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FAIRNESS ASSUMPTIONS FOR CSP IN A TEMPORAL LOGIC FRAMEWORK

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Fairness assumptions for CSP in a Temporal Logic Framework *)

by

R. Kuiper & W.P. de Roever**)

ABSTRACT

Six fairness assumptions for the repetitive construct $*[\ldots \Box\, b_\ell\,, c_\ell \rightarrow S_\ell \,\Box \ldots]$ in a subset of CSP are given and classified with respect to the programs they cause to terminate. A total correctness proof system for the subset of CSP is given, incorporating the different fairness assumptions.

KEY WORDS & PHRASES : CSP, *concurrency, correctness proofs, fairness, temporal logic*

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*) To appear in the Proceedings of the IFIP WG 2.2 Working Conference on Formal Description of Programming Concepts II (Ed. D. Bjørner), North-Holland Publishing Company (1982).

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0. INTRODUCTION

The research in this paper originated from work by FRANCEZ AND DE ROEVER [F de R]. The aim of the paper is twofold, both cases having to do with temporal logic. On the one hand, we consider six different fairness assumptions for a subset of CSP, i.e. Communicating Sequential Processes, a language for distributed computing without shared variables defined by HOARE in [H]. These assumptions will be expressed using temporal logic, which enables us to formulate them at a level convenient for intuitive understanding of their meaning as well as for use in formal proofs. They will be compared with respect to the sets of programs they cause to terminate. On the other hand we need a framework to reason about the effects of such fairness assumptions. To do so we give a (low level) temporal logic proof system for this subset of CSP. We use the idea of temporal semantics as developed for shared variable languages by PNUELI [P]. We have been helped by BEN ARI'S thesis [BA] , especially by his way of reasoning with conditional invariants. It is shown here that by this method also non-shared variables and synchronized communication as in CSP can be modelled in a natural way.

The set up is as follows. Section I gives the preliminary facts of CSP, section 2 the temporal logic semantics and section 3 the fairness assumptions; section 4 indicates the temporal logic we use. In section 5 several examples are given. Finally section 6 contains discussion.

When this paper was being typed, we received a paper by SMOLKA [S] dealing with related matters.

I. PRELIMINARIES

The syntax of the subset of CSP we use is as follows.

DEFINITION

Statements: $S ::= skip \mid x:=t \mid *[b_1,c_1 \rightarrow S_1 \,\Box \ldots \Box\, b_m,c_m \rightarrow S_m]$
where t is an integer expression
b a boolean expression and
c either $P_i!\,x$ or $P_j?\,y$ $i,j \in \{1,\ldots n\}$

Programs : $[P_1::S_1 \parallel \ldots \parallel P_n::S_n]$
where $P_i, i \in I=\{1,\ldots,n\}$, is called a process.
Processes have no shared variables.

Neither $[\ldots\parallel\ldots]$ nor $*[\ldots]$ is allowed to be used in nested fashion.

2. TEMPORAL SEMANTICS

We introduce control locations ℓ_i, ℓ_i', $i \in I$, as follows. ℓ_i (or ℓ_i') can be at S or after S for S in P_i defined in the natural way (cf.[O],[OL]). Obvious identifications like: "for $P_1::S_1;S_2$ holds after $S_1 \equiv$ at S_2 and at $P_1 \equiv$ at S_1 ; $S_2 \equiv$ at S_1" are made. The guarded command case needs some further clarification:
1) For S_ℓ in $*[\ldots \Box b_\ell\, c_\ell \rightarrow S_\ell \,\Box \ldots]$, after $S_\ell \equiv$ at $*[\ldots]$.
2) There are no control locations concerning the b_ℓ, c_ℓ construct, as, when control is active at a guarded command $*[\;\;]$, all guards are evaluated at the same time instant, after which control is still at the same point or resides either at one of the guarded statements or after the whole command.

States S are tuples $S = \langle \ell, s\rangle = \langle\langle \ell_1,\sigma_1\rangle, \ldots, \langle \ell_n,\sigma_n\rangle\rangle$ such that for each $i \in I$ ℓ_i is one of the above defined control locations in P_i. Control locations are also used as predicates , $\overline{\ell}_i$ (or $\overline{\ell}_i'$) being true in s = (ℓ,σ) iff $\ell_i = \overline{\ell}_i$ (respectively $\ell_i' = \overline{\ell_i'}$)

Auxiliary notation:
$*[i]$ denotes a guarded command in P_i; constructs like "for all $*[i]$ in P_i" assume implicit indexing of the $*[i]$. $g_{i\ell} \equiv b_{i\ell}, c_{i\ell}$ is a guard in a guarded command $*[\ldots \Box b_{i\ell}, c_{i\ell} \rightarrow S_{i\ell} \,\Box \ldots]$ belonging to the process P_i.
$c_{i\ell} \;\underline{m}\; c_{jm}$ iff $c_{i\ell}$ and c_{jm} are syntactically matching communication commands (e.g.: $P_j!x$ in P_i and $P_i?\,y$ in P_j). $g_{i\ell}$ in the guarded command $*[i]$ is true in the state s iff there is a process P_j such that ℓ_j = at $*[j]$ and $*[j]$ contains at least one g_{jm} such that $c_{i\ell} \;\underline{m}\; c_{jm} \wedge b_{i\ell} \wedge b_{jm}$. Notation $g_{i\ell} \;\underline{m}\; g_{jm}$. This indicates semantical matching. $\sigma[i\ell \;\underline{c}\; jm]$ is σ changed according to the effect of the communication between c_{jm} and c_{jm} (e.g.: $g_{i\ell} = P_j!x$ and $g_{jm} = P_i?\,y$ will lead to $\sigma[il \;\underline{c}\; jm] = \sigma[x/y]$).
Finally, to enable us to include the distributed termination convention we define: $t(g_{i\ell})$ holds in s iff the process named (as target) in $c_{i\ell}$ is terminated (e.g. ℓ_j = after P_j and $g_{i\ell} = b_{i\ell}, P_j?x$)

Now we define the temporal semantics as follows. The meaning of a program is the set of computation sequences satisfying the following axioms. O is the next time operator from temporal logic.

Exclusivity Axiom (E)
$\neg(\ell_i \wedge \ell_i')$ for all $i \in I$ and $\ell_i \neq \ell_i'$.

The Exclusivity Axiom describes that control in each process always is at just one place at the same time.

Local Semantics Axiom (LS)
(i) at skip $\wedge\, \sigma = \overline{\sigma} \supset O$ (at skip) $\vee\, O$(after skip $\wedge\, \sigma = \overline{\sigma}$)
(ii) at x:= t $\wedge\, \sigma = \overline{\sigma} \supset O$ (at x:=t) $\vee\, O$(after x:=t $\wedge\, \sigma = \overline{\sigma}\,[t/x]$) .
(iii) Let $*[i] = *[b_{i1}, c_{i1} \rightarrow S_{i1} \,\Box \ldots \Box\, b_{in_i}, c_{in_i} \rightarrow S_{in_i}]$

$$\text{at} * [i] \wedge \sigma = \bar{\sigma} \supset O\,(\text{at} * [i])$$
$$\vee \Big(\bigvee_{\substack{j=1\\ j\neq i}}^{n} \bigvee_{\ell=1}^{n_i} \bigvee_{m=1}^{n_j} (\text{at} * [j] \wedge g_{i\ell} \underline{m}\, g_{jm} \wedge$$
$$O(\text{at } S_{i\ell} \wedge \text{ at } S_{jm} \wedge \sigma = \bar{\sigma}\,[i\ell \underline{c}\, jm])) \Big)$$
$$\vee \Big(\bigwedge_{\ell=1}^{n_i} (\neg b_{i\ell} \vee t(g_{i\ell})) \wedge O\,(\text{after} * [i] \wedge \sigma = \bar{\sigma}) \Big)$$

The Local Semantics Axiom describes what is usually known (in papers not dealing with fairness) as operational semantics of these constructs. Note, that synchronization and the termination convention of CSP come to the fore in (iii).

Now to state our last axiom we have to refine our notation such that each statement in the program has a unique name.
Enumerate the control locations in process P_i of form at S_k where $S_k \equiv$ skip or $S_k \equiv x{:=}t$ by α_{ik}, $i \in I$, $K \in K_i$. Let α'_{ik} denote the corresponding after S_k location.
Likewise enumerate the control locations of form
at $*[\ldots \Box b_{iq\ell}, c_{iq\ell} \rightarrow S_{iq\ell} \Box \ldots]$ in process P_i by $\gamma_{iq}, i \in I, q \in Q_i$ with corresponding sets of locations

$$\Gamma_{iq} = \vee_{\ell} \text{ at } S_{iq\ell} \vee \text{ after } * [\ldots],\ \ell \in L_{iq}$$

Then define

$$A_{ik} = \alpha_{ik} \wedge O\,\alpha'_{ik} \quad \text{for } i \in I,\ k \in K_i$$
$$C_{iq} = \gamma_{iq} \wedge O\,\Gamma_{iq} \quad \text{for } i \in I,\ q \in Q_i$$
$$T = \bigwedge_{i \in I} (\text{after } P_i \vee (\text{at } *[i] \wedge \wedge_{\ell} \neg g_{i\ell} \wedge \neg \cdot \wedge_{\ell} (\neg b_{i\ell} \vee t(g_{i\ell}))))$$

Notice, that A_{ik} and C_{iq} describe that a statement is activated, whereas T indicates that a situation is finished or blocked.
Now let b=0 (respectively 1) denote that b is false (respectively true). Then $\Sigma_{i \in I} = 1$ indicates that exactly one of the b_i is true. Moreover, the execution of a guarded command by selecting a guard containing only the boolean part should be seen as a self-communication between two identical processes.
Then finally we state the

Multiprogramming Axiom (M)

$$\sum_{i \in I} \sum_{k \in k_i} A_{i_k} + \tfrac{1}{2} \sum_{i \in I} \sum_{q \in Q_i} C_{iq} + T = 1$$

The Multiprogramming Axiom describes that either the program is terminated or blocked (i.e.T=1) or exactly one action changing the state takes place at each time instant. Note, that communication between two processes is viewed as one action (cf.the factor ½ in M).

REMARK. Above we require that, in not terminated or blocked situations, exactly one action is performed at each time instant. Concurrency then is described by considering all sequences of such actions allowed by the semantics; this is the usual treatment in case of concurrent shared variable languages. However, as in CSP the processes have no shared variables, it is more natural to allow atomic actions in different processes to be executed at the same time instant; the same also holds for communications between disjunct pairs of processes. The system can be adapted to this as follows. We now use that s is an n-tuple $\langle\langle \ell_1 \sigma_1 \rangle, \ldots, \langle \ell_n, \sigma_n \rangle\rangle$ where each process P_i only affects (ℓ_i, σ_i). Contrary to the situation above, we cannot assume anymore that only the active process determines the state at the next instant. Therefore we explicitly denote that if a process is not activated, it does not change its part of the state.
We now have :

Local Semantics Axiom * (LS^*)

(i) $\text{at skip} \wedge \sigma = \bar{\sigma} \supset O\,(\text{at skip} \wedge \sigma_i = \bar{\sigma}_i) \vee O\,(\text{after skip} \wedge \sigma_i = \bar{\sigma}_i)$ for skip in P_i

(ii) $\text{at } x{:=}t \wedge \sigma = \bar{\sigma} \supset O\,(\text{at } x{:=}t \wedge \sigma_i = \bar{\sigma}_i) \vee O\,(\text{after } n{:=}t \wedge \sigma_i = \sigma_i[t/x]$ for $n{:=}t$ in P_i

(iii) Let $*[i] = *[b_{i1}, c_{i1} \to S_{i1} \,\square \ldots \square\, b_{in_i}, c_{in_i} \to S_{in_i}]$

$$\text{at } *[i] \wedge \sigma = \bar{\sigma} \supset O\,(\text{at } *[i] \wedge \sigma_i = \bar{\sigma}_i)$$
$$\vee\Big(\bigvee_{j=1}^{n} \bigvee_{\ell=1}^{n_i} \bigvee_{m=1}^{n_j} (\text{at } *[j] \wedge g_{i\ell} \underline{m}\, g_{jm} \wedge$$
$$O(\text{at } S_{i\ell} \wedge \text{at } S_{jm} \wedge \sigma_i = \bar{\sigma}_i[i\ell \underline{c}\, jm]$$
$$\wedge\ \sigma_j = \bar{\sigma}_j\,[i\ell \underline{c}\, jm])\Big)\Big)$$
$$\vee\Big(\bigwedge_{\ell=1}^{n_i} (\neg b_{i\ell} \vee t(g_{i\ell})) \wedge O\,(\text{after } *[i] \wedge \sigma_i = \bar{\sigma}_i)\Big)$$

Note, that the Exclusivity Axiom prevents executing more than one of the possible choices in case of a guarded command.

Multiprogramming Axiom * (M^*)

$$\sum_{i\in I} \sum_{k\in K_i} A_{ik} + \sum_{i\in I} \sum_{q\in Q_i} C_{iq} + T \geq 1$$

The further material in this paper can without change (up to *'s) be taken as based on either one of these alternatives.

3. FAIRNESS ASSUMPTIONS

Our aim is to define in the context of CSP a variety of intuitively reasonable fairness assumptions depending on different implementations of the guarded command construction (cf.[D]) as well as on synchronized communication, both being specific CSP features. We compare the different assumptions with respect to the programs they cause to terminate.

We start by considering what kind of fairness is induced by the temporal semantics so far. Note, that the multi-programming axiom (M) ensures that no unnecessary idling occurs; only a blocked or terminal state can (and always will) be repeated unchanged. (M) also ensures that as long as somewhere action is possible, some action will be taken, i.e. the temporal semantics so far imposes minimal liveness (cf.[OL]) . So

Minimal Liveness Axiom: —

Next, as in the presence of one process looping all the time this allows starvation of all other processes, it seems reasonable to impose a stronger liveness requirement. The usual one chosen is fundamental liveness (cf.[OL])ensuring that if a process is continuously enabled to proceed, it eventually will. To express this, we first give the usual axiom for atomic statements, using the temporal operators $\Diamond$ (eventually) and $\square$ (always).

Atomic Statement Liveness Axiom (ASL)

$$\square \text{ at } S \supset \Diamond \text{ after } S \text{ for } S \equiv \text{skip or } S \equiv x := t$$

We now are faced with treating the guarded command in the same way. If all boolean guards are false the axiom is obvious.

Guarded Command Skip Axiom (GCS)

$$\square\,(\text{at } *[\ ] \wedge \bigwedge_{\ell} (\neg b_\ell \vee t(g_\ell)) \supset \Diamond \text{ after } *[\ ]$$

Now to deal with enabled guarded commands there are various possibilities, depending on two parameters. Firstly, we consider two fairness assumptions: weak (respectively strong) fairness, stating that those moves which are eventually continuously (respectively eventually infinitely often) enabled are eventually taken (cf.,e.g.,[GPSS]). Secondly, in CSP we can distinguish three varieties of these two assumptions, depending on what is taken to be a move in the case of executing guarded commands. As will become clear from the assumptions to follow, we can distinguish a move with respect to a process, a guard or a pair of semantically matching guards, i.e. a channel. Hence the concept of fundamental liveness is captured by requiring the following.

Fundamental Liveness Axiom
(i) Atomic Statement Liveness Axiom
(ii) Guarded Command Skip Axiom
(iii) $\Box$ at $*[\ ] \wedge \Diamond \Box$ (at $*[\ ] \supset V_\ell g_\ell) \supset \Diamond\, V_\ell$ at S_ℓ

As will be seen below, we shall concentrate on different possibilities for (iii), having the above one as the weakest possibility.

REMARK. In the axioms we use constructs like $\Box \Diamond$ at $*[\ldots] \supset \Diamond$ at S_ℓ and $\Box$ at $*[\ldots] \supset \Diamond$ at S_ℓ , which seem self-contradictory. As to the first one, this can eventually happen: $\Box \Diamond$ at $*[true \rightarrow S_\ell] \supset \Diamond$ at S_ℓ , even $\Box \Diamond$ at S_ℓ is possible. As to the second one, the axiom is there to exclude all computation sequences for which $\Box$ at $*[\ldots]$ holds, so logically there is no contradiction: the axiom might be replaced by $\neg \Box$ at $*[\ldots]$. We have chosen the above representation as it covers all cases in a uniform way and indicates the next control location to be reached, thus providing intuition for the design of proofs.

We now formulate the fairness assumptions for the $*[\ldots \Box g_\ell \rightarrow S_\ell \Box \ldots]$ construct. When requiering one of the fairness assumptions the Atomic Statement Liveness Axiom and the Guarded Command Skip Axiom are presupposed. The abbreviations should be obvious.

Weak Process Fairness (WPF)

$$\Box \text{ at } *[\ ] \wedge \Diamond \Box (\text{at } *[\ ] \supset V_\ell g_\ell) \supset \Diamond\, V_\ell \text{ at } S_\ell$$

Weak Guard Fairness (WGF)

$$\Box \Diamond \text{ at } *[\ ] \wedge \Diamond \Box (\text{at } *[\ ] \supset g_\ell) \supset \Diamond \text{ at } S_\ell$$

Weak Channel Fairness (WCF)

$$\Box \Diamond (\text{at } *[\ ] \wedge \text{at } *[\ ]') \wedge \Diamond \Box (\text{at } *[\ ] \wedge \text{at } *[\ ]' \supset g_\ell \underline{m}\, g'_{\ell'}) \supset$$
$$\supset \Diamond (\text{at } S_\ell \wedge \text{at } S'_{\ell'})$$

Strong Process Fairness (SPF)

$$\Box \text{ at } *[\ ] \wedge \Box \Diamond V_\ell\, g_\ell \supset \Diamond\, V_\ell \text{ at } S_\ell$$

Strong Guard Fairness (SGF)

$$\Box \Diamond (\text{at } *[\ ] \wedge g_\ell) \supset \Diamond \text{ at } S_\ell$$

Strong Channel Fairness (SCF)

$$\Box \Diamond (\text{at } *[\ ] \wedge \text{at } *[\ ]' \wedge g_\ell \underline{m}\, g'_{\ell'}) \supset \Diamond (\text{at } S_\ell \wedge \text{at } S'_{\ell'}) .$$

We now compare the various fairness assumptions with respect to the sets of programs they cause to terminate.

DEFINITION. T(f), where f is one of the above fairness assumptions, is the set of CSP programs for which, when executed under the fairness assumption f in any initial state s, all execution sequences contain a state s for which ℓ_i = after P_i for all $i \in \{1,\ldots,n\}$ (i.e., the program terminates).

THEOREM.

$$\begin{array}{ccc}
T(WPF) & \subsetneq & T(SPF) \\
\not\supseteq\cap & & \not\supseteq\cap \\
T(WGF) & \subsetneq & T(SGF) \\
\not\supseteq\cap & & \not\supseteq\cap \\
T(WCF) & \subsetneq & T(SCF)
\end{array} .$$

PROOF. The inclusions and inequalities between the corresponding weak and strong cases are evident. An example for the inequality for the most interesting case, T(WCF) $\neq$ T(SCF) is the following.

$[P_1::\ x:=0;\ y:=1;\ *[x=0, P_2!\ x \rightarrow y := -y \ \Box\ y=1, P_2!\ y \rightarrow \text{skip}\ ] \ \|$
$\ P_2::\ u:=0;\ v:=1;\ *[u=0, P_1?\ u \rightarrow v := -v \ \Box\ v=1, P_1?\ v \rightarrow \text{skip}\ ]\ ]$

The inclusions and inequalities for the weak cases are easy; for the more interesting strong cases as follows.

T(SPF) $\subset$ T(SGF)
By the Local Semantics Axiom, $\Box$ at $*[\ ] \wedge \Box \Diamond V_\ell g_\ell$ is equivalent to $\Box \Diamond (\text{at} * [\ ] \wedge V_\ell g_\ell)$, as this is the only way in which control can proceed. As $g_\ell \supset V_\ell g_\ell$ and at $S_\ell \supset V_\ell$ at S_ℓ, this gives T(SPF) $\subset$ T(SGF)

T(SPF) $\neq$ T(SGF) by

b:= true; $*$ [b$\rightarrow$ skip $\Box$b $\rightarrow$ b:= <u>false</u>]

T(SGF) $\subset$ T(SCF)
This follows from the fact that there are only finitely many guards, whence $\Box \Diamond g_\ell$ implies that there is a g'_ℓ, such that $\Box \Diamond g_\ell \ \underline{m}\ g'_\ell$.
T(SGF) $\neq$ T(SCF) follows from the first example in this proof. $\Box$

4. TEMPORAL LOGIC

We assume as given a temporal logic axiom system and rules for linear time like DUX as presented in, e.g, [P]; to handle assignment we assume extension of this system to predicate logic as outlined in, e.g., [HC] .
In proofs we make use of derived rules as presented in [BA] . E.g.: if $\vdash \Box p \wedge q \supset O\, q$ then $\Box p \wedge q \supset \Box q$, the conditional invariant rule.

5. <u>EXAMPLES</u>. We start by giving a very easy example, (i), in all detail. In (ii) we show how synchronization is treated. In practice most of the elementary steps in a proof can be left out, as (iii) shows. As the examples will show, the Local Semantics Axiom and the conditional invariant rule are crucial to enable application of the fairness assumptions; namely to obtain the left hand side of the stated implication,

(i) Under the assumption of WGF a simple CSP program can model mutual exclusion and infinitely often access for two critical sections CS_1 and CS_2 consisting of sequentially composed atomic statements. Note, that WPF is not sufficient to guarantee access.

P::*[<u>true</u> $\rightarrow CS_1 \ \Box$ <u>true</u> $\rightarrow CS_2$]

PROOF. Mutual exclusion holds by the Exclusivity Axiom. Proving mutual access amounts, by symmetry, to proving $\vdash$ at $*[\ldots] \supset \Diamond$ at CS_1
As follows: (in $S \equiv$ at $S \vee V_{S'}$ at S', S' substatement of S)

1) $\vdash$ at $*[\ldots] \supset \Box \underbrace{(\text{at} *[\ ] \vee \text{in } CS_1 \vee \text{in } CS_2)}_{I:=}$. (LS)

2) $\vdash$ at $*[\ldots] \supset I \wedge$ at $*[\ldots]$ (1,T.L.,i.e.by temporal logic)

3) $\vdash$ at $*[\ldots] \supset I \wedge \Diamond$ at $*[\ldots]$ (T.L.)

4) $\vdash I \wedge \Diamond$ at $*[\ldots] \supset O(\Diamond$ at $*[\ldots])$ (LS,ASL)

5) $\vdash I \wedge \Diamond$ at $*[\ldots] \supset \Box \Diamond$ at $*[\ldots])$ (4,T.L.:cond.invariant rule)

Now the fairness assumption is used;

6) $\vdash \Box \Diamond$ at $*[\ldots] \supset \Diamond$ at CS_1 (WGF)

7) $\vdash$ at $*[\ldots] \supset \Diamond$ at CS_1 (3,5,6,T.L.)

(ii) Termination of a program with synchronization under the assumption of WCF shall be proved. Again we give the proof in much detail.

Let b and c be initially true and not depend on x and y. Then the following program terminates under WCF,

$[P_1 :: *[b, P_2 ! x \rightarrow skip_1 \Box b, P_2 ? x \rightarrow b := \underline{false}\,] \parallel$

$P_2 :: *[c, P_1 ? y \rightarrow skip_2 \Box c, P_1 ! y \rightarrow c := \underline{false}\,]\ ]$

Note, that WGF is not sufficient to guarantee termination, but SGF is.

PROOF. Proving termination amounts, by symmetry, to proving

$\vdash$ at $*[1] \wedge$ at $*[2] \wedge b \wedge c \supset \Diamond$ after $*[1]$

As follows:

1) $\vdash$ at $*[1] \wedge$ at $*[2] \wedge b \wedge c \supset \Diamond$ (at $b := \underline{false} \wedge$ at $c := \underline{false}$)
$\underbrace{\vee \Box((\text{at } *[1] \vee \text{at } skip_1) \wedge (\text{at } *[2] \vee \text{at } skip_2) \wedge b \wedge c)}_{I:=}$, (LS)

Case 1

2) $\vdash$ at $b := \underline{false} \wedge$ at $c := \underline{false} \supset \Diamond($at $*[\ ] \wedge \neg b)$ (LS,ASL)

3) $\vdash$ at $*[1] \wedge \neg b \supset \Diamond$ after $*[1]$ (GCS)

Case 2

4) $\vdash I \wedge$ at $*[1] \wedge$ at $*[2] \supset I \wedge \Diamond$ (at $*[1] \wedge$ at $*[2]$) (T.L.)

5) $\vdash I \wedge \Diamond$ (at $*[1] \wedge$ at $*[2]) \supset O(\Diamond$ (at $*[1] \wedge$ at $*[2]$)) (LS,ASL,M)

6) $\vdash I \wedge \Diamond$ (at $*[1] \wedge$ at $*[2]) \supset \Box \Diamond$ (at $*[1] \wedge$ at $*[2]$) (T.L.:cond.inv.rule)

7) $\vdash I \wedge \Diamond$ (at $*[1] \wedge$ at $*[2]) \supset \Box \Diamond$ (at $*[1] \wedge$ at $*[2] \wedge I$) (T.L.)

Now the fairness assumption is used

8) $\vdash I \wedge \Box \Diamond$ (at $*[1] \wedge$ at $*[2]) \supset \Diamond$ (at $b := \underline{false} \wedge$ at $c := \underline{false}$) (I,WCF)

9) $\vdash$ at $b := \underline{false} \supset \Diamond$ after $*[1]$ (2,3)

10) $\vdash$ at $*[1] \wedge$ at $*[2] \wedge b \wedge c \supset \Diamond$ after $*[1]$ (1,3,9,T.L.)

$\Box$

(iii) Termination of a program consisting of three processes under WGF shall be proved. We now leave out some straightforward detail to show how in practice proofs are not difficult to handle.

Let a,b and c be initially true and not depend on x,y and z. Then the following program terminates under WGF.

$[P_1 :: *[b, P_2 ! x \rightarrow skip_1 \Box b \rightarrow b := \underline{false}] \parallel$

$P_2 :: *[c, P_1 ? y \rightarrow skip_2 \Box c, P_3 ! y \rightarrow c := \underline{false}] \parallel$

$P_3 :: *[d, P_2 ? z \rightarrow d := \underline{false}\,]\ ]$

PROOF. To prove : $\vdash \bigwedge_i$ at $*[i] \wedge b \wedge c \wedge d \supset \Diamond \bigwedge_i$ after $*[i]$

As follows:

1) $\vdash \bigwedge_i$ at $*[i] \wedge b \wedge c \wedge d \supset \Diamond \bigwedge_i$ after $[i]$

$$\left.\begin{array}{l} \vee \Box\ ((\text{at } *[1] \vee \text{at skip}_1) \wedge (\text{at } *[2] \vee \text{at skip}_2) \\ \wedge\ \text{at } *[3] \wedge b \wedge c \wedge d) \end{array}\right\} =: I$$

Analogeous to (ii) this leads to

2) $\vdash I \wedge \bigwedge_i$ at $*[i] \supset I \wedge \Box \Diamond \bigwedge_i$ at $*[i]$

Now the fairness assumption is used

3) $\vdash I \wedge \Box \Diamond \bigwedge_i$ at $*[i] \supset \Diamond$(at c := false $\wedge$ at d := false) (WGF)

$\wedge \Box$ (in $*[1] \vee$ after $*[1]$) (LS)

4) $\vdash$ at c := false $\supset \Diamond$ after $*[2] \supset \Diamond \Box$ after $*[2]$ (ASL,GCS,M)

5) $\vdash$ at d := false $\supset \Diamond$ after $*[3] \supset \Diamond \Box$ after $*[3]$ (ASL,GCS,M)

6) $\vdash \Box$ (after $*[2] \wedge$ after $*[3] \wedge$ (in $*[1] \vee$ after $*[1]$)) $\supset \Diamond$ after $*[1]$ (ASL,WGF,GCS)

7) $\vdash \bigwedge_i$ at $*[i] \wedge b \wedge c \wedge d \supset \Diamond \bigwedge_i$ after $*[i]$ (1,2,3,4,5,6,T.L.) $\Box$

(iv) Changing in example (iii) P_2 to

P_2' :: $*[c_1, P_1?y \rightarrow c_2 := \neg c_2 \ \Box\ c_2, P_3\,!\,y \rightarrow c_1 := c_2 :=$ false]

gives an example of a program for which SGF is, but WGF is not sufficient to ensure termination. The termination proof is analogeous to the one for example (iii), employing an invariant I' changed accordingly to the change in P_2.

6. DISCUSSION

The above system enables us to study termination and other liveness properties of CSP programs under various fairness assumptions.
As to future goals the following:

1) Extending the system to full CSP is expected to be more or less straight forward, but careful and simple notation should be used in order not to obscure the intuition behind the axioms.

2) Termination due to properties of the natural numbers might be described by adding a well-foundednesslike rule to DUX, like

   if $\vdash \exists n \in \mathbb{N}\ P(n)$

   and $\vdash \forall u \in \mathbb{N}\ \wedge u \supset 0\ P(u) \supset \Diamond P(u-1)$

   then $\vdash \Diamond P(0)$.

3) Abstracting to a higher level axiom system might be facilitated by studying examples using the low level system; it is expected that invariants used in the proofs may indicate more general proof principles.

4) Developing a notion of completeness for the system might be helped by comparing it to other total correctness systems for CSP, like given in [A] .

5) P. van Emde Boas suggested that using branching time it might be possible to formulate fairness assumptions not defined as a restriction on one computation sequence, but involving several. It then might be possible to enforce, say, termination of programs not terminating under any of the fairness assumptions in this paper
   We consider as an example, starting with b = c = d = e = true,

$$
\begin{aligned}
[P_1&::*[b,P_2!x \to \text{skip} \;\square\; b,P_3!x \to b:= \text{false}] \parallel\\
P_2&::*[c,P_1?y \to \text{skip} \;\square\; c,P_4!y \to c:= \text{false}] \parallel\\
P_3&::*[d,P_4!z \to \text{skip} \;\square\; d,P_1?z \to d:= \text{false}] \parallel\\
P_4&::*[e,P_3?u \to \text{skip} \;\square\; e,P_2?u \to e:= \text{false}]\;]
\end{aligned}
$$

which is not guaranteed to terminate under any of the above fairness assumptions, but should terminate under the, intuitively formulated, assumption that if there always is a terminating branch in the future, then such branch will eventually be chosen.

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