MULTIPROCESSING IMPLEMENTATION OF A HIGH-LEVEL MACHINE LANGUAGE

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We present a high-level machine language called SMOM. It is a conventional zero-address machine language containing several high-level functions for defining and manipulating data types. Though SMOM does not allow parallel control regimes to be explicitly programmed, it exhibits a considerable amount of implicit parallelism, since it is an applicative language and arguments of functions may be concurrently evaluated. This observation is the guideline for the definition of a new simple scheduling discipline that allows SMOM programs to be executed by several co-operating processors.

The proposed technique consists in enqueuing a function on all processors which are still performing some subordinate computation relative to that function (i.e. evaluation of some of its arguments). Only one of this processors is then enabled to actually compute the function, namely the one which terminates the last subordinate computation. A multiprocessor based on the proposed technique can be actually realized with existing hardware.

The speed-up in the execution of SMOM programs is expected to be one order of magnitude.

1. INTRODUCTION

Several programming languages, such as ALGOL W, SIMULA 67, ALGOL 68, PASCAL, ELL and CLU, have been designed to allow for data extensibility, that is the ability of declaring (vs. explicitly programming) data types. Since most computers are not very well suited to support extensible languages (10), designers are almost inevitably induced to restrict the mechanisms for declaring data types, mostly to the purpose of minimizing run-time type-checking. The problem of designing and efficiently implementing a truly general extensible language would be greatly simplified by using fast and sophisticated memory managers.

In (3) a machine, called SMOM, is presented which allows data types to be specified at the machine language level, in a way similar to (8, 11). SMOM may be considered as a powerful memory manager which operates under the control of a zero-address, stack-oriented machine language. One of its explicit design goals has been to allow for efficient implementations of general extensible programming languages (for a somewhat elaborate discussion of this issue see (3)). Here we point out how such a machine language may be supported by a multiprocessor architecture which significantly speeds up the execution of SMOM programs by concurrently evaluating arguments of functions and by performing most type-checking at run-time, but in parallel with other significant computations.

Section 2 contains a short but self-contained description of SMOM. In Section 3 the characteristics of parallel processing of SMOM code, including a unique interprocess communication discipline, are presented. They lead to the general ideas underlying SMOM architecture. In Section 4 a multiprocessor organization is suggested which implements the ideas of Section 3. Some concluding remarks are contained in Section 5. A detailed description of some relevant SMOM ma-

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chine instructions is contained in the Appendix.

2. SMOM: A SHORT DESCRIPTION

2.1. Data types

All data are manipulated through data descriptors (dd's). A dd is a typed pointer, i.e. a pair (T,A), where T is the type of the described datum, and A is its memory address. Both types and addresses are manipulated by the hardware only; the user is not enabled to access them. This implies that memory management is completely transparent to the user. Data may be either basic (i.e. with no inner structure) or structured (i.e. arrays and records of dd's). Both basic and structured data types may be either built-in or user-defined.

A data type is introduced by defining a class. A class is a structured data type that records all information relative to a specified data type. It contains a template which defines the inner structure of all data of that type (the template being empty for basic data types), and an unspecified number of locations, called registers, whose main purpose is to record (dd's for) the definitions of the functions associated with that class (see Section 2.3 and 2.4). Thus a class may be seen as a data type with an associated behaviour.

As an example, Fig. 1 shows the declaration of the class of COMPLEX numbers, which are records with two fields, called REALPART and IMAGPART, containing two REAL numbers.

(CLASS COMPLEX
(Template REALPART REAL)
(REGISTER ADD
<code for ADDing two COMPLEX numbers>)

(REGISTER FOO
<code for FOOing two (three?) COMPLEX numbers>)

Fig. 1. The definition of the class of COMPLEX numbers.

Evaluation of class definitions is explained in Section 2.3.

2.2. Stacks

In order to process a datum, a dd for it must be present in the argument stack (A-stack), whose building blocks are the A-cells. Though the A-cells contain dd's, for short they are also said to contain data. The A-cell at the top of the A-stack is named A-top. The datum contained in the A-top is the top-datum, its type is the top-type.

Continuation points of programs (see below) are held in the control stack (C-stack), which is made of C-cells. The C-cell at the top of the C-stack is named C-top.

2.3. Microprograms

Two special built-in data types are present in SMOM, namely programs and microprograms. Microprograms implement the basic computational functions of SMOM (i.e. they are supposed to be executable by the hardware). Microprograms may be grouped into the following categories.

a) A-managers and C-managers are used for the data control (i.e. for the management of the A-stack) and for the sequence control (i.e. for the management of the C-stack) respectively. The main A- and C-managers are described in the Appendix. Their descriptors are stored in the homonymous registers of the special class ANY (see below).

b) Operations are used for standard computations. Each of them has an associated arity (i.e. number of arguments). The execution of an n-ary operation (i.e. an operation whose arity is n) causes n arguments to be popped off the A-stack and a value to be pushed onto the A-stack itself.

SMOM contains several built-in microprograms (i.e. all A- and C-managers and microprograms which specify the behaviour of built-in data types). Many others (mostly operations) are automatically synthesized when a class definition is evaluated, and dd's for them are stored in the appropriate registers. For instance, referring to the example of Fig. 1, the following functions are gene-
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rated.
a) A constructor operation for building
ew COMPLEX numbers out of two REAL
numbers. Its entry point is stored
in the register COMPLEX of the class
ANY.
b) Two selector operations for accessing
the components (i.e. the REALPART and
the IMAGPART of a COMPLEX number).
Their entry points are stored in two
registers, named REALPART and
IMAGPART, of the class COMPLEX. They
may operate either in load mode (in
which case they are unary and are
used to retrieve the components of
COMPLEX numbers) or in store mode (in
which case they are binary and are
used to update the components of
COMPLEX numbers: the first argument
replaces the appropriate component
of the second argument). The default
mode is the load mode. The store
mode is used when a selector is
invoked via the special operation
UPDATE (see Section 2.4).
c) Several utility operations for reading,
printing, editing, etc. COMPLEX
numbers according to a standard repre-
sentation. Their entry points are
stored in the registers READ, PRINT,
EDIT, etc. of the class COMPLEX.

The mechanism which allows microprograms
to be retrieved and executed is explain-
ed in Section 2.4.

2.4. Programs
Programs are linear sequences of
functions, each one being made of an
operation code and some (possibly zero)
operands. Both operation codes and
operands are represented as bytes: thus
a program is represented as a linear
sequence of bytes. Each byte is inter-
preted either as an operation code or as
an operand according to its position, as
it usually happens in a standard byte-
oriented computer.

Programs are interpreted by a fetch-
decode-execute loop which performs the
following operations.
A byte is fetched, according to the
address contained in the C-top (fetching
always increments the contents of the
C-top), and it is interpreted as an op-
eration code. This means that a register
having the same internal name as the
fetched byte is searched in the special
class ANY. If such a register is found,
the datum described by it is used as a
function according to the following
rules.
a) If the datum is a microprogram, it is
directly executed by the hardware.
It may fetch some bytes of the
calling program and use them as ope-
rands: this is the case of all the
functions described in the Appendix
(other than RETURN and the function
UPDATE (which has the name of a
selector as its only operand).
b) If the datum is a program, a dd for
it (i.e. a pointer to its first
instruction) is pushed onto the
C-stack and execution goes on with
the new program counter. Note that
recursive calls are performed natu-
really, and recursion may be imple-
mented straightforwardly, provided
that the A-stack (which is used for
passing parameters) is properly syn-
chronized with the C-stack. This
means that, at the end of a recursive
call, a program should pop its
parameters off the A-stack and repla-
ce them with a value.
c) Otherwise the datum is pushed onto
the A-stack and the standard function
APPLY is called. By the type-driven
call mechanism (see below) the
function APPLY is searched in the
class which contains the datum itself.
Thus, each datum may be used as a
function, provided that a function
APPLY (i.e. an interpreter) is
defined for it.

If the class ANY does not contain a
register with the same internal name as
the fetched byte, such a register is
searched in the class of the top-datum.
If such a register is found, processing
goes on as in the previous case, other-
wise an error is generated. The call
mechanism just described is named type-
driven, since the top-type "drives" the
access to the code of the called
function.

An extensive discussion of the relations
between the notion of class plus type-
driven function invocation and more fa-
miliar concepts like "user-defined data
types" (in the sense of PASCAL) or
"abstract data types" is outside the
scope of this paper, and may be found
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...it ourselves to ob-
...serves are more

data types" than to

A stack performs the
EX numbers is shown
...tion of the A- and
execution of such
...fig. 3. Note that,
...is written in a
memory represen-
tative sequence of bytes,
...the internal name
...one being the

C-stack = ( (SQUEEZE 2) ... )
A-stack = ( a+c i+b+d )
                                                  c+id
                                                  a+ib

C-stack = ( (RETURN) )
A-stack = ( a+c i+b+d )

Fig. 3. The evolution of SMOM stacks
while executing the program
of Fig. 2. The irrelevant
parts of the stacks (i.e.,
deeper programs and data) have
not been displayed for simpli-
city.

3. SMOM ARCHITECTURE AND PARALLELISM

3.1. General discussion

In Section 2 SMOM functions have been
supposed to be executed in a strictly
sequential order, the order being speci-
fied by contiguity and jump operations
(program calls are to be considered as
jump operations). However, the features
of SMOM make it possible to exploit the
inherent parallelism of the algorithms
in a natural way.

As it happens with high-level expression
languages (like LISP), a SMOM comuta-
tion consists of a number of function
calls, where function bodies are expres-
sions. Thus the computation graph
consists of a series of directed acyclic
graphs (i.e., partial orders). This is
not true of imperative languages (in
particular conventional assembler lan-
guages) where this property holds locally:
...ially it is confined to
...small" arithmetical and logical expres-
sions. Moreover, since SMOM functions
are more powerful than conventional
assembler statements, exploiting the
parallelism among them leads to much
faster and efficient computations and,
as we shall see, to an easily recogniz-
able modular separation of firmware-
controlled system tasks.

We now intend to show how to detect,
order and execute in parallel the
...various parts into which a program may
be decomposed. Of course, determinacy
and efficiency impose suitable synchroni-
zation requirements: they will be
defined in a unique way.

In what follows, the reader is recom-

(PRG)
   (GET 1) (REALPAR)
   (GET 1) (REALPAR)
   (GT 2) (IMAGPAR)
   (GET 2) (IMAGPAR)
   (SQUEEZE 2)
   (RETURN)

Fig. 2. A program for
COMPLEX number

A-stack = c+id
A-stack = a+ib
A-stack = a+ib
A-stack = a+ib
A-stack = c+id
A-stack = a+ib
A-stack = <value of
A-stack = <value of
A-stack = ( (COMPLEX)
A-stack = <value of
A-stack = <value of
A-stack = ( (COMPLEX)
A-stack = <value of

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Recommended not to take care of the typed-driven call mechanism of SHOM. Also the existence of functions (such as PUT and UPDATE) that perform side-effects is to be ignored by now. These features will be considered later.

Referring to Fig. 2, it is evident that the computation graph of that program is the tree shown in Fig. 4. Each leaf represents a function which starts an independent computation. Each nonterminal node with K sons represents the execution of a function with K subordinate computations.

Partially ordered computations may be reproduced in a multiprocessor environment by means of several synchronization techniques, all of them being implementations of Dijkstra's P and V primitives (9) or, equivalently, of the Conway's FORK and JOIN instructions (5). However, the efficiency of such techniques is fully exploited in the classical multitasking environment, where tasks are relatively large in size, so that a considerable processor-switching overhead is tolerable (15). Improvements can be devised when the tasks may be of any size (see for instance (6,7,14)), but all these techniques have the same characteristics: every task is dispatched to one processor only as soon as it is ready for execution. This fact prevents from employing other forms of parallelism, such as prefetch or look-ahead: we wish to employ such forms indeed, as we are concerned with the efficient execution of (high-level) machine code. Moreover, we need a synchronization strategy that agrees with the data control (i.e. A-stack management) strategy. Our solution is characterized by the fact that the fetched functions are dispatched to all the processors which are potential candidates to their execution; function execution will be actually controlled by a JOIN-type mechanism and by a data-driven control mechanism. More precisely, functions represented by different leaves are enqueued on different processors for execution. Functions represented by a nonterminal node are enqueued on all the processors which are still involved in some subordinate computation of the node itself. The number of such processors is recorded by a counter associated with that node. When a processor takes a function from its queue, it decrements the counter and executes the function only if the counter is zero. This JOIN-type mechanism prevents a function from being executed unless all of its subordinate computations have been completed.

The enqueuing strategy just explained may be realized by a specialized processor, the Control Processor (CP), which operates in parallel with the general processors (simply called processors) \( P_1, \ldots, P_n \) and masters the whole system. The CP operates by prefetching the functions, whenever possible, and by dispatching them to a number of processors and priming the synchronization mechanism.

\[ \text{(GET 1)} \]
\[ \text{(REALPART)} \]
\[ \text{(PLUS)} \]
\[ \text{(COMPLEX)} \]
\[ \text{(SQUEEZE 2)} \]
\[ \text{(RETURN)} \]

\[ \text{(GET 1)} \]
\[ \text{(REALPART)} \]
\[ \text{(PLUS)} \]

\[ \text{(GET 2)} \]
\[ \text{(IMAGPART)} \]
\[ \text{(PLUS)} \]

Fig. 4. The computation graph of the program of Fig. 2.

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The architecture of a multiprocessor SMOM interpreter is therefore of the hierarchical type. The overall organization is shown in Fig. 5. As we shall see, it is convenient that the A-stack is managed by an independent specialized processor, i.e. the A-stack processor (AP), tightly interacting with CP and the general processors.

Fig. 5. The architecture of a multiprocessor SMOM interpreter.

In the following subsections several implementation problems arising with such an architecture are examined in some detail.

3.2. The A-stack

Assume that the CP enqueues the first seven functions of the program of Fig. 2 on the three processors $P_1$, $P_2$ and $P_3$, according to the strategy explained in Section 3.1, as shown in Fig. 6. In the figure some A-cells have been labeled in order to single out the A-cells (also called source A-cells) which contain the arguments and the A-cell (also called destination A-cell) which is to contain the result of each enqueued function. Note also that the cell B is the A-top when prefetching is started.

Assume that the processors execute the prefetched functions according to the timing of Fig. 7.

Fig. 6. The state of the system after prefetching seven functions of the program of Fig. 2.

$$A\text{-stack} = \begin{cases} \text{<unused> A-cell D} \\ \text{<unused> A-cell C} \\ c + id \quad \text{A-cell B} \\ a + lb \quad \text{A-cell A} \\ \vdots \end{cases}$$

$$\text{QUEUE}_1 = \text{GET}(A+C)$$
$$\text{REALPART}(C-C)$$
$$\text{ADD}(C,D-C)$$

$$\text{QUEUE}_2 = \text{GET}(B+D)$$
$$\text{REALPART}(D-D)$$
$$\text{ADD}(C,D-C)$$

$$\text{QUEUE}_3 = \text{GET}(A-D)$$

Fig. 7. A possible timing for the execution of the prefetched functions of Fig. 6.

It is evident that the value deposited by $P_2$ into the A-cell D is overwritten by $P_3$ before $P_1$ is enabled to use it for the addition (remember that $P_2$ cannot perform the addition, since $P_1$ is still computing the first addendum when $P_2$ has already completed the computation of
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the second one).

This example shows that the A-cells cannot be simply overwritten by the processors without possibly generating disastrous side-effects on the A-stack. As mentioned before, semaphores, critical sections and other well known devices for interprocess communication are not needed to share the A-stack correctly among the various processors. A much simpler solution is sketched in Fig. 8. The A-stack is made into a stack of pointers to A-cells, which in turn still contain dd's. The A-stack proper (i.e. the stack of pointers) is

![Diagram of A-stack and A-cells]

Fig. 8. The structure of the A-stack.

known to the CP only. The A-cells are manipulated by both the CP and the various processors. When a new function (other than a C-manager, which is always executed by the CP, as explained in Section 3.6) is fetched from the memory, the CP enqueues on the appropriate processors the prefetched function and the address of its source and destination A-cells. The former are taken near the top of the A-stack proper, the latter is the address of a newly allocated A-cell, which becomes the new A-top (the A-stack proper is appropriately overwritten). The behaviour of the CP with the program of Fig. 2 is sketched in Fig. 9.

Note that no A-cell is ever overwritten: only the A-stack proper is. However, no information is lost now, since the A-cells containing useful values are still referenced from the processors' queues. When an A-cell becomes unreferenced, it may be reclaimed to free-storage, as explained in Section 3.3.

3.3. A-managers and the A-cell space

In Section 3.2 we have introduced the notion of source and destination A-cells for a function. These concepts are clear enough as far as operations (see Section 2.3) are concerned. But what about the A-managers? Few problems arise with PUSH: it may be considered as a nullary operation (i.e. an operation with zero arguments) which is completely executed by the CP. Also POP and SQUEEZE generate few problems: they may be considered as (n+1)-ary operations which return their first and last argument respectively, totally ignoring the other n arguments. They may be enqueued and executed according to the strategy explained in Section 3.2. In the case of both the three A-managers considered by now and all the operations, the following policy may be devised for the management of the A-cell space. Whenever a function is prefetched, a destination A-cell is allocated, as already explained in Section 3.2. Whenever a function is executed, its source A-cells are deallocated, since they cannot be referenced any more.

As far as GET is concerned, almost the same policy may be adopted: a destination A-cell is allocated by the CP, as shown in Fig. 9, but the source A-cell is not deallocated when GET is executed.

Unfortunately, this simple policy does not seem to be applicable to the fun-
tions PUT and UPDATE, unless either the management of the A-cell space is intolerably complicated or the CP is forced to wait until all currently enqueued functions have been completed. The reader is invited to convince himself that any simple solution which does not involve a garbage collector for the A-cell space is actually wrong. Counterexamples are easily found in which GET and PUT, from the one side, and selectors used in load and store mode, from the other side, do not properly interact, if an appropriate timing is assumed for their execution.

A totally different view may also be adopted: each A-cell is provided with a reference count which records the number of existing pointers to that A-cell. This has a number of pleasant consequences. First of all, the A-managers may now be executed directly by the CP, without allocating extra destination A-cells (see Fig. 10 for an example). Second, PUT may be completely prefetched without unnecessary waitings. Third, no A-cell is to be allocated for unary functions. The main disadvantage of this solution is that the maintenance of reference counts introduces a lot of write operations on A-cells. This may probably cause the performance of the system to be dramatically compromised unless (as already suggested) a special purpose processor, i.e. the AP, is introduced for managing the A-cell space.

3.4. The enqueuing strategy
In Section 3.1 a strategy has been outlined for reproducing computation graphs and dispatching functions to processors.

Here we make that strategy effective.

In Fig. 4 each node of the computation graph has been associated with a function. In Section 3.2 each function has been associated with a single and newly allocated A-cell (namely, the destination A-cell). This one-to-one correspondence between nodes and destination A-cells allows us to associate the counters mentioned in Section 3.1 with the A-cells. Such counters have been supposed to be positive integers in Section 3.1. Obviously, an integer counter only contains information about how many (while the CP must know which) processors are co-operating in the computation associated with a node. Hence, an array of boolean indicators is more suitable in this case. Thus, an A-cell may be patterned after Fig. 11.

At any time, the indicator $s_i$ (1 <= n) of an A-cell is TRUE if and only if the processor $P_i$ is still involved in some subordinate computation of the node represented by that A-cell. Each indicator of a newly allocated destination A-cell is initially set to the inclusive OR of the corresponding indicators of the source A-cells of the fetched function; in fact these A-cells, which are to contain the arguments of the function, also contain information about the processors which are still computing them. The function is then enqueued (with the address of the source and destination A-cells) on all the processors whose corresponding indicator in the destination A-cell is TRUE. If no such indicator is TRUE, the function may be enqueued on an arbitrary processor, and the corresponding indicator is set to TRUE.

When a processor takes a function from its queue, it sets to FALSE the corresponding indicator in the destination A-cell, and executes the function if and only if all the indicators of this A-cell are FALSE. Otherwise the function is ig-
nored, and the next one is taken from the queue.

3.5. Type-driven calls

Here we explain how the CP may perform the run-time type-checking which is necessary for the implementation of the type-driven calls.

Suppose first that the prefetched function is not a C-manager and its code is found in the special class ANY. In this case the arity of the function is known, and the type of its result may be often predicted (input functions are a major exception). So the CP may update the A-stack properly, and store the predicted type in the destination A-cell before the function is actually computed, thus communicating information to the next (possibly type-driven) call.

If the code of the prefetched function is not found in the special class ANY, the type-driven call mechanism is to be invoked. If the top-type is manifest (i.e. it has been computed by either the CP or some other processor) then the CP operates as in the previous case, using the appropriate class instead of the special class ANY. Otherwise the CP cannot do better than waiting until some processor has computed the top-type.

3.6. C-managers

They can be directly executed by the CP. The execution of TYPEJUMPT and TYPEJUMPF requires the top-type to be manifest, and the CP operates exactly as in the case of type-driven calls (see Section 3.5). The execution of JUMPT and JUMPF requires that the top-datum is manifest, hence the CP must wait until it is.

4. MULTIPROCESSOR ORGANIZATION

4.1. Overall system organization

As shown in Section 3, the overall organization proposed for a SMOM interpreter is a hierarchical multiprocessor, consisting of the following components (see Fig. 12).

a) A Control Processor (CP) at the highest level.
b) A set of identical (general) processors $P_1, P_2, \ldots, P_n$ at the lowest level.
c) An A-stack Processor (AP) which manages the processors' and CP's requests for accessing the A-stack, and controls their interactions.
d) A common Memory (M), with m modules $M_1, M_2, \ldots, M_m$.

As it often happens in a hierarchical, parallel organization, the existence of a supervisor control level makes both the design process and the achievement of high performance easier, possibly at the expense of less reliability. In our case, the performance is further improved by the use of simple and fast synchronization primitives, by an extensive use of prefetching and by the independent management of the A-stack. A modular organization of the memory, possibly with a suitable separation of information among the modules, is a standard technique for balancing the execution and the memory bandwidths.

Every system unit is microprogrammed and, whenever possible and/or convenient, dynamically microprogrammable, in order to improve system flexibility and extensibility. Moreover, the overall organization is modular in principle and thus well suited to better exploit the microprogramming characteristics. This further improves system efficiency, as each unit has its own microprogramming language and organization, both chosen in such a way as to optimize the performance/cost ratio "on a local basis" (17).

In the following subsections we describe the internal organization of the main parts of the system, according to the general behavior discussed in Section 3.

4.2. Control Processor

As a primary task, the CP must perform the sequence control of the computation. Therefore, the C-stack must be a private resource of CP. Moreover, it is convenient that the CP contains a private copy of the A-stack, called the Virtual A-stack (VA-stack), in order to reduce the number of conflicts with the processors for accessing the A-stack and to maintain a picture of the contents of the A-cells allocated for prefetched, but not yet executed, functions. It is enough that the VA-cells are composed of only two fields, i.e. the V-type and the V-address. The first is assigned the
Fig. 12. Overall system organization.

Fig. 13. Scheme of the Control Processor microcode.

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type of the result of the currently pre- fetched function according to well-defi- ned predictions as discussed in Section 3. A special mark in the V-type field signals the wait situation.

The C-stack and the VA-stack are imple- mented by means of fast memories of rela- tively small size (typically, 128-256 cells). Two other similar memories are used as branch tables for registers of class ANY and for registers of the other classes. Actually, the second one acts as a cache of the complete table sorted in main memory.

The scheme of the microprogram defining the behaviour of CP is shown in Fig. 13. Remember that the microprograms that affect the control flow are directly executed by the CP. The function APPLY, if present, is an interpreter defined for using a datum as a function: when it is called by the type-driven mechanism, it is searched in the corresponding class of the datum.

As the CP must be as fast as possible for a continuous supply of functions to the processors, it may be realized as a network of bit-slice microprogrammable microprocessors, each one corresponding to a "logical" section of the CP algo- rithm, all being controlled by a supervi- sior microprocessor (1,4,14,17).

4.3. General processors
The task of a general processor $P_i$ is that of executing the functions which do not modify the control flow. Its behaviour has been sketched in Section 3 and the scheme of its microcode is shown in Fig. 14.

The internal organization and, corre- spondingly, the microprogramming type depends not only on the characteristics of the implemented algorithms, but heavily on overall system evaluations too. More precisely, the conflicts for accessing the A-stack and the Memory, together with the degree of parallelism of the computation, impose a saturation to the system performance with respect to both the number of processors and their average speed. Unless we are willing to make the AP organization very sophisti- cated, at a non-proportional cost, the threshold speed of the processors seems to be of the same order of magnitude as the typical speed of mini- or micropro- cессors, as it usually happens with a multiprocessor architecture.

By taking into account the tree form of the computations, a number of 4-8 pro- cessors seems the most suitable, unless a multitasking feature is introduced in- to the SMOM language (by adding special primitives such as FORK and JOIN) and in the system architecture. In this case, the CP must perform the task scheduling. However, some problems arise at the level of the A-stack. It may be inter- esting to investigate the possibility of employing at the task level the same syn-chronization strategy proposed in this paper and used at the instruction level.

4.4. A-stack Processor
As discussed in Section 3, the manage- ment of the A-stack is a potential bottleneck of the system which may pro- duce serious degradation of the system performance. In fact, if this function is distributed on the CP and the gene- ral processors, their behaviour would be severely limited by an excessive over- head. Thus a specialized independent processor, the AP, is needed. The AP is assigned the task of performing functions under the command of the CP and the pro-
processors. Examples of such functions are: ALLOCATE and DEALLOCATE A-cells; READ and WRITE A-cells, either with LOCK or UNLOCK feature respectively; conflict resolution and priority updating, queues management, etc.

Commands to the AP are sent by the CP and the processors, and responses are returned from the AP through a set of I/O buffers $B_0, B_1, B_2, \ldots, B_n$ (see Fig. 12). The commands specify, together with their code, the relative A-cell address and its configuration if it has to be modified.

The indirect interaction mechanism can be realized, in a simple but effective way, by associating a lock-bit to every A-cell, and by implementing an arbitration algorithm of the general or of the circular type.

A fast memory of hardware registers is employed for implementing the A-stack. A dynamic microprogramming, though desirable, is not essential in this case, for the functions being implemented are easily foreseen during the design phase. Moreover, flexibility can be sacrificed in behalf of speed, owing to the critical task of this unit. The possibility of realizing the AP as a network of asynchronous, co-operating subunits (at the extreme, one for every A-cell) is to be taken into account. However, economy considerations, together with a much less than proportional gain in speed, recommend to follow the proposed solution.

4.5. Memory
In our case, two factors play an important role in devising a cost effective organization of the memory. First, the particular function of the CP, roughly behaving as the Instruction Preparation Unit in a look-ahead computer (15). Second, the possibility of individuating two memory areas, one essentially accessed by the CP, the other accessed by the processors. Therefore, we can assign a subset of modules to the CP and share the remaining modules among the processors. The CP is connected to its modules by a simple switch and a queue (Q in Fig. 12), while the processors are connected through a time-shared bus. This subdivision can be realized in a quite flexible way, provided that the switch and the interconnection structure are implemented in a modular way.

5. CONCLUDING REMARKS
The design goals of the machine language of SMOM were essentially two, namely it had to be particularly well suited to implement fast interpreters for extensible languages, and it had to support the good programming style of defining and using as many data types as logically required by the user's problem. In this case, the types of the components of a datum are almost always known from the definition of the data type which the datum is an instance of. This amounts to saying that the prefetching algorithm seldom falls asleep while waiting for the top-type to become manifest. In other words, a programming style that allows an almost complete compile-time type-checking also allows an equally complete run-time type-checking to be performed by the prefetching algorithm. So, the prefetching algorithm generally waits for the completion of some test having a really unpredictable result, e.g. a test that precedes a JUMPT or a JUMPF.

A hand-made analysis of several SMOM programs (most of them obtained by compiling various LISP functions to SMOM) has shown that about one half of the instructions contained in a SMOM program are A- and C-managers, and that the number of functions which are executed in parallel by the processors (other than CP) is typically varying from four to eight (this result has been recently confirmed by experiments performed with a software simulator of the parallel architecture described in this paper (11)). These numbers perfectly match the number of processors that is conjectured to be optimally supported by the proposed architecture, i.e. the maximum number of processors which does not generate too many conflicts on the A-stack (see also Section 4). This apparently amounts to saying that the maximum speed-up allowed by parallel interpreters of SMOM-like languages is about one order of magnitude. We believe that something better can be achieved, provided that the conflicts
for accessing the various memory modules and the A-stack are held to a minimum by a careful design of the algorithms for allocating new data items or new A-cells. Results obtained in implementing extensible high-level languages in paged environments are surprising in this respect. Further improvements in the performance of such systems can be probably achieved only with machine languages based on different concepts (13).

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APPENDIX

A.1. A-managers

Here n is a non-negative integer which denotes the address of an A-cell relative to the A-top (i.e. 0 is the address of the A-top, 1 is the address of the A-cell immediately below the A-top, etc.). The A-cell whose address is n is also called the n-th A-cell.

Format: (GET n)
Action: copies the n-th A-cell onto the A-stack.
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Figure:

\[
\begin{align*}
\text{dd}_0 & \quad \downarrow \\
\vdots & \quad \vdots \\
\text{dd}_n & \quad \downarrow \\
\text{(GET n)} & \quad \downarrow \\
\text{dd}_n & \quad \downarrow \\
\vdots & \quad \vdots \\
\text{dd}_0 & \quad \downarrow \\
\end{align*}
\]

Format: (GET n)
Action: copies the A-top into the n-th A-cell.

Figure:

\[
\begin{align*}
\text{dd}_0 & \quad \downarrow \\
\text{dd}_1 & \quad \downarrow \\
\vdots & \quad \vdots \\
\text{dd}_n & \quad \downarrow \\
\text{(PUT n)} & \quad \downarrow \\
\text{dd}_0 & \quad \downarrow \\
\vdots & \quad \vdots \\
\end{align*}
\]

Format: (PUT n)
Action: copies the A-top into the n-th A-cell.

Figure:

\[
\begin{align*}
\text{dd}_0 & \quad \downarrow \\
\text{dd}_1 & \quad \downarrow \\
\vdots & \quad \vdots \\
\text{dd}_n & \quad \downarrow \\
\text{(PUSH dd)} & \quad \downarrow \\
\text{dd} & \quad \downarrow \\
\vdots & \quad \vdots \\
\end{align*}
\]

Format: (PUSH dd)
Action: copies dd onto the A-stack.

Figure:

\[
\begin{align*}
\text{dd}_0 & \quad \downarrow \\
\vdots & \quad \vdots \\
\text{dd}_n & \quad \downarrow \\
\text{(POP n)} & \quad \downarrow \\
\text{dd}_n & \quad \downarrow \\
\vdots & \quad \vdots \\
\end{align*}
\]

Format: (POP n)
Action: pops n dd's off the A-stack.

Figure:

\[
\begin{align*}
\text{dd}_0 & \quad \downarrow \\
\vdots & \quad \vdots \\
\text{dd}_n & \quad \downarrow \\
\text{(SQUEEZE n)} & \quad \downarrow \\
\text{dd}_n & \quad \downarrow \\
\vdots & \quad \vdots \\
\end{align*}
\]

Format: (SQUEEZE n)
Action: pops n dd's between the A-top and the (n+1)-th A-cell off the A-stack.

A.2. C-managers

Here n is a (possibly negative) integer which is to be added to the C-top (such an operation is called a jump).

Format: (JUMP n)
Action: the jump is always performed.

Format: (JUMPF n), (JUMPT n)
Action: the jump is performed if the truth value (basic built-in data type) FALSE (resp. TRUE) is found in the A-top.

Format: (TYPEJUMPF t n), (TYPEJUMPT t n)
Action: the jump is performed if the top-type is not (resp. is) t.

Format: (CALL dd)
Action: pushes dd (which must be a program descriptor) onto the C-stack, thus suspending the program containing the function (CALL dd) and activating the program described by dd.

Format: (RETURN)
Action: pops the C-stack, thus resuming the most recently suspended program.

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