Towards Plug-and-Play Services: Design and Validation using Roles

Jacqueline Floch

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Doktor Ingeniør

Department of Telematics
Faculty of Information Technology, Mathematics
and Electrical Engineering
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La goutte de pluie
(Dieu parle)

Je cherche une goutte de pluie
Qui vient de tomber dans la mer.
Dans sa rapide verticale
Elle luisait plus que les autres
Car seule entre les autres gouttes
Elle eut la force de comprendre
Que, très douce dans l’eau salée,
Elle allait se perdre à jamais.
Alors je cherche dans la mer
Et sur les vagues, alertées,
Je cherche pour faire plaisir
À ce fragile souvenir
Dont je suis le seul dépositaire.
Mais j’ai beau faire, il est des choses
Où Dieu même ne peut plus rien
Malgré sa bonne volonté
Et l’assistance sans paroles
Du ciel, des vagues et de l’air.

Jules Supervielle, La Fable du monde.

Preface

When I was a child we had no phone at home. Only one person in our street, the local representative of the regional newspapers, had a phone. From time to time, my father who was sailing around the world called us at our neighbour's. Maybe dad was far away in Buenos Aires, or sailing close to us off Ouessant after a long journey. Maybe it was my brother's birthday or mine. Anyway, our neighbour came to warn us, and we would all run down the street and wait for the ringing tone. I was so happy. So happy. Today we all go around carrying mobile phones, and ringing tones make us by turns bored, stressed, happy, indifferent or irritated. Something has not changed though: calls still make us run.

It seems that people run faster as the pace of introduction of new communication technologies increases. While new technologies simplify our activities in many ways, they also draw us into an interminable race where bits and bytes accompany our restless dances. The faster we are able to communicate and exchange information, the more information we send and receive, the more we do or try to do, the more we run, the less we think. I sometimes wonder where this running will lead us.

As a telecommunications engineer and research scientist, I have little influence on the rhythms of the world. I contribute myself to a cacophony where "time to market", "rapid service development", "effective processes" are everyday sounds, where "cost" and "profit" are the main directors. Starting a doctoral study gave me an opportunity to get free from these market constraints, and opened new horizons for me. I have been able to compose my work freely and to perform tasks that do not necessarily relate to immediate profit. In that way, this study has brought resonance to my work and life.

Several persons have provided me with help and encouragement during this doctoral study. I would like to thank all of you. Rolv Bræk, my advisor, for his patience, wisdom and unending stream of advice. Otto Wittner, doctoral fellow at ITEM, for his enthusiasm

and unlimited optimism. Richard Sanders, my long-term colleague at SINTEF and ITEM, for his generosity and sensitivity, for his comforting words and thorough comments.

This study would not have taken place without any financial support. I would like to acknowledge the Research Council of Norway for their support through project grant no. 119395/431. I also acknowledge SINTEF Telecom and Informatics that has given me the opportunity to undertake this study. Especially I would like to thank Eldfrid Ø. Øvstedal for her comprehension, and for providing me with the means to combine work and study in a flexible way.

I am also deeply grateful to all the friends that have brought colours to my life these last years. To friends who have shared many passions with me. To friends who have helped me discover the music of Arvo Pärt and the poems of Jules Supervielle. To cordial friends who have offered me their hospitality. And especially for all the quiet, magic and inspiring moments spent at Storfosna.

My parents have always encouraged me in all of my enterprises, even my more fanciful ones. I thank you for having given me the spark of life and inspired me to curiosity.

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Jacqueline Floch

Abstract

Today telecommunication service users expect to access a similar set of services independently of what network they happen to use, they expect services to adapt to new surroundings and contexts as they move around, and they expect to get access to new and useful services as soon as they become available. Building services operating satisfactorily under such requirements poses new challenges and requires new solutions and new engineering methods for rapid service development and deployment.

The PaP project at NTNU was initiated in order to define a framework for service development and execution that supports the dynamic composition of services using Plug-and-Play techniques. By dynamic composition, we mean that services and service components can be designed separately, and then composed at run-time. In the frame of the PaP project, this doctoral work has addressed two issues: the design and the validation of Plug-and-Play services.

Service design is complex. In a PaP context, this complexity increases further as services are designed to be dynamically adapted to changing contexts. A design approach based on service roles is proposed, and role composition is proposed as a means to achieve adaptability.

We model service role behaviours and their composition using state machines that interact asynchronously. Describing system behaviours in terms of state machines has proven to be of great value, and is widely adopted in most teleservice engineering approaches. We favour the use of the modelling language SDL because of its formal semantics that enables an unambiguous interpretation of the system specification. However, our design and validation results are not bound to SDL. They may be applied on systems specified using other modelling languages that support state machines, as for example UML.

In our work, we investigate how SDL-2000 can be used to model composition. Differently from process algebra, SDL and other approaches using state machines do not explicitly

define composition operators. By defining design patterns and rules for expressing composition in SDL, this thesis contributes to promote using SDL as a behaviour composition language. SDL is not only a language for the modelling of state machines. SDL-2000 has newly been released, and to the best of our knowledge little experimentation using the new concepts of SDL-2000 has been done. We propose original and innovative employment of some of the newly introduced SDL concepts, that should be of interest for the SDL community.

Dynamic composition of services requires incremental and compositional validation methods. It should be possible to validate components introduced in a system at run-time, and to restrict the analysis to the parts of the system affected by the dynamic modifications. This thesis proposes a validation approach suited for dynamic service composition. Validation analysis is complex and requires simplification. Two simplification schemes, projection and incrementation, are proposed. Projection and incrementation are two main contributions of this thesis:

- A projection is a simplified system description or viewpoint that emphasises some system properties while hiding some others. Rather than analysing the whole system, projections are analysed. In our work, the projection only retains the aspects significant for the purpose of validation of associations between service roles.

- Incrementation means that validation can be applied incrementally. The proposed validation approach is tightly integrated with the composition of service roles. Elementary roles are first validated, and then the roles composed of elementary roles, and then the composite of composites. In that way, the proposed validation techniques enable us to validate parts of systems and the composition of system parts.

Another contribution of this thesis are design rules that enable the designer to avoid making certain dynamic errors and to develop well-formed state machines. Error search is not postponed until after the specification phase: ambiguous and conflicting behaviours can be identified already at design time.

The projection of service roles lead to interface descriptions that are described using state machines. In that way, our interface descriptions overcome the limitations of static object interfaces. In our work, the interface descriptions represent the dynamic behaviour of interactions between service roles. It is also possible to determine required interfaces from provided interfaces. The results of this thesis should then be of interest for the research related to the definition of semantic interfaces.

A major concern in our work has been to provide validation techniques that are easy to understand and apply. Current verification and validation techniques often require high competence and knowledge in formal modelling and reasoning on the part of the system developer, and their use in the software industry is rather moderate. We believe that our approach, although thoroughly justified, remains easy to understand and use. In that way, the applicability of the proposed approach is wider than the context of dynamic validation. It should also be of interest for the validation of static systems.

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1 Introduction

This chapter provides an introduction to the research problem addressed in this doctoral thesis. The background and motivation for the research are first described, and the questions to be answered are introduced. Then the main contributions are presented, and the scope is delimited. Finally an outline of the thesis is given.

1.1 Motivation and background

1.1.1 The revolution of services

The convergence of the telecommunication and information technologies is a reality. This convergence is expected to facilitate the rapid introduction of more varied and advanced services. As an example, enabling technologies such as high-capacity wireless networks and small hand-held java-enabled terminals make sophisticated mobile services possible.

At the same time, deregulation enables new actors to enter the scene, leading to increased competition. Services on the telecommunication networks are no longer owned solely by telecommunication operators. A distinction is emerging between service and connectivity providers. Competition changes the pace of service development and deployment. Slow standardisation processes are no longer an option. Short time to market, rapid response to customers needs, cost reduction and increased reuse are key requirements of service providers today.

In this competitive service business environment, customers play an active role. Their needs and expectations are in focus. Exposed to computers and the Internet, telecommunication users have increased expectations. They expect more “intelligence” in services. They expect to get access to new and useful services rapidly as they become available. Furthermore, they expect to access the same set of services independently of what network they happen to use, and they expect services to adapt to new surroundings and contexts as they are moving around.

Building services under these new settings poses several challenges. New solutions are needed that support rapid service development and deployment. Traditional approaches where users are first asked what services they need, and then new features are developed and added in a well-planned manner over a course of years is no longer an option. A trend among service providers is to try a number of new services at low cost to a limited user group, assess their success, and deploy the best more widely. The provision of dynamic services that can be configured by the users, e.g. built up from a set of service elements, is also being considered. AMIGOS, a service for creating and customizing meeting places, is an example of such dynamic services [AMIGOS 2002]. AMIGOS is developed in the AVANTEL project at NTNU [AVANTEL 2000].

1.1.2 Service quality: the main challenge?

The traditional telecommunication services and networks have several strengths that tend to be forgotten behind the excitement created by new business opportunities. Ubiquity and simplicity of usage are two main strengths: the telecommunication networks *provide services to more than 800 million terminals around the world, and enable connections to any country at any time by a simple process of dialling* (from [TINA 1999]). Guarantee of service and robustness are essential: services are available when needed, and they function as expected.

The difference between “best-effort” as provided by the Internet and the “guarantee of quality” that has always been a key point for telecommunication networks has been widely discussed and is often referred as the problem of “quality of service”. Service quality however is not restricted to connectivity and capacity in networks. In the new service environment, new challenges arise that, if not properly managed, are also threats for service quality:

- *Hybrid services provided over heterogeneous networks.* Users have access to heterogeneous networks. The new services should preferably span different networks and networks technologies. Several research activities aim to provide solutions for the provision of so-called “hybrid” services. [Vanecek and al. 1999] advocates putting common service functions in the networks. [Gbaguidi and al. 1999a; Gbaguidi and al. 1999b] propose to treat end-systems and network equipment equally allowing one to tune or program service platform elements. [Logean and al. 1999] underlines the need for using formal modelling and validation techniques for the development of services deployed in heterogeneous environments.

- *Hybrid providers*. Interacting users may access services provided and developed by different service operators and vendors. The interoperability and compatibility of services should be preserved [Floch and Bræk 2000]. Possibly support for negotiation, adaptation and learning is needed.

- *A new class of service interactions*. Service interactions occur when a combination of services behaves differently than expected [Keck and Kuehn 1998]. There exist several causes to undesirable interferences between services. Among them, the evolution of system architecture and the addition of new service features create a new environment that may violate the assumptions of existing services [Cameron and al. 1994]. A new class of service interactions are introduced in open networks [Cameron and Lin 1998]. Interactions following by the lack of co-operation in a competitive business [Kolberg and Kimbler 2000], sharing a common service layer [Kimbler 2000], moving interactions from networks to terminals [Utas 2000], interactions introduced by Internet telephony [Lennox and Schulzrinne 2000] were some of the issues discussed at the Fifth International Workshop on Feature Interactions in Telecommunications and Software Systems [Magill and Calder 2000].

In the context of open network service provisioning, there is no longer one organisation responsible for solving these kinds of problems. On another hand, the access to multiple new and useful services is exciting, and may shadow on service quality. It is a fact that poor reliability is today tolerated by users of personal computers; maybe this “user tolerance” will also be valid for new telecom services. We believe service quality is a crucial issue, and this thesis aims at providing tools for achieving better quality.

1.1.3 The Plug-and-Play project

The Plug-and-Play (PaP) project at NTNU was initiated in order to define a framework for service development and execution that supports the dynamic composition of services using Plug-and-Play techniques [Aagesen and al. 1999]. Dynamic service composition means that service components can be designed separately, and then composed and configured at run-time. By using Plug-and-Play techniques, the project aims at facilitating the deployment of new service elements, and at supporting adaptation of services to heterogeneous network environments or particular user needs.

In the frame of the PaP project, this doctoral work has addressed two issues: compositional design and validation of Plug-and-Play services. Other research topics have also been considered. An execution platform that supports the dynamic composition has been developed [Aagesen and al. 1999]. A replication management framework that simplifies the development of fault tolerant applications has been proposed [Meling and Helvik 2001; Meling and al. 2002]. Support for personal mobility in the PaP platform is under consideration [Shiaa and Aagesen 2002].

1.2 Research problem

Service design is complex. Services involve the interaction of several components that execute concurrently. These components may themselves be involved in several services. In a PaP context, this complexity increases further as services are designed to be dynamically adapted to changing contexts. This thesis addresses two main questions:

- How can we model services so that they can be easily modified - possibly at run-time?
- How can we ensure that service components that are modified or added dynamically in a system interact consistently with other system components?

The first question is a design issue and relates to the requirement of rapid service development and deployment. The second question is a validation issue and relates to the requirement of service quality. We do not address the problem of service interaction, but rather the problem of logical consistency.

1.2.1 Need for fine-grained modularity

Modification of services in order to adapt to different needs or contexts requires that is possible to add, remove or replace some functionality in a service. Modifications can be performed at different levels: the whole behaviour of a component involved in a service may be modified, or at the modification may be restricted to an element of behaviour within a service component. The introduction of changes is simplified when services are designed in a modular way. We distinguish between coarse-grained modularity where services are designed in a modular way enabling service components to be added and replaced, and fine-grained modularity where components are designed in a modular way allowing small elements of behaviours to be composed. In our work, we concentrate on fine-grained modularity, i.e. we aim at providing a method for adding or replacing *small* elementary behaviours in a service.

Different forms of modification are illustrated in Figure 1.1. They are applied at different granularity levels and require different kinds of modularity:

- Complete replacement and partial replacement are modifications performed at the service level. One or several components involved in the service are completely replaced. Complete replacement and partial replacement require coarse-grained modularity.

- Addition is also a modification performed at the service level and requires coarse-grained modularity. A new component is added that interacts with the existing components.

- Component modification is performed at the component level. A component involved in the service is partially modified. Component modification requires fine-grained modularity.

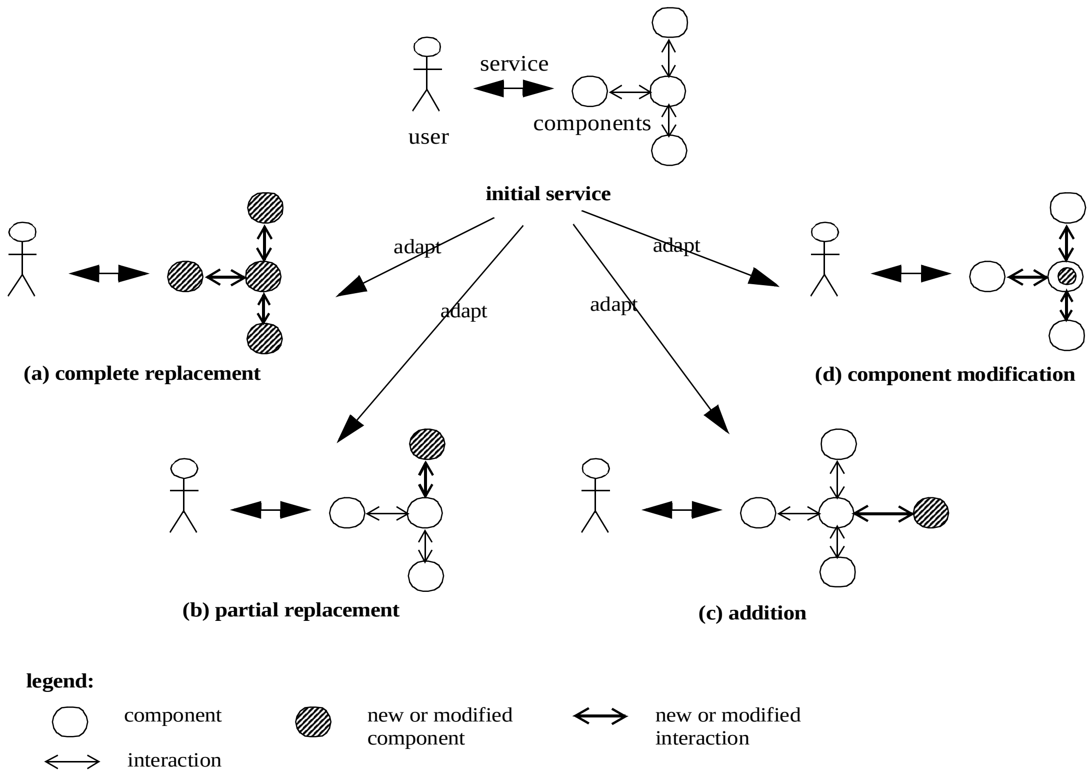

Figure 1.1 : Modifications at different granularity levels.

Partial replacement, addition and component modification are preferable over complete replacement as functionality can be reused. In these cases, the introduction of changes may have impact on the interactions between the existing and the new or modified components, and ensuring the correctness of the service after adaptation is essential.

In our work, we have chosen to address fine-grained modularity. We seek modelling techniques that enable elementary behaviours to be composed and components to be modified in a consistent way. A reason for adopting a fine-grained approach is that small modifications are essential in the provision of customizable and context-aware services to the mobile users:

- Users should be able to customise existing services to their needs. Services components should be developed with reusability and customizability in mind. A simple customization level based on toggling features on/off is too limited. Other levels of customization are discussed in [Maknavicius and al. 1999]. For example, services may be tailored at run-time, either at service instantiation or during service provision; the users may also combine their own functions with existing services. [Hiltunen 1998] proposes micro-protocols and composition as a means to achieve customizability.

- Location- and context-aware services are services that can adapt to the changing locations and context mobile of users. Mobility introduces variability in the operating environment of the provided services. Offering effective and dependable services in a mobile context poses several challenges for the service developer. Several research projects aim at developing solutions for context aware services [Nexus; Floch and al. 2001]. There is no doubt that the mobile industry will have to provide solutions to these challenges soon. An assessment of the future market for mobile multimedia services done by the UMTS forum estimates the world market for users of mobile services to be 940 million users by 2005 and more than 1.7 billion users by 2010 [UMTS Forum 1999].

Our choice is also inspired from existing service architectures:

- A fine-grained approach is successfully adopted in IN[1] where reusable functional blocks can be chained together in various combinations to realize services [ITU-T 1992]. Composition is also possible at different levels by the introduction of High level SIBs [ITU-T 1997c].

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- The TINA[1] Service Architecture defines a set of service scenarios and interfaces as basic elements of a service [TINA 1997; TINA 1998]. For example, scenarios are described for login/logout, start/end session, suspend/resume session, invite user, join session with invitation, voting, add/delete stream binding, add/delete participant to a stream binding.

1.2.2 Service modelling and composition

Having opted for fine-grained modularity, we aim to produce different services and service variants by composing service elements in various ways. We adopt a role based design approach [Reenskaug and al. 1992]. Roles and role collaborations focus on behaviours across a system boundary. Experience suggests that role modelling provides better support for system adaptation and reuse than class modelling. The unit of reuse is seldom a class, but rather a slice of behaviour [VanHilst and Notkin 1996; Mezini and Lieberherr 1998]. Using object-oriented approaches, systems and services are modelled as classes and objects. When defining classes, the emphasis is on the common object characteristics, i.e. what objects are, rather than the common object purpose, i.e. what the objects do and what roles they are playing in the system [Kristensen and Østerbye 1996; Reenskaug 2001]. When classes are defined they are allocated individual behaviours. A major problem with class decomposition is that it is difficult to understand what a whole system is doing. Roles, on the other hand, are introduced to reflect the purpose of components in a system, and collaborations are used with success to describe the relations or interactions between these roles.

In our approach, services are modelled as collaborations between functional roles. Complex roles may be decomposed into small behavioural elements or elementary roles in order to break down their complexity. Conversely, more complex roles, and thus behaviours, can be produced by composition. There exist various types of dependencies between roles that constrain how they may be composed. This thesis introduces different forms of composition, and discusses their properties. Composition, or role model synthesis, is also discussed in OORAM [Reenskaug and al. 1992]. Two forms of synthesis, superposition and aggregation, are discussed that preserve the integrity of the base model. While aggregation may hide the details of a base model, the stimuli and activity of a base model are retained by superposition. Composition in our approach is restricted to super-

1. Telecommunications Information Networking Architecture. TINA resulted from the collaboration of over 40 of the world’s leading network operators and equipment manufacturers.

position. OORAM does not formally describe the composition operations while our approach does so by using state machines and SDL.

Ideally roles should be specified without making assumptions about the other roles they are composed with, and how they are going to be composed. Dependencies between roles may exist, and role specification may require to be coordinated with the specification of other roles. We aim at defining design rules that enable roles to be specified individually and to be easily composed.

[Rößler and al. 2001] has also proposed an SDL based composition approach. An earlier version of SDL is used in that work, and a new notation is used for modelling composition. In our approach composition is also described using SDL. SDL 2000 has been recently introduced, and, as far as we know, no work related to the use of SDL 2000 for role composition has been published to this day.

1.2.2.1 Learning from IN

The idea of composing service elements is not new. It is supported in IN. However, composition is rather limited in IN. CS-1[1] lacked support for parallelism and could only accommodate single service execution performed sequentially [ITU-T 1993b]. This resulted in blocking subsequent activities until the original service execution is completed. The concepts of parallel service processing was introduced in CS-2 [ITU-T 1997b; ITU-T 1997c]. Parallel service processing enables the implementation of particular CS-2 services features that require parallel service processing, e.g. simultaneous announcements to different call parties, and call waiting with two active threads at the same time where one monitors an incoming call.

Although IN has reduced the lead time for introducing new services and gained wide acceptance due to the multitude of services installed and its application to cellular networks [Gbaguidi and al. 1999a], it suffers from several limitations that makes it inappropriate in the provision of future services. IN does not support user-oriented services, but rather call-oriented services. Service features offered by IN can be actually considered as enhancements of basic call control. It should be possible to apply the same basic features to different kind of services, e.g. forwarding may be applied to a call or an e-mail service. IN also lacks support for distributed control. CS-1 supports “single-ended” service features, i.e. features that apply at one party in a call and are independent from fea-

1. Capability Set

tures applied at other parties. This means that IN does not support the coordination and negotiation of services between users. Lack of standardized interfaces for service creation, management and deployment, lack of facilities for brokerage, and poor customization support are also limitations of IN [Brennan and al. 2000; Maknavicius 1999]. Furthermore, the current IN products are mainly based on proprietary HW/SW technologies; they are not easily scalable and clumsy to program without the support of vendors [Daoud 1999]. The opening of telecommunication systems interfaces as provided by Parlay [Parlay 2000a; Parlay 2000e] should enable higher levels of programmability. However, Parlay relies heavily on IN and also adopts a call-oriented service approach.

1.2.2.2 Building upon TINA

TINA-C[1] recognised the central role of software for the telecommunication industry. *TINA was developed with the primary objective of becoming a software architecture for services and the operation of these services* [TINA 1999]. TINA proposes generic structuring principles, and adopts state-of-the-art solutions such as object oriented design and distributed computing. Furthermore, TINA support flexible business models. There is no doubt that TINA is a rich framework that addresses the most relevant service issues. TINA is possibly too rich, thus leading to unnecessary complexity. TINA introduces a multitude of concepts, architectures, viewpoints and principles that are difficult to comprehend.

TINA prototypes have been developed, and experimentation has shown that services can be quickly and easily developed. However, the success of TINA is limited to research centres [TINA 1999]. TINA has not gained industrial strength. The migration from existing networks to the sophisticated solutions of TINA represents new investments, and telecommunication operators want to protect their existing investments. [Hubaux and al. 1999] also claims that TINA has made wrong assumptions. First, too much weight has been set on connection-oriented networks. Connectionless networks were taken into account too late. Secondly, TINA services are provided by servers within the networks. TINA does not distinguish between common service that ought to be provided by the networks, and services that can be supported in the terminals. Finally, service evolution is kept under the control of the main telecommunications stakeholders. TINA does not support an open service creation of the kind we find in the Internet.

Although TINA may not be adopted in its whole, many concepts of TINA will probably be progressively applied as solutions to the convergence of information and telecommu-

1. the TINA Consortium

nication technologies. Several ideas and concepts of TINA deserve to be retained, such as the concept of service and communication sessions and the management approach. The object oriented approach and the concept of a service factory are relevant in this thesis.

TINA Service Architecture sets the two following objectives [TINA 1997]:

- to define a set of reusable and interoperable service components to be composed in service definition and construction.
- to define mechanisms for service composition, both statically (i.e. during design and construction) and dynamically (i.e. during the service utilization).

TINA claims that the first objective is supported by the object oriented methodology underlying the computational view. Service composition is defined as the creation of a new service or service instance by composing services or service components. TINA Service Architecture also discusses the composition of service sessions and the relations between parties in a session (i.e. user, retailer and provider). TINA concentrates on coarse-grained composition rather than fine-grained composition. TINA composition concepts are defined at an abstract level. It is not clear how these concepts should be further addressed in the computational models. We believe that the adoption of an object oriented approach, although it facilitates reusability and composition, is not sufficient to support composition. Additional rules and techniques, such as roles, collaborations and composition patterns are needed.

1.2.3 Validation

An important issue when performing changes in a system is to ensure that the modified system behaves correctly after the modification. The problem of validation is not specific for telecommunication services, but is a general problem in software development. A particularity of telecommunication services is that they often involve several components that may take initiative concurrently and involve stateful behaviours (protocols). The interaction patterns between telecommunication service components are usually more complex than those between components in a client-server architecture. Thus the error probability will be higher unless counter measures are taken. Moreover, as telecommunication services provide basic support for application domain services, the consequence of errors may be severe. In an open world, where services can be provided by several actors, the need for validation increases.

TINA does not address the problem of validation. Components in TINA are described using the interface description language ODL. This language was defined as an extension of CORBA IDL [OMG 2001] with features for describing stream flows and QoS attributes. ODL suffers from the same limitations as IDL with respect to system consistency checking. With ODL, component interface definitions only deal with the declaration of operation signatures, and not the protocols used on a connection between objects. Thus, it is not possible to check the dynamic consistency of a connection.

This thesis aims at describing the dynamic behaviour of interfaces in a manner that facilitates incremental validation of interface behaviour when behaviours are composed. We seek techniques for deriving interfaces from components specifications, and for validating interfaces. We propose to integrate the validation approach with the techniques proposed for composition so that validation can be applied incrementally. Changes to a component should not require the whole component to be validated. Only the element being added or modified, and the way it is composed, should require checking.

1.2.4 Requirements to the modelling and validation approaches

A major concern in our work has been to propose modelling and validation approaches suited for the development of real services. To reach that aim, we identify the following requirements:

- The approaches should provide “designer-friendly” techniques, i.e. techniques that can be easily understood and applied by the service developers.
- The services and service components developed using these techniques should be easy to understand.
- The approaches should support incremental development. It should be possible to build services from small elements that can be developed separately, and added progressively. It should be possible to apply the validation analysis to a subset of elements.
- The approaches should support correctness. The modelling techniques should contribute to the development of correct service behaviours. Validation is then applied to detect possible remaining errors.
- The approaches should not be dependent on a particular execution framework.

- The techniques should be expressed in operative terms so that they can be easily implemented by CASE tools.

The first requirement, the designer-friendliness of the techniques, is especially important for the validation approach. Current validation techniques often require high competence in formal reasoning, which may explain their moderate use in the software industry. By seeking to define simple techniques that lead to simple results, we aim to motivate developers to using the approaches.

1.3 Main contributions

The aim of this thesis has been to provide techniques for the incremental, component based design and validation of services in a PaP context. We describe an approach based on roles. Role composition is proposed as a means to achieve adaptability. The main contributions of the thesis are:

- *Techniques for modelling services in terms of roles*. Roles are assigned dynamically to actors at run-time. SDL-2000 is used to specify service role behaviours. SDL-2000 has newly been released, and to the best of our knowledge little experimentation using the new concepts of SDL-2000 has been done. Our study identifies original and innovative employment of the composite states newly introduced in SDL. In that way, the results of this thesis should be of interest for the SDL community.

- *Techniques for modelling the composition of service roles (s-roles)*. Different forms of composition are proposed, and modelled formally using state machines. By defining design patterns and rules for expressing composition in SDL, this thesis contributes to promote using SDL as a composition language. Composition provides support for dynamic service adaptation. In addition, it augments human comprehension of the service models and contributes to reduce the complexity of the validation analysis.

- *An abstraction technique, the projection, that contributes to simplifying the validation of interactions between service roles*. The projection transformation is formally described.

- *A description of role interfaces that overcome the limitations of static object interfaces.* We call these interfaces a-roles. A-roles describe the semantics of interactions between s-roles. The a-roles required by an s-role can be determined from the a-roles provided by this s-role. A-roles are obtained by projection.

- *A classification of particular anomalous behaviour patterns.* Ambiguous and conflicting behaviours that lead to errors can be identified at design time, before the validation analysis itself. Design rules are given that enable the designer to identify and avoid potential safety problems.

- *A constructive validation method that supports the design of correct services*. Consistent complementary a-roles can be generated from particular a-roles.

- *A corrective validation method that provides support for checking that two complementary a-roles interact consistently.* Consistency can be checked at run time.

- *A validation approach tightly integrated with the composition of service roles*. Validation analysis is applied incrementally. Incremental validation contributes to simplify the validation analysis, and the compositional properties of a system can be taken into account during analysis. The same symptoms of error need to be addressed at the composite level as at the elementary level. As composition is modelled using identical mechanisms as the modelling of elementary s-roles, the design rules and validation techniques proposed at the elementary s-role level apply at the composite level.

- *A validation approach suited for the analysis of dynamic systems*. The analysis takes advantage of the system structure, and may be restricted to the parts of the system affected by changes. The analysis applies to types - not instances, and is thus suited for the validation of components bound dynamically at run-time.

- *Algorithms for the transformation of state graphs and their validation*.

The proposed validation techniques are believed to be easy to understand and apply. Current verification and validation techniques often require high competence and knowledge in formal modelling and reasoning from the system developer, and their use in the software industry is rather moderate. Our approach, although thoroughly justified, remains comparatively simple to understand and use. In that way, the applicability of the proposed approach is wider than the validation in a dynamic context. It should also be of interest for the validation of static systems.

1.4 Delimitation of scope

This doctoral work is based on a long and deep knowledge acquired from practical system development work. Rather than acquiring knowledge through the development of prototypes, earlier experimentation results and experience have been injected in the modelling approach. We propose transformation and validation algorithms that have not been integrated in design and validation tools yet. We have favoured the development of a complete and sound reasoning rather that the implementation of tools. Our experience in the development of SDL code generators [Floch 1995] makes us confident that the proposed algorithms can be implemented with reasonable effort.

Our work does not specify any service architecture and execution framework. The design and validation approach that we propose can be applied in frameworks such as TINA [1999] or ServiceFrame [Bræk and al. 2002]. Our techniques concentrate on the behaviours assigned to the service components in such frameworks. We do not prescribe any particular mechanisms that support the dynamic assignment of behaviours (roles) to components (actors). Such mechanisms are provided by the PaP platform [Aagesen and al. 1999] and ServiceFrame.

1.5 Guide to the thesis

This thesis is organised as followed:

- *Chapter 2: Fundamental concepts* introduces the main concepts used in this thesis, such as what a service is and the notion of service roles. Concepts are defined at the enterprise and computational viewpoints.

- *Chapter 3: Collaboration and service role modelling* presents the modelling approach for services. The role view and the collaboration view are complementary views. While the role view provides descriptions of the behaviour of individual computational objects or actors, the collaboration view focuses on interactions between actors and facilitates understanding the overall system behaviour. A set of basic service role examples is introduced. These roles are also used when discussing service role composition.

- *Chapter 4: Service role composition* discusses the composition of service roles (s-roles) within an actor. Through the composition of s-roles we aim to produce the complete behaviour of an actor in a service. Composition may be applied incrementally. There exist various types of dependencies between s-roles that constrain the form of composition that can be applied on s-roles. The chapter presents different forms of composition, and discusses their properties. SDL-2000 is used to model the different composition classes.

- *Chapter 5: Validation: an introduction* discusses the requirements set by dynamic composition on validation, and considers existing validation techniques with respect to these requirements. The chapter introduces the validation approach proposed in this thesis. The validation approach concentrates on the interaction behaviour between service roles, i.e. the interactions between service association roles. Focus is set on safety properties i.e. avoiding that bad behaviours occur, such as deadlocks. Two simplification schemes are proposed: projection and incrementation.

- *Chapter 6: Service association role modelling* presents the modelling of service association roles (a-roles). An a-role is defined as the visible interaction behaviour of an s-role on an association with another s-role. The set of concepts needed for a-role modelling is first identified by describing the projection from s-roles to a-roles. A-roles are described as state machines using a notation inspired from SDL. Transformations are proposed that can be applied on a-role state graphs in order to facilitate interface validation. This chapter also identifies s-role patterns that lead to ambiguous or conflicting behaviours. Ambiguous and conflicting behaviours require special consideration during interface validation.

- *Chapter 7: Interface validation* discusses the validation of interactions between elementary s-roles. The purpose of interface validation is to ensure that the interfaces, i.e. service association roles (a-roles) on associations between service roles (s-roles) interact consistently. Interface validation is used both as a constructive method that aims at generating correct systems, and as a corrective method that aims at detecting and correcting errors. In the constructive method, techniques are proposed for generating consistent complementary a-roles from particular a-roles. In the corrective method, a consistency checking technique is described. The chapter proposes solutions to handle ambiguous and conflicting behaviours. Design rules are defined that enable the designer to develop well-formed state machines.

- *Chapter 8: Composition validation* addresses the validation of composite service roles. The purpose of composition validation is to ensure that service roles are consistently composed across actors. As the sequential composition of s-roles is modelled using identical mechanisms as the modelling of elementary s-roles, the techniques developed for the validation of elementary s-roles apply to s-roles composed sequentially. Concurrent composition introduces new associations that are validated separately, also using the techniques of interface validation. The chapter discusses techniques needed by the dynamic creation of s-roles.

- *Chapter 9: Conclusions* discusses of the results of this thesis. Recommendations for further research are given.

2
Fundamental concepts

The aim of this chapter is to establish the understanding of what a service is, and of other main concepts used in this thesis. Although several of these concepts may sound well-known to the reader, we have experienced that they are often used to meaning different things. The term “service”, for example, has received different definitions in the literature depending on the viewpoints, frameworks and application domains. Service is also often used imprecisely or without being defined.

As in the ODP reference model [ITU-T 1997a] and the TINA framework [TINA 1995], we distinguish between the enterprise viewpoint and the computational viewpoint. While concepts at the enterprise viewpoint are related to the purpose, scope and policies for the system, they are, at the computational viewpoint, related to functional system decomposition and system distribution.

2.1 Service: some definitions

Intuitively, we understand service as some facility or assistance provided by some persons or systems to some other persons or systems. The term service is frequently adopted by software engineers for describing a function provided by a component. But engineers and scientists often use the term services meaning different things such as components, interfaces or capabilities.

The term service is often used without being defined or in a vague manner. While the RM-ODP overview [ITU-T 1997a] uses the term service in the introduction to the object concept, the term remains undefined. Similarly, the Internet documents discuss the concept of end-to-end quality of service without defining service. The Jini network technology, first defines service as “an entity that can be used by a person, a program or another service”. A service may be a computation, storage, a communication channel to another user, a software filter, a hardware device or another user [Sun microsystems 1999]. However it turns out that Jini services are restricted to the computational viewpoint, and refers to objects rather than properties provided by these objects.

The TINA Service Architecture [TINA 1997] defines services at the enterprise and computational viewpoints:

- In the enterprise viewpoint, a service is defined as a set of capabilities provided by an existing or intended set of systems to all who utilise it, such as subscribers, end-users, network providers and service providers.

- In the computational viewpoint, a service is defined as a set of capabilities provided by a computational object that can be used by other objects. This definition is identical to the OMG definition [OMG 1997].

Services in the enterprise viewpoint may also be considered at different functional levels. Telecommunication engineers often distinguish between bearer or carrier services, teleservices and supplementary services. ISDN and UMTS [ITU-T 1998; ETSI 1995] define:

- Bearer services support the transfer of information between two network access points (i.e. fixed access locations in the network). Carrier services designate bearer services in mobile radio networks.

- Teleservices support communication between two end-user systems (e.g. telephony or tele-conference).

- Supplementary services supplement teleservices by providing additional value to the end-users (e.g. call forwarding, call screening, billing).

Another functional classification is proposed in the TINA Service Architecture [TINA 1997]:

- Telecommunication services support the transport of bits between terminals attached to a telecommunication network, and are responsible for the establishment of connections. This definition encompasses the definitions proposed in ISDN and UMTS. TINA clearly separates between the service architecture in charge of sessions (rather than calls) from the network resource architecture in charge of connectivity.

- Management services support the fault, configuration, accounting, performance and security functionalities (so-called FCAPS), and the service life-cycle management.

- Information services handle information resources such as movies, sounds and documents.

The definition of service in the OSI reference model [ITU-T 1994] is in some way similar to the TINA definition in the computational viewpoint. In OSI, the computational object is replaced by a protocol layer, and a service designates the set of primitives that a given protocol layer provides to the upper protocol layer.

In order to avoid misunderstanding among the various definitions, we clarify the meaning of the term “service” used in this thesis. Service is defined at the enterprise viewpoint (Section 2.2). At the computational viewpoint we prefer to use the terms service role and service association role (Section 2.3).

2.1.1 Service features

IN distinguishes between services and service features [ITU-T 1993b]. While a service is defined as a stand alone commercial offering, a service feature is a specific aspect of a service that can also be used in conjunction with other services/service features as part of a commercial offering. A service is characterized by one or more core service features, and can be optionally enhanced by other service features.

There is an overlap between the defined services and service features as some features may be used both stand-alone, or in conjunction with other services. Examples of such features are abbreviated dialling and call forwarding. IN defines a relationship table that defines the core and optional service features of each service.

2.2 Enterprise viewpoint

Figure 2.1 presents[1] some fundamental concepts at the enterprise viewpoint. A *network* is a kind of system that provides computation and communication support. Networks offer *services* to human actors that we call *users*, and *systems* (e.g. autonomous systems or agent systems that act on the behalf of users). Service are defined as a functionality provided to users and systems. Several users may interact sharing a service.

We distinguish between different classes of services. The *communication services* that support communication between users and systems, and the *application domain services* that related to a domain i.e. market segment or a family of systems related to the same types of phenomena. For example, we may consider application domain services for the

1. In this section, the class diagrams that describe entities and relationships are expressed using UML [OMG 1999].

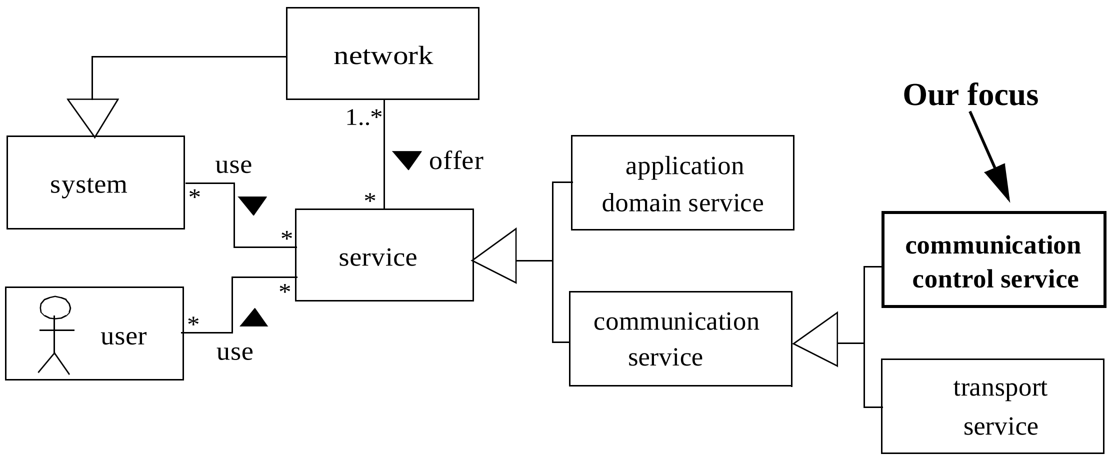


Figure 2.1 : Networks and services.

financial market or for the health sector. Application domain services are usually provided by distributed systems that use communication services.

At the communication level, we separate communication session control from information transport, and thus distinguish between *communication control services* and *transport services*.

Transport services comprise the allocation and setup of transport channels in the transport network. They allocate network resources in order to provide connectivity and transport capacity. Typical transport services are voice, video and data transfer over various network technologies such as ISDN, the GSM radio interface or IP.

Communication control services are responsible for initiating and coordinating the participation in a service. They encompass the following functionality:

- ensuring coherence between the roles and responsibilities of the participants in a service. We may distinguish between the initiator of a service and the invitee (s).

- guaranteeing consistence of the preferences of the participating parts in a service and resolving conflicts. The participating parts should agree on which services or service subsets are instantiated. For example, an invitation redirection may only be initiated if the participants in the service agree on that redirection.

- requesting the necessary transport resources from the transport network. We abstract from details of the transport network and assume that it provides a network independent interface to the service control part.

Setting up a telephony session between two or several participants is a kind of communication control service. Other examples are invitation, redirection, distribution, request queuing, callback and reminder.

Other types of services, such as management services, could also be considered. We do not define them here as they are not further discussed in this thesis.

This thesis focuses on communication control services. When used alone, the term service should be understood as communication control service.

Similarly to IN, we distinguish between services and service features, and we adopt the IN definition for service feature.

2.3 Computational viewpoint

In the computational viewpoint, we decompose networks into *nodes* and *links*. Nodes run *computational objects*. Links are communication paths that provide connectivity between nodes. Computational objects play some behaviour or *service roles* that interact or collaborate in order to provide services (as defined in the enterprise viewpoint). Thus a service is the result of a *collaboration* between services roles. These concepts are represented in Figure 2.2.

Definition: Service role (s-role)
A service role, or s-role, is the part a computational object plays in a service.

Definition: Actor
Actors are computational objects that play service roles.

Service roles enable us to better comprehend the contribution of a computational object or actor in a service [Bræk 1999]. Services involve several computational objects where some of them may be involved in several services. The concept of s-roles enables one to focus on single “slices” of behaviour and makes it possible to separate the contribution of a computational object in a service from the contribution of the other computational objects.

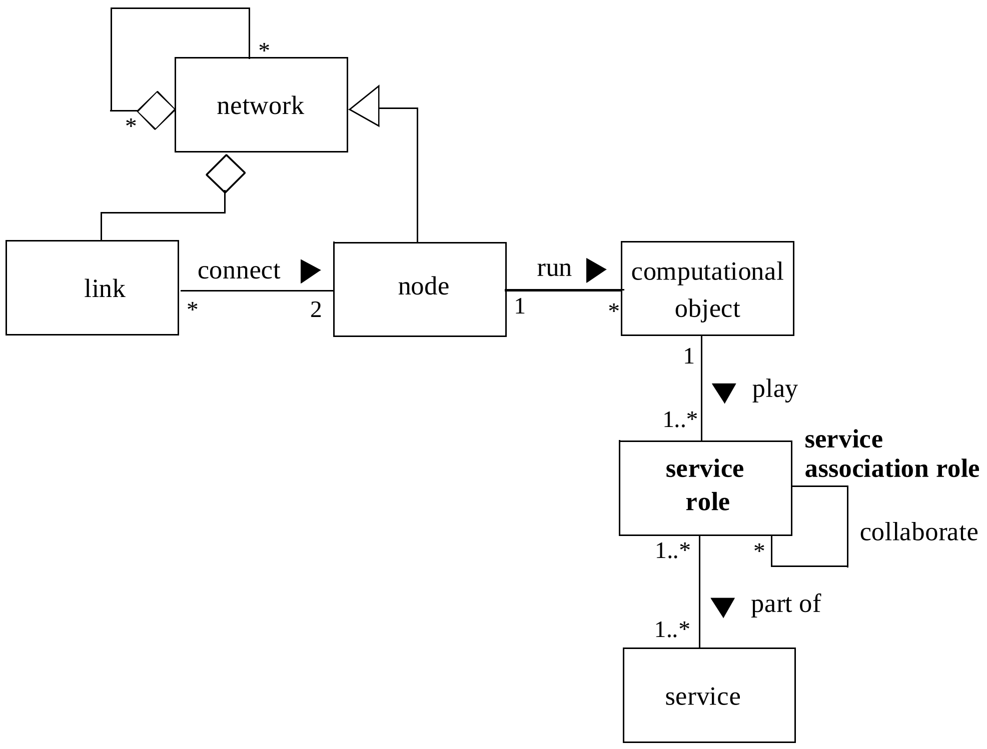


Figure 2.2 : Service roles.

Notice that there is no one-to-one relation between computational object and service. Services may require the coordinated effort of several distributed computational objects. Similarly some computational objects may be involved in several services. This is an important distinction from the notion of service as function provided by a single object as in Jini or CORBA.

S-roles interact with other s-roles over associations. A *service association role* is the visible behaviour of an s-role on an association between two s-roles. In other words, a service association role is the participation of an s-role in a dialogue with another s-role. An a-role can be seen as the projection of an s-role on an association. The concept of service association role is represented in Figure 2.2 using an UML role in the association “collaborate” between service roles.

Definition: Service association role (a-role)
A service association role, or a-role, is the interaction behaviour of an s-role visible on an association between two s-roles.

2.3.1 Service roles

Roles may be introduced in a rather intuitive way. The concept of role is used extensively every day, either to describe relations between persons, for example family roles such as mother and daughter, or to describe functions and responsibilities, for example organisational roles such as professor, secretary, librarian and student. Also in telephony, it is customary to refer to the A-subscriber and B-subscriber, or the caller and the callee in a telephony call.

The concept of role was already introduced in the end of the 70's in the context of data modelling [Bachman and Daya 1977] and has emerged again in the object-oriented literature. Roles are used both for data modelling [Wieringa and de Jonge 1991] and functional modelling [Reenskaug and al. 1992; Kristensen and Østerbye1996; Mezini and Lieberherr 1998]. In our approach, service roles (s-roles) are functional roles that encapsulate the functional properties of computational objects involved in a service.

2.3.1.1 A simple example using service roles

Service roles (s-roles) are introduced by a simple example in Figure 2.3. This figure shows a *collaboration structure diagram* for an invitation to participate in some service. We introduce a new notation for representing collaboration structures[1]. The invitation involves two users that interact with two different s-roles: "inviter" and "invitee". This figure does not represent the actors playing the s-roles; actors may be represented as shown in Figure 2.4.

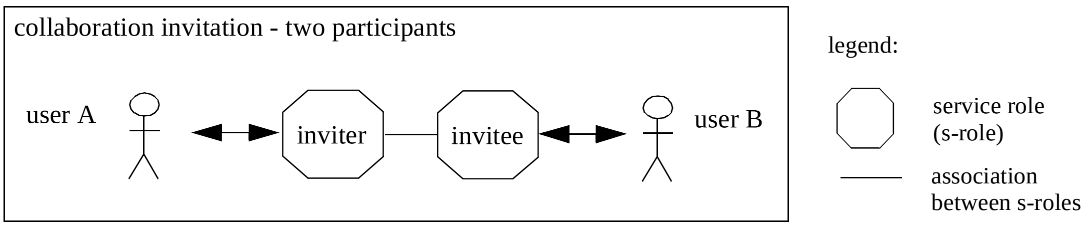

collaboration invitation - two participants
user A
inviter
invitee
user B
legend:
service role (s-role)
association between s-roles

Figure 2.3 : Collaboration structure diagram for service invitation.

Role and collaboration modelling will be further discussed in Chapter 3. Dialogues between s-roles will be described in *collaboration sequence diagram*s, and s-role behaviours in a *state machine diagrams*. Collaboration sequence diagrams get rapidly complex

1. The reason for not using UML collaborations is the distinction we make between actors and roles. This is desirable in order to have flexibility in allocating roles to actors.

when there exist multiple alternative dialogue cases. Decomposition and composition are means to reduce the size of collaborations and s-roles.

2.3.2 Collaborations

In the early phases of service and system modelling, scenarios such as use cases [Jacobsen and al. 1992], use case maps [Miga and al. 2001] and message sequence charts [ITU-T 1999b; Bræk and al. 1999] are often used. These scenarios describe collaborations between roles. They provide good support for capturing system needs and describing the main behavioural cases. Scenarios are however not used to model the complete system behaviour. The main reason is that there exist far too many cases, and among them many closely related cases. Instead of modelling the complete set of scenarios for a system, one may explore another approach based on the modelling of basic scenarios and their composition [Riehle 1997]. Basic scenarios describe simple or elementary slices of behaviour, and scenario composition provides a method for merging the basic scenarios into more complex behaviours.

In our approach, we do not focus on collaborations. Instead we describe roles and their composition.

2.3.3 Composite service roles

Service roles may be decomposed into smaller behavioural elements that interact or collaborate with other s-role elements. For example, the s-role “caller” in a telephony service may be decomposed into distinct functional elements: inviter, setup-initiator and release-initiator that are involved during the different service phases: invitation, setup and release. These functional elements are also considered as s-roles. We will use the term *elementary s-roles* to denote s-roles that are not further decomposed. A service feature may be seen as the result of a collaboration between elementary service s-roles.

Conversely we may produce more complex s-roles (and thus services) by composing s-roles possibly by reusing existing s-roles. In Figure 2.4 we combine the s-roles “inviter” and “invitee” in different collaboration schemes in order to produce an invitation with several participants. We propose two alternatives. In one case, “user A” is supported by an actor playing the s-role “inviter” twice, and able to invite two other users. In the other case, “user B” is supported by an actor that can both play the s-roles “invitee” and “inviter”. Thus “user B” may invite a new participant (“user C”) after being invited in a service (by “user A”).

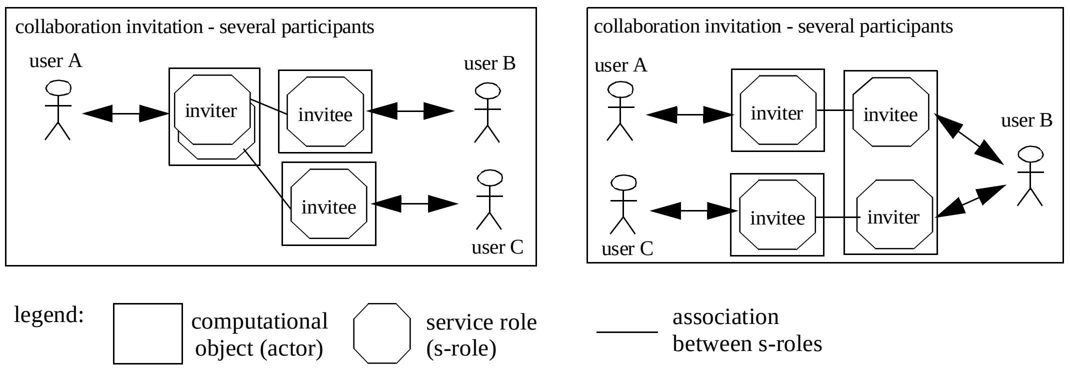

collaboration invitation - several participants
user A
user B
user C
inviter
invitee
invitee
collaboration invitation - several participants
user A
user B
user C
inviter
invitee
invitee
inviter
legend:
computational object (actor)
service role (s-role)
association between s-roles

Figure 2.4 : Service role collaborations for invitation with three participants.

Composite s-roles, obtained by composing other s-roles, may be coordinated in various manners. This will be further discussed in Chapter 4.

2.3.4 Service association roles

A service association role (a-role) is the visible interaction behaviour of an s-role on an association. Each association involves exactly two s-roles. An s-role that interacts with several other s-roles provides distinct a-roles on each association. A-roles describe the s-role behaviour visible on an interface. A-roles abstract the internal behaviour of the s-roles, and the interactions towards other s-roles. This abstraction facilitates the validation analysis (see Chapter 5).

In the current distributed processing approaches such as CORBA and DCOM, computational objects are described by static interfaces limited to the declaration of operation signatures [OMG 2001; Microsoft Corporation 1996]. Such interface descriptions may facilitate the construction of a system by providing a means for retrieving objects that may potentially offer a function or feature, but they do not provide sufficient support for building a system that behaves correctly. Architectures based on traditional object interfaces lack two main properties [Luckham and al. 1995]. They only describe the functions provided by an object, and fail to describe the functions required by an object. This makes it difficult to determine the effects that changes to an interface may have on other objects. Moreover, they do not describe the semantics of a connection between objects and the constraints on using the interfaces. For example, it is not possible to ensure that the interactions between objects will occur in a correct order. This is important when the invocation of an operation influences the behaviour of future operations, as encountered in stateful behaviours. This property is not either described by static interfaces.

Service association roles overcome the limitations of static object interfaces. Contrarily to traditional object interfaces, a-roles describe dialogues or protocols between s-roles. The association roles on each end of an association complement each other. Thus the a-roles required by an s-role can be determined from the a-roles provided by this s-role. The dialogue on an association may be influenced by the events that have previously occurred in the s-role, i.e. the state of the s-role. This will be discussed in Chapter 6.

A-roles are represented in collaboration structure diagrams as shown in Figure 2.5. A-roles are described using state diagrams, and sometimes illustrated by collaboration sequence diagrams. We use the state machine graph representation for reasoning about correctness. See Chapter 7.

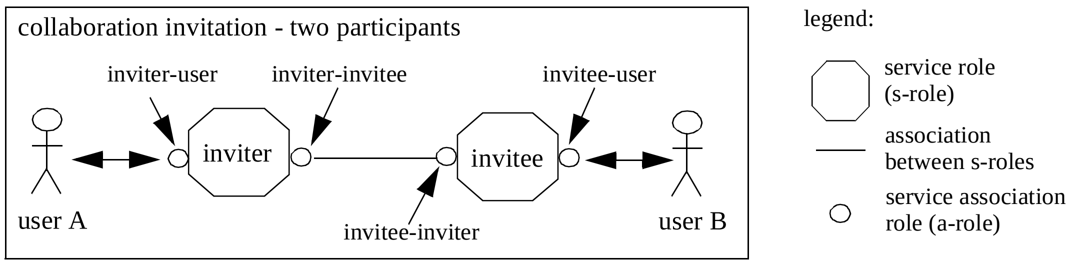


Figure 2.5 : Service association roles.

Notice that distinct service roles may provide identical association roles:

- An s-role may implement internal actions that are not visible at the s-role interfaces (i.e. the a-roles). For example, the role “invitee-with-log” may, in addition to answering to an invitation, perform logging of the operations being executed, and still provide exactly the same a-roles as the role “invitee”.

- An s-role may also be extended by adding associations to other s-roles and still maintain the same a-roles on existing associations. This is illustrated in Figure 2.6. The new s-role “invitee-with-redirect” that redirects all incoming invitations to a third party, extends the s-role “invitee”. The new s-role still provides the same a-role “invitee-inviter” to the role “inviter”.

An s-role may collaborate with several other s-roles. The behaviour on one association may influence the behaviour on other associations, and, in the worst case, conflict. S-roles and a-roles should be specified such that concurrency does not cause deadlocks or other incorrect behaviours. This will be discussed in Chapter 7.

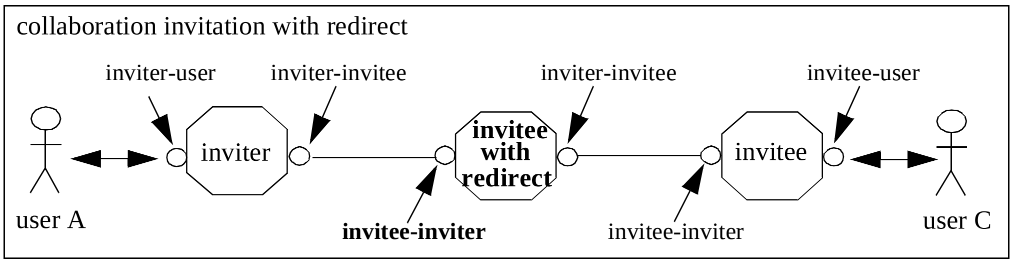


Figure 2.6 : Extended role - unchanged association role.

By maintaining the existing a-role "invitee-inviter" in the example of Figure 2.6, we guarantee that the s-roles interact consistently, and that the extended system behaves correctly with respect to the interface behaviours. Hiding the extension of an s-role may, however, lead to systems that do not behave according to the users goals. In the example of Figure 2.6, "user A" intended to invite "user B"; "user A" may not be satisfied with being redirected to "user C". We may distinguish between two levels of collaboration correctness:

- The system level: consistency among a-roles ensures consistent interactions between s-roles, and a correct behaviour from a system viewpoint.
- The user level: additional constraints are imposed on the actors by requiring actors to play specific s-roles. This ensures a correct or expected behaviour from a user viewpoint. This is not further elaborated in this thesis.

2.4 Engineering viewpoint

This thesis does not elaborate the engineering viewpoint.

We assume that actors are implemented on an object-oriented platform that supports distributed processing. This platform or distributed processing environment (DPE) controls the execution and management of applications. The DPE supports transparent communication between the network nodes, and hides the heterogeneity of the underlying systems (e.g. programming languages, operating systems, network protocols). CORBA is such a DPE [OMG 2001].

As in the TINA framework [TINA 1995], we assume that the network nodes are able to interact by means of a communication infrastructure called the kernel transport network.

2.5 Summary

In this thesis, the term service is used at the enterprise viewpoint to designate capabilities provided to systems and users. The focus of the thesis is on communication control services that coordinate the participation of multiple users in a service. When modelling services at the computational viewpoint, we use the term service role (or s-role) to designate the behaviour of a computational object (or actor) in a service. S-roles collaborate in order to provide services. S-roles interact over associations; a service association role (or a-role) is the visible participation of an s-role in an association.

3 Collaboration and service role modelling

The chapter discusses the modelling of collaborations and service roles (s-roles). The role view and the collaboration view are complementary views that contribute to the description of the system behaviour. While the role view provides descriptions of the behaviour of individual computational objects or actors, the collaboration view focuses on interactions between actors and facilitates understanding the overall system behaviour. We propose to use the MSC language to describe collaboration sequences, and the SDL language to specify service role behaviours.

A set of basic s-roles is introduced in order to discuss the application of the languages to s-role and collaboration modelling. These examples will be used later when discussing service role composition in Chapter 4.

3.1 SDL and MSC as modelling languages

When modelling systems and services, we describe their structures (in terms of components), interactions between the system components, and the detailed behaviour of the components. Two main families of languages are available today for modelling [Bræk 2000]: on one hand the ITU-T languages including SDL [ITU-T 1999a], MSC [ITU-T 1999b], on the other hand UML [OMG 1999] that defines a set of notations such as Class Diagrams, State Machines, Sequence Diagrams, and Collaboration Diagrams. We have selected SDL and MSC, mainly because SDL and MSC are formally defined. UML still lacks a complete semantics.

SDL has a formal semantics that enables an unambiguous interpretation of the system specification. Using SDL for s-role modelling, we are able to reason completely about s-role behaviours, interactions between s-roles and composition of s-roles at the design level. SDL was defined to model distributed systems that combine sequential and concurrent behaviours, and provides a set of concepts that fits our needs when composing distributed s-roles. The graphical notation augments human comprehension of the models. Of course, our long experience in using SDL [Haugen and al. 1993; Bræk and al. 1999] has also influenced our choice. Our earlier work makes us confident that complete and efficient code can be automatically generated from SDL [Floch 1995]. A new version of SDL, SDL-2000, was recently released [ITU-T 1999a]. SDL is widely used in the industry and a number of successful experiences have been reported [Færgemund and Reed 1991; Færgemund and Sarma 1993; Bræk and Sarma 1995; Cavalli and Sarma 1997; Dssouli and al. 1999; Reed and Reed 2001]. The composite state concept introduced in SDL-2000 allows one to structure state machines in the same way as Harel's statecharts [Harel 1987]. The benefit of composite states will be highlighted in Chapter 4. A drawback when using SDL-2000 is that no CASE tools that support the new version are available yet; all diagrams presented in this thesis were edited with drawing tools.

MSC is a formal language that can be used for the definition of interaction sequences. We will use MSC to describe simple basic collaborations. The focus of this thesis being s-role composition and validation, we will not make an extended use of MSC.

3.2 Collaborations

Collaborations describe the interactions between computational objects or actors; they focus on behaviours across a system rather than the behaviours of individual objects. As system behaviours will be described in terms of s-roles in this thesis, collaborations will primarily be used to describe interactions between s-roles rather than interactions between objects.

We describe collaborations using two diagram types:

- *Collaboration structure diagrams* describe structures in terms of s-roles involved in a collaboration and interaction associations between these s-roles. A-roles and the actors playing the s-roles may also be represented in collaboration structure diagrams. We propose a new graphical notation for representing collaboration structures. This notation is introduced in Figure 3.1, where a collaboration structure for invitation is described. All the concepts that may be of interest in a collaboration structure are present in this figure. The invitation behaviour enables a user to invite another user to participate in some service activity.

- *Collaboration sequence diagrams* describe the interactions between s-roles and between a-roles. We use the MSC language to describe collaborations sequences. The collaboration sequence diagram shown in Figure 3.2 describes the interactions between the s-roles in the collaboration "invitation". In addition to the system s-roles, the user roles are also represented in this diagram. The MSC alternative construct is used to represent possible alternative behaviours. More complex collaborations can be described by a set of message sequence charts (MSCs) and High Level MSCs (HMSCs) showing how the MSCs are combined. Data in messages may also be specified.

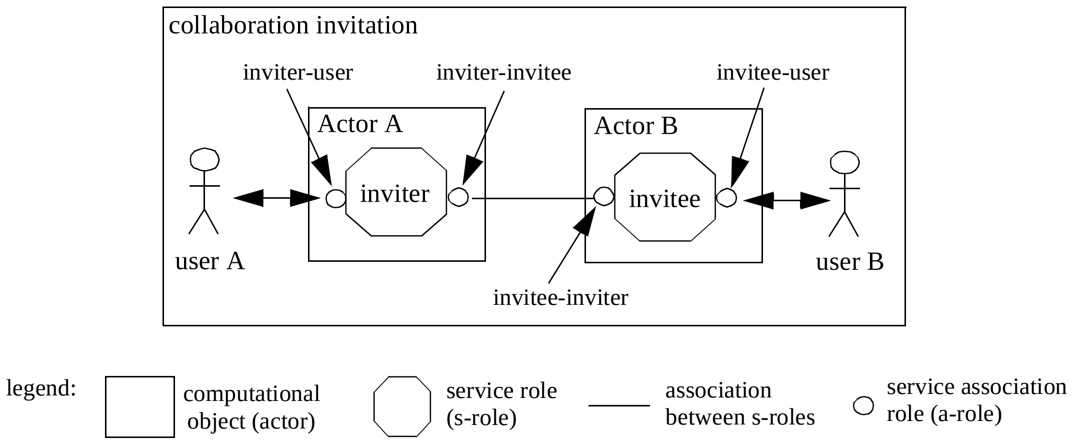


Figure 3.1 : Invitation: collaboration structure diagram.

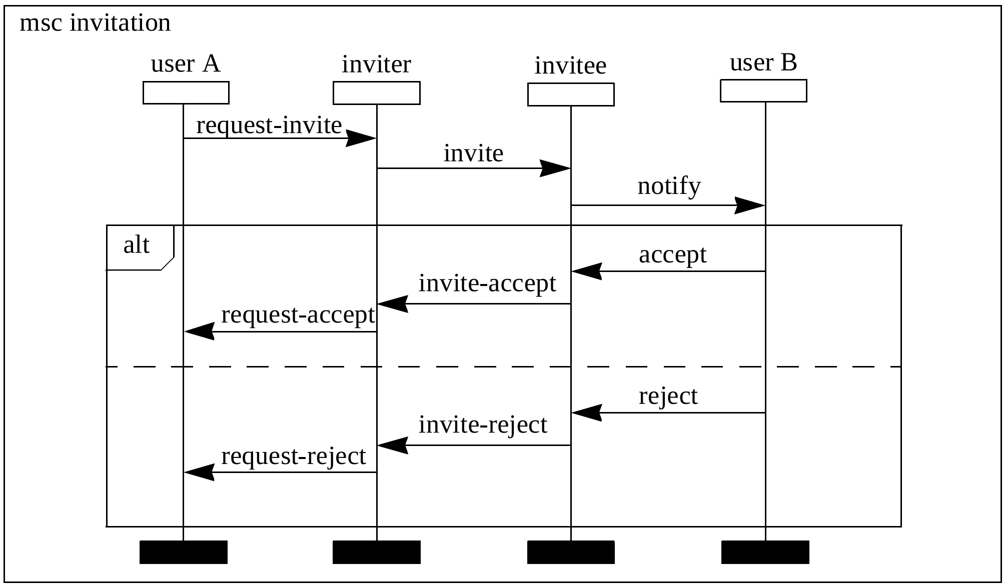


Figure 3.2 : Collaboration sequence diagram for service invitation.

In a similar way as in the invitation example, Figure 3.3 presents the collaboration structure and sequence diagrams for participation release. This behaviour enables a participant in a service to force another participant to quit the service.

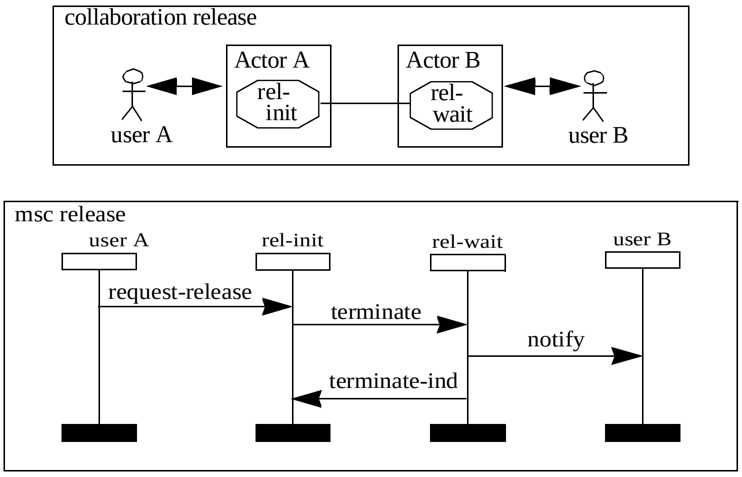


Figure 3.3 : Participation release: collaboration structure and sequence diagrams.

3.3 Service roles

Service roles describe the behaviour played by individual actors. This chapter restricts to elementary s-roles, i.e non-composite s-roles. Elementary s-roles usually describe simple behavioural elements and are composed in order to provide more complex behaviours. S-role composition is discussed in Chapter 4.

The behaviour of s-roles is described using state machines. Describing the behaviours of individual objects in terms of states and transitions has proven to be of great value, and is widely adopted in most engineering approaches [Bræk 2000]. We use the SDL language to specify the s-role and the actors playing these s-roles. As SDL does not define the concept of role, an SDL feature that fits the concept of s-role has to be selected.

SDL systems consist of a structure of communicating agents; SDL agents are meant to represent computational objects. Agent behaviours are described using state machines. SDL composite states support the structuring of state machines; they contain nested substates and transitions. As they represent parts of behaviour, we find them well suited to represent elementary s-roles. We use state types so that s-roles may be instantiated in multiple combinations with other s-roles to form a complete behaviour.

Modelling convention: In the rest of this thesis, roles will be defined as state types, and references to roles will be represented by state instances. A state reference that does not use state instantiation, indicates that the state is a basic state (i.e a non-composite state).

In Figure 3.4, the s-role “inviter” earlier introduced in the collaboration “invitation”, is specified using an SDL composite state. The definition of labelled entry and exit points will be justified later. Signal parameters and variables are not represented in this state machine diagram. Variables may be declared as part of the s-role definition or as part of the actor playing the s-role. When elementary s-roles are composed within an actor, shared variables should be declared at the actor level.

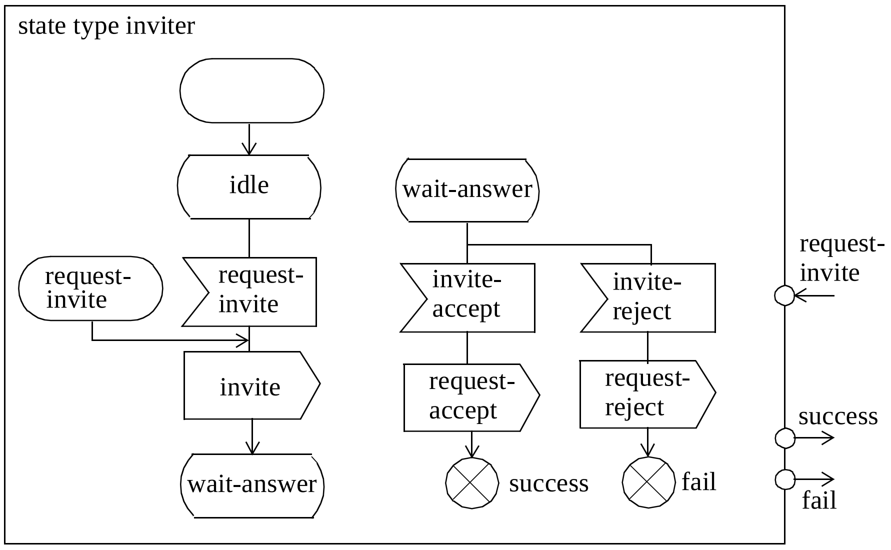


Figure 3.4 : Inviter: s-role behaviour.

In a similar way, Figure 3.5 defines the behaviour of the s-role “invitee” in the collaboration invitation, and Figure 3.6 the s-roles “rel-init” and “rel-wait” in the collaboration “release”.

3.3.1 Assumptions

An SDL state represents a condition in which the state machine may either consume a signal instance, or interpret a continuous signal or a spontaneous transition:

- States are usually applied to represent conditions for signal consumption. If a signal instance is consumed, the associated transition is interpreted.

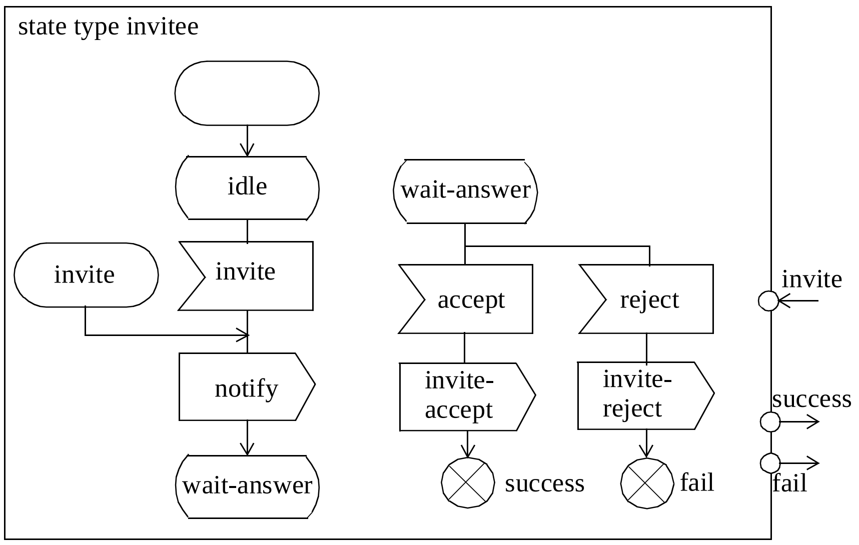


Figure 3.5 : Invitee: s-role behaviour.

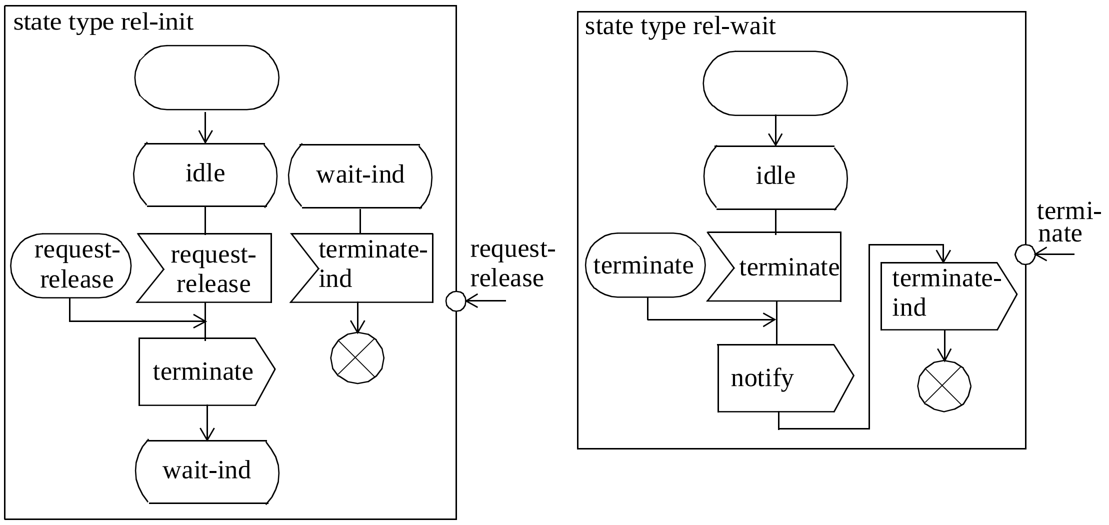


Figure 3.6 : Rel-init and rel-wait: s-role behaviours.

- A continuous signal interprets a boolean expression; it is associated to a transition that can be executed when the boolean expression is true. Continuous signals enable the designer to model that a certain condition is fulfilled.

- A spontaneous transition specifies a state transition without any signal reception. Spontaneous transitions enable the designer to model non-deterministic behaviours.

Spontaneous transitions are not needed when modelling s-roles. An s-role represents a complete behaviour i.e. any action, decision and interaction controlling the s-role behaviour is described. We will see that spontaneous transitions are of interest when modelling a-roles that hide parts of the s-role behaviour. This will be discussed in Chapter 6.

We assume that the communication between elementary s-roles can be completely described using signals. The use of continuous signals is restricted to the composition of s-roles (see Section 4.1.1 and Section 4.1.2).

Using enabling conditions, it is possible to impose a condition on the consumption of a signal. The signal is consumed if the condition is true; otherwise the signal remains in the input port. Enabling conditions are interpreted when entering the state, and while waiting in the state. We assume that enabling conditions are not used to describe any information exchange between elementary s-roles. The use of enabling conditions is restricted to the composition of s-roles (see Section 4.1.1 and Section 4.1.2).

Both assumptions reduce the complexity of the validation analysis. From our long experience of using SDL, we know that these assumptions are acceptable.

3.4 Actors

Service roles are played by actors. We represent actors using SDL process agents. The assignment of s-roles to agents is specified by instantiating composite states within these agents, and, in the case of concurrent composition, other process agents. Concurrent composition will be discussed in Section 4.2.

In Figure 3.7, the process agent “inviter” represents an actor playing the s-role “inviter”. Note that process agent types may also be used.

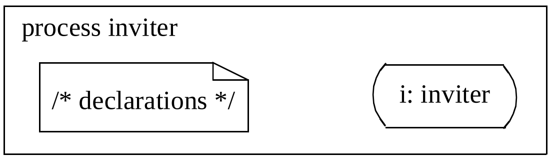


Figure 3.7 : Actor playing the s-role inviter.

3.4.1 Service role management as a service role

Actors may play several s-roles. An s-role to be played may be assigned following an external request, i.e. a request issued by another actor, or it may be selected depending on the behaviour that previously occurred within the actor. We call service role management, or s-role management, the behaviour that describes the assignment of s-roles to actors, and the selection of a specific s-role among several alternative s-roles. S-role management should be coordinated between actors: actors should play s-roles that interact consistently with each other. S-role management may also encompass negotiation between actors. Negotiation enables actors to agree on the s-roles to be played.

S-role management does not directly contribute to services, but rather supports actors in providing services. However, as s-role management requires collaboration and coordination between actors, and is also a part an actor plays in a service, we consider the behaviour related to s-role management as service roles.

The separation between s-role management and the behaviour of the s-role(s) being managed is beneficial. It augments the understanding of the system behaviour, and contributes to reducing the complexity of extending the system. Alternative behaviours may be introduced by extending the s-role management without making changes to the existing s-roles. Conversely, the s-roles being assigned may be modified without changing s-role management.

Sections 3.4.1.1 and 3.4.1.2 describe two main elements of s-role management. Service role triggering and service role assignment indication are both related to the selection and assignment of an s-role.

3.4.1.1 Service role triggering

The assignment of an s-role to be played may be decided internally in an actor, or triggered by a request from another actor. In the latter case, a request may either be expressed explicitly or implicitly. We propose three main behaviour patterns for s-role triggering: spontaneous s-role triggering, implicit s-role triggering and explicit s-role triggering.

3.4.1.1.1 Spontaneous s-role triggering

We say that an s-role is triggered spontaneously when it is instantiated as part of the logical action sequence of an actor, i.e. when the actor reaches a specific state. The s-role is triggered as part of the s-role management played by the actor. S-roles that take the initiative to start a collaboration, and thus are not triggered by any external request, are triggered spontaneously.

Figure 3.8 illustrates spontaneous s-role triggering. The s-role “inviter” that always takes place after starting the actor, is triggered spontaneously. The s-role “main”, that represents some main service activity, e.g. coordinating the allocation of stream channels, is also triggered spontaneously after a successful invitation. Notice the relevance of the state exit points “success” and “fail” defined in the s-role “inviter” (see Figure 3.4 on page 33) in this example.

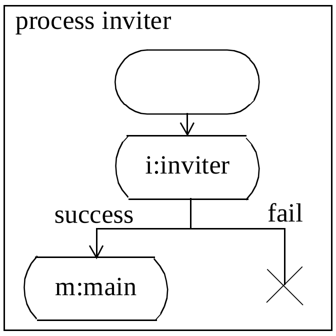


Figure 3.8 : Spontaneous s-role triggering.

3.4.1.1.2 Implicit s-role triggering

An s-role is triggered implicitly when its invocation is requested by another actor, and expressed by a stimulus defined as part of the collaboration to be started and of the s-role to be assigned.

Implicit s-role triggering is illustrated in the collaboration sequence shown in Figure 3.2 on page 31. For example, the reception of the message “request-invite” triggers the actor to play the s-role “inviter”. The message is defined as part of the definition of the collaboration between the s-roles “user A” and “inviter”. In that case, the actors playing the requested s-roles are not represented in the collaboration sequence.

The actor playing the s-role “inviter” is specified in Figure 3.9. The actor may also play other s-roles. The s-role management played by the actor handles the reception of the triggering stimuli, and selects the s-role to be played. In this example, notice the relevance of the state entry points that were defined in the s-roles “inviter” and “invitee”. An entry point allows one to enter the desired part of a state.

3.4.1.1.3 Explicit s-role triggering

An s-role is explicitly triggered when its triggering is requested by another actor, and expressed by a stimulus defined explicitly for triggering purposes. This stimulus specifies the s-role to be played.

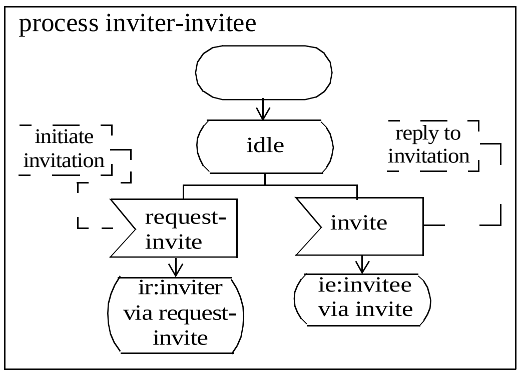


Figure 3.9 : Invitation: implicit s-role triggering.

Explicit triggering is illustrated in Figure 3.10. The message "play" represents the explicit request and contains information about the s-role to be played. The actor that is requested to play the s-role is specified in the collaboration sequence. The complete collaboration for invitation is not described here; instead an MSC reference is made to the remaining sequence in the collaboration. The s-role management played by the actor handles the reception of the explicit request message "play", and selects the s-role to be played. Similarly to the previous case, the s-role "inviter" is entered through a state entry point. The process agent "actor-inviter" may be extended allowing the selection of other s-roles.

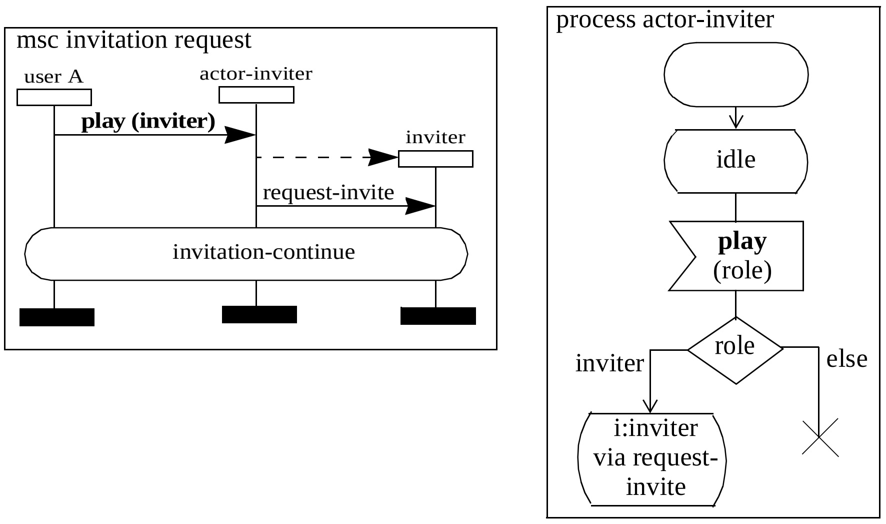


Figure 3.10 : Invitation: explicit s-role triggering.

Explicit s-role triggering is required in a Plug-and-Play approach when there is a need for negotiating or learning the s-roles to be played [Floch and Bræk 2000].

3.4.1.2 Service role assignment indication

The assignment of s-roles needs to be coordinated between actors. S-role assignment indication is used to report the assignment of an s-role. It usually takes place after a request for triggering a new s-role. Similarly to triggering, several behaviour patterns for assignment indication may be defined. We propose two main patterns: implicit s-role assignment indication and explicit s-role assignment indication.

In implicit s-role assignment indication, indication about the s-role assignment is implicitly expressed by a stimulus defined as part of the collaboration being started and of the s-role being assigned. Implicit assignment indication may be applied after explicit or implicit s-role triggering. An example of implicit indication was given in Figure 3.2 on page 31. The messages “request-accept” and “request-reject” are stimuli that indicate that the s-role “inviter” is being played.

In explicit role assignment indication, the actor, or role management played by the actor, indicates, by a stimulus defined explicitly for indication purposes, whether or not the requested s-role has been instantiated. Explicit assignment indication may be applied after explicit or implicit triggering. Explicit assignment indication may indicate that an alternative s-role to the requested s-role is preferred. Explicit assignment indication is illustrated in Figure 3.11.

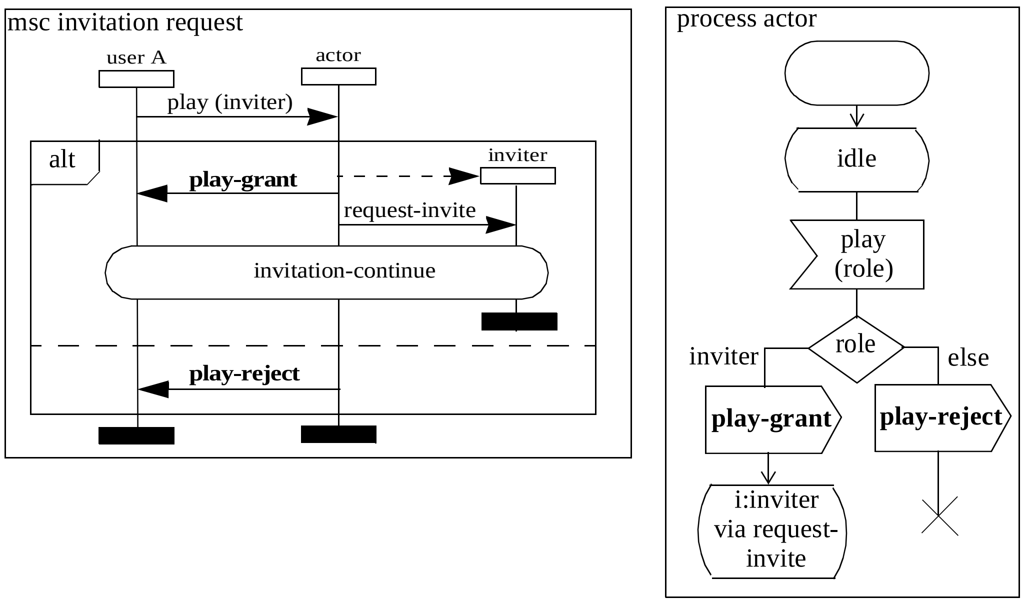


Figure 3.11 : Invitation: explicit s-role assignment indication.

Similarly to triggering, explicit s-role assignment indication requires the actors to be represented in the collaboration sequences. The explicit approach also introduces supplementary signalling leading to increased traffic and processing loads. Again, the explicit approach is attractive as a part of role negotiation.

3.4.2 Extension to the MSC language

The MSC language does not provide any notation for expressing structural relations between instances in a sequence chart. It is not possible to indicate that an s-role instance is executing as part of an actor behaviour, or that two s-roles execute within the same actor. Using instance decomposition is not a satisfying solution. One weakness of decomposition is that two charts need to be defined: one showing the collaboration between the composite instance and the other instances, one showing the collaboration within the composite instance. Another weakness is that the complete sequence of messages between the composite instance and the other instances needs to be specified on the chart where the composite is referred to.

We introduce an extension to MSC allowing us to group instances in a chart, more specifically actors and s-roles in our work. A dashed frame symbol containing several MSC instances indicates that the instances execute within the same actor. Figure 3.12 illustrates this extension to MSC. We do not differentiate between actor and s-role in the collaboration sequence diagram. The actor behaviour describes the s-role management, that is itself an s-role.

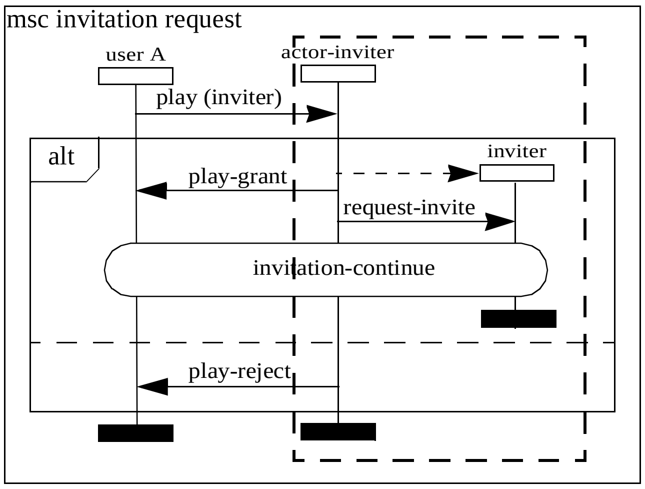


Figure 3.12 : Grouping actors and s-roles: extension to MSC.

3.5 Associations

As our work focuses on s-role composition and validation, we omit describing the modelling of system structures. S-roles interact over associations that can be described in SDL in terms of channels. *We assume that the signals exchanged between two elementary s-roles are conveyed on the same communication path*, where a communication path is constituted by a sequence of connected channels. With this assumption, we ensure that signal ordering is preserved during transport, i.e. signals are received in the same order as they are sent.

3.6 Summary

The SDL language is used to model s-roles and actors. S-roles are specified using SDL composite states, and actors using SDL process agents. We distinguish between the behaviour required to manage s-roles from the behaviour of the s-roles to be assigned.

The MSC language is used to model collaborations. An extension to the MSC language is proposed that supports the grouping of actors and the s-roles they play.

4 Service role composition

This chapter discusses the composition of service roles (s-roles) within an actor. The coordination of the composition of s-roles across actors is presented in Chapter 8. Through the composition of s-roles we aim to produce the complete behaviour of an actor in a service. Composition may be applied incrementally. Composite s-roles obtained from the composition of elementary s-roles may themselves be composed with other s-roles.

There exist various types of dependencies between s-roles that constrain the form of composition that can be applied on s-roles. This chapter presents different forms of composition, and discusses their properties. While sequential composition enforces behaviour ordering, concurrent composition supports simultaneous behaviours. Sequential composition encompasses true sequential composition, guarded sequential composition, choice and disabling. S-roles that are composed concurrently may execute more or less independently.

Ideally s-roles should be specified without making assumptions about how they are going to be composed with other s-roles. We define simple general design rules that enable s-roles to be easily composed. Using these rules, no supplementary behaviour needs to be specified within the s-roles being composed sequentially. On the other hand, s-roles that are composed concurrently may require explicit coordination behaviour. We propose design patterns for the coordination of concurrent s-roles.

SDL-2000 is used to model the different composition classes [ITU-T 1999a]. We select a set of SDL concepts for the realisation of s-role composition, and draw out general guidelines for the specification of the s-role to be composed. The basic s-roles introduced in Chapter 3 are used to illustrate composition.

4.1 Sequential composition

Two s-roles are sequentially composed if the execution of one of them precedes the execution of the other. The s-role executing first must be completed before the other can start its execution. Using LOTOS terminology, we may also say that the execution of the first s-role enables the execution of the second s-role [ISO 1989]. The sequential composition of s-roles leads to a new s-role, a composite s-role that may itself be composed with other s-roles.

We represent true sequential composition in SDL by linking the elementary s-role states in a composite state. The ordering of execution of the composed s-roles is enforced by the definition of the composite state. No adaptation needs to be done in the s-roles to be composed in order to deal with the composition.

The s-role obtained by composing sequentially “inviter” and “rel-init” (see Figure 3.4 on page 33 and Figure 3.6 on page 34) is shown in Figure 4.1. Here we enforce the s-role “rel-init” to take place after “inviter” even if the invitation has been rejected. We postpone using the exit points of “inviter” to Section 4.1.2.1, this to illustrate true sequential composition. SDL constrains us to attach the “*” symbol to the connection between “inviter” and “rel-init”. In our example, “*” means that the connection is chosen for any non-referred exit point of “inviter” (i.e. “fail” and “success”).

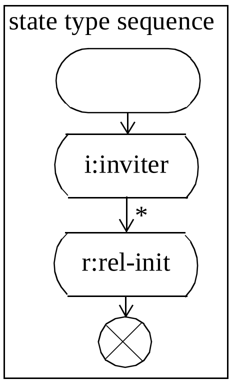


Figure 4.1 : Sequential composition of inviter and rel-init.

Guarded sequential composition, choice and disabling are extended forms of sequential composition. They all ensure mutual exclusion between the s-roles being composed and impose an order of execution. They are also described in SDL by linking the elementary s-role states in a composite state. Guards and disabling triggers are added that control the execution of s-roles. Sections 4.1.1, 4.1.2 and 4.1.3 describe these forms of composition.

4.1.1 Guarded sequential composition

Guarded sequential composition extends the basic sequential composition. Guards are used that prefix s-roles. Guards describe preconditions that must be satisfied prior to the execution of s-roles. The ordering of sequential composition is maintained.

Guards may either be expressed as predicates over local conditions (i.e. conditions set within the actor executing the s-role), or external conditions (i.e. conditions set by other actors). Guards based on internal conditions are typically used when the composite s-role executes concurrently with other s-roles within the same actor (see Section 4.2). External conditions facilitate the coordination of composition across actors. They are further discussed in Chapter 8.

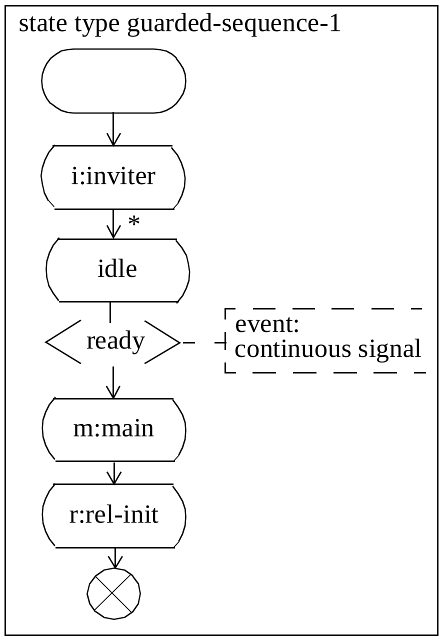
In SDL, we describe guards as continuous signals or enabling conditions. In the case where s-roles are triggered spontaneously (see Section 3.4.1.1), only continuous signals are used. A continuous signal interprets a boolean expression; it is associated to a transition that can be executed when the boolean expression is true. Continuous signals are interpreted upon entering the state to which they are attached when no signal can be consumed, and while waiting in the state. An enabling condition associates an additional condition on the consumption of a signal. The signal is consumed if the condition is true; otherwise the signal remains in the input port. Enabling conditions are interpreted when entering the state, and while waiting in the state.

Figure 4.2 illustrates guarded sequential composition in SDL. Sequence (a) uses a continuous signal as a guard. Sequence (b) uses an enabling condition. The condition “ready” may represent an internal condition such as the state of a stream channel, or an external condition such as the state of an interacting actor. The s-role “main” represents any main activity performed in the service. In sequence (a), the basic state[1] “idle” is introduced so that the continuous signal does not force the exit of the s-role “inviter”. The execution of s-role “inviter” should be completed before the continuous signal is interpreted.

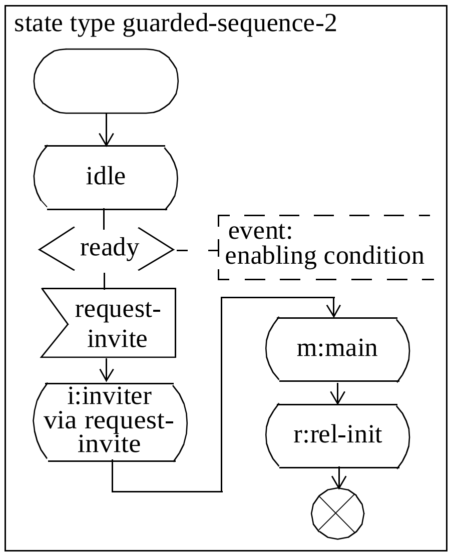
4.1.2 Choice among alternative behaviours

Choice among alternative behaviours extends the basic sequential composition. Using choice, alternative s-roles can be specified in a sequential composite s-role. The selection of a behaviour among the alternative behaviours in a choice may be controlled by guards

1. Recall the modelling convention introduced in Chapter 3. A direct reference to a state indicates that the state is a basic state (i.e. a non-composite state)



(a) guarded spontaneous triggering



(b) guarded implicit triggering

Figure 4.2 : Guarded sequential composition.

or external triggers. Guards are expressed as predicates over conditions that are either resolved locally, i.e. within the actor executing the s-role, or globally, i.e. their resolution requires some interaction with other actors. External triggers are elements of some interaction with other actors. They belong to the definition of an s-role, either the s-role to be selected and assigned (implicit triggering) or the management s-role (explicit triggering). Explicit and implicit triggering have been defined in Section 3.4.1.1.

4.1.2.1 Choice based on a condition

In SDL, guards are either specified using a named return (from a state), a set of continuous signals, or a combination of these mechanisms. A named return describes a state exit condition. State exit conditions are defined by labelled exit points. The set of continuous signals representing guards should describe a complementary set of conditions. While a named return reflects a condition set by the s-role immediately preceding the occurrence of a choice, continuous signals may be related to actions that have taken place at any time before the occurrence of a choice, or that are taking place within another s-role executing concurrently. The resolution of a condition specified using a continuous signal may require an interaction with other actors. This increases the complexity of the validation analysis and should be restricted to the synchronisation of s-role composition across actors (see Chapter 8).

Figure 4.3 illustrates a sequential composition tree where the exit conditions from the s-role “inviter” control the selection of the further behaviour. Notice that although the condition is resolved locally, it may represent a global collaboration condition.

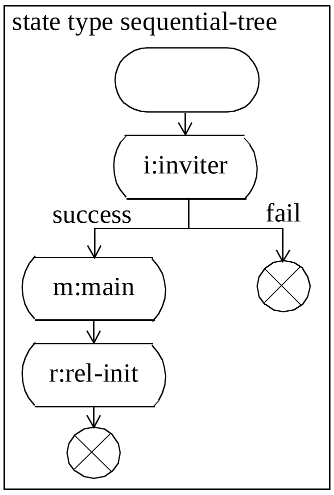


Figure 4.3 : Choice among alternative behaviours using exit conditions.

This example is extended in Figure 4.4. Here the selection of a main activity is based on a set of continuous signals representing the content of the user profile.

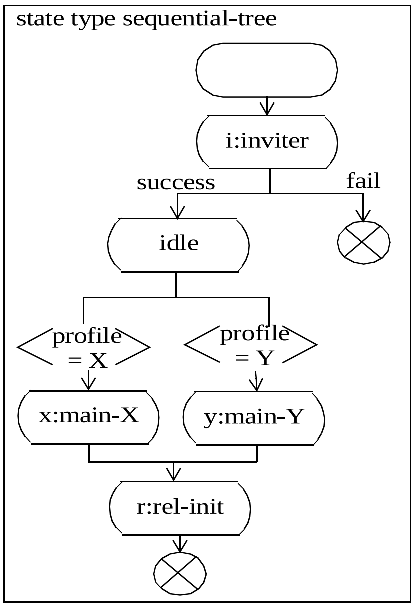


Figure 4.4 : Choice among alternative behaviours using continuous signals.

Modelling a choice based on a condition is straightforward. No supplementary signalling is needed to control the choice. The s-roles specified as alternative behaviours do not need any adaptation. Labelled exit points facilitate the specification of choices. As illustrated in Figure 4.1, labelled exit points may be defined that are not used in the composite state.

Therefore we recommend defining them in any case. We state this recommendation in our first design rule or D-rule as we call it throughout this thesis.

D-rule: Exit conditions
Labels that express exit conditions should be attached to the exit points of the states modelling s-roles.

4.1.2.2 Choice based on an external trigger

In SDL external triggers are specified using signals. The consumption of these signals is specified as part of the composite state where the choice is made. In the case of implicit triggering, triggering signals belong to the s-role to be selected. The triggered s-role is then entered through a state entry point allowing one to enter the triggered state after the consumption of the signal. No major specification change of the s-role is required in order to deal with the composition. Labelled entry points facilitate the specification of choices, and should be defined in any s-role.

D-rule: Entry conditions
Entry points that represent entry through external triggering should be defined in the states representing s-roles.

Figure 4.5 illustrates a choice based on an external trigger. Here a service user may either initiate an invitation or reply to an invitation. The user is represented by a single actor in the service framework, that either plays the s-role “inviter” or “invitee”. The selection of an s-role is triggered by the external signals “request-invite” or “invite”.

Any initialisation to be performed when entering the triggered s-roles through the default start node should also be performed when entering through entry conditions. Entry procedures can be defined that describe initialisation tasks. SDL entry procedures are called implicitly when entering or re-entering a state[1].

D-rule: Entry procedure
An entry procedure should be defined that describes the tasks to be performed when entering an s-role.

1. Re-entering a state is discussed in Section 4.2.3.5.

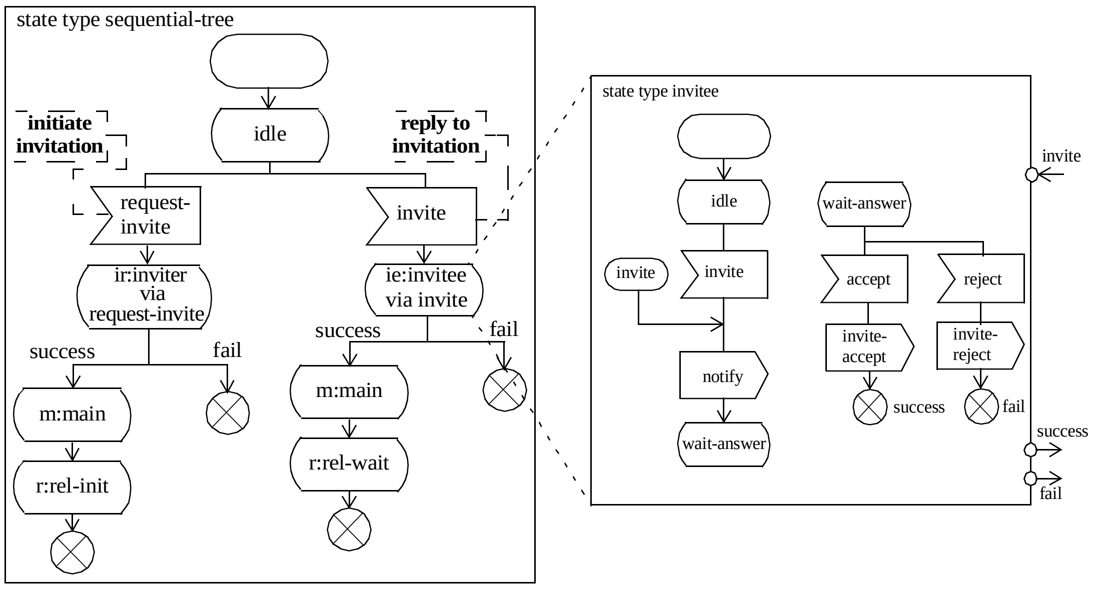


Figure 4.5 : Choice among alternative behaviours based on an external signal.

4.1.3 Disabling

An s-role disables another s-role if its execution inhibits the execution of this other s-role. Unlike suspension (see Section 4.2.3.5), disabling has a permanent interruption effect. The disabled s-role is forced to complete execution.

We represent disabling in SDL by linking the elementary s-role states in a composite state, where the disabling s-role state is triggered by the reception of a signal. The reception of the disabling signal should take priority over the reception of other signals. This is expressed by means of a priority signal. The disabling signal may either belong to the definition of the disabling s-role (implicit triggering) or the management s-role (explicit triggering). In the case of implicit triggering, the disabling s-role is entered through a state entry point. No major specification change of the disabling s-role is required. The same design rules as for choice based on an external trigger apply (see “entry conditions” and “entry procedure” in Section 4.1.2.2).

In the case where an exit procedure is defined in the disabled s-role, the exit procedure is executed upon disabling. This enables the designer to describe termination operations of the disabled state. However, SDL exit procedures can only contain a single transition, and therefore do not allow one to describe two-way interactions with other actors. When disabling occurs, the process agent queue may contain signals that have been addressed to the disabled s-role. The retrieval of these signals from the input port leads to unspecified signal reception. As unspecified signal reception is not desirable, disabling should only be applied in critical situations where interruption is necessary. This is further discussed in Chapter 8.

D-rule: Exit procedure
When designing an exit procedure, take into account that the state may be exited through an exit node, or when a transition attached to the composite state is interpreted.

Figure 4.6 illustrates disabling of the s-role “inviter”. In this example, release may be forced when the invitation or the main service activity have not yet completed, or it may take place as a normal case after the completion of the main activity.

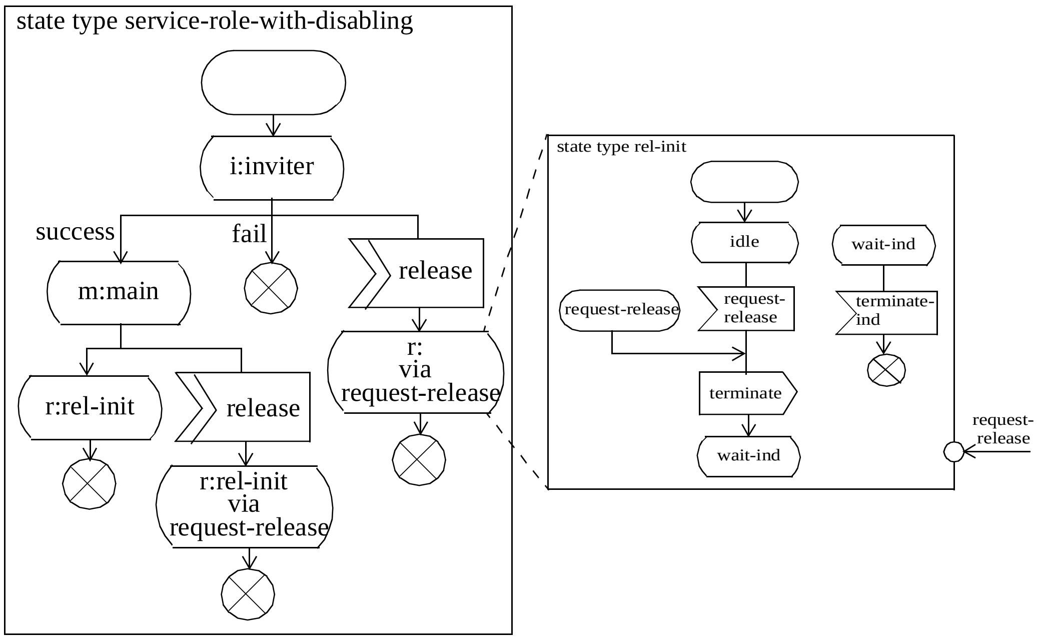


Figure 4.6 : Disabling composition.

4.2 Concurrent composition

With concurrency, we do not mean true concurrency, but rather interleaving. Two or more s-roles are composed concurrently if their executions interleave. This means that the actions in the s-roles never occur simultaneously. As s-roles are composed within a computational object and share processing resources, simultaneousness is neither necessary nor desirable. S-roles composed concurrently have overlapping lifetimes. They may execute in an independent manner, or their execution may require explicit coordination.

We distinguish between *static* concurrent composition, where the s-roles and the number of s-roles that are being composed are set at design time, and *dynamic* concurrent composition, where s-roles are created dynamically upon decisions made at run-time. Static concurrent composition is, for example, attractive for combining main tasks with background activities running continuously, such as logging or status checking. Static concurrent composition can also be applied when a fixed number of instances of an s-role run independently and concurrently. For example, a service may require one of its participants to invite exactly two other participants. Dynamic concurrent composition, on the other hand, is relevant when a variable number of s-role instances is needed.

We propose to represent concurrent composition using process agents in SDL (see Section 4.2.1). A process agent representing an actor may contain other process agents representing s-roles. Inner process agents execute in alternating manner. It is possible to specify several levels of concurrency, as inner process agents may themselves contain process agents. In the case of dynamic concurrent composition, the s-role process agents are created dynamically at run-time.

An alternative to process agents is provided by state aggregation (see Section 4.2.2). SDL state aggregation is a particular form of composite state. It defines a partitioning of a state. A state aggregation consists of multiple states, which have an interpretation that is interleaved at the transition level. The state aggregation construct replaces the SDL-92 service construct [ITU-T 1993a]. State aggregation has many limitations, and can only be used to model some cases of static independent concurrent composition of instances of distinct s-roles. In Section 4.2.2.1, we propose simple extensions to SDL that make state aggregation easier to apply.

4.2.1 Using process agents

The concurrent execution of multiple s-role instances increases the complexity of a specification. We propose structural design rules for using process agents in the modelling of concurrent composition. These rules contribute to an orderly design, and ease the readability of the descriptions.

We introduce a new role responsible for managing the set of concurrent s-roles. The manager role and the concurrent s-roles are specified within the same process agent. A generic model is presented in Figure 4.7:

- The managing role “manager” is defined as a composite state. In that way, it can be itself composed with other service roles.
- The s-roles to be composed “service-role” are defined using composite states. These composite states are instantiated within s-role process agents “service-role-agent”. In the case of static concurrent composition, the initial number of instances of the process agent should be specified.

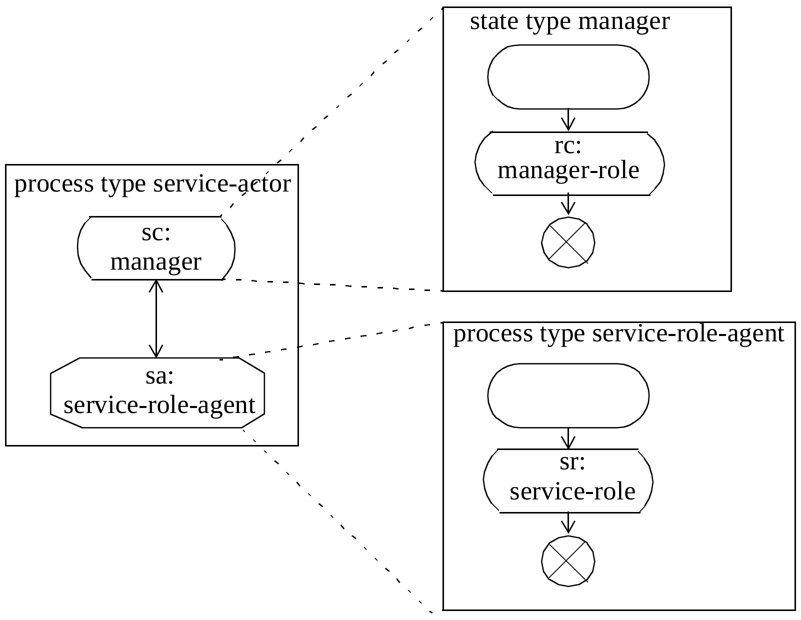


Figure 4.7 : Concurrent composition using process agents.

Two slightly different manager roles are introduced through examples in Section 4.2.1.1 and Section 4.2.1.2. In both sections, the initial service example is extended in order to let the service user invite several participants. This is achieved by concurrently composing multiple “inviter” s-roles.

4.2.1.1 Allocation manager

The purpose of an allocation manager is to assign a resource, here an s-role, to a request. This is illustrated in the collaboration diagram in Figure 4.8. The new role “allocator” is introduced that assigns an s-role “inviter” to handle the invitation request. Here the s-role “inviter” is created dynamically. The collaboration between “inviter” and “user A” is identical to the initial collaboration invitation (see Figure 3.2 on page 31). In Figure 4.8, a single invitation sequence is represented. The sequence may be re-iterated.

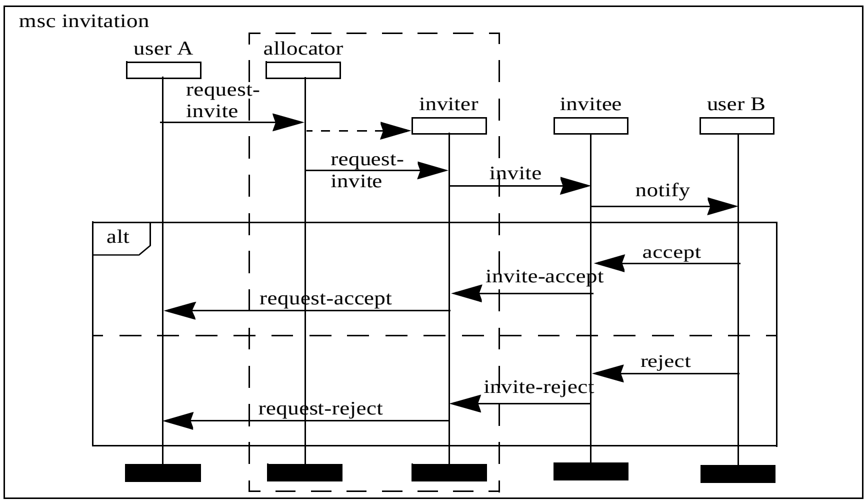


Figure 4.8 : Role allocator in concurrent composition.

The behaviour of the role “allocator” and the process agents involved in the service are described in Figure 4.9.

The introduction of the allocator role slightly changes the initial addressing scheme: the s-role “inviter” no longer replies to the sender of the request message. We recommend specifying the reference(s) of the entity(ies) to be addressed by the reply in request messages. Here the message “request-invite” should contain the address of “user A”. Using SDL gates, channels and connections, it is also possible to specify a system structure that enforces the correct addressing of the signals. However, such an approach provides a limited addressing support. It cannot be applied when the requesting instance is a member of an instance set. Furthermore, it is not appropriate for dynamic system structures.

D-rule: Addressing information
Request messages should contain the addresses of the s-roles waiting for a reply.

Using this design rule, no supplementary behaviour needs to be specified in the s-roles being composed.

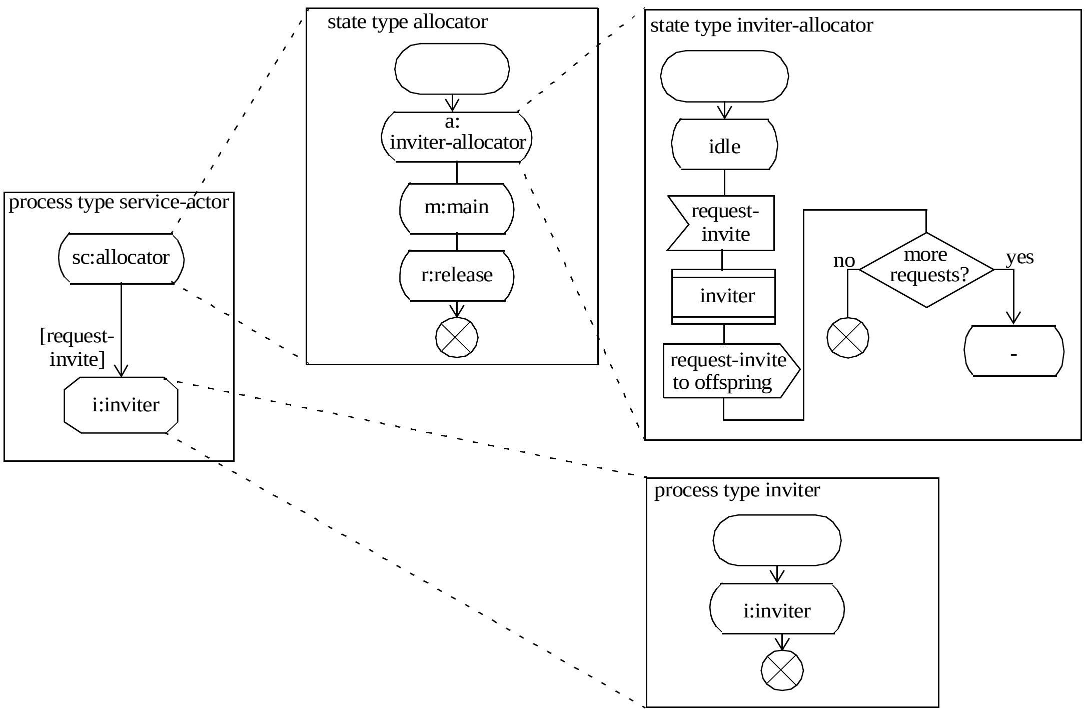


Figure 4.9 : Concurrent composition of invitation using an allocator.

4.2.1.2 Mediation manager

The purpose of a mediation manager is to assign a resource, here an s-role, to a request, and to mediate messages to and from that s-role. This is illustrated in the collaboration diagram in Figure 4.10. The new role "mediator" is introduced that assigns an s-role "inviter" to handle the invitation request, and that re-transmits the messages from the s-role "user A" to the s-role "inviter", and conversely. The role mediator provides the same service association role as the s-role "inviter" to the s-role "user A", and the same service association s-role as the s-role "user A" to the s-role "inviter". The mediator is actively involved during the whole collaboration, thereby introducing some delay in the interaction between the s-s-role "user A" and the s-role "inviter".

The mediation manager may also support other functions in addition to re-transmission. For example, it may provide support for grouping multiple requests. Instead of generating a request for each invited participant, the user may generate a single group request that is processed and split by the mediator into individual requests. Conversely, the mediator may concatenate a single answer from the individual answers. A drawback with such additional functions is that changes to the basic collaboration require modifications to be made in the mediator.

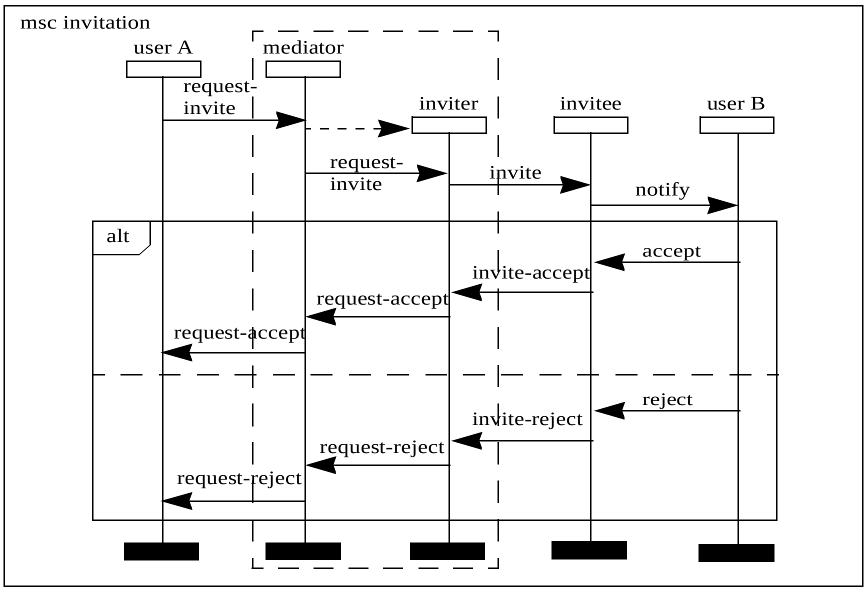


Figure 4.10 : Role mediator in concurrent composition.

4.2.2 Using state aggregation

State aggregation provides a simple approach to the modelling of the static concurrent composition of instances of distinct s-roles. It defines a partitioning of a state into multiple states. Execution interleaving is enforced by the semantics of state aggregation.

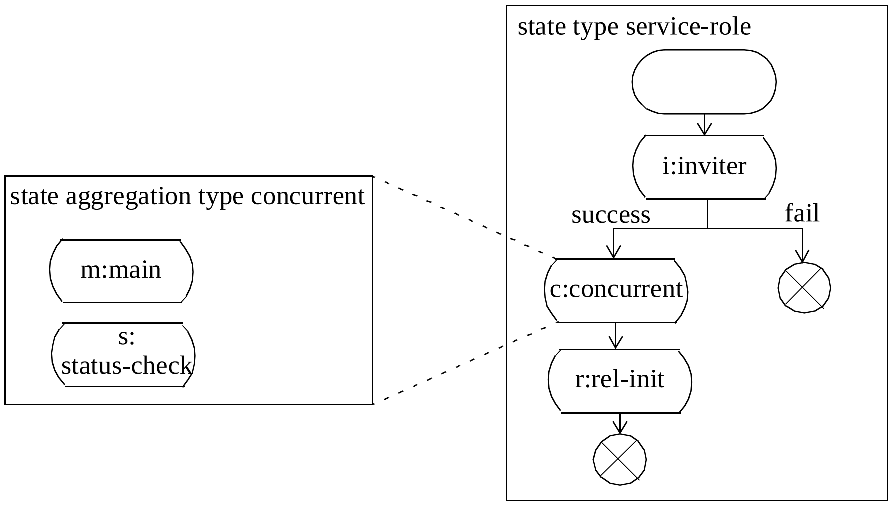


Figure 4.11 : Static concurrent composition of the roles main and status.

State aggregation is illustrated in Figure 4.11. Two s-roles “main” and “status-check” are composed concurrently. The s-role “status-check” is a background activity that enables other actors to request information about the actor state while the main activity is taking place. The composite s-role obtained by concurrent composition is itself composed sequentially with the s-roles “inviter” and “rel-init”. According to SDL semantics, the s-role “concurrent” terminates when both the s-roles “main” and “status-check” have terminated.

Using state aggregation, sequential and concurrent composition can easily be combined in a state graph. However, state aggregation is difficult to apply. The SDL definition of state aggregation introduces several restrictions:

- The input signal sets of the state partitions must be disjoint. Thus state aggregation is not the appropriate technique to model static independent concurrent composition of instances of the same s-role.

- The composite state terminates when all state partitions have terminated, or when a transition is triggered at the composite state level. SDL does not provide any support for specifying that a state partition (or a group of state partitions) forces the exit of the composite state. Additional signalling has to be defined for forcing termination as illustrated in Figure 4.12, where the termination of “main” forces the termination of the state aggregation. On termination, any exit procedure defined for the state partitions is executed. The exit procedure of the state aggregation is also executed.

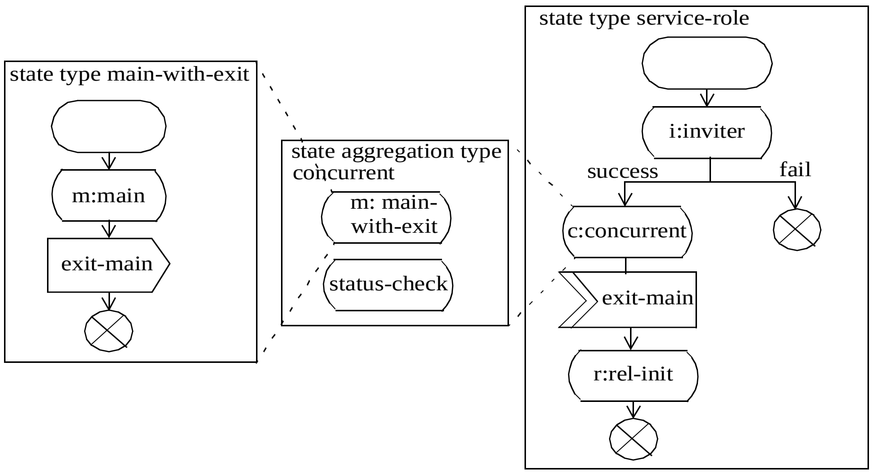


Figure 4.12 : State aggregation: forcing termination.

- Although the exit points from the state partitions may be connected to the exit points of the state aggregation, SDL restricts the appearance of each exit point in exactly one connection. Thus it is not possible to define exit conditions of the state aggregation from the exit conditions of the state partitions in a flexible way. Figure 4.13 illustrates the connection of exit points. Two exit points are defined for the state aggregation, and connected to exit points of the state partitions. According to SDL, the exit point “fail” of “role-1” must appear in exactly one connection, preventing us from specifying any exit point of the state aggregation for the case where “role-1” exits via “fail”, and “role-2” via “success”. If so happens, SDL specifies that the exit point of the state aggregation is chosen in a non-deterministic way.

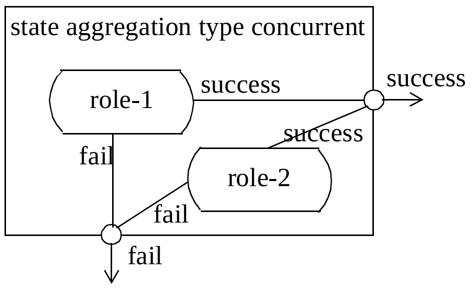


Figure 4.13 : State aggregation with exit connection points.

4.2.2.1 Extensions to the SDL language

We suggest introducing simple extensions to SDL to facilitate using state aggregation for modelling the static concurrent composition of instances of distinct s-roles. We propose two sets of extensions:

1. The termination of a state partition (or a group of state partitions) may force the termination of the state aggregation. This can be modelled as shown in Figure 4.14. The exit point of the state aggregation is connected to the exit point of the state partition “main” (here DEFAULT[1]), but not to any exit point of “status-check”. The connection of an exit point to a single state partition indicates that the termination of the partition forces the termination of the state aggregation.

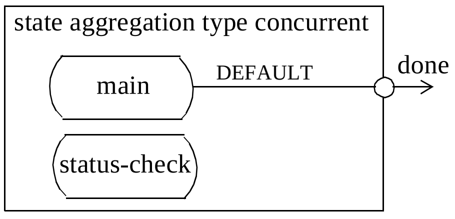


Figure 4.14 : Extension to state aggregation: termination.

2. Exit points may appear in multiple connections, and exit conditions of the state aggregation can be expressed as logical expressions of the exit conditions of the state partitions. These extensions are modelled in Figure 4.15. Connection lines are not rep-

1. DEFAULT is defined in SDL; it indicates unlabelled entry and exit points.

resented graphically here. We prefer a textual representation. Qualifiers are used that refer to the state partitions.

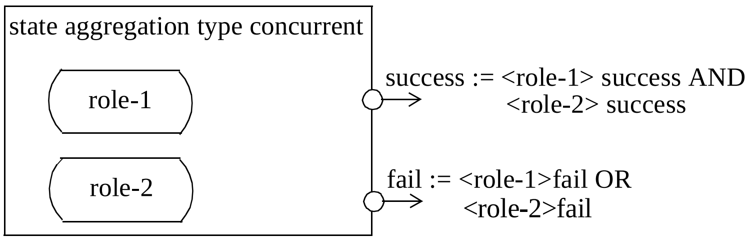

state aggregation type concurrent
role-1
role-2
success := <role-1> success AND <role-2> success
fail := <role-1>fail OR <role-2>fail

Figure 4.15 : Extension to state aggregation: exit conditions.

We have also considered a set of extensions for supporting non-disjoint input signal sets of the state partitions. Such an extension requires support for the identification and addressing of sub-states. Furthermore, the creation of states would enable dynamic concurrent composition to be described using state aggregation. In that way, it would be possible to use a single SDL concept, the composite state, to model sequential and concurrent compositions. However, with these extensions, the state concept becomes identical to the process agent concept, the main difference being that states can be linked sequentially. As this set of extensions is complex, we suggest representing concurrent composition using process agents when state aggregation cannot be used.

4.2.3 Coordination

S-roles that are composed concurrently may execute more or less independently. Their composition may require explicit coordination behaviour. For example, in the sharing of a resource, the phases in a service may have to be coordinated. Unlike the management of concurrent s-roles, coordination often requires behaviour to be added to the s-roles that are composed. Coordination is often application dependent. In this section, we propose a set of design patterns for the coordination of s-roles. As we will see, SDL provides rather poor support for the definition of generic coordination behaviours. First, let us consider some examples.

4.2.3.1 Examples

4.2.3.1.1 Alternating execution

A service enables a user to invite several other participants at any time during the service session. For logical reasons, the main activity in the service has to be suspended while a new invitation takes place.

This can be modelled by the concurrent composition of the s-roles “main” and “inviter” where their execution alternates. The s-roles have overlapping lifetimes, but the s-role “main” is suspended during invitation request. Invitation request and termination are two relevant events for the coordination of the execution of the s-roles. The case is illustrated in Figure 4.16. When “inviter” starts, it suspends “main”. “main” is resumed when invitation terminates. In this example, the invitation is simplified (i.e. no rejection).

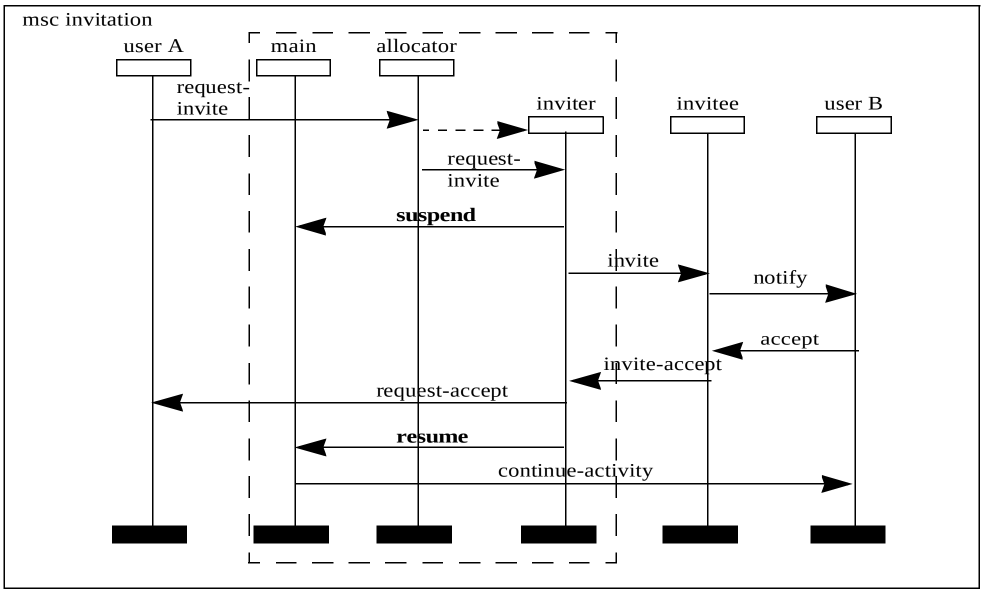


Figure 4.16 : Alternating execution between inviter and main.

4.2.3.1.2 Coordinating multiple instances

A service enables a user to invite several other participants to the service session. Invitation takes place when the service session is started and requires negotiation of the transport streams characteristics. Negotiation takes place between an invitation request phase and a confirmation phase.

This can be modelled by the concurrent composition of multiple instances of the s-role “inviter”. We assume that the actor that has initialised invitation decides upon the characteristics of the transport streams. The s-roles “inviter” execute concurrently until the negotiation phase. At that point, the s-roles should coordinate and agree on a common transport stream configuration. This configuration may be computed by a configuration coordinator that executes concurrently with the s-roles “inviter”. When a configuration has been generated, the s-roles “inviter” can further proceed concurrently. The case is illustrated in Figure 4.17. In order to simplify the message sequence, a single instance of “inviter” is shown in the diagram. Invitation has been extended to two phases, configuration and confirmation.

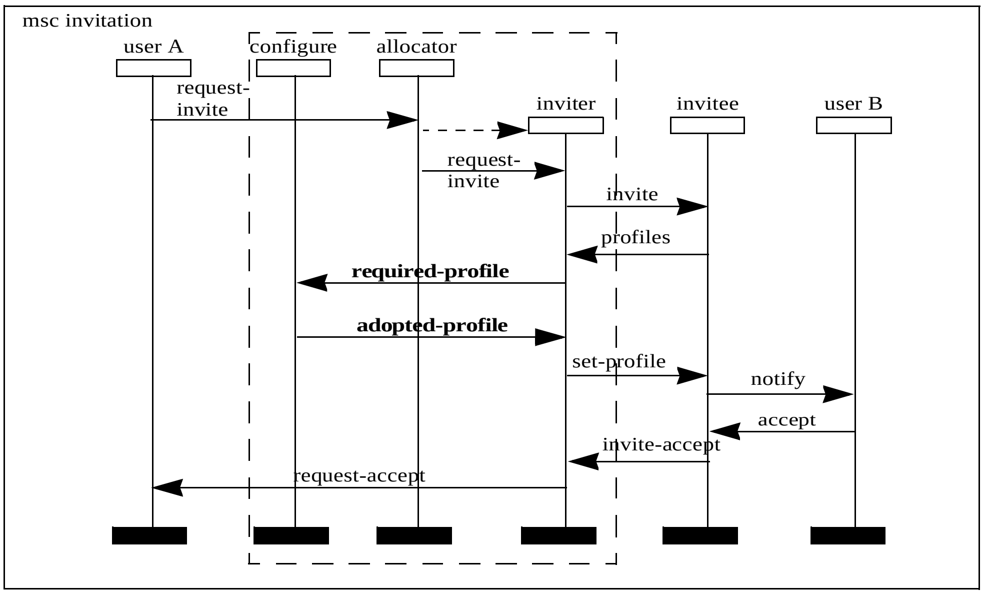


Figure 4.17 : Synchronisation: computing a common profile.

4.2.3.1.3 Resource sharing

A service may enable a user to invite several other participants to a service session. The elementary invitation s-role is extended with a dialogue with the requesting user. Through this dialogue the user is authenticated by the remote s-roles “invitee”. The user terminal supports only one dialogue at a time.

This can be modelled by the concurrent composition of multiple s-role instances “inviter”. The s-roles execute concurrently during their initial phase. Invitation is suspended if the terminal resource is not available for authentication dialogue. Invitation is resumed when the terminal resource can be allocated.

4.2.3.2 Coordination events

Coordination events trigger the coordination of concurrent s-roles. They may be related to the state of a shared resource or the stage of a service phase. As we have seen, coordination events are often service dependent. Generic events may however be defined for a set of services. Generic user states such as “busy”, “not responding” are defined in Parlay [Parlay 2000f]. The development of reusable s-roles requires generic events to be identified.

In SDL, coordination events may modelled by input signals, enabling conditions, or continuous signals.

4.2.3.3 Coordination modes

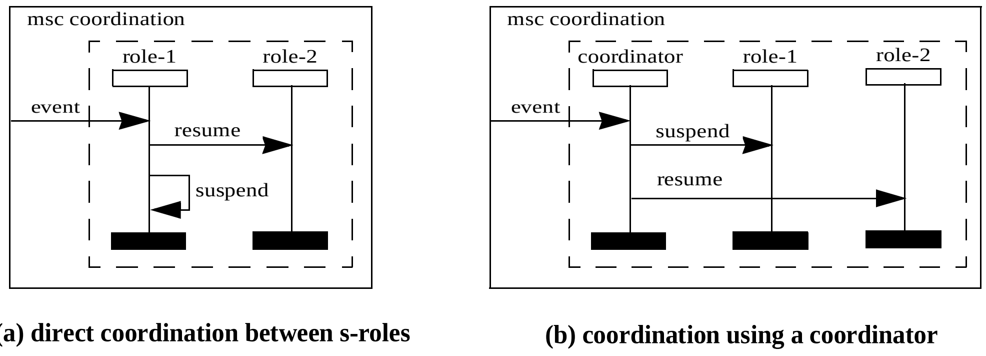
The composed s-roles may execute concurrently between two coordination events, or alternating:

- In the first case, the s-roles evolve independently until they reach coordination points, where they wait for some coordination event to occur. This is the case in the example shown in Figure 4.17. The “inviter” instances execute independently until they wait for a configuration profile to be computed.

- In the later case, only one of the s-roles can execute at a time; the other s-roles are suspended until a coordination event is reached where, possibly, one of the suspended s-role resumes while the activate s-role is suspended. Alternating execution can be employed when two s-roles share a common resource. It ensures mutual exclusion between s-roles. The coordination events serve as guards for interleaving between s-roles. In Figure 4.16, the s-role “main” and “inviter” execute alternating. Suspension is further discussed in Section 4.2.3.5.

4.2.3.4 Coordination interaction

Coordination between concurrent s-roles may be communicated directly between the concurrent s-roles or through a coordinator. This is illustrated in the case of alternating execution in Figure 4.18. The message “event” represents the notification of a coordination event. The messages “suspend” and “resume” control the alternating execution. Confirmation should be added if suspension cannot take place in every s-role state. Case (b) is better suited when the composition involves more than two s-roles. In the case of concurrent execution, the messages “suspend” and “resume” are not needed. The notification event serves as a coordination.



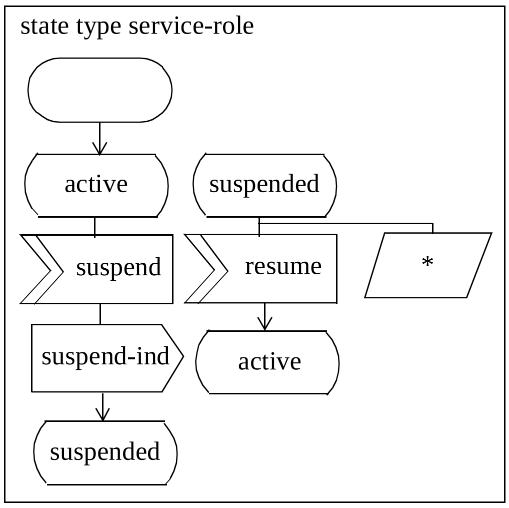
(a) direct coordination between s-roles **(b) coordination using a coordinator**

Figure 4.18 : Alternating execution: coordination patterns.

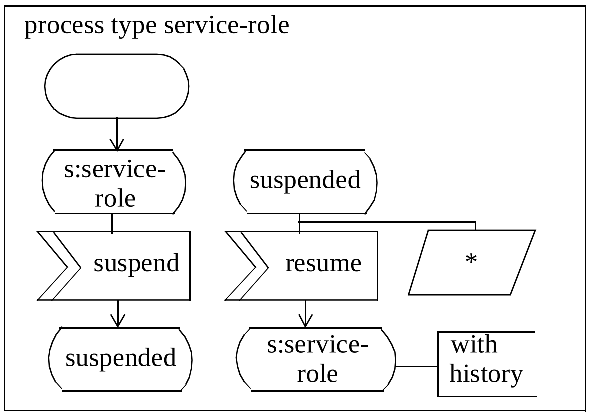
4.2.3.5 S-role suspension and resumption

The alternating execution of concurrent s-roles requires mechanisms for the suspension and resumption of s-roles. Suspension and resumption are triggered by the notification of coordination events. A suspended s-role enters a suspended state where all signals expected by the s-role, except the resumption trigger should be saved. Certain signals, e.g. exceptions, may also be enabled in a suspended state. We introduce a simple design pattern for suspension and resumption. SDL provides rather poor support for the definition of generic behaviours. This is explained in this section.

Suspension may be enabled in a subset of the s-role states or any s-role state. In the first case, suspension has to be modelled as part of the s-role definition; suspension is application-dependent. In the second case, suspension may be modelled as part of the s-role definition or at the s-role level. We prefer the later approach as it does not require any supplementary behaviour to be specified within the s-role being composed. The two cases are illustrated in Figure 4.19.



(a) suspension of a particular s-role state



(b) suspension of the whole s-role (extension to SDL)

Figure 4.19 : Suspension and resumption at different levels.

Case (a) is simplified and shows only the suspension of one state. The suspension is confirmed as it cannot take place in every s-role state. As it is not possible in SDL to test the value of a state, the value of the suspended state should either be stored in a variable, or distinct suspended states should be defined for the distinct active states that can be suspended.

In case (b), the definition of SDL composite states makes the specification of a simple design pattern for s-role suspension intricate. On resumption, the s-role should be re-entered in the state it was left. The SDL history concept supports the re-entering of a composite state. However, the state specified in the nextstate node with history must be the state in which the transition was activated. Thus, in case (b) in Figure 4.19, using history is normally not allowed. The intermediate state “suspended” introduced between leaving and re-entering “active” prevents us from using history.

Another difficulty is introduced by the SDL definition of entry procedure. When re-entering a composite state with history, the entry procedure of the composite state is invoked. No mechanism in SDL is provided to distinguish between entering or re-entering a state. Thus, in the case a state can be re-entered, entry procedures are not appropriate to describe initialisation tasks that only need to be performed on entering the state for the first time. Some intricate work-arounds using flags may be introduced. However such work-arounds introduce dependencies between composite s-roles and sub-roles. This is not desirable.

4.2.3.5.1 Application dependent behaviour

The behaviour of s-roles has often to be taken into account when suspension is introduced. As already discussed, some particular states may not be suspended. Timers, interactions with other actors, and real-time requirements may also influence the suspension of an s-role. Should timers be stopped before suspending an s-role? If not, should expired timers be taken into account in suspended states? Or should they be restarted? There is not one single answer to these questions. The application has to be taken into account. We conclude that suspension behaviour can only be defined as a pattern that the designer may refine according to the application needs.

4.2.3.5.2 Suspension vs. disabling

While suspension is defined as a temporary interruption, disabling is permanent (see Section 4.1.3). Suspension may be modelled in the same manner as disabling using triggering at the composite level. In that way, we try to model suspension and disabling without introducing changes to the s-role behaviours. A new difficulty is introduced by the SDL definition of exit procedure. When exiting a composite state, the exit procedure is invoked. No mechanism in SDL is provided to catch the cause of exit. It is not possible to test whether a return node has been reached, or a signal at the composite level has triggered the exit. In the latter case, it is not possible to test the type of the signal. These limitations of SDL also makes the definition of generic composition behaviours intricate.

4.2.3.5.3 Extensions to the SDL language

We propose the following extensions to SDL that facilitate the specification of suspension at the s-role level:

- Several transitions may be executed between leaving a composite state and re-entering this state with history. With this extension the pattern proposed in case (b) of Figure 4.19 is allowed.

- The boolean variable *re-enter* is defined for all composite states; this variable is set to true when re-entering a state. Testing this variable, it is easy to determine which tasks should be performed.

- The variable *exit-cause* is defined for all composite states, that distinguishes between exits through a return-node and exits triggered at the composite level. It should also be possible to test exit conditions attached to return-nodes, and the trigger types and values.

In general, we lack simple mechanisms in SDL for testing state and signal names, for testing entry and exit conditions, etc. This lacking support makes the specification of general patterns cumbersome. Such mechanisms do not require changes to made to the SDL semantics.

4.3 Incremental service role composition

Through the composition of s-roles, it is possible to produce complex behaviours. Composition may be applied incrementally. Composite s-roles may themselves be composed with other s-roles. Ideally s-roles are specified without knowing how they are going to be composed, i.e. sequentially or concurrently, and composition is applied in order to define different kinds of services. This is illustrated in Figure 4.20 and Figure 4.21 where the same elementary s-roles are composed in different ways leading to distinct service behaviours:

- In Figure 4.20, a user may participate in distinct service sessions. A participant may be invited in each session, and independent activities are performed. Each session is obtained by composing sequentially elementary s-roles. The sessions are themselves composed concurrently.

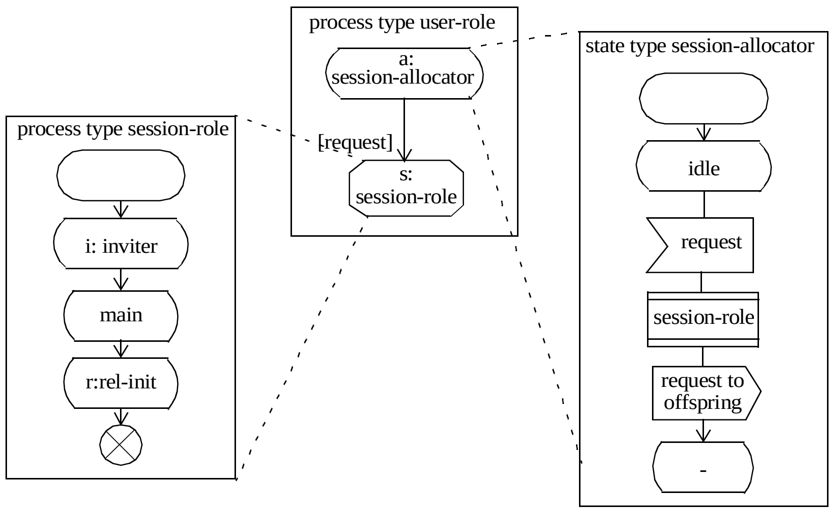


Figure 4.20 : Concurrent service sessions.

- Figure 4.21, a user may invite several participants in a service session. The participants are involved in a common activity. Invitation and release may take place at any time. The participation management and the common activity are composed concurrently. The participation management is obtained by composing sequentially elementary s-roles.

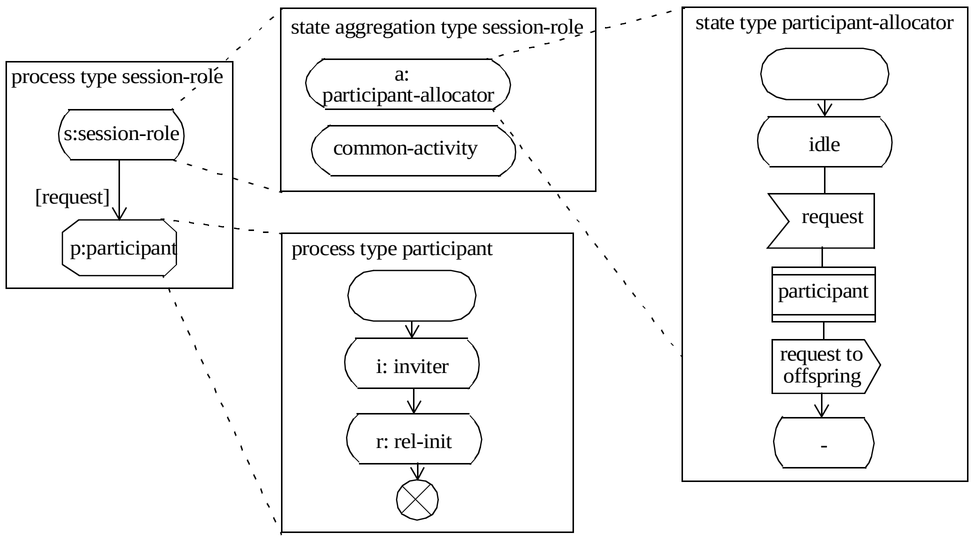


Figure 4.21 : Concurrent service participation and activity.

Normally elementary s-roles are composed sequentially. In Figure 4.20 and Figure 4.21, “inviter” and “rel-init” are composed sequentially. Service features usually result from the collaboration between elementary s-roles.

S-roles obtained from the composition of elementary s-roles may themselves be composed with other s-roles either sequentially or concurrently. In multiphase services, s-roles are usually composed sequentially.

Sequential and concurrent composition can both be applied statically at s-role design time. The introduction of new services can be achieved by defining new elementary s-roles, and by composing new and existing s-roles in different ways. Dynamic concurrent composition, on the other hand, is applied at run-time. S-role process agents are created dynamically and composed at run-time. This form of composition suits a plug-and-play approach where s-roles are designed off-line, and deployed dynamically.

The composition approach is attractive for several reasons:

- It encourages the designer to produce modular service descriptions. The elementary roles and collaborations are simple and can be easily understood.
- By nature, it provides a method for adding or replacing elementary behaviours. New functionality can also be added at run-time. In that way, the composition approach supports incremental service development and deployment.
- Dependencies between roles are highlighted during composition. Thus, the composition approach contributes to the understanding of dependencies between roles and services.
- When components are involved in several services, the contribution to different services can be modelled by different roles that are composed in order to obtain the whole component behaviour. In that way, role composition enables one to concentrate on individual services, and break down complex component behaviours.
- Composition can be exploited during validation. This helps to reduce the complexity of the analysis. As validation takes into account the compositional properties of a system, it is also suited for the validation of components bound at run-time.

The power of expression of SDL is not restricted by the design rules that have been proposed. In that way, the composition approach does not introduce any restriction as to what functionality can be defined.

4.4 Summary

In this chapter, we have proposed two main s-role composition schemes: sequential and concurrent composition.

Sequential composition ensures mutual exclusion between the s-roles being composed and imposes an order of execution. The modelling of sequential composition is straightforward in SDL. Simple design rules related to the entry and exit of s-roles have been introduced. When these rules are followed, no supplementary behaviour needs to be specified within the s-roles being composed in order to deal with the composition.

Concurrent composition is used to compose s-roles that have overlapping lifetimes. Static concurrent composition applies at design time. It requires the s-roles and the number of instances to be set at design time. Dynamic concurrent composition is applied at run-time. S-roles are created dynamically upon decisions made at run-time. Concurrent composition is modelled using process agents or state aggregation. State aggregation however involves many limitations that restricts its application to the composition of static composition of instances of distinct s-roles. Simple extensions to SDL are suggested that would facilitate using state aggregation. The extensions are related to the exit of state aggregations.

S-roles composed concurrently may execute more or less independently. When s-roles are dependent, composition requires explicit coordination behaviour. We propose design patterns for the coordination of concurrent s-roles. These patterns need to be adapted to application specific needs. Simple extensions to SDL could facilitate the specification of a suspension pattern. The extensions are related to the entry and exit of s-roles.

Composition provides support for dynamic service adaptation. In addition, it augments human comprehension of the service models, and, as we will see in the next chapters, contributes to reduce the complexity of the validation analysis.

5
Validation: an introduction

This chapter discusses the requirements set by dynamic composition on validation, and considers existing validation techniques with respect to these requirements. A short introduction to the validation techniques in our approach is presented, and some fundamental concepts are defined. The validation techniques will be described in details in Chapters 6, 7 and 8.

The validation approach deals with the interaction behaviour between service roles, i.e. visible as service association roles. The dynamic analysis considers all possible interactions that may occur during system execution, and aims at detecting interaction errors. The validation ensures that the interactions between a-roles are logically consistent. Focus is set on safety properties i.e. avoiding that bad behaviours, such as deadlocks, occur. Dynamic analysis is complex and requires simplification. Two simplification schemes are proposed: projection and incrementation.

A major concern in our work has been to provide validation techniques that are easy to understand and apply. Current verification and validation techniques often require high competence and knowledge in formal modelling and reasoning, and their use in the software industry is rather moderate. Our approach does not require that designers have detailed knowledge of formal analysis techniques. It proposes a set of design rules that can be easily applied as an integrated part of the design process, and enforced by design tools.

5.1 Validation in a dynamic context

Dynamic and incremental composition of systems sets particular requirements on validation:

- The analysis should take advantage of the system structure. If one component is replaced, modified or added, the analysis should be restricted to the parts of the system affected by the modifications.

- As components may be bound dynamically at run-time, the analysis should apply to types - not instances.

We propose to validate interfaces between components. Interfaces may be defined in different ways. A main research issue in software architectures and architecture definition languages relates to the definition of component interfaces [Medvidovic and Taylor 2000]. [Luckham and al. 1995; Kirini 1999] discuss which information should be described by interfaces so that systems can be easily and correctly built from components. Building systems out of components is difficult, and poor interface descriptions are identified as an important reason of architectural mismatch [Garlan and al. 1995]. In the current distributed processing and object-oriented approaches, interface definitions are restricted to operation signatures, i.e. operations offered by the interface, and the parameter types. Such interfaces fail to describe the semantics and dynamics of interactions between components, e.g. the ordering in which operations should be used. They also fail to describe the operations required by the component. This information is important when a component is replaced in a system. It is should be possible to determine whether or not the other components in the system provide the functionality required by the new component.

Our approach seeks to overcome these limitations by describing the dynamics of interactions by means of service association roles (a-roles). An a-role represents the observable behaviour of a service role (s-role) on an association. A-roles are derived from s-roles, and are represented by state machines. They describe operations in terms of messages received and sent on an association. Each state represents a condition for the consumption or sending of messages, and the machine represents a behaviour.

It should be noted that a-roles define bidirectional behaviour, and not just the offered operations. Each a-role interacts with a complementary a-role on the other end of an association, and the complementary a-role can be derived from an a-role behaviour. When an s-role is inserted or modified in a system, new a-roles can be derived from this s-role. We provide techniques for checking that these new a-roles behave correctly towards the a-roles provided by the other interacting s-roles in the system. We also provide techniques for determining which a-roles should be provided by these s-roles. In that way, the validation analysis only needs to be applied on the parts of a system that are affected by a modification.

Our validation approach is integrated with the composition of s-roles described in Chapter 4. Elementary s-roles are first validated, and then their composite s-roles, etc. A change to an elementary s-role requires the validation analysis to be applied on that elementary s-role, not on the composite. In that way, the validation analysis takes into account the compositional properties of a system.

The validation techniques are applied on a-role types, not just instances. This facilitates the analysis of components that are bound dynamically. Design rules are defined that enable the designer to identify errors at design time, and develop well-formed state machines. In that way, it is possible to avoid the deployment of poorly designed components.

5.1.1 Related research

Little work has been dedicated to the validation analysis of systems that are composed dynamically. [Charpentier and Chandy 1999] introduces a component-based approach for formal design and verification of distributed systems. Systems are described using an abstract formalism based on temporal logic, and system properties are expressed using logical properties. This is an academic approach, and we find it far too complex to be taken into use in an industrial context.

Within software architecture research, formal languages and analysis tools are also proposed. A major difference between our approach and the work done on software architectures is that we deal with fine-grained elements (and their composite), while software architectures concentrate on coarse-grained elements. [Medvidovic and Taylor 2000] points out the lack of consensus in the software architecture research community. Some scientists aim at providing simple, understandable architecture definition languages, but not necessarily having formally defined semantics. Others aim at providing formal languages and powerful analysis tools. In this later group, [Allen and Garlan 1994; Allen and Garlan 2000] describe a formal approach to architectural connection based on the process algebra CSP [Hoare 1985]. The small client-server cases used as examples in these articles are rather complex. We reckon that the approach is not appropriate in the case of fine-grained elements. The specification of components and the derivation of interfaces from components are not addressed. Our approach starts from the component specifications (s-roles) and describes interfaces as projection of specifications.

[Allen and al. 1998] discusses the problem of dynamic reconfiguration. This is an issue that we have not considered yet.

5.2 An alternative to reachability analysis

As we model services as state machines that communicate asynchronously, and interfaces as a-roles that describe the protocols of interaction between s-roles, we seek techniques that are suitable in that context rather than general software validation techniques. [Bochmann 1990; Perhson 1990] give an overview of the main protocol validation techniques, and [Hogrefe 1996; Hogrefe and al. 2000] present how these validation techniques can be used to validate SDL systems.

It is appropriate to compare our approach with reachability analysis. Reachability analysis is at the core of the dynamic analysis of SDL systems and other state transitions systems. Other validation techniques require a more abstract specification language than SDL. It is often combined with property languages in order to determine liveness properties.

Reachability analysis is based on the exploration of the global state space. A global state graph that represents all possible ways of combining behaviours is generated, and inspected in order to find errors, e.g. deadlocks and incorrect terminations. The main problem in this approach is that the complexity of the global state graph grows exponentially with the number of states of the constituting state machines. The number of states is often too large for exhaustive analysis. This is known as the state space explosion problem. Several techniques have been proposed in order to reduce the complexity of the reachability analysis; [Lin and al. 1987; Perhson 1990] discuss some of them. For large systems, exhaustive analysis degrades to low-quality partial search. A discussion about the limitations of exhaustive analysis, and a simplification scheme based on controlled partial searches are presented in [Holzmann 1991]. The Telelogic TAU tool explores this scheme, enabling the analysis of large SDL systems [Telelogic; Ek and al. 1997]. Despite the availability of tools, the analysis remains complex and often requires manual navigation of the unexplored branches in the state space.

Reachability analysis is not well suited to the validation of compositional systems and systems dynamically composed at run-time. It is applied on state machine instances - not types -, and thus is not appropriate for checking components bound at run-time. It poorly takes advantage of the compositional properties of a system. If one component is modified, the system needs to be analysed again. The results of the analysis done before the modification of the system cannot be directly reused.

Another drawback of reachability analysis is that the error search is postponed until after the design phase. If errors are found, the system has to be re-designed, re-analysed, etc., until no new errors can be detected. In our approach, anomalous behaviours can be identified at design time, before the validation analysis itself. We propose design rules that enable the designer to develop well-formed state machines.

By concentrating on the interactions on associations between components, our approach is not as general as reachability analysis. Variables are not taken into account, and dependencies between three or more components are ignored. As we will see, our approach enables the detection of second-order errors, but fails to identify the exact cause of these errors. This will be further explained in Section 7.3.

5.3 Simplification schemes

System validation has two parts: a static analysis and a dynamic analysis. The static analysis consists in checking the consistency of the types of messages exchanged between the system components. This static analysis is rather simple and is not discussed in this thesis. The dynamic analysis considers all possible interactions that may occur during system execution. Dynamic analysis is difficult and requires simplification in order to be practical. We propose two simplification schemes: projection and incrementation.

5.3.1 Projection

The projection is an abstraction technique. A projection is a simplified system description or viewpoint that emphasises some of the system properties while hiding some others. Rather than analysing the whole system, projections are analysed. In our work, the projection only retains the aspects significant for the purpose of validation of an association.

We use projection to hide internal actions and interactions that are not relevant in the validation of a particular association. We formally define a projection transformation for the generation of a-roles from s-roles (Chapter 6). A-roles define the visible behaviour of s-roles on associations and hide the behaviours not visible on the association. Interface validation is applied on a-roles. The purpose of interface validation is to ensure that a-roles interact consistently (Chapter 7).

Interface validation:
check the consistency
on each association between
elementary s-roles, i.e. the
consistency of elementary
a-roles.

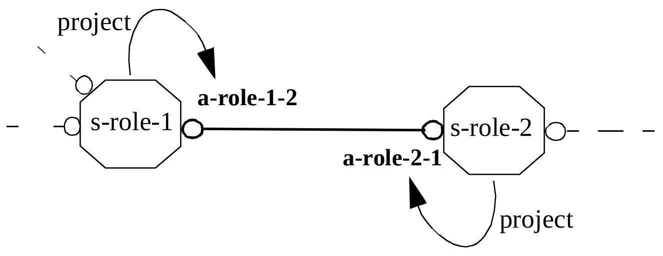


Figure 5.1 : Projection: a simplification scheme.

The concept of projection is not new. Projections were proposed in [Lam and Shankar 1984] for the analysis of single functions in a protocol. In that work, protocols are decomposed into modules that handle different functions, and each module is defined as a projection of the whole protocol. Another projection technique is proposed in [Bræk and Haugen 1993] that sketches a projection transformation and an analysis of projected interfaces. This thesis further develops this idea.

5.3.2 Incrementation

In addition to projection, incrementation is used in order to achieve simplification. The validation approach is tightly integrated with s-role composition. Elementary s-roles are first validated, then the s-roles composed from elementary s-roles, and then the composite of composites, etc. As composition is modelled using similar modelling mechanisms as elementary s-roles, the techniques developed for the validation of elementary s-roles can be reused during the validation of composite s-roles. This is discussed in Chapter 8.

[Chow and al. 1985] has described an incremental validation model for protocols built from sequential phases. The model is restricted to two interacting machines. Our approach addresses more complex cases in that each s-role may interact concurrently on several associations. Furthermore, we are not restricted to sequential composition, but consider different forms of composition.

Composition validation:
check that composite s-roles
interact consistently.

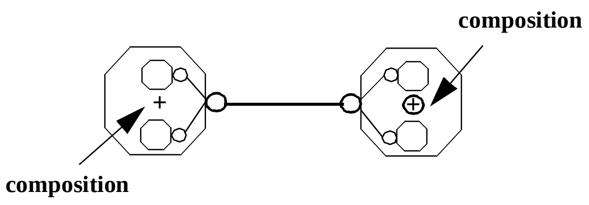


Figure 5.2 : Incrementation: a simplification scheme.

5.3.3 Related research

Using abstractions in order to reduce the complexity of a system to be analysed is also used in system verification and testing. There are many similarities between validation and testing [Hogrefe and al. 2000]. Both techniques require searching in large state spaces, and suffer from the state space explosion problem. Both exploit similar simplification techniques.

Abstraction techniques have been proposed for removing control flow redundancy [Moundanos and Abraham 1998] or for hiding variables [Bozga and al. 1999]. The preservation by abstraction of the properties to be checked is an important issue. A theoretical approach is proposed in [Loiseaux and al. 1995]. In [Boroday and al. 2002], the authors point out the lack of work related to abstracting state machines or SDL. They focus on state abstraction in test generation.

5.4 Constructive and corrective methods

In [Bræk and Haugen 1993], the authors distinguish between constructive methods that aim to generate the right systems, and corrective methods that aim to detect and correct the errors that are made. Our approach is twofold. It provides support for producing correct designs, and for detecting errors when checking a design. Interface validation is applied in two ways:

- As a constructive method, interface validation aims at generating consistent complementary a-roles from particular a-roles. Design rules are also defined for a-roles and s-roles that prevent errors. We do not address the generation of s-roles from a set of a-roles. Techniques developed for the generation of specifications from MSCs may be investigated [Robert and al. 1997; Abdalla and al. 1999].

- As a corrective method, interface validation is used to check that two complementary a-roles interact consistently. Consistency may also be checked at run time.

The concept of complementary a-role is defined as followed:

Definition: Complementary service association role
An a-role is called a complementary a-role with respect to another a-role, if it interacts with that a-role on some association. Complementary a-roles are a-roles that interact with each other.

In Figure 5.1, the a-role “a-role-2-1” is a complementary a-role of “a-role-1-2”. The a-roles are complementary. Complementary a-roles do not necessarily interact consistently.

The proposed constructive and corrective methods make use of common techniques. Rather than directly checking the consistency of two a-roles, we first check whether or not the a-roles present the right properties for interacting consistently. This is illustrated in Figure 5.3. Projection is first applied in order to generate a-roles from s-roles. The a-role graphs are then transformed in order to simplify further validation operations. The simplified definition of a-roles enables us to detect and understand ambiguous or conflicting behaviours. Design rules are proposed that support the designer in removing errors and defining well-formed s-roles. When s-roles follow the design rules, consistent complementary a-roles (or dual a-roles) can be generated, and the consistency of two complementary a-roles can be checked automatically.

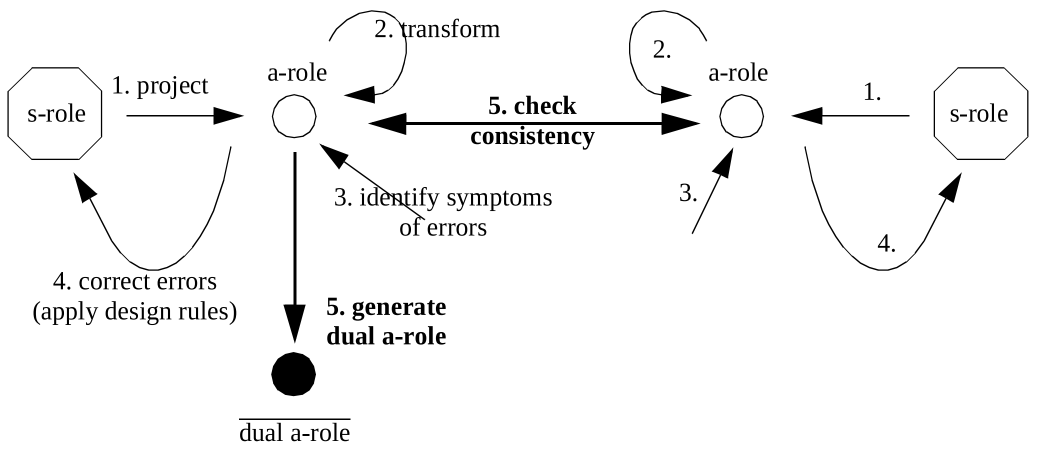


Figure 5.3 : Constructive and corrective methods.

By identifying and removing errors before consistency checking, we avoid analysing poorly designed s-roles and a-roles. The algorithm for consistency checking is thereby simplified, and the number of states in the working space used by the algorithm can be kept low. Requiring that each s-roles and a-roles adhere to design rules may sound severe. The design rules do not restrict the possibilities to make useful designs. They simply prevent designs that are likely to cause dynamic errors.

The consistency checking of a-roles is cognate to the validation of protocols. [Nitta and al. 1993] has also defined a method for converting SDL systems to protocol specifications and applying a particular protocol validation method on SDL systems. The method however is restricted to two interacting SDL machines. Our approach applies to several machines. Furthermore, we thoroughly review the properties of a-roles, and propose a classification of anomalous behaviours that are symptoms for errors. These behaviours can be identified at system design time.

The transformations applied to s-roles and a-roles are rather simple. They can be performed manually by the designer, or be supported by tools. The design rules can also be applied manually, and be enforced by design tools. It is our experience, and this is also observed by [Logean and al. 1999], that the use of automated formal validation techniques for industrial software design is still moderate. The current techniques require high competence and knowledge in formal modelling and reasoning from the system developer. We believe that our approach, although having a formal base, remains easy to understand and use. In that way, the applicability of the proposed approach is wider than the validation in a dynamic context. It should also be of interest for the validation of static systems.

5.5 Interaction consistency

Our work focuses on safety properties, i.e. bad things that should never happen. Unspecified signal receptions, deadlocks and improper terminations are classified as violations of safety properties. Liveness properties, i.e. desirable things that should eventually happen, are not addressed. We do not provide any formalism for expressing liveness requirements as done in [Holzmann 1991].

As a-roles are defined in terms of state machines that communicate by message exchanges, safety violations can be characterized in terms of signals and states. This section defines the safety violations considered here.

The approach is restricted to the avoidance and detection of logical errors. Physical errors such as signal loss, communication channel defect and actor defect are not discussed.

Definition: Unspecified signal reception
An unspecified signal reception occurs when an a-role receives a signal that is not specified as input in the current role state.

In SDL, unspecified signals are discarded, and thus unspecified signal reception may not cause any immediate failure. However, unspecified signal reception is a symptom of possible design errors. Therefore we enforce strong requirements on interacting roles: all signals sent by a role should be explicitly consumed by the associated role.

Definition: Deadlock
A deadlock occurs when two a-roles are unable to proceed because they wait endlessly for signals from each other.

Definition: Improper termination
Improper termination occurs:
- when two a-roles do not terminate in a coordinated manner: no signal should be sent to an a-role that has terminated,
- when the exit conditions attached to the a-role terminations are not consistent. Two exit conditions are consistent when they represent the same termination cases, or when one of the conditions represents a termination case that covers the termination case represented by the other condition.

The termination of an a-role should be perceived by the interacting a-role so that a-roles never send signals to their associated complementary a-roles when they have terminated. This requirement is essential to support consistent role composition.

SDL does not define the concept of exit condition, but the concept of exit label. An exit label is a means for abstracting a condition. For example, the role "inviter" introduced in Chapter 3 on page 33, is defined with two exit labels: "fail" and "success". Each label represents a condition of termination. We prefer to reason on exit conditions rather than labels. In Section 7.1.2.4 on 172, we will introduce an extension to the SDL exit label for expressing exit conditions as OR-expression of other exit conditions. This extension facilitates the composition of roles across actors. For example, using this extension, it will be possible to attach the condition "fail OR success" to a return node. The condition "fail OR success" means any of the cases "fail" or "success". It represents a termination case that covers the termination case represented by the condition "fail". Thus we consider the two conditions "fail OR success" and "fail" to be consistent.

In the following, we will use the term exit condition instead of exit label. Similarly, we will use entry condition instead of entry label.

Definition: Interaction consistency
A-roles are said to interact consistently when their interactions do not lead to any unspecified signal reception, deadlock or improper termination.

5.6 Rules

In the following chapters, we will define various rules related to the validation of a-roles and s-roles. We distinguish between three kinds of rules:

- **D-rules**, or design rules, define guidelines for the system designer. D-rules mainly describe the desirable properties of a-roles and s-roles. Some of them facilitate interface validation. D-rules apply to humans, and can be enforced by design tools.

- **T-rules**, or transformation rules, are related to the transformations that we define and apply on the role state graphs. These transformations will aim to reduce the complexity of the analysis, or to produce consistent complementary a-roles. T-rules apply to manual or automated transformations.

- **V-rules**, or validation rules, support the validation of roles. They describe required properties of roles, and the techniques that may be applied on these roles. V-rules apply to humans, and can be enforced by design and validation tools.

The rules are expressed in simple terms so that they are easy to understand and apply. However, we have tried to be precise, and we have provided a justification for each rule. We also define algorithms for the main transformations and validation rules.

6 Service association role modelling

This chapter introduces the modelling of service association roles (a-roles). Recall that an a-role is defined as the visible interaction behaviour of an s-role on an association with another s-role. We describe a-roles as state machines using a notation inspired from SDL. As a-roles are restricted to the visible behaviour of s-roles on associations, full SDL is not needed. Some extensions to the SDL notation are introduced in order to abstract non-observable behaviours, i.e. s-role behaviours not visible at the interface.

The set of concepts needed for a-role modelling is first identified by describing the projection from s-roles to a-roles. The projection of an s-role state graph generates an a-role state graph. Transformations are proposed that can be applied on a-role state graph in order to facilitate interface validation. In particular a-roles will be described using transition charts, a kind of state graph where transitions between states consist only of a single event: an input, an output or a silent event.

This chapter also identifies s-role patterns that lead to ambiguous or conflicting behaviours. An a-role behaviour is said to be ambiguous when an external observer is not able to determine which behaviour is expected by this a-role. A conflict occurs when the behaviours of an a-role and its complementary a-role diverge. Ambiguous and conflicting behaviours require special consideration during interface validation.

6.1 Modelling concepts

A-roles capture the interaction behaviour of an s-role on an association. They abstract the internal actions occurring in the s-roles and the interactions towards other s-roles. In order to identify the concepts needed for a-role modelling, it is suitable to think about a-roles as derived from s-roles. We call this derivation a projection. The projection of an s-role state graph onto an association generates an a-role state graph.

A-roles exhibit the same behaviour as the s-roles they are derived from, on the association they are attached to. This means that an s-role and the projected a-role *should be able* to generate the same sequence of outputs on an association when offered the same sequence of inputs on this association. Note that the s-role and the projected a-role are not restricted to generate a single sequence of outputs for a given sequence of inputs; alternative sequences are allowed. The behaviour determining the choice of a sequence is not visible at the association interface, and an a-role may appear to make non-deterministic choices. This non-determinism results from the abstraction of the s-roles internal decisions and the interactions on other associations.

The relation between an s-role and a projected a-role is a kind of equivalence relation. The notion of equivalence is usually introduced in program verification, and aims to establishing the equivalence of a program and its specification. Several equivalence relations have been proposed [Milner 1989]. These relations are based upon the concept of observable behaviour: “two agents are equivalent, if they exhibit the same behaviour”, where several interpretations may be given as to what behaviour is observable. In particular, the internal actions may be observable or not. In our approach, the observation is restricted to one association at a time, and the abstraction of internal actions is observed in terms of state changes, where each state represents different behaviour events.

Definition: Observable association behaviour
The behaviour provided by an s-role on an association is called the observable association behaviour.

We will also use the term *external association observer*, or simply *external observer*, to denote some external machine that interacts with the s-role on an association. An external observer perceives the signals sent by an s-role on an association. It can observe how an s-role reacts, or responds, to the reception of a signal or sequence of signals. An external observer does not observe s-role state changes directly, only indirectly when state changes lead to distinct responses. A complementary a-role is a kind of external observer.

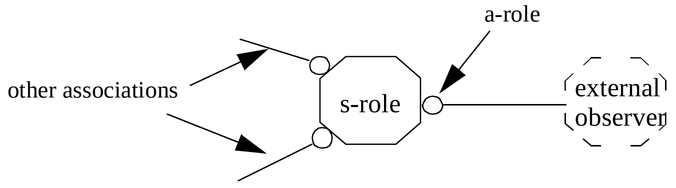


Figure 6.1 : A-role and external observer.

Sections 6.1.1 to 6.1.8 introduce the modelling concepts by describing the projection from s-roles to a-roles. Similarly to s-roles, a-roles are described as state machines. A notation inspired from SDL is introduced for the specification of a-roles. In Section 6.2, we will show that the a-roles obtained by projection provide the same observable association behaviour as s-roles.

6.1.1 Signals

We assume that all the communication between s-roles take place by the exchange of signals, and that signals exchanged on an association between two s-roles are conveyed asynchronously on the same communication path. Communication is modelled using SDL input signals and output signals. A communication path is constituted by a sequence of connected channels. With this assumption, we ensure that signal ordering is preserved during transport on an association, i.e. signals are received in the same order as they are sent. Communication through remote variables and remote procedure calls is not considered.

An association between two s-roles handles the signals that can be exchanged between these two s-roles, and does not contain any other signalling. For each s-role, the association includes the signals that can be received from the association, and the signals that can be sent on the association.

Definition: Valid association input signal set
A valid association input signal set is defined with respect to an s-role and an association related to this s-role. The valid association input signal set is the set of signals that can be received by the s-role from the association.

Definition: Valid association output signal set
A valid association output signal set is defined with respect to an s-role and an association related to this s-role. The valid association output signal set is the set of signals that can be sent by the s-role to the association.

We assume that valid association input signal sets related to distinct s-role associations are disjoint. We also assume that valid association output signal sets related to distinct s-role associations are disjoint. In practice, signal sets can be made disjoint by encoding the references to the entities involved in the association in the signal. These assumptions facilitate the identification of the signals related to an association during the projection.

We will also use the terms *visible signals* and *non-visible signals* to denote signals that are respectively exchanged and not exchanged on the association where a projection is done. Given an association, a visible signal belongs to the valid association input and/or output signal set. A non-visible signal does not belong to any of the sets.

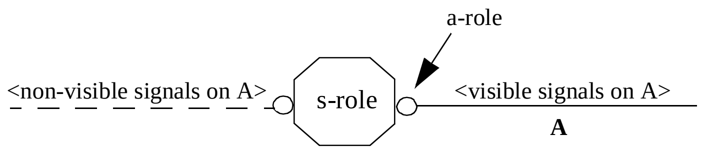


Figure 6.2 : Visible and non-visible signals.

An a-role state graph describes the sending and consumption of signals exchanged on the association the a-role is attached to, i.e. the exchange of visible signals. The consumption of signals from other associations by the s-role, i.e. non-visible input signals, may lead to state changes that influence the further behaviour on the association the a-role is attached to. These signals are abstracted from the a-role state graph and become SDL spontaneous inputs. Their accurate identification is not relevant, the state changes are. Spontaneous transitions are further explained in the next section. The signals sent on the other associations, i.e. non-visible output signals, have no influence on the state changes, and are not represented in the a-role state graph at all.

6.1.2 States and transitions

While a state in the state graph of an s-role represents a condition in which a signal may be consumed (recall the assumptions introduced in Section 3.3.1), *a state in the state graph of an a-role represents a condition in which signals may be consumed or sent.*

The s-role states that represent conditions for the consumption of signals in the valid association input signal set, are projected to states that also represent conditions for the consumption of these signals in the a-role. A simple state projection is shown in Figure 6.3. The behaviour that is not visible at the interface, here signal sending on other associations, like “X” and “Y”, is represented by a dashed symbol. This notation will be also applied in the next figures.

The consumption of signals from other associations is projected to spontaneous transitions in the a-role. The triggering of a transition without any signal consumption is defined in SDL as a *spontaneous transition*, and is intended to represent non-deterministic behaviour. When modelling a-roles, a spontaneous transition indicates that some non-visible signal consumption has taken place that leads to a transition. The fact that triggering may happen is relevant for the a-role, not the reason for triggering.

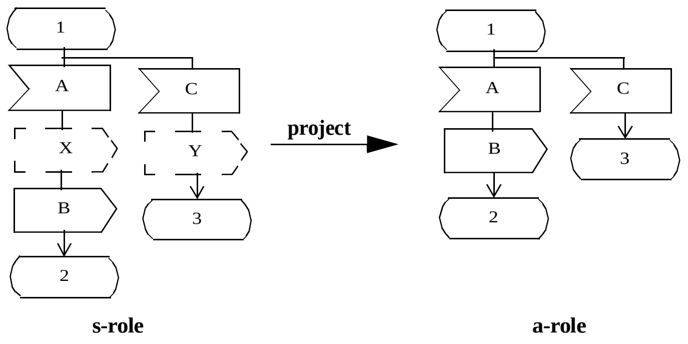


Figure 6.3 : State projection: condition for signal consumption.

Spontaneous transitions may prescribe the sending of a signal in the valid association output signal set. In that case the projected transition has a visible signal sending, while the triggering input signal is hidden from an external observer. An example is shown in Figure 6.4.

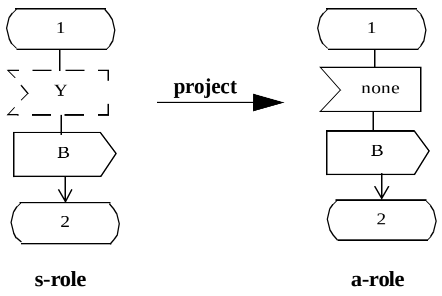


Figure 6.4 : State projection: condition for signal sending.

In order to simplify the state graphs, we omit using the SDL spontaneous input designator “none”. Signal sending, if any, is directly specified after the state. The simplified notation is shown in Figure 6.5. Using this notation, the state appears as a condition for signal sending.

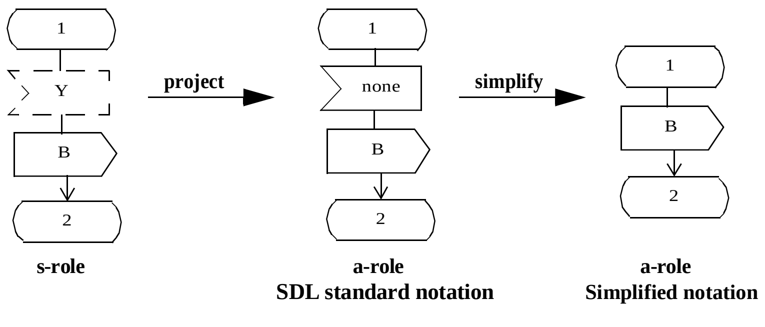


Figure 6.5 : Spontaneous transition: simplified notation (extension to SDL).

When the transitions triggered by non-visible signals do not prescribe any visible signal sending, the simplified notation leads to empty transitions. We call such empty transitions τ-transitions. The transitions are marked using the symbol “τ”.An example is shown in Figure 6.6.

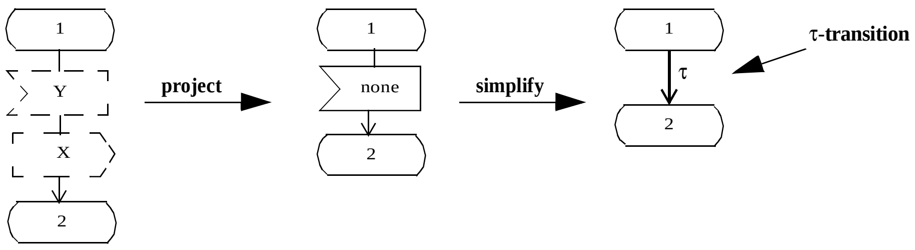


Figure 6.6 : τ-transition.

Definition: τ-transition
A τ-transition is an empty spontaneous transition.

The symbol “τ” used to mark τ-transitions may appear superfluous. This use will be justified at the composite level where it is important to distinguish between sequential and spontaneous transitions between composite states. While a sequential transition occurs at once, a spontaneous transition may occur at any time. No signal is retrieved from the input port in a sequential transition between two composite states, but signals may be retrieved from the input port before a spontaneous transition is triggered.

6.1.2.1 Mixed initiative states

An a-role state may both represent a condition for signal consumption and signal sending. Such states are called mixed initiative states. Mixed initiative states are derived from s-role states that described the consumption of visible and non-visible signals. An example is shown in Figure 6.7.

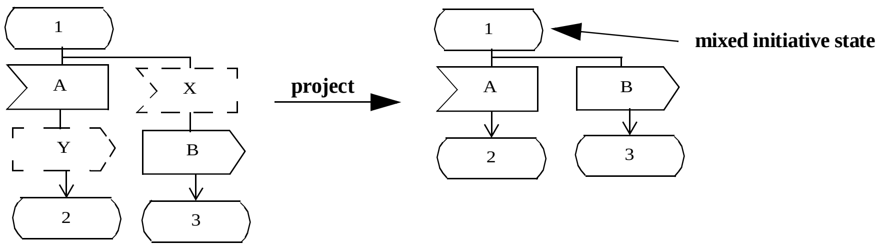


Figure 6.7 : Mixed initiative state.

Mixed initiative states are further discussed in Section 6.6.

6.1.2.2 Multiple transitions

An a-role state may enable the consumption or sending of multiple signals. In Figure 6.3, several signals can be consumed in state “1”. In Figure 6.7, sending and consumption are both allowed in state “1”. An a-role state may also prescribe the sending of multiple signals. An s-role state that prescribes the consumption of multiple signals from other associations is projected to an a-role state that prescribes the sending of multiple signals. An example is shown in Figure 6.8.

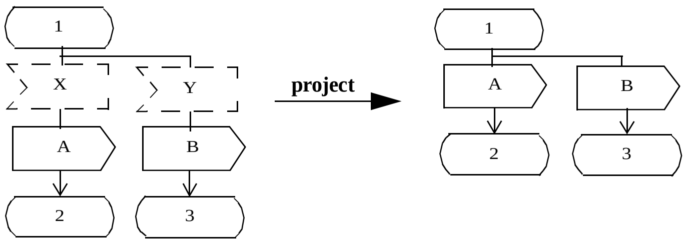


Figure 6.8 : Sending of multiple signals.

6.1.2.3 Implicit transitions

We retain the SDL semantics for the interpretation of transitions between states. A signal received in a state that is not specified as input or save in that state, is implicitly consumed, i.e. discarded.

According to our definition of interaction consistency (see Section 5.5), implicit transitions should not occur, and is treated as an error in the validation analysis.

6.1.3 Internal actions

The internal actions of an s-role, such as tasks, agent instance creations or timer operations are not visible at the interface. They are not represented in the a-roles. Thus an a-role transition is either empty, or it describes the sending of a visible signal or a set of signals. Figure 6.9 illustrates the projection of an internal task.

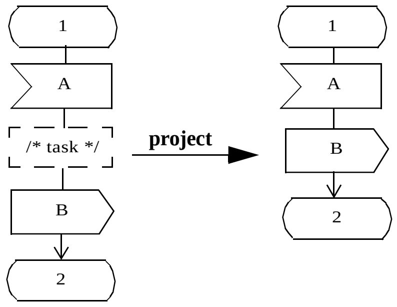


Figure 6.9 : Non-visible internal behaviour.

6.1.3.1 Decision

A decision consists in a question and a set of answers, where these answers lead to different behaviour choices. The processing of the question is an internal action that is not visible at the interface. The answers also represent internal information. The choices, on the other hand, may describe visible behaviours, e.g. the sending of a signal or a transition to a new state. Such choices are described in the a-role.

In Figure 6.10, the decision choices describe internal behaviours; they are not represented in the a-role.

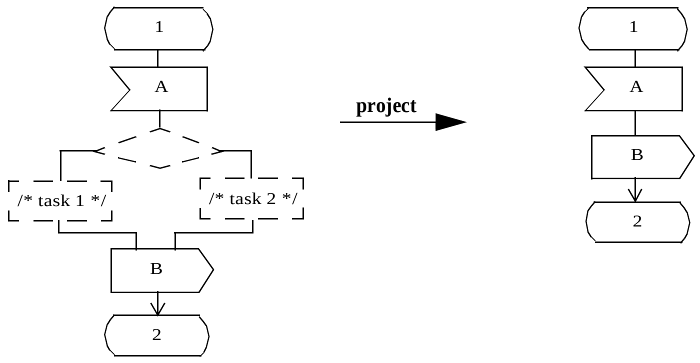


Figure 6.10 : Abstracting a decision node: internal behaviour.

In Figure 6.11, the decision choices describe the sending of signals in the valid association output signal set. The choices are represented in the a-role, but not the decision. The decision is abstracted to a non-deterministic choice. Note that we introduce an extension to the SDL notation: two transitions attached to the same input are normally not allowed.

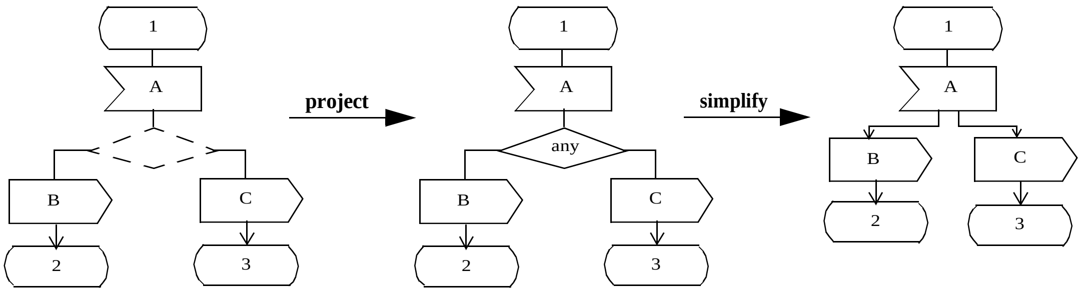


Figure 6.11 : Abstracting a decision node: before signal sending (SDL extension).

In Figure 6.12, the decision choices describe transitions to new states; they are also represented in the a-role.

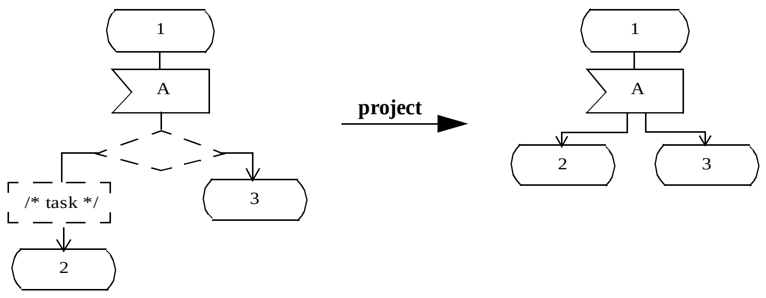


Figure 6.12 : Abstracting a decision node: before next state.

In the previous examples, decisions take place after the consumption of a signal in the valid association input signal set. Decisions may also take place after the sending of a signal in the valid association output signal set. An example is shown in Figure 6.13. Note that we introduce a similar extension to the SDL notation as in Figure 6.11: two transition parts attached from the same output are not allowed in pure SDL.

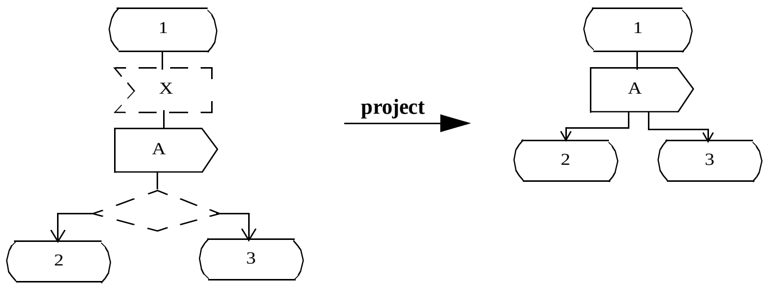


Figure 6.13 : Abstracting a decision node: after signal sending (SDL extension).

A decision taking place within a transition that does not describe any visible signal consumption and sending is projected as described in the previous examples. The projection of decision may lead to multiple τ-transitions. An example is shown in Figure 6.14.

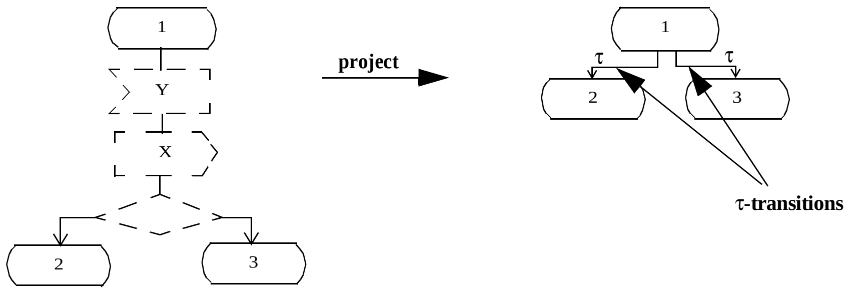


Figure 6.14 : Abstracting a decision node: τ-transitions.

6.1.4 Initial states

An a-role initial state represents the start of interactions on an association. Initial states are modelled in the a-role state graph using SDL start nodes. The SDL semantics for start node is maintained.

A-role initial states are directly derived from s-roles initial states. S-role initial transitions are projected in a similar way as other transitions. Recall that the consumption of signals is not allowed in start nodes. An a-role initial transition is either an empty spontaneous transition, i.e. a τ-transition, or it describes the sending of a signal or a set of signals.

An entry condition may be associated with an initial state. A state graph may contain several initial states. In that case, distinct entry conditions should be associated to the initial states. The projection maintains the entry conditions attached to the initial states.

6.1.5 Exit states

An a-role exit state represents the end of an interaction on an association. Exit states are modelled in the a-role state graph using SDL return nodes. The SDL semantics for return node is maintained.

A-role exit states are directly derived from s-roles exit states. An exit condition may be associated to an exit state. The projection maintains the exit conditions attached to the exit states.

6.1.6 Timer signals

Timer signals are projected to SDL spontaneous inputs similarly as for signals received from other associations.

6.1.7 Save

A saved signal in SDL is not immediately consumed, but retained in the agent input port for future processing. A saved signal is treated as a normal signal instance in the following state. A saved signal is not necessarily consumed in the successor state. The input port may contain several saved signals; signals are consumed in the order of their arrival.

The projection of save is complex. When the consumption of saved signals is combined with spontaneous transitions, the activation of spontaneous transitions may occur before the consumption of saved signals. The activation of a spontaneous transition may occur at any time, independently of the presence of signals in the input port. In order to define a simple projection of save that maintains the observable association behaviour, we propose to constrain the use of save. Constraints can be expressed by design rules.

This section first defines a simple projection of save and justifies this definition. Then, non desirable behaviours occurring when combining the projection of save and spontaneous transitions are described. Finally we define design rules that enable us to apply the simple projection of save. An alternative definition of the projection is also proposed that relaxes the constraints set by the design rules.

6.1.7.1 Save projection: a simple definition

We would like to define the projection of save so that the saving of signals belonging to the valid association input signal set is maintained in the a-role graph, while the saving of signals received from other associations is not represented in the a-role graph. Intuitively, this seems an acceptable definition. The information related to the saving of signals in the valid association input signal set is of importance, as it influences the allowed ordering of signal sending on the association. On the other hand, only the knowledge about state changes triggered by the consumption of non-visible signals is relevant, not the identification of these signals, and not the moment of their arrival. Spontaneous transitions model that non-visible signals may be received at any time.

We first assume that the projection of save is defined in this simple way and present a set of examples where the definition satisfies our requirement on observable association behaviour.

Figure 6.15 illustrates the projection of the saving of a visible signal “B”. The saving of signal “B” is maintained in the a-role graph. The machines behave in the same ways: the s-role and a-role generate the same output when offered the same inputs; signal “B” can be sent before or after “A”.

Figure 6.16 illustrates the projection of the saving of a non-visible signal “X”. The saving of signal “X” is not represented in the a-role graph. The machines behave in the same ways: an external observer that sends “A”, can receive “D”.

Figure 6.17 illustrates the projection of the saving of a visible signal “B” and a non-visible signal “X”. Only the saving of signal “B” is maintained in the a-role graph. An external observer may either send “A” before “B”, or “B” before “A”. In both cases, the two s-role behaviours described in state “2” can occur, depending on whether the saving of “X” has taken place before “B”, after “B” or not at all. An external observer either receives “C” or “D”. The same two behaviours can also be observed when interacting with the a-role, depending on whether the spontaneous transition occurs immediately when entering state “2” or not.

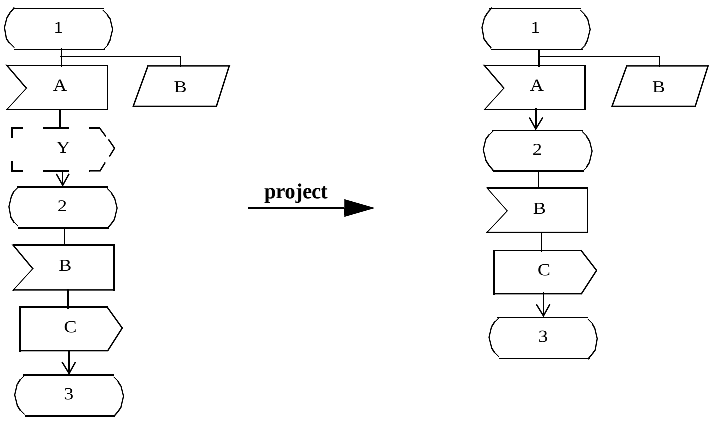


Figure 6.15 : Projection of save: visible signal.

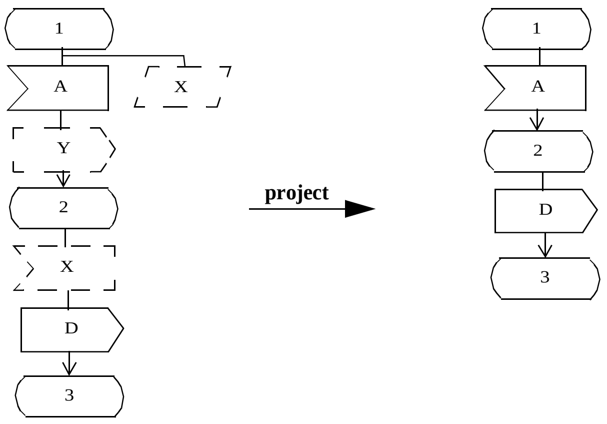


Figure 6.16 : Projection of save: non-visible signal.

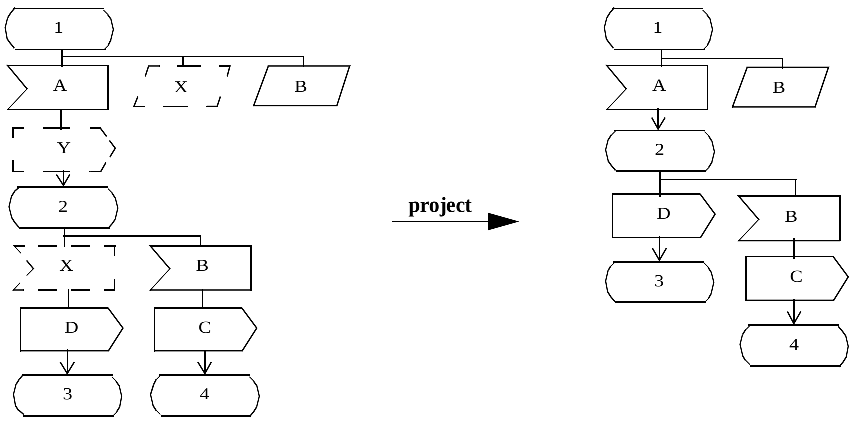


Figure 6.17 : Projection of save signals: visible and non-visible signals.

In this last example, the independent arrival of “B” and “X” in the input port and their retrieval are properly modelled by the spontaneous activation of the spontaneous transition. A spontaneous activation is however not always desirable. This is discussed in the next section.

6.1.7.2 Interference between save and spontaneous transition

The save feature is often applied in order to enforce a strict ordering on the consumption of signals on an association. When this use of save is combined with interactions on other associations, the proposed projection of save does not always maintain the observable association behaviour. The activation of spontaneous transitions in the projected a-role may interfere with the retrieval of saved signals in an unintended way.

An example is shown in Figure 6.18. Here the interaction on the association carrying “A” and “B” is combined with an interaction on another association. The visible signals “A” and “B” may be sent in various orders, and the s-role handles them in the fixed order “A” before “B”. When “B” is sent before “A”, “B” is necessarily the first signal in the input port when entering state “2”. Thus the saving of “B” enforces the s-role to always handle “B” before “X”. In that case, the s-role always sends “C”. The a-role however, may either send “C” or “D” depending on the activation of the spontaneous transition that sends “D”.

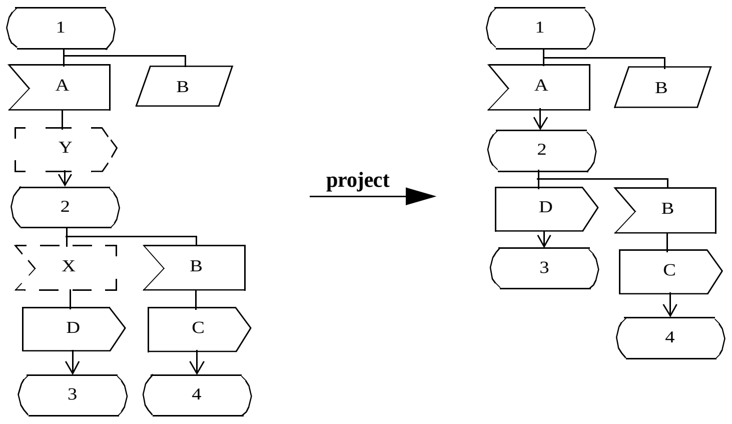


Figure 6.18 : Projection of a save signal: an undesirable a-role behaviour (1).

Similarly, the s-role described in case (a) in Figure 6.19 and its derived a-role do no provide the same observable association behaviour. While the s-role fails to interact consistently when “B” is sent before “A”: “C” (and anything) never happens, the a-role may sometimes send “C” depending on the activation of the spontaneous transition. We observe that the same a-role is obtained by projection of the s-role described in case (b). Here however, the s-role and its derived a-role behave similarly. The saving and retrieval of “X” occur independently from the saving and retrieval of “B”. This is properly modelled by the spontaneous transition.

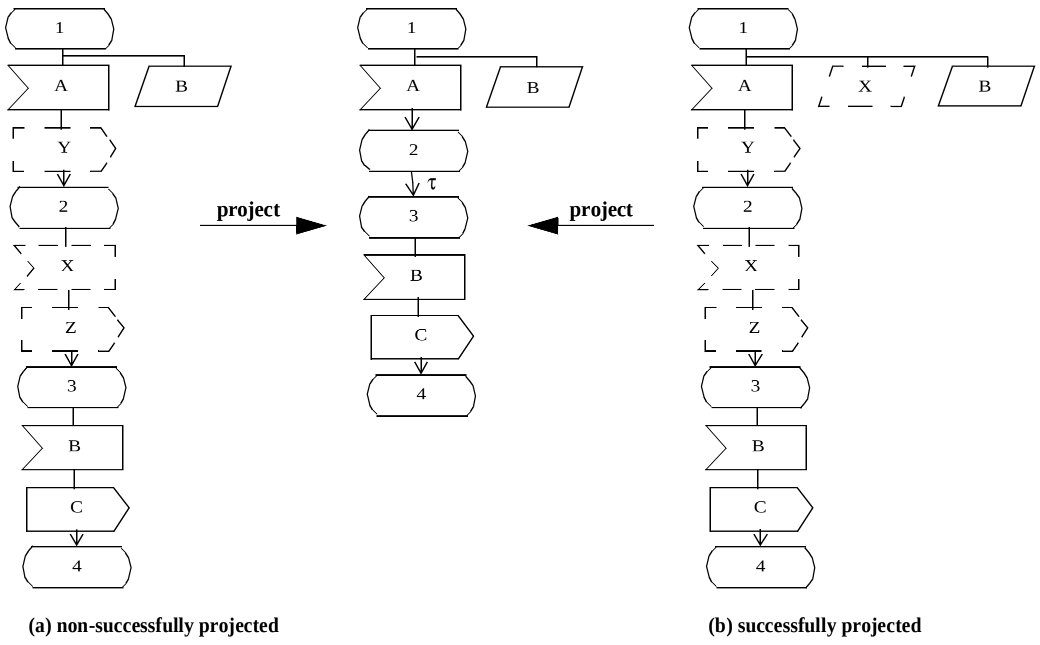


Figure 6.19 : Projection of save signals: an undesirable a-role behaviour (2).

Of course, the behaviours described in Figure 6.19 are not desirable. In both cases, “B” may be discarded in state “2”. If the saving of “B” is introduced in state “2”, we observe that the s-role and the projected a-role would provide an identical behaviour.

The interference between the spontaneous transitions and the retrieval of saved signals in the input port invalidate the proposed projection of save. The projection does not always maintain the observable association behaviour. The previous examples illustrate two types of undesirable interferences:

- The spontaneous activation of a transition may prevent a saved signal from being discarded from the input port. In some way, the interference partially repairs an incorrect behaviour specification. This was shown in case (a) of Figure 6.19.
- The spontaneous activation of a transition may prevent a saved signal from being consumed when it is stored first in the input port. This was shown in Figure 6.18.

While the first kind of interference is avoided by introducing a design rule enforcing a consistent use of save, the second may either be avoided by the redefinition of the projection of save, or by a design rule constraining how save should be used.

6.1.7.3 Save consistency

The discarding of a saved signal from the input port is not desirable neither with respect to the projection of s-roles nor with respect to the consistency of interaction between s-roles. As our definition of interaction consistency requires that unspecified signal reception never happens (see Section 5.5), saved signals should eventually be consumed in the state(s) succeeding a saving state.

D-rule: Save consistency
The saving of a signal should be repeated in the successor state(s) of the state where save is specified until the consumption of the saved signal is specified. A successor state specified according to this rule is said to maintain save consistency, or to be save consistent with its predecessor state(s). An s-role specified according to this rule is said to be save consistent.

Note that the repetition of save may introduce new saving states. The successor states of these new saving states should also be save consistent.

Using this rule, the two case examples shown in Figure 6.19, should be redefined. “B” should be saved in state “2” in both cases. Then the projection of save faithfully maintains the observable association behaviour.

The save consistency rule does not necessarily prevent the discarding of a saved signal from occurring. In Figure 6.17, for example, the rule has been enforced, but still signal “B” may be discarded in state “3”. In that case, rules related to mixed initiative states should be applied. This will be explained in Section 7.1.3.

In the following, we assume that s-roles are designed according to the design rule "Save consistency".

6.1.7.4 Retrieval of saved signals

The rule "Save consistency" addresses the problem of the discarding of saved signals, but not that of retrieval as shown in Figure 6.18. We may consider two kinds of solutions to the retrieval problem:

- One is to redefine the projection of the retrieval of a saved signal by adding control on the activation of the spontaneous transition.

• Another is to constrain the use of save. Save is a complicating feature and should not end up modelling both alternative orderings and concurrent association behaviours.

6.1.7.4.1 Controlling the activation of spontaneous transitions

Control can be set on the activation of a spontaneous transition by associating a precondition to the activation. In SDL, preconditions can be expressed using continuous signals. Figure 6.20 illustrates this approach. The precondition only depends on the interaction on the association where the projection is done. “B not sent before A” means that B is not saved. Note that in the case where “B” is sent after “A”, both transitions in state “2” of the the projected may also occur. According to the SDL semantics, signals in the input port are retrieved before continuous signals are interpreted when entering a new state.

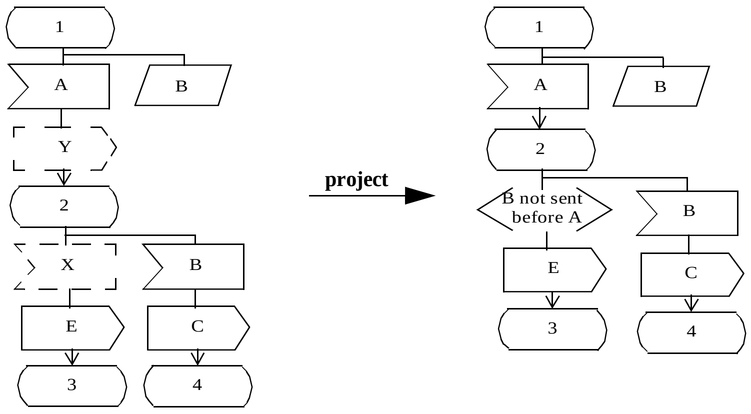


Figure 6.20 : Projection of a save signal: using a continuous signal.

Preconditions should only be applied in the case where the non-visible signals projected to spontaneous inputs may interfere with the retrieval of a saved signal in an undesirable way. In the case where non-visible signals can be stored in the input port before the visible saved signal, preconditions should not be added. For example, in Figure 6.17 the non-visible signal “X” may be saved before “B”. Preconditions are not needed in that case.

In this approach, preconditions are defined by comparing the possible ordering of the signals sent by the complementary a-role. The ordering of two signals, one sent and one received cannot be compared. As communication between a-roles is asynchronous, the reception of a signal is perceived some time after its sending, and a complementary a-role is not able to determine when the sending of a signal exactly occurs. In Figure 6.21, an external observer cannot determine whether “B” is received before or after sending “C”.

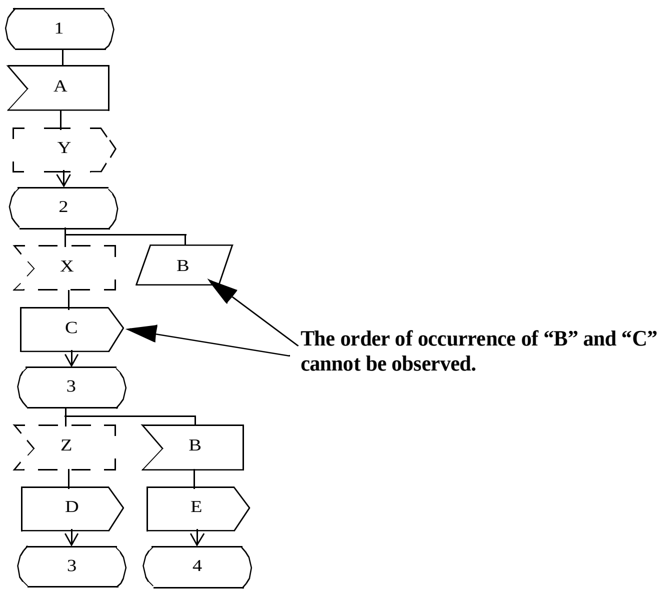


Figure 6.21 : Projection of save signals: comparing signal ordering.

To sum up, preconditions should be defined for each visible signal that is saved in a state that can consume a visible signal when:

- The saved signal can be retrieved in a state that can consume non-visible signals.
- These non-visible signals cannot be not saved before the visible saved signal.

Preconditions control the triggering of the transitions projected from the transitions triggered by these non-visible signals. They describe the ordering of a pair of visible events (saved signal, consumed signal).

When several visible signals can be saved in the same state, preconditions should be defined for each pair of signals (saved, consumed). The preconditions should be logically combined such that any possible ordering combination is described. Such a case is however a symptom of complex - and possibly bad - design, and should be avoided.

6.1.7.4.2 Constraining the use of save

The refined projection of save defined in Section 6.1.7.4.1 is rather simple. However having in mind that the save concept introduces complexity, we propose to introduce constraints on using save.

Save serves two main purposes:

- It may be used to enable alternative signal sending orderings while a strict order on the consumption of signals is enforced. Seen from the complementary a-role, the ordering of signal sending is relaxed.

- It may be used to facilitate the description of concurrent behaviours on multiple associations. For example, save may be used to enable an interaction on an association not to be interrupted by the arrival of signals from other associations.

In order to limit the complexity of a design, we advise not to use save to relax the ordering of signal sending. Alternative orderings should only be specified when required for optimisation purposes, or when constrained by external interfaces. Furthermore, we recommend not to combine the use save for alternative orderings together with the description of concurrent behaviours. This constraint applies both when the modelling of concurrent behaviours involves save or not.

In Figure 6.18, save is used to describe alternative sending orderings. This use of save overlaps with the description of a concurrent behaviour: “X” can be received when “B” is retrieved. The s-role should be re-designed, avoiding the saving of “B”. The constraint on the usage of save will permit to generate a projection that provides an identical observable association as the s-role.

In Figure 6.17, save is used to describe alternative sending orderings and concurrent behaviours: both “X” and “B” are saved. The s-role should be re-designed. Although it is possible in that case to generate a projection that provides an identical observable association as the s-role, the s-role behaves in a non-deterministic manner.

D-rule: Save and ordering
Using save for the modelling of alternative signal orderings on one association should be restricted to special cases, for example when required for optimisation purposes, or when constrained by external interfaces.

Alternative orderings can easily be identified: a state that can both save and consume signals received from the same association models alternative orderings.

D-rule: Ordering with save and concurrency
Using save for the modelling of alternative signal orderings on one association should not

overlap with the modelling of concurrent behaviours.

Overlapping can easily be identified: a signal saved in a state that can consume signals from the same association, should not be retrieved in a state that can consume signals from other associations. When this rule is enforced, the projected a-role does not describe any spontaneous transition in the state where the saved signal is retrieved. Thus interferences between spontaneous transitions and the retrieval of a saved signal do not occur.

The rules do not constrain the use of save for modelling concurrency when no alternative orderings are described. Saved signals not involved in alternative orderings may be retrieved in any state, also states receiving signals from other associations. In this way, it is possible to describe complex concurrent behaviours that occur on three associations or more. This is illustrated by Figure 6.22. Here the s-role provides three association roles “A-1”, “A-2” and “A-3”. The s-role is first involved in an interaction on “A-3”; any of the other associated roles may send the role a request “A” or “K”. When the interaction on “A-3” is finished (in state “2”), the s-role handles one of the requests, possibly the request that was first saved, if any.

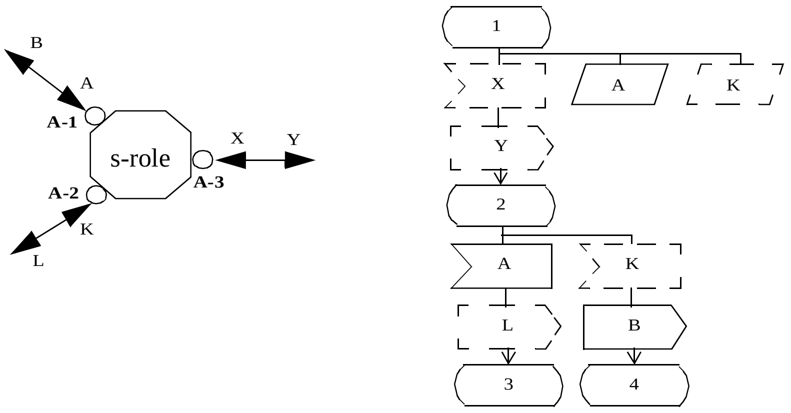


Figure 6.22 : Save and concurrent behaviours.

In the case where a spontaneous transition occurring in the retrieval state does not introduce any visible behaviour (i.e. the sending of a visible signal), the rule "Ordering with save and concurrency" may be too strict. An example is shown in Figure 6.23. The behaviour described by state “2” is not allowed by the rule. As the spontaneous transition does not introduce any visible behaviour, this case is acceptable. We have chosen to maintain the rule as already defined. The case of Figure 6.23 may be considered in further work. Note that this kind of behaviour would be removed by state gathering (Section 6.3.2).

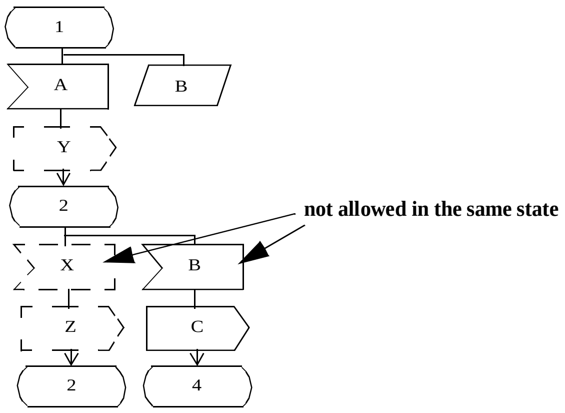


Figure 6.23 : Design rule "Ordering with save and concurrency": a restricting case.

In the following, we assume that s-roles are designed according to the design rule "Ordering with save and concurrency". When this rule is enforced, interferences between spontaneous transitions and the retrieval of a saved signal do not occur. The initial definition of the projection of save can then be used. Justifying that the observable association behaviour is maintained through the projection is further discussed in Section 6.2.

In the following, we assume that the simple projection of save defined in Section 6.1.7.1 is used.

6.1.8 Enabling condition

We have assumed that communication between elementary s-roles take place through signal exchange. Thus enabling conditions are not used to describe any information exchange between s-roles. They represent local conditions that are set before entering the state that the enabled conditions apply to. The graph can be transformed by replacing the enabling condition with a decision. This is shown in Figure 6.24. The transformation does not modify the s-role behaviour. Here the enabling condition is set on the consumption of a visible signal. It could also be set on the consumption on a non-visible signal. Using such transformation, it is not necessary to define the projection of local enabling conditions. The graph can be transformed before projection. In the following, we will assume that the s-role graph has been transformed in order to remove enabling conditions.

Enabling conditions that describe information exchange between s-roles are more complex. They may lead to implicit signal saving. The conditions may change after entering the state that describes the enabling condition. They are not considered.

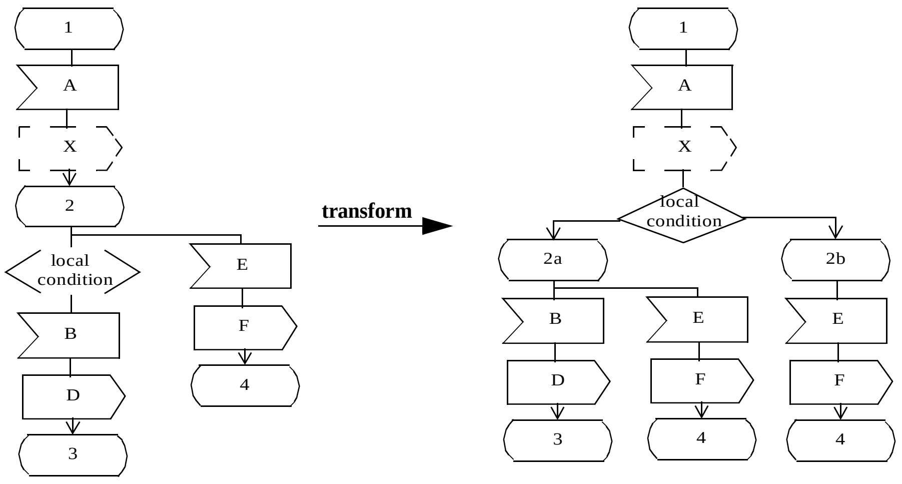


Figure 6.24 : Local enabling condition: graph transformation.

6.2 Projection and observable association behaviour

Section 6.1 has proposed a set of projection operations that transform s-roles to a-roles. As the main purpose of a-roles is to validate the interaction behaviour of an s-role with other s-roles, it is essential that the a-roles obtained by projection provide the same observable association behaviour as the s-roles. An a-role should be able to generate the same sequences of outputs on an association as the s-role it is derived from, when offered a sequence of inputs on this association.

When comparing the s-role behaviour with a particular a-role behaviour, we assume that any behaviour described by the s-role on the other associations may occur, i.e. any non-visible input signal may be received, and any behaviour triggered by non-visible input signals may occur.

6.2.1 Simple behaviour: no signal saving

Let us first reason assuming that save is not used in the s-role state graph, i.e. signals are consumed or discarded in the order of their arrival.

The projection transformation presented in Section 6.1 has the following properties:

- The projection maintains the structure of the state graph. Distinct states in the s-role state graph are projected to distinct states in the a-role state graph. The transitions between states are maintained, and no new transitions are added in the projected a-role state graph.

- The projection maintains the valid association input and output signal sets. The a-role is able to receive and send the same signals as the s-role on the association.

- The projection maintains the triggering of transitions by the consumption of a signal in the valid association input set. The projected states can consume the same signals from the association as the s-role states. No signal consumption is added in any projected state.

- The projection hides non-visible signals, but transitions and state changes triggered by non-visible signals are maintained. A spontaneous transition obtained from the projection of the triggering by the consumption of a non-visible signal may occur, in a similar way as the transition in the s-role may occur when the non-visible signal is received and consumed.

- The projection maintains the sending of signals on the association in transitions between identical states. The transitions where signal sending on the association occurs are transformed to transitions where identical sending occurs.

A projected state is triggered by the same set of visible input signals as the initial state it is derived from, or by hidden non-visible signals. Thus each projected state may be triggered in a similar way as its initial state. Each triggered projected transition may generate the same outputs on the association, and lead to a new projected state that may also be triggered in a similar way as its initial state and, again, the triggered transitions behave as in the initial graph. Thus all association behaviour sequences described in an s-role graph are also described in an a-role graph. As the projection does not introduce new state triggers or transitions, no new behaviour sequences are introduced.

As long as the concept of save is not used, it is not possible to force a signal to be first in the queue when entering a state. The signals are retrieved from the input port in the order of their arrival. The immediate activation of a spontaneous transition in an a-role occurs in the same way as the corresponding transition in the s-role when the non-visible signal is stored before a visible signal in the s-role input port.

Thus, a-roles and s-roles represent the same interface behaviour included eventual errors.

6.2.2 Adding save

Let us now add the save concept. We assume that the design rules "Save consistency" and "Ordering with save and concurrency" have been applied. The simple projection of save defined in Section 6.1.7.1 is used.

As previously, the projected states provide the same set of transitions as the initial states they are derived from. We have to consider how signal saving influences the triggering of a transition. Using save, it is possible to control, or partially control, the ordering of signals in the input port when entering a new state. The design rule "Ordering with save and concurrency" enforces that using save for alternative signal orderings does not overlap with concurrent behaviours.

We first consider that save has been used to describe alternative orderings on the association where the projection is done. The design rule "Save consistency" enforces the saved signal (s) to be maintained in the input port until a state is reached where it (they) can be consumed. The design rule "Ordering with save and concurrency" enforces that non-visible signals are not received in such a state, and thus the visible signals are retrieved as enforced by the save ordering. The projected a-role describes the same behaviour: the projected state does not describe any spontaneous transition that can interfere with the retrieval of a visible saved signal.

Let us now consider that save has been used in the modelling of concurrent behaviours. This means that visible and non-visible signals can be saved and consumed in overlapping states. Following the design rule "Ordering with save and concurrency", an external observer cannot perceive when a visible signal is saved with respect to the occurrence of other visible signals, and then cannot force a saved signal to be stored first in the input port. A saved signal may be retrieved in any state. This retrieval may occur in a state when only visible signals are retrieved, or in a state where other non-visible signals are retrieved concurrently. The projected a-role describes the same interface behaviour as the s-role in both cases.

From this reasoning, we deduce that projected a-roles provide the same observable association behaviour as s-roles, provided that the design rules "Save consistency" and "Ordering with save and concurrency" are enforced.

6.3 A-role state graph refinement

The state graph obtained by projection may be transformed in order to simplify interface validation. Reasoning on transition charts rather that state graphs will facilitate the generation of consistent complementary a-roles and other validation operations (see Chapter 7). Section 6.3.1 defines transition charts, and describes the transformation from a-role state graphs to transition charts. Section 6.3.2 and Section 6.3.3 define transformations for reducing the size of the graph.

6.3.1 Transition charts

A transition graph is a kind of state graph where transitions between states are attached a single event: an input, an output or a silent event. The event attached to a transition is said to trigger the transition. Signal sending is not considered as an action occurring within a transition, but rather as a triggering output event for a transition.

Definition: τ-event
τ-transitions are triggered by a silent event called the τ-event.

A transition chart is a particular state graph, and the notation defined for modelling a-role state graphs can also be used to describe transition charts. Notice that, using the simplified notation for spontaneous transitions, signal sending appears as a triggering output event of a spontaneous transition (see Figure 6.5 on page 85).

In the case where every signal sending described in an a-role state graph occurs in a spontaneous transition (i.e. signal sending is never described in a transition triggered by the consumption of a visible signal), and signal sending never succeeds any other signal sending within a transition, the a-role state graph is a transition chart. Otherwise, the a-role state graph has to be transformed to a transition chart. The transformation consists in inserting a new state before signal sending, when the sending is not described as the first action of a spontaneous transition.

An a-role transition chart should exhibit the same behaviour as the initial a-role state graph derived from an s-role state graph. The insertion of a state before signal sending should not modify the observable association behaviour. To that end, we introduce a new kind of state: the σ-state.

6.3.1.1 σ-state

Definition: σ-state

A σ-state is a specialization of the SDL state that *implicitly* saves all signals in the valid association input signal set. σ-states do not define any input event or τ-event. At least one of the output events described in a σ-state always occurs.

The transformation of an a-role state graph to a transition chart is performed by inserting a σ-state before the sending of a signal, when no state already precedes signal sending. A transition part is added between the event preceding the signal sending and the σ-state. Figure 6.25 illustrates the insertion of a σ-state. A naming convention is introduced in order to distinguish σ-states from other states: the prefix "σ-" is added to the σ-state names. The saving symbol is normally not represented in the a-role chart; it is shown here to underline the implicit saving.

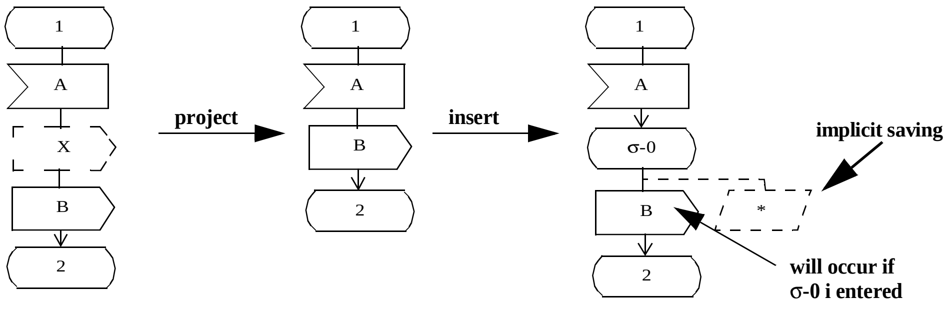


Figure 6.25 : σ-state insertion.

The σ-state insertion is performed on a-role state graphs after the projection from s-roles. For this reason, it is possible to restrict saving to signals in the valid association input signal set. Signals received from other associations are not described in a-role state graphs.

As σ-states are inserted before the sending of signals, we can restrict input events and τ-events not to happen in σ-states. Differently from other states, output events do not occur spontaneously. There is no non-determinism in the occurrence of the events described in a σ-state. When a σ-state is entered, one of the events described in the state always occurs.

The implicit saving of signals enables the transformed machine to handle the input signals as the initial machine. Assume that the machine described in Figure 6.25 receives a signal in the valid association input signal set during the transition between the states "1" and "2" in the initial machine. The signal is handled in state "2". After the insertion of the σ-state, the signal may either be received between the states "1" and "σ-0", in the state "σ-

0” or between the states “σ-0” and “2”. In the two first cases, the signal is saved in the σ-state, and handled in state “2”. In the later case, the signal is handled in state “2”.

Furthermore, as the output signal in the σ-state always occur, we observe the same behaviour before and after the insertion of the σ-state in this example.

Figure 6.26 illustrates the insertion of a σ-state in a state graph that describes a non-deterministic choice. In that case, we observe that the transformed machine also handles the input signals as the initial machine as the initial machine. Assume that a signal in the valid association input signal set is received during the transition between state “1” and one of its successor states “2” or “3” in the initial machine. The signal is retrieved from the input queue when one of these successor states is entered. After the insertion of the σ-state, the signal may be received between the state “1” and one of its successor states “σ-0” or “3”, or while in state “σ-0” or between the states “σ-0” and “2”. Because of implicit saving in the state “σ-0”, a signal received before entering the state “σ-0”, in state “σ-0” is then retrieved from the signal queue in state “2”. Similarly as in the initial machine, the signal is either retrieved in the state “2” or “3”.

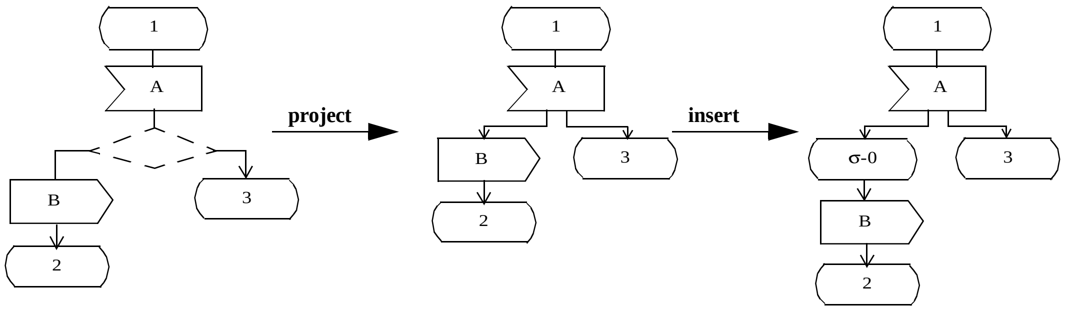


Figure 6.26 : σ-state insertion after a non-deterministic choice.

T-rule: σ-state insertion

σ-states are inserted before signal sending, when no state immediately precedes the signal sending. After the insertion of a σ-state, a state machine exhibits the same behaviour as the original machine.

Justification:

A transition where no σ-state is inserted may be triggered in the same way as in the initial machine, and behave similarly.

A transition where some σ-state is inserted, may be triggered in the same way as in the initial machine. It also behaves similarly:

- A signal sent in the transition before σ-state insertion (in a sending action) is also sent

in the sequence of transitions after σ-state insertion (as a triggering output event). There is no non-determinism in the occurrence of the event.
- The signals stored in the signal queue when triggering the transition or received during the transition before σ-state insertion, are handled in the same way after σ-state insertion: they are retrieved from the queue in the same states, this because of the implicit saving.

In the following, we will assume that the a-role state graphs are transformed by σ-state insertion to transition charts.

6.3.1.2 Initial states

In order to be able to treat initial states in a similar way as other states in the generation of consistent complementary a-roles (see Chapter 7), we also introduce σ-states between initial states and signal sending. After this transformation, all initial transitions are described as empty transitions. Figure 6.27 illustrates the insertion of an σ-state after the initial state.

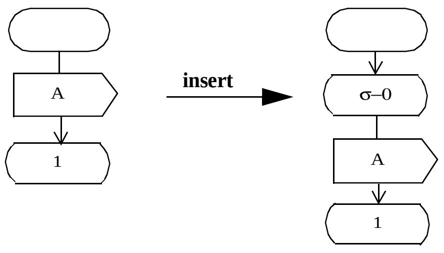


Figure 6.27 : σ-state insertion in an initial transition.

Observe that the empty transitions after initial states differ from τ-transitions. The is no non-determinism in the occurrence of an empty transition, i.e. an empty transition always occurs.

T-rule: σ-state insertion in initial transitions
σ-states are inserted between initial states and signal sending. After the insertion of a σ-state in an initial transition, a state machine exhibits the same behaviour as the original machine.

Justification:
The original empty transitions from the initial state(s) remain unchanged, and may be triggered at any time in the same way as in the original machine.
The empty transition before the inserted σ-state may occur at any time; it does not require any external triggering. The inserted σ-state supports the same signal sending as the orig-

inal initial state. Thus the transformed initial transitions provide the same sending behaviour as in the original transitions.
The implicit signal saving enforces that signals received during the initial transitions are handled in the same way (i.e. retrieved in the same states) as before the σ-state insertion.

In the following, we will assume that the a-role state graphs are transformed adding σ-states between initial states and signal sending.

6.3.2 State gathering

The transformation from s-roles to a-roles may lead to graphs where several τ-transitions follow each other successively. In some cases, these τ-transitions have no influence on the observable association behaviour. Gathering is a transformation that merges states linked by τ-transitions by a single state, and, in that way, reduces the size of a transition chart. Gathering will be defined such that the transition chart transformed by gathering exhibits the same behaviour as the initial transition chart. Before proposing a definition, this section discusses examples where states can be gathered and examples where states cannot be gathered.

We will use the term τ-*successor* to denote the successor of a state triggered by a τ-event, and τ-*predecessor* to denote the predecessor state of a τ-successor.

6.3.2.1 Successive τ-transitions

An external observer cannot distinguish multiple successive τ-transitions from a single τ-transition. This is illustrated by Figure 6.28. An external observer cannot distinguish the τ-transition state “1” to state “2” from the τ-transition state “2” to state “3”. The states “1” and “2” are gathered to “1-2”. The new state machine behaves like the initial machine. The non-deterministic occurrence of the τ-transition is preserved.

6.3.2.2 Output behaviour

An external observer cannot distinguish whether a signal sending in a spontaneous transition occurs following a τ-transition or not. This is illustrated in Figure 6.29. An external observer does not perceive the τ-transition between the states “1-2” and “3”. The states can be gathered without modifying the a-role behaviour. The new state machine behaves just as the initial machine. The non-deterministic occurrence of the output event is preserved.

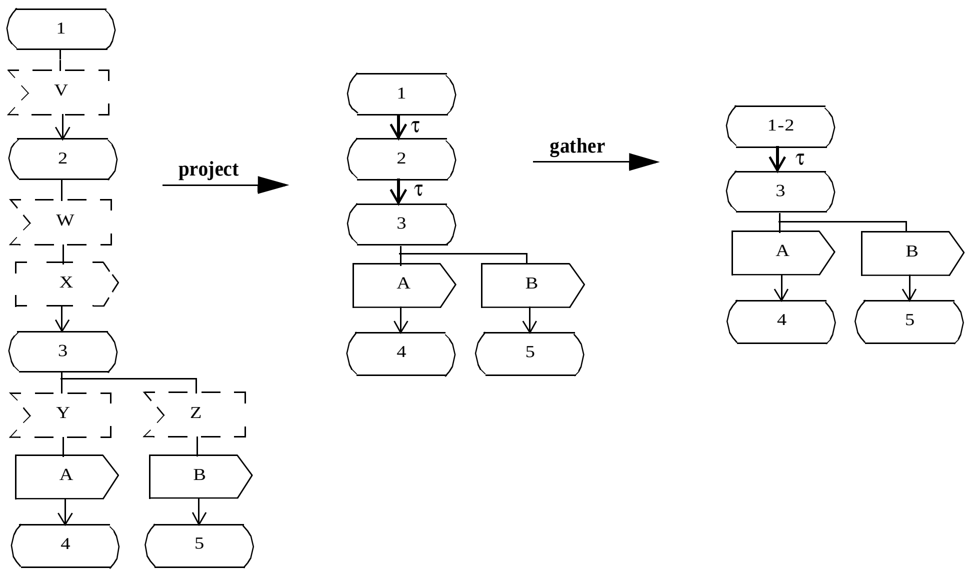


Figure 6.28 : Gathering: successive τ-transitions.

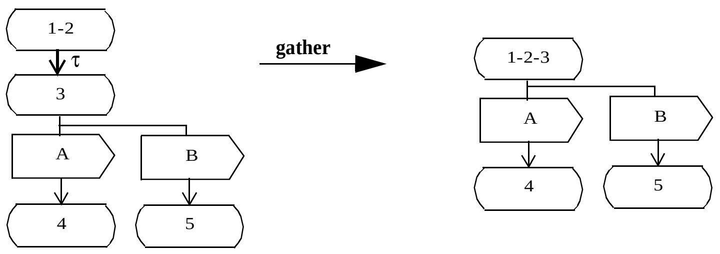


Figure 6.29 : Gathering: output behaviour.

Gathering may also be applied to a τ-successor in a choice as illustrated by the two cases in Figure 6.30. In case (b), state “1” can be gathered with the two τ-successors in the two choices. In both cases, the new state machine behaves similarly as the initial machines. The non-deterministic occurrence of the sending is preserved. Whether the signals “A” and “B” are sent from distinct states or not, does not influence the observable association behaviour.

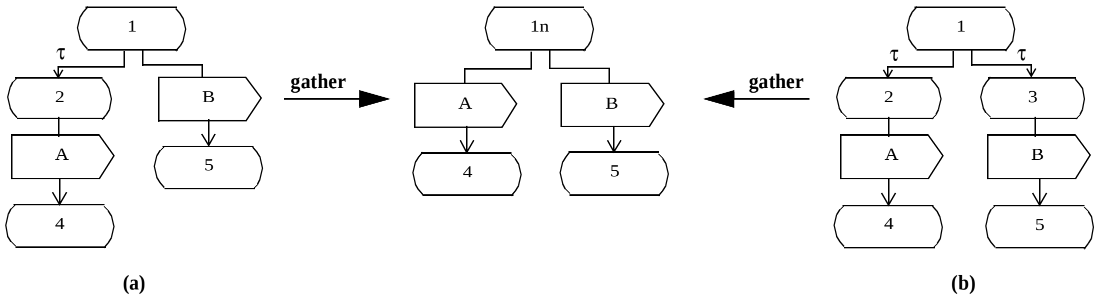


Figure 6.30 : Gathering and choice (1).

The behaviour taking place after the gathered states remains unchanged. The same successor states are specified. In Figure 6.31, the two transitions triggered by “A” lead to different states. After gathering, two transitions leading to different states are specified.

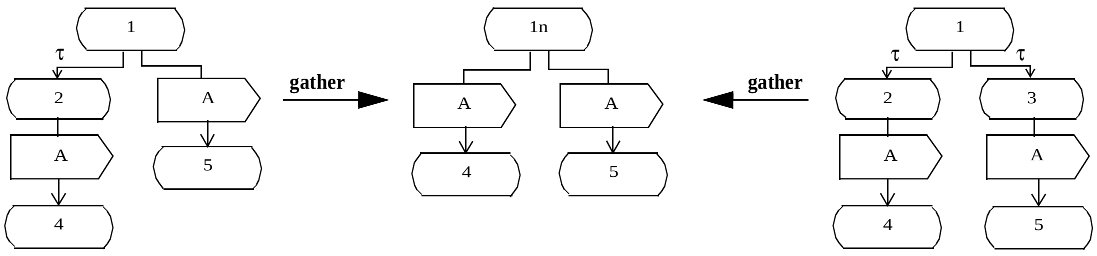


Figure 6.31 : Gathering and choice (2).

6.3.2.3 Input behaviour

In the case where a τ-successor is triggered by one or more input events, gathering can be applied if the τ-predecessor is triggered by the same set of input events, and if, for each input event, the transitions lead to equivalent states, i.e. states that exhibit the same observable behaviour. In order to simplify the definition of gathering, we propose to restrict gathering to states that describe the same *input behaviour*, i.e. the states should be able to consume the same signals and make transitions leading to *identical* states. This restriction will be justified in Section 6.3.3.2 on page 121.

Definition: Input behaviour
The input behaviour of a state describes the set of input signals consumed by the state, and for each input, the successor state(s) triggered by this input.

In case (a) shown in Figure 6.32, the states “1” and “2” describe the same input behaviour: they both can consume signal “B”, and triggering by “B” leads to the same state, state “3”. After gathering, the machine behaves similarly. In case (b), the states “1” and “2” cannot be gathered. While signal “B” is discarded when received in state “1”, it is consumed in state “2”. Note that, in case (a), there is no observable non-determinism on the association before gathering. The machine can always consume “B”.

6.3.2.4 Mixed input and output behaviours

In the case where a τ-successor is triggered by output and input events, gathering can be applied if the τ-predecessor defines the same input behaviour. An example is shown in Figure 6.33. Here state “2” is both triggered by an input event and an output event. As

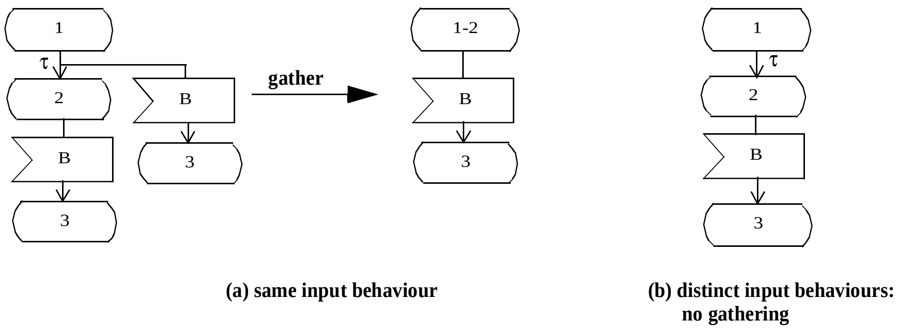


Figure 6.32 : Gathering: input behaviour.

states “1” and “2” describe the same input behaviour, they can be gathered. The new state “1-2” is able to send the same output as the states before gathering.

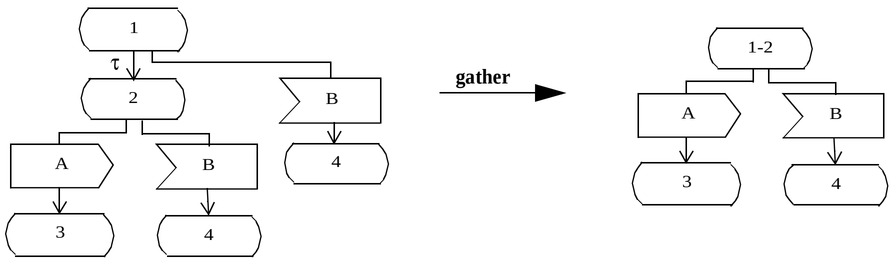


Figure 6.33 : Gathering: mixed input/output behaviour.

Note that, in that the non-deterministic occurrence of the output event “A” is preserved by gathering.

A τ-successor and a τ-predecessor that define distinct input behaviours cannot be gathered. In Figure 6.34, states “1” and “2” cannot be gathered. While signal “B” can be consumed in state “1”, it is discarded in state “2”. If states “1” and “2” were gathered, the reception behaviour would be modified; this is not desirable.

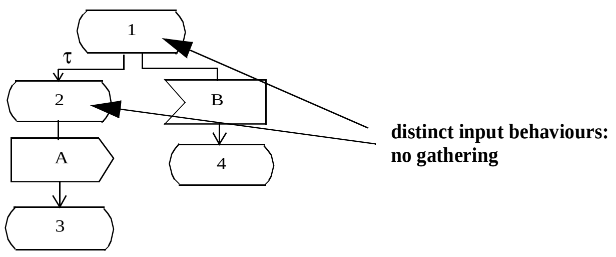


Figure 6.34 : Gathering: distinct input behaviours.

6.3.2.5 Save behaviour

We extend the previous examples by adding save behaviour. Providing the same conditions as in the previous examples, a τ-successor can be gathered with its predecessor when the states describe the same save behaviour, i.e. they are able to save the same signals.

Definition: Save behaviour
The save behaviour of a state describes the set of signals that can be saved by the state.

This is illustrated by Figure 6.35. The A states “1” and “3” describe the same save behaviour; hence they can be gathered. The non-deterministic occurrence of the sending of “B” is preserved. On the other hand, the states “1” and “2” cannot be gathered because while signal “C” is saved when received in state “1”, it is discarded in state “2”. According to the design rule "Save consistency", this should not occur. The saving of “C” should be reiterated in state “2” or “C” should be consumed in state “2”.

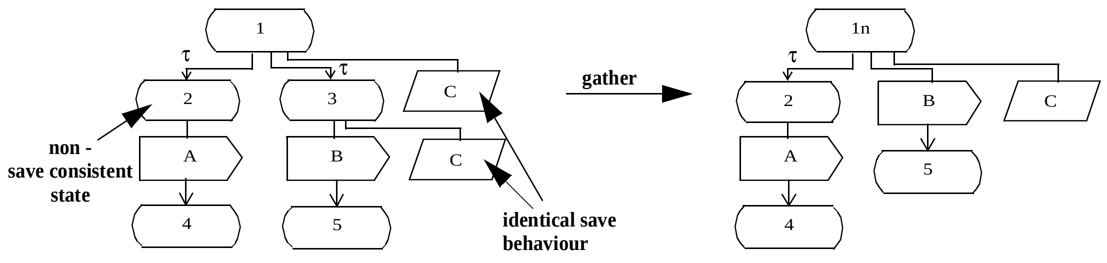


Figure 6.35 : Gathering: output and save behaviours.

Similarly, we can gather the states “1” and “2” in Figure 6.36. The states describe the same input behaviour. Both can consume “A” and triggering leads to the same state. Both states describe the same save behaviour.

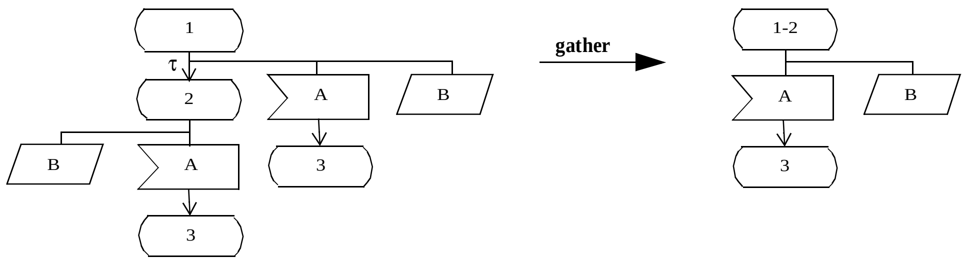


Figure 6.36 : Gathering: input and save behaviours.

The rule "Save consistency" enforces successor states to be defined consistently with their predecessors, but not conversely. Two case examples are shown in Figure 6.37. An external observer cannot distinguish state “1” from its τ-successor, and thus cannot determine when the signal “B” can be saved or not. We call this kind of behaviour “save ambiguity”. The states cannot be gathered. While signal “B” can be saved in state “2”, it is discarded in state “1”. Gathering would modify the reception behaviour; this is not desirable.

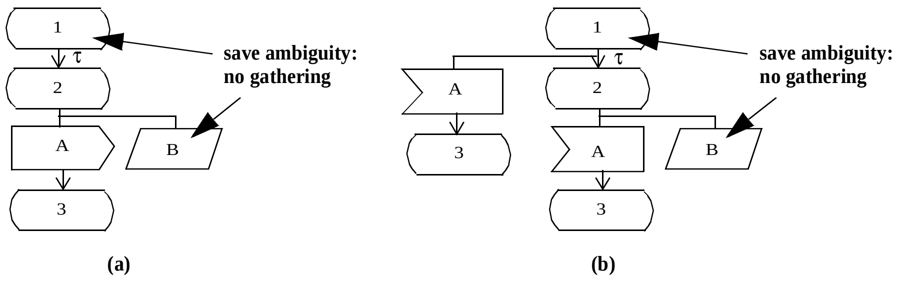


Figure 6.37 : Gathering: save ambiguity.

Definition: Save ambiguity
A save ambiguity occurs when, at some stage of an interaction, an external observer cannot determine from any observable events that a signal can be saved by the a-role state machine. The behaviour of the a-role is said to present a save ambiguity, or to be save-ambiguous.

6.3.2.6 Distinct input and save behaviours

In the previous examples, the τ-successors and τ-predecessors being gathered have described identical input behaviours and identical save behaviours. When the states describe the same input and save events, but distinct behaviours, we fail to gather them without changing the observable behaviour.

This is illustrated in Figure 6.38. The states “1” and “2” defines the same events “A” and “B”. If we assume that the τ-transition always occurs, an external observer of the machine (a) cannot perceive when the transition from “1” to “2” occurs, and cannot determine whether or not signals are saved in state “1” before being consumed in “2”. When gathering is applied as shown in (b), the signals may be consumed in the same way (storing a signal in the input port also occurs when a signal is received while a transition is being executed). However, as long as we cannot ensure that the τ-transition always occurs, gathering cannot be applied. The behaviours before and after gathering are different. The signal “A” sent to the machine (a) in state “1” may remain in the input port for ever, this is a deadlock case. On the other hand, the signal would be consumed in case (b) and triggering occur. The same reasoning also applies to show that behaviours differ when an input signal is added (for example “C” shown in dash line).

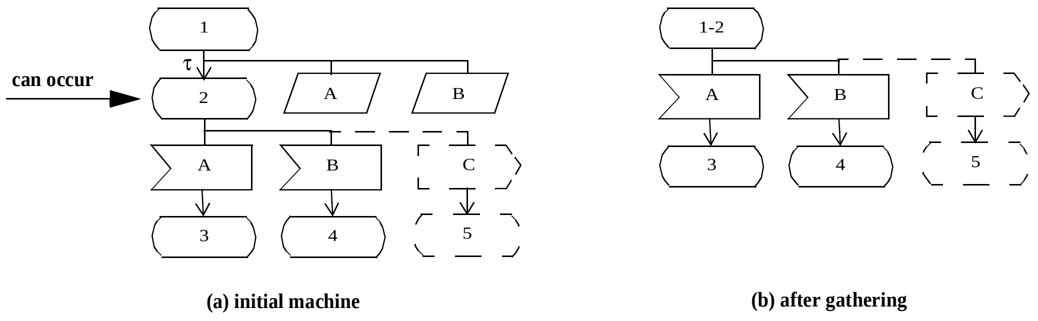


Figure 6.38 : Gathering and non-determinism (1).

In Figure 6.39, the save and input states have been permuted. If we assume that the τ-transition and the sending of “B” always occur, an external observer cannot distinguish between the machines (a) and (b). In (a) an external observer cannot determine when the transition from “1” to “2” occurs, and whether the signal “A” will be consumed in “1”, or saved in “2” and then consumed in “4”. In (b), as machines communicate asynchronously, an external observer cannot observed when the sending “B”, if any, takes place. An observer cannot determine whether the signal “A” is consumed in “1-3” or “4”. However, as long as we cannot ensure that the τ-transition and the sending of “B” always occur, gathering cannot be applied. Note that if we assume that the τ-transition occurs, but not the sending of “B”, the machine (a) deadlocks in state “3”. The machine (b) does not deadlock with the same condition on “B”: it always can consume “A”.

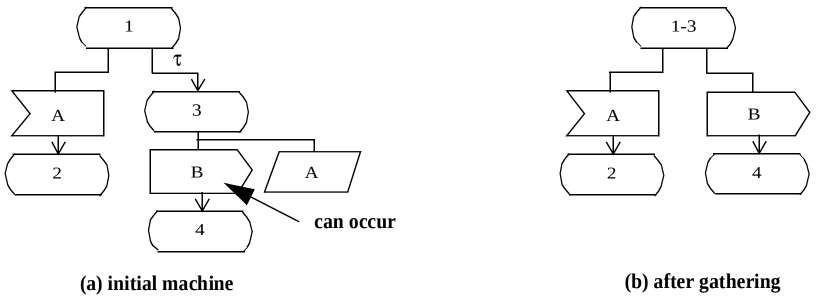


Figure 6.39 : Gathering and non-determinism (2).

In resume, in these two examples, gathering can be applied without changing the machines observable behaviour provided that the spontaneous transitions, i.e. the τ-transitions and transitions triggered by output events, always occur.

6.3.2.7 Ordering behaviour

Even when the assumption that the spontaneous transitions always occur is made, gathering cannot be always applied to a machine that defined the same input and save events.

This is the case when a τ-successor and its predecessor describe distinct ordering behaviours.

This is illustrated in Figure 6.40. In both machines, an external observer that sends the signal sequence “B” followed by “A”, may either observe that “A” is handled first or “B” is handled first. This depends on the state in which the machine is when receiving the signals. When “1” and “2” are gathered, the first behaviour, i.e. “A” first, is removed. The observable behaviour is modified.

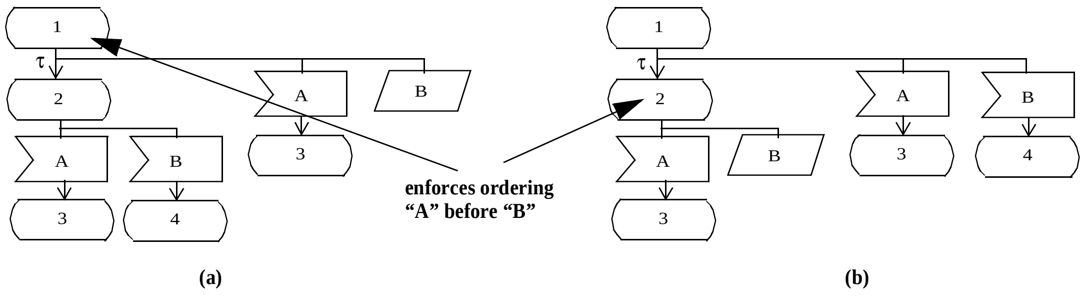


Figure 6.40 : Gathering and ordering.

6.3.2.8 Definitions

We propose two definitions of gathering: strong and weak gathering. Strong gathering maintains the machine observable behaviour. It is defined taking into account that τ-transitions may not occur. Weak gathering only maintains the observable behaviour provided that spontaneous transitions can occur. Thus cases similar to those introduced in Section 6.3.2.6 will be simplified by weak gathering, but not by strong gathering. Strong gathering is safe. Weak gathering may hide some error behaviours that occur following errors of the non-visible behaviour. This will be further discussed in Section 7.1.4 and Section 7.3.

6.3.2.8.1 Strong gathering or gathering

Definition: Strong gathering (gathering)

Strong gathering or gathering is a transformation that applies to non-exit states. Gathering merges two states that are linked by a τ-transition, i.e. a τ-successor and its τ-predecessor, to a single state provided that:

- The τ-successor and τ-predecessor define the same input behaviour.
- The τ-successor and τ-predecessor define the same save behaviour.

The new state describes any spontaneous transitions defined for the non-gathered states, except the τ-transition being gathered. It provides the input behaviour and save behaviour of the states before gathering. In the transition graph, the transitions to a τ-predecessor state merged by gathering, are replaced by transitions to the new state obtained by gathering.

Notice that:

- Gathering is never applied to σ-states. σ-states never succeed or precede τ-transitions.
- Gathering is never applied to initial states. Initial states never precede τ-transitions, but empty transitions.
- Gathering is not applied when a τ-transition links a non-exit state to an exit state. Whether termination takes place immediately after some interaction on the association has occurred or not, is of importance when roles are composed.
- Gathering is applied iteratively when a transition chart describes a sequence of τ-transitions or choices. As illustrated by Figure 6.28 and Figure 6.29, or Figure 6.30, states “1” and “2” are first gathered; then the new state and state “3” are gathered.
- A state obtained by gathering may define τ-transitions. In Figure 6.35, the transition between “1n” and “2” is a τ-transition.

After gathering, the τ-predecessor states are removed from the state graph because they are no longer reachable from the initial states. τ-successor states, on the other hand, cannot always be removed from the state graph. This is the case when a τ-successor is reachable from other states through a non τ-transition. An example is shown in Figure 6.41. Gathering is a transformation that suppresses τ-transitions rather than τ-successors from the state graph. τ-successor states that are no longer reachable from the initial states, can be removed applying Algorithm 7.5 on page 167.

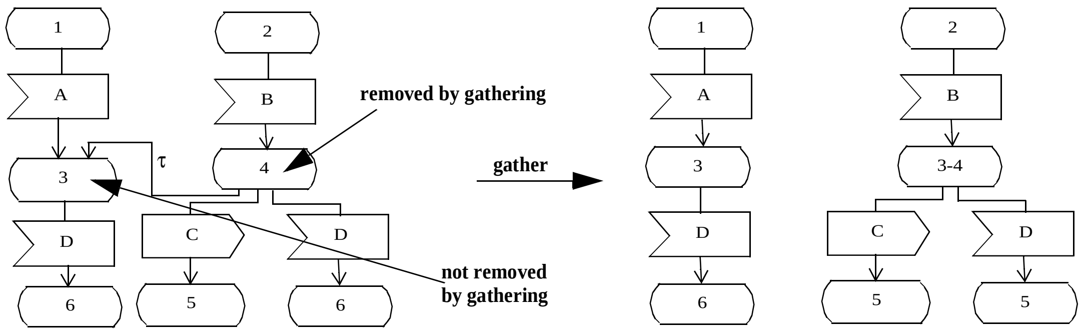


Figure 6.41 : Gathering and state removal.

T-rule: Strong gathering

After strong gathering or gathering, a transition chart exhibits the same observable association behaviour as the initial transition chart.

Justification:

A state obtained by gathering behaves as the states it is gathered from:
- It can consume any signal specified as inputs in the gathered states. The triggered transitions lead to the same states as in the initial chart. No other signal can be consumed.
- It saves any signal specified as save in the gathered states.
- It maintains the ordering in which signals are consumed. Ordering can be enforced using save. The new and gathered states specify the same save and input behaviour.
- The new state may send spontaneously any signal specified as outputs in one of the initial states. The triggered transitions lead to the same states as in the initial chart.
- τ-transitions leading to states exhibiting distinct input or save behaviours are maintained.

6.3.2.8.2 Weak gathering

The definition of weak gathering is more complex as various input and save combinations are taken into account.

Definition: Weak Gathering

Weak gathering is a transformation that applies to non-exit states. Gathering merges two states that are linked by a τ-transition, i.e. a τ-successor and its τ-predecessor, to a single state provided that:
- Any signal specified as an input in the τ-successor is either specified as an input or as a save signal in the τ-predecessor. In the input case, the τ-successor and τ-predecessor should transit to identical successor states. In the save case, no other input should be specified in the τ-predecessor.
- Any signal specified as a save in the τ-successor is either specified as an input or as a save signal in the τ-predecessor. In the input case, no other input should be specified in the τ-successor.
- Any signal specified as an input in the τ-predecessor is specified as an input in the τ-successor. The τ-successor and τ-predecessor should transit to identical successor states.
- Any signal specified as a save in the τ-predecessor is either specified as an input or as a save in the τ-successor. In the input case, no other input should be specified in the τ-predecessor.

The new state describes all spontaneous transitions defined for the non-gathered states, except the τ-transitions removed by gathering. It provides the input behaviour of the states being gathered. It provides the save behaviour of the states being gathered, except for signals already described as inputs. In the transition graph, the transitions to a τ-predecessor state merged by gathering are replaced by transitions to the new gathered state.

The observations made for strong gathering also yields for weak gathering.

T-rule: Weak gathering
After weak gathering, a transition chart exhibits the same observable association behaviour as the initial transition chart provided that spontaneous transitions can occur.

Justification:
Any state obtained by weak gathering behaves as the states it is gathered from:
- The new state can consume any signal specified as inputs in both gathered states. The triggered transitions lead to the same states as in the initial chart. No other signal can be consumed.
- Signals that were saved in both gathered states are saved. No other signal can be saved.
- A signal specified as save in one state and input in the other before gathering is specified as input in the new machine provided that ordering is not changed. If a signal specified as a save signal in one of the gathered states is specified as an input in the other state, no other input can be specified in the save state. Otherwise if ordering is enforced in one of the initial states, gathering can only be applied if the same ordering is enforced in the other initial states.
- As the spontaneous transitions occur, the transformation of a save signal to an input signal is harmless: a save signal can always be retrieved from the input port in the initial machines.
- The new state may spontaneously send any signal specified as output in the initial states. The triggered transitions lead to the same states as in the initial chart.
- τ-transitions leading to states exhibiting distinct input or save behaviours are maintained.

6.3.3 State equivalence

Transition charts may contain equivalent states that exhibit the same observable association behaviour and lead to states that also exhibit the same observable association behaviour. In order to facilitate interface validation, it is desirable to identify such states, and replace them by a single state. This replacement, called minimisation, reduces the size of the state graph. It also facilitates the identification of equivoque transitions (see Section 6.5).

Equivalence may be defined in different manners depending on whether τ-events are observed or not [Milner 1989]. In our approach, we wish to retain τ-events that contribute to state changes that influence the visible association behaviour. As gathering is a transformation that removes τ-transitions that do not influence the visible association behaviour, we propose to take into account τ-events in the definition of state equivalence, and to combine gathering and minimisation in order to remove redundant and non-observable behaviour from the transition graph.

We first introduce the definition of strong state equivalence, and show that gathering and minimisation based on this definition fail to identify all states that exhibit the same observable association behaviour. In order to be able to remove any redundant behaviour, we refine the definition of strong state equivalence to the definition of state equivalence. The definitions of equivalence are expressed in terms of triggering events, so that it is possible to easily define operational minimisation algorithms. Minimisation algorithms will be proposed in Section 6.9.

6.3.3.1 Strong state equivalence

Definition: Strong state equivalence
States are strongly equivalent if they define the same triggering and save events, and their successor states are strongly equivalent. Exit states are strongly equivalent if they define the same exit conditions.

Recall that triggering events encompass inputs, outputs and τ-events. A triggering event may lead to several successor states. Examples were shown in Figure 6.12 and Figure 6.13. Two states S_1 and S_2 are not equivalent unless for each triggering event E and for each possible successor state of S_1 triggered by E, there is at least one equivalent successor state of S_2 triggered by E, and conversely.

Equivalent states exhibit the same observable association behaviour, as they can accept and generate the same visible association signals, and they can execute the same internal actions in terms of spontaneous state changes, i.e. τ-transitions. As their successor states are equivalent, the successor states also define the same triggering and save events, and lead to new successor states that also have these properties.

The definition of strong state equivalence is similar to the definition of equivalence proposed by [Holzman 1991], and cognate of the definition of [Hennie 1968]. A main difference with the latter approach is that Hennie defines a state as a condition in which signals may be consumed; signal sending does not occur spontaneously, but is triggered by the consumption of a signal. In addition, in Hennie's approach, the consumption of a signal leads to a single successor state. The definition of strong state equivalence relates to the definition of strong equivalence in [Milner 1989]. However Milner defines the equivalence of agents rather than agent states, and the definition applies to synchronous communication rather than asynchronous communication.

The state machine shown in Figure 6.42, inspired from [Holzmann 1991], illustrates the equivalence of states: states "1" and "4", "2" and "5", "3" and "6" are equivalent. Note that, in this example, we have to assume that "2" and "5", and "3" and "6" are equivalent in order to establish the equivalence of the states "1" and "4". Similarly, in order to establish the equivalence of the states "2" and "5", and "3" and "6" we have to assume that "1" and "4" are equivalent. As none of these pairs can be found non-equivalent, the assumptions hold.

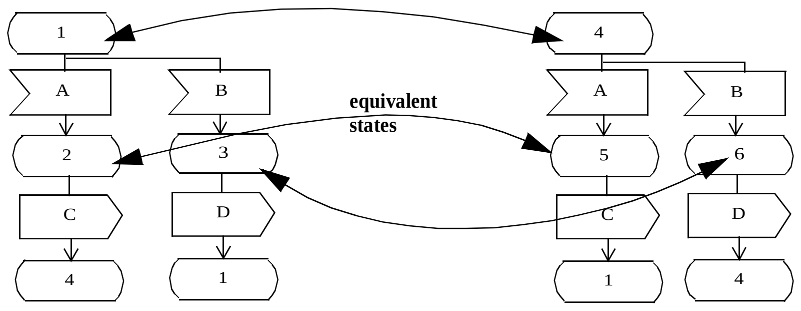


Figure 6.42 : Strongly equivalent states.

This example describes a special case of cyclic dependency. Usually, a pair of equivalent states lead to pairs of identical states.

Definition: Strong minimisation

Strong minimisation is a transformation that replaces strongly equivalent states by a single state. The new state defines the same triggering and save events as the original states, and each successor state is either the same original state, or a new state obtained from the replacement of the original strongly equivalent successor states. Strong minimisation maintains exit conditions. Strong minimisation merges entry conditions by a logical "or"[1].

T-rule: Strong minimisation

After strong minimisation, a transition chart exhibits the same observable association behaviour as the initial transition chart.

1. See Section 6.3.3.1.1.

Justification:
Any new state defines the same triggering and save events, and leads to states that also have these properties. Entry and exit properties are maintained through the constraints set on entry and exit conditions.

Strong minimisation also applies to σ-states. As σ-states have a particular semantics, a σ-state can only be strongly equivalent to a σ-state, not to an ordinary state.

6.3.3.1.1 Extension to the SDL language

OR-logical expressions of entry conditions are introduced here as an extension to SDL. A composite state is entered through the initial state attached the condition “c1 or c2” when at least one of the conditions is true.

In the case of minimisation, two strongly equivalent initial states S1 and S2 attached the entry conditions c1 and c2 are replaced through strong minimisation by a new initial state attached the entry condition “c1 or c2”.

6.3.3.2 Strong state equivalence and gathering

The strong state equivalence relation takes τ-transitions into account. As the gathering transformation removes some τ-transitions in a transition chart, states that are not strongly equivalent before gathering, may become equivalent after gathering.

Gathering has not been applied to the transition chart shown in Figure 6.43. It would be transformed to the transition chart shown in Figure 6.42 by gathering. However, states “2a” and “5” are not equivalent. Thus states “1” and “4” are not equivalent, and states “3” and “6”, and “2” and “5” are not equivalent.

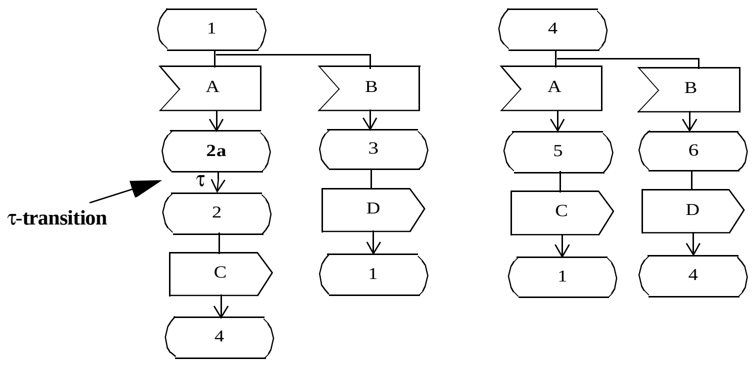


Figure 6.43 : Equivalence and gathering.

When gathering is applied before minimisation, non-observable τ-transitions can be removed. On the other hand, minimisation may lead to a new transition graph that can be further reduced by gathering. It may not be possible to gather two states because they define an input event that leads to distinct successor states before minimisation, while after minimisation these two successor states may be replaced by a single state. Therefore gathering should be re-applied after minimisation. Again, this new gathering transformation may introduce new states that are strongly equivalent with other states. Thus gathering and minimisation should be applied in an iterative manner on the transition chart until one of the transformation does not modify the transition chart any more. As the graph has a finite number of states, the number of transformations is finite. In most cases, there will be no need for iterating the transformations several times. The need for many iterations is a symptom of a complex - and possibly bad - design, where distinct states describe identical triggering conditions.

Gathering and strong minimisation may fail to identify states that exhibit the same observable association behaviour. This is the case when some states in the transition chart cannot be found equivalent before some other states are gathered, and conversely. An example is shown in Figure 6.44. The machine has a simple observable behaviour: it can consume the signals “A” and “B” successively in an iterative manner. The complex transition chart can not be reduced by gathering and strong minimisation however. States “1” and “2” cannot be gathered before states “3” and “5” are found to be equivalent. States “3” and “5” cannot be found to be equivalent before states “3” and “4” are gathered. States “3” and “4” cannot be gathered before states “2” and “1” are found to be equivalent.

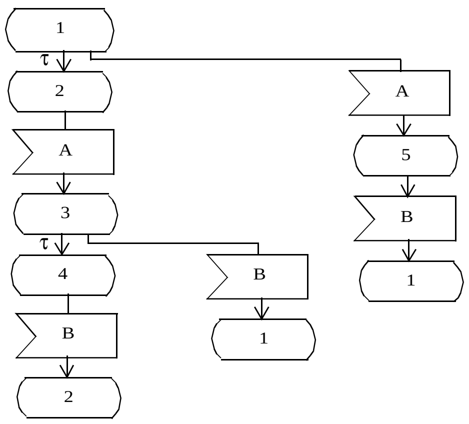


Figure 6.44 : Strong equivalence and gathering: failing to reduce chart.

This example describes a special case of cyclic dependency that is quite similar to the case shown in Figure 6.42. The τ-transitions between states “2” and “1”, and between states

"3" and "4" prevent us from considering the states as equivalent. We need to slightly change the definition of state equivalence in order to be able to resolve such cyclic dependencies.

6.3.3.3 State equivalence (revised)

The new definition of state equivalence uses the concept of τ-state defined as follows:

Definition: τ-state

The τ-state of a state S is a state that describes the same triggering events as the state S and provides the same save behaviour. Each triggering event leads to the same state when applied to S and its τ-state. In addition to these triggering events, the τ-state defines a τ-transition to itself.

Thus a τ-state can be seen as the result of a transformation that adds a τ-transition from a state to itself. An example is shown in Figure 6.45. A naming convention is introduced: the prefix "τ-" is added to a state name to designate its τ-state.

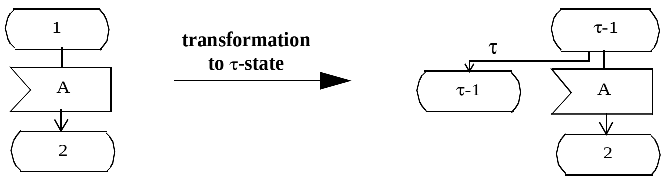


Figure 6.45 : τ-state.

Definition: State equivalence

Two states are equivalent if their τ-states define the same triggering and save events, and their successor states are equivalent. Exit states are equivalent if they define the same exit conditions.

The τ-transition introduced in the τ-state is not observable. However it is essential when comparing the triggering events of two states, when one of them defines a τ-transition to the other one. Using this definition of state equivalence, the τ-states "τ-1" and "τ-2" of states "1" and "2" on Figure 6.44 define the same triggering events. They may thus be assumed to be equivalent. The state "τ-1" defines two τ-transitions, one to "τ-1" and one to "τ-2". For each successor state of "τ-1" triggered by τ, i.e. "τ-1" and "τ-2", there is one equivalent successor state of "τ-2" triggered by τ: "τ-2", and conversely.

Definition: Minimisation

Minimisation is a transformation that replaces equivalent states by a single state. The new state defines the same triggering and save events as the initial states, and each successor state is either the initial successor state, or a new state obtained from the replacement of the initial equivalent successor states. Any τ-transition defined from the new state to itself is removed. Minimisation merges entry conditions by a logical “or”.

T-rule: Minimisation

After minimisation, a transition chart exhibits the same observable association behaviour as the initial transition chart.

Justification:

The introduction of a τ-transition from the states to themselves in the definition of equivalence is harmless. The new τ-transition does not introduce any observable behaviour.

For the same reasons as for strong equivalence, gathering and minimisation should be applied in an iterative manner to the transition chart. *In the following, we will assume that these transformations have been applied to the a-role transition charts.*

6.4 Event ordering and causality

The transformation of a-role state graphs to transition charts lead to a-roles where internal behaviours and non-visible interactions taking place before the sending of a signal are represented in a quite similar way: by a state. This is illustrated on Figure 6.46: the two s-roles are projected to identical a-role behaviours. While the σ-state “σ-2” in case (a) indicates that the signal “B” is sent as a direct consequence of the consumption of the signal “A”, the state “2” in case (b) indicates that the signal “B” is sent following some non-visible action made after signal consumption. Case (a) describes the causality of signal sending (i.e. receiving “A”). Case (b) hides it.

The two a-roles provide slightly different observable behaviours:

- In case (a), “B” always occurs if the state “σ-2” is entered, and no other event can occur between “A” and “B”. An observer can send the signal “C” immediately after “A” is sent. The signal is stored in the input port and consumed in state “3”.
- In case (b), on the other hand, “B” may occur. It occurs provided that some non-observable behaviour triggers the transition. When an observer sends “C” immediately after

"A", the signal may be discarded "C". In case (b), "C" should not be sent before "B" has been received.

While hiding causality, case (b) also sets strong requirements on the ordering in which events take place in the complementary a-role. Note that the behaviour required by the a-role in case (b), also interacts consistently with the a-role in case (a).

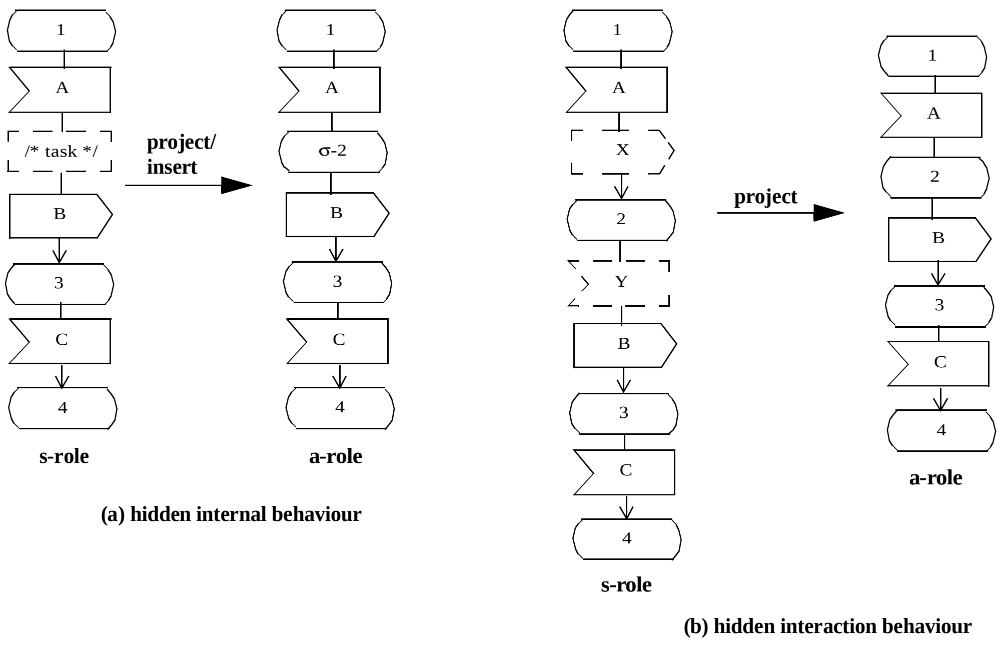


Figure 6.46 : Causality and event ordering.

By hiding the nature of the a-role states to an external observer, we may enforce a strict signal ordering on the complementary a-role. A complementary a-role that behaves well with strict ordering interacts consistently independent of the nature of the internal states provided that the spontaneous transitions in the initial a-role occur.

Conversely, when it is desirable to relax the ordering requirements on the complementary a-role, for example for optimisation purposes, save may be introduced. An example is shown in Figure 6.47. Recall the design rule "Save and ordering": using save for enforcing input ordering should only be applied in special cases. Note that the rule "Ordering with save and concurrency" has been followed in Figure 6.47: signal "C" is retrieved in state "3" where no non-visible signals can be consumed.

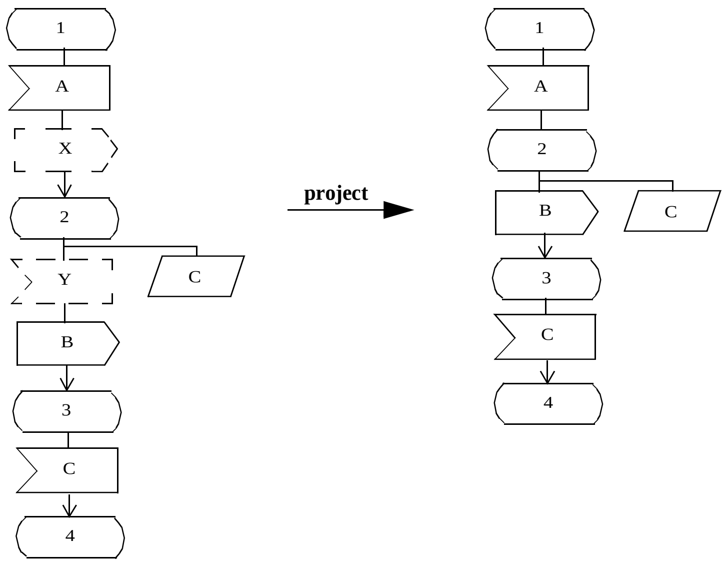


Figure 6.47 : Relaxing event ordering.

6.5 Equivoque transitions

Definition: Equivoque transitions

Two or more transitions are equivoque[1] when they are defined for the same state and the same event (i.e input, output or τ-event), and lead to distinct non-equivalent states.

Equivoque transitions lead to non equivalent-states, and then to divergent behaviours. In in some cases, these divergent behaviours are perceived as ambiguous, i.e. an external observer is uncertain about which further behaviour initiative should be taken. A-roles and the s-roles they are derived from should be specified such that ambiguous behaviours are avoided. This will be discussed in Chapter 7. Sections 6.5.1 to 6.5.3 introduce different kinds of ambiguity.

In Figure 6.48, the two transitions triggered by the input event “A” in state “1” lead to non-equivalent states, states “2” and “3”. The transitions are equivoque. However no ambiguity is introduced: as the states “2” and “3” represent conditions in which signals are sent, an external observer is able to perceive which behaviour has been selected.

1. According to Merriam-Webster, equivoque means subject to two or more interpretations and usually used to mislead. Synonyms: equivocal, obscure, ambiguous.

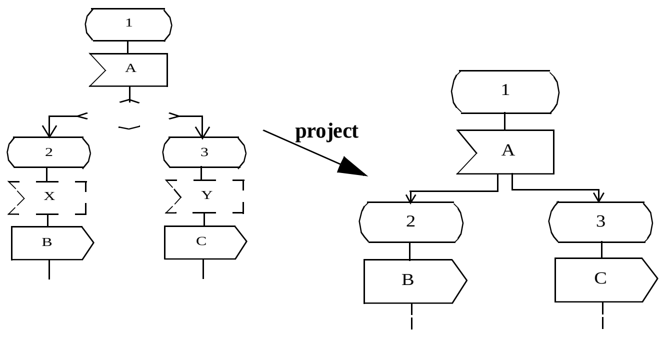


Figure 6.48 : Equivoque transitions triggered by an input event.

In Figure 6.49, the equivoque transitions are triggered by an output event. Case (a) results from the abstraction of a decision, and case (b) from the abstraction of an interaction on another association. The equivoque transitions are described in two slightly different ways in the transition charts, but they represent identical observable behaviours.

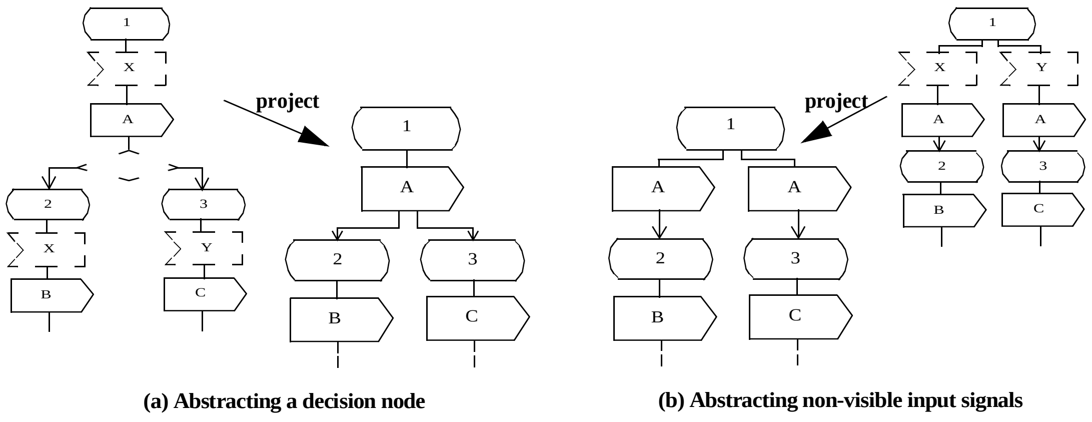

1
X
A
2
3
X
Y
B
C
project
1
A
2
3
B
C
(a) Abstracting a decision node
1
A
A
2
3
B
C
project
1
X
Y
A
A
2
3
B
C
(b) Abstracting non-visible input signals

Figure 6.49 : Equivoque transitions triggered by an output event.

In Figure 6.50, the equivoque transitions are triggered by τ-events. As state “1” and “2” have distinct input behaviours, they cannot be gathered. Similarly “1” and “3” cannot be gathered.

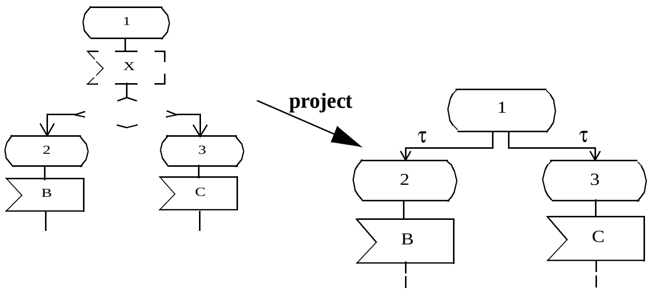


Figure 6.50 : Equivoque transitions triggered by a τ-event.

6.5.1 Input ambiguity

When equivoque transitions lead to non-equivalent states in which different signals are consumed, an external observer may not be able to determine which signals are being expected. An example was given in Figure 6.50, and similar cases where the equivoque transitions are triggered by an output or input events are shown in Figure 6.51. An external observer cannot distinguish state “2” from state “3”, and thus cannot determine which signals are expected after A. We call this kind of ambiguous behaviour an “input ambiguity”. The behaviour of the a-role is not predictable, or non-deterministic.

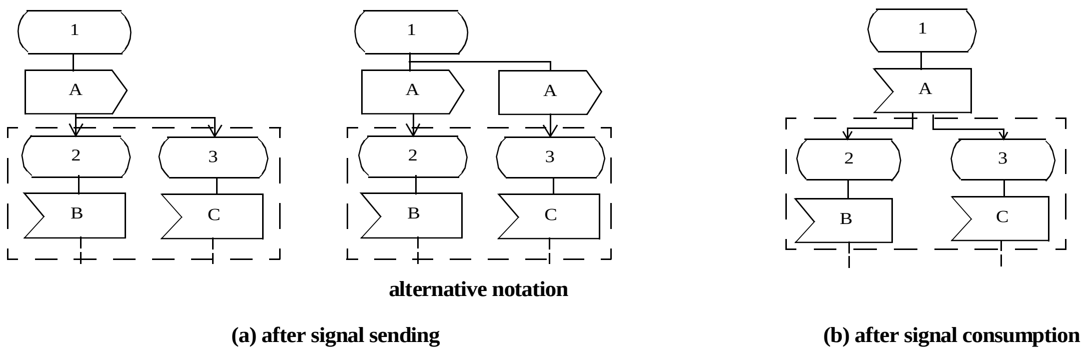


Figure 6.51 : (Strong) input ambiguity.

We distinguish between two forms of input ambiguity: weak and strong input ambiguities. In weak input ambiguity, an external observer may determine some of the signals that are expected by the a-role state machine, but not all. In that case the machine can enter distinct states, and there is an overlap between the set of input signals expected in the states. In strong input ambiguity, that we will simply call input ambiguity, there is no such overlap. Examples of strong and weak input ambiguity are shown in Figure 6.51 and Figure 6.52.

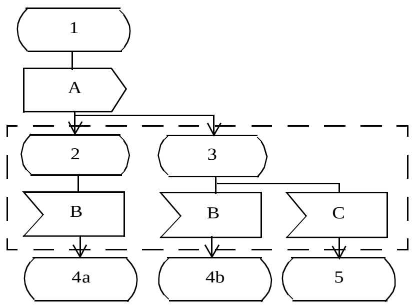


Figure 6.52 : Weak input ambiguity.

Definition: Weak input ambiguity

A weak input ambiguity occurs when at some stage of an interaction, an external observer knows that only input(s) may occur, but is only able to determine some of the input(s) expected by the a-role state machine, but not all. The behaviour of the a-role is said to present a weak input ambiguity, or to be weakly input-ambiguous.

Definition: Strong input ambiguity or input ambiguity
A (strong) input ambiguity occurs when at some stage of an interaction, an external observer knows that only input(s) may occur, but is not able to determine any of the input(s) expected by the a-role state machine. The behaviour of the a-role is said to present a (strong) input ambiguity, or to be (strongly) input-ambiguous.

Branching in a state graph does not necessarily represent an ambiguous input behaviour. The behaviour in the example shown in Figure 6.53 appears to be quite similar to the behaviour in case a of Figure 6.51. Both state machines provide the same sets of traces: (“A”, “B”) and (“A”, “C”). However while in the first example the consumption of “B” (or “C”) may fail after the sending of “A”, the consumption of signal “B” (and “C”) is always possible after the sending of “A” in the second example.

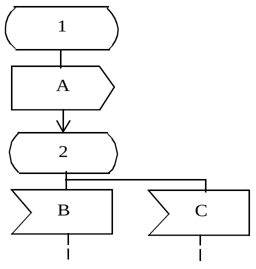


Figure 6.53 : Branching, but deterministic behaviour.

Input ambiguity does not necessarily occur immediately after the equivoque transitions. Several transitions that exhibit an identical behaviour may succeed equivoque transitions before the ambiguity takes place. This is illustrated in Figure 6.54. Notice that although the states “2” and “3” provide the same observable transitions, they are not equivalent, since their successors are not equivalent.

Also in Figure 6.52, the weak input ambiguity that occurs immediately after the equivoque transitions may lead to new ambiguous behaviours. An external observer may not be able to determine the behaviour occurring after “B”. In the case where the states “4a” and “4b” are distinct, and are not followed by distinct signal sending, a new ambiguity may occur.

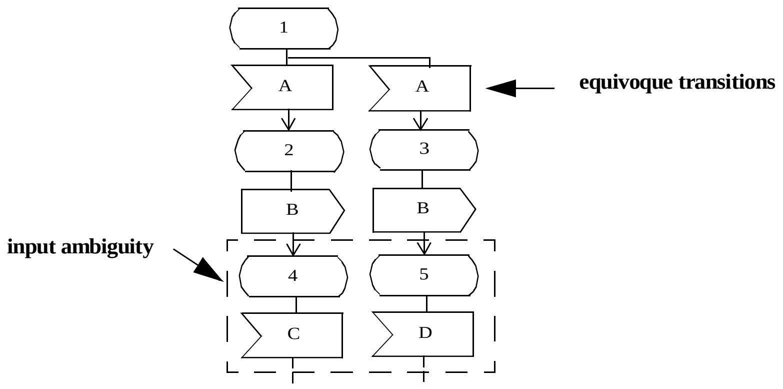


Figure 6.54 : Input ambiguity occurring after identical signal sequences.

In Section 6.7 we will see that input ambiguity can occur when τ-events are combined with output events in a state.

6.5.1.1 Input ambiguity withdrawn by save

An ambiguity indicates that an external observer is uncertain about which further behaviour initiative is expected. By considering only input events, our definitions of input ambiguity are too strict. The introduction of save may clear away an input ambiguity. An example is shown in Figure 6.55. The equivoque transitions lead to states where “B” and “C” may be consumed in different orders. An external observer may send “B” and “C” in any order. Note that in the case where the states “6a” and “6b” are distinct, and are not followed by distinct signal sending, a new ambiguity may occur.

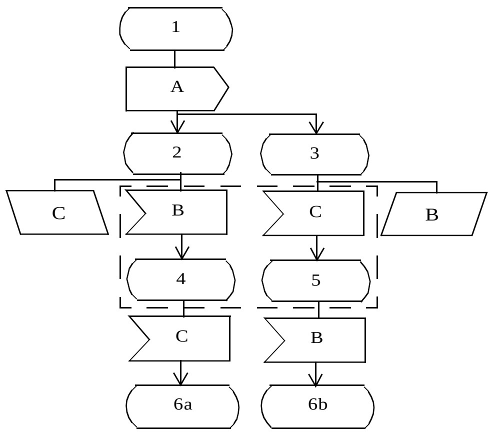


Figure 6.55 : Strong input ambiguity and save.

This case is seldom encountered when the design rule "Save and ordering" is enforced. It will not be further considered in this thesis.

6.5.2 Mixed ambiguity

In the previous examples, the equivoque transitions lead to states were distinct signals are either sent or consumed. Sending and consumption may also be mixed as shown in Figure 6.56. Here one state sends a signal while the other is waiting for the reception of a signal. An external observer is able to perceive the sending of “C”, but this sending does not necessarily take place. An external observer cannot distinguish whether the a-role state machine has entered state “2”, and is waiting for signal “B”, or whether the machine has entered state “3”, and is waiting for some non-visible event to happen before sending signal “C”. We call this kind of ambiguous behaviour a “mixed ambiguity”.

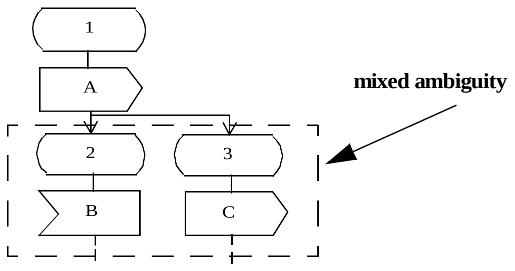


Figure 6.56 : (Strong) mixed ambiguity.

Similarly to input ambiguity, we distinguish between two forms of mixed ambiguity: weak and strong mixed ambiguities. In weak mixed ambiguity, an external observer may determine some of the events expected by the a-role state machine. This means that the machine can enter distinct states, and that there is an overlap between the set of input and output events triggering these states. We use the terms “input overlap” to denote that common input events may occur in these states, and “output overlap” to denote that common output events may occur in these states. In strong mixed ambiguity, that we will simply call mixed ambiguity, there is no such overlap. Strong and weak mixed ambiguity are illustrated in Figure 6.56 and Figure 6.57

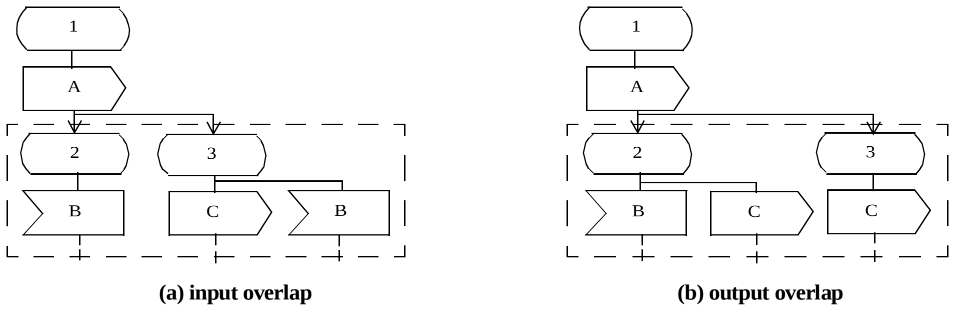


Figure 6.57 : Weak mixed ambiguity.

Definition: Weak mixed ambiguity

A weak mixed ambiguity occurs when at some stage of an interaction, an external observer knows that both input(s) and output (s) may occur, but is only able to determine some of the input or output events expected by the a-role state machine, but not all. The behaviour of the a-role is said to present a weak mixed ambiguity, or to be weakly mixed-ambiguous.

Definition: Strong mixed ambiguity or mixed ambiguity

A (strong) mixed ambiguity occurs when at some stage of an interaction, an external observer knows that both input(s) and output (s) may occur, but is not able to determine any of the input or output events expected by the a-role state machine. The behaviour of the a-role is said to present a (strong) mixed ambiguity, or to be (strongly) mixed-ambiguous.

6.5.2.1 Mixed ambiguity withdrawn by save

Similarly to input ambiguity, save may clear away a mixed ambiguity. An example is shown in Figure 6.58. For the same reasons as with input ambiguity, this case will not be further considered in this thesis.

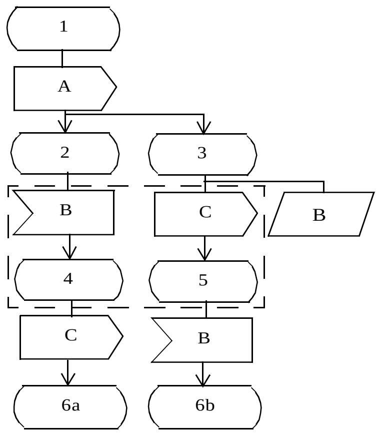


Figure 6.58 : Strong mixed ambiguity and save.

6.5.3 Termination ambiguity

When combined with the sending or consumption of a signal, termination may also create ambiguity. This is shown in Figure 6.59. In case (a), an external observer cannot determine whether the a-role state machine has terminated, or is waiting for the reception of a signal. This is a special form of input ambiguity. In case (b), an external observer cannot determine whether the state machine has terminated, or is waiting before sending a signal. This is a special form of mixed ambiguity.

Definition: Termination ambiguity
A termination ambiguity occurs when at some stage of an interaction, an external observer is not able to determine whether the a-role state machine has terminated, or is waiting for an input or output event to occur. The behaviour of the a-role is said to present a termination ambiguity, or to be termination-ambiguous.

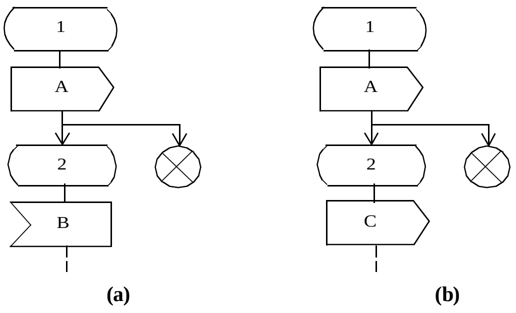


Figure 6.59 : Termination ambiguity.

6.5.4 Exit condition ambiguity

Equivoque transitions may lead to exit states attached distinct exit conditions. In that case, an external observer is not able to determine which exit condition applies. An example is shown in Figure 6.60.

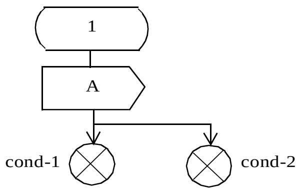


Figure 6.60 : Exit condition ambiguity.

Definition: Exit condition ambiguity
An exit condition ambiguity occurs when an external observer knows that the a-role state machine has terminated, but is not able to determine which exit condition is attached to the termination. The behaviour of the a-role is said to present an exit condition ambiguity.

6.6 Mixed initiatives

In most of the examples discussed so far, states have represented conditions where signals were either sent or consumed. Such states describe asymmetric obligations between a-roles, where an interaction can be initiated by only one of the a-roles, and where each new interaction step can be triggered by only one of the a-roles. More complex interactions may be defined in which both a-roles are allowed to take the initiative to trigger a new interaction step, i.e. to send a signal. We call this form of behaviour *mixed initiatives*. In the a-role state graph, mixed initiatives are represented by states where both the consumption and sending of signals are enabled.

Definition: Mixed initiative state
A mixed initiative state is a state where both signal consumption and sending can occur.

As a-roles communicate asynchronously, they perceive the occurrence of communication at different moments of time. The reception of a signal is perceived some time after its sending. When an a-role and its complementary a-role are both enabled to send a signal during the same interaction step, the signals may cross each other. Such behaviour may lead to unspecified signal reception, and deadlocks where each a-role state machine waits for the other machine's answer.

Mixed initiatives serve two main purposes:

- Mixed initiatives may describe concurrent behaviours, where each interacting a-role state machine may take the initiative to select one of the behaviours. In that case, the crossing of signals leads to a conflict. This form of behaviour is called "conflicting initiatives" in [Bræk and Haugen 1993]

- Mixed initiatives may describe alternative orderings of input and output events, i.e. an event may be sent indifferently before or after the reception of another event. In that case, two interacting a-roles do not necessarily perceive the same orderings of events.

Figure 6.61 illustrates these two purposes:

- In case (a), the machine either selects the behaviour ("A", "C"), or is requested by the complementary machine to perform the other behaviour ("B", "D"). If the signals "A" and "B" cross each other, the signal "B" is received while the machine is in state "2" leading to an unspecified signal reception. In the worst case, the complementary machine behaves similarly, leading to a deadlock.

- In case (b), the two sequences describe the same events occurring in different orders. The two alternative sequences lead to the same state; thus the further behaviour does not depend on the ordering of events. This is an essential point as the machine and the complementary machine may not perceive the same orderings: when the machine receives the signal “B” before it sends “A”, it can deduce that the complementary machine has sent “B” before receiving “A”; on the other hand, if the machine receives “B” after it has itself sent the signal “A”, it cannot determine whether the complementary machine has sent “B” after or before receiving “A”, i.e. in the same order or in a different order.

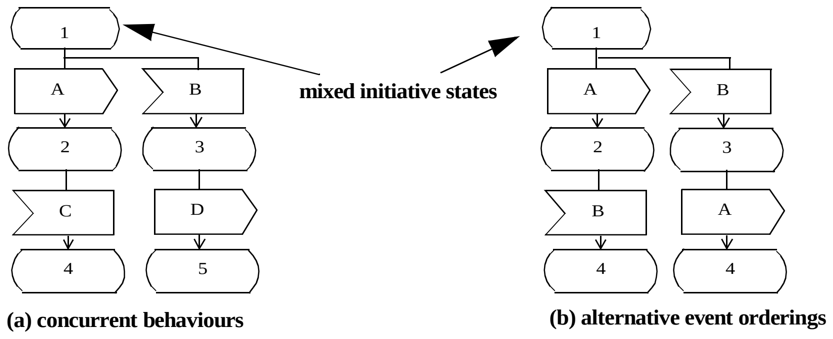


Figure 6.61 : Mixed initiatives: two main purposes.

A-roles and the s-roles they are derived from should be specified in such a way that potential conflicts are detected and resolved. In the case of alternative orderings, the alternative behaviour sequences should converge to a common behaviour. This will be discussed in Chapter 7.

6.7 Acute τ-transitions

Definition: Acute τ-transitions

Acute[1] τ-transitions are τ-transitions that cannot be removed from the a-role transition chart by gathering and minimisation.

The states linked by acute τ-transitions are states that provide distinct input or save behaviours, that introduce save ambiguity, or do not enforce input ordering consistently. Section 6.3.2 about "State gathering" has described those cases. Acute τ-transitions require special attention. They may lead to ambiguous behaviours, either as triggers of equivoque transitions as explained in Section 6.5, or when combined with other transitions. This section focuses on the combination of τ-transitions with other transitions.

Note that acute τ-transitions are a symptom of ambiguity, but do not necessarily mean that a machine presents ambiguity. Gathering requires the successor states triggered by identical input events to be identical. Successor states may be distinct without introducing ambiguity, but only output divergence. This is shown in Figure 6.62. States “1” and “2” cannot be gathered as the triggering by “A” lead to distinct states. However, an external observer is able to determine the further machine behaviour after receiving “B” or “C”.

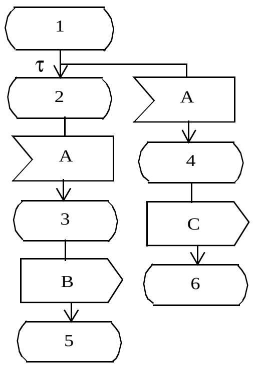


Figure 6.62 : Acute τ-transition with no ambiguity.

6.7.1 Mixed ambiguity

In Figure 6.63, the τ-events link states that provide distinct input behaviours. In both cases the τ-event is combined with an output event “A”. As the τ-transitions cannot be perceived by an external observer, the combination of these triggering events introduces ambiguity. Case (a) describes a mixed ambiguity: an external observer is not able to deter-

1. According to Merriam-Webster, the term “acute” can be associated with the ideas of sudden onset, urgent attention and uncertain outcome.

mine whether output “A” or input “B” will occur. Case (b) describes a weak mixed ambiguity: output “A” can always occur, but input “B” may not always be consumed. In case (b), the behaviour “A” may lead to new ambiguity depending on the definition of the states “2a” and “2b”. Note that in both cases it is possible to transform the graph by inserting a state between state “1” and the sending of signal “A” without modifying the observable association behaviour. This is the reverse operation of gathering. After this transformation, state “1” describes equivoque τ-transitions. Thus, the analysis of this case can be done in a similar way as the analysis of equivoque transitions.

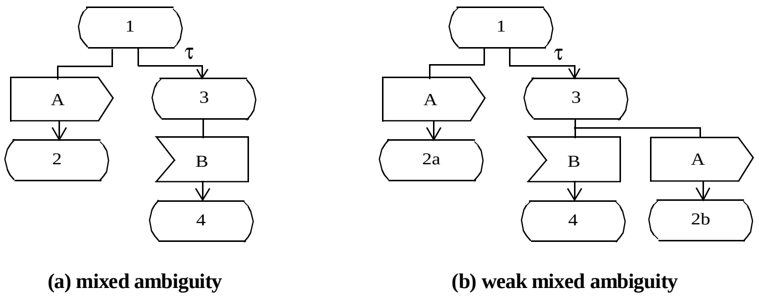


Figure 6.63 : Acute τ-transition and mixed ambiguity (1).

Similarly, a mixed ambiguity can occur when acute τ-events are combined with input events. This is illustrated in Figure 6.64. Here the insertion of a state between state “1” and “B” modifies the observable association behaviour. Thus the graph cannot be transformed so that state “1” describes equivoque τ-transitions.

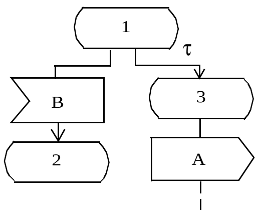


Figure 6.64 : Acute τ-transition and mixed ambiguity (2).

6.7.2 Input ambiguity

The combination of τ-events with input events may also lead to input ambiguity. This is illustrated in Figure 6.65. Here the states linked by the acute τ-transitions also provide distinct input behaviours. Case (a) describes an input ambiguity: an external observer is not able to determine whether input “A” or input “B” is expected. Case (b) describes a weak input ambiguity: input “A” is always expected, but input “B” is not always expected. In case (b), the behaviour “A” may lead to new ambiguity depending on the definition of the states “2a” and “2b”.

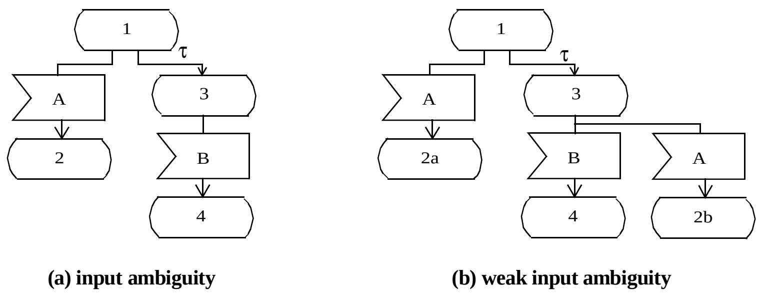


Figure 6.65 : Acute τ-transition and input ambiguity.

A slight difference exists between input ambiguity occurring after equivoque transitions and input ambiguity occurring in relation with an acute τ-transition. While equivoque transitions lead to a particular behaviour condition (i.e. one state is entered that sets a condition for signal consumption), the acute τ-transition describes a change of behaviour condition. This change may occur at any time. In the case of equivoque transitions, a complementary a-role wonders *which* signals are expected. In the case of acute τ-transition, it wonders *which* signals and *when*. However, this difference does not influence the validation analysis.

6.7.3 Termination ambiguity

As a special form of input or mixed ambiguity, termination ambiguity can also occur when a τ-event is combined with an input or output event. This is illustrated in Figure 6.66. An external observer is not able to determine whether the a-role state machine has terminated, or is waiting for a triggering event to occur.

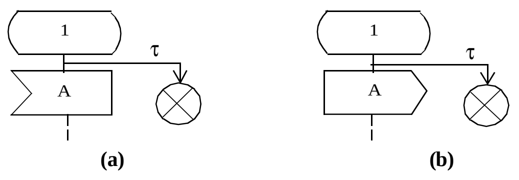


Figure 6.66 : Acute τ-transition and termination ambiguity.

6.7.4 Termination occurrence ambiguity

Termination occurrence ambiguity is a weak form or ambiguity. As gathering is not applied to exit states, τ-transitions may remain before exit states. In that case, an external observer is able to determine that the a-role will terminate, but not when. This is illustrated in Figure 6.67.

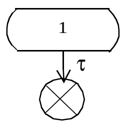


Figure 6.67 : Acute τ-transition and termination occurrence ambiguity.

Definition: Termination occurrence ambiguity

A termination occurrence ambiguity occurs when an external observer knows that the a-role state machine will terminate, but is not to determine when. The behaviour of the a-role is said to present a termination occurrence ambiguity.

6.7.5 Save ambiguity

Save ambiguity is a weak form of ambiguity. As an external observer cannot determine whether or not a signal can be saved, it may reserve itself from sending the signal. Figure 6.68 illustrates this form of ambiguity. An external observer should not send “B”.

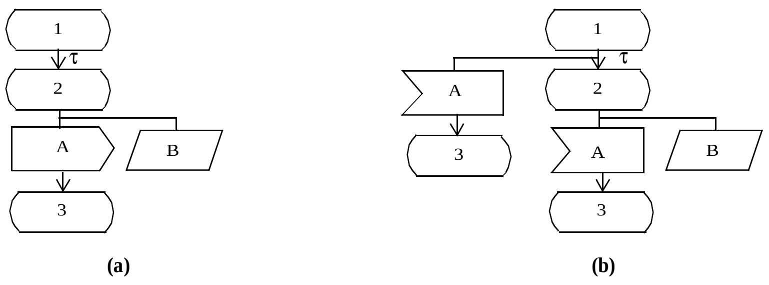


Figure 6.68 : Save ambiguity.

6.7.6 Ordering ambiguity

Ordering ambiguity is also a weak form of ambiguity. As an external observer can only determine one of the input ordering, it may restrict to that order. Figure 6.69 illustrates this form of ambiguity. An external observer should restrict to sending “A”.

6.8 Set-based notation

This thesis defines several algorithms for the manipulation and analysis of transition charts. As the graphical state machine representation is not suited for the definition of

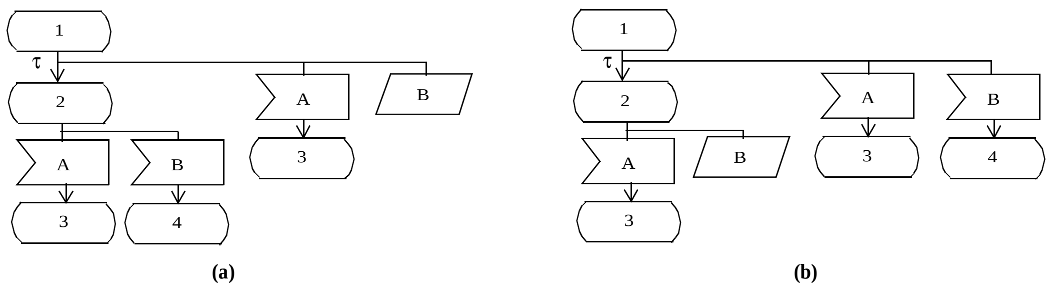


Figure 6.69 : Ordering ambiguity.

algorithms, we introduce a notation based on the definitions of sets and functions that associate elements in these sets.

We assume that the a-role state machines have been transformed adding σ-states. Thus transitions between states are attached a single event. The a-role state machines are defined by:

- a finite set $S = \{s_1, s_2, ..., s_n\}$ of states.
- a finite set $E = \{e_1, e_2, ..., e_r\}$ of events that trigger transitions. This set is the union of four disjoint sets:
    - $I = \{i_1, i_2, ..., i_s\}$, a set of inputs
    - $O = \{o_1, o_2, ..., o_t\}$, a set of outputs
    - *Empty* = {ε}, where ε represents the empty event. It only triggers initial states.
    - *Tau* = {τ}, where τ represents the τ-event.
- a state transition relation *T*. To each pair (*s*, *e*) of *S* x *E*, *T* associates a set of zero or more immediate successor states (a subset of *S*).
    - If *T* (*s*, *e*) is empty, there exists no transition from the state *s* for the event *e*.
    - If *T* (*s*, *e*) contains several states, the successors states are either equivalent or the transitions are equivoque.
- a save relation *Sv*. *Sv* associates a boolean value true or false to each pair (*s*, *e*) of *S* x *E*.
    - *Sv* (*s*, *e*) is true if *e* is saved in *s*, otherwise it is false.

  - *Sv* (*s*, *e*) is false when *T* (*s*, *e*) is not empty.

In addition to these sets and relation, we define:

- a finite set $S_\sigma = \{\sigma_1, \sigma_2, ..., \sigma_m\}$ of σ-states. S_σ is a subset of *S*.
- a finite set $S_o = \{s_{o1}, s_{o2}, ..., s_{ol}\}$ of initial states. S_o is a subset of *S*. An entry condition c_i may be associated to state s_{oi}[1].
  - There exists no transition leading to an initial state.
  - As we assume that the machine has been transformed adding σ-states, *T* (s_{oi}, *e*) is empty for all events except the empty event ε.
- a finite set $S_e = \{s_{e1}, s_{e2}, ..., s_{en}\}$ of exit states. S_e is a subset of *S*. An exit condition c_i may be associated to state s_{ei}.[1]
  - S_e can be derived from *S*, *E* and *T*. For all *e* in *E*, *T* (s_{ei}, *e*) is empty, since no transition from the state s_{ei} is defined.
- the relation *enable*. To each state *s* of *S*, *enable* associates the set of events that trigger transitions from s. The event *e* belongs to *enable* (*s*) if and only if *T* (*s*, *e*) is not empty.
- the relation *input-enable*. To each state *s* of *S*, *input-enable* associates the set of input events that trigger transitions from s. The event *e* belongs to *input-enable* (*s*) if and only if *e* belongs to *I* and *T* (*s*, *e*) is not empty.
- the relation *output-enable*. To each state *s* of *S*, *output-enable* associates the set of output events that trigger transitions from s. The event *e* belongs to *output-enable* (*s*) if and only if *e* belongs to *O* and *T* (*s*, *e*) is not empty.
- the relation *save*. To each state *s* of *S*, *save* associates the set of events that may be saved s. The event *e* belongs to *save* (*s*) if and only if *Sv* (*s*, *e*) is true.

1. Conditions attached to the s-roles are maintained during projection to a-roles. Conditions in SDL are expressed as labels.

We define the complement relations on the sets of states and events. These relations will be relevant in Chapter 7 for the generation of complementary a-roles. The complement relations are represented by an overline. They are defined such that:

- Each state s of S is associated a complement state $\overline{s}$. $\overline{S}$ is the set of $\overline{s}$.
    - The complement relation does not maintain the save behaviour. The complement of a σ-state is not a σ-state.
    - The complement state of an initial state is an initial state, and we define $\overline{s_{oi}} = s_{oi}$. Thus $\overline{S_o} = S_o$. If a condition is attached to an initial state, it is also attached to its complement state.
    - The complement state of an exit state is an exit state, and we define $\overline{s_{ei}} = s_{ei}$. Thus $\overline{S_e} = S_e$. If a condition is attached to an exit state, it is also attached to its complement state.
- Each event e of E, is associated a complement event $\overline{e}$. $\overline{E}$ is the set of $\overline{e}$.
    - for each i of I, $\overline{i}$ is defined as the output of the same signal. $\overline{I}$ is the set of $\overline{i}$.
    - for each o of O, $\overline{o}$ is defined as the input of the same signal. $\overline{O}$ is the set of $\overline{o}$.
    - the complement event of ε is defined as $\overline{\varepsilon} = \varepsilon$, and $\overline{Empty} = \{\overline{\varepsilon}\}$
    - the complement event of τ is defined as $\overline{\tau} = \tau$, and $\overline{Tau} = \{\overline{\tau}\}$
    - $\overline{E}$ is the union of $\overline{I}$, $\overline{O}$, $\overline{Empty}$ and $\overline{Tau}$.

6.9 Minimisation algorithm

The aim of minimisation is to reduce the size of a state machine by replacing equivalent states by a single state. Minimisation is usually applied before the analysis of large state machines, for example when performing reachability analysis, or at design time when requirements are set on the maximum size of machines, for example when developing logical circuits. In our approach, as we first validate elementary a-roles, the size of state machines we deal with is quite modest; obtaining size reduction is not absolutely necessary. Minimisation is however of interest when applied together with gathering:

- It facilitates the identification of equivoque transitions. Equivoque transitions lead to non-equivalent states. As minimisation removes the equivalent states, equivoque transitions are easily identified after minimisation: equivoque transitions are defined for the same state and same event.

- It enables one to generate the canonical form of the specification of the consistent complementary a-role. It should be applied to a-roles before the generation of consistent complementary a-roles (see Section 7.1).

Recall that states are said to be equivalent when their τ-states define the same triggering and save events, and their successor states are equivalent. By replacing equivalent states by a single state, a state machine can be reduced to an equivalent state machine, i.e. a machine that shows the same observable behaviour. The example in Figure 6.70, taken from [Holzmann 1991], illustrates the minimisation of a state machine.

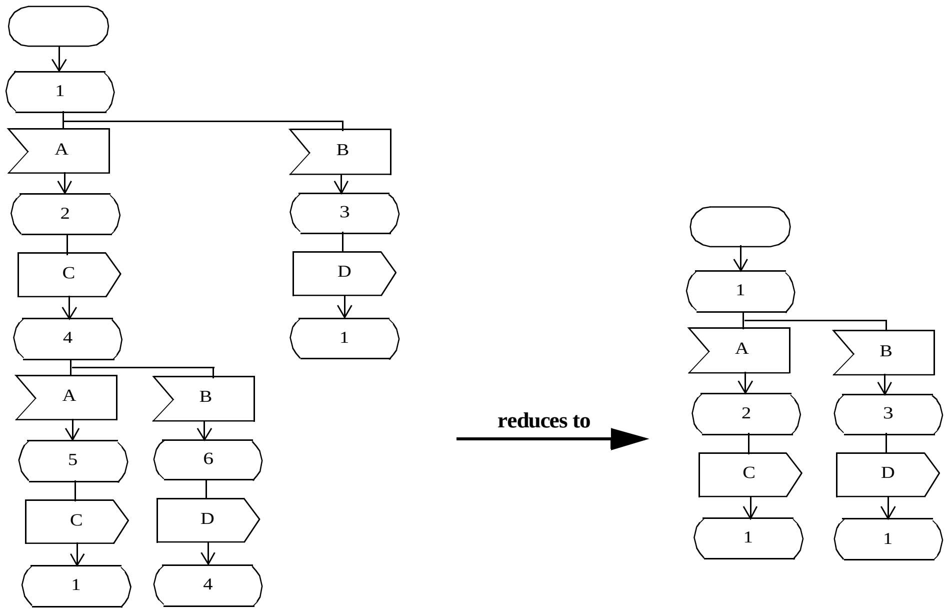


Figure 6.70 : Minimisation to an equivalent state machine.

We propose a minimisation algorithm inspired by [Hennie 1968] and [Holzmann 1991]. Hennie's algorithm is based on the notion of k-equivalence where states are k-equivalent if they are not distinguishable by an experiment[1] of length k. The algorithm generates par-

1. i.e. a sequence of observable events.

titions of k-equivalent states; partitions are refined step-wise. Hennie's algorithm only applies to deterministic machines. Holzmann proposes a similar algorithm that makes use of a state matrix instead of partitions, and that handles both deterministic and non-deterministic machines. Our algorithm combines the partition approach and applies to deterministic and non-deterministic machines.

As σ-states have a particular semantics, a σ-state can only be equivalent to a σ-state, not to an ordinary state.

Algorithm 6.1: Minimisation

```
1. Generate τ-states

 /* add a τ-transition from a state to itself */
 For each state p in S
  set T(p,τ) = p

2. Build a partition $P_1$ of 1-equivalent states

 /* compare set of enabled and saved events */
 For all states p,q in S
  if enable(p) = enable (q) and save (p) = save (q)
   if p is not an exit state
    set p and q in the same block of partition P1
   else
    if p and q define identical exit conditions
     set p and q in the same block of partition P1

3. Build the partition $P_k$ of k-equivalent states from $P_{k-1}$
 /* if the successors of (k-1)-equivalent states
 in a block B of the partition $P_{k-1}$ are not equivalent,
 split block B */

 For each block B in $P_{k-1}$
  For all states p, q in B
   If for each e in enable(p)
    {
    for each s in T(p,e), ∃ s′ in T (q,e)
     such that s, s′ belong the same block of $P_{k-1}$
    and
    for each s in T(q,e), ∃ s′ in T (p,e)
     such that s, s′ belong the same block of $P_{k-1}$
    }
   set p and q in the same block of partition B

4. If ($P_{k-1}$ and $P_k$ differ) and
   some block in $P_k$ contains more than one state
       repeat step 3 with k=k+1

5. Define a reduced state machine by

 - retaining a single state from each block in $P_k$.
   If the state is an initial state, deduce an
   OR-condition from the conditions associated
   to the states in the block. Attach this entry
   condition to the state.
   If the state is an exit state, maintain the
   condition of the state.
 - redefining the transition T using the equivalent states.
 - remove any $\tau$-transition from a state to itself.
```

When each state has only one successor after the occurrence of any event e (i.e. T(s, e) is either empty or contains one state), the step 2 of the algorithm can be simplified as described in Algorithm 6.2. In that case the machine does not contain any equivoque state, and has a deterministic behaviour.

Algorithm 6.2: Minimisation (simplified - no potential equivoque transitions)

```
1. Generate $\tau$-states: as step 1 in Algorithm 6.1

2. Build a partition $P_1$: as step 2 in Algorithm 6.1

3. Build the partition $P_k$ of k-equivalent states from $P_{k-1}$

  For each block B in $P_{k-1}$
   For all states p, q in B
    If for each e in enable(p)
     T(p,e) and T (q,e) belong the same block of $P_{k-1}$
    set p and q in the same block of partition B

4. Repeat: as step 4 in Algorithm 6.1

5. Define a reduced machine: as step 5 in Algorithm 6.1
```

When applying Algorithm 6.2 on the state machine described in Figure 6.42 on page 120, we obtain the following partitions of 1-equivalent states: P_1 = {(1,4), (2,5), (3,6)}. P_1 is then refined into a partition of 2-equivalent states P_2. The block (1,4) of P_1 is first considered. The successors of state 1 by event A and B are respectively 2 and 3. The successors of state 4 by event A and B are respectively 5 and 6. As the states 2, 5 and 3, 6 belong the same blocks in the partition of P1, the block (1,4) remains unchanged in P2. By reasoning similarly on blocks (2,5) and (3,6), the partition P_2 is found to be identical to P_1. Thus step 2 of the algorithm need not to be repeated. A reduced machine is defined that contains the states 1, 2, 3.

6.10 Summary

In this chapter, we have defined a projection from s-roles to a-roles. The projection abstracts non-observable behaviours of s-roles. Internal actions and non-visible signals are hidden. The consumption of non-visible signals is transformed to spontaneous transitions. A notation inspired from SDL is proposed for modelling a-roles. A set-based notation is also defined; this notation will be used in the definition of validation algorithms in Chapter 7.

The proposed projection assumes that:

- All communication between s-roles take place by the exchange of signals, and that signals exchanged on an association between two s-roles are conveyed on the same communication path.
- The s-role state graph has been transformed in order to remove enabling conditions. This is possible as communication between s-roles is restricted to signal exchange.
- The valid association input signal sets and valid association output signal sets related to distinct s-role associations are disjoint.

The projection maintains the observable association behaviour provided that:

- S-roles are designed according to the design rule "Save consistency". This means that the saving of a signal should be re-iterated in the successor state(s) of the state where save can occur until the consumption of the saved signal is specified.
- S-roles are designed according to the design rule "Ordering with save and concurrency". This means that using save in the modelling of alternative signal orderings should not overlap with the modelling of concurrent behaviours.

The a-role state graph obtained by projection can be transformed in order to facilitate interface validation. The chapter has proposed three transformations:

- A-role state graphs are transformed to transition charts. A transition chart is a kind of state graph where transitions between states are attached a single event: an input, an output or a silent event (τ-event). The transformation is performed through the insertion of σ-states.

- State gathering is applied in order to remove non observable τ-transitions. We define two transformations: strong gathering and weak gathering. Weak gathering only maintains the observable behaviour provided that spontaneous transitions can occur. Strong gathering always maintains the observable behaviour.

- Minimisation is applied in order to replace equivalent states by a single state. A minimisation algorithm based on the classification of states into equivalence partitions is defined.

In the following, we will assume that these transformations have been applied to the a-role transition charts.

Finally, we have also identified particular anomalous specification patterns:

- Equivoque transitions and acute τ-transitions may lead to ambiguous behaviours.

- Mixed initiative states may lead to conflicting behaviours.

Ambiguous and conflicting behaviours are usually symptoms of errors, and will require special care during interface validation. Ambiguous and conflicting behaviours are properties of state machine types - not instances. They can be identified at system design.

7 Interface validation

The purpose of interface validation is to ensure that the interfaces, i.e. service association roles (a-roles), on associations between service roles (s-roles) interact consistently. This chapter discusses the validation of interactions between elementary s-roles. The validation of interactions between composite s-roles is presented in Chapter 8.

Depending on the specification approach, a-roles may be specified before s-roles are themselves defined, or they may be obtained by projections of s-roles on an association. In other words, a-roles may either be seen as the desirable behaviour of an s-role on an association, or the actual behaviour of an s-role on an association. Similarly, interface validation can be used as a method for producing desirable behaviours or checking actual behaviours. Applied as a constructive method, interface validation aims to generate a dual consistent a-role from a particular a-role. Applied as a corrective method, interface validation aims to check the consistency of two a-roles.

This chapter describes first the constructive method. When discussing the generation of dual a-roles, we propose solutions to handle ambiguous and conflicting behaviours. The discussion results in a set of design rules that support the development of well-formed machines. These rules are also essential in the corrective method. Rather than directly checking the consistency of two a-roles, we identify first whether or not the a-roles present the right properties for interacting consistently with other a-roles. Thus we can avoid to apply consistency checking on poorly designed s-roles and a-roles.

A main advantage of the approach is that the techniques that are proposed, can be easily understood. Simplicity is however achieved at the sacrifice of some shortages. They are discussed in Section 7.3.

The assumptions and design rules introduced in Chapter 6 apply. The signals exchanged between a-roles are conveyed on the same communication path, and thus signal ordering is preserved during transport. A-roles are described by transition charts, and equivalent states have been reduced by minimisation.

7.1 Dual service association role

In this section, we discuss the problem of specifying an a-role that interacts consistently with a given a-role. Intuitively, we tend to believe that a consistent a-role can be produced by mirroring, where mirroring is a transformation that maintains the structure of the graph, and transforms inputs to outputs and outputs to inputs. We will show that mirroring fails to work when equivoque transitions or acute τ-transitions are introduced. Mixed initiatives states also require special care.

In our discussion, we consider the whole behaviour of the initial a-role state machine, not only parts of it. We aim to specify complementary a-roles that, through interaction with the initial a-roles, provide the full behaviour expected by the initial a-roles. *We assume that any state in the initial a-role machine is reachable from an initial state through some sequence of events.* With that assumption, we know that any anomalous behaviour specified in the machine can be reached and execute.

Definition: Dual service association role
A dual a-role is a complementary a-role of a given a-role, that interacts consistently[1] with this given a-role. The full behaviour of the a-role can be covered through interaction between the a-role and the dual a-role.

Recall that the consumption of signals from other associations, are projected to spontaneous transitions in the a-role. Spontaneous transitions may occur at any time. As our aim is not identify deadlocks[2] that may occur following errors of the non-visible behaviour of an s-role, e.g. errors on other associations, *we assume that any spontaneous sending described by the a-roles can occur.* With this assumption, we are able to check that a-roles interact consistently when they provide the expected behaviour.

7.1.1 Mirroring

Definition: Mirroring
Mirroring is a transformation on a state graph that produces a complement state graph: the structure of the graph is maintained, inputs are transformed to outputs, outputs to inputs,

1. Interaction consistency has been defined in Section 5.5
2. A deadlock may occur when none of the spontaneous sending described in a state ever occurs.

and empty events and τ-events remain respectively empty events and τ-events. Save is not maintained by mirroring. Conditions associated with initial and exit states are associated with the complement states.

Observe that:

- As save is not maintained by mirroring, σ-states are mirrored to normal states.
- As the graph structure is maintained, exit nodes are transformed to exit nodes, and cycles are preserved.

Figure 7.1 illustrates the mirroring of a state graph. Notice that without the insertion of an σ-state, the signal sending in the initial state would be transformed to a signal consumption in an initial state; this is not allowed in SDL. The insertion of σ-states facilitates the mirroring transformation.

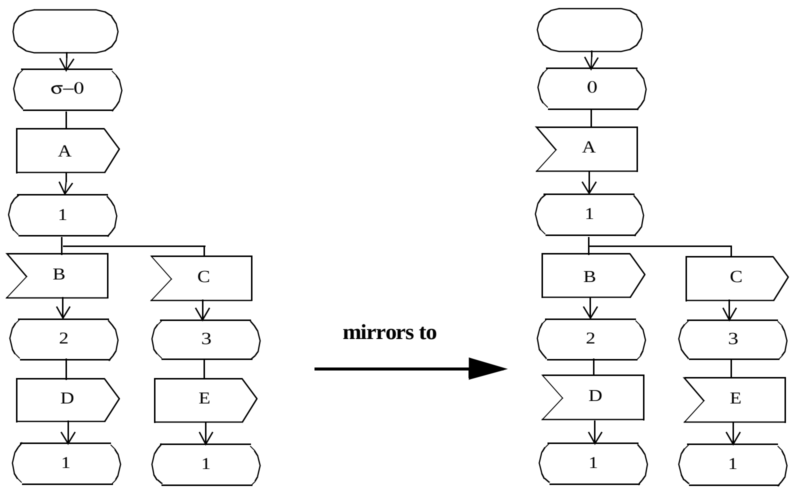


Figure 7.1 : Mirroring a state machine.

Algorithm 7.1 defines a mirroring algorithm in a pseudo-code form. The state graph is transformed in depth-first manner starting from each initial state (a graph may contain several initial states). The algorithm may apply to any state graph showing deterministic or non-deterministic behaviour. It makes use of the notation introduced in Section 6.8.

Algorithm 7.1: Mirroring

```
main ()
{
 /* define graph elements: states and events */
 $\bar{S}$ = $S$; /* maintain any associated condition */
```

```
  $\overline{I} = I$; $\overline{O} = O$;
  /* set of mirrored states, initialise to empty */
  $M$ = {};

  /* start from all initial states */
  for each $s_O$ in $S_O$
   if $s_O$ is not in $M$
    mirror ($s_O$);
 }

 mirror ($s$) /* mirror the transition relation */
 {
  add $s$ to $M$;

  if s is a σ-state
   generate new state name $\overline{s}$

  for each $e$ in $E$
   define $T(\overline{s}, \overline{e}) = \overline{T(s, e)}$;

  for each successor $n$ of $s$
   if $n$ is not in $M$
    mirror ($n$);
 }
```

7.1.1.1 Mirroring simple machines: no equivoque transitions, no mixed initiative

V-rule: Mirroring and duality

The dual a-role of an a-role that
- does not contain any equivoque transitions, and
- does not contain any acute τ-transition, and
- does not contain any mixed initiative state,

can be obtained by mirroring.

The initial a-role and the a-role obtained by mirroring interact consistently provided that
- they both start execution consistently, i.e. the machines should be entered using consistent entry conditions, and
- any spontaneous sending can occur.

Notice that, as we assume that machines are minimized before applying mirroring, the initial states, if several exist, are not equivalent, and thus are associated different entry conditions.

In the example shown in Figure 7.1, the a-role obtained by mirroring is a dual a-role of the initial a-role. This can easily be checked by considering all possible behaviours.

Justification:
We first prove that each state is mirrored to a consistent state (i.e. a state it interacts consistently with):
- As a state is mirrored to a complement state that is enabled by complement events and no other events: a state can consume any event sent its complement state, and any event sent by a state can be consumed by its complement state. The full behaviour of each state is covered.
- Following the assumption that any spontaneous sending can occur, at least one of the output event described by a state that only describes spontaneous event sendings, occurs. No deadlock following that the machine never sends in such state occurs.
- As states are not mixed initiative states, their mirrored states are not mixed initiative states. Only one of the machines initiates a new transition; as any trigger is specified as input in the complement state, unspecified signal reception does not happen. Only one machine waits for an event sent by the other; thus deadlock following machines waiting for each other is also avoided.
- An exit node is mirrored to an exit node and exit conditions are maintained. Thus, improper termination is avoided.
Now that we have proved that states and their mirrored states are consistent, we prove that transitions and their complement transitions preserve consistency:
- As transitions are not equivoque, each state have a unique successor *succ* for each event. The successor state of a complement state triggered by the complement event, i.e. $\overline{T}(\overline{s}, \overline{e})$, is defined in mirroring as $\overline{T\ (s, e)}$. It is the complement state of the successor state *succ*, and thus is consistent with the successor *succ*. Each transition is transformed, and each successor state can be reached providing full behaviour.
- As the graph does not contain any equivoque transitions, an empty transition in an initial state leads to a single state. Such empty transition is mirrored to an empty transition. They lead to states that interact in a consistent manner.
- As the graph, and thus the mirrored graph, does not contain any acute τ-transition, the transitions occur in a coordinated manner: a transition in one graph is triggered by a transition in the complement graph, and conversely.
Finally, as we have proved that states and their mirrored states are consistent, and that transitions and their complement transitions preserve consistency, we prove that execution is started consistently:
- Mirroring maintains entry conditions, i.e. a mirrored state is attached the same entry con-

dition as the initial state.
- The initial machine and the mirrored machine are entered using consistent entry conditions. In the same manner as any transition, initial transitions preserve consistency and lead to consistent states.

From this justification, we can also deduce that the full behaviour of the dual a-role can be covered through interaction between the a-role and the dual a-role.

7.1.1.2 Event ordering and save

The information about signal saving is not maintained in the mirrored graph. This is not needed, as mirroring preserves the structure of the state graph, and thus the ordering of event sequences. Mirroring enforces a strict ordering on the dual a-role. As explained in Section 6.4 on page 124, it may be desirable to relax the ordering requirements. This is possible if the list of events that may be saved in the initial state is attached to the mirrored state. In that case, events may be re-ordered. Information about σ-states can also be attached to the mirrored states. The design rule "Save consistency" facilitates the re-ordering operation: we know that any save signal can be consumed after saving.

Figure 7.2 illustrates the pertinence of save information. In case (a), the dual role is obtained by mirroring, and events are strictly ordered. If information about the saving of “C” in state “2” is made available in the mirrored role, the sequence of events in the dual role can be re-ordered. This is shown in case (b). As “B” may be sent at any time, the signal “B” should be saved in state “2a”. In the new dual role, the sending of “C” may be done at once without waiting for “B”.

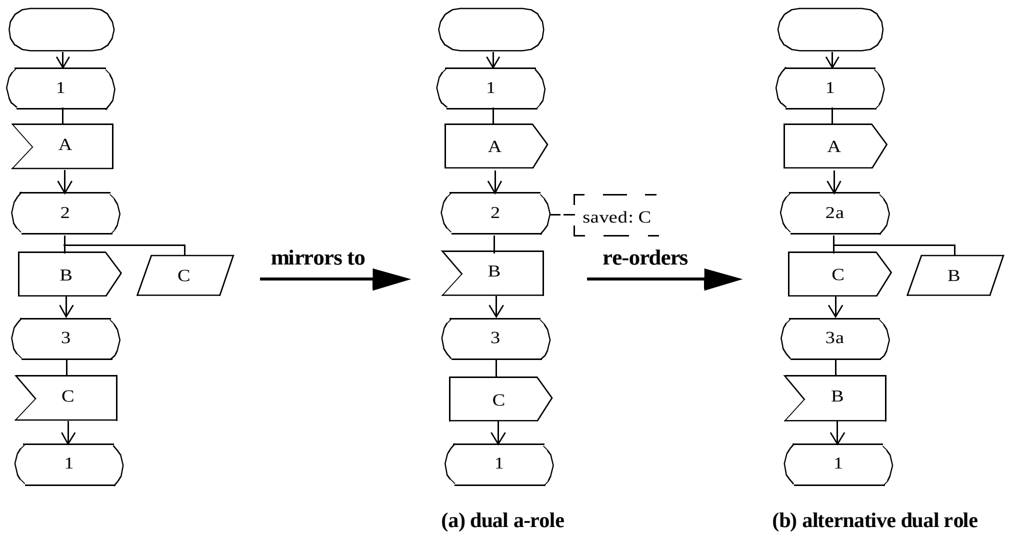


Figure 7.2 : Mirroring and event re-ordering.

In the rule "Save and ordering", we have advised that the use of save for modelling alternative ordering should be restricted to special cases. The detailed description of re-ordering is left for further work.

7.1.2 Equivoque transitions

In this section, complexity is added to the a-role graphs by introducing equivoque transitions. We show that it is not possible to define dual a-roles for a-roles that contain strong input ambiguity or strong mixed ambiguity. Mirroring also fails to produce dual a-roles when applied directly to a-roles that contain equivoque transitions, even if they do not present any strong behaviour ambiguity. The machine should be transformed before mirroring. We first define a set of transformation and validation rules that apply to machines containing equivoque transitions. Then we introduce algorithms for the manipulation of such machines.

As an illustration of the problem, Figure 7.3 presents a state machine containing equivoque transitions. In this example, the equivoque transitions do not lead to any input or mixed ambiguity. An external observer is able to perceive which behaviour is selected when receiving “C” or “D”. However, the state machine obtained by mirroring presents an input ambiguity. The initial machine cannot, after the consumption of “B”, determine whether the mirrored machine is waiting for “C” or “D”, and thus whether “C” or “D” should be sent.

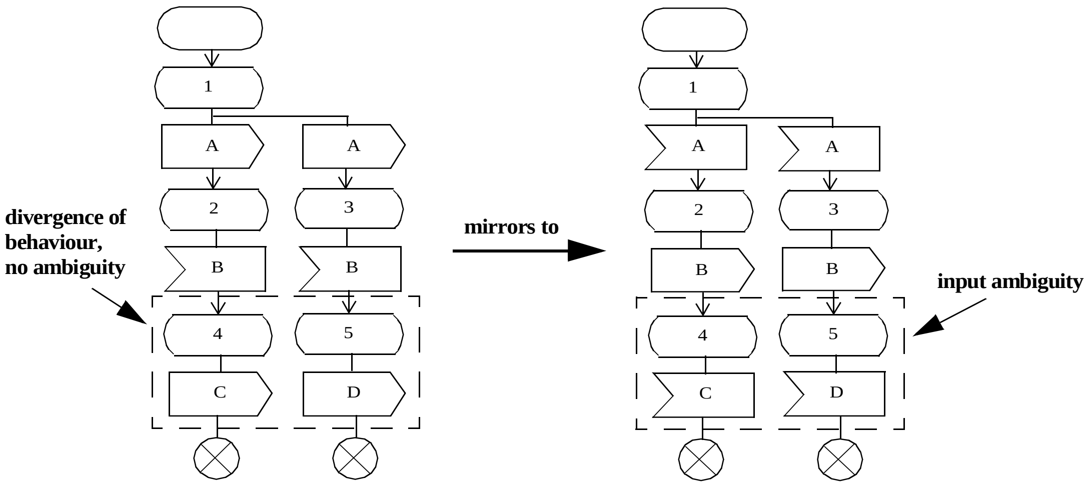


Figure 7.3 : Mirroring and equivoque transitions.

7.1.2.1 Basic rules

T-rule: Mirroring and equivoque transitions
The a-role obtained by mirroring an a-role that contains equivoque transitions, contains equivoque transitions. Equivoque transitions are mirrored to equivoque transitions.

Justification:
This is obvious. As mirroring maintains the structure of graph, i.e. both states and transitions, distinct behaviour sequences occurring after equivoque transitions are mirrored to distinct behaviour sequences.

This straightforward rule will be needed in the justification of some of the next rules.

T-rule: Mirroring and equivoque transitions, but no ambiguity
The a-role obtained by mirroring an a-role that contains equivoque transitions, but does not present any strong or weak input ambiguity, any strong or weak mixed ambiguity, any termination ambiguity, nor exit condition ambiguity always presents an input ambiguity.

Justification:
We know that equivoque transitions are mirrored to equivoque transitions. The equivoque transitions lead to distinct behaviour. As the initial machine does not present any ambiguity, the initial divergent behaviour necessarily occurs as signal sending. These outputs are transformed to inputs by mirroring, and thus the complementary behaviour of the initial divergent behaviour occurs by signal consumption. This means that the mirrored machine presents an input ambiguity.

V-rule: Duality and strong input ambiguity
Provided that strong input ambiguity is not withdrawn by save[1], it is not possible to specify a dual a-role for an a-role that presents an input ambiguity.

Justification:
There exists some stage of the interaction where an external observer knows that the a-role state machine expects only input(s), but is not able to determine which input(s) is (are) expected. Since strong input ambiguity is not withdrawn by save, the machine does not save any of the expected input. At that stage, sending a signal may lead to an unspecified signal reception. Thus it is not possible to specify a complementary a-role that interacts consistently with the initial a-role.

1. See Section 6.5.1.1.

T-rule: Mirroring and duality: equivoque transitions, no ambiguity
The a-role obtained by mirroring an a-role that contains equivoque transitions, but does not present any ambiguity, is not a dual a-role of that a-role.

Justification:
We know that the a-role obtained by mirroring presents an input ambiguity. At some stage of the interaction, the a-role does not know which input(s) is (are) expected by the mirrored a-role. Thus sending a signal may lead to an unspecified signal reception. The two a-roles do not interact consistently.

V-rule: Duality and strong mixed ambiguity
Provided that strong input ambiguity is not withdrawn by save[1 on Page 156], it is not possible to specify a dual a-role for an a-role that presents a mixed ambiguity.

Justification:
There exists some stage of the interaction where an external observer knows that both input(s) and output (s) may occur, but is not able to determine any of the input or output events expected by the a-role state machine. Since strong input ambiguity is not withdrawn by save, the machine does not save any of the expected input. At that stage, sending a signal may lead to an unspecified signal reception, and waiting for a signal to a deadlock. Thus it is not possible to specify a complementary a-role that interacts consistently with the initial a-role.

V-rule: Duality and termination ambiguity
It is not possible to specify a dual a-role for an a-role that presents a termination ambiguity.

Justification:
As termination ambiguity is either a special case of input ambiguity or mixed ambiguity, the rule can be deduced from the validation rules related to input and mixed ambiguities.

T-rule: Mirroring and duality: weak input ambiguity
Provided that weak input ambiguity is not withdrawn by save, the a-role obtained by mirroring an a-role that presents a weak input ambiguity, is not a dual a-role of that a-role.

Justification:
There exists some stage of the interaction where the a-role state machine expects only input(s), but the set of expected inputs vary. The machine may enter different states in a

non-deterministic manner. Mirroring transforms any input expected at that stage to an output in the mirrored machine. Non-determinism is preserved by mirroring, meaning that the mirrored machine may enter a state where it sends an event that is not expected by the initial machine. This is an unspecified signal reception. Thus the mirrored a-role is not a dual a-role of the initial a-role.

In order to facilitate the understanding of that rule, an example is shown in Figure 7.4. The initial and mirrored machines enter state “2” or “3” in a non-deterministic manner. If the mirrored machine enters state “3” and sends signal “C” while the initial machine enters state “2”, an unspecified signal reception occurs.

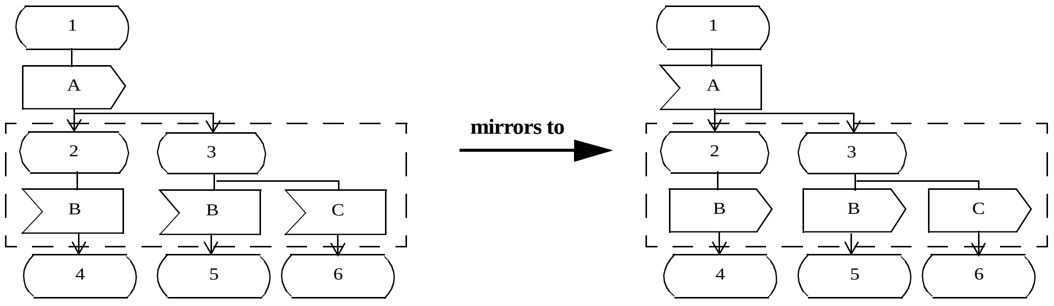


Figure 7.4 : Mirroring and weak input ambiguity.

T-rule: Mirroring and duality: weak mixed ambiguity

Provided that weak mixed ambiguity is not withdrawn by save, the a-role obtained by mirroring an a-role that presents a weak mixed ambiguity, is not a dual a-role of that a-role.

Justification:

The justification is similar to that of the previous rule. There exists some stage of the interaction where the both input and output events may happen, but the set of expected events vary. Both machines may enter different states in a non-deterministic manner, and one of the machine may send an event that is not expected by the complementary machine. Thus the mirrored a-role is not a dual a-role of the initial a-role.

In order to facilitate the understanding of that rule, an example is shown in Figure 7.5. The initial and mirrored machines enter state “2” or “3” in a non-deterministic manner. If the initial machine enters state “3” and sends signal “C” while the mirrored machine enters state “2”, an unspecified signal reception occurs. Notice that the input overlap in the initial machine is transformed to an output overlap in the mirrored machine.

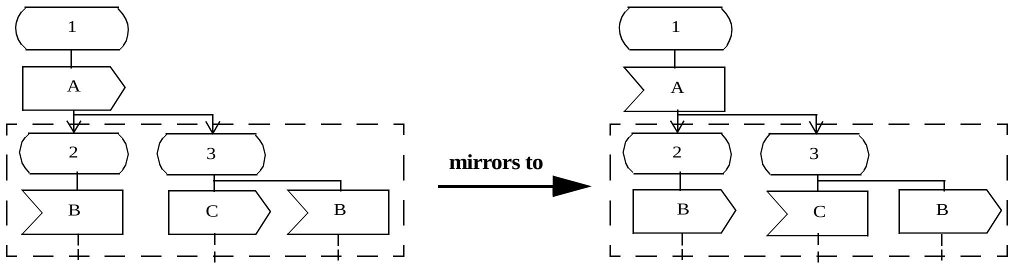


Figure 7.5 : Mirroring and weak mixed ambiguity.

7.1.2.2 Identifying equivoque transitions and divergent behaviour

As a-roles containing equivoque transitions cannot be mirrored to dual a-roles, it is essential to be able to detect equivoque transitions. We propose algorithms for marking the states where equivoque transitions happen, and categorising the divergence of behaviour they lead to. The categorisation is important as we know that it is not possible to produce a dual a-role of an a-role presenting a strong input, strong mixed or termination ambiguity. In the case such ambiguity is found, the designer should re-specify the a-role. Design rules for removing ambiguity are presented in Section 7.1.2.5.

A divergence of behaviour does not necessarily occur in the states immediately following equivoque transitions. The identification of divergent behaviour requires traversing the state graph. Figure 7.6 describes a case where several and different kinds of behaviour divergency occur after equivoque transitions.

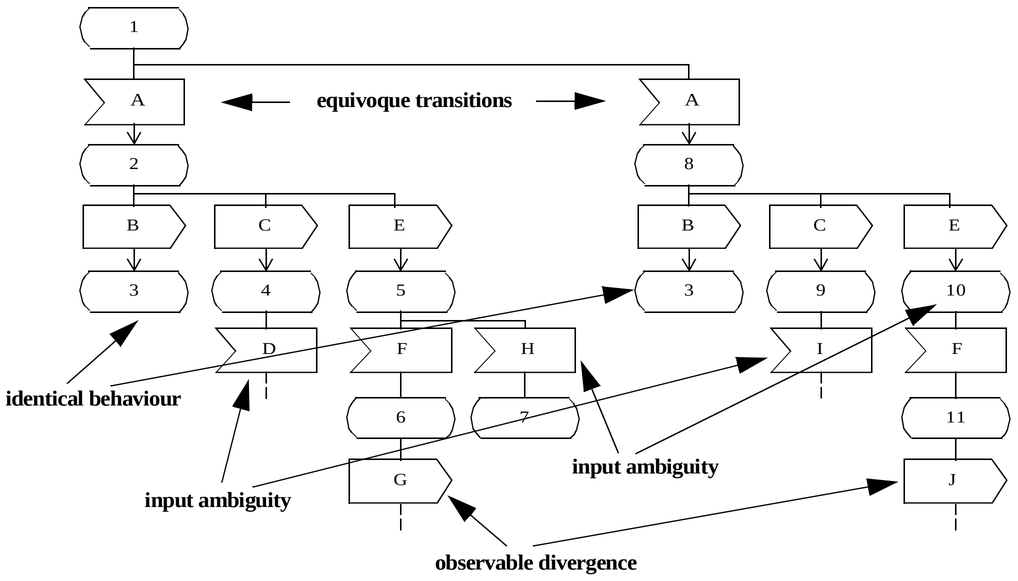


Figure 7.6 : Divergent behaviour occurring after identical signal sequences.

Algorithm 7.2 supports the identification of states that define equivoque transitions. The state graph is analysed in depth-first manner starting from each initial state. We assume that the graph has been minimized and does not contain any equivalent states. The algorithm makes use of the notation introduced in Section 6.8.

Algorithm 7.2: Identifying equivoque transitions

```
main ()
{
 /* Assumption:
   - the graph has been minimized - no equivalent states
 */
 EQ = {}; /* set of equivoque states */
 W = {}; /* working set */
 /* start from all initial states */
 for each $s_o$ in $S_o$
  if $s_o$ is not in W
   identify-equivoque($s_o$);
}

identify-equivoque (s)
{
 add s to W;
 for each e in enable (s)
  if T (s, e) contains more than one element add s to EQ;
  for each successor n of s /* element of T (s, e) */
   if n is not in W
    identify-equivoque (n);
}
```

Algorithm 7.3 supports the characterisation of divergence of behaviour occurring after equivoque transitions. Equivoque transitions should first be identified using Algorithm 7.2. The divergence of behaviour is either classified as output divergence, strong or weak input ambiguity, strong or weak mixed ambiguity, termination ambiguity, or exit condition ambiguity. When a divergence of behaviour is identified, the states where it occurs, are stored together with the state where the equivoque transitions occur. The state graph is analysed in a depth-first manner starting from each state where equivoque transitions occur:

- The algorithm first identifies which kind of divergence occurs in the states triggered by the equivoque transitions. In the case of input or mixed ambiguity, the divergence is classified as “weak” if the successor states describe some behaviour overlap.

• The analysis is repeated step-wise, when distinct successor states can be reached by identical behaviour sequences after the occurrence of equivoque transitions.

The algorithm fails to identify when distinct sets of equivoque transitions lead to the same states. In order to avoid non-progress cycles in the algorithm, the analysis of states that have already been analysed is not repeated. This means that a divergence of behaviour is related to a single set of equivoque transitions, while it may also occur after some other set of equivoque transitions.

The algorithm does not take into account save signals attached to states, and does not identify when input or mixed ambiguities are withdrawn by save (see Section 6.5.1.1 and Section 6.5.2.1). This means that some behaviours may be classified as ambiguous while they in fact are not.

Algorithm 7.3: Classifying the divergence of behaviour after equivoque transitions

```
main ()
{
 /* Assumption:
   - equivoque states are stored in EQ (Algorithm 7.2)
 */
 $I_{eq}$ = EQ; /* initial set of equivoque states*/
 W = {}; /* working set - contains analysed state tuples */

 /* The following sets contain elements of the form:
   (eq, div) where
      eq is an equivoque state,
      div a state tuple ($s_i$, $s_j$,...) where behaviour
      diverges
 */
 D-out = {}; /* output divergence */
 D-in-s = {}; /* strong input ambiguity */
 D-in-w = {}; /* weak input ambiguity */
 D-mix-s = {}; /* strong mixed ambiguity */
 D-mix-w = {}; /* weak mixed ambiguity */
 D-term = {}; /* termination ambiguity */
 D-term-cond = {}; /* exit condition ambiguity */

 /* start from all equivoque states */
 for each eq in $I_{eq}$
  remove eq from $I_{eq}$
  for each a in enable (eq)
   if T (eq, a) contains more than one element
```

```
    if T (eq, a) is not in W
     identify-divergence (eq, T(eq, a));
}

identify-divergence (s-eq, SUCC)
{
 add SUCC to W;

 Events = {}; /* events in successor states */
 for each p in SUCC
  add enable(p) to Events;

 if Events is empty /* successors are exit states */
  add (s-eq, SUCC) to D-term-cond; /* exit cond. ambig. */
  return;

 Common-Events = {}; /* common events in successor states */
 for one p in SUCC
  set Common-Events to enable(p);
 for each p in SUCC /* find intersection of event sets */
  set Common-Events to Common-Events ⊕ enable(p);

 /* identify divergence */
 if for some e in Events,
  e is not in enable(p) for some p in SUCC /* divergence */
  {
   if T(q, e) is element of $S_e$ for some q in SUCC /* exit */
    if T(r, e) is not element of $S_e$ for some r in SUCC
     add (s-eq, SUCC) to D-term; /* termination ambig. */

   if Events is included in O /* output divergence */
    add (s-eq, SUCC) to D-out;

   else if Events is included in I /* input ambiguity */
    if Common-Events is empty
     add (s-eq, SUCC) to D-out-s; /* strong */
    else
     add (s-eq, SUCC) to D-out-w; /* weak */

   else /* mixed ambiguity */
    if Common-Events is empty
     add (s-eq, SUCC) to D-mixed-s; /* strong */
    else
     add (s-eq, SUCC) to D-mixed-w; /* weak */
  }
 /* identify partially common behaviour and analyse it */

 for each e in Events
  s-num = 0; /* number of successor states */
  S-SUCC = {}; /* set of successor states */
  for each p in SUCC if e is in enable(p)
   add T(p, e) to S-SUCC;
   s-num = s-num + 1;
   n-eq = p;

  if S-SUCC contains more than one element
    if S-SUCC is not in W
     if s-num is equal to 1 /* equivoque transitions */
      remove n-eq from $I_{eq}$
      identify-divergence (n-eq, S-SUCC);
     else
      identify-divergence (s-eq, S-SUCC);
}
```

7.1.2.3 Equivoque transitions with no ambiguity

Given an a-role that contains equivoque transitions, but does not present any ambiguity, we have shown that a dual a-role cannot be obtained by mirroring. However, it is possible to specify a dual a-role for such an a-role. We will show that a simple transformation that merges the behaviour occurring after the equivoque transitions should be applied before mirroring.

Figure 7.7 illustrates this transformation. Mirroring failed to generate a dual a-role for the initial machine (see Figure 7.3). However, the machine obtained after “merging” and mirroring, as described in case (c) on Figure 7.7, is a dual a-role of the initial machine. This can be easily checked by considering all possible behaviours. The initial machine was first transformed to an intermediary machine by merging the states exhibiting the non-distinguishable behaviours and occurring after the equivoque transitions. The transformation removes ambiguity, and enables to produce, by mirroring, a machine that presents no ambiguity. Notice that the initial machine does not need to be modified: the equivoque transitions are not removed. As the initial machine controls the interaction when the divergence of behaviour occurs (i.e. the machine sends a signal), it is possible to specify a dual machine.

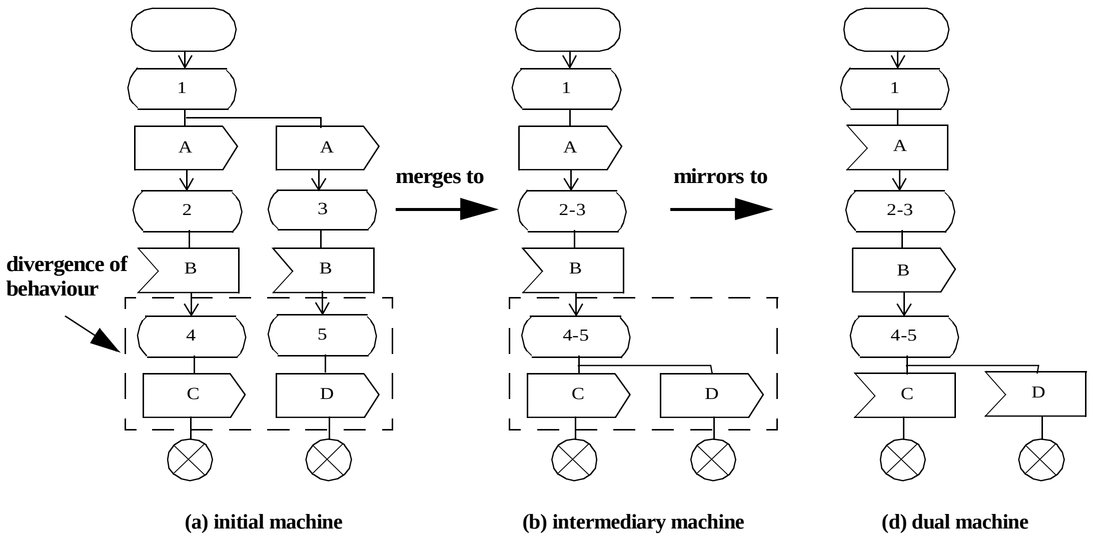


Figure 7.7 : Equivoque transitions: merging behaviour before mirroring.

7.1.2.3.1 Merging

Definition: Merging

Merging is a transformation that applies distinct states reachable from a state triggered by equivoque transitions through the same sequence of events. Merging produces a new state that exhibits the behaviour of the merged states (i.e. can be triggered by all events that can trigger any of the merged states). The transitions from the state triggered by equivoque transitions to the states being merged are replaced by a transition to the merged state. Merging does not apply to exit states.

Merging will mainly be applied on state machines that do not present any input, mixed or termination ambiguity. However as discussed in Section 7.1.2.5, merging is also of interest when re-designing an a-role that presents input or mixed ambiguity. Merging is never applied on machines that present a termination ambiguity, this because exit states have a particular semantics (the machine stops), and should not be merged with non-exit states. The merging transformation may be extended in order to handle the merging of distinct exit states. This is actual when a state machine presents an exit condition ambiguity. This is further explained in Section 7.1.2.4

A state machine may present several ambiguities after the occurrence of equivoque transitions. Every branch in the graph that succeeds a set of equivoque transitions is merged. Figure 7.8 illustrates the merging transformation on a slightly more complex example than in Figure 7.7. First, the states following the equivoque transitions are merged: states

“2” and “9” are merged to state “2-9”. The new state can be triggered by the events of state “2”, i.e. “B”, “C” and “G”, and the events of state “9”, i.e. “B” and “C”. The transitions triggered by “B” and “G” lead to single states; they remain unchanged. The transitions triggered by “C” lead to distinct states “4” and “10”. The states “4” and “10” can be reached by the same sequence of events from state “1”, i.e. “A” and “C”; they are merged to state “4-10”. The new state is triggered by a single event D. The merging continues until no more distinct states need to be merged.

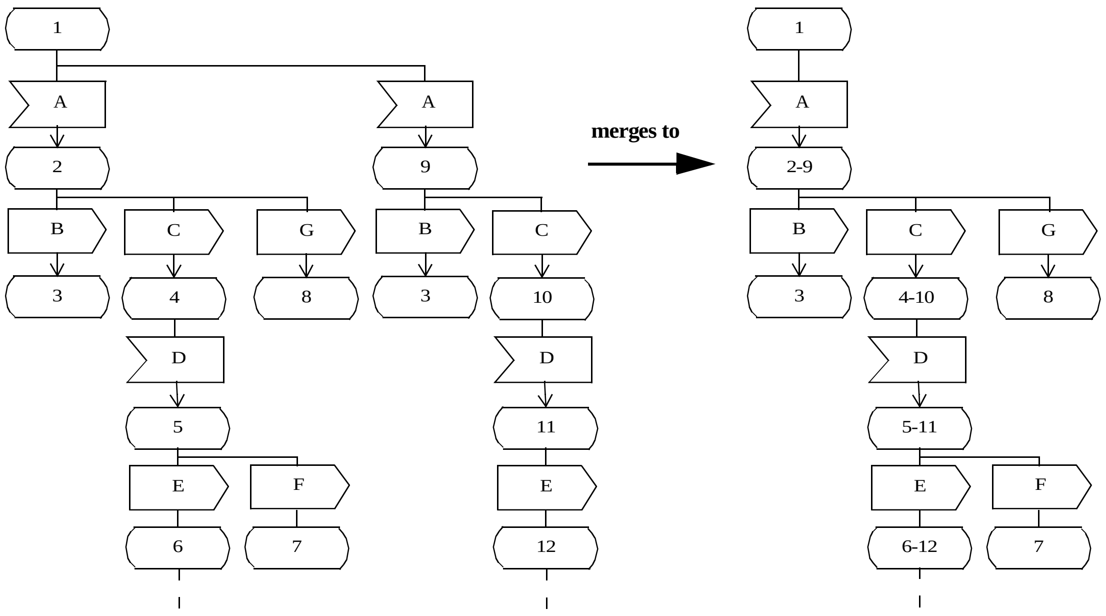


Figure 7.8 : Merging.

T-rule: Merging and equivoque transitions

An a-role that contains equivoque transitions and does not present any termination ambiguity is transformed by merging to an a-role that does not contain any equivoque transitions.

Justification:

By definition of merging, states reachable from a state triggered by equivoque transitions are merged to a single state. Thus equivoque transitions are merged to a single transition.

Algorithm 7.4 defines a merging algorithm in a pseudo-code form. We assume that the machine does not present any termination ambiguity or exit condition ambiguity (merging is never applied on exit states). We also assume that the machine does not contain any equivalent states. The state graph is transformed step-wise in depth-first manner starting from each state where equivoque transitions occur. Distinct states that are reachable from that state through the same sequence of events are merged to a new state; this state is defined with the transitions of the merged states. The merging is repeated for the distinct successor states triggered by the same event.

Algorithm 7.4: Merging

```
main ()
{
 /* Assumptions:
   - no equivalent states
   - no termination ambiguity
 */
 /* Equivoque states are stored in EQ (Algorithm 7.2) */

 W = {}; /* working set - contains merged state tuples */

 /* merged-state is a relation that keeps track of
 the association between a tuple of merged states
 and their merged state */

 /* start from an equivoque state */
 for each s in EQ
  remove s from EQ
  for each e in enable(s)
   if T (s, e) contains more than one element
    merge (s, e);
}

merge (s, e)
{
 if every p of T(s, e) is element of $S_e$ /* any exit */
  report-error (exit condition ambiguity);
  return;

 if some p of T(s, e) is element of $S_e$ /* one exit */
  report-error (termination ambiguity);
  return;

 if T(s, e) is not in W
 {
  add T(s, e) to W;

  create new state n; /* add n to S */
  set merged-state(T(s, e)) to n;
  SUCC = T(s, e);
```

```
   T(s, e) = n; /* redefine transition */

   for each a in E, set T(n, a) = {}; /* initialisation */
   for each q in SUCC
    for each a in enable(q)
     add T(q, a) to T(n, a)
     add a to enable(n);

   for each a in enable(n)
    if T(n, a) contains more than one element
     merge (n, a)
  }
  else /* the merged state already exists */
  T(s, e) = merged-state(T(s, e));
 }
```

The merging algorithm does not remove any state from the graph. Some of the merged states may, after merging, no longer be reachable from the initial states. These states can be easily removed by applying Algorithm 7.5. The merging transformation may also introduce new equivalent states. Equivalent states should be replaced by a single state by minimisation (Algorithm 6.2). When these two transformations have been performed, the mirroring transformation can be applied.

Algorithm 7.5: Removing non-reachable states

```
 main ()
 {
  W = {}; /* working set - reachable states */

  /* start from all initial states */
  for each $s_0$ in $S_0$
   if $s_0$ is not in W
    mark-successor ($s_0$);
  set S to W;
 }

 mark-successor (s)
 {
  add s to W;

  for each successor n of s
   if n is not in W
    mark-successor (n);
 }
```

7.1.2.3.2 Merging and save

The proposed definition of merging ignores the saving of signals. As a consequence, an a-role is transformed by merging to an a-role that may provide a modified observable association behaviour.

Two case examples are shown in Figure 7.9. In the case (a), the states to be merged define identical sets of saved signals. The design rule "Save consistency" is enforced by consuming the signal in the successor state “3”. An external observer may send “D” immediately after “A”. When it receives “B” or “C”, the machine proceeds. After merging, the same behaviour may lead to the discarding of “D” and a deadlock. In case (b), the states to be merged define distinct sets of saved signals. This case illustrates a kind of save ambiguity: an external observer cannot determine from any observable event that the signal “D” can be saved. Also in that case, an external observer perceives distinct behaviours before and after merging. When sending “D” immediately after “A”, the a-role before merging always proceeds after “B” is received. After merging, it sometimes deadlocks.

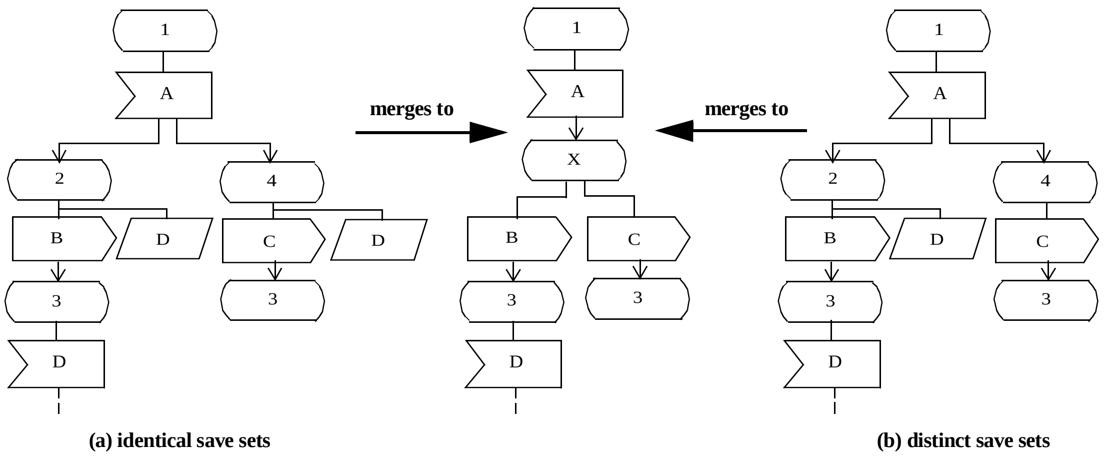


Figure 7.9 : Merging and save.

We may redefine the merging transformation so that the save set of a state obtained by merging, is defined as the intersection of the save sets of the states being merged. For example, state “X” merged from case (a) of Figure 7.9 would define the save set “D”. In the case where the state being merged defined distinct save sets, the new merging transformation does not maintain the observable association behaviour. For example, state “X” merged from case (b) in Figure 7.9 would not define any save set as when using the initial merging transformation. Algorithm 7.4 is easily extended so that a save set is computed and attached to the merged state.

The merging of two or more σ-states is a particular case and should lead to a σ-state. Recall that the semantics of σ-states is also different from other states, in that one of the output events described in σ-state always occurs.

We intend to apply merging before mirroring. Merging and mirroring should be defined consistently. When the information about signal saving is not maintained in the mirrored graph, maintaining save during merging is not needed. Both merging and mirroring enforces a strict ordering on the dual a-role. Otherwise, when mirroring maintains the save information[1], merging should maintain save.

V-rule: Merging and save ambiguity
Assume an a-role containing equivoque transitions, but no input, mixed, termination or exit condition ambiguity. If some of the states being merged define distinct save sets, the a-role presents a save ambiguity.

Justification:
As the a-role does not present any input, mixed, termination or exit condition ambiguity, the divergence of behaviour occurring after the equivoque transitions is perceived through output events. The states between the state triggered by the equivoque transitions and the states triggered by these output events are merged. An external observer cannot distinguish between the states being merged. If some of these states define distinct save sets, an external observer cannot determine which signals can be saved, except the common signals in the save sets.

When an a-role presents a save ambiguity, a complementary a-role cannot take advantage of save, except for the common signals in the save sets. Therefore it is acceptable that merging ignores signals that are not common to the save sets.

D-rule: Merging and save ambiguity
We advice to redefine a-roles[2] presenting save ambiguities such that save sets of states being merged define identical save sets.

T-rule: Merging and σ-state
The merging of a σ-state with a non σ-state may modify the observable association behaviour provided by an a-role.

1. as described in Section 7.1.1.2.
2. When a-roles are derived from s-roles, the s-roles need to be redefined.

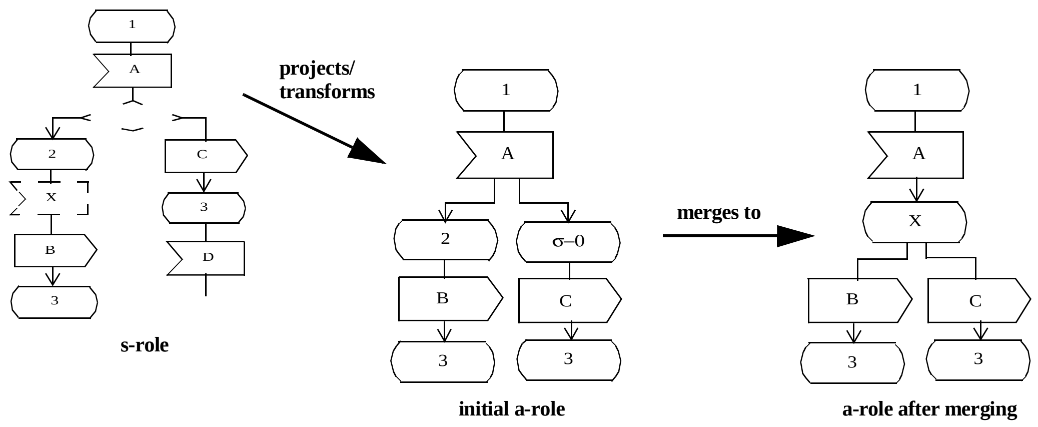


Figure 7.10 : Merging and σ-state.

Justification:
The state obtained by merging is not a σ-state and then behaves differently from the initial σ-state. An example is shown in Figure 7.10. When interacting with the initial role, an external observer that sends “D” immediately after “A” observes that the a-role always proceeds after “C” is received. When interacting with the a-role obtained by merging, an external observer that sends “D” immediately after “A” observes that, in some cases, the a-role deadlocks after “C” is received.

In that case, redesigning the a-role is more complex. We rather propose to enforce a strong ordering on the complementary a-role.

Definition: Merging with save
“Merging with save” extends the merging transformation:
- The save set of a state obtained by merging, is defined as the intersection of the save sets of the states being merged.
- σ-states are merged to a σ-state.

T-rule: “Merging with save” and observable behaviour
An a-role that contains equivoque transitions, but that
- does not present any input, mixed, termination or exit condition ambiguity,
- and does not contain any acute τ-transitions,
is transformed by “merging with save” to an a-role that exhibits the same behaviour provided that the states being merged define identical save sets, and that σ-states are only merged with other σ-states.

Justification:
States being merged are distinct states that are reachable from a state triggered by equivoque transitions through the same sequence of events. We have to show that a merged state and its successor states behave as the states being merged and their successors. The states should be triggered by the same events, and signals should be stored and retrieved in/from the input port in the same manner.
As the a-role does not present any input, mixed, termination or exit condition ambiguity, the divergence of behaviour only occurs through output events. The states being merged either define the same set of events, or they define different output events.
- If the states being merged define the same events, the merged state also defines this set of events. Thus, the merged state is triggered in the same manner as the initial states. For each event, the successor state(s) of the initial states is (are) either identical or differ. In the first case, triggering obviously leads to the same behaviour. In the second case, the successor states are merged. By applying the reasoning recursively, the successor states can be shown to be triggered by the same events.
- If the states being merged define different output events, the merged state defines the union of the output events, and no other event. Thus, the merged state is triggered by the same events as the initial states. Each event defined in a single initial state leads to the same successor in the merged state, and triggering obviously leads to the same behaviour. For each other event, the successor state(s) of the initial states is (are) either identical or differ. In the first case, triggering obviously leads to the same behaviour. In the second case, the successor states are merged. By applying the reasoning recursively, the successor states can be shown to be triggered by the same behaviour.
The states being merged define the same save set, and that save set is maintained by merging. Thus, signals are stored in the input port in the same manner before and after merging. Thus, signals remain in the input port similarly before and after merging.
σ-states are only merged to a σ-states, thus a signal sending always occurs as in the initial σ-state.

7.1.2.3.3 Merging and duality

V-rule: Merging and duality
The dual a-role of an a-role that contains equivoque transitions, but that
- does not present any input, mixed, termination or exit condition ambiguity, and
- does not contain any acute τ-transitions, and
- does not contain any mixed initiative state,
can be obtained by mirroring the a-role obtained by merging the initial a-role.

The initial a-role and the a-role obtained by merging and mirroring interact consistently provided that
- they both start execution consistently, i.e. the machines should be entered using consistent entry conditions, and
- any spontaneous sending can occur.

Justification:
This can be easily shown when the states being merged define identical save sets, and the merging transformation maintains the save sets. In that case the merged a-role exhibits the same behaviour as the initial a-role. We know that the merged a-role does not contain any equivoque transitions. It is easy to show that it does not contain any acute τ-transition, and any mixed initiative state. According to the validation rule "Mirroring and duality", a dual a-role of the merged role can then be obtained by mirroring. The merged a-role and dual a-role interact consistently providing they start execution consistently and the spontaneous transitions can occur. As the merged a-role and initial a-role exhibit the same behaviour, the dual a-role of the merged a-role is also a dual a-role of the initial a-role.
The validation rule "Mirroring and duality" applies for a mirroring transformation that does not maintain the save information. As we assume that spontaneous sendings can occur, signal sending in a σ-state behaves as in a non- σ-state. A strict ordering is enforced on the a-role obtained by mirroring. Thus, this a-role interacts consistently with the initial a-role also when no save assumptions are made on the merging transformation and on the roles being merged.

It is possible to relax the ordering requirements on the dual a-role. Save sets should be maintained by merging, and save information attached to the mirrored a-role such that re-ordering can be applied. A-roles presenting save ambiguities should be redefined before the generation of dual roles. When transformations are applied on a-roles that present save ambiguities, the dual a-roles enforce stricter event sequence ordering.

7.1.2.4 Exit condition ambiguity

Recall that an exit condition ambiguity occurs when an external observer is not able to determine which exit condition is associated to a termination. The identification of the exit condition is especially relevant when roles are composed sequentially. Exit conditions may be used to control the choice of the further behaviour. However, we will see in Chapter 8 that the composition of roles across actors does not require roles to be composed similarly in two interacting actors. A composite role may not need to know which exit condition is associated to a termination of its complementary role.

A simple approach has been chosen for the projection of exit state: the exit condition is maintained by projection. In some cases, the condition may however only be relevant for interactions on other associations. In order to deal with such cases, we rather introduce an extension to SDL and make use of this extension in the definition of improper termination (see Section 5.5). Recall that two a-roles may terminate properly even though their conditions of termination are not identical. The conditions should be consistent, i.e. one of the condition should cover the other condition.

We introduce the OR-logical expression of exit conditions in SDL. When a composite state exits through a return node attached the condition “c1 or c2”, this means that any of the condition may be true - indifferently. The condition “c1 or c2” covers the two conditions “c1” and “c2”. The exit condition “any” is represented by the SDL “DEFAULT” (i.e. no label is attached to the return node), and represents any other condition than those specifically expressed in the graph. Thus if the exit condition “c1” is defined in the graph, “any” does not cover “c1”.

We propose to extend the merging transformation so that it handles the merging of exit states attached distinct exit conditions.

Definition: X-merging

X-merging is a transformation that applies distinct states reachable from a state triggered by equivoque transitions through the same sequence of events. It applies to all states except the exit states in a similar way as merging. Through x-merging, exit states attached distinct exit conditions are merged to a state attached the OR-expression of these conditions. Exit states are not merged with non-exit states.

Figure 7.11 illustrates the transformation. The machine obtained by x-merging can be mirrored to a machine that interacts consistently with the initial machine.

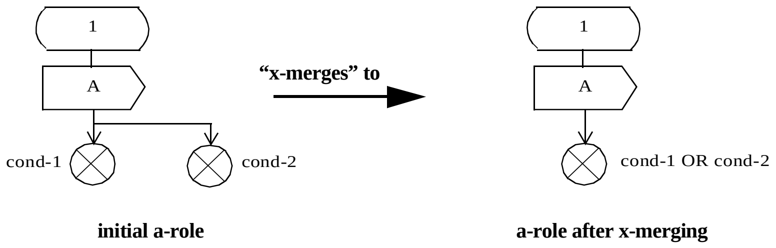


Figure 7.11 : X-merging.

V-rule: X-merging and duality
The dual a-role of an a-role that contains equivoque transitions, but that
- does not present any input, mixed, termination ambiguity, and
- does not contain any acute τ-transitions, and
- does not contain any mixed initiative state,

can be obtained by mirroring the a-role obtained by transforming the initial a-role by x-merging.
The initial a-role and the a-role obtained by x-merging and mirroring interact consistently provided that
- they both start execution consistently, i.e. the machines should be entered using consistent entry conditions, and
- any spontaneous sending can occur.

Justification:
This rule is based on the previous validation rule “"Merging and duality". Exit condition ambiguity is added, and merging replaced by x-merging. We can follow the same reasoning as previously. “X-merging with save” preserves the observable behaviour except the exit conditions. However the exit states after x-merging are attached an exit condition that covers the initial exit conditions. That condition is maintained in the mirrored role, that according to the definition of improper termination, will then interacts consistently with the initial role.

Algorithm 7.4 is easily extended to x-merging so that exit states and their attached conditions are merged. *In the following, we will use the term merging instead of x-merging.*

7.1.2.5 Strong ambiguities

As shown previously, it is not possible to specify dual a-roles for a-roles that present input, mixed or termination ambiguity. Designers need therefore to re-specify the s-roles and a-roles in order to remove the ambiguity. In this section, we propose simple design rules. Designers may prefer to modify the state machine differently; designers’ choices may depend on the application being designed.

D-rule: Removing input ambiguity
Input ambiguity should be removed. Input ambiguity in the a-role may be removed by merging. When a-roles are derived from s-roles, re-design applies to s-roles.

Figure 7.12 illustrates this design rule. The states where input divergence occurs are merged to a new state that can consume any of the inputs of the states to be merged. Algorithm 7.4 can be easily extended in order to remove input ambiguity in the a-role by merging. States with input ambiguity were identified in Algorithm 7.3.

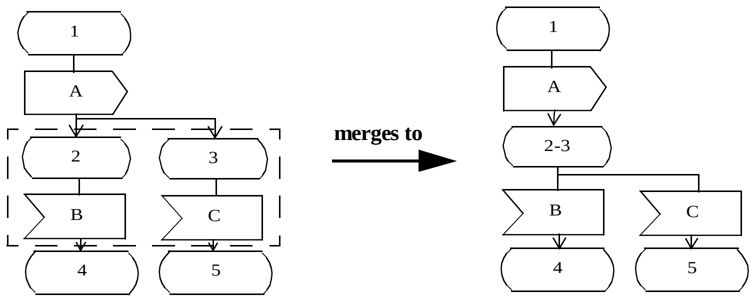


Figure 7.12 : Re-design: removing input ambiguity.

D-rule: Removing mixed ambiguity

Mixed ambiguity should be removed. Mixed ambiguity may be removed by merging. When a-roles are derived from s-roles, re-design applies to s-roles. The states where mixed ambiguity occur are merged to a mixed initiative state. The rules defined for mixed initiative states should then be applied (see Section 7.1.3).

Figure 7.13 illustrates this design rule. The states where behaviour divergence occurs are merged to a new state "2-3" that can consume any of the inputs and send any output of the states to be merged. As we will see in Section 7.1.3, a dual state of the mixed initiative state cannot be derived by simple mirroring. Algorithm 7.4 can be easily extended in order to remove mixed ambiguity in the a-role by merging. States with mixed ambiguity were identified in Algorithm 7.3.

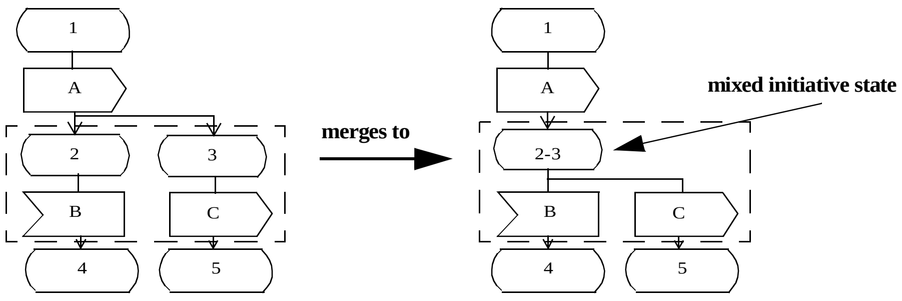


Figure 7.13 : Re-design: removing mixed ambiguity.

Recall that merging should not be applied on machines that present termination ambiguity. Exit states that have a particular semantics should not be merged with non-exit states. Adding the sending of a signal before the exit state solves only partially the problem. This is illustrated by the examples on Figure 7.14. In case a, the modified machine contains equivoque transitions, but does not present any ambiguity. A dual association can be obtained by merging and mirroring (see Section 7.1.2.3.3). In case b, the modified machine presents a mixed ambiguity. The ambiguity may be removed by merging; however merging leads to an undesirable form of mixed initiative state; this is further explained in Section 7.1.3.5.

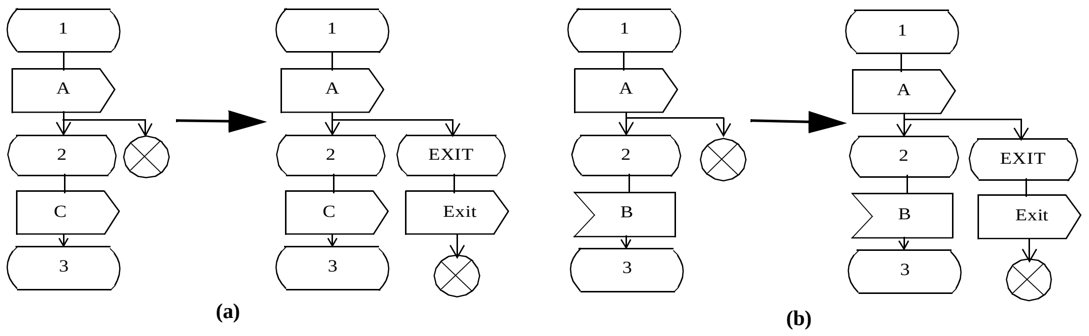


Figure 7.14 : Re-design: removing termination ambiguity.

D-rule: Removing termination ambiguity

Termination ambiguity should be removed. Adding the sending of a termination indication signal before the exit state is a satisfying solution in the case where the other state(s) triggered by the other equivoque transition(s) defines (define) only outputs. Otherwise the state machine should be re-defined; the rules specified for mixed initiative states may be followed (see Section 7.1.3.5). When a-roles are derived from s-roles, re-design applies to s-roles.

7.1.2.6 Weak input and mixed ambiguities

By definition of a dual a-role, the full behaviour of the initial a-role should be covered through interaction between the a-role and the dual a-role. Observe that when we relax the constraint of full behaviour, a consistent complementary a-role can be generated by an extended mirroring transformation. The generated a-role interacts consistently with the initial a-role, also when the state presenting a weak ambiguity is reached.

This is illustrated in Figure 7.15. The initial a-role presents a weak input ambiguity. This a-role is first reduced in order to remove non-common input behaviours from the state presenting ambiguity. Here the input “C” is removed. Then merging and mirroring can be applied on the reduced a-role. The complementary a-role does not provide the full behaviour expected by the initial a-role. The behaviour “C” never occurs when these two roles interact. It is not a dual a-role. We call it a “reduced” dual a-role.

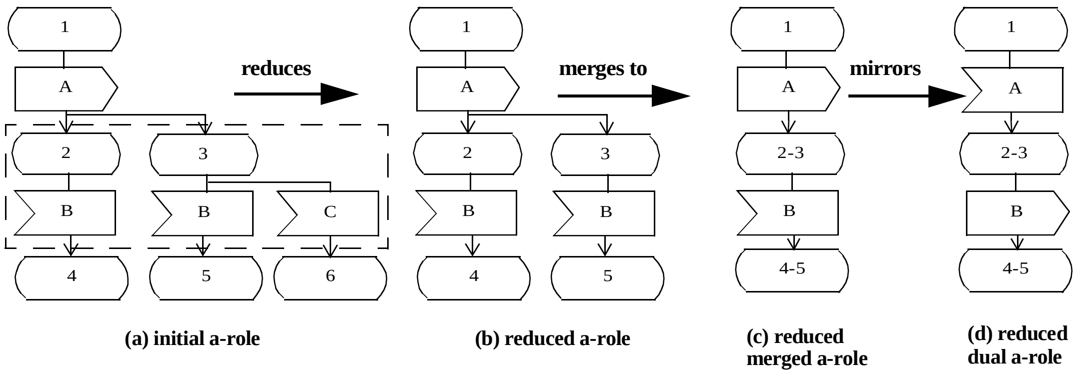


Figure 7.15 : Weak input ambiguity: reducing and merging before mirroring.

Figure 7.16 shows a similar case with weak mixed ambiguity. The non-common input “B” is removed. The a-role in case (d) interacts consistently with the initial a-role. However the behaviour “B” never occurs when these two roles interact.

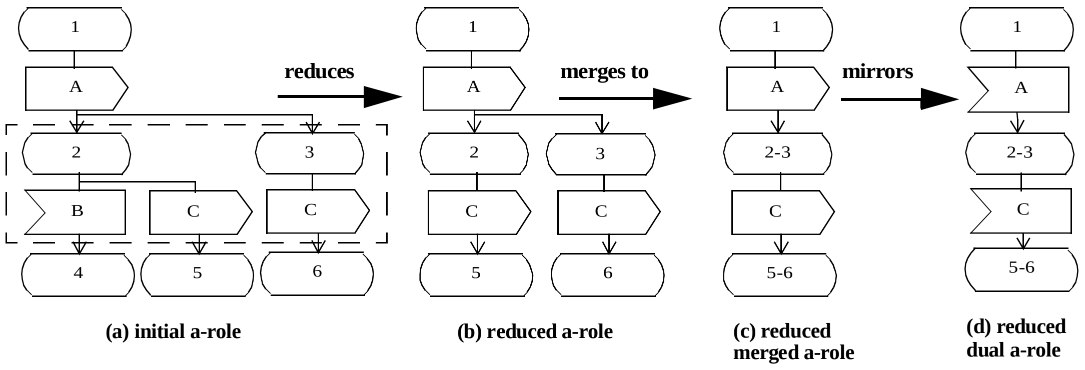


Figure 7.16 : Weak mixed ambiguity: reducing and merging before mirroring.

Although these transformations enable the generation of partial complementary consistent a-roles, they cannot be considered as a satisfying solution. Weak input and mixed ambiguities are a symptom of poor design, and s-roles should be re-designed. The approach using behaviour reduction may be used when s-roles cannot be re-designed. Otherwise the following design rule should applied.

D-rule: Weak input and mixed ambiguities

Weak input and mixed ambiguities should be removed. They may be removed following the rules defined for strong ambiguities.

7.1.3 Mixed initiatives

Mixed initiatives occur when an a-role and its complementary a-role both can take an initiative to send during the same interaction step. If two associated a-roles take the initiative to send simultaneously, the signals may cross each other, and the a-roles perceive the order of occurrence of events differently. This should be taken into account when specifying a-roles. In state machines, mixed initiatives are represented by mixed initiative states. This section define rules applying to such machines. Recall that mixed initiatives may either represent concurrent behaviours or alternative orderings (see Section 6.6). These two forms of mixed initiative require slightly different rules.

7.1.3.1 Input consistency

When two machines take the initiative to send simultaneously, the signals they send are received in the states triggered by signal sending in the other machines. In order to avoid unspecified signal reception, the signals specified as inputs in mixed initiative states should be specified as inputs in the states following signal sending in the mixed initiative states. This is a form of input consistency as described by [Bræk and Haugen 1993].

Definition: Input consistency
A state is input consistent with another state, if the set inputs enabled in this state contains the set of inputs enabled in the other state. Two states are input consistent if they accept the same set of inputs.

A simple example of input consistency is shown in Figure 7.17. The initial machine may either take the initiative to send “A”, or may consume “B”. If the signals “A” and “B” cross each other, the signal “B” is received while the machine is in state “2” leading to an unspecified signal reception. To avoid this unspecified signal reception, the machine is made input consistent, i.e. the signal “B” is added as input in state “2”. The behaviour occurring in the new state “6” will be discussed in Section 7.1.3.2.

D-rule: Mixed initiative and input consistency
Any state triggered by an output from a mixed initiative state should be defined input consistent with the mixed initiative state.

Justification:
We assume that any of the inputs specified in a mixed initiative state may be sent by the complementary machine. Any of these inputs may be received after an output specified in

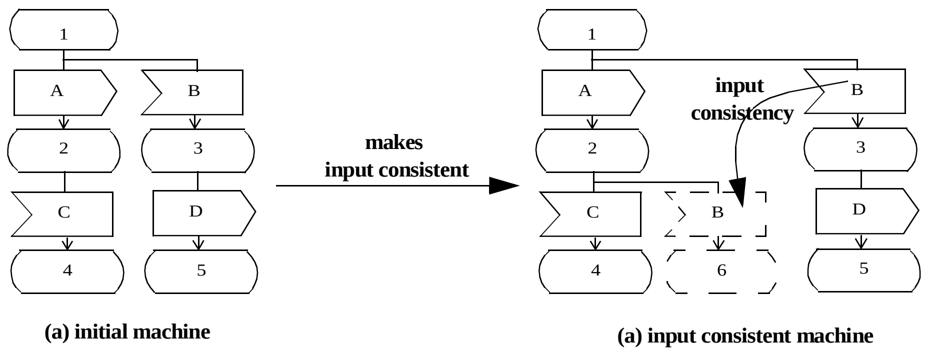


Figure 7.17 : Mixed initiatives: input consistency.

the mixed initiative state is sent; this is the case when the signals cross each other. Thus, in order to avoid unspecified signal reception, any of the inputs specified in a mixed initiative state should also be specified in any state triggered by an output from a mixed initiative state.

Note that alternative event orderings as introduced in Section 6.6 enforces this design rule.

Applying this design rule may lead to the introduction of new mixed initiative states. This is the case if the successor state of the mixed initiative state defines some output. An example is shown in Figure 7.18. Of course, in that case the rule should also be applied on the successor state “4” of the new mixed initiative state “2”. Concurrent behaviours that encompass successive sendings (as in this example “A”, “C”) may lead to complex specifications and should be avoided; this is discussed in Section 7.1.3.2.2.

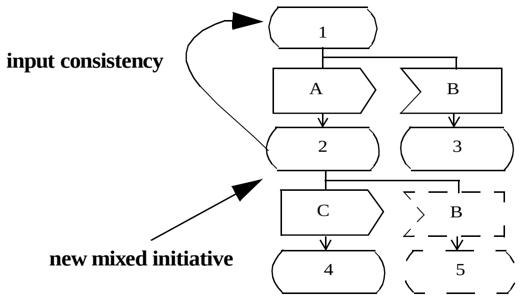


Figure 7.18 : Mixed initiative state introduced by input consistency.

V-rule: Mixed initiative and input consistency

An a-role and its complementary a-role involved in a mixed initiative may interact in a non-consistent way if their machines are not specified following the design rule “mixed initiative and input consistency”.

Justification:
As both a-roles are involved in a mixed initiative, they may both take initiative to send a signal. If they take the initiative to send simultaneously, the signals are received in the states triggered by sending from the mixed initiative states. If these states are not input consistent with the mixed initiative states as recommended by the design rule, unspecified signal receptions occur: the a-roles do not interact consistently.

Note that it is possible to produce a consistent complementary a-role for an a-role whose machine contains a mixed initiative state, but does not follow the design rule “mixed initiative and input consistency”. The a-roles interact consistently when the complementary a-role is *not* enabled to take an initiative in the complement state of the mixed initiative state. In that case, the full behaviour expected by the a-role is not covered.

7.1.3.2 Concurrent behaviours: conflict resolution

In the case of concurrent behaviours, conflicts may occur. State machines should be specified such that conflicts can be detected and resolved. In this section, we propose some design patterns for the resolution of conflicts.

Conflicts occur when a machine and its complementary machine send signals to each other simultaneously. A conflict is perceived when an input specified in a mixed initiative state is received in the state following signal sending in the mixed initiative state. A conflict can be detected in both interacting machines. Enforcing the input consistency design rule provides a means to detect conflicts.

Machines involved in a conflict should agree on how to further proceed. The purpose of conflict resolution is to come to an agreement. Conflict resolution requires coordination between the interacting machines. Two main coordination patterns may be defined:

- A coordinator may be assigned at design time. An example is described in Figure 7.19. The machine on the left-hand side coordinates the conflict resolution. The signal “resolve” represents the decision taken at conflict resolution. For example, the signal “D” may be sent if the behaviour (“B”, “D”,...) is retained. Note that the machine and the complementary machine interact consistently. This can be checked by considering all possible behaviours. We observe that the states where the conflict is detected, i.e. state “2” in the machine (a) and state “3” in the complementary machine (b), do not mirror their complement states. The states describing conflict resolution, i.e. state “6” in both machines, mirror each other.

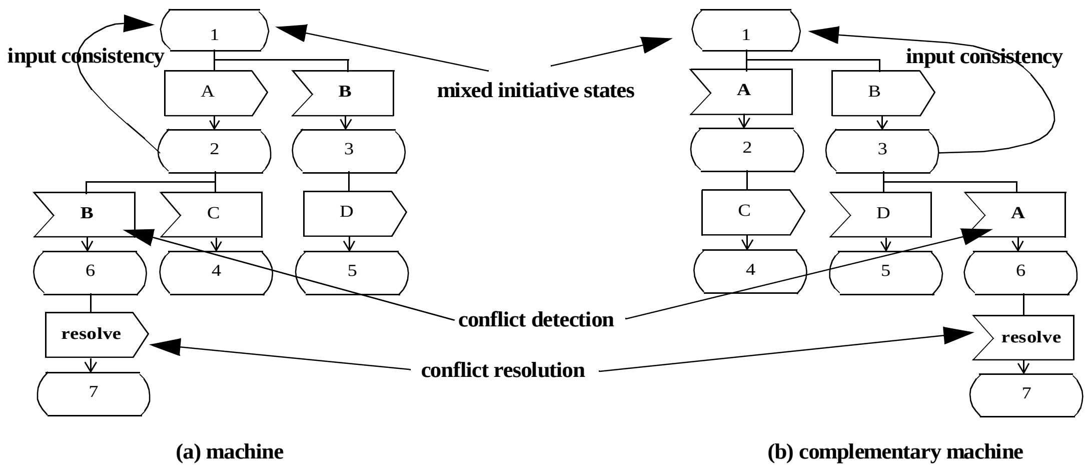


Figure 7.19 : Mixed initiative: conflict detection and resolution, one coordinator.

- A coordinator may be selected at run-time as shown in Figure 7.20. The selection should result from a commonly defined analysis. This approach introduces a new mixed initiative state (state "6") in both machines. Following the analysis, one and only one side should take the coordination of the conflict resolution: the signal "resolve" should be sent by only one side. If not, the analysis has failed: divergent decisions have been reached on the distinct sides. This is an error case. As in the previous example, the machine and the complementary machine interact consistently. We also observe that the conflict detection states, i.e. "2" and "3", do not mirror their complement states, while the conflict resolution states, i.e. "6", do. As the states "6" are mixed initiative states, they lead to new conflict detection states, "7" and "8", that do not mirror their complement states.

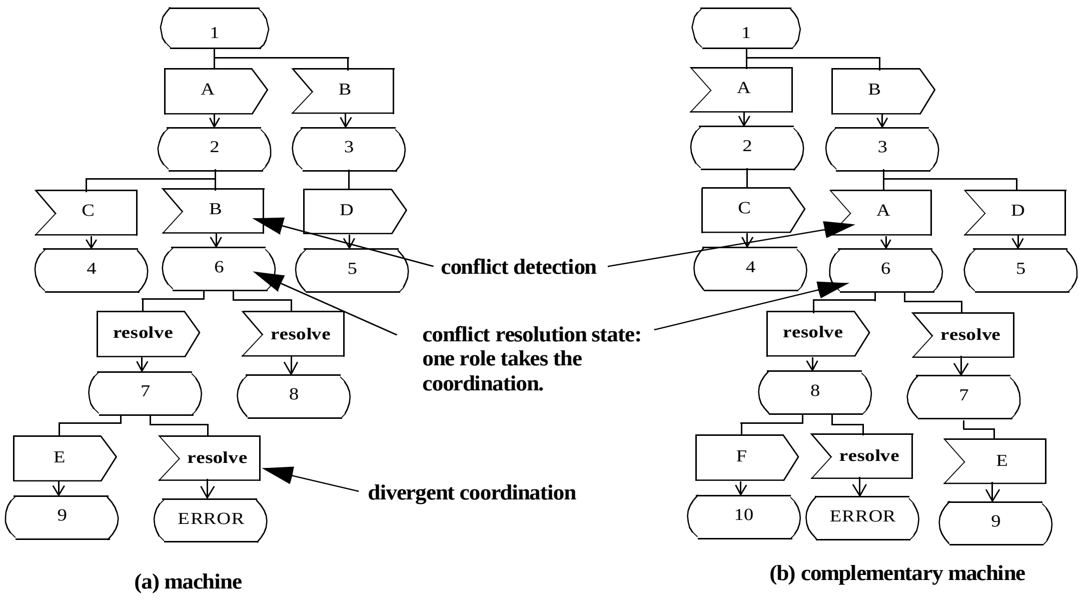


Figure 7.20 : Mixed initiative: dynamically assigned conflict coordinator.

D-rule: Mixed initiative and conflict

In the case where a mixed initiative state describes concurrent behaviours, a behaviour conflict is detected when some state following signal sending in a mixed initiative state receives a signal specified as input in the mixed initiative state. Conflict resolution requires coordination. A conflict resolution coordinator can be assigned either at design time or at run-time.

7.1.3.2.1 Negotiation

The selection of a coordinator at run-time may be refined by adding a negotiation phase. This is shown in Figure 7.21. Conflict resolution does not take place at once, but after a negotiation leading to the selection of a coordinator. In this example, negotiation is initiated by both sides; this introduces new mixed initiative states “1n”. Note that these new mixed initiative states represent alternative orderings, not concurrent behaviours. These states and their successors “2n” mirror their complement states; the alternative orderings lead to the common state “3n” and its complement state “3n”.

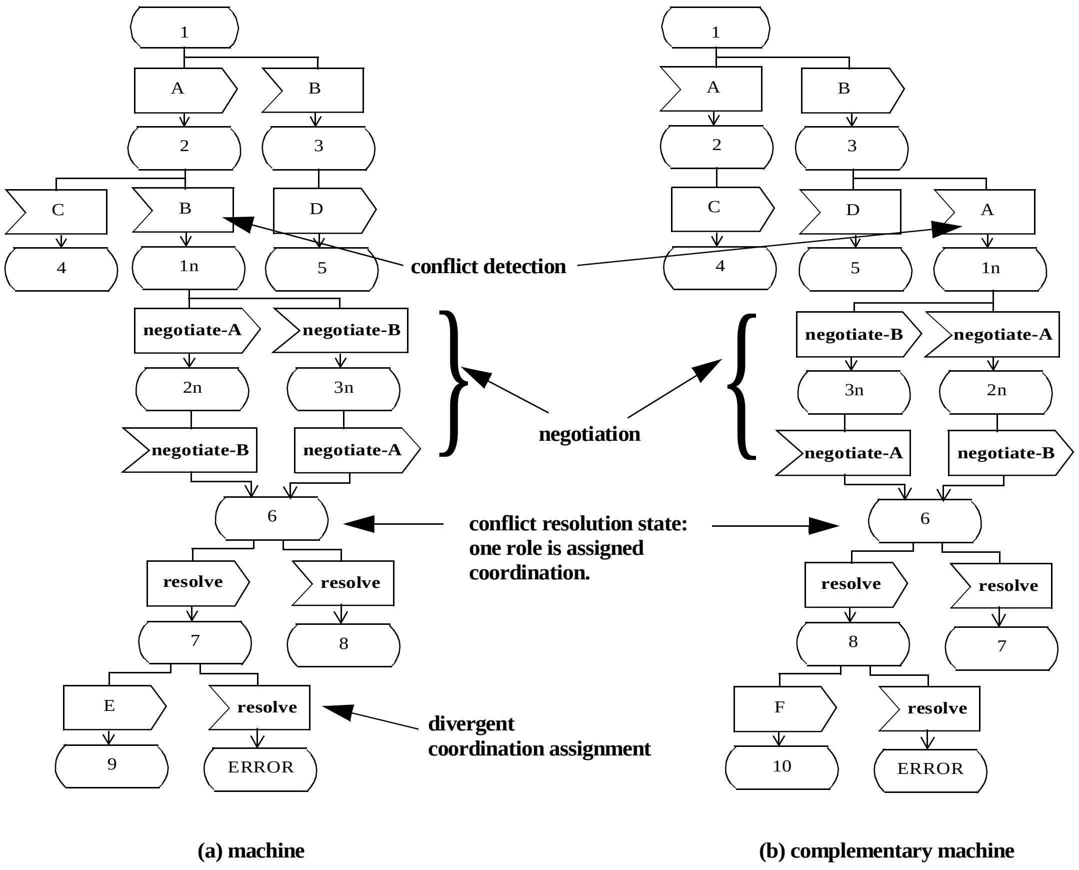


Figure 7.21 : Mixed initiative: negotiation.

7.1.3.2.2 Signal sending sequences

A particular case occurs when a concurrent behaviour describes the sending of a sequence of signals. The detection of conflict may occur at any step in the sending sequence.

An example is shown in Figure 7.22. The signals “A” and “C” may be sent successively. If both machines take initiative simultaneously, the signal “B” may either be received before or after the sending of “C”. The conflict is perceived by the machine in state “2” or “4” when “B” is received. In the complementary machine, the conflict may either be detected by the reception of “A” or “C”. On entering the state “1d”, the complementary machine is not able to determine whether the signal “C” has been sent or not. In order to avoid the introduction of a new mixed initiative state, the conflict resolution should be coordinated by the machine. If multiple sendings can take place after the sending of “A”, new conflict detection and resolution states are added in a cascade manner. As the structure of the state graph is not preserved in the complementary machine, the relations between the conflict resolution states of the machine and the complementary machine may become very complex.

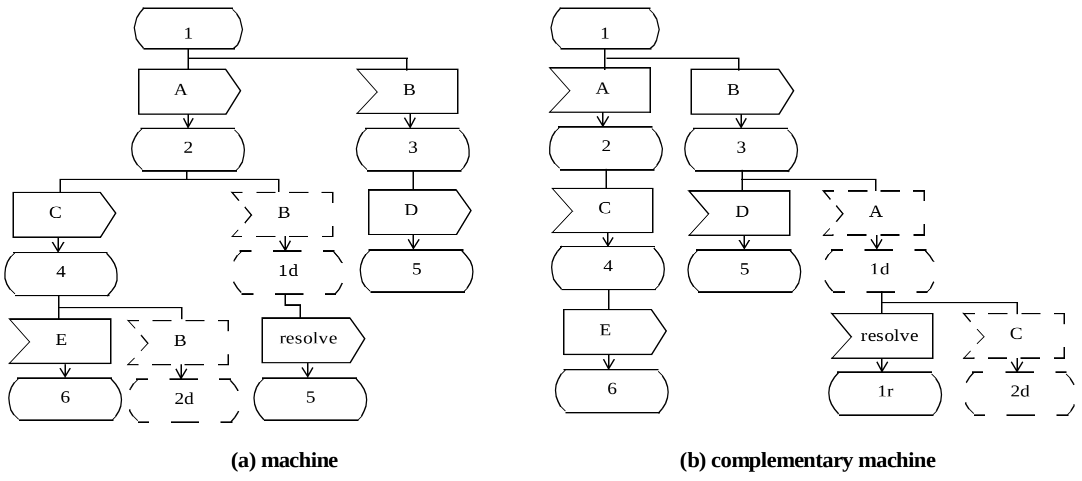


Figure 7.22 : Concurrent behaviours: sending sequence.

In this example, the machine in case (a) is able to determine at which step in the sending sequence the conflict occurs. When both machines are able to send a sequence of signals, the conflict detection becomes cumbersome. An example is shown in Figure 7.23. The different conflict detection states correspond to different conflict sequences. The same names are used in both machines for the identical conflict sequences. For example, the states “3d” correspond to signals “B”, “D” crossing “A”. On entering the state “1d”, none of the machine is not able to determine whether the second signal in the sequence has been sent or not. Therefore the conflict cannot be resolved without the introduction of a new mixed initiative state. On the other hand, on entering the state “2d”, the machine is not able to determine whether the signal “D” has been sent or not. On entering the state “3d”, the complementary machine is not able to determine whether the signal “C” has been sent or not. In these states mixed initiatives may be avoided. As shown by this example, the structure of the graph becomes complex and it is cumbersome to establish the relations between conflict detection states when multiple sendings are allowed in a mixed initiative state.

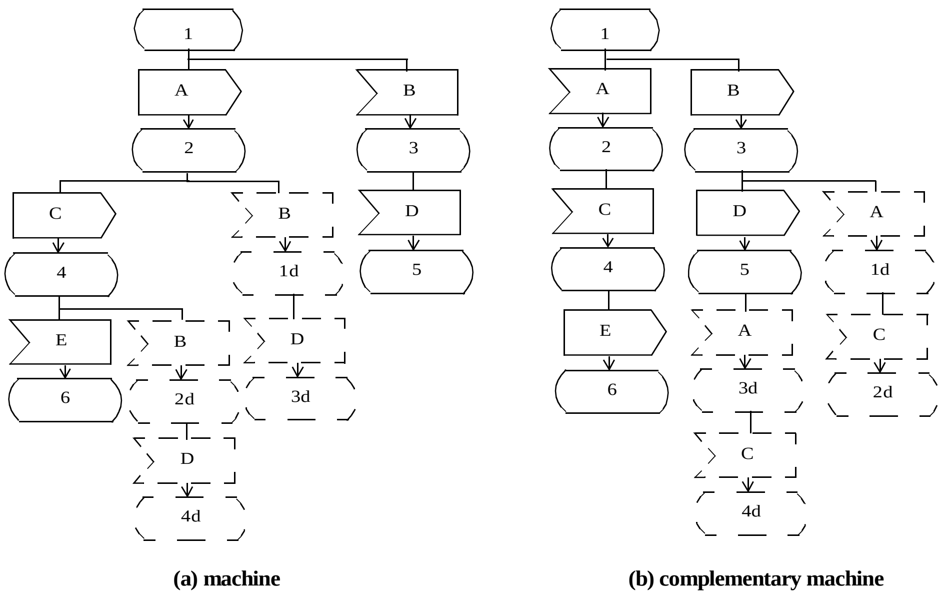


Figure 7.23 : Concurrent behaviours: multiple conflict detection states.

We recommend to avoid specifications that make the specification of the dual machine difficult, and that do not maintain simple relations between the conflict detection states of the machine and the complementary machine. We advice to avoid sending sequences in concurrent behaviours.

D-rule: Mixed initiative and signal sending sequences

Concurrent behaviours described by mixed initiatives should not specify signal sending sequences. Signal sending and consumption should take place alternatively.

As a consequence of this rule, signal reception sequences do not occur.

7.1.3.3 Alternative input and output event orderings

A mixed initiative behaviour that describes alternative input and output event orderings has the following characteristics:

- The same set of events take place in the alternative sequences. The sequences differ in their ordering of events.
- A machine and its complementary machine may perceive different input and output orderings. As interactions on an association are sent over a single communication path, inputs are received in the same order as sent.
- The same behaviour takes place after any of the alternative sequences. Thus the alternative sequences lead to a common state.

Alternative event orderings do not require conflict resolution. The main concern during validation is to ensure that the sequences lead to the same state.

Figure 7.24 illustrates an example where the sequences lead to distinct states (state “4” or “5”); we assume these states to be non-equivalent. A machine that sends a signal before it receives a signal, is not able to determine the event ordering chosen at the other machine. For example, when in state “4”, the machine in case (a) cannot determine if the complementary machine has reached state “4” or “5”. When two machines send signals to each other simultaneously (signal crossing), none of them is able to determine the event ordering at the complementary machine, and further behaviour is not predictable. This ambiguity may be removed by letting the machines exchange some status information. One machine should coordinate this ambiguity resolution, otherwise new mixed initiative states are introduced. This approach introduces extra signalling, and any optimisation benefit gained from letting the machines communicate in any order is lost.

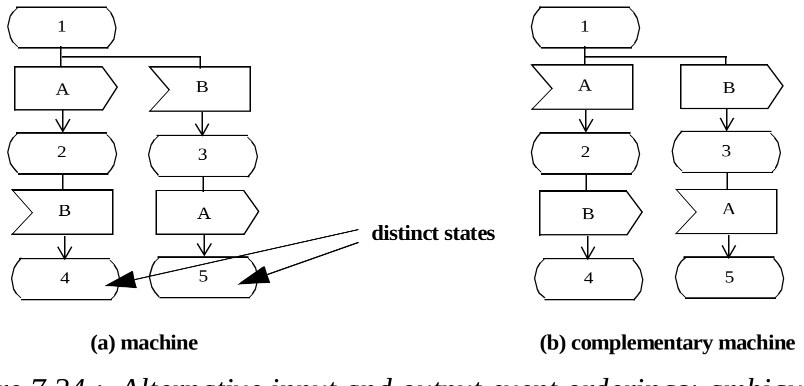


Figure 7.24 : Alternative input and output event orderings: ambiguity.

D-rule: Input/output event orderings and further behaviour
Alternative input/output event orderings should lead to a common state.

Alternative input/output events orderings may involve more than two events. An example is shown in Figure 7.25. Notice that the input consistency rule is enforced. When more than two events are introduced, the state graph becomes complex, and the identification of orderings cumbersome. We advice therefore to avoid using multiple event orderings except in special cases, such as negotiation or error indication, and to limit the number of events to two in the sequences.

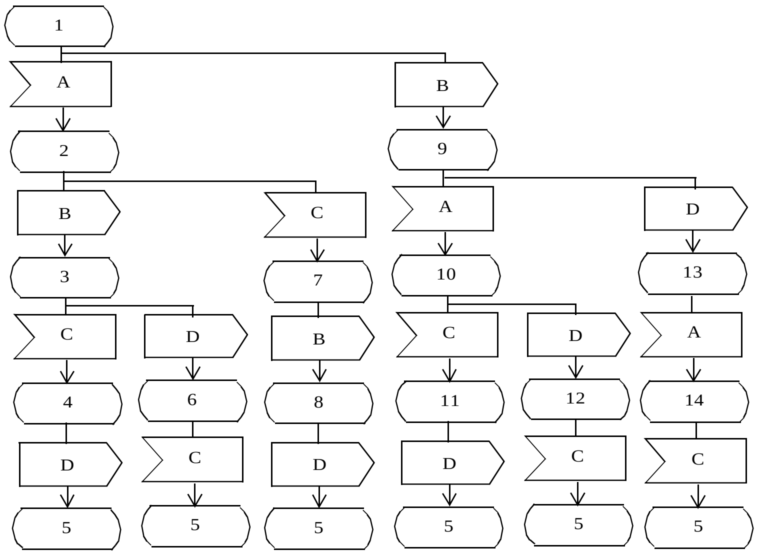


Figure 7.25 : Event ordering: four events.

D-rule: Input/output event orderings and event sequence length
The event sequence in alternative input/output event orderings should not contain more than two events, i.e. one input and one output.

Note that this design rule does not restrict the number of events sent or received in a state to two. The mixed initiative state may specify several input and output events. Only the length of sequence is restricted.

Differently from concurrent behaviours, the dual machine of a machine describing alternative event orderings mirror each other. The negotiation phase in the example shown in Figure 7.21 illustrates this property.

7.1.3.4 Concurrent behaviours and input/output event ordering

A particular case occurs when a signal specified as input in a mixed initiative state can also be consumed “normally” in a state following signal sending in the mixed initiative state. By “normally”, it is meant that the input is not specified in order to enforce input consistency, but is part of a normal behaviour. This input may either occur first in the mixed initiative state, or after sending a signal.

An example is shown in Figure 7.26. The signal “B” may either be consumed in the mixed initiative state “1”, or after sending “A” in state “2”. In the complementary machine the sending of “B” may occur after the consumption of “A”. However, when “B” is received in the machine in state “2”, we cannot deduce that “B” was sent after “A”; “B” may also has been sent by the complementary machine in state “1” meaning that the two machines have taken conflicting initiatives. We observe that only the complementary machine is able to detect whether a “normal” behaviour or a conflict has occurred. The machine is not able to distinguish state “4” from state “7” in the complementary machine. This is a form of ambiguity that is cognate to the ambiguity introduced by equivoque transitions. A simple way to remove any ambiguity is to define the states “4” and “7” identical. This corresponds to the case of alternative input/output event orderings. If states “4” and “7” are kept distinct, they should lead to further behaviours that are distinguishable. For example, distinct signals may be sent in the transitions from the states “4” and “7” of the complementary machine. The state “4” of the machine should be able to consume any of these signals.

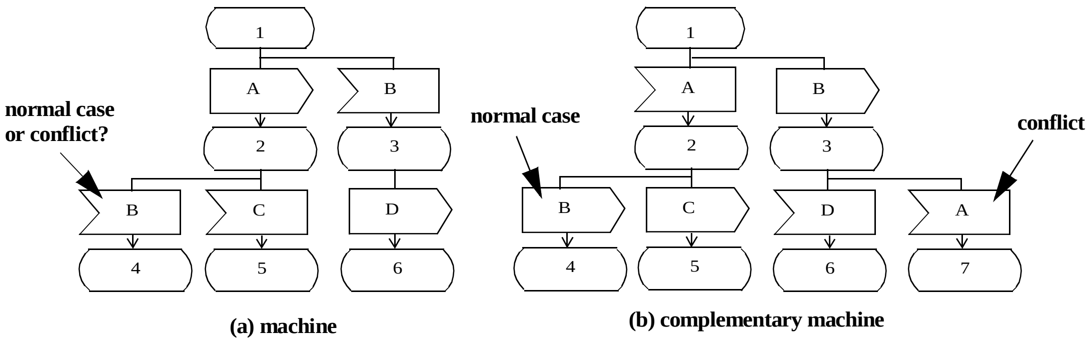


Figure 7.26 : Concurrent behaviours and event ordering.

In this example, the complementary machine can easily detect the occurrence of a conflict. In the case where both machines define “normal” behaviours that may be mistaken for concurrent behaviours, the conflict detection becomes cumbersome. An example is shown in Figure 7.27. If the machine is in state “4”, and the complementary machine in state “7”, none of the machines can deduce immediately that a conflict has occurred. An interaction is needed to do so. A simple approach is to define the states “4” and “7” identical dealing with the case as alternative orderings.

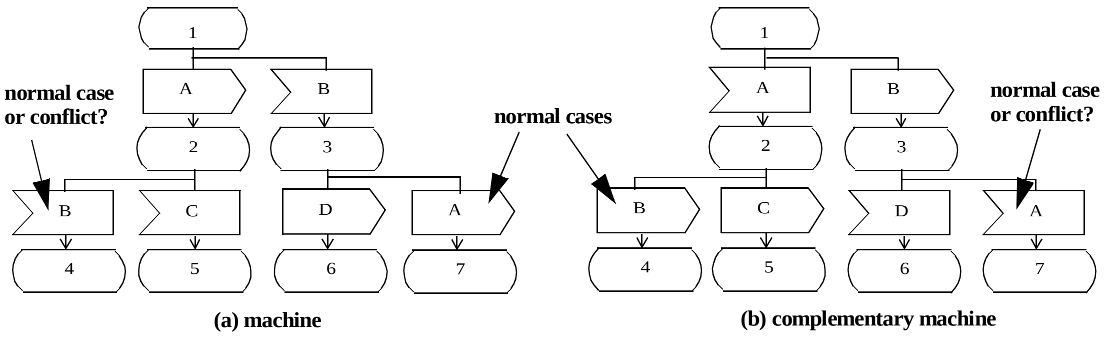


Figure 7.27 : Concurrent behaviours: ambiguous conflict.

We recommend to avoid specifications that make the detection of conflicts difficult, or the specification of states following the conflict detection dependent of other states. Mixed initiatives should either describe concurrent behaviours or alternative orderings.

D-rule: Mixed initiative purposes
Mixed initiatives should either describe concurrent behaviours or alternative orderings, not both.

7.1.3.5 Exit states

A special case of mixed initiative occurs when the successor state of the mixed initiative after signal sending is an exit node. As an exit state has no successor, the design rule “mixed initiative and input consistency” cannot be followed.

An example is given in Figure 7.28. In the case where a mixed initiative takes place, the signal “A” arrives when the machine has stopped. The conflict can be detected in the complementary machine. Only one choice is open to avoid improper termination: the complementary machine should terminate. In this example, although the signal “A” may be lost, the termination is done properly, and the a-role interaction is considered as consistent[1].

In some cases, mixed initiatives may lead to improper termination as shown in Figure 7.29. In this example, both behaviours lead to exit nodes attached distinct exit conditions.

1. Our definition of interaction consistency does not encompass the loss of signal.

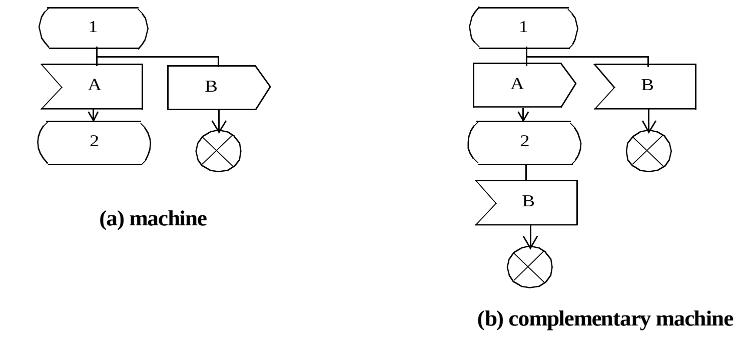


Figure 7.28 : Mixed initiative: termination.

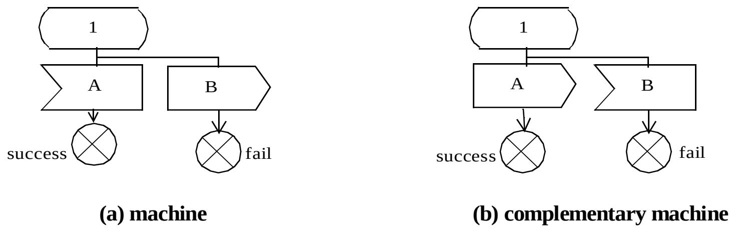


Figure 7.29 : Mixed initiative: improper termination.

V-rule: Mixed initiative and termination

An a-role and its complementary a-role involved in a mixed initiative leading to exit nodes attached distinct exit conditions, may interact inconsistently.

Justification:

As both a-roles are involved in a mixed initiative, they may both take initiative to send a signal. If they take the initiative to send simultaneously in the mixed initiative states preceding the exit nodes, they terminate with inconsistent exit conditions. Such interaction leads to improper termination: the a-roles do not interact consistently.

Note that it is possible to produce a dual a-role for an a-role whose machine contains a mixed initiative state followed by exit nodes with distinct exit conditions. For example, the a-roles interact consistently when the complementary a-role is *not* enabled to take an initiative in the complement state of the mixed initiative state. In that case the dual a-role does not provide the full behaviour expected by the a-role.

Although consistent, the kind of behaviour shown in Figure 7.28 is problematic when s-roles are composed. Signal “A” may be received by an s-role executing after the termination of the s-role providing the a-role described in case (a). S-roles should be specified without making too many assumptions about the s-roles they are composed with. The following design rule contributes to this aim.

D-rule: Mixed initiative and termination
A-roles should be designed such that exit states do not directly succeed any mixed initiative state.

7.1.3.6 Specifying a dual a-role

After this discussion about the desirable properties of an a-role whose machine contains mixed initiative states, we now proceed to produce a dual a-role for such an a-role. As the the full behaviour of the a-role can be covered through interaction between the a-role and the dual a-role, any mixed initiative behaviour specified in the a-role may occur.

We assume that input, mixed and termination ambiguity have been removed (see Section 7.1.2.5). We also assume that the design rules defined for mixed initiatives have been followed. Recall these design rules:

- "Mixed initiative and termination" on Page 190
- "Mixed initiative purposes" on Page 188
- "Mixed initiative and input consistency" on Page 178
- "Mixed initiative and conflict" on Page 182
- "Mixed initiative and signal sending sequences" on Page 184
- "Input/output event orderings and further behaviour" on Page 186
- "Input/output event orderings and event sequence length" on Page 186

V-rule: Event ordering and duality
The dual a-role of an a-role that
- does not present any input, mixed and termination ambiguity, and
- does not contain any acute τ-transitions, and
- does not present any mixed initiative that describes concurrent behaviours, and
- enforces the design rules defined for mixed initiatives,
can be obtained by merging and mirroring.
The initial a-role and the a-role obtained by this transformation interact consistently provided that
- they both start execution consistently, i.e. the machines should be entered using consist-

ent entry conditions, and
- any spontaneous sending can occur.

Justification:
Reasoning is performed on all states, except the mixed initiative states and their successors, in the same manner as for machines that do not contain mixed initiative states. Each state is merged/mirrored to a consistent state, and transitions from those states preserve consistency.
When mirroring mixed initiative states to complement states, we ensure that the states interact consistently with the complement states when initiatives are not taken simultaneously by both sides. The states following the mixed initiative states mirror each other and thus interact consistently.
If initiatives are taken simultaneously, the sent signals cross each other:
- As we assume that the event sequence length is restricted to two, and as the mixed initiatives do not describe any concurrent behaviours, no other signal than the signals sent in the mixed initiative state and its complement mixed initiative state may cross.
- In the initial machine, input consistency ensures that the next state after sending is enabled to consume the crossing signal sent by the other machine.
- As the event sequence length is restricted to two, any signal that may be sent in the mixed initiative state may also be sent in the next state after consumption of a signal in a mixed initiative state. When mirrored these transitions enforce input consistency in the complementary machine: any signal that may be consumed in the complement mixed initiative state may also be consumed in the next state after sending a signal. Input consistency in the complementary machine ensures that the next state is enabled to consume any crossing input.
Thus we can deduce that the machine interact consistently with the complementary machine in any state following the mixed initiative state. Both orderings lead to a common state in the initial machine that is mirrored to a common complement state. This common state is either a non-mixed initiative state and is consistent with is complement state, or a mixed initiative state representing new alternative orderings and the previous reasoning can be repeated.

V-rule: Mixed initiative and duality
The dual a-role of an a-role that
- does not present any input, mixed and termination ambiguity, and
- and does not contain any acute τ-transitions, and
- enforces the design rules defined for mixed initiatives,

can be obtained by merging and mirroring all states, except the states following mixed initiative states that represent concurrent behaviours. Such states should be transformed as followed:
- A state following signal sending is transformed to a complement state. Any signal and transition from the state that do not serve conflict detection are transformed by mirroring. The consumption of any signal enabling the detection of a conflict in the a-role is not mirrored. As conflict detection is defined relative to the preceding mixed initiative state, distinct complement states are generated for states that have several predecessors.
- A state following signal consumption is transformed to a complement state. Any signal and transition in that state are transformed by mirroring. The complement state is made input consistent with its preceding mixed initiative state. The state following the consumption of a signal enabling the detection of a conflict in the complementary a-role mirrors the next state after the detection of the same conflict in the initial a-role.
The initial a-role and the a-role obtained by this transformation interact consistently provided that
- they both start execution consistently, i.e. the machines should be entered using consistent entry conditions, and
- any spontaneous sending can occur.

Justification:
Reasoning is performed on all states, except the mixed initiative states and their successors, in the same manner as for machines that do not contain mixed initiative states. Reasoning on mixed initiative states that represent alternative event orderings has been done above. As we assume that mixed initiative states either describe concurrent behaviours or alternative orderings, we just need to reason on concurrent behaviours.
By mirroring mixed initiative states to a complement state, we ensure that the states interact consistently with the complement state when initiatives are not taken simultaneously by both sides. The states following the mixed initiative states can also be shown to interact consistently in that case:
- If the initiative was taken by the initial a-role, only the complementary a-role is enabled to send some signal, this because of the rule "Mixed initiative and signal sending sequences". The complementary a-role is only enabled to send signals expected by the initial machine, this because we have restricted mirroring to signals not involved in conflict detection. Here note the importance of generating distinct successors for distinct mixed initiatives.
- If the initiative was taken by the complementary a-role, only the initial a-role is enabled to send some signal, this because of the rule "Mixed initiative and signal sending

sequences". As the states triggered by signal consumption have been transformed by mirroring, the complementary a-role can consume the signals sent by the initial a-role.
In the case where both a-roles take the initiative to send simultaneously, the signals cross each other:
- As we assume that no successive signal sendings occur in a concurrent behaviour, only two signals may cross each other.
- The consumption of these signals is enforced as both machines follow the input consistency design rule. The conflict is detected in both machines. As the behaviours occurring after conflict detection complement each other, the machines interact consistently after the detection of a conflict.

The transformation described by the rule does not require distinct complement states to be generated for states succeeding the mixed initiative state after signal consumption. The generation of distinct states would however ensure that the complement state is not enabled to consume more signals than strictly necessary.

Given this validation rule, we are able specify an algorithm that generates a dual a-role for an a-role containing mixed initiative states. Before the generation of a dual a-role, the mixed initiative states should be identified, and the machine should be checked against the design rules defined for mixed initiatives. Algorithm 7.6 performs these operations. The algorithm considers first a mixed initiative state as an alternative ordering. If the rule "Mixed initiative purposes" is not enforced, an error is generated when checking the ordering sequences. We assume that the graph has been minimized (Algorithm 6.1), and that merging has been applied in order to remove input, mixed and termination ambiguity. The algorithm makes use of the notation introduced in Section 6.8.

Algorithm 7.6: Identifying mixed initiative states and checking design rules

```
main ()
{
 /* Assumptions:
   - the graph has been minimized
 */

 /* set of mixed initiative states */
 CB = {}; /* conflicting behaviours*/
 AO = {}; /* alternative orderings*/

 W = {}; /* working set */
 /* start from all initial states */
 for each $s_o$ in $S_o$
  if $s_o$ is not in $W$
   identify-mixed-state ($s_o$);

 /* design rule: "Mixed initiative and termination"*/
 for each $s$ in $AO$ or $CB$
  check-termination ($s$);

 /* design rule: "Mixed initiative and input consistency"*/
 for each $s$ in $AO$ or $CB$
  check-input-consistency ($s$);

 /* design rules:
 "Input/output event orderings and further behaviour"
 and
 "Input/output event orderings and event sequence length"*/
 for each $s$ in $AO$
  check-I/O-orderings ($s$);

 /* design rule:
 "Mixed initiative and signal sending sequences" */
 for each $s$ in $CB$
  check-sending-sequence ($s$);

}

identify-mixed-state ($s$)
{
 add $s$ to $W$;

 if input-enable ($s$) is not empty
 and output-enable ($s$) is not empty /* mixed state */
  for each $i$ in input-enable ($s$)
   $n$ = T ($s$, $i$);
   /* seek after event permutation */
   if some $o$ in output-enable ($s$) belongs to enable ($n$)
    add $s$ to $AO$; /* alternative orderings */
  if $s$ is not in $AO$
   add $s$ to $CB$;

 for each $e$ in enable ($s$)
  for each successor $n$ of $s$ /* element of T ($s$, $e$) */
   if $n$ is not in $W$
    identify-mixed-state ($n$);
}
```

```
check-termination (s)
{
 for each e in enable (s)
  for each successor n of s /* element of T (s, e) */
   if n belongs to $S_e$
    report-termination-error (s);
}

check-input-consistency (s)
{
 for each o in output-enable (s)
  n = T (s, o);
  for each i in input-enable (s)
   if i is not in enable (n)
    report-input-consistency-error (s, n);
}

check-I/O-orderings (s)
{
 for each o in output-enable (s)
  if enable (T (s, o)) differs from input-enable (s)
   report-event-ordering-error (s, o);

 for each i in input-enable (s)
  if enable (T (s, i)) differs from output-enable (s)
   report-event-ordering-error (s, i);

 for each i in input-enable (s) and o in output-enable (s)
  if T (T (s, o), i) differs from T (T (s, i), o)
   report-further-behaviour-error (s, i, o);
}

check-sending-sequence (s)
{
 for each o in output-enable (s)
  if output-enable (T (s, o)) is not empty
   report-sending-sequence-error (s, T (s, o));

 /* check also successive consumptions with respect to
    the complementary a-role */
 for each i in input-enable (s)
  if input-enable (T (s, i)) is not empty
   report-consumption-sequence-error (s, T (s, i));
}
```

Algorithm 7.7 enables one to generate a dual a-role of an a-role that does not present any input, mixed and termination ambiguity, and enforces the design rules defined for mixed initiatives. It also assumes that the a-role does not contain any acute τ-transitions. The mixed initiative states are identified by applying Algorithm 7.6. A machine that contains equivoque transitions should be transformed by merging (Algorithm 7.4). Note that a new complement state is generated for each state following a mixed initiative state. As conflict detection is relative to the preceding mixed initiative, this ensures that the proper signals are transformed by mirroring.

Algorithm 7.7: Generating a dual a-role

```
main ()
{
 /* Assumptions:
   - the graph has been minimized
   - no input,mixed or termination ambiguity
   - no acute τ-transitions
   - mixed initiative states have been identified
   - mixed initiative rules are enforced
   - merging has been applied
 */
 /* Mixed initiative states represented concurrent
 behaviours are stored in $CB$ (Algorithm 7.6) */

 /* define graph elements: states and events */
 $\overline{S}$ = $S$; /* maintain any associated condition */
 $\overline{I}$ = $I$; $\overline{O}$ = $O$;

 /* set of mirrored or transformed states */
 $W$ = {};

 /* start from all initial states */
 for each $s_o$ in $S_o$
  if $s_o$ is not in $W$
   mirror ($s_o$);
}

mirror ($s$)
{
 add $s$ to $W$;
 for each $e$ in $E$
  define $\overline{T}(\overline{s}, \overline{e}) = \overline{T(s, e)}$;
 if s is not in CB
  for each successor n of s
   if n is not in W
    mirror (n);
 else
  generate-initiative-successors (s);
}

generate-initiative-successors (s)
{
 /* transform states after signal sending */
 for each o in output-enable (s)
  create new state x; /* add x to $\overline{S}$ */
  set $\overline{T}(\overline{s}, \overline{o}) = x$;

  for each e in E /* initialise */
   define $\overline{T}(x, e)$ = {};

  for each i in input-enable (T(s, o))
   if i is not in enable (s)
    set $\overline{T}(x, \overline{i}) = \overline{T(T(s, o), i)}$;

 /* transform states after signal consumption */
 for each i in input-enable (s)
  create new state x; /* add x to $\overline{S}$ */
  set $\overline{T}(\overline{s}, \overline{i}) = x$;

  for each e in E /* initialise */
   define $\overline{T}(x, e)$ = {};

  for each o in output-enable (T(s, i)) /* mirror */
    set $\overline{T}(x, \overline{o}) = \overline{T(T(s, i), o)}$;

  for each o in output-enable (s) /* input consistency */
    set $\overline{T}(x, \overline{o}) = \overline{T(T(s, o), i)}$;

 /* proceed in the graph */
 for each successor of successor n of s /* T (T(s, e), e) */
  if n is not in W
   mirror (n);
}
```

7.1.4 Acute τ-transitions

Finally after equivoque transitions and mixed initiatives, complexity is added to the a-role graphs by introducing acute τ-transitions. Acute τ-transitions often lead to ambiguity, but not always. The validation rules related to input and mixed ambiguity introduced in Section 7.1.2.1 apply. It is not possible to produce dual a-roles when τ-transitions lead to ambiguity.

This section proposes two kinds of techniques:

- Re-design of the s-roles following design rules that enable remaining τ-transitions to removed from the a-role state graph.
- Transformations that ensure that a dual a-role can be generated even though some τ-transitions are not removed.

Notice that re-design towards the removal of τ-transitions applies to s-roles. As τ-transitions in the a-role graphs are obtained by projection of non-visible interactions in the s-role graphs, their removal require re-design the s-roles.

Acute τ-transitions are τ-transitions that have not been removed by gathering from the a-role because their removal would modify the observable behaviour. Recall that we have proposed two definitions of gathering: strong and weak gathering. Strong gathering maintains the machine observable behaviour in any case. Weak gathering only maintains the observable behaviour provided that the spontaneous transitions can occur. We reconsider any case of non-gathering in our reasoning. When a τ-transition is not removed by strong gathering, potential errors that can be introduced by weak gathering are considered.

τ-transitions remain in the graph in the following cases (the cases where τ-transitions can only be removed by weak gathering are marked by *):

1. A signal specified as an input in the τ-successor is not specified as input or save* in the τ-predecessor.
2. A signal specified as an input in the τ-successor is specified as input in the τ-predecessor, but the τ-successor and τ-predecessor transit to distinct successor states.
3. A signal specified as an input in the τ-successor is specified as save in the τ-predecessor, but other inputs are also specified in the τ-predecessor.*

4. A signal specified as a save in the τ-successor is not specified as input* or save in the τ-predecessor.

5. A signal specified as a save in the τ-successor is specified as input in the τ-predecessor, but other inputs are also specified in the τ-successor.*

6. A signal specified as an input in the τ-predecessor is not specified as input in the τ-successor.

7. A signal specified as an input in the τ-predecessor is specified as input in the τ-successor, but the τ-successor and τ-predecessor transit to distinct successor states.

8. A signal specified as a save in the τ-predecessor is not specified as input* or save in the τ-successor.

9. A signal specified as a save in the τ-predecessor is specified as input in the τ-successor, but other inputs are also specified in the τ-predecessor.*

10. When the τ-transitions links an exit state with a non-exit state. This case leads to termination occurrence ambiguity (see Section 6.7.4).

Figure 7.30 to Figure 7.33 and Figure 7.37 illustrate the different cases. We have grouped cases that may be handled in a similar way.

Recall that σ-states never precede or succeed τ-transitions, and thus, save is always explicitly specified in τ-successors and τ-predecessors.

7.1.4.1 Re-design towards the removal of τ-transitions

7.1.4.1.1 Input consistency

Figure 7.30 illustrates the case (6) where a signal specified as input in a τ-predecessor is not specified as input in the τ-successor. Here an external observer cannot determine when the machine is enabled to handle the signal “A”. This is a form of input inconsistency. The machine can be re-designed specifying “A” as input in the τ-successor.

Specifying “A” as save (instead of input) in the τ-successor is an alternative approach that at the first glance seems simpler. However as the rule "Save consistency" is enforced, “A” has to be specified as input in some successor states of state “3”. This may require other modifications to be done to the graph. In the case where this alternative using save is chosen, the τ-transition from state “2” to “3” in Figure 7.30 is only removed by weak gathering. Gathering may hide a potential deadlock in state “2”. The designer should consider the s-role behaviour projected to that τ-transition before applying weak gathering.

We recommend to choose the alternative using input. In this alternative, “A” can be consumed in any state.

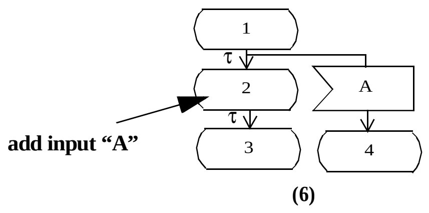


Figure 7.30 : Acute τ-transitions withdrawn through input consistency.

D-rule: τ-transitions and input consistency

A signal input should be re-iterated in the successor states of a state where input is specified, when the transitions to these successors describe non-visible interactions[1]. The successor states should then be input consistent with the state where input is specified.

This rule does not set any constraint on the successor state triggered by the added input and may lead to the case (7) illustrated in Figure 7.33.

It may be possible to produce a consistent complementary a-role of an a-role that does not follow the rule. This is the case when the machine can further proceed without consuming the signal whose input is not re-iterated. In case (6) in Figure 7.30, the machine may proceed in state “3” by sending a visible signal. Then, a complementary machine that ignores “A” may interact consistently with the machine. Input inconsistency is however a symptom of poor design, and the corresponding s-roles should be re-designed.

The rules "τ-transitions and input consistency" and "Mixed initiative and input consistency" are cognate. In the first rule, successor states are triggered by transitions that describe non-visible interactions. In the second rule, successor states are triggered by non-visible signals, but do send some visible signal. We propose to define a single rule:

D-rule: Input consistency

A signal input should be re-iterated in the successor states of a state where input is specified, when the transitions to these successors are triggered by non-visible signals. The

1. i.e. the transitions are triggered by non-visible signals and do not send any visible signal.

successor states should then be input consistent with the state where input is specified.

In the following, we assume that s-roles are designed according to the rule "Input consistency".

7.1.4.1.2 Backward save and input consistencies

Figure 7.31 illustrates the cases (1), (4) and (8) where an external observer cannot determine when the machine is enabled to handle a received signal. Note that case (8) is an error case as we assume that s-roles are designed according to the rule "Save consistency". In case (4), the machine can be simply re-designed adding “A” as save in the τ-predecessor. Adding save enforces backward save consistency. The τ-transition from state “1” to “2” can then be removed by strong gathering.

In case (1), the machine can be re-designed adding “A” as save or input in the τ-predecessor. The alternative using save is simple but the τ-transition from state “1” to “2” can then only be removed by weak gathering. The alternative using input usually requires more complex modifications to be made in the graph. Again the designer should consider the s-role behaviour projected to that τ-transition before applying weak gathering.

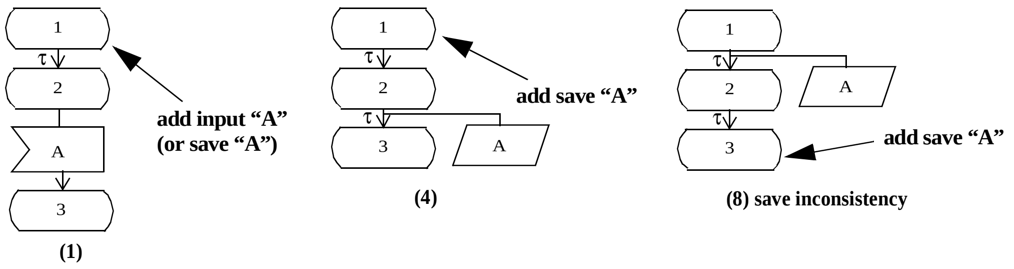


Figure 7.31 : Acute τ-transitions withdrawn through save.

We introduce two design rules "Backward input consistency" and "Backward save consistency". Depending on the s-role behaviour projected to τ-transitions, the designer can select which rule is appropriate. The rule "Backward input consistency" is a safe choice, but may not be appropriate in some applications. The rule does not set any constraint on the successor state triggered by the added input and may lead to the case (7) illustrated in Figure 7.33.

D-rule: Backward input consistency

The consumption of a signal should be specified in the predecessor state(s) of a state in which the signal is specified as input, when the transitions from these predecessors describe non-visible interactions[1 on Page 200]. A predecessor state specified according to this rule is said to maintain backward input consistency, or to be backward input consistent with its successor state(s). An s-role specified according to this rule is said to be backward input consistent.

D-rule: Backward save consistency
The saving of a signal should be specified in the predecessor state(s) of a state in which the signal is specified as input or save, when the transitions from these predecessors describe non-visible interactions[1 on Page 200], and when the signal is not specified as input in these predecessors. A predecessor state specified according to this rule is said to maintain backward save consistency, or to be backward save consistent with its successor state(s). An s-role specified according to this rule is said to be backward save consistent.

In some cases, consistent complementary a-roles may be produced for a-roles that are non-backward consistent. This is true if, in each state, backward consistency is supported for some signals, but not all. However, non- backward consistency is a symptom of poor design, and the corresponding s-roles should be re-designed.

In the following, we assume that s-roles are designed according to the rules "Backward input consistency" and "Backward save consistency".

7.1.4.1.3 Ordering

Figure 7.32 illustrates the cases (3), (9) and (5) where an external observer cannot determine in which order signals are handled. Both machines present an ordering ambiguity. The τ-transitions are neither removed by strong or weak gathering.

In order to limit the complexity of s-roles, we have earlier advised to avoid using save for modelling alternative orderings (recall the design rule "Save and ordering"). In the case where ordering is necessary, we advice to design s-roles such that ordering is maintained by transitions triggered by non-visible signals. In Figure 7.32, the s-roles should be re-designed such that states “1” and “2” either enforce no orders, or identical orders.

D-rule: τ-transitions and ordering
Input orderings enforced using save should be maintained by transitions triggered by non-visible signals.

When this rule is applied on the cases of Figure 7.32, signal “A” is either saved in both states “1” and “2”, or specified as input in both states.

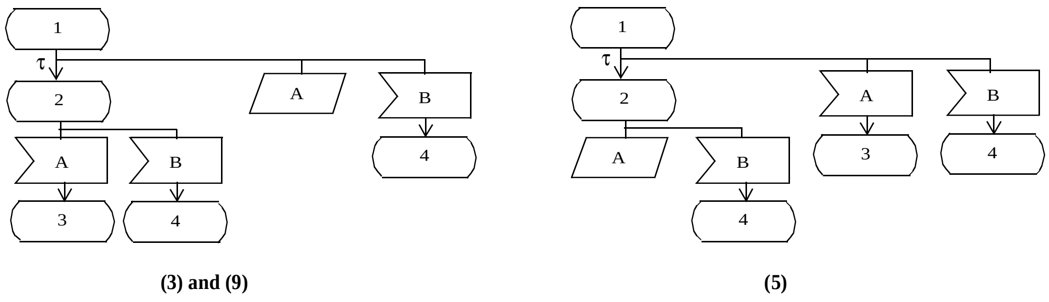


Figure 7.32 : Acute τ-transitions withdrawn through ordering.

In the following, we assume that s-roles are designed according to the rule "τ-transitions and ordering".

7.1.4.2 Removing ambiguities

We assume that the design rules defined in Section 7.1.4.1 have been applied allowing most cases of acute τ-transitions to be removed. The cases (2), (7) and (10) may remain. These cases are often symptoms of ambiguity. We first present cases (2) and (7). We postpone the discussion of case (10) to Section 7.1.4.2.1. This case relates to termination occurrence ambiguity, a form of ambiguity that has not yet been discussed.

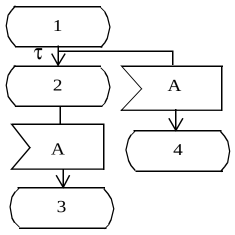
An example of the cases (2) and (7) is illustrated by Figure 7.33. Here the consumption of “A” leads to divergent behaviours represented by the distinct states “3” and “4”. In the worst case, the machine presents an input or mixed ambiguity.

We may consider two approaches:

- τ-transitions can be removed by aligning the behaviours occurring in the τ-predecessor and τ-successor. In Figure 7.33, this means re-designing the s-role such that state “3” and “4” are made identical.

- Ambiguities, if any, can be removed in a similar way as proposed in Section 7.1.2.5 and Section 7.1.2.6. When the graph does not contain any ambiguity, but only presents an output divergence, τ-transitions will remain in the graph. This is not a symptom of errors, but of desirable interaction between associations.

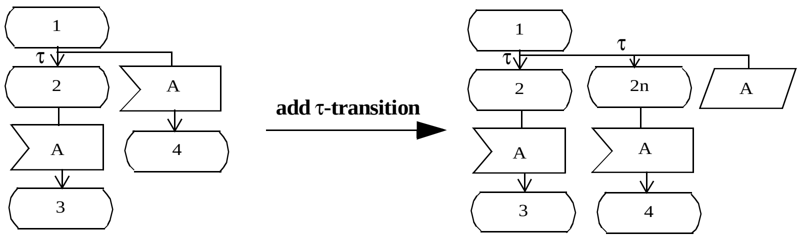
We propose to apply the second approach. The second approach is less strict as it does not require the re-design of s-roles that do not present any ambiguity.



(2) and (7)

Figure 7.33 : Acute τ-transitions leading to divergent behaviours.

As illustrated in Figure 7.34, an acute τ-transition case can be transformed to an equivoque transition case by the insertion of a new state and a τ-transition. We call this transformation a τ-insertion. The two machines behave in a similar way provided that the inserted τ-transition can occur. This can easily be checked by considering all possible behaviours.



(2) and (7)

Figure 7.34 : τ-insertion: transformation to equivoque τ-transitions.

Definition: τ-insertion

τ-insertion is a transformation that applies to states triggered by both τ-events and input events. For each input event, τ-insertion inserts a τ-transition to a new state triggered by that input. The input events are saved in the states where τ-transitions have been added.

T-rule: τ-insertion

After τ-insertion, a transition chart exhibits the same observable association behaviour as the initial transition chart provided that the new inserted τ-transition (s) can occur.

Justification:

τ-insertion is a reverse operation of weak gathering, and thus similarly to weak gathering maintains the observable association behaviour with the assumption that the τ-transition can occur.

When the a-role graph has been transformed by τ-insertion, the identification of ambiguous behaviours can be done applying Algorithm 7.3. S-roles that present input, mixed or termination ambiguity should be re-designed. Input and input ambiguities can be removed by merging. Termination ambiguity requires a more complex re-design. This was explained in Section 7.1.2.5. Re-design by merging leads to identical s-roles as when τ-transitions are removed by aligning the behaviours of the τ-predecessor and τ-successor.

An example is shown in Figure 7.35. After merging, the states “1” and “2-2n” can be gathered, and thus the τ-transition can be removed.

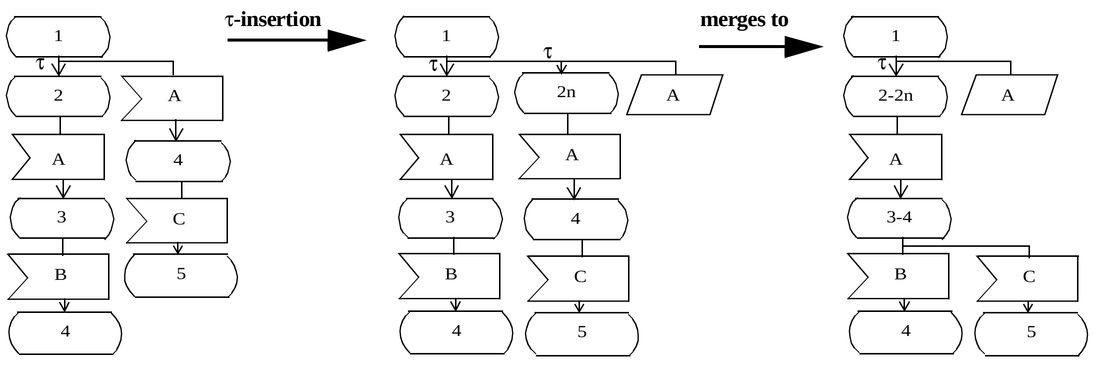


Figure 7.35 : Re-design: removing input ambiguity and acute τ-transitions.

When ambiguities have been removed, the graph may still contain τ-transitions. These τ-transitions necessarily lead to a divergent output behaviour. In a similar way as for equivoque transitions (see Section 7.1.2.3.3), a dual a-role can be obtained by mirroring the a-role obtained merging the initial a-role. The τ-transitions should be ignored during mirroring. They may be removed by gathering before mirroring. An example is shown in Figure 7.36. Cases (b) and (c) are intermediary machines. Gathering is applied on the intermediary machine (c) before mirroring. The initial machine and the machine in (d) interact in a consistent manner. This can easily be checked by considering all possible behaviours.

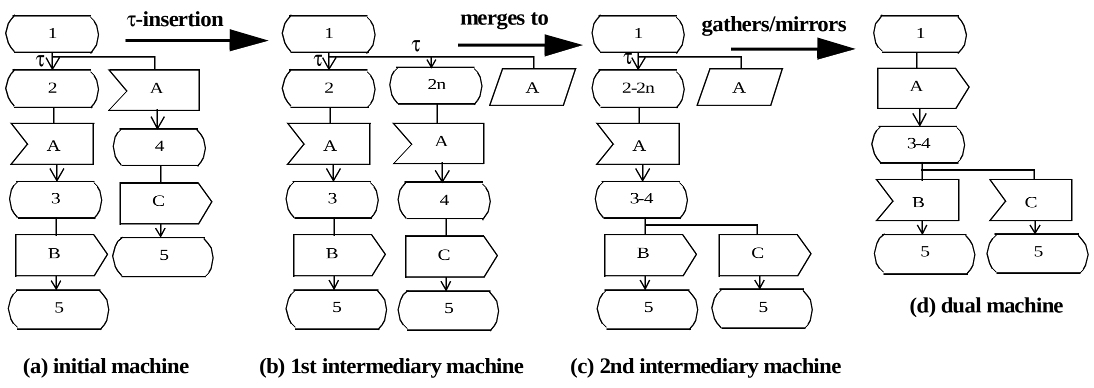


Figure 7.36 : τ-insertion, merging, gathering and mirroring.

7.1.4.2.1 Termination occurrence ambiguity

A termination occurrence ambiguity occurs when an external observer knows that the a-role state machine will terminate, but is not able to determine when. An example is shown in case (a) of Figure 7.37. The τ-transition here indicates that some interaction is taking place on other associations before termination.

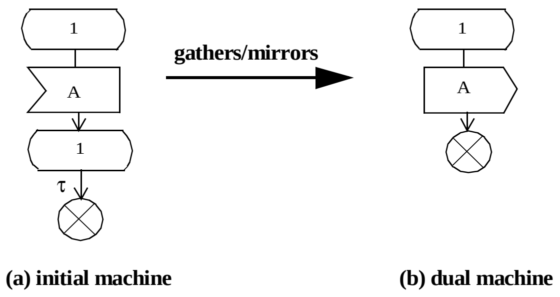


Figure 7.37 : Acute τ-transition and termination occurrence ambiguity.

As it is a usual case that interactions on the different associations an s-role is involved in, do not terminate simultaneously, we do not propose to re-design s-roles in order to avoid termination occurrence ambiguity. Such re-design would require a strict ordering of termination leading to less flexible bindings between s-roles. It would also introduce supplementary signalling leading to increased traffic load. Instead, we rather propose to take into account termination occurrence ambiguity when composing roles across actors. This will be explained in Chapter 8.

Interaction consistency does not require the simultaneous termination of two interacting a-roles. We only need to ensure that no signal is sent to an a-role that has terminated, and that exit conditions are consistent. An a-role that present a termination occurrence ambiguity may never terminate. This represents errors in the s-role following interaction errors on other associations. Provided that any spontaneous behaviour described by the a-roles can occur, a-roles terminate even when they present an occurrence ambiguity. A dual a-role can then be specified for an a-role that presents a termination occurrence ambiguity. The non-exit state node and exit state should be gathered before mirroring. The transformation is shown in Figure 7.37. In the case of equivoque τ-transitions leading to exit states, the exit states should be merged before gathering and mirroring.

7.1.4.3 Specifying a dual a-role

We are now also able to handle a-roles that contain τ-transitions. We assume that the design rules defined for machines containing τ-transitions have been followed. Recall these design rules:

- "Input consistency" on Page 200
- "Backward input consistency" on Page 201
- "Backward save consistency" on Page 202
- "τ-transitions and ordering" on Page 202

We propose a rule that is built upon the rule defined for mixed initiative states. τ-transitions are added.

V-rule: Duality
The dual a-role of an a-role that
- does not present any input, mixed and termination ambiguity, and
- enforces the design rules defined for acute τ-transitions, and
- enforces the design rules defined for mixed initiatives,
can be obtained by transforming the a-role chart by τ-insertion, and then merging and mirroring all states, except the states following mixed initiative states that represent concurrent behaviours.
Acute τ-transitions leading to an exit state should be removed before mirroring i.e. the non-exit state and exit state should be replaced by an exit state. This transformation should maintain any exit condition attached to the exit node. In the case of equivoque τ-transitions leading to exit states, merging should be applied first.
Other acute τ-transitions should be removed before mirroring, i.e states linked by a τ-transition are replaced by a single state.
The states that follow mixed initiative states that represent concurrent behaviours, should be transformed as followed:
- A state following signal sending is transformed to a complement state. Any signal and transition from the state that do not serve conflict detection are transformed by mirroring. The consumption of any signal enabling the detection of a conflict in the a-role is not mirrored. As conflict detection is defined relative to the preceding mixed initiative state, distinct complement states are generated for states that have several predecessors.

- A state following signal consumption is transformed to a complement state. Any signal and transition in that state are transformed by mirroring. The complement state is made input consistent with its preceding mixed initiative state. The state following the consumption of a signal enabling the detection of a conflict in the complementary a-role mirrors the next state after the detection of the same conflict in the initial a-role.

The initial a-role and the a-role obtained by this transformation interact consistently provided that

- they both start execution consistently, i.e. the machines should be entered using consistent entry conditions, and
- any spontaneous transition can occur.

Justification:

This rule is built upon the rule defined for mixed initiative states. Acute τ-transitions are added. Reasoning can be performed for all states and transitions as previously, except for the states linked by τ-transitions.

As the design rules defined for acute τ-transitions have been enforced, we know that the τ-successors and τ-predecessors linked by τ-transitions cannot be gathered because they define identical inputs that lead to distinct states, or because they lead to exit states.

- Let us first consider τ-transitions leading to an exit state. Provided that the τ-transition, a spontaneous transition, can occur, the removal of these τ-transitions do not influence the interaction at termination. When the interaction before this transition is consistent before the removal, it is also after the removal.
- Let us consider the other case. As the initial machine does not present any mixed ambiguity, the τ-successors and τ-predecessors necessarily define the same sets of input events, and no output events.

We focus on the transformation of the states linked by τ-transitions. After τ-insertion and merging, the states are linked by a single τ-transition. This τ-transition is removed before mirroring. The new single state defines the same set of events as the merged τ-successor. As the initial machine does not present any mixed ambiguity, this state defines only input events. This set is also the sets of events defined by the τ-successor and τ-predecessor in the initial machine. The state obtained by mirroring complements the merged τ-successor, and thus defines only output events. Any of these outputs can be received by the initial machine either before or after the triggering of the τ-transition. Thus the mirrored state interacts consistently with the τ-successor and τ-predecessor in the initial machine.

As for states and transitions succeeding the τ-transition, the same reasoning as for machines that do not contain τ-transitions apply.

A simple algorithm can be defined for τ-insertion. In that way, acute τ-transition cases are transformed to equivoque τ-transition case. This algorithm should be applied before Algorithm 7.2. Equivoque τ-transitions are then identified as other equivoque transitions by the algorithm. Then behaviour divergence can be classified using Algorithm 7.3. No change to the algorithm is required. Merging can be performed using Algorithm 7.4. No change to the algorithm is required. Algorithm 7.7 should be extended such that τ-transitions are removed before mirroring.

7.1.5 Summary

In Section 7.1 interface validation has been applied as a constructive method in order to produce a dual consistent a-role from a particular a-role. We have proposed design rules and algorithms that enable the generation of dual a-roles. The method applies on s-roles and a-roles independently of any connected roles. As many considerations have to be taken into account, this section presents a short summary of the validation steps.

Validation is applied on an a-role transition chart. We assume that the chart has been gathered and minimized as explained in Section 6.3. Minimisation facilitates the identification of equivoque transitions. The following design and transformation rules are then applied:

1. The state graph is checked against the design rules defined for acute τ-transitions. A list of these rules is provided in Section 7.1.4.3 on page 207.

2. τ-insertion is applied on the state graph before the identification of equivoque transitions (Algorithm 7.2) and the classification of divergent behaviour (Algorithm 7.3).

3. The state graph is re-designed in order to remove any termination ambiguity. See Section 7.1.2.5 on page 174.

4. The state graph is re-designed in order to remove any strong or weak input or mixed ambiguity. This can be achieved by merging. See Section 7.1.2.5 on page 174 and Section 7.1.2.6 on page 176.

5. The state graph is checked against the design rules defined for mixed initiative states. A list of these rules is provided in Section 7.1.3.6 on page 190. Note that input consistency is already enforced by design rules defined for acute τ-transitions.

6. When the state graph contains equivoque transitions, merging is applied before generating a dual a-role (Algorithm 7.4). Any non-reachable states and equivalent states introduced by merging should be removed (Algorithm 7.5). See Section 7.1.2.3 on page 163.

7. A dual a-role can be obtained by applying a variant of Algorithm 7.7 where the τ-transitions in non-initial states are removed by gathering before mirroring. This algorithm takes mixed initiatives into account.

7.2 Consistency checking

In this section, we discuss the corrective issues of interface validation i.e. the problem of checking that two a-roles interact consistently. While dual a-roles are specified such that the full behaviour expected by the initial a-roles can be covered, we do not, at consistency checking, constrain two interacting a-roles to explore the full behaviour. This is possible as our definition of interaction consistency does not address non-executable transitions, i.e. our definition does not require every a-role transition to be executed.

Despite this difference, several of the issues related to the specification of dual a-roles are relevant. A-roles (or s-roles) should be defined without making the assumption that interactions with particular complementary a-roles make it possible to relax design constraints. A-roles should not present any ambiguity, and patterns that introduce complexity such as alternative orderings should be avoided.

For the same reasons as in Section 7.1, we assume that any spontaneous behaviour described by the a-roles can occur.

Section 7.2.1 introduces partial interaction behaviours and defines the concepts of containment and obligation. Section 7.2.2 addresses some issues related to entry conditions. Section 7.2.3 shortly discusses the rules introduced when specifying dual a-roles in the context of consistency checking. Algorithms for consistency checking are specified in Section 7.2.4. Finally, we address the problem of state space explosion in Section 7.2.4.3.

7.2.1 Containment and obligation

For two s-roles to interact consistently, each s-role should at least provide the a-role behaviour “required” by its complementary s-role. The provided a-role behaviour should “contain” the required a-role behaviour [Bræk 1999]. Required a-roles can be defined in different ways leading to different containment relations. An s-role may require the complementary s-role to provide an a-role that enables the full interaction behaviour provided by its own a-role to be covered, or it may accept the interaction behaviour to be partially covered. From a consistency checking viewpoint, an s-role should be able to handle any request received from its complementary s-role. On the other hand, whether or not an s-role should be able to reply a request by any alternative answer expected by its complementary s-role may be discussed. This issue is related to the concept of contract between s-roles [Heiler 1995], and is outside the scope of consistency checking. Instead of elaborating the concept of required a-roles, we rather define of containment as a relation between two interacting a-roles.

Definition: Containment

A containment relation exists between two interacting a-roles when, in each state reached during the interaction, any a-role is able to at least consume any of the signals received from its complementary a-role. We also say that the input behaviour of each a-role contains the output behaviour of the other a-role.

The definition does not constrain signals to be consumed at once when they are received. Signals may be saved in the input port. An a-role may be able to consume more signals than those actually produced by the complementary a-role, hence the name of containment. The containment relation between a-roles ensures that unspecified signal reception does not occur.

The containment relation between a-roles is illustrated in Figure 7.38. In state “1”, the input behaviour of the complementary machine (b) contains the output behaviour of the machine (a). Conversely in state “2”, the input behaviour of the machine contains the output behaviour of the complementary machine. In that case, although the sequence behaviour (“B”, “D”) never occurs, the machines interact consistently. The events that never occur during the interaction are represented by a dash line.

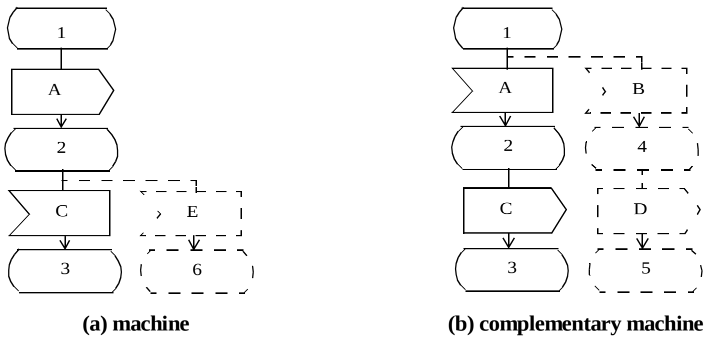


Figure 7.38 : Containment.

In this example, each interaction step leads to a transition to a new state in both machines. The states of the machines can easily be associated, and the containment relation can easily be checked. The introduction of save increases the complexity of containment checking. The state of a machine that saves a signal remains unchanged, and thus machine states cannot always be easily associated. An example is shown in Figure 7.39. When the machine (a) sends the signal “A”, it transits to state “2”. On the other hand, the state of the complementary machine (b) remains unchanged. Later, in state “2a” the complementary machine retrieves the saved signal “A” from the input port and transit to state “3”. The state of the machine (a) remains unchanged.

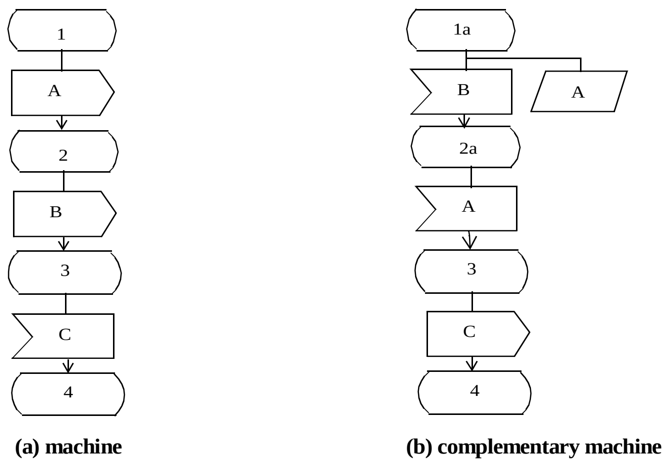


Figure 7.39 : Containment and save.

The containment relation between a-roles does not ensure that the a-roles interact consistently in all cases. If, at some point of the interaction, none of the interacting a-roles is able to send a signal and the input ports of both machines are empty, a deadlock occurs. Another constraint, that we call obligation, has to be set on the a-roles.

Definition: Obligation

An obligation relation exists between two interacting a-roles when, at each interaction step where the input ports of the a-role machines are empty, at least one of the interacting a-roles can send a signal.

The obligation relation between a-roles ensures that deadlocks do not occur following the a-roles waiting endlessly for each other. When all received signals have been consumed, one of the a-roles should be able to send a signal.

A designer should especially observe that the obligation relation is enforced in the case of mixed initiatives. Figure 7.40 describes the containment and obligation relations of a mixed initiative case. In state “1”, only one of the machines, machine (a), takes the initiative to send. Note that the machine is specified to handle a mixed initiative, and thus is input consistent. A general rule is that machines should be specified making the assumption that their complementary machines provide a full behaviour. Here the machine (a) is designed without taking into account that the complementary machine never sends “B”

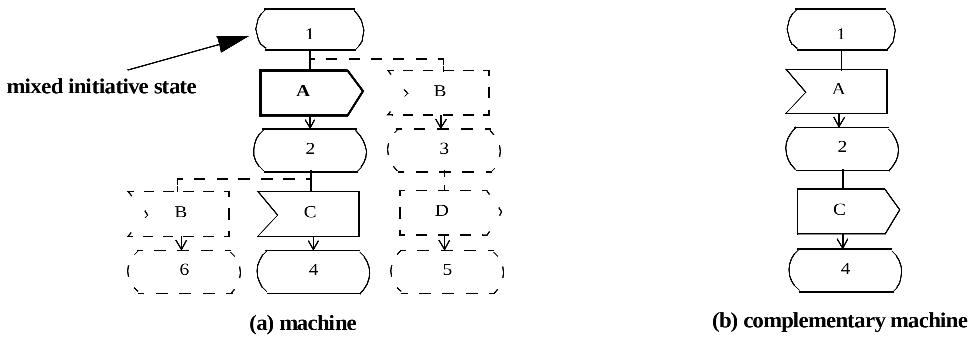


Figure 7.40 : Containment and obligation.

Both the containment and obligation relations between a-roles ensure that improper termination does not occur. Assume that one of the a-roles terminates. The other a-role is either still active or terminates. In the case it is active, it is only enabled to retrieve saved signals from the input port, if any. Then it should terminate. The active a-role cannot send any signal, otherwise the containment would not be enforced. When all saved signals have been consumed, the active a-role cannot wait for any signal, otherwise the obligation relation would not be enforced. Thus the two a-roles necessarily terminate in a coordinated manner. As any exchanged signal can be consumed, the a-roles necessarily agree on the exit condition.

V-rule: Containment and obligation

Two a-roles interact consistently if and only if they are related by both containment and obligation.

Justification:

Containment ensures that unspecified signal reception does not occur. Obligation ensures that deadlock does not occur. Containment and obligation ensure that improper termination does not occur. Thus together the two relations between a-roles ensure that the a-roles interact consistently.

Conversely, if two a-roles interact consistently, any signal received from the complementary a-role can be consumed. This leads to containment. No deadlock occurs, and thus at least one a-role is able to send when the input ports are empty. This leads to obligation.

In order to check that two a-roles interact consistently, we propose to check that they are related by containment and obligation. As a following of containment, this means that we do not require the full behaviour described by the a-roles to be covered.

7.2.2 Entry conditions

During the generation of dual a-roles, the entry conditions of the initial a-role have been transformed to identical entry conditions in the complementary a-role. All the validation rules have assumed that machines are entered using consistent entry conditions. At consistency checking, we do not require that each entry condition in one a-role can be associated with a consistent entry condition in the complementary a-role. One reason is that we do not constrain a-roles to explore the full behaviour described by their graphs. Thus some entries in a graph may never be used during interaction. Another reason is that we have introduced entry conditions in order to enable different forms of s-role triggering (see Chapter 3) and to facilitate sequential composition (see Section 4.1). Different forms of triggering may be applied in two interacting actors using different entry conditions.

At consistency checking, we will mark in the graph the entries that have no matching consistent entry in the complementary graph. These entries should only be used in implicit triggering. We will also ensure that there exit at least two consistent entries in the interacting a-roles.

7.2.3 Reviewing rules and assumptions

Following the containment relation, we do not require two interacting a-roles to be able to execute the complete behaviour specified by their transition charts. Some of the transitions in the charts may never execute. These transitions may be ignored at consistency checking (i.e. in the corrective validation approach), and in some cases this means that design rules defined in the constructive validation approach can be relaxed.

In the example shown in Figure 7.40, the consumption of “B” in state “1” can be ignored, and the input consistency constraint set on the machine (a) may be relaxed. In a similar way, an input ambiguity introduced by non-executable equivoque transitions may be ignored.

We recommend a-roles to be designed assuming a full behaviour coverage, even if we can identify, at consistency checking, that some behaviour is not executed. In that way, a-roles are able to interact with complementary a-roles that either provide partial or full behaviours. A-roles should be defined such that it is possible to generate dual a-roles. The design rules introduced in Section 7.1 yield for any part of the a-role transition graph independently of a particular interaction the a-role is involved in. A-roles should not present any input or mixed ambiguity, and they should be input consistent.

Furthermore, we also recommend a-roles to be designed such that analysing their interactions with other a-roles is facilitated. The rules that lead to reduced complexity in the constructive method also reduce the complexity of consistency checking. For example, sending signal sequences in mixed initiative states should be avoided. A list of the rules is given in Section 7.1.5 on page 209.

D-rule: A-role and consistency checking
A-roles should be designed independently of any particular interaction they are involved in. They should be designed assuming that their full behaviour is to be executed.

7.2.4 Algorithms

In this section we define two algorithms that support the consistency checking of two interacting a-roles. The first algorithm, Algorithm 7.8, assumes that the save feature is not used in the a-role state graphs. This assumption simplifies the analysis and enables us to first introduce the basic elements of consistency checking. Save is added in Algorithm 7.9.

Both algorithms assume that the design rules defined in Section 7.1 have been applied. The a-role state graphs do not present any ambiguity and conflicts are properly handled after mixed initiative states. Also the design rules related to mixed initiatives and ordering are enforced facilitating the analysis of the graphs.

The algorithms are performed on merged machines. This enables us to handle output divergence. Given the assumptions made on the machines, we know that the merged machines exhibit the same observable behaviour as the initial machines when the merged states define identical save sets, and σ-states are maintained. In that case, we can deduce that the initial machines interact properly, when the merged machines do. In the case where some of the merged states define distinct save sets, the machines present save ambiguity and the ambiguous save should not be exploited. Thus merging removes a superfluous behaviour. If the merged machines that reduce the reception behaviour of the initial machines interact consistently (without save), the initial machines also do. Note that as a following of merging, any event triggers a single transition.

Following the design rules related to acute τ-transitions and the assumptions on ambiguity, it is possible to remove any remaining τ-transition from the graph after merging.

7.2.4.1 Simple checking: no save

Algorithm 7.8 checks that any signal sent by an a-role is properly handled by the complementary a-role. The state graphs are analysed in a depth-first manner. States that have been analysed are stored in a working set so that analysis is not repeated. Note that pairs of states, not single states, are stored in that set. Each pair of states consists in a state of the machine and a state of the complementary machine Following containment, a state in a machine may interact with several states in the complementary machine. Any reachable state combination needs to be checked.

Algorithm 7.8: Consistency checking (no save signals)

```
main ()
{
 /* Assumptions:
   - no save signals
   - the graphs have been minimized
   - no input,mixed or termination ambiguity
   - mixed initiative states have been identified
   - mixed initiative rules are enforced
   - $\tau$-insertion and merging has been applied
     on both graphs, and $\tau$-transition introduced
     by $\tau$-insertion gathered.
   - $\tau$-transitions before exit states have been
     gathered.
   - no acute $\tau$-transitions.
 */

 /* The two state machines are represented by sets
 indexed by 1 and 2, e.g. $S_1$ and $S_2$ */

 /* Mixed initiative states represented concurrent
 behaviours are stored in $CB_1$ and $CB_2$ (Algorithm 7.6) */

 /* set of checked pairs of states e.g. ($s_{i1}$,$s_{i2}$)*/
 $W$ = {};

 /* check entry conditions */
 for each $s_{1o}$ in $S_{1o}$
  if $c_o$ is not an entry condition for any $s_{2o}$ in $S_{2o}$
   report-warning (no complementary entry condition);

 for each $s_{2o}$ in $S_{2o}$
```

```
  if $c_o$ is not an entry condition for any $s_{1o}$ in $S_{1o}$
   report-warning (no complementary entry condition);

 /* start from all initial states */
 entry_flag = false;
 for each $s_{1o}$ in $S_{1o}$
  get consistent $s_{2o}$ in $S_{2o}$
  entry_flag = true;
  if ($s_{1o}$ ,$s_{2o}$) is not in $W$
   /* initial states are triggered by ε */
   if (T($s_{1o}$ , ε), T($s_{2o}$, ε)) is not in $W$
    check-consistency (T($s_{1o}$ ,ε), T($s_{2o}$ ,ε))

 if entry_flag = false
  report-error (inconsistent entry conditions);

}



check-consistency ($s$,$t$)
{
 add ($s$,$t$) to $W$;

 /* exit states */
 if enable($s$) or enable($t$) is empty
  check-exit-consistency($s$, $t$)

 /* non-exit states */
 else
  if enable($s$) is included in $O_1$ /* only output events*/
   check-s-output ($s$,$t$)
 else
  if enable($s$) is included in $I_1$ /* only input events */
   check-s-input ($s$,$t$)
 else /* mixed state */
   check-s-mixed ($s$,$t$)
}



check-exit-consistency ($s$,$t$) /* $s$ or$t$: exit state */
{
 if enable($s$) is not empty
  report-error-inconsistent-termination ($s$,$t$);
  return;
 else
  if non-consistent exit conditions
   report-error-inconsistent-termination (s,t);
   return;
}



check-s-output (s,t) /* s: only output events */
{
 /* interacting state triggered by an output event */
 if some e in enable(t) belongs to $O_2$
  report-inconsistent-state (s,t);

 /* no containment */
 if enable(s) is not included in $\overline{enable}$(t)
  report-inconsistent-state (s,t);

 /* check next states */
 for each e in enable(s)
  if $\overline{e}$ belongs to enable(t)
   if (T(s, e), T(t, $\overline{e}$)) is not in W
    check-consistency (T(s, e), T(t, $\overline{e}$))
}



check-s-input (s,t) /* s: only input events */
{
 /* missing obligation */
 if enable (t) is included in $I_2$
  report-inconsistent-state (s, t);

 /* no containment */
 if output-enable (t) is not included in $\overline{enable}$(s)
  report-inconsistent-state (s, t);

 /* check next states */
 for each e in output-enable (t)
  if $\overline{e}$ belongs to enable(s)
   if (T(s, $\overline{e}$), T(t, e)) is not in W
    check-consistency (T(s, $\overline{e}$), T(t, e))
}
```

```
check-s-mixed (s, t) /* s: mixed initiative state */
{
 /* no containment */
 if output-enable (s) is not included in $\overline{\text{enable}}$(t)
  report-inconsistent-state (s, t);

 /* no containment */
 if output-enable (t) is not included in $\overline{\text{enable}}$(s)
  report-inconsistent-state (s,t);

 /* t: mixed initiative state */
 if output-enable (t) is not empty
  if s belongs to $CB_1$ /* concurrent behaviour */
   if t does not belong to $CB_2$ /* purpose mismatch */
    report-inconsistent-mixed-state (s,t);
  if s does not belong to $CB_1$ /* ordering */
   if t belongs to $CB_2$ /* purpose mismatch */
    report-inconsistent-mixed-state (s,t);

 /* check next states */
 for each e in output-enable(s)
  if $\bar{e}$ belongs to enable (t)
   if (T(s, e), T(t, $\bar{e}$)) is not in W
    check-consistency (T(s, e), T(t, $\bar{e}$))

 for each e in output-enable(t)
  if $\bar{e}$ belongs to enable (s)
   if (T(s, $\bar{e}$), T(t, e)) is not in W
    check-consistency (T(s, $\bar{e}$), T(t, e))

 /* check conflict resolution */
 if s belongs to $CB_1$ and t belongs to $CB_2$
 for each e in output-enable(s)
  for each f in output-enable(t)
   if $\bar{e}$ belongs to enable (t) and $\bar{f}$ belongs to enable (s)
    if ( T(T(s,e),$\bar{f}$), T(T(t,f),$\bar{e}$) ) is not in W
    check-consistency ( T(T(s,e),$\bar{f}$), T(T(t,f),$\bar{e}$) )
}
```

7.2.4.2 Adding save

Algorithm 7.9 takes into account the save feature. The algorithm is built in a similar way as Algorithm 7.8 with the addition of a save queue. Unlike in the previous algorithm, the interacting machines do not necessarily transit to a new state simultaneously. The state of a machine that saves a signal remains unchanged.

When entering a new state, the presence of a signal in the save queue that can be consumed leads to two kinds of behaviour:

- If the new state is only triggered by input signals, the first saved signal is retrieved from the save queue and the machine transits to a new successor state. The state of the complementary machine remains unchanged.
- If the new state can be triggered by output signals, the first saved signal may either be retrieved, or an output may be sent spontaneously. Thus only one of the machine transits to a new state, or both do.

Since the state of the save queue, i.e. its content, influences the behaviour of a machine, the state of the save queue has to be taken into account during checking. A pair of interacting states is considered as checked, when the states together with save queues in identical states have already been checked. In Algorithm 7.9, the working set is extended to a set of tuples describing a pair of states and their associated save queues. The addition of save increases the number of global states to be consistency-checked. As the analysis restricts to one association, the number of signals in the save queue normally remains low. A high number of saved signals is a symptom of bad design.

The save queue of a machine should be empty on exit. This check is performed by Algorithm 7.9.

The combination of save and mixed initiatives increases the complexity of conflict resolution. An example is shown in Figure 7.41. The mixed initiative state can save signal “C”. Suppose that “C” has been saved in the predecessor of state “1”. A conflict following the crossing of signals “A” and “B” is not detected immediately in state “2”. As “C” is stored before “B” in the input port, the conflict detection takes place in state “5”. We recommend to avoid such behaviour specifications. “C” should either be consumed before entering state “1” or saving should be re-iterated in state “2”.

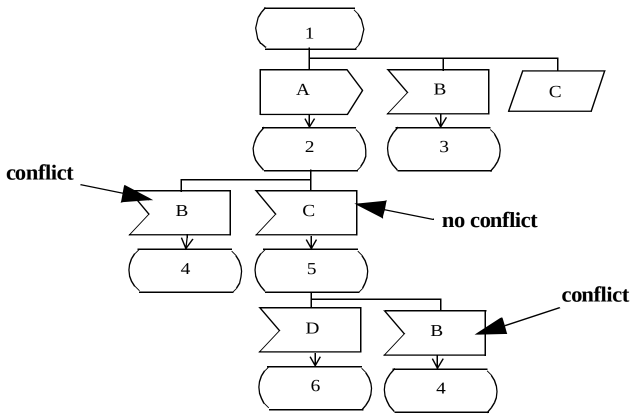


Figure 7.41 : Save and mixed initiative state (1).

A special case occurs when a new save event, i.e. a save that is not re-iterated from the predecessor state, is described in the mixed initiative state. An example is shown in Figure 7.42. The signal “C” is first saved in “1”. Thus, after sending “C”, the complementary machine expects the events occurring in “1” to appear. The reception of “A” in state “3a” is a normal case. On the other hand, the reception of “A” in state “3” indicates a conflict following the crossing of “A” and “B”. Note that according to the design rule "Mixed initiative and signal sending sequences", the signal “B” should not be sent in state “3a”. Furthermore, according to the design rule "Mixed initiative purposes", mixed initiatives should either describe concurrent behaviours or alternative orderings, not both.

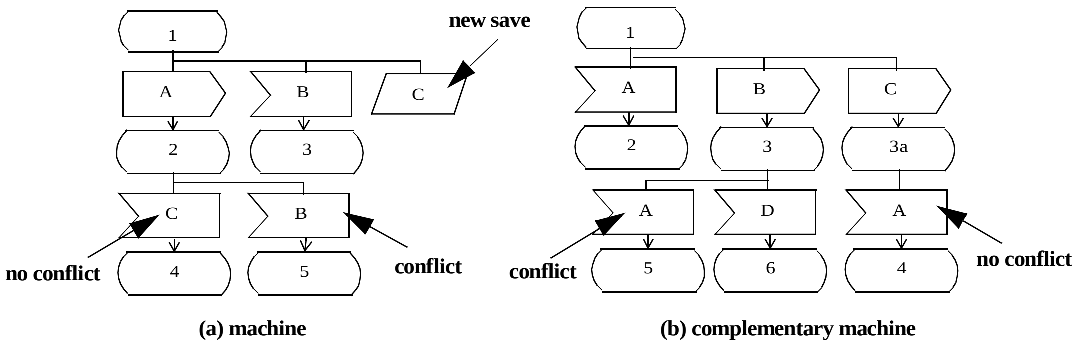


Figure 7.42 : Save and mixed initiative state (2).

In addition to the design rules related to mixed initiatives already introduced, we propose a new rule that facilitates consistency checking.

D-rule: Mixed initiative and save

A signal specified as save in a mixed initiative state should be specified as save in any successor state triggered by an output from the mixed initiative state.

In Algorithm 7.9, we assume that this design rule has been enforced.

Algorithm 7.9: Consistency checking

```
main ()
{
 /* Assumptions:
   - the graphs have been minimized
   - no input,mixed or termination ambiguity
   - mixed initiative states have been identified
   - mixed initiative rules are enforced - including the
     re-iteration of save after output.
   - $\tau$-insertion and merging has been applied
     on both graphs, and $\tau$-transition introduced
     by $\tau$-insertion gathered.
   - $\tau$-transitions before exit states have been
     gathered.
   - no acute $\tau$-transitions.
 */

 /* The two state machines are represented by sets
 indexed by 1 and 2, e.g. $S_1$ and $S_2$ */

 /* Mixed initiative states represented concurrent
 behaviours are stored in $CB_1$ and $CB_2$ (Algorithm 7.6) */

 /* set of checked tuples of states and save queues
 e.g. ($s_{i1}$, $\kappa_1$, $s_{i2}$, $\kappa_2$)*/
 $W$ = {};

 /* check entry conditions */
 for each $s_{1o}$ in $S_{1o}$
  if $c_o$ is not an entry condition for any $s_{2o}$ in $S_{2o}$
   report-warning (no complementary entry condition);

 for each $s_{2o}$ in $S_{2o}$
  if $c_o$ is not an entry condition for any $s_{1o}$ in $S_{1o}$
   report-warning (no complementary entry condition);

 /* start from all initial states */
 entry_flag = false;
```

```
  for each $s_{1o}$ in $S_{1o}$
   get consistent $s_{2o}$ in $S_{2o}$
   entry_flag = true;
   if ($s_{1o}$ ,$\kappa_o$,$s_{2o}$ ,$\kappa_o$) is not in $W$ /* $\kappa_o$ empty queue */
    /* initial states are triggered by $\varepsilon$ */
    if (T($s_{1o}$ ,$\varepsilon$),$\kappa_o$, T($s_{2o}$ ,$\varepsilon$),$\kappa_o$) is not in $W$
     check-consistency (T($s_{1o}$ ,$\varepsilon$),$\kappa_o$, T($s_{2o}$ ,$\varepsilon$),$\kappa_o$);

  if entry_flag = false
   report-error (inconsistent entry conditions);
 }
```

```
 check-consistency ($s$, $\kappa_1$,$t$, $\kappa_2$)
 /* $\kappa_1$ and $\kappa_2$ are the machine save queues */
 {
  add ($s$, $\kappa_1$,$t$, $\kappa_2$) to $W$;

  /* exit states */
  if enable($s$) or enable($t$) is empty
   check-exit-consistency($s$, $\kappa_1$,$t$, $\kappa_2$);

  /* non-exit states */
  else
   if enable($s$) is included in $O_1$ /* only output events*/
    check-s-output ($s$, $\kappa_1$,$t$, $\kappa_2$);
  else
   if enable($s$) is included in $I_1$ /* only input */
    check-s-input ($s$, $\kappa_1$,$t$, $\kappa_2$);
  else /* mixed state */
    check-s-mixed ($s$, $\kappa_1$,$t$, $\kappa_2$);
 }
```

```
 check-exit-consistency ($s$, $\kappa_1$,$t$, $\kappa_2$) /* $s$ or$t$: exit state */
 {
  /* both states are exit states */
  if enable($s$) and enable($t$) are empty
   if $\kappa_1$ or $\kappa_2$ is not empty
    report-error-save-termination ($s$, $\kappa_1$,$t$, $\kappa_2$);
   if non-consistent exit conditions
```

```
      report-error-inconsistent-termination($s$, $\kappa_1$,$t$, $\kappa_2$);

  /* $s$. not an exit state */
  else if enable($s$) is not empty
   /* $s$ sends to exit state $t$ */
   if output-enable($s$) is not empty
    report-error-inconsistent-termination ($s$,$\kappa_1$,$t$,$\kappa_2$);
   else
    /* retrieve signals from save queue */
    if $\kappa_1$ is not empty
     if some event e in $\kappa_1$ belongs to input-enable ($s$)
      n$\kappa_1$ = get ($\kappa_1$, e);
      if (T($s$, e), n$\kappa_1$, $t$, $\kappa_2$) is not in $W$
       check-consistency (T($s$, e), n$\kappa_1$, $t$, $\kappa_2$);
    else
     report-error-save-termination ($s$, $\kappa_1$,$t$,$\kappa_2$);

  /* $t$: not an exit state */
  else if enable($t$) is not empty
    /* $t$ sends to exit state $s$ */
   if output-enable($t$) is not empty
    report-error-inconsistent-termination($s$,$\kappa_1$,$t$, $\kappa_2$);
   else
    /* retrieve signals from save queue */
    if $\kappa_2$ is not empty
     if some event e in $\kappa_2$ belongs to input-enable ($t$)
      n$\kappa_2$ = get ($\kappa_2$, e);
      if ($s$, $\kappa_1$, T($s$, e), n$\kappa_2$) is not in $W$
       check-consistency ($s$, $\kappa_1$, T($s$, e), n$\kappa_2$);
    else
     report-error-save-termination ($s$,$\kappa_1$,$t$,$\kappa_2$);
}


check-s-output ($s$,$\kappa_1$,$t$,$\kappa_2$) /* $s$: only output events */
{
 /* $s$: check save consistency */
 if $\kappa_1$ is not empty
  if some event e in $\kappa_1$ does not belong to save($s$)
   report-save-inconsistency ($s$,$\kappa_1$);
```

```
/* $t$ defines only output */
if enable($t$) is included in $O_2$

 /* $t$: check save consistency */
 if $\kappa_2$ is not empty
  if some event e in $\kappa_2$ does not belong to save($t$)
   report-save-inconsistency ($t$,$\kappa_2$);

 /* $t$: signals sent by $s$ can be saved */
 for each e in output-enable($s$)
  if $\bar{e}$ belong to save($t$)
   n$\kappa_2$ = add ($\kappa_2$, $\bar{e}$);
   if (T($s$, e), $\kappa_1$, $t$, n$\kappa_2$) is not in $W$
    check-consistency (T($s$, e), $\kappa_1$, $t$, n$\kappa_2$);
  else
   report-inconsistent-state (T($s$, e), $\kappa_1$, $t$, n$\kappa_2$);

 /* $s$: signals sent by $t$ can be saved */
 for each e in output-enable($t$)
  if $\bar{e}$ belong to save($s$)
   n$\kappa_1$ = add ($\kappa_1$, $\bar{e}$);
   if ($s$, n$\kappa_1$, T($t$, e), $\kappa_2$) is not in $W$
    check-consistency ($s$, n$\kappa_1$, T($t$, e), $\kappa_2$);
  else
   report-inconsistent-state ($s$, n$\kappa_1$, T($t$, e), $\kappa_2$);

/* $t$ defines only input */
else if enable($t$) is included in $I_2$
 /* retrieve saved signal if any */
 if some event e in $\kappa_2$ belongs to input-enable($t$)
  n$\kappa_2$ = get ($\kappa_2$, e);
  if ($s$, $\kappa_1$, T($t$, e), n$\kappa_2$) is not in $W$
   check-consistency ($s$, $\kappa_1$, T($t$, e), n$\kappa_2$);

 /* no saved signal retreived */
 else
  /* no containment */
  if enable($s$) is not included
    in union ( $\overline{\text{enable}}$($t$), save ($t$) )
   report-inconsistent-state ($s$, $\kappa_1$,$t$, $\kappa_2$);

  for each e in enable($s$)
   if $\bar{e}$ belongs to enable($t$)
    if (T($s$, e), $\kappa_1$, T($t$, $\bar{e}$), $\kappa_2$) is not in $W$
```

```
      check-consistency (T($s$, e), $\kappa_1$, T($t$, $\overline{e}$), $\kappa_2$);
    if $\overline{e}$ belongs to save($t$)
     n$\kappa_2$ = add ($\kappa_2$, $\overline{e}$);
     if (T($s$, e), $\kappa_1$, $t$, n$\kappa_2$) is not in $W$
      check-consistency (T($s$, e), $\kappa_1$, $t$, n$\kappa_2$);

 /* $t$ is a mixed state */
 else
 /* should not happen as $s$ is not able to handle
    the crossing of signals.
 */
  report-inconsistent-state ($s$,$\kappa_1$,$t$,$\kappa_2$);
}


check-s-input ($s$,$\kappa_1$,$t$,$\kappa_2$) /* $s$: only input events */
{
 /* $t$ defines only input */
 if enable ($t$) is included in $I_2$

  /* check for deadlock */
  if $\kappa_1$ and $\kappa_2$ are empty
   report-inconsistent-state ($s$, $\kappa_1$, $t$, $\kappa_2$);

  /* retrieve saved signal if any */
  else
   if no event e in $\kappa_1$ belongs to input-enable ($s$) and
      no event e in $\kappa_2$ belongs to input-enable ($t$)
    report-inconsistent-state ($s$, $\kappa_1$, $t$, $\kappa_2$);

   if some event e in $\kappa_1$ belongs to input-enable ($s$)
    n$\kappa_1$ = get ($\kappa_1$, e);
    if (T($s$, e), n$\kappa_1$,$t$, $\kappa_2$) is not in $W$
     check-consistency (T($s$, e), n$\kappa_1$,$t$, $\kappa_2$);

   if some event e in $\kappa_2$ belongs to input-enable ($t$)
    n$\kappa_2$ = get ($\kappa_2$, e);
    if ($s$, $\kappa_1$, T($t$, e), n$\kappa_2$) is not in $W$
     check-consistency ($s$, $\kappa_1$, T($t$, e), n$\kappa_2$);
```

```
/* t defines only output */
else if enable (t) is included in $O_2$

 if $\kappa_2$ is not empty
  if some event e in $\kappa_2$ does not belong to save(t)
   report-save-inconsistency (t, $\kappa_2$);

 /* s: retrieve saved signal if any */
 if some event e in $\kappa_1$ belongs to input-enable (s)
  n$\kappa_1$ = get ($\kappa_1$, e);
  if (T(s, e), n$\kappa_1$, t, $\kappa_2$) is not in W
   check-consistency (T(s, e), n$\kappa_1$, t, $\kappa_2$);

 /* s: no saved signal retreived */
 else
  /* no containment */
  if output-enable (t) is not included
     in union ( $\overline{\text{enable}}$(s), save (s) )
   report-inconsistent-state (s, $\kappa_1$, t, $\kappa_2$);

  /* s: signals sent by t are consumed or saved */
  for each e in output-enable (t)
   if $\bar{e}$ belongs to enable(s)
    if (T(s, $\bar{e}$), $\kappa_1$, T(t, e), $\kappa_2$) is not in W
     check-consistency (T(s, $\bar{e}$), $\kappa_1$, T(t, e), $\kappa_2$);
   if $\bar{e}$ belongs to save(s)
    n$\kappa_1$ = add ($\kappa_1$, $\bar{e}$);
    if (s, n$\kappa_1$, T(t, e), $\kappa_2$) is not in W
     check-consistency (s, n$\kappa_1$, T(t, e), $\kappa_2$);

/* t is a mixed state */
else

 /* s: retrieve saved signal if any */
 if some event e in $\kappa_1$ belongs to input-enable (s)
  n$\kappa_1$ = get ($\kappa_1$, e); /* extract signal from queue */
  if (T(s, e), n$\kappa_1$, t, $\kappa_2$) is not in W
   check-consistency (T(s, e), n$\kappa_1$, t, $\kappa_2$);

 /* s: no saved signal retrieved */
 else
  /* t: check re-iteration of save */
  if some event e in $\kappa_2$ does not belong to save(t)
```

```
        report-save-inconsistency ($t$, $\kappa_2$);

      /* no containment */
      if output-enable ($t$) is not included
        in union ( $\overline{\text{enable}}$($s$), save ($s$) )
       report-inconsistent-state ($s$, $\kappa_1$, $t$, $\kappa_2$);

      for each e in output-enable ($t$)
       if $\overline{\text{e}}$ belongs to enable($s$)
        if (T($s$, $\overline{\text{e}}$), $\kappa_1$, T($t$, e), $\kappa_2$) is not in $W$
         check-consistency (T($s$, $\overline{\text{e}}$), $\kappa_1$, T($t$, e), $\kappa_2$);
       if $\overline{\text{e}}$ belongs to save($s$)
        n$\kappa_1$ = add ($\kappa_1$, $\overline{\text{e}}$);
        if ($s$, n$\kappa_1$, T($t$, e), $\kappa_2$) is not in $W$
         check-consistency ($s$, n$\kappa_1$, T($t$, e), $\kappa_2$);
}


check-s-mixed ($s$,$\kappa_1$,$t$,$\kappa_2$) /* $s$: mixed initiative state */
{
 /* check re-iteration of save */
 if $\kappa_1$ is not empty
  if some event e in $\kappa_1$ does not belong to save($s$)
   report-save-inconsistency ($s$, $\kappa_1$);

 /* $t$ defines only input */
 if enable ($t$) is included in $I_2$

  /* $t$: retrieve saved signal if any */
  if some event e in $\kappa_2$ belongs to input-enable ($t$)
   n$\kappa_2$ = get ($\kappa_2$, e);
   if ($s$, $\kappa_1$, T($t$, e), n$\kappa_2$) is not in $W$
    check-consistency ($s$, $\kappa_1$, T($t$, e), n$\kappa_2$);

  /* $t$: no saved signal retreived */
  else
   /* no containment */
   if output-enable ($s$) is not included in $\overline{\text{enable}}$($t$)
    report-inconsistent-state ($s$, $\kappa_1$, $t$, $\kappa_2$);

   for each e in output-enable ($s$)
    if $\overline{\text{e}}$ belongs to enable($t$)
     if (T($s$, e), $\kappa_1$, T($t$, $\overline{\text{e}}$), $\kappa_2$) is not in $W$
```

```
      check-consistency (T($s$, e), $\kappa_1$, T($t$, $\overline{e}$), $\kappa_2$);
    if $\overline{e}$ belongs to save($t$)
     n$\kappa_2$ = add ($\kappa_2$, $\overline{e}$);
     if (T($s$, e), $\kappa_1$,$t$, n$\kappa_2$) is not in $W$
      check-consistency (T($s$, e), $\kappa_1$,$t$, n$\kappa_2$);

/* $t$ defines only output */
else if enable ($t$) is included in $I_2$

 /* should not happen as $t$ is not able to handle
    the crossing of signals.
 */
 report-inconsistent-state ($s$,$\kappa_1$,$t$,$\kappa_2$);

/* $t$ is a mixed state */
else

 /* t: check re-iteration of save */
 if some event e in $\kappa_2$ does not belong to save($t$)
  report-save-inconsistency ($t$, $\kappa_2$);

 /* no containment */
 if output-enable ($s$) is not included in $\overline{\text{enable}}$($t$)
  report-inconsistent-state ($s$, $\kappa_1$, $t$, $\kappa_2$);

 /* no containment */
 if output-enable ($t$) is not included in $\overline{\text{enable}}$($s$)
  report-inconsistent-state ($s$, $\kappa_1$, $t$, $\kappa_2$);

 /* check purposes of mixed initiative */
 if $s$ belongs to $CB_1$ /* concurrent behaviour */
  if $t$ does not belong to $CB_2$
   report-inconsistent-mixed-state ($s$, $\kappa_1$, $t$, $\kappa_2$);
 if $s$ does not belong to $CB_1$ /* ordering */
  if $t$ belongs to $CB_2$
   report-inconsistent-mixed-state ($s$, $\kappa_1$, $t$, $\kappa_2$);

for each e in output-enable($s$)
 if e belongs to enable ($t$)
  if (T($s$, e), $\kappa_1$, T($t$, $\overline{e}$), $\kappa_2$) is not in $W$
   check-consistency (T($s$, e), $\kappa_1$, T($t$, $\overline{e}$), $\kappa_2$);

for each e in output-enable($t$)
 if e belongs to enable ($s$)
```

```
    if (T(s, e), $\kappa_1$, T(t, $\overline{e}$), $\kappa_2$) is not in W
     check-consistency (T(s, e), $\kappa_1$, T(t, $\overline{e}$), $\kappa_2$);

  /* check conflict resolution */
  if s belongs to $CB_1$ and t belongs to $CB_2$
  for each e in output-enable(s)
   for each f in output-enable(t)
    if e belongs to enable (t) and f belongs to enable (s)
     if ( T(T(s, e),$\overline{f}$), $\kappa_1$, T(T(t,f),$\overline{e}$), $\kappa_2$) is not in W
     check-consistency ( T(T(s, e),$\overline{f}$), $\kappa_1$, T(T(t,f),$\overline{e}$), $\kappa_2$);
}
```

7.2.4.3 Working space size

The introduction of the save feature prevents us from using a simple technique like mirroring for consistency checking. At the first glance, Algorithm 7.9 may appear complex. However, even though several different cases have to be considered, the working set generated by the algorithm, i.e. the set of tuples of states and associated save queues, remains small. As opposed to algorithms used for the generation of global state graphs in reachability analysis, our algorithm does not require a large working space.

Recall that the main problem to be addressed in reachability analysis is that of state space explosion problem. The complexity of global state graph grows rapidly with the number of states of the constituting state machines. The number of states is often too large for exhaustive analysis. Consider the following example inspired from [Holzman 1991]:

- A protocol is implemented by two state machines having each 100 states and 1 message queue. The queues are restricted to 5 slots each, and the number of messages exchanged is 10. Each process can be in 10^2 different states, so the two processes can be in 10^4 states. Each queue may hold between 0 and 5 messages, where each message is 1 out of 10. The total number of states in the worst case is

$$10^4 . (\Sigma_{i=0,5} 10^i)^2$$

In the worst case, the number of states is in the order of 10^{14} different states. Hopefully the number of effectively reachable states is much smaller than this worst-case number. But still it remains high for small protocols, from 10^5 to 10^9 according to [Holzman 1991].

In our approach, the number of states in the machines to be analysed is normally low:

- The analysis is performed on projection of s-roles, not on s-roles. In the case where an s-role is involved in 3 associations, we may assume that 1/3rd of the s-role states are dedicated to the interaction on each association. Thus, the number of states in each projection is approximately 1/3rd of the number of states in the s-role.

- The analysis is performed on elementary s-roles, e.g. the phases of a protocol. In the case an s-role is composed of three elementary s-roles, the number of states of each elementary s-role is approximately 1/3rd of the number of states in the composite s-role.

The number of states in each machine to be analysed is then approximately be reduced with a factor of about 10, and in the global state space with a factor of 10^2.

The number of states in the global state space can be reduced even more when the size of the message queue is decreased. This is possible in our approach where Algorithm 7.9 does not make use of a message queue, but of a save queue. The design rules "Mixed initiative and signal sending sequences" and "Input/output event orderings and event sequence length" contribute to simplifying the analysis:

- Following the rules related to mixed initiatives states, each machine is designed input consistently, and the potential combinations of signal crossing are also kept low. The purposes of the mixed initiatives are clearly identified, and conflict resolution, if any, handled. This enables us to check each branch following a mixed initiative state against a single branch in the complementary graph. No message queue is needed to perform the analysis.

As the analysis restricts to one association, the number of signals in the save queue normally remains low. The design rules related to event ordering also contribute to limit the number of slots in the save queue. We may reduce this number to 2, and then reduce the total number of states in the worst case with a factor of 10^6.

Following these two reductions, the number of states in the global space in the worst case is in the order of 10^6 different states instead of 10^{14}. The number of effectively reachable states is in fact much smaller. Both merging and the design rules related to mixed initiatives states contribute to that reduction:

- As explained above, each branch following a mixed initiative state is checked against a single branch in the complementary graph

- As the machines are merged before Algorithm 7.9 is applied, the machines do not contain any equivoque transitions. A branch in the graph that would be checked against several branches in the complementary graph before merging, can be checked against a single branch after merging.

As every branch in one state graph can be checked against a single branch in the complementary graph, we have not to consider the product of states of the two machines. If each machine can be in 10 different states, the two can be in 20 different states. The introduction of the save queue of 2 slots increases the number of states in the global space with a factor of 10^4. As the design rules "Save and ordering" and "Ordering with save and concurrency" constrain the use of save, signals are normally saved in a few states of the graph reducing even more the number of states in the global space. Actually, the save queue of 2 slots is a generous assumption. One slot should hold in most cases.

7.3 Accuracy of the validation results

A main advantage of the approach is that the techniques that are proposed, can be easily understood. However, although these techniques are simple, they enable us to identify several anomalous behaviours. Simplification is achieved by emphasising the details significant for the purpose of validation of the interfaces, and hiding other details. In that way, the designer is able to comprehend single interfaces. Simplification, however, causes some shortcomings that are discussed in this section.

7.3.1 Overspecification

Decisions and signals on non-visible associations are hidden by projection. The projection of an s-role may produce a non-deterministic a-role behaviour, and non-determinism may lead to ambiguity. We fail to produce dual a-roles for a-roles that present ambiguity, and have proposed the re-design of s-roles.

In some cases, however, decisions and signals on non-visible associations are observable from complementary s-roles. Decisions are observable when there exist dependencies between decisions across s-roles. Signals on non-visible associations are observable when there exist dependencies between interactions on distinct associations.

An example is shown in Figure 7.43. The collaboration sequence between three s-roles “R1”, “R2 and “R3” describes two alternative behaviours: “R1” sends either signal “X” or “Y” to both “R2 and “R3”. In the first case, the s-role “R2” further expects the signal “B” from “R3”. In the second case, “R2” further expects the signal “C” from “R3”. The interactions between “R1” and “R2”, and between “R1” and “R3” are dependent, and further govern the interaction between “R2” and “R3”.

The state machine of the s-role “R2” as seen from “R3” is also described in Figure 7.43. By projection, the signals “X” and “Y” are hidden. Seen from “R3”, the a-role presents an input ambiguity. According to our design rules, the s-role “R2” should be re-designed. In any case after “A”, the s-role should be prepared to both receive “B” and “C”. Furthermore, backward consistency should be enforced, and the state “2” should be able to save “B” and “C”. After re-design, the s-role “R2” is overspecified.

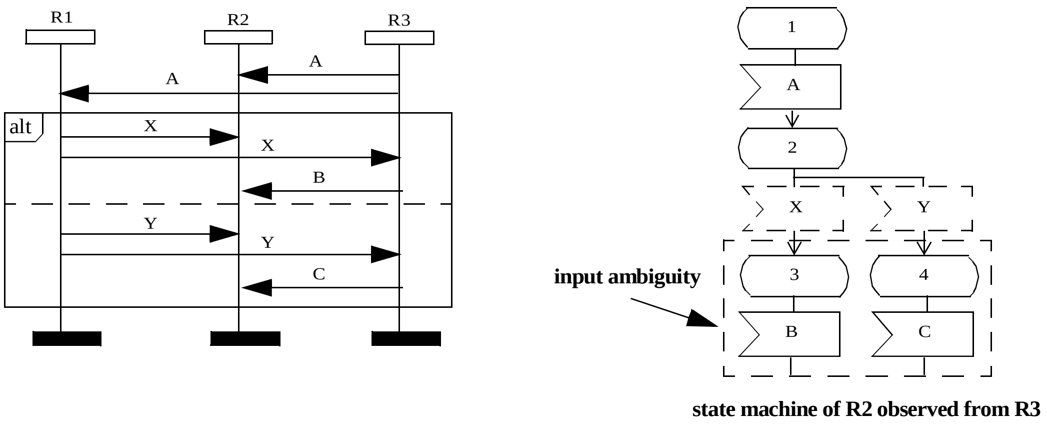


Figure 7.43 : Dependent and consistent interactions on distinct associations.

As illustrated by this example, the projection may hide dependencies between interactions on distinct associations, and lead to overspecification of the s-role graphs. The s-role graphs become more complex. Overspecification is however harmless with respect to consistency. It enforces the designer to produce robust specifications.

The projection transformation can be extended so that important dependencies between s-roles can be maintained in the a-role graph. The introduction of a new projection transformation does not require changes to be made to the other validation techniques. In the previous example, dependencies between “X” and “B”, and “Y” and “C” can be taken into account such that the projected a-role defines a new state “2” that can both receive “B” and “C”. The description of a new projection transformation is left for further work.

7.3.2 Second order errors

An important assumption in the validation of a-roles is that each a-role provides the expected behaviour. We assume that spontaneous sending derived by projection from the consumption of non-visible signals can occur. As the interactions on other associations have been validated, we expect them to behave consistently and to not lead to any error.

The assumption is erroneous when applied on spontaneous τ-transitions, and may hide deadlocks resulting from dependencies between s-roles. An example is shown in Figure 7.44.

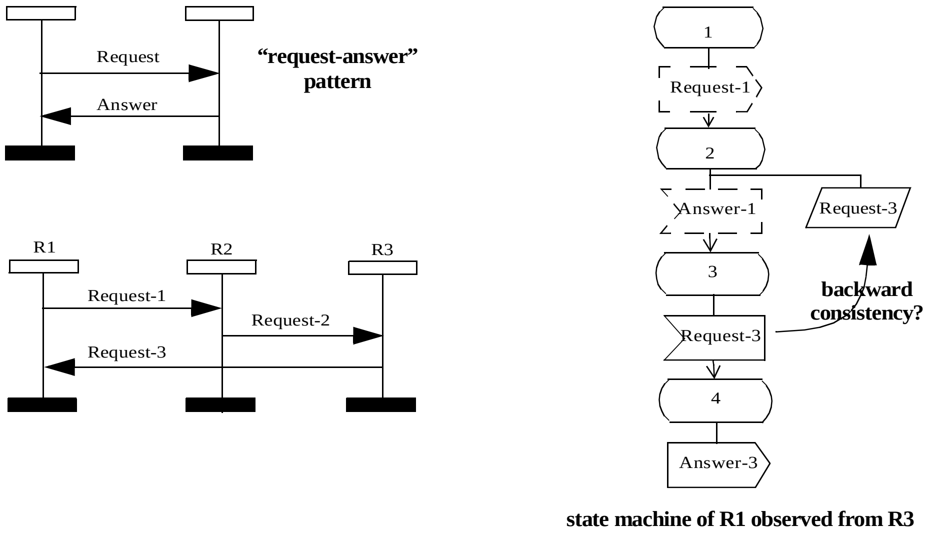


Figure 7.44 : Dependent and inconsistent interactions on distinct associations.

In the example on Figure 7.44, a "request-answer" pattern is applied between three s-roles. A machine cannot proceed before a request has been answered. The interactions between "R1", "R2" and "R3" are inconsistent and lead to deadlock. A symptom of the deadlock can be found in the a-role graphs, but not its cause. Seen from "R3", the a-role derived from the role graph of "R1" contains τ-transitions. A way to remove the τ-transition between the states "2" and "3" is to enforce backward input consistency, and apply gathering. However, here, the request sent by "R1" should first be answered in state "2", before "R1" further proceeds and handles itself the request received from "R3". Another way to remove the τ-transition in that case is to enforce backward save consistency, and apply weak gathering. Weak gathering only maintains the observable behaviour provided that spontaneous transitions can occur. Here applying weak gathering would hide the deadlock error.

The projection of s-roles lead to graphs that may contain acute τ-transitions. Acute τ-transitions are symptoms of errors. Without the knowledge of the behaviour occurring on other associations, we are not always able to handle properly the τ-transitions. Their removal may lead to second order errors. Backward save consistency and weak gathering should be applied with care.

7.4 Summary

In this chapter, we have proposed an approach to interface validation. The approach encompasses a constructive method for the specification of dual interfaces, and a corrective method for consistency checking.

Dual a-roles can be specified provided that initial a-roles do not present any strong input, mixed or termination ambiguity. When a full interaction behaviour is desirable, the initial a-roles should support input consistency. Design rules have also been proposed that reduce the complexity of the a-role descriptions and facilitate the specification of dual roles. The design rules are simple and can easily be enforced by the designer manually or with some design tool support. Mirroring and merging are the main techniques proposed for the generation of dual roles.

At consistency checking, we require the a-roles to enforce the design rules introduced in the constructive method. No assumption about the complementary a-roles are made. In that way, a-roles are not dependent on a particular behaviour of their complementary a-roles, and these complementary a-roles may easily be changed. The introduction of the save feature forces us to introduce a consistency checking algorithm that is cognate to the algorithms used for the generation of global state graphs. However our algorithm differs from those algorithms in that it does not use any message queue, but a save queue. Both merging and the design rules applied on s-roles and a-roles contribute to simplify the analysis and to maintain the number of states in the global state low.

The proposed validation approach has the following properties:

- Ambiguous and conflicting behaviours that lead to errors can be identified at design time, before the validation analysis itself. The design rules enable the designer to develop well-formed state machines.

- Validation is performed on state machine types - not instances. In that way, it can be applied to the analysis of systems bound at run-time, and suits the needs of compositional systems.

- The removal of acute τ-transitions simplifies the analysis, and also enables the designer to comprehend single interfaces.

- When a component is replaced or added in a system, the analysis restrict to the components of the system that interact with that new component. Other parts of the system are not affected.

- Modifications of the s-role that only have impact on one interface, do not require the analysis to be repeated on all interfaces, but only to the modified interface.

While using projections simplify the validation analysis, it may lead to overspecification. The identification of second order errors requires more knowledge than what is described by the specification of single interfaces.

8 Composition validation

The purpose of composition validation is to ensure that service roles are consistently composed across actors. While Chapter 7 has addressed the validation of elementary s-roles, this chapter addresses the validation of composite s-roles. Assuming that the s-roles being composed interact consistently, we discuss how composition can be applied across actors so that the composite s-roles also interact consistently.

As the sequential composition of s-roles is modelled using identical mechanisms as the modelling of elementary s-roles, the techniques developed for the validation of elementary s-roles apply to s-roles composed sequentially. Concurrent composition introduces new associations that are validated separately, also using the techniques of interface validation. The dynamic creation of s-roles requires new techniques.

8.1 Sequential collaboration composition

In this section, we assume that the identical form of composition, sequential composition, is applied to the elementary s-roles in the interacting actors. In that case we say that the elementary collaborations the actors contribute to, are composed sequentially. We first discuss basic sequential composition. Then complexity is added by introducing guards, choices and disabling.

As illustrated in Figure 8.1, different patterns of sequential collaboration composition may be introduced depending on whether the actors involved in the composite collaboration participate in any of the collaborations being composed or not. The notation introduced in Chapter 2 is used to represent actors, s-roles and a-roles. In addition, sequential composition is represented by an arrow that indicates the order of execution.

In case (a) of Figure 8.1, the composite collaboration consists of two collaborations composed sequentially. The two collaborations involve the same three actors that respectively first play the s-roles “A”, “B” and “C”, then the s-roles “D”, “E” and “F”. Case (b) differs from (a) in that one of the actors is not involved in the first phase of the composite collaboration. Case (c) is a variant of case (b). It illustrates that an actor may be involved at different phases of a composite collaboration.

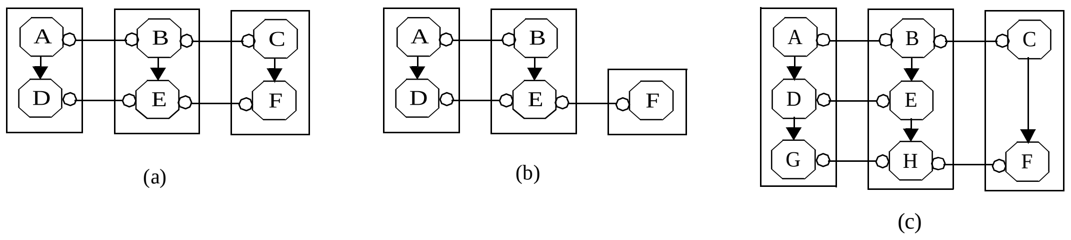


Figure 8.1 : Sequential collaboration composition.

In a similar way as for interface validation, we consider the composite s-roles from the different associations they interact on. In that way, we also reason on projections at the composite level. In case (a) of Figure 8.1, the transition from “B” to “E” will be observed from two viewpoints: from the actor playing the composite s-role “A” followed by “D”, and from the actor playing “C” followed by “F”.

We assume that the s-roles contributing to the elementary collaborations interact consistently. In case (a) of Figure 8.1, “A” and “B” interact consistently as well as “B” and “C”. So do their successors “D” and “E”, and “E” and “F”. According to interface validation, we know that elementary s-roles execute consistently until they terminate, provided that they start executing in a coordinated way. Inconsistency will then be introduced by composition if some transition from an s-role to its successor leads to a non-coordinated start of execution of the s-roles. Two kinds of non-coordinated start may be happen:

- Interacting s-roles are entered through non-consistent entry conditions.
- Interacting s-roles do not start executing simultaneously. In that case, a signal may be sent to a complementary s-role that has not yet started, leading to unspecified signal reception.

We first discuss the second case, i.e. “non-simultaneous start”. The case of “non-consistent entry conditions” is especially of interest in a composition with choice, where the instantiation of an s-role may depend on some condition. This case is discussed in Section 8.1.4.

8.1.1 Non-simultaneous execution start

As s-roles are composed sequentially, s-roles start execution when their predecessors terminate. Thus non-simultaneous execution start occurs when the predecessor s-roles, if any, do not terminate simultaneously. In Figure 8.2, the s-role “B” continues to interact with “A” after the interaction between “B” and “C” has terminated. Seen from “C”, this is a termination occurrence ambiguity. In that case, the s-role “C” and its successor “F” are not able to observe the termination of “B”.

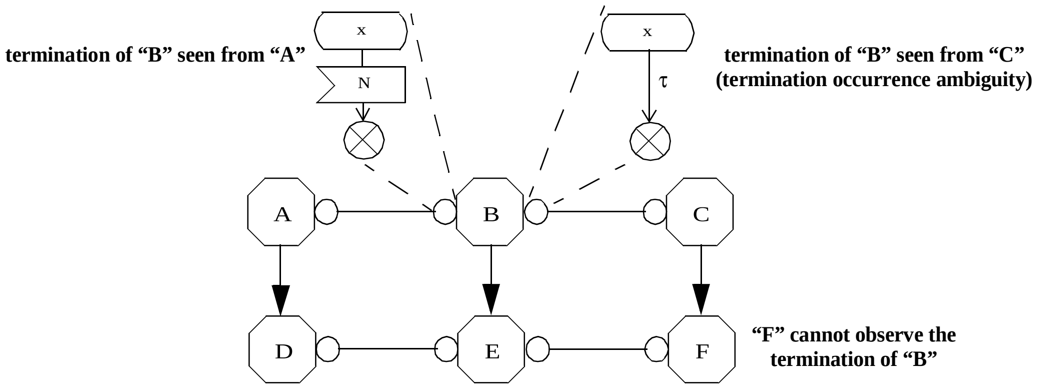

termination of “B” seen from “A”
x
N
x
τ
termination of “B” seen from “C” (termination occurrence ambiguity)
A
B
C
D
E
F
“F” cannot observe the termination of “B”

Figure 8.2 : Sequential composition and termination occurrence ambiguity.

Cases of non-simultaneous execution start also occur when the interacting actors are involved in different phases of the composite collaboration. An s-role may not have any predecessor, or its predecessor may not be involved in the previous phase of in the composite collaboration. Both cases are illustrated in Figure 8.1. In (b), the s-role “F” has no predecessor, and cannot determine when the s-role “B” terminates. In (c), the predecessor of “F” does not interact with “E”, the predecessor of “H”, and then “F” cannot determine when “H” starts. From a projection viewpoint, “E” is hidden from the composite s-role “C” followed by “F”.

The problem of unspecified signal reception caused by non-simultaneous execution start can be handled in two ways:

- Constraints may be set on the composition of s-roles. S-roles should be composed so that no signal is sent to an s-role that has not yet started. An s-role that cannot observe the termination of the predecessor of its complementary s-role should not take the initiative to send a signal. We refer to this approach using the term “constraint based approach” throughout this section.

- Signals that may be received before the start of execution of an s-role should be handled at the enclosing composite s-role level. The signals should be saved so that they can be retrieved from the input port when the s-role the signal is addressed to, starts. We refer to this approach using the term “save based approach” throughout this section.

Figure 8.3 and Figure 8.4 present some cases of composition and give an introduction to the constraints of composition[1]. The composite s-role, “A” followed by “D”, and the termination of “A” and the start of “D” are expanded.

In Figure 8.3, the projection of “A” does not present any termination occurrence ambiguity. A complementary a-role can then observe the termination of “A” and the start of execution of “D”. A complementary a-role may then take the initiative to send to “A”. The composition shown in case (a) is consistent. In case (b) however, we cannot determine if the composition is applied consistently without considering the termination of the complementary of “A”.

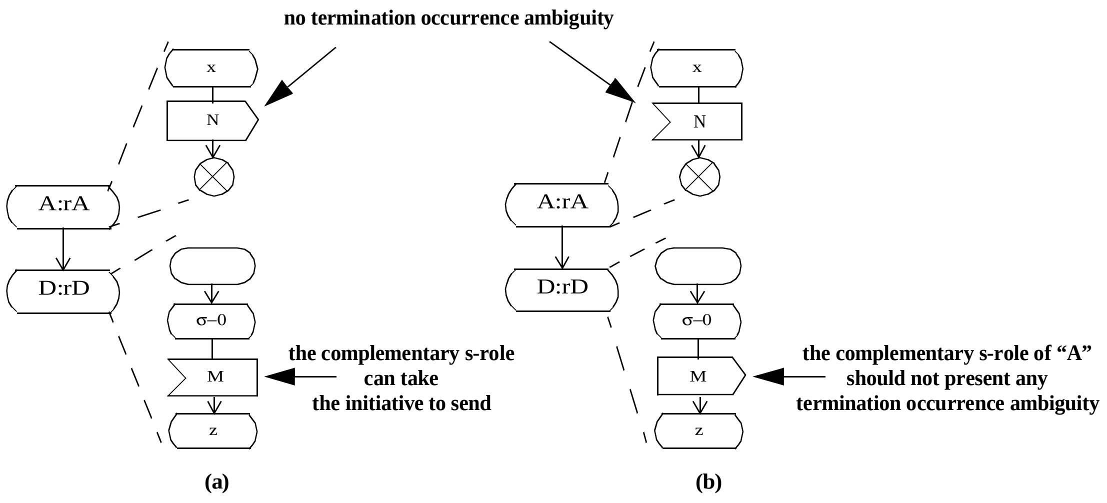

no termination occurrence ambiguity
x
N
A:rA
D:rD
σ–0
M
z
the complementary s-role can take the initiative to send
(a)
x
N
A:rA
D:rD
σ–0
M
z
the complementary s-role of “A” should not present any termination occurrence ambiguity
(b)

Figure 8.3 : Constraints and sequential composition (1).

In Figure 8.4, the projection of “A” presents a termination occurrence ambiguity. The case (a) shows a symptom of error. As a complementary a-role cannot determine the start of execution of “D”, it should not send any signal. In case (b), similarly to the previous figure, the termination of the complementary of “A” needs to be considered.

Note that the transition between “A” and “D” in those figures occurs at once (before any signal is retrieved in the input port) when “A” has terminated. This behaviour differs from

1. In the figures of this chapter, the modelling convention proposed for s-roles in Chapter 3 is followed: all references to s- roles are shown as instances of composite state types.

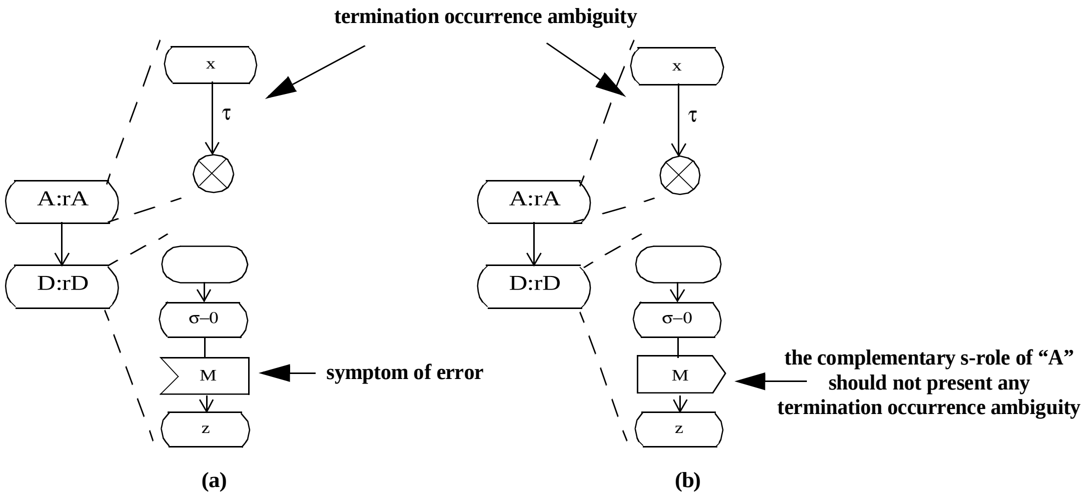

termination occurrence ambiguity
x
τ
A:rA
D:rD
σ–0
M
z
symptom of error
the complementary s-role of “A” should not present any termination occurrence ambiguity
(a)
(b)

Figure 8.4 : Constraints and sequential composition (2).

a spontaneous transition behaviour (τ-transition) where signals may be retrieved from the input port before the spontaneous transition is triggered.

The graph of the composite s-role remains simple when a constraint based approach is used. It is not necessary to specify any information related to the interaction of the elementary s-roles at the composite level. However this solution is not always applicable. It requires that at least one of the interacting s-roles is able to observe the start of its complementary. Otherwise none of them is enabled to send and a deadlock occurs. An example is shown in Figure 8.5. Neither “B” nor “C” can observe the termination of each other. Thus neither “E” nor “F” should take the initiative to send to each other.

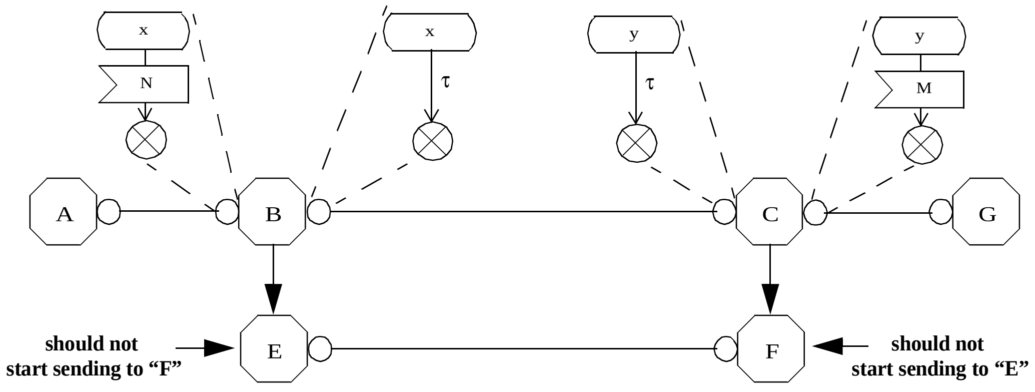

x
N
x
τ
y
τ
y
M
A
B
C
G
E
F
should not start sending to “F”
should not start sending to “E”

Figure 8.5 : Sequential composition and deadlock.

Another drawback of a constraint based approach is that it prevents us from designing elementary s-roles independently from the s-roles they are composed with, and the way they are composed. Ideally no assumption should be made about the context of execution start, because assumptions make service adaptation difficult. A change in an s-role that influences the observation of its termination on one association, should not have impact on the design of the successor s-roles, or on the design of the complementary s-roles on that association.

Contrary to the constraint based approach, the save based approach introduces some complexity in the graph of the composite s-roles, but service adaptation remains flexible. Figure 8.6 presents an example where signal reception is handled at the composite level. Here the occurrence of the termination of “A” cannot be observed by a complementary s-role. In order to ensure that no signal sent to “D” is received and discarded before the start of “D”, the signals received in the initial state of “D”, here “M”, are saved at the composite level in the state before “D”.

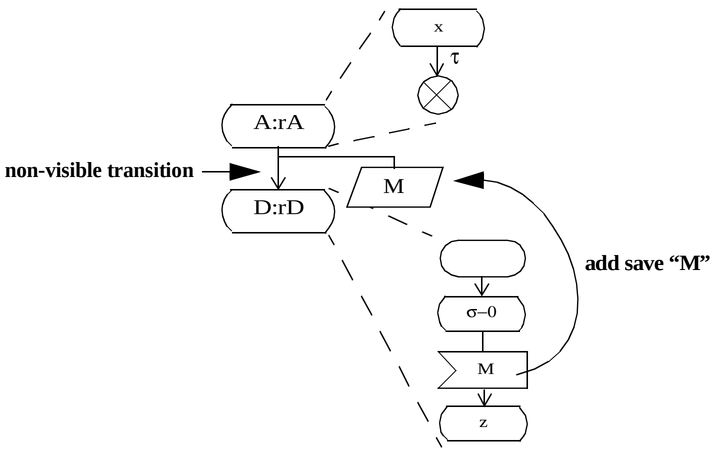


Figure 8.6 : Save and sequential composition.

This approach using save is a kind of backward save consistency (see Section 7.1.4.1.2). The occurrence of the termination of “A” is not observable, and the transitions between the end of interaction with “A” and the start of the s-role “D” is a non-visible behaviour. By specifying save, backward save consistency is enforced at the composite level.

Another form of non-visible behaviour is introduced when an elementary s-role is not observable by the complementary composite s-role. In that case, save can also be used to enforce backward consistency at the composite level. Two examples are shown in Figure 8.7. The s-role “E” is not observable from the composite s-role that sends “M” to “H”. The sender of “M” then cannot observe the start of “H”. In order to ensure that the signal is not received and discarded before the start of “H”, the signal is saved at the composite level. In case (a), the termination of “B” is observable, and the signal “M” needs only to be saved during the execution of “E”. In case (b), the termination of “B” is not observable, and the signal “M” is also saved in “B”.

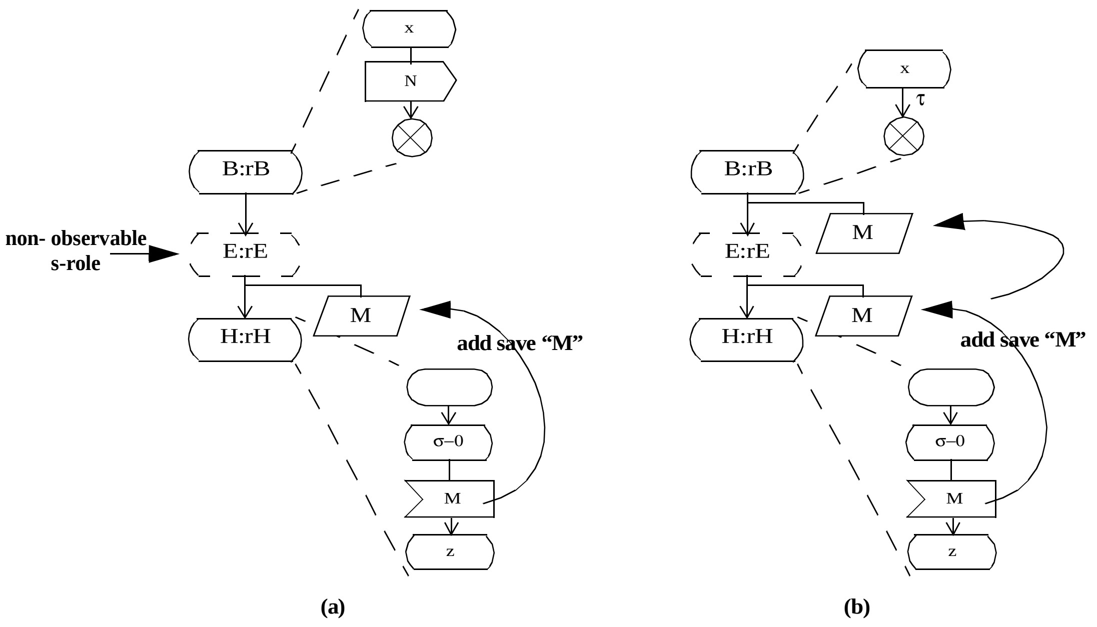


Figure 8.7 : Backward save consistency and sequential composition.

Observe that any signal specified as save in the initial state(s) of the elementary s-roles should be handled in a similar way as signals being consumed. Backward save consistency also applies to signals specified as save.

D-rule: Backward save consistency and composite s-roles

A signal specified as input or save in the initial state of an s-role being composed sequentially should be saved at the composite level in the predecessor s-role (s) of this s-role when the predecessor s-role does not describe any visible interaction[1], or when it presents a termination occurrence ambiguity according to the association from which the signal is sent. Saving should be re-iterated backward at the composite level for the predecessor s-roles until an s-role that describes an observable termination is reached. A composite s-role specified according to this rule is said to be backward save consistent.

Justification:

When this design rule is applied, unspecified signal reception due to non-simultaneous execution start does not occur.

1. i.e. the transitions of this s-role are triggered by non-visible signals and do not send any visible signal.

The rule applies locally on the composite s-role. No assumption about the termination of the complementary elementary s-roles needs to be done. For example, in case (b) of Figure 8.3 on page 242, the role “D” can send a signal without taking into account whether the predecessor of its complementary presents a termination occurrence ambiguity or not. Furthermore, extensions of the complementary s-role that modify the occurrence of termination, have no impact on the design of “D”.

A designer may prefer to redesign the elementary s-roles and the composite s-role so that no termination occurrence ambiguity and no non-observable s-role behaviour occur before the reception of a signal in a starting s-role. Redesign along these lines is not always possible. Backward save consistency is.

In the following, we assume that composite s-roles are designed according to the design rule "Backward save consistency and composite s-roles".

8.1.2 Implicit and explicit triggering

Recall that three patterns of s-roles assignment or triggering have been introduced in Chapter 3. These triggering patterns are also shown in Figure 8.8:

- Spontaneous triggering: an s-role is instantiated as part of a logical sequence of actions of an actor.
- Implicit triggering: triggering is requested by another actor, and expressed by a stimulus defined as part of the collaboration to be started and of the s-role to be assigned.
- Explicit triggering: triggering is requested by another actor, and expressed by a stimulus defined explicitly for triggering purposes. This stimulus specifies the s-role to be played.

The results of Section 8.1.1 restrict to the first form of triggering. In this section, we extend these results to implicit and explicit triggering. Although these triggering patterns usually apply in the case of sequential composition with choice (see Section 8.1.6), we first consider them in basic sequential composition.

Again, we assume that the elementary s-roles interact consistently. Inconsistency can then be introduced in the transition between s-roles. If we assume that s-roles are composed sequentially with no disabling (see Section 8.1.7), a predecessor s-role in a sequence

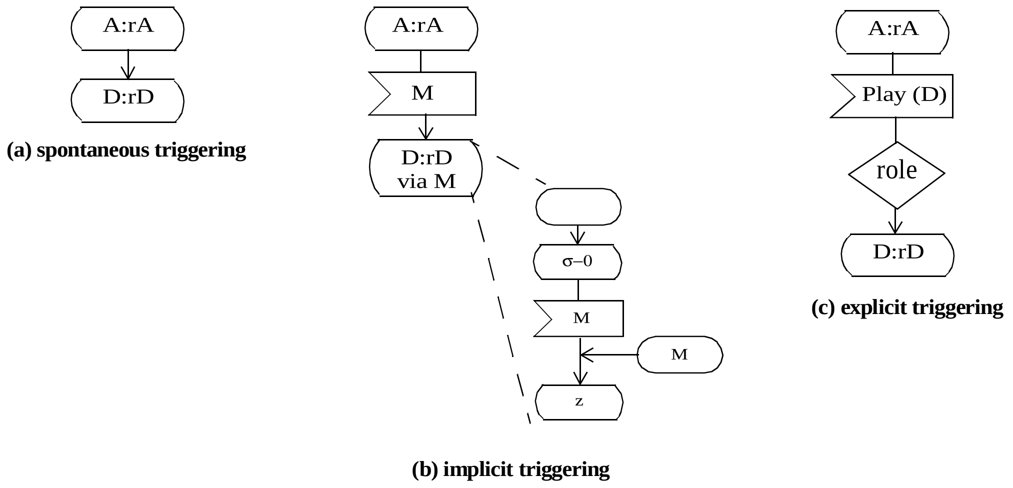


Figure 8.8 : S-role triggering patterns.

should terminate before its successor is triggered. The triggering signal should not force the termination of the predecessor s-role, i.e the triggering signal should not be consumed before the predecessor s-role has terminated its execution. In the case the sender of the triggering signal cannot observe the termination of the predecessor, backward save consistency should be enforced. As the input and save of a signal cannot be both specified in a state, we propose to insert a new non-composite state at the composite level that handles the reception of the triggering signal. Two examples are shown in Figure 8.9. The projection of the termination of "A" is considered from the association where "M" is sent in case (a), and from the association where "Play" is sent in case (b).

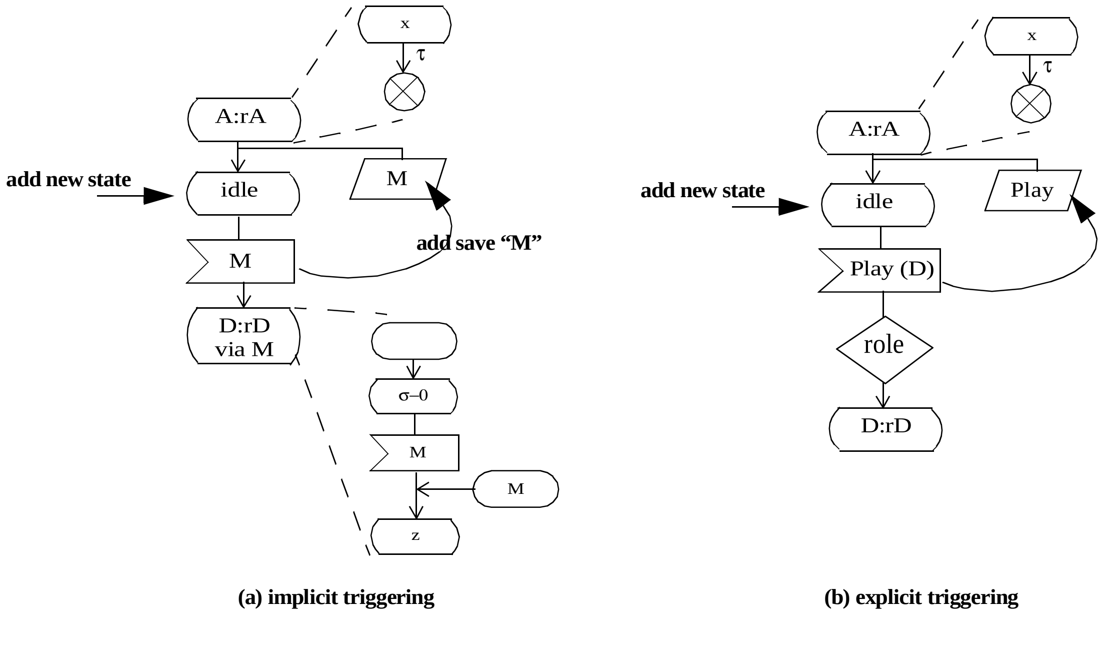


Figure 8.9 : Triggering and termination occurrence ambiguity.

D-rule: Triggering and consistency
A non-composite state that handles the reception of the implicit or explicit triggering signal should be inserted in the composite s-role graph between the triggered s-role and its predecessor, when the predecessor s-role does not describe any visible interaction[1], or when it presents a termination occurrence ambiguity according to the association from which the triggering signals are sent. The saving of triggering signals should be re-iterated backward at the composite level for the predecessor s-roles until an s-role that describes an observable termination is reached.

This design rule describes an extended backward save consistency. It ensures that signals are saved as in backward save consistency, but also that they do not force termination.

In the following, we assume that composite s-roles are designed according to the design rule "Triggering and consistency".

Note that when implicit triggering is used, the triggered s-role is entered through an entry point. The operations performed in the composite s-role graph on the consumption of the triggering signal should be consistent with the operations that are performed when the triggering signal is consumed after entering the elementary s-role.

8.1.3 Granularity

In the previous examples, the same s-role granularity is enforced across actors, i.e. an s-role in one actor interacts with a single s-role in another actor. This assumption on similar granularity is acceptable as we have proposed to consider services and service features as collaborations between roles. A role is justified by a collaboration.

The kind of collaboration pattern shown in Figure 8.10, or more complex patterns, are left to further work. In Figure 8.10, we may choose to expand the composite s-role “B followed by C”, or consider two distinct associations from “A” to “B” and from “A” to “C”.

In the following, we assume that the same s-role granularity is enforced across actors.

1. i.e. the transitions of this s-role are triggered by non-visible signals and do not send any visible signal.

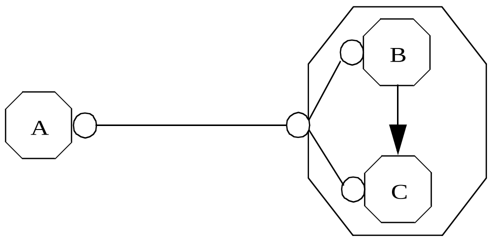


Figure 8.10 : S-role granularity across actors.

8.1.4 Checking entry consistency

Inconsistency may be introduced when interacting s-roles are entered through non-consistent entry conditions. This section gives guidelines for checking the consistency of entry conditions.

During interface validation, consistent entries between interacting a-roles have been identified. The entries that have no matching consistent entries in the complementary graph(s) are also marked. These marked entries should never be used in spontaneous or explicit triggering.

When interacting s-roles are triggered spontaneously or explicitly, we simply verify that the entry conditions of s-roles are consistent. Recall the extension introduced in SDL that enables us to express entry conditions as OR-logical expressions (Section 6.3.3.1.1 on page 121). Using that extension, the expression “c1 or c2” is allowed, and consistent with “c1”. The default entry covers any condition except those explicitly defined in the s-role. Thus the default entry in one s-role may be consistent with the named entry condition of an other s-role.

When implicit triggering is used, the triggered s-role should always be entered through an entry condition that refers to the point that follows the reception of this signal in the s-role graph. It is not that entry condition which is used when checking the consistency of the entry conditions between interacting s-role; it is the entry condition attached to the elementary s-role before the reception of the triggering signal that is used. For example, in Figure 8.9 (a), it is not the entry condition “M” that is used, but the default entry condition in the graph, as the default entry precedes the reception of the triggering signal “M”.

8.1.5 Guards

Guards have been proposed in Section 4.1.1 that prefix (or guard) the transition to a new s-role. Again, inconsistency may be introduced in the transition between s-roles. Several kinds of errors may occur:

- The guard forces the predecessor s-role to terminate before it has reached an exit node. To avoid such improper termination (seen from the analysis point of view), a non-composite state should be inserted in the graph of the composite s-role before the guard is specified. In Figure 8.11, the non-composite state “idle” is inserted before the guard.

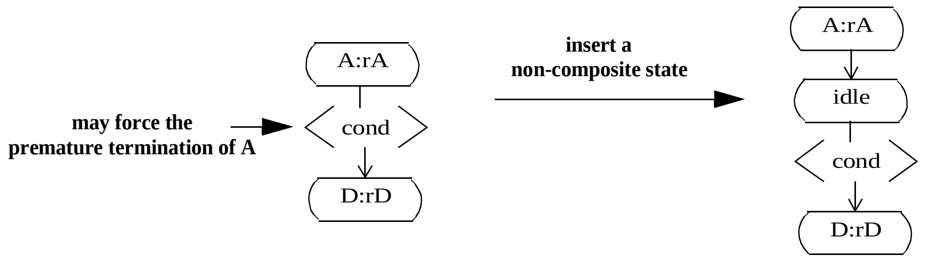

A:rA
cond
D:rD
may force the premature termination of A
insert a non-composite state
A:rA
idle
cond
D:rD

Figure 8.11 : Termination and guarded sequential composition.

- A complementary s-role takes the initiative to send before the guard becomes true. This may happen when the condition expressed by the guard is not taken into account by the complementary s-role or is non-observable from this s-role. It can be avoided by applying backward save consistency as illustrated in Figure 8.12.

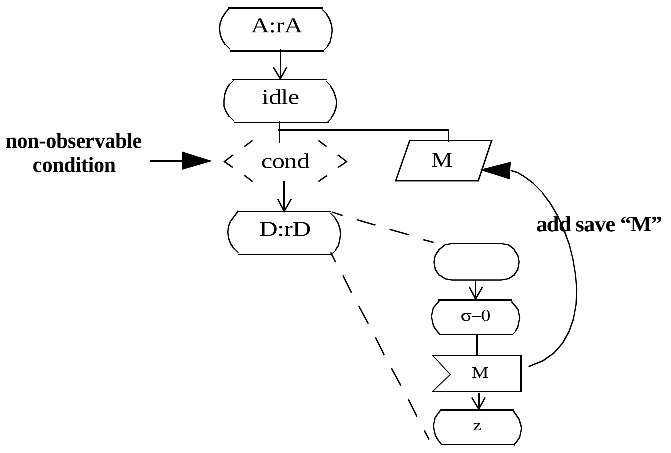


Figure 8.12 : Backward save consistency and guarded sequential composition.

- The guard never becomes true.The value of a guard may depend on operations that have already occurred in the collaboration, on operations being performed by the interacting s-roles that have not yet terminated, or on operations performed in collaborations performing concurrently. The identification of these operations and their tracing during interaction may be complex. Techniques for the abstraction of variables that contribute to the simplification of the analysis are proposed in [Boroday and al. 2002]. In our approach we do not further elaborate on these techniques for checking that guards behave correctly. We rather advise to restrict the use of guards to conditions that can be easily checked. The conditions may describe a local event, e.g. the release of a local resource, or global event, e.g. the termination of some s-role contributing to the collaboration. In the case where complex conditions need to be expressed, we propose to use timers for the detection of deadlocks. This is illustrated by Figure 8.13.

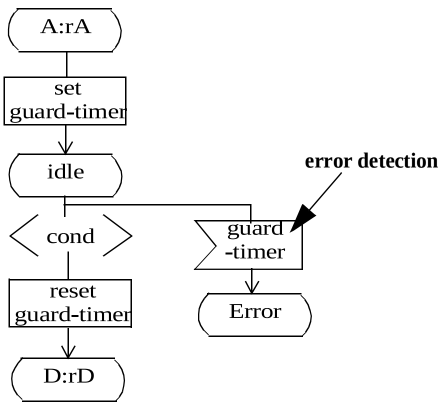


Figure 8.13 : Deadlock detection in guarded sequential composition.

D-rule: Guards and composite s-roles

The preconditions expressed by a guard in sequential composition should relate to local or global conditions that can easily be checked. A non-composite state should be inserted in the composite s-role graph between the guarded s-role and its predecessor when a precondition can become true before the termination of the predecessor. Timers that enable the detection of deadlocks should be specified in the case where the validation analysis fails to ensure that deadlocks do not occur.

Observe that conditions that relate to the termination of an s-role are checked using the techniques proposed for interface validation.

8.1.5.1 Synchronisation guards

Guards may be used as a mean to synchronise the transition to new s-roles across actors. Guards are specified as continuous signals and describe global conditions. The conditions expressed by the guards usually relate to the termination of the complementary s-roles. This is illustrated in Figure 8.14.

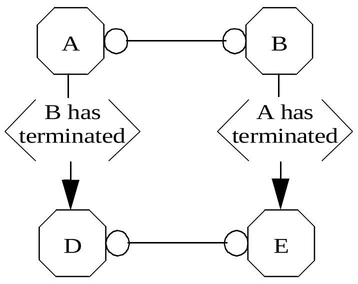


Figure 8.14 : Guards and synchronisation across actors.

Using synchronisation guards, none of the s-roles start sending before its complementary has started, and the specification of save in the composite graph can be avoided. Thus the composite graph is simplified. Notice that, however, backward save consistency is still maintained in Figure 8.14. The conditions expressed by the guards are observable from the complementary s-roles, and can be considered as a visible interaction. Of course, guards should not force any s-role termination, and a non-composite state should possibly be inserted in the graph.

Avoiding save through synchronisation guards is not always possible. When a condition expressed by a guard is not observable, using save is needed. An example is shown in Figure 8.15. Here, “D” starts when “B” (and “A”) has (have) terminated. “D” may not however be able to determine when “E” starts. This is the case when the s-role cannot observe the composite s-role “C followed by F”. Using save may be required in the composite s-role “B followed by E”. This is a normal case of backward save consistency.

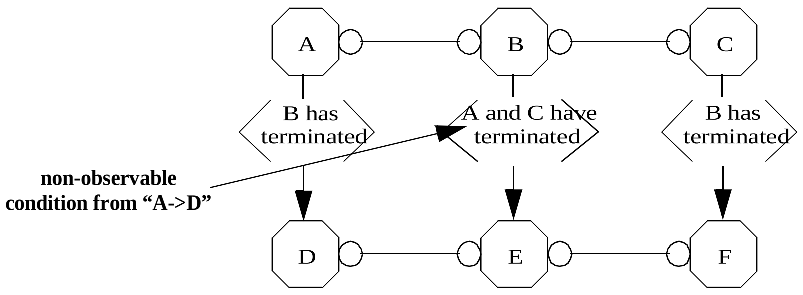


Figure 8.15 : Non-observable conditions and synchronisation across actors.

In this example, the condition “C has terminated” may implicitly be observed when “A” interacts with “C”, or explicitly observed when the guard in the composite s-role “A followed by D” is extended to include the termination of “C” (i.e. the guard is specified as “A and C have terminated”). We advise that guards explicitly describe the condition of synchronisation. This facilitates the understanding of service models, their reuse and extension.

Synchronisation guards contribute to simplify the composite s-role graph in the case where a few s-roles are involved in the elementary collaborations. The specification of save in the composite graph can be avoided. When several s-roles are involved, the complexity of this form of synchronisation increases. A drawback with the solution is that the addition of new s-roles in the collaboration may require modifications to be done to guards in several composite s-roles. In that way, the solution is not flexible enough for the purposes of service adaptation in a dynamic context. Backward save consistency is a more robust approach.

8.1.6 Choices

Using choice, alternative s-roles can be specified in a sequential composite s-role. Guards and signals are used to control the selection of an s-role among alternative s-roles. The same kinds of errors as described for basic and guarded sequential compositions may occur, and can be avoided using identical solutions. In addition to these errors, the consistency of the selection of behaviours across actors must be ensured.

Optionally, choice is applied in order to enter a single s-role through alternative entry conditions. This case can be treated in a similar way as the selection of one s-role among several s-roles.

Choice is not necessarily enforced in every actor participating into the composite collaboration. Two composition patterns are shown in Figure 8.16. In case (a), distinct s-roles are chosen in every actor at the end of the first elementary collaboration. While in (b), choice is only applied in two of the three actors. In that case, the s-role “F” should interact consistently with both “E1” and “E2”. “E1” and “E2” may provide identical or distinct a-roles to “F”.

Again, as in the case of basic sequential composition, we assume the s-roles contributing to the elementary collaborations interact consistently. While in basic sequential composition it is straightforward to identify the s-roles that an s-role interact with, and to perform the consistency checks, choice introduces some difficulty. In each actor, the composite role is described as graph of elementary s-roles, and each elementary s-role may possibly interact with several other elementary s-roles in each other actor. In case (a) of Figure 8.16, the s-role “D1” may interact with the two successors of “B”, “E1” and “E2”.

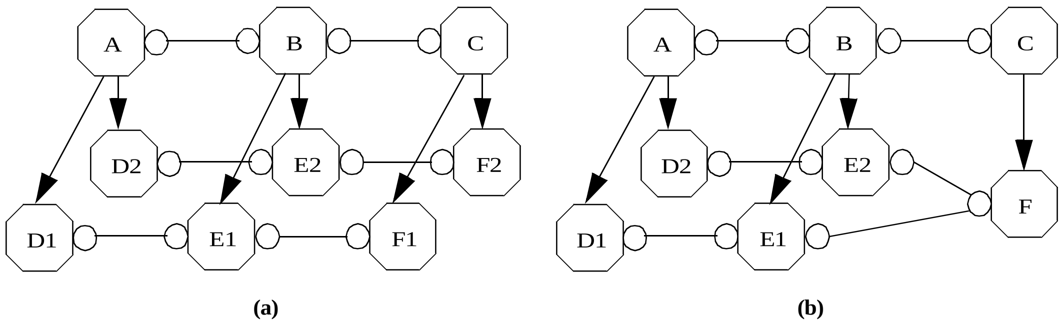


Figure 8.16 : Choice in collaboration composition.

The successors of “D1” may themselves interact with the successors of “E1” and “E2”. Of course, we wish to reduce to number of consistency checks to be performed on elementary s-roles.

We assume that each s-role selected after a choice within an s-role interacts with a single s-role in another actor and that the interacting s-role pairs can be easily identified. This assumption is acceptable as s-roles belong to collaborations. It is a collaboration rather than an s-role that is selected in a choice. Behaviour overlap between collaborations is however possible, as described as in case (b) of Figure 8.16.

We also assume that the guards controlling the selection in choice represent abstract states, and that the values of guards can be easily compared across actors. This means that guards across actors should represent the same abstract states or closely related states. For example, guards may represent global termination conditions, e.g. “success” and “failure”, in a collaboration. This assumption is acceptable as the composite s-roles link together elementary behaviours. We do not need to express detailed information in the graph of a composite s-role as we do in the graph of an elementary s-role.

Recall that two main mechanisms have been proposed for the selection of s-roles in a choice:

- The selection of a behaviour is controlled by guards expressed as predicates over conditions. The initiative to select an s-role in a choice is taken locally. Of course, the conditions may relate to a global event. Conditions are represented in SDL using exit conditions or continuous signals, as shown in Figure 8.17.

- The selection of a behaviour is triggered by a signal, as shown in Figure 8.18. The initiative to select an alternative s-role is then taken externally.

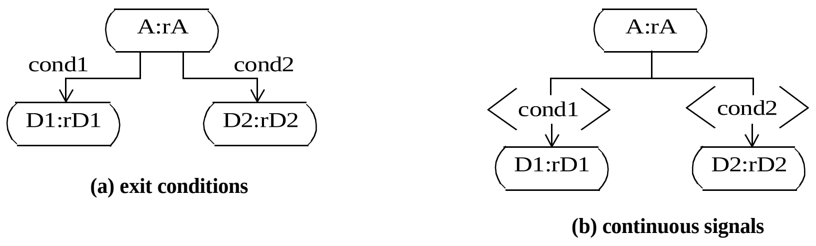


Figure 8.17 : Choice using predicates over conditions.

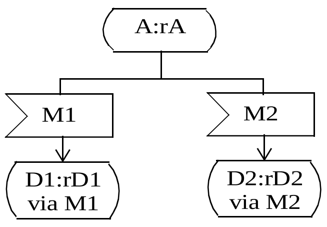


Figure 8.18 : Choice using triggering signals.

Different selection mechanisms may be applied in interacting actors. An example is shown in Figure 8.19.

As identical concepts are used to model choice and to model elementary s-roles, the same kinds of anomalous behaviours may occur:

- The conditions that control the selection of an s-role may be non-observable from some interacting s-role. The projection of the composite s-role on the association with that actor contains equivoque s-role transitions, and a behaviour ambiguity may occur. Ambiguity can be avoided when the s-roles the equivoque transitions lead to, take the initiative to send a signal in their initial state; the s-roles should send distinct signals in this case. When choice is applied in the interacting s-role, the selection of a behaviour can be triggered by these signals. This approach is illustrated in Figure 8.19. Another solution is to define signals that explicitly describe the choice (i.e. as part of a management s-role). This solution introduces complexity in the graph of the composite s-roles, but does not set any constraint on the modelling of s-roles.

- The signals that control the selection of an s-role are sent by distinct s-roles. The projections of the composite s-role on the two associations towards these s-roles contain a mixed initiative state, and a conflict may occur. Input consistency should be enforced at the composite level, and conflict resolved in a similar way as in elementary s-roles. This case illustrated in Figure 8.20 which shows a general solution to conflict resolution. Other solutions may be proposed.

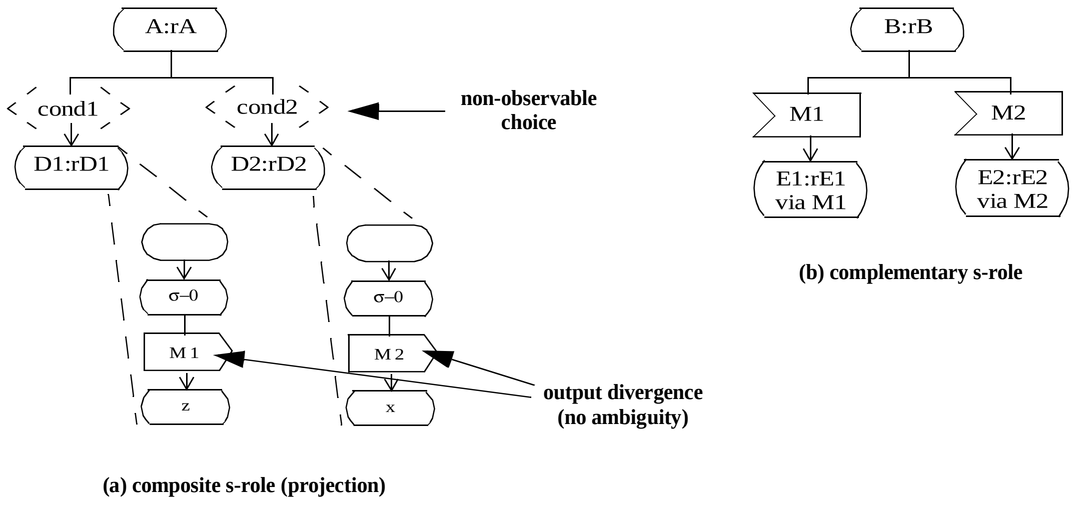


Figure 8.19 : Choice: equivoque s-role transitions.

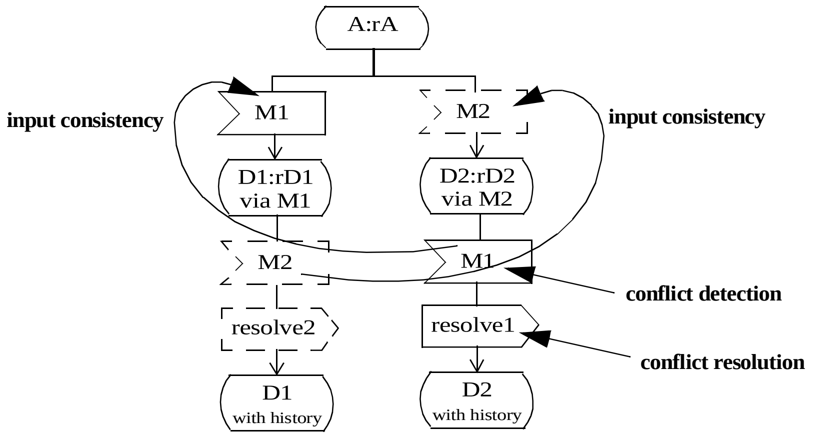


Figure 8.20 : Choice: input consistency and conflict resolution.

D-rule: Ambiguity and composite s-roles

Ambiguity may occur when a choice made in a composite s-role is not observable by some of the interacting s-roles. Ambiguity can be avoided by the sending of triggering signals.

D-rule: Conflict and composite s-roles

Conflict may occur when the selection of a behaviour in a composite s-role is triggered by concurrent s-roles. By enforcing input consistency at the composite level, deadlock can be avoided and conflict detected. Conflict resolution can be provided in a similar way as for elementary s-roles.

In addition to these anomalous behaviours, non-consistent behaviours may be selected across actors. The consistency of guards should be checked. We have assumed that guards represent abstract states, and that guards values can be easily compared across actors. It should also be straightforward to check that a selection triggered by signals sent by an actor is consistent with the selection done in that actor.

Similarly to guarded composition, none of the conditions controlling a selection may become true. The design rule "Guards and composite s-roles" also applies in choice, and timers can be defined in order to detect deadlocks.

8.1.7 Disabling

Recall that disabling has been defined as a permanent interruption of a currently executing s-role. The disabled s-role is forced to complete its execution. Disabling should be distinguished from suspension where interruption is temporary. By inhibiting the execution of an s-role, disabling also inhibits the normal execution of a collaboration. Disabling should only be applied to handle error cases. An example is shown in Figure 8.21.

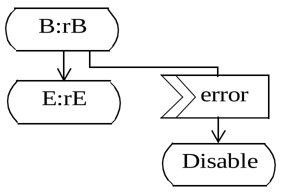


Figure 8.21 : Disabling using a priority signal.

We have proposed to describe disabling using a priority signal, i.e. a signal that is retrieved from the input port before any other signals in the queue. In that way disabling occurs immediately. The exit procedure of the disabled s-role, if any, is executed. Some important termination operations may be performed, but no signal can be consumed from the input port when executing this procedure. Neither is it possible to describe the emptying of the input port in SDL. Note that as s-roles execute asynchronously, the disabled s-role may also be addressed signals after the execution of the exit procedure. We cannot then ensure that the input port is empty when entering the disabling s-role.

The discarding of the signals addressed to the disabled s-role[1] may be handled in the disabling s-role, or at the composite level. As disabling s-roles usually handle general error cases, their behaviour should not depend on the disabled s-roles. The specification of signal discarding in the composite s-role increases the complexity of the graph of this s-role. When discarding has occurred, the discarding of the signals addressed to the disabled state is normally not critical. Therefore we propose, as an exception, to tolerate the consumption of those signals not to be described after disabling. This is a form of inconsistency that we tolerate.

When an s-role is disabled, it should inform the s-roles it interacts with. Usually these s-roles will also be disabled. The termination of s-roles and release of resources should be properly handled across actors. A collaboration that aims to handle disabling should be described. This collaboration is critical, and its consistency should be carefully checked. A simple collaboration pattern is proposed in Figure 8.22.

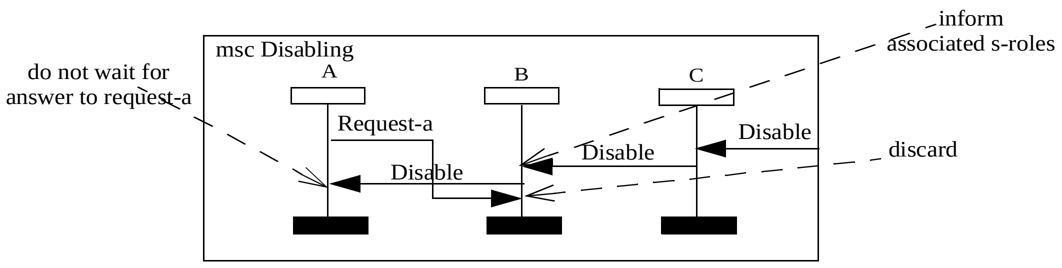

msc Disabling
A
B
C
Request-a
Disable
Disable
Disable
do not wait for answer to request-a
inform associated s-roles
discard

Figure 8.22 : Disabling all s-roles.

8.2 Concurrent collaboration composition

In this section, we assume the identical form of composition, concurrent composition, is applied to the elementary s-roles in the interacting actors. In that case we say that the elementary collaborations the actors contribute to, are composed concurrently. As illustrated in Figure 8.23, different patterns of collaboration composition may be introduced.

The concurrent s-roles may execute more or less dependently. In case (a) of Figure 8.23, the s-roles “A” and “C” are dependent. The coordination between these s-roles is modelled as an interaction on an association. On the other hand, the s-roles “B” and “D” are independent. Case (b) is quite similar to (a). The independent s-roles “B” and “D” are assigned to distinct actors. From a validation viewpoint, the two cases are identical in that the interaction on each association is validated separately. In case (c), the s-role “A” inter-

1. i.e. the signals in the s-role valid input list.

acts with two independent s-roles “B” and “D” that are composed concurrently. The interactions between “A” and “B” and “A” and “D” are modelled using two distinct associations. The interaction on each association is validated separately.

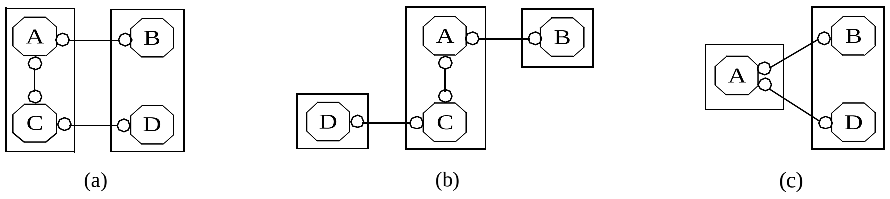


Figure 8.23 : Concurrent collaboration composition (1).

In the examples, concurrent collaboration composition introduces new associations that are validated separately. In that way, no new mechanism is needed in the validation analysis.

Complexity is added when the composed s-roles are dependent. Dependencies between s-roles are illustrated in Figure 8.24. In (a), the s-roles “A” and “C” are dependent, as well as “B” and “D”. A deadlock may be introduced when the concurrent s-roles “A” and “C”, share some resource, the concurrent s-roles “B” and “D” also do so, and the allocation of the resource is not coordinated across the actors. Case (b) is a simplification of (a) where two concurrent s-roles are replaced by a single s-role.

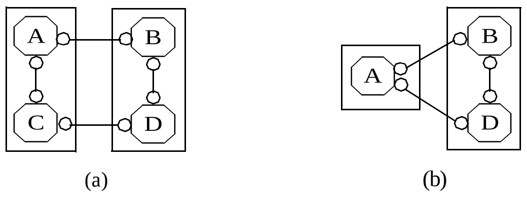


Figure 8.24 : Concurrent collaboration composition (2).

The projection hides dependencies between interactions on distinct associations. This may lead to overspecification of the s-role graphs, and in the worst case to second order errors. The problem is not new. It was also a possible problem encountered by elementary s-roles and has been discussed in Section 7.3. However the concurrent composition of s-roles highlights the dependencies between associations. Recall that acute τ-transitions are symptoms of errors, and their removal may lead to second order errors.

8.2.1 Dynamic s-role composition

On way to model concurrent composition is to use process agents. Dynamic s-role composition can then be modelled by the creation of process agents at run-time. Following the dynamic composition of s-roles, new associations are added at run-time. An example is shown in Figure 8.25.

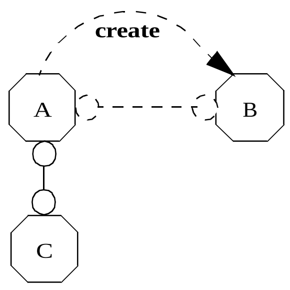


Figure 8.25 : Dynamic s-role composition.

In that example, the s-role “B” is created by “A”. The interactions between “A” and “B” and “A” and “C” are validated separately. During the validation of the interactions between “A” and “B”, one of the design rules "Backward input consistency" or "Backward save consistency" is enforced ensuring that any signal sent by “B” to “A” is handled in any non-observable state preceding the consumption of that signal in “A”. As the creation of “B” is hidden in the projection transformation, the enforcement of the design rule may lead to overspecification of the graph of the s-role “A”. This is the case when “A” interacts with “C” before creating “B”, and when “B” sends a signal to “A” immediately after its creation.

In order to avoid this kind of overspecification, we propose to extend the projection transformation, and to maintain the create operation in the projection on associations the create relates to. This means that the creation of “B” is maintained in the projection of “A” on the association between “A” and “B” in the previous example. This extension of the projection transformation is justified by the fact that the creation operation is observed by the s-role being created. The creation of “B” can be observed by “B” of course. We propose to represent the creation operation by a special output event “create”. This is illustrated in Figure 8.26.

When the extension of the projection is applied, no modification needs to be done in any of the design rules "Backward input consistency" or "Backward save consistency". The event “create” should be transformed to an initial state by mirroring during the production of dual s-roles. Similarly, it should be considered as an entry point in consistency checking. The validation analysis should be extended in order to ensure that no signal is sent before the creation of the complementary s-role: no interaction on that association is allowed between the a-role initial state(s) and the creation operation. This extension applies both in the constructive and corrective approaches.

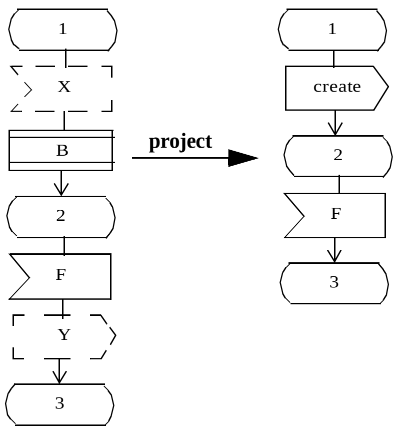


Figure 8.26 : Projection extension: adding create.

The creation example is extended in Figure 8.27 by adding an interaction between the s-roles “B” and “C”. Here the design rule "Backward save consistency" enforces that any signal sent by “B” to “C” is saved in any non-observable state preceding the consumption of that signal in the s-role “C”. Again, the enforcement of the design rule may lead to over-specification of the graph of an s-role, here “C”. In that case, the extension proposed for the projection of create does not apply.

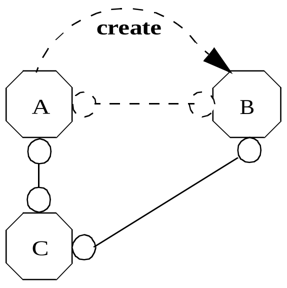


Figure 8.27 : Dynamic composition (2).

Overspecification is a drawback in a validation approach using projections. In order to avoid overspecification, it is possible to extend the projection transformation so that dependencies between visible and non-visible interfaces are highlighted and maintained during projection. Particular events can be marked in the s-role graph and attached a particular semantics, so that they can be handled in special ways during projection. For example, an event may be attached an s-role start semantics. Using marks should be applied with care. Marks should be consistent with the semantics of interactions, and should be kept consistent with the semantics of interactions when changes are introduced in the system.

Event marks are appropriate in the case where stable design patterns are followed in a system. For example, marks may be applied to the request pattern as proposed for the dynamic assignment of s-roles to actors in ServiceFrame [Bræk and al. 2002]. This pattern is shown in Figure 8.28. Here the signal “request” may be attached a start semantics, and maintained in the projection on the association between the requesting and invoked roles.

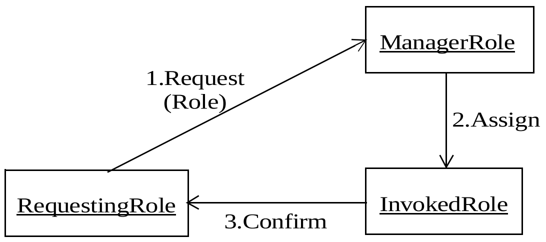


Figure 8.28 : Request pattern.

The detailed description of this extension is left for further work.

While overspecification is harmless with respect to interaction consistency, errors can be introduced in dynamic composition when an s-role sends to an s-role that has not yet started. In Figure 8.27, the s-role “C” should not send to “B” before “B” has been created. In SDL, this kind of error can be introduced as signals can be sent using gates and signal routes rather that using the receiver identifier (PId). It is simply avoided by enforcing the following design rule.

D-rule: Addressing and dynamic s-role composition
The explicit address of the receiver should always be used when signals are sent to s-roles that are created dynamically.

8.2.2 State aggregation: forcing termination

Static concurrent composition of instances of distinct s-roles can be modelled using state aggregation. Again, interactions towards the different states in the partition should be validated separately.

Recall that we have introduced an extension to the termination of a state aggregation (see Section 4.2.2.1 on page 57). Using this extension the termination of a state in the partition can force the termination of the state aggregation. While this extension facilitates the modelling of concurrent composition, it complicates the specification of an s-role that interacts consistently. Similarly to the disabling problem discussed above, errors can be introduced by the forced termination of the state. It is not possible to ensure that the input port of the aggregate s-role is empty when the termination takes place. The designer should be aware of this weakness. The discarding of the signals addressed to the aggregate s-role may be handled in the successor state or at the composite level. However the discarding of the signals may also be tolerated as in the case of disabling.

8.3 Sequential and concurrent compositions

In this section, we assume that different forms of composition, sequential or concurrent composition, can be applied within the interacting actors. This is illustrated in Figure 8.29. Sequential composition is applied in one actor and concurrent composition in the other actor. The concurrent s-roles may execute more or less dependently. Again, the interactions towards the concurrent actors are validated separately. The start of execution of the s-roles should be coordinated. The techniques proposed in Section 8.1 can be applied.

In case (a) of Figure 8.29, the s-role “D” cannot observe the termination of the predecessor of “C”. Backward save consistency can be enforced in the composite s-role “A followed by C” so that unspecified signal reception does not occur. In that case, whether “B” and “D” are composed sequentially or concurrently does not matter.

In case (b), the s-roles “B” and “D” are dependent. The interaction between “D” and “C” should not start before “A” has terminated. Dependencies between the interactions between “B” and “D”, and “D” and “C” may lead to a deadlock. The ordering enforced between “A” and “C” can be handled in a similar way as an s-role creation, i.e. as if “A” creates “C”. The discussion of Section 8.2.1 applies here.

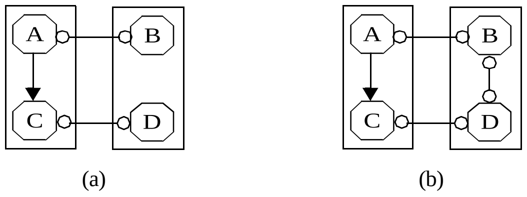


Figure 8.29 : Sequential and concurrent composition.

Again, the concurrent composition of s-roles highlights any dependencies between s-roles. The marking of events may enhance the validation method. Dependencies between associations that propagate through composition complicate service adaptation. They should thus be avoided.

8.3.1 State aggregation: exit conditions

Recall that we have introduced an extension to exit points in state aggregation (see Section 4.2.2.1 on page 57). Using this extension, an exit condition of a state aggregation can be expressed as a logical expression of exit conditions of the states in the partition. Checking the consistency of choices requires special attention if choice is based on exit conditions. The designer should distinguish between the termination of state aggregation and the termination of a state partition.

An example is shown in Figure 8.30. Here, in each composite role, the choice is based on the exit condition of the elementary predecessor s-role “success” or “fail”. The elementary s-role “B” is modelled using state aggregation and the exit condition of “B” is expressed as conditions of the state partitions “B1” and “B2”. Observe that the exit condition of “B” is not observable from “A”; it is the exit condition of “B1” that can be observed from “A”. The exit conditions of “A” and “B” may not be consistent even though the exit conditions of “A” and “B1” are consistent. Similarly the exit condition of “B” is not observable from “C”.

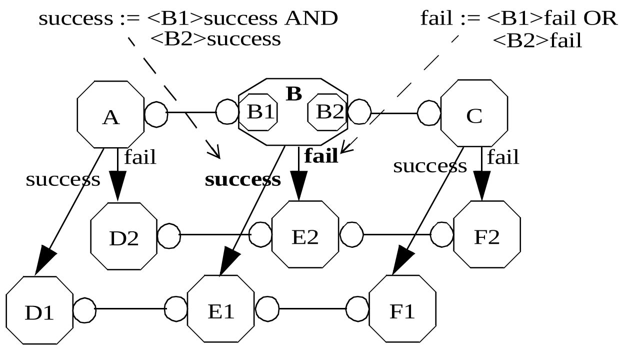

success := <B1>success AND <B2>success
fail := <B1>fail OR <B2>fail
A
B
B1
B2
C
fail
success
success
fail
success
fail
D2
E2
F2
D1
E1
F1

Figure 8.30 : Choice and state aggregation exit condition.

8.4 Summary

In this chapter, we have discussed the consistency of interactions between composite s-roles. The same symptoms of error need to be addressed at the composite level as at the elementary level, and the design rules proposed at the elementary level apply at the composite level:

- The non-coordinated occurrence of events may lead to unspecified signal reception. Unspecified signal reception can be avoided by enforcing backward save consistency.

- Non-observable selection of behaviours may lead to ambiguity. Ambiguity can be avoided by the sending of triggering signals.

- Conflicts may occur when a composite s-role interact with two or more concurrent s-roles. Conflicts are detected, and deadlocks avoided by enforcing input consistency.

Concurrent composition introduces new associations that are validated separately.

Dependencies between associations are highlighted when reasoning at the composite level. A validation approach based on projections provides restricted support for handling errors following dependencies. Errors can be identified, but not their specific causes. A solution based on the marking of dependent events has been shortly introduced. Dependencies between associations should be avoided in a dynamic context where it is desirable to adapt service at run-time.

9 Conclusions

This thesis has addressed two main questions:

- How can we model services so that they can be easily modified - possibly at run-time?
- How can we ensure that service components that are modified or added dynamically in a system interact consistently with other system components?

Composition has been proposed as a means to achieve modularity and adaptability. Our work has concentrated on fine-grained modularity enabling the partial modification of the components involved the service.

In this chapter, we discuss the achieved results with respect to these research questions, identify the limitations of the results and propose recommendations for further research.

9.1 Summary of results

This thesis provides:

- *Design rules* that should be applied during the definition of services. We distinguish between two kinds of design rules:
  - Modeling rules that aim at defining modular services. The rules relate to the composition of elementary behaviours. When these modeling rules are followed, elementary behaviours can easily be composed.
  - Correctness rules that aim at defining service components that interact consistently. These rules are identified during the discussion of validation. When the correctness rules are followed, typical anomalous behaviours can be avoided. The rules are applied before the validation analysis, and contribute to facilitating the analysis.

- *Validation transformations and algorithms* that are applied in order to analysis services. We may distinguish between two kinds of validation results:
  - Consistency checking results that aim at validating the interactions between service components.
  - A means for describing semantic interfaces. Interfaces are described in terms of service association roles (a-roles) that describe the visible interaction behaviour of a service role (s-role) on an association. The modelling of interfaces using a-roles should be of interest to the software architecture research community. The definition of component interfaces is a main research issue in software architectures; no common architecture definition language has yet been agreed on.

9.2 Main contributions

The main contributions of the thesis are:

1. *Techniques for modelling services in terms of roles.* Earlier experience suggests that role modelling provides better support for system adaptation and reuse than class modelling. Roles and role collaborations focus on behaviours across a system boundary, and enable us to better comprehend the contribution of a computational object or actor in a service. In Chapter 3, we proposed to describe service roles (s-roles) in terms of state machines using composite states. Roles can be assigned dynamically to actors at run-time. We favour the use of the modelling language SDL because of its formal semantics. However, our results are not bound to SDL. They may be applied on systems specified using other modelling languages that support state machines, for example UML. Our study identifies original and innovative employment of the composite states newly introduced in SDL 2000.
2. *Techniques for modelling the composition of service roles (s-roles).* In Chapter 4, we have proposed different forms of composition, and modelled them formally using state machines. Ideally s-roles should be specified without making assumptions about how they are going to be composed with other s-roles. We define simple general design rules that enable s-roles to be composed in a modular way. Using these rules, no supplementary behaviour needs to be specified within the s-roles being composed

sequentially. On the other hand, s-roles that are composed concurrently may require explicit coordination behaviour. We have proposed design patterns for the coordination of concurrent s-roles. The composition approach is attractive for several reasons:

- It encourages the designer to produce modular service descriptions. The elementary roles and collaborations are simple and can be easily understood.
- By nature, it provides a method for adding or replacing elementary behaviours. New functionality can also be added at run-time. In that way, the composition approach supports incremental service development and deployment.
- Dependencies between roles are highlighted during composition. Thus, the composition approach contributes to the understanding of dependencies between roles and services.
- When components are involved in several services, the contribution to different services can be modelled by different roles that are composed in order to obtain the whole component behaviour. In that way, role composition enables one to concentrate on individual services, and break down complex component behaviours.
- Composition can be exploited during validation. This contributes to reduce the complexity of the analysis. As our validation approach takes into account the compositional properties of a system, it is also suited for the validation of components bound at run-time.

The power of SDL to express useful behaviours is not restricted by the design rules that have been proposed. The composition approach does not introduce any restriction as to what functionality can be defined.

3. *An abstraction technique, the projection, that contributes to simplifying the validation of interactions between service roles*. A projection is a simplified system description or viewpoint that emphasises some system properties while hiding others. Rather than analysing the whole system, projections are analysed. In our work, the projection only retains the aspects significant for the purpose of validation of associations between s-roles. The projection transformation of each SDL concept is formally described in Chapter 6. An important property of the defined projection transformation is that it maintains the observable association behaviour.

4. *A description of role interfaces that overcome the limitations of static object interfaces.* These interfaces called service associations roles (a-roles) are obtained by projection. A-roles describe the dynamics of interactions between s-roles. In Chapter 6, we have proposed a set of transformations on a-roles that aims at simplifying validation analysis, but that also enables the designer to better comprehend interfaces. Three transformations are proposed:

   - A-role state graphs are transformed to transition charts, i.e. state graphs where transitions between states are attached a single event: an input, an output or a silent event (τ-event).
   - State gathering is applied in order to remove non-observable τ-transitions.
   - Minimisation is applied in order to replace equivalent states by a single state.

   An important property of these three transformations is that they maintain the observable association behaviour.

5. *A classification of particular anomalous behaviour patterns.* Ambiguous and conflicting behaviours that can lead to errors can be identified at design time, before the validation analysis itself. In Chapter 7, we have discussed the influence of these behaviours on the interaction between s-roles. We have proposed design rules that enable the designer to avoid ambiguous behaviours and solve conflicting behaviours, and thus develop well-formed state machines. These design rules promote quality (in terms of design errors being removed) without imposing restrictions on what functionality can be described.

6. *A constructive validation method that supports the design of correct services.* In Chapter 7, we have proposed transformations for the generation of consistent complementary a-roles from particular a-roles.

7. *A corrective validation method that provides support for checking that two complementary a-roles interact consistently.* In Chapter 7, we have proposed a consistency checking algorithm. This algorithm may be applied at run time. The proposed consistency checking algorithm stem from the algorithms used for the generation of global state graphs. However our algorithm differs from those algorithms in that it does not

use any message queue, but a save queue. The transformations and design rules applied on s-roles and a-roles before consistency checking contribute to simplifying the analysis and to maintain the number of states in the global state low.

8. *A validation approach tightly integrated with the composition of service roles*. Validation analysis is applied incrementally. The validation approach is tightly integrated with s-role composition. Elementary s-roles are first validated, and then their composite. Incremental validation contributes to simplifying the validation analysis, and the compositional properties of a system can be taken into account during analysis. The same symptoms of error need to be addressed at the composite level as at the elementary level. As sequential composition is modelled using similar modelling mechanisms as elementary s-roles, the techniques developed for the validation of elementary s-roles can be reused during the validation of s-roles composed sequentially. Concurrent composition introduces new associations that are validated separately, also using the techniques of interface validation. The dynamic creation of s-roles requires new techniques.

9. *A validation approach suited for the analysis of dynamic systems*. The analysis concentrates on the logical consistency of the interaction behaviour between s-roles. The analysis can be restricted to particular associations between s-roles. It is integrated with the composition approach, and thus can take advantage of the system structure. The analysis is applied on types, and is thus suited for the validation of components bound dynamically at run-time.

10. *Algorithms for the transformation of state graphs and their validation*. Algorithms are a means to express the validation techniques in operative terms. We believe that they can be easily implemented by CASE tools. In Chapter 6, we have proposed a minimisation algorithm based on the generation of partitions of k-equivalent states. In Chapter 7, we have proposed algorithms for the identification of anomalous behaviours, for the generation of consistent complementary a-roles, and for consistency checking.

9.3 Usability of results

A main question is whether or not the proposed design rules reduce the power of expression of SDL (or other modelling approach that uses state machines). We contend that the validation approach does not restrict this power of expression, provided that one wishes to design correct services. The design rules aim at eliminating logical interaction errors. They make it difficult to develop incorrect services, and thus they are relevant for all designers.

Another question is of course whether or not the kind of dynamic errors that are captured frequently occur, and whether or not the effort required for performing validation is worthwhile. Although we are not able to provide metrics for the frequency of dynamic errors, we know from our long experience in system development, that almost every system contains dynamic errors, and that new errors are frequently introduced when systems are developed incrementally. Our approach contributes to identifying dynamic errors, which are often the most costly errors to find. As for the effort required for performing validation, we propose design rules that can be supported by design tools, and operational validation algorithms that can be easily implemented. In that way, no effort is required from the designers.

9.4 Requirements to the approaches

The proposed validation techniques are considered easy to understand and apply. Current verification and validation techniques often require high competence and knowledge in formal modelling and reasoning from the system developer, and their use in the software industry is rather moderate. Our approach, although thoroughly justified, remains comparatively simple to understand and use. In that way, the applicability of the proposed approach is not limited to the validation in a dynamic context. It should also be of interest for the validation of static systems.

Comparing with the requirements identified in Section 1.2.4 on page 11, the following may be said:

- *Simplicity of the approaches*. We have provided design rules that we believe are easy to understand. They can be applied by the service developers, and possibly enforced with the support of tools. The projection transformation is simple. The removal of τ-transitions enables the designer to comprehend single interfaces, and simplifies the analysis techniques.

- *Simplicity of the results*. Service roles enable designers to better comprehend the contribution of a computational object or actor in a service. The concept of s-roles enables one to focus on single “slices” of behaviour that are easier to understand than complete behaviours.

- *Incremental development*. The modelling approach supports incremental development. So does the validation approach.

- *Correctness*. The design rules defined during the discussion of validation contribute to the development of well-formed components.

- *Execution framework independency.* The proposed techniques can be used in any framework where an object-oriented approach has been adopted.

- *Operative terms*. The transformations are described in terms of states, signals and transitions.

9.5 Limitations

9.5.1 Hiding dependencies between associations

The main limitations of the validation approach have been presented in Section 7.3 on page 233. While the projection transformation proposed contributes to simplifying the validation analysis, it also ignores dependencies between interactions on hidden associations. Hiding may cause two kinds of shortcomings:

- *Overspecification of s-roles*. Hiding may introduce a non-deterministic a-role behaviour, while complementary s-roles are aware of the behaviour choice. The design rules we have proposed will in such cases lead to overspecification. Overspecification is harmless with respect to consistency. We have sketched some extensions of the projection transformation that enable dependencies to be taken into account. These extensions should be further developed.

- *Second order errors*. The projection of s-roles lead to graphs that may contain acute τ-transitions. Acute τ-transitions are symptoms of errors. They may for example hide deadlocks between several s-roles. Without the knowledge of the behaviour occurring on other associations, we are not always able to handle the τ-transitions properly. Their removal may lead to second order errors.

9.5.2 UML vs. SDL

We have chosen to use the MSC language to describe collaboration sequences, and the SDL language to specify service role behaviours rather than using the notations defined in UML. A main reason for this choice is that the ITU-T languages have a formal semantics that enables an unambiguous interpretation of the system specification.

To the best of our knowledge the latest SDL version, SDL-2000, is not yet widely used in the industry. No CASE tools that support SDL-2000 are available yet. Since Telelogic, one of the main SDL tools provider, is now focusing on the new version UML, UML 2.0, we may wonder whether or not SDL-2000 will be adopted in the future, and whether or not the results of this thesis are relevant at all. However, we observe that effort has been made in order to support the concepts of SDL-2000 in UML 2.0 [U2 2002]. The new UML language is also formally defined, and should also enable an unambiguous interpretation of the system specification. For those reasons, we believe that it will be possible to convey the techniques proposed in this thesis over to systems specified using the coming UML 2.0.

9.5.3 Lacking experimentation

The techniques proposed in this thesis have not yet been applied on any large prototype case. This was a deliberate decision when faced with a trade-off between prototyping and theoretical progress. It should be mentioned though that the author has a long experience from system design and tool design [Floch 1995] which has been used as input and references to ensure relevance and feasibility of the results.

9.6 Further research

The results of thesis and its limitations inspire several areas for further work:

- *Tool development.* The proposed rules and algorithms should be integrated in CASE tools. Tool support would facilitate the adoption of the techniques in the design community.

- *Abstracting dependencies between associations.* As discussed in Section 9.5.1, hiding may introduce shortages in the approach. We have sketched some extensions of the approaches. These proposed extensions should be further developed, and possibly other extensions identified and investigated.

- *Dynamic adaptation and reconfiguration.* Although the methods aims at defining dynamic systems, we do not propose solutions for the dynamic adaptation of systems. The techniques proposed in this thesis are rather a foundation for further working with adaptation. Work is needed in order to describe which kinds of adaptation can be supported through composition.

- *Role learning.* The dynamic adaptation of services to new contexts may require the downloading and assignment of new roles to a component. Components should be able to execute new role behaviours, and combine these new behaviours with existing ones. This is what we call role learning. Learning is a known concept from the agent technology [Nwana 1996; Green and al. 1997]

- *Role negotiation.* Several components are involved in a service, and divergent roles may be selected in distinct components. For example, in a basic call, this may be the case when a caller and callee have defined conflicting roles to be selected when the callee user is busy. In that case, the selection of a behaviour may be the result of a negotiation between components. Techniques for negotiation are proposed in the agent technology.

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