Component-based systems : from design to implementation

Imane Ben Hafaiedh

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Présentée par

« Imene BEN HAFAIEDH »

Thèse dirigée par **« Susanne GRAF »**

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Systèmes à base de Composants: du Design à l'Implémentation

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devant le jury composé de :

Mr. Jean-Claude FERNANDEZ
Professeur , Université de Grenoble I (Président)
Mr. Elie NAJM
Professeur, Telecom ParisTech (Rapporteur)
Mr. Iulian OBER
Maître de conférence HDR, Université de Toulouse (Rapporteur)
Mr. Gerardo SCHNEIDER
Professeur, Université de Gothenburg (Membre)
Mme. Susanne GRAF
Directeur de recherche au CNRS (Membre)

Abstract

The goal of the thesis is to provide theory, methods and tools for the design and implementation of component-based systems.

To master the complexity of systems of components, we first propose a contract-based design and verification approach which is both compositional and incremental. Then we provide a distributed implementation of these systems allowing to preserve some global properties.

The proposed verification approach uses contracts as a means to constrain, refine and implement systems. It is based on a generic contract framework that we instantiate for a component framework allowing to express progress properties. We also extend the approach to reason about systems of arbitrary size and we show its usefulness for proving safety and progress properties in networked systems.

In the context of distributed settings, these systems must later be executed in a distributed fashion. We also propose in this thesis a protocol that allows executing systems in a distributed way while preserving some global requirements namely priorities and synchronizations and where components interact by message exchange. Then, we provide an implementation of this protocol in a particular platform.

Key words: Component-based design, contract, compositional verification, distributed control, synchronization, priority.

Résumé

Dans cette thèse, nous nous sommes intéressés aux design, vérification et implémentation des systèmes à base de composants.

Nous proposons d'abord une méthodologie de design et de vérification compositionelle et incrémentale à base de contrats pour les systèmes de composants. Nous proposons ensuite une implémentation distribuée qui permet de préserver certaines properiétés globales de ces systèmes.

La méthodologie de design proposée utilise les contrats comme un moyen de contraindre, raffiner et d'implémenter les systèmes. Elle est basée sur un formalisme de contracts générique, que nous instancions pour un formalisme de composants permettant la description des propriétés de progrés.

Nous étendons cette méthodologie pour raisonner sur des systémes de taille arbitraire et nous prouvons son utilité pour vérifier des propriétés de sûreté et de progrés d'un réseau de noeuds distribués.

Dans le contexte des systèmes distribués, les systèmes doivent être implémenter de manière distribuée. Nous proposons dans cette thèse un protocole qui permet l'exécution distribuée des systèmes tout en préservant certaines propriétés globales à savoir des synchronisations et des priorités et où les composants interagissent par échange de messages. Nous proposons également une implémentation du protocole pour une plateforme particulière.

Mots clés: Design à base de composants, contrat, vérification compositionelle, contrôle distribué, synchronisation, priorité.

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Context

Chapter 1

Introduction

1.1 Problems and needs

With the growing of the demand about scalability and complexity of systems, it becomes more and more difficult to design correctly their models. In particular, when the major goal is to build a system which ensures a set of desired properties during its execution, such important scale and complexity not only increases potential violations of these properties but also makes them harder to detect and to handle. Some of these violations may cause loss of money, time or even human life. The construction of a system that operates reliably despite of complexity is highly needed but also not always feasible. Therefore the check of the correctness of the system is essential and important to ensure that all requirements and desired properties are respected.

Designing *concurrent* and *distributed* systems with such a complex architecture while preserving a set of high-level requirements through all design steps is not a trivial task. An approach which is both compositional and incremental is mandatory to master this complexity. Such approaches generally rely on building complex systems using *components*. In deed, a central idea in system engineering is that complex systems are built by assembling components defining building blocks. Components are usually characterized by abstractions that ignore implementation details and describe properties relevant to their composition, e,g., transfer functions, interfaces. This allows to split the complex system under study into a set of subsystems which are in general less complex. It is also possible to build larger components by *gluing* together simpler ones. *Gluing* or *composition* can be formalized as an operation that takes in components and their integration constraints, then from these, it provides a description of a new, more complex composite component.

System designers deal with a large variety of components, each having different *behaviors* and each highlighting different viewpoints of a system. A central problem is the meaningful composition of these components so as to ensure some global properties.

There are two main approaches for detecting property violations of a system: *formal testing* and *formal verification*. Consider a model of a system, an environment in which the system interacts, and some properties that the designed system is expected to guarantee, one can choose one of the following approaches depending on their goal.

Formal testing [Bei90, Tre90, Mye04, FFMR07] is a method used to find defects on a system implementation, either during the development or after the complete construction of the system. To do that, testing generates some inputs from environment (test cases) and executes the system to determine whether it produces the required results. It is a quick and direct way to detect bugs or violations in the system. However, testing is not capable of covering all the possibilities that may happen while running the system in reality. The number of possible situations is usually so large that we can test a tiny proportion of them. The absence of property violations provided by testing can not conclude the correctness of the system.

Formal verification [UP83, BM79, QS82a] can both search for input patterns which violate the desired properties or prove the correctness of the system if such input patterns do not exist. In contrast to formal testing, formal verification covers all the possibilities that the system can behave. Hence it proves the correctness of the system in the case of the absence of property violation.

It relies on the use of mathematical techniques to prove or disprove the correctness of a design with respect to a certain formal specification. Formal verification has been successfully applied to verify both software and hardware systems. The verification of these systems is done by providing a formal proof on an abstract mathematic model of the system. The mathematic objects that are often used to model these systems are: *labeled transition systems*, *petri nets*, *finite state machines*, *boolean formula*, etc.

The goal of this thesis is to provide theory, methods and tools for the design, verification and implementation of *component-based* systems of arbitrary size with complex architectures preserving a set of high-level requirements through all design steps. Our approach is based on formal verification as it allows to achieve the satisfaction of properties by systems.

As mentioned above, when reasoning about complex systems, decomposing such systems into a set of simpler sub-systems may improve considerably the results of their verification. For this reason, different developments in component-based frameworks have been performed. For example, Ptolemy II [DII$^+$99, EJL$^+$03a] allows simulation of models but not their verification; Software framework component models based on classical concepts of Component-Based Software Engineering (CBSE) like FRACTAL [Fra] with its implementations, e.g., THINK [FSLM02] which also does not provide tools or analysis techniques, whether for simulation or verification; Metropolis [BWH$^+$03] which provides a frontend which produces an internal representation from the meta-model which can be used for simulation or generation model used with the SPIN model-checker [Hol97]. There are also different theoretical frameworks based for example on process algebras e.g., the Pi-Calculus [Mil98] or based on automata e.g., [RC03].

When using a component-framework to model systems for verification checks afterwards, different properties have to be ensure by this framework. Indeed, this requires the framework to be founded on rigorous semantics and provide concepts supporting separation of concerns, e.g., decoupling behavior from interaction. This is particularly absent in the case of modeling, as well as for middleware and software development standards, like CORBA. They use ad hoc mechanisms for building systems from components and offer syntax level concepts only.

Moreover, such frameworks need to encompass heterogeneous descriptions, as most of the platforms and languages, support specific interaction mechanisms and computation models. For instance, software design frameworks are based on interaction by method call and do not allow direct model-

ing of atomic interaction mechanisms. On the contrary, other frameworks such as SystemC and Matlab/Simulink have built in mechanisms for synchronous execution, and are not adequate for describing asynchronous systems. Thus a component framework which provides rich and complex interaction models – where *glues* are used for different purposes such as data transfer, synchronizations, etc, may allow large scale description possibilities. Such frameworks describing such rich *glues* are for example the Kell calculus [BS03] or the *glue* calculus Reo [Arb04]. Kell is, however, mainly concerned with obtaining correctly typed *glues*, and Reo supposes independence amongst *glues* and does not take into account constraints imposed by components. Among such frameworks, we are particularly interested in the BIP framework [BS08a, BS07a, BS07b, BBS06a, BBS06b] developed at Verimag. *Glues* in BIP are interaction models (composition operators) built by a set of *connectors* describing different interaction modes such as *rendez-vous* and *broadcast*. Furthermore, it is possible to define hierarchical connectors, which are connectors defined as a composition of other connectors. Thus BIP also addresses the problem of composition of operators and of their properties, which can be exploited for structural verification [BS07a].

BIP is related to process algebras such as CCS [Mil80] or CSP [Hoa84, Mil83] by its rendez-vous-like interaction mechanism and the restriction to a strictly local notion of state. In this thesis we focus in a first time on the design and verification of these complex systems. Then, in a second time, we study the implementation of such systems. Thus, this thesis is organized mainly in two parts. First, in Part II, we propose a design and verification approach based on *contracts*. This approach allows to verify top-level properties of component-based systems of arbitrarly size. Second, in Part III, we focus on properties of systems specified by their *glues* namely *synchronizations* and *priorities*. We transform the satisfaction of these properties into a problem of control where properties defined by the *glues* are seen as *memoryless* controllers. Then, we propose a distributed implementation of these controlled systems such that the additional properties induced by their *glues* hold.

1.2 Design and verification of complex systems

As we are interested in formal verification to reason about complex systems, *model checking* [QS82a, CE, CGP99] is one of the most well-known fully automated verification approaches. However, model checking is not always scalable, in particular for systems becoming nowadays more and more complex. Indeed, model checking techniques examine all possible paths through the system's model to determine whether or not the property being verified is violated. However, to check all possible executions of a model, *model-checking* has to deal with the well-known problem of *state space explosion*. A lot of work has been done to overcome this problem. The major goal is to make the formal verification scalable in order to increase the size of the systems that can be handled. They can in general be categorized into two approaches: optimization/improvement of model-checking's algorithms [McM93, BCM$^+$90] and compositional reasoning.

1.2.1 Compositional reasoning

Compositional reasoning [CLM89, CMP94, Lon93, dRdBH$^+$01a, dRdBH$^+$01b] allows to verify each component of the system in isolation and allows global properties to be inferred about the entire

system. The basic idea is that the system is decomposed into subsystems and these subsystems are analyzed individually. Since subsystems are smaller than the whole system, the individual analysis of the subsystems reduce the effects of the state space explosion problem. The guarantee of global property is then determined by composing the results of these individual analysis. Since through this thesis, we propose a compositional method for the verification of component-based systems, we present below several existing compositional methods.

Abstraction [CC77, Lon93, CGL94, DF95, LGS$^+$95a] is a popular technique which verifies properties on a system by first simplifying it. The simplification is often based on the conservative aggregation of states. The simplified system, which is called *abstract system*, is usually smaller than the original system (*concrete system*), so the state space is reduced. For a system obtained from the parallel composition of a set of components, i.e $S = K_1 \parallel \cdots \parallel K_n$, the compositional abstraction first computes, for each component K_i, an abstract component K_i^a, then it composes the abstract components $S^a = K_1^a \parallel \cdots \parallel K_n^a$ to obtain an abstract system S^a of S. The abstraction is required to be exact, i.e. the properties that hold on the abstract system also hold on the concrete system. However, the abstraction is often not complete, i.e. not all true properties of the concrete system are also true on the abstract system so that a process of abstraction refinement may be necessary to guarantee property preservation throughout the abstraction process.

Assume-Guarantee [Pnu85a, Jon83a, HQR98, GPB02, CGP03] is a compositional approach that decomposes properties into two parts. One is an assumption about the global behavior of the environment and the other is a property guaranteed by the component when the assumption about its environment holds. The assumption is needed since when a subsystem is verified it may be necessary to assume that the environment behaves in a certain manner. Often the behavior of a subsystem depends on the subsystems with which it interacts, thus we need to provide an assumption about its environment to verify properties of that subsystem. Consider a system S which is decomposed into two subsystems S_1 and S_2. P is a property to be verified on the parallel composition of S_1 and S_2, denoted by $S_1 \parallel S_2$. The basic assume-guarantee rule is: if under assumption A, subsystem S_1 satisfies property P and A is satisfied by subsystem S_2, then the system resulting from the parallel composition $S_1 \parallel S_2$ satisfies the property P. Despite of being largely advertised, many issues make the application of assume-guarantee rules difficult. They are discussed in detail in a recent paper [CAC08a]. The paper provides an evaluation of automated assume-guarantee techniques. The main difficulty is finding decompositions into sub-systems in the case of many parallel sub-systems $S_1 \parallel \cdots \parallel S_n$. The verification performance depends on the way of decomposition but finding a good decomposition is not always feasible. Another problem is choosing adequate assumptions for a particular decomposition. The assumption should be weak enough to be satisfied by a sub-system but also be strong enough to prove the global property.

1.2.2 Using contracts

Contract-based design is an expressive paradigm for a modular and compositional specification of systems. The use of contracts has been advocated for a long time in computer science[Hoa69, AL93]

and, more recently, has been successfully applied in object-oriented software engineering [Mey97].

Like in contract-based design [Mey92, NMO09, LMS07], in our approach we use contracts to constrain, reuse and replace implementations.

The basic idea of design-by-contract is to consider the *service* or the property provided by a component as a contract between this component and its environment. Thus a contract is usually expressed as a pair of an *assumption*, or a property that the environment must satisfy, and a *guarantee*, the properties that must be satisfied by each particular component. As in Assume/Guarantee reasoning [GGTG10] and in [GQ07], such a separation between assumptions and guarantees allows more flexibility in finding compatibility relations between components. Moreover, defining multiple contracts, thus multiple views, of a given system allows better isolation between systems and hence better compositionality.

In the theory of interfaces [dAH01a, LNW06a, GLS96], they offer a notion of contracts to check interface compatibility between reactive systems. In that context, it is irrelevant to separate the assumptions from guarantees and only one contract needs to be and is associated with a given system. Separation and multiple contracts become of importance in a more general-purpose software engineering context.

In [MM04b, BM09], a notion of *synchronous* contracts is proposed. The contracts described are executable specifications (synchronous observers). Such an approach is satisfactory to verify safety properties of individual modules (synchronous) but can hardly be applied to the modeling of globally asynchronous architectures.

In the context of software engineering, this notion of assertion-based contract has been adapted for a wide variety of languages and formalisms but the notion of rich exogenous composition operators and interaction models needed to represent abstractions of protocols, middleware components and orchestrations is not always taken into account. In [QG08a], a first framework generalizing interface theories by adding a structural part to contracts is proposed.

In interface theories [LNW07], then in [QG08a], authors use modal specifications [Lar89, LX90] to enrich their contract frameworks. Modal specification are interesting to deal with loose specifications and properties implying some progress insurance in absence of input enabledness: in a modal transition system, a *must*-transition represents a progress guarantee of all its implementations while *may*-transitions define safety properties as in usual transition systems.

1.2.3 Property verification

In this thesis, we use contracts to reason about safety and progress properties. We are interested in the description of progress properties. During the last decade an important progress in the ability of tools to verify properties of hardware and software systems has taken place [CGJ+03, Hol97]. This success has in a great part concerned safety properties such as absence of run-time errors, deadlocks etc. However, the progress in verification of *progress* properties has been less prominent as they are harder to verify than safety properties. Indeed, in [MCMM08], authors prove that deciding liveness of a set of components is NP-hard.

Progress properties are also called *liveness* properties. A component is considered to be *live* if it will repeatedly participate in some step of the system, independently of how the global system evolves

and of the point of time we considered.

Among the methods dealing with this kind of properties, we mention invisible invariant [FMPZ06, FPPZ04], counter abstraction [AFK88, FK84, FMPZ06, FPPZ04] which are based on a set of *fairness* requirements (weak or strong) that enable proofs of liveness properties of a parameterized systems [PPR]. Invariant generation [CS02] which handles termination of sequential programs and Backwards Reachability [AJRS06] presents complement to other methods for proving termination, in that it transforms a termination problem into a simpler one with a larger set of terminated states.

1.2.4 Our contribution

A first contribution of this thesis is providing a scalable methodology for design and verification of component-based complex systems. We focus on systems of arbitrary size and we preserve a set of high-level properties (requirements) through all design steps. Like in contract-based design [Mey92], we use contracts to constrain, reuse and replace implementations. As described above, one of the shortcomings of such reasoning is that it does not take into account the interaction model between components and how they are composed.

Thus our notion of contract has a structural part, which makes this definition very general by encompassing any composition model, in particular rendez-vous like composition. A more practical advantage is related to system design: it allows separating the architecture and the properties (requirements) of the system under construction, which evolve separately during the development process. In particular, in frameworks where interaction is rich, refinement can be ensured by relying heavily on the structure of the system and less importantly on the behavioral properties of the environment.

This structural part of our contracts encode rich exogenous composition operators which allow to represent abstractions of protocols, middleware components and orchestrations whereas assumptions and guarantees should constrain peers at the same or at an upper layer.

Interfaces [dAH01b] as described previously cannot encode such rich composition operators as they are based on a fixed rather than a generic model of composition — usually synchronous Input/Output (I/O) composition. In this work we are more expressive than the previously described approaches.

Other formalisms for describing such rich composition operators abstractly have been proposed, e.g., the Kell calculus [BS03] or the connector calculus Reo [Arb04]. Kell is, however, mainly concerned with obtaining correctly typed connectors, and Reo supposes independence amongst connectors and does not take into account constraints imposed by components. Thus we choose in this thesis to use a subset of the rich composition operators of the BIP component framework [BBS06a] as they provide the required expressiveness, define interaction with component behaviors and handle conflicting connectors. Using a formalism like BIP for wide area systems allows using layered specifications where different layers can be analyzed separately by abstracting complex lower layer protocols by an atomic multi-party interaction. Using connectors as abstractions of lower level protocol stacks leads to clearly structured models.

In our contracts, we also keep assumptions and guarantees separate and moreover we describe them on different alphabets which allows improving reusability.

To apply our verification methodology, we formalize and extend the framework introduced

in [QG08a] to distributed component systems of arbitrary size and we show its usefulness for proving safety and progress properties in networked systems.

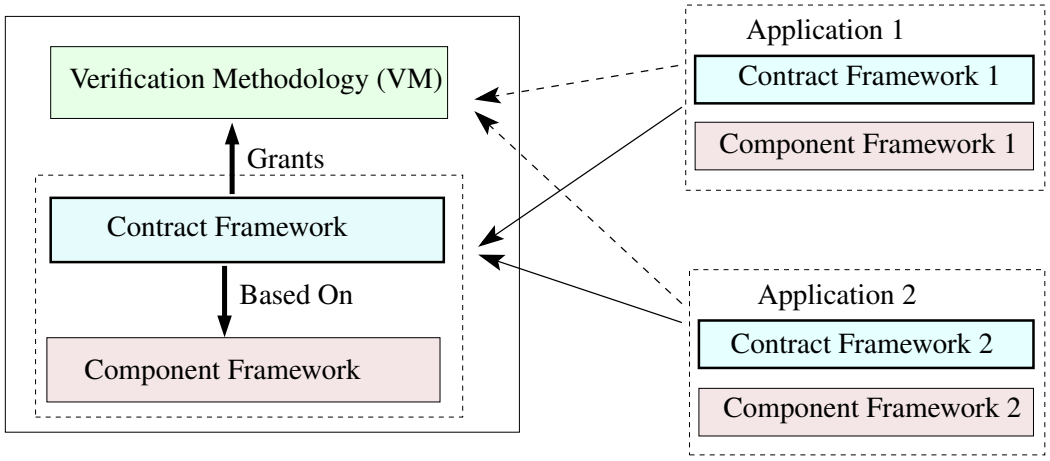


Figure 1.1: Approach to the Design of Contract Frameworks.

In this thesis, in addition to a compositional verification methodology using a contract framewok, we provide a design approach that uses the results of this methodology to verify new properties of different applications with no further proofs. More precisely, this generic design approach consists in two phases:

1. define a general notion of contract framework stating the necessary ingredients to apply our verification methodology. Then rules for establishing validity conditions for these relations are provided.

2. for any particular application, one only has to define instantiations of these generic notions and check the validity conditions. Once the concrete framework has been defined, the rules and the verification methodology can be applied without any further proofs (see Figure 1.1).

The generic contract framework, we use, is based on some notion of *refinement*, which allows to define the following relations: *conformance* which is refinement with respect to a given specification, *dominance* which is refinement between contracts and *satisfaction* which is refinement of an implementation with respect to a contract. To prove the validity conditions for these realtions we use *circular reasoning* which allows to derive an interesting rule to prove dominance, with no need to compose contracts.

We apply the proposed design and verification methodology to an application, where we have focused on *progress* properties. To reason about progress, we propose a formalism similar to symbolic transition systems as introduced in [MP91], which we extend in several ways. We define progress constraints close to the usual strong and weak fairness [AFK88, FK84, FMPZ06, FPPZ04] and we decorate control states with invariants on state variables.

We also consider an explicit interaction model (*glue*) represented by sets of *connectors*. Each connector defines a set of interactions and a transformation on (non persistent) port variables, where *ports* name transitions of the local components involved in the interaction.

For achieving scalability, we base verification on an abstract semantics in which explicit values of state variables are abstracted by the defined state invariants. Given the complexity of the specifications, not having to prove the correctness of the proof rules in this concrete setting is very helpful.

We apply the methodology to a resource sharing algorithm in a networked system of arbitrary size. The different verification steps and proofs are automated in a tool developed for this purpose.

Although this is not presented in this thesis, we have also addressed the problem model-based design and validation [PBHG+09, IBHR09]. We have applied in [IBHR09] a design approach using the OMEGA-RT profile [OGO03, GOO05] for a design phase and the IF toolset [OGY06, BGO+04a] for a validation phase.

1.3 Distributed systems with rich interaction models

In Part III, we are interested in giving a distributed implementation of component-based systems. These systems represent rich interaction models defining a set of properties. We propose a distributed implementation with respect to these properties, which are seen as controllers. The satisfaction of these properties defined by the interaction model, can be generalized to the problem of controlling an existing system in order to force it to satisfy some additional safety constraints [RW92b]. Component-based systems are likely to be implemented in a distributed fashion, as each component can be hosted by a different site. When the constraints added by the interaction model are *global*, distributing the controlled system is not a trivial task. Indeed, this is proven in [PR90] to be undecidable for concurrent systems. We focus on two types of properties namely *synchronization* and *priority*. Typical frameworks used to express synchronization-based specifications are (prioritized) Petri nets, process algebras [Mil80, Hoa84, BB87] or their UML incarnation, namely activity diagrams. BIP [GS05, BBS06a] generalizes the basic concepts of these formalisms (see [BS08b]). Interaction by synchronization is an expressive modeling paradigm as it encompasses all commonly used communication and interaction primitives. Specifying *priorities* amongst a set of alternative synchronizations is interesting in many contexts. For example, it is likely that amongst a set of enabled synchronizations amongst subsets of components, one will prefer those involving larger subsets. Another typical example of the use of priorities are components which for different activities require one or more resources amongst a shared pool of resources. There exist several abstract frameworks allowing to represent *priorities* such as process algebras with priorities or prioritized Petrinets [BBBS08, BBPS, GS04].

1.3.1 Distributed control

At the implementation level, a distributed system is defined by a set of components that interact using the communication mechanisms provided by a distributed platform. Typically, such a platform allows communication via message passing and the level of abstraction that is provided determines the properties that can be guaranteed by the message passing mechanism. The platforms defined by

component frameworks such as Corba, JavaBeans or .NET aim at making transparent their distributed nature to a designer using standard (sequential) programming languages, where interaction is through method call. In this context, one generally distinguishes between *active* components — threads or processes — driving the computation and *passive* ones which get activated temporarily when needed. A requirement (i.e., a property to be ensured) is in general a property of complete executions of some thread. In service-oriented systems, different processes (initiated for example by different clients) are often considered to be functionally independent: they may share resources (data and platform capacities), however the problems resulting from this are often ignored at early design stages and the primitives provided for specifying systems consisting of several interacting threads (or ongoing activities) are often low-level mechanisms such as semaphores or time-based scheduling.

Different algorithms have been proposed to describe message passing distributed protocols. For instance, in [Bag89b, Hoa78] a first algorithm ensuring *binary* synchronization between components has been described. Then algorithms handling *multiparty* synchronizations have been proposed in [PCT04, Bag89a, FF96]. Distributed implementations preserving some global properties are not trivial to achieve as, we cannot determine the exact global state of a distributed system, we can only approximate it (see [CL85, Tri04, Thi05]). Some approaches propose the use of statically computed *knowledge* about the possible global states to decide about the satisfaction of some global constraints in a distributed system [BBPS, GPQ10, RR00a, RW92a].

1.3.2 Our contribution

We study the design and implementation of systems in which correct interaction between components is essential in order to achieve functional properties defining the services to be provided by the system and/or non-functional properties specifying some constraints on their quality. For this purpose, we view a system as a set of active components which interact by synchronizing certain activities. A *synchronization* between a set of components is the abstraction of a sequence of messages between these components that results in the atomic execution of some local transition in each of these components. The motivation for specifying interaction using synchronizations is that these may represent some global activity that is in fact distributed over several components. Thus, it is possible to abstract away the detailed specification of a particular order in which the local activities have to be executed or how atomicity is achieved on some actual platform — which may offer message-based communication, but which might as well be a CAN-bus or a multi-core processor where communication is by shared memory. We introduce an abstract representation of components and systems where components are identified with an abstraction of their behavior and represented by transition systems labeled by actions (which are also called ports). In a first phase, we totally abstract from how such a synchronization is realized; then, we provide a distributed implementation for it as a message-passing protocol. We define *synchronizations* between components and *priorities* defined on the set of their interactions as memoryless controllers.

We propose also to use controllers defined by *priorities* to avoid *deadlocks* in a given specification. More precisely, we propose that instead of systematically asking the user to rework a given specification when a reachable deadlock is detected, we propose to restrict the possible executions to those avoiding deadlock by means of a *priority order*. Why do we choose priorities as a means for

avoiding deadlocks? One reason is that we suppose that specifications explicitly specify a (close to) maximal degree of concurrency and may therefore have a high degree of non-determinism. Adding buffers and reordering messages as proposed in [SB09] has the inconvenient of being tied to a lower level of abstraction — at which state explosion is a big issue for verification — and moreover, it is not adequate when interaction is by synchronization and each component already exhibits its maximal potential of concurrency. But restricting non determinism may be very useful, and priorities are an interesting means for doing so.

Another reason is that, when it is guaranteed that prioritized executions are deadlock free, a set of priority rules is a *memoryless controller*, that is, deciding which next transition is possible requires neither history nor look-ahead. In fact, the construction of the priority rules does eliminate statically the look-ahead required to avoid deadlocks without additional memory, thus keeping the specification small at that level of abstraction.

Our problem is that of synthesizing a distributed memoryless controller, where we define what it means to distribute a controller, and what a correct implementation should be. Furthermore, this general presentation shows that our approach applies not only to interaction models and priorities, but to all memoryless properties. We distribute these memoryless controllers by proposing a protocol that transforms a (global) system specification into a distributed implementation consisting of a set of components communicating through message passing where we suppose that the underlying communication platform ensures reliable and order-preserving transmission of messages. As already described, there exist several protocols achieving such implementations. However, specifications requiring in addition global priorities to be respected have rarely been considered. [BBPS, GPQ10] address the problem of distributing prioritized Petri nets, but for an underlying platform on which synchronization is provided as a primitive, whereas we try here to improve the efficiency of the resulting implementation by means of a combined algorithm. In [BBPS, GPQ10] they consider the same problem but with a different progress property, namely deadlock freedom, whereas our protocol ensures what we call *maximal progress*, which is also the progress criterion adopted in [RW92a, RR00a, PCT04]. Given a system S of components, we propose to build, from a *global* memoryless controller defined by an interaction model ($\mathcal{I}$) and a priority order ($<$), a set of *local* controllers (denoted C_i) associated to each component so as to ensure the constraints defined by $\mathcal{I}_<$ in a completely ditributed way (see Figure 1.2).

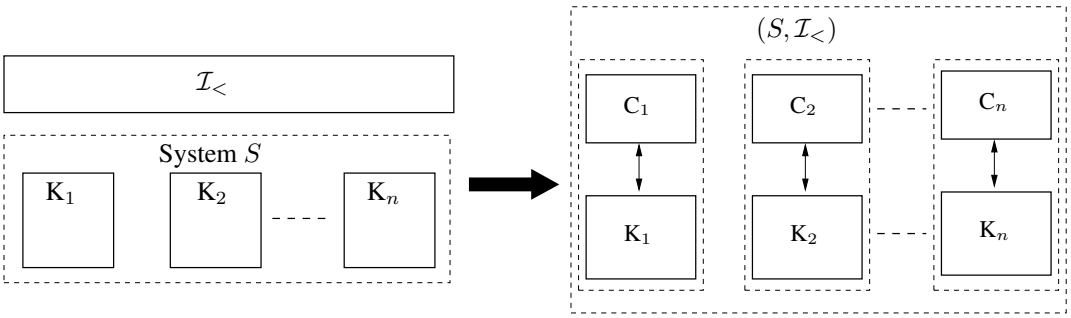


Figure 1.2: Distributed Controllers.

We give an implementation of this protocol using the Message Passing Interfaces (MPIs) [GLS99, SOHL$^+$96], and we give an evaluation of different performance metrics. We also compare our algorithm to the existing α-core algorithm presented in [PCT04].

1.4 Organization of the thesis

The thesis is split into four parts, Part I presents the context and the needed concepts (Chapter 2). Part II describes the proposed design and verification methodology [IBHQ10c, IBHQ10b], the framework used to apply it (Chapter 3 and 4) and its application to a case study using a tool developed for this purpose (Chapter 5). Part III proposes a distributed implementation of systems with priorities [IBHQ10a, QBHG09, IBH10] (Chapter 6, 7 and 8). The last Part IV draws the conclusions and future work (Chapter 9). The details of all chapters are as follows:

- Chapter 2 presents preliminaries and concepts used in the sequel of this thesis. It describes the basic notions about component-based frameworks, in particular the version we use of the BIP component framework, its interaction models based on connectors and how it allows to express priorities. This chapter also provides the different basic notions of the contract-framework that we need in our approach.

- Chapter 3 presents a formal description of the different design steps of our verification approach based on a generic notion of contract framework. In particular, it discusses relations and properties that contract frameworks have to provide so that our approach could be applied. We also detail how this methodology can be applied in the case of systems of arbitrary size once these systems can be built using a grammar of components.

- In Chapter 4, we formalize the different ingredients of the contract framework used to apply the methodology described in Chapter 3. We focus on progress properties, thus we provide rich specification that allows expressing such kind of properties. Progress properties are described by progress conditions which adapt the usual weak and strong fairness conditions to component systems. The proposed contract-framework handles variables and data exchange between components. We give proofs that such contract-framework allows indeed to apply the proposed methodology.

- In Chapter 5, We apply our methodology to a networked system for sharing resources. We verify a top-level progress requirement of this case-study and we detail the different verification phases applied. We also provide a tool that implements the main verification checks of our methodology and we use this tool to validate the case-study results.

- Chapter 6 focuses on the properties defined by the interaction models of component-based systems, where these properties are seen as memoryless controllers. It also discusses the synthesis of such controllers.

- In Chapter 7, we present the protocol that transforms a system (with binary synchronizations) and its memoryless controller into a distributed implementation based on message-passing. We

give proofs of its correctness with respect to the usual properties of distributed algorithms and we describe through an example how we deal with deadlocks due to circular configurations.

- Chapter 9 concludes the thesis and hints at worthwile future developments.

Chapter 2

Preliminaries

In this chapter, we first recall some basic definitions about labeled transition systems and their usual refinement relations, which are used to describe behaviors of components throughout this thesis. Then, we present the BIP framework [GS05, BBS06a, BS07a], which is one of the motivations for our work. We briefly discuss BIP in its generality. Then we present a variant of this framework that we use in this thesis. Finally, we review the basic notions of the generic contract framework proposed in [QG08a], from which our work on contract frameworks is inspired. In particular, we emphasize the properties of such a framework allowing to reason about contracts in a component framework with rich interaction models such as BIP.

2.1 The BIP modeling framework

2.1.1 Labeled Transition Systems

Labeled transition systems are used to describe abstractly the behavior of systems. They define how these systems can evolve from one state to another by firing a transition associated with a label that names the operation performed during the transition.

Definition 2.1.1 (Labeled Transition System (LTS)) *A labeled transition system is a tuple* $TS = (Q, q^0, \mathcal{P}, \longrightarrow)$*, where:* Q *is a set of* states*,* $q^0 \in Q$ *is the* initial state*,* $\mathcal{P}$ *is a set of* labels *(actions).* $\longrightarrow \subseteq Q \times \mathcal{P} \times Q$ *is a set of* transitions *each labeled by an action.*

As usual, for any pair of states $q, q' \in Q$ and an action $p \in \mathcal{P}$, we write $q \xrightarrow{p} q'$, iff $t = (q, p, q') \in \longrightarrow$. The state q is called the *start* state of t and q' its *target* state. If such q' does not exist, we write $q \not\xrightarrow{p}$. These labeled transition systems could be enriched with variables for example, and thus called *extended labeled transition systems* which we denote ELTS.

Definition 2.1.2 (Extended Labeled Transition System (ELTS)) *An extended labeled transition system is a tuple* (TS, X, g, f) *where:*

- $TS = (Q, q^0, \mathcal{P}, \longrightarrow)$ *is a labeled transition system:* Q *is a set of* control states, $q^0 \in Q$ *is the* initial state, $\mathcal{P}$ *is a set of labels.* $\longrightarrow \subseteq Q \times \mathcal{P} \times Q$ *is a set of transitions each labeled by an element of* $\mathcal{P}$*. Elements of* $\mathcal{P}$ *are* ports*;*
- X *is a set of* variables*. Some variables are associated with a (unique) port;*
- g *associates with every transition* t *a* guard g_t*, i.e. a predicate on* X*;*
- f *associates with every transition* t *a* function f_t *defined on* X *and corresponding to local state transformations.*

If $t = (q, p, q') \in \longrightarrow$, g_t is a pre-condition for interaction through p, and f_t is a computation step consisting of local state transformations. g_t is also known as the guard of the transition and the transition can be executed if the guard is true.

Definition 2.1.3 (Execution, Extended prefix, Reachable states, Deadlocks) *Let be* $TS = (Q, q^0, \mathcal{P}, \longrightarrow)$ *an LTS, Then:*

- *an* execution σ *is a (possibly infinite) maximal (i.e. cannot be extended) sequence* $q_0 \cdot p_0 \cdot q_1 \cdot p_1 \cdot \ldots$ *starting in the initial state* q_0 *and such that for any* $i \geq 0$ *such that* q_i *and* $q_{i+1} \in \sigma$*, it holds that* $q_i \xrightarrow{p_i} q_{i+1}$*. Thus* σ *could be also written a sequence of states and transitions, that is* $\sigma = q_0 \cdot t_0 \cdot q_1 \cdot t_1 \cdot \ldots$*, where* $t_i = q_i \xrightarrow{p_i} q_{i+1}$*.*
  We suppose without loss of generality, that executions are infinite, that is always extended by some ϵ *transitions. We denote by* $exec(TS)$ *the set of infinite executions of* TS*.*
- *a* prefix *on* $\mathcal{P}$ *and* Q *which we denote* β *is a finite sequence* $q_0 \cdot p_0 \cdot q_1 \cdot \ldots \cdot q_\beta$ *with* $q_i \in Q$ *and* $p_i \in \mathcal{P}$*;*
- *an* extended prefix *on* $\mathcal{P}$ *and* Q *is a pair* (β, A) *where:* β *is a prefix on* $\mathcal{P}$ *and* Q *and* A *is a set of labels in* $\mathcal{P}$ *which we call an* acceptance set*.*
- *A state* $q \in Q$ *is* reachable *if there exists an execution* σ *containing* q
- $q \subseteq Q$ *is a* deadlock *if* $\nexists (q', p) \in Q \times \mathcal{P},\ q \xrightarrow{p} q'$

TS *is called* deadlock free *if it has no reachable deadlock state.*

We now introduce *simulation* [Mil89] which is a preorder on LTS and allowing to compare them.

Definition 2.1.4 (Simulation) *Let* S_1 *and* S_2 *be two LTS. A relation* $\mathcal{R} \subseteq Q_1 \times Q_2$ *is a* simulation *relation of* S_2 *by* S_1 *iff* $q_1^0 \mathcal{R} q_2^0$ *and for any pair* $(q_1, q_2) \in Q_1 \times Q_2$ *and any* $q_1' \in Q_1$*:*

$$q_1 \mathcal{R} q_2 \text{ and } q_1 \xrightarrow{a}_1 q_1' \text{ implies that there exists } q_2' \in Q_2 \text{ such that } q_2 \xrightarrow{a}_2 q_2' \text{ and } q_1' \mathcal{R} q_2'$$

S_1 simulates S_2 *if and only if there exists such a relation.*

Intuitively, an LTS S_1 simulates S_2 if any reachable state q_1 of S_1 can be mapped to a state q_2 in S_2 such that all labels enabled in q_1 (w.r.t S_1) are also enabled in q_2 (w.r.t. S_2).

We now define an equivalence relation between LTS called bisimulation.

Definition 2.1.5 (Bisimulation) *Let K_1 and K_2 be two LTS. A relation $\mathcal{R} \subseteq Q_1 \times Q_2$ is a* bisimulation *if it is a simulation and furthermore $\mathcal{R}^{-1}$ is a simulation of K_1 by K_2.*

2.1.2 Component-based design with BIP

BIP [BS08a, BBS06a, BJS09a, BBS06b] is a component framework for designing component-based systems with complex interactions. Its main principle is that there should be a clear separation between the behavioral and the architectural parts of systems. Indeed, such a separation allows efficient structural verification techniques.

BIP framework supports a component construction methodology based on the thesis that components are obtained as the superposition of three layers (see Figure 2.1). The lower layer contains atomic components described by their *behavior*. The intermediate layer includes *glues* which are represented by *interaction models* built as a set of *connectors* linking ports of different components. The upper layer is a set of *priority* rules describing scheduling policies and preferences between interactions.

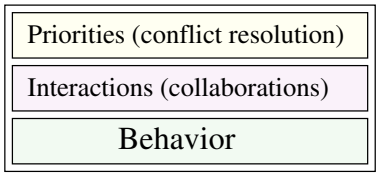


Figure 2.1: BIP Layers.

In BIP, hierarchical components are defined inductively from atomic ones:

- *atomic* components defined as basic element that only represents *behavior* which means an LTS or an extended LTS.
- *composite* or *compound* defined as a composition of a set of components using glues. A composite component could be *flat* or *hierarchical*. A *composite* component is *flat* if it is a composition of only atomic components and it is *hierarchical* if it is not flat.

A component is denoted graphically by a box with a well defined interface allowing to interact with its environment. Interfaces are defined as a set of *ports*. The box of an atomic component contains behavior inside and the box of a composite component contains other components and glues.

Given a set of atomic components $\{K_1, K_2, \dots K_n\}$ and a glue GL. The composition of $\{K_1, K_2, \dots K_n\}$ using GL produces a composite component K, as shown in Figure 2.2, where

$$K = GL(K_1, K_2, \dots K_n)$$

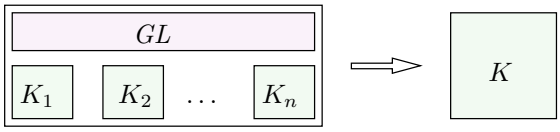


Figure 2.2: Component Composition.

Hierarchical components are obtained as composition of such composite components. This is allowed by the fact that glues in BIP could be also composed. For example, in Figure 2.3, components K_1 and K_1' are composed with glue GL_1, and the resulting composite component is integrated with K_2 by GL_{12} to produce a hierarchical component. In BIP, glues and their composition operators

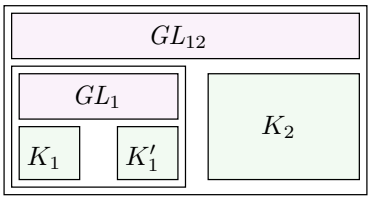


Figure 2.3: Hierarchical Components.

provide a set of properties, namely *incrementality*, *compositional reasoning* and *composability*.

Incrementality. means that composite systems can be considered as the composition of smaller parts. Incrementality provides flexibility in building systems by simply adding or removing components and the result of construction is independent of the order of integration. It is necessary for progressive analysis and the application of compositionality rules. Incrementality allows coping with the complexity of the heterogeneous and large-scale systems in both construction and verification phases.

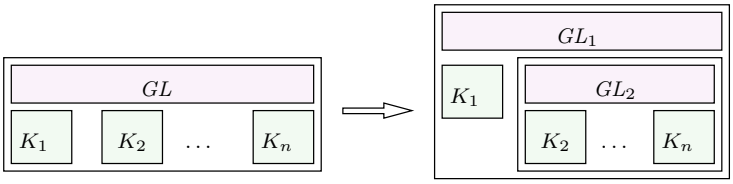


Figure 2.4: Structuring.

Incrementality means the two following properties:

– *Flattening*: means that any given structure can be flattened to a component which is the composition of its atomic components by using a single glue operator.

$$GL_1\left(K_1, GL_2\left(K_2, \ldots\right)\right) = GL\left(K_1, \ldots, K_n\right)$$

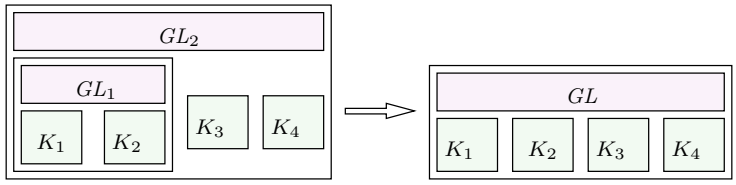


Figure 2.5: Flattening.

An example is shown in Figure 2.5. Flattening allows to avoid reasoning on hierarchical components by only reasoning on their flattened version. Note that flattening is a weak property that is in general satisfied by component frameworks.

– *Structuring*: means that an n-ary glue operator could be obtained by successive application of a binary glue operator, as shown in Figure 2.4. In general, we should be able to write

$$GL\left(K_1, \ldots, K_n\right) = GL_1\left(K_1, GL_2\left(K_2, \ldots, K_n\right)\right)$$

That is, any *composite* component can be obtained by successive composition of its atomic components. This property is useful when one wants to build the glue that relates some particular component to the rest of the composite component (the system). Notice that structuring is a very strong property. For the definition of contract frameworks which we will propose, we will require a weaker condition, inspired by this one which is easier to satisfy and sufficient for contract-based reasoning.

By the above two mechanisms, a given system of behavior can be partitioned into any required structure.

Compositional reasoning. Compositional reasoning rules allow inferring global system properties from the local properties of the sub-systems. (e.g inferring global deadlock-freedom from the deadlock-freedom of the individual components). Compositional reasoning is necessary for obtaining correctness-by-construction. This is interesting when applying incremental verification approaches.

Composability. Composability rules guarantee that, under some conditions, essential properties of a component will be preserved after integration. Composability means stability of previously established component properties across integration, e. g. a deadlock-free component will remain deadlock-free after gluing together with other components. Composability is essential for incremental construction as it allows building large systems without disturbing the behavior of their components.

2.1.3 Basic concepts of BIP

In this section as well as in the sequel of this thesis, components are denoted K_1, K_2, etc and given a set of ports $Ports$, the interface of an atomic component K is defined by a set of *ports*

denoted $\mathcal{P} \subseteq Ports$ defining what can be observed from the component by its environment and then used for synchronization with other components. We describe now the variant of BIP that we use in this thesis. As mentionned previously, several semantics could be provided to BIP components. In this thesis, in particular in Part II, the syntactic description of a component is represented by an extended labeled transition system (see Definition 2.1.2), and its semantics is described as an LTS (see Definition 2.1.7).

Definition 2.1.6 (Atomic component) *An atomic component K on an interface $\mathcal{P}$ is an extended labeled transition system (TS, X, g, f), where $TS = (Q, q^0, \mathcal{P}, \longrightarrow)$.*

Note that some variables of X are associated to the ports $\mathcal{P}$ of K. We now define the semantics of an atomic component.

Definition 2.1.7 (Semantics of atomic component) *The semantics of $K = (TS, X, g, f)$, where $TS = (Q, q^0, \mathcal{P}, \longrightarrow)$, is a labeled transition system $((Q \times \mathcal{V}_X), (q^0 \times v_X), \mathcal{P}, \hookrightarrow)$ such that:*

- *$(Q \times \mathcal{V}_X)$ is a set of states, where $\mathcal{V}_X$ denotes the set of valuations of variables X.*
- *$\hookrightarrow$ is the set including transitions $(q, v_x) \overset{p}{\hookrightarrow} (q', v_{x'})$ where, v_x, $v_{x'} \in \mathcal{V}_x$ such that $g_t(x) \wedge (x' = f_t(x))$ holds for some $t = (q, p, q') \in \longrightarrow$.*

At the semantic level some transitions of the ELTS may disappear in the computed labeled transition system and thus some control states of the ELTS may become unreachable. This is due to the fact that the semantics is computed taking into account the possible valuations of the variables and the soundness of the guards associated to transitions.

To distinguish the syntactic and the semantic level of a given component, in the rest of this thesis, we denote by *control states*, the states of the extended labeled transition systems and by $\longrightarrow$ its set of transitions. Then we denote by only *states* the states of the corresponding computed labeled transition system and by $\hookrightarrow$ the set of its transitions.

Figure 2.6 shows an example of an atomic component, with an interface consisting of two ports in with x as associated variable and the port out with y as associated variable. The behavior of the component represents two control states s_1 and s_2. The transition labeled by the port in takes place if the component is in state s_1 and if $x > 0$. Then the variable y is computed from x according to the function f.

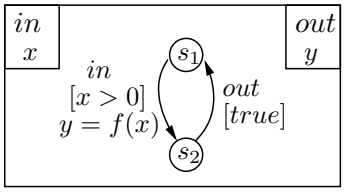


Figure 2.6: Atomic Component.

2.1.4 Glues in BIP: Interaction models

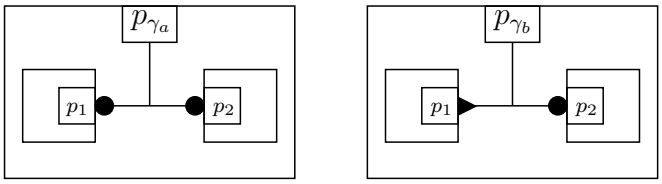
In BIP, the *interaction layer* is defined by a set of possibily hierarchical *connectors* [BS07a, BS08b]. Connectors are used to specify possible *interaction* patterns between the ports of components. Interactions in BIP are used to allow synchronization and communication between components.

Connectors

Composition of components allow to build a system as a set of components that interact by respecting constraints of an interaction model. In BIP interactions are structured by *connectors*. A *connector* is a macro notation for representing sets of related interactions in a compact manner. To specify the interactions of a connector, two types of synchronizations are defined:

- strong synchronization or *rendez-vous*, when the only interaction of a connector is the maximal one, i.e., it contains all the ports of the connector.
- weak synchronization or *broadcast*, when interactions are all those containing a complete port which initiate the broadcast.

To characterize these two types of synchronizations, a connector may associate to the ports it connects two types. A *trigger* port of a connector is a complete port which can initiate an interaction without synchronizing with other ports of the connector. It is represented graphically by a triangle. The second type is *synchron* port of a connector which is an incomplete port, hence needs synchronization with other ports, and is denoted by a circle.



(a) (b)

Figure 2.7: Example of Connectors.

Let γ be a connector connecting a set of ports $\{p_i\}_{i=1}^n$, then γ is defined as follows:

Definition 2.1.8 (Connector) *A connector γ is defined as a tuple $(p_\gamma[x], \mathcal{P}_\gamma, \delta_\gamma)$ where:*

- $p_\gamma[x]$ *is a port called the* exported *port of γ with x as associated variable,*
- $\mathcal{P}_\gamma = \{p_i[x_i]\}_{i=1}^n$ *is the set of connected ports called the* support set *of γ. These ports are typed by the information whether they are* trigger *or* synchron. *x_i is a variables associated to p_i.*
- $\delta_\gamma = (G, U, D)$ *where,*

- *G is a guard of γ, an arbitrary predicate $G(\{x_i\}_{i\in I})$,*
- *$\mathcal{U}$ is an upward update function of γ of the form, $x := F^u(\{x_i\}_{i\in I})$,*
- *$\mathcal{D}$ is a downward update function of γ of the form, $\cup_{p_i}\{x_i := F^d_{x_i}(x)\}$.*

The intuition behind the notion of exported port, as illustrated in Figure 2.7, is that a connector allows to relate a set of inner ports (of connected components) to a new port (the exported port) which allows to provide a notion of encapsulation by defining the interface of the obtained composite component. Besides, the notion of the exported port, allows the connector to be used as a port by other connectors, and thus create hierarchical components. The exported port represents set of interactions rather than a single interaction.

Note that the *support set* defines ports of distinct components, which means that a connector connects at most one port of each component. The variables associated to ports of a connector γ as well as its upward and downward functions defined on these variables allow the exchange of data between components connected by γ. Local variables of γ can be associated with its exported port p_γ.

The interactions of a connector are all the subsets of its ports which contain at least one trigger, and in addition the set of all its ports, representing the maximal interaction of the connector, taking into account the soundness of the guard associated to the connector and the guards associated to transitions of the connected components.

Definition 2.1.9 (Interaction of a connector) *Given a set of components $\{K_i\}_{i=1}^n$, where $K_i = (Q_i, q_i^0, \mathcal{P}_i, \longrightarrow_i, X_i, g_i, f_i)$. A connector $\gamma = (p_\gamma[x], \mathcal{P}_\gamma, \delta_\gamma)$, $\delta_\gamma = (G, U, D)$ connecting these components, such that $\mathcal{P}_\gamma \cap \mathcal{P}_i = \{p_i\}$. An interaction a defined on a set of ports $\{p_j\}_{j=1}^J \subseteq \mathcal{P}_\gamma$ is an interaction of γ if one of the following conditions holds:*

- *$\exists\, j \in J$ such that p_j is* trigger*;*
- *$\forall\, j \in [1, J]$, p_j is* sychron *and $\{p_j\}_{j=1}^J = \mathcal{P}_\gamma$.*

In both cases the interaction a has a guard, an upward and a downward functions denoted (G_a, U_a, D_a), where we suppose that they are respectively obtained by a projection of G, U and D on the variables of the ports involved in a.
We denote by $I(\gamma)$ the set of interactions of γ.

Thus like a connector, an interaction a is of the form $(p_a, \mathcal{P}_a, (G_a, U_a, D_a))$, where p_a is the exported port of a, $\mathcal{P}_a$ the set of ports involved in a. In this thesis to simplify notation, an interaction a defined on the set of ports $\{p_1, \ldots, p_J\}$ is denoted by the expression $a = p_1, \ldots, p_J$, where we abstract away its guard and function if we do not need to explicit them.

Example 2.1.10 *Example of connectors is depicted in Figure 2.7. In (a), the connector γ_a relates the ports $p1$ and $p2$, which it defines as synchron, to an exported port p_{γ_a}. In this connector, if we suppose that there is no variables, then the only feasible interaction is $p1p2$ which is also the interaction represented by the exported port p_{γ_a}. In (b), the interaction between $p1$ and $p2$ is asymmetric as $p1$ is a trigger and can occur alone, even if $p2$ is not possible. Nevertheless, the occurrence of $p2$ requires*

the occurrence of $p1$*. Thus, if no variables are defined, the interactions defined by* γ_b *are* $p1$ *and* $p1p2$*. Thus* p_{γ_b} *represents both interactions.*

A connector, as well as a set of connectors, define a structural description of a possible set of interactions. As interaction models are defined as a set of interactions, then a structural description of interaction models could be given as a set of connectors.

Definition 2.1.11 (Interaction model) *A set of disjoint connectors with distinct exported ports and disjoint interfaces* $\{\mathcal{P}_i\}_{i=1}^n$ *defines an interaction model* $\mathcal{I}$ *that is defined on* $\bigcup_{i=1}^n \mathcal{P}_i$ *which we call the* support set *of* $\mathcal{I}$ *and we denote* $S_\mathcal{I}$ *and which defines an interface* $\mathcal{P}_\mathcal{I} = \{p_\gamma | \gamma \in \mathcal{I}\}$.

The interface of the component resulting from a composition using $\mathcal{I}$ is defined by $\mathcal{P}_\mathcal{I}$. The variables associated to an interaction model, denoted $X_\mathcal{I}$, are the set of variables associated with the ports $\mathcal{P}_\mathcal{I}$ of the interface of $\mathcal{I}$. The interactions of $\mathcal{I}$, denoted $I(\mathcal{I})$, is the set of interactions defined by the set of its connectors, i.e., $I(\mathcal{I}) = \bigcup_{\gamma \in \mathcal{I}} I(\gamma)$.

Note that connectors in an interaction model are not required to have pairwise disjoint support sets, this means that a port may be connected by several connectors.

Structured connectors

So far we have seen a notation for connectors, which are essentially flat, i.e., having types (triggers and synchrons) associated to the individual ports (support set) only. However, connectors sometimes need to be structured, i.e., having types associated to groups of ports. This is necessary to represent some interactions, which otherwise cannot be represented by a flat connector. Structured connectors are created by the combined mechanism of exporting port from a connector and instantiating connectors, where a port of the connector is an exported port of another instantiated connector. Figure 2.8 shows an example of a structured connector. The connector γ_0 relates the port p_0 (trigger)

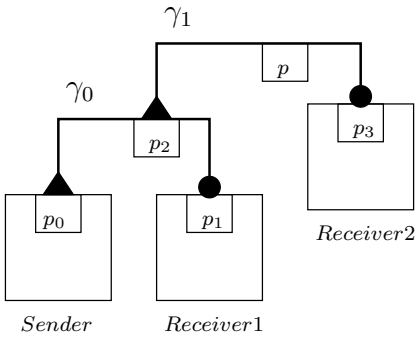


Figure 2.8: Structured Connector.

of the $Sender$ component with the port p_1 (synchron) of the $Receiver1$ component, and exports the port p_2. It represents a set of interactions involving respectively the port sets $\{\{p_0\}, \{p_0p_1\}\}$. γ_1 is a structured connector joining the port p_2 (trigger) of connector γ_0 with the port p_3 (synchron)

of the $Receiver2$ component and exports the port p. It represents the set of interactions involving respectively the port sets $\{\{p_0\}, \{p_0, p_1\}, \{p_0, p_3\}, \{p_0, p_1, p_3\}\}$.

2.1.5 Composition of components in BIP

Composition of components in BIP is performed using interaction models.

Definition 2.1.12 (Composite component) *A composite component consists of a composition of a set of components $\{K_i\}_{i=1}^n$ with disjoint interfaces $\{\mathcal{P}_i\}_{i=1}^n$ using an interaction model $\mathcal{I}$ on $\bigcup_{i=1}^n \mathcal{P}_i$. Such a component is denoted $\mathcal{I}\{K_i\}_{i=1}^n$.*

Note that the interface of the composite component is defined by the interface of the used interaction model $\mathcal{P}_\mathcal{I}$.

Definition 2.1.13 (Flat and Hierarchical component) *A component is called flat if it is atomic or of the form $\mathcal{I}\{K_i\}_{i=1}^n$, where all K_i are atomic components. A component is called hierarchical if it is not flat.*

To compose a set of components $\{K_i\}_{i=1}^n$, it is assumed that their respective interfaces are pairwise disjoint, i.e., for any two $i \neq j$ from $1..n$ we have $\mathcal{P}_i \cap \mathcal{P}_j = \emptyset$.

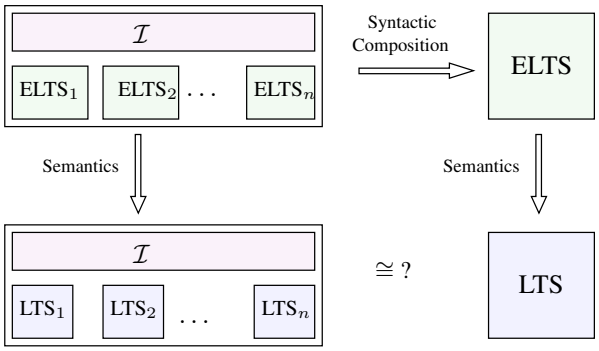


Figure 2.9: Semantics of a composition.

We now provide how to compute the semantics of a composite component. First, we propose in Definition 2.1.14 a syntactic composition, allowing to transform a composite component $\mathcal{I}\{K_i\}_{i=1}^n$, given by a set of atomic components defined by extended labeled transition systems, into a new atomic component K defined also as an extended labeled transition system. Then, the semantics of the composition is computed as the semantics of the atomic component K. In this thesis, as we are interested in describing the behavior of components as extended labeled transition systems and our interaction models, in particular in Part II, are defined on ELTS, thus we choose to compute the semantics only at the level of atomic components (ELTS) (see Figure 2.9).

Definition 2.1.14 (Syntactic composition) *The syntactic composition of n components $\{K_i\}_{i=1}^n$, where $K_i = (TS_i, X_i, g_i, f_i)$, with respect to an interaction model $\mathcal{I}$ with an interface $\mathcal{P}_\mathcal{I}$ and a set of variables $X_\mathcal{I}$, is an ELTS $K = (TS, X, g, f)$ where:*

- $TS = (Q, q^0, \mathcal{P}, \longrightarrow)$ *is an LTS where:*
  - Q *is set of control states, which is the cartesian product of the sets of control states of the composed components* $Q = \prod_{i=1}^{n} Q_i$*,*
  - $q^0 = (q_1^0, q_2^0, \ldots, q_n^0)$*,*
  - $\mathcal{P}$*, the interface of* K*, defined by the interface of the interaction model,* $\mathcal{P} = \mathcal{P}_{\mathcal{I}}$
  - $\longrightarrow$ *a set of transitions of the form* $t = (q, p_\gamma, q')$*, where:*
    - $q = (q_1, \ldots, q_n)$*,* $q' = (q_1', \ldots, q_n')$*,* q_i *and* q_i' *being control states of the* i^{th} *component.*
    - $p_\gamma \in \mathcal{P}_{\mathcal{I}}$ *is an exported port of a connector* $\gamma \in \mathcal{I}$*, corresponding to an interaction* α *of* γ*, such that there exists a subset* $J \subseteq \{1, \ldots, n\}$ *of components with transitions* $\{(q_j, p_j, q_j')\}_{j \in J}$ *and* $\alpha = \{p_j\}_{j \in J}$*.*
    - *if* $j \notin J$*,* $q_j' = q_j$*. That is, the control states from which there are no transitions labeled with ports in* α*, remain unchanged.*

- $X = \bigcup_i^n X_i \cup X_{\mathcal{I}}$ *the union of the sets of variables of the composed components and the interaction model,*

- g *associates with every transition* $t = (q, p_\gamma, q')$*, corresponding to an interaction* $\alpha = \{p_j\}_{j \in J}$ *of a connector* $\gamma \in \mathcal{I}$*, a guard defined by* $g = (\bigwedge_{j \in J} g_j) \wedge G_\alpha$*. Intuitively, the guard of the new obtained transition takes into account the guards of the composed transitions as well as the guard of the connector used to compose them.*

- f *associates with every transition* $t = (q, p_\gamma, q')$*, corresponding to an interaction* $\alpha = \{p_j\}_{j \in J}$ *of a connector* $\gamma \in \mathcal{I}$*, a function* $f = \mathcal{U}_\alpha; \mathcal{D}_\alpha; [f_j]_{j \in J}$*. That is, the computation starts with the execution of* $\mathcal{U}_\alpha$ *then* $\mathcal{D}_\alpha$ *followed by the execution of all the functions* f_j *in some arbitrary order. The result is independent of this order as components have disjoint sets of variables.*

Note that components which are not involved in an interaction do not move when it is fired.

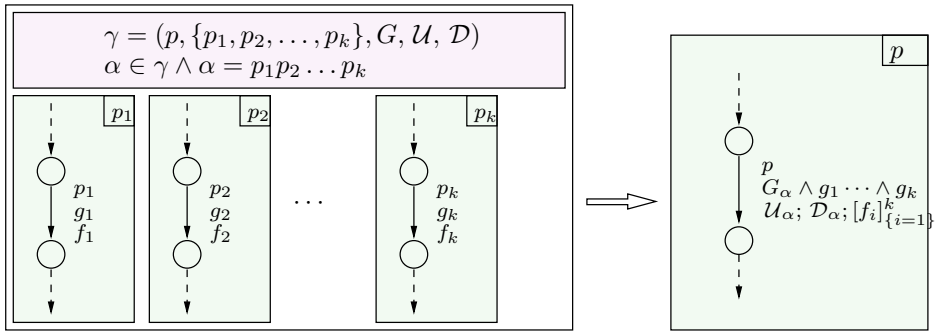


Figure 2.10: Composition of Components.

Figure 2.11 depicts an example of composition of BIP components. The connector γ connects the set of ports $\{p_i\}_{i=1}^k$. The example depicts the transition resulting from an interaction α of γ. α corresponds to a rendez-vous between all ports of γ. The obtained transition is then labeled by p the exported port of γ, its guard is then computed from the guard G_α and the guards of the transitions labeled by the ports involved in α. Similarly, the function of transition labeled by p is computed by applying first the upward function of γ, then its downward function and finally the functions corresponding to the synchronized transitions.

2.1.6 Priorities in BIP

Previously, we have focused on the first two layers of the BIP framework, namely behavior and interaction. Now let us focus on priority.

Priorities are a powerful tool for restricting nondeterminism. They allow straightforward modeling of urgency and scheduling policies for distributed systems. For example, execution constraints like run to completion and synchronous execution can be modeled by priority models on threads.

Definition 2.1.15 (Priority) *A priority order $\prec$ on a set of interactions is a strict partial order on these interactions.*

A priority order $\prec$ on an interaction model $\mathcal{I}$ is a strict partial order on the interactions of $\mathcal{I}$.

We define now the notion of composite component taking into account priority.

Definition 2.1.16 (Composite component) *A composite component consists of a composition of a set of components $\{K_i\}_{i=1}^n$ with disjoint interfaces $\{\mathcal{P}_i\}_{i=1}^n$ using an interaction model $\mathcal{I}$ on $\bigcup_{i=1}^n \mathcal{P}_i$ and a priority order $\prec$ on $I(\mathcal{I})$. Such a component is denoted $\mathcal{I}_\prec\{K_i\}_{i=1}^n$.*

The pair $(\mathcal{I}, \prec)$ is denoted $\mathcal{I}_\prec$ and it is a glue as it describes how to compose a set of components so as to make them interact.

In this thesis, we only use priorities in Part III where components are defined as simple labeled transition systems with neither variables nor guards. Thus the semantics of an atomic component is itself. Similarly the semantics of a composite component built as a composition of a set of LTS using an interaction model $\mathcal{I}_\prec$ is also an LTS obtained by applying first $\mathcal{I}$ then $\prec$ to the obtained component.

Definition 2.1.17 (Semantics of a priority order) *A priority order $<$ defines an operator that associates with an LTS $TS = (Q, q^0, \mathcal{P}, \longrightarrow)$ on an LTS $TS' = (Q, q^0, \mathcal{P}, \longrightarrow_<)$ where $\longrightarrow_<$ is the least transition relation satisfying the following rule:*

$$\frac{q^1 \xrightarrow{a} q^2 \qquad \nexists b \in \mathcal{P},\ (a < b \wedge q^1 \xrightarrow{b})}{q^1 \xrightarrow{a}_< q^2}$$

Figure 2.11 depicts an example of composition of BIP components with priorities. Two interactions between the set of k components are defined. In this example to simplify notation we suppose

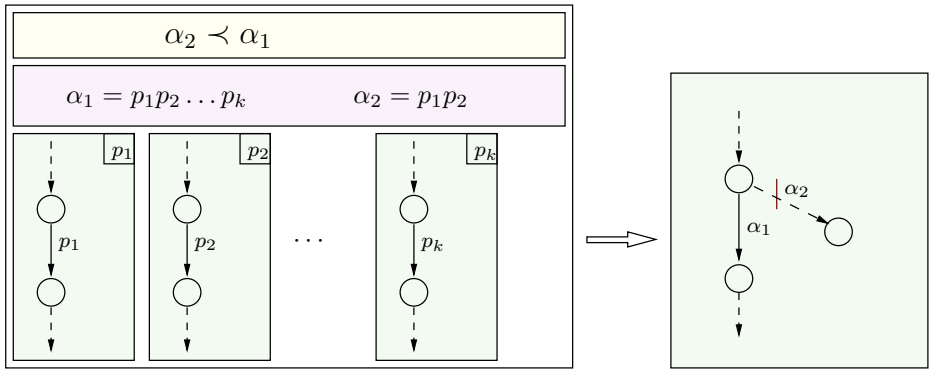


Figure 2.11: Semantics of Composite Component with Priorities.

that transitions are labeled by interactions, and not by the exported port of the corresponding connector. In the semantics of the composition and with respect to priorities, stating that $\alpha_2 \prec \alpha_1$, only the transition corresponding to the interaction with higher priority appears.

Note that the priorities we use in this thesis are called *static*. In BIP another type of priorities called *dynamic* is also defined [BBBS08, GS04], where priorities between interactions of a given component K, depend on its state.

We now provide an example showing the application of priorities to enforce execution constraints on a composite component.

Example 2.1.18 (Mutual Exclusion)

In this example, we show the enforcement of *mutual exclusion*, a very common execution constraint, needed when we have multiple components (tasks) sharing a single resource similar to the famous example of the dining philosophers. In the example shown in Figure 2.12, we have two identical tasks, T_1 and T_2, modeled as BIP components. The control states of the i-th task are I_i (Idle), R_i (Ready) and E_i (Executing). The actions (ports) are a_i (activate), b_i (begin) and f_i (finish). Each task is initialized to state I_i, from where it can activate through the action a_i and become ready (R_i) for execution. The start of execution is marked by the action b_i, by which the task acquires the resource and moves to the execution state (E_i).

The interaction model allows every action to be activated independently. Under mutual exclusion, a task cannot acquire the resource if the other task is already in the execution state. As in this simple example we suppose that only unitary actions can occur, violation of *mutual exclusion* would mean that after the occurrence of b_1, b_2 occurs before f_1. Then we can enforce *mutual exclusion* by the priority model, which assigns the actions to obtain the resource, lower priority than the actions to release the resource, i.e., $b_1 \prec f_2$ and $b_2 \prec f_1$. For T_1, the priority $b_1 \prec f_2$ prevents it from obtaining the resource, unless T_2 releases it (by the action f_2). Similarly, T_2 is restricted by $b_2 \prec f_1$ as long we suppose that f_i is always enabled after b_i.

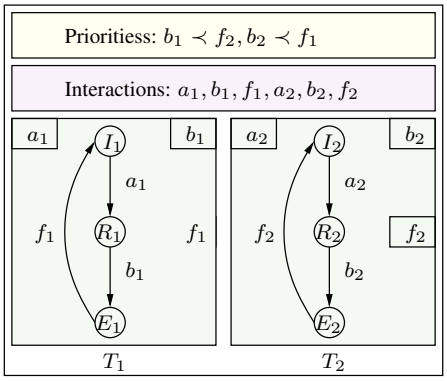


Figure 2.12: Example: Priorities to enforce Mutual Exclusion.

When both tasks are at state R_i, either of them can acquire the resource in a non-deterministic fashion. However, static priority rules can be used to prioritize the tasks in any desired order. For example, $b_2 \prec b_1$ sets a higher priority for T_1 to acquire the resource, compared to T_2.

We can also define *mutual exclusion* in the case where we suppose that actions of different processes may occur independently. This can be expressed by an interaction model that allows any pairs of actions involving the two processes except the pairs $b_1 b_2$ of course. The same priority rules can be used. If we suppose that f_i may be disabled for a while after the occurrence of b_i, priorities are not sufficient anymore. We need the so-called *timed priorities* as they have been proposed in [BS00].

Maximal Progress Priority in Connectors A particular priority rule, that favors, among the enabled interactions of a connector, the maximal one, i.e., the one with maximum number of ports, is known as maximal progress priority. This can be explicitly represented through priority rules amongst the interactions, of the form $p_1 \prec p_1 p_2$, where p_1 and $p_1 p_2$ are interactions of the same connector. As an example, maximal progress is necessary to model a broadcast. Maximal progress is implicitly assumed in connectors for their compact and natural representation.

2.2 Contract framework concepts

A main part of this thesis aims at the definition of a scalable design and verification methodology for systems of components based on *contracts*. Contracts are design constraints for implementations which are maintained throughout the development and life cycle of the system. We describe in this section the basic concepts about contracts. In particular, we introduce a formal definition of the generic *contract framework* presented in [QG08a] and a description of the component framework on which it is based. We also provide key relations and properties required to reason about contracts namely *satisfaction* and *dominance*.

The generic notion of *contract framework*, described in [QG08a], relies on a notion of *component framework* supporting hierarchical components as well as some powerful mechanisms to reason about

composition. We therefore introduce next the notions a component framework must define.

Definition 2.2.1 (Component framework) *A* component framework *is a structure of the form* $(\mathcal{K}, GL, \circ, \cong)$ *where:*

- $\mathcal{K}$ *is a set of* components *— describing their* behavior *or* properties.
  Each component $K \in \mathcal{K}$ *has as its* interface *a set of* ports*, denoted* $\mathcal{P}_K$.

- $\cong \subseteq \mathcal{K} \times \mathcal{K}$ *is an equivalence relation. In general, this equivalence is derived from equality or equivalence of semantic sets.*

- GL *is a set of* glue (composition) operators.
  Operators $gl \in GL$ *are partial functions* $2^{\mathcal{K}} \longrightarrow \mathcal{K}$ *transforming a set of components into a new component. Each* gl *is defined on a set of ports* S_{gl} *— of the original set of components, called its* support set *— and defines a new interface* $\mathcal{P}_{gl}$ *— on the new component, called its* exported interface *(see Definition 2.1.11) . Thus,* $K = gl\{K_1, \ldots, K_n\}$ *is defined if* $K_1, \ldots, K_n \in \mathcal{K}$ *have disjoint interfaces,* $S_{gl} = \bigcup_{i=1}^{n} \mathcal{P}_{K_i}$ *and the interface of* K *is* $\mathcal{P}_{gl}$*, the exported interface of* gl.

- $\circ$ *is an operation on* GL *allowing to compose glues. It is such that* $(GL, \circ)$ *is a commutative monoid. Formally,* $gl \circ gl'$ *is defined on* $(S_{gl} \cap S_{gl'}) \cup (S_{gl} \backslash \mathcal{P}_{gl'}) \cup (S_{gl'} \backslash \mathcal{P}_{gl})$ *and defines as interface* $(\mathcal{P}_{gl} \cup \mathcal{P}_{gl'}) \backslash S_{gl \circ gl'}$*. Note that* $gl \circ gl'$ *must be defined even if* $(S_{gl} \cap S_{gl'}) \neq \emptyset$*. Furthermore, this operation must be consistent with* $\cong$ *in the sense that* $gl\{gl'\{\mathcal{K}^1\}, \mathcal{K}^2\} \cong (gl \circ gl')\{\mathcal{K}^1 \cup \mathcal{K}^2\}$ *for any sets of components* $\mathcal{K}^i$ *such that all terms are defined.*

To simplify the notation, we write $gl\{K_1, \ldots, K_n\}$ instead of $gl(\{K_1, \ldots, K_n\})$.

Note that the operation $\circ$ over glues is commutative not in the order of applying composed glues but in the sense that the resulted glue of their composition is the same. In this definition of component framework, the notion of component is intentially kept abstract to encompass different frameworks. It may be for example a labeled transition system or an extended labeled transition system as defined previously. For example, components are defined in the framework defined in [QG08a] as Modal Transition Systems (MTS) and they could be also defined as BIP components which include a structural layer. Note that in this definition, there is no explicit distinction between atomic and hierarchical components, if there is a way to represent an hierarchical component as an atomic one. In many frameworks that work at the semantic level, they are the same.

Figure 2.13 shows how hierarchical components (the colored ones) are built from atomic ones (the white components). It also illustrates the flattening property the composition model. Note that the representation of glues is just one among other possible sets of glues. Dashed lines show how the exported interface is defined based on inner ports and glues.

Note that BIP framework as defined previously represents such a component framework with its definition of components and glues. In this thesis, we are interested in a variant of BIP defining such a component framework.

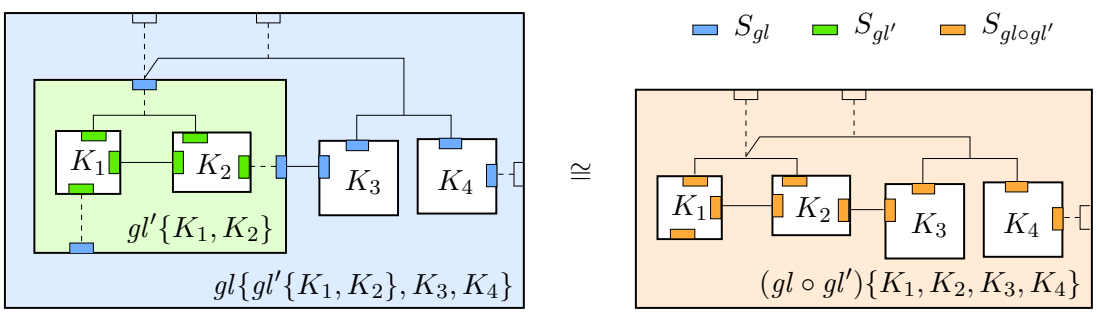


Figure 2.13: A hierarchical component and its equivalent *flattened* form.

2.2.1 Contract frameworks

We give in this section the different notions presented in [QG08a] allowing to use contracts to reason about components and their properties. In particular, how to build a contract framework which provides basic rules to reason about systems of components.

Before giving the formal definition of contract framework, we introduce the notion of context, to describe how a component may be connected to the rest of the system and to express a property of the environment. Thus, a context limits the way in which a component may be further composed.

Definition 2.2.2 (Context) *A* context *for an interface $\mathcal{P}$ is a pair (E, gl) where $E \in \mathcal{K}$ a component defined on $\mathcal{P}_E$, and where we suppose $\mathcal{P} \cap \mathcal{P}_E = \emptyset$ and gl is defined on $\mathcal{P} \cup \mathcal{P}_E$.*

Definition 2.2.3 (Contract framework) *A* contract framework *is a tuple $(\mathcal{K}, GL, \circ, \cong, \{\sqsubseteq_{E,gl}\}, \preccurlyeq)$ where:*

- *$(\mathcal{K}, GL, \circ, \cong)$ is a component framework.*
- *$\preccurlyeq \subseteq \mathcal{K} \times \mathcal{K}$ is a* conformance *relation relating components with the same interface. Given $K_1, K_2 \in \mathcal{K}$, for $K_1 \preccurlyeq K_2$ we may say K_1 conforms to K_2.*
- *$\{\sqsubseteq_{E,gl}\}$ is a* refinement under context *relation parameterized by a context. Given a context (E, gl) for an interface $\mathcal{P}$, $\sqsubseteq_{E,gl}$ is a preorder over the set of components on $\mathcal{P}$ which is expected to be compositional. It is a preorder such that for any K_1, K_2 on the same interface $\mathcal{P}$ and for any context (E, gl) for $\mathcal{P}$, $K_1 \sqsubseteq_{E,gl} K_2 \implies gl\{K_1, E\} \preccurlyeq gl\{K_2, E\}$.*

The notion of refinement and substitutability is recognized as being a fundamental requirement [DHJP08] in the context of component and contract-based approaches. *Conformance* is a kind of refinement with respect to a given specification and it relates properties of *closed systems*, where a closed system is a component that we cannot or do not want to further compose. Open systems are components that may be composed with an unknown environment. Even though a closed system is not intended to be composed anymore, it has an interface allowing not to *observe* its behavior and thus to define properties of a closed system on ports of this interface.

Refinement under context is usually considered as a derived relation and chosen as the weakest relation implying *conformance*.

Example 2.2.4 *Typical notions of conformance $\preccurlyeq$ are* trace inclusion *and* simulation. *For these notions of conformance, refinement under context (denoted $\sqsubseteq^{\preccurlyeq}$) is usually defined as the weakest preorder included in $\preccurlyeq$ that is compositional:*

$$K_1 \sqsubseteq^{\preccurlyeq}_{E,gl} K_2 \triangleq gl\{K_1, E\} \preccurlyeq gl\{K_2, E\}$$

Note that there are cases where a stronger notion of refinement under context allows more powerful reasoning.

Example 2.2.5 *Conformance itself is another candidate for refinement under context if it is preserved by composition, that is, if: $K_1 \preccurlyeq K_2$ implies $gl\{K_1, E\} \preccurlyeq gl\{K_2, E\}$ for any E.*

However, defining refinement under context as $K_1 \sqsubseteq_{E,gl} K_2 \triangleq K_1 \preccurlyeq K_2$ means in fact not taking the environment into account, thus it is of limited interest. In some cases, as the frameworks presented in [QG08a], conformance actually corresponds to refinement in any context. In the contract framework we propose in Chapter 4, our definition of conformance is defined as refinement in a particular context.

Now we can define the notion of contract which allows to describe properties that a component should offer in a given context.

Definition 2.2.6 (Contract) *A contract $\mathcal{C}$ for an interface $\mathcal{P}$ consists of:*

- *a context $\mathcal{E} = (A, gl)$ for $\mathcal{P}$ where A is called the* assumption
- *a component G on $\mathcal{P}$ called the* guarantee

We write $\mathcal{C} = (A, gl, G)$ rather than $\mathcal{C} = ((A, gl), G)$. gl implicitly defines the interface of the environment while A expresses a constraint on it and G a constraint on the refinements of K. The "mirror" contract $\mathcal{C}^{-1}$ of $\mathcal{C}$ is (G, gl, A).

A contract $\mathcal{C} = (A, gl, G)$ defines a closed system namely $gl\{A, G\}$ as a composition of its assumption and guarantee using its glue. The exported interface of gl defines the interface of the closed system on which properties are expressed.

Definition 2.2.7 (Satisfaction of contract) *A component K* satisfies *a contract $\mathcal{C} = (A, gl, G)$, denoted $K \models \mathcal{C}$, if and only if $K \sqsubseteq_{A,gl} G$. K is called a possible* implementation *of $\mathcal{C}$.*

Intuitively, a component K satisfies a contract $\mathcal{C} = (A, gl, G)$, if K and its environment are composed by the glue gl and K behaves according to G provided that the environment behaves according to A.

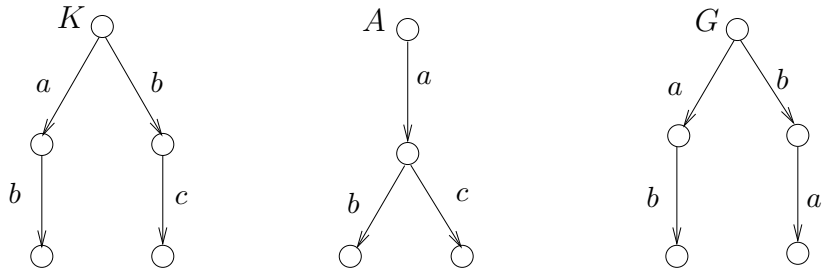


Figure 2.14: $K \sqsubseteq^{\preccurlyeq}_{A,gl} G$ for conformance defined as simulation.

Example 2.2.8 *Suppose that components are LTS, conformance is simulation and refinement under context is the usual derived notion defined in Example 2.2.4. Suppose also that composition gl is defined as the synchronization between actions with the same letter and interleaving of others. Then Figure 2.14 shows K, A and G such that K satisfies the contract (A, gl, G). Indeed, even though K does not simulate G (after b is fired it offers c instead of a), it still behaves like G in the context of (A, gl), which prevents b from taking place.*

2.2.2 Dominance

To reason about contracts, in the proposed contract framework, an additional relation called *dominance* is introduced. *Dominance* means for contracts what refinement means for components. Contract $\mathcal{C}$ is said to dominate contract $\mathcal{C}'$ if every implementation of $\mathcal{C}$ — i.e., every component satisfying $\mathcal{C}$ — is also an implementation of $\mathcal{C}'$. Intuitively, this is achieved by a $\mathcal{C}$ that has a stronger promise or a weaker assumption than $\mathcal{C}'$.

Let us start with a first definition of dominance for two contracts with the same glue part.

Definition 2.2.9 (Binary dominance) *Let $\mathcal{C}$ and $\mathcal{C}'$ be two contracts for the same interface $\mathcal{P}$ and the same glue gl, with $\mathcal{C} = (A, gl, G)$ and $\mathcal{C}' = (A', gl, G')$.* $\mathcal{C}$ dominates $\mathcal{C}'$ *iff:*

$$\textit{for any } K \textit{ on } \mathcal{P}, \textit{ if } K \models \mathcal{C} \textit{ then } K \models \mathcal{C}'$$

A component which satisfies the *concrete* contract $\mathcal{C}$ does also satisfy the more *abstract* contract $\mathcal{C}'$.

There are several ways to "refine" a contract $\mathcal{C}'$. A typical way consists in strengthening the guarantee G. Another typical situation is the one of a hierarchical component. Then $\mathcal{C}'$ would be contract associated with the higher level of hierarchy and $\mathcal{C}$ is defined implicitly by a set of contracts and the glue gl defining their composition.

In this case, we have two options: define for each glue gl a composition of contracts $\tilde{gl}$ or define dominance explicitly for such a situation. Here we choose the second option, as composition of contracts is not possible in all cases of interest for us, and moreover not even desirable for achieving efficient verification. We thus need a broader notion of dominance than the binary version, that is

dominance defined directly for a set of contracts $\{\mathcal{C}_i\}_{i=1}^n$ and a contract $\mathcal{C}$ to be dominated w.r.t a composition operator gl_I.

In order to hide ports of the lower-level contracts which do not appear at the interface of the top-level contract, the constraints on the composition operators are relaxed by only requiring that they agree on their common ports. For this, a notion of *projection* of a component K onto a subset $\mathcal{P}'$ of its interface is needed, denoted $\Pi_{\mathcal{P}'}(K)$, which is quite natural and must preserve the following properties.

Definition 2.2.10 (Projection) *If* Π *is a* projection*, then for any components* K_i *and* A *on disjoint interfaces* $\mathcal{P}$ *and* $\mathcal{P}_A$*, and any composition operator* gl *on* $\mathcal{P} \cup \mathcal{P}_A$*:*

1. *for* $\mathcal{P}' \subseteq \mathcal{P}$ *and for any* gl_1, gl_2 *with* $S_{gl_1} = \mathcal{P}' \cup \mathcal{P}_A$*,* $S_{gl_2} = \mathcal{P} \backslash \mathcal{P}'$ *s.t.* $gl = gl_1 \circ gl_2$*:*

$$(K_1 \sqsubseteq_{A,gl} K_2 \wedge \Pi_{\mathcal{P}'}(K_2) \sqsubseteq_{A,gl_1} G) \implies \Pi_{\mathcal{P}'}(K_1) \sqsubseteq_{A,gl_1} G$$

   Note that G *is defined on* $\mathcal{P}'$*.*

2. $\forall\, \mathcal{P}'_A \subseteq \mathcal{P}_A$ *and for any* gl_1, gl_2 *on* $\mathcal{P}_{gl_1} = \mathcal{P} \cup \mathcal{P}'_A$*,* $\mathcal{P}_{gl_2} = \mathcal{P}_A \backslash \mathcal{P}'_A$ *s.t.* $gl = gl_1 \circ gl_2$*:*

$$(K \sqsubseteq_{\Pi_{\mathcal{P}'_A}(A),gl_1} G) \implies K \sqsubseteq_{A,gl} G$$

   Note that G *is defined on* $\mathcal{P}$*.*

These properties state that ports of the component (and symmetrically of the environment) which do not appear in interactions with the environment (resp. the component) may be abstracted away when checking refinement.

We now provide the definition of dominance relating a set of contracts.

Definition 2.2.11 (Dominance) *Let* $\mathcal{C}$ *be a contract for* $\mathcal{P}$*,* $\{\mathcal{C}_i\}_{i=1}^n$ *a set of contracts defined on disjoint interfaces* $\{\mathcal{P}_i\}_{i=1}^n$ *and* gl_I *a glue defined on* $\bigcup_{i=1}^n \mathcal{P}_i$*. Then* $\{\mathcal{C}_i\}_{i=1}^n$ *dominates* $\mathcal{C}$ *w.r.t.* gl_I *iff for any set of components* $\{K_i\}_{i=1}^n$*:*

$$(if\ for\ every\ i \in [1,n], K_i \models \mathcal{C}_i,\ then\ \Pi_{\mathcal{P}}(gl_I\{K_1, \dots, K_n\}) \models \mathcal{C}$$

Intuitively, a set of contracts $\{\mathcal{C}_i\}_{i=1}^n$ dominates a contract $\mathcal{C}$ w.r.t. a glue gl_I if and only if any set of components satisfying the contracts $\mathcal{C}_i$, when composed using gl_I, makes a component satisfying $\mathcal{C}$.

The definition we have given is semantic, and concretely one does not want to manipulate implementations in order to establish dominance. More generally, what are the additional proof rules and properties that one needs in order to reason within contract frameworks? The following chapter answers those questions.

Part II

A Contract Framework for Reasoning about Safety and Progress

Chapter 3

Contract-Based Verification Approach

It is a well-known fact that formal verification based on model-checking suffers from the state space explosion problem. Compositional design and verification are mandatory for making verification feasible. One possibility is to infer global properties of a system from properties of its subsystems. Instead of verifying globally the entire system, compositional approach first decomposes it into small subsystems and verifies each of them individually. The size of a subsystem is often quite smaller compared to the size of the whole system, hence there is less risk of explosion of state space. Then, properties of the global system are inferred from the verified properties of its subsystems.

In this chapter, we present a compositional design and verification methodology. In particular, we focus on an approach allowing to verify some top level requirement of a given system represented by a composition of a set of components (subsystems). We propose to infer this global property to a set of "sub-properties" associated to each of the components.

The idea is to deduce the satisfaction of this global property from the satisfaction of the "sub-properties" at the level of each component. Such an approach is in general possible if the set of subsystems are independent. However, if it is not the case, when building their "sub-properties", one would take into account the interference of this subsystem with the rest of the system. Thus, we have chosen to use *contracts*, so as one could describe properties of the subsystems and also properties of their environment that is the rest of the system.

Moreover, to describe how each subsystem interacts with the rest of the system, and as mentioned previously, we rely on a notion of contract allowing to describe the glues used to compose components. Thus, the proposed approach does not only encompass properties of systems but also how they interact and how they are composed to their environment.

This chapter is organized as follows: Section 3.1 describes the different steps of our methodology. In particular how we use the notion of contract framework and it relations. Then, we describe how to extend our methodology to verify recursively defined systems, that is systems which can be built according to a grammar of components. This allows to encompass systems of arbitrary size. Section 3.2 details first how we can establish the soundeness of our methodology. Then, properties that the component framework has to ensure so that we can apply the methodology. In Section 3.3, we describe the property that we use to prove *dominance* which is a key notion in our methodology as

it allows to infer properties of some top-level contract from the properties of a set of inner contracts with respect to some glue operator.

3.1 Design and verification methodology

In this section we propose first a design methodology which is compositional and incremental and defined for the generic contract framework described in Section 2.2.1. In particular, it uses its notion of contracts and its relations of *conformance*, *dominance* and *satisfaction*.

Then, we describe how we extend this methodology to verify properties of systems with arbitrary size. The idea is to describe these systems by a grammar of components, allowing to describe the system by a set of rules, then we adapt the steps of the methodology to these rules.

3.1.1 Methodology

We present now our compositional and incremental design and verification methodology defined for any contract framework that is an instance of the generic notion of contract framework as introduced in Section 2.2.

We present the methodology in a top-down fashion. However, it could be also applied in a bottom-up fashion to achieve the same verification purposes but in a different order by using the same reasoning and relations. Note that in general design approaches allow both top-down and bottom-up reasoning.

We consider here the simple case of a unique top-level requirement – that will be denoted φ throughout this section – that is pushed progressively from the overall system into *atomic* components which we call *implementations*.

In the entire section we use the notions introduced in Section 2.2, in particular, the notion of contract and the relations conformance, satisfaction and dominance. We first present an overview of the methodology steps, then we detail the different steps separately. Our methodology is given by the following steps:

1. We first provide the property φ, which we want that the system K satisfies in a given context. That is a property of the closed system obtained by the composition of K through its interface $\mathcal{P}$ to its environment E.

2. Then, we define a *contract* $\mathcal{C}$ for $\mathcal{P}$ which *conforms* to the property φ. That is defining the following:

   - the glue gl connecting K to its environment which allows to define the interface of the environment denoted $\mathcal{P}_A$;
   - a property A on the environment E of K defined on $\mathcal{P}_A$;
   - a property G on $\mathcal{P}$ which K has to satisfy in the context (A, gl).

3. We define K as a structural composition of a set of subcomponents $\{K_i\}$ using a glue gl_I (see Figure 3.2). Then we associate a contract $\mathcal{C}_i$ for each subcomponent K_i and we prove that any set of implementations (components) for K_i *satisfying* these contracts $\mathcal{C}_i$, when composed using gl_I, satisfies the top-level contract $\mathcal{C}$ and thus guarantees φ. This corresponds to the verification of the relation of *dominance* between contracts (see Figure 5.8). This step can possibly be iterated if needed by similarly decomposing each K_i;

4. Finally, for components K_i, which we do not want to further decompose because for example they are sufficiently simple, we provide implementations I_i and we prove that these implementations *satisfy* the contracts $\mathcal{C}_i$.

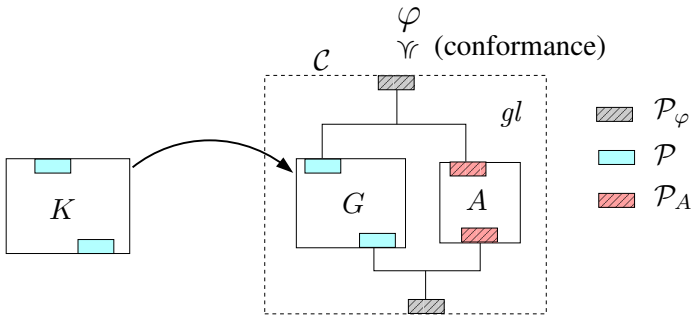


Figure 3.1: Step 2: Conformance.

The first step provides a description of the property φ, which the designer wants to verify. The designer has to precise in which context, the system K under study has to ensure this property. Indeed, φ has to be ensured by K together with its environment and thus the description of φ has to be defined on the interface of the closed system defined by the composition of K and its environment.

For this purpose, the next step is based on the *conformance* relation (see Definition 2.2.3) which is a relation defined on closed systems with the same interface.

In [Qui11], closed systems do not have interfaces as they are not supposed to be connected and their properties are described on the set of internal interactions. Here we propose to define an interface for closed systems in which we export the set of interactions and possibly variables that one wants to use to describe the desired property. Thus, if one wants to describe a property on the set of all internal interactions of a closed system, it has to export by means of an "exported interface" all these interactions. For example, in the Input/Output (I/O) contract framework proposed in [Qui11], input completeness is verified by checking that whenever an output o occurs, a corresponding input i occurs as well, that is only interaction $o.i$ occurs. This is possible by exporting to the interface of the closed system the interaction involving only an output o and verifying that this interaction will never take place.

As previously described, a contract allows to define a closed system built by the composition of K and its environment. A contract on the interface $\mathcal{P}$ of K, defines a gl describing how K is connected

to it environment, and thus defines the interface of this environment $\mathcal{P}_A$. The contract, describes then a property of the environment A defined on $\mathcal{P}_A$ and a property G on the interface $\mathcal{P}$ that K has to provide in the context (A, gl). In Figure 3.1, φ and the closed system defined by the contract (A, gl, G) are defined on the same interface $\mathcal{P}_\varphi$. This relation has to be reflexive and transitive. In the frameworks presented in [QG08a] for example, the relation of conformance is defined as inclusion of traces between MTS.

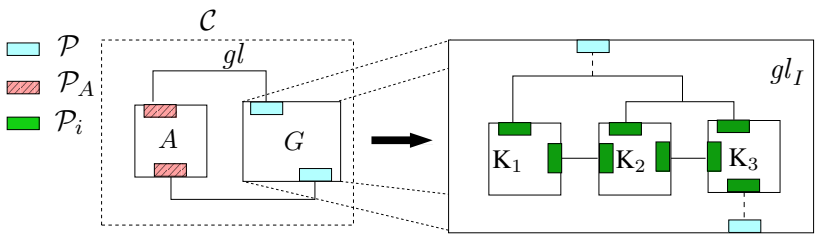


Figure 3.2: Step 3: K defined as a composition of $\{K_i\}_{i=1}^n$ using gl_I.

The third step of our methodology uses the characteristics of the component framework used to build the system in particular its set of glues. In the first part of this step, see Figure 3.2, the designer provides a description of the system K as a composition of a set of components $\{K_i\}$ with respect of a given glue gl_I. $\{K_i\}$ are also called *subsystems* of K. If the component framework provides the so-called property of *flattening*, then it is possible to build from the glues gl and gl_I, a glue gl_{flat} relating directly the components $\{K_i\}$ to the environment of K. That is $gl_{flat}\{A, K\} \cong gl\{A, gl_I\{K_1, \ldots, K_n\}\}$. In the second part of third step, we define for each subsystem K_i a contract $\mathcal{C}_i = (A_i, gl_i, G_i)$ describing a property of its environment A_i and a property G_i that it is supposed to guarantee in the context of such an environment. Thus, to define such contracts for each subsystem, the designer has to provide a property of the environment of this subsystem, that is the rest of the system, and in particular how it is composed to this environment that is the glue gl_i. These glues $\{gl_i\}$ must provide a property called *structural compatibility* with the glue gl_{flat} obtained by flattening. This property is needed to relate the glue gl_i provided in each $\mathcal{C}_i$ to the actual environment of the component K_i. For example, as illustrated in Figure 5.8, the actual environment of the subcomponent K_1 consists of components K_2, K_3 and A, the top-level assumption. However, the glue gl_1 provided in the contract for K_1 has been defined for an abstract environment A_1, hence the need for a glue representing the environment of K_1 as a single component with the same interface as A_1. More details about this property are provided in Section 3.2.

The preservation of the top level requirement φ by the set of contracts $\{\mathcal{C}_i\}$ is guaranteed by the properties of the relation of *dominance* that must hold between these contracts $\{\mathcal{C}_i\}$ and the global contract $\mathcal{C}$.

Thus a key issue of the third step of the proposed approach is *dominance* relation (see Definition 2.2.11), as shown in Figure 5.8, once we define a contract, for each subsystem, a *dominance*

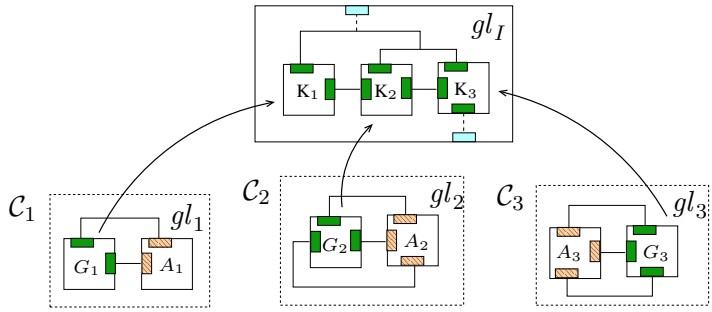


Figure 3.3: Step 3: Dominance ($\{\mathcal{C}_1, \mathcal{C}_2, \mathcal{C}_3\}$ dominates $\mathcal{C}$ w.r.t. gl_I).

relation has to be checked between these contracts $\{\mathcal{C}_1, \mathcal{C}_2, \mathcal{C}_3\}$ and the top-level Contract $\mathcal{C}$. Intuitively, dominance means for contracts what refinement means for components as the goal of contract frameworks in general is to reason about contracts and dominance rather than about components and refinement.

The last step of our methodology, is to provide implementations that satisfy contracts of components which are not further refined, at least at the current stage of design (see Figure 3.4. This means, giving a concrete specification of the different subsystems of the global system. As our methodology is incremental, this step can be pushed as far as possible to lower levels. Indeed, for a given subsystem K_i we can either provide an implementation, which can be described using the same formalism as properties or using any language if the implementation is provided as a program, or it can be further described as a composition of a set of components and for which we apply again the third step of our methodology.

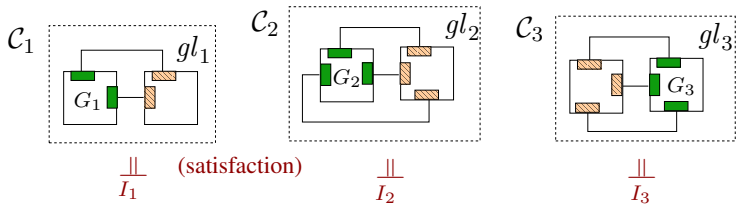


Figure 3.4: Step 4: Satisfaction.

Figure 3.5 summarizes the overall description of the different steps of our methodology. The global property φ appears at the top, while the implementations I_i are at the bottom.

Given a set of implementations $\{I_i\}$ satisfying the contracts $\{\mathcal{C}_i\}$, then if the different steps of our approach have been applied successfully, means that conformance, dominance and satisfaction have been successfully checked, then the system obtained as a composition of these implementations, that is $gl_{flat}\{A, I_1, \ldots, I_n\}$, guarantees the property φ. The soundness of these results rely on the properties of the relations of the contract framework we use to apply this methodology. These properties will be detailed in the next section.

An additional step is represented on the right hand side: it allows the integration of the system K in an actual environment E while preserving φ. For this purpose, E must satisfy the *mirror* contract of $\mathcal{C}$ or any contract dominating this mirror contract. This step can be added if the contract framework allows a property called *circular reasoning*, which intuitively allows to infer that if K conforms to φ in an environment A, than it also conforms to φ in any environment refining this environment. Details about this property and its usefulness are described in Section 3.3.1.

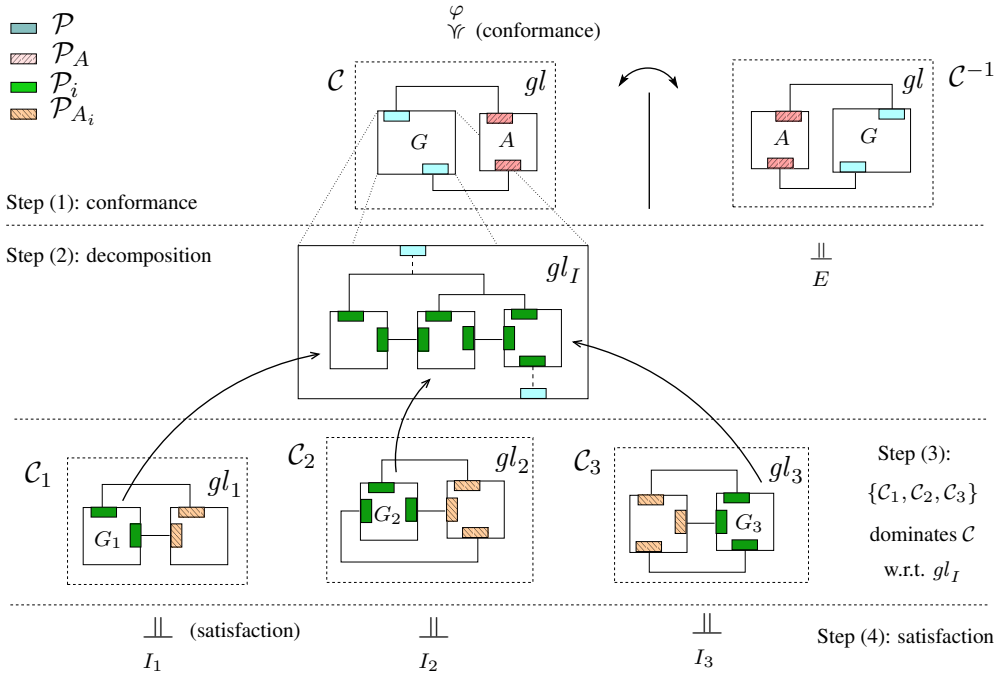


Figure 3.5: Methodology steps ensuring that $gl\{A, gl_I\{I_1, I_2, I_3\}\} \preccurlyeq \varphi$.

3.1.2 Extension to recursively defined systems

In this Section, we extend our design and verification methodology to hierarchically structured and recursively defined systems so that we can handle systems representing component networks of arbitrary size. We propose to apply our methodology to systems that can be defined by a component grammar as follows:

- a set of terminal symbols $\{A, I_1, \ldots, I_k\}$ representing implementations;
- a set of nonterminal symbols $\{S, K_0, K_1, \ldots, K_n\}$ representing hierarchical components; S, which defines the top-level closed system, is the axiom;
- a set of rules corresponding to design steps which define each non-terminal either as a composition of subsystems or as an implementation:

- $S \longrightarrow gl\{A, K_0\}$.
- For $i \in [0, n]$, at least one rule either of the form $K_i \longrightarrow I_j$ ($j \in [1, k]$) or $K_i \longrightarrow gl_{\Sigma_i}\{K_j\}_{j\in\Sigma_i}$, where Σ_i a set of indices and gl_{Σ_i} a composition operator on the union of the interfaces of the K_j.

Where S is a hierarchical component (a system) and $\{K_i\}_{\{1,..,k\}}$ are either hierarchical or leaf components for which an implementation is to be given.

Terminal symbols correspond to actual implementations, nonterminal symbols to hierarchical components and rules to design steps. In particular, K_0 represents the global system under design, A is a property of its real environment. Thus, S stands for the system *along with* its environment. Note that a decomposition rule of some non-terminal K_i may also contain a set of the same non-terminal. Thus, to ensure the unicity of ports, we suppose that the name of each port is prefixed by its path from the root symbol and indexed if the rule contains a set of the same non terminals. Unlike classical network grammars, we use *rich* composition operators and are not limited to flat regular networks, as for example in [SG89].

We now instantiate the methodology of Figure 3.5 for such component networks. We choose again a top-down presentation. To do so,

The same four steps are presented, namely conformance, decomposition, dominance and satisfaction.

1. formulate a top-level requirement φ characterizing the closed system S defined by the system K_0 and a property A of its environment;
2. define a contract $\mathcal{C} = (A, gl, G)$ associated with K_0 and prove that $gl\{A, G\} \preccurlyeq \varphi$;
3. define for every non terminal K_i a contract $\mathcal{C}_{K_i} = (A_{K_i}, gl_{K_i}, G_{K_i})$ such that for every rule $K_l \longrightarrow gl_{\Sigma_l}\{K_j\}_{j\in\Sigma_l}$ having an occurrence of K_i on the right hand side, there exists gl_{A_i} such that $gl_{K_l} \circ gl_{\Sigma_l} = gl_{K_i} \circ gl_{A_i}$. Then, for each $K_i \longrightarrow gl_{\Sigma_i}\{K_j\}_{j\in\Sigma_i}$, show that $\{\mathcal{C}_{K_j}\}_{j\in\Sigma_i}$ dominates $\mathcal{C}_{K_i}$ w.r.t gl_{Σ_i}
4. prove that implementations satisfy their contracts: $K_i \longrightarrow I_j \implies I_j \models \mathcal{C}_{K_i}$.

The steps 3 and 4 can be combined, by proving for each non terminal K_i either satisfaction if it is described by an implementation, or dominance, if it is described by a composition rule.

In the next section we provide a proof that, given an grammar of components, for which all the methodology steps have been successfully applied to verify a property φ, then any component system built as a derivation tree accepted by this grammar satisfies also φ.

3.2 Soundness of the methodology

In Section 2.2, we have described the definitions of the different relations used in our methodology, namely *conformance*, *dominance* and *satisfaction*. In this section, we describe how we prove soundness of this methodology using the definitions of these relations provided in the definition of

contract framework. We then, describe a condition a designer has to ensure on glues when defining the contracts for dominance.

3.2.1 Soundness

To prove the soundness of the methodology described in Section 3.1.1, we rely on the properties of the contract framework defined in Section 2.2.

Theorem 3.2.1 *Suppose for a system K, a top level property φ, and a contract $\mathcal{C} = (A, gl, G)$ defined on K together with its environment such that $\mathcal{C}$ conforms to φ. Suppose a decomposition of K into $gl_I\{K_1, \ldots, K_n\}$, where for each K_i we associate a contract $\mathcal{C}_i = (A_i, gl_i, G_i)$ such that the contracts $\{\mathcal{C}_i\}$ dominate $\mathcal{C}$ w.r.t gl_I and we provide an implementation I_i satisfying C_i. Then, we have:*

$$gl\{A, gl_I\{I_1, \ldots, I_n\}\}\ conforms\ to\ \varphi$$

Proof According to the definition of dominance (see Definition 2.2.11), $\{\mathcal{C}_i\}$ dominate $\mathcal{C}$ w.r.t gl_I implies that any components satisfying the contracts $\{\mathcal{C}_i\}$ when composed together using gl_I satisfies $\mathcal{C}$. As the implementations $\{I_i\}$ satisfy their corresponding contracts, we obtain $gl_I\{I_1, \ldots, I_n\}$ satisfies $\mathcal{C}$, that is, $gl_I\{I_1, \ldots, I_n\} \sqsubseteq_{A,gl} G$ (according to the Definition 2.2.7 of satisfaction). As we have that refinement implies conformance in our contract framework, this implies that $gl\{A, gl_I\{I_1, \ldots, I_n\}\}$ conforms to $gl\{A, G\}$. Then as $gl\{A, G\}$ conforms to φ and as conformance is transitive, we obtain $gl\{A, gl_I\{I_1, \ldots, I_n\}\}$ conforms to φ. □

We can now based on this Theorem 3.2.1, prove the soundness of the extended methodology.

Theorem 3.2.2 *Let $\mathcal{G}$ be a grammar such that all methodology steps have been completed to guarantee a requirement φ. Any component system corresponding to a word accepted by $\mathcal{G}$ satisfies φ.*

Proof By induction on the number of steps required for deriving the accepted word from S, we can prove that the system represented by K_0 satisfies its contract (A, gl, G), that is, $K_0 \sqsubseteq_{A,gl} G$. This implies, as one of the conditions of our contract framework, that $gl\{A, K_0\} \preccurlyeq gl\{A, G\}$. As conformance is transitive, we have $gl\{A, K_0\} \preccurlyeq \varphi$. □

3.2.2 Compatibility of glues

As previously described, the soundness of our methodology relies on the definition of dominance. However, before using dominance, we need first to associate contracts $\{\mathcal{C}_i\}$ for subsystems $\{K_i\}$ of K, which requires to define the glues $\{gl_i\}$ allowing to compose each subsystem to the rest of the system. As already mentionned in the methodology, these glues have to provide a property of *structural compatibility* with the glue $gl \circ gl_I$.

Definition 3.2.3 (Structural compatibility of glues) *Consider two glues gl and gl_2. Now suppose $\mathcal{P} \subseteq S_{gl}$. gl and gl_2 are called compatible if there exists gl_1 with $\mathcal{P}_{gl} = \mathcal{P}_{gl_1}$ and $S_{gl} = \mathcal{P} \cup \mathcal{P}_{gl_2}$*

such that $gl_1 \circ gl_2 \cong gl$ *where by abuse of notation, this equivalence between glues means that* $gl_1 \circ gl_2\{\mathcal{K}^1\} \cong gl\{\mathcal{K}^1\}$ *for any set of components* $\mathcal{K}^1$ *such that all terms are defined.*

In the context of the dominance problem, the goal is to relate the glue gl_i provided in each $\mathcal{C}_i$ to the actual environment of component K_i, as illustrated in Figure 3.6: gl is the glue defined in the top-level contract and gl_I defines how subcomponents are composed. Thus, the actual environment of subcomponent K_1 consists of components K_2 to K_4 and A, the top-level assumption. However, the glue gl_1 provided in the contract for K_1 has been defined for an abstract environment A_1, hence the need for a glue gl_{E_1} representing the environment of K_1 as a single component with the same interface as A_1.

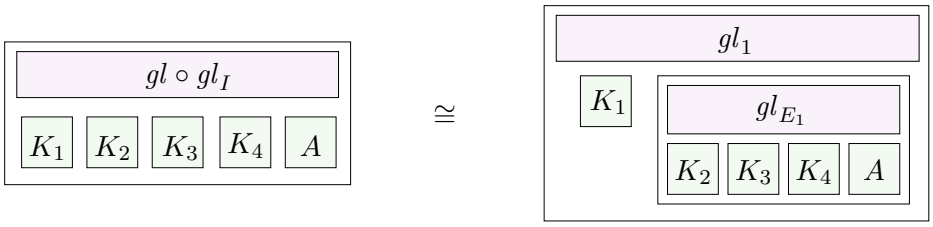


Figure 3.6: gl_{E_1} allows relating the glue gl_1 provided in $\mathcal{C}_1$ to the actual environment for K_1.

3.3 Proving dominance

The steps of the methodology described in Section 3.1 consists in proving basically three relations, namely conformance, dominance and satisfaction. In general, proving conformance and satisfaction uses analytical methods. For example, when components are LTS and conformance is inclusion of traces, then to prove conformance it is sufficient to prove simulation.

However, to prove dominance, according to the Definition 2.2.11, one has to manipulate concrete implementations of contracts. To avoid this, we propose to use a particular property called *circular reasoning* in order to prove dominance. Thus, in this section, we first discuss this property and we provide examples for which *circular reasoning* is not sound. Then, we describe how this property allows to deduce a sufficient condition to prove dominance.

3.3.1 Circular reasoning

Circular reasoning is a powerful property which allows to derive the property of *independent implementability*. Which means that we do not need to prove that an implementation refines its specification in the *actual* context in which it is used. This is highly undesirable for at least two reasons: one is that implementations are expected to be very complex, thus manipulating them is likely to be intractable; the other is that whenever a small change occurs in the implementation of a part of the system, all the proofs have to be started all over again. This is why, we have already

mentionned this property of circular reasoning in the additional step of our methodology related to the refinement of the environment (see the top right-hand side of Figure 3.5). Using circular reasoning, we can prove that a set of given implementations conforms to a given property in any context refining the mirror contract of the top level contract.

To avoid this situation, circular reasoning allows proving refinement using the abstract environment provided by the specifications rather than the concrete one provided by the implementations. Thus, circular reasoning is a property provided by the relation of refinement under context and it is defined as follows:

Definition 3.3.1 (Circular Reasoning) *If a component K refines G in an abstract context (A, gl) and if E refines A in the abstract context (G, gl), then K refines G in the concrete context (E, gl).*

$$\frac{K \sqsubseteq_{A,gl} G \qquad E \sqsubseteq_{G,gl} A}{K \sqsubseteq_{E,gl} G}$$

This property can be proved in a given framework by an induction based on the semantics of composition and refinement [McM99a, Mai03c].

However, circular reasoning is not sound in general. In particular, it is unsound when composition is based on synchronizations (as they exist in e.g. Petri nets or process algebras) or instantaneous mutual dependencies between inputs and outputs (as they exist in synchronous formalisms). For example, in the framework based on Input/Output automata defined in [QG08a], circular reasoning is sound because exactly one behavior has control over each interaction.

Example 3.3.2 explains two reasons for the non validity of circular reasoning for $\sqsubseteq^{\preccurlyeq}$ which are illustrated in Figures 3.7 and 3.8.

Example 3.3.2 *Suppose, as in the previous examples, that components are LTS and composition gl is defined as the synchronization between actions with the same letter and interleaving of others. Suppose also that conformance is simulation and refinement under context is the usual derived notion:*

$$K_1 \sqsubseteq^{\preccurlyeq}_{E,gl} K_2 \triangleq gl\{K_1, E\} \preccurlyeq gl\{K_2, E\}$$

The examples in Figures 3.7 and 3.8 are both counterexamples to the circular rule, that is: $K \sqsubseteq^{\preccurlyeq}_{A,gl} G$ and $E \sqsubseteq^{\preccurlyeq}_{G,gl} A$ but $K \not\sqsubseteq^{\preccurlyeq}_{E,gl} G$. Figure 3.7 shows that non-determinism of the abstract environment is a problem. In Figure 3.8, both the assumption A and the guarantee G forbid b to occur. This allows their respective refinements according to $\sqsubseteq^{\preccurlyeq}$, E and K, to offer b — since they can rely on G respectively A to forbid its actual occurrence. However obviously, the composition of the implementations $gl\{E, K\}$ now allows b.

Because circular reasoning is not sound for all refinements under context, it may be useful to use a stronger (more restrictive) definition of refinement under context in order to make circular reasoning sound which is the case of the refinement under context relation proposed in the contract framework that will be provided in Chapter 4.

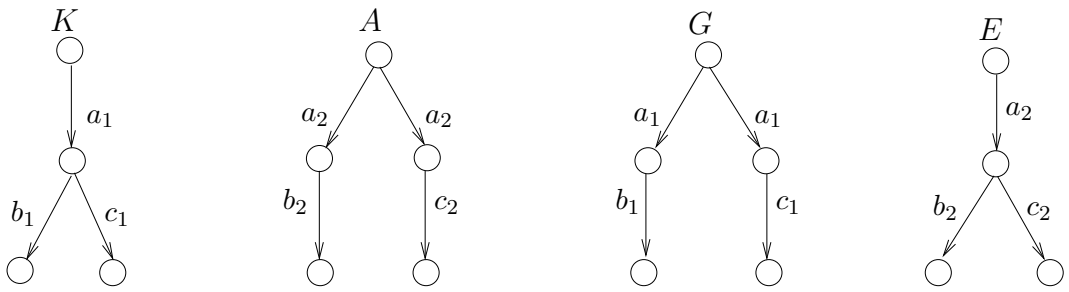


Figure 3.7: A counterexample to circular reasoning due to non-determinism.

Figure 3.8: A counterexample to circular reasoning due to strong synchronization.

We first, provide the sufficient condition to prove dominance when circular reasoning is sound in the case of binary dominance, we extend this condition to the more general case for a set of contracts.

Theorem 3.3.3 (Binary dominance) *Let $\mathcal{C}$ and $\mathcal{C}'$ be two contracts for the same interface $\mathcal{P}$ and the same glue gl, with $\mathcal{C} = (A, gl, G)$ and $\mathcal{C}' = (A', gl, G')$. If circular reasoning is sound, then to prove that $\mathcal{C}$* dominates *$\mathcal{C}'$ it is sufficient to prove that:*

$$G \models \mathcal{C}' \ \wedge A' \models \mathcal{C}^{-1}$$

Theorem 3.3.4 (Sufficient Condition for Dominance) *If circular reasoning is sound and $\forall i.\ \exists gl_{E_i}.\ gl \circ gl_I = gl_i \circ gl_{E_i}$, then to prove that the set $\{\mathcal{C}_i\}_{i=1..n}$ dominates $\mathcal{C}$ w.r.t. gl, it is sufficient to prove that:*

$$\begin{cases} \Pi_P(gl_I\{G_1, \dots, G_n\}) \models \mathcal{C} \\ \forall i, \Pi_{\mathcal{P}_{A_i}}(gl_{E_i}\{A, G_1, \dots, G_{i-1}, G_{i+1}, \dots, G_n\}) \models \mathcal{C}_i^{-1} \end{cases}$$

Proof For every $i \in [1, n]$, let K_i be a component on $\mathcal{P}_i$. Suppose the following:

1. $\forall i,\ \exists gl_{E_i},\ gl \circ gl_I = gl_i \circ gl_{E_i}$
2. $gl_I\{G_1, \dots, G_n\} \sqsubseteq_{A,gl} G$
3. $\forall i,\ gl_{E_i}\{A, G_1, \dots, G_{i-1}, G_{i+1}, \dots, G_n\} \sqsubseteq_{G_i,gl_i} A_i$

4. $\forall i,\ K_i \sqsubseteq_{A_i, gl_i} G_i$

We aim at proving $gl_I\{K_1, \ldots, K_n\} \models \mathcal{C}$, that is: $gl_I\{K_1, \ldots, K_n\} \sqsubseteq_{A,gl} G$. For this, we show by induction that for any l in $[0, n]$, for any partition $\{J, K\}$ of $[1, n]$ such that $|J| = l$:

$$\begin{cases} gl_I\{\mathcal{K}^J \cup \mathcal{G}^K\} \sqsubseteq_{A,gl} G \\ \forall i \in K,\ gl_{E_i}\{A, \mathcal{E}_i^{J,K}\} \sqsubseteq_{G_i, gl_i} A_i \end{cases}$$

with $\mathcal{K}^J = \{K_j\}_{j \in J}$, $\mathcal{G}^K = \{G_k\}_{k \in K}$ and with $\mathcal{E}_i^{J,K} = \mathcal{K}^J \cup (\mathcal{G}^K \backslash \{G_i\})$.

- $l = 0$. By (2) and (3) the property holds.
- $0 \leq l < n$. We suppose that our property holds for l. Let $\{J', K'\}$ be a partition of $[1, n]$ such that $|J'| = l + 1$. Let q be an element of J'. We fix $J = J' \backslash \{q\}$ and $K = K' \cup \{q\}$.

Step 1 We first prove that $gl_I\{\mathcal{K}^{J'} \cup \mathcal{G}^{K'}\} \sqsubseteq_{A,gl} G$.

$$\begin{cases} K_q \sqsubseteq_{A_q, gl_q} G_q \text{ from (4)} \\ gl_{E_q}\{A,\ \mathcal{E}_q^{J,K}\} \sqsubseteq_{G_q, gl_q} A_q \end{cases}$$

The second property is our recurrence hypothesis, as $q \in K$. Thus, by circular reasoning:

$$K_q \sqsubseteq_{gl_{E_q}\{A, \mathcal{E}_q^{J,K}\}, gl_q} G_q$$

As refinement under context is preserved by composition, we obtain :

$$gl_I\{K_q, \mathcal{E}_q^{J,K}\} \sqsubseteq_{A,gl} gl_I\{G_q, \mathcal{E}_q^{J,K}\}$$

This is equivalent to $gl_I\{\mathcal{K}^{J'} \cup \mathcal{G}^{K'}\} \sqsubseteq_{A,gl} gl_I\{\mathcal{K}^J \cup \mathcal{G}^K\}$.
Finally, by using the recurrence hypothesis: $gl_I\{\mathcal{K}^{J'} \cup \mathcal{G}^{K'}\} \sqsubseteq_{A,gl} G$.

Step 2 We now have to prove that:

$$\forall i \in K',\ gl_{E_i}\{A, \mathcal{E}_i^{J',K'}\} \sqsubseteq_{G_i, gl_i} A_i$$

We fix $i \in K'$. We have proved in step 1 that:

$$K_q \sqsubseteq_{gl_{E_q}\{A, \mathcal{E}_q^{J,K}\}, gl} G_q$$

$K = K' \cup \{q\}$, so $i \in K$. Thus, by compositionality, we obtain:

$$gl_{E_i}\{K_q, A, \mathcal{E}_q^{J,K\backslash\{i\}}\} \sqsubseteq_{G_i, gl_i} gl_{E_i}\{G_q, A, \mathcal{E}_q^{J,K\backslash\{i\}}\}$$

This boils down to $gl_{E_i}\{A, \mathcal{E}_i^{J',K'}\} \sqsubseteq_{G_i, gl_i} gl_{E_i}\{A, \mathcal{E}_i^{J,K}\}$.
Hence, using the recurrence hypothesis: $gl_{E_i}\{A, \mathcal{E}_i^{J',K'}\} \sqsubseteq_{G_i, gl_i} A_i$.

Conclusion By applying our property to $l = n$, we get:

$$gl_I\{K_1, \ldots, K_n\} \sqsubseteq_{A,gl} G$$

□

Theorem 3.3.4 shows that the proof of a dominance relation boils down to a set of refinement checks, one for proving refinement between the guarantees, the second for discharging individual assumptions. This result is particularly useful as it allows to check dominance without having to compose neither implementations nor contracts.

The proof of Theorem 3.3.4 relies, in addition to the circular reasoning, on a second property of the relation of refinement, that is *compositionality*, and which means preservation of refinement by composition. Compositionality is usually based on the rule that: if an implementation I conforms to its specification S, then whenever composed with any component E it still conforms to S. However, for refinement in a given context we cannot compose with any component as the context is already fixed by the relation. Thus we suppose a composite context and we integrate a part of this context in I and S to obtain refinement in the remaining part of the composite context. This property is in general easily satisfied by refinement relations in contract frameworks, where its always relevant to choose a refinement relation which can be preserved by composition.

Definition 3.3.5 (Compositionality) *A set of refinement under context relations $\{\sqsubseteq_\omega\}_{\omega\in\Omega}$ is said to be* preserved by composition *if and only if the following rule applies whenever all terms are defined:*

$$\frac{I \sqsubseteq_{E,gl} S \qquad E = gl_E\{E_1, E_2\} \qquad gl \circ gl_E = gl_2 \circ gl_1}{gl_1\{I, E_1\} \sqsubseteq_{E_2,gl_2} gl_1\{S, E_1\}}$$

In the next chapter, we propose a component framework as well as a contract framework, allowing to apply the proposed methodology, with a refinement relation ensuring circular reasoning and compositionality.

Chapter 4

A Contract Framework for Components with Data

In this Chapter, we first define a component framework. That is a notion of component enriched with variables, and a set of glue operators describing how to compose these components so as to obtain systems of components. We choose to use and extend the set of composition operators of the BIP interaction model [Sif05, BS07a, BJS09b], defined in Section 2.1.2. In particular, we define a notion of *observation* connectors useful for our verification purposes. Second, we propose, based on this component framework, a contract framework, that is, we define conformance and a notion of refinement under context and show that they have the required properties. In particular, that the relation of refinement under context allows the property of circular reasoning. To allow to encompass progress, our definition of components is extended with a notion of *progress conditions*.

In this chapter, we detail in Section 4.1 our definition of components and its semantics. Then we define in Section 4.2 how to compose components using our rich interaction model and how hierarchical components are obtained by the composition of these glues. In Section 4.3, we focus on progress description and how we deal with their composition. Finally, in Section 4.4, we provide relations of the proposed contract framework and the proofs of the conditions it has to ensure.

4.1 Components with data

Let us first recall the ingredients required to define a component framework as described in Definition 2.2.1, that is, a notion of atomic component, representing *abstract behavior* or *properties* of the components we want to design, an equivalence relation $\cong$ on components and a set of glues GL defining composition operators which can be composed by an associative operation $\circ$.

In this section, we first focus on the two first ingredients, that is the definition of components and the equivalence relation between them.

We first provide the syntactic definition of components (see Definition 4.1.1), then their semantics. In the variant of BIP component framework described in Section 2.1.2, components are defined as extended labeled transition system (ELTS). Here, we also define atomic components as extended

labeled transition systems but we yield a more abstract notion of components that we want to use for the expression of properties, not only implementations.

- We consider control states with an attribute Inv, a predicate on the set of *state variables* X^{st} of the component. This predicate is guaranteed to hold in that control state. The variables which are not *state variables* are *transient* X^{tr}. Their values are calculated twice during the execution of a step of the system that involves this component: first their values are assigned depending on X^{st} (we use a relation R for expressing their possible values), then they may be assigned again by the interaction between the involved components (such a function will be defined by the glues) and then be used in the data transformations operated by individual components (which we represent by predicates Fu on $X = X^{st} \cup X^{tr}$). Also data transformations of state variables (which may depend on the values of transient variables) are not given as a function but more abstractly by a predicate.

- We explicitly distinguish *internal* actions which we denote by τ. As usually, they cannot participate in interactions with other components and they are used to define weaker notions of equivalence and refinement. Modeling internal actions is very useful when we need to model "uncontrollable" actions. This is in general the case when a component has some local actions for which it does not need to synchronize or to exchange data with other components (see Example 4.1.2).

As in BIP, we may consider that the transient variables are associated to ports through which they are exported and imported and in that case we may write $p[x_1, ..., x_n]$ to express that $x_1, ..., x_n$ are transient variables only meaningful in steps involving an interaction on p. Without loss of generality, we suppose in the following that a port is associated with exactly one variable. We suppose given a set of predicates that is closed by $\wedge$ and $\vee$.

Definition 4.1.1 (Component) *A* component *is an ELTS defined by a tuple* $(TS, X, Inv, g, Fu, Prog)$ *and an interface defined by a set of ports* $\mathcal{P}$*:*

- $TS = (Q, q^0, \mathcal{P} \cup \{\tau\}, \longrightarrow)$ *is a labeled transition system:* Q *is a set of* control states*,* $q^0 \in Q$ *is the* initial state*,* $\mathcal{P} \cup \{\tau\}$ *is a set of labels.* $\longrightarrow \subseteq Q \times \mathcal{P} \cup \{\tau\} \times Q$ *is a set of* control transitions*. Elements of* $\mathcal{P}$ *are* ports *and* τ *labels* internal *transitions;*

- $X = X^{st} \cup X^{tr}$ *is a set of* variables*.* X^{st} *contains* state variables *and* X^{tr} *contains* transient *variables. A boolean expression* R *on* X *defines the possible values of transient variables before the execution of a step depending on the current values of the state variables in the current state;*

- Inv *associates with every* $q \in Q$ *a* state invariant Inv_q *that is a predicate on* X^{st}*;*

- g *associates with every transition* t *a* guard g_t*, i.e. a predicate on* X^{st}*;*

- *Fu associates with every transition t an* action *Fu_t defined as a predicate on $X^{st} \cup x_\gamma \cup X^{st}_{next}$, where as usually, we introduce the auxiliary variables X_{next} to represent the values of the state variables after the transition and the original variables X^{st} for representing the values before the transition and which are also used in the guard. x_γ is the transient variable associated with the port labeling t;*

- *$Prog$ a set of* progress conditions *(more details are given in Section 4.3).*

If a given transition t is not labeled by a port but by τ, then, the function associated is a predicate Fu_t defined on variables $X^{st} \cup X^{st}_{next}$. Indeed, when no interaction with the environment is performed, there is no need to transient variables which allow to import or export values, and thus the predicate Fu_t is completely local and it only depends on state variables.

Note, however, that we do not require that a port must have an associated variable. Indeed, a synchronization of a component with the environment may do not involve data transfer. Moreover, in the next section we propose a variant of connectors connecting ports without variables, which we use only to detect that some action is performed. These connectors are called *observation* connectors.

Invariants associated with states, represents the knowledge that the component has on its *state variables* in this state.

Example 4.1.2 *Figure 4.1 shows a component K with an interface consisting of $\mathcal{P} = \{in, out\}$. The ports in and out label the transitions of K, which has also an internal transition labeled by τ and which corresponds to an internal computation performed by K and which does not synchronize with the environment to be performed. The invariants of the two states of K are defined on the state variable y. Similarly, guards on transitions are also defined on state variables y_1 and y_2. However to exchange data with its environment, K uses the transient variables x_1 and x_2 associated to its ports. In fact, the transfer of data is performed within the functions predicates associated to the transitions labeled by these ports. The overall behavior of K is getting a value from the environment (other components), making some local computations using these values, then giving the resulting new values back to the environment through the port out.*

Our syntactic definition of components provides a description of some progress conditions which we denote $Prog$. For the sake of clarity, and as the description of these properties depends of the semantics of our definition of components, we propose next to give the semantics of a component, then to detail our notion of progress in Section 4.3.

4.1.1 Semantics

We define the semantics of components, that is extended labeled transition system (ELTS) K, as usually as a simple labeled transition system (LTS), where states are control states of K extended by valuations of state variables of K and transitions are labeled by ports extended by valuations of transient variables.

Moreover, we also have variables associated with ports and which can be interpreted differently depending on the semantics we are interested in.

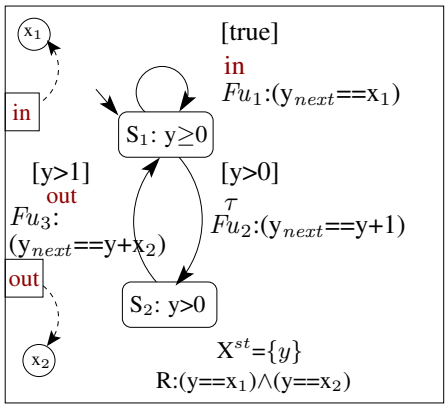


Figure 4.1: Example: Component with data.

Definition 4.1.3 (Safety Semantics of atomic component) *The semantics of* $K = (TS, X, Inv, g, Fu, Prog)$*, where* $TS = (Q, q^0, \mathcal{P} \cup \{\tau\}, \longrightarrow)$*, is a labeled transition system* $((Q \times \mathcal{V}_{X^{st}}), (q^0 \times v_{X^{st}}), \mathcal{P} \cup \{\tau\}, \hookrightarrow)$ *such that:*

- $(Q \times \mathcal{V}_{X^{st}})$ *is a set of states, where* $\mathcal{V}_{X^{st}}$ *denotes the set of valuations of state variables* X^{st}*;*
- $\hookrightarrow$ *is the set including transitions* $(q, v_{x^{st}}) \overset{l}{\hookrightarrow} (q', v_{x^{st}{}_{next}})$ *where:*
  - $l \in ((\mathcal{P} \cup \{\tau\}) \times \mathcal{V}_{X^{tr}})$*;*
  - $\exists v_{x^{tr}} \in \mathcal{V}_{X^{tr}}$ *such that* $Inv_q(v_{x^{st}}) \wedge g_t(v_{x^{st}}) \wedge R(v_{x^{st}}, v_{x^{tr}}) \wedge Fu_t(v_{x^{st}}, v_{x^{tr}}, x^{st}{}_{next}) \wedge Inv'_q(v_{x^{st}{}_{next}})$ *holds for some* $t = (q, l, q') \in \longrightarrow$*.*

We denote by Sem_K*, the LTS defining the semantics of* K*.*

In this thesis, we opt for a *safety* semantics.

We suppose that K needs not to synchronize on any of its ports which means that all states in which a transition on port p is enabled in K have indeed this transition. On the other hand, we consider value of the port variables, which will be determined by the downward function of connectors when K is composed, as unknown that is any possible value. In other words, the set of transitions we obtain is the maximal set of transitions that a component could fire in a given environment which means that when composed to its environment, the component could only have any set that is equal or a subset of these transitions.

Once we have defined the semantics of our description of components, we now provide the second ingredient to the definition of the component framework that is the equivalence relation between components.

Definition 4.1.4 (Equivalence relation) *Equivalence on components is bisimulation. That is, two components* K_1 *and* K_2 *are equivalent, denoted* $K_1 \cong K_2$*, whenever their associated semantic transition systems are bisimilar.*

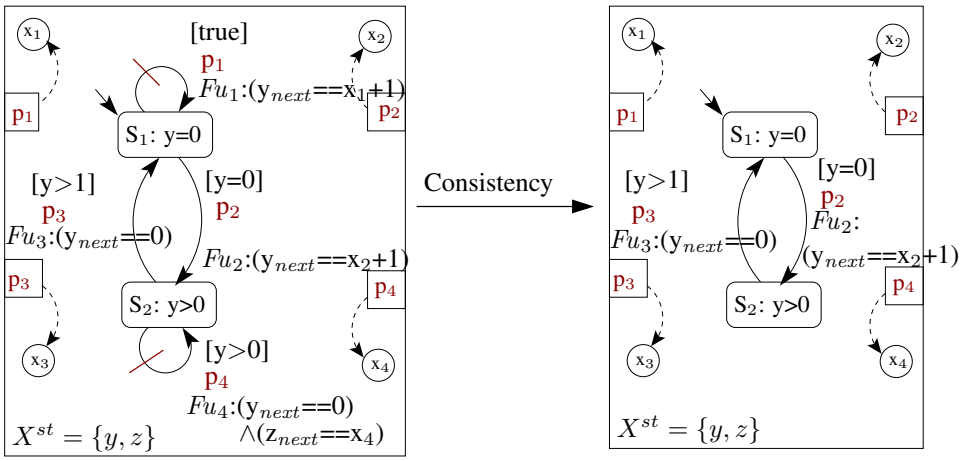


Figure 4.2: Consistent version of a component with data.

The relation of equivalence that we concretely use in the application we propose in the next chapter, is stronger than such equivalence of semantics. We use a syntactic equivalence, that is the equality between the extended labeled transition systems possibly after renaming of control states and variables and after proving equivalence of expressions corresponding to predicates.

Some transitions of a component description may be *unfeasible*. Usually, detecting unfeasible transitions requires taking into account the dynamics of the system, at least when we suppose that no guard is trivially equivalent to false. Here we have declared invariants which are enforced, that is, for a given transition $t = (q \xrightarrow{p} q')$ whenever it is not possible to satisfy jointly the invariant of q, the guard of t the transition predicate of t and the invariant in q', the transition is infeasible and thus called *inconsistent*. This notion of consistency is particularly relevant in the case of *composite* components where their syntactic composition may lead to several inconsistent transitions.

Definition 4.1.5 (Inconsistent transition) *Let $K = (TS, X, Inv, g, Fu, Prog)$ be a component where $TS = (Q, q^0, \mathcal{P} \cup \{\tau\}, \longrightarrow)$. A transition $t = (q \xrightarrow{p} q') \in \longrightarrow$, $p \in \mathcal{P} \cup \{\tau\}$ is said to be* inconsistent *iff the predicate: $Inv_q \wedge g_t \wedge Fu_t \wedge Inv_{q'}^{next}$ is not* Satisfiable*, where $Inv_{q'}^{next}$ is applied on the $next$ new version of variables.* Satisfiable *means that it exists a concrete valuation of the variables of K for which this predicate holds.*

We call a component *consistent* if it has no *inconsistent* transitions. Note that any component could be made consistent by removing all its inconsistent transitions.

Example 4.1.6 *Figure 4.2, gives a small example of how one can simplify the definition of component according to the proposed condition of consistency. If we suppose that all the component variables are natural numbers, then then transition labeled by the port p_1 is not consistent with the invariant of its target state S_1. Indeed, for any possible value of x_1, the corresponding function predicate Fu_1*

implies $y > 0$ which is inconsistent with the invariant of S_1 namely $y = 0$. Similarly this is the case of the transition labeled by the port p_4.

4.2 Glues: Rich interaction model

As mentioned previously, the purpose of this chapter is the definition of a contract framework, and the first ingredient of its definition is a component framework. As in the previous section we have defined atomic components and a notion of equivalence. Now we focus in this section, on the two last ingredients, namely, the set of glues GL and their composition operators $\circ$.

Like in BIP we define composition by means of a set of connectors defining an interaction-model used as a parameter of the composition operator. Indeed, we define composition by means of a set of specific connectors, namely *rendez-vous*, extended with data, and abstract *observation* connectors. We have made this choice, because the notion of component we have proposed handles variables, and thus what we need is an interaction model rich enough to handle data exchange between components. In this section, we first describe the variant of BIP glues we are using. Second, we describe how we use these glues to compose components and thus to build composite components from atomic ones. Then, we defined the composition of interaction models using the operator $\circ$ allowing to flatten hierarchical components.

4.2.1 Connectors

Interaction models are defined by a set of connectors. Here, we propose a variant of BIP connectors that have mainly two differences w.r.t the previously defined BIP connectors:

- First, we limit connectors to only two types. of synchronizations and The first one is the usual BIP *rendez-vous connector* requiring *all* ports to be activated in order for the interaction to take place. The second type of connectors called *observation connector* connects only *trigger* ports and an interaction of this connector can take place as soon as any port is activated.

- The second difference concerns the upward and downward update functions of connectors. BIP connectors have concrete update functions which manipulate valuations of variables, however, in our connectors, these functions are simply predicates on these variables. We choose this abstract representation of connectors, because it allows like for components to provide abstract descriptions that can be instantiated in different ways. For us this is in particular important as in systems obtained as instances of a grammar, the actual concrete connectors depend on the actual instance whereas proofs are made at the level of the grammar using abstract connectors.

We now provide the syntax of *rendez-vous* and *observation* connectors.

Definition 4.2.1 (Rendez-vous connector) *A* rendez-vous *connector is of the form* $\gamma = (p_\gamma[x], \mathcal{P}_\gamma, \delta_\gamma)$ *where:*

- p_γ, *the* exported port *and* $\mathcal{P}_\gamma = \{p_1, ..., p_k\}$, *the* support set *of ports, where* x *is the transient variable associated with* p_γ *and we denote by* $\{x_1, ..., x_k\}$ *the transient variables associated with the ports of the* support set*;*
- $\delta_\gamma = (G, \mathcal{U}, \mathcal{D})$ *where:*
  - G *is the* guard*, that is, a predicate on* $\{x_1, ..., x_k\}$
  - $\mathcal{U}$ *is the* upward update function *defined from* $\{x_1, ..., x_k\}$ *into* x*, and we choose to represent it as a predicate on* $\{x_1, ..., x_k\} \cup \{x\}$
  - $\mathcal{D}$ *is a set* $\{\mathcal{D}_{x_i}\}$ downward update functions *for each* $x_i \in \{x_1, ..., x_k\}$ *allowing to define* x_i *using* x*, and which we define as a predicate on* $\{x\} \cup \{x_i\}$

The definition of *observation* connectors does not involve data transformations, they have neither guard nor $\mathcal{U}$ nor $\mathcal{D}$ predicates.

Definition 4.2.2 (Observation connector) *An* observation *connector* $\gamma = (p_\gamma, \mathcal{P}_\gamma)$ *is defined by an* exported port p_γ *and a* support set $\mathcal{P}_\gamma = \{p_1, ..., p_k\}$.

Note that this type of connectors allow to detect when a given transition is fired, which is particularly useful if one wants to prove some properties related to the occurrence of a given transition. This is relevant when dealing with safety and progress properties where to prove that a property is valid one has to detect that an interaction occurs.

To avoid cyclic connectors, we require also that $p_\gamma \notin \mathcal{P}_\gamma$.

Definition 4.2.3 (Disjoint connectors) *Given two connectors* $\gamma_1 = (p_1, \mathcal{P}_1, \delta_1)$ *and* $\gamma_2 = (p_2, \mathcal{P}_2, \delta_2)$*,* γ_1 *and* γ_2 *are said to be* disjoint *if* $p_1 \neq p_2$*,* $p_1 \notin \mathcal{P}_2$ *and* $p_2 \notin \mathcal{P}_1$*. Note that* $\mathcal{P}_1$ *and* $\mathcal{P}_2$ *may have ports in common, as a port may be connected to several connectors.*

Note that each connector defines a set of interactions.

Definition 4.2.4 (Interactions of connectors) *A rendez-vous connector* $\gamma_{rdv} = (p_\gamma[x], \mathcal{P}_\gamma, \delta_\gamma)$*, defines a unique interaction* $\alpha = (p_\gamma, \mathcal{P}_\gamma, \delta_\alpha)$ *defined by the synchronization of all ports of* $\mathcal{P}_\gamma$ *with* $\delta_\alpha = \delta_\gamma$.
An observation connector $\gamma_{obs} = (p_\gamma, \mathcal{P}_\gamma)$ *defines as interactions any non-empty subset of* $\mathcal{P}_\gamma$.

An interaction model is defined by a set of interactions which are structured using connectors. Thus connector represent a syntactic description of interaction models. As in Section 2.1.2 we define an interaction model for a set of connectors as follows:

Definition 4.2.5 (Interaction models) *An interaction model* $\mathcal{I}$ *is defined by a set of disjoint connectors* $\{\gamma_i = (p_i[x], \mathcal{P}_i, \delta_i)\}_{i=1}^n$ *where its support set* $S_\mathcal{I} = \bigcup_{i=1}^n \mathcal{P}_i$ *and its associated interface is defined by* $\mathcal{P}_\mathcal{I} = \{p_i | \gamma_i \in \mathcal{I}\}$ *consisting of the set of the exported ports of its connectors.*

We denote by $\mathcal{I}_{rdv}$ *the set of rendez-vous connectors of* $\mathcal{I}$ *and* $\mathcal{I}_{obs}$ *the set of its observation connectors.*

The interface of an interaction model allows to define the interface of the component resulting from a composition using $\mathcal{I}$. The set $X_\mathcal{I}$ denotes the set of variables associated with the ports of $\mathcal{P}_\mathcal{I}$ and which defines the set of variables of $\mathcal{I}$.

4.2.2 Composition

We now define how to compose a set of components, by means of an interaction model, that is how to build composite components from atomic ones. Similarly as in the definition of the BIP component framework (Section 2.1.2),

To define the semantics of a composition, we first define a syntactic composition associating with the composite component an atomic component defined on the product of control states. Then to compute semantics of composition as the semantics of this atomic component.

The definition of composition proposed here differs from the one of BIP in that; first, our set of transitions can be labeled by a port or by τ. Second, we use two particular types of connectors that we have to precise how components synchronize and exchange data for each type.

In our definition of component (see Definition 4.1.1) we do not allow sets of ports as labels of transitions. Thus we require that connectors of the interaction model $\mathcal{I}$ have at most one port of the same component in their support set.

Definition 4.2.6 (Syntactic composition) *Let $K_1, \dots, K_n$ be a set of components defined on pairwise disjoint interfaces, such that $K_i = (TS_i, X_i, Inv_i, g_i, Fu_i, Prog_i)$ where, $TS_i = (Q_i, q_i^0, \mathcal{P}_i \cup \{\tau\}_i, \longrightarrow_i)$. Let $\mathcal{I}$ be an interaction model defined on $\bigcup_{i=1}^n \mathcal{P}_i$, and which defines an interface $\mathcal{P}_\mathcal{I}$ with the set of variables $X_\mathcal{I}$. Then, the* syntactic composition *of $K_1, \dots, K_n$ using $\mathcal{I}$ is a component $(TS, X, Inv, g, Fu, Prog)$ such that:*

- *$TS = (Q, q^0, \mathcal{P}_\mathcal{I} \cup \{\tau\}, \longrightarrow)$ with $Q = \prod_{i=1}^n Q_i$, $q^0 = (q_1^0, \dots, q_n^0)$ and where $\longrightarrow$ a set of transitions of the form $t = (q, p_\gamma, q')$, where:*

  - *$q = (q_1, \dots, q_n)$, $q' = (q_1', \dots, q_n')$, q_i and q_i' being control states of the i^{th} component.*
  - *$p_\gamma \in \mathcal{P}_\mathcal{I}$ is an exported port of a connector $\gamma \in \mathcal{I}$, corresponding to an interaction α of γ, such that there exists a subset $J \subseteq \{1, \dots, n\}$ of components with transitions $\{(q_j, p_j, q_j')\}_{j \in J}$ and $\alpha = \{p_j\}_{j \in J}$.*
  - *if $j \notin J$, $q_j' = q_j$. That is, the control states from which there are no transitions labeled with ports in α, remain unchanged.*
  - *$X^{st} = \bigcup_{i=1}^n X_i^{st}$, $X^{tr} = \bigcup_{i=1}^n X_i^{tr} \cup X_\mathcal{I}$ and thus $X = X^{st} \cup X^{tr}$*
    The relation R between variables in X^{st} and $X^{tr} \in X_\mathcal{I}$ is defined as:
    $x^{tr} \in X_\mathcal{I}$, then x^{tr} is associated with an exported port p_γ of a rendez-vous connector $\gamma = (p_\gamma, \mathcal{P}_\gamma, \delta) \in \mathcal{I}_{rdv}$. Let $I = |\mathcal{P}_\gamma|$. $\mathcal{U}_\gamma$ is a predicate on $\{x_1, \dots, x_I\} \cup \{x^{tr}\}$, where every x_i is associated with a port of $\mathcal{P}_\gamma$. Without loss of generality, we suppose each x_i is a variable of component K_i.
    Then $R(x^{tr}, X^{st})$ is defined iff:

$$\exists x_1, \dots, x_I.\ (\forall i \in [1, I].\ R_i(x_i, {X_i}^{st})) \wedge \mathcal{U}_\gamma(x_1, \dots, x_I)$$

  - *Inv associates with every state $q \in Q$ an invariant Inv_q defined by $Inv_q = \bigwedge_{\{i=1\}}^n Inv_{q_i}$;*

  - *g associates with every transition $t = (q, p_\gamma, q')$, corresponding to an interaction $\alpha = \{p_j\}_{j\in J}$ of a connector $\gamma \in \mathcal{I}$, a guard defined by $g_t = (\bigwedge_{j\in J} g_j \wedge R_i) \wedge G_\gamma$. Intuitively, the guard of the new obtained transition takes into account the guards of the composed transitions as well as the guard of the connector used to compose them. Note that if α corresponds to an interaction of an observation connector, then $g_t = \bigvee_{i=1}^{I} g_{t_i}$.*
  - *Fu associates with every transition $t = (q, p_\gamma, q')$, corresponding to an interaction $\alpha = \{p_j\}_{j\in J}$ of a connector $\gamma \in \mathcal{I}$, a predicate $Fu_t = \mathcal{U} \wedge \mathcal{D} \wedge \bigwedge_{i=1}^{I} Fu_{t_i}$. if α corresponds to an interaction of an observation connector, then $Fu_t = \bigvee_{i=1}^{I} Fu_{t_i}$.*

- *The set $Prog$ of progress conditions of the composition will be discussed separately in Section 4.3.2.*

Our composition of components is rather technical but not surprising. It does not involve hiding of ports. Indeed the interaction model $\mathcal{I}$ has to be defined on the set of all ports of the composed components.

Note that a *rendez-vous* connector leads to a new control transition, in the composed component, labeled by its exported port. This transition is enabled if all local transitions are enabled and the connector guard holds, that is the guard of a transition corresponding to a rendez-vous is the conjunction of all these guards.

For an observation connector, an observation transition is enabled if at least one of the corresponding local transitions is enabled, thus the corresponding guard is the disjunction of local guards. Remember that an observation connector has an interaction (a transition in the syntactic product) for each subset of local transitions which each one has its own guard. Note that there is no maximal progress for observations: even if all local transitions are enabled, any subset may go for an observation. This is why we call it an observation transition: we can observe at the higher level of hierarchy whether at least one of the local transitions has been executed but the execution of a transition in a connected component does not influence the behavior of any other component.

Note that this syntactic composition may lead to the appearance of inconsistent transitions, thus it could be interesting to apply the consistency condition, described in Section 4.1.5, to the obtained component.

Example 4.2.7 *Figure 4.3 depicts a set of two components K^1 and K^2 (each component represents an instance of the component given in Example 4.1.2 and an interaction model $\mathcal{I}$ represented by two connectors γ_1, γ_2. The composite component $\mathcal{I}(K^1, K^2)$ obtained as a composition of K^1 and K^2 using $\mathcal{I}$ is given in Figure 4.4. As described in Definition 4.2.6, the new transitions of the composite component obtained as a synchronization between ports of K^1 and K^2 are now labeled by the exported ports $1to2$ and $2to1$ of the connectors. Guards and local functions of these new transitions are computed as given in Figure 4.4. Variables of $\mathcal{I}(K^1, K^2)$ are given by $X_\mathcal{I} \cup X^1 \cup X^2$.The transitions labeled by τ represent internal transitions which still possible locally but not exported to the interface of the new composite component.*

Note, in this composition as well as in the definition of components, we did not discuss how we

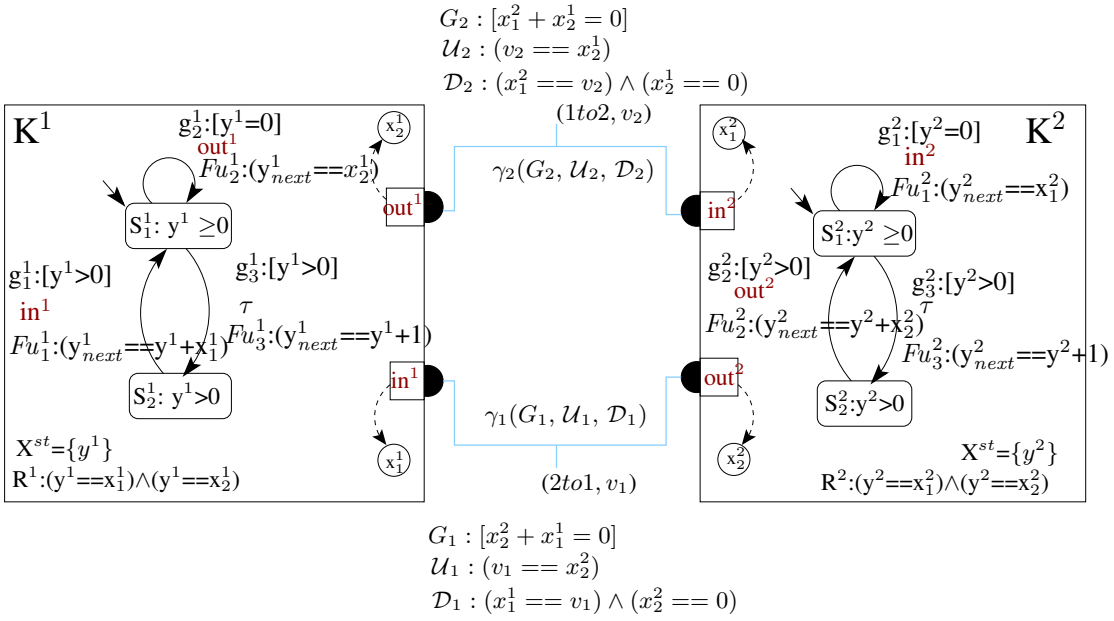


Figure 4.3: Composition of components.

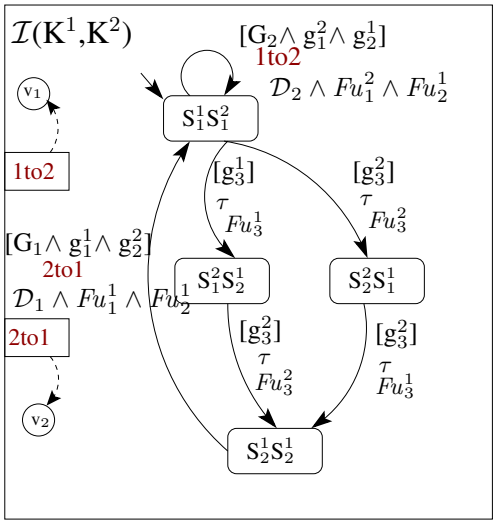


Figure 4.4: Composite component.

describe progress conditions associated with each component and how to compose them. This will be detailed in Section 4.3.

4.2.3 Composition of interaction models

As already explained, we want to be able to define components and connectors hierarchically, and we want to be able to flatten a hierarchical component. This means that we must be able to compose connectors and transform a hierachically defined connector into a single "flat" connector. We call this "merge" of connectors.

The *merge* of connectors is only defined on connectors of the same type. It is the operation that takes two connectors defining together a *hierarchical* connector and returns a connector of a basic type (see Figure 4.5). More precisely, the merge of two rendez-vous connectors defines a new rendez-vous connector and similarly, the merge of two observation connectors defines a new observation connector. The merge for rendez-vous connectors is already defined in [BJS09b], where it is called flattening. Here we restrict this definition so as to preserve associativity of the upward and downward functions.

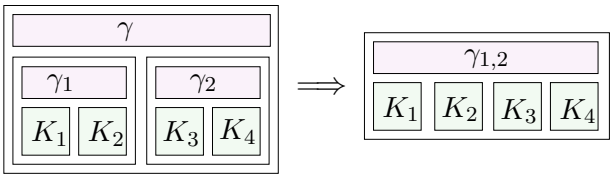


Figure 4.5: Merge of Connectors.

Definition 4.2.8 (Merge of rendez-vous connectors) *Let* $\gamma_1 = (p_1[x_1], \mathcal{P}_1, \delta_1)$ *and* $\gamma_2 = (p_2[x_2], \mathcal{P}_2, \delta_2)$ *be two rendez-vous connectors such that* $\mathcal{P}_1 \cap \mathcal{P}_2 = \emptyset$ *and* $p_1 \neq p_2$*. The merge of* γ_1 *and* γ_2*, denoted* $\gamma_1 \bullet \gamma_2$*, is defined as follows:*

- *if* $(p_1 \notin \mathcal{P}_2$ *and* $p_2 \in \mathcal{P}_1)$ *then* $\gamma_1 \bullet \gamma_2 = (p[x], \mathcal{P}, \delta)$ *with:*
  - $p[x] = p_1[x_1]$
  - $\mathcal{P} = \mathcal{P}_1 \cup \mathcal{P}_2 \setminus \{p_2\}$
  - $\delta = (G, \mathcal{U}, \mathcal{D})$ *is defined as follows:*
    - $G = G_2 \wedge \exists v_2.\ G_1[v_2/x_2] \wedge \mathcal{U}_2[v_2/x_2]$
    - $\mathcal{U} = \exists v_2.\ \mathcal{U}_2[v_2/x_2] \wedge \mathcal{U}_1[v_2/x_2]$
    - $\mathcal{D}_{x_k} = \begin{cases} \mathcal{D}_{1,x_k} & \text{if } x_k \in P_1 \setminus \{x_2\} \\ \exists v_2.\ \mathcal{D}_{1,x_2}[v_2/x_2] \wedge \mathcal{D}_{2,x_k}[v_2/x_2] & \text{if } x_k \in P_2 \end{cases}$
- *if* $(p_1 \in \mathcal{P}_2$ *and* $p_2 \notin \mathcal{P}_1)$ *then* $\gamma_1 \bullet \gamma_2 = \gamma_2 \bullet \gamma_1$.

Definition 4.2.9 (Merge of observation connectors) *Let $\gamma_1 = (p_1, \mathcal{P}_1)$ and $\gamma_2 = (p_1, \mathcal{P}_1$ be two observation connectors such that $\mathcal{P}_1 \cap \mathcal{P}_2 = \emptyset$ and $p_1 \neq p_2$. The merge of γ_1 and γ_2, denoted $\gamma_1 \bullet \gamma_2$, is defined in the following situations:*

- *if $(p_1 \notin \mathcal{P}_2$ and $p_2 \in \mathcal{P}_1)$ then $\gamma_1 \bullet \gamma_2 = (p, \mathcal{P}, \delta)$ with:*
  - $p = p_1$
  - $\mathcal{P} = \mathcal{P}_1 \cup \mathcal{P}_2 \setminus \{p_2\}$
- *if $(p_1 \in \mathcal{P}_2$ and $p_2 \notin \mathcal{P}_1)$ then $\gamma_1 \bullet \gamma_2 = \gamma_2 \bullet \gamma_1$.*

If $(p_1 \in \mathcal{P}_2$ and $p_2 \in \mathcal{P}_1)$, then $\gamma_1 \bullet \gamma_2$ is not defined because this would result in a cyclic connector. Besides, if $(p_1 \notin \mathcal{P}_2$ and $p_2 \notin \mathcal{P}_1)$, then γ_1 and γ_2 are disjoint, thus they cannot be merged.

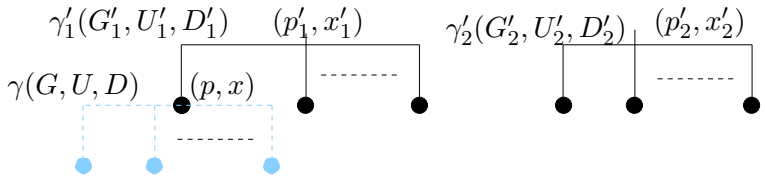


Figure 4.6: $\mathcal{I} \circ \mathcal{I}' = \{\gamma \bullet \gamma'_1,\ \gamma'_2\}$

We can now define the composition of interaction models as the union of the set of disjoint connectors of each interaction model, and the connectors obtained by a merge for connectors that are not disjoint. Note that merge of connectors and thus composition of interaction models are by definition commutative and allows flattening according to the definition of merge. They are also associative because $\wedge$ operator on update predicates of connectors is associative.

Definition 4.2.10 (Composition of interaction models) *The merge of connectors $\bullet$ is extended to interaction models as follows. The composition $\circ$ of two interaction models $\mathcal{I}_1$ and $\mathcal{I}_2$ is obtained from $\mathcal{I}_1 \cup \mathcal{I}_2$ by inductively composing all connectors which are not disjoint.*

Examples of composition of interaction models are depicted in Figures 4.6 and 4.7.

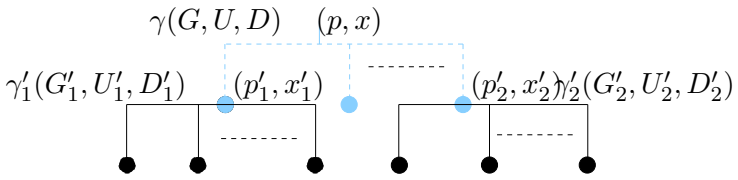


Figure 4.7: $\mathcal{I} \circ \mathcal{I}' = \{(\gamma \bullet \gamma'_1) \bullet \gamma'_2\}$

4.3 Progress description

In this section, we provide a description of progress conditions associated to the syntactic definition of components. Then, we give rules allowing to derive some progress conditions of a composition.

4.3.1 Progress in components

Progress conditions are useful to exclude behaviors staying forever in some particular states or loops. We adapt usual weak and strong fairness conditions [AFK88, FK84] to component by defining a set of progress conditions $Prog$. In this section, we provide first the syntax of progress conditions. Then, their semantics defined as a constraint on infinite executions of the semantics of our components, that is a labeled transition system. As usually, we consider progress conditions as an assumption which will have to be satisfied later on by an implementation.

Definition 4.3.1 (Progress Condition) *Let be $K = (TS, X, Inv, g, Fu, Prog)$ a component. A* progress condition *$pr \in Prog$ is a pair (T_c, T_p), where:*

- *T_c is either a set of transitions of TS or the symbol $\top$. T_c is called the* condition*;*
- *T_p is a set of transitions called* promise*.*

The set of start control states of transitions of T_p are denoted $start(T_p)$ and called progress states*.*

We now define the semantics of a progress condition on a component K as a constraint on the set of executions $exec(Sem_K)$ of the LTS defining its semantics according to the Definition 4.1.3. We recall here that according to the semantics of a component it is supposed that its ports are not connected and that the variables of these ports could take any value meaning that they are used like inputs. When a component K guarantees progress by a transition t in a state q_K, it ensures the same progress in any environment E which from some point on permanently *allows* the transition t. The environment E *allows* a transition t of K in a state q_E if either t is a transition of K that does not need to synchronize with E or if E has a transition synchronizing with t that is enabled in q_E.

Definition 4.3.2 (Semantics of a progress condition) *Let be a component K where its semantics is given by the LTS $Sem_K = (Q, q^0, \mathcal{P} \cup \{\tau\}, \hookrightarrow)$ and σ an infinite execution in Sem_K. Then, σ* respects *the progress condition (T_c, T_p) if the following holds:*

- *If $T_c = \top$, σ contains infinitely many states in $start(T_p)$ implies that it also contains infinitely many transitions in T_p.*
- *If $T_c = \{t_i\}_{i=1}^k$, $t_i \in \hookrightarrow$, σ contains infinitely many t_i transitions implies that it also contains infinitely many transitions in T_p.*
- *If $T_c = \emptyset$, then the progress condition is trivially satisfied.*

σ is called to be a legal *execution of Sem_K if it* respects *all progress condition in $Prog$. We denote by $exec(K)$ the set of* legal *executions of Sem_K.*

Intuitively, the set T_c defines the set of prefixes for which progress has to be ensured. No prefixes satisfy $\emptyset$, thus if $T_c = \emptyset$ there is no progress to guarantee. On the other hand, all prefixes satisfy $\top$, which means that if $T_c = \top$ any execution of the component containing infinitely many a state of $start(T_p)$ must guarantee progress. This is what we call *unconditional* progress.

Our notion of progress is close to the notion of *strong fairness* described in [AFK88, FK84, PPR, PXZ02] and where fairness is defined on states and not transitions. Here, the choice of expressing progress using transitions is highly motivated by the properties we want to verify on our application, described in Chapter 5, and where the progress is guaranteed by the occurrence of some transitions. We now define what it means to guarantee a progress condition by a component.

Definition 4.3.3 *Let be $K = (TS, X, Inv, g, Fu, Prog)$ and (T_c, T_p) be a pair of sets of transitions of TS. K* guarantees *(T_c, T_p), denoted $K \Vdash (T_c, T_p)$, if one the following conditions holds:*

- *$(T_c, T_p) \in Prog$.*
- *$\forall\, \sigma \in exec(K)$, σ respects (T_c, T_p).*

Intuitively, this means that a component guarantees a progress condition if it is indeed one of its progress conditions in *Prog* or if it is implied by its progress conditions. A few rules guaranteeing such implication between progress conditions are given below.

Note also that a progress condition $pr = (T_c, T_p)$ of K is *trivially satisfied* if no T_c transition can be fired infinitely often or when $T_c = \top$ there is no executions containing infinitely many states in $start(T_p)$. A progress condition that cannot be satisfied by a component is called *inconsistent* and it is defined as follows:

Definition 4.3.4 *A progress condition (T_c, T_p) is called* inconsistent *with a component K, if there exist finite prefixes of $exec(Sem_K)$ that cannot be extended to* legal *executions.*

We suppose that all progress conditions in *Prog* of K are *consistent* with K. Note that a progress condition (T_c, T_p) with a set T_p which is empty or not reachable from any sequence of transitions containing T_c-transitions is *inconsistent* with K.

We now provide some rules, that allow reasoning about progress conditions. In particular, these rules allows to deduce new progress conditions from a set of progress conditions. These rules are of particular interest, when one wants to compare components (such as to establish refinement) and thus needs to define some implication between their progress conditions. In the following, let be a component $K = (TS, X, Inv, g, Fu, Prog)$.

Rule 4.3.5 (monotonicity) *$K \Vdash (T_c, T_p)$ implies that $K \Vdash (T_c, T_p \cup \{t\})$, where t is a transition of K.*

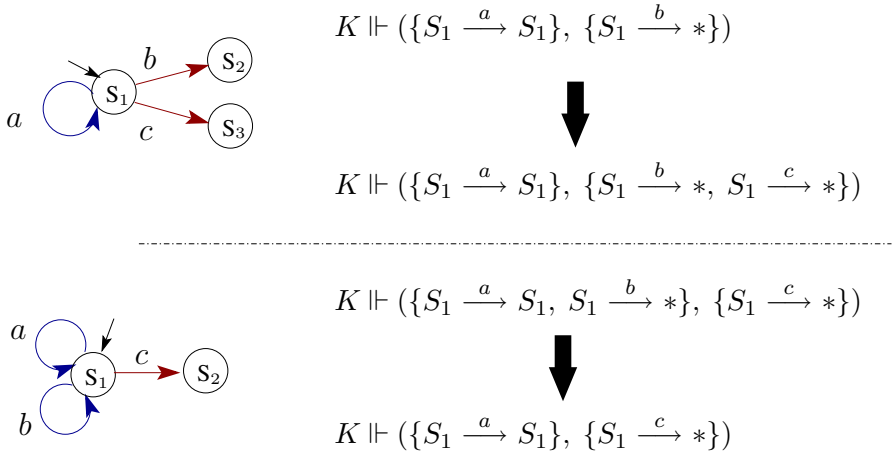


Figure 4.8: Inferring Progress Conditions.

Proof Suppose that $K \Vdash (T_c, T_p)$. Then according to Definition 4.3.3, this means that either $(T_c, T_p) \in \mathit{Prog}$ or $\forall\, \sigma \in exec(K)$, σ respects (T_c, T_p).
If $(T_c, T_p) \in \mathit{Prog}$, then $\forall\, \sigma \in exec(K)$, σ contains infinitely many T_c-transitions implies that it also contains infinitely many transitions in T_p which means also that it also contains infinitely many transitions in $T_p \cup \{t\}$, for any transition t of K. Similarly if $\forall\, \sigma \in exec(K)$, σ respects (T_c, T_p) then it also respects $(T_c, T_p \cup \{t\})$. Thus we obtain that $\forall\, \sigma \in exec(K)$, σ respects $(T_c, T_p \cup \{t\})$, that is $K \Vdash (T_c, T_p \cup \{t\})$. □

The Rule 4.3.5 means that the smaller the set T_p, the stronger the progress constraint. Indeed, when the set T_p is larger, more possibilities are given to guarantee the progress condition, as it is sufficient to fire one of the T_p transitions to ensure the condition. However, the opposite implication does not hold in general. It is only guaranteed when either T_p or $\{t\}$ is not enabled in K when it is possible to fire infinitely many transitions in T_c.

Rule 4.3.6 *$K \Vdash (T_c \cup T'_c, T_p)$ implies that $K \Vdash (T_c, T_p)$; that is, the larger the set T_c, the stronger the progress constraint.*

Proof Suppose that $K \Vdash (T_c \cup T'_c, T_p)$, Then according to Definition 4.3.3, this means that either $(T_c \cup T'_c, T_p) \in \mathit{Prog}$ or $\forall\, \sigma \in exec(K)$, σ respects $(T_c \cup T'_c, T_p)$.
Both cases means that $\forall\, \sigma \in exec(K)$, σ contains infinitely many $T_c \cup T'_c$-transitions implies that it also contains infinitely many transitions in T_p. Thus if σ contains infinitely many T_c transitions it has also to contain infinitely many transitions in T_p, that is σ respects (T_c, T_p). □

The opposite implication of Rule 4.3.6 is only guaranteed if $exec(Sem_K)$ has no executions with loops containing transitions in T'_c or if (T'_c, T_p) is also guaranteed by K.

Example 4.3.7 *Figure 4.8 illustrates the Rules 4.3.5 and 4.3.6 for simples examples of progress conditions. In the left of the figure, there is a representation of the LTS describing the semantics of two components. The set of transitions T_c is presented by blue transitions, and T_p by red ones.*

Example 4.3.8 *Suppose a component K whose description is given by the Figure 4.1 which we suppose has no variables and thus no guards or invariants. We may define for K the progress condition $pr = (\{S_1 \xrightarrow{in} S_1\}, \{S_2 \xrightarrow{out} S_1\})$ which means that K cannot perform the transition labeled by the port in infinitely often, without firing the out transition. Now consider the component in Figure 4.1 with variables, guards and invariants as a possible implementation of K which indeed guarantees pr. In this description whenever the transition in takes place, the associated function f_1 will update the new value of the state variable y using the value of the port variable x_1. As $x_1 > 0$, y will take a positive value ($y > 0$) and then the guard of in will be set to false and the transition could not be fired again. However, the guard corresponding to the internal τ transition will be equal to true and thus performed if we suppose that this implementation guarantees progress by their enabled transitions. This forbids in transition to be fired again, before out transition takes place.*

4.3.2 Progress of a composition

The methodology of Chapter 3 requires proving properties of compositions of components. More precisely, in step 3 of the methodology, the dominance of a set of contracts over a global contract requires a set of refinement proofs showing that a composition refines a property in some context. Concerning progress, this means that one has to show, that the finer, composed property guarantees at least the progress required by the looser global property, and therefore we do not need to compute the strongest but only a sufficient progress condition for products.

Thus, we only provide some rules which allow to derive some progress conditions of a composite component from progress conditions of its sub-components. The idea is based, first, on defining a projection of this property of K on the set of properties corresponding to $\{K_i\}$. Then providing conditions on these projections so as to guarantee to global property of the composition.

To define such a projection, we provide first a notion of projection of a transition of K into a set of *local* transitions corresponding each one to a transition in K_i. This projection, as well as the condition provided in Definition 4.3.10, are defined on the syntax of components. Thus it takes into account how this transition is obtained and it is computed w.r.t the interaction model used to build this composite component.
In the following, we suppose $\{K_1, ..., K_n\}$ a set of components such that $K_i = (TS_i, X_i, Inv_i, g_i, Fu_i, Prog_i)$ where, $TS_i = (Q_i, q_i^0, \mathcal{P}_i, \longrightarrow_i)$. $\mathcal{I}$ an interaction model defined on $\bigcup_{i=1}^{n} \mathcal{P}_i$ and defining an interface $\mathcal{P}_\mathcal{I}$. $K = \mathcal{I}(K_1, ..., K_n)$ a composite component obtained as described in Definition 4.2.6. $K = (TS, X, Inv, g, Fu, Prog)$ where $TS = (Q, q^0, \mathcal{P}_\mathcal{I}, \longrightarrow)$.

Definition 4.3.9 (Projection of a transition) *Let $t = (q_1, ..., q_n) \xrightarrow{p} (q'_1, ..., q'_n)$ be a transition of K ($t \in \longrightarrow$) where p is the exported port of a connector γ with a support set $\mathcal{P}_\gamma$. Then the projection of t on the component K_i denoted $\pi_i(t) \in \longrightarrow_i$ is defined as follows:*

- *if $\mathcal{P}_i \cap \mathcal{P}_\gamma = \{p_i\}$ then, $\pi_i(t) = q_i \xrightarrow{p_i}_i q'_i$*

- *if* $\mathcal{P}_i \cap \mathcal{P}_\gamma = \emptyset$ *then,* $\pi_i(t) = \emptyset$

The projection of a set of transitions $T \subseteq \longrightarrow$ *is* $\pi_i(T) = \{\pi_i(t) | t \in T\}$.

Control transitions and control states of the composite component K are called *global*, and their corresponding projections are called *local*.

Note here, that we do not treat the case of τ transitions as they are not relevant in a composition, however we will discuss progress by τ-transitions when defining refinement in Section 4.4.

We now provide sufficient conditions allowing to deduce that a given progress condition is guaranteed by a composition of components using progress condition guaranteed by these components. For the sake of clarity and w.l.o.g , in the following definition, we treat the case of K obtained as a composition of two components K_1, K_2 as it can be naturally extended to a composition of n components.

Theorem 4.3.10 (Progress condition of a composition) *Let* $pr = (T_c, T_p)$ *be a pair of sets of transitions of* K*. Let be the set* T_{c_i} *defined by* $T_{c_i} \subseteq \pi_i(T_c)$ *if* $\pi_i(T_c) \neq \emptyset$ *and* $T_{c_i} = \top$ *otherwise. If one of the following conditions holds then we have* $K \Vdash pr = (T_c, T_p)$ *:*

1. *If* T_p *is a set of transitions labeled by ports representing* observation *connectors, then to guarantee* pr *it is sufficient that* $\exists\ i \in [1, 2]$*, such that* $K_i \Vdash (T_{c_i}, \pi_i(T_p))$*; This means that to guarantee* pr *it is sufficient to guarantee a looser progress implying* pr*, that is the progress by any transitions which do not require synchronization.*

2. *If* T_p *is of the form* $T_p^{obs} \cup T_p^{rdv}$ *where* T_p^{obs} *a set of transitions labeled by ports of* observation *connectors and* T_p^{rdv} *a set of transitions for* rendez-vous *connectors. Then to guarantee* pr*, it is sufficient to guarantee either the progress condition* (T_c, T_p^{obs}) *as described above, or one the following conditions:*

   - *It exists a set* $T \subseteq T_p^{rdv}$ *of transitions labeled by the same port* p *and at least one of two components, let it be* K_1*, guarantees* $(T_{c_1}, \pi_1(T))$ *and the other, that is* K_2*, guarantees that in any situation* compatible with T_{c_2} *some transitions in* $\pi_2(T)$ *will eventually be enabled forever unless no* T_c*-transitions are infinitely taken or one of the transitions in* T *is taken. A situation is compatible with* T_{c_2} *if it exists executions containing infinitely many* T_{c_2}*-transitions. Note that in the case of* n *components, the second condition has to be ensured by (n-1) components.*
   - *It exists a set* $T \subseteq T_p^{rdv}$ *of transitions labeled by the same port* p *and in any state* $q = (q_1, q_2) \in Q$ *a global state of* K *in which a infinite sequence of transitions containing* T_c*-transitions is possible and for at least one of the two components (*K_1*) we have* $q_1 \in start(\pi_1(T))$ *and for the other (*K_2*) we have* $q_2 \notin start(\pi_2(T))$ *then* K_2 *must also guarantee that a transition labeled by* p *will eventually be enabled in* q_2*. This guarantees that whenever a component guarantees a transition for synchronization in a given global state, the rest of components involved in the synchronization will offer this transition in the same global state.*

     In both cases K *satisfies the much stronger progress condition* (T_c, T).

Note that we can weaken these conditions to guarantee $(T_c, T_p^{obs} \cup T)$ *by requiring that* K_1 *guarantees* $(\pi_1(T_c), \pi_1(T_p^{obs}) \cup \pi_1(T))$ *and that* K_2 *guarantees* $(\pi_2(T_c), \pi_2(T_p^{obs}))$ *or the additional condition required to guarantee* T.

Note that the additional condition that K_2 has to guarantee in case 2 is semantic and a syntactic approximation of this condition is possible using the syntactic description of components.

This definition distinguishes two cases related to the type of connectors used to compose components. When the promise of the progress condition involves transitions of *observation* connectors, then to guarantee this progress, it is sufficient that at least one component guarantees this progress locally. However, as shown in Definition 4.3.10, it is much complicated when the promise of the progress condition involves transitions corresponding to strong synchronizations between the $\{K_i\}$.

Note that these conditions are sufficient means that if they are not satisfied by the set of components $\{K_i\}$, they do not help us to decide whether pr is indeed a progress condition of K or not. New weaker conditions could also be defined, however in the application described in Chapter 5, the conditions provided here are sufficient to deduce progress of the built compositions.

Example 4.3.11 *Let be the composite component* $\mathcal{I}(K^1, K^2)$ *described in the Example 4.2.7 built as a composition of components* K^1 *and* K^2 *(see Figure 4.3). We have already explained in Example 4.3.8 how* $K^1 \Vdash (\{S_1^1 \xrightarrow{out^1} S_1^1\}, \{S_2^1 \xrightarrow{in^1} S_1^1\})$*, as in addition* K^2 *guarantees that the transition* $S_2^2 \xrightarrow{out^2} S_1^2$ *is always enabled in* S_2^2*, then we can deduce, according to the second condition of Definition 4.3.10, that* $\mathcal{I}(K^1, K^2)$ *guarantees the progress condition* $(\{S_1^1S_1^2 \xrightarrow{1to2} S_1^1S_1^2\}, \{S_2^1S_2^2 \xrightarrow{2to1} S_1^1S_1^2\})$.

4.4 Relations of the contract framework

In this Section, we provide the remaining ingredients to the definition of the contract framework. For this purpose, let us first recall that a contract framework is defined by (1) a component framework, (2) a conformance relation $\preccurlyeq$ that is transitive and (3) a refinement under context relation $\{\sqsubseteq_{(E,\mathcal{I})}\}$ parameterized by a context and implying conformance.

In the previous sections we have provided a component framework enriched with variables and data transfer. We now provide a description of conformance and refinement under context relations.

Usually, conformance relation is given first and refinement is a preorder implying conformance, where very often it is chosen to be the weakest such relation that is compositional. In order to be able to use the property of circular reasoning, we may need stronger refinement relations. Here we inverse the presentation for presentational reasons only. In fact, it turned out easier to define conformance in terms of refinement under context rather than the other way round.

4.4.1 Refinement

We provide here, the relation of refinement under context we have chosen for the already described component framework. Remember that refinement relates two components

with respect to a given context. In this section, a context is denoted $(E, \mathcal{I})$, where $E = (TS_E, X_E, Inv_E, g_E, Fu_E, Prog_E)$ with $TS_E = (Q_E, q_E^0, \mathcal{P}_E, \longrightarrow_E)$ and $\mathcal{I}$ is an interaction model given by a set of connectors defined on the set of ports $S_\mathcal{I}$. $\mathcal{I}$ defines an interface $\mathcal{P}_\mathcal{I}$ that is the exported ports of its connectors.

Let be two components K_{abs} and K_{conc} where K_{abs} is called the *abstract* component and K_{conc} the *concrete* component and we want to define a refinement of K_{abs} by K_{conc} in the context $(E, \mathcal{I})$.

K_{abs} and K_{conc} are given as follows: $K_{abs} = (TS_{abs}, X_{abs}, Inv_{abs}, g_{abs}, Fu_{abs}, Prog_{abs})$ and $K_{conc} = (TS_{conc}, X_{conc}, Inv_{conc}, g_{conc}, Fu_{conc}, Prog_{conc})$ where $TS_{abs} = (Q_{abs}, q_a^0, \mathcal{P}, \longrightarrow_a)$ and $TS_{conc} = (Q_{conc}, q_c^0, \mathcal{P} \cup \{\tau\}, \longrightarrow_c)$.

Note that the interaction model $\mathcal{I}$ connects K_{abs} and K_{conc} to their environment E, thus it is defined on $S_\mathcal{I} = \mathcal{P} \cup \mathcal{P}_E$ and it contains structured connectors of the form $\gamma = (p_\gamma, \mathcal{P}_\gamma)$ where $card(\mathcal{P}_\gamma) \leq 2$. Indeed, as connectors do not connect more than one port of the same component, $\mathcal{P}_\gamma$ contains either two ports one of $\mathcal{P}_E$ and the other of $\mathcal{P}$ or only one port that is of $\mathcal{P}_E$ or of $\mathcal{P}$.

We denote also by $Sem_{\mathcal{I}(K_i,E)}$ the LTS defining the semantics of the ELTS given by $\mathcal{I}(K_i, E)$ according to the Definition 4.1.3 and by $Sem^{Tr}_{\mathcal{I}(K_i,E)}$ the set of its transitions.

For the sake of clarity of our definition of refinement, we suppose the following:

1. K_{abs} has no internal (τ) transitions;
2. E has no no internal (τ) transitions;

These assumptions imply no loss of generality as internal transitions do not involve any interaction with the environment.

The refinement we propose is defined by the means of two relations:

- α is a boolean expression on variables of K_{conc} and K_{abs} representing a relation between abstract and concrete valuations.
- $\mathcal{R}$ relates the control states of K_{conc} and its environment E to the control states of K_{abs} and thus defines which concrete states refine the abstract ones.

It is a well-known fact that any property expressed by a *Buchi* automaton can be written as an intersection of a safety and a progress property [AS87], and this holds also for our properties. Thus our definition of refinement consists of two parts. The *safety* part allows to describe that any transition that is offered in K_{conc} is also allowed by K_{abs}. This guarantees that in the concrete component K_{conc}, we do not have executions that are non permitted by the abstract component K_{abs}. Note that to preserve *safety*, we have to take into account the context. Indeed, a given transition of K_{conc} that is structurally forbidden by the context, does not have to be allowed by K_{abs}. *Safety* preservation is defined by the relation $\mathcal{R}$ defined on control states of components.

The *progress* part of our refinement relation takes into account the set of progress properties of components K_{conc} and K_{abs}. To preserve progress by refinement, we propose to define some particular relation of *projection* with respect to the relation $\mathcal{R}$ of the refinement relation (see Definition 4.4.1). This projection allows to infer from the set of progress properties of K_{abs}, a new set of progress properties that K_{conc} has to provide. More precisely, we use the relation $\mathcal{R}$ obtained by

the *safety* preservation of the refinement relation, to compute the inverse image, by $\mathcal{R}$, of transitions K_{abs} that is a set of transitions of K_{conc}. Thus we provide now this definition of the projection of a transition with respect to a given relation between control states of components K_{conc}, K_{abs} and E.

Definition 4.4.1 (Projection of a relation) *Let $\mathcal{R}$ be a relation on $(Q_{conc} \times Q_E) \times Q_{abs}$. We say $\overline{\mathcal{R}} \subseteq Q_{conc} \times Q_{abs}$ is the projection of $\mathcal{R}$ and $q_c \,\overline{\mathcal{R}}\, q_a$ iff $\exists q_E$ s.t. $(q_c, q_E)\,\mathcal{R}\, q_a$.*

For $Q_a \subseteq Q_{abs}$, let be $\overline{\mathcal{R}}^{-1}(Q_a) = \{q_c \in Q_{conc} | \exists q_a \in Q_a \wedge q_c \,\overline{\mathcal{R}}\, q_a\}$ the inverse image of Q_a under $\overline{\mathcal{R}}$. Thus we have $\overline{\mathcal{R}}^{-1}(Q_a) \subseteq Q_{conc}$.

Similarly, we denote by $\overline{\mathcal{R}}_T^{-1}$ the inverse image of a transition $t \in \longrightarrow_a$ defined as follows: $\overline{\mathcal{R}}_T^{-1}(\{q_a \xrightarrow{p}_a q'_a\}) = \{(q_c \xrightarrow{p}_c q'_c) \in \longrightarrow_c \ such\ that\ q_c \in \overline{\mathcal{R}}^{-1}(\{q_a\}) \wedge q'_c \in \overline{\mathcal{R}}^{-1}(\{q'_a\})\}$ which denotes the set of p-transitions of K_{conc} between states in $\overline{\mathcal{R}}^{-1}(\{q_a\})$ and in $\overline{\mathcal{R}}^{-1}(\{q'_a\})$. If such transitions do not exist then $\overline{\mathcal{R}}_T^{-1}(\{q_a \xrightarrow{p}_a q'_a\}) = \emptyset$. This notation extends naturally to transition sets.

Definition 4.4.2 (Refinement under context) *K_{conc} refines K_{abs} in the context of $(E, \mathcal{I})$, denoted $K_{conc} \sqsubseteq_{E,\mathcal{I}} K_{abs}$, iff:*

- *Safety part: $\exists \alpha$ a relation in $X_{conc} \cup X_{abs}$ and $\exists \mathcal{R} \subseteq (Q_{conc} \times Q_E) \times Q_{abs}$ s.t. $(q_c^0, q_E^0)\,\mathcal{R}\, q_a^0$ and s.t. $(q_c, q_E)\,\mathcal{R}\, q_a$ implies:*
  1. *$Inv_{q_c} \wedge \alpha(X_{conc}, X_{abs}) \implies Inv_{q_a}$*
  2. *$\forall p[x] \in \mathcal{P}$, $\exists \gamma = (p_\gamma, \mathcal{P}_\gamma) \in \mathcal{I}$ such that $p \in \mathcal{P}_\gamma$, then the following holds: $t_c = (q_c, q_E) \xrightarrow{p_\gamma} (q'_c, q'_E) \in Sem^{Tr}_{\mathcal{I}(K_{conc},E)}$ implies $\exists q'_a$ such that $t_a = (q_a, q_E) \xrightarrow{p_\gamma} (q'_a, q'_E) \in Sem^{Tr}_{\mathcal{I}(K_{abs},E)}$ and $(q'_c, q'_E)\,\mathcal{R}\, q'_a$. If t_c is independent of the context, i.e., if $\mathcal{P}_\gamma = \{p\}$, then $q'_E = q_E$.*
  3. *$q_c \xrightarrow{\tau}_c q'_c \Longrightarrow (q'_c, q_E)\,\mathcal{R}\, q_a$: states related by τ-transitions refine the same state*
- *Progress part:*

$$\forall\, (T_c, T_p) \in Prog_{abs},\ K_{conc} \Vdash (\overline{\mathcal{R}}_T^{-1}(T_c), \overline{\mathcal{R}}_T^{-1}(T_p)).$$

Note that if $(\overline{\mathcal{R}}_T^{-1}(T_c) \neq \emptyset)$ then the progress condition $(\overline{\mathcal{R}}_T^{-1}(T_c), \overline{\mathcal{R}}_T^{-1}(T_p))$ is *trivially satisfied* by K_{conc}. However, if $(\overline{\mathcal{R}}_T^{-1}(T_p) \neq \emptyset)$ then the progress condition $(\overline{\mathcal{R}}_T^{-1}(T_c), \overline{\mathcal{R}}_T^{-1}(T_p))$ is *inconsistent* with K_{conc} and thus that K_{conc} does not guarantee this progress.

Our relation of refinement preserves safety as it is based on the usual notion of simulation and it also preserves progress from the abstract component to the concrete one. Note that the progress part of our definition of refinement takes into account the context, as the progress conditions that K_{conc} has to satisfy are computed using the inverse image of $\mathcal{R}$ that is a relation involving the context. Note that for a given transition t in T_p, the projection of its abstract start state by $\overline{\mathcal{R}}^{-1}$ may correspond to a set of concrete states due to the presence of τ transitions in K_{conc}. Thus proving the progress by t is then transformed into proving the progress between the states refining $start(t)$ to a state guaranteeing

t. This is detailed in the following rule where we suppose that (T_c, T_p) a pair of sets of transitions of K_{abs}, where $T_p = \{t_p = q \xrightarrow{p} q'\}$, $K_{abs} \Vdash (T_c, t_p)$ and $K_{conc} \sqsubseteq_{E,\mathcal{I}} K_{abs}$ according to the Definition 4.4.2 of refinement. We also suppose that $\overline{\mathcal{R}}_T^{-1}(T_c) \neq \emptyset$ and $\overline{\mathcal{R}}_T^{-1}(t_p) \neq \emptyset$.

Rule 4.4.3 (Progress with τ-transitions) *Let $\overline{\mathcal{R}}^{-1}(q) = Q_c$ be the set of states of K_{conc} refining q the start state of t_p. Then to prove that $K_{conc} \Vdash (\overline{\mathcal{R}}_T^{-1}(T_c), \overline{\mathcal{R}}_T^{-1}(t_p))$ it is sufficient to prove the following:*
$\forall\, q_c \in Q_c$ either $K_{conc} \Vdash (\overline{\mathcal{R}}_T^{-1}(T_c), q_c \xrightarrow{p})$ or all finite sequences of τ transitions $t_1 t_2, \ldots, t_n$ starting from q_c, relating states in Q_c, lead to a state $q_{conc} \in Q_c$ such that $K_{conc} \Vdash (\overline{\mathcal{R}}_T^{-1}(T_c), q_{conc} \xrightarrow{p})$ and $\forall\, i \in [1, n]$, $K_{conc} \Vdash (\overline{\mathcal{R}}_T^{-1}(T_c), t_i)$.

Proof Suppose that $\forall\ q_c \in Q_c$ either $K_{conc} \Vdash (\overline{\mathcal{R}}_T^{-1}(T_c), q_c \xrightarrow{p})$ or all finite sequences of τ-transitions $t_1 t_2, \ldots, t_n$ starting from q_c, relating states in Q_c, lead to a state $q_{conc} \in Q_c$ such that $K_{conc} \Vdash (\overline{\mathcal{R}}_T^{-1}(T_c), q_{conc} \xrightarrow{p})$ and $\forall\, i \in [1, n]$, $K_{conc} \Vdash (\overline{\mathcal{R}}_T^{-1}(T_c), t_i)$. What we have to prove is that it does not exist an execution σ of $exec(Sem_{K_{conc}})$ such that σ contains infinitely many transitions in $\overline{\mathcal{R}}_T^{-1}(T_c)$ and visiting infinitely often states in Q_c without guaranteeing a transition labeled by p. Suppose that such execution exists, then visiting infinitely often states in $Q'_c \subseteq Q_c$ without firing a transition p means that all states in Q'_c do not guarantee p and no finite sequence to such state is guaranteed from these states, which is in contradiction with our assumption. In addition, a state $q_{conc} \in Q_c$ such that $q_{conc} \xrightarrow{p}$ indeed exists as it is guaranteed by the fact that $\overline{\mathcal{R}}_T^{-1}(t_p) \neq \emptyset$ (see Definition 4.4.1).

□

The choice of refinement under context is one among other possible relations, however this choice is highly motivated by the fact that this relation allows the property of *circular reasoning*. A proof is given in Section 4.5.1.

Example 4.4.4 *Figure 4.9 gives an example of an abstract component K^a and a concrete component K^c such that $K^c \sqsubseteq_{K^E,\mathcal{I}} K^a$. The relation between variables is given by α denoting that the variable y of K^a is computed as the sum of two variables x_1 and x_2 of K^c. The interaction model $\mathcal{I}$ specifies how each component interact with the environment K^E. Note that labels which are not ports and thus are not connected by $\mathcal{I}$ represent internal transitions of components (τ-transitions).*

To check if the component K^c refines K^a in the context $(K^E, \mathcal{I})$ and according to Definition 4.4.2, we start by the initial states of these components and check if they are related by $\mathcal{R}$. For this purpose we have first to prove that, given the relation α between concrete and abstract variables, we have an implication from the concrete invariant to the abstract one. This is verified for the initial states as $(x_1 = x_2 = 0) \wedge (y = x_1 + x_2) \implies (y = 0)$. Second we have to check that all (non internal) outgoing transitions of S_1^c, which are allowed by the environment K^E and by the interaction model $\mathcal{I}$, are also outgoing transitions of S_1^a, which is the case of the transition labeled by get. Similarly, we have to prove now that the target states of this transition (get) are also related by $\mathcal{R}$.

The different refinement conditions are successfully applied to the different states of these components and the obtained states in relations are: $(S_1^c, S_E)\,\mathcal{R}\,S_1^a$, $(S_2^c, S_E)\,\mathcal{R}\,S_2^a$ *and* $(S_3^c, S_E)\,\mathcal{R}\,S_2^a$. *$\tau$-Transitions are internal transitions, thus they may not be offered by* K^a. *Note that the abstract state* S_2^a *is refined by two concrete states. This is in general the case when one wants to give more details about the concrete variables of a component or to explicit some (implicit) actions that have been hidden in the abstract description of some states. Figure 4.9 describes only the safety part of*

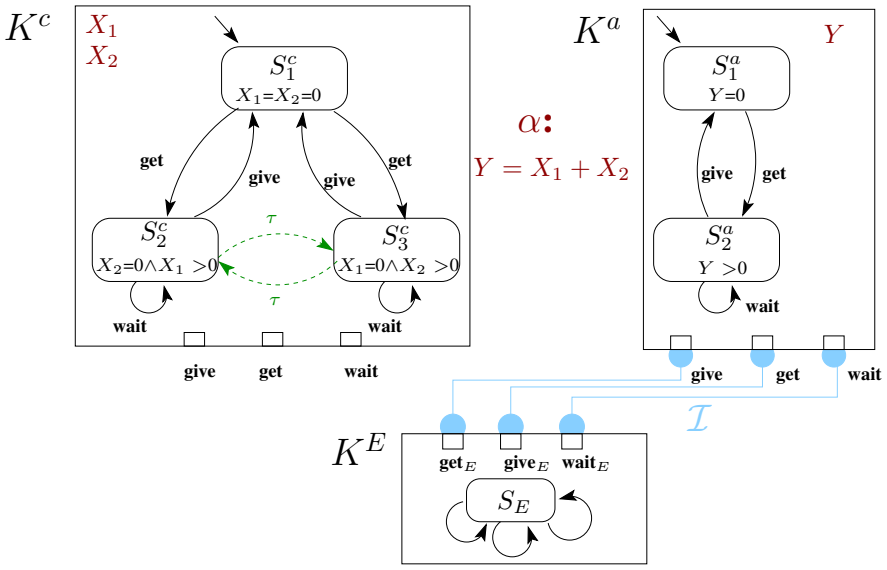


Figure 4.9: Refinement: $K^c \sqsubseteq_{K^E,\mathcal{I}} K^a$.

K^b and K^c.
To illustrate the progress refinement part, let suppose that $Pr^a = (S_2^a \xrightarrow{wait} *, S_2^a \xrightarrow{give} *) \in Prog_{K^a}$. *There are several ways to guarantee this progress by* K^c. *We have* $\overline{\mathcal{R}}^{-1}(\{S_2^a\}) = \{S_2^c, S_3^c\}$, $\overline{\mathcal{R}}_T^{-1}(\{S_2^a \xrightarrow{wait} *\}) = \{S_2^c \xrightarrow{wait} *, S_3^c \xrightarrow{wait} *\}$ *and* $\overline{\mathcal{R}}_T^{-1}(\{S_2^a \xrightarrow{give} *\}) = \{S_2^c \xrightarrow{give} *, S_3^c \xrightarrow{give} *\}$. *Then to guarantee* Pr^a *it is sufficient that* K^c *guarantees one of the following conditions:*
(1) $(\{S_2^c \xrightarrow{wait} *\}, \{S_2^c \xrightarrow{give} *\})$ *and* $(\{S_3^c \xrightarrow{wait} *\}, \{S_3^c \xrightarrow{give} *\})$.
(2) $(\{S_2^c \xrightarrow{wait} *\}, \{S_2^c \xrightarrow{give} *\})$ *and* $(\{S_3^c \xrightarrow{wait} *\}, \{S_3^c \xrightarrow{\tau} S_2^c\})$.
(3) $(\{S_3^c \xrightarrow{wait} *\}, \{S_3^c \xrightarrow{give} *\})$ *and* $(\{S_2^c \xrightarrow{wait} *\}, \{S_2^c \xrightarrow{\tau} S_3^c\})$.

4.4.2 Conformance

To define conformance we first introduce the notion of *empty context* for an interface of a component.

Definition 4.4.5 (Empty context) *An* empty context *for an interface $\mathcal{P}$ is a pair $(E, \mathcal{I})$ where, E defines any component and $\mathcal{I}$ is the interaction model defined by the set of observation connectors $\{\gamma_i = (p_i, \{p_i\})\, \forall p_i \in \mathcal{P}\}$ and thus $\mathcal{P}_\mathcal{I} = \mathcal{P}$.*

Intuitively, an empty context $(E, \mathcal{I})$ for an interface $\mathcal{P}$ of a component K means a context that does not connect K to E and an $\mathcal{I}$ that exports only ports of K which means that the behavior of E is irrelevant. We now define conformance as a refinement in an *empty* context.

Definition 4.4.6 (Conformance) *Let be K_2 and K_2 two components defined on the same interface $\mathcal{P}$. Let $(E, \mathcal{I})$ be an empty context on $\mathcal{P}$.*

$$K_1 \preccurlyeq K_2 \textit{ iff } K_1 \sqsubseteq_{(E,\mathcal{I})} K_2$$

Intuitively, this relation of conformance is a simulation of the safety part of K_1 to K_2 and an inclusion of infinite executions of the progress description of K_2 into those of K_1.

Example 4.4.7 *Figure 4.9 represents the component K^c which refines the component K^a in the context $(K^E, \mathcal{I})$. This allows to deduce that the closed system obtained as $\mathcal{I}(K^c, K^E)$ conforms to the closed system $\mathcal{I}(K^a, K^E)$.*

We now have all the necessary ingredients that define a contract framework.

Theorem 4.4.8 *We have defined a contract framework. Furthermore, if assumptions are deterministic, then circular reasoning is sound for the refinement under context of Definition 4.4.2.*

We now have to prove that such a framework is well formed to support the methodology, described in Chapter 3, that is its a well-defined contract framework with a refinement under context ensuring the property of circular reasoning. See Proof 4.5.1.

4.5 Proofs

In this section we detail the proof of the Theorem 4.4.8 and the proofs of all related properties.

4.5.1 Well-definedness of the contract framework

We detail here the proof steps required to show that we have first a component framework as required in Definition 2.2.1. Second, we prove that this component framework together with the relations of *refinement under context* and *conformace*, described in Section 4.4, define indeed a contract framework in which *circular reasoning* is sound.

Well-defined Component framework. In the proposed component framework, we are using a variant of BIP component framework. GL is the set of interactions models given as connectors described in Section 4.2, Their compostion operator $\circ$ defined in Section 4.2.3 allows *flattening* as the merge of two connectors, that is a hierarchical connector, allows to build a new flat connector. Composition of interaction models is thus defined as a union of a set of disjoint connectors, which allows to deduce that $(GL, \circ)$ is a commutative monoid, i.e. it ensures associativity, identity and of course commutativity (see [BS08a]):

1. $\forall \mathcal{I}_1, \mathcal{I}_2, \mathcal{I}_3 \in GL.\ (\mathcal{I}_1 \circ \mathcal{I}_2) \circ \mathcal{I}_3 = \mathcal{I}_1 \circ (\mathcal{I}_2 \circ \mathcal{I}_3)$
2. $\exists \mathcal{I}_e \in GL.\ \forall \mathcal{I} \in GL.\ \mathcal{I}_e \circ \mathcal{I} = \mathcal{I} \circ \mathcal{I}_e = \mathcal{I}$
3. $\forall \mathcal{I}_1, \mathcal{I}_2 \in GL.\ \mathcal{I}_1 \circ \mathcal{I}_2 = \mathcal{I}_2 \circ \mathcal{I}_1$

We have also to prove that $\mathcal{I}_1\{\mathcal{I}_2\{\mathcal{K}^1\}, \mathcal{K}^2\}\} \cong (\mathcal{I}_1 \circ \mathcal{I}_2)\{\mathcal{K}^1 \cup \mathcal{K}^2\}$, where $\mathcal{K}_1$ and $\mathcal{K}_2$ are set of components. In other words, composition of components is consistent with composition of composition operators. Here, the equivalence is defined as the syntactic equality.
Proof We write the proof for $\mathcal{K}^1 = \{K_1, K_2\}$ and $\mathcal{K}^2 = \{K_3\}$ and. The generalization should be clear. We also suppose w.l.o.g that each interaction model consists into only one connector. This equivalence is trivial if the two connectors of each interaction model are disjoint as in this case $\circ$ is defined by the union operator which guarantees this equivalence. Thus we can reduce the proof to a merge of two connectors. Let be $\mathcal{I}_1 = \gamma_1$ and $\mathcal{I}_2 = \gamma_2$, where the exported port of γ_2, $p_{\gamma_2} \in \mathcal{P}_{\gamma_1}$, $\mathcal{P}_{\gamma_1} = \{p_{\gamma_2}, p_3\}$ with $p_3 \in \mathcal{P}_{K_3}$ and $\mathcal{P}_{\gamma_2} = \{p_1, p_2\}$. For the sake of clarity and w.l.g we also suppose that each component K_i has only $\{p_i\}$ as interface that is $\mathcal{P}_{K_i} = \{p_i\}$.
$\mathcal{I}_1\{\mathcal{I}_2\{K_1, K_2\}, K_3\} = (TS, X, Inv, g, Fu, Prog)$, where:

- $TS = (Q, q^0, \mathcal{P} \cup \{\tau\}, \longrightarrow)$
- $Q = ((Q_1 \times Q_2) \times Q_3)$
- $q^0 = ((q_1^0, q_2^0), q_3^0)$
- $\mathcal{P} = p_{\gamma_1}$
- $X^{st} = (X_1^{st} \cup X_2^{st}) \cup X_3^{st}$, $X^{tr} = (X_1^{tr} \cup X_2^{tr} \cup X_{\mathcal{I}_2}) \cup X_2^{tr} \cup X_3^{tr} \cup X_{\mathcal{I}_1}$
- $Inv_q = ((Inv_{q_1} \wedge Inv_{q_2}) \wedge Inv_{q_3})$
- for $q = ((q_1, q_2), q_3) \in Q$ and $q' = ((q_1', q_2'), q_3') \in Q$, the transition $t = q \xrightarrow{p} q' \in \longrightarrow$ iff $p = p_{\gamma_1}$ and it exists local transitions $t_{12} = (q_1, q_2) \xrightarrow{p_{\gamma_2}} (q_1', q_2') \in \longrightarrow_{\mathcal{I}_2\{K_1,K_2\}}$ and $t_3 = q_3 \xrightarrow{p_3} q_3') \in \longrightarrow_{K_3}$ with $g_t = g_{t_{12}} \wedge g_{t_3} \wedge R_{12} \wedge R_3 \wedge G_{\gamma_1}$. Besides $t_{12} = (q_1, q_2) \xrightarrow{p_{\gamma_2}} (q_1', q_2') \in \longrightarrow_{\mathcal{I}_2\{K_1,K_2\}}$ means that it exists $t_1 = q_1 \xrightarrow{p_1} q_1') \in \longrightarrow_{K_1}$ and $t_2 = q_2 \xrightarrow{p_2} q_2') \in \longrightarrow_{K_2}$ with $g_{t_{12}} = g_{t_1} \wedge g_{t_2} \wedge R_1 \wedge R_2 \wedge G_{\gamma_2}$.

$(\mathcal{I}_1 \circ \mathcal{I}_2)\{K_1, K_2, K_3\} = (TS, X, Inv, g, Fu, Prog)$, where:

- $TS = (Q, q^0, \mathcal{P}_{\mathcal{I}} \cup \{\tau\}, \longrightarrow)$
- $Q = (Q_1 \times Q_2 \times Q_3)$
- $q^0 = (q_1^0, q_2^0, q_3^0)$
- $\mathcal{P} = p_{\gamma_1}$ (according to the definition of merge of connectors).
- $X^{st} = (X_1^{st} \cup X_2^{st}) \cup X_3^{st}$, $X^{tr} = (X_1^{tr} \cup X_2^{tr} \cup X_3^{tr}) \cup (X_{\mathcal{I}_2} \cup X_{\mathcal{I}_1}$ according to the Definition 4.2.8 of merge of connectors. Note that if the two connectors are observation connectors then, not variables are associated to them.
- $Inv_q = Inv_{q_1} \wedge Inv_{q_2} \wedge Inv_{q_3}$
- for $q = (q_1 \times q_2 \times q_3) \in Q$ and $q' = (q_1' \times q_2' \times q_3') \in Q$, the transition $q \xrightarrow{p} q' \in \longrightarrow$ iff $p = p_{\gamma_1}$ according to the definition of merge of connectors and it exists local transitions as follows: $t_1 = q_1 \xrightarrow{p_1} q_1') \in \longrightarrow_{K_1}$ and $t_2 = q_2 \xrightarrow{p_2} q_2') \in \longrightarrow_{K_2}$ and $t_3 = q_3 \xrightarrow{p_3} q_3') \in \longrightarrow_{K_3}$. such that $g_t = g_{t_1} \wedge g_{t_2} \wedge R_1 \wedge R_2 \wedge g_{t_3} \wedge R_3 \wedge (G_{\gamma_2} \wedge G_{\gamma_1})$

Thus after renaming of states of $\mathcal{I}_1\{\mathcal{I}_2\{K_1, K_2\}, K_3\}$ which are $((q_1, q_2), q_3)$ become of the form (q_1, q_2, q_3) and if we extend as below to deal with observation connectors, we can obtain easily the syntactic equality between both of the composite components. □

Well-defined Contract framework. Here, we prove that conformance is transitive, then that refinement implies conformance and finally that our relation of refinement is preserved by composition and it allows circular reasoning.

- The transitivity of conformance is trivially deduced from the transitivity of the relation of refinement.
- Preservation of refinement by composition: $K_1 \sqsubseteq_{\mathcal{I}_E\{E_1,E_2\},\mathcal{I}} K_2 \implies \mathcal{I}_1\{K_1, E_1\} \sqsubseteq_{E_2,\mathcal{I}_2} \mathcal{I}_1\{K_2, E_1\}$ where $\mathcal{I}_1$ and $\mathcal{I}_2$ are the composition operators obtained from $\mathcal{I}$ and $\mathcal{I}_E$ using flattening and decomposition.
  Proof Let suppose that $K_1 \sqsubseteq_{\mathcal{I}_E\{E_1,E_2\},\mathcal{I}} K_2$ and that $K_i = (TS_i, X_i, Inv_i, g_i, Fu_i, Prog_i)$, $E_i = (TS_{E_i}, X_{E_i}, Inv_{E_i}, g_{E_i}, Fu_{E_i}, Prog_{E_i})$ where $TS_i = (Q_i, q_i^0, \mathcal{P}_i, \longrightarrow_i)$ This means according to Definition 4.4.2 of refinement that it exists a relation $R \subseteq (Q_1 \times (Q_{E_1} \times Q_{E_2})) \times Q_2$ with the stated properties. We define the relation $R' \subseteq ((Q_1 \times Q_{E_1}) \times Q_{E_2}) \times (Q_2 \times Q_{E_1})$ by
  $$((q_1, q_{E_1}), q_{E_2}) R' (q_2, q_{E_1}) \triangleq (q_1, (q_{E_1}, q_{E_2})) R q_2$$
  Let us prove that R' has the expected properties:
  - $(q_1^0, q_{E_1}^0), q_{E_2}^0) R' (q_2^0, q_{E_1}^0$ holds by definition.
  - We have that $Inv_{q_1} \wedge \alpha(X_1, X_2) \implies Inv_{q_2}$, we have to prove that $\exists \alpha'(X_1 \cup X_{E_1}, X_2 \cup X_{E_1})$ $(Inv_{q_1} \wedge Inv_{q_{E_1}}) \wedge \alpha'(X_1 \cup X_{E_1}, X_2 \cup X_{E_1}) \implies (Inv_{q_2} \wedge Inv_{q_{E_1}})$. For it is sufficient to

choose α' such that $\alpha' \implies \alpha$.
- Suppose now that $((q_1, q_{E_1}), q_{E_2}) R' (q_2, q_{E_1})$ and that $t_1 = ((q_1, q_{E_1}), q_{E_2}) \xrightarrow{p_{\mathcal{I}_2}} ((q'_1, q'_{E_1}), q_{E_2}) \in Sem^{Tr}_{\mathcal{I}_2\{\mathcal{I}_1\{K_1,E_1\},E_2\}}$ we have to prove that $\exists (q'_2, q'_{E_1})$ such that $t_2 = ((q_2, q_{E_1}), q_{E_2}) \xrightarrow{p_{\mathcal{I}_2}} ((q'_2, q'_{E_1}), q_{E_2}) \in Sem^{Tr}_{\mathcal{I}_2\{\mathcal{I}_1\{K_2,E_1\},E_2\}}$ and $((q'_1, q'_{E_1}), q'_{E_2}) R' (q'_2, q'_{E_1})$. $t_1 = ((q_1, q_{E_1}), q_{E_2}) \xrightarrow{p_{\mathcal{I}_2}} ((q'_1, q'_{E_1}), q_{E_2}) \in Sem^{Tr}_{\mathcal{I}_2\{\mathcal{I}_1\{K_1,E_1\},E_2\}}$ implies w.l.o.g that $p_{\mathcal{I}_1}, p_{E_2} \in \mathcal{P}_{\mathcal{I}_2}$ such that t_2 corresponds to the synchronization of the two transitions labeled by these ports. Note that here we suppose w.l.o.g that $\mathcal{I}_2$ and $\mathcal{I}_2$ have only rendezvous connectors as the case of observation connector can be then easily deduced. We suppose that $\mathcal{I}_2$ has only the connector γ_2 connecting $p_{\mathcal{I}_1}$ and p_{E_2}, similarly $\mathcal{I}_1$ has only the connector γ_1 connecting p and p_{E_1} where p is a port of K_i. This implies that $(q_1, q_{E_1}) \xrightarrow{p_{\mathcal{I}_1}} (q'_1, q'_{E_1}) \in \longrightarrow_{\mathcal{I}_1\{K_1,E_1\}}$ and $q_{E_2} \xrightarrow{p_{E_1}} q'_{E_2} \in \longrightarrow_{E_1}$. Moreover, $t \in Sem^{Tr}_{\mathcal{I}_2\{\mathcal{I}_1\{K_1,E_1\},E_2\}}$ implies that it exists a valuations of the variables X_1, X_{E_1}, X_{E_2} for which the following predicate holds: $(Inv_{q_1} \wedge Inv_{q_{E_1}} \wedge Inv_{q_{E_2}}) \wedge (G_{\gamma_1} \wedge G_{\gamma_2} \wedge (Inv_{q'_1} \wedge Inv_{q'_{E_1}} \wedge Inv_{q'_{E_2}})$ which implies that $(Inv_{q_1} \wedge Inv_{q_{E_1}}) \wedge (G_{\gamma_1}) \wedge (Inv_{q'_1} \wedge Inv_{q'_{E_1}})$. Which means that $(q_1, q_{E_1}) \xrightarrow{p_{\mathcal{I}_1}} (q'_1, q'_{E_1}) \in Sem^{Tr}_{\mathcal{I}_1\{K_1,E_1\}}$ and as $(q_1, (q_{E_1}, q_{E_2})) R q_2$ we obtain that it exists q'_2 such that $(q_2, (q_{E_1}, q_{E_2})) \xrightarrow{p_{\mathcal{I}_1}} (q'_2, (q'_{E_1}, q'_{E_2})) \in Sem^{Tr}_{\mathcal{I}\{K_2,\mathcal{I}_E\{K_2,E_1\}\}}$ and $(q'_1, (q'_{E_1}, q'_{E_2})) R q'_2$ which implies by definition that $((q'_1, q'_{E_1}), q'_{E_2})) R' (q'_2, q'_{E_1})$.
- τ transitions of $\mathcal{I}_1(K_1, E_1)$ are τ transitions of K_1 as we suppose that the environment does not have τ transitions. Then we use R to establish the needed relation.
- for the progress part, we have that $K_1 \sqsubseteq_{\mathcal{I}_E\{E_1,E_2\},\mathcal{I}} K_2$ this means that progress that K_2 can guarantee in $\mathcal{I}_E\{E_1, E_2\}$, K_1 also will guarantee in the same environment $\mathcal{I}_E\{E_1, E_2\}$. As refinement implies conformance we obtain that $\mathcal{I}\{K_1, \mathcal{I}_E\{E_1, E_2\}\} \preccurlyeq \mathcal{I}\{K_1, \mathcal{I}_E\{E_1, E_2\}\}$, besides we have that $\mathcal{I}\{K_i, \mathcal{I}_E\{E_1, E_2\}\} \cong \mathcal{I}_2\{\mathcal{I}_1\{K_i, E_1\}, E_2\}$ this allows to deduce that $\mathcal{I}_2\{\mathcal{I}_1\{K_1, E_1\}, E_2\} \preccurlyeq \mathcal{I}_2\{\mathcal{I}_1\{K_2, E_1\}, E_2\}$ which means that preservation of progress conditions.

□

- Conformance is consistent with refinement under context:
  $K_1 \sqsubseteq_{E,\mathcal{I}} K_2 \implies \mathcal{I}\{K_1, E\} \preccurlyeq \mathcal{I}\{K_2, E\}$. *Proof* Suppose that $K_1 \sqsubseteq_{E,\mathcal{I}} K_2$ to prove conformance we have to prove that $\mathcal{I}\{K_1, E\} \sqsubseteq_{(E,\mathcal{I}_{\mathcal{P}_\mathcal{I}})} \mathcal{I}\{K_2, E\}$ which is deduced from the preservation of refinement by composition. □

Circular reasoning.

- Circular reasoning is sound: $K \sqsubseteq_{A,\mathcal{I}} G \wedge E \sqsubseteq_{G,\mathcal{I}} A \implies K \sqsubseteq_{E,\mathcal{I}} G$.

Proof Let K be a component on an interface P, $(E, \mathcal{I})$ a context for P and $\mathcal{C} = (A, \mathcal{I}, G)$ a contract for P. We suppose that $K \sqsubseteq_{A,\mathcal{I}} G \wedge E \sqsubseteq_{G,\mathcal{I}} A$. We have to prove that $K \sqsubseteq_{E,\mathcal{I}} G$.

Given two relations $\alpha_1(X_K, X_G)$ and $\alpha_2(X_E, X_A)$ and as $K \sqsubseteq_{A,\mathcal{I}} G$ and $E \sqsubseteq_{G,\mathcal{I}} A$, there exist two relations $\mathcal{R}_1$ and $\mathcal{R}_2$ on respectively $(Q_K \times Q_A) \times Q_G$ and $(Q_E \times Q_G) \times Q_A$ verifying the conditions of Definition 4.4.2.

We define $\mathcal{R} \subseteq (Q_K \times Q_E) \times Q_G$ as follows: for $q_K \in Q_K$, $q_E \in Q_E$, $q_G \in Q_G$, we define $(q_K, q_E)\,\mathcal{R}\,q_G$ iff there exists q_A such that $(q_K, q_A)\,\mathcal{R}_1\,q_G$ and $(q_E, q_G)\,\mathcal{R}_2\,q_A$. ($\mathcal{V}_i$ denotes a valuation of X_i)

Safety part. We have $(q_K^0, q_A^0)\,\mathcal{R}_1\,q_G^0$ and for all $q_K \in Q_K, q_G \in Q_G, q_A \in Q_A$, $(q_K, q_A)\,\mathcal{R}_1\,q_G$ implies:

1. $I_{q_K}(X_K) \wedge \alpha^1(X_K, X_G) \implies I_{q_G}(X_G)$
2. $\forall p[x] \in P$, the following holds :
   (a) for any value v of x: $\exists t_K = q_K \xrightarrow{p}_K q'_K$ and $\mathcal{V}_K, \mathcal{V}_K^{new}$ satisfying Sem_{t_K} implies $\exists q'_G, t_G = q_G \xrightarrow{p}_G q'_G$ and $\mathcal{V}_G, \mathcal{V}_G^{new}$ consistent with α^1 and satisfying Sem_{t_G}.
   (b) $\exists \gamma.\ P_\gamma = \{p, p_A\} \wedge (q_K, q_A) \overset{p_\gamma}{\hookrightarrow} (q'_K, q'_A) \implies (q'_K, q'_A)\,\mathcal{R}_1\,q'_G$ with q'_G as above.
3. $q_K \overset{\tau}{\hookrightarrow}_K q'_K \implies (q'_K, q_A)\,\mathcal{R}_1\,q_G$

Besides, we have $(q_E^0, q_G^0)\,\mathcal{R}_2\,q_A^0$ and for all $q_E \in Q_E, q_A \in Q_A, q_G \in Q_G$, $(q_E, q_G)\,\mathcal{R}_2\,q_A$ implies:

1. $I_{q_E}(X_E) \wedge \alpha^2(X_E, X_A) \implies I_{q_A}(X_A)$
2. $\forall p[x] \in P$, the following holds :
   (a) for any value v of x: $\exists t_E = q_E \xrightarrow{p}_E q'_E$ and $\mathcal{V}_E, \mathcal{V}_E^{new}$ satisfying Sem_{t_E} implies $\exists q'_A, t_A = q_A \xrightarrow{p}_A q'_A$ and $\mathcal{V}_A, \mathcal{V}_A^{new}$ consistent with α^2 and satisfying Sem_{t_A}.
   (b) $\exists \gamma.\ P_\gamma = \{p, p_G\} \wedge (q_E, q_G) \overset{p_\gamma}{\hookrightarrow} (q'_E, q'_G) \implies (q'_E, q'_G)\,\mathcal{R}_2\,q'_A$ with q'_A as above.
3. $q_E \overset{\tau}{\hookrightarrow}_E q'_E \implies (q'_E, q_G)\,\mathcal{R}_2\,q_A$

We prove now that $\mathcal{R}$ is the relation we are looking for. Let $q_K \in Q_K$, $q_E \in Q_E$, $q_G \in Q_G$ be such that $(q_K, q_E)\,\mathcal{R}\,q_G$. Let q_A be such that $(q_K, q_A)\,\mathcal{R}_1\,q_G$ and $(q_E, q_G)\,\mathcal{R}_2\,q_A$. We have to prove that:

1. $I_{q_K}(X_K) \wedge \alpha'(X_K, X_G) \implies I_{q_G}(X_G)$
2. $\forall p[x] \in P$, the following holds :
   (a) for any value v of x: $\exists t_K = q_K \xrightarrow{p}_K q'_K$ and $\mathcal{V}_K, \mathcal{V}_K^{new}$ satisfying Sem_{t_K} implies $\exists q'_G, t_G = q_G \xrightarrow{p}_G q'_G$ and $\mathcal{V}_G, \mathcal{V}_G^{new}$ consistent with α and satisfying Sem_{t_G}.

(b) $\exists \gamma.\ P_\gamma = \{p, p_E\} \wedge (q_K, q_E) \overset{p_\gamma}{\hookrightarrow} (q'_K, q'_E) \implies (q'_K, q'_E)\, \mathcal{R}\, q'_G$ with q'_G as above.

3. $q_K \overset{\tau}{\hookrightarrow}_K q'_K \implies (q'_K, q_E)\, \mathcal{R}\, q_G$

- Condition 1. Given $\alpha' = \alpha^1$, condition 1 is the same as condition 1 of $\mathcal{R}_1$
- Condition 2.
  Part (a): Deducted from condition 2, part (a) for $\mathcal{R}_1$.
  Part (b): Let us suppose that $q_K \overset{p}{\hookrightarrow}_K q'_K \wedge\ q_E \overset{p_E}{\hookrightarrow}_E q'_E \wedge\ (\exists \gamma\ s.t.\ P_\gamma = \{p,\ p_E\})$. Condition 2 for $\mathcal{R}_2$ implies that $\exists q'_A \in Q_A\ s.t.\ q_A \overset{p_E}{\hookrightarrow}_A q'_A$.
  Hence: $q_K \overset{p}{\hookrightarrow}_K q'_K\ \wedge\ q_A \overset{p_E}{\hookrightarrow}_A q'_A \wedge\ (\exists \gamma\ s.t.\ P_\gamma = \{p,\ p_E\})$.
  Thus Condition 2 for $\mathcal{R}_1$ implies that there exists a q''_G s.t. $(q_G \overset{p}{\hookrightarrow}_G q''_G)$ and $\forall q'_A, q_A \overset{p_E}{\hookrightarrow}_A q'_A \implies (q'_K, q'_A)\, \mathcal{R}_1\, q''_G$. We now want to prove that $\forall q'_E,\ q_E \overset{p_E}{\hookrightarrow}_E q'_E \implies (q'_K, q'_E)\, \mathcal{R}\, q''_G$. Let us fix q'_E such that $q_E \overset{p_E}{\hookrightarrow}_E q'_E$. So we have :
  - $q_E \overset{p_E}{\hookrightarrow}_E q'_E$
  - $(\exists \gamma\ s.t.\ P_\gamma = \{p,\ p_E\})$ and $q_K \overset{p}{\hookrightarrow}_K q'_K$,

  Thus condition 2 part (2) for $\mathcal{R}_1$ implies that $\exists q''_G \in Q_G\ s.t.\ q_G \overset{p}{\hookrightarrow}_G q''_G$ So condition 2 for $\mathcal{R}_2$ implies that it exists a q''_A such that $q_A \overset{p}{\hookrightarrow}_A q''_A$ and $\forall q'_G,\ q_G \overset{p}{\hookrightarrow}_G q'_G \implies (q'_E, q'_G)\, \mathcal{R}_2\, q''_A$. We apply this relation to q''_G and Similarly we apply $\forall q'_A,\ q_A \overset{p_E}{\hookrightarrow}_A q'_A \implies (q'_K, q'_A)\, \mathcal{R}_1\, q''_G$ to q''_A, Thus we get:
  - $(q'_E, q''_G)\, \mathcal{R}_2\, q''_A$
  - $(q'_K, q''_A)\, \mathcal{R}_1\, q''_G$

  Hence $(q'_K, q'_E)\, \mathcal{R}\, q''_G$.
- Condition 3. Let us suppose that $q_K \overset{\tau}{\hookrightarrow}_K q'_K$. Thus condition 3 of $\mathcal{R}_1$ implies that $(q'_K, q_A)\, \mathcal{R}_1\, q_G$. Besides we have $(q_E, q_G)\, \mathcal{R}_2\, q_A$. Hence $(q'_K, q_E)\, \mathcal{R}\, q_G$

Progress part. As the progress part does not involve the context, the progress part for $\mathcal{R}$ is deduced from the progress properties for $\mathcal{R}_1$. □

Chapter 5

An Application: Resource Sharing in a Networked System

In this Chapter we apply our approach to a case-study "Sharing resource system" to verify some global requirement. We choose this system because it can be defined recursively, thus we can apply the extension of our methodology proposed to verify recursively defined systems. We also apply our methodology to verify a top-level progress requirement of this system using the rich contract framework proposed in the previous chapter. In addition, we report experimentations of the different verification steps using a tool we have developed for this purpose.

5.1 Sharing resource system

We apply the proposed methodology to a variant of an algorithm for sharing resources in a network presented in [DDHL08]. The overall structure of the application is given in Figure 5.1, where the system structured as binary trees of nodes defining a token ring. We may also consider more realistically, trees with arbitrary branching, but We restrict ourselves to binary branching for simplifying the presentation.

Resources shared between nodes are represented by *tokens* circulating in packets containing one or more tokens along the token ring. Red arrows in Figure 5.1 gives how these resources circulate in the network. The *value* of a packet is the number of tokens it contains. Nodes are trying to collect tokens so that they can perform some computation. There is a particular unique token in the network called the *privilege* and denoted P. This *privilege* allows nodes to accumulate tokens. A node without this (unique) privilege may either use the tokens of the just received packet or, if it needs no or more resources, it must keep the tokens circulating and wait until it receives a larger packet or the privilege. According this resource sharing algorithm, a node in the network behaves as follow (see Figure 5.2):

- A node may *request* tokens and a variable Req indicates the numbers of tokens requested;
- When it has enough tokens for satisfying its request, it is expected to *use* them, and relax the privilege P if it has it;

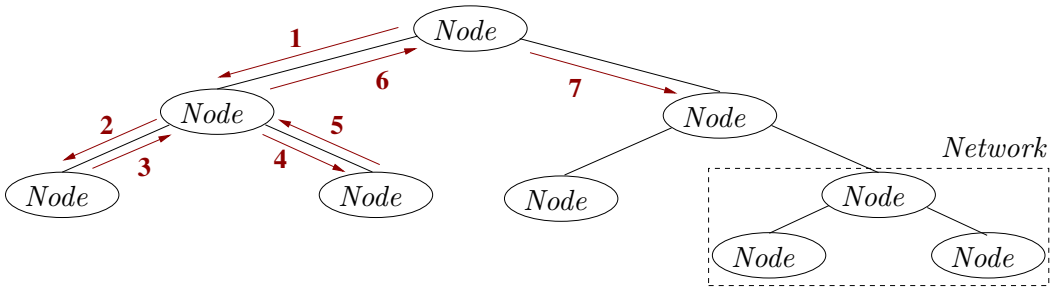


Figure 5.1: The overall structure of the application.

- When it has resources (tokens) in use, it cannot request additional ones; it may later *free* them or keep them forever;
- A node can rise a request only when it has no resource in use and no pending request means when $Req = 0$.

The number of tokens circulating in the network (and not in use) are denoted by the variable Tk.

We assume that connectivity of the network is guaranteed and tokens are never lost. Here, this assumption is encoded in the composition operator. This allows separating completely design and correctness proofs from the resource sharing algorithm and the algorithm guaranteeing connectivity, which is typically implemented in a lower layer of the overall network protocol.

We represent networks of arbitrary size by a grammar and associating a contract with each node, such that the correctness proof boils down to a set of small verification steps as proposed by the methodology steps detailed in Section 3.1.

As described in Figure 5.1, a network can be built as just one node, or as a node connected to two networks. Thus the system can be defined by the following grammar $\mathcal{G}$, where $\{E, Node\}$ are terminals and $\{Sys, Net\}$ nonterminals with axiom Sys. The rules are:

1. $Sys \longrightarrow \mathcal{I}_{Net}(E, Net)$
2. $Net \longrightarrow Node$
3. $Net \longrightarrow \mathcal{I}(Node, Net, Net)$
4. $Node \longrightarrow I_{Node}$

Note here that Sys defines a closed system built as a composition of the network and its environment. The goal is to use our methodology to verify that the described system ensures some top-level requirement. The starting point is both a high-level requirement and an abstract description of the behavior of an individual node

The described algorithm ensures, under weak assumptions, a safety, a progress and a fairness property. The safety property expresses that the global number of tokens in the system is constant.

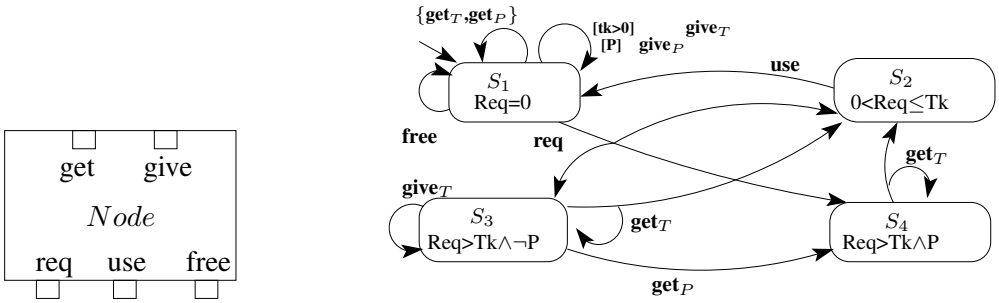


Figure 5.2: (a) Node Structure. (b) Node Behavior.

The progress property is that, as long as there are tokens available, some node will be served. Fairness ensures that if there are tokens available for long enough, every node making a request will get into a privileged position where it is served with some priority. In this chapter we focus on the progress property.

We use components given by the Definition 4.1.1 to model the behaviors and the interfaces of nodes and networks. The node interface is given in Figure 5.2, where tokens (and the privilege) are exchanged through ports get_T (get_P) and $give_T$ ($give_P$). The port req models the action of requesting some resources by the node. The port use represents the action of using some resources by the node. When the resources are no more in use by the node, it liberates them by an action labeled by the port $free$.

The *Node* has state variables indicating whether it has the privilege (P), the number of tokens it has (Tk), the number of token it requests (Req). It has also some port variables used during interactions. In the initial state of the node, see Figure 5.2 (b), the node has no request which means that $Req = 0$ (State S_1). Once it makes a request, then 3 cases are possible. The first case (State S_2) corresponds to a request that is smaller than the number of token in the node ($0 < Req < Tk$), in this state, the node has enough token to perform the action use. The second case corresponds to state S_3, where the node does not have enough tokens ($Req > Tk$) and the node does not have the privilege ($\neg P$). Thus the node has to keep circulating packets of tokens until it gets a packet with a sufficient number of tokens or it gets the privilege token and thus goes to state S_4 which corresponds to the third case. This means that the node does not have enough tokens but it has the privilege ($Req > Tk \wedge P$) which allows it to accumulate tokens until it reaches the requested number.

Note that in the interface of the node, depicted in Figure 5.2 (a), ports get_T (get_P) and $give_T$ ($give_P$) are *synchron* ports, as a node has to synchronize with the rest of the network when it has to give or to get a token (similarly for the privilege). However, ports use, req and $free$ are *trigger* ports as the node can perform these actions locally with no synchronization.

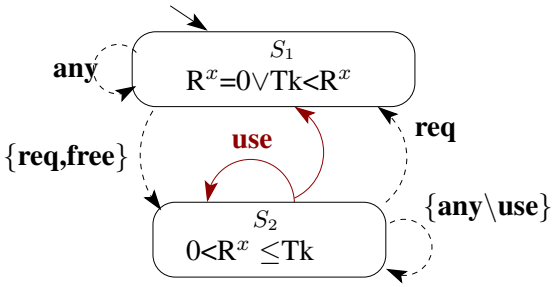
In this application what we have is the given description of a node and some top-level requirements that a network built as a composition of these nodes has to ensure. Here we choose to verify a *progress* top-level requirement.

5.1.1 The top-level requirement φ.

We consider here one of the top-level requirements of the algorithm, a progress requirement φ. This requirement has to be ensured by the closed system Sys defined by a network, built by a set of nodes according to the structure depicted in Figure 5.1, and an environment (see the first rule of the grammar $\mathcal{G}$ given previously in Section5.1).

To specify the network and its requirement, we define a variable R^x denoting the maximal request among the set of requests of the nodes of the closed system and we denote by Tk the number of tokens circulating in this system.

The top-level requirement φ states that "as long as the requests of nodes are *reasonable*, some of the nodes will be served." Let be *Reasonable* requests means that there is no request made by a node that is bigger than the number of tokens in the system $0 < R^x \leq Tk$. According to the description given in Figure 5.2, a node is served means that it performs the transition labeled by the port use. Thus φ means that whenever $0 < R^x \leq Tk$, some use action will occur.



$$pr_1 = (\top, S_2 \overset{use}{\hookrightarrow} *)$$
$$pr_2 = (\{S_1 \overset{free}{\hookrightarrow} S_2, S_2 \overset{req}{\hookrightarrow} S_1\}, S_2 \overset{use}{\hookrightarrow} *)$$

Figure 5.3: Top-level requirement φ

Figure 5.3, gives a description of φ in our formalism. This progress requirement is particularly specified by the two progress properties pr_1 and pr_2. The first property pr_1 says that "it is not possible to stay forever in state S_2, without performing a *use*-transition". The progress property pr_2 says that "it is not possible to switch infinitely often between states S_1 and S_2 (that is, *free* occurs infinitely often) without that a *use* occurs infinitely often as well" (progress transitions *use* are represented by red arrows). When the system has no request pending or when there are not enough tokens to serve the maximal request (state S_1), the system has not to guarantee any progress.

5.1.2 Methodology

Now we apply the previously described verification methodology to the system described by the given grammar $\mathcal{G}$ so as to verify if it ensures the top-level progress requirement φ. For this purpose,

we instantiate the different methodology steps detailed in Section 3.1.2, to a network built according to grammar $\mathcal{G}$, together with an actual environment E:

1. We formulate a contract $\mathcal{C}_{\mathrm{Net}} = (A_{\mathrm{Net}}, \mathcal{I}_{\mathrm{Net}}, G_{\mathrm{Net}})$ associated with Net (which plays here the role of K_0) and we show that $\mathcal{I}_{\mathrm{Net}}(A_{\mathrm{Net}}, G_{\mathrm{Net}}) \preccurlyeq \varphi$.

2. We define $\mathcal{C}_{\mathrm{Node}} = (A_{\mathrm{Node}}, \mathcal{I}_{\mathrm{Node}}, G_{\mathrm{Node}})$ a contract for $Node$ (note that we already have a contract for Net).

3. We show that $\mathcal{C}_{\mathrm{Node}}$ dominates $\mathcal{C}_{\mathrm{Net}}$ and that $\{\mathcal{C}_{\mathrm{Node}},\ \mathcal{C}_{\mathrm{Net}},\ \mathcal{C}_{\mathrm{Net}}\}$ dominates $\mathcal{C}_{\mathrm{Net}}$ w.r.t. $\mathcal{I}$.

4. We prove that I_{Node} satisfies $\mathcal{C}_{\mathrm{Node}}$ and that E satisfies $\mathcal{C}_{\mathrm{Net}}^{-1} = (G_{\mathrm{Net}}, \mathcal{I}_{\mathrm{Net}}, A_{\mathrm{Net}})$.

Note that this proof implies that all networks that can be built according to this grammar satisfy φ. The first step consists in defining a top-level contract of of the closed system Sys and check conformance between the description of the system given by this contract and the already given specification of the top-level requirement φ. Here we rely on the already given description of φ (see Figure 5.3). To define the top-level contract, we have to give a description of the network G_{Net}, of a property of its environment A_{Net} and how they are connected $\mathcal{I}_{Net}$ (glues). Then we have to a define a contract for each subsystem consisting the network Net that is contracts: $\mathcal{C}_{Net}$ for a network and $\mathcal{C}_{Node}$ for a node. Note that the different rules of the grammar $\mathcal{G}$ are transformed into a dominance check between contracts.

If we want to further refine the $Node$ component, we may start by a contract $\mathcal{C}_{\mathrm{Node}} = (A_{\mathrm{Net}},\ \mathcal{I}_{\mathrm{Net}},\ G_{\mathrm{Node}})$. Indeed, we can always refine terminal symbols by iteratively applying the same approach to this symbol. This means that we can either give an implementation of the node or any abstract description that can be refined later.

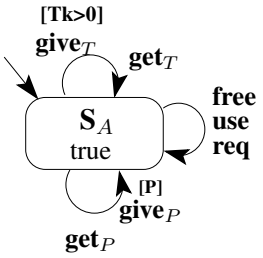
5.1.3 Interaction models and contracts

Now we detail the steps 1 and 2 of the proposed methodology, where we have to define contracts for each subsystem. Our system can be either a node or a composition of a node with two networks, this is detailed by the rules 2 and 3 of the grammar $\mathcal{G}$. Thus the contracts that we have to define are $Node$ and $Network$ contracts. To define these contracts we have to give a description of the properties that the $Node$ and the $Network$ have to ensure, a description of their environments and how they are connected to these environments. We recall that these subsystems $Node$ and $Network$ are modeled as components according to the definition of component given in the previous section.

Network and node contracts

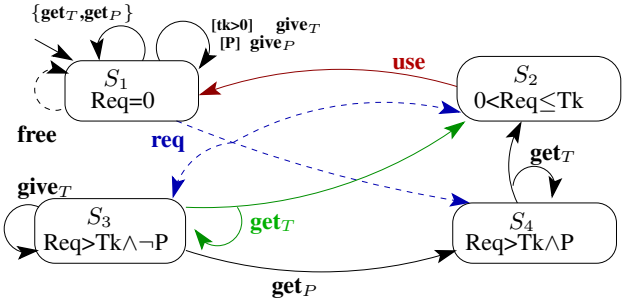
To define the contracts $\mathcal{C}_{\mathrm{Net}} = (A_{\mathrm{Net}}, \mathcal{I}_{\mathrm{Net}}, G_{\mathrm{Net}})$ and $\mathcal{C}_{\mathrm{Node}} = (A_{\mathrm{Node}}, \mathcal{I}_{\mathrm{Node}}, G_{\mathrm{Node}})$, we first give a description of their assumptions namely A_{Net} and A_{Node}.

Here we choose to give the same assumption to both contracts $A_{\mathrm{Net}} = A_{\mathrm{Node}}$, as the environments of both the node and the network are supposed to ensure the same properties. This assumption is described in Figure 5.4. A_{Net} represents the environment of an arbitrary network component, and it



$$pr_1^A = (\overset{use}{\hookrightarrow}, \overset{give_P}{\hookrightarrow})$$
$$pr_2^A = (\top, \{\overset{use}{\hookrightarrow}, \overset{get_T}{\hookrightarrow}, \overset{get_P}{\hookrightarrow}\})$$
$$pr_3^A = (\top, [\neg P] \overset{give_T}{\hookrightarrow})$$

Figure 5.4: Assumption of the network and the node contract.



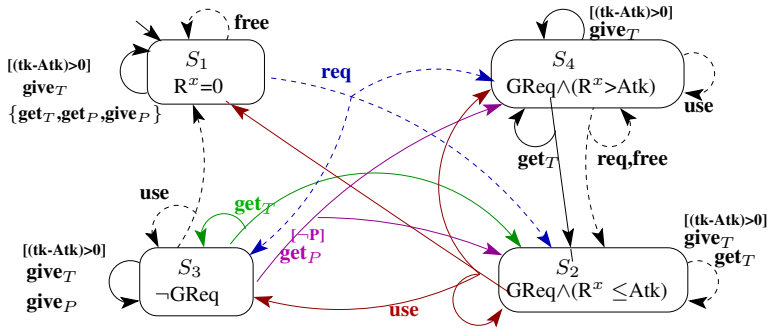
$$pr_1^N = (\top, S_i \overset{give_T}{\hookrightarrow} *)_{i\in\{1,3\}} \qquad pr_4^N = (\top, S_1 \overset{give_P}{\hookrightarrow} S_1)$$
$$pr_2^N = (\top, S_i \overset{get_T}{\hookrightarrow} *)_{i\in\{1,3,4\}} \qquad pr_5^N = (\top, S_2 \overset{use}{\hookrightarrow} S_1)$$
$$pr_3^N = (\top, S_i \overset{get_P}{\hookrightarrow} *)_{i\in\{1,3\}} \qquad pr_6^N = (S_4 \overset{get_T}{\hookrightarrow} S_4, S_4 \overset{get_T}{\hookrightarrow} S_2)$$

Figure 5.5: Guarantee of the Node Contract.

has just one state, from which it can perform all its actions. The progress properties given in the right hand side of Figure 5.4 describes the following:

- pr_1^A : A_{Net} cannot perform infinitely many *use*, without giving back tokens or P, this ensures that the assumption cannot keep always the tokens and P;
- pr_2^A : the assumption has to always offer the interaction use, and also the interactions get_P and get_T so that we guarantee that it cannot refuse tokens given by the $network$ or the $node$.
- pr_3^A: this property ensures that the assumption has to give back tokens if it does not have the privilege P.

The guarantee G_{Net} of the contract $\mathcal{C}_{\text{Net}}$ is described in Figure 5.6 and the guarantee G_{Node} of the contract $\mathcal{C}_{\text{Node}}$ is given in Figure 5.5. Their transitions $give_T$ and get_T decrease, respectively increase, the local state variable Tk of the network and the node as they allow exchange tokens with their environment. Similarly, transitions $give_P$ and get_P determine when they release and take



$$pr_1^{Net} = (\top, S_i \overset{give_T}{\hookrightarrow} *)_{i=\{1,3\}} \quad pr_5^{Net} = (\top, S_i \overset{give_P}{\hookrightarrow} *)_{i\in\{1,3\}}$$
$$pr_2^{Net} = (\top, S_i \overset{get_T}{\hookrightarrow} *)_{i\in\{1,3,4\}} \quad pr_6^{Net} = (S_4 \overset{get_T}{\hookrightarrow} S_4, S_4 \overset{get_T}{\hookrightarrow} S_2)$$
$$pr_3^{Net} = (\top, S_i \overset{get_P}{\hookrightarrow})_{i\in\{1,3\}} \quad pr_7^{Net} = (\{S_3 \overset{get_T}{\hookrightarrow} S_3\} \setminus \{S_3 \overset{give_T}{\hookrightarrow} S_3\}, S_3 \overset{use}{\hookrightarrow} S_3)$$
$$pr_4^{Net} = (\top, S_2 \overset{use}{\hookrightarrow} *) \quad pr_8^{Net} = (\{S_i \overset{use}{\hookrightarrow} *\}_{i\in\{2,4\}}, \{S_i \overset{give_P}{\hookrightarrow} *\}_{i\in\{1,3\}})$$

Figure 5.6: Guarantee of the Network Contract

the privilege from their environment. Some Transitions of the guarantee of the node perform local functions on variables: $f_{give_T} : (Tk := Tk - tk; tk := 0)$, $f_{get_T} : (Tk := Tk + tk)$, $f_{give_P} : (\neg P)$, $f_{get_P} : (P)$, $f_{use} : Req = 0$.

The guarantee of the $node$ is similar to the behavior of node already described in Figure 5.2, however to reason about progress, some progress properties are added in the guarantee of the $node$. Colored transitions represents the transitions of the promise set of the progress properties. The first 4 progress properties of the G_{Node} (pr_1^N, pr_2^N, pr_3^N, pr_4^N), which represent unconditional progress, guarantee that the node has to always circulate tokens and P and it cannot keep them forever. The property pr_5^N, ensures that the $node$ cannot stay forever in state S_2 without performing use. pr_6^N provides that the node cannot do infinitely many get_T transitions in state S_4, without performing a get_T allowing the node to go to state S_2.

Note that transition $give_T$ has a guard to make sure that Tk is never negative, and transition $give_P$ has also a guard to make sure that they have P.

The guarantee of the network contract is slightly more nondeterministic and more complex than the node guarantee. In particular, additional variables are added comparing to the node guarantee. Variable R^x, as defined for the description of φ denotes the maximal request among the set of requests of the nodes of the network. Moreover, it is not enough that a network has the privilege for being able to collect tokens. Indeed, the network may have the privilege, but it may be located in a node with no request. Thus this node cannot collect token and so does the network.

This ability of a network to collect tokens is indicated by the boolean state variable $GReq$ (see Figure 5.6). For example, in states with R^x=0, all that the network has to guarantee is that it circulates the tokens and the privilege. When R$^x \neq 0$, the request could be a *good* or a *bad* request denoted

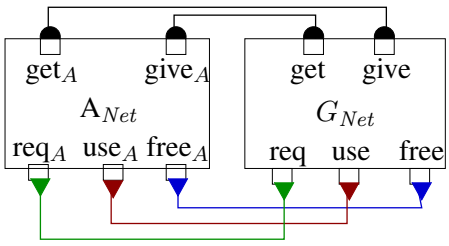


Figure 5.7: $\mathcal{I}_{\text{Net}}$ for contract $\mathcal{C}_{\text{Net}}$.

also by the boolean variable $GReq$. A request is *good* if the network has P and P will be catched by a node with a pending request or when there is a packet with enough tokens for some node of the network. With a good request and enough tokens, the network ensures progress with the transition *use*. The guarantee G_{Net} describes also a set of progress properties (see Figure 5.6) which are similar for the first 6 properties of the node. The additional progress properties of the $network$ are due to the fact that its behavior is less deterministic than the $node$ behavior. For example, in state S_2 of the node, it cannot perform infinitely often use without going to state S_1 where it will give back P. However, in state S_2 of the network a loop labeled by use is possible, as this use may be performed by any node of the network, thus pr_8^{Net} guarantees that the network cannot keep always P when staying in S_2 or S_4.

Interaction models To define contracts, we need to provide the interaction model used to compose guarantees and assumptions. For both contracts $\mathcal{C}_{\text{Net}}$ and $\mathcal{C}_{\text{Node}}$ the interaction models are the same that is $\mathcal{I}_{\text{Net}} = \mathcal{I}_{\text{Node}}$ depicted in Figure 5.7. Interaction models are defined by a set of connectors, as already described in the framework presented in Chapter 4. In the description of our application we do not use the proposed an abstract description of connectors presented in the Definitions of Section 4.2, where functions on data are represented as predicates. Here, concrete upward and downward functions on data are used in connectors. We use a concrete description of connectors, because we do not propose to refine them.

Figure 5.7 describes the interaction model $\mathcal{I}_{\text{Net}}$ relating a network — and therefore also a node — to the rest of the system. We represent by get and $give$ respectively port sets $\{get_T, get_P\}$ and $\{give_T, give_P\}$ for token and privilege exchange. For example, connector $\{give_T[tk] \mid get_{TA}[tk_A], \delta_G : [tk > 0], tk_A := tk\}$ pushes a positive number of tokens from the Network to the environment. Connectors relating ports use, req and $free$ allows to observe when a network or its environment fires a transition labeled by one these ports by exporting the corresponding ports of terminals.

The dominance problem

Once the different contracts are defined, the third step of the methodology is to prove dominance for each rule defined by the grammar $\mathcal{G}$. That is $\mathcal{C}_{\text{Node}}$ dominates $\mathcal{C}_{\text{Net}}$ and that $\{\mathcal{C}_{\text{Node}}, \mathcal{C}_{\text{Net}}, \mathcal{C}_{\text{Net}}\}$

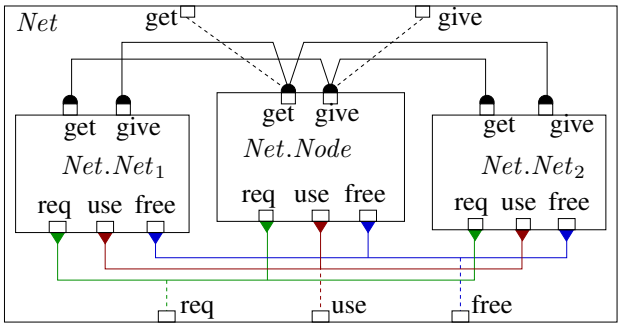


Figure 5.8: Inner structure of a network component.

dominates $\mathcal{C}_{\text{Net}}$ w.r.t. $\mathcal{I}$.

Figure 5.8 shows the inner structure of a network component Net. The interaction model $\mathcal{I}$ builds a tree from a (root) node and two networks Net_1, Net_2. Interactions performed by the connectors depicted here are similar to those of Figure 5.7, except that they also ensure that tokens circulate in the correct order. Tokens are exchanged by the node and its connected networks through the following connectors:

- $\{\text{get}_{Net.Node}[(\{tk_i\}_{i\in\{0,1,2\}})]\ |\text{give}_{Net.Net_i}[tkn]\}$:

$$\delta\text{:[tkn>0]} \begin{cases} Tk_{Net.Node} := Tk_{Net.Node} + tkn; \\ tk_{(i+1)MOD3} := tk \\ Tk_{Net.Net_i} := Tk_{Net.Net_i} - tkn; tkn := 0 \end{cases}$$

- $\{get_{Net.Net_i}[\text{tkn}]\ |\text{give}_{Net.Node}[tk, tk_i]\}$:

$$\delta\text{:[tk}_i\text{>0]} \begin{cases} tk := tk_i \\ Tk_{Net.Node} := Tk_{Net.Node} - tk_i; \\ tk_i := 0 \end{cases}$$

The set of n-ary connectors γ_{use}, γ_{req} and γ_{free} are used to verification goals, Indeed they help updating the values of variables and allow to detect at a higher level some actions performed locally. To prove dominance, we use the sufficient condition of circular reasoning. Thus to prove that $\mathcal{C}_{\text{Node}}$ dominates $\mathcal{C}_{\text{Net}}$, we need that $\mathcal{I}_{\text{Node}} = \mathcal{I}_{\text{Net}}$, which is already true and to prove that:

- $G_{\text{Node}} \sqsubseteq_{A_{\text{Net}},\mathcal{I}_{\text{Net}}} G_{\text{Net}}$
- $A_{\text{Net}} \sqsubseteq_{G_{\text{Node}},\mathcal{I}_{\text{Node}}} A_{\text{Net}}$

Then, to prove that $\{\mathcal{C}_{\text{Node}},\ \mathcal{C}_{\text{Net}},\ \mathcal{C}_{\text{Net}}\}$ dominates $\mathcal{C}_{\text{Net}}$ w.r.t. $\mathcal{I}$, we have to prove the following:

1. $\Pi_{\mathcal{P}_{\text{Net}}}(\mathcal{I}(G_{\text{Node}}, G_{\text{Net}}, G_{\text{Net}})) \models \mathcal{C}_{\text{Net}}$
2. $\Pi_{\mathcal{P}_{\text{Node}}}(\mathcal{I}_1(A_{\text{Net}}, G_{\text{Net}}, G_{\text{Net}})) \models \mathcal{C}^{-1}_{\text{Node}}$

3. $\Pi_{\mathcal{P}_{\mathrm{Net}}}(\mathcal{I}_2(A_{\mathrm{Net}}, G_{\mathrm{Node}}, G_{\mathrm{Net}})) \models \mathcal{C}_{\mathrm{Net}}^{-1}$

These different relations are checked automatically using our prototype tools described in the next section.

5.2 Implementation and experimental results

As described previously, dominance, conformance and satisfaction problems are reduced to refinement under context. We have implemented a prototype tool, so that refinement under context is checked and discharged automatically by a *Java* tool. In this Section, we presentation a description of this tool with its main features. We also give some results about the application described in Section 5.1. Our tool consists basically in two modules:

- Refinement Checker Module: given two components K_{abs}, K_{conc} and a context $(E, \mathcal{I})$, this module checks if $K_{conc} \sqsubseteq_{E,\mathcal{I}} K_{abs}$, according the our defined refinement relation (see Definition 4.4.2).
- Composition Module: to prove dominance, we have to perform composition of components w.r.t. a given interaction model (see the sufficient condition for dominance given in Theorem 3.3.4). Thus, this module allow to compute the composition of a set of components according to Definition 4.2.6.

The front-end of our implementation takes as input a description of a component given in Definition 4.1.3. This description written in a simple markup language (*xml*) and allows to describe the different parameters of a component (ports, variables, states ...). Each input file is then parsed to build an instance of a *Java* class called *Behavior*.

5.2.1 Refinement checker module.

Figure 5.9 shows the overall structure of this module. *xml* input files of this module describes three components representing K_{conc}, $(E, \mathcal{I})$ and K_{abs}. A parser allows to build a model of a component from each *xml* file. Then, the checker performs the refinement test by testing the safety part then the progress part of the refinement relation. Indeed, both parts (safety and progress) are independent so they can be checked separately.

1. Safety Test: this part of our implementation has to ensure the conditions given in the safety part of the refinement relation (Definition 4.4.2). To check the first condition, we have to manipulate invariants of states and prove implication ($I_{q_c} \wedge \alpha(X_{conc}, X_{abs}) \implies I_{q_a}$). For this purpose, we use the *Sat-Solver* tool Yices [DdM06] to prove implication of invariants of states variables. If the safety part is not satisfied, our tool precise that it is due to safety conditions.
2. Progress Test: progress properties of each component are specified in the xml file by a dedicated element denoted *progressP*. We have implemented a computation of the inverse image of the projection given in Definition 4.4.1 to check the progress condition. If progress conditions

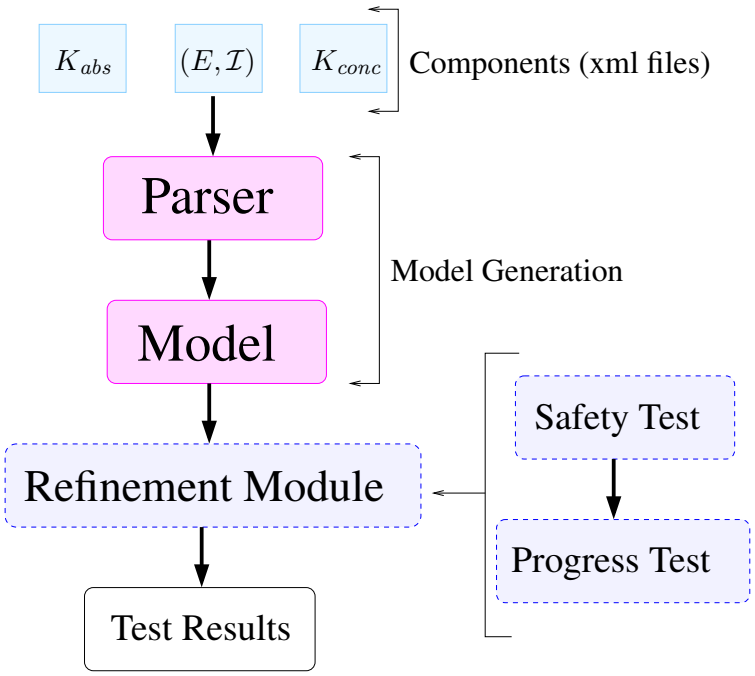


Figure 5.9: Refinement Checker Structure.

are not satisfied, our implementation report that the refinement is not sound due to progress conditions.

When the refinement relation is verified between K_{conc} and K_{abs} in the context $(E, \mathcal{I})$, our implementation provides the different states in relation.

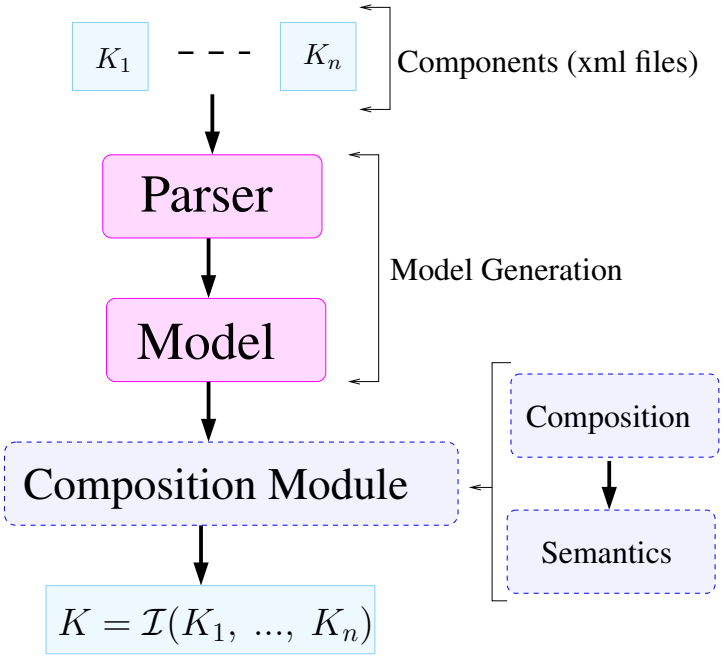


Figure 5.10: Composition Module Structure.

5.2.2 Composition module.

Figure 5.10 describes the overall structure of the composition module of our implementation. This module allows to build the composition of a set of input components w.r.t. a given interaction model. The output of this module is an instance of the *Java* class "Behavior" denoting the composition. The interaction model $\mathcal{I}$ of a composition, which corresponds to the set of connectors connecting the input components, is given within the components input files. Thus each component gives the set its connected ports and how they are connected.

To obtain the composition of the set of n components we are performinf two main operations:

1. Syntactic composition: in this step we only perform the composition described in Definition 4.2.6. We build all possible transitions, states and we compute invariants as given in the composition rules.

2. Semantics: Once the syntactic composition is built, a semantic computation is needed as some

States	S_1^{Node}	S_2^{Node}	S_3^{Node}	S_4^{Node}
S_1^{Net}	$\mathcal{R}$			
S_2^{Net}		$\mathcal{R}$		
S_3^{Net}			$\mathcal{R}$	
S_4^{Net}				$\mathcal{R}$

Table 5.1: $\mathcal{C}_{\mathrm{Node}}$ dominates $\mathcal{C}_{\mathrm{Net}}$: Related States.

states and transitions may not be reachable. The semantics computation is performed according to the abstract semantics given in Definition 4.1.3.

5.2.3 Results.

The implementation of our prototype tool has been performed using 20 *Java* class and approxmately *Java* functions of about 4820 l.o.c.

We have discharged the different dominance and conformance problems using our tool and we have proved the needed conditions given by the methodology steps detailed in Section 5.1.2. Table 5.2 gives the different states related by the refinement relation given by the fact that $\mathcal{C}_{\mathrm{Node}}$ dominates $\mathcal{C}_{\mathrm{Net}}$ (generated by our tool). Note that here we do not have to precise with which state of the assumption $Node$ and $Network$ states are related because the given assumption has just one state (see Figure 5.4). The next relation to prove is that $\{\mathcal{C}_{\mathrm{Node}},\ \mathcal{C}_{\mathrm{Net}},\ \mathcal{C}_{\mathrm{Net}}\}$ dominates $\mathcal{C}_{\mathrm{Net}}$ w.r.t. $\mathcal{I}$ and which boils down to the following conditions:

- Relation 1: $\Pi_{\mathcal{P}_{\mathrm{Net}}}(\mathcal{I}(G_{\mathrm{Node}}, G_{\mathrm{Net}}, G_{\mathrm{Net}})) \models \mathcal{C}_{\mathrm{Net}}$
- Relation 2: $\Pi_{\mathcal{P}_{\mathrm{Node}}}(\mathcal{I}_1(A_{\mathrm{Net}}, G_{\mathrm{Net}}, G_{\mathrm{Net}})) \models \mathcal{C}_{\mathrm{Node}}^{-1}$
- Relation 3: $\Pi_{\mathcal{P}_{\mathrm{Net}}}(\mathcal{I}_2(A_{\mathrm{Net}}, G_{\mathrm{Node}}, G_{\mathrm{Net}})) \models \mathcal{C}_{\mathrm{Net}}^{-1}$

To compute the product of *Relation 1*, we use the composition module, which generates a component with 64 states and 1276 transitions. The composition needed to check *Relation 2* generates a component with 16 states and 394 transitions. *Relation 3* needs the composition $\mathcal{I}_2(A_{\mathrm{Net}}, G_{\mathrm{Node}}, G_{\mathrm{Net}})$ which leads to a component with 16 states and 262 transitions.

States ($Node$, $Net1$, $Net1$)	S_1^{Net}	S_2^{Net}	S_3^{Net}	S_4^{Net}
(s1,s1,s1)	$\mathcal{R}$			
(s2,s1,s1)		$\mathcal{R}$		
(s2,s2,s1)		$\mathcal{R}$		
(s2,s1,s1)		$\mathcal{R}$		
(s2,s2,s1)				$\mathcal{R}$
(s4,s2,s1)				$\mathcal{R}$
(s1,s4,s1)				$\mathcal{R}$
(s2,s1,s1)			$\mathcal{R}$	
(s2,s1,s3)			$\mathcal{R}$	
(s1,s2,s2)				$\mathcal{R}$
(s4,s4,s2)		$\mathcal{R}$		
(s1,s2,s1)				$\mathcal{R}$
(s4,s2,s1)		$\mathcal{R}$		
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

Table 5.2: Relation1: Related States.

Part III

Building Distributed Controllers for Systems with Priorities

Chapter 6

Controllers for Systems with Priorities

We have proposed in Part II, a compositional design methodology for systems of components so as to verify some global property. We have shown that component frameworks in particular their interaction models provide a powerful mechanism for design and verification of large scale systems because they allow enforcing several properties structurally. In this part we study these interaction models and the question of how they can be implemented in a distributed setting. In particular, we focus here on interaction models defined by *interactions* and *priorities* on these interactions. We propose to model them as properties which have to be enforced in the system and which thus define *controllers* of this system.

Interactions are here simple synchronizations between components where we abstract away their guards and functions.Indeed, in Part II, interactions are structured using connectors. This structural aspect is relevant in the previous chapters, because our purpose have been to define a compositional design methodology based on the structure of the system. However, to study interactions and to implement them we abstract away their structural aspect.

In this chapter, we also abstract away the details about how these interactions are actually performed and which will be described at the implementation issue in Chapter 7.

We use in the following chapters, a formalism that is similar but more abstract than the one proposed in Part II as components are described by simple labeled transition systems rather than extended labeled transition systems.

In this chapter, we first present, in Section 6.1, a notion of component that is simpler than those already defined in the previous chapters. Indeed the components we consider here are just labeled transition system as the data transfer issue is not interesting for our purpose here. We also define a notion system corresponding to the notion of closed systems already defined. Then, we discuss how interaction models can be described as properties defining controllers of these systems. In Section 6.2, we provide a lightweight method for imposing the property of *deadlock freedom*, using a controller defined by *priorities*.

6.1 Systems and controlled systems

We introduce here an abstract representation of components and systems which is simpler than the description already used in Part II (see Definition 2.1.2). Indeed, here components are identified with an abstraction of their behavior and represented by transition systems labeled by ports without variables, guards or functions.

An interaction between these components is simply defined as sets of ports from different components where the transition corresponding to such an interaction is the synchronization of the corresponding local transitions labeled by the ports of this interaction. We consider here two types of interaction models: a first type that is interaction models defined by a set of interactions synchronizing transitions of different components and a second type that is interaction models defined by a set of interactions and a set of *priorities* between these interactions.

6.1.1 Components, interaction models and systems

We suppose given a set of ports $Ports$.

Definition 6.1.1 (Component) *A* component K on *a set of ports* $\mathcal{P} \subseteq Ports$ *is a* labeled transition system *(LTS) where transitions are labeled by* $\mathcal{P}$.

We also define for a given component the notion of executions, deadlock and reachable states as previously described in Definition 2.1.3.

Interaction models and parallel composition

A set of components $\{K_i\}_{i=1}^n$ for some $n > 0$ may be composed by means of an *interaction model* $\mathcal{I}$ which defines the set of allowed global *interactions* corresponding to a joint execution of actions of a (non empty) subset of $\{K_i\}_{i=1}^n$.

Here, we do not use connectors to structure interactions as previously defined in the previous chapters. Note, however, that an interaction can always be described as a rendez-vous connector without data exchange. In the sequel of this thesis, we only focus on the notion of interactions as simple synchronizations and on the semantics of interaction models as a set of interactions. Thus we provide the following simple definition.

Definition 6.1.2 (Interaction, Interaction model) *Consider a set* $\{\mathcal{P}_i\}$ *of disjoint interfaces* $\mathcal{P}_i \subseteq Ports$. *An* interaction a *on* $\{\mathcal{P}_i\}$ *is a pair* (p, α) *where* $p \in Ports$ *is called the* exported port *of* a *and* α *is a non empty subset of* $\bigcup_i \mathcal{P}_i$ *which contains at most one action in each interface* $\mathcal{P}_i$.
An interaction model $\mathcal{I}$ *on* $\{\mathcal{P}_i\}$ *is a non empty set of interactions with distinct exported ports denoted* $I(\mathcal{I})$. *The exported ports of these interactions define the interface* $\mathcal{P}_\mathcal{I}$ *of* $\mathcal{I}$.

In the sequel, we adopt the convention that exported ports have the same name as their corresponding interaction, which we both denote by $a, b, \ldots$. Also, for an interaction $(a, \alpha) \in I(\mathcal{I})$, α, which we denote α_a, is given in the form $\{a_i\}_{i \in I_a}$ where $I_a \subseteq [1, n]$ is a subset of indices such that $a_i \in \mathcal{P}_i$ for $i \in I_a$.

We recall here the semantics of a composite component $\mathcal{I}\{K_i\}$ obtained as a composition of a set of components $\{K_i\}$, using the interaction model $\mathcal{I}$ defined as a set of interactions $I(\mathcal{I})$. That is, the interactions in $\mathcal{I}$ define the possible transitions of the composition both as they appear at the interface of the composite component and at the level of the constituting components, which may be required to synchronize.

Definition 6.1.3 (Composition) *Let be $\mathcal{I}$ an interaction model on $\{\mathcal{P}_i\}$ where $\forall i$, $\mathcal{P}_i \subseteq Ports$ and $\{K_i\}$ a set of components on $\{\mathcal{P}_i\}$ as above with $K_i = (Q_i, q_i^0, \mathcal{P}_i, \longrightarrow_i)$. We denote by $\mathcal{I}\{K_i\}$ the component $(Q, q^0, \mathcal{P}, \longrightarrow)$ on $\mathcal{P}_\mathcal{I}$, where:*

- $Q = \prod_{i=1}^{n} Q_i$ *with* $q^0 = (q_1^0, \ldots, q_n^0)$
- $\mathcal{P} = \mathcal{P}_\mathcal{I}$
- $\longrightarrow$ *is the least set of transitions satisfying the rule:*

$$\frac{a \in I(\mathcal{I}) \qquad \forall i \in I_a,\ q_i^1 \xrightarrow{a_i} q_i^2 \qquad \forall i \in [1,n] \backslash I_a,\ q_i^1 = q_i^2}{(q_1^1, \ldots, q_n^1) \xrightarrow{a} (q_1^2, \ldots, q_n^2)}$$

As usually, this means that the component $\mathcal{I}\{K_i\}$ has a transition with label a in state $q = (q_1^1, \ldots, q_n^1)$ iff a is in interactions of $\mathcal{I}$ and for each $i \in I_a$, the corresponding K_i has a transition with label $a_i \in \alpha_a$ in q_i. Firing this transition in $\mathcal{I}\{K_i\}$ consists in synchronously firing the corresponding transitions in the K_i such that $i \in I_a$ while letting unchanged the states of the components not involved in a (i.e., the K_i with $i \notin I_a$).

Note that an interaction model $\mathcal{I}$ may "compose" a single component by allowing only a subset of its ports to be executed. In this case, $\mathcal{I}$ defines a restriction operator as in CCS [Mil80].

Notation 6.1.4 *Given an interaction (a, α_a). Without loss of generality, if a port can be part of at most one interaction, we simplify further the notation of interaction by renaming also the $a_i \in \alpha_a$ into a. Thus given a set of disjoint interfaces $\{\mathcal{P}_i\}$, we can deduce by a simple name matching of their ports, the set of interactions defined on these interfaces. Such an interaction model is denoted $\|$. $\|$ is defined by the maximal interaction model which allows arbitrary interactions while still containing at most one port of each component to be composed.*

Priorities

Components are called non-deterministic if they have a state in which there is a choice of several outgoing transitions. Those transitions may have different labels, in which case non-determinism is called controllable because the environment is able to choose a label and thus decide which interaction should take place, or they may have the same label (uncontrollable non-determinism).

We allow reducing controllable non-determinism by means of *priorities* which allow specifying that an interaction should be preferred over another whenever both are possible in a state.

A detailed description of how priorities are defined and how they can define a composite component is given in Definitions 2.1.15 and 2.1.16 of Section 2.1.6 where priorities on an interaction model $\mathcal{I}$ define a new interaction model denoted $\mathcal{I}_{\prec}$.

The semantics of the composition of a set of components using $\mathcal{I}_{\prec}$ is obtained by first applying $\mathcal{I}$ according to Definition 6.1.3, then by applying $<$ according to the semantics detailed in 2.1.17. Definition 6.1.3, where in any state of the composite component K, the transitions that can be executed according to $\mathcal{I}_{<}$ are those executable according to K that are not inhibited by an interaction with higher priority. Thus $\mathcal{I}_{<}(K)$ has generally fewer executions and fewer reachable states than K, and thus defines a restriction of K which nevertheless preserves deadlock freedom, as expressed later in Lemma 6.1.8. The interest of priorities over a restriction operator as in CCS is that priorities do not introduce new deadlocks.

Systems

Now, we introduce the notion of *system* which corresponds to the previously notion of composite component but which cannot be further composed, that is a closed system. Indeed, in Part II, composite components can be further composed to built hierarchical components and which is a key notion on which rely the previously defined methodology. However, in this part, we only reason about closed systems defined as a composition of components. This structured representation is needed to distinguish between local and global information below, and also to define a distributed implementation in Chapter 7.

Definition 6.1.5 (System) *A* system Sys *is a pair* $(\{K_i\}, \mathcal{I}_{<})$*, where the* K_i *are components on disjoint interfaces* $\{\mathcal{P}_i\}$*,* $\mathcal{I}$ *is an interaction model on* $\{\mathcal{P}_i\}$ *and* $<$ *is a priority order on* $\mathcal{P}_{\mathcal{I}}$*.*

We distinguish between the system $Sys = (\{K_i\}, \mathcal{I}_{<})$ and the component K_{Sys} representing the behavior of Sys by an explicit global transition system, defined by $\mathcal{I}_{\prec}\{K_i\}$. That is, K_{Sys} is obtained by applying first $\mathcal{I}$ to $\{K_i\}$, then $\prec$ on the resulting component. All notations defined for components extend to systems by identifying $Sys = (\{K_i\}, \mathcal{I}_{<})$ with K_{Sys}.

As the main motivation of the work presented in this part is to provide a distributed implementation of systems with respect to the properties defined by the interaction models used to build these systems, we provide now some definitions allowing to distinguish between global and local notions.

Definition 6.1.6 (Global and local states, Global and local priorities) *Consider a system* Sys *of the form* $(\{K_i\}, \mathcal{I}_{<})$*, where* $K_i = (Q_i, q_i^0, \mathcal{P}_i, \longrightarrow_i)$*. Then:*

- *a tuple* $(q_1, \ldots, q_n)$ *with* $q_i \in Q_i$ *is called a* global state *of Sys (note that it is a state of* K_{Sys}*) and* $q_i \in Q_i$ *a* local state *of* K_i*. A local state* q_i *is* compatible *with a global state* q *if the* i*th element of the tuple* q *is* q_i*.*

- *a priority* $a < b$ *is called* local *if the interactions* a *and* b *have a common component, i.e.,* $\alpha_a \cap \alpha_b \neq \emptyset$*. Otherwise, we call this priority* global*.*

Definition 6.1.7 (Locally ready interaction, Globally ready interaction, Enabled interaction) *Let be Sys as above. Consider a global state $q = (q_1, \ldots, q_n) \in Q$, where Q is the set of states of K_{Sys}, and an interaction $a \in \mathcal{I}$.*

- *a is* locally ready *in q_i iff $q_i \xrightarrow{a}_i$*
- *a is* globally ready *in q iff $\forall i \in I_a$, $q_i \xrightarrow{a_i}_i$*
- *a is* enabled *in q iff a is globally ready in q and no interaction with higher priority is also globally ready in q.*

If a is globally ready in q, we denote ind_a^q the set of indexes of the components which must participate in a, that is, $ind_a^q = \{i_1, \ldots i_k\}$ such that $\{K_j \mid j \in [1, k]\}$ is exactly the set of components involved in a (and therefore in which a is locally ready in q).

The distinction between an interaction that is locally ready, globally ready or enabled can be used to characterize the phases of the algorithm presented in Chapter 7 and which describes how a given interaction could be fired with respect to a given interaction model.

Lemma 6.1.8 *Consider a system $Sys = (\{K_i\}, \mathcal{I}_<)$. If there exists in some (global) state q an interaction a that is* globally ready*, then there exists in q some interaction b (possibly equal to a) that is* enabled*.*

This means that the application of priority rules cannot introduce any new deadlock (for a proof, see e.g. [GS04]). This is a motivation for using priorities to control a system.

6.1.2 Controllers defined by properties

The practical motivation for the work presented in this part of the thesis is to propose a distributed implementation of systems with respect to their interaction models. For this purpose, we propose, first to define the interaction models described in the previous section as properties and second to enforce these properties. In other words, our aim is controlling systems using properties defined by their interaction models. We now describe in this section different notions related to the control problem. In particular, we define what it means to *control* a system by some *property*, and to *implement* or *refine* a controller. We show that our systems can be seen as particular instances of a control problem. We are interested in *controlling* systems so as to enforce some given properties. Intuitively, given an interface $\mathcal{P} \subseteq Ports$ and a property φ on this interface, a controller for φ transforms a system K_{Sys} on $\mathcal{P}$ into a component K'_{Sys} on the same interface such as:

- K'_{Sys} ensures the property φ
- K'_{Sys} has only executions that are also executions of K_{Sys}.

To achieve this, a controller may forbid some transitions while allowing the rest of them to be fired.

Generally, in control theory, one distinguishes between the *property* that must be enforced by restricting the behavior of a given component, and the *controller* realizing such a restriction, where the property may be specified in a declarative manner as it is the case in Part II, but the controller must be a (deterministic) operational specification, for example an algorithm or a program. In this chapter, we are not interested in the technical means of forbidding transitions in a system. Thus we do not formalize this distinction here. However, a concrete controller described by an algorithm will be provided in the next chapter. Rather, we focus on how to define that (1) a system satisfies a property, (2) a system is controlled to enforce a property, and later (3) a property is distributed so that controlling locally its components is sufficient to control globally a system. Thus, we consider properties as (possibly non-deterministic) controllers, and we define a *refinement* or *implementation relation* between properties/controllers.

Typical properties φ to be enforced are *safety properties* such as invariants (allowing executions to visit some subset of global states), transition invariants (allowing in a given global state only a subset of its outgoing transitions), or more general temporal logic properties. However, the controller forbidding all transitions trivially refines any controller defined by an arbitrary safety property. Therefore, controllers also make *progress* requirements.

As a result, a property φ representing a controller is generally given in the form $\varphi_S \cap \varphi_{pr}$ where φ_S is a safety property and φ_{pr} defines a progress property.

Typical progress properties φ_{pr} are for example absence of new deadlocks. New deadlocks are deadlock states that are not already specified in the system as final states. Fairness is also a progress property as it defines progress of all individual components of a system. *Maximal progress* with respect to a property φ, is an example of progress property which states that the controller may forbid a transition only if it leads to an unavoidable violation of φ.

Providing an executable controller refining a controller defined by both progress and an arbitrary safety property is of high complexity, and it does not always exist. This is due to the presence of so-called uncontrollable transitions or choices in the behavior of the system K_{Sys} to be controlled. It is possible that allowing in state q some transitions, may lead to a violation of φ many steps later if beyond that transition, the transitions or choices in K_{Sys} cannot be controlled. Thus, in this work, we are interested in controllers represented by a particular class of properties:

- Among safety properties, we consider only those which are not sensitive to the fact that some transitions cannot be controlled. Such properties only use their current state to forbid some transitions (based on their label). In other words, they are *memoryless*. Note that interaction models and priority orders as presented in the previous section define such properties.

- We consider *deadlock freedom*. This progress property is meaningful for example if non-determinism in the specification represents possible design choices which can be exploited to optimize an actual implementation. In Section 6.2, we propose a step towards "correctness by construction" and exploit this freedom in an algorithm generating (whenever possible) a priority order avoiding existing deadlocks in a given specification.

- We also consider *maximal progress*. This progress property is typical for the case where non-

determinism represents choices of the environment, in which case one would like to constrain the environment only as much as necessary to guarantee safety. In Chapter 7, we propose a message-based protocol for controlling a system by an interaction model and a priority order in a distributed setting. Here also, the idea is to achieve "correctness by construction", this time by proposing an algorithm generating a distributed implementation from a set of local components and a global safety and progress constraint.

We now formalize the notions needed for discussing controllers and controlled systems which we have used informally so far. As already mentioned, we do not formally distinguish a controller and a property to be enforced. Properties are represented semantically, by sets of *extended prefixes* with certain closure properties, an extended prefix being a pair consisting of a finite history (state-action sequence) and the set of actions possible after that history. Satisfaction (of a property by a component) and refinement (between properties) are defined by comparing sets of extended prefixes.

Definition 6.1.9 (Property) *Let $\mathcal{P}$ be an interface and Q a set of states.*
a property *φ on $\mathcal{P}$ and Q is a set of extended prefixes that is prefix- and suffix-closed, i.e.:*

- *if $(\sigma, \mathrm{A}) \in \varphi$ then $\forall a \in \mathrm{A},\ \exists q,\ \exists \mathrm{A}',\ (\sigma \cdot a \cdot q, \mathrm{A}') \in \varphi$*
- *if $\exists a \in \mathrm{A},\ \exists q,\ \exists \mathrm{A}',\ (\sigma \cdot a \cdot q, \mathrm{A}') \in \varphi$ then $(\sigma, \mathrm{A}) \in \varphi$*

Definition 6.1.10 (Systems as properties, Conformance, Refinement)

- *a component K on $\mathcal{P}$ with state set Q defines a property Acc_K as the set of extended prefixes (σ, A) such that σ is a prefix of an execution of K, and A is a subset of the set of outgoing labels from q_σ with the constraint that A may only be $\emptyset$ if q_σ is a final state (in F) or a deadlock.*
- *a system Sys defined a component K_{Sys} on $\mathcal{P}$ with state set Q defines a property Acc_{Sys} as the set of extended prefixes (σ, A) such that σ is a prefix of an execution of K_{Sys}, and A is the set of outgoing labels from q_σ with the constraint that A may only be $\emptyset$ if q_σ is a deadlock.*
- *K_{Sys}* conforms *φ (denoted $K_{Sys} \preccurlyeq \varphi$) iff $Acc_K \subseteq \varphi$. Moreover, φ* refines *(also called* implements*) φ' iff $\varphi \subseteq \varphi'$.*

Note that the notion of conformance defined here is consistent with the notion of conformance defined in the previous chapters, as it defines a relation between closed systems.

Note the difference between Acc_K of a component K and Acc_{Sys} of a system Sys is due to the fact that the first represents an open system and the second a closed one. Thus Acc_K represents what is usually called an acceptance semantics of a component K in any context. Acc_{Sys} represents an acceptance semantics of Sys in an empty context, that is the context used to define conformance in Section 4.4. Note Acc_K is indeed a property, as it is prefix- and suffix-closed.

Definition 6.1.11 (Memoryless property, Safety property, Progress property)

- *φ is* memoryless *(history independent) iff $(\sigma, \mathrm{A}) \in \varphi$ implies that $(\sigma', \mathrm{A}) \in \varphi$ for any σ' such that $q_{\sigma'} = q_\sigma$, that is, A does only depend on q_σ, not on the* history *expressed by σ.*

- *φ is a* safety property *iff for a given prefix σ, the corresponding set of acceptance sets is subset closed, that is, $(\sigma, \mathrm{A}) \in \varphi$ implies that for all* A' *included in* A, *$(\sigma, \mathrm{A}') \in \varphi$.*

- *Symmetrically, φ is a* progress property *iff it is superset closed, that is, it defines which executions a component satisfying it should have at least.*

Note that the property Acc_K defined by a component K is a memoryless property on $\mathcal{P}$ and Q_K.It is almost a safety property, as it specifies an overapproximation of the behavior of K. It is not fully a safety property though, because only final states and deadlocks may have an empty acceptance set. Thus, for a given prefix σ, the set of acceptance sets is not subset closed. Note that this definition is consistent with the set of executions of K defined in Section 6.1. As a result, K represents a very weak progress property, and we need an additional controller if we want to enforce stronger ones. Hence the following properties.

- *Deadlock freedom* is defined by a property φ defined by: iff $(\sigma, \mathrm{A}) \in \varphi$ implies that $\mathrm{A} \neq \emptyset$.

- *Maximal progress*, denoted φ_{mp}, is defined with respect to a given component K and safety constraint φ_S. It consists in determinizing $Acc_K \cap \varphi_S$ by choosing for each prefix σ only the acceptance sets A which are maximal with respect to set inclusion.

Now, interestingly, the notions of interaction model and priority order that have already been introduced also define properties.

Definition 6.1.12 (Property of an interaction model) *An interaction model $\mathcal{I}$, with the set of interactions $I(\mathcal{I})$, defines the memoryless property $\varphi_{\mathcal{I}}$ consisting of all pairs (σ, A) where $\mathrm{A} \subseteq I(\mathcal{I})$: in any state, the corresponding acceptance sets contain only interactions allowed by $\mathcal{I}$.*

Definition 6.1.13 (Property of a priority order) *A priority order $<$ defines the memoryless property $\varphi_<$ consisting of all pairs (σ, A) such that for all $a, b \in \mathrm{A}$, a and b are not related by $<$. That is, in any state, any enabled transition disables all those with lower priority.*

Now, we still have to define what it means to control a system by a property.

Definition 6.1.14 (Controlled system) *Let K_{Sys} be a component on $\mathcal{P}$. Then:*

- *Any property φ on $\mathcal{P}$ and the set of states Q_{Sys} may be used as a controller for K_{Sys}.*

- *The* controlled system *defined by K_{Sys} and φ, denoted (K_{Sys}, φ), is the property $Acc_{Sys} \cap \varphi$.*

- *An* implementation *of (K_{Sys}, φ) is a system K'_{Sys} confroming to $Acc_{Sys} \cap \varphi$.*

Similarly, we can define what it means to control a component by a property, using the acceptance semantics of a component that is Acc_K as define above.

Note that if φ is memoryless, then $Acc_K \cap \varphi$ is also memoryless. Note that we are interested here only in memoryless controllers. And we can now establish very easily the fact that an interaction model $\mathcal{I}_<$ as defined in Section 2.1.6 defines a memoryless controller for a system of the form $\|\{K_i\}$.

Lemma 6.1.15 (Interaction models and priority orders as memoryless controllers) *Consider a system Sys of the form $(\{K_i\}, \mathcal{I}_<)$ with $\mathcal{I}$ an interaction model and $<$ a priority order defining, according to Definition 2.1.16, a component $K_{Sys} = \mathcal{I}_<\{K_i\}$. Then $\mathcal{I}$ and $<$ define a* memoryless controller *for the component $\|\{K_i\}$ in the sense that $\mathcal{I}_<\{K_i\}$ is an implementation of the controlled component $(\|\{K_i\}, \varphi_\mathcal{I} \cap \varphi_<)$.*

Proof Interaction models and priority orders define memoryless properties as they define the set of allowed interactions independently of the history, in fact, they do even not depend on the current state. The combined effect of an interaction model and a priority order is represented by the intersection of these properties, which is memoryless as well. The executions of $\mathcal{I}_<\{K_i\}$ are also executions of $\| \{K_i\}$. Moreover, after a prefix σ, the corresponding acceptance sets in $Acc_{\mathcal{I}_<\{K_i\}}$ are exactly the same as those in $Acc_{\|\{K_i\}} \cap \varphi_\mathcal{I} \cap \varphi_<$. Hence: $Acc_{\mathcal{I}_<\{K_i\}} \subseteq Acc_{\|\{K_i\}} \cap \varphi_\mathcal{I} \cap \varphi_<$. That is, $\mathcal{I}_<\{K_i\} \models Acc_{\|\{K_i\}} \cap \varphi_\mathcal{I} \cap \varphi_<$, which means by definition that $\mathcal{I}_<\{K_i\}$ implements $(\|\{K_i\}, \varphi_\mathcal{I} \cap \varphi_<)$. □

6.2 Synthesis of priorities for avoiding deadlocks

In this section, we propose a small algorithm allowing to enforce the property of deadlock freedom using the property defined by priorities. More precisely, we propose an algorithm that generates for a system which has some deadlocks a controller in the form of a priority order $<$ in order to avoid these deadlocks. Later, in Chapter 7, we propose a generic algorithm that generates a distributed implementation for a distributed system controlled by an interaction model and a priority order.

In terms of the notations introduced earlier, the problem we want to solve is the following: given a system of the form $Sys = (\{K_i\}, \mathcal{I}_\emptyset)$ which has deadlocks, determine a priority order $<$ such that $(\{K_i\}, \mathcal{I}_<)$ is deadlock-free if such a $<$ exists. Otherwise, report that no appropriate priority order $<$ exists.

Given a system K_{Sys} and a set Tr of transitions to be avoided, the algorithm computes, if possible, a set of priority rules which make these deadlocks unreachable by either *inhibiting* the transitions in Tr or making them unreachable by inhibiting earlier transitions.

Before presenting the full algorithm, we illustrate how it works — or fails — on simple examples.

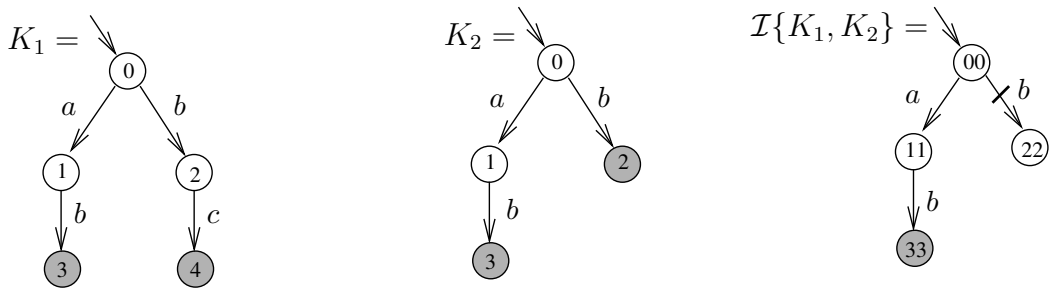


Figure 6.1: An example where reducing non-determinism eliminates a deadlock.

A simple system controllable with priorities Consider two components K_1 and K_2 defined on $\{a, b, c\}$ and depicted in Figure 6.1 and which are composed by the already mentioned interaction model $\mathcal{I}$ requiring that transitions with the same name must interact. The obtained system has a deadlock which is reached if initially the two components choose b, as after that, K_1 expects an interaction on c while K_2 has already terminated.

This deadlock is avoided if in the initial state 00, a is chosen instead. We can achieve this by choosing the priority order defined by $\{b < a\}$. It forbids the b-interaction in the initial state where also an a-interaction is enabled, and it allows a b-interaction after the execution of the a-interaction, (in state 11), where it is the only enabled interaction

A simple system not controllable with priorities Figure 6.2 shows a slightly different system defined by two components K_1' and K_2' composed using the same convention as before. For this system, there exists no priority order that avoids deadlocks. We sketch below how this is detected by our algorithm:

1. The composed component $K' = \mathcal{I}\{K_1', K_2'\}$ is (partly) computed and transitions leading to deadlocks are marked as *error* transitions, as shown in Figure 6.2.

2. In the initial state (1), b must be preferred to a in order to prevent a deadlock, and we conclude that any priority order making K' deadlock free includes the rule $a < b$.

3. In state 2, there are two possibilities to forbid the b-transition leading to a deadlock: either b has lower priority than a or state 2 is made unreachable. The first option is impossible as it would mean that $a < b$ and $b < a$ which violates the requirement that a priority is a strict partial order. The second option implies that the transition from 1 to 2 labeled by b should be inhibited by a transition with higher priority enabled in the initial state which leads to exactly the same contradiction.

We conclude that no priority order can control the given example to guarantee deadlock freedom. Note that *dynamic* priorities can deal with this example, as it is sufficient to define as priorities, $a < b$ in state 1 and then $b < a$ in state 2.

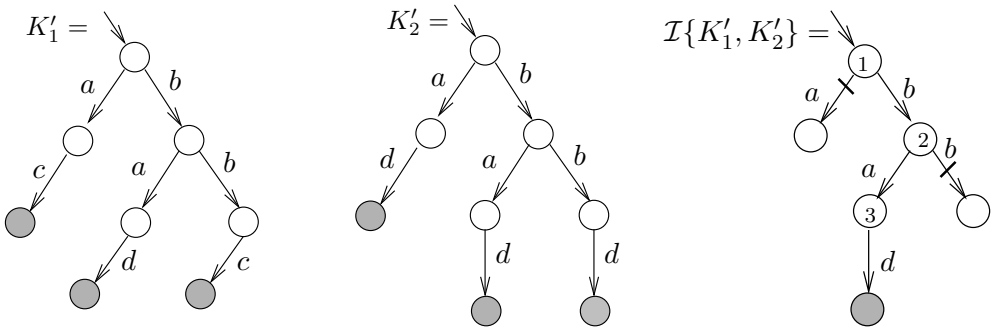


Figure 6.2: A simple system not controllable with priorities.

Note that we only consider *static* priorities which do not depend on the state of the system. Obviously, *dynamic* priorities defined in [BBBS08, GS04] — which are allowed to be different in different states of the system — are more powerful in the sense that they allow to always eliminate all deadlocks. But this can be generally done at the price of drastically reducing — or even eliminating — concurrency. Indeed, dealing with dynamic priorities requires generally a precise knowledge about the current global state in order to decide whether a given transition has highest priority or not and "precise knowledge about the global state" can generally be only achieved by adding more communications, that is, reducing the degree of concurrency.

The general algorithm is given below, and it is quite easy to see how it could be extended for generating dynamic priorities — if needed.

The dining philosophers We consider a variant of the dining philosophers problem inspired from [Pad]. Philosophers are components providing thoughts if they have got two forks. These forks represent shared resources given in form of a unique component providing forks and expecting to get thoughts in return. Figure 8.6 shows a configuration with two philosophers and a resource with two forks. A deadlock arises if both philosophers have each one a fork and wait forever for a second one.

This deadlock can be avoided by always giving the highest priority to the request closest to completion. This is a classical method for managing resources. The priority order that is needed here is $\{fork_1^\alpha < fork_2^\beta,\ fork_1^\beta < fork_2^\alpha\}$. For readability reasons, we simplify in Figure 8.6, the names of the interactions of the composed behavior in a straightforward manner. $fork_{1,2}^{\alpha,\beta}$ in the behavior of the component $Forks$ corresponds to the interactions $\{fork_1^\alpha,\ fork_2^\alpha,\ fork_1^\beta,\ fork_2^\beta\}$ of the two philosophers.

Note that in this example priorities are *local* as there exists a unique pool of forks involved in all interactions. If instead of a resource pool, we define a set of resource components, each one administrating one fork that is shared by two neighbors, then the corresponding priorities,which are still useful, are *global*.

Algorithm 1 Priority4Tr($K = (Q, q^0, \Sigma, \delta, F)$, Tr, π): priorityOrder or $\perp$

if $Tr = \emptyset$ **then**
  return π // *there are no* error *transitions, so* π *is a solution*
else
  $Pot \longleftarrow \emptyset$
  Initialize(K, Tr, π, Pot) // *initialize sets* π, Pot*; simplify* K, Tr *accordingly*
  if $Tr = \emptyset$ **then**
    return π
  else if $Pot = \emptyset$ **then**
    return $\perp$ // error *transitions cannot be avoided, so there is no solution*
  end if
  $\mathcal{O} \longleftarrow$ PotentialOrders(Tr, π, Pot) // *calculate the set of potential priority orders*
  return FindOrRefine(K, Tr, $Pot, \mathcal{O}$) // *find* O *of* $\mathcal{O}$ *being a solution or refine it*
end if

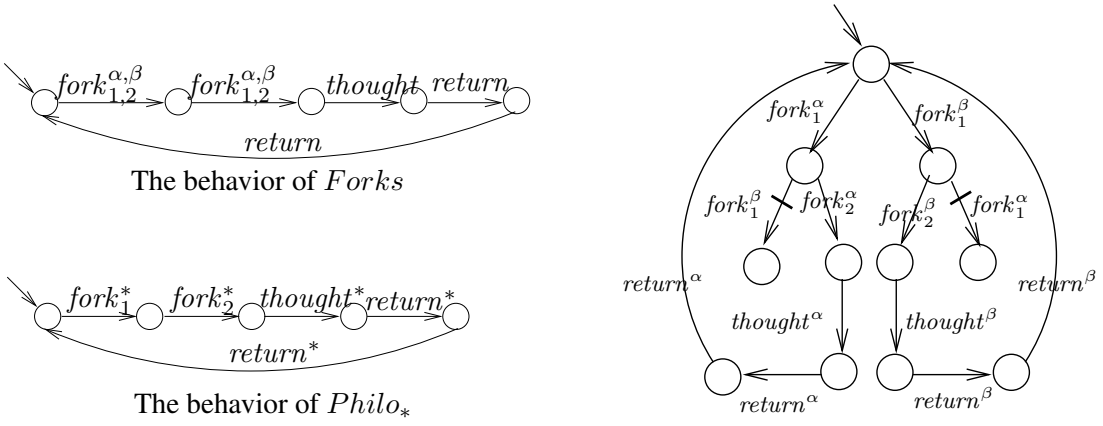


Figure 6.3: A solution to the dining philosophers problem.

Algorithm for inferring priorities For simplicity, we suppose that the following are precalculated before calling the main algorithm which is *Priority4Tr*:

1. the global behavior of the component or system of interest, that is K if it is a component and K_{Sys} if it is a system Sys.
2. the set Tr of *error transitions*, namely those leading into a deadlock state.

The set π is initialized as the empty set. Then, at any step of the algorithm, Tr holds the set of error transitions which are not yet forbidden by some priority in π. π contains at any time a valid priority order $<$ forbidding the error transitions not inhibited by forbidding transitions in Tr, and at successful termination it contains a desired solution.

Algorithm 2 Initialize(K, Tr, π, Pot)

for all $t = (s, a, s') \in Tr$ **do**
  if $q^0 \longrightarrow^*! \ s$ and $s \xrightarrow{b} \in \delta$ implies $(b < a \in \pi \vee b = a)$ **then**
    $Pot \longleftarrow \emptyset$ **break**
  else if $q^0 \longrightarrow^*! \ s$ and $\exists b \in \Sigma$ s.t. $\{b\} = \{l |\ s \xrightarrow{l} \wedge\ l \neq a \wedge (l < a \notin \pi)\}$ **then**
    if $b < a \in \pi$ **then**
      $Pot \longleftarrow \emptyset$ **break**
    end if
    add$(\pi, a < b)$ *// add $a < b$ to Prio and normalize by adding induced priorities*
    $Tr' \longleftarrow \{t\} \cup \{(q, a, q') \in \delta \mid q \xrightarrow{b}\}$ *// remove from δ transitions inhibited by $a < b$*
    simplify(Q, δ) *// simplify δ and Q by removing unreachable transitions and states*
    $Tr \longleftarrow Tr \cap \delta$ *// simplify Tr in accordance with the new δ*
  else
    $Pot_t \longleftarrow \{a < b \mid s \xrightarrow{b} \wedge\ b \neq a \wedge (b < a \notin \pi)\}$
    if $Pot_t = \emptyset$ **then**
      $\delta \longleftarrow \delta \backslash \{t\}$ *// since t cannot be inhibited, its origin state must be made unreachable*
      simplify(Q, δ) *// simplify δ and Q*
      $Tr \longleftarrow (Tr \cup \{(q, l, s) \in \delta\}) \cap \delta$ *// simplify Tr according to δ*
    end if
  end if
end for

The *Priority4Tr* algorithm successively calls the algorithms *Initialize*, *PotentialOrders* and *FindOrRefine*, which play the following roles:

1. *Initialize* computes the priority rules $Prio$ that are *necessary* to avoid all deadlocks from any reachable state of K. If $Prio$ contains a contradiction the overall algorithm terminates with failure.

2. *PotentialOrders* computes a set of alternative priority rules Pot which may be used to control the execution,

3. *FindOrRefine* picks one such priority order and explores it. If it fails, then another alternative in Pot is explored until success or failure — if none of them works.

Note that a priority order is represented explicitly by a set of rules $a < b$ where for simplicity, also those rules which can be deduced by transitivity are explicitly represented. We also do not detail here the basic straightforward algorithms for manipulating priorities (adding or deleting rules, building the union of priority order, ...) in this normal form and maintaining them in this form.

Moreover, we use the following notations:

- For any transition $t \in Tr$, Pot_t represents the set of potential priority rules that can inhibit t. $Pot \backslash \{r\}$ denotes that rule r is removed from pot and thus from all sets Pot_t.

Algorithm 3 PotentialOrders(Tr, π, Pot): Set of priorityOrders

choose $t \in Tr$
$O \longleftarrow \{r \in Pot_t \mid \text{add}(Prio, r) \text{ is defined}\}$ *// some priorities in Pot_t may contradict π*
for all $r \in O$ **do**
  $Tr^r_{ok} \longleftarrow \{t' \mid r \in Pot_{t'}\}$ *// transitions in Tr inhibited by r*
end for
$Unreachable_t \longleftarrow$ PotentialOrders($Tr\backslash\{t\}, \pi, Pot$) *// suppose t needs not be inhibited*
$Inhibited_t \longleftarrow \bigcup_{r \in O}$ PotentialOrders($Tr\backslash(\{t\} \cup Tr^r_{ok})$, add($\pi, r$), $Pot\backslash\{r\}$) *// t is inhibited by r*
return $Unreachable_t \cup Inhibited_t$

- $q^0 \longrightarrow^*! s$ denotes that s is reachable from q^0 by a (possibly empty) sequence of transitions for which there exists no alternative, that is, transitions of the form (s_1, α, s_2) such that δ has no other transition with s_1 as origin.

Theorem 6.2.1 *Given a component K, the algorithm terminates, and at termination, π defines a priority order $<$ such that $\langle < \rangle(K)$ is deadlock free or the algorithm terminates with failure if no such priority order exists.*

Proof The correctness of the algorithm is guaranteed by the following facts:

1. if $Prio$ does not define strict partial order, the algorithm terminates unsuccessfully, and $Prio$ contains only rules which must be used to inhibit some error transitions.

2. at any point of time, $Prio$ together with avoiding Tr guarantees avoidance of deadlocks because initially avoiding Tr obviously guarantees deadlock freedom, and a transition t is only eliminated from Tr if there is a rule in $Prio$ forbidding it or if t is replaced by some transition (set) leading to the start state of t. On termination, Tr is empty, thus $Prio$ — which is a priority order — is able to prevent all deadlocks.

3. The fact that the algorithm terminates unsuccessfully implies that indeed there is no appropriate priority order is guaranteed by the fact that the algorithm systematically explores transition sets allowing to block the access to a deadlock state without introducing a new deadlock, and such a set is rejected only if avoiding requires contradictory priorities.

4. the algorithm does indeed terminate as (1) the main algorithm is called each time with a set Tr of error transitions that decreases or contains transitions closer to the initial state and (2) the other algorithms explore a finite set of alternative orders, pick one of them or abandon if none of them works.

□

For readability, the parameters of *Initialize* are call-by-reference, while those of *Priority4Tr*, *PotentialOrders* and *FindOrRefine* are call-by-value.

Algorithm 4 FindOrRefine(K, Tr, Pot, $\mathcal{O}$)

if $\exists O \in \mathcal{O}$ s.t. $\forall t,\ Pot_t \cap O \neq \emptyset$ **then**
  return O *// O inhibits all* error *transitions, thus O is a solution*
else
  while $\mathcal{O} \neq \emptyset$ **do**
    choose $O \in \mathcal{O}$
    $\mathcal{O} \longleftarrow \mathcal{O} \backslash \{O\}$
    $Tr_{bad} \longleftarrow \{t \mid Pot_t \cap O = \emptyset\}$ *// transitions not inhibited by O*
    $\delta \longleftarrow \delta \backslash (Tr \backslash Tr_{bad})$ *// remove inhibited transitions from δ*
    simplify(Q, δ) *// simplify δ and Q*
    $Tr \longleftarrow (Tr \cup pre(Tr_{bad}))$ *// add predecessors of transitions not inhibited to Tr*
    $Tr \longleftarrow Tr \cap \delta$ *// simplify Tr according to δ*
    $Result \longleftarrow$ Priority4Tr$(B,\ Tr,\ O)$
    if $Result \neq \bot$ **then**
      return $Result$
    end if
  end while
  return $\bot$
end if

Chapter 7

Distributed Controllers for Systems with Priorities

The practical motivation of the work presented in this part of the thesis, is to provide a distributed implementation of systems controlled by properties of their interaction models. In particular, our purpose is enforcing the properties of the interaction models with priorities which, as already described, define a memoryless controller. The obtained controlled system correspond actually to a simple BIP system with priorities. In this chapter, we propose such a distributed implementation by synthesizing a distributed memoryless controller.

Distributed characterization of a system consists of a set of components communicating through message passing where we suppose that the underlying communication platform ensures reliable and order-preserving transmission of messages.

We have adopted previously a very abstract view of a controller as a property. Thus, in this chapter, we first define, in Section 7.1, what it means to distribute a controller, and what a correct implementation should be. Then, in Section 7.2, we propose a protocol allowing to implement such a distributed controller based on message-passing.

7.1 Distributing systems and controllers

We suppose from now on that we work with systems $Sys = (\{K_i\}, \mathcal{I}_<)$ in which a port is part of at most one interaction. Thus, local properties (defined on $\mathcal{P}_i$ and Q_i) and global properties (on the interface $\mathcal{P}$ and the set Q of states of K_{Sys}) share their interfaces. This can be done without loss of generality, and does drastically simplify the presentation.

For a system Sys of the form $(\{K_i\}, \|)$ on which a global property φ, typically $\varphi_{\mathcal{I}} \cap \varphi_< \cap \varphi_{mp}$, must be enforced, we are now interested in defining a *distributed controller*. Such a controller consists of a set of local controllers i.e., local properties φ^i, taking decisions about the next transitions that can be executed. Those decisions are based on the local information of the corresponding component K_i in such a way that the union of local decisions is a decision allowed by the global property φ, which means that we are yielding a disjunctive controller.

In Section 7.2, we implement such a distributed controller for the specific case where the global property to be enforced is of the form $\varphi_{\mathcal{I}} \cap \varphi_{<} \cap \varphi_{mp}$, that is, for systems in which a set of components are constrained by an interaction model and a priority order, and for which we want a controller achieving maximal progress. Note that:

- $\varphi_{\mathcal{I}} \cap \varphi_{<}$ is a safety property that it is union closed: indeed, for every state q the set of acceptance sets has a maximal element (π, A) where A is the set of interactions that are enabled with maximal priority in q. Remember that $\varphi_{\mathcal{I}}$ and $\varphi_{<}$ are memoryless, thus $\varphi_{\mathcal{I}} \cap \varphi_{<}$ is memoryless too.

- Maximal progress, i.e. property φ_{mp}, consists in allowing for each prefix only the set of acceptance sets which are maximal with respect to set inclusion. Thus, in our special case, there exists in every state exactly one element of the form (π, A), namely the maximal element mentioned in the previous item meaning that every allowed interaction is also required.

More generally, the properties we want to distribute are characterized for each prefix by (1) a set of *allowed* interactions and (2) a set of *required* interactions, the two sets are identical for deterministic specifications when maximal progress is required. This means that if local properties are *correct* in the sense that they allow only globally enabled interactions, and *complete* in the sense that for every interaction allowed by φ at least one component allows it, then the union of the locally allowed interactions is exactly the set of globally allowed interactions. On the other hand, if each of the local properties ensures maximal progress, then the union of the locally required interactions is exactly the set of globally required interactions. Note that other progress requirements, in particular fairness and deadlock freedom can be also achieved in that way.

Moreover, note that the properties that we consider are memoryless. We will see in Section 7.2 that this greatly simplifies the construction of the local controllers.

We now formally define the notion of distributed controller as a composition of local controllers.

Definition 7.1.1 (Composition of local properties) *Consider a set of properties $\{\varphi^i\}$ on $\{Q_i\}$ and $\{\mathcal{P}_i\}$ and the interaction model $\mathcal{I}_{\|}$ defining the set of all possible interactions in $\mathcal{P} = \bigcup_i \mathcal{P}_i$. We define the composition of the φ^i, denoted $\oplus_i\{\varphi^i\}$, as the set of extended prefixes $\{(\pi, \bigcup_i \mathrm{A}_i) \mid \forall i,\ (\pi_i, \mathrm{A}_i) \in \varphi^i\}$ where π is an alternating sequence of states in $Q = \prod_i Q_i$ and actions in $\mathcal{I}_{\|}$, and π_i can be obtained from π by replacing states in π by their i-th component.*

The property $\oplus_i\{\varphi^i\}$ defined by the set of properties $\{\varphi^i\}$ can be seen as a controller and it implements a controller φ when $\oplus_i\{\varphi^i\} \subseteq \varphi$. Before we give a formal definition of distributed controller, we first extend the composition of properties to properties on *extended local states*.

This means that we must either extend local properties also to the global interface $\mathcal{P}$ or we must restrict the set of properties which we want to distribute. We make the second choice as we are mainly interested in controllers which are memoryless and where φ is of the form $\varphi_S \cap \varphi_{pr}$ for φ_S a safety property and φ_{pr} a progress property. We have seen that safety properties are subset and union closed which means that indeed in a given situation, the union of locally identified next interaction is a valid global set of next interactions.

In general, none of the individual components is able to decide locally whether in a state an interaction a is enabled. Some minimal *knowledge* about the current global state is then necessary to take a decision locally. In [BBPS, GPQ10], it is proposed to use statically computed knowledge derived from the set of reachable states. A more classical solution — which we adopt here — consists in letting local controllers compute dynamically the knowledge required to take a correct decision locally. On a platform where communication is by message passing, this is achieved via messages as well, and this requires a minimal degree of stability of the information transmitted by messages. Here, we also follow this approach.

As a consequence, we consider properties φ^i which are not defined on the set of local states Q_i but on a set of *extended local states* Q_i^{ext} of the form $Q_i \times Q_i^{kn}$ where in a state (q_i, q_i^{kn}), q_i^{kn} represents a set of global states which are compatible with q_i, the intention being that in (q_i, q_i^{kn}), φ^i *knows* that the current global state is in q_i^{kn}, which helps deciding for a sufficient subset of interactions whether they are enabled. Concretely, we do not formalize here how these φ^i are built, only how we check that they implement indeed a correct distributed controller. We can now adapt composition of local properties to these properties defined on extended local states. This only requires, in addition to the previous definition, to check that each global state q of an execution is compatible with the extended local state (q_i, q_i^{kn}) of the corresponding executions, i.e., q_i is the i-th component of q and $q \in q_i^{kn}$.

Definition 7.1.2 (Composition of local properties defined on extended local states) *$\oplus_i\{\varphi^i\}$ for a set of properties on extended local states is the set of extended prefixes $\{(\pi, \bigcup_i \mathrm{A}_i) \mid \forall i,\ (\pi_i, \mathrm{A}_i) \in \varphi^i\}$ where π is an alternating sequence of states in $Q = \prod_i Q_i$ and actions in $\mathcal{I}_{\|}$, and π_i is obtained from π by replacing each state q in π by a pair consisting of its i-th component and a set of global states including q.*

Definition 7.1.3 (Distributed controller) *Let be $Sys = (\{K_i\}, \|)$ and φ as above. A distributed controller for (Sys, φ) is a set of properties $\{\varphi^i\}$ such that $\oplus_i\{Acc_{K_i} \cap \varphi^i\} \subseteq Acc_{K_{Sys}} \cap \varphi$, where $K_{Sys} = \|\{K_i\}$.*

In the case that we consider the property of maximal progress, $Acc_{K_{Sys}} \cap \varphi$ contains for every prefix exactly one set A, the set of globally enabled interactions, and therefore, inclusion means indeed equality. Note also that such a distributed controller always exists for memoryless properties as those considered. Indeed, a set of local controllers defined on the global state space can clearly decide for every interaction whether it is enabled or not.

7.1.1 Concurrency and confusion

We aim at distributed executions, thus interactions which are independent, denoted *concurrent* in Definition 7.1.4 below, can be executed concurrently, however, interactions which are not concurrent, that is in conflict, cannot. Throughout this section, consider a system $Sys = (\{K_i\}, \mathcal{I}_<)$. We can now define the usual notions of *concurrency* and *conflict* of interactions, where in a distributed setting we want to allow the independent execution of concurrent interactions, so as to avoid global sequencing. We distinguish explicitly between the usual notion of conflict which we call structural conflict, and a conflict due to priorities.

Definition 7.1.4 (Concurrent interactions, Conflicting interactions) *Let a, b be interactions of $\mathcal{P}$ and $q \in Q$ a global state in which a and b are globally ready.*

- *a and b are called* concurrent *in q iff $ind_a^q \cap ind_b^q = \emptyset$ (see Definition 6.1.7). That is, when a is executed then b is still globally ready afterwards, and vice versa, and if executed, both interleavings lead to the same global state.*
- *a and b are called* in structural conflict *in q iff they are not concurrent in q, that is a and b are alternatives disabling each other.*
- *a and b are in* prioritized conflict *in q iff a and b are concurrent in q but $a < b$ or $b < a$ holds.*

Note that in case of prioritized conflict, it is known which interaction cannot be executed, whereas in case of structural conflict, the situation is symmetric. We use the notations $Concurrent_q(a)$, $Conflict_q(a)$, $PrioConflict_q(a)$ to denote the set of interactions that in state q are concurrent to a, respectively in structural or prioritized conflict to a.

Our local controllers are defined on extended local states, and an implementation of the distributed controller has to collect the required knowledge for being able to take a decision. However, collecting this information may take time and some concurrent transition t may be executed concurrently. Thus, the notion of concurrency chosen must provide sufficient stability of the collected information for it to be useful: indeed, after receiving this information, the local controller does not know whether t has taken place, and thus its extended local state contains both source states and target states of t. Thus, the usual notion of concurrency is not sufficient to detect such situations which are called *Confusion*.

Confusion is a situation where concurrency and conflict are mixed. More precisely, confusion arises in a state where two interactions a_1 and a_2 may fire concurrently, but firing one modifies the set of interactions in conflict with the other. It is a situation occurring in distributed systems [Bol07, Bol05]. Typically, detecting those situations is important for designing correct algorithms for partial order reduction. In presence of priorities, confusion situations may compromise correctness of a distributed implementation of a specification. We first define some preliminary notions which allow us to characterize different situations of confusion.

Figure 7.1 illustrates a situation of structural conflict: interactions a_1 and a_3 are in *structural conflict* as they both involve component K_1 (respectively K_2). Figure 7.2 illustrates a *prioritized conflict* of a_1 with a_3 as these interactions are concurrent but $a_1 < a_3$ holds.

A *symmetric* (left) and an *asymmetric* (right) situation of confusion are shown in Figure 7.1: in the symmetric case, interactions a_1 and a_2 of K_1 and K_1' are concurrent but are both in conflict with a_3 and the execution of a_1 (resp. a_2) changes the set of interactions in conflict with a_2 (resp. a_1). In the asymmetric case, the interactions a_1 and a_2 of K_2 and K_2' are concurrent but a_1 will enter in conflict with a_3 if a_2 fires before a_1.

Definition 7.1.5 (Confusion) *Let a_1 and a_2 be interactions, and q a global state of Sys. We suppose that a_1 and a_2 are concurrent — and thus globally ready — in q.*

- *a_1 is in* structural confusion *with a_2 iff $\exists q' \in Q, q \xrightarrow{a_2} q'$ implies $Conflict_q(a_1) \neq Conflict_{q'}(a_1)$*

- a_1 *is in* prioritized confusion *with* a_2 *iff* $\exists q' \in Q$, $q \xrightarrow{a_2} q'$ *implies* $\mathit{PrioConflict}_q(a_1) \neq \mathit{PrioConflict}_{q'}(a_1)$

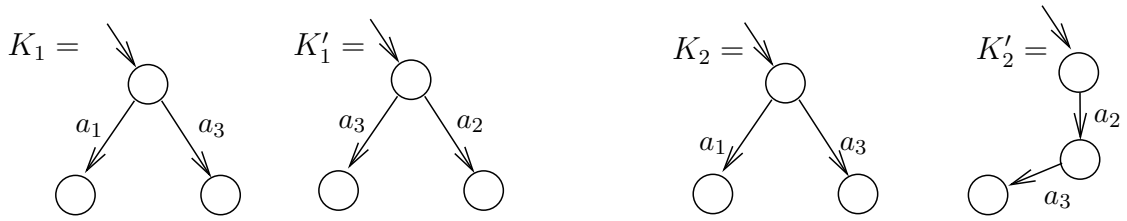


Figure 7.1: Symmetric and asymmetric confusion.

Figure 7.2(left) illustrates a situation of *prioritized confusion*: a_1 and a_2 of components K_1 and K_1' are concurrent, however firing a_2 enables a_3 which has higher priority than a_1 which means that a_1 is no more enabled after the execution of a_2.

The classical notion of confusion is what we call structural confusion. Note that all situations of confusion are important for designing partial order reductions which are very important for making the verification of global properties of $Sys = (\{K_i\}, \mathcal{I}_<)$ feasible. The reason is that eliminating arbitrarily one of the two interleavings of a_1 and a_2 may change the set of reachable states, and thus lead to different verification results.

For designing a distributed implementation of Sys, only the situation of Figure 7.2, where executing a_2 disables a_1 due to a new priority conflict, is problematic. The reason is that in this case a_1 and a_2 are not really "concurrent", whereas in all other cases, it does still hold that a_1 and a_2 can be executed in any order and both orders lead to the same global state.

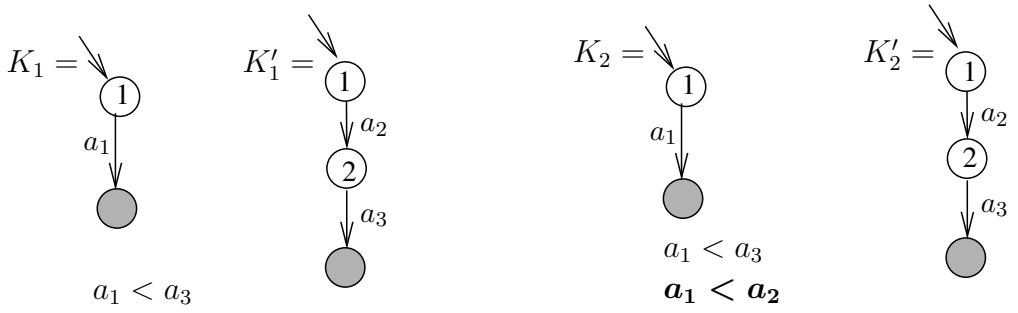


Figure 7.2: Prioritized confusion.

In Section 7.2, we propose a distributed implementations of systems $Sys = (\{K_i\}, \mathcal{I}_<)$ in which concurrent interactions are executed independently, based on the notion of concurrency of definition 7.1.4. This means that our algorithm does not support systems Sys with such prioritized conflict situations.

In order to deal with this kind of confusion, we could use a more appropriate notion of concurrency which however would lead to inefficient implementations. We rather propose to eliminate such confusions statically by adding a priority $a_1 < a_3$ or $a_2 < a_1$ (see Figure 7.2(right)) such that either a_1 and a_2 are not anymore considered concurrent or at least it is guaranteed that executing concurrent interactions does not introduce priority conflicts which destroy this concurrency. Note that adding *priorities* between *concurrent* interactions in a given system does not add new deadlocks.

7.2 Implementation of a distributed controller as a protocol

Given a system $Sys = (\{K_i\}, \mathcal{I}_<)$ defined by a set of components $\{K_i\}$, an interaction model $\mathcal{I}$ and a priority order $<$ to be enforced, our goal is to define a distributed implementation for Sys. In this section, we define an algorithm which constructs such a distributed implementation by defining for each component a local controller C_i ensuring a property φ^i such that the joint execution of all components K_i and their corresponding controllers guarantees the following:

1. all executions are executions of Sys, that is executions of $K_{Sys} = \mathcal{I}_\prec\{K_i\})$
2. if Sys is deadlock free, then no deadlock will ever occur

This means according to Definition 7.1.3 that the properties φ^i of C_i have to ensure the following:

$$\oplus_i\{Acc_{K_i} \cap \varphi^i\} \subseteq Acc_{\|\{K_i\}} \wedge \varphi_{\mathcal{I}} \wedge \varphi_< \wedge \varphi_{mp}$$

As presented in Section 7.1, local controllers use messages to accumulate the knowledge required to extend their local state. For simplification, we do not formally represent knowledge as sets of global states. Instead, we use, as an abstract representation of this sets, a set of properties with respect to interactions, e.g. that interaction a is globally possible etc. Absence of confusion ensures that this knowledge is sufficient. Based on this knowledge, for every enabled interaction, at least one local controller in any global state can determine that it is enabled. A local controller in a local state in which a transition labeled by a is locally possible exchanges messages with the local controllers of other components involved in a (to determine whether a is globally possible) and with the local controllers of other components involved in an interaction b with higher priority than a to determine whether a is enabled. In the latter case, it is sufficient to communicate with one component involved in b.

Here we represent local controllers ϕ_i as protocols interacting with the controlled component K_i and with other controllers by exchanging messages.

Besides, we rely on Sys to guarantee deadlock-freedom and fairness. That is, any distributed implementation of Sys that does not introduce new deadlocks, not defined by Sys, is considered correct. Indeed, we suppose that, if needed, Sys has been obtained using the algorithm of Section 6.2 that eliminates deadlocks. For this reason, we suppose in the following that Sys has no deadlock.

7.2.1 Description of the protocol

The system is supposed to have a fixed number of components, although it may be arbitrarily large. In order to simplify the presentation of the algorithm, we suppose here only binary interactions; an extension to arbitrary multi-party interactions is discussed at the end of this chapter. We also assume that the internal activities of components are terminating and that there exists no prioritized confusion (see Section 7.1.1), that is, the notion of concurrency used by the algorithm is correct. Without this last condition, we may observe global executions which are witnesses of a priority violation. As quite usually in distributed protocols [Bag89b, Bag89a, PCT04], we assume that the message passing mechanism ensures the following basic properties:

1. any message is received at its destination within a finite delay;

2. messages sent from location L_1 to L_2 are received in the order in which they have been sent;

3. there is no duplication nor spontaneous creation of messages.

For each interaction a involved in at least one priority rule, one of the involved components K_i place the role of the *negotiator* for a. If there exists at least one interaction with higher priority, the role of the *negotiator* is to check for the enabledness of a, and if there exists at least one interaction with lower priority, its role is to answer readiness requests. This notion of *negotiator*, is introduced to deal with priority, thus no similar notion exist in related algorithms. The choice of negotiators is discussed later.

We now describe the controllers of individual components which enforce correct executions, and in particular adherence to the global priority order. It is understood that what is called component K_i is in fact *controlled* by a *local* controller C_i.

The controller associated with each component, maintains a set of data structures shared and maintained by the different subtasks of the controller: $readySet$ (resp. $enabledSet$) contains the set of interactions which are known to be globally ready (resp. enabled) in the current local state q, and involved and $possibleSet$ maintains the set of interactions that are locally ready. Note that $possibleSet$ contains purely local information which can be calculated immediately when entering a new local state. The other two sets are calculated by a series of message exchanges, and the complete information is generally not calculated but as soon as an interaction is known to be enabled, its triggering will be initiated.

The general structure of the controller for each individual component C_i is shown in Figure 7.3. The overall controller — and the component to be controlled — are represented as a set of concurrent activities (which we call threads, and which in our implementation are realized as Java threads) with a shared memory and shared message buffers.

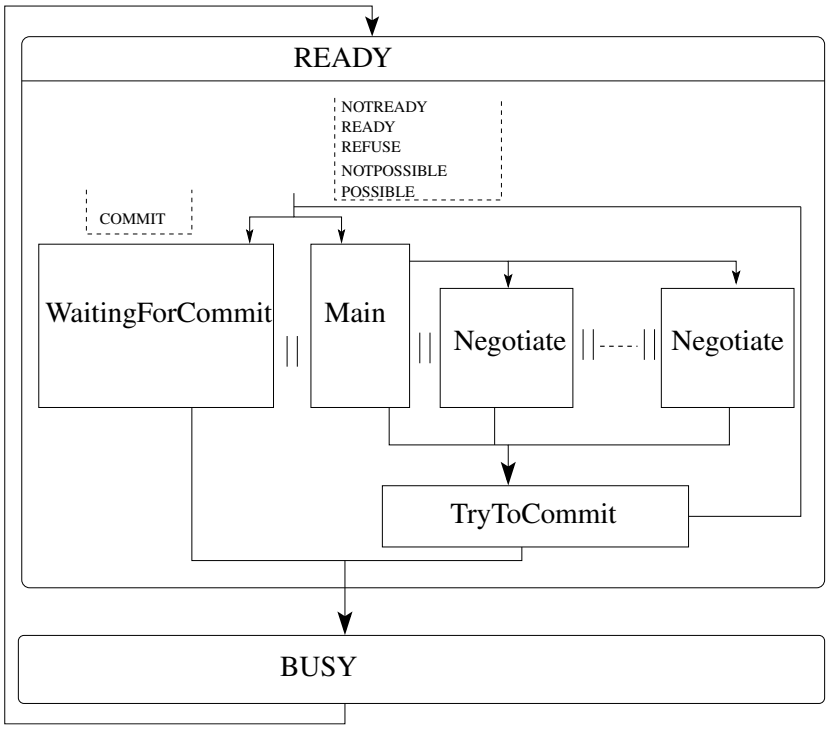


Figure 7.3: Structure of the protocol for C_i.

Indeed, incoming messages are stored until one of the activities is ready to handle them. We use several FIFO buffers which are chosen such that the order amongst messages stored in different buffers does not influence the algorithm; in particular, they are used by concurrent threads. A buffer, which is read only by the thread $Main$, stores messages of the form $POSSIBLE(a)$, $NOTPOSSIBLE(a)$, $READY(a)$, $NOTREADY(a)$, and $REFUSE(a)$. A second buffer stores messages of the form $COMMIT(a)$, this buffer is read first by thread $WaitingForCommit$, then by $TryToCommit$. The role of each message is described in Table 7.1. Given that we are handling binary interactions, we do not explicit the recipient or the sender.

Note that the message $READY$ denotes a question and a response at the same time. More precisely, when a negotiator of a sends $READY(a)$, it informs another negotiator about the readiness of a. However, when a negotiator which is not the negotiator of a sends $READY(a)$, then, it asks about its readiness.

C_i is either in state $READY$ or in state $BUSY$. In state $BUSY$, C_i waits for K_i to execute the local action of the interaction that has been chosen. Incoming messages are stored and will not be handled until the controller moves to state $READY$. In state $READY$, the controller C_i looks for a next interaction to fire, proceeding as follows:

Algorithm 5 Main

Require: $toNegotiate = \{a \in possibleSet \mid negotiator(a) = K\}$
// The set of interactions for which K is a negotiator **Input:** set of interactions $possibleSet \neq \emptyset$
Output: interaction i
$prioFree = \{a \in possibleSet \mid \nexists b, .\, b < a\}$
$waitingSet \longleftarrow \emptyset$
checking global readiness:
$notReadySet \longleftarrow \emptyset$
$readySet \longleftarrow \emptyset$
$lessPrio(a) = \{b \in readySet \mid b < a\}\}$
for all $a \in possibleSet$ **do**
  send $POSSIBLE(a)$
end for
create WaitingForCommit($possibleSet$)
if receive $POSSIBLE(a)$ and $a \in toNegotiate$ **then**
  create Negotiate(a) and $readySet \longleftarrow readySet \cup \{a\}$ and
  for all $b \in lessPrio(a)$ **do**
    kill Negotiate(b)
  end for
end if
WHEN $\exists a,\ s.t.$ Negotiate(a)= OK or (**receive** $POSSIBLE(a)$ and $a \in prioFree$)
call TryToCommit(a) and **kill** WaitingForCommit($possibleSet$) and $\forall b \in readySet$ **kill** Negotiate(b)
if TryToCommit(a)= OK **then**
  return a
else
  goto checking global readiness
end if
if $\forall a \in readySet$ Negotiate(a)= NOK **then**
  goto checking global readiness
end if
if receive $REFUSE(b)$ and $b \in readySet$ **then**
  kill Negotiate(b) and $readySet \longleftarrow readySet \backslash \{b\}$
end if
if receive $POSSIBLE(b)$ and $b \in possibleSet \backslash \{toNegotiate \cup prioFree\}$ **then**
  send $POSSIBLE(b)$ and $readySet \longleftarrow readySet \cup \{b\}$
end if
if receive $NOTPOSSIBLE(b)$ and $b \in possibleSet \backslash prioFree$ **then**
  $notReadySet \longleftarrow notReadySet \cup \{b\}$
end if
if receive $POSSIBLE(b)$ and $b \notin possibleSet$ **then**
  send $NOTPOSSIBLE(b)$
end if

Message	Description
$POSSIBLE$	Offer an interaction (which is locally ready)
$NOTPOSSIBLE$	respond that an interaction is not locally ready
$READY$	Ask about the global readiness of an interaction
$NOTREADY$	Respond that an interaction is not globally ready
$COMMIT$	Commit to an interaction (cannot be undone by K_i)
$REFUSE$	Inform that a component cannot commit to an interaction

Table 7.1: Messages used by the algorithm.

- The $Main$ thread starts by checking its locally ready interactions ($possibleSet$) for interactions that are globally ready (see Algorithm 5). To check the global readiness of an interaction a, messages of the form $POSSIBLE(a)$ are exchanged, and peers in which a is currently not locally enabled respond with $NOTPOSSIBLE(a)$ after which the requesting component "abandons" a until it changes state or the peer enters a state in which a is locally enabled and sends a $POSSIBLE(a)$.

  Whenever it is detected that an interaction a for which it plays the role of a negotiator is globally ready, a thread $Negotiate(a)$ is created which checks whether a is enabled (which corresponds to transition 1 of Figure 7.7 and Figure 7.3). If an interaction with maximal priority is globally ready, it is immediately known to be enabled.

- $Negotiate(a)$ checks the enabledness of an interaction a (see Algorithm 6). It asks all negotiators of interactions with higher priority than a, in the set $higherPrio(a)$, if their interactions are globally ready by sending a $READY(b)$ message to all negotiators of these interactions.

  In turn the negotiators of these interactions, if not $BUSY$, respond positively or negatively as soon as they have the information available.

- $Main$ handles local priorities locally. Whenever an interaction b is known to be globally ready, $Main$ kills all threads $Negotiate(a)$ with $a < b$ because the readiness of b inhibits a.

- Concurrently to $Main$, $WaitingForCommit$ handles incoming $COMMIT$ messages (see Algorithm 7). Whenever a $COMMIT(a)$ is received — which implies that a is enabled. Indeed, if a is involved in a priority rule, then the message $COMMIT(a)$ is first sent by its negotiator. Otherwise,the first controller finding a globally ready will commit to it (transition 5 in Figure 7.7). As our goal is firing an interaction as fast as possible, the $WaitingForCommit$ activity is added concurrently to allow detecting such $COMMIT$ messages and thus to terminate all other negotiation activities and to response back by a $COMMIT$ (which corresponds to transition 11 in Figure 7.7).

- $Main$ tries to commit to the first interaction found enabled (as a way to handle local conflicts) by activating $TryToCommit$ (transitions 4, 5 and 6 in Figure 7.7). $WaitingForCommit$

Algorithm 6 Negotiate

Require: $higherPrio(a) = \{c \mid a < c\}$
Input: interaction a **Output:** OK or NOK
$toCheck \longleftarrow higherPrio(a)$
for all $b \in toCheck$ **do**
send $READY(b)$
end for
while $toCheck \neq \emptyset$ **do**
if receive $READY(b)$ **then**
return NOK
else if receive $NOTREADY(b)$ **then**
$toCheck \longleftarrow toCheck \backslash \{b\}$
end if
end while
return OK

Algorithm 7 WaitingForCommit

Require: set of interactions $waitingSet$
Input: set of interactions $possibleSet$ **Output:** interaction a
if $waitingSet \neq \emptyset$ **then**
choose $a \in waitingSet$ and **kill** main and **send** $COMMIT(a)$ and **send** $REFUSE(b)$ for all b in $possibleSet$ and **goto** $BUSY(a)$
else if $waitingSet = \emptyset$ and **receive** $COMMIT(a)$ and $a \in possibleSet \backslash toNegotiate$ **then**
kill main and **send** $COMMIT(a)$ and **send** $REFUSE(b)$ for all b in $possibleSet$ and **goto** $BUSY(a)$
end if
if receive $COMMIT(a)$ and $a \notin possibleSet$ **then**
send $REFUSE(a)$
end if

is terminated once $TryToCommit$ is activated, in order to avoid multiple commits at the same time. Note that the incoming $COMMIT$ messages that are used to be handled by $WaitingForCommit$, will be stored in the variable $waitingSet$ and will be treated if $TryToCommit$ returns NOK.

- $TryToCommit(a)$ sends a $COMMIT(a)$ message to the corresponding peer and waits for a response (see Algorithm 8). Note that if $TryToCommit$ fails committing to a because it receives a $REFUSE$ message — in that case the peer has committed to a conflicting interaction — the controller starts again by checking the global readiness of its locally ready interactions. Indeed, as the peer has committed to another action its state may have changed. For the interactions a for which there exists at least one interaction with higher priority, the commit procedure is always initiated by the negotiator of a who is the first one to know about a's enabledness.

Algorithm 8 TryToCommit

Require: **Input:** interaction a **Output:** OK or NOK
  send $COMMIT(a)$
  if receive $COMMIT(a)$ **then**
    return OK and **send** $\forall b \in$ readySet$\backslash\{a\}$ $REFUSE(b)$
  else if receive $COMMIT(b)$, $b \neq a$ and $((a,b) \notin cyclesof(K)$ or $(a,b) \in notRefuse(K))$ **then**
    $waitingSet \longleftarrow waitingSet \cup \{b\}$
  else if receive $COMMIT(b)$, $b \neq a$ and $((a,b) \in cyclesof(K)$ and $(a,b) \notin notRefuse(K))$ **then**
    send $REFUSE(b)$ and $readySet \longleftarrow readySet\backslash\{b\}$
  else if receive $REFUSE(a)$ **then**
    return NOK
  end if

- Finally, $AnswerNegotiators$ is a simple thread which is always active if the component K_i is the negotiator for at least one interaction that dominates some other interaction. It receives messages of the form $READY(a)$ for interactions a for which K_i is the negotiator. It returns $READY(a)$ if a is currently in the $readySet$ of K_i, $NOTREADY(a)$ if it is in the $notReadySet$ or if it is not in its $possibleSet$, and otherwise defers the answer until the status of a is known.

Example 7.2.1 *Now we propose to illustrate how the proposed algorithm works in a small example, where global priorities are defined. In Figure 7.4, we give a system consisting in a set of 4 components. As previously, interaction between components is represented sunchronization on common labels. The system modeled in Figure 7.4 represents 4 components K_1, K_2, K_3 and K_4. Components K_1 and K_3 synchronize on a. K_1 synchronizes with K_2 on b and K_3 with K_4 on c. This system represents a priority rule stating that $c < b$. Thus we have to assign a negotiator for each of these*

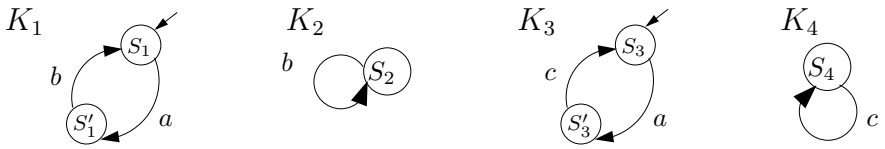


Figure 7.4: An example with global priorities $c < b$.

two interactions. Note that this priority is global as b and c do not have any component in common, so we assign negotiators arbitrary. Here we choose K_1 as the negotiator of b and K_3 as the negotiator of c. Figure 7.5 gives a possible scenario of leading to the execution of the interactions in the system. In the initial state, each component proposes its possible interactions by sending a $POSSIBLE$ message to the corresponding peer. As the interaction a is possible for both components K_1 and K_3, they will both send and receive $POSSIBLE(a)$ which means that a is globally ready. a is not involved in any priority rule, thus once it is globally read, it is also enabled and both components exchange $COMMIT(a)$ message to execute a. Components K_2 and K_4 cannot execute any interaction because they are waiting for their peers to synchronize.

When interaction a is performed by K_1 and K_3 (they enter in $BUSY(a)$ in Figure 7.5), both components change their State. However components K_2 and K_4 are still asking about the readiness of their interactions (resp. b and c) by sending $POSSIBLE$ messages. When K_3 changes its state the interaction c becomes possible, and then globally ready once K_3 receives $POSSIBLE(c)$ from K_4. K_3 is the negotiator of c and $c < b$, thus K_3 has to ask about the enabledness of c, means that it has to ask the negotiator of b (K_1) about the readiness of b. Therefore K_3 sends $READY(b)$ to K_1 and waits for response. In the scenario depicted in Figure 7.5, when K_1 receives this message, it does not yet know if b is ready, so, it waits for a message from K_2 so that it can answer. When $POSSIBLE(b)$ is received, K_1 answers K_3 with $READY(b)$ which inhibits the enabledness of c. c has maximal priority, thus no negotiation is needed. K_1 and K_2 can commit for it once it becomes ready. As K_3 has only the interaction c in his $possibleSet$, it still negotiating c by sending $READY(b)$ until it receives $NOTREADY(b)$.

7.2.2 Avoiding deadlocks due to potential decision cycles

In order to avoid deadlocks due to decision cycles amongst interactions in conflict, we introduce the notion of *cycle*.

Definition 7.2.2 *A cycle is a set of interactions $A = \{a_i\}_{i=1}^{n}$ involving a set of components $\{K_i\}_{i=1}^{n}$ for which the following holds: For all $i \in [1, n]$, a_i is an interaction involving the two components K_i and $K_{\{i+1 mod n\}}$ and there exists at least one global state in which all these interactions are enabled. We denote the fact A is a cycle by $Cycle(A)$ Note that, in such global state, each K_i has at least two enabled interactions, in the corresponding local state, one interaction with its right neighbor and the other with its left neighbor.*

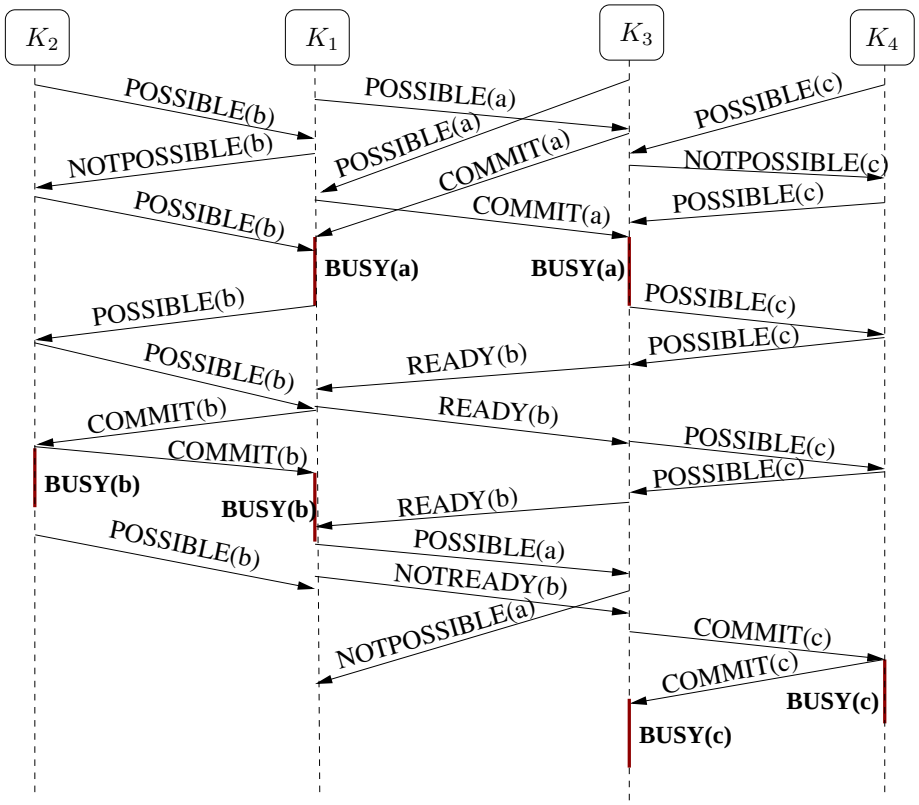


Figure 7.5: Scenario of possible executions of interactions a, b and c.

A *cycle* A bears a risk of deadlock or livelock in a state in which all interactions of A are enabled. Indeed, it represents a symmetric situation for all involved components, where a component could wait forever for all others (deadlock) or propose a different choice than all others, reject it and start all over forever. In [Bag89b] for example, to deal with this problem, a total order over the system interactions is defined, which allows to avoid deadlock by executing the interaction with higher order. In [PCT04], a similar solution is proposed by imposing a total order over all components, which breaks the cycle by executing the interaction proposed by the component with higher order.

The solution we propose is to detect statically the set of (minimal) cycles of the system. Then, in a second step, we define for each cycle statically a *Cyclebreaker*, which is one of the components of the cycle. This particular component will arbitrate when a blocking situation actually occurs. This means that whenever a potential deadlock may occur, the interaction that is committed by the *Cyclebreaker*, will be fired. This approach avoid to a define a total order of all interactions or components which is useless if there is no cycle.

Thus to avoid deadlocks due to cycles and as given in Algorithm 8, if a given controller sends a $COMMIT$ message, then it receives another $COMMIT$ message to a different interaction, then either there is no cycle involving these two interactions or it exists at least one. In the second case, if the received $COMMIT$ concerns the interaction committed by a *Cyclebreaker*, then the controller cannot send back a $REFUSE$. However, if this interaction is not the one committed by the *Cyclebreaker*, in this case the controller can send back a $REFUSE$ which breaks the cycle (more details are given in the following illustrative example).

Notation 7.2.3 *We denote by $cyclesof(K)$, the set of pairs of interactions of K involved in some cycles. $(a, b) \in cyclesof(K)$ implies that a and b are interactions of K and $\exists$ A such that $Cycle(A) \wedge \{a, b\} \subseteq A$.*
We denote by $Cyclebreaker(A, K)$ the predicate which holds if the component K is the Cyclebreaker *of $Cycle(A)$.*
We denote also by $notRefuse(K)$ the set of pairs of interactions of the form (a, b) such that $(a, b) \in notRefuse(K)$ implies:

1. $(a, b) \in cyclesof(K)$
2. $\forall$ $Cycle(A)$ *such that* $\{a, b\} \subseteq A$, $Cyclebreaker(A, K_a)$ *holds, where K_a is the peer of K in the interaction a. This means that whenever K sends $COMMIT(b)$ message, and then it receives $COMMIT(a)$, it cannot send back $REFUSE(a)$.*

Note that the order of interactions of a pair in $notRefuse(K)$ is relevant as the first interaction is the one that cannot be refused by K. Note that a pair of interactions $(a, b) \notin notRefuse(K)$ means that either there is no cycles involving these two interactions ($(a, b) \notin cyclesof(K)$) or that there exist such cycles ($(a, b) \in cyclesof(K)$) but if K commit for b and receives a $COMMIT$ message for a then it can send back a $REFUSE(a)$ to its peer K_a because the latter is not the *Cyclebreaker* of these cycles. Theorem 7.3.5 proves that this way to deal with cycles allows indeed to avoid deadlocks.

Example 7.2.4 *Figure 7.6 depicts an example representing a feasable cycle. The system consists of 4 components: 3 components $\{K_1, K_2, K_3\}$ forming with their set of interactions $A = \{a, b, c\}$ a*

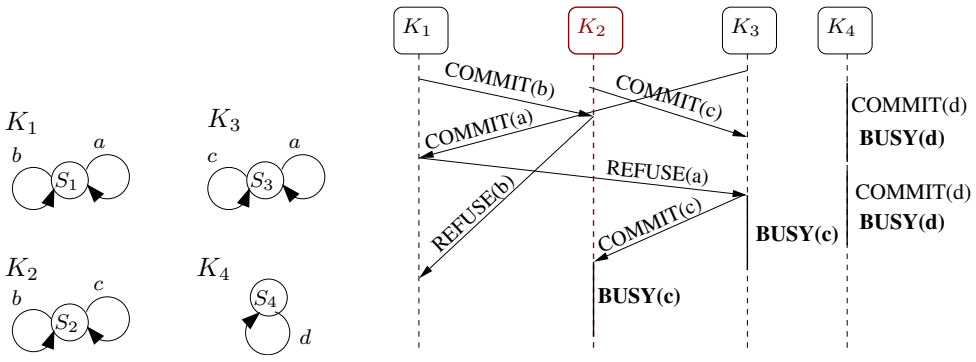


Figure 7.6: An example with cycle and independence.

cycle. The component K_4 represents a completely independent component. The existence of a cycle can be concluded from the structure and the behaviors of the components (the interactions a, b, c are always enabled). If no priority rules are defined on the set of interactions A, then the cycle A may lead to a deadlock. A possible deadlock scenario is depicted on the right side of Figure 7.6. This occurs when K_i sends a $COMMIT$ message to K_{i+1} and waits for it. Which means that each component is waiting its peer who has made another choice. According to the proposed solution, let suppose that K_2 is chosen as the Cyclebreaker *of A.*

According to Algorithm 8 (as described in Figure 7.6), whenever component K_i which is already engaged in committing an interaction and which receives a $COMMIT$ for a different interaction, will send back a $REFUSE$ message if this $COMMIT$ is about an interaction which does not form with the already committed interaction a pair in $notRefuse(K_i)$. However, if it is the case no $REFUSE$ message will be sent back. Thus only the interaction committed by the Cyclebreaker *of A will not be refused and will be indeed fired. Note that $cyclesof(K_1) = \{(a, b)\}$, $notRefuse(K_1) = \{(b, a)\}$, $cyclesof(K_2) = \{(b, c)\}$, $notRefuse(K_2) = \emptyset$, $cyclesof(K_3) = \{(c, a)\}$ and $notRefuse(K_3) = \{(c, a)\}$. Independently, the component K_4 can perform whenever it is possible the interaction d.*

7.3 Correctness of the protocol

In this section we prove that our protocol defined by the proposed algorithms guarantees the following properties:

1. Exclusion, i.e., interactions in conflict cannot be committed simultaneously.

2. Safety, i.e., if an interaction is fired then it is enabled.

3. Liveness (progress), i.e., if an interaction is enabled, it will eventually become disabled either because it is executed or because a component offering it commits to another interaction.

To provide a proof check, we use the state transition diagram of Figure 7.7 where for a local controller, transitions represent steps of the algorithm and states represent the modes of the algorithm. Transitions may have a *guard* and an *action* and are depicted in Table 7.2.

Definition 7.3.1 *We denote by* waits(K_1, a, K_2)*, the global predicate which holds when the component K_1 has sent a COMMIT(a) message to its peer K_2 involved in the interaction a but has not yet received an answer in a global state in which a is enabled.*

Lemma 7.3.2 *If* waits(K_1, a, K_2)*, then K_1 will receive a $REFUSE(a)$ or a $COMMIT(a)$ message within a finite delay.*

Proof As we assume that the actual execution of an action a as well as all the basic functions used in our algorithm terminate and every message reaches its recipient within a finite delay. If K_1 waits for an answer, after sending a $COMMIT(a)$ message to K_2, this means that it exists a global state of the system in which a is enabled and that K_2 is in $Committing(a_1)$ in the diagram of Figure 7.7. Indeed in the rest of states of this diagram $Waiting$, $Active$ and $Negotiating$, the activity $waitingForCommit$ depicted in Algorithm 7 catches this $COMMIT(a)$ message and sends back a $COMMIT(a)$ to K_1. Similarly, K_2 is in $Committing(a_1)$ means that it exists a global state of the system where a_1 is enabled and one of the following cases holds:
1- $(a, a_1) \in cyclesof(K_2)$ and $(a, a_1) \notin notRefuse(K_1)$ (according to the guard of transition 10 of Table 7.2), in this case K_2 sends back a $REFUSE(a)$ to K_1 within a finite delay.
2- $(a, a_1) \notin cyclesof(K_2) \vee (a, a_1) \in notRefuse(K_2)$, in this case K_2 is also waiting for an answer from K_3 about a_1. Similarly, if K_3 does not answer with a $REFUSE(a_1$, then it exists an interaction a_2 such that $(a_1, a_2) \notin cyclesof(K_3) \vee (a_1, a_2) \in notRefuse(K_3)$. As there exists a finite number n of components in the system, this means that there exists some cycle of size k of the form: waits(K_1, a, K_2)$\wedge$waits(K_2, a_1, K_3)$\wedge$ $\ldots$ $\wedge$waits(K_k, a_{k-1}, K_1) and where the following holds:

$$(a, a_1) \notin cyclesof(K_2) \vee (a, a_1) \in notRefuse(K_2)$$
$$(a_1, a_2) \notin cyclesof(K_3) \vee (a_1, a_2) \in notRefuse(K_3)$$
$$\ldots$$
$$(a_{k-2}, a_{k-1}) \notin cyclesof(K_k) \vee (a_{k-2}, a_{k-1}) \in notRefuse(K_k)$$

This is a contradiction. Indeed, the first part of each property means that there is no cycle containing these interactions, which is not true as we have a circular sequence which means a cycle. The second part does not hold as we assume that each cycle has just one Cyclebreaker which can try to commit to only one interaction. □

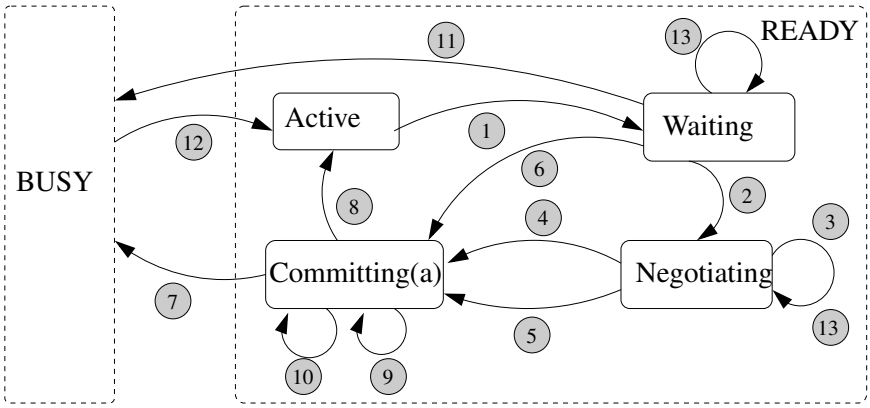


Figure 7.7: State diagram of the algorithm.

Theorem 7.3.3 (Safety property) *Let be q a state, then an interaction a is fired in q implies that a is enabled in q.*

Proof Let suppose given a global state q, that a is fired and that a is not enabled in q. An interaction a is fired if each component involved in a enters state $BUSY(a)$ and thus it sent and received a $COMMIT(a)$. Let suppose that K_1 and K_2 are the components involved in a in respectively the local states q_1 and q_2 of q. a is not enabled in q means two cases: either a is not globally ready in q, or that a is globally ready in q but not enabled.
1- Let suppose the first case that is a is not globally ready in q, this means that a is not locally ready for at least one of the involved components, that we suppose w.l.o.g K_1. This means that $a \notin possibleSet$ of K_1 in q_1 and thus according to transition 11 of Table 7.2, K_1 will never send a $COMMIT(a)$ to K_2 even if the latter sends a $COMMIT(a)$ to K_1. Indeed, K_2 may send a $COMMIT$ to K_1, if it receives for example an old $POSSIBLE$ message from K_1 before the latter sends the $NOTPOSSIBLE$ according to transition 13 of the Table 7.2. Thus if a is not globally ready, a cannot be fired.
2- The second case is that a is globally ready but not enabled. First a is globally ready means that both components have exchanged a $POSSIBLE$ message as described in transition 1 of Table 7.2. Once a is found globally ready, than a is not enabled means that $a \notin prioFree$ which means that the transitions 4 and 5 of Table 7.2 cannot be fired and thus that the state $committing(a)$ in the state diagram of Figure 7.7 is not reached. This means that to fire a each component has to fire either the transition 11 or the sequence of two transitions 4 then 7.

$a \notin prioFree$ means that a is involved in at least one priority rule. Let suppose w.l.o.g that K_1 is the negotiator of a, which means that to fire a, K_2 cannot commit for a before receiving the $COMMIT$ from K_1. To send a commit K_1 has to fire the transition 4 which has as guard that Negotiate(a)=ok which means that a is enabled and which is in contradiction with our assumption that a is not enabled. Thus we conclude that if a is fired than it is enabled. Note that this is guaranteed by the fact that we suppose that there is no confusion. Indeed, if a situation of confusion occurs there is no guarantee that the algorithm negotiate will get a consistent information about the global

readiness of interactions with higher priority. □

Theorem 7.3.4 (Exclusion property) *Let be q a state, a an interaction and denote $A = \{a_i\}_{i=1}^{n}$ the set Conflict$_q(a) \cup$ PrioConflict$_q(a)$ of interactions that are in conflict with a in state q. Our algorithm guarantees that if a is fired in state q, no interaction in A is fired in q.*

Proof What we have to prove is that if in state q a component commits to interaction a, by executing one of the transitions 4, 5 or 6 of Figure 7.7, no interaction in A can be committed before the execution of a is terminated.

Suppose that $a \in \mathcal{P}_i$. For all $b \in A$ we have either $b \in \mathcal{P}_i$, which means in structural conflict with a, or $b \in$ *prioConflict*$_q(a)$ that is in prioritized conflict, this holds because two interactions can only be in structural conflict if they share a common component. We prove the theorem separately for these two cases:
1- First case: $b \in \mathcal{P}_i$, that is a and b share the same component K_i. First of all, only interactions committed by both peers are executed. Then, if K_i has sent a COMMIT(a) message executing one of the transitions 4, 5 or 6 of Figure 7.7, then according to the same table it is impossible to send a $COMMIT(b)$ message before either a $REFUSE(a)$ is received or the BUSY state is entered, then exited and the next state reached.

2- Second case $b \in$*prioConflict*$_q(a)$ holds, that is a and b are concurrent (and thus belong to different components) and either $a < b$ or $b < a$. Suppose that K_j is the negotiator for b.

If $b < a$, then b should not be executed before the execution of a — which has started — has been completed and K_i enters READY for the successor state of q. We have now to prove that from that moment on K_j cannot "believe that a is *not ready*" which is the condition for committing to b.

Indeed, if K_j does not yet know about the readiness of a, before committing b, it will send a $READY(a)$ message to K_i, but as a is already engaged for execution, K_i will not send any response before the execution of a is terminated the next state reached, and the readiness of a evaluated in the new state; and K_j remains blocked for b during this time.

Now, we must prove that K_j cannot have old, depreciated knowledge that a is not ready. This can only be the case, if at some point a was not ready and K_i has sent $NOTREADY(a)$ to K_j, and then transitions concurrent to b have been executed leading to the current state q in which a is ready and executed, and K_j may use incorrect knowledge and execute b. This corresponds exactly to a situation of confusion, which we have excluded.

If $a < b$, the situation is almost symmetric. We must prove that in this case b is not ready. If K_i is the negotiator for a, asks the negotiator of b whether b is ready, and only if the answer is negative, it will consider a to be enabled and may initiate the commitment of a. Again, only if confusions exist K_i may use old knowledge. If the negotiator of a is the peer, then P_i will only commit to a on reception of a $COMMIT(a)$ from its peer which uses the same procedure for deciding to commit to a.

□

Theorem 7.3.5 (Liveness property) *Let a be a* enabled *interaction. Our algorithm guarantees that a will eventually become disabled either because it is executed or because a component offering it commits to another interaction..*

Proof An enabled interaction a may become disabled because it is executed or because a component offering it commits to another interaction. When a is enabled for a component K_i, a COMMIT(a) message is sent to the corresponding peer and K_i goes to state $committing(a)$. a becomes disabled when K_i leaves this state. In other words what we have to prove is that K_i cannot stay in this state eternally. When K_i is in state $committing(a)$, there must exists a component K_j such that *waits(K_i, a, K_j)*. Thus the proof follows directly from Lemma 7.3.2. In fact, when receiving message COMMIT(a) or REFUSE(a), K_i will leave state $committing(a)$ through transition 7 or 8. □

Choosing the negotiators For each interaction a involved in at least one priority rule, we choose one of the components involved in a as its negotiator. This negotiator will send requests to negotiators of interactions with higher priority and answer requests from negotiators for lower priority interactions. Thid means that whenever a is globally ready, the negotiator communicates with the negotiators for interactions with higher priority to find out whether a is enabled or not. A component may be the negotiator for several interactions. Various strategies may be proposed to allocate negotiators to components. The criterion we use is to minimize for each interaction the maximal number of distinct components to which its negotiator has to send requests. This is meant to minimize the number of communications added due to priorities.

As already explained, local priorities — that means when $a < b$ and a and b have negotiators hosted by the same component K_i — are decided locally. In the dining philosophers example (see figure 8.6), all the priority rules involve the component $Forks$, which will thus be designated as negotiator and it will enforce priorities locally. In some systems, priorities may include interactions which do not necessarily have a common component. In this case, for each interaction we choose as negotiator the component that is involved in the largest set of interactions, as it may have more knowledge about readiness of more interactions.

Extension to multiparty interactions Given a system $Sys = (\{K_i\}_{i=1}^n, \mathcal{I}_<)$ defined by a set of components $\{K_i\}_{i=1}^n$ and a memoryless controller defined by $\mathcal{I}$ and $<$, we have proposed in the previous section a distributed implementation of Sys by defining to each component a local controller allowing to guarantee $\varphi_{\mathcal{I}}$ and $\varphi_<$. The interaction model $\mathcal{I}$ of the algorithm previously proposed allows to define only *binary* interactions. Extending this algorithm to an interaction model with n-ary interactions does not affect the way priorities are checked. This extension to multiparty interactions can be done as in α-core algorithm [PCT04], where a particular component called *coordinator* is associated to each interaction. Similarly, we define for each interaction a negotiator. This negotiator has previously the task of checking only the enabledness of the interaction, now it will have also to check its readiness. The criterion to assign negotiators could still be the same as proposed previously.

Algorithm $Negotiate$ is unchanged as each negotiator has to ask other negotiators about the readiness of a given interaction, this does not depend on the number of components involved in the interaction. The rest of algorithms proposed have to be slightly modified to deal with multiparty interactions. For this purpose we propose that, for each interaction a, the corresponding negotiator collects the responses of all the components involved in a and checks that all of them are ready to execute the interaction. This is done using the exchange of messages $POSSIBLE$. We propose to add two new messages:

- $START(a)$ message sent by the negotiator of a to inform all other components involved that a could be fired;
- $CANCEL(a)$ message sent by the negotiator of a to the participants to inform them that the interaction cannot be fired.

In the Algorithm 7, $WaitingForCommit$, whenever a component K receives a $COMMIT$, it kills thread $Main$, sends back a $COMMIT$ and waits for $START$. If it receives the $START$ message, it executes the interaction. If it receives a $CANCEL$ message, it restarts the Main thread again. Note that the operations performed in this algorithm concerns only interactions for which P is not the negotiator.

In the Algorithm 8, $TryToCommit$, the component sends a $COMMIT$ message to all participants involved in the interaction and waits for a $COMMIT$ answer from all of them. If it receives at least one $REFUSE$ message, it sends back $CANCEL$ message to all participants. If it receives $COMMIT$ from all participants, it sends back $START$ to all of them and goes to state $Busy$ to execute the corresponding interaction. Note that all the operations performed in this algorithm concerns only interactions for which P is the negotiator.

In this chapter, we have proposed a protocol allowing to implement a controller enforcing some priority order in a distributed way. In the next chapter, we present a concrete implementation of this protocol and we present some performance analysis results.

Transition	Guard	Action
1	possibleSet$\neq \emptyset$	$\forall a \in$ possibleSet, send(POSSIBLE(a))
2	receive(POSSIBLE(a))$\wedge$ $a \in$possibleSet$\cap$toNegotiate	call(Negotiate(a)$\wedge$readySet:=readySet$\cup\{a\}$
3	receive(POSSIBLE(a))$\wedge$ $a \in$possibleSet$\cap$toNegotiate	call(Negotiate(a)$\wedge$readySet:=readySet$\cup\{a\}\wedge$ $\forall b \in$lessPrio(a), kill(Negotiate(b))
4	Negotiate(a)=ok	send(COMMIT(a))$\wedge$ kill(WaitingForCommit)$\wedge$ $\forall b$ kill(Negotiate(b))
5	receive(POSSIBLE(a))$\wedge$ $a \in$prioFree	send(COMMIT(a))$\wedge$ kill(WaitingForCommit)$\wedge$ $\forall b$ kill(Negotiate(b))
6	receive(POSSIBLE(a))$\wedge$ $a \in$prioFree	send(COMMIT(a))$\wedge$ kill(WaitingForCommit)
7	receive(COMMIT(a))$\wedge$Committing(a)	goto(BUSY(a))$\wedge$ $\forall b \in$readySet, send(REFUSE(b))
8	receive(REFUSE(a))$\wedge$Committing(a)	goto(Active)$\wedge$reset(readySet)$\wedge$ keep(possibleSet)
9	receive(COMMIT(b))$\wedge$Committing(a) $\wedge(a \neq b)$ $(a,b) \notin cyclesof(K)$ or $(a,b) \in notRefuse(K)$	waitingSet:=waitingSet$\cup\{b\}$
10	receive(COMMIT(b))$\wedge$Committing(a) $\wedge(a \neq b)\wedge$ $((a,b) \in cyclesof(K)$ and $(a,b) \notin notRefuse(K))$	send(REFUSE(b))$\wedge$readySet:=readySet$\backslash\{b\}$
11	receive(COMMIT(a))$\wedge a \in$ possibleSet$\backslash$toNegotiate	send(COMMIT(a))$\wedge$ $\forall b \in$possibleSet and $b \neq a$, send(REFUSE(b))
12	true	set(possibleSet)
13	receive(POSSIBLE(a))$\wedge$ $a \notin$possibleSet	send(NOTPOSSIBLE(a))

Table 7.2: Transitions of the protocol state diagram.

Chapter 8

Implementation and Experimental Results

This chapter presents an implementation of the protocol described as algorithms in the previous chapter. In particular, we describe how we evaluate the performance of our protocol on hand of the implemented prototype. We have implemented the proposed protocol, using Java 1.6 and Message Passing Interfaces (MPI) and we experiment its efficiency on different examples. We have used the MPI library [SOHL$^+$96] to perform the communication layer of our algorithm because of its good performance, usage facility and its portability [GLS99]. In this chapter, we analyze the performance of the algorithm on hand of a number of experiments and we measure three different metrics, namely message count, synchronization time and selection time.

8.1 Sensitivity of the prototype

In our prototype, the exchange of messages between components is performed at the MPI layer and all computations of our protocol are performed at the Java program level (see Figure 8.1). Tests have been run on a set of 2.2 GHz Intel machines with 2 GB RAM, in a configuration where each physical machine hosts only one component.

Our experiments evaluated essentially two metrics which are comparable to those used also in [PCT04]: the first is a metric called *message count* which measures the (average) number of messages required to schedule an interaction for execution, starting from the moment on that it is ready in one of the involved components. The second one is called *response time* and is defined as the sum of two other metrics *sync time* and *selection time*:
sync time (synchronization time) measures the (mean) time taken by the algorithm to ensure that a given interaction is globally ready, again starting from the moment where it is locally ready in at least one of the peers. An alternative option would be to measure only from the moment on where the interaction is already enabled, that is only the time required to "detect" this enabledness; this is however quite difficult to evaluate in a distributed setting.
selection time measures the (mean) time taken by the algorithm to select an interaction for execution

once it has been found globally ready.

All metrics are measured for a given system by experimenting with different choices of parameters. We then analyze how variations of parameters affect the considered metrics and compare them to theoretical analysis on the algorithm.

We also compare for an example without priorities the *message count* metric obtained for our algorithm and for an implementation of the α-core algorithm. We could not compare execution times because the implementation of α-core we have at hand cannot be run in the same setting and the data provided in [PCT04] are obtained in a incomparable setting as well.

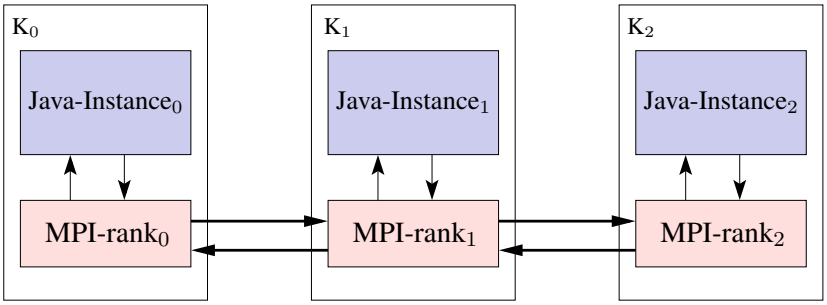


Figure 8.1: Implementation layers

In this Section, we study the sensitivity of our algorithm to the degree of conflict in a given system. The degree of conflict (d) is measured by the number of interactions that may be in actual conflict with any (or a particular) interaction. Remember that we distinguish between *structural* and *prioritized* conflict (see Definition 7.1.4).Thus in this section, we study first the sensitivity of our prototype to the prioritized conflicts, then to the structural one.

8.1.1 Sensitivity to prioritized conflicts

The purpose of the algorithm that we implement is to ensure correct synchronization between components by respecting global priorities. We first show some results concerning *prioritized* conflicts.

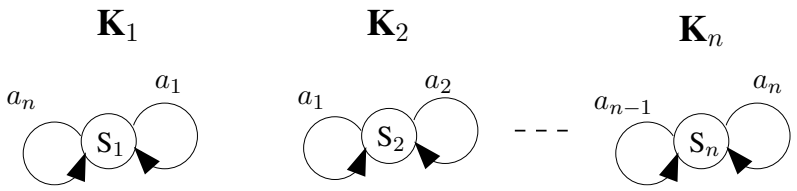


Figure 8.2: System pattern for experiments

An evaluation has been undertaken using the example depicted in Figure 8.2 with a single global state. For each considered configration, the system has been executed several times, and each execution has been terminated at the execution of the first interaction. The system consists of a set of n components, and a set of n interactions building a circular chain. This pattern is flexible and it allows as to observe how our algorithm performs in different situations. In fact, we can easily add both local and global priorities.

Considering a given system, that is a composition $\{K_1, ..., K_n\}$, the degree of conflict d can be increased by adding priority constraints. Here, we simply count the maximal number of priorities in which a single component is involved, in order to obtain the degree d, but as the discussion will reveal, finer measures could also be considered. If there are no priorities in the system, then $d = 0$. The degree of conflict of $(S, <_1)$ is greater than the one of $(S, <_2)$, if $<_1$ involves more interactions of different components of S than $<_2$.

As already explained, our experiments are performed on a system as depicted in Figure 8.2, for $n = 4$ and using the following priorities to achieve different degrees of conflict, where component K_2 — which is chosen as the negotiator of a_1 — is the component which in all cases is involved in all the priorities, whereas other components are involved in at most two of them: $d = 0$: no priorities, $d = 1$: $a_2 < a_1$, $d = 2$: $a_2 < a_1 \ \wedge a_3 < a_1$, $d = 3$: $a_2 < a_1 \ \wedge a_3 < a_1 \ \wedge a_4 < a_1$, $d = 4$: $a_2 < a_1 \ \wedge a_3 < a_1 \ \wedge a_4 < a_1 \ \wedge a_3 < a_2$. We have measured the average *message count*, *response time*, *sync time* and the *selection time* for all cases.

Variation of metric message count Figure 8.3 shows that, as expected, the number of messages exchanged in order to execute the first (and unique) interaction increases with the degree d of the system. Increasing d means that more interactions are involved in priority rules, and thus more messages of type $READY$ are exchanged, and globally less interactions can be executed. In the case chosen for $d = 1$, the priority is defined by the rule $a_2 < a_1$ which is a *local* priority involving only component K_2. Thus, no negotiations and no $READY$ messages are needed which makes in principle, the same *message count* as for $d = 0$. This is confirmed by Figure 8.3 showing a non significant difference between $d = 0$ and $d = 1$. For the case $d = 2$, the selected priorities are $a_2 < a_1$ and $a_3 < a_1$. This means that the negotiator of a_3 (K_3) has to send a $READY$ message to the negotiator of a_1 (K_2) and the latter has to send back as a response a $READY$ message which

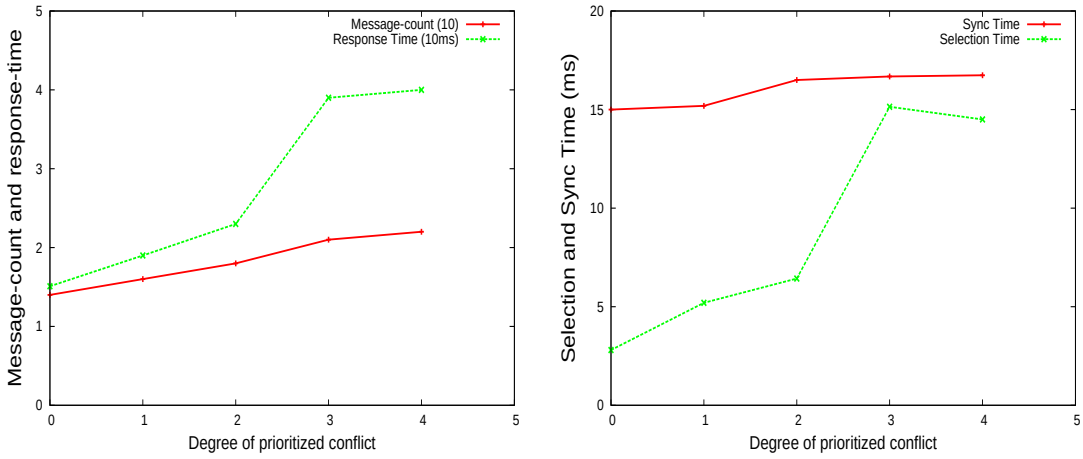


Figure 8.3: Sensitivity to the degree of *prioritized* conflict

makes 2 extra messages added comparing to the case of $d = 0$. This is confirmed by the experimental results.

Variation of metric response time As expected, also the time required to execute the first interaction increases with the degree d of the system, which can also be seen in Figure 8.3. Again, adding a local conflict (as in the step from $d = 0$ to $d = 1$) leads only to a small increase of the response time as the situation is handled locally. The increase is larger when a global priority is added. Note also that the increase in response time is more important than the increase of the number of messages: up to 20% for adding a (first) local priority and up to 50% for adding a (first) global priority. This may look surprising. but indeed, adding a priority requires adding some explicit threads for negotiation, and on the system configuration we use, the time is mainly spent for execution, whereas the communication time is relatively small. Figure 8.3 shows also the sensitivity of the *sync time* and the *selection time* of our prototype to the variation of d. Theoretically, the average synchronization time is independent of the number of conflicting interactions in our system. Indeed, to decide the global readiness of a given interaction, a component has to send and receive a $POSSIBLE$ message for this interaction, which is completely independent of whether this interaction is involved or not in a priority rule. This is confirmed by the results of *sync time* for $d = 0$, $d = 1$ and $d = 2$ (given in Figure 8.3), for which the synchronization time is almost the same.The synchronization times are slightly greater in case $d = 3$ and $d = 4$. This is due to the order in which messages are received. More precisely, for $d = 2$ priorities are $a_2 < a_1$ and $a_3 < a_1$ which implies that the component negotiating a_3 will send a $READY$ message to the negotiator of a_1 to check its readiness. Thus, the negotiator of a_1 may receive and treat this $READY$ message before reacting to the $POSSIBLE$ messages for the other interaction. We can observe however that for increasing d, the time required to actually choose an enabled interaction, increases considerably. This is not surprising. The fact that

the selection time remains relatively small with respect to the synchronization time allows the overall response time increase to remain moderate.

8.1.2 Sensitivity to structural conflicts

Now we provide experimental results about the sensitivity of our prototype to the variation of the structural conflict of a system. *Structural* conflict arises between interactions when they are all in the $possibleSet$ of a common component. To study how our algorithm performs with an increasing number of structural conflicts, we have carried out a series of experiments on a system as depicted in Figure 8.4. We use a set of systems $T_1, T_2, ..., T_n$ where each T_k has k binary interactions, referred to as a_i ($i = 1, 2, ..., k$), and $k + 1$ components, referred to as K_i ($i = 1, 2, ..., k + 1$). Components K_i participate in interaction a_i, and K_{k+1} participates in any interaction. Therefore, all interactions are in *structural* conflict, and the degree of the structural conflict can be measured by the number of components in the system.

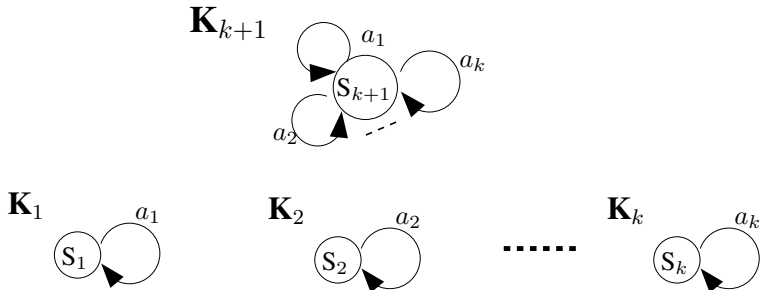


Figure 8.4: System pattern for experiments (T_k)

Each experiment consisted in executing 100 interactions, and we have evaluated our metrics for up to 5 conflicting interactions (a system with six components) for several executions of this experiment for each degree of structural conflict.

Variation of message count We can see in the left side of Figure 8.5 that our algorithm requires considerably less messages than α-core, where we compare with the results provided in [PCT04] for this same example. This is due to the fact that α-core is *connector-centric*, that is, it creates an additional component for each interaction whereas our algorithm is component centric, that is all negotiations are hosted by some component and share the same memory space. This means that our algorithm can exploit more local *knowledge* to execute interactions which reduces the number of messages exchanged. When there is no conflict at all (in T_1) both algorithms exchange the same number of messages, then when the degree of conflict increases, our algorithm performs better. The system T_1 has no conflict, and to execute a_1, 3 messages are exchanged (one $POSSIBLE$ and two $COMMIT$), thus 300 messages are transmitted during the experiment. When there are conflicts,

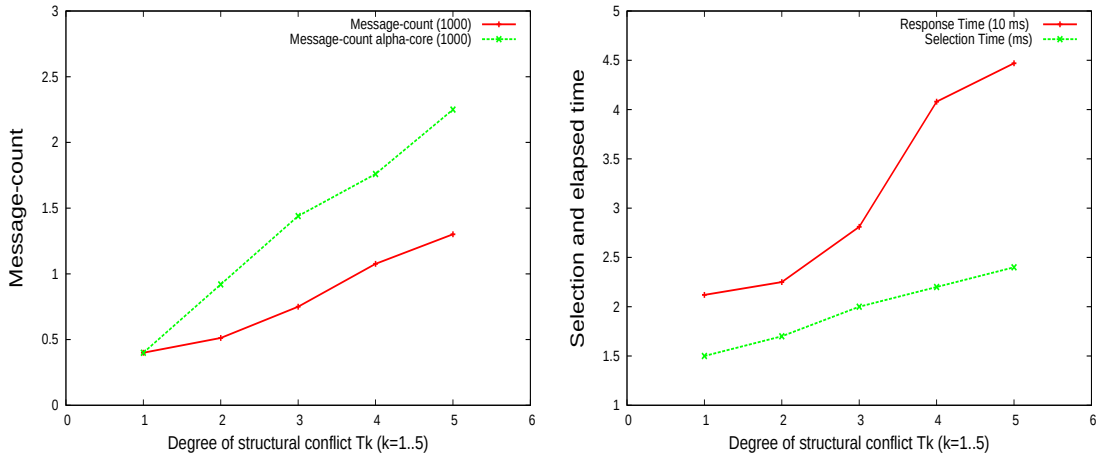
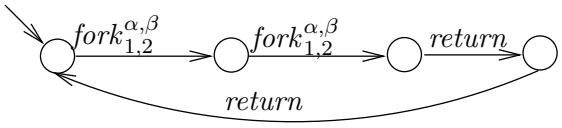


Figure 8.5: Sensitivity to the degree of *structural* conflict

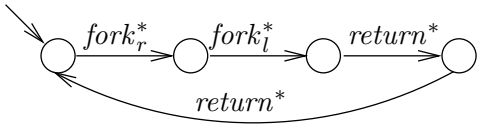
for T_2 for example, again 3 messages are needed to execute an interaction in the best case, but every time an interaction is refused, at the worst case, a penalty of 3 messages is added (one $POSSIBLE$, one $COMMIT$ and one $REFUSE$). To execute 100 interactions, 300 messages are needed in the best case, and 212 extra messages have been added for the situations where an interaction has been refused.

Variation of response time Figure 8.5 shows also the *selection* and the *response time*. Again, the average selection time is in principle independent of the number of interactions in *structural* conflict. Because, when no priorities are added and when an interaction becomes *ready*, only two $COMMIT$ messages are exchanged to execute an interaction. Thus the average selection time should be of about $2 * \lambda$, where λ is the average message transmission time which in our experimental architecture is $\lambda = 0.2$ ms.

Figure 8.5 shows that the measured *response time* is higher. The reason for this is that our implementation is written in Java, and the loop used to send k $POSSIBLE$ messages by the component K_{k+1} leads to computational overhead. More precisely, when K_{k+1} enters the loop to send k $POSSIBLE$ messages to the different peers, the component K_i which will get the first message sent, will set the interaction i to ready and send back a $COMMIT$. However, K_{k+1} will not treat this message before the termination of this loop. As the actual communication time is low, the $possibleSet$ of K_{k+1} may contain many interactions, which increases the *selection time* (only one interaction is committed, all others must be refused).



The behavior of $Forks$



The behavior of $Philo_*$

Figure 8.6: The dining philosophers problem with priorities.

8.2 The dining philosophers example

In this section, we focus on the well-known Dining philosophers problem, for which we have carried out a series of tests. We consider a variant of the dining philosophers problem inspired from [Pad] and we propose here to deal with this problem using priorities. Philosophers are seen as components who provide thoughts if they are given two forks. These forks represent a shared resource. A problem may arise if each philosopher grabs the fork on its right, and then waits for the fork on its left to be released. In this case a deadlock occurs and all philosophers starve.

This deadlock can be avoided by giving higher priority to requests closer to completion. The priority order that is needed here is $\{fork_1^\alpha < fork_2^\beta,\ fork_1^\beta < fork_2^\alpha\}$. For readability reasons, in Figure 8.6, the interaction $fork_{1,2}^{\alpha,\beta}$ in the behavior of the component $Forks$ corresponds to the interactions $\{fork_1^\alpha,\ fork_2^\alpha,\ fork_1^\beta,\ fork_2^\beta\}$ of the two philosophers. As the component $Forks$ participates in all interactions involved in these priorities, $Forks$ is designated negotiator for involved interactions and can ensure locally that priorities are respected.

Experiments have been carried out for the system with the mentioned priorities (depicted in Figure 8.6); then we have also considered a system with two philosophers and separate components for each fork, where deadlock is avoided by the fact that both philosophers first request $Fork_1$, and then $Fork_2$.

Dining philosophers	*message count*	*execution time*(ms)	*execution time*$_{Philo^*}$(ms)
With priorities	6	8	30
Without priorities	6	11	45

Table 8.1: Message count for the dining philosophers.

Table 8.1 shows our measurements for the *message count* and the *response time* metrics for both systems. We have also measured the average time required for one philosopher to execute a complete cycle (take forks, think and release forks) which we denote by *execution time*$_{Philo^*}$.

We observe that the number of messages exchanged is identical in these two systems. Indeed, priorities are local thus do not induce additional messages. However, using priorities leads to a slight increase of the *execution time*, as we have already observed in our first example, and the explanation remains unchanged. An additional reason is that the system with priorities has only one component to handle both forks, this making the system less concurrent than the system without priorities. This effect of concurrency is particularly visible in the results for *execution time*$_{Philo^*}$.

Part IV

Conclusions and Perspectives

Chapter 9

Conclusion and Perspectives

In this chapter, we conclude the thesis describing the main objectives of the work, the goals we have achieved, the future work directions and its perspectives.

9.1 Conclusions

In this thesis, we have focused on three aspect to reason about complex systems namely design, verification and implementation. We have proposed in a first time (Part II) a contract-based design and verification methodology where systems are modeled as component-based systems. Then, in a second time (Part III) we have focused in their implementation in particular in a distributed setting.

The proposed methodology have been extended to reason about arbitrary sized systems by building systems according to a given grammar of components and where the verification steps of a top level property are reduced to the verification of a dominance problem for each grammar rule.

In this methodology we have used contracts as a means to constrain, refine and implement systems. The notion of contract we use, makes a clear separation between the assumption, that is property of the environment, and the guarantee, that is the property that the system under study has to ensure. Such a separation improves reusability, which is useful in particular when dealing with a system acting in different possible environments. In addition, the contracts we use take into account the structural aspect of the system under study. In fact, glues (interaction models) used to compose components are explicitly represented in our contracts. This allows us to easily model, refine and implement these glues which represent in general low level protocols used for communication between the parts of the system.

We have based our work on a generic contract-framework, that we have instantiated for a component framework allowing the expression of progress properties. This instantiation handles variables and data transfer between components using a rich description of glues.

We have also successfully applied our extended design and verification approach to a case study which consists of an algorithm of sharing resources in a networked system of arbitrarily size for which a progress property has been checked. Then a prototype tool have been developed to perform the different design and verification steps automatically.

In the second part of this thesis, we have focused the problem of synthesis of controllers, to provide an implementation of these controllers in a distributed setting. In particular, we have focused in controllers defined by interactions and priorities by proposing a protocol for their distribution. This protocol defines a transformation of controlled systems into a distributed implementation in which every component is composed with a local controller exchanging messages with its peers in order to realize interactions exclusively by message exchange. We have also implemented a version of this algorithm handling binary interactions and we have analyzed its performance.

9.2 Perspectives

In this section, we discuss about interesting work directions which are either currently being undertaken, or will be planned for future work.

There are several interesting directions to be explored concerning the proposed contract-based design methodology. First, we have excluded the use of contracts for assume/guarantee reasoning: we use contracts as design constraints for implementations which are maintained throughout the development and life cycle of the system. On the other hand, in assume/guarantee based compositional verification, assumptions are used to deduce global properties (see [dRdBH$^+$01a]). We could integrate this into our methodology: as an example, in our network application, it would be enough to ensure that assumptions express sufficient progress to show conformance of a node contract to *node progress*. We would like also to use our methodology to verify multiple requirements, possibly by using multiple contracts and multiple hierarchical decomposition of the system. A second interesting direction could be to focus on non-functional properties which are in general properties of the glues by applying the same approach, that is defining contracts for these glues and thus refining them later by protocols for example. In the second part of this thesis, we have proposed a protocol to distribute a global controller into a set of local controllers ensuring given properties. The proposed protocol handles binary interactions between these controllers, an extension of this protocol to multiparty interactions as well as an implementation are actually under work. Another improvement on our protocol would be to combine it with the *knowledge* approaches [RR00a, RW92a, GPQ10]. Indeed, improving the algorithm by adding a first phase of knowledge computation to find out when a locally enabled interaction is guaranteed to be (not) enabled might in some cases significantly reduce the number of message exchanges without reducing the potential degree of concurrency. The reasoning about interaction models and properties as controllers in Part III could be applied to web service applications, when interactions between services and resources play an important role. In this context, our notion of global memoryless controller could be seen as an orchestrator and the distribution of such a controller as a choreography.

We think that this may lead to different challenges for achieving distribution than those considered generally in the domain of web services. In [CHY07, MH05, NCS04], for example, efficient distributions of web service orchestrators have been proposed, where the system description is based on WS-CDL and WS-BPEL. The use of our concepts of interaction models may lead to more concise specifications of webservices which can be more adequate to provide an understanding of the global behavior, and which are also more adequate for the verification of global properties of web services

applications. Similar formal and abstract specification has been proposed in [QZCY07] with a simple process language for describing behaviors of services from a local viewpoint with formal syntax and semantics.

We can provide some new emerging service through the composition of a set of existing services which may execute a set of tasks on their local memory and may impose constraints on the order in which these tasks can be executed. The new service is then defined by set of service components, and a set of interactions and priorities. If such a service specification contains a component that is involved in all interactions and that imposes order constraints on them, this component corresponds then typically to what is called an orchestrator in the domain of web services. This component would then also interact with the client(s) In absence of such a centralizing component, the emerging service is given in the form of a choreography.

High-level functional and non-functional properties have to be verified on this kind of systems. This is the reason why we propose to keep them as concise and readable as possible, and whenever appropriate, describe interactions amongst several services that should be executed in an atomic fashion by a rendez-vous rather than describing them in the form of some protocol. In this respect, our approach could be more efficient as it allows writing more concise specifications. On the other hand, an obvious drawback is that a generic protocol implementing systems with arbitrary multi-party interactions and global priorities is likely to be less efficient than a hand-crafted protocol for a given purpose and a given set of components.

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