Manifold Version 1.0 Programming: Programs and Problems

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Abstract

MANIFOLD is a new programming language designed to control multiple concurrent activities by managing the communications among a number active communicating entities. The present initial version of the MANIFOLD language is a minimal language attempting solely to implement a conceptual model of asynchronously communicating processes, called the MANIFOLD model. Such a model can be useful in an implementation environment where processes and inter-process communication are fast and amply available (e.g. massive parallelism).

This document contains a tutorial introduction to the first experimental Version of the MANIFOLD language (using listings of simple working example programs), followed by four larger working programs. The detailed operation of each of these latter four programs is described with the help of illustrations, and a number of language features and problems are explained. We conclude, that the MANIFOLD conceptual model and language are both implementable and actually work, but also that in their initial first experimental versions, they have some imperfections which must be taken into account in the design and implementation of the next version of the MANIFOLD system.

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1 Introduction.

MANIFOLD is a new programming language designed to control multiple concurrent activities by managing the communications among a number active communicating entities.

The communications between these entities imply transfer of information from one entity to another. The actual communication links may form arbitrary complex networks and change dynamically in a controlled fashion.

The basic entities are called processes which in fact may stand for anything that can be regarded as active, such as a computer running, a machine working, a person playing. In practice, these processes are cooperating programs running on various computers; MANIFOLD is instrumental in coordinating these processes.

The present initial version of the MANIFOLD language is a minimal language attempting solely to implement a conceptual model of communicating processes, called the MANIFOLD model, which is explained in detail in the language specification document[1], and from which much of the material in the present document is cited. Such a model can be useful in an implementation environment where processes and inter-process communication are fast and amply available (e.g. massive parallelism).

The present implementation of MANIFOLD consists of a compiler and a run-time system. The latter is written in Concurrent C++ [4] and is described in [3].

This document started as a Programmers Guide for the first version of the MANIFOLD language; however in gaining experience with the first experimental version of this language some lacunae and deficiencies were detected in both the conceptual model, the language and the implementation. Therefore the character of the document has changed into an account of experiments carried out with MANIFOLD Version 1.0, preceded by an informal introduction to the language.

In Section 2 we introduce the MANIFOLD language informally using simple working examples.
In Section 3 we present some larger working programs and discuss some features and problems. In the concluding Section, we discuss some of the lessons learned and make some recommendations for a next version of MANIFOLD.

2 An informal tour through the MANIFOLD programming language.

2.1 Basic concepts and characteristics.

The basic components of the MANIFOLD programming language are processes, streams, events and ports. The latter are associated with processes and define communication points, which processes may use to exchange information with each other through streams.

There are two kinds of processes, manifold processes and atomic processes.

A manifold process is the execution of a set of actions specified in the MANIFOLD programming language.

An atomic process is any active entity which is not specified in the MANIFOLD programming language (e.g. a FORTRAN or C program) but for which a well-defined interface with the MANIFOLD programming language exists.

According the MANIFOLD model, a manifold process is always in one of several predefined states, and may change from one state to another whenever the process detects the occurrences of certain events. Each state has a label, defining the event(s) which trigger the execution of the actions contained in that state. These actions include activation and deactivation of processes, and the creation of connections between output ports and input ports of these processes. Ports are passages at the bounds of MANIFOLD processes, which control the flow of units of information.

This is probably best clarified by a simple familiar example.

/*
 * hello1.m – first Manifold program
 */
main
{
  start: "Hello, programmer !\n" –> sysoutput.
}

Figure 1: hello1.m: a simple example.

In Figure 1 sysoutput is a builtin name (for which a full specification exists outside the current source file) which happens to be an atomic process that has been built into the MANIFOLD run-time system. Its purpose is to wait for a connection to be established on its port named input, then forward everything it receives onto the standard output channel of the operating system where the MANIFOLD run-time system is installed (e.g. a terminal or a window) until all connections on its input port have been broken, whereupon it halts.

Next the predefined name main is declared followed by a list of state specifications (called blocks) between { and }. There is only 1 block, labeled start which contains only one action, namely “–>”.

This action creates connections, in this case a connection between the string “Hello programmer !\n” and an instance of the aforementioned atomic process sysoutput, and waits for the connection(s) to be broken.

The command:

Manifold> manif –o hello1 hello1.m
compiles the MANIFOLD program contained in the file hello1.m and produces an executable file hello1. Next, the command:
Manifold> hello1

initializes the MANIFOLD runtime system, after which this system activates the manifold main, which
must always be defined by the MANIFOLD programmer. As part of the initialization protocol, the event
start is raised by the runtime system in main, consequently the block labeled with start becomes active.
Entering this state results in the implicit activation of an instance of the atomic process sysoutput and
the creation of a connection between the string constant (which is a process by itself) and the port input of
the atomic process sysoutput, whereupon the main process waits until this connection is broken. As soon
as the connection has been established one unit (the string) will be sent over this connection, whereupon
the process representing the string halts, by which the connection will be broken. The sysoutput process

/*
 * hello2.m – some primitive actions in Manifold
 */
main
{
    process sysoutput_proc is sysoutput.

    start.self:
        activate sysoutput_proc; // activate
        "Hello, programmer !\n" -> sysoutput_proc.input; // connect
        sysoutput_proc.proc. // await death of
            // 'sysoutput_proc'
    death.sysoutput_proc:
        halt. // terminate
}

Figure 2: hello2.m: actions made explicit.

instance takes the unit from its input port and send it to the outside world as specified above. Detecting
that all connections to its input port have been broken, sysoutput consequently halts.

In the meantime, the process main also halts, since the connection it had established has been broken,
and no subsequent actions are specified.

The MANIFOLD runtime system, discovering that all manifold processes and atomic processes have
halted, finally, also halts.

There are a couple of notable points in the description of the workings of this program.
Firstly, in MANIFOLD transfer of control is managed by raising events. In main, the block is entered
since it has been labeled with the event start and this event has been raised by the runtime system.
Secondly, what a manifold process ultimately does is: activating and deactivating atomic processes,
and creating and breaking up connections between the ports of these atomic processes. Therefore
MANIFOLD can be regarded more like a coordination language, rather than a conventional computational
programming language. This implies, that for many rather simple programming tasks other languages
may be more appropriate than MANIFOLD, whereas MANIFOLD comes into play when a number of heter-
ogeneous active entities must be put together to work on a common problem. This will be illustrated
in the sequel.

For now, in order to become familiar with MANIFOLD concepts and language, initially a number of
simple examples will be treated in detail to show the properties of MANIFOLD as clearly as possible.

2.2 Processes.

To illustrate how in MANIFOLD processes can be created, we rewrite the program in Figure 1 using more
primitive constructs of the MANIFOLD language as shown in Figure 2, making every single step in the
description above explicit. In main, there are now two blocks, of which the second will be entered as
soon as the predefined event death has been raised by sysoutput_proc. The death event is actually
raised by the MANIFOLD runtime system as part of the termination protocol when a process, such as
/*
 * hello3.m - the 'group' construct in Manifold
 */

main
{
    process sysoutput_proc is sysoutput.

    start.self:
    (activate sysoutput_proc,       // activate
         "Hello, programmer !\n" --> sysoutput_proc.input, // connect
         sysoutput_proc)                // await death of
    death.sysoutput_proc:
    halt.                           // terminate
}

Figure 3: hello3.m: actions in a group.

sysoutput_proc, halts. The action halt in this block halts the process main. In the first block, there are
now three distinguished actions, separated by “;” symbols. The “;” is an operator meaning sequential
execution of its operands. Thus the connection is guaranteed to be made after the process activation has
been completed. However, this is not necessary.

In Figure 3, all actions in the first block are grouped together between “(” and “)” and separated from
each other by comma’s. This implies that all of these actions will be executed in some non-deterministic
order, possibly in parallel.

This construct, grouping together a number of actions between “(” and “)” separated by commas, is
called the group construct and is a fundamental construct in MANIFOLD.

2.3 Events.

/*
 * event1.m - internal events causing state transitions.
 */

main
{
    event state1, state2.

    start.self: do state1.
    state1.self: "This is state1.\n" --> sysoutput; do state2.
    state2.self: "This is state2.\n" --> sysoutput; halt.
}

Figure 4: event1.m: internal events.

As mentioned before, a MANIFOLD program consists of a number of labeled states and the transitions
between the various states are controlled by events. The label of each state consists of a list of events (and
optional sources) upon detection of which the state will be executed. Event occurrences are generated by
executing one of two primitive actions, do and raise, and by the MANIFOLD run-time system when some
predefined condition is met (e.g. start).

The do action can be used to switch from one state to another inside a manifold; as illustrated in
Figure 4, where main goes trough several separate states before halting; do has no effect outside its
executing manifold.
Note that all user-defined events must be declared.
Switching to another state is done as follows:

- an event is picked non-deterministically from the incoming event list
- a circular search through all available states is performed, starting at the current state downwards
- when a match is found with a block label then the state corresponding with the block is entered
- otherwise the next event is taken from the incoming event list until that list is empty, whereupon a
  manifold enters the halt state and halts (unless the current state contains an active connection).

```c
/*
 * event2.m - external events causing state transitions.
 */
event event1, event2, wait.

main
{
    process slave is Slave.
    start: activate slave; do wait.

event1.slave:
    "main has received event1 from slave.\n"->sysoutput;
    raise event2; do wait.

wait: slave.
}

Slave
{
    start.self:
        raise event1; do wait.
    event1: "slave has received event1.\n"->sysoutput;
        raise event2; do wait.
    event2: "slave has received event2.\n"->sysoutput;
        raise event1; do wait.

wait: parent.
}

Figure 5: event2.m: external events.
```

The action `raise` can be used to inform other processes `outside` a manifold of certain conditions; it
has no effect inside its executing manifold. This is illustrated in Figure 5, where main activates another
process `slave`, declared as an instance of the manifold `Slave`. The latter starts by raising `event1`,
then goes into a wait state; meanwhile main picks up this event from process `slave`, raises `event2` and
goes also into a wait state. At the same time the process `slave` finds `event2` to be raised, for which it
has a label in a handler block, so it leaves its wait state, and executes the corresponding block, outputs
a message and raises the `event1` again, etc. etc. in an eternal loop.

Note that the second handler block of `Slave` which is labeled `event1` is never entered although it is
raised by `Slave` but not by anyone else and `raise` has no effect inside that manifold.
Note further, that each manifold in this example has an additional handler block labeled \textit{wait} (which is just a user-defined name) to which a jump is made after handling the current block in order to receive the next occurrence of the event which was mentioned in the label of the current block. This is done, since once the manifold enters a block, it is immune to any of the events handled by that block.

Note finally, that each \textit{wait} block contains a list of so-called \textit{preemptable event sources}, which may “kick you out” of that block. The \textsc{manifold} language defines the \textit{preemption set} of a block to contain only those observable events whose sources appear in that block and the \textit{permanent} event sources (see § 3.2.3). Observable events are, loosely speaking, events for which the manifold has a handler block.

\section*{2.4 Ports and Streams.}

Recall, that the basic components in the \textsc{manifold} programming model are \textit{processes}, \textit{events}, \textit{ports} and \textit{streams}. A \textit{process} is a black box with a number of well defined \textit{ports} on which \textit{connections} can be made with the ports of other processes so that these processes can communicate with each other by exchanging \textit{units} of information. These connections are called \textit{streams}.

The management of these streams, how and when they are created and destroyed, is controlled by raising and receiving \textit{events}, which is a \textit{control} mechanism between processes independent of the existence of any stream, as illustrated in Figure 6.

Manifolds may setup streams between their own ports, between their ports and the ports of other manifolds, or between the ports of other manifolds, possibly in parallel, while at the same time other manifolds can make connections with their own ports!

In \textsc{manifold} ports are one-way passages and there are consequently two types of ports: \textit{in} and \textit{out} for receiving and sending information respectively. Each process has three predefined ports, named \textit{input} (type: \textit{in}), \textit{output} and \textit{error} (both type: \textit{out}).

In Figure 7, besides \textit{main} there are two other manifolds defined: \textit{manifold.A} and \textit{manifold.B}. They each have a port \textit{in} and a port \textit{out} declaration in their \textit{public} declaration section (after the name of the manifold, but before the opening bracket). As it stands, the port declaration in \textit{manifold.B} could have been omitted, since these are provided by default.
/*
 * port1.m - port declaration and stream connections
 */
main
{
process a is manifold_A.
process b is manifold_B.

start: (activate a, activate b,
   "Unit\n"->a.i, a.o->b.input, b.output->a.i, 
b.output->sysoutput).
}

manifold_A
port in i.
port out o.
{
start: i->o.
}

manifold_B
port in input.
port out output.
{
start: input->output.
}

Figure 7: port1.m: port declaration and stream specification.

Figure 8: Stream connections between ports of processes in MANIFOLD.
At start-up time, both manifolds setup a stream between their ports for incoming and outgoing units using the pipe operator (right-arrow ‘→’), as illustrated in Figure 8. The left-hand side of a ‘→’ is called the source, the right-hand side the sink of a pipe. Effectively this means, that both manifolds copy all units through their declared port in to their declared port out.

These manifolds are used in main, where instances of both manifolds are declared (in the private declaration of main). These instances are the processes a and b, which are both activated after receiving the start event, while at the same time (i.e. atomically, within a group) connections are made between the ports out of a and b and the ports in of b and a respectively. Furthermore, a unit (the string “Unit\n”) is sent to the incoming port i of a. Inside a units are moved from i to o. In main there is a stream from port o of a (a.o) to port input of b (b.input). Inside b units are moved from input to output. Finally in main there is a stream from b.output to a.i, so that all units are moved around. This is verified by creating a stream from b.output to sysoutput (implicit process activation) so that each unit passing through port output of b is also copied into the stream to sysoutput (multiple connections on an outgoing port).

Consequently this program prints the initial string “Unit\n” repeatedly on the screen in an endless loop.

Note that inside a manifold its incoming ports (e.g. i in manifold.A) appear as a source on the left-hand side of a ‘→’ while the “other side of” these same ports, when used by other manifolds, appear as a sink on the right-hand side of a ‘→’ (e.g. a.i in main).

Note, further, that manifolds may be used before defined.

```c
/*
 * port2.m - short-hand notation for default ports; pipeline.
 */
main
{
  process a is manifold_A.
  process b is manifold_B.

  start: (activate a, activate b,
         "Unit\n"->a.i, a.o->b->a.i,
             b->sysoutput).
}

manifold_A
port in i.
port out o.
{
  start: i->o.
}

manifold_B
{
  start: ->.
}
```

Figure 9: port2.m: short-hand notations and pipeline construct.

Figure 9 is effectively the same program using system supplied defaults, omitting ‘input’ and ‘output’ where possible.

Note the use of the pipeline construct ‘a.o->b->a.i’ in main, which is almost the same as the group construct ‘(a.o->b.input, b.output->a.i)’. The difference between the two is, that should one of the connections (streams) in the group construct break, the other remains intact, whereas when any connection in the pipeline construct breaks, the whole pipeline is dismantled and all other connections
are also broken up.

Finally it should be noted, that in MANIFOLD these constructs may be recursively combined to form arbitrary complex networks of communicating processes, which may (partly) change at any time one of the managing manifolds reacts on an incoming event.

/*
 * port3.m - switching connections
 */
event passed.

main
{
process a is manifold_A.
process b is manifold_B.

start: (activate a, activate b, do passed).
passed.self,
passed.a: ("Unit1 "->a, a->b->sysoutput).
passed.b: ("Unit2 "->b, b->a->sysoutput).
}

manifold_A
{
    event state1, state2.
    start: do state1.
    state1: getunit(input)->;
    "passed a "->; do state2.
    state2: getunit(input)->; getunit(input)->;
    "passed a.
"->; raise passed; do state1.
}

manifold_B
{
    event state1, state2.
    start: do state2.
    state1: getunit(input)->;
    "passed b "->; do state2.
    state2: getunit(input)->; getunit(input)->;
    "passed b.
"->; raise passed; do state1.
}

Figure 10: port3.m: event driven pipeline switching.

This is illustrated in Figure 10, a somewhat more complex example and yet not a perfect one! The idea is to illustrate the passing of units trough pipelines by printing them, and the switching between pipelines by reacting on observed events.

In this example, manifold_A is always in one of its two states, state1 (initially) or state2. In state1 a single unit is moved from port input to port output using the getunit primitive action. Thereafter, the string "passed a" is moved to output. Then state2 is entered.

In state2 two single units are moved from port input to port output, the string "passed a.
" is moved to output, the event passed is raised and state1 is reentered.

The definition of manifold_B is identical, except that it is initially in state2.

These manifolds are used in main as processes a and b. In the next state after start when the processes are activated, one unit, the string "Unit1" is copied to a and a pipeline from a via b to sysoutput is constructed. Consequently a in state1 consumes one unit and produces two. These units are taken by b (initially being in state2) and moved to its output whereupon b also adds a unit (the string "passed
b.\"n\") and raises the global event passed. In the meantime the pipeline constructed in main moves the all units from the output port of b to the i port of a with a copy of each to sysoutput.

Both a and b switch their states, while in parallel (but not necessarily simultaneously) main receives the event passed from b, breaking up the pipeline and switching to another state in which a different pipeline is constructed. The execution of this MANIFOLD program results in the output:

Unit1 passed a passed b.
Unit2 passed b passed a.
Unit1 passed a passed b.
Unit2 passed b passed a.
Unit1 passed a passed b.
Unit2 passed b passed a.
Unit1 passed a passed b.

... 

If you try this example you might notice that some lines get interspersed due to the fact that the multiple implicit activations of sysoutput result in multiple processes concurrently outputting on the same screen, without proper synchronization. This will be dealt with in § 3.2.

Note further, that in this example manifold_A and manifold_B do logically almost the same thing. It is thus desirable to combine them into one parameterized manifold declaration. This is done in 2.5.

2.5 Parameters.

/* port4.m - parameterized switching connections */
event passed.
main
{
  process a,b is pass_units.
  start: (activate a("a"), activate b("b"), do passed).
  passed_self,
  passed.a: ("Unit1 "-->a, a-->b-->sysoutput).
  passed.b: ("Unit2 "-->b, b-->a-->sysoutput).
}
pass_units(id_string)
  port in id_string.
  {
  event state1, state2.
  start: if (id_string == "a", do state1, do state2).
  state1: getunit(input)-->
  "passed "-->; id_string -->; ","-->; do state2.
  state2: getunit(input)-->; getunit(input)-->
  getunit(input)-->; getunit(input)-->
  "passed "-->; id_string-->; ".\"n"-->
  raise passed; do state1.
}

Figure 11: port4.m: a parameterized manifold.

In Figure 11 the previous example has been rewritten so that the two manifolds are replaced by a single slightly more complex one with one parameter.

The types of formal parameters are declared in the public declaration section of the manifold definition and can be process, port in, port out, or event.

Process parameters can be (de)activated, appear in pipelines, appear as "source" in the label of a handler block and can be passed on as actual parameter for process or port formal parameters in activating other manifolds.
Port parameters can appear in pipelines (as source/sink for port in/port out, respectively) and can be used as port parameters in activating other manifolds.

Event parameters can appear in the primitive actions do and raise and as event parameters in activating other manifolds. They cannot be used in the label of a handler block.

Manifold names can be overloaded, thus the same manifold name can be used in multiple manifold definitions, provided that their formal parameter type lists differ.

Actual parameters should match their corresponding formal parameters, except that processes are allowed for port in/out formal parameters, where the process name is replaced by process.output or process.input respectively.

2.6 Manners.

/* port5.m - switching connections with a manner. */

event passed.

main
{
    process a,b is pass_units.
}

start: (activate a("a"), activate b("b"), do passed).

passed.a: ("Unit1 "—>a, a—>b—>sysoutput).

passed.b: ("Unit2 "—>b, b—>a—>sysoutput).

} / the keyword 'export' makes a module accessible from

// other files

event state1, state2.

start: if (id_string == "a", do state1, do state2).

state1: getunit(input)—>
    "passed "—>; id_string —>; ", "—>; do state2.

state2: getunits (input, output, 4);
    "passed "—>; id_string—>; ".\n"—>;
    raise passed; do state1.

} manner getunits (source, sink, number)
    port in source. port out sink. process number.
{
    event loop, next, exit.
    process n is variable.

    start: activate n; n = number; do loop.

    loop: if (n <= 0, do exit);
    getunit(source)—>sink; n=n−1; do next.

    next: do loop.

    exit: deactivate n; return.
}

Figure 12: port5.m: manners (subroutines) with parameters.

In the previous example the construct "if" was used, which in MANIFOLD is not a language primitive, but rather a built-in manner, which is a subroutine-like language construct in MANIFOLD. An example is in Figure 12, where the repeated use of getunit in state2 has been replaced by one manner call to getunits, designed to move a parameterized number of units from one port to another.
Manners look very much like manifolds. They may have parameters, private processes and events, and labeled blocks with the same expressions and primitive actions as manifolds.

They do not have their own ports (other than parameters), but may have free access to their calling manifold's ports. Also there is no process associated with manners, each process may call any manner using the same syntax as for implicit activation. They cannot appear in pipeline or group constructs, however, since they do not have ports.

Manners have two additional formal parameter types: \textit{manner} and \textit{group}. The actual parameter must be: a possibly nested manner call or a possibly nested expression containing pipelines, groups, and primitive actions.

Manners differ from manifolds primarily by their behaviour: when in a manner, any label in that manner overrides the same label in the calling environment. Thus they enable the calling manifold to change the way (or the manner) in which it reacts to events from the outside world, hence the name.

```c
/* \texttt{port6.m} - delayed switching connections. */
extern event passed. // \textit{extern events} can be shared across files.

\text{pass units (id\_string)} // to import a module defined in another file,
\text{port in id\_string.} // its declaration must be repeated and the
\text{import.} // keyword \textit{import} replaces the body

\text{of the manifold.}

\textbf{main}
\{
  \text{process a,b is pass units.}
  \text{start: (activate a("a"), activate b("b"), do passed).}
  \text{passed.self,}
  \text{passed.a: delay (10); ("Unit1"->a, a->b->sysoutput).}
  \text{passed.b: delay (10); ("Unit2"->b, b->a->sysoutput).}
\}

\text{manner delay (number) port in number.}
\{
  \text{event loop,next, exit.}
  \text{process n is variable.}
  \text{start: activate n; n = number; do loop.}
  \text{loop: n = n - 1; if (n == 0, do exit); do next.}
  \text{next: do loop.}
  \text{exit: deactivate n.}
\}
```

Figure 13: \texttt{port6.m}: manner delay.

More often, however, they are used just like a subroutine: to isolate parts of code that group naturally together and/or occur often, so that a decomposition of code into more manageable smaller modules can be achieved.

When the Manifold processor enters a manner, the set of observable events increases by the events in the handler block of the manner and decreases when the manner is left.

When in a manner a preemptable event is caught for which the manner has no handler, but its calling environment (e.g. the manifold) has one, the manner execution is abandoned and the corresponding handler block in the calling environment is invoked.

Preemptable events are events whose sources appear in the current block, some system-defined events, and all events whose sources have been declared permanent by the MANIFOLD programmer.

Preemption of manners will be treated in more detail in \S 3.2.3.

Some final notes about the example. First, the built-in manner \textit{if} is used twice with a different parameter set. This is an example of overloading and the two if's are really implemented as different manners. In both cases the first parameter is an expression involving logical operators e.g. "$=\" and "$\leq\". This will be explained in more detail in the next section. The second parameter is "do event". This is
an example of a primitive action as an actual parameter for a group type formal parameter.

Finally, if you try these examples, your output should become increasingly interspersed beyond the point where it is meaningful. In Figure 13 a simple delay has been inserted before setting up new connections; the delay itself is programmed as a manner containing an adjustable idle loop. This has the effect, that the process setting up a new instance of sysoutput is delayed sufficiently to allow the previous instance to finish. This method is not generally usable since the loop count causing the delay may need to be adjusted for each run; a sound method to accomplish synchronization using semaphores will be discussed in § 3.2.

/* port7.m - separate compilation of modules */

// 'extern events' can be shared across files
extern event passed.

// 'export' manifolds/manners can be 'import'ed in other files
export pass_units (id_string)

{ port in id_string,
    event state1, state2.
start: if (id_string == "a", do state1, do state2).
state1: getunit(input)->;
    "passed "->; id_string ->; ","->; do state2.
state2: getunits (input, output, 4);
    "passed "->; id_string->; ".\n"->;
    raise passed; do state1.
}

manner
getunits (source, sink, number)

{ port in source. port out sink. process number.
    event loop, next, exit.
    process n is variable.
start: activate n; n = number; do loop.
loop: if (n <= 0, do exit);
    getunit(source)->sink; n = n - 1; do next.
next: do loop.
exit: deactivate n; return.
}

Figure 14: port7.m: export modules to allow separate compilation.

The program in Figure 13 is not complete, the parts that have not been changed have been stored in another file as in Figure 14; the modules that are to be used in other files are prepended with the keyword export and the events that are to be shared between files are prepended with the keyword extern. These files are typically suited to build object libraries from. The header of the modules which are defined in other files must be declared in all files where they are used, with the keyword import as their bodies. These declarations typically go into include files corresponding to object files in libraries. The commands:

Manifold> manif -M3 port6.m
Manifold> manif -o port7 port7.m port6..o

will compile the MANIFOLD program contained in the file port6.m and halt after the third stage of the compilation process, leaving the object code in port6..o; then the program modules in port7.m will be compiled and linked with that object file to produce an executable port7.
2.7 Atomic Processes and Operators.

In MANIFOLD the real computation is done by atomic processes. In all examples so far, we silently used some of them, which are already built-in in the MANIFOLD language and compiler (e.g. `sysoutput`, `variable` and operators like "=" (equal), "-" (minus)).

```c
sysoutput atomic.
pragma atomic internal sysoutput.

main
{
    start: "Hello programmer.\n" -> sysoutput.
}
```

Figure 15: atom1.m: atomic process wrapper declaration.

The MANIFOLD programmer can also define and activate his own atomic processes. Not using the built-in mechanisms, the “Hello” program in Figure 1 can be rewritten as in Figure 15, containing the declarations for the necessary atomic process wrapper, which consists of an atomic declaration similar to an `import` declaration, and a `pragma` specification. The latter is not part of the MANIFOLD language proper, but gives the MANIFOLD compiler instructions on how to generate the correct code.

```c
#include "ap_interface.h"

void sysoutput(mf, parent)
    void *mf, *parent;
{
    int port, size;
    char unittype;
    apEvent event;
    apSource *source;

    while (1) {
        switch (ap_wait Anything (mf, &port, &event, &source)) {
            case EVENT:
                if (ap_events_equal (&event, mTerminate)
                    || ap_events_equal (&event, mDisconnected)))
                    ap_terminate (mf);
                    break;
            case UNIT:
                unittype = ap_unit_type (mf, port);
                if (unittype == STRING)
                    printf ("%s", ap_peek_unit_data (mf, port));
                ap_delete_unit (mf, port);
                    break;
            }
        }
```

Figure 16: atom1.c: an atomic process in C.

For the MANIFOLD compiler, the atomic declaration really defines a complete module. It is to be regarded as a `manifold` containing the MANIFOLD part of the atomic process interface.

If the same atomic process is to be used in another file, the same `import` declaration is needed in that file as for manifolds. In the file that generates the wrapper manifold, the `export` keyword must be
inserted before the atomic declaration.

The guest-language dependent interface consists of a function library and an associated include file: ap_interface.h. An example of how you can write your own sysoutput atomic process in the language "C" (capable of only printing strings) is given in Figure 16; more complete information is available in the reference manual[6].

With this interface a number of built-in atomic processes have been realized, these are listed in Table 1 and are used in our examples.

Further, some arithmetic (+,-,*, /, % and mod) and logical (<, >, <=, >= and !=) operators are recognized by the MANIFOLD compiler and transformed into the implicit activation of appropriate atomic processes. All these processes take two operands and (if operands each deliver one unit with matching types) produce one unit containing the result on their output ports and then terminate when their output ports become empty.

2.8 Debugging.

A limited low-level debugging facility is available by specifying the "-d1" flag in the "manif" compile-and-link command. This results in logging the flow of control of the user program by the MANIFOLD run-time system on stderr (state transitions, manner calls, process switching and process termination). The debugging output log of the program in Figure 12 may look like:

```
1000007 : enter __main__block_169__
1000007 : leave __main__ block
1200008 : enter __pass_units_iblock_83__
1400009 : enter __pass_units_iblock_83__
1000007 : enter __main__block_170__
1200008 : continue __pass_units_i block
1400009 : continue __pass_units_i block
1200008 : leave __pass_units_i block
1400009 : leave __pass_units_i block
1200008 : enter __pass_units_iblock_84__
...
1400009 : enter __getunits_iopblock_128__
1400009 : continue __getunits_iop block
1400009 : jump out __getunits_iop block
1400009 : enter __getunits_iopblock_130__
...
1200008 : leave __getunits_iop block
1200008 : enter __getunits_iop_halt_block__
1200008 : leave __getunits_iop_halt_block__
```

The first column identifies each process, the next column a control action and an identifier referring to the current state; this identifier consists of a manifold/manner name and a block number; each labeled block in the original MANIFOLD program becomes a numbered block at run-time, in the same order. The control actions displayed during logging are:

- enter - control has been transferred to the displayed block
- leave - control will be transferred from the end of the displayed block to another block
- continue - a preemptable point (";" and implicit activation) in the displayed block has been passed
- jump out - control will be transferred from the displayed block to another block by preemption, that is before the actions at the end of the current block have been executed

When logging is enabled, relative timing of processes may change, so the program behaviour may differ from the behaviour with logging disabled (compiled without "-d1" flag); consequently the interpretation of the logging output must be done with an appropriate pinch of salt.
| pass | D | move all units from ‘input’ to ‘output’ |
| pass1 | DT | move one unit from ‘input’ to ‘output’, then halt |
| count(limit,event) | D | as ‘pass’, but raises ‘event’ for each unit passed after ‘limit’ units have been passed silently |
| count1(limit,event) | DT | as ‘count’, except that it halts after raising ‘event’ once |
| CountThenPass(limit,event) | D | as ‘count’, except after raising ‘event’ it waits to be reconnected on its ‘output’ port (receives both ‘disconnected_o’ and ‘connected_o’), then passes the remaining units silently |
| trigger(pattern,event) | DT | as pass, but it raises ‘event’ and halts as soon as a unit matches ‘pattern’; that unit is not passed |
| PermConn(prod, cons) | P | set up the pipeline “prod > cons”, ‘prod’ and ‘cons’ are processes; this pipeline is permanent in the sense that it will not be broken until either this instance of ‘PermConn’, ‘prod’ or ‘cons’ halt. |
| PermConn(pi,po) | P | as ‘PermConn’ above, except that formal parameter types are: ‘port in’ and ‘port out’ for ‘pi’ and ‘po’ respectively |
| variable | P | whenever ‘connected_i.input’ is received, take one unit from ‘input’, store it and produce it on ‘output’ whenever ‘connected_o.output’ is received |
| read (filename,mode,size) | E | I/O interface processes. |
| write(filename) | D | ‘read’ and ‘sysinput’ will produce units on ‘output’, ‘mode’ can be any valid unit type (BOOL, CHAR, INT, FLOAT, STRING, PROCESS_REF, PORT_REF, EVENT_REF) |
| sysinput (mode,size) | E | the others (output processes) take units from ‘input’. |
| sysoutput() | D | ‘mode’ can be any valid unit type (BOOL, CHAR, INT, FLOAT, STRING, PROCESS_REF, PORT_REF, EVENT_REF) |
| perm_sysoutput() | P | ‘filename’ must be a string representing a valid filename; |
| perm_syserror() | P | otherwise event ‘bad_filename’ will be raised. |
| perm_write(filename) | P | The output processes postpone halting until they have received ‘disconnected_i.input’. |
| if(cond, then) | M | manner that executes ‘then’ if ‘cond’ delivers ‘true’ |
| if(cond, then, else) | M | as ‘if’ above, plus ‘else’ (same types as ‘then’) is executed when ‘cond’ delivers ‘false’ |

**Termination conditions:**

- **D** = Disconnect, halt after receiving ‘disconnected_i.input’
- **E** = EOF, halt after receiving EOF in the file and port ‘output’ is empty
- **M** = Manner
- **P** = Perpetual, halt after receiving ‘terminate’
- **T** = Temporary, halt after performing its function once

Table 1: **MANIFOLD** builtin process library.
3  Manifold Programs.

In this section some larger working MANIFOLD programs are presented, each with a short description of their operation.

3.1 Fibonacci series.

![Diagram of Fibonacci series program]

In the middle is of the figure a process named \texttt{add}, an instance of the manifold \texttt{add2streams}, which has two input ports (input and input2). This process repeatedly takes one unit from each of its input ports, adds them, and puts the result on its output port. This unit is copied and moved both to the implicitly activated manifold \texttt{io} (for outputting on the screen) and the process \texttt{Fn\_1}, an instance of \texttt{pass}, which copies each unit from its input port to its output port. This unit is copied and moved both to process \texttt{Fn\_2} and the input2 port of \texttt{add}. The \texttt{add} process also needs the previous unit on input from \texttt{Fn\_2}, to produce the next unit $F(n + 1) = F(n) + F(n - 1)$ in the Fibonacci series.

3.1.1 Program description.

Figure 17 shows a network of processes aimed to produce the Fibonacci series at the input port of \texttt{io}. This series is defined as:

$$
\begin{align*}
    f(0) &= 1 \\
    f(1) &= 1 \\
    f(n) &= f(n - 1) + f(n - 2)
\end{align*}
$$

Annotations used:

\begin{itemize}
    \item \texttt{Fibonacci} - Manifold 1.0 program to compute Fibonacci series,
    \item $F(n) = F(n-1)+F(n-2)$ for $n>=2$, $F(0) = 1$, $F(1) = 1$.
    \item first unit on ‘stdin’ is # of iterations;
    \item on ‘stdout’ the index and the Fibonacci number are printed.
    \item Annotations used:
\end{itemize}
/* M - manner
 * P - permanent process  (does not die)
 * L - long living process (does not die immediately)
 * T - temporary process  (dies immediately after activation and/or connecting)
 */
#include <built_in.i>  // contains declarations for builtin (atomic) processes

/* P
 * main - setup network of processes to compute and the Fibonacci series up to
 * 'limit' elements, which is the first unit on port 'input'.
 */
main
{
    process add  is add2streams.  // P.
    process Fn_1,
           Fn_2  is pass.  // P.

    /* read # of iterations from standard input */
    start: activate limit; activate Fn_1; activate Fn_2; activate add;

    syserror = "Please enter limit (max 47): ";
    limit    = sysinput(mINT, 32);
    syserror = "Limit = ";
    syserror = limit;
    syserror = "\n";

    /*
     * 'Fn_1' lags behind 1 unit, 'Fn_2' lags behind 2 units, so that:
     * on 'add.output' each unit F(n) = F(n-1)+F(n-2).
     */
    (0->Fn_1,
     1->Fn_2,
     Fn_1->add.input2,
     Fn_1->Fn_2->add->Fn_1->io
    ).
}

/* P
 * add2streams - take pairwise all units from both port 'input' and 'input2',
 * and put the sum of each pair in port 'output'
 */
add2streams port in input2.
{
    process a,b  is variable.  // P.
    event  get, loop.

    start: activate a; activate b; do get.
    get: getunit(input) ->a;  // variables 'a' and 'b' needed, because
        getunit(input2) ->b;  // 'getunit' cannot be an argument of '+'
        a+b->;
        do loop.
    loop: do get.
}

/* P
 * io - print and count each unit arriving on port 'input';
 */
* shutdown if 'limit' (global) is reached
*/

process limit is variable. // P.

io
{
    event loop, next, exit.
    process sysout is perm_sysoutput.
    process index is variable. // P.

start: activate sysout;
activate index;
index = 0;
do loop.

loop: index ->pass1 ->sysout;
     "\t" ->sysout;
getunit(input) ->sysout;
     "\n" ->sysout;
index = index + 1;
if (index >= limit, do exit);
do next.
next: do loop.

exit: cancel.
}

3.1.3 Comments.

The program starts with activating the necessary processes, then asks the user for input and sends the user input (from sysinput) to the process limit, which is an instance of variable.

Here the use of an auxiliary process, the implicitly activated instance of pass1 (which copies one unit from its input port to its output port and then halts) is needed because otherwise the program would hang (the pipeline 'sysinput(...) -> limit') would never break because neither of these two processes halt [1].

This is an example of the pipeline breakup problem. Other problems when using pipelines with multiple ->'s may arise when one or more participating processes halt, because the resulting flow of units is then undetermined in general.

For example, if the pipeline containing the welcome message
"Please enter limit:"->syserror
would contain a pass1, e.g:
"Please enter limit:"->pass1->syserror
there is a great probability that this whole pipeline will be broken before the unit containing the string reaches syserror because a constant is defined on page 35 in [1] to behave like an implicitly activated process, putting one unit on its output port and terminating subsequently. As a result, nothing would be visible in most runs of the program.

Therefore multiple ->'s are only safe to use when all processes in the pipeline are perpetual (i.e. they never halt).

To move one unit between processes or ports it is generally safe to use the assignment operator "=".

3.2 Binary semaphores.

A binary semaphore is an entity S upon which two operations are defined: P(S) and V(S) defined (see, for example ref.[8]). When the operation P(S) completes, the process executing that operation has
exclusive access on the semaphore $S$ until it executes the operation $V(S)$, meaning that during this time the operation $P(S)$ will not be completed for any other process. Such a process will be delayed until the process for which $P(S)$ has been completed executes $V(S)$. The operation $P(S)$ is an *indivisible operation*, which means that if two or more processes execute $P(S)$ simultaneously, the operation completes for one of them while the other processes will be delayed until the process that has been granted the lock, executes a $V(S)$.

### 3.2.1 Program description.

![Diagram of semaphore operations](image)

connections involved in requesting/releasing a semaphore

connections involved in processing a lock request

connections involved in releasing a lock and granting the next request waiting

Figure 18: Processes involved in semaphore implementation; process networks needed for both setting and releasing a lock are shown.

The operations on semaphores are implemented as two manners `getlock` and `freelock` for $P$ and $V$ respectively, each having one process argument. The actual argument when called must be a global process being an instance of manifold lock which is also defined in this file.

`getlock` activates the lock process (which is a no-op if it was already active) and sends a unit to it containing a unique reference to the process requesting the lock (&self). Next it repeatedly checks on the output of the lock process until the lock has been granted\(^1\), then returns to the caller.

`freelock` releases the lock by sending a special unit to the lock process (containing a unique reference to predefined void).

The lock process itself works as follows. When lock requests units are available on its input port, each unit is taken, stored in the variable `tmp` and inspected to see if it is a $P$ or a $V$ request (a reference to `void` is $V$).

For a $P$, lock request, when the lock is available (`procref == &void`), the request is granted: the process reference of the requestor is put both in `procref` and on the output port. When the lock is not

---

\(^1\)This is busy waiting. A more efficient implementation is possible by declaring a private event in `getlock`, sending a reference to that event to `lock`, and wait until `lock` raises that event. This method is used in § 3.3.
available, the process reference of the requestor is put on "the other side" of the input port \texttt{waitbuffer}, where it will remain queued up behind other request until all lock requests in front have been granted and released.

For \texttt{V}, release request, the next unit in \texttt{waitbuffer} will be granted as before; if \texttt{waitbuffer} is empty, the port event disconnected\_i.\texttt{waitbuffer} will be raised by the system to indicate that fact and then \texttt{procref} is reinitialized to \&\texttt{void}.

### 3.2.2 Program listing.

\begin{verbatim}
// sema.m - binary semaphore in Manifold 1.0
#include <built_in.i>
define manifold
#define P(x) getlock(x)
define V(x) freelock(x)

  export manner
getlock (p)  
  process p.
  {
    permanent p.
    event check, waitp, put.

    start: activate p;     // init lock process
    do put.
  }

  put: putunit(&self,p);
    do check.       // lock events while
    // setting the lock
  
    check: if (p != &self, do waitp);
      return.       // was granted
  
  waitp: do check.     // else wait for p

  export manner
freelock (p)  
  process p.
  {
    start: &void->p.     // free the lock
  }

  export manner
putunit (pi,po) // put one unit 'pi' on destination 'po'
  port in pi.
  port out po.
  {
    process p1 is pass1.

    start: (activate p1, pi->p1, p1->po);
    deactivate p1.
  }

  manner
grant
  process tmp, procref dynamic.
  event wait, give dynamic.
  {
    start: putunit (tmp, procref);

\end{verbatim}
do give.
}
manner
release
    process procref dynamic.
    event wait, give dynamic.
    port in waitbuffer dynamic.
{
start:  getunit (waitbuffer) => procref;
do give.
disconnected_i.waitbuffer:
    &void => procref.
}
manner
handle_unit
    process tmp, procref dynamic.
    port in waitbuffer dynamic.
{
start:  if (tmp == &void, release);
        if (procref == &void, grant);
        putunit (tmp, self.waitbuffer).
}
export manifold // read and store process references from 'input',
lock  // or references to 'void' to release the lock.
    port in waitbuffer.
{
    // on output port, produce ref. to process
    // to which the lock has been granted.
    process procref, tmp is variable.
    event give, wait, getunits, nxtunit.

connected_o.output:
    // if the lock is available, grant it,
    // otherwise the consumer will hang until it is released
    if (procref == &void, &void=>output);
do wait.
c connected_i.input: save.
g getunits:
    getunit(input) => tmp;
    handle_unit;
do nxtunit.
g give:  putunit(procref, output);
do getunits.
nxtunit: do getunits.

start:  activate procref; &void=>procref;
        activate tmp; &void=>tmp;
do wait.
c connected_i.input: save.
c connected_o.output: save.
wait: void.
c connected_i.input: do getunits.
}/*
 * test program for getlock, freeloack.
process testlock is lock.

test (p) process p.
{
  event next.
  start: P(testlock);
    syserror = p; syserror = "has lock.\n";
    V(testlock);
    do next.
  next: do start.
}

manner

starttest (n) process n.
{
  event exit.
  process nm is variable. // ‘n’ minus 1
  process ntest is test. // ‘n’th instance of test
  start: activate nm1;
    nm1 = n - 1;
    activate ntest (n);
    if (nm1 == 0, do exit);
    starttest (nm1).
  exit: deactivate nm1.
}

main
{
  process Nproc is variable.
  start: activate Nproc;
    syserror = "Please enter Nproc (# of parallel test processes): ";
    Nproc = sysinput(mINT, 32);
    syserror = "Nproc = ";
    syserror = Nproc;
    syserror = "\n";
    starttest (Nproc).
}

process printlock is lock.
    export manner

print(x) port in x.
{
  start: P(printlock);
    sysoutput = x;
    V(printlock).
}

/*
 * usage of getlock, freelock.
 */
    export manner

print(x1,x2) port in x1,x2.
{
  start: P(printlock);
    sysoutput = x1;
    sysoutput = x2;
V (printlock).
}

export manner
print(x1,x2,x3) port in x1,x2,x3.
{
start: P (printlock);
sysoutput = x1;
sysoutput = x2;
sysoutput = x3;
V (printlock).
}

// clean up print lock process
export manner
deactivate_print (mess) port in mess.
{
start: print (mess);
deactivate printlock.
}

export manner
deactivate_print
{
start: deactivate_print ("Deactivating printlock...\n").
}

3.2.3 Comments.

This example shows various aspects of the usage of (input) ports. Since non-flushing streams have unlimited capacity used as FIFO queues ([1], page 6), the input port waitbuffer can be used as a storage buffer for pending lock requests.

The connections between various ports in this example are all transient, they are broken as soon as one unit has passed (e.g. manner putunit).

Multiple connections to and from each port may exist at any time (e.g. port input of lock in Figure 18); each time when the first connection is made to or from a port the event connected_i or connected_o is raised respectively ([1], page 37-38); similarly each time when the last connection to or from a port is broken (and buffers are empty) the event disconnected_i or disconnected_o is raised respectively.

The source of these events is self, and they are always permanent event sources (the MANIFOLD programmer may declare permanent event source using the permanent declarative, see [1], page 22).

Great care has to be taken in utilizing permanent event sources simultaneously with manner calls, which are used passim (e.g. assignment "=" and sequential operation ";" are manner calls). These manner calls may end prematurely when preempted by a permanent event source such as a port producing an event. For example, when this happens in the manner print in the above program after the call P(printlock) but before the call V(printlock), this lock will never be released and on the next call P(printlock) deadlock will result.

This is an example of the manner preemption problem. The only method to avoid this, is that the originator of permanent event sources defines a save block for these events, placed in such a way that all manner calls used in the whole MANIFOLD program may return normally, i.e. not being preempted by an event from a permanent source. The place for a save block must be chosen such that when a circular search is initiated through all handler blocks to find a handler for that event, a handler containing the keyword save will be found.

This is shown in the above program, the manifold lock needs to utilize both connected_i.input' and connected_o.output' and has all handler blocks protected where manners are used by appropriate save handler blocks.

24
3.3 Dining Philosophers.

The dining philosophers problem is a classical example of resource sharing between a number of simultaneously active entities (see e.g. ref [8]). Five active entities ("philosophers") are sitting at a round table each equipped with one chopstick and wanting to eat; however to be able to eat each philosopher needs two chopsticks; after completing the meal (in finite time) each philosopher drops both chopsticks so that they become available for other neighboring users.

The problem is to devise and implement a scheme (algorithm) so that each of them will be able to eat, with equal probability in the long run. For example, when they all would start attempt to eat together at the same time, nobody gets two chopsticks and nobody would ever eat while waiting for their neighbor's chopstick to become available (deadlock); when they would release the left chopstick when the right chopstick is not available (so that a neighbor gets a change to eat), there exists the probability that when they all do this repeatedly at the same time, nobody ever gets two chopsticks (starvation).

This problem can be elegantly modelled and solved using binary semaphores as shown in ref [8]; here we model the problem using the communication mechanisms available in MANIFOLD after an original idea of F. Arbab.

Figure 19: The Dining Philosophers Problem in MANIFOLD.
To the left, two philosophers competing for two chopsticks to the right. Philosopher 1 got both chopsticks, they send them events for which philosopher 2 has no handler. The stream of units is depicted as to be just after philosopher 1 requested both chopsticks, but prior to this moment the events shown have been raised by the chopsticks.

3.3.1 Program description.

Philosophers and chopsticks are implemented as communicating processes implemented in MANIFOLD. In Figure 19 the minimum configuration of two philosophers and two chopsticks is shown.
In the recursive manner create_philosopher (initially called by main) two new process instances are declared and activated, one for a philosopher and one for its right chopstick, while the left chopstick, belonging to its previously declared neighbor, is passed as a parameter. Only for the last philosopher a different scheme is used, its right chopstick is the globally declared process firstchopstick, which has been activated by main.

Each philosopher in its start block sends three units to both its right and left chopsticks under global semaphore protection. These units are references, denoted by a "&", to a local event ready, self (the philosopher process) and name (an integer only used for printing purposes), in that order. Thereafter, the philosopher goes into a wait state, to be taken out by events from any of the chopsticks he wants.

Now if two philosophers send this package of three units at the same time to the same chopstick, by the semaphore protection one package will be queued after the other.

The chopsticks, in the manner waitfor_user, take these units from their input ports, and dereference them to local names goahead, user, and user_id.

Having done this, the event goahead is raised. Since this was originally a local event, it can only be picked up by the philosopher from which it originated. The chopstick, in *waitfor_user*, waits there until an event from *user* breaks this group.

The philosopher awakes, find that the event ready had been fired from one of its chopsticks, goes into the corresponding state, and waits in a manner for the other chopstick to become available. When this happens, the statement "do ev" is executed, for which there is no handler in the manner. But there is one in the calling scope, eat. Thus the manner execution is preempted (returned from) and the state labeled *eat* in philosopher is entered. In this state the event done is raised, which is picked up by all processes which are susceptible for it (i.e. preemptable by it). These are both chopsticks, in the manner *waitfor_user*. Again, a "do" is executed, for which there is no handler, but there is one in the calling scope, chopstick. So the manner execution is preempted and the actions at the label next are executed, which is simply "do start". Therefore the process repeats its cycle calling the manner *waitfor_user*, in there dereferencing the triple, etc.

At the same time, the philosopher repeats its cycle by executing "do start", putting three reference units under semaphore protection on the input ports of both its chopsticks.

### 3.3.2 Program listing.

```c
/* dinphi.m - dining philosophers problem in Manifold 1.0 */
#define NUMBER_OF_PHILOSOPHERS 5
#include <built_in.i>
#include "sema.i" // contains declarations for processes defined in "sema.m"

event done.
  manner
  waitfor_user
    process n dynamic.
    event next dynamic.
  
  event goahead deref input.
  process user deref input.
  process user_id deref input.

start: (raise goahead, user).

done user:
  print("Philosopher ", user_id, "drops chopstick ", n, ", ".\n"");
  do next.
}

chopstick (n) process n.

port in input.
```
{  
  event next.

start: waitfor user.
next: do start.
}

manner
waitfor rightchopstick (ev)
  event ev.
  process name dynamic.
  process rightchopstick, rightchopstick_id, leftchopstick_id dynamic.
  event ready dynamic.
{
  event wait.

start: print ("Philosopher ", name,
  "takes in left hand chopstick ", leftchopstick_id, ".\n")
  do wait.

ready.rightchopstick:
  save.
wait: rightchopstick.
ready.rightchopstick:
  print("Philosopher ", name,
  "takes in right hand chopstick ", rightchopstick_id, ".\n")
  do ev.
}

manner
waitfor leftchopstick (ev)
  event ev.
  process name dynamic.
  process leftchopstick, leftchopstick_id, rightchopstick_id dynamic.
  event ready dynamic.
{
  event wait.

start: print ("Philosopher ", name,
  "takes in right hand chopstick ", rightchopstick_id, ".\n")
  do wait.

ready.leftchopstick:
  save.
wait: leftchopstick.
ready.leftchopstick:
  print ("Philosopher ", name,
  "takes in left hand chopstick ", leftchopstick_id, ".\n")
  do ev.
}

process put 3 units is lock.

philosopher (name, leftchopstick, rightchopstick,
  leftchopstick_id, rightchopstick_id)
  process name, leftchopstick, rightchopstick,
leftchopstick_id, rightchopstick_id.

{ event ready, next, eat, restart.

ready.leftchopstick:
    waitfor_rightchopstick (eat).
ready.rightchopstick:
    waitfor_leftchopstick (eat).
eat:
    print("Philosopher ", name, "is dining.\n");
    raise done;
    print("Philosopher ", name, "is thinking.\n");
    do start.
start: P (put3units);
    &ready→(→leftchopstick, →rightchopstick);
    &self→(→leftchopstick, →rightchopstick);
    &name→(→leftchopstick, →rightchopstick);
    V (put3units);
    do next.
ready: save.
next: (leftchopstick, rightchopstick).
}

} process
firstchopstick is chopstick.
manner
create_philosopher (nparam, leftchopstick, leftchopstick_id)
    process nparam, leftchopstick, leftchopstick_id.

{ process n is variable.
    process rightchopstick is chopstick.
    process this_philosopher is philosopher.
    event last, quit.

start: activate n;
    n = nparam;
    if (n < 1, do quit);
    if (n == 1, do last); // if commented out, sit at straight table
    activate rightchopstick (n);
    activate this_philosopher (n, leftchopstick, rightchopstick,
    leftchopstick_id, n);
    create_philosopher (n-1, rightchopstick, n).
last: activate this_philosopher (n, leftchopstick, firstchopstick,
    leftchopstick_id, 1).
quit: deactivate n.
}

main
{
start:
    activate firstchopstick (1);
    create_philosopher (NUMBER_OF_PHILOSOPHERS, firstchopstick, 1).
}
3.3.3 Comments.

In this example several new features of the MANIFOLD language are introduced:

- the reference operator `&`, which can be used for event names, process names and local port names. This is a primitive action, producing one unit representing its operand that can be forwarded through pipelines.

- the keyword `deref`, which can be used as an attribute after event, process or port declarations in the private declaration section of a manifold or manner. The keyword `deref` must be followed by a port name (of type `port in`), a process name or a process `port` (of type `port out`) construct. It is the programmers responsibility to guarantee that the type of the units coming out of the specified port at run-time match the specified declarative, otherwise the result is unpredictable and the manifold may hang. In the example this is achieved by placing semaphores around the reference producing actions. (Another method is packing multiple units into one, and unpacking them in the deref port using regular expressions, a topic which is not treated in this document).

The result of the deref declarative is that the declared name can be used in the same way as the original object that was the operand of the matching reference action, except that dereferenced events cannot appear in the label section of handler blocks.

- distribution of a pipeline over a group: the reference units are passed to multiple destinations in one action using the `group` construct `("",",",",")` and properly placed `"->"` operators (MANIFOLD specification [1], page 30-31).

Note that in the manner `create_philosopher` the first parameter `nparam` is copied into the active local process `n` (variable). This is not necessary when actual parameters are constant processes, variable processes, or other processes which are designed to repeat producing the unit on an output port each time they are connected on that port. It is necessary, however, if the actual parameter is an expression (e.g. `n-1`), since the processes to which operators like `"-"` (minus) map are designed to terminate after producing one unit (MANIFOLD specification [1], page 42).

In other words, in MANIFOLD, there is no call-by-value mechanism since the notion of a value, variable or data does not exist in the MANIFOLD language. The only notions are events, processes, ports and connections between ports. If in the example program the `formal` parameter `nparam` would have been used everywhere instead of the locally declared `variable` process `n`, the program would hang at the second `if` manner call in the second call of the manner `create_philosopher` (first recursive call).

3.4 Bucket sort.

The idea of the "bucket sort" example is to split an unsorted input stream into a number of unsorted "buckets" to be sorted in parallel by an equal number of sorters; then merge the output of all of them together to form one sorted output.

Since in general the sort is the hard part, parallelism is potentially advantageous here; splitting and merging are obviously potential bottlenecks.

This example originally appeared in ref. [2].

3.4.1 Program description.

The program consists of two manifolds and one atomic process which are instantiated (created and activated) recursively, called `sort`, `merge` and `AtomicSort`. Further, there is an atomic process `read`, and one instance the manifold `CountCheck` (Figure 20). The actual sorting is performed by the atomic process `AtomicSort`. In the example it sorts only two units but the idea is that it can take any number of units. In a loop, `CountCheck` passes units from its `input` port to its `output` port while counting them until the parameter limit has been reached. Then it raises the global event `CountReached` and waits for the event `connected` on its `output` port, whereupon it reenters its main loop. Moreover, all units are inspected to match a second parameter (`target_var`). When this happens, the event `TargetFound` is raised and the manifold attempts to terminate, but does not do so before all pending units (if any) on its
Figure 20: Bucket sort in MANIFOLD for 5 unsorted units (5,3,4,2,1).
output port have left the port (disconnected_p.output must be received after connected_p.output). This manifold is used to distribute the unsorted units in pairs (limit == 2) over a number of sorter processes. After receiving CountReached, each except the last sorter process, instantiates another sorter, a merge process and an atomic_sorter process in the manner SplitSort. The last sorter connects the (sorted) output from its atomic_sorter to its own output port, which, in the recursive network of processes one level higher, is connected to one of merge's two input ports. The other input port of merge is connected to the output port of the next atomic_sorter and the output port of merge is connected to the output port of the next sorter, etc.

In main, the unsorted units are read from file and pipelined to counter followed by a special unit EOF on which counter checks; further the output of the topmost sorter is pipelined to sysoutput, so that the sorted units may be inspected and/or stored.

The code of the merge manifold is straightforward and its explanation is left as an exercise (except for the manner Getunit it uses, which is explicated below).

3.4.2 Program listing.

```c
// sort.m - Bucket sort in Manifold 1.0. Input from file 'unsorted'.

// CountCheck - copy units, count and hold them, and check each one.
// SplitSort - recursively create and set up sorters and mergers.
// Sort - sort units coming from the global 'counter' process,
//        putting the first N in an atomic sorter and calling
//        SplitSort to take care of the rest
// main - read units, send them to 'counter', start up the sort.

#define EOF "EOF"
#define NUNITS 2

#include "built_in.i"
#include "sema.i"

AtomicSorter() atomic.
   pragma atomic internal AtomicSorter().

manifold
Merge() port in a. port in b. import. extern event MergeDone.

manner
Getunit (pi, unt, label)
   port in pi. process unt. event label. import.

   extern event
   TargetFound, CountReached, PortEmpty.

/*******************/
// CountCheck - copy all units from port 'input' to port 'output'
// counting until 'limit' is reached and checking them to see if
// there is a unit matching 'target_var'.
// In the former case, 'CountReached' is raised and the manifold
// suspends copying units until it senses a 'new' connection on its
// output port.
// In the latter case (there is a unit matching 'target_var'):
// - if there are units left in 'output', 'TargetFound' is raised
//   and the manifold waits until its 'output' port has become
//   empty, then terminates;
```
// - if there are no units left in 'outport', 'PortEmpty' is raised
// and the manifold terminates.

manifold
CountCheck (limit, target_var)
process limit, target_var.
{
    process n is variable.
    process unit is variable.
    process targetVar is variable.
    process limitVar is variable.
    process ok_to_die is variable.
    process want_to_die is variable.
    event copy, found, counted,
        loop, next, wait, compare, try_to_die, exit.

start: activate n;
    activate unit;
    activate targetVar;

limitVar;
    activate ok_to_die;
    activate want_to_die;
    limitVar = limit;
    ok_to_die = false;
    want_to_die = false;
    n = limitVar;
    targetVar = target_var;
    do wait.

copy:
    ok_to_die = false;
    n = limitVar;
    do loop.

loop:
    Getunit (input, unit, found);
    if (unit == targetVar, do found);
    unit->pass1->output;
    n = n-1;
    if (n<1, do counted, do next).

next: do loop.

counted: raise CountReached;
    do wait.

found: if (n == limitVar, raise PortEmpty, raise TargetFound);
    want_to_die = true;
    do try_to_die.

disconnected_input, // save for handling by Getunit
disconnected_output,
connected_output:
    save.
wait: (input, output).
connected_o.output:
do copy.
disconnected_o.output:
  ok_to_die = true;
  if (want_to_die == true, do try_to_die, do wait).
disconnected_o.output,
connected_o.output:
save.

try_to_die:
  if (ok_to_die == false, do wait);
  if (want_to_die == false, do wait, 
do exit).
terminate, exit:
  deactivate n;
  deactivate unit;
  deactivate targetVar;
  deactivate limitVar;
  deactivate ok_to_die;
  deactivate want_to_die;
  halt.
}
process
counter is CountCheck.

/**
// SplitSort - create and connect another sorter and merger.
/**

manner

SplitSort

process atomic_sorter dynamic.
{
  process merge is Merge.
  process next_sorter is Sort.

start:
  activate next_sorter,
  activate merge,
  atomic_sorter->merge.a,
  next_sorter ->merge.b, merge->output
}).
MergeDone. merge:
  return.
}

/**
// Sort - sort units originating from the global ‘counter’ process, 
// putting the first N in an atomic sorter and calling ‘SplitSort’ 
// to take care of the rest. When the input (from ‘counter’) has 
// dried up, direct the output of the atomic sorter, if any, on 
// port ‘output’. If the call is recursive, ‘output’ will be 
// connected by ‘SplitSort’ to a merger process.
/**

manifold

Sort
{ event wait_empty.
    process atomic_sorter is AtomicSorter.
}

start: (activate atomic_sorter,
    counter => atomic_sorter).

TargetFound.counter:
    atomic_sorter => output;
    do wait_empty.

disconnected_i.output:
    save.
    wait_empty:
    output.

PortEmpty.counter,
    disconnected_i.output:
    halt.
    disconnected_i.output:
    save.

CountReached.counter:
    SplitSort;
    do wait_empty.

CountReached.counter,  // these events from 'counter' will be handled
    PortEmpty.counter,  // in nested calls, must be ignored
    TargetFound.counter,  // in this environment
    terminate:
        ignore.
}

/******************************************************************************
// main - read units from file 'unsorted', send them to 'counter', start up
// the sort, connect its output to 'sysoutput' to print them,
*******************************************************************************/

main()
{
    event exit.
    process sorter is Sort.

start: read( "unsorted", mINT, 0 ) => counter;
    EOF => counter;
    activate sorter;
    ( activate counter (NUNITS, EOF),
        sorter => sysoutput).

death.sorter:
    do exit.

exit: deactivate counter;  // cleanup
    halt.
}

merge.m - merge part of sort program in Manifold 1.0
// Getunit - "safe" version of 'getunit'
// Merge - merge two streams from port 'a' and port 'b' to 'output'.
#include <built_in.i>
#include "sema.i"

//****************************************************************************
// Getunit – read unit from input port ‘pi’ into process
// ‘unit’ (is variable); jump to ‘label’ if port is empty.
// Prerequisites:
// ‘unit’ must be activated in the calling environment;
// the caller must have ‘disconnected_i.pi: save.’
//****************************************************************************

export manner
Getunit (pi, unit, label)
  port in pi. process unit. event label.
{
    event it, goon, disncnd.

  start: unit = &goon;
          do it.
  disconnected_i.pi:
    save.
  it:    getunit(pi)->unit;
          do goon.
  disconnected_i.pi:
    do disncnd.
  disncnd:    // regenerate ‘disconnected_i’ to avoid
               // hang in ‘getunit’ on next call
               if (unit != &goon,    // hang in ‘getunit’ on next call
                  (&system->self.pi,
                   getunit(pi)->void
                  ));
          do goon.
  goon:   if (unit == &goon, do label);
           if (unit == &system, do start);
      return.
}

extern event
TargetFound, CountReached, PortEmpty.

extern event
MergeDone.

//****************************************************************************
// Merge – merges all incoming units from port ‘a’ and port ‘b’ to port
// ‘output’. Raises ‘MergeDone’ when ready, then waits for
// ‘disconnected_i.output’ (output flushing).
//****************************************************************************

export manifold
Merge  port in a.
        port in b.
{
  process aVar, bVar    is variable.
  event compare, a_smaller, b_smaller, exit,
        a_loop, a_next, b_loop, b_get, bnext.

  start: activate aVar;
            activate bVar;

Getunit(a,aVar,b_get);
Getunit(b,bVar,a_loop);
do do compare.

compare:
if (aVar < bVar, do a_smaller, do b_smaller).

a_smaller:
output = aVar;
Getunit(a,aVar,b_loop);
do do compare.

b_smaller:
output = bVar;
Getunit(b,bVar,a_loop);
do do compare.

disconnected_i.a,
disconnected_i.b:
save.

b_loop: output = bVar;                      // move rest in b
do b_get.
b_get: Getunit(b,bVar,exit);
do b_loop.

a_loop: output = aVar;                      // move rest in a
Getunit(a,aVar,exit);
do a_next.
a_next: do a_loop.
disconnected_o.output:
save.
exit: raise MergeDone;
output.
disconnected_o.output:
deactivate aVar;
deactivate bVar;
halt.
}

#include <ap_interface.h>

void AtomicSorter (mf, parent)
    void *mf, *parent;
{
    int    port    = ANY_PORT;
apEvent event;
apSource* source = ANY_SOURCE;
int    val[2]; /* value of unit */
int    n = 0;
boolean eoi = false;
while (n < 2 && eoi == false) {
    switch (ap_wait anything( mf, &port, &event, &source)) {
        case UNIT:
            if (port == INPUT) {
                if (ap_getint( mf, INPUT, val+n) != WRONG_TYPE)
                    n++;
            } else ap_delete_unit ( mf, port );
            break;
        case EVENT:
            if (ap_events_equal( &event, mTerminate))
                ap_terminate ( mf );
            else if (ap_events_equal( &event, mDisconnected))
                eoi = true;
            break;
        default:
            break;
    }
}

if (n == 0)
    ap_terminate ( mf );
else if (n == 1)
    ap_putint ( mf, OUTPUT, val[0] );
else if (val[0] <= val[1])
    { ap_putint ( mf, OUTPUT, val[0] );
      ap_putint ( mf, OUTPUT, val[1] );
    } else 
    { ap_putint ( mf, OUTPUT, val[1] );
      ap_putint ( mf, OUTPUT, val[0] );
    }

ap_wait_port_empty ( mf, OUTPUT );
ap_terminate ( mf );
}

void AtomicSorter_cleanup(mf) void* mf; {}
Count would have been implemented as a *synchronous* stream, where each unit leaves its producer port indivisibly at the same time as it is consumed by its consumer port(s).

However, in MANIFOLD streams are *asynchronous* (ref [1], page 6) and many units may have left the local port input, as many as the run-time system can handle, waiting for consumption at Count’s input port, when its counter expires and the process Count dies, together with all these waiting units in its input port.

This is the *lost units* problem; it has been remedied in the present program by taking care that CountCheck does not terminate, but hold its units for the next consumer, until all units have been passed and the last connection on its output port has vanished.

- Next, the manifold *merge* uses a rather peculiar manner *Getunit* to get the units from its input ports instead of the primitive action *getunit*.

This manner gets a unit from its first parameter pi, puts this unit in its second parameter *unit*, and jumps to the label in its third parameter when there are no more units in the specified input port and all connections on this port have been broken. The *disconnected_i* event is used to determine this: when a transfer is attempted on a disconnected input port using *getunit*, the event *disconnected_i* is raised (ref [1], page 28 and 38), which can be used to determine that this port has become empty. However, this same event will also be raised by the system when the number of connections at that port drops from one to zero. This may happen by some external cause, e.g. another process having made and broken a connection to that port.

When this happens simultaneously with the *getunit* primitive action *while preemptable* by the *disconnected_i* event (to check for empty port) and a unit is available (so the port is not empty) the event is nevertheless raised (since the last connection has broken) which could rightly be interpreted to mean that this port has become empty (so there was no unit). In this case sometimes the last unit is lost non-deterministically.

This is the *last unit* problem; it has been remedied by initializing the destination unit (second parameter of Getunit) with a value that nowhere else in the system can exist (*&goon*). After the getunit primitive action it is checked whether the *unit* still has this initial value. If so, it must be concluded that there was no *unit* available. This alone is not sufficient, however. If the last unit is being processed and the event *disconnected_i* is raised simultaneously by breaking the last connection, the next time the getunit primitive action is performed on this port, *disconnected_i* will not be raised any more, because this has already been done. Since there are no more units, the program will hang on this *getunit* primitive action. In order to avoid this, the *disconnected_i* event will be forced in this case, by producing a dummy unit *&system* on this port and a getunit to get rid of the dummy so that on the next call, the desired event will be raised.

As mentioned in the introduction to the present example, it is potentially advantageous to do the hard work in parallel by distributing the *atomicSorter* processes. Since the CountCheck and the Merge manifolds are potential bottlenecks, they should be rewritten as atomic processes. Further, the *atomicSorter* processes should be rewritten to take a more substantial number of units and do an efficient sort on them.

Having done all that, setting up a real distributed application in MANIFOLD is now simple: for instance if it is desired to have all instances of AtomicSorter run in parallel on different processes, the only thing that needs to be added in the source file is the line:

```
pragma weight 10000 distribute AtomicSorter.
```

This instructs the MANIFOLD compiler to generate the code that will enable a primitive load balancer to distribute these processes over a run-time determined number of processors, the weight (by default 100) is the number used for balancing. The load balancer tries to maintain a equal sum of weights on each physical processor.

A more sophisticated example, distributed ray-tracing, where this has been exploited has been described in [7].

---

2 Actually, this is an irreparable error in the implementation of *getunit*. 

4 Conclusions.

A number of actually working programs have been made in MANIFOLD Version 1.0. In implementing and using this new language, a number of problems have been encountered, which probably could not have been detected otherwise.

The most interesting of these are: the last units problem; the manner preemption problem and the last unit problem.

However, despite these imperfections, the MANIFOLD conceptual model based on event-driven asynchronously communicating processes has proven to be implementable and it works.

It is believed that by constraining the programmer to asynchronous communication, the points in a program where synchronization is mandatory will be better understood and the number of these points will be minimized.

Although such a program will be more difficult to design and implement with current programming methodologies, it will run faster than similar programs built on a synchronous language paradigm (as almost all conventional programming languages are) and it will be more easily adaptable to future hardware configuration changes (e.g., massive parallelism).

Therefore a new coherent version of the MANIFOLD language must be designed, implemented and tested taking into account as much as possible from what has been learned in the first experimental version. Furthermore the importance of the development of new programming methodologies must be stressed (e.g., visualization of MANIFOLD program execution, proof systems for correctness of MANIFOLD programs, object-oriented MANIFOLD on top of the base language to deal with more complex problems).

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References