Composition of Service Specifications*

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Abstract

The service specification $ss(P)$ of a protocol $P$ defines the services provided by the protocol and its protocol specification $ps(P)$ specifies the rules of message exchange to ensure the service. Protocol composition has been advocated as an attractive way to design complex protocols. Several techniques have been studied for composition of protocol specifications. In these techniques, to combine component protocols $P$ and $Q$ to design $R$, $ps(P)$ and $ps(Q)$ are first combined to obtain $ps(R)$ and then inference rules are used to derive $ss(R)$. In this paper, we explore an alternative strategy in which we allow composition to be specified at the service specification level (that is, $ss(P)$ and $ss(Q)$ are first combined to obtain $ss(R)$). Given $ss(R)$, we provide an algorithm to mechanically combine $ps(P)$ and $ps(Q)$ to generate $ps(R)$ such that $ps(R)$ satisfies $ss(R)$. We show that analysis of $ss(R)$ is sufficient to ensure that $ps(R)$ satisfies certain safety and liveness properties. This results in efficient validation as state space of $ss(R)$ is typically significantly smaller than that of $ps(R)$.

1 Introduction

The problem of designing a correct network protocol is a challenging task and should be based on formal engineering principles. A protocol can be viewed as a service provider offering some communication services. A protocol has a set of service access points (SAPs) via which its services can be accessed. Each service access point may have a set of actions (service primitives) associated with it. Service specification and protocol specification are two important stages of the protocol engineering cycle. At the service specification stage, the designer must specify the properties (services) to be provided by the protocol. The service specification, $ss(P)$, of a protocol $P$ gives the possible sequences in which actions at different SAPs may occur.

In the protocol specification stage, the protocol is described as a set of communicating processes, one for each SAP. The designer must specify details such as format of the messages, rules for message exchange, local state maintained by each entity and properties of the communication channels. Protocol validation is a part of this stage to ensure that the protocol specification meets the service specification. Protocol specifications typically are much more complex than service specifications due to factors such as lossy communication channels, locality of the processes, etc.

The complexity of designing correct network protocols has led researchers to propose compositional techniques to design protocols. The main idea in these techniques is to first design the protocols for the subfunctions independently and then combine them in a disciplined manner to obtain the composite protocol. A number of techniques have been proposed for composition of protocol specifications such as sequential composition alternative composition and parallel composition [1, 2, 8, 9, 10, 13, 14, 15, 16, 17].

Let $P$ and $Q$ be two component protocols used to design a composite protocol $R$. Each of these techniques provide inference rules that ensure certain properties of $R$ by placing some restrictions on the component protocols that can be combined. Since these restrictions are sufficient conditions, we can construct several protocols from component protocols that do not satisfy these restrictions. To increase the applicability of the compositional techniques, such compositions must be allowed. However, for such compositions, the inference rules may not be applicable and therefore, we would have to analyze the composite protocol specification directly, whose state space may be very large.

To overcome this problem, we study composition at the service specification level. We provide a framework

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in which \( ss(R) \) can be obtained by specifying a set of constraints on \( ss(P) \) and \( ss(Q) \) where the constraints specify how the services offered by \( P \) and \( Q \) have to be combined. Given \( ss(R) \), we give an algorithm to generate the protocol specification, \( ps(R) \), by combining \( ps(P) \) and \( ps(Q) \). In defining these compositions, we do not impose any restrictions on the constraints. This flexible use of constraints increases the applicability of the composition techniques to allow a larger set of protocols to be designed and composed. However, a designer may specify constraints that do not result in the desired composite protocol (for example, the resulting protocol may contain deadlocks). However, we show that the analysis of \( ss(R) \) is sufficient to infer certain safety and liveness properties of \( ps(R) \). This results in efficient verification as the state space of \( ss(R) \) is typically significantly smaller than that of \( ps(R) \).

We feel that defining composition of service specification is more intuitive and useful as the main aim of composition is to combine the services provided by \( P \) and \( Q \) in a certain way. Composition at service specification level also supports a building block approach to protocol construction wherein a library of basic protocols is made available. The library may consist of the service specification and protocol specification of each protocol. A designer can select a subset of protocols from the library (depending on the services they provide) and specify how to combine their services. We are currently building a software tool based on this methodology.

## 2 Model

We define an extended finite state machine (EFSM) \( X \) as a tuple \( < S_X, A_X, F_X, M_X, V_X, T_X, s_X > \), where \( S_X \) is a set of states, \( A_X \) is a set of actions, \( F_X \) is a set of terminal states, \( M_X \) is a set of messages that may be sent or received, \( V_X \) is a set of variables and \( T_X \) is a transition function \( S_X \times A_X \rightarrow S_X \), and \( s_X \) is the initial state. Each action \( a \) in \( A_X \) has a boolean guard \( en(a) \) associated with it which can refer to variables in \( V_X \) (we will omit \( en(a) \) if it is identically true). A state machine may be viewed as a directed labeled graph where \( S_X \) forms the set of nodes, \( T_X \) defines the edges and \( A_X \) defines the labels of the edges. We use \( Seq(X) \) to denote the set of action sequences allowed by \( X \).

We define a cross product operator \( \times \) for \( P \) and \( Q \) as follows: \( G = P \times Q \) is an EFSM such that \( A_G = A_P \cup A_Q, V_G = V_P \cup V_Q, M_G = M_P \cup M_Q, F_G = \{ (p, q) : (p \in F_P) \land (q \in F_Q) \}, S_G = \{ (p, q) | (p \in S_P) \land (q \in S_Q) \} \) and \( s_G = (s_P, s_Q) \). The transition relation \( T_G \) consists of tuples of the form \( (s_1, c, s_2) \), where \( s_1 = (u_1, v_1) \), \( s_2 = (u_2, v_2) \) and \( s_1, s_2 \in S_G \). Tuple \( (s_1, c, s_2) \in T_G \) iff:
\[
c \in A_P \land c \not\in A_Q, (u_1, c, u_2) \in T_P \text{ and } v_1 = v_2,
\]
\[
c \in A_P \land c \not\in A_Q, (v_1, c, v_2) \in T_Q \text{ and } u_1 = u_2,
\]
\[
c \in A_P \cap A_Q, (u_1, c, u_2) \in T_P \text{ and } (v_1, c, v_2) \in T_Q.
\]

A protocol has a set of service access points (SAPs) associated with it. Each protocol \( P \) has a set of service primitive actions \( s_{act}(P) \) associated with SAPi. For ease of presentation of definition in this section, we consider protocols with two SAPs only (namely, SAP1 and SAP2). We define \( s_{act}(P) = s_{act}(P_1) \cup s_{act}(P_2) \). The service specification \( ss(P) \) of a protocol \( P \) is the cross product of a set of finite state machines \( \{ l_1, l_2, g_1, \ldots, g_m \} \), where \( l_i \) is the local specification at SAPi and \( g_j \) is a global service specification. The local specification \( seq(l_i) \) defines the possible sequences in which actions at SAPi may occur and we require that \( A_i = s_{act}(P_i) \) and \( V_i \cap V_n = \{ \} \). The global specification \( g_i \) specifies the order in which actions at different SAPs can occur. We do not allow variables to appear in \( g_i \) (therefore, \( V_{g_i} = \phi \)\(^1\)). We may omit \( l_i \) if the sequence of actions defined by \( l_i \) can be derived from the global specifications (that is, some \( g_j \) completely defines the possible ordering of actions at SAPi). Figure 2 gives the service specification of a connection establishment protocol \( Connect_{12} \). In this protocol, the connection is initiated by site 1 (\( CReq_{12} \)) and site 2 may either accept it (\( CPos_{12} \)) or reject it (\( CNeg_{12} \)). If the connection is established, site 1 can disconnect using primitive \( DReq_{12} \).

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\(^1\)This assumption has been made to simplify the presentation. Variables in \( g_i \) can be used as global variables in the service specification and must be translated into local variables in the protocol specification.
where $P_i$ is an EFSM for $SAP_i$. $P_i$ may contain actions in addition to those associated with $SAP_i$. Thus, $A_{P_i} = s_{act}(P_i) \cup A_i$. Each action $a$ in $A_i$ may contain local computation and send statements or a receive statement (we use $m$ to denote “send $m”$ and $+m$ to denote “receive $m”$). Furthermore, each action in $s_{act}(P_i)$ may be modified so that its computation may include local computation and send statements. Figure 2 gives the protocol specification for $Connect_{12}$ assuming reliable and FIFO channels.

![Figure 2: Connection Establishment Protocol: protocol specification](image)

The global state of $ps(P)$ is given by $< u, v, x, y >$, where $u$ ($v$) is the state of $P_1$ ($P_2$) and $x$ ($y$) is the sequence of messages in transit to $P_1$ ($P_2$). In this paper, we will assume that communication between processes is asynchronous. The global state may change due to a transition in either $P_1$ or $P_2$. If the global state changes from $S$ to $S'$ due to a transition labeled $t$ in either $P_1$ or $P_2$, then we say that $S'$ is a successor state of $S$ via $t$. The sequence $ex \equiv S^0 \rightarrow t_1 S^1 \rightarrow t_2 \cdots \rightarrow t_n S^n$ is an execution of $P$ if $S^0$ is the initial state and $S^n$ is the successor of $S^{n-1}$ via $t_i$. Let $transition(ex)$ denote the sequence $t_1; t_2; \ldots; t_k$. We say that $ex'$ is an extension of $ex$ via action sequence $s = t_{k+1}; \ldots; t_{k+m}$ if $ex' = ex \rightarrow t_{k+1} S^{k+1} \cdots \rightarrow t_{k+m} S^{k+m}$. A state $u$ of $P_i$ is a receiving state if all transitions incident from $u$ involve receiving a message. A state $u$ is a final state if it has no transitions incident from it. Let $\lambda$ denote an empty sequence. A state pair $(u, v)$ is stable if $(u, v, \lambda, \lambda)$ is a reachable global state and if $(u, v, x, y)$ is a reachable state then $x = y = \lambda$.

**Definition 1:** $ps(P)$ is deadlock free if there does not exist a reachable state $(u, v, x, y)$ such that both $u$ and $v$ are non-terminal states such that no transition is enabled from $u$ and $v$.

**Definition 2:** $ps(P)$ is free from unspecified receptions if there does not exist a reachable state $(u, v, x, y)$ such that (a) $first(x) = m$ and there is no enabled transition incident from $u$ that receives $m$, or (b) $first(y) = m$ and there is no enabled transition from $v$ that receives $m$.

**Definition 3:** $ss(P)$ is deadlock free if there does not exist a non-terminal state $s$ such that there is no enabled transition from $s$.

$ps(P)$ is safe iff $ps(P)$ is deadlock free and free from unspecified receptions. $ss(P)$ is safe iff $ss(P)$ is deadlock free. We define $proj(seq, A)$ as the sequence of actions obtained by removing from seq all actions not in $A$.

**Definition 4:** $ps(P)$ satisfies $ss(P)$ if:
1. for each sequence $seq \in Seq(ss(P))$, there exists an execution $ex$ of $ps(P)$ such that $proj(transition(ex), s_{act}(P)) = seq$ and $seq; a \in Seq(ss(P))$ then there exists an extension $ex'$ of $ex$ via $s; a$, where $s$ does not include any action in $s_{act}(P)$.
2. for each execution $ex$ of $ps(P)$, $proj(transition(ex), s_{act}(P)) \in Seq(ss(P))$ and if there exists an extension $ex'$ of $ex$ via $s; a$, where $s$ does not include any action in $s_{act}(P)$ then $proj(transition(ex'), s_{act}(P)) \in Seq(ss(P))$.

### 3 Problem definition

Several techniques have been proposed for composition at the protocol specification level such as:

- sequential composition, that allows a multiphase protocol to be constructed by composing protocols for the individual phases in sequence [2, 1, 9, 17],
- alternative composition, that combines a set of protocols such that at most one component protocol can be active at any given time [9, 16], and
- parallel composition, that allows protocols in which multiple functions can be performed concurrently to be constructed [8, 14, 15].

In [13], each of these techniques were studied for specifications involving timing information. Each of these techniques can be viewed as imposing some constraints on the combined execution of the component protocols. These constraints may be based on actions or states of the component protocols. For instance, the sequential composition operator in [2] specifies a constraint that $Q_i$ cannot start executing until $P_i$ reaches a final state. Similarly, constraints that inhibit execution of certain actions in $Q$ on the occurrence of a specific action in $P$ have been used in [9, 17] to define transition between protocols. However, to ensure the safety of the
composite protocol, each technique provides inference rules that may restrict the actions or states that can be used in specifying the constraints and also the type of protocols that can be combined. For example, the inference rule for sequential composition in [9, 17] requires that the execution of \( Q \) may start when \( P \) has reached a stable state pair and that the set of stable state pair satisfy a closure property. Finally, the inference rules in [14, 15] restrict the type of invariants and liveness properties of the component protocols that can be inferred in the composite protocol.

![Example diagram](example_diagram.png)

**Figure 3:** (a) Connection protocol, (b) Disconnection protocol

We find these restrictions to be conservative in most cases. Since they are not necessary conditions, one might still be able to construct composite protocols from a set of component protocols that do not satisfy these conditions. To take full advantage of the compositional techniques, we must allow such compositions. This would however require a more flexible use of constraints in defining compositions. The following examples illustrate these compositions:

**Example 3.1:** Figure 3 gives the protocol specifications of the connection and disconnection phases separately. We may wish to combine these phases to obtain the connection management protocol shown in Figure 2. To perform this composition, we must specify that each execution of \( D\text{Req}_{12} \) must be preceded by an occurrence of \( C\text{Conf}_{12} \). In addition, a new request \( C\text{Req}_{12} \) can be made only after \( D\text{Req}_{12} \) has occurred. This protocol cannot be designed directly using existing sequential composition techniques (it is possible to derive it indirectly by first converting the component protocols to non-iterative versions and combining them).

**Example 3.2:** Consider the protocol, \( C\text{Connect}_{12} \), shown in Figure 2 in which site 1 establishes a connection with site 2. We can obtain a similar protocol \( C\text{Connect}_{21} \) in which site 2 establishes a connection with site 1. Consider the alternative composition of these two protocols in which connection can only be established in one direction at a time. If both attempt to establish a connection at the same time, \( C\text{Connect}_{12} \) is given priority (thus, in \( C\text{Connect}_{12} \), we want a positive response, \( C\text{Pos}_{12} \), to be generated whereas in \( C\text{Connect}_{21} \), we want a negative response, \( C\text{Neg}_{21} \) to be generated). This can be accomplished by imposing a constraint that if site 1 has sent a request to site 2 (\( C\text{Req}_{12} \)), then site 1 is not allowed to execute \( C\text{Pos}_{21} \). Only after the occurrence of \( C\text{Req}_{12} \) or \( D\text{Req}_{12} \) (which marks the termination of the connection from site 1 to site 2), \( C\text{Pos}_{21} \) is allowed to execute. Similar restrictions have to be placed for other cases. This is an example of a constraint that allow temporary inhibition of actions in one protocol on the occurrence of an action in the other protocol.

In the full paper, we also give an example to illustrate the flexible use of constraints in the context of parallel composition. These examples illustrate the need for more flexibility in specifying constraints than allowed by the existing techniques. [8] proposes a similar approach in which constraints are defined by strengthening guards in one protocol using proposition involving variables of the other protocol. However, it is possible that if we allow constraints to be imposed in an arbitrary manner, it may lead to deadlocks or other undesirable behavior in the composite protocol. Hence, protocols constructed using such an approach would have to be analyzed directly. Since the state space of a composite protocol is typically large, this analysis will be expensive.

In this paper, we discuss an alternative approach in which composition is performed at the service specification level. In defining these compositions, we do not impose any restrictions in defining the constraints. Although the protocol specifications are complicated (many times due to message loss, timeouts, etc), the service specifications are relatively much simpler. Thus, even though we allow arbitrary compositions of service specifications, we can analyze them as their state space is not very large.

More formally, the contributions can be stated as follows: Assume that we are given \( ss(P), ss(Q), ps(P) \) and \( ps(Q) \) such that \( ps(P) \) satisfies \( ss(P) \) and \( ps(Q) \) satisfies \( ss(P) \). We give a constraint based methodology to combine service specifications of \( P \) and \( Q \). Thus, if \( R \) is the composite protocol, then \( ss(R) \) is given by \( ss(P) \times ss(Q) \) subject to a set of constraints...
Given this composition, we give an algorithm to construct \( \text{ps}(R) \) from \( \text{ps}(P), \text{ps}(Q) \) and \( SC \). We show that if \( ss(R) \) is safe, then we can conclude that \( \text{ps}(R) \) is safe and satisfies \( ss(R) \). Thus, the technique avoids the analysis of \( \text{ps}(R) \).

In performing compositions of service specifications, we can only impose constraints on actions belonging to \( s\text{.act}(P) \) and \( s\text{.act}(Q) \) (thus, we cannot impose constraints on sending and receiving actions). However, we find that in most cases, imposing constraints on service primitives is not a stringent restriction as the main aim of protocol composition is to combine the services of \( P \) and \( Q \) in a certain manner. This combination can be defined in a more intuitive and clear manner at the service specification level.

There has been significant amount of work in the area of synthesizing protocol specifications from service specifications [3, 6, 12]. In some techniques, service specifications have been structured using composition operators and algorithms to implement these operators at the protocol specification level have been provided. We defer the detailed comparison to these synthesis techniques after the presentation of our approach.

4 Composition of service specifications

In this section, we discuss our framework for composition of service specifications. We first present a basic set of constraints to illustrate the technique. More complex constraints can be added to the framework, some of which are discussed subsequently. Given two service specifications, \( ss(P) \) and \( ss(Q) \), we define their composite specification using a set of constraints. Let \( ss(R) = ss(P) \times ss(Q) \). Then, the constraints are imposed on the set of executions of \( ss(R) \). Let \( ex = S^0 \rightarrow t_1 S^1 \rightarrow t_2 \cdots \rightarrow t_b S^k \) be an execution sequence of \( R \), where \( S^0 \) is the initial state of \( ss(R) \). Let \( l_a \) and \( l_b \) be the number of occurrences of \( a \) and \( b \) in \( ex \), respectively.

1. The synchronizing constraint is specified as \( \text{synch}(a, b) \), where \( a \in s\text{.act}(P_i) \) and \( b \in s\text{.act}(Q_i) \) (both actions must belong to the same SAP). Constraint \( \text{synch}(a, b) \) requires that if \( a \) or \( b \) occurs in \( ex \), then except for the last occurrence of \( a \) or \( b \) when \( l_a \neq l_b \), the execution of \( a \) and \( b \) in \( ex \) be delayed until \( a \) and \( b \) are enabled and then both are executed in either order but atomically, i.e., no other action at site \( i \) can be interleaved between the execution of \( a \) and \( b \).

2. The ordering constraint is specified as \( \text{order}(A, B) \), where \( A, B \subseteq s\text{.act}(P_i) \cup s\text{.act}(Q_i) \).

Constraint \( \text{order}(A, B) \) requires that the execution of actions in \( A \) and \( B \) must alternate and the first action in \( B \) cannot occur until an action in \( A \) occurs.

3. The interrupt constraint is specified as \( \text{interrupt}(A, B, C) \), where \( A, C \subseteq s\text{.act}(P_i) \) and \( B \subseteq s\text{.act}(Q_i) \). Constraint \( \text{interrupt}(A, B, C) \) requires that after the occurrence of any action in \( A \), an action in \( B \) cannot be executed until an action in \( C \) occurs. The interrupt constraint in which \( A, C \subseteq s\text{.act}(Q_i) \) and \( B \subseteq s\text{.act}(P_i) \) is defined similarly.

4. The enabling constraint is specified as \( \text{enable}(A, Q_i) \), where \( A \subseteq s\text{.act}(P_i) \). Constraint \( \text{enable}(A, Q_i) \) requires that \( Q_i \) can begin execution only after the occurrence of an action in \( A \). The constraint \( \text{enable}(B, P_i) \) is defined similarly.

Given a set of constraints \( SC \), the service specification of the composite protocol \( R \) is a state machine whose executions are those of \( ss(P) \times ss(Q) \) that satisfy \( SC \). The set of constraints discussed above only restrict the set of executions of \( ss(P) \times ss(Q) \) (each constraint either delays the execution of an action or limits the choice of actions available in a state). Hence, we have the following lemma (the proof of the lemma is straightforward).

**Lemma 4.1** If \( ss(R) \) is deadlock free then for any execution sequence \( ex \in \text{Seq}(ss(R)) \), \( \text{proj}(ex, \text{act}(P)) \in \text{Seq}(ss(P)) \) and \( \text{proj}(ex, \text{act}(Q)) \in \text{Seq}(ss(Q)) \).

Although we can explicitly construct \( ss(R) \) to perform its analysis, we use an alternative approach. To perform analysis of \( ss(R) \), we have implemented an algorithm that performs reachability analysis by taking \( ss(P) \), \( ss(Q) \) and \( SC \) as input. These constraints are enforced during the generation of the state space. Thus, the composite state machine for \( ss(R) \) is generated on-the-fly. For each constraint, the algorithm keeps track of appropriate state information (for instance, for the constraint \( \text{enable}(A, Q_i) \), it keeps track of whether an action of \( A \) has already occurred and allows execution of an action in \( Q_i \) only if this condition holds). At present, the algorithm is able to detect deadlocks and verify invariants.

In the following, we give examples of compositions of protocols (in specifying the constraints, for simplicity, a singleton set \( \{a\} \) will be written as \( a \)).

**Example 4.1:** We can combine \( ss(\text{Connect}) \) and \( ss(\text{Disconnect}) \) of Example 3.1 using the following constraints: We have to specify that generations of \( \text{Connect} \) and \( \text{Disconnect} \) must alternate. The constraint \( \text{order}(\text{CConf}_{12}, \text{DReq}_{12}) \) ensures that the \( x^{th} \)
iteration of Disconnect is initiated only after the $x^{th}$ establishment of the connection. We also need to specify $\text{order}(C\text{Req}_{i_k}, D\text{Req}_{j_{i_k}})$ to ensure that the $x^{th}$ connection request can be generated only after the termination of $x-1^{st}$ iteration of Disconnect. However, this constraint results in a deadlock. We must impose the constraint $\text{order}(C\text{Req}_{i_k}, \{D\text{Req}_{j_{i_k}}, C\text{Req}_{j_{i_k}}\})$ instead as each connection request may not result in a connection establishment. □

**Example 4.2:** Consider the composition of the protocol $\text{Connect}_{12}$ and $\text{Connect}_{21}$ as discussed in Example 3.2. The constraint $\text{interrupt}(C\text{Req}_{12}, C\text{Pos}_{21}, \{D\text{Req}_{i_{12}}, C\text{Req}_{j_{12}}\})$ specifies that after site 1 has requested connection to site 2, site 1 cannot accept the connection request from 2 until the connection from site 1 to site 2 is either terminated or denied. Similarly, $\text{interrupt}(C\text{Ind}_{21}, C\text{Req}_{12}, \{C\text{Neg}_{21}, D\text{Ind}_{12}\})$ specifies that if site 1 has already received a connection request from site 2, then site 1 cannot send a connection request to site 2 until the connection from site 2 to site 1 is terminated or denied. $\text{interrupt}(C\text{Ind}_{12}, C\text{Req}_{21}, \{C\text{Neg}_{12}, D\text{Ind}_{21}\})$ specifies a similar constraint for the opposite direction. These constraints result in a deadlock-free service specification that has the desired properties. □

**Example 4.3:** In many complex protocols such as those for multimedia collaboration, several sessions may have to be established. Each session may be controlled by a separate connection management protocol. These protocols could have been designed independently and may have different rules for connection establishment and disconnection. Composing such protocols can be a non-trivial task as these sessions may interact with one another in a complex manner. Specifying these interactions require the type of constraints that we have proposed. In the full paper, we design a multimedia protocol by composing protocols to managing a control session, an audio session and a text session. We show how constraints can lead to deadlocks in the composite session management protocol. □

**Example 4.4:** Consider the sequential composition of the protocols in Figure 4. Sequential composition of $P$ and $Q$ implies that at each site, all actions of $P$ must precede any action of $Q$. However, for the specification in Figure 4, we cannot define $ps(R_i) = ps(P_i) \cup ps(Q_i)$ (after reaching state 4, $P_i$ cannot switch to $Q_i$ because it does not know whether $m2$ will arrive or not). On the other hand, we can define $ss(R_i) = ss(P_i) \cup ss(Q_i)$ using the enabling constraints $\text{enable}(\{A, B\}, Q_i)$ and $\text{enable}(\{C, D\}, Q_2)$ (as discussed in the algorithm later, this sequential execution of $ss(R)$ is not translated into a sequential execution at the protocol specification level). This example illustrates the case where existing composition operators cannot be applied to the protocol specifications but are applicable to the corresponding service specifications. □

5 Composition of protocol specifications

In this section, we give an algorithm to combine $ps(P)$ and $ps(Q)$ to obtain $ps(R)$ using the set of constraints $SC$ specified at the service specification level. When combining $P_i$ and $Q_i$, we require that the send and receive statements from $P_i$ and $Q_i$ operate on the same set of input channels and output channels of $R_i$. Without loss of generality, we have the following two assumptions regarding communications in $R$: (1) The message sets of $P_i$ and $Q_i$ are disjoint; and (2) The bound on a channel in $R$ is the sum of the bounds on the same channel in $P$ and $Q$. We further assume that the local variable sets of $P_i$ and $Q_i$ are disjoint. Finally, an action $a \in act(P)$ may appear as a label in more than one transition in $ss(P)$ or $ps(P)$. We assume that a constraint on $a$ refers to all transitions with label $a$.

Due to property shown in Lemma 4.1, the enforcement of the constraints at the protocol specification level is simple. The algorithm involves three steps. The first step introduces new variables and states for each constraint. The next step transforms $P_i$ and $Q_i$ by adding new conjuncts and/or local statements to their respective transitions.

**Step 1:**
- If $\text{synch}(a, b) \in SC$, then add variable $\text{syn}_{ab}$ with
possible values $\{0,1,2\}$ and with initial value $0$.

- If $\text{order}(A,B) \in SC$, then add a boolean variable $ord_{AB}$ with initial value $false$.
- If $\text{interrupt}(A,B,C) \in SC$, then we add a new variable $inh_{ABC}$ with initial value $false$.
- If $\text{enable}(A,Q_i) \in SC$, then we add a new variable $enb_{Q_i}$ with initial value $false$.

In addition, we introduce a variable $\text{synch}_i$ for each site $i$.

**Step 2:** We modify each action in $P_i$ and $Q_i$ by adding conjunct(s) and/or local statement(s) to its enabling condition and computation. Specifically, for each $a \in A_{P_i}$, we do the following:

1. if $a$ is not involved in a synchronization constraint then add $\neg \text{synch}_i$ to $en(a)$ as a conjunct.
2. $\text{synch}(a,b) \in SC$. Then for $a$, add $(\text{synch}_i \land \text{synch}_{ab} = 2) \lor (\neg \text{synch}_i)$ and $en(b)$ as conjuncts to $en(a)$ and add statement:
   
   "if $\text{synch}_{ab} = 0$ then $\text{synch}_{ab} := 1$; $\text{synch}_i = true$ else $\text{synch}_{ab} := 0$; $\text{synch}_i = false$"

   to its computation. For $b$, add $(\text{synch}_i \land \text{synch}_{ab} = 1)\lor (\neg \text{synch}_i)$ and $en(a)$ as conjuncts to $en(b)$ and add statement:
   
   "if $\text{synch}_{ab} = 0$ then $\text{synch}_{ab} := 2$; $\text{synch}_i = true$ else $\text{synch}_{ab} := 0$; $\text{synch}_i = false$"

   to its computation.
3. $\text{order}(A,B) \in SC$. Then for all $a \in A$, add conjunct $\neg ord_{AB}$ to $en(a)$ and add statement "$ord_{AB} := true$" to its computation. For all $b \in B$, add conjunct $ord_{AB}$ to $en(b)$ and add statement "$ord_{AB} := false$" to its computation. A similar action is taken if $\text{order}(B,A) \in C$.
4. $\text{interrupt}(A,B,C) \in SC$. Then, for all $a \in A$, add the statement "$inh_{ABC} := true$". For all $c \in C$, add the statement "$inh_{ABC} := false$". For all $b \in B$, add $\neg inh_{ABC}$ as conjunct to $en(b)$.
5. $\text{enable}(A,Q_i) \in SC$. Then, for all $a \in A$, add the statement "$enb_{Q_i} := true$". For all actions $b \in s_{act}(Q_i)$ such that $b$ is reachable from the initial state via a sequence of send or receive statements, add $enb_{Q_i}$ as conjunct to $en(b)$.

**Step 3:** We compute $R'_i = P_i \times Q_i$ (note that $P_i$ is different from the original one. For notational simplicity, we still denote it as $P_i$ instead of $P'_i$). The same remark applies to $Q_i$). Each state in $R'_i$ is of the form $u,v$ where $u$ is a state of $P_i$ and $v$ is a state of $Q_i$. We construct $R_i$ from $R'_i$ by removing the following transitions: Let $\text{synch}(a,b) \in SC$. Let $head(a)$ (tail($a$)) be the set of states in $P_i$ with transitions labeled $a$ incident from (to) them. $head(b)$ and tail($b$) are defined similarly. Then, we remove all transitions from $R'_i$ labeled $a$ except those incident from states of the form $u,v$, where $u \in head(a)$ and $v \in head(b) \cup tail(b)$. Similarly, we remove all transitions from $R'_i$ labeled $b$ except those incident from states of the form $u,v$, where $v \in head(b)$ and $u \in head(a) \cup tail(a)$.

**Lemma 5.1** Let $ss(R)$ be a specification obtained by composing $ss(P)$ and $ss(Q)$ using a set $SC$ of constraints, and $ps(R)$ be obtained from $ps(P)$, $ps(Q)$ and $SC$ using our algorithm. Then, $ps(R)$ is safe and satisfies $ss(R)$ if:

- $ps(P)$ satisfies $ss(P)$ and $ps(Q)$ satisfies $ss(Q)$
- $ps(P)$ and $ps(Q)$ are safe
- $ss(R)$ is deadlock free.

Lemma 5.1 allows us to infer properties of $ps(R)$ by analyzing $ss(R)$. In particular, we can infer that $ps(R)$ is deadlock free by analyzing $ss(R)$. In the examples discussed earlier, the analysis of the composite protocol specification for deadlock freedom directly would require a much larger state space search as compared to the analysis of the service specification (especially if the protocol specifications are designed under assumptions of message loss or reordering etc). Another advantage is that we can derive safety and liveness properties of $ps(R)$ by analyzing $ss(R)$ since $ps(R)$ satisfies $ss(R)$.

### 6 Extensions of the framework

In this section, we discuss several ways in which our framework can be extended:

- **Alternative composition:** A protocol designed using alternative composition of $P$ and $Q$ provides the functionality of either $P$ or $Q$, one at a time. Several different semantics of alternative composition have been studied in the literature. For example, consider the composition of $Connect_{12}$ and $Connect_{21}$ of Example 3.2. Consider the case in which both protocols attempt to establish a connection at the same time. In the composition discussed in Example 3.2, we assign priority to $Connect_{12}$ so that if a request is made in this protocol, a concurrent request by $Connect_{21}$ can either be denied (by $CNeg_{21}$) or withheld until the connection in $Connect_{12}$ terminates. Other type of compositions have been discussed in which both protocols are denied the request [13] or only one of them is denied by assigning priorities [9]. In these compositions [9, 13], if a protocol is denied the connection, its execution is “aborted” and restarted from the initial state at a later time. The notion of “aborting” introduces new executions in the composite protocol (if $Q$ is aborted then there may exist a partial execution of $Q$) and hence, Lemma 4.1 is not satisfied. To ensure
the safety of the composite protocol, the abort actions must be performed in a disciplined manner (for example, in [9], if \( P_i \) can abort \( Q_i \), then \( Q_i \) is aborted on the initiation of \( P_i \) and before it receives any response from its peer process). In our framework, we can introduce a new constraint of the form \( \text{abort}(a, Q_i, b) \), where \( a, b \in s_{act}(P_i) \), such that \( Q_i \) is aborted on the occurrence of \( Q_i \) and is reset to its initial state on the occurrence of \( b \). Such a constraint can not only model the alternative composition but other types of compositions in which, for instance, \( P \) and \( Q \) may initially execute concurrently and if certain actions occur in \( P, Q \) is aborted. The implementation of the \( \text{abort} \) constraint at the protocol specification level requires introduction of new messages and new states. In particular, on the execution of \( a \), a special message \text{Abort} is sent to \( Q_j \) and \( Q_j \) enters a special abort state. In this state, it discards all message it may receive from \( Q_j \). Process \( Q_j \) responds with an \text{Abort ack} message on receiving the \text{Abort} message.

- **Conditional and state-based constraints:** At present, our framework allows specification of constraints on actions only. In some cases, we may want to use a combination of states and actions to specify constraints. For instance, we may want to specify that a constraint between actions be imposed only when the protocol is in a specific state. As another example, we may want to specify that an action \( a \) in \( P_i \) be enabled only when \( Q_i \) has reached a specific state. In the full paper, we discuss the incorporation of these constraints in our framework.

- **Shared Actions, Global Variables and Timing Information:** Our framework currently assumes that the actions and variables of \( P \) and \( Q \) are disjoint. In some cases, we may want to allow \( ss(P) \) and \( ss(Q) \) to share actions and variables. We can incorporate this feature in our framework with the following provisions: If \( a \in s_{act}(P) \) and \( b \in s_{act}(Q) \) are shared then \( \text{synch}(a, b) \in SC \). This restriction is similar to the one in [14] where we studied sharing of actions and variables at the protocol specification level.

We also assume that an EFSM for a global specification does not include variables. Allowing variables in the global specification is advantageous as it allows very high-level specifications. Incorporating global variables is a subject of future research (the main problem encountered is that with global variables, an action in \( ss(P) \) may be broken into several actions in \( ps(P) \), and therefore, there may not exist a one-to-one correspondence between actions in \( ss(P) \) and \( ps(P) \)). Finally, we would like to extend our work to include timed extended finite state machines. In [13], the problem of composing timed specifications at the protocol specification level has been studied. As in techniques for non-timed specifications, some restrictions have been placed to ensure safe compositions. For example, if \( \text{synch}(a, b) \in SC \) then [13] requires the time interval associated with \( a \) and \( b \) to be \([0, \infty)\). We believe that by studying composition of timed specifications at the service specification level, we can weaken such restrictions.

**7 Related Work**

Protocol composition operators have been studied extensively in the literature. In particular, Lotos provides enabling, disabling and choice operators that can be used to combine service specifications [5]. For example, the enabling operator, \( P \gg Q \), specifies that after the completion of \( P, Q \) must be enabled (this requires actions at all SAPs in \( P \) to precede all actions in \( Q \). [18] proposed the idea of “specification engineering” which advocates more flexibility in combining specifications. In [18], a number of extensions of Lotos operators were proposed. For instance, consider the Lotos process \( A = A_{\text{Req}}; A_{\text{Ind}}; A_{\text{Res}}; A_{\text{Conf}} \). To use the enabling operator to specify that process \( B \) is enabled after the occurrence of \( A_{\text{Req}} \), we have to decompose \( A \) into two subprocesses: \( A_1 = A_{\text{Req}} \) and \( A_2 = A_{\text{Ind}}; A_{\text{Res}}; A_{\text{Conf}} \). To overcome this problem, [18] defined operators such as \( \text{enables}_{\text{async}}, \text{enables}_{\text{try}}, \text{interrupts}_{\text{after}}, \text{interleaves}, \text{alternate}, \text{overtakes}, \) etc. For example, \( \text{enables}_{\text{try}}(A, B) \) specifies that service \( B_{\text{Req}}; B_{\text{Ind}}; B_{\text{Res}}; B_{\text{Conf}} \) can be enabled after action \( A_{\text{Req}} \) has occurred (this action represents the fact that \( A \) has attempted to provide the service). The work in [18] share the same goals as our approach of providing more flexibility in combining services. We find that several of the operators in [18] can be specified using constraints in our framework.

A number of algorithms to synthesize protocol specifications from service specifications have been proposed [3, 6, 4, 5]. Using this approach, \( ss(R) \) can be first derived from \( ss(P) \) and \( ss(Q) \) and then \( ps(R) \) can be derived from \( ss(R) \) using a synthesis algorithm. Our work differs in two respects. First, the synthesis algorithms have been proposed for a fixed set of operators. For example, [4] considers the enabling, disabling and choice operators of Lotos. Similarly, [12] discussed sequential, iterative and alternative composition operators for combine service specifications in the FSM model. The motivation of our work is to allow more flexible com-
positions than those allowed by such operators. It may be possible to encode some of the constraints using Lotos expressions (which can be composed in parallel with ss(P) and ss(Q)). However, this may require extensive decomposition of ss(P) and ss(Q) into smaller expressions. Second, our framework allows the use of any protocol specification ps(P) that satisfies ss(P). In particular, we can use manually designed protocol specifications that may be more efficient. The synthesis approach derives a protocol specification from the composite service specification, and are therefore restricted to only those protocols that can be synthesized (the proposed algorithms typically place restrictions on the service specification that can be translated into protocol specification).

Another approach is the refinement methodology proposed in [11,7]. In this approach, one starts with a high-level specification A that is refined in a stepwise manner to a more detailed specification refined(A), such that refined(A) satisfies A. This approach can be used to refine ss(P) to ss(R). In [11], specifications are given as I/O automata and a parallel composition operator (||) is defined, where A || B is an I/O automata in which A and B are synchronized on common actions. It is shown that A || B satisfies refined(A) || refined(B). We believe that the I/O automata model can be extended to include composition using constraints (in addition to synchronization) discussed in our framework.

8 Conclusion

Protocol composition has been advocated as an attractive way to design complex protocols. Several techniques have been studied to perform composition at the protocol specification level. In this paper, we studied the problem of combining protocols at the service specification level. The composition of ss(P) and ss(Q) is defined with respect to a set of constraints. These constraints provide a very flexible approach to combine protocols. Given the composite service specification ss(R), we provided an algorithm to derive ps(R) from ps(P) and ps(Q). We show that analysis of ss(R) is sufficient to ensure that ps(R) satisfies certain safety and liveness properties. This results in efficient validation as state space of ss(R) is typically significantly smaller than that of ps(R).

References


