means to guide the system through a sequence of automatic program transformations.

1 INTRODUCTION

Five years ago the subject of Parallel Computation was an exotic sub-field of computer science that consisted largely of theoretical studies of potential parallel algorithm performance, a few university hardware projects, even fewer software design efforts and (with the exception of Denelcor) no industrial products. Five years later, we now find that all U.S. supercomputers, and over one dozen mini-supercomputer vendors have entered the market with some form of general purpose parallel processing system. It is expected that every computer company will offer a scalable multiprocessor by the end of the decade.

Unfortunately, very few of these systems provide a software environment for building parallel programs that goes beyond a standard sequential language compiler and a microtasking library to support parallelism. None of our most widely used programming languages (C, Fortran, Lisp) have been given official extension to support concurrency and no two vendors agree on any of the unofficial extensions. The task of porting parallel codes from one machine to another now involves large amounts of recoding to make a program work, and large amounts of restructuring of the algorithm organization to make it work well.

The primary concern of the vast majority of users is to be able to exploit the power of a supercomputer without sacrificing portability. Consequently, these users want an automatic system such as those provided by Pacific-Sierra or KAI which will provide substantial improvement in a code without any effort by the programmer.

On the other hand, there are still a large number of hardy users of these new systems who are not content to live with the results of an automatic vectorizer or parallelizer. These are the users who are willing to invest a "reasonable" amount of extra effort if it might mean a doubling of performance beyond what the automatic system delivers. The key to this extra performance is the cost. How much is a "reasonable" amount of extra work?

In this paper we describe a programming tool designed to help users of parallel supercomputers retarget and optimize application codes. In a sense, the system can be viewed as a tool to help users "fine-tune" the output of an automatic system or, if he or she has been so inspired, optimize the design of a new parallel algorithm.

The system is an interactive program editing and transformation system that helps the user with this task. Each program that enters the system is completely parsed and all data dependences are recorded. The user then works with the system to restructure his code to a form suitable for a given target architecture. If the target is known to the system, it monitors the users transformations to the code. If the user attempts to transform the program in violation of the original semantics of the code he is warned that a change in the meaning of his program has taken place. At any time the user can ask the system to tell him what legal parallelizing transformation can be applied to a segment of selected code. More important, he can ask the system to make the program modifications the user desires. In this mode, the user is assured of the correctness of the changes in his code.

In its current form, the system, known as the Blaze Editor or "Bled", can support either FORTRAN (with Cedar and Alliant 8x extensions) or Blaze (a Pascal based functional language designed by Mehrotra and Van Rosendale [14]). In the future we plan to support C, C++ and Cedar Parallel C [9]. The target machines supported currently include the BBN Butterfly, the Alliant FX/8 and the Cedar System [7].

This tool is one part of a much larger programming environment known as the Faust Project. This effort, based at the Center for Supercomputer Research and Development in Urbana, Illinois has designed a common software platform for a number of programming tools including a performance analysis package, a program debugger, Bled, and a graphics based program maintenance system. All the software has been written to use the X system from the MIT project, Athena and, therefore, it will run on any Unix-based workstation.

In this paper we describe the current Bled system as well as two important extensions that are being added at the time of this writing.

One extension is a performance prediction package that can be invoked from within Bled to help the user choose which formulation of his algorithm will run best. There are two components to this performance prediction package. First is a code generation estimator that can give the user feedback in the form of estimates of such quantities as the ratio of vector instructions to data movement, or the amount of code devoted to synchronization overhead. Second, this package provides estimates of cache behavior and local memory utilization.

The second extension is a portable runtime environment that supports a dynamic "microtasking" facility that incorporates ideas from the Argonne Schedule package [5] and the MIT multilisp system [10].

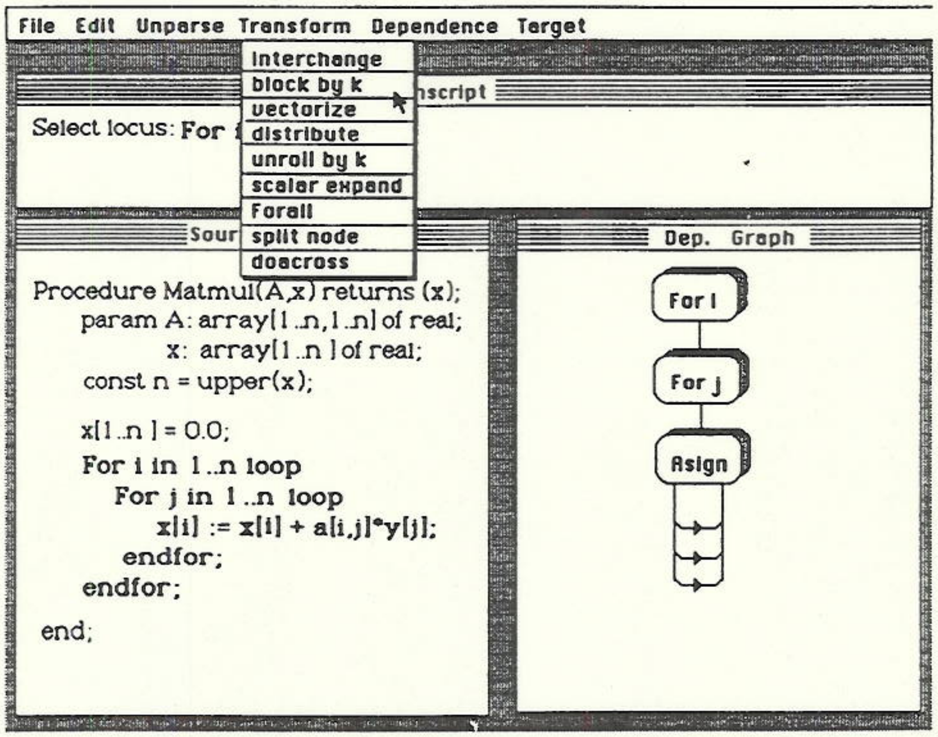
2 A SAMPLE USER SCENARIO

To illustrate how a user would interact with this system we shall step through a very simple example. The Blaze subroutine below is a simple matrix times vector routine.

```
Procedure MatVec(n,A,x) returns: y;
param A: array[1..n, 1..n] of real;
    x,y: array[1..n] of real;
    n: integer;
begin
    for j in 1..n loop
        for i in 1..n loop
            y[i] := y[i]+A[i,j]*x[j];
        end;
    end;
end;
```

The user loads this program into the system as if he were entering a text editor. The result is a window displaying the program and a list of menu headers (as illustrated in Figure 2.1). The first thing he may wish to do is to tell the system which machine is the intended target of this optimization. Currently this menu only lists three active choices: the BBN butterfly, the Alliant FX/8 and the Illinois Cedar. (We plan to extend this list to include the IBM RP3, the CRAY 2, the Connection Machine, and the ETA-10 during the next two years.)

The significance of having the user tell the system about the choice of target is three-fold. First, and most obvious, we would like to have the system generate code for the given target. We will say more about this later. Second, it is important that program transformations that are inappropriate for the target machine be disabled. Third, and of most immediate concern to the user, selecting a target will enable the appropriate performance estimators which are described below.



Select locus: For

```
Procedure Matmul(A,x) returns (x);
    param A: array[1..n,1..n] of real;
          x: array[1..n] of real;
    const n = upper(x);

    x[1..n] = 0.0;
    For i in 1..n loop
       For j in 1..n loop
           x[i] := x[i] + a[i,j]*y[j];
       endfor;
    endfor;

  end;
```

Figure 2.1. BLED Screen After Program Load.
The Window on the Right is the Data Dependence Graph.

Optimizing Code For The BBN Butterfly

To begin working with the system the user selects a segment of code, which we call a 'focus', on which to apply the tools BLED provides. For example, suppose the target is the BBN Butterfly and the user picks the innermost loop (by a mouse selection) as his focus. Among the menu headings he has at the top of the screen, is one called "Transforms". This menu contains a list of program restructuring transformations that can be used to expose concurrency or make parallelism explicit. For example, the user may have decided that he wishes the innermost "for" loop to be run in parallel. By selecting the transformation "forall" the system will first verify that the transformation can be legally applied. This requires a search of the data dependence graph to make sure that the appropriate conditions are satisfied so that the transformation can be legally applied. (A more detailed discussion of this process is given in Section 3.) In this case the transformation is legal and the code now takes the form

```
for j in 1..n loop
     forall i in 1..n do
          y[i] := y[i]+A[i,j]*x[j];
     end;
end;
```

Following this operation, the user could invoke the code generator, but a better use of the system is to first invoke the analysis tool. This involves the selection of a menu item "analysis: Parallel Loop". Because the target machine, the Butterfly, executes such loops at the cost of a function call and an atomic increment to the index, the reply will be in the form

```
Loop Overhead to Body ratio > 50%.
Suggestion: increase granularity by blocking,
     merging or loop interchange.
```

Of the three suggestions, loop interchange is the easiest. After this operation the loop takes the form

```
forall i in 1..n do
     for j in 1..n loop
          y[i] := y[i]+A[i,j]*x[j];
     end;
end;
```

The "forall" loop body will now be large with respect to the loop overhead, but another problem that may inhibit performance is memory contention for shared data. In this case a second analysis tool called "analysis: Cache Management" can be invoked. As will be described in more detail in section 4, this tool will report the following information when the program focus is the "forall" loop.

```
Cache/Local memory analysis for iterate i:
     Suggest local copies of: A[i,1..n], x[1..n]
     for n=100 hit ratios will be 0.99, 0.9999
```

This (too cryptic) message suggests that local copies of these variables be made in each processor. A major shortcoming of this form of the analysis is that the user is not informed of the penalty for failing to take this advise. In section 4 we discuss the future extensions of this analysis that will provide expected improvements in multiprocessing efficiency as a result of this memory management. The resulting program will take the form

```
forall i in 1..n do
var: x_local, A_local: array[1..n] of real;
     A_local[1..n] := a[i,1..n];
     x_local[1..n] := x[1..n];
     for j in 1..n loop
          y[i] := y[i]+A_local[j]*x_local[j];
     end;
end;
```

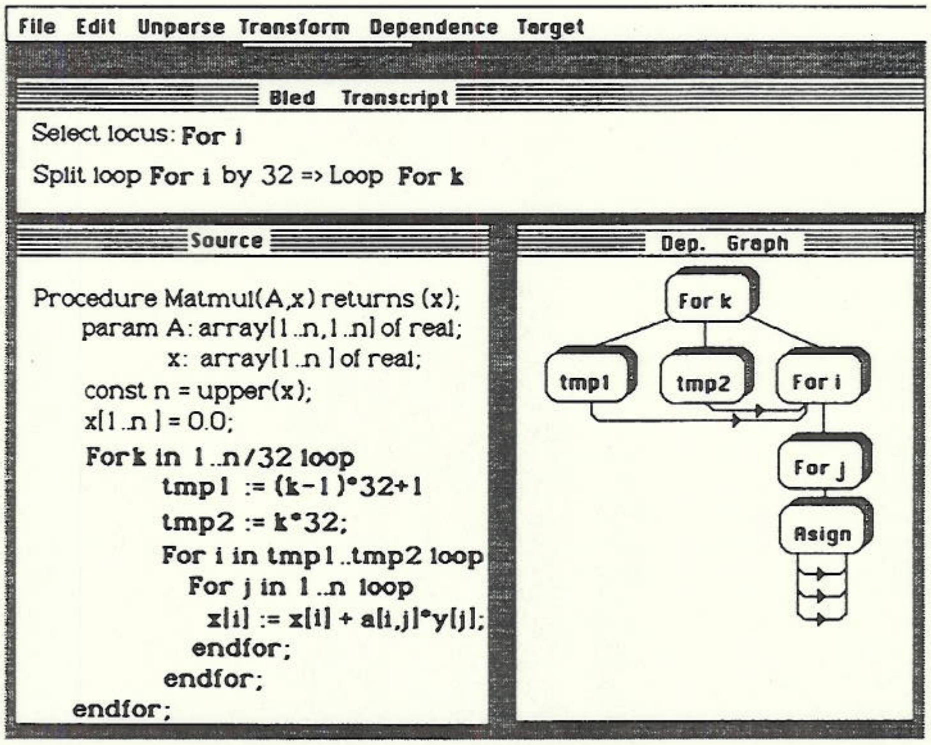
Clearly *x_local* need only be initialized once per processor but in Blaze we have no way to express this, so this task is left to the code generation step.

Optimizing Code For The Alliant FX/8.

Suppose the target machine were chosen to be the Alliant FX/8. Each processor on this machine has a vector instruction set and a vector register set that generalizes and extends the M68020 which forms the basis of the rest of the processor design. The execution of parallel loops requires almost no overhead, but best performance is achieved only if the shared cache memory and the vector instruction set is optimally utilized.

To optimize the matrix-vector routine for the FX/8 we would begin by recognizing that the vector instructions operate from registers of length 32. For this reason, the user may wish to "block" the inner loop in vector segments of length 32. This requires two steps. First the user selects "block by 32" from the transformation menu as illustrated by the screen dumps in Figures 2.1 and 2.2. In the second step the inner loops are vectorized.

The result of these two operations is shown below.



Select locus: For i

Split loop For i by 32 => Loop For k

```
Procedure Matmul(A,x) returns (x);
    param A: array[1..n,1..n] of real;
          x: array[1..n ] of real;
    const n = upper(x);
    x[1..n ] = 0.0;
    Fork in 1..n/32 loop
          tmp1 := (k-1)*32+1
          tmp2 := k*32;
          For i in tmp1..tmp2 loop
            For j in 1..n loop
              x[i] := x[i] + a[i,j]*y[j];
            endfor;
          endfor;
   endfor;
```

Figure 2.2. System State After Loop Blocking Transformation.

```
for j in 1..n loop
     for k in 0..n/32-1 loop
          k1 := 32*k+1;
          k2 := 32*(k+1);
          y[k1:k2] := y[k1:k2] + A[k1:k2,j]*x[j];
     end;
end;
```

At this point, a third component of the performance analyzer can be invoked. The **Vector Code Analyzer** will make an estimate of the quality of the vector instruction utilization for this loop. In this case it will report

```
Vector instructions   Frequency
Load/Store            2*n*n/32
Multply-Add           1*n*n/32
Arith. Efficiency = 33% (for n=100)
```

The vector efficiency term is computed based on the fact that for diadic vector instructions the processor is capable of two floating point operations every clock cycle. Vector loads and stores do not contribute to the total number of arithmetic operations but they do consume large amounts of time. If we look at the inner loop we notice that the indecies on the vector segments for *y* do not depend upon *j*. In this case one simple "loop interchange" transformation will bring the *j* loop inside and the processor need only load and store each *y* segment once. The rest of the time it can remain in a vector register. Parallelizing the outer loop gives the code below and the corresponding statistics.

```
forall k in 0..n/32-1 do
     k1 := 32*k+1;
     k2 := 32*(k+1);
     for j in 1..n loop
          y[k1:k2] := y[k1:k2] + A[k1:k2,j]*x[j];
     end;
end;
```

The output from the code analyzer is now

```
Vector instructions   Frequency
Load/Store            2*n/32
Multiply-Add          1*n*n/32
Arith. Efficiency = 99% (for n=100)
```

Notice that this simple transformation has had the effect of a three fold improvement in vector unit efficiency. The resulting code is, in fact, the fastest matrix-vector form for this machine.

3 SYSTEM ORGANIZATION AND THE TRANSFORMATION MODULES.

The system is organized as a set of four interacting modules: the parser/analyzer, the transformation module, the performance estimator, the code generator, and the user interface manager. In this section we describe the Parser/analyzer, the user interface and the program transformation modules.

The Program Parser and Analyzer.

At the time a program module is loaded into the system it is completely parsed and a full control dependence graph and symbol table is constructed. The control dependence graph is based on a statement level version of the PDG of Feranti and Ottenstein [6]. Each program statement is represented by a graph node in the control dependence graph. An arc goes from one node to another if the latter is "control dependent" (in the sense of [6]) on the former. In the case of structured programs this graph is always a tree as illustrated in Fig 3.1.

The nodes of the control dependence graph, called BIF nodes, represent program statements, declarations and control forms. Of course, this is not enough detail to describe a program. Within each program statement there are one or more expressions describing the parameters of the statement. For example, a "for loop" in Blaze or FORTRAN takes the form

For <var> from <lower_bound> to <upper_bound> by <increment>.

```
For i in 1..n loop
   x[i] :=1.5;
   if( i > 3) then
       x[i]:= 2;
   else
       y[i] := 3;
   endif;
endloop;
```

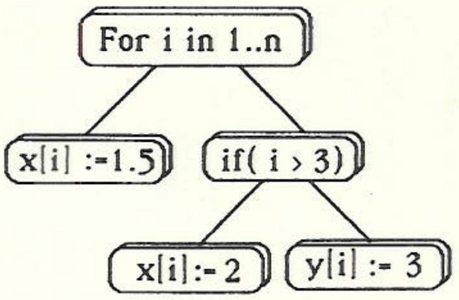


Figure 3.1. Program Control Dependence Graph

Each such expression is represented by a low-level dataflow graph which is attached to the BIF node which forms a template for the statement. While there is nothing new about this type of representation, we have found that its simplicity provides for great generality in the language it supports. Hence, the same graph can be used to represent several different programming languages.

The basic program graph has been defined with a general imperative programming language in mind. Using the same internal structure we currently represent either Blaze or FORTRAN programs. The extensions to support C are not complete, but only require the addition of a pointer type and the corresponding dereferencing operators. The way this works is that common control constructs, i.e. "for" loops, if-then-else blocks, case statements, variable assignments and function calls, form the core of the common semantics of each of these languages. There is one node type for each of these fundamental forms. For those features that exist in one language but not the others, we add extra node types. For example, FORTRAN has a "goto" statement and Blaze does not; also Blaze and C have record type variables and FORTRAN does not. The most important point is that, at the level of program semantics, and, especially in the area of control structures, there is very little difference between these languages. This means that we can write general program transformation modules that work at the level of common semantics.

We provide a special parser and "unparser" for each language. The unparser is the devise for recovering the original source for display in the text window of the system. This works by simply traversing the control dependence graph and, using the symbol table generated by the parse, reproducing the original source up to, but not including the programmer's use of white space. (We do save comments and try our best to put them back in the original positions. This can be difficult if the "original position" no longer exists after a transformation step.) By labeling each graph with the source language type we know how to resolve any minor differences at the control structure level.

It is important to note that this syntactic independent internal representation of the language does not give us the ability to parse a FORTRAN program and unparse it as a Blaze program. Rather, it gives us the ability to design program transformation and analysis tools that are relatively independent of the syntax of the original program. The most important shortcoming of this program dependence graph is that it is limited to representing simple imperative languages. Higher order constructs such as Object and Class structures or first class functions and continuations have not been addressed.

The data dependence analyzer adds data flow information edges to the Control Dependence Graph. These take the form of distance vectors representing flow, anti, output or input dependences in the form described in [4] and [15]. In addition we have added special information about the structure of uniformly generated dependences so that cache performance modeling can be done. This is described in more detail in section 4.

The data dependence analyzer is invoked each time the program is modified by transformation or special dependence information is needed by another unit of the system. To keep this from creating excessive computational overhead the dependence analyzer works in an incremental manner. In the case of structured programs where the control graph is a tree, this works in a manner similar to the Cornell Program Synthesizer which uses an attributed grammer to build an internal representation of a program.

The User Interface And Program Transformation Modules.

The style of user interaction is identical to that of most modern software tools. The user is given a "work space" into which the program under study is loaded. By means of menu selection, the user is also equipped with a large palette of tools that he can apply to selected parts of his program. They take the form of program editing, transformation and evaluation tools.

Because the system is built on top of a solid library of graphics, menu and text manipulation routines provided by the FAUST environment, the user interface is the simplest part of the system. It consists of a loop which responds to user generated events. Events are interpreted as either a resetting of the program focus or as a call to invoke one of the tools and apply it to the current focus.

The program transformation module is organized as a collection of routines that each implement one of the transformation theorems. (These are given in various places in the literature, see [19], [17], [11], [13], [1], [2], [4], [15], [18]). Each routine first verifies that all the conditions are satisfied to guarantee that the transformation is correct, then it carries out the transformation, updates the dependence graph and redisplays the text on the screen. For example, to interchange two nested loops in a program segment we must invoke the theorem

LOOP INTERCHANGE: Let L_i and L_{i+1} be a perfectly nested pair of loops with $L_{i+1} \subset L_i$. The two loops can be interchanged if and only if doing so will not violate a data dependence constraint associated with any statement or pair of statements nested within L_{i+1}.

The data dependence constraint translates into a simple mathematical condition on the distance vectors associated with the dependence. (In particular, if interchanging the i^{th} and $(i+1)^{th}$ component of the distance vector causes the vector to have a negative leading non-zero term, then the constraint will be violated.) The loop interchange module first checks to see if the current focus is rooted by a loop and that the next level down is a loop perfectly nested within the first. The dependence test is then made. If the test is passed the operation is carried out. If the test fails, the user is notified as to why the transformation could not be applied.

The user is free to override the system and to insist that the transformation be done. There are two reason for allowing this. First, the data dependence analysis may not be able to completely decide if a dependence is real. (For example, subscripts in arrays that involve function calls). In cases where it cannot decide if a dependence exists, the system takes a conservative approach and assumes the dependence is there. The programmer may have additional information that the parser and dependence analyzer does not have. For example, knowing that the function call in the index expression is of a special form that would rule out the existence of a dependence. In this case it may be safe to complete the transformation. The second reason for overriding the system is that the user may, in fact, wish to change the meaning of the program.

4 PERFORMANCE ESTIMATION

The performance module consists of two main components: The cache/local memory modeling package and the vector code generation estimator. It is important to understand that this is not a performance evaluation package that gives a detailed analysis of program behavior based on actual execution statistics. Rather, it is a tool that makes *a priori* estimates of *potential* program execution behavior. The objective is to provide the programmer some immediate feedback about the suitability of his algorithm constructs and potential problems he may encounter during execution as the code is being designed. Once the code is running on the target, the programmer will probably switch to a performance evaluation package to do final fine tuning. For the most part, this component of the system is far from complete and only a simple prototype is currently running.

The Cache/Local Memory Modeling Package

The Alliant FX/8 has a unique memory organization. All 8 CEs are connected by a crossbar switch to a shared cache. The bus bandwidth between cache and main memory is approximately one half of the total bandwidth between the cache and processors. While this provides a simple solution to the cache coherency problem, it does have major implications in the way parallel programs are organized. In particular, if one processor is using a large amount of data that is not used by the other processors, it can cause the cache to be filled at the expense of the performance of the other processors. Consequently, it is best to organize the code so that processors can share cached data if possible.

For the Butterfly machine a different problem dominates system performance. In this machine every word of memory can be reached by every processor. However, the memory that is local to a processor is significantly faster to access than that part of the address map that is nonlocal. A related issue is that of memory "hotspot" contention. This refers to the degradation problem caused by a large number of serial accesses to the same data item by a large number of processors (see [16]). It has been shown that by careful use of local memory, many of these problems can be avoided (see [3]).

Both the cache problems of the Alliant and the local memory problems associated with the BBN Butterfly can be treated by using a new theory of memory management based on dependence analysis that we have designed [8]. The key idea behind this work is that each data dependence is described by a *cache window*, which is the set of data values which when kept in cache after being referenced by the head of the dependence, will result in a cache hit after the tail of the dependence. It is shown in [8] that an algebraic model can be given to the structure of these cache windows. The model is powerful enough to allow us to give a first order estimate of both cache and local memory behavior and tell us how to optimize the program to improve memory hierarchy use.

Vector Instruction Efficiency Estimator

Like the multiprocessors from Cray and ETA, the Alliant makes extensive use of a vector instruction set. Our experience has shown that one of the first things a programmer wants to know when he is optimizing code is how well his FORTRAN 8X was translated into vector and parallel code. In many cases he can decide to restructure a program if, for example, he realizes that the current form does not permit the code generator to use any diadic operations. On the Alliant, this type of reorganization can provide a 30% improvement in performance.

One of the estimation tools that we are adding to the system works by a pass over the selected program focus and makes a simple estimate of scalar code and loop overhead, as well as an estimate of how well the Alliant Code generator will be able to generate vector code.

This tool is related to another tool that we are adding to the Faust Workbench. We are building a code analysis package that will examine the output of the compiler and give statistics about the density of vector operations and the frequency of use of parallel constructs. Of particular concern in both tools is the effective use of diadic operation and a measure of how much time is spent moving data in and out of registers.

5 GENERATING TARGET SYSTEM CODE

Once a program has been optimized for a given architecture, a programmer will want to have it run. This means that code will need to be generated for the target. Our approach to this problem follows the tradition of other restructuring systems. Rather than generate object code, we output source code that utilizes the language extensions and special function calls that are specific to that machine. The advantage is that we can take advantage of the native code generators and optimizers that exist for that machine.

In the case of FORTRAN, we generate Alliant vector-concurrent FORTRAN 8X for that machine. For Blaze programs we generate C code for the Alliant. In the case of the Butterfly we generate a C program that utilizes the BBN "uniform system" runtime environment for both FORTRAN and Blaze.

The first problem that one confronts in mapping the computational model defined by a parallel programming language like Cedar Fortran or Blaze to a target like the Alliant or the Butterfly is the following:

How does one provide efficient parallel execution of a language that is historically rooted in sequential stack based semantics?

The first instance of where this problem arises is in the execution of concurrent loops where the body of the loop contains references to names defined outside the loop. We would like to have a runtime stack which, at the point of a parallel loop invocation, can branch so that each processor has a private stack branch, but they share the part of the stack before the parallel execution call.

With the Alliant FX/8 the solution to this problem is built into the hardware. There are special instructions to set up this type of "cactus stack" and have each processor start execution at the appropriate place and time.

Unfortunately, the Butterfly presents a different computational model. Using the "uniform system" on that machine each processor gets a copy of the C program static data and has its own stack in private memory space. All shared data must be explicitly allocated in global memory. Consequently, if one processor updates a static variable or pushes an item on the stack it is invisible to all other processors. The solution to the problem for the Butterfly is to make the code generator allocate a copy of the activation record in global memory that is reachable by all processors. Any reference to data outside the scope of the loop is made through this record.

It would seem that the Alliant solution is by far superior, but there are other problems when one tries to extend the semantics in directions suggested by Schedule [5] and other portable concurrency packages. Dongarra and Sorenson have argued that parallel programmers should have the ability to write code that permits tasks to be generated dynamically and scheduled for execution when the appropriate data is available. It is important that these tasks be "light weight", i.e. unlike a Unix process, the creation and scheduling of a task should involve no more overhead that a typical function call.

The ability to do this was supported directly by the hardware of the Denelcor HEP, but is missing from most of the current designs. The logical extension of the light weight task idea is the *future* used by Halstead in MultiLisp [10]. The principle concept is that any function call

$$x = Foo(a,b,c,d)$$

can be replaced by

$$x = future(Foo,\ a,b,c,d)$$

The use of *future* causes a task to be created and start executing when the appropriate value for the parameters are known. Meanwhile, the calling task continues to execute until the value of x (or any other value computed by *Foo* and assigned by side effect) is needed. At that time the caller must be suspended until *Foo* terminates.

The key problem is that suspending the caller cannot keep a processor tied up or a deadlock situation will result. Consequently, the system must encapsulate a state for the caller. Because we must assume that any processor is able to continue the execution of the caller, we cannot keep this state on the private stack of any one processor. Consequently, the task state must be saved in the global heap.

We are currently extending the code generator to support this *future* construct. There are a number of problems that we are trying to solve while completing this task.

1. How do we generate the synchronization mechanisms needed to schedule the futures?
2. How can we find an efficient implementation for our list of target machines?
3. How do we keep the implementation of *futures* consistent with the execution model for parallel loops?
4. Can we detect when a function is a good candidate for execution by futures rather than a straight sequential call?
5. In what way can we use this execution model to help us implement object oriented programming?

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