A Mathematical Model and Refinement Relation for a CSP-Like Language

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WUCS-90-25
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June 28, 1990

Abstract

In this paper we present a mathematical model for a CSP-like language. This model handles both safety and liveness properties of "purely parallel" CSP processes, as well as CSP processes with internal machine states. A refinement order is defined in this model which is a combination of the refinement order in CSP's failure model and the refinement order for sequential programs. Finally, related work and applications are discussed.

1 Introduction

In the past decade, there has been a substantial increase in the understanding of the nature of sequential and parallel languages. This increase is very much due to the study of the underlying mathematical models.

A number of models have already existed for CSP-like languages [Ros84], [So84] and [Zw88], etc.. None of them is quite satisfactory, as far as unifying the techniques for sequential and parallel languages is concerned. Some of them do not handle liveness properties or nondeterminism [So84] and [Zw88], and some of them do not model sequential programs appropriately [Ros84]. But a most salient feature is that they all support the so-called compositional and text-independent development and verification method. This means that the specification of an abstract parallel system (or program) can be deduced from the specifications of its subsystems independent of their implementation. This gives us the hope to develop a top-down development method for a CSP-like parallel programming language, like the method developed for "purely parallel" CSP in [LS87].

The most successful models for those "purely parallel" languages are Hoare's CSP and Milner's CCS. By "purely parallel", we mean that the machine states of a communicating process are hidden.

The fact that CSP does not facilitate modelling of machine states may not, however, be advantageous when we handle CSP-like languages, like OCCAM.

*Supported in part by a gift from the southwestern Bell Foundation
In the failures model of CSP, the safety properties of a process are specified by its communication traces \((tr)\) which are finite sequences of communications that it can commit on its input and output channels, and liveness properties can be specified by means of failures \((tr, ref)\), where \(ref\) called refusal, is a set set of channels on which the process can not send or receive any messages after having performed trace \(tr\). Therefore the observation set of a process in CSP is a set whose elements are of the form \((tr, ref)\), called failures and denoted \(Fr\).

To describe a process with machine states, this kind of observation is certainly not enough. In contrast to “purely parallel” CSP, the mathematical model taken in this thesis aims to make machine states explicit.

An observation of a process in our model is a quadruple \((s_0, tr, ref, s)\), or a triple \((s_0, Fr, s)\). The interpretation is that a process (or a computation), starting in an initial state \(s_0\), after having performed communications in trace \(tr\), if it does not diverge, e.g. \(s \neq 1\), nor deadlock, i.e. \(\not\exists \neq ref\), then it will terminate in a final state \(s\). A process may be able to do many of this kind of computations. Therefore the observation set of a process is a set of all these computations performed by it.

In order to give a simpler denotational semantics to our CSPL language in this paper, we separate the failure set and the internal machine state transitions, and define a process as a pair

\[
( Fr, Tr )
\]

where \(Fr\) is a total function which takes a machine state and produces a failure set and \(Tr\) is a total function which takes a machine state and a trace and produces a set of machine states.

The advantages of the above definition are that the first element \(Fr(s_0)\) is, in fact, the failure set of a process in “purely parallel” CSP and has all the properties proved in [BHR84], and that the second element defines the internal machine state transitions and can be used to model sequential programs. Therefore the only thing we have to do is to establish the relationship between these two models.

It is easy to extend our CSPL language to include a so-called specification statement in our model which is of the form

\[
Sp :: L_\alpha, \bar{w} : [pre, post],
\]

where \(L_\alpha\) specifies the failure set of \(Sp\), \(pre\) and \(post\) are predicates over trace-state pairs, \(\alpha\) is the set of channels \(Sp\) has and \(\bar{w}\) is the set of variables that can be changed in \(Sp\).

In Section 2 we give a formal method of describing processes with communications and define a refinement order on the process domain. The resulting process domain under the refinement order is a complete semi-lattice.

In Section 3 we extend the semantic domain to include specifications. Then we give denotational semantics to mixed terms which forms the mathematical foundation of refinement calculi and proof systems.

Finally, related models and application areas are discussed.
2 The Description of Processes

The description of the behaviour of a process depends on the observations that can be made on the process while it is being executed.

2.1 Traces

In our model, a process can communicate with other processes or its environment via the channels linking them. Communications are the only way that one process can affect another. No shared program variables are allowed between processes. The atomic unit of communication of a process is called a communication event, denoted c.v, where c is a channel name and v is the message communicated on c. A trace tr is a finite sequence of communication events that have occurred during the execution of P.

The set of all finite traces is denoted by Comm* with <> being the empty trace.

The following notational conventions are also used throughout this thesis:

- \( tr[i] \) the ith element in trace tr;
- |tr| the length of the finite sequence, or trace, tr;
- \( tr_1 \leq tr_2 \) tr_1 is a prefix of tr_2;
- \( first(tr) = a \) if tr = \( a >^\infty tr' \);
- \( last(tr) = a \) if tr = \( tr'^\infty < a > \);
- \( tr \uparrow A \) is the trace obtained from tr by removing all the c.v whose c is not in A. If A is a singleton, \( tr \uparrow \{ c \} \) is abbreviated as c which denotes the sequence of messages passed on channel c.

\( \alpha P \) is a finite set of channel names that P has. The set of channels is denoted by Chan.

Definition 2.1 (Safety Property)
The safety properties of a process are what the process is allowed to do, in other words, the process does not do anything wrong.

Examples of safety properties are: a two-place buffer can buffer at most two messages, a variable x is nonnegative, etc. We do not give a formal definition here. The safety properties of the communication behaviour of a process can be specified by means of its traces.

Example 2.1
The safety properties of a one-place buffer with \( \alpha P = \{ in, out \} \) can be specified by stating that output is a prefix of input which is at most one element shorter:

\[
\text{Buffs} \equiv 0 \leq \text{in} - \text{out} \leq 1 \land \text{out} \leq \text{in}. \tag{1}
\]

\( \Box \)

2.2 Failures

It is a well-known fact that, under the CSP’s refinement order, the liveness properties of the communication behaviour of a process can not be captured solely by its traces.
Definition 2.2 (Liveness Property)
The liveness properties of a process are what the process is supposed to do, i.e. something good will eventually happen.

Therefore, in order to specify the liveness properties of a process, another observation element, called refusal and denoted ref, was introduced [BHR84].

Definition 2.3 (Refusals)
A refusal of a process $P$ is a subset of $\alpha P,\triangledown$ on which $P$ can refuse to communicate with its environment at the very beginning of its execution, where $A,\triangledown \equiv A \cup \{\triangledown\}$ and $\triangledown$ indicates termination.

Putting $tr$ and $ref$ together, we obtain a new element $(tr, ref)$, called a failure.

Definition 2.4 (Failures)
A failure $fr$ of a process is a pair $(tr, ref)$ where $tr$ is a trace of $P$ and ref is a refusal of the process after having performed the communication events in $tr$.

The meaning of a failure $(tr, ref)$ of a process $P$ is that, after having been engaged in trace $tr$, $P$ may refuse to take part in any communication on all the channels in $ref$, even though the environment of $P$ is prepared to do so. If $\triangledown$ is in $ref$, $P$ may fail to terminate successfully. If $P$ can not refuse $\{\triangledown\}$, then $P$ must terminate in a generalized state $(tr, s)$, and $tr$ is called a terminating trace of $P$. If $P$ cannot refuse $\{c\}$ after $tr$, then the communication event on $c$ must take place after some finite time in spite of internal actions.

The domain of all failures, $Comm^* \times P(Chan,\triangledown)$, is denoted Failures.

Example 2.2
The liveness properties of the one-place buffer can be specified by its failures.

$$BufferL \equiv \begin{cases} |in|=|out| \implies in \notin ref \\ \land |in|>|out| \implies out \notin ref, \end{cases}$$

where $ref$ ranges over $\{in, out, \triangledown\}$.

(2.2) states that, when the buffer is empty, it is ready and able to take in the next message; and (2.3) states that, when the buffer has already buffered one message in it, it must output it on channel $out$ before it takes another one. In fact, $BufferL$ does not say that the buffer can take at most one message. This property is specified in $Buffers$. Therefore, the complete specification of a one-place buffer is $Buffers \land BufferL$.

2.3 Processes

In order to model divergence and internal machine state transitions, a third observable has to be introduced.

The domain of machine states is defined by

$$State : Var \rightarrow S^0,\uparrow,$$
where $\text{Var}$ is the domain of variables, $\text{Sv}$ is the domain of values and $\text{Sv}^+ = \text{Sv} \cup \{\omega\}$. If a variable is assigned to $\omega$, it is said to be undefined. In order to give a simpler and continuous semantics for the "hiding" operator, we postulate that both $\text{var}$ and $\text{Sv}$ are finite.

A state $s \in \text{State}$ maps each variable onto its current value which belongs to $\text{Sv}$ or an $\omega$.

A process may be engaged in a computation which never reaches a final stable state $s$ because of having been involved in an infinite sequence of internal actions. In this case, the process is said to have been diverging. A special state $\bot_{\text{State}}$ (or simply $\bot$) is introduced to indicate such a divergent state. Thus, if $(s_0, tr, ref, \bot)$ is an observation of a process $P$, then $P$ diverges after $tr$ which is called a divergence trace of $P$ from the initial state $s_0$.

We adopt the conventions that $A \subseteq \bot$ and $A \cup \bot = \bot$ for all $A \subseteq \text{State}$.

Then a process $P$ can be defined by a pair

$$( Fr, Tr),$$

where $Fr$ is a total function which takes a state and produces a failure set, and $Tr$ is a total function which takes a state and a trace and produces a set of states.

The interpretation of $(Fr, Tr)$ is as follows:

1). The first element $Fr$ of a process $P$ determines the failures of process $P$, started in some initial state $s_0$. If a set of channels are not a current refusal of $P$, then the communications on some of these channels must take place if the environment insists in doing so; If $\checkmark$ is a current refusal of $P$ after $tr$, then, the process may fail to terminate successfully after $tr$ even though there may be some final states possible for that trace $tr$. Termination must take place (if desired by the environment) only when the set $\{\checkmark\}$ cannot be refused after $tr$.

2). Termination can take place on any trace $tr$ for which $Tr(s_0, tr)$ is nonempty. When $Tr(s_0, tr)$ contains more than one element, the choice of which final state occurs is nondeterministic.

3). If a $Tr(s_0, tr) = \bot$, then the process is considered to be broken after $tr$, started in the initial state $s_0$. In this case, we allow the possibility that it might diverge or do anything else.

The trace set of $P$, started in a state $s_0$, is denoted $\text{traces}(P_{s_0})$, and so is the failure set, $\text{failure}(P_{s_0})$.

**Definition 2.5** A process $P$ is a pair

$$P \equiv (Fr, Tr),$$

where $Fr : \text{State} \rightarrow \text{Comm}^* \times \mathcal{P}(\text{Chan}_d)$ is a total function and so is $Tr : \text{State} \times \text{Comm}^* \rightarrow \mathcal{P}(\text{State}) \cup \{\bot\}$. $Fr$ and $Tr$ satisfy the following conditions, started in an initial state $s_0 \in \text{State}$:

$P_1$. $\text{traces}(P_{s_0})$ is nonempty and prefix-closed;

$P_2$. $(tr, ref) \in Fr(s_0) \& X \subseteq ref \implies (tr, ref) \in Fr(s_0)$;
\(P_3\). \((tr, \text{ref}) \in Fr(s_0) \land (\forall v. tr^v < c.v > \in \text{traces}(P_{s_0})) \implies (tr, \text{ref} \cup \{c\}) \in Fr(s_0);\)

\(S_1\). \(Tr(s_0, tr) \neq \phi \implies tr \in \text{traces}(P_{s_0});\)

\(S_2\). \((tr, \text{ref}) \in Fr(s_0) \land Tr(s_0, tr) = \phi \implies (tr, \text{ref} \cup \{\sqrt{\}\}) \in Fr(s_0);\)

\(S_3\). \(Tr(s_0, tr) = \bot \land tr' \in Comm^* \implies Tr(s_0, tr^v tr') = \bot;\)

\(S_4\). \(Tr(s_0, tr) = \bot \land X \subseteq Chan \implies (tr, X) \in Fr(s_0).\)

The space of all processes with alphabet \(Chan\) and state set \(State\) is denoted \(Proc\).

We define a partial order \(\sqsubseteq_r\), called refinement order on \(Proc\).

**Definition 2.6** A process \(P_1 = (Fr_1, Tr_1)\) is said to be refined by another process \(P_2 = (Fr_2, Tr_2)\), denoted \(P_1 \sqsubseteq_r P_2\), if and only if, for any \(s_0 \in State\),

1). \(Fr_2(s_0) \subseteq Fr_1(s_0);\)

2). \(Tr_2(s_0, tr) \subseteq Tr_1(s_0, tr), \text{ for all } tr \in Comm^*\)

where \(\alpha P_1 = \alpha P_2\).

The intuitive meaning of the refinement order \(\sqsubseteq_r\) is as follows:
Condition 1) means that the communication behaviour of \(P_2\) is more deterministic than \(P_1\); Condition 2) means that the final states of \(P_2\) after trace \(tr\) are included in \(P_1's\).

The least element \(\bot_{Proc}\) (or simply \(\bot\)) on \(Proc\) under \(\sqsubseteq_r\) is defined

\[\bot_{Proc} \equiv (Fr_{\bot}, Tr_{\bot});\]

where \(Fr_{\bot}(s_0) = \text{Failures} \text{ and } Tr_{\bot}(s_0, tr) = \bot_{State}, \text{ for any } s_0 \in State \text{ and } tr \in Comm^*.\)

Then, we have the following theorem.

**Theorem 2.1** \((Proc, \sqsubseteq_r, \bot_{Proc})\) is a complete semi-lattice.

\(\square\)

**Proof**

See Appendix.

### 3 The Denotational Semantics For CSPL

In this section, we give a denotational semantics to the CSP-like parallel language CSPL.

#### 3.1 The Syntax of CSPL

In the following, \(x\) stands for a program variable, \(e\) for an expression and \(b\) for a boolean expression.
Definition 3.1 (The syntax of CSPL)
The syntax of CSPL is defined as follows:

\[ P \equiv x := e \mid \text{div} \mid \text{skip} \mid \text{stop} \mid c?x \mid c!e \mid P_1 \parallel_A P_2 \mid \text{if } \square_i G_i \text{ fi} \mid \text{while } b \text{ do } P \text{ end} \mid P_1 ; P_2 \mid \text{chan } c \text{ in } P \text{ end} \mid \text{var } x \text{ in } P \text{ end}; \]

\[ G \equiv b \& \sigma \rightarrow P; \]

\[ \sigma \equiv c?x \mid c!e \mid \text{skip}. \]

The syntactic domain of programs (or processes) is denoted \( \text{Prog} \).
The intuitive meanings of these program constructs (or processes) are as follows:

- \( x := e \) is the usual assignment statement in sequential languages;

- \text{div} is the most nondeterministic process which pursues an infinite sequence of internal events. These internal events might be either internal communications or nonterminating sequential loops;

- \text{skip} is a process which terminates successfully with its internal machine states unchanged;

- \text{stop} is a process which terminates unsuccessfully and no internal states can be observed even though there might exist some. Actually, \text{stop} describes a process which is deadlocked;

- \( c?x \) is an input process which inputs a message on channel \( c \) and stores it in a program variable \( x \);

- \( c!e \) is an output process which outputs the value of \( e \) to its environment through channel \( c \);

- \( P_1 \parallel_A P_2 \) is a process which runs two processes in parallel. As the only way in which one process can influence another is via communications along their common channels, \( P_1 \) and \( P_2 \) do not share any program variables. Therefore, each process has a distinct portion of the state of \( P_1 \parallel P_2 \) and the state will be reconstructed at the termination of the parallel construct by the "distributed termination" property — a parallel process can only terminate when each of its component processes can terminate (and thus yield its own final state). If any of its component process diverges, the parallel process diverges.

- \( P_1 ; P_2 \) is the sequential composition of \( P_1 \) and \( P_2 \);

- The if-statement implement deterministic choice, as well as nondeterministic choice. Whenever there are some boolean guards \( b_i \) in \( b_i \& \text{skip} \) which are \text{true} at that moment, the if-statement nondeterministically picks up one of the processes following these guards and execute it. In this case, the guarded processes with input or output in their guards will never be pick up even though some of their boolean guards may be \text{true}. The purely sequential nondeterministic choice is a special case of the
if-statement when all the guards have \texttt{skip} in them and the guarded processes do not have any communications. Only when all the boolean guards in b1 & \texttt{skip} are false and some of the boolean guards for input or output guards are true, the choice between these input or output guards are deterministic.

- The while-statement have the similar meaning as in sequential languages. It repeatedly executes \texttt{P} while \( b \) is evaluated to \texttt{true}. When \( b \) is false, the while-statement skips.

- \texttt{chan} \( c \) \texttt{in} \texttt{P} \texttt{end} is a process which has channel \( c \) as its internal channel, i.e. all the communications of the form \( c.v \) are hidden from the outside. This operator is used to introduce internal channels;

- \texttt{var} \( x \) \texttt{in} \texttt{P} \texttt{end} is a process with \( x \) being its local variable. Usually we use this operator to introduce local variables.

3.2 The Semantics

In this subsection we give a denotational semantics to our parallel language CSPL.

The main semantic function is

\[ \mathcal{S} : \text{Prog} \rightarrow \text{Proc}. \]

The intuitive meaning of \( \mathcal{S} \) is that, given a process or a piece of program, \( \mathcal{S} \) produces an element on \( \text{Proc} \)

\[ (Fr, Tr). \]

We also define

\[ f(\mathcal{S}[P]) = Fr_P \text{ and } t(\mathcal{S}[P]) = Tr_P. \]

For expressions \( e \) and boolean expressions \( b \), the value of \( e \) and \( b \), evaluated in a state \( s \), is denoted \( E[e]_s \), where \( E : \text{Exp} \rightarrow \text{State} \rightarrow Sv \cup \text{Bool} \cup \{\text{error}\} \), where \( \text{Exp} \) is the domain of all expressions and \( \text{Bool} \equiv \{\text{true}, \text{false}\} \). If anything goes wrong, like a variable is undefined, etc, the value of \( E \) is \texttt{error}. Whenever this happens, the above semantic function produces a divergence process.

1). Primitive Processes

- The divergent process is the worst process. It is identified with the least element \( \perp_{\text{Proc}} \) on \( \text{Proc} \).

\[ \mathcal{S}[\text{div}] = \perp_{\text{Proc}}, \]

where \( f(\perp_{\text{Proc}}) = Fr_{\perp} \) and \( t(\perp_{\text{Proc}}) = Tr_{\perp} \) as defined in the previous subsection.

- The process \texttt{skip} is defined as follows: for any \( s_0 \in \text{State} \),

\[ f(\mathcal{S}[	ext{skip}](s_0)) = \{ (<> , X) \mid X \subseteq \text{Chan} \}, \]

and

\[ t(\mathcal{S}[	ext{skip}](s_0, tr)) = \begin{cases} \{s_0\}, & \text{if } tr = <> \\ \emptyset & \text{otherwise} \end{cases} \]
skip is a process which terminates successfully with its final states unchanged and refuses any communication on any subset of the channels connected to it.

- The process stop is slightly different from skip in that it terminates unsuccessfully by some faults, such as power breakdown, etc.. Therefore, its final machine states can never be observed or may be lost. Its semantics is defined as follows: for any $s_0 \in \text{State}$,

$$f(\exists[\text{stop}](s_0) = \{ (\langle >, X) | X \subseteq \text{Chan} \},$$

and

$$t(\exists[\text{stop}](s_0, tr) = \phi, \quad \text{for all } tr \in \text{Comm}^*$$

- The assignment statement is, more or less, the same as that in sequential languages. In CSPL, processes do not share program variables. Consequently, there is no interference between them and the nontrivial interference-free test (see [AFR80]) is not needed in our method. For any $s_0 \in \text{State}$, we define

$$f(\exists[x := e])(s_0) = \{ (\langle >, X) | X \subseteq \text{Chan} \},$$

and

$$t(\exists[x := e])(s_0, tr) = \begin{cases} s_0[\mathcal{E}[e]s_0/x], & \text{if } tr = \langle > \\ \phi & \text{otherwise} \end{cases}$$

provided that $\mathcal{E}[e]s_0 \neq \text{error}$.

In the following, whenever $\mathcal{E}[e]s = \text{error}$, the semantic function always produces $\bot_{\text{Proc}}$.

- The semantics of the output process is relatively simple because it does not change any machine state. We define, for any $s_0 \in \text{State}$,

$$f(\exists[\text{!}e])(s_0) = \begin{cases} \{ (\langle >, X) | c \notin X \} \\ \cup \{ (\text{< } c.v \text{ >}, X) | v = \mathcal{E}[e]s_0 \land X \subseteq \text{Chan} \} \end{cases},$$

$$t(\exists[\text{!}e])(s_0, tr) = \begin{cases} \{ s_0 \}, & \text{if } tr = \text{< } c.v \text{ >} \land v = \mathcal{E}[e]s_0 \\ \phi & \text{otherwise} \end{cases}$$

- The most important primitive process is the input process $c?x$. Different explanations can result in different verification and development methods. The semantics defined in the following is natural and supports a modular verification and development method, i.e. the verification and development of the component processes in a parallel process can be carried out independently.

The definition of the failure set of $c?x$ is the same as that in the “purely parallel” CSP’s failures model [BHR84]: for any $s_0 \in \text{State}$,

$$f(\exists[c?x])(s_0) = \begin{cases} \{ (\langle >, X) | c \notin X \} \\ \cup \{ (\text{< } c.v \text{ >}, X) | v \in Sv \land X \subseteq \text{Chan} \} \end{cases}.$$
For the machine state part, we take the explanation of $c?x$ as follows: a process $P$ containing $c?x$ is going to input a message along channel $c$. There might be some constraints on the message received by $P$. But the process itself cannot control what kind of message it will actually receive on channel $c$ from the environment. Therefore we have

$$t(\mathcal{S}[c?x])(s_0, tr) = \begin{cases} \{ s_0[v/x] \}, & \text{if } tr = <c.v> \ (v \in Sv) \\ \phi, & \text{otherwise} \end{cases}$$

2). Compositional Processes

- The first compositional process we are going to define is the sequential composition construct ";". Because the composition of failure sets (not only relations about the machine states) is involved, the semantics of ";" becomes a bit more complex. We have to consider the termination of the first component and the catenation of the traces of the two components.

$$f(\mathcal{S}[P_1 ; P_2])(s_0) = \begin{cases} & \{ (tr, X) \mid (tr, X \cup \{\Box\}) \in f(\mathcal{S}[P_1])(s_0) \} \\ & \bigcup \{ (tr_1 \uparrow tr_2, X) \mid \exists s'. s' \in t(\mathcal{S}[P_1])(s_0, tr_1) \land (tr_2, X) \in f(\mathcal{S}[P_2])(s') \} \\ & \bigcup \{ (tr_1 \uparrow tr_2, X) \mid t(\mathcal{S}[P_1])(s_0, tr_1) = \bot \land tr_2 \in Comm^* \land X \in Chan \} \end{cases}$$

$$t(\mathcal{S}[P_1 ; P_2])(s_0, tr) = \begin{cases} t(\mathcal{S}[P_2])(s', tr_2) \mid \exists tr_1, tr_2. tr = tr_1 \uparrow tr_2 \land s' \in t(\mathcal{S}[P_1])(s_0, tr_1) & \text{if } t(\mathcal{S}[P_1])(s_0, tr) \neq \bot, \text{or if } tr = tr_1 \uparrow tr_2 \text{, and there exists } s' \text{ such that } s' \in t(\mathcal{S}[P_1])(s_0, tr_1) \text{ and } t(\mathcal{S}[P_2])(s', tr_2) = \bot \\ \bot, & \text{otherwise} \end{cases}$$

Note that $P_1$ cannot refuse a set $X$ unless it can refuse $X \cup \{\Box\}$; otherwise it would be able to terminate (invisibly) and let $P_2$ take over.

- The difference between deterministic choice and nondeterministic choice lies in the beginning of their execution. In "purely parallel" CSP, the internal machine states are hidden (or omitted). Therefore, for the deterministic choice, its environment is able to make the choice among its guards at the beginning of its execution; but, for the nondeterministic choice, its environment is not able to do so, i.e. the choice is totally uncontrollable. In our CSPL language, the situation is a bit different. A guard (or guarded process) can be "disabled" by setting its boolean part $b$ false. Therefore, for both deterministic and nondeterministic choices, the choice is machine-state related. For a deterministic choice, the environment can only make choice among those guards whose boolean parts are evaluated to true in the machine state at that point in time during its execution. For a nondeterministic choice, the choice can only be controlled internally by the machine itself. This difference is reflected in the following definition of our general choice which combines the two kinds of choice constructs.
We first define a boolean function which distinguishes between internal guards whose communication parts are skip and external guards whose communication parts are either $c?x$ or $c!x$:

\[
\begin{align*}
B[b \& c?x \rightarrow P] & = \text{false}, \\
B[b \& c!x \rightarrow P] & = \text{false}, \\
B[b \& \text{skip} \rightarrow P] & = \begin{cases} 
\text{true}, & \text{if } E[b]s \text{ is true} \\
\text{false}, & \text{if } E[b]s \text{ is false} 
\end{cases} \quad \text{provided that } E[b]s \neq \text{error}, \\
B[\text{if } □_i G_i \text{ fl}] & = \bigvee_i B[G_i]s,
\end{align*}
\]

where $\bigvee$ is the error-strict version of the usual boolean $\lor$.

We extend our semantic function to guarded processes and define, for any $s_0 \in \text{State}$ and $tr \in \text{Comm}^*$,

\[
\begin{align*}
f(∅[b \& σ \rightarrow P]) & = \{((>,X) \mid X \in \text{Chan},\}) \quad \text{if } E[b]s_0 \text{ is false} \\
& = f(∅[σ; P])s_0, \quad \text{otherwise,} \\
t(∅[b \& σ \rightarrow P])(s_0, tr) & = \emptyset, \quad \text{if } E[b]s_0 \text{ is false} \\
& = t(∅[σ; P])(s_0, tr), \quad \text{otherwise,} \\
& = \text{false} \quad \text{provided that } E[b]s_0 \neq \text{error}
\end{align*}
\]

Then the failure part of $\text{if } □_i G_i \text{ fl}$ can be defined as follows: for any $s_0 \in \text{State},$

\[
\begin{align*}
f(∅[\text{if } □_i G_i \text{ fl}]) & = \{((>,X) \mid \exists i. B[G_i]s_0 \& (>,X) \in f(∅[G_i])s_0 \} \\
& \cup \{((>,X) \mid \forall i. \neg B[G_i]s_0 \& (>,X) \in f(∅[G_i])s_0 \} \\
& \cup \{((>,X) \mid \exists i. t(∅[G_i])(s_0,>) = 1 \} \\
& \cup \{ (tr, X) \mid tr \neq <> \& (tr, X) \in f(∅[G_i])s_0 \}.
\end{align*}
\]

The internal machine state transitions are defined by

\[
t(∅[\text{if } □_i G_i \text{ fl}])s_0, tr = \bigcup_i (t(∅[G_i])s_0, tr), \quad \text{for any } tr \in \text{Comm}^*.
\]

Note that if none of the boolean guards is true, then the if-statement is equivalent to stop.

- To implement iteration, we introduce a while-construct. It has the usual meaning as in sequential languages except that it involves communications and may not terminate. The semantics of while-construct is similar to that of the sequential composition construct "$;" except that it repeats the execution of $P$ until the boolean guard $b$ evaluates to false. Therefore we have

\[
∅[\text{while } b \text{ do } P \text{ end}] = (\bigcup_{n=0}^{\infty} H^n(⊥_{Proc})),
\]

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where \( H : \text{Proc} \rightarrow \text{Proc} \), is defined, for any \( s_0 \in \text{State} \) and \( \text{tr} \in \text{Comm}^* \),

\[
\begin{align*}
\text{f}(H(A))(s_0) &= \text{f}(\text{g}[P] ; A)(s_0), & \text{if } \text{g}[b]s_0 &= \text{true} \\
&= \{ (\leftrightarrow, X) | X \in \text{Chan} \}, & \text{if } \text{g}[b]s_0 &= \text{false}, \\
\text{t}(H(A))(s_0, \text{tr}) &= \text{t}(\text{g}[P] ; A)(s_0, \text{tr}), & \text{if } \text{g}[b]s_0 &= \text{true} \\
&= \text{t}(\text{g}[\text{skip}])(s_0, \text{tr}) & \text{if } \text{g}[b]s_0 &= \text{false}, \\
& \text{provided that } \text{g}[b]s_0 \neq \text{error}
\end{align*}
\]

- Now it is time to define the most important and difficult construct, the parallel composition \( \parallel \). It is the key construct of any parallel languages.

In our mathematical model, when a process runs in parallel with some other processes, it can only be affected in two ways: one is by communications and the other is by its own internal state changes. The communication with its environment or processes changes both its communication traces and its internal machine states by inputing a message and storing it into a program variable. Therefore, the machine state after an input command depends on the value input from its environment. To ensure that a process terminates in a required final state, we have to know the exact values input on its input channels. This can be done by looking up the communication traces committed by the process during its execution. If the input values satisfy the assumptions made by the process, all the results derived about the process’s machine states hold. Otherwise, we can reach nowhere near the correct conclusions about the process’s final machine states. We adopt the “distributed termination” properties that the parallel process can terminate only when all of its component processes terminate.

The failure set of \( P_1 \parallel P_2 \) is defined as follows: for any \( s_0 \in \text{State} \),

\[
\begin{align*}
\text{f}(\text{g}[P_1 \parallel P_2])(s_0) &= \{ (\text{tr}, X) | \exists X_1, X_2. (\text{tr} \uparrow \alpha P_1, X_1) \in \text{f}(\text{g}[P_1])(s_0) \\
& \quad \& (\text{tr} \uparrow \alpha P_2, X_2) \in \text{f}(\text{g}[P_2])(s_0) \& X = X_1 \cup X_2 \} \\
& \quad \bigcup \{ (\text{tr}^\text{a} \text{tr}', X) | \exists i. i(\text{g}[P_i])(s_0, \text{tr} \uparrow \alpha P_i) = \bot_{\text{State}} \\
& \quad \& \text{tr} \uparrow \alpha P_j \in \text{traces}(P_j) \},
\end{align*}
\]

where \( i \neq j \) and \( i, j \in \{1, 2\} \).

The termination component function is defined, for any \( s_0 \in \text{State} \) and \( \text{tr} \in \text{Comm}^* \),

\[
\begin{align*}
\text{t}(\text{g}[P_1 \parallel P_2])(s_0, \text{tr}) &= \bot_{\text{State}} & \text{if there exists } \text{tr}' \leq \text{tr} \text{ such that } \text{tr}' \uparrow \alpha P_i \in \text{traces}(P_j) \text{ for all } i, \\
& & \text{and there is some } j \text{ with } \text{t}(\text{g}[P_j])(s_0, \text{tr} \uparrow \alpha P_j) = \bot_{\text{State}}, \\
&= \{ s_1 \oplus s_2 | s_1 \in \text{t}(\text{g}[P_1])(s_0, \text{tr} \uparrow \alpha P_1) \& s_2 \in \text{t}(\text{g}[P_2])(s_0, \text{tr} \uparrow \alpha P_2) \}, \quad \text{otherwise}
\end{align*}
\]

where \( \oplus \) is defined as follows:

\[
(s_1 \oplus s_2)(x)
\]

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\[ s_1(x) \quad \text{whenever } s_1(x) \neq \omega \]
\[ s_2(x) \quad \text{whenever } s_2(x) \neq \omega \]
\[ \omega \quad \text{otherwise} \]

If \( s_1 \) and \( s_2 \) map \( x \) into different non-\( \omega \) values, the parallel combination is broken from the point of this error. The disjointness constraints of \( \parallel \) guarantee that this error cannot arise.

The parallel composition construct works by allowing each process to communicate only in its own alphabet, and only allowing a given communication occur when each process whose alphabet it belongs to agrees. Termination can only take place when all processes agree, the final state being formed by joining together the states of the individual processes. As soon as one process breaks, the entire system is considered broken.

- To obtain good abstraction in CSPL, we introduce a hiding operator \texttt{chan} \( c \) in \( P \) \texttt{end}, which conceals the channel "c" in \( P \). Its semantics is as follows:

\[
f(\exists[\text{chan } c \text{ in } P \text{ end}]) (s_0) = \{ (tr \setminus c, X) \mid (tr, X \cup \{c\}) \in f(\exists[P]) (s_0) \} \]
\[
\cup \{ (tr, X) \mid \{ tr' \mid tr' \in traces(P_{S_0}) \& tr \setminus c \leq tr \text{ is infinite} \},
\]

where \( tr \setminus c = tr \setminus (\alpha P - \{c\}) \).

\[
t(\exists[\text{chan } c \text{ in } P \text{ end}]) (s_0, tr) = \bot_{\text{State}} \quad \text{if } \{ tr' \mid tr' \in traces(P_{S_0}) \& tr \setminus c \leq tr \text{ is infinite} \}
\]
\[
= \bigcup \{ t(\exists[P]) (s_0, tr') \mid tr \setminus c = tr \}.
\]

- The operator for introducing local variables is much simpler because it has nothing to do with a process's failure set. Its semantics is defined as

\[
f(\exists[\text{var } x \text{ in } P \text{ end}]) (s_0, tr) = f(\exists[P]) (s_0),
\]

and

\[
t(\exists[\text{var } x \text{ in } P \text{ end}]) (s_0, tr) = \{ s \setminus x \mid s \in t(\exists[P]) (s_0, tr) \}, \quad \text{for all } tr \in \text{Comm}^*
\]

where \( s \setminus x \) is defined as follows:

\[
(s \setminus x)(y) = s(y), \quad \text{if } y \neq x
\]
\[
= \omega, \quad \text{otherwise}
\]

This completes the definitions of the semantics of all the constructs in CSPL.

\textbf{Theorem 3.1} All the constructs defined above are well-defined and continuous.

\textbf{Proof}: See [lai90].
4 Applications and related work

The mathematical model and refinement order developed in the previous Section can be used as the mathematical foundation for developing proof systems and refinement calculi for CSP-like languages. In the following, we give an example of how to extend the above model to mixed terms (programming language with specifications) which can be used to develop proof rules and refinement laws in a unified framework.

4.1 Mixed terms

First, we introduce our specification formulas.

The specification of a program is a description of the way it is intended to behave. The specification is normally written in some formal mathematical language. Unlike program code, specifications generally are not executable. A specification can be regarded as an abstract program. On a more practical level, however, a programmer starts with a specification which gives the idea of a program's role in the system. Insight into the structure of the program points to a series of refinement of the original specification until an executable specification or a program is obtained.

A specification of a communicating sequential process describes not only the communication behaviour, but also the relationship between communications, initial values of the program variables, and their final values. To denote the initial value of a program variable $x$, we decorate the variable name with a subscription 0, as in $x_0$. To denote the final value of $x$, we simply use the variable name $x$ by itself. The value $x$ is not observable until the process has terminated. Because the internal states of a communicating sequential process is related to its traces, we have the following predicates to describe the initial states, final states, and the communication behaviour of a process.

\[
\begin{align*}
\text{pre} & : \text{Comm}^* \times \text{State} \rightarrow \text{Bool} \\
\text{post} & : \text{Comm}^* \times \text{State} \times \text{State} \rightarrow \text{Bool} \\
I_\alpha & : \text{State} \times \text{Failures} \rightarrow \text{Bool} 
\end{align*}
\]

Note that the pre- and post-conditions in our specifications are no longer assertions on machine states, but rather assertions on the combination of communication traces and machine states, $(tr, s)$, which are called generalized states in [Zw88].

Thus the pre-condition specifies over what subset of the possible generalized states the program may work, the post-condition specifies the terminating traces and the required relationships between initial and final states, and the communication invariant specifies the communication behaviour of the program.

Sometimes we distinguish between the safety and liveness properties of the communication behaviour of a process by $I^S_\alpha$ and $I^L_\alpha$, respectively. Then, we have

\[I_\alpha = I^S_\alpha \land I^L_\alpha.\]

We postulate that traces in the expressions can only be related by the channel projection operator $\dagger$ as $tr \dagger A$. 

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The specification formulae, or specification statements, as called in [Mor88], is defined as follows.

**Definition 4.1 (Specification statement)**
A specification statement $Sp$ is a quadruple

$$I_{\alpha}, \bar{\omega} : \{ \text{pre}, \text{post} \},$$

where $\bar{\omega}$ is a subset of variables $\bar{\nu}$ $Sp$ has, which can be changed in $Sp$, $\alpha$ is the set of channels of $Sp$, and $I_{\alpha}$, pre and post are predicates of the types as defined in (3).

The domain of all specification statements is denoted by $Spec$.
A specification statement $Sp$ can be understood as a generalized state transformer. Its intuitive meaning is as follows:

A computation $Cp$ of $Sp$ starts in one of the initial generalized states $(tr_0, s_0)$ described by pre, with $tr_0$ and $s_0$ satisfying $I_{\alpha}$; then, at any moment during its execution, $I_{\alpha}$ always holds for the communication behaviour of $Cp$; if $Cp$ terminates, $Cp$ will terminate in one of the final generalized states $(tr, s)$ described by post, with the terminating trace $tr$ satisfying $I_{\alpha}$. If there are more than one possible final states described by the postcondition, any one of them may be chosen nondeterministically. If $Cp$ starts in an initial state which is not described by the precondition, then everything could happen, including divergence.

We give some examples of the specification statements of some concurrent systems.

**Example 4.1**
A one-place buffer $B_1$, with "in" being its input channel and "out" its output channel, can be specified by means of our specification statement as follows:

$$I_{\alpha}, x : \{ in = out = <> , \text{false} \},$$

where $\alpha = \{ in, out \}$, and

$$I_{\alpha}^S \equiv 0 \leq |in| - |out| \leq 1 \land out \leq in$$

$$I_{\alpha}^L \equiv |out| < |in| \implies out \notin ref$$

$$\land |out| = |in| \implies in \notin ref.$$

where $ref \subseteq {\alpha \setminus \bar{\omega}}$. This usually omit in the following when it is obvious.

The postcondition false merely indicates that $B_1$ will never terminate, i.e. the final stable internal state false can never be reached. $I_{\alpha}^S$ states that the one-place buffer can keep at most one message and the sequence of the input messages is not changed in order and content while being output. $I_{\alpha}^L$ states that, when the buffer is empty, $B_1$ must input a message before it outputs any. When the buffer has one message in it, it must output it before it take another.

The following example is a bit more complicated than the above one. It involves communications as well as internal states.

**Example 4.2**
A process $B_1'$ is a one-place buffer which inputs ten integers and adds up the integers in
even-numbered positions in the input trace $\text{in}$ and the integers in odd-numbered positions.

\[
\begin{array}{c}
\text{in} \quad \text{Addition} \quad \text{out}
\end{array}
\]

\[
B_1' \equiv I^{S}_\alpha \land I^{L}_\alpha, \ x, y, z : \ [\text{pre}B_1', \ \text{post}B_1']
\]

where

\[
\begin{align*}
I^{S}_\alpha & \equiv 0 \leq |\text{in}| - |\text{out}| \leq 1 \land |\text{out}| \leq |\text{in}| \\
I^{L}_\alpha & \equiv |\text{in}| < 10 \lor |\text{out}| < 10 \implies (|\text{in}| = |\text{out}| \implies \text{in} \not\in \text{ref} \land |\text{in}| > |\text{out}| \implies \text{out} \not\in \text{ref}) \\
\land |\text{in}| = |\text{out}| = 10 \implies \text{ref} \subseteq \{\text{in}, \text{out}\} \\
\text{pre}B_1' & \equiv \text{in} = \text{out} = < > \\
\text{post}B_1' & \equiv |\text{in}| = |\text{out}| = 10 \land x = \sum_{i=1}^{5} \text{in}[2i] \land y = \sum_{i=1}^{5} \text{in}[2i-1].
\end{align*}
\]

$I^{S}_\alpha$ and $I^{L}_\alpha$ state that $B_1'$ behaves like a one-place buffer and must terminate after having received and output ten messages.

$\text{pre}B_1'$ describes the initial states in which the process can start and $\text{post}B_1'$ states that, when $B_1'$ terminates, the sums of integers in the even- and odd-numbered positions are stored in $x$ and $y$, respectively.

\[\square\]

### 4.2 Semantics of Program Constructs

In order to give a formal definition of the specification statement, we expand the process (or program) domain $\text{Prog}$ to mixed terms $\text{Prog}'$, which includes specification statements.

\[
P \ ::= \ I_\alpha, \bar{\omega} : [\text{pre}, \text{post}] \mid x := e \mid \text{div} \mid \text{skip} \mid \text{stop} \mid c?x \mid c!e \mid \]
\[
P_1 \parallel_P P_2 \mid \text{if } \Box_i \ G_i \ F_i \mid \text{while } b \text{ do } P \text{ end} \mid P_1 ; P_2 \mid \\
\text{chan } c \text{ in } P \text{ end} \mid \text{var } x \text{ in } P \text{ end}.
\]

\[
G \equiv b \& \sigma \rightarrow P; \\
\sigma \equiv c?x \mid c!e \mid \text{skip}.
\]

As we regard a communicating sequential process as a generalized state transformer, the state domain $\text{State}$ in the previous Section has to be extended to the domain of generalized states, denoted $\text{Gstate}$ ($\cong \text{Comm}^{*} \times \text{State}$). Then, a mixed term or program can also be modeled by a pair $(F\prime_r, T\prime_r)$, where $F\prime_r$ and $T\prime_r$ are the same as those defined before, except that the $\text{State}$ is replaced by the $\text{Gstate}$. As a specification statement may not be implementable, the element $(F\prime_r, T\prime_r)$ of the domain $\text{Proc}'$ does not have to satisfy the conditions in the definition of a process in the previous section.

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We define $f'$ and $t'$ as
\[ f'(P) = Fr'_P \quad \text{and} \quad t'(P) = Tr'_P \]

We define a total function $ft : \text{Failures} \rightarrow \text{Failures}$
\[
ft(A) = \{ (tr, X) \mid (tr, X \cup \{\sqrt{\}}) \in A \} \\
\bigcup \{ (tr, \phi) \mid (tr, \phi) \in A \& (tr, \{\sqrt{\}) \notin A \} 
\]

$ft$ is used to make the refusal of a terminating trace empty. This is important in the definition of the refinement order on $\text{Prog}'$.

The refinement order on $\text{Proc}'$ is modified accordingly as follows.

**Definition 4.2 (Refinement Order)**
A mixed term $P_1$ is said to be refined by another $P_2$, denoted
\[ P_1 \sqsubseteq_M P_2, \]
if and only if, for all $(tr_0, s_0) \in \text{Gstate}$ and $tr \in \text{Comm}^*$

1) $ft(f'(P_2)(tr_0, s_0)) \subseteq ft(f'(P_1)(tr_0, s_0));$

2) $t'(P_2)(tr_0, s_0)(tr) \subseteq t'(P_1)(tr_0, s_0)(tr)$.

The least element $\bot_{\text{Proc}'}$ on $\text{Proc}'$ under $\sqsubseteq_M$ is defined
\[ \bot_{\text{Proc}'} \doteq (Fr'_1, Tr'_1) \]
where $Fr'_1(tr_0, s_0) = \text{Failures}$ and $Tr'_1(tr_0, s_0)(tr) = \bot_{\text{State}}$.

**Theorem 4.1** ($\text{Proc}', \sqsubseteq_M, \bot_{\text{Proc}'}$) is a complete lattice.

**Proof:**
The proof is similar to that of Theorem ??.

### 4.3 Semantics

In the following, we give a denotational semantics to the mixed terms.

The main semantic function is
\[ \mathcal{M} : \text{Prog}' \rightarrow \text{Proc}' \]

The intuitive meaning of $\mathcal{M}$ is: given a piece of mixed term, it produces an element on $\text{Proc}'$.

1. **Semantics of The Specification Statement**
The semantics of a specification statement is defined as follow:

\[ \mathcal{M}[I_{\alpha}, \vec{w} : [\text{pre}, \text{post}]] \doteq SP, \quad \text{where} \]
\[ f'(SP)(tr_0, s_0) = \begin{cases} \{(tr, X) \mid L_\alpha(s_0, tr_0^\wedge tr, X)\} & \text{if } \text{pre}(tr_0, s_0) \\ \{(tr, X) \mid X \subseteq Chan_{\wedge} \wedge tr \in \text{Comm}^*\} & \text{otherwise} \end{cases} \]

\[ t'(SP)(tr_0, s_0)(tr) = \begin{cases} \{s \mid \text{post}(tr_0^\wedge tr, s_0, s) \wedge L_\alpha(s_0, tr_0^\wedge tr, \phi)\} & \text{if } \text{pre}(tr_0, s_0) \\ \bot_{\text{State}} & \text{otherwise} \end{cases} \]

We give some examples to explain the meaning of a specification statement.

**Example 4.3**

\[ \text{true}_\alpha, \bar{\omega} : [\text{false, true}]. \]

The intuitive meaning is: the above process cannot starting in any initial generalized state; it is considered to be diverging at the very beginning. It is the weakest specification statement which can be refined by any thing, as indicated by its semantics,

\[ M[[\text{true}_\alpha, \bar{\omega} : [\text{false, true}]] = P_{div} \]

where, for any \((tr_0, s_0) \in \text{Gstate},\)

\[ f'(P_{div})(tr_0, s_0) = \begin{cases} \{(tr, X) \mid X \subseteq \alpha_{\wedge} \wedge tr \in \text{Comm}^*\} & \text{for all } tr \in \text{Comm}^* \end{cases} \]

\[ t'(P_{div})(tr_0, s_0)(tr) = \bot_{\text{State}}, \text{ for all } tr \in \text{Comm}^* \]

We call it Miracle as in [Mor88]. div is its counterpart on process domain \(\text{Proc}.\)

**Example 4.4**

\[ \text{false}_\alpha, \bar{\omega} : [\text{true, false}]. \]

Its semantics is defined as follows:

\[ M[[\text{false}_\alpha, \bar{\omega} : [\text{true, false}]] = P_{mac} \]

where

\[ f'(P_{mac})(tr_0, s_0) = \phi \]

\[ t'(P_{mac})(tr_0, s_0)(tr) = \phi, \text{ for all } tr \in \text{Comm}^* \]

This is the strongest specification statement which refines any other specification statements. But, unfortunately, it itself is not implementable. It is similar to the "Magic" in [Mor88].

**Semantics of Program Constructs**

**Divergence**

\[ M[[\text{div}]] = \bot_{\text{Proc}'}, \]

where \(\bot_{\text{Proc}'}\) is the bottom element on \(\text{Proc}'.\)
• Termination

\[ f'(M[\text{skip}](t_{r0}, s_0)) = f(\emptyset[\text{skip}](s_0)). \]
\[ t'(M[\text{skip}](t_{r0}, s_0)(t_{r})) = t(\emptyset[\text{skip}](s_0, t_{r})). \]

• Deadlock

\[ f'(M[\text{stop}](t_{r0}, s_0)) = f(\emptyset[\text{stop}](s_0)). \]
\[ t'(M[\text{stop}](t_{r0}, s_0)(t_{r})) = t(\emptyset[\text{stop}](s_0, t_{r})). \]

• Assignment

\[ f'(M[x := e](t_{r0}, s_0)) = f(\emptyset[x := e](s_0)). \]
\[ t'(M[x := e](t_{r0}, s_0)(t_{r})) = t(\emptyset[x := e](s_0, t_{r})). \]

• Output

\[ f'(M[c!e](t_{r0}, s_0)) = f(\emptyset[c!e](s_0)). \]
\[ t'(M[c!e](t_{r0}, s_0)(t_{r})) = t(\emptyset[c!e](s_0, t_{r})). \]

• Input

\[ f'(M[c?x](t_{r0}, s_0)) = f(\emptyset[c?x](s_0)). \]
\[ t'(M[c?x](t_{r0}, s_0)(t_{r})) = t(\emptyset[c?x](s_0, t_{r})). \]

• Sequential Composition

\[ f'(M[P_1 ; P_2](t_{r0}, s_0)) = \{ (t_{r}, X) | (t_{r}, X \cup \{\sqrt{v}\}) \in f'(M[P_1](t_{r0}, s_0)) \}
\cup \{ (t_{r1} \land t_{r2}, X) | t'(M[P_1](t_{r0}, s_0)(t_{r1})) = \perp \land t_{r2} \in \text{Comm}^* \land X \in \text{Chan} \}
\cup \{ (t_{r1} \land t_{r2}, X) | \exists s', s' \in t'(M[P_1](t_{r0}, s_0)(t_{r1})) \land \land t_{r2}, X \in f'(M[P_2])(t_{r1}, s') \}. \]

\[ f'(M[P_1 ; P_2](t_{r0}, s_0)(t_{r})) = \perp, \text{ if } f'(M[P_1](t_{r0}, s_0)(t_{r})) = \perp, \text{ or if } t_{r} = t_{r1} \land t_{r2}, \]
where \( s' \in t'(M[P_1](t_{r0}, s_0)(t_{r1})) \) and \( t'(M[P_2](t_{r1}, s')(t_{r2})) = \perp \)
\[ = \bigcup \{ t'(M[P_2](t_{r1}, s')(t_{r}) | \exists t_{r1}, t_{r2}, s', t_{r} = t_{r1} \land t_{r2} \land s' \in t'(M[P_1](t_{r1}, s_0)(t_{r1}) \}
\text{otherwise} \]

• Iteration

\[ M[\text{while } b \text{ do } P \text{ end}] = ( \bigsqcup_{s=0}^{\infty} H_{M}^{n}(\perp_{\text{Proc}}) ) \]
where $H_M : \text{Proc} \rightarrow \text{Proc}'$, is defined, for any $s_0 \in \text{State}$, $tr_0$ and $tr \in \text{Comm}^*$,

\[
\begin{align*}
\text{if } \mathcal{E}[b]s_0 = \text{true} & \quad \Rightarrow \quad f'(\mathcal{M}[P])(tr_0, s_0) = f'(\mathcal{M}[P] ; A)(tr_0, s_0), \\
\text{if } \mathcal{E}[b]s_0 = \text{false}, & \quad \Rightarrow \quad \{(<> , X) \mid X \in \text{Chan} \}, \\
\text{if } \mathcal{E}[b]s_0 = \text{true} & \quad \Rightarrow \quad t'(\mathcal{M}[P] ; A)(tr_0, s_0)(tr), \\
\text{if } \mathcal{E}[b]s_0 = \text{false}, & \quad \Rightarrow \quad t'(\mathcal{M}[\text{skip}])(tr_0, s_0)(tr)
\end{align*}
\]

provided that $\mathcal{E}[b]s_0 \neq \text{error}$

- Parallelism

\[
\mathcal{M}[P_1 \mid P_2](tr_0, s_0) = (\mathcal{M}[P_1](tr_0 \uparrow \alpha P_1), s_0) \parallel_{\text{Prog}} (\mathcal{M}[P_2](tr_0 \uparrow \alpha P_2), s_0)
\]

where $\parallel_{\text{Prog}}$ is the same as that defined before.

- Choice

\[
\begin{align*}
f'(\mathcal{M}[\text{if} a_1 \text{g} ; G_1; a_2]) (tr_0, s_0) & \quad = \quad \{(<> , X) \mid \exists i. B[G_i]s_0 \& (<> , X) \in f'(\mathcal{M}[G_i])(tr_0, s_0) \}
\cup \{(<> , X) \mid \forall i. \neg B[G_i]s_0 \& (<> , X) \in f'(\mathcal{M}[G_i])(tr_0, s_0) \}
\cup \{(<> , X) \mid \exists i. t'(\mathcal{M}[G_i])(tr_0, s_0)(<> ) = \bot_{\text{State}} \}
\cup \{(tr, X) \mid tr \neq <> \& (tr, X) \in f'(\mathcal{M}[G_i])(tr_0, s_0) \}.
\end{align*}
\]

\[
t(\mathcal{M}[\text{if} a_1 \text{g} ; G_1; a_2])(tr_0, s_0)(tr) = \bigcup_i(t'(\mathcal{M}[G_i])(tr_0, s_0)(tr))
\]

- Channel Hiding

\[
\begin{align*}
f'(\mathcal{M}[\text{c in P end}]) (tr_0, s_0) & \quad = \quad \{(tr \setminus c, X) \mid (tr, X \cup \{c\}) \in f'(\mathcal{M}[P])(tr_0, s_0) \}
\cup \{(tr, X) \mid \{tr' \mid tr' \in \text{traces}(P_{(tr_0,s_0)}) \& tr' \setminus c \leq tr\} \text{ is infinite } \}
\end{align*}
\]

\[
f'(\mathcal{M}[\text{c in P end}]) (tr_0, s_0)(tr) = \bot_{\text{State}}, \quad \text{if } \{tr' \mid tr' \in \text{traces}(P_{(tr_0,s_0)}) \& tr' \setminus c \leq tr\} \text{ is infinite}
\]

\[
\bigcup \{t'(\mathcal{M}[P])(tr_0, s_0)(tr') \mid tr' \setminus c = tr \}
\]

- Local Variable

\[
f'(\mathcal{M}[\text{var x in P end}]) (tr_0, s_0) = f'(\mathcal{M}[P])(tr_0, s_0),
\]

and

\[
t'(\mathcal{M}[\text{var x in P end}]) (tr_0, s_0)(tr) = \{s \setminus x \mid s \in \text{t'(\mathcal{M}[P])(tr_0, s_0)(tr)} \}, \quad \text{for all } tr \in \text{Comm}^*
\]

This completes the definitions of the semantics for the mixed terms.
4.4 Related Work

- The Features of Our Mathematical Model
  The mathematical model developed in this paper is based on the divergence model for the purely parallel version of CSP [Ho85].

  However, since the divergence model has omitted several central sequential constructs, like assignment, it can not model the transitions of internal machine states appropriately. The framework chosen in this paper for dealing with this problem is the well-known idea of regarding a program as a state transformer between initial and final states [HH85]. We add to the divergence model the initial states and termination components, i.e. the final states after its termination. Doing so, our model is capable of modelling both the communication behaviour of a program, as well as its internal state transitions. The purpose of this is to obtain a unified formalism to combine the techniques developed for purely parallel processes and sequential programs.

  A closely related model is that of A. W. Roscoe's for Occam [Ros84]. The main difference between his and ours is that: although the internal states is modelled in his model by functions from traces to states, the initial states of a process are assumed to be arbitrary. In our model, we assume that a program can start in only certain set of initial states like a sequential program does. The result of this is that sequential programs can be properly modelled. It is also easy to extend our model to include specification statements and give a denotational semantics to the specification statement and mixed terms. In this end, we can handle specifications and programs in a unified framework as Carroll Morgan did in [Mor88].

- The Features of Our Specification Formulas
  The correctness formula in our formalism is inspired by C. Morgan's "specification statement calculus"[Mor88].

  In [Zw88], a similar specification formula was developed. As the communication invariant $I$ does not contain any program variables, his specification languages cannot specification internal-state related communication conditionals precisely, such as if $x = 1 \rightarrow a?x \Box x = 2 \rightarrow b?x \Box$. We will discuss this problem in a forthcoming paper.

  Our specification statements can also specify certain liveness properties of a communicating process, such as nondeterminism and deadlocks, etc.. However, as CSP is not suitable for specifying fairness properties, nor is ours.

5 Conclusion

In this paper, we present a formalism for modeling and specifying communicating sequential processes with internal states.

Our model and specification statements can handle both communicating processes as well as purely sequential programs. The model is a hybrid model. It has the advantages in that, on purely parallel programs, the results obtained would correspond
closely to the old failure-sets model, and that, on purely sequential programs, the results would be relations on states.

We will develop a refinement calculus based on this model for CSP-like parallel languages in a forthcoming paper. Since there is not only one way to Rome, we would like to investigate some other kind of specification methods, like temporal logic. As the way of specifying a system is very vital to the application of the development method, this research direction is of great interest.

We also need to do more examples to explore the refinement laws which would help to reduce the development efforts.

Another area of application of our method might be the design of VLSI.

6 Acknowlagement

The first author would like to thank Wei Chen and Jifeng He for many fruitful discussions.

References


A Mathematical Properties of Process Space Proc

To give a denotational semantics to our CSPL, we need the following mathematical concepts and properties on the process domain.

Let $D$ be a set with a partial order $\sqsubseteq$.

**Definition A.1** Consider a partially ordered set $(D, \sqsubseteq)$. $a$ is a lower bound of a set $X \subseteq D$, and $b$ is an upper bound, provided that $a \sqsubseteq x$ for all $x \in X$, and $x \sqsubseteq b$ for all $x \in X$, respectively. If the set of upper bounds has a unique smallest element, we call it the least upper bound and write it as $\sqcup X$ or $\sup X$. Similarly the greatest lower bound is written as $\sqcap X$ or $\inf X$.

**Definition A.2** A semilattice is a partially ordered set $(D, \sqsubseteq)$ in which every nonempty finite subset has an inf. A sup-lattice is a partially ordered set in which every finite subset has a sup. $(D, \sqsubseteq)$ is called a lattice if it is both a semilattice and a sup-lattice.

**Definition A.3** A lattice is called a complete lattice if every subset of it has an inf.

**Definition A.4** An operator $f : D \to \xi$ from one cpo $D$ to another $\xi$ is called strict if it preserves the least element, monotonic if it preserves the partial order, and continuous if it preserves the least upper bound, i.e. if $x_1 \sqsubseteq x_2 \sqsubseteq \cdots$ is an ascending chain in $D$, then

$$f(\bigsqcup_i x_i) = \bigsqcup_i f(x_i).$$

By Knaster-Tarski's fixed point theorem [Tar49], every monotonic operator $f : D \to D$ has a least fixed point $\fix(f)$ in $D$. If $f$ is continuous, $\fix(f)$ can be represented as

$$\fix(f) = \bigsqcup_{n \geq 0} f^n(\bot),$$

where $f^0(d) = d$ and $f^{n+1}(d) = f^n(f(d))$ for all $d \in D$.

We define a partial order $\sqsubseteq_r$ on $Proc$.

**Definition A.5** A process $P_1 = (Fr_1, Tr_1)$ is said to be refined by another process $P_2 = (Fr_2, Tr_2)$, denoted $P_1 \sqsubseteq_r P_2$, if and only if, for any $s_0 \in \text{State}$,

1) $Fr_2(s_0) \sqsubseteq Fr_1(s_0)$;
2. \( T_r(s_0, tr) \subseteq T_r(s_0, tr) \), for all \( tr \in \text{Comm}^* \)

where \( \alpha P_1 = \alpha P_2 \).

The least element \( \bot_{\text{Proc}} \) (or simply \( \bot \)) on \( \text{Proc} \) under \( \sqsubseteq_r \) is defined

\[
\bot_{\text{Proc}} \equiv ( Fr_\bot, Tr_\bot ),
\]

where \( Fr_\bot(s_0) = (\text{Comm}^* \times \mathcal{P}(\text{Chan}_j)) \) and \( Tr_\bot(s_0, tr) = \bot_{\text{State}} \), for any \( s_0 \in \text{State} \) and \( tr \in \text{Comm}^* \).

To prove that \( (\text{Proc}, \sqsubseteq_r, \bot_{\text{Proc}}) \) is a complete semilattice, we define two binary operators, the union operator \( \sqcup \) and the intersection operator \( \cap \) on \( \text{Proc} \).

**Definition A.6** Let \( P_1 = ( Fr_1, Tr_1 ) \) and \( P_2 = ( Fr_2, Tr_2 ) \) be two processes on \( \text{Proc} \) with \( \alpha P_1 = \alpha P_2 \). Then, we define

\[
P_1 \sqcup P_2 \equiv ( Fr_1 \cap Fr_2, Tr_1 \cap Tr_2 )
\]

\[
P_1 \sqcap P_2 \equiv ( Fr_1 \cup Fr_2, Tr_1 \cup Tr_2 )
\]

where \( \cap \) and \( \cup \) are set intersection and union, respectively, \( (f_1 \cup f_2)(x) = f_1(x) \cup f_2(x) \) and \( (f_1 \cap f_2)(x) = f_1(x) \cap f_2(x) \).

Then we have the following lemmas.

**Lemma A.1** The intersection, \( P_1 \sqcap P_2 \), of two processes \( P_1 \) and \( P_2 \) is a process.

\( \square \)

**Proof:**

Let \( P_1 = ( Fr_1, Tr_1 ) \) and \( P_2 = ( Fr_2, Tr_2 ) \) be two processes and \( P = ( Fr, Tr ) = P_1 \sqcap P_2 \), so that \( Fr = Fr_1 \cup Fr_2 \) and \( Tr = Tr_1 \cup Tr_2 \).

We want to prove that, starting in any initial state \( s_0 \), \( P \) satisfies all the properties in the definition of a process, i.e. \( P_1 \sim P_3 \) and \( S_1 \sim S_4 \).

The proofs of \( P_1 \sim P_3 \) are similar to those in [BHR84]. By way of illustration, we give the proof of \( P_3 \) here.

- The proof of \( P_3 \)

Suppose

\[
(tr, \text{ref}) \in Fr(s_0) \quad \text{and} \quad \forall v. (tr^v < c.v, >, \phi) \notin Fr(s_0).
\]

By the definition of \( P \) and the finiteness of \( S_\nu \), there is a process, say \( P_1 \), with

\[
(tr, \text{ref}) \in Fr_1(s_0) \quad \text{and} \quad \forall v. (tr^v < c.v, >, \phi) \notin Fr_1(s_0).
\]

But \( P_1 \), being a process, has property \( P_3 \), which gives

\[
(tr, \text{ref} \cup \{c\}) \in Fr_1(s_0).
\]

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Hence, it follows that 

\[(tr, ref \cup \{c\}) \in Fr(s_0),\]

as required.

The proofs of \(S_1 \sim S_4\) are similar. We only give the details of the proof of \(S_3\).

- The proof of \(S_3\)

Suppose

\[Tr(s_0, tr) = \bot\quad \text{and} \quad tr' \in Comm^*.\]

By definition of \(P\), there is a process, say \(P_1\), with

\[Tr_1(s_0, tr) = \bot.\]

But \(P_1\), being a process, has property \(S_3\), which gives

\[Tr_1(s_0, tr^{\wedge}tr') = \bot\quad \text{for} \quad tr' \in Comm^*.\]

And hence, by definition of \(P\), it follows that

\[Tr(s_0, tr^{\wedge}tr') = \bot\quad \text{for} \quad tr' \in Comm^*.\]

as required.

This completes the proof.

**Lemma A.2** The intersection of two processes \(P_1\) and \(P_2\), \(P_1 \prod P_2\), is the greatest lower bound of them under \(\subseteq_r\).

\(\Box\)

**Proof:**

Let \(P_1 = (Fr_1, Tr_1)\) and \(P_2 = (Fr_2, Tr_2)\) be two processes and \(P = (Fr, Tr) = P_1 \prod P_2\), so that \(Fr = Fr_1 \cup Fr_2\) and \(Tr = Tr_1 \cup Tr_2\).

We first prove that \(P_1 \prod P_2\) is a lower bound of \(P_1\) and \(P_2\) under \(\subseteq_r\). Then, we prove that it is the greatest lower bound.

\(P_1 \prod P_2\) is a lower bound of \(P_1\) and \(P_2\), i.e. \(P_1 \prod P_2 \subseteq_r P_1\) and \(P_1 \prod P_2 \subseteq P_2\)

The proofs of \(P_1\) and \(P_2\) are the same. We only give details for \(P_1\). We check the three conditions of \(\subseteq_r\), for any state \(s_0 \in State:\)

1). By definition of \(\prod\), we have

\[Fr_1(s_0) \subseteq Fr(s_0) \quad (= Fr_1(s_0) \cup Fr_2(s_0));\]

2). Also by definition of \(\prod\), we have

\[Tr_1(s_0, tr) \subseteq Tr(s_0, tr) \quad (= Tr_1(s_0, tr) \cup Tr_2(s_0, tr)),\]

as required.
$P_1 \prod P_2$ is the greatest lower bound of $P_1$ and $P_2$.

Suppose $P' = (F_{P'}, T')$ is a lower bound of $P_1$ and $P_2$.

1). We have, for any $s_0 \in \text{State}$,

$$F_{r_1}(s_0) \subseteq F_{r'}(s_0) \quad \text{and} \quad F_{r_2}(s_0) \subseteq F_{r'}(s_0),$$

and hence,

$$F_{r_1}(s_0) \cup F_{r_2}(s_0) \subseteq F_{r'}(s_0),$$

as required.

2). We have

$$T_{r_1}(s_0, tr) \subseteq T_{r'}(s_0, tr) \quad \text{and} \quad T_{r_2}(s_0, tr) \subseteq T_{r'}(s_0, tr),$$

and hence

$$T_{r}(s_0, tr) = T_{r_1}(s_0, tr) \cup T_{r_2}(s_0, tr) \subseteq T_{r'}(s_0, tr),$$

as required.

This completes the proof.

The union of two processes $P_1$ and $P_2$, $P_1 \cup P_2$ may not be in Proc, i.e. it may not be a process. For example, the intersection $F_{r_1} \cap F_{r_2}$ of the failure sets of $P_1$ and $P_2$ may be empty which does not satisfy the definition of a process. Therefore we can, at most, prove that (Proc, $\sqsubseteq_r$, $\perp_{Proc}$) is a complete semi-lattice.

**Lemma A.3** The union of an ascending chain of processes, $P_1 \sqsubseteq_r P_2 \sqsubseteq_r P_3 \sqsubseteq_r \cdots$, exists, that is

$$P = \bigcup_i P_i = \left( \bigcap_i F_{r_i} \right) \cup \bigcup_i T_{r_i}.$$

\[\square\]

**Proof:**

We only need to prove that $\bigcap_i F_{r_i}$ and $\bigcup_i T_{r_i}$ exist, for any initial state $s_0 \in \text{State}$ and $tr \in \text{Comm}^*$.

- Firstly, By definition of $\sqsubseteq_r$, we have

$$F_{r_1}(s_0) \supseteq F_{r_2}(s_0) \supseteq F_{r_3}(s_0) \supseteq \cdots,$$

and $F_{r_1}(s_0)$ is finite. Hence, $\bigcap_i F_{r_i}(s_0)$ exists as required.

- Secondly, from

$$T_{r_1}(s_0, tr) \supseteq T_{r_2}(s_0, tr) \supseteq T_{r_3}(s_0, tr) \supseteq \cdots,$$

and $T_{r_i}(s_0, tr)$ is finite, we have $\bigcap_i T_{r_i}(s_0, tr)$ exists, for every $s_0 \in \text{State}$ and $tr \in \text{Comm}^*$. 

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This completes the proof.

Lemma A.4 The union of an ascending chain of processes, \( P_1 \subseteq_r P_2 \subseteq_r P_3 \subseteq_r \ldots \),

\[
P = \bigcup_i P_i = (\bigcap_i Fr_i, \bigcup_i Tr_i),
\]

is a process.

\(\Box\)

Proof:

Let \( P = (Fr, Tr) = \bigcup_i P_i \) with

\[
Fr = \bigcap_i Fr_i \quad \text{and} \quad Tr = \bigcap_i Tr_i.
\]

We want to prove that \( P \) starting in any state \( s_0 \in State \), satisfies all the properties in the definition of a process, i.e. \( P_1) \sim P_3) \) and \( S_1) \sim S_4) \).

The proofs of \( P_1) \sim P_3) \) are trivial. By way of illustration, we only give the proof of \( P_3) \) here.

- The proof of \( P_3) \)

Suppose

\[
(tr, ref) \in Fr(s_0) \quad \text{and} \quad \forall v. (tr^< c.v>, \phi) \notin Fr(s_0).
\]

This means that, for every \( P_i \),

\[
(tr, ref) \in Fr_i(s_0),
\]

and there is at least a process, say \( P_k \), such that

\[
\forall v. (tr^< c.v>, \phi) \notin Fr_k(s_0)
\]

because \( S_v \) is finite. We want to prove that \( (tr, ref \cup \{c\}) \in Fr(s_0) \), and this will be true unless there is a process, say \( P_j \), with

\[
(tr, ref \cup \{c\}) \notin Fr_j(s_0).
\]

If such a process existed, we would be able to find a process \( P_n \) in the chain with \( n > k \) and \( n > j \) such that

\[
P_k \subseteq_r P_n \quad \text{and} \quad P_j \subseteq_r P_n,
\]

that is

\[
Fr_n(s_0) \subseteq Fr_k(s_0) \quad \text{and} \quad Fr_n(s_0) \subseteq Fr_j(s_0).
\]

Then we have

\[
Fr_n = Fr_k(s_0) \cap Fr_j(s_0).
\]
But, we should have, by the assumptions, that

\[(tr, \text{ref}) \in Fr_n(s_0),\]

\[\forall v. (tr^v < c.v >, \phi) \notin Fr_n(s_0),\]

\[(tr, \text{ref} \cup \{c\}) \notin Fr_n(s_0).\]

This contradicts \(P_3\) for \(P_n\). Therefore, it must be the case that

\[(tr, \text{ref} \cup \{c\}) \in Fr(s_0).\]

The proofs of \(S_1\) \(\sim S_4\) are as follows:

- **The proof of \(S_1\)**
  Suppose
  \[Tr(s_0, tr) \neq \phi \quad \text{for } s_0 \in \text{State and } tr \in \text{Comm}^*.\]
  Because \(Tr(s_0, tr) = \bigcap_i Tr_i(s_0, tr)\), we have

  \[Tr_i(s_0, tr) \neq \phi, \quad \text{for all } i.\]

  Hence, \(P_i\) being a process, by \(S_1\), we have

  \[tr \in traces(P_i(s_0)), \quad \text{for all } i.\]

  Therefore we have

  \[(tr, \phi) \in Fr(s_0) ( = \bigcap_i Fr_i(s_0)),\]

  as required.

- **The proof of \(S_2\)**
  Suppose
  \[(tr, \text{ref}) \in Fr(s_0) \quad \text{and} \quad Tr(s_0, tr) = \phi.\]
  We want to prove that \((tr, \text{ref} \cup \{\sqrt{}\}) \in Fr(s_0)\). By definition of \(\sqsubseteq_r\), we have

  \[Tr(s_0, tr) = \bigcap_i Tr_i(s_0, tr) = \phi\]

  By the finiteness of \(\text{State}_\perp\), there must exist a \(k\) such that

  \[Tr_k(s_0, tr) = \phi, \quad \text{for all } i \geq k.\]

  Hence, \(P_i\) being a process, by \(S_2\), we have

  \[(tr, \text{ref} \cup \{\sqrt{}\}) \in Fr_i(s_0), \quad \text{for all } i \geq k.\]

  \(\{P_i \mid i \geq 1\}\) being a chain, we have

  \[(tr, \text{ref} \cup \{\sqrt{}\}) \in Fr(s_0) ( = \bigcap_i Fr_i(s_0)),\]

  as required.
- The proof of $S_3$)
  Suppose
  \[ Tr(s_0, tr) = \phi \quad \text{and} \quad tr' \in \text{Comm}^* . \]
  By definition of $P$, we have
  \[ Tr_i(s_0, tr) = \bot \quad \text{for all } i. \]
  $P_i$, being a process, has the property $S_3$, which gives
  \[ Tr_i(s_0, tr^\land tr') = \bot \quad \text{for } tr' \in \text{Comm}^*. \]
  Hence, it follows, by definition of $P$, that
  \[ Tr(s_0, tr^\land tr') = \bigcap_i Tr_i(s_0, tr^\land tr') = \bot, \]
  as required.
- The proof of $S_4$)
  The proof of $S_4$) is similar to that of $S_3$), and is omitted.

This completes the proof.

**Lemma A.5** The union of an ascending chain of processes, $P_1 \subseteq_r P_2 \subseteq_r P_3 \subseteq_r \ldots$,
\[ \bigcup_i P_i = (\bigcap_i Fr_i, \bigcap_i Tr_i), \]
is the least upper bound of them.
\[ \Box \]

**Proof:**

Let $P = (Fr, Tr) = \bigcup_i P_i$, with
\[ Fr = \bigcap_i Fr_i \quad \text{and} \quad Tr = \bigcap_i Tr_i, \]
We want to prove that $P$ is the least upper bound of $P_1 \subseteq_r P_2 \subseteq_r P_3 \subseteq_r \cdots$, i.e. for any $P'$ which is an upper bound of all $P_i$'s, $P \subseteq_r P'$. We first prove that $P$ is an upper bound of all $P_i$'s.

- $P$ is an upper bound of all $P_i$'s
  For any $P_i$ in $\{P_i|i \geq 0\}$, we check the two conditions of $\subseteq_r$: for any $s_0 \in \text{State}, 1)$. we have, by definition of $\bigcup$
  \[ Fr_i(s_0) \supseteq Fr(s_0) ( = \bigcap_i Fr_i(s_0)); \]
2). and, also by definition of $\bigcup$ and the fact that $P_i$'s is a chain, we have

$$Tr_i(s_0, tr) \supseteq Tr(s_0, tr) \subsetneq \bigcap_i Tr_i(s_0, tr)$$

for every $tr \in \text{Comm}^*$ as required.

Then we prove that it is the least upper bound.

- $P$ is the least upper bound

Suppose $P'$ is an upper bound of all $P_i$'s.

1). We have, for any $s_0 \in \text{State}$ and $tr \in \text{Comm}^*$

$$Fr'(s_0) \subseteq Fr_i(s_0), \text{ for all } i,$$

and hence,

$$Fr'(s_0) \subseteq Fr(s_0) \subseteq \bigcap_i Fr_i(s_0),$$

2). and

$$Tr'(s_0, tr) \subseteq Tr_i(s_0, tr),$$

and hence

$$Tr'(s_0, tr) \subseteq Tr(s_0, tr) \subseteq \bigcap_i Tr_i(s_0, tr),$$

as required.

This completes the proof.

Now we can give the following main theorem.

**Theorem A.1** (Proc, $\sqsubseteq_r$, $\bot_{\text{Proc}}$) is a complete semi-lattice.

$\square$

**Proof:**

This follows by the definition of a semilattice, Lemma A.1, Lemma A.2, Lemma A.3, Lemma A.4 and Lemma A.5.