

List Processing on A Data Flow Machine

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1. Introduction

The data flow machine, whose basic idea was offered by J. B. Dennis [1] and for which several researches are pursued at several places in the world [2,3,4,5,6], is very attractive concept as a computer architecture from the following view points:

- (1) The data flow machine exploits parallelism inherent in problems, and executes it in a highly concurrent manner.
- (2) The recent advances in VLSI technology are noteworthy. One of the main problems of computer architecture is the way to construct the systems which utilize a large amount of VLSI devices. The data flow machine enables the implementation of distributed control mechanism which is a key problem when making use of VLSI devices.
- (3) It is a serious problem in software engineering how to make a program highly productive and easy to verify, test and maintain. One solution for this problem is to write side-effect free programs based on functional programming concept. The data flow

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machine effectively executes the side-effect free programs written in a functional language such as pure lisp, due to the parallelism.

(4) Non-deterministic execution will become one of the important mechanism in computer systems, when making the problem solving concept obtained in the AI research more applicable to the real world problems. The data flow machine is expected to execute non-determinism effectively due to parallel processing.

However, there exist many problems to be solved in order to make the data flow machine actual in real environment. Especially, from the view points of (3) and (4), it is necessary to make clear the applicability of the data flow machine to the non-numerical problem. This implies the necessity of solving the problem of structure memory construction. List processing is typical of non-numerical data processing. This paper discusses list processing on a data flow machine, with the Lisp data structure and operations in mind. The main reasons why Lisp is considered are that Lisp has simple and transparent structure in program and data, and that it contains the basic problems in the structure data manipulation even in the simple structure.

In conventional Lisp implementations, it is inevitable to introduce the side-effect facilities such as prog-feature in order to obtain efficient executions on von-Neumann type computers, i.e., high speed execution under the sequential execution control environment and efficient memory usage under the centralized memory management. However, if machines obtain highly parallel execution under the data flow control

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environment, and if VLSI technology offers computer architecture the high level functional memory devices, side-effect free and pure functional list processing will make sense in practical use.

This paper shows that the data flow control is effective in list processing. First, the parallelism in list processing is discussed and it is pointed out that it can be achieved by parallel evaluation of function arguments and partial execution of function body. Then it is shown that the parallelism increases dramatically by introducing lenient cons concept into the data flow execution control; that is, the lenient cons brings data flow systems the pipelined execution among activated functions because each activated function executes each data item (in list) as soon as it is partially constructed. The effect of lenient cons on list processing is shown through analyses of several programs.

Finally a garbage collection algorithm based on the reference count method is discussed. The garbage collection is also important problem in list processing in order to utilize the memory cells effectively. The algorithm is essentially parallel in the sense that cells are reclaimed whenever it becomes useless, independently of the foreground list manipulation.

All programs throughout this paper are described in the language Valid [7] which is designed as a high level programming language for the data flow machine presented in this paper.

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2. List processing under the data flow control environment

The remarkable effects of data flow execution control are the followings.

(1) It exploits maximal parallelism inherent in a given program both on a low level (primitive operation level) and on a high level (function activation level).

(2) It effectively executes programs constructed based on the concept of functional programming which has no notion of program variables and side effects (i.e., re-writing the global variables).

The parallelism of primitive operation level is obtained by the data driven control principle; that is, each operation is initiated without attention to other operations when all of its operands have arrived. The parallelism of function activation level is obtained by the partial evaluation mechanism:

(a) Each argument of a function is evaluated concurrently. (b) The execution of a function is initiated when one of the arguments of the function is evaluated, and the caller function resumes its execution when one of the return values is obtained in the invoked function execution.

In conventional list manipulation, there exists a case in which the partial execution of function evaluation is not effective, since an execution using a list data which is generated by another function has to wait until its construction is completed. However if lenient cons concept is introduced, the consumer function which uses list elements partially can start

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its execution as soon as the producer function generates a fragment of the list partially before it constructs the whole list.

In this section, these parallel execution mechanisms are examined through several examples, whose programs are written in Valid. (Some of Valid features are described in Appendix A.)

2.1 Parallel evaluation of arguments

Programs written in Valid are equivalently transformed to pure functional representation, i.e., the form of prefix notation, and equally translated to data flow graphs. For instance, Program1 which reverses a given list in each level is translated by the Valid compiler into the data flow graph shown in Fig.2.1. Block2 in Program1 is equivalently represented in the prefix notation

```
fulrev(cdr(x), cons(fulrev(car(x), nil), y)) .
```

In this expression, the two arguments `cdr(x)` and `cons(...)` of the function `fulrev` are evaluated in parallel, and before evaluating the argument `cons(...)`, its two arguments `fulrev(...)` and `y` are evaluated in parallel, and so on. Thus the evaluation of a function, in general, proceeds from the inner to the outer (i.e., innermost evaluation), and this results in the highly parallel evaluation of the innermost arguments. This is equivalently said in other words; each evaluation is independent of the other evaluations under the condition that the evaluation is initiated only when the values of all of the arguments are

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Evcon also has a possibility for parallel execution. The implementation in Appendix B uses loop control according to the Lisp 1.5 semantics in which the predicate parts of cond expression are evaluated sequentially. However if evcon is implemented by recursion as shown below, eval which evaluates the predicate part is activated in parallel.

```
Evcon: function(s,c,a) return(list)
      = if c=nil then novalue
        else clause
          if Eval(caar(c),a) then Eval(cdar(c),a)
          else novalue;
        Evcon(s,cdr(c),a)
      end
```

Where a signal value is used for the top level activation of evcon; Evcon('s',c,a).

In order to make effective use of parallel control in evcon, the conventional Lisp program must be modified. For instance, the conventional equal function is modified to

```
equal[x;y]
= [and[atom[x];atom[y]] -> eq[x;y];
  not[or[atom[x];atom[y]]] -> and[equal[car[x];car[y]];
  equal[cdr[x];cdr[y]]];
  t -> f]
```

Parallel execution of evcon has the potential to non-deterministic control [9], though the incarnation of mechanism and integration to semantics of Valid are the problems to be solved.

2.2 Partial execution of function body

The parallelism based on the parallel evaluation of

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arguments of each function is limited because the nesting of arguments is limited in source text. This restrictions on parallelism, however, can be overcome by executing function body partially.

If the data-driven control principle is applied to the function activation, as in the case of primitive operations, every function is activated only after all of its arguments are evaluated. In this case, the unnecessary time is wasted in each function activation by waiting for the completion of all its argument evaluations. On the other hand, the partial execution of function body enables each value of arguments to be passed into the function body immediately when it is evaluated, and the execution of the body to proceed partially every time the value is passed into. In the same way, it enables each of the return values to be passed back to the calling function as soon as it is generated, and the calling function to resume and proceed the execution partially every time the return value is passed back from the called function. Where each function is permitted to return multiple values (i.e., the tuple of values) under the data flow control environment.

This mechanism has an effect that each function call has been replaced by its body initially, and that the parallel evaluation of arguments goes beyond the barrier of function invocation and restrictions mentioned above.

For instance, the function partition is activated when the argument `cdr(x)` or `y` is evaluated in the function `sort` of Program2, which sorts a list `x` by Quicksort algorithm. In the

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case of this program, as the evaluation of y means the evaluation of the expression $\text{list}(\text{car}(x))$, the value of $\text{cdr}(x)$ will be generated just before the y is generated. So that, when the second argument is passed into the partition body, then-part or else-part will be ready to run. The function partition returns three values. In the else-part of the partition body, for instance, the values w_1 , w_2 and w_3 are generated by the function partition and are used in return expression, so if each of w_1 , w_2 and w_3 is returned immediately when it is generated, each of these values is used and passed back to the calling function; for example, in case of $x_1=y_1$, w_1 and w_3 are passed back to the calling function directly, while w_2 is appended to $\text{list}(x)$ to generate a new list which is passed back. The innermost recursion phase of partition returns each of three values nil , y , and nil , independently.

Program2 -- Quicksort program

```

sort: function (x) return (list)
= if x=nil then x
  else clause
    y = list(car(x));
    [y1,y2,y3] = partition(cdr(x),y);
    return append(sort(y1),append(y2,sort(y3)))
  end;

partition: function (x,y) return (list,list,list)
= if x=nil then (nil,y,nil)
  else clause
    [w1,w2,w3] = partition(cdr(x),y);
    x1 = car(x); y1 = car(y);
    return
      case
        x1=y1 -> (w1,append(list(x1),w2),w3);
        x1<y1 -> (append(list(x1),w1),w2,w3);
        x1>y1 -> (w1,w2,append(list(x1),w3))
      end
    end;

```

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In this way, many partition functions are activated and are executing their body partially. As the same may be said of the function sort, Program2 sorts the input list x in the highly parallel execution.

The partial execution of function body has also an effect on the Lisp 1.5 interpreter, because the interpreter executes Lisp programs in high parallelism due to the partial execution of each body of the function eval, evlis, and evcon.

The function activation and argument passing mechanism for the partial function execution is implemented as shown in Fig.2.2. The data flow graph of Fig.2.2(c) represents the activation control of the function

$$[y_1, y_2, \dots, y_n] = f(x_1, x_2, \dots, x_m)$$

The copy node, which creates a new environment for the activated function (or makes a new copy of the body in logical), is initiated by the or-gating nodes when one of the tokens (values) has arrived. The orgate implementation uses t/f switch as shown in Fig.2.2(b). When the new environment is created and the body is ready to run, the token "in" (instantiation name of the activated function) is sent to link nodes and rlink nodes. Each link node passes each argument value x_1, x_2, \dots, x_m to the body of the activated function every time each value has arrived. Each rlink node passes information of the place where the return value is sent to. This information y_1', y_2', \dots, y_n' , each of which is determined at compilation time corresponding to y_1, y_2, \dots, y_n , are attached to each return value to identify its

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destination.

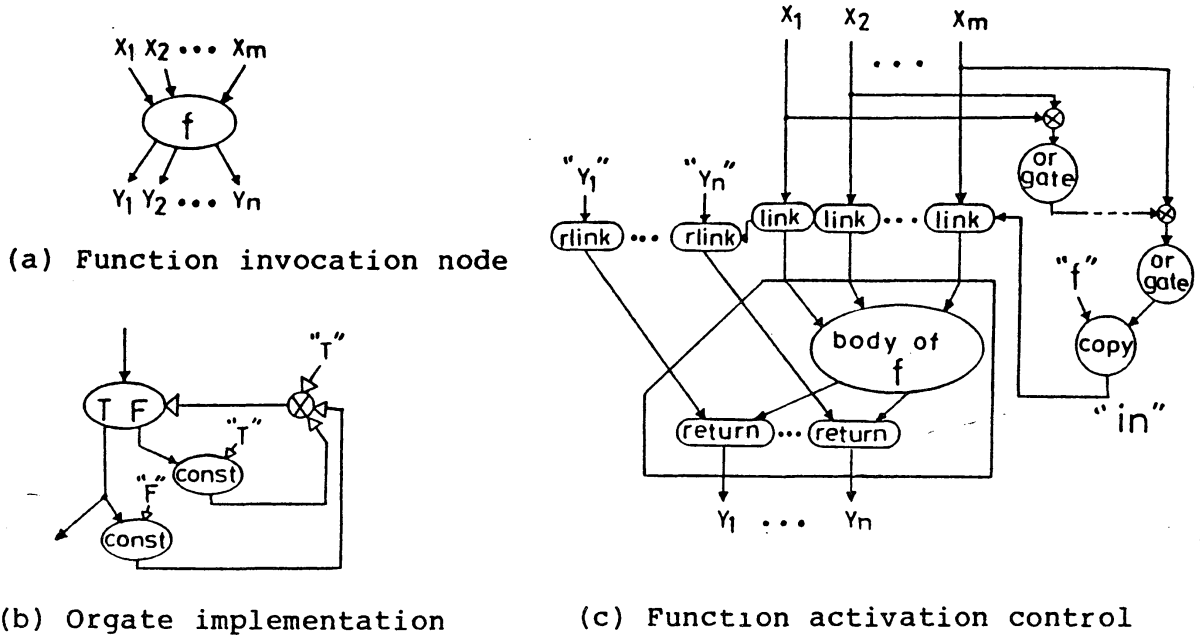


Fig.2.2 Fuction activation mechanism

2.3 Lenient cons and parallelism by pipelined processing

Although the partial execution of function induces higher parallelism, it is not sufficient for maximally exploiting the parallelism inherent in the given program. For instance, Program2 is expected to execute in a highly parallel fashion among activated functions of sort and partition. This parallelism, however, does not work well for reducing the execution time in the order, because the time spent to sort the list of length n is proportional to the square of n in the worst case. (Though it is proportional to n in the best case.) The reason is that; as each of the value y_1, y_2 and y_3 is not returned until the append operation is completed in the partition body, the execution of sort function which uses those values must

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wait until they are returned, and the waiting time is proportional to the length of the list data made by the append operation.

The Lisp interpreter is another example which shows that the parallelism is not maximal. As the operation of the apply to each evaled value which is returned from the function evlis must wait until all of the evaled values are constructed to a list by the cons operation which resides in the last part of the evlis body, the execution of lisp function body can not proceed partially.

If the former parts of the list which are partially generated are returned in advance during the latter parts are appended, the execution which uses the former parts of the list can proceed. Thus the executions of the producer and the consumer overlap each other. As the append is the repeated operations of cons as Program3 shows, this problem can be solved by introducing leniency into the cons operation.

Program3 -- append

```
append: function (x y) return (list)
= if x=nil then y
  else cons(car(x),append(cdr(x),y))
```

The lenient cons, which is slightly different from the idea of "suspended cons" [10], means the following. For the operation of cons(x,y), the cons operator creates a new cell and returns its address as a value in advance before its operand x or y arrives. Then the value x and y are written in the car field and the cdr field of the cell respectively, when each of them has

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arrived at the cons node. In the implementation, the cons operator is decomposed into three primitive operators, getcell, writecar, and writcdr as shown in Fig.2.3. The getcell node is initiated on the arrival of a signal token, which is delivered when the new environment surrounding the cons operation is created. The getcell operator creates a new cell, and sends its address to the writecar node, the writcdr node, and the nodes waiting for that cons value. Each memory cell has, in addition to the garbage tag, the car-ready tag and the cdr-ready tag each of which controls read accesses to the car field and the cdr field. The getcell operator resets the both ready tags to inhibit read accesses. The writecar (or writcdr) operator writes the value x (or y) to the car field (or cdr field), and sets the ready tag to allow read accesses to the field.

The lenient cons has a great effect in list processing. It naturally implements the stream processing feature in which each list item is processed as a stream [4,11] for programs which are normally written without the notion of stream according to list processing concept.

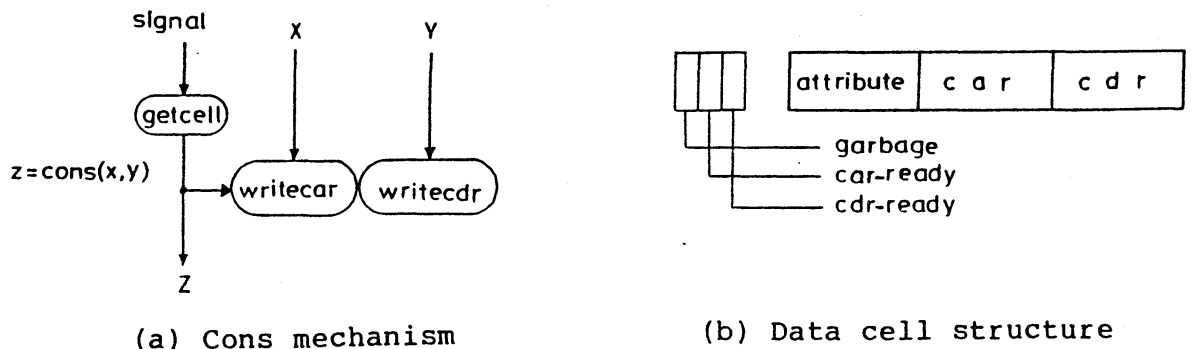


Fig.2.3 Lenient cons implementation

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3. Evaluation of the lenient cons effect

The parallelism enhanced by the effect of pipelined processing which lenient cons brings about is analyzed so as to estimate the lenient cons effect. The sieve algorithm to find prime numbers and the Quicksort algorithm in chapter 2 are taken as examples.

The followings are assumed in the evaluation of parallel algorithm:

- (1) There exist an infinite number of resources, namely the operation units (processors) required for calculations are available at any time, and the time for resource allocation and the network delay is ignored.
- (2) The execution of any operation completes in a unit time.
- (3) The time required for function linkage is ignored.

3.1 Sieve program to find prime numbers

Program4 finds prime numbers using the sieve method of Eratosthenes. Each cons operation appeared in this program is implemented with lenient cons. The cons operation is initiated by a signal s when a block which contains the cons operation is opened.

Primenumber(n) obtains the sequence of prime numbers by sieving the sequence $(2\ 3\ \dots\ n)$ generated by $\text{intseq}(2,n)$. The lenient cons enables intseq to send out the sequence of numbers $(2\ 3\ \dots\ n)$ one after another. To illustrate it more clearly, a data flow graph of $\text{intseq}(m,n,s)$ is shown in Fig.3.1. Where s

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is a signal value name which does not appear in source text but is generated by compiler.

When the function `intseq(m,n,s)` is initiated, if `m` is not greater than `n` the `getcell` node is fired and the new cell address obtained is returned immediately. Then the value `m` and the value of `intseq(m+1,n,s)` is written into the `car` and `cdr` part of the new cell respectively when each of them has arrived. Consequently, `intseq` sends out new numbers one by one every time it is initiated. `Sieve(n,s)` holds the first (`car(n)`) of the sequence sent from `intseq`, and invokes the function `delete` to remove the numbers in the rest (`cdr(n)`), which are divisible by `car(n)`. The function `delete` sends out the elements indivisible by `car(n)` one by one, which in turn are passed to the `sieve` function recursively. In this way, the executions of `intseq`, `sieve` and `delete` are overlapped.

Table 1 traces the invocations of `intseq`, `sieve` and `delete`, and depicts how the algorithm works. Each row gives the sequence of numbers generated in each invocation. The `intseq` generates the sequence of numbers (2 3 ... `n`) one by one in a unit time. The top level `sieve` is initiated immediately when the first element of the sequence is returned from the `intseq`. After the activation, the `sieve` immediately invokes the `delete1`, where the suffix represents invocation sequence number.

The `delete1` takes the sequence (2 3 ... `n`) from the `intseq`, and deletes the numbers which are divisible by 2. The `deletei` which is initiated in the `i`-th level `sieve` takes the output sequence of the `deletei-1`, and deletes the numbers which are

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divisible by the i -th prime number. The `deletei` returns values one unit time after the `intseq`, as seen from the table.

As the time needed for invocation of the `delete` in the sieve is constant and the `deletei` returns values one unit time after the `deletei-1` returns the value, the sieve returns the i th prime number i units time after the `intseq` returns that number.

Since there are $n/\log n$ primes asymptotically in $\{2,3,\dots,n\}$, the computation time needed in this program is $n+n/\log n$, i.e. the order of n .

Program4 -- Sieve program

```

primenumber: function (n) return (list)
= sieve(intseq(2,n))

sieve: function (n) return (list)
= if n=nil then nil
  else cons(car(n),
            sieve(delete(car(n),cdr(n))))

delete: function (x,n) return (list)
= if n=nil then nil
  else if remainder(car(n),x)=0
    then delete(x,cdr(n))
    else cons(car(n),delete(x,cdr(n)))

intseq: function (m,n) return (list)
= if m>n then nil
  else cons(m,intseq(m+1,n))

```

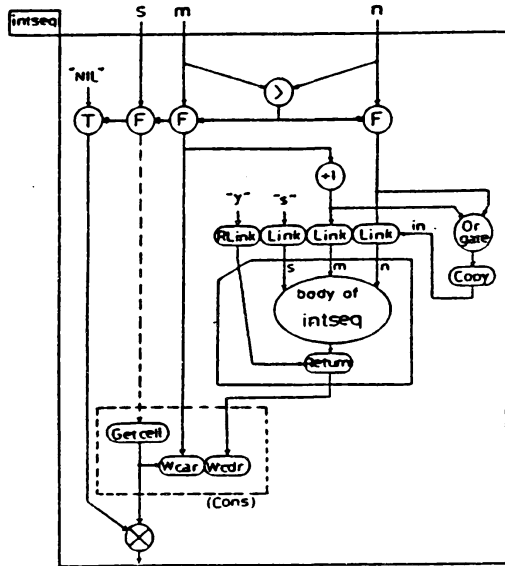
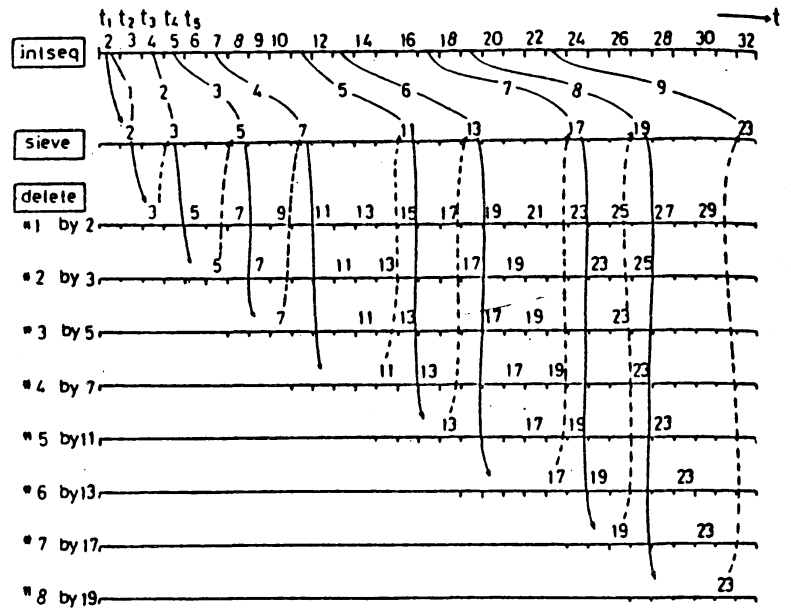



Fig.3.1 Data flow graph of intseq

Table 1 Execution of primenumber(2,n)



3.2 Quicksort program

This section analyzes the computation time of the quick sort program described in Section 2.3. To simplify the analysis, the worst case behavior of the algorithm is investigated. (Where the worst case means the case in which input data are in the reverse order.) It is assumed that the time required for the append operation is proportional to the length of a list to which another list is appended. Table 2 traces the function invocation sequence to illustrate the action of sort((3 2 1)).

Let y be $(x_1 x_2 \dots x_n)$, where $x_i > x_{i+1}$ for $i = 1, 2, \dots, n-1$. The function $\text{sort}(y)$ acts as follows. The activated

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function `partition1` partitions a list into three lists `y11`, `y12`, and `y13` each of which contains the elements less than, equal to, and greater than `x1`, respectively. For the input data of the worst case `y11` is $(x2\ x3\ \dots\ xn)$, `y12` is `x1`, and `y13` is `nil`. The result of `sort(y)`, the top level activation of the `sort`, is obtained by appending the result of `append(y12, sort(y13))` to the result of `sort(y11)`. Due to the lenient `cons` effect, the function `sort(y11)` is invoked immediately after the first element of `y11`, i.e. `x2`, is obtained. The values `y12` and `y13` are returned from the `partition1` $2N(y11)$ units time after the first value of `y11` is returned from that function, since it takes $N(y11)$ units time for the first element of `y` ($=x1$) to be passed into the innermost recursion phase of the `partition1` where `y12` ($=x1$) and `y13` ($=nil$) is generated, and it takes the same time for those values to be returned. (where $N(yi)$ means the number of elements in `yi`.)

Then, in the computation of `sort(y11)`, the second level activation of the `sort`, the function `partition2` generates three values `y21`, `y22`, and `y23`. ($y21=(x3\ x4\ \dots\ xn)$, $y22=x2$, $y23=nil$.) Due to the lenient `cons` effect, the `partition2` returns the first element of `y21`, i.e. `x3`, one unit time after the `partition1` returns the element `x3`. As it takes C (a constant, which equals 2 in this case) units time for each activated `partition` to generate the second element after generating the first element, the first element of `y21` is returned $C1$ ($=C+1$) units time after the first element of `y11` is returned. Since `y12` and `y13` are returned at time $2N(y)=2n$, and `y22` and `y23` are

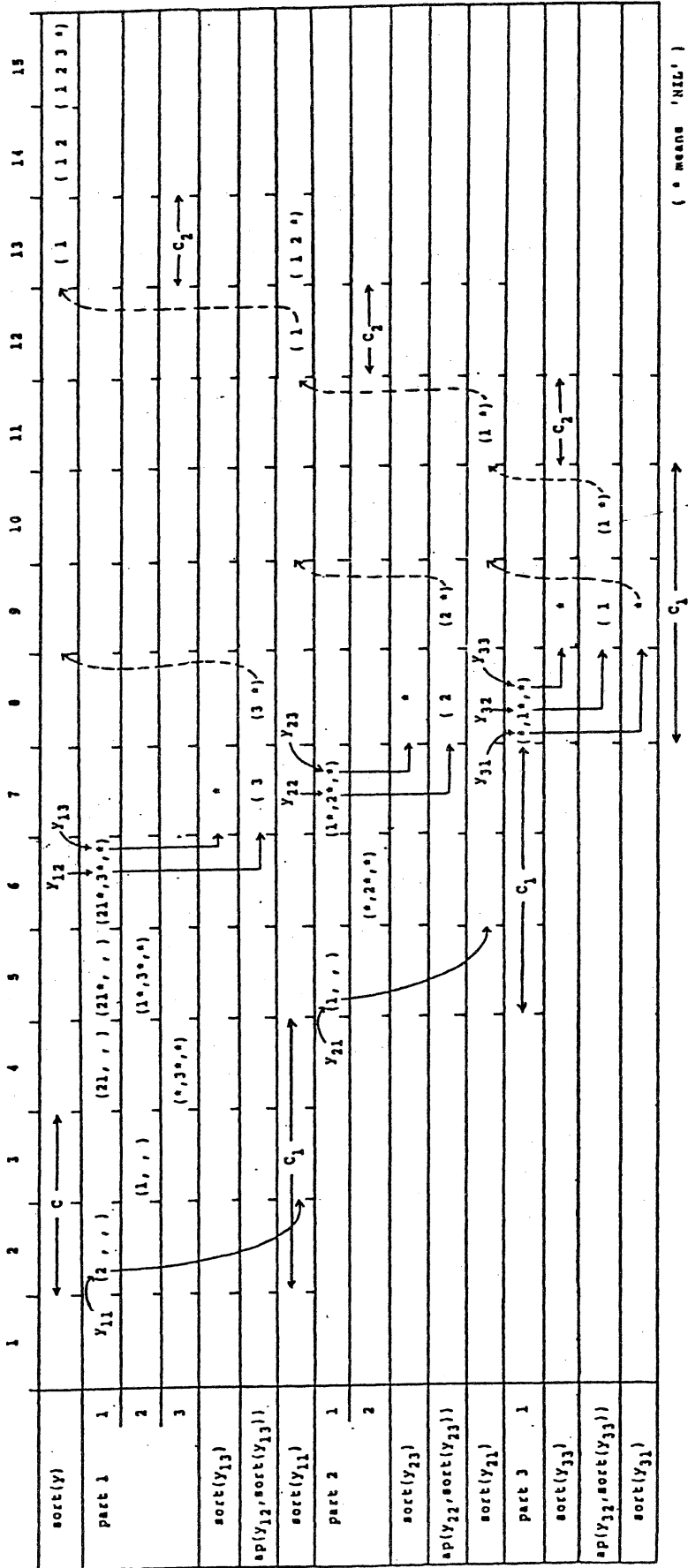
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returned at time $C1+2N(y11)=2n+C-1$, $y22$ and $y23$ are returned $C-1$ units time later than $y12$ and $y13$. In the same way, the partition3 which is invoked in the computation of $\text{sort}(y21)$ returns the result $y31 (=x4 x5 \dots xn)$ $C1$ units time after the partition2 returns the result $y21$, and returns the results $y32 (=x3)$ and $y33 (=nil)$ $C-1$ units time later than the results $y22$ and $y23$, and so on.

Since the n partition functions are activated for sorting n elements, it takes $n(C1)$ units time until the last partition completes. Each result of the partitions has to be constructed to a list by the append operation. Since it takes n units time for the first element to be returned from the top level append, and it takes $n-1$ units time for the append operation to be completed, the total computation time for sorting n elements is $C1n+2n-1$, i.e. the order of n .

In the best case, the total computation time is the order of $\log n$, because the partitioning operation reduces the length of each list to the half, and the invocation tree of the sort function is balanced with the height of $\log n$; that is, the execution acts on the divide and conquer strategy.

Table 2 Example of the worst case -- sort(3 2 1)



4. Garbage collection

As many data are copied, used, and thrown away very often in the course of the side-effect free data manipulation, it is very important to resolve the problem of how to utilize structure memory cells effectively, namely the effective garbage collection method under the parallel processing environment.

Although mark-scan methods are generally used as a garbage collection method in the conventional machine, the reference count method is adopted here. The reason is that; (a) Since the data tokens which are pointers to list data entries in the structure memory are scattered in the various parts of the machine such as instruction memory units, communication networks and operation units [11,12], it is very difficult to extract the active cell without suspending the execution. (b) As the list manipulations have no side effect and every list is made only by the cons operation, no circular lists are created.

This section presents a fundamental method, though it is not efficient, in order to introduce the basic idea at first, then describes a revised method which is much more efficient.

In the method presented here, each data cell has the reference counter field which is updated every time the data cell is accessed. The reference counter handling algorithm in the fundamental method is written in Algol-like language for each primitive list operation in the following. Where $r(x)$, z and d denote the reference count field of the cell x , the value of each operation, and the number of operation nodes which are waiting

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for the value z , respectively.

```
procedure Car(x,d);
  begin
    z := car(x);
    Red(x);
    r(z) := r(z)+d
  end
```

```
procedure Cdr(x,d);
  begin
    same as Car(x,d)
  end
```

```
procedure Atom(x);
  begin
    z := atom(x);
    Red(x)
  end
```

```
procedure Eq(x,y);
  begin
    z := eq(x,y);
    Red(x);
    Red(y)
  end
```

```
procedure Cons(x,y,d);
  begin
    z := cons(x,y);
    r(z) := d
  end
```

```
procedure Red(x);
  begin
    r(x) := r(x)-1;
    if r(x)=0 then begin
      Red(car(x));
      Red(cdr(x))
    end
  end
```

One problem of completeness in the reference count method occurs in the execution of a conditional expression. In the case of $\text{if } p \text{ then } f(x) \text{ else } g(y)$, for example, as $g(y)$ is never executed when p is true, the reference count of cell y is left un-decremented, and as a result, the cell y is never reclaimed

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though it is a garbage in virtual. In order to avoid this, a special operator erase, which executes only the procedure Red, is prepared. (Fig.4.1)

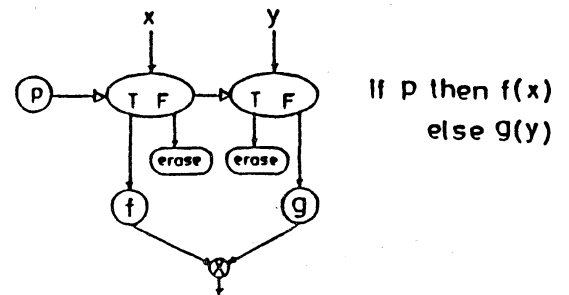


Fig.4.1 Conditional expression and erase operation

The reference count handling overhead is serious because updating the reference count is needed in all operations, not only in the five primitive operations but in the switch and gate operations as shown in the case of conditional expression. The number of reference count updating can be reduced by eliminating the redundant updating if it is possible to make use of the structure in high level language, i.e. the block structure and scope rule.

In stead of implicitly updating the reference count in every operation, the revised method explicitly updates it by using the increment and decrement operators which the Valid compiler generates by making use of several Valid features which are suitable for eliminating the redundant reference count handling. The reference number of a cell indicates the number of value names which denote the cell in the program text. Where the value names are explicitly defined in the value definition or implicitly defined in such cases as cons values and function

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values. The reference number of the cell which is newly denoted in a block is incremented when the block is opened and decremented when closed. As all value names are defined uniquely in a block and are local to the block defining them, due to the features of Valid, each value name refers only one cell and the cell is never referred by the value name outside the block. Therefore the reference number is incremented only once even if a number of operations refer the value within the block.

A Valid source program fragment, for instance,

```
[x,y] = clause
    x = E1; y = E2; z = E3;
    return(E(x,y),x)
end;
```

is compiled to the data flow graph shown in Fig.4.2. Where E1, E2, E3, and E represent expressions. The return expression generates two values which are implicitly denoted by ret1 and ret2 then explicitly denoted by x and y in the environment outside the block. The reference number of local values x, y and z should never be decremented before the reference number of return value ret1 and ret2 are incremented, so as to prevent the cells pointed by the return values from being reclaimed during the transient time of return value passing. The and-gating node and gating nodes keep the order of increment and decrement operation safe for garbage collection.

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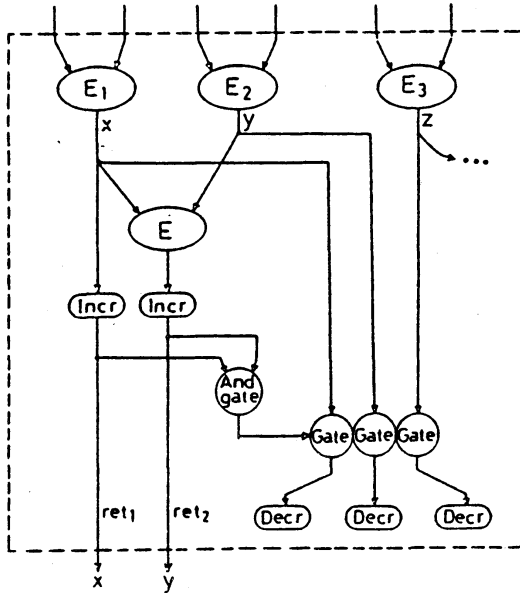


Fig.4.2

Reference count management of local value name

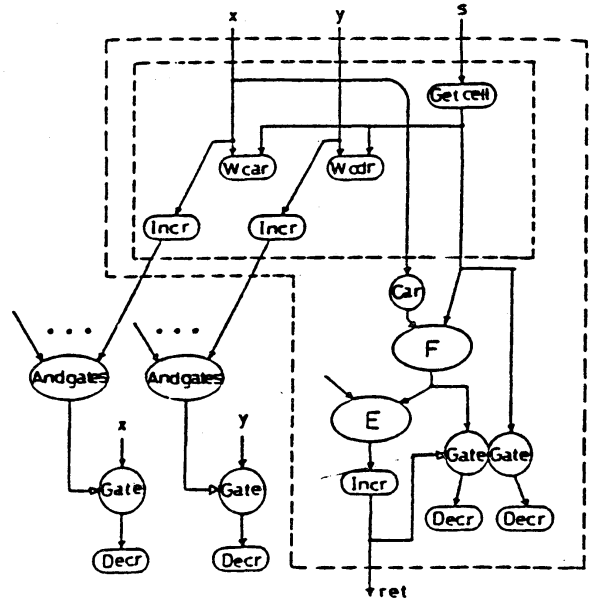


Fig.4.3

Reference count management in the expression with cons operation

Even if they are not denoted explicitly but are obscured in expressions, values of cons operations or function invocations have to be treated as denoted in order to prevent cells created by cons operation or function body from being reclaimed. So the expression containing cons operation or function invocation as sub-expressions is interpreted as being composed of the pseudo blocks. For example, the expression

$$E(\dots, f(\text{cons}(x, y), \text{car}(x)), \dots)$$

is interpreted as

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clauseu' = clause z'=cons(x,y); return z' end;

v' = f(u',car(x));

. . .

return E(...,v',...)end

and compiled to the graph shown in Fig.4.3. Where f represents a function invocation. The readers should note that the getcell operator initializes the reference number of the created cell to one, and the function body, when it returns values, increments the reference number of the cell pointed by the returned value.

Another problem on safety arises in the case of lenient cons. As for the above example, if the value x or y is pointed to by the cell newly created in this block, its reference count must not be decremented before it is made sure that the increment operation of each reference count is completed, since, through the write-car or write-cdr operation, each of the cells is to be pointed by the cell created by getcell operation.

The general rule for the cons operation to guarantee the safeness in garbage collection is :

In the cons operation

$$\begin{aligned} \text{cons}(u,v) \quad u &\equiv E_x(x_1,x_2,\dots,x_n) \\ &v \equiv E_y(y_1,y_2,\dots,y_m) , \end{aligned}$$

where E_x and E_y are expressions composed of value names x_1,\dots,x_n , and y_1,\dots,y_m each of which is a name denoting each value explicitly or implicitly (; namely, cons or function

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invocation is replaced by x_i or y_i), the decrement operation of the reference count of each cell pointed by $x_1, \dots, x_n, y_1, \dots,$ and y_m is postponed until the increment operation of the reference count of the each cell pointed by u or v is completed.

5. Conclusions

This paper discussed some issues in list processing under the data flow control environment from the view point of parallelism. The basic philosophy of the data flow machine architecture presented in this paper is that the highly parallel execution is achieved by the data flow control concept both on the primitive operation level and on the function activation level. The mechanism of partial execution in each function was shown to be effective to exploit the parallelism in list processing through some examples including an implementation of lisp interpreter, then the lenient cons mechanism was shown to exploit the parallelism maximally, through the analysis of two programs, parallel sieve program to find prime numbers and Hoare's quick sort program, which proved each execution is the order of linear time.

Then the garbage collection mechanism based on the reference count method was described. The algorithm works well as a parallel garbage collection algorithm in the sense that the garbage is reclaimed all the time, concurrently with the foreground list operations.

Although the architecture of the data flow machine was

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omitted in this paper, the characteristics of the machine, which is based on associative memory and logic-in-memory concept, are that the machine is composed of many modules so as to realize the parallelism which can be exploited logically. The details are described in [10,11].

There remains many problems to be solved in order for the machine to be available in practical use. Several works are in progress to examine the effectiveness of the theory described in this paper. These include the construction of software simulator, the design of experimental hardware system, and the implementation of Valid compiler. The simulator, the first version of which is now running, is to collect the statistical data which exhibit the effect of lenient cons, the effect of cons strategy and memory partition, the garbage collection overhead, etc. The design of experimental hardware system offers the data to estimate the cost performance. The Valid compiler which generates the object code for the simulator and experimental hardware is a tool for establishing the programming system based on the functional programming methodology, on the data flow machine.

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Appendix A. Brief description of Valid language features

Valid is a high level language designed for programming on a data flow machine. The name "Valid" is the abbreviation of VALUE IDENTIFICATION language. The basic philosophy of design is that Valid semantics supports programming based on functional concept, while its syntax offers the conventions to write programs in Algol style. This appendix describes some features which helps readers to understand sample programs in this paper.

The characteristics of Valid are as follows.

(1) The basic structure of Valid is expressions and definitions, i.e. Valid has no concept of program variables and assignments, instead the values are denoted by value names, if necessary. This concept is different from single assignment concept in the sense that variables only mean the names which are assigned to each value.

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(2) A Valid program consists of function definitions, macro definitions and value definitions. A function (or macro) definition defines a function name and its body which returns multiple values. The body is an expression. Functions are invoked in the execution time by their names, while macros replace their names by their bodies at the compilation time. Value definitions also define multiple values. For example, the value definition

$$[x_1, x_2, \dots, x_n] = \text{expression}$$

defines n values generated by expression and denotes them by value names x_1, x_2, \dots, x_n .

The function definition

$$f: \text{function } (a_1, a_2, \dots, a_n) \text{ return } (b_1, b_2, \dots, b_m) \\ = \text{expression}$$

defines the function f which has formal arguments (value names) a_1, a_2, \dots, a_n and returns values of type b_1, b_2, \dots, b_m .

(3) Valid has a block structure. A block is a set of definitions. In a block all value definitions are sequence free, namely each value definition is evaluated in parallel within the block. In Valid, the delimiter semicolon (;) which delimits value definitions is used in the different meaning from Algol. The semicolon (;) separates two constructs in parallel, i.e. $A;B$ is identical to $B;A$, while the delimiter comma (,) separates two constructs keeping the sequence, i.e. A,B is not same as B,A .

Functions and macros may be defined in any block locally.

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All function names, macro names and value names can be referred from other places in the program text under the constraints of scope rule as in Algol; i.e., every identifier denotes a local value which may be referred within a block surrounding its definition. A block becomes an expression, and value(s) of the block is generated by a return expression occurring in the block.

(4) All iterations are described based on the recursion. The conventional loop is described in the recurrence expression of the following form.

```
for (<iteration value names>) : (<initial values>)
do <block including recur expression>
```

Other features of Valid as a general purpose high level language whose explanation is omitted because they have nothing to do with the discussion of this paper includes;

(5) Valid permits several data types. Those include Boolean, integer, real, array, record, list, and signal. Each value is specified with its type name (if necessary). Since this paper deals with only the list type, type specification is omitted.

(6) Parallel expression based on fork-join concept which is powerful for describing blocks executable parallelly such as vector operation.

Appendix B. Data flow implementation of Lisp 1.5 interpreter

Though each function of Lisp 1.5 interpreter is defined as a

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recursive function, it is necessary to reconstruct those functions so as to realize the efficient execution control as in the case of the conventional von Neumann machines. The functions implemented from this view point on the data flow machine are described in Valid. The implementation is based on the principles of that: (1) The tail-recursive structure, which has no parallelism, is implemented by the loop control so as to reduce the function invocation overhead. (2) The parallelism is exploited only from the non tail-recursive structure. For example, the functions apply and eval are implemented by the loop in which programs apply1 and eval1 execute alternatively, while the function evalis which has non tail-recursive structure forks eval functions.

Program5 -- Lisp 1.5 interpreter

```

Apply: function (fn,args,alist) return (list)
= for (x,y,z):(fn,args,alist)
  do clause
    [t,xx,yy] = Apply1(x,y,z);
    xxx = if t then xx
          else clause
            [t1,x1,y1,z1] = Evall(xx,yy);
            x2 = if t1 then x1
                  else recur(x1,y1,z1);
            return(x2)
          end;
    return(xxx)
  end;

```

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```

Apply1: macro (fn,args,alist) return (list,list,list)
= for (x,y,z):(fn,args,alist)
  do case
    atom(x) -> case
      x='car' -> return('t',caar(y),nil);
      x='cdr' -> return('t',cdar(y),nil);
      x='cons' -> return('t',cons(car(y),cadr(y)),nil);
      x='eq' -> return('t',eq(car(y),cadr(y)),nil);
      others -> recur(Eval(x,y),y,z)
    end;
  car(x)='lambda' -> clause
    x' = caddr(x);
    y' = Pairlis(x,y,z);
    return(nil,x',y')
  end;
  car(x)='label' -> clause
    x' = caddr(x);
    z' = cons(cons(cadr(x),caddr(y)),z);
    recur(x',y,z')
  end
end;

```

```

Eval: function (e,a) return (list)
= for (x,y):(e,a)
  do clause
    [t,z1,z2,z3] = Evall(x,y);
    xx = if t then z1
          else clause
            [t1,y1,y2] = Apply1(z1,z2,z3);
            if t1 then y1 else recur(y1,y2)
          end;
    return(xx)
  end;

```

```

Evall: macro (e,a) return (list,list,list,list)
= for (x,y):(e,a)
  do
    case
      atom(x) -> return('t',cdr(Assoc(x,y),nil,nil);
      car(x)='quote' -> return('t',cadr(x),nil,nil);
      car(x)='cond' -> clause
        [x',y'] = Evcon(cdr(x),y);
        recur(x',y')
      end;
    others -> clause
      y1 = car(x);
      y2 = Evlis(cdr(x),y);
      y3 = y;
      return(nil,y1,y2,y3)
    end
  end;

```

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```

Evconl: macro (c,a) return (list,list)
= for (x,y):(c,a)
  do if Eval(caar(x),y) then return(cadar(x),y)
    else recur(cdr(x),y) ;

```

```

Evlis: function (m,a) return (list)
= if null(m) then nil
  else clause
    x = Eval(car(m),a);
    y = Evlis(cdr(m),a);
    return(cons(x,y))
  end;

```

```

Assoc: function (x,a) return (list)
= for (y1,y2):(x,a)
  do case
    null(y2) -> return(nil);
    equal(y1,caar(y2)) -> return(car(y2));
    others -> recur(y1,cdr(y2))
  end;

```

```

Pairlis: function (v,e,a) return (list)
= for (x,y,z):(v,e,a)
  do if null(x) then return(z)
    else clause
      x' = cdr(x);
      y' = cdr(y);
      z' = cons(cons(car(x),car(y)),z);
      recur(x',y',z')
    end;

```