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Two Normal Form Theorems for CSP Programs

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We define two normal forms for CSP programs. In the First Normal Form, each process contains only one I/O repetitive command and all its I/O commands appear as guards of this command. In the Second Normal Form, it is moreover required that all guards of this I/O repetitive command are in fact I/O guards. We describe an inductive method which transforms any CSP program into an equivalent program in first or second normal form. The involved equivalence notion is discussed. It is shown in particular that no transformation into second normal form can preserve deadlock-freedom.

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1. Introduction

One of the best known theorems in Theoretical Computer Science states that every while program is equivalent to a program with one loop only (see e.g. [Ha]). We prove here a similar result for CSP programs. CSP is the language for distributed programming introduced by Hoare in [Ho1]. We exhibit two normal forms to which every CSP program can be brought. A CSP program is in a normal form (a **normal** program, in short) if each of its component processes contains only one I/O repetitive command and all its I/O commands appear as guards in this command. There are various reasons why the study of normal programs can be of interest.

1) Program construction — In the case of CSP programs, in opposition to the case of while programs, several algorithms can be naturally expressed as normal programs. For example, most solutions to the distributed termination problem of Francez [F] are normal programs (see e.g. Francez *et al.* [FRS] and Apt and Richier [AR]). For other algorithms written as normal programs, see e.g. Bougé [B].

2) Verification — We found (see [A]) that there is a very simple proof system allowing us to prove correctness of normal programs.
Moreover, Queille and Sifakis [QS] built a system allowing an automatic verification of finite state normal programs. Adding to their system a preprocessor implementing the transformations described in this paper allows us to extend the use of their system to arbitrary finite state CSP programs.

3) Event-driven computing — In an event-driven concurrent system, local actions are triggered by the occurrence of external events. This type of computing is typical in the case of network protocols. It is often modeled by means of interacting automata (see e.g. Gouda [G]). Normal programs exhibit a structure which makes this view of distributed computing more explicit as each process alternates between communications and resulting local actions.

Equivalence of concurrent programs is a delicate and difficult issue. In the last section of this paper we analyze the notion used in this paper and indicate its limitations.

2. Normal forms in CSP

We assume from the reader knowledge of the language of Communicating Sequential Processes (*CSP* for short) as defined by Hoare [Ho1]. We consider here a variant of *CSP* without nested parallelism and where output guards are allowed. We do not consider the Distributed Termination Convention. For simplicity, we omit all kinds of declarations.

A *CSP* program P is a parallel composition of named processes which operate on disjoint memories:

$$[\ P_1::S_1\ \|\ \ldots\|\ P_k::S_k\ ]\ .$$

Each process S is generated by the following grammar ($m \geq 1$):

$$\begin{aligned} S\ &::=\ \texttt{skip}\ \mid\ cmd\ \mid\ \alpha\ \mid\ S_1;S_2\ \mid \\ &\quad [\ \Box_{j=1}^{m}\ G_j\ \texttt{->}\ S_j\ ]\ \mid\ *[\ \Box_{j=1}^{m}\ G_j\ \texttt{->}\ S_j\ ] \\ G\ &::=\ b\ \mid\ b;\alpha \end{aligned}$$

Here, *cmd* denotes an assignment, b a Boolean expression and α an I/O command. If a guard G is of the form b then it is called a *purely Boolean guard*, and otherwise an *I/O guard*. $Bool(G)$ denotes the Boolean part of a guard. A guard G is *enabled* when the control is in front of it if $Bool(G)$ evaluates to true. In the sequel, $b_1;b_2$ denotes the conjunction $b_1 \wedge b_2$ of Boolean expressions.

Definition 1. *A process S is in* **first normal form** *if it is either of the form S_0 or*

$$S_0;\ *[\ \Box_{j=1}^{m}\ G_j\ \texttt{->}\ S_j\ ]$$

where $m \geq 1$ and none of the S_j, $j = 0, 1, \ldots, m$ contains an I/O command.

Definition 2. *A process S is in* **second normal form** *if it is either of the form S_0 or*

$$S_0;\ *[\ \Box_{j=1}^{m}\ G_j\ \texttt{->}\ S_j\ ]$$

where $m \geq 1$, none of the S_j, $j = 0, 1, \ldots, m$ contains any I/O command, and moreover all *of the G_j, $j = 1, \ldots, m$ are I/O guards.*

Thus the only difference between the first and second normal form is in the condition imposed on the guards G_i. A *CSP* program is in **first** (*resp.* **second**) **normal form** if all its component processes are.

3. The transformations

3.1. First normal form

We now describe a procedure NF_1 which transforms each process S into a process $S' = NF_1(S)$ in first normal form. We proceed by induction on the structure of S. We assume an infinite set Z of fresh Boolean variables $z_1, z_2, \ldots$ We omit indices when no confusion can arise.

Base case

When S is `skip` or an atomic assignment command *cmd*, S is already in first normal form and we put $NF_1(S) = S$.

I/O command

Suppose S is an I/O command α. We select a fresh variable z from Z. We define $NF_1(S)$ to be

$$z\texttt{:= true; *[} z\texttt{;}\alpha \texttt{ -> } z\texttt{:= false]}.$$

Sequential composition

Suppose S is of the form $S_1 ; S_2$. By induction, each S_i, $i = 1, 2$, has been transformed using a set Z_i of fresh variables into the process

$$NF_1(S_i) \texttt{ = } Init_i \texttt{; *[} \Box_{j=1}^{m_i} G_j^i \texttt{ -> } S_j^i \texttt{]}$$

in first normal form. We can assume that sets Z_1 and Z_2 are disjoint. Let z_1 and z_2 be two variables of $Z \setminus Z_1 \cup Z_2$. Then we define $NF_1(S)$ as follows:

$$\begin{array}{l} Init_1 \texttt{; } z_1\texttt{:= true; } z_2\texttt{:= false;} \\ \texttt{*[} \Box_{j=1}^{m_1} z_1 \texttt{; } G_j^1 \texttt{ -> } S_j^1 \texttt{; } TEST \\ \quad \Box_{j=1}^{m_2} z_2 \texttt{; } G_j^2 \texttt{ -> } S_j^2 \texttt{]} \end{array}$$

where $TEST$ stands for

$$\begin{array}{l} \texttt{[} \Box_{j=1}^{m_1} Bool(G_j^1) \texttt{ -> skip} \\ \quad \Box \bigwedge_{j=1}^{m_1} \neg Bool(G_j^1) \texttt{ -> } z_1\texttt{:= false; } z_2\texttt{:= true; } Init_2 \texttt{]} \end{array}$$

Intuitively, z_1 is true when the control is still in S_1 and z_2 is true when the control is in S_2.

Repetitive command

Suppose S is of the form $*[\ \Box_{i=1}^{m}\ H_i\ \texttt{->}\ R_i\ ]$. By induction, each R_i, $i = 1, \ldots, m$, has been transformed using a set Z_i of fresh variables into the process

$$NF_1(R_i)\ \texttt{=}\ Init_i\texttt{;}\ *[\ \Box_{j=1}^{m_i}\ G_j^i\ \texttt{->}\ S_j^i\ ]$$

in first normal form. We can assume without loss of generality that sets Z_i are pairwise disjoint. Let $turn_i$, $i = 1, \ldots, m$ be fresh variables of $Z \setminus \bigcup_{i=1}^{m} Z_i$. Then we define $NF_1(S)$ as follows:

$$\begin{array}{l} turn_1\texttt{:= false; } \ldots\texttt{; } turn_m\texttt{:= false;} \\ *[\ \Box_{i=1}^{m}\ \bigwedge_{i=1}^{m} \neg turn_i\texttt{; } H_i\ \texttt{->}\ turn_i\texttt{:= true; } Init_i\texttt{; } TEST_i \\ \qquad \Box_{\substack{i=1,\ldots,m \\ j=1,\ldots,m_i}}\ turn_i\texttt{; } G_j^i\ \texttt{->}\ S_j^i\texttt{; } TEST_i\ ] \end{array}$$

where $TEST_i$ stands for

$$\begin{array}{l} [\ \Box_{k=1}^{m_i}\ Bool(G_k^i)\ \texttt{->}\ \texttt{skip} \\ \qquad \Box\ \bigwedge_{k=1}^{m_i} \neg Bool(G_k^i)\ \texttt{->}\ turn_i\texttt{:= false }]\texttt{.} \end{array}$$

Intuitively, $turn_i$ holds when the control is inside subprogram R_i. Then, $TEST_i$ tests whether R_i is terminated, and $turn_i$ is reset to false if it is the case.

Alternative command

Suppose S is of the form $[\ \Box_{i=1}^{m}\ H_i\ \texttt{->}\ R_i\ ]$. By induction, each R_i, $i = 1, \ldots, m$, has been transformed using a set Z_i of fresh variables into the process

$$NF_1(R_i)\ \texttt{=}\ Init_i\texttt{;}\ *[\ \Box_{j=1}^{m_i}\ G_j^i\ \texttt{->}\ S_j^i\ ]$$

in first normal form. Using a new variable z from $Z \setminus \bigcup_{i=1}^{m} Z_i$, we first transform S into the following process S':

$$\begin{array}{l} z\texttt{:= true;} \\ [\ \Box_{i=1}^{m}\ Bool(H_i)\ \texttt{->}\ \texttt{skip }]\texttt{;} \\ *[\ \Box_{i=1}^{m}\ z\texttt{; } H_i\ \texttt{->}\ R_i\texttt{; } z\texttt{:= false }] \end{array}$$

Those two processes are related as follows. Suppose first that S fails. This occurs when all conditions $Bool(H_i)$ evaluate to `false` initially. Then S' fails much in the same way. If now S does not fail then at least one of those conditions evaluates to `true`. In S', the alternative command boils down then to `skip`. In the repetitive command, the conditions are evaluated again, and yield the same results as before, because processes operate on disjoint memories. At least one of them is thus guaranteed to evaluate to `true`, S' does not fail either, and behaves subsequently like S. $NF_1(S)$ is result of applying the transformation NF_1 to process S'.

This concludes the presentation of the transformation NF_1

Property 1. *For each process S, $NF_1(S)$ is a process in first normal form. The only atomic commands in $NF_1(S)$ in which variables from Z appear are of the form* z:= `true` *or* z:= `false`.

3.2. Second normal form

We now describe a procedure NF_2 which transforms each process S in first normal form into a process $NF_2(S)$ in second normal form. A process S in first normal form whose all external guards contain an I/O command (or which contains no I/O command) is already in second normal form and we put $NF_2(S) = S$. Otherwise, it can be written as

$$\begin{array}{l} Init; \\ *[\ \displaystyle\Box_{i=1}^{m}\ G_i\ \texttt{->}\ S_i \\ \quad \displaystyle\Box_{j=1}^{n}\ H_j\ \texttt{->}\ T_j\ ] \end{array}$$

with $m > 0$ and $n > 0$, where all guards G_i are purely Boolean, and all guards H_j do contain an I/O command. Let now $CHOOSE$ be the following command:

$$\begin{array}{l} turn_1 \texttt{:= false; } \ldots \texttt{; } turn_n \texttt{:= false;} \\ *[\ \displaystyle\Box_{i=1}^{m}\ \bigwedge_{k=1}^{n} \neg turn_k \texttt{; } G_i\ \texttt{->}\ S_i \\ \quad \displaystyle\Box_{j=1}^{n}\ \bigwedge_{k=1}^{n} \neg turn_k \texttt{; } Bool(H_j)\ \texttt{->}\ turn_j \texttt{:= true }]. \end{array}$$

The execution of $CHOOSE$ consists of some iterations of the repetitive command

$$*[\ \Box_{i=1}^{m}\ G_i\ \texttt{->}\ S_i\ ]$$

which contains no I/O command followed by the selection of an I/O guard H_j, provided its Boolean part $Bool(H_j)$ evaluates to `true`. We then define $NF_2(S)$ to be the following process

$$\begin{array}{l} Init;\ CHOOSE; \\ *[\ \displaystyle\Box_{j=1}^{n}\ turn_j;\ H_j\ \texttt{->}\ T_j;\ CHOOSE\ ]. \end{array}$$

Observe that $Bool(H_j)$ is evaluated twice, once within $CHOOSE$ and then again within H_j. Both evaluations return necessarily the same result because processes operate on disjoint memories.

Property 2. *For each process S in first normal form, $NF_2(S)$ is in second normal form. The only atomic commands in $NF_2(S)$ in which variables from Z appear are of the form* z:= `true` *and* z:= `false`.

3.3. Homogeneous processes

For certain processes however, it is possible to describe a direct transformation which yields a process in second normal form. A process is **homogeneous** if in each repetitive or alternative command either all guards are purely Boolean or all of them contain an I/O command. Observe that a homogeneous process is in first normal form if and only if it is in second normal form. If we can modify procedure NF_1 so as to preserve homogeneity, then it will transform homogeneous processes into processes in *second* normal form. It can be seen that the only part of NF_1 which does not preserve homogeneity is that dealing with a repetitive command S

$$*[\ \Box_{i=1}^{m}\ H_i\ \texttt{->}\ R_i\ ]$$

whose all guards are purely Boolean. In this case, let $SWITCH$ be

$$\begin{array}{l}[\ \Box_{i=1}^{m}\ H_i\ \texttt{->}\ turn_i\texttt{:= true;}\ Init_i \\ \quad \Box\ \bigwedge_{i=1}^{m} \neg H_i\ \texttt{->}\ \texttt{skip}\ ].\end{array}$$

Then, assuming the notation used in $NF_1(S)$, the transformed process is

$$\begin{array}{l} turn_1\texttt{:= false; ...;}\ turn_m\texttt{:= false;} \\ SWITCH\texttt{;} \\ *[\ \Box_{\substack{i=1,\ldots,m \\ j=1,\ldots,m_i}}\ turn_i\texttt{;}\ G_j^i\ \texttt{->}\ S_j^i\texttt{;}\ TEST_i\texttt{;} \\ \qquad\qquad\qquad\qquad [\ turn_i\ \texttt{->}\ \texttt{skip}\ \Box\ \neg turn_i\ \texttt{->}\ SWITCH\ ]]. \end{array}$$

Denote this modified transformation by NF_1'. Here, variables $turn_i$ are used for the same purpose as before. Setting a variable $turn_i$ to `true` can take place in the $SWITCH$ command only.

Property 3. *For each homogeneous process S, $NF_1'(S)$ is in second normal form. The only atomic commands in NF_1' in which variables from Z appear are of the form z:= `true` and z:= `false`.*

4. A notion of equivalence

We now wish to make precise in what sense every process S is equivalent to the process S' generated in section 3 by the transformations NF_1, NF_2 and NF_1'. To this purpose, we first associate to each process S a regular language $L(S)$. Intuitively, $L(S)$ is the set of all uninterpreted possible computations of process S according to Plotkin's semantics [P].

The language $L(S)$ is over the alphabet consisting of atomic actions *cmd*, I/O commands α, Boolean conditions b, plus two special tokens $\langle skip \rangle$ and $\langle fail \rangle$ which denote

respectively termination and failure. $L(S)$ is defined inductively as follows.

$$
\begin{aligned}
L(\texttt{skip}) &= \{\langle skip\rangle\},\\
L(cmd) &= \{\langle cmd\rangle\},\\
L(\alpha) &= \{\langle \alpha\rangle\},\\
L(G) &= \begin{cases} \{\langle b\rangle\langle \alpha\rangle\} & \text{if } G = b;\alpha,\\ \{\langle b\rangle\langle skip\rangle\} & \text{if } G = b,\end{cases}\\
L(S_1;S_2) &= L(S_1).L(S_2),\\
L(\texttt{[}\ G_1\ \texttt{->}\ S_1\ \texttt{[]}\ \ldots\texttt{[]}\ G_m\ \texttt{->}\ S_m\ \texttt{]}) &= \\
&\quad [(L(G_1).L(S_1)) \cup \ldots \cup (L(G_m).L(S_m))].\{\langle Bool\rangle\langle fail\rangle\},\\
L(\texttt{*[}\ G_1\ \texttt{->}\ S_1\ \texttt{[]}\ \ldots\texttt{[]}\ G_m\ \texttt{->}\ S_m\ \texttt{]}) &= \\
&\quad [(L(G_1).L(S_1)) \cup \ldots \cup (L(G_m).L(S_m))]^*.\{\langle Bool\rangle\langle skip\rangle\},
\end{aligned}
$$

where $Bool$ stands for

$$\neg Bool(G_1) \wedge \ldots \wedge \neg Bool(G_m).$$

Observe how the appropriate exit conditions are reflected.

To obtain the desired equivalence, we partially interpret the computations by evaluating the commands and conditions associated with auxiliary variables. In the processes generated by the transformations of section 3, they can be of the following type exclusively:

$$
\begin{aligned}
&z\texttt{:= true},\\
&z\texttt{:= false},\\
&B(z_1,\ldots,z_m,b_1,\ldots,b_n)
\end{aligned}
$$

where B is some Boolean combination of its arguments. When evaluating the condition, variables z_i's are substituted with their current value, *true* or $false$. The condition is said to be *unsatisfiable* if the resulting formula is equivalent to $false$ as a formula of the predicate calculus with variables b_j's. The condition is *satisfiable* if it is not satisfiable. Then we exclude contradictory computations, i.e. those which violate the rule that the selected Boolean conditions are all satisfiable. Finally, we erase all *skip*'s and assignments z:= true and z:= false to auxiliary variables. Also, we merge adjacent Boolean formulas into their Boolean conjunction, and reduce the resulting formula to some normal form (say, a conjunction of disjunctions for definiteness). Tautologies are then erased. Let $L'(S)$ be the resulting language. It is a language over the alphabet consisting of atomic actions cmd, I/O commands α, Boolean formula $B(b_1,\ldots,b_n)$, and token $\langle fail\rangle$. We say that two processes S_1 and S_2 are *equivalent* with respect to a set Z of auxiliary variables if

$$L'(S_1) = L'(S_2).$$

This equivalence can be best understood with a example. Consider the processes

$$S_1 = \alpha$$

and

$$S_2 = \texttt{z:= true; *[z;}\alpha \texttt{ -> z:= false]}.$$

Then

$$L(S_1) = L'(S_1) = \{\langle\alpha\rangle\}$$

On the other hand,

$$L(S_2) = \langle \texttt{z:= true}\rangle(\langle z\rangle\langle\alpha\rangle\langle \texttt{z:= false}\rangle)^*\langle\neg z\rangle\langle skip\rangle.$$

After the interpretation of actions related to the variable z we obtain the following set of words

$$\{\langle \texttt{z:= true}\rangle\langle true\rangle\langle\alpha\rangle\langle \texttt{z:= false}\rangle\langle\neg false\rangle\langle skip\rangle,$$
$$\langle \texttt{z:= true}\rangle\langle true\rangle\langle\alpha\rangle\langle \texttt{z:= false}\rangle(\langle false\rangle\langle\alpha\rangle\langle \texttt{z:= false}\rangle)^*\langle\neg false\rangle\langle skip\rangle\}.$$

Here, only the computation

$$\langle \texttt{z:= true}\rangle\langle true\rangle\langle\alpha\rangle\langle \texttt{z:= false}\rangle\langle\neg false\rangle\langle skip\rangle$$

is not contradictory. Deleting from it all assignments to the variables of Z and *skip*'s, reducing sequences of adjacent Boolean formula to their normal form and erasing tautologies, we get $\langle\alpha\rangle$ as desired.

We have the following theorems whose tedious but straightforward proofs are omitted.

Theorem 1. *Both $NF_1(S)$ and $NF_1'(S)$ are equivalent to S with respect to set Z of auxiliary variables.*

Theorem 2. *$NF_2(S)$ is equivalent to S with respect to set Z of auxiliary variables.*

These equivalences are on the level of processes considered in isolation. The following theorem states some of its semantic consequences. By a *state* we mean a function assigning values to each of the variables. We consider $\perp$ as a special state indicating divergence. Given a CSP program P, we define its meaning $\mathcal{M}[P]$ by putting

$$\mathcal{M}[P](\sigma) =$$
$$\{\tau,\ \tau \text{ is the final state of a properly terminating computation starting in state } \sigma\}$$
$$\cup\ \{\perp,\ \text{there exists a diverging computation of } P \text{ starting in state } \sigma\ \}.$$

For two sets Σ_1 and Σ_2, and a set of variables Z we put

$$\Sigma_1 = \Sigma_2 \bmod Z \text{ iff } \{\sigma \setminus Z,\quad \sigma \in \Sigma_1\} = \{\sigma \setminus Z,\quad \sigma \in \Sigma_2\}$$

where $\sigma \setminus Z$ is the restriction of σ to the variables not in Z. We now say that two programs CSP P_1 and P_2 are *equivalent modulo* Z if for all states σ

$$\mathcal{M}[P_1](\sigma) = \mathcal{M}[P_2](\sigma) \bmod Z.$$

Note that this equivalence definition does not take into account possible deadlocks. We can finally state the appropriate theorem.

Theorem 3. *Let S_1 and S_2 be two equivalent processes with respect to a set Z of auxiliary variables. Let*

$$C = [\ Q_1::T_1 \ \|\ \ldots \|\ Q_k::[\ ]\ \|\ \ldots \|\ Q_n::T_n\ ]$$

be a context, and let $P_i = C[S_i]$, $i = 1, 2$, be the CSP programs obtained by plugging process S_i into the context C. Then P_1 and P_2 are equivalent modulo Z.

Thus, up to deadlock, P_1 and P_2 exhibit the same functional behaviors.

5. Discussion

The equivalence relation introduced in section 4 seems at first sight very strong as it is basically a syntactic equivalence. However, this equivalence is concerned only with some form of traces (in the sense of [Ho2]) of computations. Semantically, it assures only theorem 3. In particular, it does not capture all relevant semantic properties naturally associated with concurrent programs, like deadlock freedom.

Indeed, consider two processes S and S' where

S = [true; $Q?x$ -> skip
  □ true; $Q!x$ -> skip],

S'= [true -> $Q?x$; skip
  □ true -> $Q!x$; skip].

Then S and S' are equivalent in the sense of section 4. However, the program

$$[\ P::S \ \|\ Q::P?y\ ]$$

cannot deadlock whereas the program

$$[\ P::S' \ \|\ Q::P?y\ ]$$

can. Thus, plugging equivalent processes in the same context, here

$$[\ P::[\ ]\ \|\ Q::P?y\ ],$$

can yield two programs which behave differently. Currently, we look for a simple, stronger form of equivalence for which theorem 1 holds and moreover such that substituting in any context a process by a an equivalent one preserves at least deadlock freedom.

We can however prove that theorem 2 cannot be strengthened so that deadlock freedom is preserved in the above sense. This follows from the following theorem.

Theorem 4. *Let*

$$[\ P::S \ \|\ Q::T\ ]$$

be a program in second normal form. Suppose that it admits two properly terminating computations, C_1 with some communication, and C_2 without any communication. Then it admits a deadlocked computation.

Proof Construct the deadlocked computation as follows. First take all steps carried out by P in C_1 until the I/O command selected for its first communication is reached. Then append to it all step carried out by Q in C_2. In the resulting computation, Q properly terminates whereas P reaches an entry to a repetitive command with all guards containing an I/O guard. Thus a deadlock arises (observe that this would not necessarily hold if the Distributed Termination Convention of CSP were used). □

Indeed, take the program [$P::S \parallel Q::T$] with

$$S = [\ Q!x \text{ -> skip } \square \text{ true -> skip }]$$

and

$$T = [\ P?y \text{ -> skip } \square \text{ true -> skip }].$$

Consider now an arbitrary pair S', T' of processes in second normal form such that S' is equivalent to S and T' to T. Then the program [$P::S' \parallel Q::T'$] satisfies the conditions of theorem 4. So it admits a deadlocked computation. But [$P::S \parallel Q::T$] is deadlock free.

This shows that first normal form cannot be reduced to second normal form when also deadlock freedom is to be preserved. This can be interpreted as a statement that use of non-homogeneous guards strictly increases the expressive power of CSP.

Note

First version of this paper appeared as Apt and Clermont ([AC]). After having written the present version, we learned of a related work by Zöbel ([Z]). Zöbel proposes transformations similar to ours, but does not elaborate on the underlying notion of equivalence.

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