Coroutines and Networks of Parallel Processes

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COROUTINES AND NETWORKS OF PARALLEL PROCESSES

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Résumé:

Les concepts de *coroutine* et de *processus* interviennent dans une grande variété d'applications, où il est en général nécessaire de produire ou de transformer des données de façon progressive. Nous présentons un langage, fondé sur une vue sémantique précise de l'interaction entre processus, qui facilite la programmation de réseaux de processus qui évoluent dynamiquement. Ces réseaux ont un comportement externe unique, qu'ils soient exécutés de manière séquentielle ou parallèle. Les avantages d'une sémantique dénotationelle simple sont illustrés par des preuves de programmes. Ce langage de programmation permet aussi de clarifier les relations entre plusieurs concepts: coroutines, appel par nécessité, structures de données dynamiques et calcul parallèle.

Abstract:

The concept of coroutine *or* process *is useful in a large class of applications, usually involving incremental generation or transformation of data. We present a language based on a clear semantics of process interaction, which facilitates well-structured programming of dynamically evolving networks of processes These networks exhibit the same input/output behavior whether they are executed sequentially or in parallel. Sample program proofs are used to illustrate the benefits of the language's simple denotational semantics. The language serves also to clarify the relationships between coroutines, call-by-need, dynamic data structures, and parallel computation.*

1. INTRODUCTION

　　　　Many algorithms are naturally organized as systems of independent
processes which coexist and interact with one another. In this paper, we
present a structured approach to the programming of such systems. This
approach is embodied in a programming language which subordinates control
to structure, relieving the programmer of the burden of control management
and permitting process systems to be executed either sequentially or
concurrently with the same result. The language was designed to reflect
the clear semantic conception of process interaction which is presented
in [1], with the result that programs are relatively easy to verify.

1.1. Coroutines, multipass algorithms, and pipelines.

　　　　Our notion of a *process* is derived from Conway's original concept of
coroutines [2], which he introduced as an improved way of executing multipass
algorithms. In his words, "... *a coroutine is an autonomous program which
communicates with adjacent modules as if they were input and output
subroutines*". The coroutines represent successive passes each of which
*incrementally transforms a stream of data, so that their execution can be
interleaved in time according to a "demand-driven" scheduling strategy*.
This mode of execution was described succinctly: "*When coroutines A and B
are connected so that A sends items to B, B runs for a while until it
encounters a read command, which means it needs something from A. The
control is then transferred to A until it wants to write, whereupon control
is returned to B at the point where it left off*".

　　　　Conway went on to note that coroutines can be executed *simultane-
ously* if parallel hardware is available. This is possible without time-
dependent side effects because the coroutines communicate with each
other only via input/output instructions, and this in turn follows from
the fact that the coroutines are modelling separate passes of a multipass
algorithm. When executed in parallel, such a system is called a "pipeline",
and many studies of parallel program schemata have been concerned with
generalizing this simple linear organization ([3-5]).

　　　　The classic illustration of coroutines is the cooperation between
the lexical analyzer and the parser in a compiler. But algorithms
structured as a set of interacting coroutines occur in many applications

besides compiling, such as input/output handling [6], text manipulation [7], algebraic manipulations [8], sorting [9], numerical computation [10], and artificial intelligence [11]. The UNIX operating system [12] provides a "pipelining combinator" in its command language which is used to connect programs together in linear pipelines for quasi-parallel execution.

1.2. Alternative approaches to coroutines.

A different approach to coroutines, typified by the SIMULA control primitives *call*, *detach* and *resume*, is fairly widespread [13-14]. The SIMULA primitives can be used to *implement* Conway's style of coroutines, where control transfers are hidden in the input/output commands. But they also allow many other types of interaction which often result in intricate control relationships. Use of the *resume* command in particular leads to obscure control structures, because it resembles a *go to* command with a moving target. For the sake of program reliability and verification one needs to impose discipline on the use of these primitives, and when this is done [16-18] it leads to the structuring of process interaction along the lines of Conway's original proposal.

1.3. Related ideas

The evaluation mechanism used in our system has its origins in theoretical work [19-20] on "call-by-need" parameter passing. The same work has inspired "lazy evaluators" for LISP [21,22] which in some respects behave like our process networks and can execute slightly modified versions of some of our examples. These systems, however, do not have any analogue of our cyclic network structures.

Communication channels are related to the *streams* of Landin [23], who foresaw their connection with coroutines. In fact, our language can be viewed as a powerful stream processing language. A simplified version of streams already exists in POP-2 [24] in the form of *dynamic lists*, but their usefulness is limited because the lack of processes in POP-2 makes it awkward to define stream transformations.

2. THE PROGRAMMING LANGUAGE

2.1. Introduction

The language presented here provides concise and flexible means for creating complex networks of processes which may evolve during execution. Its key concepts are *processes* and structures called *channels* which inter-connect processes and buffer their communications. Channels carry information in one direction only from a *producer process* to one or more *consumer processes*, and they behave like unbounded FIFO queues.

In this section we explain how processes are declared, how they communicate via channels, and how networks of processes are created and transformed. Then we introduce a more powerful functional notation and discuss iterative versus recursive reconfiguration of processes.

The language has been implemented in Edinburgh as an extension of POP-2 [20]. While its concrete syntax follows the style of POP-2 (E.g. the Algol assignment "A:=B" is written B → A in POP-2), no feature of POP-2 that departs significantly from PASCAL or ALGOL is used.

2.2. Processes

The behaviour of each process is specified in a *process declaration*, patterned after a procedure/function declaration in POP-2 :

```
Process <name>  <parameter-list> ;
        <process body>
Endprocess
```

The parameter list is partitioned into two sublists : the *ordinary* parameters and the *port* parameters. Parameters in the first group are evaluated according to the rules of POP-2 (i.e. by value). Port parameters [25] will be bound to communication channels so that a process may communicate with its neighbors in the network. In the declaration of TRANSDUCER (see fig. 1) A is an ordinary parameter, called by value, while I and O are respectively input and output ports. In a typed language, say PASCAL, the process heading would appear like this :

Process TRANSDUCER (A : *integer* ; I : *in integer* ; O : *out integer*) ;
The body of a process declaration is similar to the body of a procedure

in POP-2 : variables and functions may be declared local to the process
(thus no restriction is placed on the amount of memory available to a
process). Conceptually, each process is thought of as executing on a
separate machine so that it cannot communicate with any other process
except through interconnecting channels. Hence :

(1) No global variable may be *updated* by a process
(2) Arrays, but *not* references to arrays, may be sent along
    communications lines
(3) More generally, if a reference to the dynamic storage area is
    sent by a process, the area that may be reached through this
    reference must become read-only.

(Note that (3) is automatically satisfied in purely applicative languages).
The constraints above do not mean that two processes cannot access a
common file or table, but a process should be responsible for the
management of all accesses to such a shared object, in the manner
advocated in [26]. This is the way, for example, in which we deal with
input/output in our system.

All constructs of POP-2 may occur in the body of a process. Two
primitive functions are provided to transmit information between processes,
and a *reconfiguration instruction* allows the redefinition of the network.

2.3. Transmission primitives

A process is connected to its neighbours via one-way communication
channels. The function GET is used to obtain data : if I is an input port,
the evaluation of the *expression* GET(I) yields the next item arriving via
port I. If no value ever arrives, this evaluation does not terminate.
Consecutive evaluations of GET(I) yield consecutive items, as if I was
a sequential input file. The *procedure call* PUT(<expression>,0) sends the
result of the evaluation of the first argument along the channel bound to
output port 0.

Availability of an item at an input port *cannot* be tested. This is not
an oversight but a deliberate decision to exclude time-dependent input/
output behaviour. Certain sections of an operating system *demand* a primitive

of this kind, but the absence of time-dependencies gives its distinct
flavour to pipelining as opposed to other kinds of parallel processing
and permits the simulation of a pipeline by a set of coroutines. Note
also that including such a primitive changes drastically the mathematical
semantics of the language [27].

2.4. Reconfiguration

While a process program is running, it may be visualised as a
directed graph where nodes represent processes and edges stand for
communication   channels. During computation, this graph may evolve
in a top-down fashion : a node may be replaced by a subgraph, provided
this subgraph can be appropriately *spliced* into the incoming/outgoing
edges (i.e. channels) of the original node. A *reconfiguration instruction*
has the form :

> *doco*   <body>   *closeco*

and its body specifies a transformation of this sort. The keyword *doco*
stands for "do concurrently" or "do coroutines". *Closeco* is just the
matching closing bracket. The body of the instruction has two parts :

   (i) the declaration of new communication's lines (edges in the new
       subgraph)

  (ii) a list of *process calls*. Port parameters in these calls may be
       bound either to channels that have just been declared or to ports of
       the *parent* process, i.e. the process in which this reconfiguration
       instruction occurs.

In fig.1 , the process GO contains a reconfiguration instruction. Its
evaluation provokes the graph transformation displayed on fig.2.

The two calls to TRANSDUCER set up two *distinct* instances of this
process. As a reconfiguration instruction merely *specifies* a new setup,
the order in which process calls occur is, for the moment, irrelevant.[*]

[*]As the reader realizes by now, the program of fig.1 doesn't achieve very
much. It just serves to illustrate the first features of the language.

```
Process PRODUCER out QO ;
     vars N ; Ø → N ;
     repeat INCREMENT N ; PUT(N,QO) forever
Endprocess ;
Process TRANSDUCER A in I out O ;
     repeat PUT(A + GET(I),O) forever
Endprocess ;
Process CONSUMER in QI ;
     repeat 20 times PRINT(GET(QI)) close
Endprocess ;
Process GO ;
     doco queues Q1 Q2 Q3
     PRODUCER(Q1); TRANSDUCER(1,Q1,Q2); TRANSDUCER(-1,Q2,Q3) :
     CONSUMER(Q3)
     closeco
Endprocess ;

Start doco GO( ) closeco ;
```

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
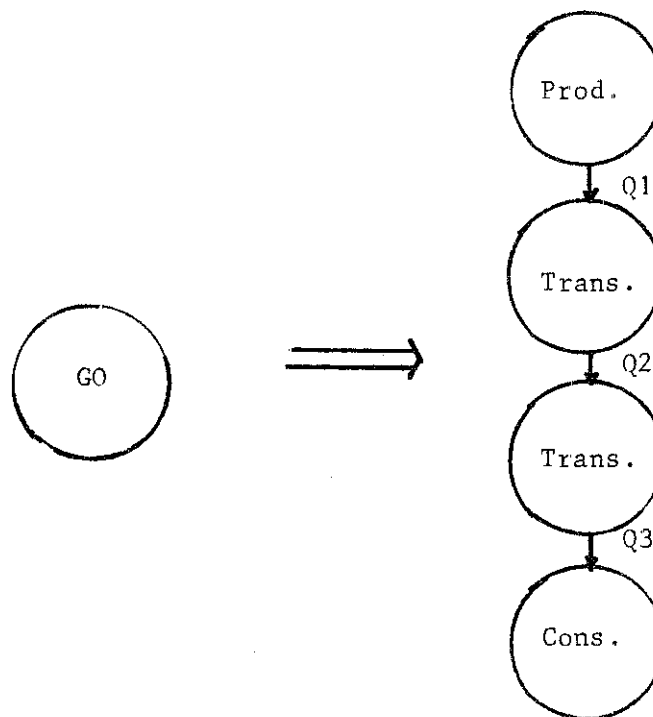
:

Fig. 1 First example.

Fig. 2 Reconfiguration.

Remark : In ALGOL, a procedure call lumps together three distinct operations :
the creation of new procedures, the binding of formal to actual parameters
and control transfer. In ISWIM [28] or SL5[29] some of these actions may be
performed separately. Here, processes are bound to their arguments as soon as
they are created, but control is transferred in an entirely separate manner.

Conway's original coroutine scheme requires the coroutine network
to be acyclic. The theory tells us that this restriction is unnecessary.
From a pragmatic point of view, the extra cost incurred at execution time
when it is lifted is minimal and feedback loops in coroutine programs are
in fact quite useful. Another constraint, implicit in Conway's paper, is
essential. Call a process a *producer* (resp. *consumer*) for Q if it is bound
to channel Q via an output port (resp. input port). The sequence of items
that will be sent on Q during execution of the program is the *history* of Q.
If the history of every communication variable is determined by the value
of the program's parameters, a parallel program is called *determinate*. A
simple rule guarantees determinacy of process programs : at any given time
during execution, a channel must be bound to a single producer, and to a
single output port of that producer. Note that several consumers may share
the same input line : the system ensures that the activity of one consumer
cannot modify the sequence of items received by the others.

2.5. Activation

Within a POP-2 program, an activation instruction of the form :

start <reconfiguration instruction>

may be issued to request execution of a process program. This instruction
terminates when the process program terminates. Once an initial network
has been set up by the reconfiguration instruction, it is set in motion and
from then on control transfer is automatic. In the simple-minded program of
fig.1, an activation instruction is issued at top-level. The occurrence of
the POP-2 prompt character(':') after the results shows that the program
did terminate.

The program of fig.3 is more interesting. This form of the sieve of
Eratosthenes appears, to the author's knowledge, for the first time in [30] :
for each newly discovered prime, a FILTER process is created by SIFT, whose
task it is to remove all multiples of that prime from the integers to be
considered. A proof of the correctness of this program is sketched in
section 4.

```
Process INTEGERS out QO ;
     Vars N ; 1 → N ;
     repeat INCREMENT N ; PUT(N,QO) forever
Endprocess ;
Process FILTER PRIME in QI out QO ;
     Vars N ;
     repeat  GET(QI) → N ;
             if  (N mod PRIME) ≠ ∅ then PUT(N,QO) close
     forever
Endprocess ;
Process  SIFT in QI out QO ;
     Vars PRIME ; GET(QI) → PRIME ;
     PUT (PRIME,QO) ; Comment emit a discovered prime ;
     doco queues Q ;
       FILTER(PRIME,QI,Q) ; SIFT(Q,QO)
     closeco
Endprocess ;
Process  OUTPUT in QI ;  Comment this is a library process ;
     repeat  PRINT(GET(QI))
Endprocess ;
start doco queues  Q1 Q2 ;
     INTEGERS(Q1) ; SIFT(Q1,Q2) ; OUTPUT(Q2)
     closeco ;
```

Fig.3. Sieve of Eratosthenes.

2.6. Functional notation

The constructs explained so far are sufficient for all programming.
However, we can write much more elegant programs in a functional notation.
Most processes have a single output line so that they are functions from
streams to streams [23]. So, in the way ALGOL 60 permits functions along
with procedures, processes may be declared functional and used to build
stream expressions. In process calls occurring in reconfiguration ins-
tructions, such expressions may be provided as arguments where input
channels are expected. For example, the program in fig.3. will now look
like this :

```
          Process  INTEGERS => QO ;
            ...
          Process  FILTER PRIME  in QI => QO ;
            ...
          Process  SIFT in  QI => QO ;
            ...
          Process  OUTPUT in  QI ;
            ...
          start doco  OUTPUT(SIFT(INTEGERS())) closeco ;
```

This new notation is very convenient because many channels are created implicitly. But stream expressions denote only acyclic subnets. A simple construct (akin to Landin's WHEREREC) allows networks to be built with cycles. In a reconfiguration instruction, we allow now a list of *elementary reconfigurations* where, in the familiar BNF notation :

<elem.reconf>::= <process call>

  | <elem.reconf>*WHERE*<channel list>$\{^{IS}_{ARE}\}$<list of stream-expressions>

In the program of fig.4, a reconfiguration written in this style can be found in the activation . Since X occurs both in the channel list and within the stream expression on the right of *IS*, a network with a cycle is being specified. Note also that X is shared as input by the three instances of TIMES and the process OUTPUTF.

Finally, a difficulty crops up when, as a consequence of a reconfiguration, the newly created network has to output values on a channel previously bound to an output port of the parent process, as it happens in SIFT for example (see fig.3). Another kind of elementary reconfiguration, called *splicing* must be included :

  <list of stream expressions> => <list of output ports>

This specifies that the stream expressions on the left are to provide data to the channels bound to the ports on the right. So the reconfiguration in SIFT is now :

  doco SIFT(FILTER(PRIME,QI)) => QO *closeco*

Note that this device offers a simple way to have a network shrink rather than expand. For example the process QCONS :

  Process QCONS A *in* I => O ;
          PUT(A,O) ;
          doco I => O *closeco*
  Endprocess

first emits A and then ties its input to its output channel and vanishes.

2.7. Optimizing recursion.

The situation of the process SIFT is a common one. This process reconfigures into a subgraph containing a new instance of SIFT and disappears. Instead, SIFT could merely create in front of itself new FILTERs upon receiving new inputs and thus be iterative rather than

recursive. To indicate that the parent process is to be included in a new
configuration, the dummy process call *CONTINUE* is used. Usually the bindings
of the parent process have to change. An assignment permits switching
inputs, splicing is needed to reconnect outputs. The transformed version
of SIFT is :

```
Process SIFT in QI => QO ;
       Vars  PRIME ;
       repeat
          GET(QI) → PRIME ; PUT(PRIME,QO)
          doco FILTER(PRIME,QI) → QI ; CONTINUE closeco
       forever
    Endprocess ;
```

In our implementation, significant time and space savings result from this
transform.

2.8. An example.

The programming style is now much less imperative. To illustrate this,
consider a problem treated by Dijkstra in his book [31]. One is requested
to generate the first N elements of the sequence of integers of the form
$2^a 3^b 5^c (a,b,c \geq 0)$ in increasing order, without omission nor repetition. The
idea of the solution is to think of that sequence as a single object and
to notice that if we multiply it by 2, 3 or 5, we obtain subsequences. The
program of fig.4. embodies the idea that the solution sequence is the
least sequence containing 1 and satisfying that property. The process
MERGE assumes two increasing sequences of integers as input and merges
them, eliminating duplications on the fly. The process TIMES multiplies
all elements of its input channel by the scalar A. The process OUTPUTF
is a library process.
Notice how control considerations do not intervene in the design of this
program.

Remarks : (1) What is an implicit quantity in other coroutine systems, the
history of a communication's variable ("mythical" variable in [16]), is now
explicit and subject to calculations. The style of programming also recalls
LUCID [34], which has a similar semantics. The obvious pay off will be in
easier correctness proofs. Note also that this programming language is just
what is needed to compute over real numbers with unlimited accuracy [35].

```
Process MERGE in QI1 QI2 => QO ;
     Vars I1 I2 ;           Comment local buffers ;
     GET(QI1) → I1 ; GET (QI2) → I2 ;    Comment initialisation ;
     loopif I1<I2 then PUT(I1,QO) ; GET(QI1) → I1
     elseif I1>I2 then PUT(I2,QO) ; GET(QI2) → I2
     else   comment I1 = I2. Remove duplications ;
          PUT(I1,QO) ; GET(QI1) → I1 ; GET(QI2) → I2
     close
Endprocess ;

Process TIMES A in I => O
     repeat PUT(A*GET(I),O) forever
Endprocess ;

start doco OUTPUTK(20,X) comment print first 20 elements of X ;
     where queues X is
               QCONS(1,MERGE(TIMES(2,X),MERGE(TIMES(3,X),TIMES(5,X))))
     closeco

1 2 3 4 5 6 8 9 10 12 15 16 18 20 24 25 27 30 32 36

:
```

Fig.4. An example from Dijkstra.

(2) Returning to the particular program of fig.4, it can be made much more efficient if we eliminate redundant number generation, calling it with :

```
start doco OUTPUTF(20,X)
     where queues X,Y,Z are
          QCONS(1,MERGE(TIMES(2,X),Y)),
          QCONS(3,MERGE(TIMES(3,Y),Z)),
          QCONS(5,TIMES(5,Z))
     closeco
```

3. EXECUTION

3.1. Outline

From an operational point of view, a process network is a collection of independent machines which interact by making demands upon or sending data along communication channels. Processes are represented by data structures containing local access environments and control continuations. A channel is represented by a linear list containing items stored in the channel and terminating with a reference to the current producer for the channel. Consumers have pointers into this list which are updated by the GET operation, while the producer inserts new items at the end of the list via the PUT operation. A reconfiguration instruction results in :

      (1) creation of new processes and channels,

      (2) initializing or updating input channel pointers, and

      (3) initializing or updating channel producer information.

A single constraint regulates the activity of processes : if a process requests input data from an empty channel, it must stop and wait until that data is provided by the channel's producer, which must be activated if possible. Given this constraint, a range of scheduling strategies are possible, from *pure coroutine* execution where a single process is active at any time to *full parallelism* where all processes run except when they are waiting for input. These scheduling strategies all yield the same input/output behavior, because the exclusive use of channels for interprocess communication and the careful choice of data transmission primitives serve to insulate processes from scheduling-dependent information.

3.2. Coroutine mode of execution

In this mode, activation of processes is strictly *demand driven*. Since the demand must originate somewhere, a process is selected to drive the whole network, and the demands of this driving process propagate through the network via the execution of transmission primitives and reconfiguration instructions.

    (i) Selection of the driving process

In last process created in the execution of the activation instruction is designated as the initial driving process and is the first process activated. Normally, it is that process which is responsible for producing (e.g. printing) the ultimate outcome. [*]

    (ii) Transmission primitives

Both GET and PUT *may* involve transfer of control. Applying GET to an empty input channel C causes suspension of the running process and activation of the producer for C. The channel C is made *hungry* to indicate that there is a consumer waiting on it. Applying PUT to an hungry output channel causes suspension of the running process and resumption of the waiting consumer, whereupon the interrupted GET operation is completed.

---

[*]The last process created in a reconfiguration is the outermost one in the last elementary reconfiguration.

Remarks : (1) There is no transfer of control when GET is applied to a nonempty input channel or PUT is applied to a nonhungry output channel.

(2) If as a result of a GET operation the scheduler attempts to activate a producer which is itself waiting, further computation is impossible and deadlock has been detected.

(iii) Reconfiguration

Except for the driving process, any process which is active is trying to satisfy some hungry output channel. After such a process reconfigures the scheduler gives control to the (possibly new) producer for that hungry channel.

When the driving process reconfigures it may survive (i.e. remain in the new configuration) in which case it retains control, or it may disappear, in which case the last process created is chosen as the new driving process and is activated.

3.3. Parallel mode of execution

After a PUT instruction sends an item on an hungry channel, the waiting consumer must be reactivated. But if additional processors are available there is no need to deactivate the producer process ; it may continue to run in *anticipation* of further demands for its output. In this way, computations that were interleaved in time can be made to overlap, and some process switching overhead is saved as well, without increasing the programmer's burden. The one drawback is that the process which was not deactivated *may* carry out *inessential* computation, i.e. computation that is not needed to produce the final outcome of the program. This inessential computation may even involve the recursive creation of superfluous processes.

We have developed a method of restraining such over-anticipation and verified its effectiveness in quasi-parallel simulations. The idea is to associate with each channel C a non-negative integer A(C), called the anticipation coefficient. Once activated, the producer for C will not be deactivated by PUT until C contains at least A(C) many unconsumed items. Note that the coroutine mode of execution results when A(C) = 0 for all channels C. The anticipation coefficient can only be accessed by the primitives GET and PUT. It is   set by a special primitive ANT(n,C).

Normally, the anticipation coefficient should be set as the channel is passed as an input parameter to a new process. In any case, the specifications for anticipation will not affect the semantics of the program, nor will they require alterations to its basic design.

4. Program proofs

For a detailed presentation of the mathematical semantics of the programming language, the reader is referred to [1]. Roughly, to any program one associates a set of recursive equations. Standard proof techniques **can** then be used ([19],[32]). A form of *structural induction* is used repeatedly. Suppose one wishes to prove that a sequence X has property P :

      (1) First one proves, usually by induction, that P holds for a sufficiently rich set of *finite* initial segments of X.

      (2) Second one proves that P *admits induction*, that is that if it holds for sufficiently many finite initial segments of some sequence, it must hold for the whole sequence as well.

Formal proofs are too long to be given here in detail, so we present only the articulating lemmas.

4.1. Program of fig.4

Lemma 1 (Properties of MERGE) : If I_1 and I_2 are strictly increasing sequences of integers then

      (1) MERGE(I_1,I_2) is strictly increasing

      (2) As sets, MERGE(I_1,I_2) $\subseteq I_1 \cup I_2$ and if I_1 and I_2 are infinite, equality holds.

      (3) length (MERGE(I_1,I_2)) $\geq$ min(length(I_1),length(I_2))

Lemma 2 (Properties of TIMES) : if A is a positive integer, I a strictly increasing sequence of integers then :

      (1) TIMES(A,I) is a strictly increasing sequence of integers.

      (2) Each element of TIMES(A,I) is the product of A by some element of I.

      (3) length(TIMES(A,I)) = length(I)

Lemma 3 : The variable X denotes a sequence of infinite length.

Lemma 4 : The solution sequence satisfies the recursive equation defining X.

A special case of McCarthy's recursion induction [33] is applicable here and so we conclude from lemma 3 and lemma 4 that X is the solution sequence. (The proof of the improved version presents no difficulty).

4.2. Sieve of eratosthenes (recursive form).

Lemma 1 : INTEGERS() is exactly the increasing sequence of all integers starting with 2.

Lemma 2 : For any integer p and sequence I, the sequence FILTER(p,I) is a subsequence of I that contains

(1) no multiples of p

(2) all members of I that aren't multiples of p.

Lemma 3 : For any sequence I, SIFT(I) is a subsequence of I.

Lemma 4 : If I is an increasing sequence and p occurs in SIFT(I) no other multiple of p occurs in SIFT(I).

Lemma 5 : If the first element of I is greater than 1 and if p is a prime occurring in I, then p occurs in SIFT(I).

By lemma 5 and lemma 1, the output of the program must contain all primes. By lemma 4, composite numbers cannot occur. Hence the program generates exactly the primes, in increasing order by lemma 3.

Remark : Notice that, in constrat to [21-22], our semantics involves recursively defined data as well as recursively defined functions.

5. CONCLUSION

In the course of developing this language we have written a considerable number of applications programs, including four types of sorting, a formal power series package with 17 series operations, and a pipeline version of the discrete Fourier transform. This experience has confirmed most of our expectations, indicated limitations, and suggested generalizations.

We have found the language conducive to clear, well-structured programming. Programs are conceived *functionally* and operational concerns such as process scheduling do not enter into their design. The reconfiguration statement encourages top-down development, and the functional notation provides a concise way of expressing the relationships between processes. Programs proofs can be carried out at a level of abstraction which avoids the intricacies of dynamic behavior - i.e. in terms of operations on abstract data rather than machine state transitions.

As our ideas about process networks evolved, channels, considered as data structures, assumed a more central role. A channel is an example of a *dynamic data structure*, i.e. a structure which is gradually generated by processes embedded within itself. To a consumer, these structures behave *as though they were already fully defined*, because as soon as one accesses a new part of the structure it *becomes defined*. Our experience, together with theoretical work by Kahn and Plotkin, suggests that process networks should be generalized by broadening the class of dynamic data structures used for process communication - from linear lists to trees, tableaux, etc. For example, in a compiler the abstract syntax tree might be a dynamic tree generated from the input text by a number of parser processes operating in parallel, while several consumer processes work from the top down generating code.

As a final comment, this study seems to provide further evidence for developing the model theory of programming languages along the lines first suggested by Scott [36]. As the level of expression in programming languages increases, their interpreters will also become increasingly sophisticated. In the design and proof of programs, a firm grip on the model theory of the language will prove more useful than the knowledge of a delicate (and mythical) interpretive mechanism.

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