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Realizing Parallel Reduction Operations in Sisal 1.2

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Abstract: *Often the tasks of a parallel job compute sets of values that are reduced to a single value or gathered to build an aggregate structure. Since reductions may introduce dependencies, most languages separate computation and reduction. For example, Fortran 90 and HPF provide a rich set of predefined reduction functions but only for extant arrays. Sisal 1.2 is unique in that it supports seven reduction operations as a natural consequence of loop expressions. These reductions are limited and cannot express the variety of reduction operations found in parallel programs. In this paper, we present compilation techniques that recognize pairs of computation-reduction expressions in Sisal 1.2 and fuse them into single parallel loops. This optimization overlaps computation and reduction, reduces runtime overhead, and reduces storage requirements. We describe an implementation and we present performance numbers that demonstrate the utility of our techniques.*

1.0 Introduction

Often the tasks of a parallel job compute values in two phases. First, the computation expression computes a set of values, and then the reduction expression reduces the set of values to a scalar value or gathers the values to build an aggregate structure. An array sum reduction adds together the elements of an array and returns a scalar value. A histogram is a transformational reduction that counts the number of occurrences of a value in one array and stores the count in another. A recurring theme in particle physics codes is the calculation of bond forces. The forces between particles are calculated, and then the force incident on each particle. Since the forces are symmetric, an efficient program calculates each force only once and then adds together the forces incident on each particle. Since reduction operations occur frequently in application programs, they are good targets for optimization. The efficient expression and implementation of reduction operations can reduce the cost of parallel programming.

A reduction operator is a function of a set of values such as an array or list. If we execute the computation and reduction concurrently, then the memory used to store the result of the reduction expression is shared by the tasks computing the set of values. Since reductions may introduce dependencies, most languages separate the computation and reduction tasks. For example, Fortran 90 [1] and HPF [2] provide a rich set of predefined reduction functions but only for extant arrays.

```
C  find the minimum value in z_array
   z_min = MINVAL(z_array)

C  return the first location of the minimum value in z_array
   z_min_loc = MINLOC(z_array)
```

Despite the lack of explicit memory, functional languages also support reduction operations. Haskell [3] provides reduction and accumulation operations on extant lists or list expressions.

```
-- compute the sum of the integers 1 through 10
sum[1..10]

-- return a table of the number of occurrences of each value
-- within bounds in list z
accumArray (+) 0 bounds [i := 1 | i <- z, (inRange bounds i)]
```

Sisal 1.2 [4] is unique in that it supports seven reduction operations as a natural consequence of loop expression. The reduction operation appears as a keyword in the returns clause of the *for* or *for initial* expression.

```
% find the minimum value in z_array
for z in z_array
returns value of least z
end for

% inner product of arrays of length 10
for i in 1, 10
  c := A[i] * B[i]
returns value of sum c
end for
```

Since a *for* expression includes both computation and reduction, the Sisal compiler can overlap the operations, implementing both tasks to take best advantage of the underlying architecture.

A shortcoming of all languages is that they support only a few predefined reduction operations. The HPF Journal of Development [2] has suggested additional language features be added for user-defined reduction functions, and in the final section of this paper we discuss syntax for user-defined reductions in Sisal 90. Without special language features, a user must use extant loop forms to express the computation and reduction operations, and rely on the compiler to generate efficient code. For example, the Fortran D compiler [6] seeks to recognize reductions for optimization in traditional imperative code.

In this paper we present compiler techniques to identify pairs of computation-reduction expressions in Sisal 1.2. We describe how we manipulate the code's intermediate form to construct a single parallel loop similar to the loops constructed for the seven intrinsic reduction operations. Our techniques require no changes to the language definition or intermediate form. Section two presents the form of computation-reduction expressions we recognize and the constraints that the expressions must satisfy. Section three illustrates the rewiring of the intermediate form and discusses implementation issues. Section four presents performance numbers demonstrating the utility of our techniques. In section five, we discuss the syntax for user-defined reductions in Sisal 90, the analysis required to insure determinancy, and the possible implementations of different classes of reduction operations.

2.0 Computation-reduction expressions

The Sisal 1.2 language definition supports seven reduction operations: *sum*, *product*, *least*, *greatest*, *array*, *stream*, and *catenate*. The reductions may appear in the returns clause of *for* or *for initial* expressions. While useful, the reductions are inadequate. For example, finding the first location of the minimum value of an array cannot be expressed efficiently in Sisal 1.2. A programmer must either write two *for* expressions,

```
min_value := for x in A returns
             value of least x end for;
min_index := for x in A at i returns
             value of least i when x = min_value end for;
```

or one *for initial* expression

```
min_index := for initial
               i := 1;
               min_value, min_index := A[1], 1
             while i < array_size(A) repeat
               i := old i + 1;
               min_value,
               min_index := if A[i] < old min_value then A[i], i
                            else old min_value, old min_index
                            end if
             returns value of min_index
             end for
```

The first solution doubles the computation's overhead, and the second solution eliminates all parallelism.

The situation is more dire if we want to generate a set of values, and then count or accumulate the values. A common pair of computation-reduction expressions occurs when computing the forces between a set of particles. Consider a set of n particles and m bonds in a *bond_list*. Each bond represents a force between two particles. We want to calculate the force of each bond and then accumulate the force incident on each particle,

```
Force_update := for bond in 1, m
                  index_1, index_2 := end_points(bond);
                  Force_record     := energy(index_1, index_2, Positions)
                returns array of Force_record
                end for;

Force_out    := for initial
                  i            := 0;
                  Forces       := array_fill(1, n, 0.0)
```

```
while i < array_size(Force_update) repeat
  i            := old i + 1;
  index_1      := Force_update[i].ii;
  index_2      := Force_update[i].jj;
  bond_energy  := Force_update[i].bond_energy;
  Forces       := old Forces[
                    index_1: old Forces[index_1 + bond_energy;
                    index_2: old Forces[index_2 - bond_energy
                              ]
returns value of Forces
end for
```

The first expression is a *for* expression. The second and third lines constitute the loop body. An instance of the body is computed for each bond, and defines a *force_record*. The record has three fields: the indices of the two particles participating in the bond (*index_1* and *index_2*) and the bond's energy. The expression returns the array of force records. The second expression is a *for initial* expression. It returns the array *Forces*, where *Forces[j]* is the incident force on the *j*-th particle. The second and third lines initialize the counter *i* and the *Forces* array. The loop body, lines five through ten, reads the *i*-th force record and updates the *Forces* array accordingly.

On highly parallel computer systems, the presence of the *for initial* expression curtails the code's efficiency—an effect of Amdahl's Law. Notice that the size of the sequential code grows linearly with problem size. On medium or small systems, there may be insufficient memory to store the intermediate array of force records. The extra storage may increase the number of page faults and secondary memory accesses diminishing performance. We have extended the Sisal compiler to recognize pairs of computation-reduction expressions and to fuse each pair of expressions into a single parallel loop. The compiler applies the optimization to pairs of *for* and *for initial* expressions that satisfy the following five criteria:

1. the *for initial* expression depends directly on the *for* expression, and does not depend on any descendant of the *for* expression,
2. the initialization clause of the *for initial* expression is independent of the array of values consumed,
3. the *for initial* expression consumes every value of the produced array, once and in order,

4. the *for initial* expression has no loop carried dependencies other than an index value and the shared accumulator, and
5. the *for initial* expression depends on the *for* expression for only an array of values.

The shared accumulator refers to the scalar value or aggregate structure returned by the *for initial* expression—the array *Forces* in the example above. If the first criterion is false, then we can not execute the *for initial* computation until the descendent terminates preventing us from fusing the *for* and *for initial* expression. The second criterion permits us to move the initialization of the *for initial* expression before the *for* expression. The third and fourth criteria guarantee that we may fuse the bodies of the *for* and *for initial* expressions, eliminate the index value, and place only the accumulator in a critical section. The fifth criterion is solely a limitation of the current compiler. Currently, we do not prove that the reduction function is commutative; consequently, the user may introduce non-determinism. Some Sisal aficionados argue that the introduction of non-determinism in such a tightly controlled manner is good because it expands the domain of Sisal programming; others disagree. In the final section, we discuss ideas regarding analysis and implementation techniques to guarantee determinancy.

3.0 Rewiring the graphs

Consider the expressions for *Force_update* and *Force_out* given in the previous section. Figure 1 is a logical view of the IF1 graphs [5] of the two expressions. The top node is the graph of the *for* expression. It has three subgraphs: generator, body, and returns. The generator defines a set of index values. An instance of the body is executed for each value, and each body constructs a *Force_record*. The records are passed to the returns subgraph that gathers them into an array. The bottom node is the graph of the *for initial* expression. It has four subgraphs: initial, test, body, and returns. The initial subgraph initializes the index value *i* and the shared accumulator *Forces*. The body is executed once for each force record. The body updates two elements of *Forces* and passes the new array to the returns subgraph. The returns subgraph selects the final value of *Forces* and passes it out from the compound node. We refer to this implementation as unoptimized.

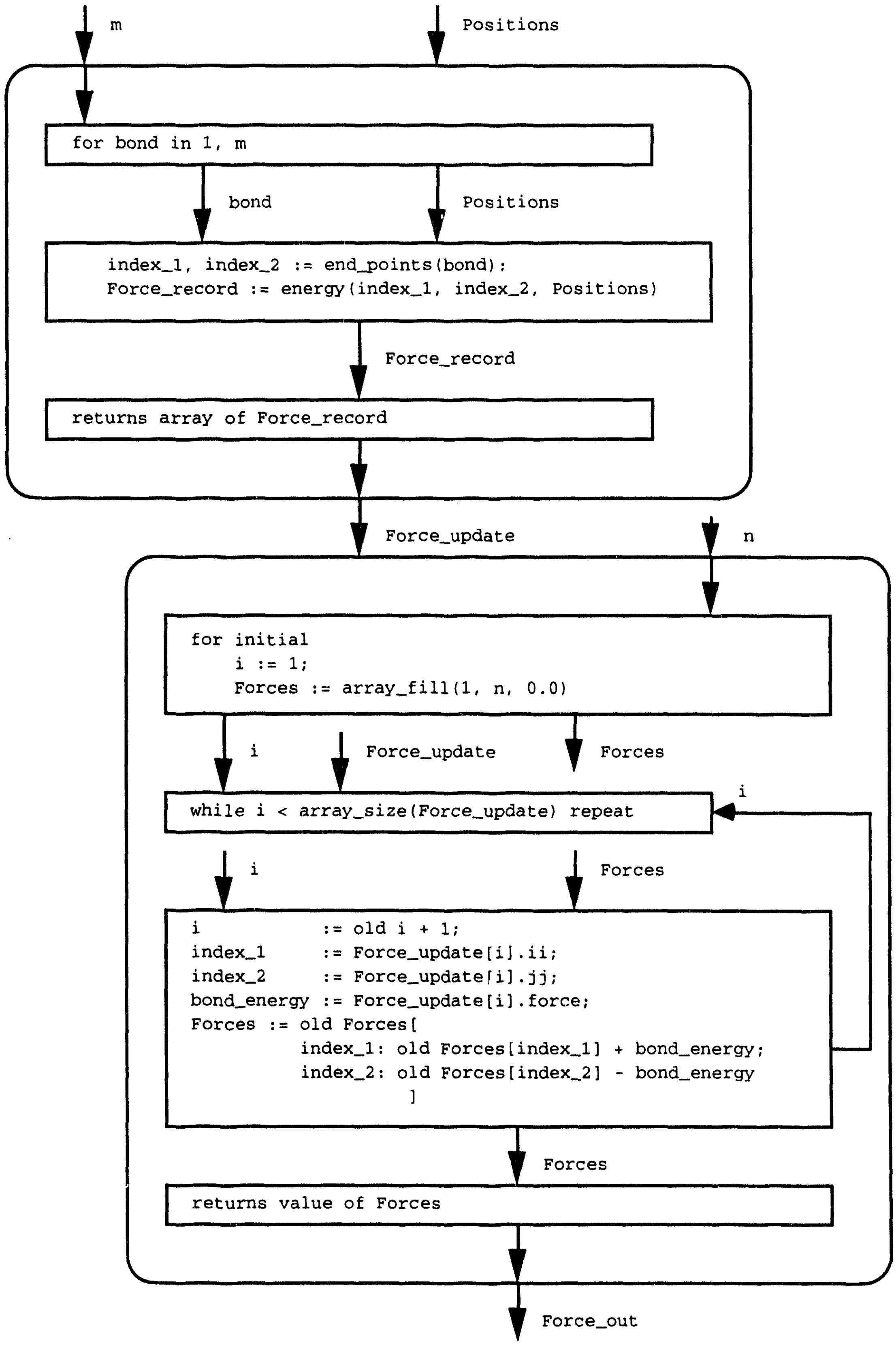


Figure 1 – A pair of computation–reduction expressions

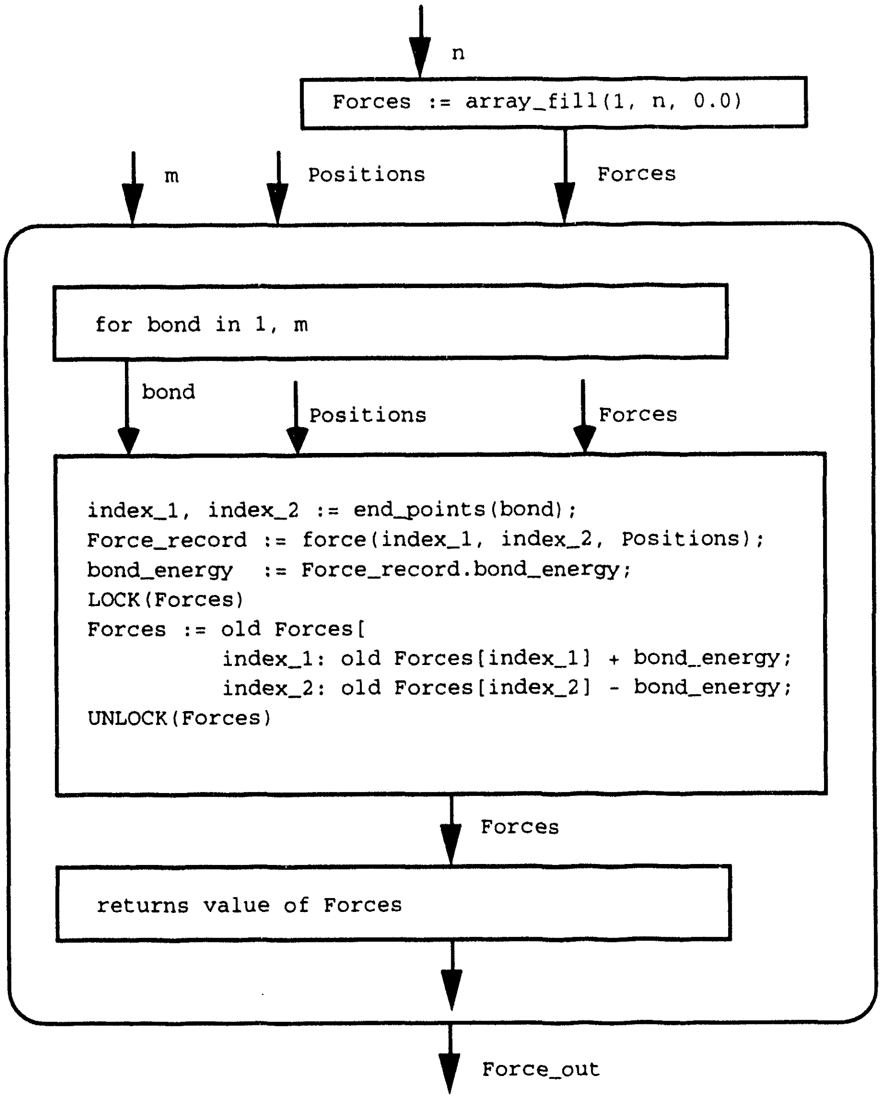


Figure 2 – A parallel computation–reduction graph

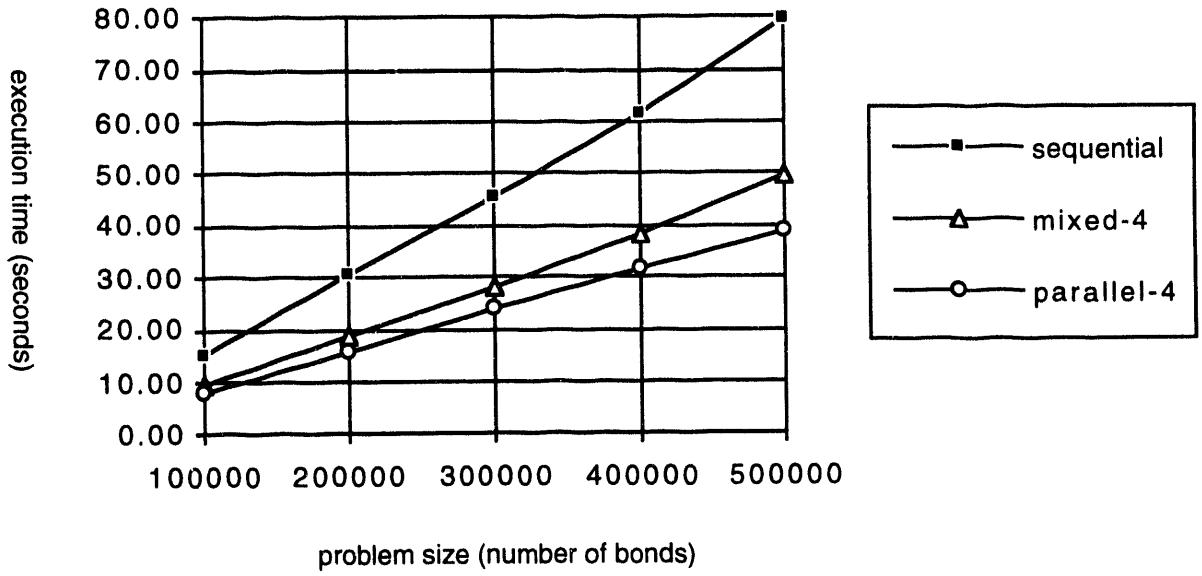
Since the two expressions met the five criteria listed in the previous section, our compiler transforms the graph shown in Figure 1 into the graph shown in Figure 2. The first node initializes the shared accumulator *Forces* and passes it to the second node. The second node is a parallel *for* computation. Its generator is identical to the generator of the original *for* compound node. Its body and returns subgraphs are compositions of the body and returns subgraphs of the original compound nodes. Since *Forces* is a shared resource, we place a lock about any read and write accesses to insure mutual exclusion. Notice that we have eliminated the test subgraph in the original graph, and that we no longer build the array of force records. We refer to this implementation as optimized.

There are a variety of ways to build the new graph and control access to the shared accumulator. Instead of locking all of *Forces*, we could lock individual elements or sections of the array. Maintaining a lock per element would be expensive unless the memory had presence bits. Since the Sisal runtime system slices *for* expressions into sets of iterations, we can eliminate the lock from the body by having each set of iterations initialize and maintain a local accumulator. As the sets finish, we could "merge" the local accumulators to derive the final result. Such an implementation reduces the number of lock operations and contention for the lock, but uses more memory. Moreover, if the merge operator is different than the reduction operation, as in the example used in this paper, the compiler would have to synthesize it automatically.

4.0 Performance

We ran a series of experiments to evaluate the performance of our optimization. We used a computation and reduction expression from molecular dynamics similar to the expressions used in the previous section. Table 1 gives the execution times and space requirements for different problem sizes. Graph 1 shows the graph of the execution times. Sequential and mixed are the one and four processor execution times, respectively, of the unoptimized implementation (Figure 1). Parallel is the four processor execution time of the optimized implementation (Figure 2). As expected, the optimized code uses less space than the unoptimized code. It also runs faster; however, we did not always see appreciable performance gains.

There are many factors that influence the execution time of the optimized code versus the execution time of the unoptimized code: the time to set and release locks, the time to write and read a record, lock contention, size of the computation expression, size of the reduction expression, number of processors, etc. If the size of the computation expression is at least p (number of processors) times greater than the size of the reduction expression, then there is little lock contention. Essentially, the concurrent tasks contend for the lock the first time, and then become staggered arriving at the critical section at different times. In the molecular dynamics code, all computation expressions are much larger than the reduction expressions. However, small reduction expressions minimize the effect of parallelizing the reduction operation. On large systems, Amdahl's Law may magnify the effect, but then the large number of processors increases lock contention. Overall, the optimized code



Graph 1 – Execution times of computation–reduction expressions

may run five to twenty percent faster than the unoptimized code, but the real savings is in memory costs. An average three-dimensional force computation in a molecular dynamics simulation code, if unoptimized, can generate a 64MB array!

Sequential Reduction	11.6 MB 9.37 sec	23.2 MB 18.97 sec	34.8 MB 28.25 sec	46.4 MB 38.18 sec	58.0 MB 49.76 sec
Parallel Reduction	8.4 MB 7.73 sec	16.8 MB 15.60 sec	25.2 MB 23.83 sec	33.6 MB 31.47 sec	42.0 MB 39.02 sec
Problem Size	100000	200000	300000	400000	500000

Table 1 – Time and memory usage of computation–reduction graphs

5.0 Future work

We plan to include specific syntax in Sisal 90 to support user defined reduction. A possible form for the computation expression is:

```
for bond in 1, m
    index_1, index_2 := end_points(bond);
    bond_energy      := Force(index_1, index_2, Positions)
returns Force_histo(n) of index_1, index_2, bond_energy
end for
```

The reduction function might be written as:

```
reduction Force_reduction(n: integer
                  repeat  ii, jj: integer; bond_energy: real
                  returns array[real])
   for initial
     Forces := array_fill(1, n, 0.0)
   repeat
     Forces := old Forces[index_1: old Forces[index_1] + bond_energy;
                         index_2: old Forces[index_2] - bond_energy ]
   returns value of Forces
   end for
end reduction  % Force_reduction
```

The names enclosed in parentheses prior to the keyword *of* at the reduction call site are values required to initialize the reduction; i.e., consumed in the initialization clause of the reduction function. The names listed to the right of the keyword *of* are the set values computed by each instance of the body of the computation expression and reduced by the reduction. The reduction function is a *for initial* expression. The *for initial* expression has an implied test: the body executes once for each set of reduction values computed by the computation expression.

To insure determinate results, we are developing analysis to classify reductions and to choose automatically a parallel implementation of the computation-reduction operation that returns the same results as the sequential implementation. Although few function are commutative in general, most reductions are either comparative or accumulative in nature. These types of functions are easier to analyze and a greater number are commutative, permitting an implementation with some degree of parallelism. Preliminary studies seem to indicate that reductions divide into classes that support different parallel implementations. For example, the class of non-commutative reductions supports no parallelism and requires a sequential implementation. Some reductions require a single shared accumulator, while others permit each processor to maintain a local accumulator that are merged at the end.

We hope to report soon on our analysis techniques, implementation, and performance of user-defined reductions in Sisal 90.

Acknowledgments

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