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Introduction

WOFACS '94: The Second Workshop on Formal Aspects of Computer Science

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Following the success of WOFACS '92 (for the Proceedings of which see SACJ 9 1993) another such event was held at the University of Cape Town, from 27 June to 8 July 1994.

These Workshops on Formal Aspects of Computer Science serve several purposes. First, they help to strengthen a culture of studying formal aspects and developing formal methods in Computer Science. Second, in doing so they provide an impetus towards collaboration and interdisciplinarity – in this case bringing together Logic, Mathematics and Computer Science. Third, they provide a vehicle for the inter-institutional training of postgraduate students. And fourth, they contribute to international collaboration by bringing a number of eminent scientists to South Africa.

WOFACS '94 was co-hosted by the Departments of Mathematics and Computer Science at the University of Cape Town, and was organised by the Laboratory for Formal Aspects and Complexity in Computer Science. It offered 2-week lecture courses as follows:

- Dr Falko Bause (Dortmund University, Germany), Petri Nets
- Prof Ed Brinksma (Technological University of Twente, Netherlands), Formal Design of Distributed Systems
- Prof Robert Goldblatt (Victoria University of Wellington), Modal Logics of Programs
- Prof Austin Melton (Michigan Technological University), Denotational Semantics
- Dr Carroll Morgan (Oxford University), The Refinement Calculus

About 80 participants attended WOFACS '94; of these roughly half were academic staff and half were graduate students from a number of Southern African Universities. Participation from neighbouring countries was very encouraging. The lecture courses were again made available to all attending students as credit-bearing courses at their home Universities (by prior arrangement with the Departments concerned). About 30 students were eventually evaluated and had their WOFACS results incorporated into their respective Honours programmes. Apart from travel and accommodation costs and a small administrative charge for registration WOFACS '94 was a free service to the community – no lecture fees of any kind were involved.

This volume of SACJ contains the Proceedings of WOFACS '94: papers relating to their lecture courses by Brinksma, Goldblatt, Melton and Morgan (and co-authors). Unfortunately the Bause contribution to WOFACS '94 was committed to a publisher before the event, and hence could not be included here.

For the success of WOFACS '94 I would like to express my grateful thanks to:

- our invited speakers, for their hard work and the quality of their presentations;
- the Foundation for Research Development, the participants of the Programme for Research Manpower in Computer Science, the UCT Research Committee and the Department of National Education, for direct and indirect sponsorship;
- my co-host, Professor Pieter Kritzinger;
- the indefatigable FACCS-Lab staff, particularly Diana Dixon, and
- all participants.
Proceedings

Functionality Decomposition by Compositional Correctness Preserving Transformation

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Abstract

We present an algorithm for the decomposition of processes in a process algebraic framework. Decomposition, or the refinement of process substructure, is an important design principle in the top-down development of concurrent systems. In the approach that we follow the decomposition is based on a given partition of the actions of a system specification, such that for each partition class a subprocess must be created that realizes the actions in that class. In addition a suitable synchronization structure between the subprocesses must be present to ensure that the composite behaviour of the subprocesses is properly related to the behaviour of the original specification. We present our results for the process-algebraic specification language LOTOS and give a compositional algorithm for the transformation of the original specification into the required subprocesses. The resulting specification is observation congruent with the original, and, interestingly enough, the subprocesses inherit much of the structure of the original specification. The correctness preserving transformation has been implemented in a tool and has been used for the derivation of protocol specifications from formal descriptions of the desired service. This is possible as it can be shown that the required synchronization mechanisms between the subprocesses can be readily implemented over (reliable) asynchronous media.

Keywords: Process algebra, correctness preserving transformation, decomposition, bisimulation

Computing Review Categories: D.2.10, F.3.1

1 Introduction

In order to make process algebraic calculi a useful tool for engineering concurrent systems the existing unifying theories must be complemented by non-elementary concepts and constructions that correspond to the designer's needs. In the area of open distributed systems this has led to the definition of the formal specification language LOTOS [20, 6], which was based on ideas in CCS [31] and CSP [18], but has specially adapted constructs for parallel and sequential composition, disruption and the representation of data types. In order to support the actual design of open systems such linguistic facilities must be accompanied by suitably constructed 'high-level' laws that correspond to practically useful design steps. In a top-down design strategy such correctness-preserving transformations can be applied to refine a high-level specification into successively better representations of the system as it will be ultimately realized, without further obligations for a posteriori proofs of correctness. Examples of such high-level transformations are the regrouping of subprocesses, the rearrangement of interaction points, from multi-way to binary synchronization, etc. [5, 7, 3]. An elaborate example of the stepwise transformation of a serial memory into a distributed caching memory can be found in [8].

The transformation principle that we study in this paper, functionality decomposition, is used to decompose a given process into a number of subprocesses that interact concurrently. Such refinement of process substructure can be used to modularize monolithic behaviour into more specialized parts for which implementations or realizations can be found more readily. It can also be used to express a notion of geographical distribution, where the different parts correspond to functionalities at different locations. In the approach that we follow the decomposition is based on a given partition of the actions of a system specification, such that for each partition class a subprocess must be created that realizes the actions in that class. In addition a suitable synchronization structure between the subprocesses must be present to ensure that the composite behaviour of the subprocesses is properly related to the behaviour of the original specification.

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*This work has been supported in part by the CEC research programme ESPRIT BRA (project 6021 REACT)
The decomposition of functionality is a natural and frequently occurring design step that can be used for many purposes. Well-documented examples are the design of the PANGLOSS high performance gateway [2, 35], the design of Manufacturing Planning and Control (MPC) systems [11], the design of the LOTSOPHIRE MiniMail system [34, 3], and the derivation of upper and lower testers in conformance test methods [21, 37]. As we will show in an example, the decomposition transformation also makes an important contribution to the problem of deriving protocol specifications from service descriptions.

The work that we present uses the specification language LOTOS as a notational vehicle, but our results can be easily adapted, mutatis mutandis, to other process algebraic calculi that can represent similar forms of parallel composition, such as e.g. CSP [18] and CIRCAL [30]. The correctness criterion that we use is the notion of observation congruence, because of its elegant proof technique of constructing (rooted) weak bisimulations, and the fact that it is a rather fine relation and thus implies many other interesting semantic relations, such as for example testing preorders [14].

This paper extends earlier work by one of the authors in [23], where the same transformation is studied under the more restricting assumption that the behaviour of the process that is to be split is given in its fully expanded format (the so-called monolithic specification style in [40]). One drawback is that this restricts the application of the transformation to a particular syntactic (normal) form. More seriously, however, is that it has the drawback that the algorithm generates elaborate synchronization schemes between subprocesses where these are not needed. By the interleaving interpretation of parallel composition information about the independence of actions in different components is lost when an already structured behaviour expression is expanded. The algorithm would in such cases enforce synchronizations to maintain the various interleaving orders, which is clearly inefficient.

A possible solution for this problem would be to conduct confluence analysis on the expanded behaviour, but it is much better to avoid the problem altogether by following a compositional approach, in which the already available structural information of the behaviour expression is taken into account. The latter approach, which proves feasible under reasonable assumptions, is the one that we follow in this paper. It turns out that most spurious synchronizations can be avoided in this way, and, interestingly enough, that the subprocesses inherit much of the structure of the original specification.

The rest of the paper is organized as follows: section 2 gives an introduction to the formalisms that we use and contains a formal statement of the problem of functionality decomposition; in section 3 we present the compositional transformation algorithm; section 4 contains (a part of) the correctness proof of our algorithm and discusses its restrictions and extensions; section 5 contains a small elaborated example of the application of the transformation and discusses the available tool support; finally, in section 6 we give an overview of related work and present our conclusions.

2 Notations and formal statement of the problem

As indicated in the introduction we use the process algebraic language LOTOS as our notational vehicle. As parametrization and value passing are not essential to our formulation of the decomposition problem we restrict ourselves to so-called Basic LOTOS [6]. Note that the action i in LOTOS denotes the internal action or silent step (cf. \( \tau \) in CCS).

Let \( L \) be a set of action labels and \( PN \) a set of process names. Let \( g \in L \cup \{i\}, a \in L \cup \{i, \delta\}, G \subseteq L \), and \( P \in PN \). Let \( H \) be a function \( H : L \cup \{i, \delta\} \rightarrow L \cup \{i, \delta\} \) with \( H(i) = i \) and \( H(\delta) = \delta \).

The syntax of a process definition is \( P ::= B \), where \( B \) is a behaviour expression. A set of process definitions \( \{P ::= B \mid P \in PN\} \) is called a process environment. A LOTOS specification is a behaviour expression in the context of a process environment.

The syntax and operational semantics of Basic LOTOS behaviour expressions is given by Table 1. In the formal statement of the problem we need the following definition:

Definition 2.1 We define the set of all action labels that occur in a specification \( B \), denoted by \( Act(B) \), by:

\[
\begin{align*}
Act(stop) &= \emptyset, \quad Act(exit) = \emptyset \\
Act(g; B) &= \mathbb{if} \; g \neq i \; \text{then} \; Act(B) \cup \{g\} \; \text{else} \; Act(B) \\
Act(B[H]) &= Act(B) \cup H(Act(B)) \\
Act(hide \; G \; \text{in} \; B) &= Act(B) \\
Act(P) &= Act(B) \; \text{if} \; P ::= B \\
Act(B_1 \oplus B_2) &= Act(B_1) \cup Act(B_2) \; \text{for all other operators} \; \oplus
\end{align*}
\]

So \( Act(B) \) contains all the syntactical actions, so also those actions that semantically do not occur because they are renamed or hidden. \( Act(B) \) can be obtained by a simple sequential scan of the specification. Note that \( Act(B) \) is in general a superset of the set of labels \( L(B) \) as defined in e.g. [9]; this is because \( L(B[H]) = H(L(B)) \) and \( L(hide \; G \; \text{in} \; B) = L(B) - G \).

In this paper we restrict ourselves to a decomposition into two processes as more complicated substructures can be achieved by its repeated application. In general the two processes are not independent but need to synchronize their behaviours somehow. For this reason we synchronize them over a distinguished gate sync.

The behaviour of the two synchronizing processes should not be different from that of the initial process. This has two consequences:

- the synchronization gate sync has to be hidden;

---

SACJ/SART, No 13, 1995
We now give a precise statement of the problem of decomposition of functionality:

**Functionality**

Let

\[
g: \mathcal{B} \rightarrow \mathcal{B}'
\]

be a function for which \(\text{name}(i) = i\), \(\text{name}(g) = g\), and \(\text{name}(g|m) = g\), then the inference rules for the parallel operator are given by

1. if \(B_1 \overset{\alpha}{\rightarrow} B_1'\) and \(\text{name}(a) \notin \{g_1, \ldots, g_n, \delta\}\) then
   \[
   B_1[[g_1, \ldots, g_n]]B_2 \overset{\alpha}{\rightarrow} B_1'[[g_1, \ldots, g_n]]B_2
   \]
2. if \(B_2 \overset{\alpha}{\rightarrow} B_2'\) and \(\text{name}(a) \notin \{g_1, \ldots, g_n, \delta\}\) then
   \[
   B_1[[g_1, \ldots, g_n]]B_2 \overset{\alpha}{\rightarrow} B_1[[g_1, \ldots, g_n]]B_2'
   \]
3. if \(B_1 \overset{\alpha}{\rightarrow} B_1', B_2 \overset{\alpha}{\rightarrow} B_2'\) and \(\text{name}(a) \in \{g_1, \ldots, g_n, \delta\}\) then
   \[
   B_1[[g_1, \ldots, g_n]]B_2 \overset{\alpha}{\rightarrow} B_1'[[g_1, \ldots, g_n]]B_2'
   \]

We now give a precise statement of the problem of decomposition of functionality:

**Given:**

- an expression \(B\) with set of actions \(\text{Act}(B) \subseteq A\), \(\text{sync} \notin A\).
- a partitioning of \(A\) into \(A_1\) and \(A_2\), i.e. \(A_1 \cup A_2 = A\) and \(A_1 \cap A_2 = \emptyset\).

**Problem:** find two expressions \(B_1\) and \(B_2\) with the following properties:

- \(\text{Act}(B_1) \cap A \subseteq A_1\), \(\text{Act}(B_2) \cap A \subseteq A_2\).
- \(\text{hide sync in } B_1[[\text{sync}]][B_2 \approx B.\)

In order to solve this problem in a general way we would like to have two mappings \(T_1\) and \(T_2\) that, given a partitioning of \(A\), provide us with a \(B_1\) and \(B_2\) for every \(B\), by having \(T_1(B) = B_1\) and \(T_2(B) = B_2\). We define \(T\) by \(T(B) = \text{hide sync in } T_1(B_1) [[\text{sync}]][T_2(B_2)].\) In the next section we define such mappings \(T_1\) and \(T_2\).

<table>
<thead>
<tr>
<th>Name</th>
<th>Syntax</th>
<th>Axioms and inference rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>successful termination</td>
<td>(\text{exit})</td>
<td>(\text{exit} \stackrel{\delta}{\rightarrow} \text{stop})</td>
</tr>
<tr>
<td>action prefix</td>
<td>(g:B \rightarrow B)</td>
<td>(g:B \rightarrow B)</td>
</tr>
<tr>
<td>choice</td>
<td>(B_1 \parallel B_2)</td>
<td>(B_1 \parallel B_2 \rightarrow B_1 \parallel B_2)</td>
</tr>
<tr>
<td>enabling</td>
<td>(B_1 \rightarrow B_2)</td>
<td>(B_1 \rightarrow B_2 \rightarrow B_1 \rightarrow B_2)</td>
</tr>
<tr>
<td>disabling</td>
<td>(B_1 \rightarrow B_2)</td>
<td>(B_1 \rightarrow B_2 \rightarrow B_1 \rightarrow B_2)</td>
</tr>
<tr>
<td>hiding</td>
<td>(\text{hide} G \in B)</td>
<td>(B \rightarrow B', a \in G \rightarrow \text{hide} G \in B \rightarrow B)</td>
</tr>
<tr>
<td>renaming</td>
<td>(B[H])</td>
<td>(B \rightarrow B' \rightarrow B[H])</td>
</tr>
<tr>
<td>parallel composition</td>
<td>(B_1 [[G]]B_2)</td>
<td>(B_1 [[G]]B_2 \rightarrow B_1 [[G]]B_2)</td>
</tr>
<tr>
<td>process instantiation</td>
<td>(P)</td>
<td>(P := B, B \rightarrow B' \rightarrow P \rightarrow B')</td>
</tr>
</tbody>
</table>

Table 1. Basic LOTOS syntax and semantics
3 Solution

In this section we define mappings \( T1 \) and \( T2 \) as discussed in the previous section. We define these mappings in a compositional way, i.e. for each top-level operator of \( B \) we define \( T1(B) \) and \( T2(B) \) in terms of its operands.

It appears that for several operators we have to make some restrictions on \( B \) in order to be able to define the mappings. These restrictions are collected and discussed in section 6.

Inaction and successful termination

In these two simple cases the inaction or the successful termination is simply copied to both components of the decomposition:

Definition 3.1

\[
\begin{align*}
B = \text{stop} & : T1(B) = \text{stop}, \quad T2(B) = \text{stop} \\
B = \text{exit} & : T1(B) = \text{exit}, \quad T2(B) = \text{exit}
\end{align*}
\]

Action prefix

The mappings for this operator are based on the following idea: if an action in e.g. \( T1(B) \) has happened, \( T2(B) \) should be notified of this fact in order to produce the appropriate behaviour after the action. This notification is done by synchronizing on messages via the \( \text{sync} \) gate. So in principle the structure is as follows: suppose \( a \in A_1 \), then \( a; B \) is decomposed into \( a; \text{sync!m}; T1(B) \) and \( \text{sync!m}; T2(B) \), respectively.

The synchronization message should be unique for each occurrence of an action. For this purpose we assume that each action is subscripted with a unique occurrence identifier, e.g. \( a_x; B \). The exact nature of the occurrence identifiers is irrelevant; they could be for instance integers, handed out to action occurrences in order of appearance in an expression.

The occurrence identifiers are used to produce unique synchronization messages: an action \( a_x \) may lead to a unique synchronization message \( \chi \), so we use the occurrence identifiers as synchronization messages. In the rest of this paper we adopt as a convention that \( a \in A_1 \) and \( b \in A_2 \).

We treat internal actions just like ordinary actions, i.e. they each have a unique occurrence identifier and lead to unique synchronization messages. This implies that in addition to the bipartition of \( \text{Act}(B) \), the user has to specify for each internal action in an expression \( B \) whether it belongs to \( T1(B) \) or \( T2(B) \). We will not bother with formalizing this, but simply assume that \( \text{Act}(B) \) has been extended by including all occurrences of internal events, and we assume the bipartition of \( A \) into \( A_1 \) and \( A_2 \) includes the bipartitioning of all occurrences of internal events. This poses no intrinsic difficulties; this point will be discussed in section 4.

It is not always necessary that an action prefix results in a synchronization. Suppose we have \( a; B \) and all initial actions of \( B \) are in \( A_1 \). Then the first two actions of \( a; B \) are in \( T1(a; B) \) so it is not necessary to synchronize after \( a \). In such a case we get a decomposition into \( a; T1(B) \) and \( T2(B) \), respectively. The set of initial actions of an expression \( B \) is denoted by \( \text{init}(B) \) and is defined by \( \text{init}(B) = \{ a \in L \cup \{ i \} \mid B \xrightarrow{a} \} \). These considerations lead to the following definition:

Definition 3.2

\[
\begin{align*}
\text{If } B = a_x; B' \text{ and } \text{init}(B') & \subseteq A_1 \\
\text{then } T1(B) = a_x; T1(B'), T2(B) = T2(B') \\
\text{else } T1(B) = a_x; \text{sync!} ; T1(B'), T2(B) = \text{sync!} ; T2(B') \\
\text{If } B = b_z; B' \text{ and } \text{init}(B') & \subseteq A_2 \\
\text{then } T1(B) = T1(B'), T2(B) = b_z; T2(B') \\
\text{else } T1(B) = \text{sync!} ; T1(B'), T2(B) = b_z; \text{sync!} ; T2(B')
\end{align*}
\]

Choice

Consider the expression \( B = a; B_1 \mid b; B_2 \). In this expression we have a choice between an action \( a \) that after the decomposition resides in \( T1(B) \), and an action \( b \) that will be in \( T2(B) \). We call such a choice between actions from different components a \textit{global} choice. The difficulty with such a global choice is that two demands have to be fulfilled:

- both \( a \) and \( b \) should be offered to the environment
- once the environment chooses e.g. \( a \), immediately \( b \) should not be offered anymore.

These two demands cannot be fulfilled simultaneously by synchronization after one action has occurred since this synchronization cannot prevent an action from the other component happening first. In order to solve this problem more sophisticated solutions are needed, like the polling mechanism in [23]. However, such a mechanism conflicts with the compositional approach in this paper. In fact, the occurrence of global choices can often also be interpreted as the inadequacy of the given partition of actions as a basis for the distribution of functionality. For this reason we restrict ourselves in this paper to those cases where global choice does not occur.

Restriction 1:

\[
\text{If } B = B_1 \mid B_2, \text{ then either } \text{init}(B_1) \cup \text{init}(B_2) \subseteq A_1 \text{ or } \text{init}(B_1) \cup \text{init}(B_2) \subseteq A_2.
\]
With this restriction it turns out that the definition for the mappings is quite simple:

**Definition 3.3**

\[ B = B_1 || B_2 : T_1(B) = T_1(B_1) || T_1(B_1), \quad T_2(B) = T_2(B_1) || T_2(B_2) \]

### Hiding and renaming

The mappings for these operators pose no problems. Only for the renaming operator there is the requirement that the renaming should be consistent in the following sense: actions from \( A_1 \) can only be renamed into actions from \( A_1 \) and actions from \( A_2 \) can only be renamed into actions from \( A_2 \). This restriction can be weakened by parameterizing the mappings \( T_1 \) and \( T_2 \) with the partition at stake, and instantiating it with a suitably renamed partition when the algorithm is applied to a renaming expression. We choose to avoid such complications, however, and work with the restriction as stated.

**Restriction 2:**

If \( B = B'[H] \), then \( H(A_1) \subseteq A_1 \) and \( H(A_2) \subseteq A_2 \)

**Definition 3.4**

\[ B = B'[H] : T_1(B) = T_1(B'[H]), \quad T_2(B) = T_2(B'[H]) \]

\[ B = \text{hide } G \text{ in } B' : T_1(B) = \text{hide } G \text{ in } T_1(B'), \quad T_2(B) = \text{hide } G \text{ in } T_2(B') \]

If we denote the restriction of mapping \( H \) to e.g. \( A_1 \) by \( H[A_1] \), then we could replace the \( H \) in the definition of \( T_1(B) \) and \( T_2(B) \) for renaming by \( H[A_1] \) and \( H[A_2] \), respectively; this could be more clear in practice, but it is not necessary for the correctness of the mappings.

Similarly, we could in the definitions of \( T_1(B) \) and \( T_2(B) \) for hiding replace the \( G \) by \( G \cap A_1 \) and \( G \cap A_2 \), respectively.

### Parallelism

The mappings for the parallel operator are compositional in a direct way. The idea behind the mapping is given in the following picture:

![Parallelism Diagram]

The reason we can make this transformation is the following fact (see e.g. [4]):

- synchronizations over \( G \) are either between actions from \( T_1(B_1) \) and \( T_1(B_2) \) or between actions from \( T_2(B_1) \) and \( T_2(B_2) \)
- synchronizations over \( \text{sync} \) are either between actions from \( T_1(B_1) \) and \( T_2(B_1) \) or between actions from \( T_1(B_2) \) and \( T_2(B_2) \)

**Definition 3.5**

\[ B = B_1 || B_2 : T_1(B) = T_1(B_1) || T_1(B_1), \quad T_2(B) = T_2(B_1) || T_2(B_2) \]

For reasons of clarity the \( G \) in the definitions of \( T_1(B) \) and \( T_2(B) \) for parallelism could be replaced by \( G \cap A_1 \) and \( G \cap A_2 \), respectively, without changing the semantics.

### Enabling

For the enabling operator we would like to have mappings that share the structural simplicity of the mappings for parallelism, i.e. we would like to have \( T_1(B_1) >> B_2 = T_1(B_1) >> T_1(B_2), \quad i = 1, 2 \), There is however one problem with this idea:

**Example 3.6**

Suppose \( B_1 = a_x; B_1' \text{ exit} \) and \( B_2 = b_z; B_2' \).

Then

\[ T_1(B_1) >> B_2 = (a_x; T_1(B_1)' \text{ exit}) >> \text{sync}!c; T_1(B_2') \]

\[ T_2(B_1) >> B_2 = (\text{sync}!x; T_2(B_1)' \text{ exit}) >> b_z; \text{sync}!c; T_2(B_2') \]

But now the decomposition has an undesirable transition sequence: the second component could first execute the exit and then the \( b_z \), after which the first component could still execute the \( a_x \). This is not possible for \( B_1 >> B_2 \) so the decomposition is not correct.

The source of this problem is the fact that once an exit is within the scope of an enable operator, the exit is (semantically) turned into an internal action, and therefore not synchronized anymore with an exit in the other component. This leads to
a problem when the exit is in a choice-context since then the two components may make different unrelated choices. This problem can be avoided by adopting the following restriction:

**Restriction 3:**

If \( B = B_1 \parallel B_2 \) then \( B_1 \not\parallel^d \) and \( B_2 \not\parallel^d \)

**Definition 3.7** \( B = B_1 >> B_2 \):

\[
T_1(B) = T_1(B_1) >> T_2(B_2)
T_2(B) = T_2(B_1) >> T_1(B_2)
\]

**Disabling**

This is the most tricky operator for this transformation. First of all we make a restriction that is similar to the one we made for choice, where we did not allow global choice. For if e.g. \( B = a :: \text{stop} \mid b :: \text{stop} \) we face a similar problem as for global choice: \( a \) and \( b \) should both be offered, but at the moment e.g. \( b \) happens \( a \) instantly cannot happen anymore. This cannot be achieved by just synchronizing after actions. For this reason we want all the actions of \( B_2 \) and all initial actions of \( B_2 \) to be either all in \( A_1 \) or all in \( A_2 \).

**Restriction 4:** If \( B = B_1 > B_2 \) then

\[
\text{Act}(B_1) \cup \text{init}(B_2) \subseteq A_1 \text{ or } \text{Act}(B_1) \cup \text{init}(B_2) \subseteq A_2
\]

The definition of the mappings for disabling is more complicated than for the other operators. We first give the definition and then discuss it.

**Definition 3.8** \( B = B_1 > B_2 \):

\[
\text{if Act}(B_1) \subseteq A_1 \text{ then } T_1(B) = (B_1 > T_1(B_2)) >> \text{sync}!m_6 ; \text{exit}
T_2(B) = (\text{sync}!m_6 ; \text{exit}) \parallel (T_2(B_2) >> \text{sync}!m_6 ; \text{exit})
\]

\[
\text{if Act}(B_1) \subseteq A_2 \text{ then } T_1(B) = (\text{sync}!m_6 ; \text{exit}) \parallel (T_1(B_2) >> \text{sync}!m_6 ; \text{exit})
T_2(B) = (B_1 > T_2(B_2)) >> \text{sync}!m_6 ; \text{exit}
\]

The main trick of this definition is that any \( \delta \) happening in \( B_1 \) or \( B_2 \) is "caught" by an enabling operator, after which a synchronization takes place on a special message \( m_6 \) (which should be unique for each occurrence of \( > \)), followed by an exit in order to again generate a \( \delta \). In this way the problem of unsynchronized successful termination as illustrated in example 3.6 is avoided. Since all actions of \( B_1 \) happen in one component there is no need to apply a mapping to \( B_1 \); we only have to add \( \text{sync}!m_6 ; \text{exit} \) in a choice with the other component in order to synchronize with the other side in case a \( \delta \) occurs in \( B_1 \).

There is only one situation in which definition 3.8 goes wrong, namely in the case that \( B_2 \not\parallel \). Suppose we would have \( \text{Act}(B_1) \subseteq A_1 \); then \( T_2(B) \) could perform an initial event, enabling thereby \( \text{sync}!m_6 ; \text{exit} \), whereas \( T_1(B) \) could still perform an action from \( B_1 \), thereby potentially causing a deadlock. It is hard to repair this defect; therefore we simply add the restriction that \( B_2 \) cannot have \( \delta \) as an initial action:

**Restriction 5:** If \( B = B_1 > B_2 \) then \( B_2 \not\parallel \)

### 4 Correctness

In this section we discuss the correctness for the operators that have been dealt with so far. Process definition and instantiation is treated in the next section.

**Correctness**

**Theorem 4.1** Let \( B \) be a Basic LOTOS behaviour expression without process instantiation. Then

\[
\text{hide } \text{sync in } T_1(B) [[\text{sync}]] T_2(B) \approx B
\]

**Proof:** by structural induction; for example, for each binary operator \( \ast \) we prove that

\[
T(B_1 \ast B_2) = \text{hide } \text{sync in } T_1(B_1 \ast B_2) [[\text{sync}]] T_2(B_1 \ast B_2)
\]

is observation congruent with \( B_1 \ast B_2 \), under the induction hypothesis that \( T(B_1) \) and \( T(B_2) \) are observation congruent with \( B_1 \) and \( B_2 \) respectively.

As an example we prove the above theorem for the parallel operator; the proof details for the other operators can be found in [11]. We need the following two laws:

**Law 1** [9]

If \( (G - G') \cap (\text{Act}(B_1) \cup \text{Act}(B_2)) = \emptyset \) then \( B_1[[G]]B_2 \cong B_1[[G \cap G']]B_2 \)

**Law 2** [40]

If \( \text{Act}(A) \cap (S2 \cup I2) = \emptyset, \text{Act}(B) \cap (S2 \cup I1) = \emptyset, \text{Act}(C) \cap (S1 \cup I2) = \emptyset, \)

\[
\text{Sacj/Sart, No 13, 1995} 7
\]
The idea of the parametrization of the mappings T1 and T2 is that in e.g. T1(B, .) we assume that occurrence identifiers can hold for T2(B, .) and T2(B, .) and that occurrence identifiers (just like actions) are parameterizing the mappings T1 and T2 with occurrence identifiers, respectively.

We rename T1(B1) and T2(B1) into T1'(B1) and T2'(B1), with the renaming \([\text{sync1}, \text{sync2}].\) Analogous for T1(B2), T2(B2) and \([\text{sync2}\text{sync}]\). This can be done since T1(B1) only synchronizes with T2(B1) and T1(B2) only synchronizes with T2(B2); the synchronization messages generated for B1 and B2 are disjoint, as the occurrence identifiers in B1 and B2 are all unique.

\[\text{Definition 5.1 Process definition:}\]
\[T1(P) = \begin{cases} \text{T1}(B), & \text{if } P = \text{T1}(B) \\ \text{T1}(P_{\xi}), & \text{if } P = \text{T1}(P_{\xi}) \end{cases}\]

\[\text{Definition 5.2 Process definition:}\]
\[T1(P_{\xi}) = P1(\eta \xi), T2(P_{\xi}) = P2(\eta \xi)\]

The idea of the parametrization of the mappings T1 and T2 is that in e.g. T1(B, \eta) each synchronization message is prefixed with \eta. The definition of the mappings for action prefix:

\[\text{Definition 5.3}\]
If \(B = a_{\lambda}; B' \text{ and } \text{init}(B') \subseteq A1\)
then T1(B, \eta) = a_{\lambda}; T1(B', \eta), T2(B, \eta) = T2(B', \eta)
else T1(B, \eta) = a_{\lambda}; \text{sync1}; T1(B', \eta), T2(B, \eta) = \text{sync1}; T2(B', \eta)
\[\text{If } B = b_{\zeta}; B' \text{ and } \text{init}(B') \subseteq A2\]
then T1(B, \eta) = T1(B', \eta), T2(B, \eta) = b_{\zeta}; T2(B', \eta)
else T1(B, \eta) = \text{sync1}; T1(B', \eta), T2(B, \eta) = b_{\zeta}; \text{sync1}; T2(B', \eta)

The other mappings are adapted in a similar straightforward way.

It is now easy to prove the use of Theorem 4.1 in order to prove that \(\text{T}(B)\) is a bisimulation relation up to \(\approx [31]\), where \(\text{T}(B) = \text{hide} \text{sync} \text{in} \text{T1}(B, \varepsilon) [[\text{sync}]] \text{T2}(B, \varepsilon)\) where \(\varepsilon\) is the null element for concatenation.
Example 5.4 Let \( P := B \) where \( B = a; b; P_1 \), then \( P1(\theta) := T1(B, \theta) = a; \text{sync}! x; \text{sync}! y; \theta; P1(\theta x) \) and \( P2(\theta) := T2(B, \theta) = \text{sync}! x; b; \text{sync}! y; P2(\theta) \).

For example, \( T1(P_3 \gg X_1) \mid (P_2 \gg Y_1) \epsilon = (P_i(a) \gg X_i(B)) \mid (P_i(y) \gg Y_i(\theta)). \) Without the parameterization it would be possible for \( P_2 \) to synchronize with \( P_1 \) instead of \( P_2 \), leading to incorrect results.

This parametrization of processes bears some similarity to the event prefixing in [24]. In [29] a different approach is taken where the synchronization messages are determined by the choice and parallel contexts, leading to somewhat more complicated definitions.

6 Discussion

Restrictions

The mappings in the previous section were defined under the following five restrictions:

1. If \( B = B_1 \mid B_2 \) then either \( \text{init}(B_1), \text{init}(B_2) \subseteq A_1 \) or \( \text{init}(B_1), \text{init}(B_2) \subseteq A_2 \)
2. If \( B = B'[H] \), then \( H(A_1) \subseteq A_1 \) and \( H(A_2) \subseteq A_2 \)
3. If \( B = B_1 \mid B_2 \) then \( B_1 \not= \) and \( B_2 \not= \)
4. If \( B = B_1 \gg B_2 \) then \( \text{Act}(B_1) \cup \text{init}(B_2) \subseteq A_1 \) or \( \text{Act}(B_1) \cup \text{init}(B_2) \subseteq A_2 \)
5. If \( B = B_1 \gg B_2 \) then \( B_2 \not= \)

Restriction 2 seems reasonable and poses no real difficulties as actions in \( B' \) can often be syntactically renamed, instead of being renamed by \( [H] \), in order to meet the restriction.

Also restrictions 3 and 5 are not very restrictive. For example, consider \( (a; \text{stop} [\text{exit}] \gg b; \text{stop}) \). This expression does not meet restriction 3. However, it can be changed into the weak bisimulation congruent expression \( (a; \text{stop} [\text{exit}] \gg b; \text{stop}) \). Similarly, \( (a; \text{stop} [\text{exit}] \gg b; \text{stop} \) (violating restriction 5) can be replaced by the observation congruent \( (a; \text{stop} [\text{exit}] \gg b; \text{stop}) \).

Restrictions 1 and 4, prohibiting global choice and global disabling, are met by a large class of specifications. Often it is quite unnatural to specify a choice between actions at different locations. Still there are specifications that inherently have such a global choice. In such a situation we might be able to circumvent restriction 1 by incorporating a kind of polling mechanism along the lines of [23].

We do not see how restriction 4 could be avoided in a natural way. The only way seems to be to transform the expression in an expression without the disabling operator, and then applying a polling mechanism for the resulting global choices.

Internal actions

In section 3 it was remarked that internal actions are to be treated just like observable actions and have to be bipartitioned by the user. In practice the constraints 2 and 4 take away a lot of freedom of choice, thereby lessening the burden of bipartitioning for the user. Many choices can be made automatically. For example, in the expression \( a; B \mid i; B' \) the only possibility is that \( i \) is allocated to the same component as \( a \), in order to meet restriction 1. In fact the only thing the user really has to decide is in which component symmetric nondeterministic choices like \( i; B \mid i; B' \) have to take place.

Asynchronous communication

The components \( T1(B) \) and \( T2(B) \) as defined in the previous section interact by synchronous communication. It may not always be realistic to expect that such a synchronous communication can be realized. Most notably, if \( T1(B) \) and \( T2(B) \) reside at geographically different locations we may not be able to implement in an efficient way synchronous communication. In this case asynchronous communication using some reliable communication medium is needed. This means we have to replace the sync actions by send and receive actions, in the following way:

- component \( T1(B) \) sends and receives messages over process \( \text{Medium} \) via gates send1 and receive1
- component \( T2(B) \) sends and receives messages over process \( \text{Medium} \) via gates send2 and receive2

For example, definition 3.2 has to be changed into the following definition:

Definition 6.1

\[
\begin{align*}
\text{if } B &= a; B' \text{ and } \text{init}(B') \subseteq A_1 \\
& \quad \text{then } T1(B) = a; T1(B'), T2(B) = T2(B') \\
& \quad \text{else } T1(B) = a; \text{send1}; T1(B'), T2(B) = \text{receive2}; T2(B')
\end{align*}
\]

\[
\begin{align*}
\text{if } B &= b; B' \text{ and } \text{init}(B') \subseteq A_2 \\
& \quad \text{then } T1(B) = T1(B'), T2(B) = b; T2(B') \\
& \quad \text{else } T1(B) = \text{receive1}; T1(B'), T2(B) = b; \text{send2}; T2(B')
\end{align*}
\]

The correctness proof of the transformation using asynchronous communication is quite involved. Since the components are now less tightly coupled, the construction of a bisimulation relation for proving the correctness is not that easy. We
plan to study the correctness for the asynchronous case with the help of an alternative semantics for LOTOS that is defined in [25, 24]. In [23] the asynchronous solution has been proven correct for behaviour expressions in action-prefix form.

7 Example and tool support

We give an example of the transformation by considering a simple example of a service. The service SimpleService starts with a connect phase in which an entity at location a can establish a connection with an entity at location b. After the connection has been established the two entities can exchange data in both directions.

SimpleService := Connect >> (DataAB ||| DataBA)

Connect := a_conreq ; b_conind ; exit
DataAB := a_datareq ; b_dataind ; DataAB
DataBA := b_datareq ; a_dataind ; DataBA

Since there are no multiple instantiations of the same process we can use the simpler (unparameterized) version of process definition/instantiation of section 5. The protocol derived using our transformations:

SimpleProt := hide sync in Connect1 >> (DataAB1 ||| DataBA1)
                   ||| (sync)
           Connect2 >> (DataAB2 ||| DataBA2)

Connect1 := a_conreq ; sync!1 ; sync!2 ; exit
Connect2 := sync!1 ; b_conind ; sync!2 ; exit
DataAB1 := a_datareq ; sync!3 ; sync!4 ; DataAB1
DataAB2 := sync!3 ; b_datareq ; sync!4 ; DataAB2
DataBA1 := sync!5 ; a_dataind ; sync!6 ; DataBA1
DataBA2 := b_datareq ; sync!5 ; sync!6 ; DataBA2

Note how the structure of the service specification is preserved in the two components after transforming. We have chosen integers as occurrence identifiers; actions in the specification are implicitly subscripted in order of appearance. Often a designer would like to change the messages 1, 2 etc. into messages with more meaningful names, making the specification more readable. This has been done in the next specification, together with the transformation into asynchronous communication over a medium (using the LOTOS receive operation (see [6]) for the medium):

SimpleProt := hide send1, send2, rec1, rec2 in
                        (Connect1 >> (DataAB1 ||| DataBA1)
                        ||| (Connect2 >> (DataAB2 ||| DataBA2))
                        ||| (sync)
           Medium

Connect1 := a_conreq ; send1!creq ; rec1!conf ; exit
Connect2 := rec1!creq ; b_conind ; send2!conf ; exit
DataAB1 := a_datareq ; send1!adreq ; rec1!adconf ; DataAB1
DataAB2 := rec2!adreq ; b_dataind ; send2!adconf ; DataAB2
DataBA1 := rec1!bdreq ; a_dataind ; send1!bdconf ; DataBA1
DataBA2 := b_datareq ; send2!bdreq ; rec2!bdconf ; DataBA2

Medium := Medium1 ||| Medium2
Medium1 := send1!x:message ; rec1!x ; Medium1
Medium2 := send2!x:message ; rec2!x ; Medium1

The above transformation can be obtained automatically using the transformation tool Cleaver [11]. This is a prototype tool implementing the transformations in section 3. It makes use of an abstract syntax for LOTOS called Common Representation (CR); the CR was developed in the ESPRIT/LOTOSPHERE project [16] for the integrated LOTOS tool environment LITE [12, 3]. Cleaver was written in C with the help of a metatool, the term processor Kimwitu [38]. Currently
work is being undertaken in order to change Cleaver from a prototype into an industrially applicable tool that can be integrated into the LITE environment.

8 Conclusion

In this paper we have presented a compositional algorithm for the decomposition of processes in a process algebraic framework based on a partition of their action sets. Our presentation was given in terms of the specification language LOTOS, but the result carries over to other formalisms with similar combinators for parallel composition such as CSP and CIRCAL [18, 30]. We have sketched the correctness proof of the algorithm and given the detailed proof for one of the LOTOS combinators, viz. parallel composition. The algorithm can be applied only in the context of a number of restrictions that measure in some sense the adequacy of the given partition as the basis for the distribution of functionality and in particular avoid the creation of so-called global choices. We have analysed the proposed restrictions and indicated how they may be circumnavigated if so desired. In particular we have indicated how the method can be adapted to achieve synchronization over a reliable asynchronous communication medium. We have given a simple example of its application for the derivation of a protocol from a simple service description. We have also included a short report on a tool, Cleaver, that has been implemented to support the application of this correctness preserving transformation on Basic LOTOS specifications.

As we reported in the introduction our work is an extension of that reported in [23]. There global choices are handled by inserting a polling mechanism, but the algorithm is noncompositional and works on fully expanded specifications only, which greatly increases the number of synchronization actions between parallel components (before expansion). In [39] it is shown how the transformation from [23] could be combined with another transformation, the regrouping of parallel processes from [4], in order to formally derive a protocol. In [11] it is demonstrated that the same derivation can be carried out by only using the improved transformation reported here. An earlier version of this paper [10] only provided for single process calls.

It is interesting and informative to compare our current work to other related approaches. One of the first attempts to study a design transformation from a formal point of view can be found in [17]. There the implementability of synchronization events over an asynchronous medium is studied as a LOTOS to LOTOS transformation. The transformation results are shown to be testing equivalent to their originals. An explicit semantic confluence condition is given instead of our static syntactic restrictions. Decomposition is only feasible if processes already have a (synchronous) parallel composition as their outermost operator, and the algorithm is therefore a distribution rather than a decomposition transformation.

In [22] it is shown how to derive a protocol from a service by incorporating message passing over a reliable medium, using a kind of attribute grammar. It is more general in the sense that more than two protocol entities can be handled at a time. It is rather restricted, however, as it does not include the general parallel, enabling, and disabling combinators. The correctness of the transformation is not discussed. A proposal for handling global choice by inserting dummy interactions is suggested though not elaborated, but it does not seem to preserve any branching time semantics.

A similar approach can be found in [28]. There a large subset of Full LOTOS is handled. Some restrictions are made that are quite similar to ours, e.g. no initial exits in a choice and no global choice. However, again no correctness proof is provided, probably due to the complexity of attribute grammar formalism that is used. In [29] a decomposition theory is presented for a LOTOS-like calculus (not including enabling and disabling), based on asynchronous communication. The complexity of the approach makes it hard to compare it to ours.

A related and formally well-investigated problem is that of factorization of behaviours into parallel components in a process algebraic set-up. First results are due to Parrow [33] and Shields [36] that study the solution of equations of the form $P[[X \approx Q$ for given $P$ and $Q$, where $[]$ is some (generalized) parallel composition combinator. The difference with our approach is that we work, so to speak, from $Q$ and specify the distribution of its actions to guide the decomposition, and do not suppose or require further knowledge about the desired substructure in the form of $P$.

Future work on the decomposition of functionality transformation includes its extension to Full LOTOS, i.e. the inclusion of data structures in communication and parameterization, and the consequent adaptation of the tool Cleaver. This should be relatively straightforward. The extension to full LOTOS suggests, however, the possibility of new decomposition criteria, such as the partition of the action labels (gates in LOTOS parlance) in combination with the type attributes that characterize the data that is communicated. This suggests the possibility of combining gate-splitting transformations [5] with decomposition. Another aspect that still needs some attention is the incorporation of synchronization over asynchronous media in the proof for the compositional algorithm, as it is currently only available for the [23]-version. As we indicated earlier we expect no fundamental problems there, and hope to exploit the benefits of the partial-order semantics for LOTOS as given in [25, 24].

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References

Contents

INTRODUCTION

WOFACS '94: The Second Workshop on Formal Aspects of Computer Science
  C Brink ................................................................. 1

PROCEEDINGS

Functionality Decomposition by Compositional Correctness Preserving Transformation
  E Brinksma and R Langerak ........................................... 2

Modal Logics for Programs
  R Goldblatt ................................................................... 14

A Gentle Introduction to Domain Theory: Domains and Powerdomains
  J Goslett and A Melton ................................................... 45

The Refinement Calculus
  C Morgan .................................................................. 64