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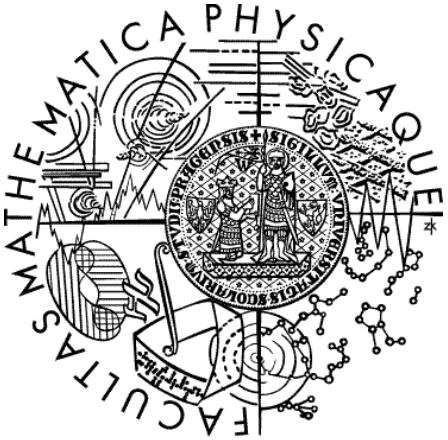
DOCTORAL THESIS



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Hierarchical Component Models – “A True Story”

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I declare that I carried out this doctoral thesis independently, and only with the cited sources, literature and other professional sources.

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In Prague, June 7th, 2012 Pavel Ježek

Abstract

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Abstract

First, this thesis presents an analysis of diversity of component-based software engineering (CBSE) concepts and approaches, and provides a summary of selected runtime-aware component models structured according to newly proposed criteria. As a result of the analysis, hierarchical component models are identified as a CBSE domain still not sufficiently explored in the current research with respect to their lacking penetration into regular industrial use. The major part of the thesis consequently almost exclusively focuses on problems related to application of hierarchical component models to real-life applications development.

The motivations for hierarchical structuring of application architectures are presented in the thesis and key advantages of hierarchical component models are thoroughly discussed and shown on examples from commercial software development. To verify the claims, two major case-studies are presented in the thesis and the Fractal component model is successfully applied to model and implement them focusing on formal verifiability of correctness of resulting component-based applications. The thesis proposes novel approaches to model dynamic architectures changing at runtime, to deal with complex error traces and a novel specification language for component environments, all resulting from our evaluation of the case-studies.

Keywords: hierarchical component models, formal behavioral specification, case-study, dynamic architectures, error traces, specification language

Abstract in Czech

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Abstrakt

Práce se nejprve zabývá analýzou širokého spektra konceptů a přístupů ke komponentově orientovanému návrhu software a předkládá přehled vybraných komponentových modelů s běhovým prostředím strukturovaný podle nově navržených kritérií. Hierarchické komponentové modely jsou identifikovány jako jeden z přístupů, který ještě není dostatečně prozkoumán, vzhledem k jejich minimálnímu proniknutí do světa průmyslových aplikací. Zbytek práce se pak téměř výhradně věnuje problémům spojeným s nasazením hierarchických komponentových modelů v reálném vývoji softwarových aplikací.

Práce představuje motivace vedoucí k nutnosti hierarchického strukturování aplikačních architektur a dále na příkladech z komerční sféry uvádí hlavní výhody vývoje aplikací pomocí hierarchických komponentových modelů. Jako důkaz jsou předvedeny dvě případové studie, které jsou úspěšně vymodelované a implementované pro komponentový model Fractal – práce se zaměřuje hlavně na formální ověřitelnost správnosti takto vytvořených aplikací. Na základě zkušeností z případových studií jsou v práci též předloženy návrhy nového přístupu pro modelování dynamických architektur, identifikování chyb v chybových výstupech a specifikační jazyk pro modelování okolí komponent.

Klíčová slova: hierarchické komponentové modely, formální specifikace chování, případová studie, dynamické architektury, chybové výstupy, specifikační jazyk

Contents

Chapter 1

Introduction

Software engineering is a very wide discipline of computer science covering many aspects of today's applications' development. As research always tries to move forward frontiers of the state-of-the-art in its target domain, it is only natural to analyze current trends in software engineering in order to come with a viable topic, where some enhancements can be done. By looking at popular technology assessment whitepapers (e.g. last year's release of ThoughtWorks Technology Radar [168]), one can conclude that currently the most important topics are service oriented architectures (SOA), cloud computing or concurrent programming ([168] mentioning "service choreography", "WS-*", "WCF-HTTP" implying SOA; "Azure", "vFabric" implying cloud computing; "concurrency abstractions and patterns", "C# 4.0", "Clojure" implying concurrency). General focus on these technologies or technology directions is understandable, as a boom of publicly available services, cloud systems, and multi-processor systems (multicore systems) is easily observable in current market. Increasing penetration of these technologies leads to natural demand for better software engineering techniques to enable more efficient and less expensive development of software applications for customers using current computer systems.

In the light of these observations it might seem that topics very popular in past, like component-based software engineering (CBSE), are either widely used without any further problems emerging or at least well understood, but not useful anymore and superseded by more modern development techniques. Such conclusions would be however wrong and can be easily refuted: (1) reading several recent volumes of the CBSE conference proceedings (the most narrowly specialized conference/workshop on component-based software engineering) shows the number of accepted papers decreased a bit over the years (25 full papers in 2004, 23 full papers in 2005, 23 full and 9 short papers in 2006; and 16 full papers in 2009, 14 full papers in 2010, 17 full and 6 short papers in 2011), but there are still many open problems in the domain of programming with software components and there is still a reasonable amount of papers shifting the state-of-the-art frontier in the field; (2) an ongoing acknowledgement of the benefits of component-based software engineering by developers' community and the currently increasing penetration of component systems into major platforms – to give at least two examples: (a) an increasing role of OSGi component platform [139] in the Java world (Equinox [66], an OSGi platform implementation, being a basis of the Eclipse IDE [62] – currently a de-facto standard for building Java based tools; acknowledgement of the OSGi importance by Oracle/Sun company itself, incorporating it into the NetBeans IDE [136][135] in 2010, and OSGi probably being the platform of choice as an application packaging and deployment framework for upcoming releases of the Java platform), (b) the Managed Extensibility Framework (MEF) component system [112] being one of the key new features in the .NET framework 4.0 released in 2010, and reimplementation

of Visual Studio module system using the MEF as a basic composition platform in its 2010 release (with a little simplification and extension of the notion of C# 4.0 – being mentioned in the ThoughtWorks Technology Radar [168] – to the whole .NET 4.0 platform, the CBSE can be in fact identified as one of the techniques proposed to be currently adopted).

As shown in the previous paragraph CBSE is becoming an important paradigm in current software engineering, and is still a live research area with its open problems. Surprisingly one of the key problems in the CBSE domain are the foundations of the CBSE itself – the software components – more precisely a definition of what a component does and how having a system decomposed into components helps with the system development and future maintenance. Every component framework (a software framework allowing application development taking a special advantage of a specialized concept of a unit of code – a component) defines its notion of a component that fits the whole framework and other concepts defined in its context. A definition of a component as understood by a particular component framework is often very specialized and component definitions of different component frameworks have often a very different set of requirements on and services provided by a software component. This makes the term "component" or "software component" one of the most overridden terms in the whole software engineering domain. Authors of many component frameworks are probably aware of this problem as many frameworks come with their own name for a software component (see a "bean" in JavaBeans [94], or a "part" in MEF [112]).

In order to be able to state the basic goals of this thesis, rest of this section presents an example showing differences in understanding of basic concepts of CBSE by different component frameworks. Another purpose of the following text is also to show a few basic advantages of how incorporating the ways of CBSE design can help software developers to produce better maintainable applications.

1.1 Basic CBSE Concepts

A typical user of modern commercial component frameworks is a mainstream developer implementing his or hers applications in an object oriented (OO) programming language. As further elaborated in Section 2.5, in fact most of the component frameworks (either commercial or academic) try to position themselves against the basic paradigms of object oriented programming (OOP) – i.e. a typical goal of a component framework or component modeling platform is to introduce several new concepts (at least a concept of a component) enhancing the chosen target OO programming language (or set of such languages) or platform. In order to present the CBSE concepts, it is then only natural to begin an example with a snippet of program written in a classic OO language without any CBSE concepts present at first (let's assume a declaration of the following class written in the C# programming language):

C#

```
public class Debug {
     public static void Print(string message) {
          ...
     }
}
```

The intent of this class is to provide a basis for a library implementing logging services for other applications (similar to the capabilities of the .NET's standard `System.Diagnostics.Debug` class). Just a reminder, in C# `public` methods are accessible by any code outside of the declaring class, `static` methods are methods of the class (and not of an instance) and can be used without a possession of a valid instance. To implement the `Print` method a backing store to save the logged messages is needed - a simple call to standard `System.Console.WriteLine` might seem sufficient. However using this simple approach is not very well suited for a library class implementation, as the potential users of the library will probably like to use it in a very wide spectrum of cases, e.g.: (a) implementing a GUI (Graphical User Interface) application that lacks any standard output capability, thus anything written using `Console.WriteLine` is lost; (b) debugging an application, thus requiring a live view of the logged messages – either via a standard output (then is `Console.WriteLine` sufficient) or via a debug pane in an integrated development environment (IDE); (c) or tracing of key checkpoint of a deployed application for post-mortem analysis after an application crash. To allow usage in all these and any other scenarios, the message target store should not be hardwired in the `Debug` class – this can be easily accomplished by holding a reference to a message store service provided by another class implementing for example the following interface:

C#
```
public interface ITraceListener {
     void Write(string message);
}
```

The new implementation of the `Debug` class taking advantage of the `ITraceListener` interface then would look like this (adding a newline to the message serves as an example of potential added value/functionality of the `Debug` class):

C#
```
public class Debug {
     public static ITraceListener traceListener;

     public static void Print(string message) {
          traceListener.Write(message + Environment.NewLine);
     }
}
```

Having such an infrastructure prepared, anyone can now implement a class following the `ITraceListener` interface, e.g. to support printing the debug information to the system console (standard output) following `ConsoleTraceListener` class could be implemented:

C#
```
class ConsoleTraceListener : ITraceListener {
     public void Write(string message) {
          Console.Write(message);
     }
}
```

So far this has been a classical approach of decoupling an API (application programming interface) and its actual implementation. The fact that this pattern can be easily and effectively described in a programming language is in fact implication of the key advantages of OOP against plain structured programming.

However, having this improved implementation introduces a new problem – when and by who will the `traceListener` static field get initialized. In standard OOP approach the initialization has to be hard-wired somewhere in the library or the application using the preceding classes (i.e. creation of a new instance of the `ConsoleTraceListener` class and assignment of the instance reference to the `traceListener` field). If we rewrite the example into the Java programming language, then a partial solution to the problem mentioned comes, if the code is enhanced by programming patterns suggested by the JavaBeans [94] component framework:

Java

```
interface TraceListener extends java.util.EventListener {
     void write(String message);
}

public class Debug {
     private ArrayList<TraceListener> traceListeners =
          new ArrayList<TraceListener>();

     public Debug() {
     }

     public void addTraceListener(TraceListener tl) {
          Listeners.add(tl);
     }

     public void removeTraceListener(TraceListener tl) {
          Listeners.remove(tl);
     }

     public void Print(string message) {
          for (TraceListener tl : listeners)
               tl.Write(message + "\n");
     }
}
```

The example uses a design pattern of events and event listeners from JavaBeans component model, which enhances the previously shown implementation with an ability to notify multiple clients of an event occurrence – in this case a request to write some message into a logging facility. Now only one instance of `Debug` class (or bean in JavaBeans terminology – i.e. JavaBeans component) is logically expected exist (implementation of a singleton design pattern has been omitted from the example to keep it simple) and it does not have to locate the logging service (which would be another bean/component) by itself, but it delegates this duty to the actual logging service (bean/component) that needs to register itself by calling the `addTraceListener` method. The `Debug` bean serves as a JavaBeans event source in this example. Furthermore by adhering to the event listener pattern (i.e. implementing the `TraceListener` interface, becoming an event listener), any logging service only has to take care for itself (e.g. eventually unregister itself properly), and does not have to know whether there are any more logging services using the same `Debug` bean (class).

All the core features that JavaBeans extend the Java language with are in fact build into the C# language itself (since its first version 1.0) and, what it even more important, are not only a syntactic sugar of the language, but are also explicitly supported by the underlying platform runtime as well (i.e. by the .NET's Common

Language Runtime – the CLR). However as C#/.NET events build upon a concept of delegates (managed references to static/class or instance methods), a C# reimplementation of the `Debug` class following the JavaBeans implementation would be a bit different.

C#

```
delegate void WriteDelegate(string message);

public class Debug {
     public event WriteDelegate Write;

     public void Print(string message) {
          if (Write != null)
               Write(message + Environment.NewLine);
     }
}
```

The key difference to observe is the following: should the `Debug` class provide more events, each of the events has to be represented by its own field in the class declaration. Whereas in JavaBeans multiple events can be covered by a single listener (e.g. MouseListener in standard Java's Swing library defining 5 distinct events – all mouse related). Both approaches have their pros and cons, and neither of them is clearly better than the other, but an important lesson to learn is: even though both C# and JavaBeans define a similar concept of "events", they are not the same and semantically can often differ a lot.

Note: the .NET's implementation of a similar `Debug` class in fact follows the JavaBeans style implementation (as the full implementation of trace listeners requires provision of several callback methods, is requires provision of an interface and not a single method).

The previous enhancements of the example with either JavaBeans' event listeners or C#'s events still did not fully solve the problem of responsibility of binding the two classes together (or beans/components in case of JavaBeans). All the solutions required either the `Debug` class to find available trace listeners (services) – the original C# solution – or required the trace listeners to proactively register themselves in the `Debug` class (component) instance – the latter implementations in Java and C#. This requires that at compile time a piece of code to do the registration is provided on one place or the other. However such requirement does complicate scenarios where the choice of a right implementation of a required interface (i.e. right trace listener implementing the `ITraceListener` interface in this example) should be done at deploy-time or at runtime by the final user of the application (e.g. via a configuration file) and not by the programmer at compile time. Fortunately other component models exist, that target to solve exactly this problem – for example in the Managed Extensibility Framework (MEF) [112] the `Debug` class would become a MEF part and could have a private collection of listeners (initially empty) annotated with an `ImportMany` attribute defined by MEF:

C#/MEF

```
public class Debug {
     [ImportMany]
     private IEnumerable<ITraceListener> traceListeners;

     public void Print(string message) {
          foreach (var tl in traceListeners)
               lt.Write(message + Environment.NewLine);
     }
}
```

Then by correctly initialing the MEF framework, it will automatically locate all parts (MEF components) that are implementing the required functionality (the `ITraceListener` interface). An example implementation of such a component follows:

C#/MEF

```
[Export(typeof(ITraceListener))]
class ConsoleTraceListener : ITraceListener {
     public override void Write(string message) {
          Console.Write(message);
     }
}
```

Again an attribute (this time `Export`) is used to mark a valid MEF component and to specify the provided functionality (interfaces) of that component. By using MEF in this way the application would implement only a generic initialization method of the MEF framework and the rest will be done automatically by MEF – i.e. instantiation of the `ConsoleTraceListener` class (part/component) and filling out a reference to it into the `traceListeners` field of the `Debug` class (part/component).

As one can observe from the examples presented, the concept of a component in JavaBeans is quite different from the concept of a component in MEF. In fact the overlap of the two definitions is minimal and if a MEF implementation for Java existed, we can imagine these two component frameworks can be combined in a single application. As JavaBeans' bean describes a different concept than a MEF's part and both JavaBeans and MEF serve a different purpose (each of them was designed with a specialized problem to solve in mind), thus if an application developer faces both problems during development of a single application, he or she can benefit from incorporating both technologies into the developed software. This again leads to an urgent need to clearly differentiate between different concepts being described as components (JavaBeans and MEF are the good examples here). If several concepts are all defined by the "component" term, it might be hard for a developer to correctly grasp and fully understand both of the concepts. Further challenge is then to even identify the concepts as different and be able to free of the idea that a choice must to be made to have a single component framework used in the whole application.

1.2 Problem Statement

As the CBSE concepts introduced in the previous Section 1.1 were presented on basic features of two of the mainstream programming languages/platforms, it is clear that CBSE is appreciated as a valuable approach to software engineering. In fact as the presented features form cornerstone aspects of the respective technologies, software developers cannot easily opt-out of them and are actually forced to use them

and design software using the CBSE concepts in mind. Even on these few concepts it was clear the understanding of a component and component-oriented software design is perceived very differently by orthogonal technologies. There are at least several dozens of CBSE related techniques in the world from ones coming from the commercial world (as the examples from Section 1.1) to purely academic or research ones. Moreover the various CBSE techniques cover a very broad spectrum of problems and issues from mostly any phase of software development. There are pure theoretical approaches designed to cope with general software design problems (e.g. UML components [137]), techniques targeting formal reasoning about software architecture, dependencies and their functional and non-functional properties (e.g. Darwin [109] or Palladio [23]), component models combining a formalized view on software architecture together with support for some advanced runtime features (e.g. SOFA 2 [40], Fractal [27][3]), component models specialized for a special domain (e.g. SafeCCM [6], ProCom [158], Koala [171], SOFA HI [160][150][84] for domain of real-time and/or embedded systems), as well as component systems designed to "just" simplify some complex day-to-day tasks developer often have to face during complex software implementation and deployment (e.g. COM [49] or OSGi [139]), and many, many more. Actually there is not a single rule defining what techniques fit the CBSE domain, but the other way around is true – i.e. both the existing and newly emerging techniques define the component-based software engineering as a discipline. Being that broad and broadening every day, it is not easily possible to analyze problems related to CBSE in general and in fact it would not be even reasonable as the theories on opposing sides of CBSE domain are conceptually so far, it is hard to identify even a single common point, where they would meet.

Thus for sake of this thesis we will choose just a subset of CBSE, where our experience and expertise can be mostly utilized to advance the current state-of-the-art techniques. Our CBSE approach of choice is enhancements of runtime software frameworks by incorporation of advanced CBSE techniques and provision of technologies and methodologies bridging the design phase of software development and the phase of actual code implementation. So our reasoning about CBSE concepts will be always either directly or indirectly related to some component-oriented software framework. As a matter of fact the technologies presented in Section 1.1 would fall into such a category.

Even in such narrowed CBSE subdomain, there are still a lot of different approaches to software design using a concept of a component – an overview of the commonly used component models can be found in for example in [54] and [107], an overview of component models specialized for real-time embedded systems can be found in [88]. If we go through the existing component models, try to gather the features supported by the models, and divide the features on the typically understood to be more advanced ones (these are mostly support for complex solutions to most of the modeling, implementation, packaging and deployment phases of component developments) and the rest, an interesting observation can be made. The commercial component models that are widely used in today's regular software development do typically incorporate the more "basic" CBSE concepts from the set. On the other hand the complex features are mostly promoted by the component models with academic or research background in general.

The obvious question one has to ask is what the academic models do wrong, that they are not able to persuade commercial component model writers of the benefits the advanced features they can provide. Unfortunately the key problem is probably inherent to the non-commercial research-oriented framework development – i.e. the framework are prepared with a vision of providing some new revolutionary features, but often a vision of a final product is missing. The reason for such state are quite understandable – the actual advance in the state-of-the-art can be easily sold to the research community, but quality of the implementation backing the ideas is not predominant for general good acceptance the research results. Prevailing attitude in the community tends to underestimate both the importance and overall cost of implementation of the ideas. It is often perceived the original idea is the key to success and the transition to the actual code implementing it is quite simple and every experience programmer can do it.

However software development is not an easy task and especially the with growing complexity of the technology, it is very important how the implementation is designed and whether a set of features of the underlying technology has been carefully chosen with respect to the assignment and the target domain. This can be nicely summarized with a classical problem regarding algorithm complexity – the asymptotic complexity matters, but the constants often matter as well in the actual implementation – i.e. poor choice of instruments of the target platform or incorrect usage of the provided features can slow the final program (algorithm implementation) in orders of magnitude (e.g. in case of inappropriate utilization of system caches) or can render it unusable being inherently incorrect (e.g. a very typical misuse or misunderstanding of target system memory models – usually wrong assumptions make about volatile accesses to program variables on weak ordering memory architectures).

In context of component model this problem arises much more often than in regular software development. As the advanced features can be often very nicely designed to seamlessly fit into the existing theory, and their formal specification can be quite simple, but the actual implementation can be overwhelmingly complex. The reason for it is the component model runtime stands at the bottom levels for software stack typically directly interfacing the operating system or the platform in general. However for the reasons presented above such complex component principles are in research component models often well-defined only on the conceptual level. And even if an implementation is provided, integration into existing tools is often not very well maintained or a complex tool-chain supporting the component software development is not provided.

A closely related problem is the component models often lack more complex examples or case-studies that would not only prove the implemented concepts work, but more importantly also clearly show the benefits of the used CBSE approach and be able to persuade wider developer community about usefulness and maturity of the component model. To communicate the CBSE advantages better to the developer community it is necessary, the existing as well as any new emerging CBSE principles are validated on close-to-real software implementation. Furthermore, as the implementation oriented CBSE aspects do not float in the air, or are not beneficial on their own, it needs to be comprehended the CBSE related research have to mostly fall into a domain of applied research. Such classification means that new CBSE concepts need a clear motivation on their applicability especially regarding

any potential industrial use or advancements for broader software development community in general.

1.3 Goals and Structure of the Thesis

Goals: We feel the concepts introduced by many of the current component models are very interesting and we see their huge potential to qualitatively change the course of software engineering, even with respect to slow adoption of these advanced techniques by the software developers' community as presented in the previous Section 1.2. However as the advanced CBSE related concepts like hierarchical components, controllers, connectors, etc. are not in focus of mostly spread software development frameworks and technologies, we are afraid a lot of the great results of current research in the domain of component-based software engineering slowly dim without any broader and deeper attention of developer community and the work of the researchers it then a bit underappreciated. This thesis aims at helping the CBSE community to be able to compete with the main stream of software engineering and bring the interesting CBSE oriented systems' ideas to real life. Thus, the following goals of the thesis are proposed:

(1) To identify common features of CBSE design principles adopted in current technologies, as well as the promising directions lacking wide common adoption in software industry.

(2) To show key strengths and weaknesses of the component modeling approaches incorporating promising CBSE principles, especially with respect to their application onto actual software implementation. This requires verifying the approaches on real-life case-studies.

(3) To provide solution to most severe of identified weaknesses of the advanced component modeling approaches (namely hierarchical component models).

Structure: This Chapter 1 provides an introduction to the CBSE domain and presents a problem statement with regard to current software development with CBSE concepts and proposed goals of the thesis are stated. Chapter 2 shows current state of the art publications in CBSE domain sort of inherently imply a general quest for a holy grail of an ideal component model. The chapter continues with an overview of a few component models incorporating typical CBSE concepts from our point of view. The survey of component models is organized in a way, so that it can be naturally followed up with a summary of goals of different approaches to CBSE. Finally, the chapter concludes with a need to refine the goals proposed in Chapter 1. Aim of the following Chapter 3 it to provide a bridge between Chapter 1 and Chapter 2 (more or less covering an extended problem statement) and the rest of the thesis which is mainly based on published results and on our participation in several projects and on their results.

As most of the presented results are tackling with a notion of behavioral specification and verification of its correctness in context of behavior protocols formalism in context of hierarchical component models, the Chapter 4 provides an overview of the key behavior protocol concepts that are necessary to comprehend Chapter 5 to Chapter 7. This introduction to thesis background is followed by chapters presenting the two major case-studies - Chapter 5 presents an Internet access management

system developer as part of a CRE project, Chapter 6 presents our approach to an assignment of the CoCoME international contest. Chapter 7 then proposes a solution to the identified need of modeling of dynamic architectures and includes an evaluation of the proposed concept as well as its applicability on the presented case-study, whereas Chapter 8 shows an alternative approach to modeling component environments in context of Windows kernel drivers.

Chapter 9 summarizes the related work from the published papers covering the presented contribution. As in a limited space of the thesis it was not possible to provide a definitive solution to all the identified problems, Chapter 10 provides a short conclusion of all achievements of the thesis, and then Chapter 10 iterates again through the problems and show the areas where we were not able to provide sufficient solution. Also some future direction how to improve our solution and where to advance the research are presented in Section 10.2.

1.4 Contributions and Publications

A novel contribution of the thesis can be divided into several areas, that are covered in respective chapters of the thesis: (1) an overview of diversity CBSE concepts and approaches, (2) an analysis of current components models with a runtime environment and a consecutive summary of component models structured according to newly identified criteria, (3) an analysis of hierarchical component models' goals and motivations, (4) introduction of a case-study and an analysis of suitability of hierarchical component models and their application correctness verification techniques in context of two major case-studies, (5) introduction of an approach to model dynamic entities and architectures changing at runtime in domain of hierarchical component models, and (6) introduction of an approach to model component environment.

An overview of published results relevant to context of this thesis follows:

Book chapters

[38] **Bulej L., Bureš T., Coupaye T., Děcký M., Ježek P., Parízek P., Plášil F., Poch T., Rivierre N., Šerý O., Tůma P.**: *CoCoME in Fractal*, Chapter in The Common Component Modeling Example: Comparing Software Component Models, Springer-Verlag, LNCS 5153, Aug 2008

Reviewed articles

[42] **Bureš T., Ježek P., Malohlava M., Poch T., Šerý O.**: *Strengthening Component Architectures by Modeling Fine-grained Entities*, in proceedings of 37th Euromicro SEAA 2011, Oulu, Finland, IEEE CS, Aug 2011

[95] **Ježek P., Bureš T., Hnětynka P.**: *Supporting Real-life Applications in Hierarchical Component Systems*, in proceedings of SERA 2009, Haikou, China, Studies in Computational Intelligence (SCI), Springer, Dec 2009

[113] **Matousek T., Ježek P.**: *DeSpec: Modeling the Windows Driver Environment*, in proceedings of FESCA, ETAPS'07, Braga, Portugal, ENTCS, Mar 2007

[96] **Ježek P., Kofroň J., Plášil F.**: *Model Checking of Component Behavior Specification: A Real Life Experience*, in Electronic Notes in Theoretical Computer Science, Vol. 160, pp. 197-210, Elsevier B.V., ISSN: 1571-0661, Aug 2006

[99] **Kofroň J., Adámek J., Bureš T., Ježek P., Mencl V., Parízek P., Plášil F.**: *Checking Fractal Component Behavior Using Behavior Protocols*, presented at the 5th Fractal Workshop (part of ECOOP'06), July 3rd, 2006, Nantes, France, Jul 2006

Technical reports

[41] **Bureš T., Ježek P., Malohlava M., Poch T., Šerý O.**: *Fine-grained Entities in Component Architectures*, Tech. Report No. 2009/5, Dep. of SW Engineering, Charles University in Prague, Jun 2009

Presentations

Ježek P.: *Model-Driven Development on .NET Platform*, Model-driven Software Development in the Real World Workshop, MDD-RW 2010, Karlsruhe, Germany, Jul 2010

Ježek P.: *Behavior Protocols: Formal Specification of Services Behavior in a Component Environment*, 16th Annual Conference of Doctoral Students, WDS'07, Prague, Czech Republic, Jun 2007

Ježek P.: *Behavior Protocols: Using Behavior Protocols to Model Real-Life Software Components*, 15th Annual Conference of Doctoral Students, WDS'06, Prague, Czech Republic, Jun 2006

Adámek, J., Bureš, T., Ježek, P., Kofroň, J., Mencl, V., Parízek, P., Plášil, F.: *Real-life Behavior Specification of Software Components*, 11th EMEA Academic Forum, Dublin, Ireland, May 2006

Ježek P.: *Behavior Protocols: A Real Life Experience*, 14th Annual Conference of Doctoral Students, WDS'05, Prague, Czech Republic, Jun 2005

Ježek P.: *Combining OMG Target Data Model and JMX Technology*, 13th Annual Conference of Doctoral Students, WDS'04, Prague, Czech Republic, Jun 2004

1.5 Note on Conventions Used

The text of this thesis is partially based on the papers referenced in the previous Section 1.4 and manual of the project mentioned below. In order to emphasis this fact, the paragraphs taken from the papers are in the thesis marked by a side paragraph marker.

This is an example of a paragraph that is copied verbatim from the published book chapter, a reviewed paper or a technical report and is marked by a vertical bar.

This is an example of a paragraph that is copied verbatim from the manual of the France Telecom funded project *Component Reliability Extensions for Fractal component model* [2] and is marked by a vertical wavy line. The project manual is available on-line [3], however has not been previously officially published at any

conference or workshop. Contributors to the text of the manual are **Jiří Adámek**, **Tomáš Bureš**, **Pavel Ježek**, **Jan Kofroň**, **Vladimír Mencl**, **Pavel Parízek**, **František Plášil**.

Where it was necessary, the original text is slightly modified to make the thesis easy to read. But these modifications are only in several sentences at beginnings of the copied text in order to fit together with the rest of the thesis. Also, phrases like "in this paper" are changed to "in this thesis", etc., for obvious reasons. Furthermore the original text was often slightly reformatted and several small structural changes were made to fit the formatting and structuring style of the thesis. Also a few typos found in the camera-ready versions published were corrected in the thesis.

The source of the text copied verbatim is denoted by the margin notes (in the right margin of the text) at the beginning of the each copied section. We use the following abbreviations for distinguishing the sources:

CREman for text copied from [3]
CoCoME for text copied from [38]
DeSpec for text copied from [113]
Entity for text copied from [42]
EntityTR for text copied from [41]
FACS for text copied from [96]

To further enhance readability of the text, paragraphs comprising only from source code of a programming, specification or modeling language are indented more than regular paragraphs and are denoted by the margin notes (in the left margin of the text) identifying the target language, the paragraph is written in:

Java

```
This is an example of a paragraph written entirely in the Java
programming language.
```

Chapter 2

Quest for an Ideal Component Model

2.1 Different Views on Basic Concepts

To fulfill the first two goals as presented in Section 1.3 we need to analyze the current approaches to CBSE. As mentioned before, the CBSE conference is a respected source of CBSE related papers that usually form or are positioned near the frontier of state-of-the-art in the CBSE domain. Browsing through the papers published at CBSE conferences in recent years one can easily notice that most of the papers sooner or later in the text end up by anchoring themselves in the CBSE domain by defining a notion of a component or CBSE itself. The motivation is natural as to be able to reason about CBSE concepts and to provide some enhancements to the domain, it is necessary to have a clear understanding of what the concepts are and where the paper results are applicable. While most of the papers provide just a short definition of CBSE or a component (often just referencing relevant definition in literature) and thus implicitly postulating their authors' assumption of fundamental roots of CBSE as being well-established without any need to further elaborate, the authors of few other papers are obviously aware of a complicated situation regarding a clear and sound definition of a component, and are trying to provide an analysis of various CBSE approaches to show a relevant CBSE subdomain, that their results fit in (thus providing a more constrained view of CBSE). As the third goal of this thesis expects us to provide a solution to some of CBSE related problems, it is for us also necessary to define an area of software engineering, where we believe our results can be ideally applicable.

In Sections 1.1 and 1.2 we have shown the basic CBSE concepts (mainly a concept of a component) are not that clear as one would expect. On the other hand as mentioned in the previous paragraph authors of many CBSE related papers do not feel the same way and present or reference their "generic" definition of a CBSE component. One of the most cited one is the component definition by Clemens Szyperski as presented in his book "Component Software – Beyond Object-Oriented Programming" – as it requires more analysis, a reference will be given in Section 2.1.1 which presents some problems regarding the definition. Another commonly referenced definition of a component is the one by Heineman and Councill from [81], Section 2.1.2 is dedicated to analysis of problem related to this latter definition.

2.1.1 Issues with Szyperski's Definition

Typical references to Szyperski's book unfortunately introduces already first problem – while a verbatim copy of Szyperski's definition is often presented, some papers only reference the book as such. By carefully reading the book reader can in fact find two different component definitions there (so that if a paper references just

the book itself, it is not clear which definition had the authors in mind). The first definition of component presented in [167] is partially implicit by stating a set of its characteristic properties:

(1) "A component is a unit of independent deployment."

(2) "A component is a unit of third-party composition."

(3) "A component has no persistent state."

Presented in the 1997's print of the book these properties reflected the contemporary Szyperski's insight and personal view on software components. As he later admitted over the years (with the evolution of the software engineering domain) he gradually shifted to slightly different understanding of components as is reflected in an updated definition of component presented in second edition of the book [165]:

(1) "A component is a unit of independent deployment."

(2) "A component is a unit of third-party composition."

(3) "A component has no (externally) observable state."

Although the definition is presented in the book first, we understand it more as an explanation or annotation of the second component definition presented later in the book. Having its own subsection the second definition can be probably considered as the grand-definition of component (which can be incidentally supported by a fact, that should a Szyperski's component definition be provided as a verbatim copy in a paper, it would be this second one). While the first definition was updated between editions, the following one has remained the same throughout the years (in both [167] and [165] editions of the book):

> *"A software component is a unit of composition with contractually specified interfaces and explicit context dependencies only. A software component can be deployed independently and is subject to composition by third parties."*

And as it is stated in the book, the above definition is in fact an outcome of a very deep and long discussion in one of the workshops of 1996's European Conference on Object-Oriented Programming (ECOOP) and was originally published in [166].

One can observe that the both definitions are quite general – in fact as noted for example in [80], a component defined by properties of "a unit" does not necessarily imply any connection to software engineering (so it can define a hardware component as well), nor even any connection to the computing world in general at all (thus being valid in potentially any domain with suitable "units"). The book presents a very thorough discussion on the topic; the definitions were carefully prepared as a result of an intensive research of the contemporary component-based systems and general state-of-the-art of CBSE as well. However when trying to analyze current software component-oriented software systems based on a provision of a runtime environment/platform, it will soon become clear that many of the systems do not fully fit with their approach to component modeling the definitions presented so far (in spite of their generality mentioned above). In fact, one could say that these

"problematic" component systems and their components do not conform to the definitions, as often one of the key requirements on a software component does not hold in the respective component system. Few examples of such inconsistencies with Szyperski's definitions are as follows:

One of component-oriented systems commonly considered in published CBSE related papers is the JavaBeans [94] component model. One of the explicit requirements on a JavaBean (bean = a JavaBeans' component) is that it has to expose parts of its internal state via properties – which is in a direct contradiction with the (3) rule of the updated version of the first Szyperski's definition of component ("*A component has no (externally) observable state.*"). One might argue the properties can be viewed as an optional feature of a bean and that a bean without properties (thus with only internal state) can exist – but such a bean would go directly against the JavaBeans' basic concept, since beans are designed to encapsulate units of user interface interaction (UI components), where state sharing between a component (representing a subset of possible user interaction – gathering parts of user input and providing features for user output) and its environment is the key way of interaction between components. Windows Presentation Foundation (WPF) [132], Silverlight [130], Metro UI API for upcoming Windows 8 OS [131] are examples of graphical user interface (GUI) frameworks that are even more data oriented and the data exposed by respective UI components play there even more important role than in JavaBeans. In these technologies, the interaction with the user is not (only) defined by application's code, but by application's data relations as well (the relations are expressed as connections – or connectors – between the components the application's architecture is built from) – and this focus on the data is believed to be the key success point of these technologies. This implies the data-centric approach of component frameworks targeting UI development should in fact strengthen in future and not weaken as Szyperski's definition suggests.

Furthermore component systems not able to fully fit the second Szyperki's component definition can be also identified. As statistics of web browser popularity [174] show the Windows operating system with market share of 83.9% as of January 2012 is still the most popular operating system on desktop computers (assuming the vast majority of desktop systems is connected to internet and is used to regularly access the world wide web). And COM [49] component model being a cornerstone of many basic application-to-OS and application-to-application interactions in Windows OS is, at time of writing of this thesis, probably the most commonly used component system in the world. The COM is based on the exposure of well-specified interfaces that define an interaction point between components. Even though a COM component does have "*contractually specified interfaces*", it does not have "*explicit context dependencies only*" – in fact the component's dependencies are rarely defined explicitly, a common approach is the dependencies are implicitly given by the code that tries to instantiate required components at runtime.

Yet another problematic example is "the .NET components", as the CBSE concepts are incorporated in many aspects of the .NET platforms. These different component-oriented aspects of .NET are however not directly related to each other and in fact exist on different levels of abstraction. That is why the phrase "the .NET components" is quoted in the first sentence of this paragraph. Unfortunately this is a common problem of many CBSE related papers as their authors often do reference ".NET (components)" (without the quotes), but to not specify exactly which

component concept of the .NET platform they have in mind. We will get back to this problem later, so for now let's assume a .NET component equals to a .NET assembly (as Szyperski does in his book) – a simplified view is that an assembly is a unit of binary code distribution and deployment on the .NET platform (typically it is a single EXE or DLL file, but multi-file assemblies can exist as well).

Even if considering only the assemblies as .NET components, a problem with their view as Szyperski-style components arises. Whilst .NET assemblies do have explicitly specified dependencies (each assembly contains a list of required assemblies in its so-called manifest), the problem lays in the "*a unit of composition with contractually specified interfaces*" part of the component definition. The interface of an assembly as a unit of composition is just its "strong name" (in terms of .NET: plain text name, version, its language of localization, and cryptographically unique publisher's ID) – i.e. relationships among assemblies as defined by their mutual requirements are explicit only in sense of their names and not their actual contents. However the assembly's contents defines its true contract – i.e. all the features the assembly provides – and, as such, it does not form the assembly's interface. Furthermore, even if the contract was understood to be a part of the assembly's interface then the assemblies as components will get in conflict with the "*explicit context dependencies only*" rule, as the actual dependencies on another assembly's contents are provided only implicitly in the assembly's code.

Interestingly enough, these dependencies are not even verified during assembly lookup process done by the Common Language Runtime (.NET's virtual machine) [89][63], nor during loading a dependent assembly into process memory. The dependencies are always verified only lazily at the time of their actual need during application progress. Though such a feature might seem very odd from point of view of a software engineering theoretician, it makes a perfect sense in the world of real life desktop applications. Namely the lazy dependency verification allows silently ignoring any missing dependencies (e.g. missing classes, methods, etc.), and postponing any potentially fatal errors until a request to use such a missing feature arises. In a typical desktop application this approach manifests itself by a very user-friendly behavior, where an application with missing dependencies would start usually start without problems and if a user does not click (for example) a menu item accessing the missing dependency, he or she will not notice any application usability problems.

2.1.2 Issues with Heineman and Councill's Definition

It seems that trying to define the CBSE by establishing a component concept by its own is not the best direction. In reality the component abilities, behavior and constraints are tightly coupled to the component technology being considered. Thus it seems an opposite view on a component definition should be taken, i.e. not to try to define a component in isolation, but try to define it with respect to its context. Fortunately others already came to a similar conclusion, and for example Heineman and Councill in [81] provide a relevant definition of a component model as an abstraction of specific component context:

> *"A component model defines a set of standards for component implementation, naming, interoperability, customization, composition, evolution and deployment."*

Having a component model defined this way component can be now redefined with respect to that component model definition – such component definition reads [81]:

> *"A software component is a software element that conforms to a component model and can be independently deployed and composed without modification according to a composition standard."*

This definition of component does not enforce very specific constraints, and it rather leaves an exact definition and constraints to the specific component model the components are considered in. Being so open, it allows a component model to freely define components' constraints to fully fit its goals and needs, for example, as a bean conforms to the JavaBeans model's specification and as much as a COM component conforms to a COM model's specification, both JavaBeans and COM components (not conforming to Szyperski's component definitions) do conform to Heineman and Councill's component definition.

On the other hand, strictly speaking, the .NET assemblies viewed as components might not adhere to the Heineman and Councill's component definition, as their (contract) modification via publisher's policy, or user/machine configuration might be required to allow them to participate in specific composition scenarios.

Unfortunately Heineman and Councill's component definition is not as trouble-free as the previous text might imply (the note above shows a sign of a potential glitch). The key problem of the definition is that it silently expects from the reader some previous intuitive understanding of the concept of component model and component. Let's illustrate this on an example:

The Java programming platform represents a quite broad spectrum of concepts – for typical cases four of them form the key parts of the platform: (1) the Java runtime for execution of Java binary code (i.e. the Java Virtual Machine or JVM [91][93]), (2) the binary code to be executed in context of a JVM itself (i.e. the Java bytecode [91][93]), (3) the Java programming language [91][92] (i.e. textual notation of a typical programming language used to create programs for the Java platform – to be compiled to Java bytecode), (4) the Java standard library (i.e. predefined set of code artifacts distributed in binary form of Java bytecode). The Java programming language defines some constraints on the structure of the source code – one of them being a rule of exactly one package public type per a Java source file and any number of package private classes per a Java source file – a Java source file is a plain text file typically with a `.java` file extension. In a binary form the code is divided into separate class files (files with a `.class` file extension) – where each binary class, either public or private, resides in its own class file. An important note is that the Java programming language and the Java bytecode are two generally unrelated concepts on different levels of abstraction - i.e. Java source code can be compiled into other binary forms as well (e.g. to .NET's CIL intermediate code [89][63], or in a more typical case to Dalvik bytecode [56] of the Android [11] platform), and other then Java programming language source codes can be compiled into Java bytecode (in fact currently there are many newly emerging languages for the Java platform – common examples would be Scala [156][157] and Groovy [79] programming languages).

Though a JAR file (Java Archive [90]) is now in most cases a typical unit of deployment of binary Java code, for the JVM core a Java bytecode class is a most basic unit of code loading and thus of deployment too[1]. From JVM's point of view a JAR file is just an optional simplification of bytecode class file distribution. As JVM imposes the rules all Java bytecode classes have to adhere to, if we defined JVM as a component model (according to Heineman and Councill's definitions), then any Java bytecode class would be a component. However, there is something obviously wrong here as, common sense dictates that plain classes should not be equivalent to components as it would make explicit definition components redundant. As mentioned before, the problem lays in the Heineman and Councill's definition expecting an implicit understanding of a component model. A typical CBSE developer with a good knowledge of a CBSE domain would obviously did not define Java classes as components as he or she would expect some added value for the classes to become (a part of) components.

A clear conclusion that can be summarized from the previous paragraphs is that a commonly accepted opinion that a component definition clearly defines the CBSE can be unfortunately easily refuted. The presented and commonly referenced definitions of a component are (a) either too strict, so that software frameworks also commonly considered as component frameworks do not fit them, or (b) too general, so that many other concepts and frameworks fit the definition. Though the presented definitions of components are not the only one and in fact many tens of them exist all around in the literature (a nice summary of several other common ones can be found in [149]), they all inherently share the same problems mentioned. While any too generalized definitions are not useful to fulfill our goal of ultimately be able to define a CBSE domain where certain technological enhancements can be applied, having a too strict definition in fact can help to define exactly such a subdomain of CBSE.

In this sense the Szyperski's definition can be used to differentiate compatible component models that do fit the definition and the others. However the problem is that the definition is not perceived as defining a subset of CBSE instead of the whole CBSE (the definition's wording itself suggests it is aiming at defining component in general). Thus referencing the Szyperski's definition to define a CBSE subset only would be probably misleading as it would be often misunderstood as just a regular whole CBSE problem domain definition (as the many papers show, by mixing both a reference to this definition and referencing component models being in conflict with it).

2.1.3 Issues with Categorizing Component Models

Instead of a common all-encompassing component definition it looks more promising to try to find some common characteristics of component models. Each of these potentially identified characteristics would then form a separate definition of a component feature. Using these multiple component-wise definitions, component models can be classified into separate categories according to some rules defining compliance with these characteristic features. In fact this is not a novel idea and a

[1] When loading the individual Java bytecode classes the JVM behaves in a similar way as the CLR (.NET) does in context of its assembly components. Java class files does not have any explicit dependencies on other classes and any external dependencies are discovered only at runtime as the JVM lazily loads the classes required by the code (i.e. the external dependencies are implicitly stated in the code – similar as in COM or .NET assemblies [if considering the actual assembly contract, as mentioned before, the assembly exported types]).

few very thorough papers have already been published providing exactly such a component model classification, see [54][107]. If trying to use these papers as basis for defining a CBSE domain, where a certain additional feature can be implemented, one can very soon run into problems again. Let's illustrate it on a few examples presented below.

In [107] authors present JavaBeans as a component model where "*components are classes*", while COM component model is assigned into a category of component models where "*component are objects*" according to the methodology used in the paper. However as the JavaBeans are in facts just introducing missing features to the underlying programming language of Java, the execution model has to retain the same properties as the underlying Java platform has. Though in the proposed new version of JavaBeans the basic idea of a bean is more complex (allowing multiple classes to implement a single bean, etc.), the proposal is on the table for several years and it's not probable it will be ever brought to life. And in the current version of JavaBeans a bean (type, i.e. component type) is just an enhanced Java class, i.e. an entity that has to be explicitly instantiated at runtime to get an object instance. However exactly the same is true for COM components – if a COM component is implemented in C++ programming language then a component type is a C++ class (in fact, a component type is named a class in COM terminology and is identified by a unique class ID). Only at runtime such a class is instantiated into a component instance by explicit call to `CoCreateInstance` function or similar (accepting the unique class ID as an identifier of a component to create). There is obviously a glitch or misunderstanding somewhere if JavaBeans and COM are classified differently vis-à-vis a classes versus objects criterion in [107] – unfortunately the reasoning behind such a conflicting classification is not presented in the paper.

Similarly in [54] the JavaBeans are classified as having explicit distinction of provided and required interfaces. Thought the topic is in general discussed in the paper, this specific decision is not clarified there. While there can be many different views on specific component model features, we understand the JavaBeans dependencies differently. Services provides by a bean are defined by interfaces it implements (provided interfaces), and while a bean can be externally connected to another bean, should a bean require services of another bean the requirement would be present implicitly in the beans code. Thus only the provided interfaces are explicitly given, which is similar to the COM component model, and also behaves and has same implications as dependencies between ".NET components" (the problem of their missing requirements were discussed above).

Another challenging point of [54] paper is a claim that "*a component is executable*". While an exact definition of executable code is not given, the paper elaborates the statement with a footnote: "*Executable property does not necessarily mean binary code. For example the execution can be achieved through an interpreter or by a virtual machine, or even through compilation before the execution*". This clarifies the authors' understanding of executable code, but does not provide reader with exact definition. Even though the text implicitly permits looser interpretations of executable code and environment, from the choice of the component models we feel the authors tend to give precedence to a more typical algorithmic or imperative-wise concept of executable code. This might however contradict with some modern approaches to component-oriented software development where a more declarative way of behavioral description is often preferred. If the JavaBeans component model

is considered then other graphical component frameworks should be considered as well, so the reader can get a better understanding of the common CBSE related concepts – an example can the .NET platform with its WPF (Windows Presentation Foundation [132]) framework, where an application can be created from visual components just by declaratively instantiating and interconnecting them, while also providing data-driven behavioral dependencies between them. In extreme cases an application can be there created just by XAML-only assemblies (enhanced instance of a XML meta-format) without any regular executable code.

As both these papers cope with many component models and present many different views on them providing a detailed elaboration of many CBSE related aspects, the examples above might seem marginal inconsistencies without any serious impact. On the contrary an important observation they imply can be made: Even being an expert on CBSE and thus having an excellent understanding of component modeling concepts is sometimes not enough when coping with real-life component models having many target language, platform or domain specifics. And as it is hard to become an expert of a specific component model, when someone tries to reason about one while having a specific understanding of CBSE concepts, he or she tries to map any new or unusual component model's concepts to these previously known and understood ones, as well as abstract any very specific implementation details. The problem is such a generalization can then hide an important aspect of the new concept that can induce a thin, but impenetrable, barrier that stands between practical applicability and inapplicability of a new general component model feature idea. Unfortunately this leads to a pitfall of any summarizing paper that would try to categorize or classify component models into a reasonable number of generic easily understandable categories. As an inexperienced reader (i.e. non-expert in a specific domain – i.e. example of the reader targeted by a summarization paper) can easily draw false conclusions from it and imply some statements for a set of component models that are not true.

The problem is not inherently in the classification process itself, but it lays in too abstract or generalized categories. Should the categories be selected to closely match the actual component model and its components implementation aspects, it should mitigate the problem. While papers [54][107] have their own motivation on selection of the classification criteria and are as exhaustive as possible in their component model selection, we believe that to be able to provide a brief summary of component models considered with respect the their features related to their runtime environment (see Section 2.4), we need an alternative approach to component model classification (see Section 2.3).

Up to this point we aimed at fulfilling the first two goals of the thesis (as presented in Section 1.3) by analyzing the CBSE engineering domain, i.e. our initial believe was, we can first grasp the key CBSE concepts and with their good understanding apply them on commonly used component frameworks and to reason about them. This approach however does not seem to get us any closer to providing a solution to the proposed goals, as the CBSE concepts definitions leads to much confusion and as shown above it needs an interpreter to give it a correct meaning in context of each and every component model. As the real component-oriented technologies are in fact our main focus after all, the opposite direction to the component technologies analysis should be more feasible.

2.2 Conceptual Evolution of "Component"

With the wide range of definitions of component identified in Section 2.1 it is quite hard to grasp a component based software engineering (CBSE) as a single well defined technique. However if we look at the mentioned definitions from a further perspective a common goal begins to unveil. All the definitions at least implicitly try to define themselves vis-à-vis classes, a key concept of the object oriented programming (OOP), leading to CBSE positioning itself as an enhancement of OOP. If we try to order the definitions causally, it can be observed the older concepts are more and more considered a standard and are superseded by newer (from a specific point of view, more advanced) concepts. We believe this continuous shift of component paradigm emerges from the continuous evolution of OOP languages and their runtime environments, and an ongoing desire of the CBSE community to further improve developers' experience in developing of software applications. At least several stages of the CBSE evolution can be identified – they are structured according to the original motivations behind the component concept introduction to the software engineering:

2.2.1 Component = Class and Beyond

In the early days of Windows programming, there was a strong demand on bridging the gap between multiple OO programming languages like C++, Visual Basic or Delphi – all sharing a similar concept of class, but implemented differently in each of them. This led to the notion of components as classes enriched by concept of binary code compatibility as defined by the COM component model. The COM defined a required organization of classes in memory, i.e. most importantly the format of a virtual method table (VMT) and its localization based on knowledge of a class instance reference. Furthermore COM defines another now standard OOP concept not commonly present in programming languages of that time – a concept of an interface. And as with the classes themselves, a specification how interfaces should be implemented on binary level is provided (including support for implementation of multiple interfaces by a single class – which must have been make with languages without multiple inheritance [e.g. Pascal] in mind). There two concepts together with ability to portably specify metadata of a OO program or library (in form of so called Type Libraries or TypeLibs for short) allowed increased penetration of OO programming concepts into regular software development. In this view a component is simply a class that follows some constrains and is as such portable at binary level (all of this implemented only using concepts already supported by programming languages).

Such a specialized concept however became inherent part of OO environments with a wide spread use of Java and .NET languages, or more precisely with use of Java Virtual Machine (JVM) and Common Language Runtime (CLR) runtime environments having the binary code compatibility and code's metadata specification as the defining features of the platform. It is worth noting that during design of the .NET platform, aiming at supporting very diverse set of programming languages, it became obvious that a common subset of language features would be quite small (in fact similar to the set of concepts supported by JVM), which would lead to more complicated porting of some advanced languages and it would be hard to incorporate many state-of-the-art software design concepts. So in order to support both

contradicting goals (seamless code compatibility and support of variety of programming languages) the set of supported language features had to be divided into two categories – (a) features complying a so called Common Language Specification (CLS) required to be supported by all .NET languages (all public API in .NET world should be ideally CLS compliant) and (b) the rest, that can be optionally supported by .NET languages and that should be primarily used to implement private (non-public) code.

2.2.2 Component as a UI Building Block

As the arrival of Java environment rendered distinction components as units of binary compatibility unnecessary, components, as a term, became unbound to any specific concept. The Java programming language was devised as a clear and sound language with minimum of concepts - however, it was found quite early that some concepts are missing from the language, should it be employed in some specific types of applications – mainly development of applications with a graphical user interface (UI). In an UI development process, developers typically expect an integrated development environment (IDE) to be able to help them visually design graphical look of an UI application. This requires the IDE is able to gather information about settable properties of UI controls and ideally register developer's code as reactions to events responding to application's user actions. And these are the key concepts introduced by the JavaBeans component model and thus defining a component as a class with explicit properties and events (again implemented only using concepts of the underlying Java language). The current use of .NET environment however again made this explicit distinction of components unnecessary as the concepts of properties and events are the core features of the CLR and all the programming languages have to support them. Furthermore it is recommended that all the classes use these concepts (i.e. all of class's data should be exported via public properties and not public fields, listener design pattern should be implemented exclusively via events) as the standard .NET libraries do. Thus in this sense all .NET classes are components in JavaBeans' point of view.

On the other hand the .NET platform itself a concept of "components" – again related to development of application's UI and its design in IDE. .NET components, i.e. classes implementing `IComponent` interface have two main features: (a) explicit knowledge about their location in applications architecture – identified via a reference to an implementation of `ISite` interface – i.e. ability to perceive the context in which a component is used and to be able to behave or layout itself accordingly, (b) knowledge of mode of component instantiation (at runtime or at design time), i.e. whether a component instance should exhibit its standard behavior (at runtime) or it should behave more as a design editor for itself (at design time).

Even so the general goals of .NET components and JavaBeans are the same, just the underlying platform implied a different view on a UI component concept.

2.2.3 Component as a Unit of Deployment and Versioning

For at least two decades the world of Microsoft Windows had to live with a very serious problem arising from implementation of better software engineering concepts – more precisely software modularization. Developers quickly learned to take advantage of Windows dynamically linked libraries (DLLs) and almost every

Windows application sets off some of its functionality into separate libraries. One of the key advantages of DLLs perceived at that time was, that if multiple applications require a same functionality, its implementation can be share among these applications via a common DLL library. Applying this approach both saves the overall disk space occupied by all applications installed on the system (as the shared code does not have to be present multiple times) and any future updates of a library can be done centrally on one place for all the installed applications.

During the 90's (being the time of a large shift of users to Windows operating systems) as software was becoming less and less constrained by hardware limitations (with fast growing storage capacities available commercially to end-users) and with an emerging phenomenon of Internet, priorities for applying DLLs began to shift in benefit of ease of software updates. As data sharing was spreading and more and more computers were available on-line, computer viruses, Trojan horses and malware taking advantage of software bugs in general began to spread as well. Thus software had to become more dynamic, i.e. discovered bugs had to be corrected as fast as possible before they can be abused by remote computer attacks. At first glance the concept of shared libraries seem to be perfectly suited to such a scenario as if a bug is present in a library then all applications using that library are updated at once by a single update of it. Unfortunately this is a very idealistic view of software as the new versions of software often break backwards compatibility with any of its older versions. This problem is inherent to the update process in general and cannot be simply solved, which can be shown on a simple, yet unfortunately very typical example: if a bug is discovered by an application developer before its discovery by a library developer, the application has to come somehow with it; then if in a new version this bug is corrected, the original application often breaks as the library begins to behave differently (the bug was accepted as a feature by the application).

Furthermore with an increasing popularity of software platform, thus increasing amount of available applications for that platform, there is also an increasing number of misbehaving installation programs that simply always copy all the required libraries to the target system. If another application depending on a same library is already installed, such rude installation process can lead to overwriting of a global copy of the library with its older version – in most cases leading to breakage of the original application installed.

This problem of single globally shared copy of a library leading to the problems mentioned is in context of the Windows operating system typically referred to as the "DLL hell" problem [9]. Should the libraries in a system be shared, the obvious requirement to solve the DLL hell problem is to be able to transparently support parallel (or side-by-side) installation of multiple versions of a single library at the same time. The first solution to the problem was on the Windows platform again provided by means of COM components that explicitly support component and interface versioning.

It is quite surprising that authors of the Java language and Java Virtual Machine were not aware of this problem, and did not provide a solution for it as a standard part of the Java platform [86]. However a need for such feature in the Java world is as strong as it was before in the world of Windows application development. This led to several external solutions emerging in parallel to the basic Java platform. Currently the most spread one is the OSGi component model (as already mentioned in Chapter

1, OSGi is currently heading to be a part of the Java platform in future versions) – while OSGi defines several concepts, the most basic one is a concept of a bundle (an OSGi component), which is exactly a unit of versioning and deployment in OSGi. The OSGi platform also defines a sophisticated means of inter-bundle dependencies and ability to locate and load all required bundles and in correct order. On this basic level the OSGi serves a very similar purpose as assemblies on the .NET platform, that (though being an inherent part of the .NET platform) also provide a solution to the problem described in this section for the .NET platform, as OSGi does for the Java platform.

2.2.4 Component as a Service

More than a decade ago as enterprise systems grown larger and more complex and also became more interconnected to Internet solutions, a strong pressure on better software engineering approaches especially designed according to needs of enterprise systems became apparent. The systems' need to serve many purposes was leading to a need of better code structuring and ability to easily reuse existing code in new applications. Further as the systems became more globally available (also increasing their size) the requirements on the systems' implementation started to change in the enterprise domain, aiming to solve problems related to especially high availability and scalability of the systems.

This led to a new view on software components, where the important features were the ones that allowed large magnitude of connected clients to the component-based application, easily incorporation of external components (running on different computers on the Internet), ability to easily load balance the system providing the application services in cluster systems. Several component systems targeting such this domain were introduced, among the most commercially used ones is the EJB [65] component model in the Java world, and later introduced COM+ [48] component model for native Windows Server based enterprise application. These component models give the following features of components the main priority:

(1) Remote components: Ability to publish components and allow remote access to their provided interfaces. In general an ability to create distributed applications just by wiring inter-component bindings between multiple computers. While this feature was already present in component technologies before EJB and COM+ (thus it is not a defining feature per se), we have included it in this list as it is a key to meaningfully support the rest of the features.

(2) Stateless components: All the state is maintained by a client and all necessary information about the state is transmitted with every request to a component with allows high scalability by greatly reducing a component size, while providing ability to reuse components for multiple clients without problems of state synchronization.

(3) Queued components: Communication with components is not in a form of direct method calls, but is handled as messages transmitted via a message queue service and received by possibly multiple copies of a component. This decoupling of client components from server components (requires from provides) increases system scalability by giving clients a single point of

communication in from of a message queue and allows server to change number of servicing component according to actual system load, also allowing for easy dynamic update on server side without any need to reject client requests (which are automatically postponed in the message queue, should a target component be currently unavailable – e.g. undergoing an update process).

(4) Transactional components: Support for transactions on a component level means not only support for distributed transaction and components being automatically enrolled in active transaction along a sequence of calls between components, but also closely related to the previous point. If a message queue is transactional as well, it will allow automatic recovery in case of component failures (e.g. unexpected exceptions thrown from methods, etc.). Should a component fail, the original message it was processing is still stored in the message queue and another instance of the component can try later to reprocess it again.

(5) Persistent components: To support long running client sessions and reusing system resources components with inner state can be saved to a persistent storage (persisted) and unloaded from memory. This not only allows system to actively maintain in memory only state for currently communicating clients, but also allows for seamless system restarts for maintenance or component migration.

While both EJB and COM+ are commonly perceived as component models, from the list of the features we can see that currently they should be rather perceived as service frameworks – as the features described above are now considered a cornerstone of software services. The development of service-oriented applications is currently considered a specific software engineering domain – domain of Service Oriented Architectures (SOA) – that studies the problems typically originating from the key features of software services. However as shown above the SOA and CBSE are not two distinct approaches, but can be in fact seen as different points of view on a same problem. It implies that CBSE is not only black and white, but must be viewed very broadly, and even technologies that do not explicitly work with components can be evaluated in CBSE context and some CBSE techniques can be applicable to them as well – an example can be the Windows Communication Foundation framework introduced in .NET 3.0, which is a natural evolution of COM+ as a service-oriented framework for Windows platform – and in fact obsoletes COM+ (do not confuse it with pure/basic COM which is still an up-to-date component-based framework for native Windows applications): if COM+ is viewed as a component model the same should apply to WCF, even though WCF only describes and works with “services”.

Moreover even specific technologies can change and during their evolution process can gradually move between SOA and CBSE views on application engineering. The reason is that as the software platforms change in time, so can the motivations of a component model change to compensate. An example can be the EJB component model – where is an important change in many basic concepts with EJB version 3.0. The technological shift since the first version of EJB, let to gradual change of motivations and priorities of EJB designers, which finally led to a shift in the base EJB component concepts as well. While originally the EJB was a mixture of several

software engineering approaches, the specification since version 3.0 clearly accents the service-oriented features as described above.

2.2.5 Component as a Unit of Dependency Injection

As typical desktop applications have grown larger and larger it has become more obvious that traditional development techniques do not provide enough flexibility to allow coping with the growing complexity effectively. While technologies like OLE or ActiveX components brought the unseen possibilities at the time of their arrival, their primary goal was to allow a smooth composition of more complex applications from 3rd party components during the application development. These technologies were cornerstones of the first public component repositories or stores, were necessary components for application development could be purchased and downloaded from (as mentioned in [165]). This simplified typical desktop application development process as the ActiveX components were ready to use, it was possible to seamlessly compose them into the application being developed. While this was an important step forward the classical approach to composition remained in place, i.e. any respective ActiveX components an application is built from were very tightly coupled or glued together by the application's main code (it is the same approach as is used to compose a GUI oriented application from JavaBeans components). Important note here is that only the development process for applications designed in such way is greatly simplified – after the application is deployed, its configurability is very limited (while it is still composed from components at runtime, any component interdependencies are given at compile time and as such these applications can be viewed as monolithic at runtime).

The problem is that in recent years there is a new trend in desktop application domain to allow much greater customizability or extensibility by the end-users. It is often motivated by several reasons, two of them being: (a) to give the application producer option to provide end-users with much more variants of the application software, i.e. to have more diversified feature and pricing scenarios, or even to allow end-users to a basic version of an application and only to later buy more functionality if required, (b) to attract more potential users to producer's application by developing it not as a closed application with predefined feature set, but to provide at least a semi-open application platform that can be further extended by extensions developed by forming application's community. Obviously it is hard to achieve this goal using only traditional OO programming techniques, even when enhanced by abilities of component frameworks with components defined at level similar to ActiveX or JavaBeans (as the component dependencies are hardcoded into application's code which implies difficulty of any updates at runtime whenever a new feature set is required from the application). To provide a solution to the goal a new view on software component had to be taken – the two basic requirement on the solution were: (a) application's components have to explicitly state any requirements on any functionality that has to be provided by their environment (the application itself or possibly any other components loaded side-by-side), (b) the requirements should not be hardcoded into application's or component's code, and the application has to have an ability to enforce fulfillment of the requirement to its components (so-called dependency injection).

As the idea of a component as presented above is in harmony with the common component definition of Szyperki's books [167][165] (as presented in Section 2.1), it

is not such a surprise that one of the first widely used component models following this paradigm is the MEF component model (developed by a group at Microsoft Research lead by Clemens Szyperski). As we already know from Chapter 1 a component is called a part in the MEF. The Visual Studio 2010 integrated development environment (IDE) is a nice case-study of this approach – the MEF model has been adopted there as the new mechanism to provide a versatile extensibility mechanism of the IDE and allowed to transform the Visual Studio into a software platform with wide community (as the one mentioned in previous paragraph).

2.2.6 Nested Components Not by Accident

The concept of software component has probably originated from term component in the domain of electrical or hardware engineering. While the general idea of having reusable well-defined parts that software can be built from as a machine or hardware design as engineered and build holds an interesting parallel with hardware design has not been mentioned in previous motivations. In electrical design an engineer does not have to design a system solely based on basic electrical elements as resistors, diodes, transistors, etc., but in complex designs a more higher level components can be used, e.g. and, or gates or even buses or adder units on even higher levels of abstraction. While for example for an adder unit its design can be explored and one can learn that it is actually built using logical gates, which in turn can be explored further again to learn, they are built using transistors, etc., when someone is designing a processor (a component on a very high level of abstraction), he or she would not be interested in these "implementation" details of an adder unit (or component), but would need to know just the number or input and output lines (how many bits can it add), plus a few basic working parameters (like operational voltage, etc.). Thus, the adder unit will be viewed just as a black box with some define interface, even though that one can trace back its actual design down to the basic elements. And it is important if an added does comply do its specification (adheres to a specified interface), its actual implementation (i.e. for example which model or type of a transistor is used inside of it) is not important. The same would be true for logical gates on a lower level of abstraction, should one have a task of designing an adder unit instead of a processor.

This approach has been also applied to domain software components – i.e. explicitly allowing two views on components: (1) as a black box with well-defined interfaces (importance of which is discussed in [30]), but without externally known implementation, (2) an actual implementation of such a component, i.e. giving the internals some structure, possibly creating a (*composite*) component from other components recursively down to some basic blocks (*primitive components*). While previously components could be also logically nested, the change lays in an explicit knowledge of the nesting by a component model. So, should an analysis of the internal structure of the components be required, it can be achieved.

While there are many component models taking advantage of explicit hierarchical architecture of a component application like the Palladio Component Model [23], in this thesis we focus on component models with a runtime environment support. For us the main representatives will be hierarchical component models Fractal [27][3] and SOFA 2 [40], that both support the concept of explicitly nested components both at design time and at runtime.

As it will be explained later in Section 2.6 the main focus of the thesis since Chapter 3 is exclusively on hierarchical component models. However we do not analyze motivations for hierarchical component models in detail in this section, as more details on hierarchical component nesting is given in Section 2.3, G and a whole Section 3.1 is dedicated to analyze and describe motivations and advantages of hierarchical component models, as well as discussion about design time vs. runtime support for explicit component nesting.

2.2.7 The Summary

The summary of CBSE concepts presented above tried to put motivation behind implementation of these concepts into various component models in both temporal and domain-wise contexts. It should be clear that not only the different approaches to CBSE (thus an actual concept behind a "component") are semantically very distant from each other, but the component concepts in different component oriented technologies are in fact very orthogonal and cannot be simply compared together. Each and every one is simply trying to introduce solution of some domain-inherent problems to separate domains of software engineering. Nowadays it is in fact very typical that a single application would utilize multiple orthogonal component concepts – e.g. a typical web-based application (i.e. and application with front-end running at client side inside a web browser, for example as a Silverlight application, and with back-end running at a web server): (a) can be implemented in a .NET programming language – taking advantage of .NET assemblies as units (components) of versioning, packaging and deployment, (b) should it be an information system, its server-side part can be implemented also using MEF components, to take advantage of a runtime composability and ability to easily extend the system with new modules, and finally (c) the application distribution itself can be achieved by utilizing the WCF framework to expose the server-side API as a set of web-accessible components – services.

As the CBSE is so diverse world of technologies and concepts, as shown above it is not possible to try to find a single all-encompassing definition of a component, what would suffice in all situations. The CBSE should be rather perceived a unifying view of how to enhance the current software engineering approaches. The common point where CBSE approaches agree is a notion of a component as a unit of some more or less defined properties giving it some advantages over code from a same domain without these properties defined. The basic unit of abstraction, many of CBSE oriented approaches begin with, is just a class. Thus a specific CBSE approach, when applied to a concrete programming or design or modeling environment/platform, introduces new advantages the platform previously lacked. A class being a concept to start with, concrete CBSE goals are typically achieved either by enhancing the class concept with more concepts than originally present in the platform considered (e.g. JavaBeans introducing properties and events), or vice versa by constraining it (e.g. COM allowing only specially crafted classes of a programming language to be exposed as components). A simplest definition of CBSE then would be:

> *The CBSE (component-based software engineering) is an infinite quest to define a better OOP (object-oriented programming).*

If in section 2.1 we mentioned several component concept definitions and showed why they are not ideal for our cause, there is in fact one existing component

definition that with respect to the previous text and component model goals analysis nicely fits our vision of software components – it is a definition by Michael Feathers presented in [149]: "*A component is an object in a tuxedo. That is, a piece of software that is dressed to go out and interact with the world.*" Though we did not find any references to it in scientific papers, it seems the definition is beginning to spread and many found it as compelling as us (as also its incorporation into e.g. University of Wisconsin [170] or University of Pennsylvania [169] curriculums shows, it provides a clear and gentle introduction to the most fundamental term of CBSE by capturing the essence of general component understanding and bringing it closer to CBSE non-experts).

To summarize the Section 2.1 and Section 2.2, our primary message from the text presented should be clear: it is all about the added value, i.e. it is not that important what a component is, but what it provides. So in order for the state-of-the-art in the CBSE domain to be pushed further, it is important for the research not to just come with new fancy component-oriented features, but in the first place to come with new goals the CBSE can help to solve. As shown in this section the CBSE is in fact defined right by these goals established by various component technologies.

2.3 A Guide to Component Models Overview

In the previous Section 2.2, we presented an overview of gradual evolution of CBSE related concepts in respective component models throughout the recent history with focus on their motivation and goals. In the next Section 2.4 we will give an overview of several common component models. This section provides a bridge from the less structured ideas presented in Section 2.2 and the component models overview presented in Section 2.4. We will first defend the choice of component models in Section 2.4 and later we will provide a guide on what information can be found in Section 2.4 for each component model considered, and how the component models are categorized and their features structured.

As there currently exist tens of different component models [54][107] and with respect to our statement for need of a quite deep understanding of a component model for its analysis, we decided to choose the component models according to the following criteria:

1. As already stated in the introduction to the thesis, only component models with a runtime are considered.

2. Selected component models must be used by a large developer community, in order to be representative of a current general understanding of CBSE concepts (mainly by the regular software developers and not only by CBSE researchers – in fact we have especially focused on models typically not very well understood in the CBSE research community).

3. There are many target domains of component models, and other papers do analyze some of the specialized ones (e.g. realtime and embedded systems [88]). We narrowed our search on component models from domains of development of desktop and/or enterprise applications.

4. From the component models by 1 to 3 we further choose the ones we have a lot of experience with and where we are confident to provide a well-grounded analysis.

5. We also added two research component models (Fractal, SOFA) that are extending the concepts of models selected according to 1 to 4, and which we believe to be a promising step forward in the CBSE research.

Though in Section 2.1.3 several issues with categorization of component models were presented, we will present the selected component models with respect to several attributes. However these attributes were not selected to give a set of general high level concepts that would help developers to select a correct component model by assessment of these attributes, nor to give understanding of general CBSE concepts. The attributes were rather selected according to our experience to point out the key specific features of each component model and their selection should quite easily imply from the text of previous Section 2.1 and Section 2.2, where was the experience presented. All of the component models are described elsewhere in more detail (some of them are presented in [69] technical report, which provides a very important annex to the [54] paper – each of the models presented in the technical report is described in a well-arranged and readable summary spanning just a few pages), but what we are missing is a detailed comparison of the component models not based on generic categories. The attributes are thus selected to provide the key characteristics of the component models where a set of models stands apart from the others. An important note is that although the selected attributes can be applied to a wide variety of component models (quite further beyond the restrictions 1 to 5 presented above; and even to some component models without runtime component representation), their actual values are very specific to each of the component models (or at least to a set of similar component models). Thus a domain of attribute values for a larger set of selected component models would be superset of the attribute values presented here. And as the values tightly correspond to the actual features of each component model (the correct knowledge of which in turn requires deep understanding of the specific model), it was not our goal to provide a universal and definite set of possible attribute values. Instead we present only the values that exhibit themselves in an attribute of at least one of the selected component models. List of the attributes considered follows:

A. Role of component

B. Underlying platform

C. Definition of component concept

D. Unit of code deployment

E. Support for explicit provisions

F. Support for explicit requirements

G. Runtime's knowledge of component nesting

2.3.1 A: Role of Component

The Section 2.2 concluded with a key observation – motivation and goals of component model are the key aspects by which was the component model's design driven. All other features, aspects and many conceptual and implementation details are only more or less implied by establishment of the basic aspects. Thus the first and most important attribute of a component model we have defined is a role of component in the model – i.e. if we take a software platform without applying the specific component model, what are the weaknesses of the platform, and where does the component model enhance the platform with some previously unsupported features. The features themselves are either directly the components of the model or the components serve as a tool to achieve the component model's goals.

We consider the role of component as the only truly differentiating characteristics of a component model, which is an exception to our rather negative opinion on component model classification. We believe the role of component is a defining aspect of a component model and as such developers not only can, but must use it to identify the right platform for implementation of an application they are working on. Though we will present six distinct types of component roles, these are only the roles identified by analysis of the selected component model (so there definitely exist other roles of a component should one consider a broader domain of component models). Furthermore while the role of component uniquely characterizes a component model, it does not mean that a single component model has to provide only a single role for its component concepts. This situation can manifest itself in two ways: (a) component model has a single component concept that serves multiple roles or (b) component model has multiple component concepts, each of them implementing only a single role (or a subset of roles in general). In the second case the component model M often in fact comprised of two district component models that are both covered by the single encompassing model M. While technically the two sub-models should be utilizable separately, they often interconnected conceptually or in some specific implementation detail. Moreover they often build one on the other, thus one of them can be used separately, but the second one requires usage of the first one. If it makes sense in the specific case, we described both sub-models separately in Section 2.4, each having its own set of attributes assigned (i.e. also each having its own role of a component).

With the motivation for distinction of component roles as described above, the actual roles identified match the motivations for component model development as they were presented in Section 2.2 (the roles are also presented in the same order as were the motivations presented). As the motivations behind the actual roles were already quite extensively described, only a list of the roles follows:

1. Binary compatibility and metadata
2. UI building blocks
3. Support for versioning and deployment
4. Services
5. Dependency injection

6. Units of architectural nesting and composition

2.3.2 B: Underlying Platform

As we consider only component models with runtime in this thesis, it is natural the supported platform or platforms are another distinctive attribute of a component model. While some of the component models can be designed with platform independence in mind, most of them are tightly coupled to the underlying platform. While this can limit usability of a component model, as the models are typically meant to enhance an existing platform, the tight coupling is not only understandable, but often necessary so the model can achieve its goals. As the features provided by the model are in many cases platform specific, looser coupling to the platform of usually undesirable, if not even impossible (one of a common problem would be possible lack of optimality of the implementation, should the component model's concepts be designed platform independently).

An important note is that we consider the whole software and hardware stack of required features to be the underlying platform of a component model. And if model is tightly coupled to at least part of its required platform, it cannot be considered as platform independent (as porting it to another platform would require incompatible changes to some of its founding concepts). An example can be the OSGi model classified in [107] as platform independent, because to paraphrase [107]: "*it is implemented in Java, which is platform independent, thus it is platform independent*". However the tight coupling of OSGi concepts to the Java platform makes it highly platform dependent, as implementing OSGi e.g. for the .NET platform would not be a straightforward task, and some of its concepts could be even in conflict with similar concepts of .NET.

2.3.3 C: Definition of Component Concept

Component defining attribute provides for each component model our view on what artifact is a component in that specific model. The component will be described in terminology of the component model considered, we will also provide the names under which are components used in the model. While for some component models distinction between component type and component instance is natural and does not require any detailed explanation, for some of them (e.g. the COM model), where the terminology is different and the distinction is not very clear, we will provide a separate definition of component type and component instance concepts.

2.3.4 D: Unit of Code Deployment

Although it is often assumed as a key property of a component, granularity of a component often does not correlate to granularity of units of code deployments in a respective component model. In fact many component models (e.g. COM) do not provide its own solution to the problem of code deployment, but reuse some other (pre-existing) technique available on the target platform of a component model.

2.3.5 E: Support for Explicit Provisions

May component be defined in many different ways, it always is defined to provide some features or functionality to its surrounding environment. All the component

technologies presented build on concepts of OOP, are mostly some sort of object encapsulation and a basic nature of every object is provision of its features available to the environment. Thus in most of the component models a component is always accompanied with a variant of provided functionality descriptions (component provisions by short – in a common case this functionality is exposed by implementing a set of interfaces by the component or its underlying class, i.e. provided interfaces). On the other hand some component models do not directly define components as classes (mostly the ones from with the "Support for versioning and deployment" component role) – e.g. .NET assemblies – leading to not such an automatic and clear definition of component provisions. However even in component models with components reflecting classes of the underlying platform, the requirement on explicitly supplying the component's provided functionality is not always as automatic as the previous text suggests. An example can be a COM component without a provided optional type library does not have any information associated with the component type identification. Such a COM component does not explicitly promise any functionality, thus the COM component model runtime cannot take advantage of any such information to locate a suitable component for a client requiring a specific functionality. Any functionality provided by a component can be identified only at runtime by dynamic query by the client code.

An explicit support for provisions defined as part of a component type is a key attribute of a component model as is if this feature is missing; it changes the programming model in a significant way. It may also imply further problems especially related to any enhancement of such a component model (e.g. components and their possible relations cannot be analyzed without executing or at least interpreting component's code).

2.3.6 F: Support for Explicit Requirements

While most component models implement mandatory publishing of component provisions, the situation is more complicated on the other side, the side of publishing explicit component requirements (i.e. features or other or their functionality components required by a component from its environment; in a component model with provided interfaces specified on components this requirement typically transforms into a need for components to somehow specify a set of required interfaces – this means, the component expects the component model will provide a suitable implementation of such interface, usually in form of another component instance). As discussed in Section 2.1.1 whereas the Szyperski's definition of a component dictates that explicitly specified requirements is a must for a component model, we show that for many component models that is not true.

Although not that commonly supported the support for explicit requirements is very important attribute from a software engineering point of view, and as such it is also a key distinguishing feature of component models – which implies its inclusion in our set of component model's characteristic attributes. Without knowledge of component requirements the component model has to rely on the component's code to ask for any required features at runtime, and to correctly acquire and release any such resources dynamically provided by the component model. This leads to at least two problems:

(1) It is not possible (or at least it is very hard, as code analysis is required) to verify correctness of component composition beforehand, i.e. during design time. Especially for large and evolving applications this could pose a serious problem, as any inconsistencies in the component composition, or their interdependencies would lead to runtime exceptions. Thus having explicitly specified requirements can be of a similar advantage as statically typed programming languages have over dynamically typed ones. While using a dynamically typed language typically lowers immediate cost on software developments (as the software can be developed more easily and faster and less skilled developers are often required), in a long run cost of maintaining such applications increases dramatically as extensive testing is required often even for small localized changes to the code base. Similarly the explicit specification of component dependencies (requirements) can enable introduction of a verification system, what would verify the software's correctness before its deployment.

(2) The component model does not have full information about application's runtime architecture (its information is separated into islands of knowledge, which are interconnected in reality due to the references components hold internally and that they interchange without component model's supervision). While knowledge of the runtime architecture is not required for successful implementation and deployment of a component-based application, having this information can give the component model a great advantage that would in turn enable implementation of quite complex features otherwise unreachable. Example can be various means of application reconfiguration after it has been compiled – ranging from dependency injection allowing declarative way of component composition depending of specific end-used needs to a more dynamic component lifetime management allowing exchange of running component for their new versions without restarting the application, etc.

With the explicit requirements knowledge any of the possibilities drafted above would be hardly achievable. On the other hand it is important to note, that missing support for explicit requirement does not limit component models in general. It again depends on the intended role of a component in the component model, as in many scenarios a simpler component model very tightly coupled with the underlying platform and very narrowly implementing a set of required features is sufficient and in fact can be more beneficial that a more complex model.

2.3.7 G: Runtime's Knowledge of Component Nesting

This last attribute is in a sense an extension of the previous explicit requirements attribute (Section 2.3.6). Motivations for runtime's explicit knowledge of component nesting are similar as the ones presented as the (2) problem for missing explicit component requirements in previous Section 2.3.6 – i.e. it is about runtime's knowledge of application's runtime architecture, that is detailed enough to enable some even more complex features.

Especially in larger applications it is a must to structure the application into separate modules providing a specific functionality to rest of the application. In a plain OO application each of these modules would provide some public classes and interfaces

available for use by rest of the application (i.e. other modules of the application, or module's environment), plus it would also contain some private code (private classes and interfaces), that is used solely to internally implement the public API of the module. While sometimes it is beneficial to separate these modules into distinct units of code distribution (Java's JARs or .NET assemblies), often such separation is done only logically by structuring the source codes accordingly. In a typical scenario these two approaches are combined as the modules are often further structured into smaller units of functionality – this exhibits itself as a typical tree hierarchy of source files in nested file system directories (some OO environments, for example Java, even enforce such source code structuring, in case of Java it is source code structuring according to package hierarchy; While the Java type of hierarchy enforcement seem to be a good idea, in larger project it turns out, it is not the best approach – as the package structuring, i.e. structuring of the public API, might not be equivalent to the internal structuring of the application. By forcing the source code structure to be equivalent to package structure, the application is either required to reveal its internals to the outside world – by introducing new sub-packages induced not by API structure, but by its implementation – or mixing different application's modules into a same source code directory, thus abandoning the foreseen application structuring).

The component-based design often allows admitting such code structuring more explicitly. The typical approach is that a component is viewed as a black box, i.e. only the provisions and/or requirements are visible to the component model. Anything inside code, artifacts or features of a component is supposed to be its internals and the component model runtime does not have any knowledge about it. An application composed of many components will be probably logically structured in a similar way a plain OO application would be (as described above). This means that there will be some private components (implementing just some internal functionality, that should not be made separately available, thus is not part of application's public API), and some public components providing the public API implementation via their exposed provided interfaces.

Figure 1 shows example of such an application composed of two components: component A exposing the application's API via its public interface; A's code however does not implement the whole functionality, but it delegates part of its implementation to another component B. The component B is intended to be private, i.e. not exposed from the application (should it be implemented using MEF in .NET, A would be assembly public class, while B would be assembly internal class).

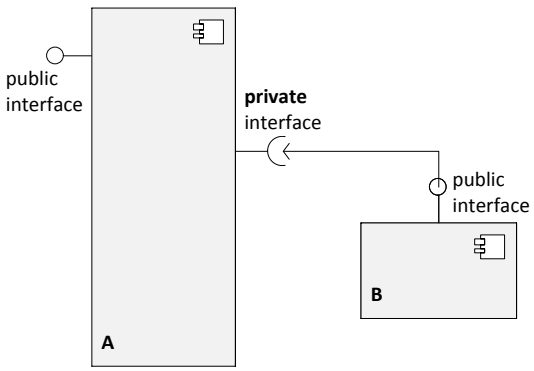

Figure 1. Sample component application composed of public component A and private component B.

If a component model used to implement the application does not have knowledge of the hierarchical code (component) nesting, the application would have to be implemented exactly as shown on Figure 1. However this approach hides the originally intended applications structure, where the B component is in fact logically nested inside A component as illustrates Figure 2. In the MEF component model one can emulate similar architecture by defining the field to reference the B component as private (as is denoted on Figure 1 and Figure 2). However even in MEF both components A and B would be physically on the same level of nesting as far as MEF's runtime is concerned, i.e. as shown on Figure 1.

Under the "Runtime's Knowledge of Component Nesting" attribute of a component model we would like to capture a unique characteristic of some component models, which explicitly support more structured component applications. These component models usually define two types of components: (a) primitive components – they are similar to the file in a structured application's source code file system (i.e. they contain the applications code), and (b) composite components – they are often defined similarly as directories, i.e. their basic mission is to provide structuring of the application, however they do not have do contain any code (an in some component models this is a typical case).

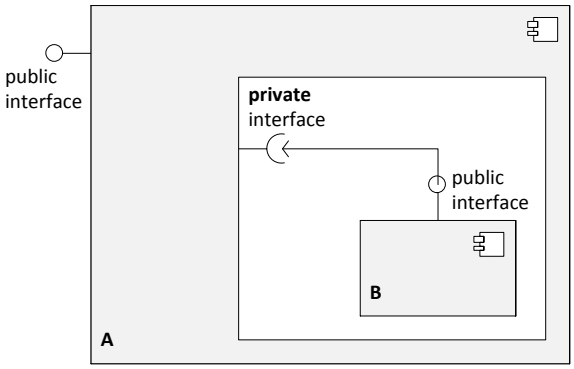

Figure 2. Logical nesting of A and B components in MEF.

SOFA is an example of such component model (as will be described in next section). An application similar to the one presented on Figure 1 and Figure 2 would be implemented in SOFA using two primitive components A and B (that would contain roughly the same code as in the previous scenarios), but the new artifact would be declaratively defined composite component C (without any actual implementation), that wraps both component A and B and delegates A's public API as its own. Thus the new application's public API is not defined by component A, but by the public interface of component C. The architecture is shown on Figure 3.

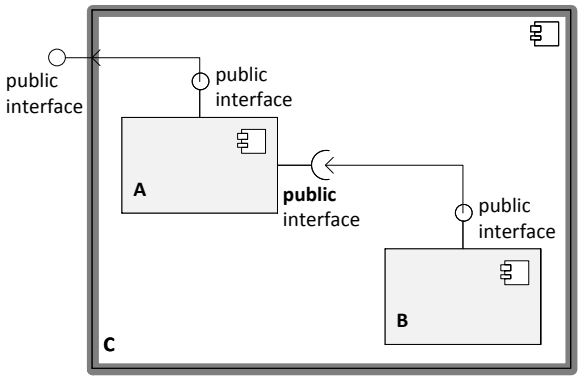

Figure 3. Hierarchical component architecture in SOFA

Another characteristic of component models with support for component nesting, they have more control of the inter-component dependencies. The ideal scenario is if a component model's runtime has (almost) exclusive control of component dependencies, i.e. a component communicates with its environment only via its explicitly specified provisions and requirements (no communication with the environment is hidden inside component's implementation).

2.4 Component models overview

With respect to the criteria described in the Section 2.3 we have selected several typical industry-supported component models (+ Fractal and SOFA 2 models). While we have analyzed the model in detail it turned out that preparation of a detailed description of each of the 15 component models in each of the proposed attributes is out of a scope of this thesis – we are preparing this description as our future work, and here we present only a short except of our key observation summarized into a following table (frameworks commonly referred to as "component models" are marked with a star [*], rest are frameworks with identified CBSE features):

COM (Component Object Model) [49] *	
A - Role	1 (*Binary compatibility and metadata*)
B - Platform	Core programming language (OO optional, COM runtime not required in principle)
C - Component	• Component type = CLSID (GUID) = COM class = e.g. C++ class (but supports non-OO languages) [= class factory instance] • Component instance = object = e.g. C++ class instance or instances of multiple C++ classes (in case of aggregation)
D - Unit of deployment	PE binary file (multiple components per file)
E - Explicit Provisions	Partially (only with optional Type Library)
F - Expl. Requirements	No (component instantiated and bound in code)
G - Runtime nesting	No (allows aggregation and delegation patterns - but only component internals, structure always hidden from dependent components/runtime)

JavaBeans (required subset - properties, event listeners, constructor**)** [94] *		
	A – Role	1 (*Binary compatibility and metadata*) - standard for enhancement of platform by advanced OO constructs
	B – Platform	Java language
	C – Component	Bean = Java class
	D - Unit of deployment	Java class file
	E - Explicit Provisions	Yes (via Java reflection)
	F - Expl. Requirements	No (event source is a provided interface of a bean, event listener must be instantiated and bound in code)
	G - Runtime nesting	No
WinRT [176][59]		
	A – Role	1 (*Binary compatibility and metadata*) - standard for enhancement of platform by advanced OO constructs
	B – Platform	COM
	C – Component	COM component with WinMD metadata + convention for advanced OO features (properties, generics, etc.)
	D - Unit of deployment	PE binary file (multiple components per file)
	E - Explicit Provisions	Yes (via WinMD metadata)
	F - Expl. Requirements	No (component instantiated and bound in code)
	G - Runtime nesting	No
JavaBeans (optional subset - BeanInfo, DesignMode, prototypes, property editors, etc.**)** [94] *		
	A - Role	2 (*UI building blocks*)
	B - Platform	JavaBeans (required part of the specification)
	C - Component	Core JavaBeans bean + additional features (persistence, control hosting, design support, etc.)
	D - Unit of deployment	JAR file (containing the bean itself, serialized prototype instances, property editors, etc.)
	E - Explicit Provisions	Yes (via BeanInfo)
	F - Expl. Requirements	No
	G - Runtime nesting	No

.NET components [128]		
	A – Role	2 (*UI building blocks*)
	B – Platform	.NET platform (CLR)
	C - Component	• .NET class implementing IComponent interface • IComponent provides only support for hosting the class instance (reference to ISite interface) + information about design mode
	D - Unit of deployment	.NET assembly (multiple components per assembly)
	E - Explicit Provisions	Yes (via .NET reflection)
	F - Expl. Requirements	No (component instantiated and bound in code)
	G - Runtime nesting	No
ActiveX [129]		
	A – Role	2 (*UI building blocks*)
	B – Platform	COM
	C - Component	ActiveX control = COM component implementing recommended interfaces (persistence, late dispatch, control hosting, design support, etc.)
	D - Unit of deployment	COM component (usually single component per PE binary file with `.ocx` extension)
	E - Explicit Provisions	Partially (optional Type Library or IProvideClassInfo interface)
	F - Expl. Requirements	No (component instantiated and bound in code)
	G - Runtime nesting	No
.NET assemblies [63][89] *		
	A – Role	3 (*Support for versioning and deployment*)
	B – Platform	.NET's CLR execution engine (EE)
	C – Component	.NET assembly (main PE binary file + manifest + optional additional files) = strong name
	D - Unit of deployment	.NET assembly (usually single PE binary file, but multifile assemblies are also possible)
	E - Explicit Provisions	Yes (via .NET reflection)
	F - Expl. Requirements	Partialy (only assembly without contract)
	G - Runtime nesting	No
OSGi (Open Services Gateway initiative) [139] *		
	A – Role	3 (*Support for versioning and deployment*)
	B - Platform	Java plaform (JVM)
	C - Component	Bundle = JAR file + metadata (manifest)
	D - Unit of deployment	Bundle
	E - Explicit Provisions	Yes
	F - Expl. Requirements	Partially (only bundle without contract)
	G - Runtime nesting	No

EJB (Enterprise JavaBeans) 3.1 [65] *		
	A - Role	4 (*Services*) + 5 (*Dependency injection*)
	B - Platform	Java platform (JVM)
	C - Component	Bean = Java class
	D - Unit of deployment	EAR file = JAR file + metadata
	E - Explicit Provisions	Yes
	F - Expl. Requirements	Partially (component instantiated and bound in code + option for simple dependency injection)
	G - Runtime nesting	Partially (similar to MEF as described in Section 2.3.7)
COM+ [48] *		
	A - Role	4 (*Services*)
	B - Platform	COM
	C - Component	COM component + additional features (application & services configuration)
	D - Unit of deployment	PE binary file (multiple components per file)
	E - Explicit Provisions	Yes (Type Library is required)
	F - Expl. Requirements	No
	G - Runtime nesting	No
WCF (Windows Communication Foundation) [117]		
	A - Role	4 (*Services*)
	B - Platform	.NET platform (CLR)
	C - Component	WCF service = .NET class
	D - Unit of deployment	.NET assembly (multiple components per assembly)
	E - Explicit Provisions	Yes
	F - Expl. Requirements	No
	G - Runtime nesting	No
MEF (Managed Extensibility Framework) [112] *		
	A - Role	5 (*Dependency injection*)
	B - Platform	.NET platform (CLR)
	C - Component	Part = .NET class
	D - Unit of deployment	.NET assembly (multiple components per assembly)
	E - Explicit Provisions	Yes
	F - Expl. Requirements	Yes
	G - Runtime nesting	Partially (see Section 2.3.7)

Spring [163][164]		
	A – Role	5 (*Dependency injection*) + 4 (*Services*)
	B – Platform	Java (JVM) or .NET (CLR) platforms
	C - Component	Bean = Java class/.NET class
	D - Unit of deployment	Java class file/.NET assembly (multiple components per assembly)
	E - Explicit Provisions	Yes
	F - Expl. Requirements	Yes
	G - Runtime nesting	No
Fractal [35][27][3] *		
	A – Role	6 (*Unit of architectural nesting and composition*) + 5 (*Dependency injection*)
	B – Platform	Java platform (JVM)
	C - Component	• Primitive component = Java class, • Composite component = architectural unit (Fractal runtime entity)
	D - Unit of deployment	Component
	E - Explicit Provisions	Yes
	F - Expl. Requirements	Yes
	G - Runtime nesting	Yes
SOFA 2 [40] *		
	A – Role	6 (*Unit of architectural nesting and composition*) + 5 (*Dependency injection*)
	B – Platform	Java platform (JVM) - (or similar OO language platform)
	C - Component	• Primitive component = Java class, • Composite component = architectural unit (SOFA runtime entity)
	D - Unit of deployment	Component
	E - Explicit Provisions	Yes
	F - Expl. Requirements	Yes
	G - Runtime nesting	Yes

2.5 Lessons Learnt from Analyzing the Selected Component Models

Ability to combine multiple component models is not limited to having disjoint set of attributes of the participating component models – easiest way to see it is on the support for explicit provisions attribute: as most of the model support this feature, combining two of them will lead to "conflicting" set of provisions. However if look at the problem from a wider perspective (not restricting our view on the single attribute only), we will discover no conflict occurs in reality – if both component

models assume a different role of a component, thus themselves being on different levels of abstraction, each of them will define its own component provisions for each respective level of abstraction. The combination of "conflicting" attributes is then similarly possible as is the combination of two different component models.

Furthermore two component models can be combinable even if they both define a same or similar role of a component. Compatibility of such models then depends on deeper analysis of respective features and their implementation of the two models. An example is the WinRT component model that falls into a same category according to the role of a component attribute as the COM component model. However as the WinRT is designed to enhance the COM features and uses the COM component model as part of its underlying platform, the two models are not only combinable, but the WinRT component model cannot be used without COM.

Related to services interpretation there was a very interesting discussion among participants of FESCA 2007 [70] workshop. Ralf Reussner initiated a quite deep and long dispute on what is a relationship between components and services. The final result the community came up with was a statement that: "*Services are defined on a different level of abstraction than components. A service can be implemented using one of the component technologies. And if so, a service is than equivalent to a deployed component (instance)*". While this seems to define services and components as two very distinct concepts, the statement is in fact coherent with our view on services and the conclusions presented. If we look at services as specific type of components, then according to our conclusion, one can choose another component model not in conflict with the "service" component model and create an application utilizing both of them. The "service" components will then provide the "service" features for the application, while the underlying components provide some other lower level features (e.g. dependency injection). The components from the lower component model will then be the "deployed components" from the FESCA statement. These components will then in turn use some features of the upper "service" component model that will allow them exhibit service oriented aspects. Example of such connection can be development of an enterprise application taking benefits of both EJB and Spring technologies – the EJB being the upper "service" component model, and the Spring being the lower component model serving as a dependency injection container – i.e. an example EJB bean (EJB components) could be composed of several Spring beans (Spring components) via dependency injection.

2.6 Problem Statement Revisited

Although there are many hierarchical component models (we presented the Fractal and SOFA representatives), to the best of our knowledge none of them is used in regular software development by a wide community of developers nor is acknowledged by the industry. At the first glance this situation seems puzzling as the hierarchical component models are of the farthest CBSE modeling approaches currently existing. Thus if we take a premise that CBSE should bring advantages over the classical OO programming techniques and common monolithic software design principles, the hierarchical component models should bring most advantages to the CBSE field.

For example, when trying to understand the advantages of the Fractal component model, one would typically look at the project's web site first – to cite from two available project overviews at Fractal's project page [72]:

> *Fractal is a modular and extensible component model that can be used with various programming languages to design, implement, deploy and reconfigure various systems and applications, from operating systems to middleware platforms and to graphical user interfaces.*

and

> *The Fractal component model heavily uses the separation of concerns design principle. The idea of this principle is to separate into distinct pieces of code or runtime entities the various concerns or aspects of an application: implementing the service provided by the application, but also making the application configurable, secure, available, etc. In particular, the Fractal component model uses three specific cases of the separation of concerns principle: namely separation of interface and implementation, component oriented programming, and inversion of control.*

The description is clearly feature oriented, i.e. it is trying to sell the most interesting and important features of the Fractal component model. There are also many Fractal or its Julia implementation related papers. Among them the original defining one [36] presents a thorough list of requirement on a component model as viewed by the authors. However the text is more oriented to again give a good understanding of Fractal component model features and to analyze their relationship to other existing component models and their features. The other key papers describing the implementability of Fractal in Java programming language [34][35] are then purely oriented to give readers introduction into the advanced concepts implemented. The most recent paper summarizing up-to-date state of the Fractal ecosystem [27] provides a nice overview of Fractal, but is written mostly with respect to the interesting feature set. While there are papers trying to put Fractal into a real life context (e.g. an extension of Fractal to allow seamless implementation of grid oriented applications [22]), papers describing the background goals the authors had in mind when designing Fractal are missing.

The SOFA 2 component model as complex as it is, has a similar problem as the overview on its web site or contents of summary papers are also oriented towards the features SOFA provides.

As many of the features of both Fractal and SOFA component model are quite complex and unorthodox (one of them is even the simple notion of component nesting into hierarchical architectures), the general lack of clear statements about component model goals and clear visions of how and where the provided features can be beneficial can be the key problem behind the low penetration of these component models into wider developer community. If we look at the component models presented in thesis, we can see a common pattern of all of the industrial component models falling into categories/roles (1) to (5) as defined in Section 2.3.1, and none of them being of the hierarchical nature. While it is hard to distinguish a cause and a consequence – i.e. whether the industrial component models have clearly

stated goals and whether they target specific developer needs because they are driven by a professional software company, that needs the solution; or whether the clear goals led to the wide adoption and later to adoption in the industry as well – it appears to be clear that a lack of well-defined goals or desired properties and some common case studies illustrating the key advantages of hierarchical component models is one of the common and key reasons for the low adoption. Simply said, the potential users of hierarchical component models just do not understand their key features due to their inherent complexity, and thus are not able to foresee the advantages they are able to deliver them.

2.7 Revised Goals of the Thesis

With respect to the current state-of-the-art in CBSE as analyzed in Section 2.1, Section 2.2 and Section 2.3 and the problems presented in previous Section 2.6 the goals of the thesis should be revised to closely reflect the current CBSE problems that we feel a necessary to solve. The goals are:

(1) To identify the desired properties the hierarchical component models should expose in order to support wide use in software industry. We will provide examples of two industrial domains, where applying the hierarchical component models can be most beneficial.

(2) To evaluate hierarchical component models in two major case-studies and present problems encountered.

(3) To provide a novel contribution partially solving the problems identified while addressing the goal (2): approach to deal with complex error traces, support for modeling dynamic changes in hierarchical component architectures, and specification language for modeling component environment behavior.

Chapter 3

Hierarchical Component Models Coming to Rescue – Identifying Benefits and Key Problems

This chapter is structured according to the revised goals presented in Section 2.7. In Section 3.1 we identify and present the key areas where we see hierarchical component models most advantageous and propose their desired properties, whereas in Section 3.2 we provide an overview and summary of the published results. The latter section and the rest of the thesis are ordered again according to the goals presented. First we present two case studies to evaluate advantages and disadvantages of hierarchical components models (they are presented as a verbatim copy of parts of CRE project manual [3] and two of the published papers/book chapters [96][38]). In Section 3.2 we further present a summary of the key problem identified when modeling the case studies using a hierarchical component model – modeling an application with dynamic nature of its potential components and modeling the components environment behavior to allow its behavior verification without the whole application being completed – this presents summary of the remaining two papers coping with these problems [42][113].

3.1 Target Domain of Hierarchical Component Models

This section forms our response to the first of the revised goals of the thesis, i.e. we analyze the concepts available in hierarchical component models and show their key advantages.

3.1.1 Hierarchical Component Models from Program Correctness Verification Perspective

During many of our projects (e.g. CRE project presented in Chapter 5, and CoCoME presented in Chapter 6) we gained a lot of experience with component based software engineering. While CBSE can be viewed from many different angles and covers many software engineering aspects (as presented in Chapter 1 and Chapter 2), our main focus lies in the domain of software correctness verification and performance prediction (which is unfortunately a very complex problem by itself and as such it is out of the scope of this thesis). An ability to apply some correctness verification techniques to component-based applications is a crucial feature we require to be present in any component-oriented modeling and/or development approach. Being this of our top priority, let us show advantages of hierarchical component models in the domain of software correctness verification first.

During development of component-based applications two common approaches are usually taken: (1) the whole application code base is created from scratch and a CBSE approach is used to enhance application maintainability and extensibility, (2) there exists a repository of existing components (while it is common to think about a public component repository or a component store in this context, see [165], a private

repository of in-house developed components is also a valid case for the presented scenario), and the target application is "developed" just by selecting right set of components and interconnecting them accordingly (so called Commercially available Off-The-Shelf or COTS approach applied on software components – see [173]; for a more recent analysis of the idea see Chapter 15 in [53]). These two approaches are in fact very extreme cases of a real development process. On the one hand, it is virtually impossible to create a new application just from purely pre-implemented components, as at least some glue or transformation code is required in non-theoretical cases. Furthermore the probability of having all the required components somewhere in a repository and at the same time not having an application with required features combining the components is fairly low. On the other hand in a typical situation with a constrained budget and deadlines, developers try to reuse as much code as possible, and do not try to develop everything from scratch. So a common scenario in component-based application development would be a combination of (1) and (2).

In any case, the number of software components (whether newly developed or reused from some repository) can grow quite high, and it becomes a key problem to keep the whole application in a coherent state. The problem can even worsen if different components are developed by different developers or developer teams (this is inherently highly probable in case of components pulled from a repository of existing components). While initially it might seem the problem is easily solvable just by features of common programming environments – i.e. that it is sufficient just to verify compatibility of components based on syntactic compatibility of each other interfaces – it is generally not true. Each method implicitly assumes some preconditions are holding before its call, and the component itself usually maintains a set of invariants that have to hold for it to work properly.

In our approach of behavior protocols (see Chapter 4) we cope with this problem by specifying all possible correct behaviors of a component by a behavior protocol (a combination of valid method calls on a component and all variations of responses the component can exhibit as a reaction to a sequence of method calls). For each of the components considered to be used in an application we have to have a single behavior protocol describing all the possible traces of incoming and outgoing calls on that component exhibiting component's correct behavior (none of the preconditions and invariants of the component are broken). As in a typical application the components are not directly communicating only with their adjacent neighbors, but via them they are logically communicating also with the others (the rest), for a verification of a correct incorporation of a component we need to verify the composition as a whole (e.g. a component A might be so general, that a component B is not compatible with it [A exhibits some behavior the B is not able to accept); but adding a component C into the composition [connected just to the A component directly] might constrain the A's behavior in a way it becomes compatible with component B). This then leads to a need to model the state space of the whole application at once, which in turn leads an exponential growth in number of states (so called state space explosion problem – see Chapter 4) – which is roughly a Cartesian product of the state spaces of individual components.

Thus lowering a number of components needed in a single verification step would decrease the problem complexity in an order of magnitude. Such a simplification is natural result of hierarchical structuring of software components. With an application

modeled as a set of nested composite components, each of them being potentially composed of either primitive components (leafs of the hierarchy) or further nested composite components, the verification problem scales well by falling apart to smaller sub-problems. Now we have a behavior protocol for each of the primitive components (as in the original scenario of a flat model with all components on a single level of nesting), and add new behavior protocols for each of the new composite components. A behavior protocol for a composite component will describe only the expected behavior of the whole component (exhibited by its inner components), that is observable from the outside. With all this information, the verification then can be done step by step, i.e. for each composite component a composition of (behavior protocols) its subcomponents is verified against its own expected behavior to the outside world (composite component's behavior protocol).

When modeling the CRE case-study (see Chapter 5 for more details) we started with an initial simple model of several components and created behavior protocols describing their behavior. However after trying to verify correctness of their composition we ran into a dead end, as the all the possible interleavings of their behavior was simply too complex and we were not able to finish the verification in a reasonable time (in no more than a few hours). As a next step we naturally separated the applications components into subsets according to their functionality and created respective composite components encompassing the subsets behavior. It turn out this was a clear step that we should have done already during the original modeling of the application. Not only it would better allow us to reuse the composite components (behavior groups) in another projects, but more importantly, the problem of composition correctness verification shrunk at each level of nesting that much, that we were able to verify each of the smaller compositions in matter of hours (we had to verify correctness of composition inside each of the new composite components at each level of nesting, one by one). This final application architecture is the one presented in Chapter 5 and in Appendix A.

3.1.2 Hierarchical vs. Flat Component Architectures at Runtime – A General View

An important aspect has not been analyzed in detail yet – do we need the hierarchical component view both at the design time and at runtime? From the perspective of basic formal verification of the program correctness the answer seems quite straightforward – the model being the program's abstraction seems to be the most important part by itself (or more precisely its structure – i.e. its hierarchical composition). A property verification tool can analyze the model and effectively decide if the required properties are satisfied by the model or not. The next step, i.e. the verification of the compliance of the actual program's code to the model specification, would be typically done piece by piece – component by component (similar to some other static verification techniques – e.g. .NET Code Contracts Static Verifier verifying the preconditions and postconditions on method-by-method basis). The system would take each of the primitive components and verify whether their implementation complies with the appropriate portion of the model (primitive component behavior specification). And for this system to work it is not necessary, that the actual runtime components (as constituted by the implementation – e.g. actual Java class implementing the component) are still organized in a hierarchical manner – i.e. the system can be flattened.

A simplest approach to the flattening is to retain all the primitive components in the system and just erase the composite components – nonetheless all the bindings between the components will be retained as well. As a path formed by typical follow-up of bindings in a hierarchical component architecture begins and ends at primitive components (e.g. A and B), during the flattening process these two components are just bound together directly (direct binding between A and B).

A clear advantage of such approach is that the target system does not have to have any support for the component oriented code at all – i.e. no special component system runtime is needed and the application can be deployed to any regular software platform or software application framework without any need of special configuration. This is very advantageous in many common scenarios as it is minimizing external code dependencies – so the installation and distribution of the application is simplified (as a lot of complex component systems required complicated installation and configuration process which is often in contradiction to the more and more promoted XCOPY style installation experience on desktop/end-user oriented platforms), or it can even enable using the componentized application code in situations unrealizable with common component systems (typical example is embedding the code into a more complex software system – e.g. using it as a sort of a plug-in or user-definable extension – as such systems typically define their own programming model and code distribution and localization inherently incompatible with a component system implementation).

An interesting component system in this context is the MEF component model – as described in Section 2.3.7 and 2.4 – MEF can be considered to be somewhere halfway in between hierarchical and flat component models. The architecture as described by a MEF initialization code can be hierarchical in general, however such multilevel structure is only used during the component description phase and for component look-up and instantiation, but during the "composition" process the actual class instances implementing the available components are interconnected directly with each other – i.e. the flattening occurs at runtime during the last step of component architecture creation. This behavior allows developers to use the MEF in most .NET-based software development scenarios, as the MEF typically does not interfere with any other development paradigm required by the developer at the same time (in a same application).

In component models more oriented on the architecture's hierarchy, e.g. Fractal and SOFA 2, the flattening can be a bit more complex process. While composite components in this case often do not encompass any business code, they often contain a lot of application control features (e.g. life cycle controllers, interceptor and aspect waving infrastructure, implementation of other non-functional properties) that have to be somehow present in the final application's code as well (so the applications behavior reflects all the features and properties induced by the application model or architecture design). This typically leads to generation of pieces of "glue" code during the flattening that will reside in the final executable along the code of all the primitive components. The glue code can be for example generated from connector description capturing the non-functional properties, see [43].

To sum up the flat component representation at runtime seems to be rather straightforward approach without any disadvantages. While this might be true during

development of a typical desktop application, this observation does not hold in other more specialized scenarios as will be shown in the following Section 3.1.3.

3.1.3 Importance of Hierarchical Runtime Architectures in Industrial Scenarios

During our research in the component oriented software domain we have participated in several international projects with industrial partners involved. Aside from focusing on delivering the required results of the individual projects, we also intensively tried to listen to all the industrial partners' needs and to gather as much of their experience as possible. Although companies do not always use component technology directly, they do often use similar concepts or are searching for new approaches to software development in directions, where the component oriented software design can be of a huge advantage. The following text presents our apprehension of needs two typical examples (ABB and ESA) relevant to the context of this thesis.

ABB

ABB is a large international corporation developing and selling many products and providing services in a broad spectrum of domains. In context of this thesis its German branch [1] and its German research and development center are particularly interesting as one of their target domains is development of control and monitoring systems for large industrial plants (ranging from gas-processing and chemical plants to wide range of power plants including nuclear power plants). When a new plant is built and an ABB control system is installed, it is expected to be in service for several decades. And for the types of plants mentioned the only admissible scenario is, that after the plant begins its regular operations, the owning company cannot afford some long lasting outages in the services provided by the plant. This implies that the control and monitoring system has to run without interruption or shut down for mostly the whole life-span of the plant where it has been deployed. However during such a long uptime (of several decades) the system definitely needs some maintenance, in context of the deployed software it naturally means deployment of new versions of the software (whether to correct any bugs or inconsistencies, should any be found, but mostly to shape it according to the changing needs in evolving production processes of the plant).

Hierarchical component models/systems can bring a nice solution to this problem. If the system is modeled, designed and implemented correctly in agreement with ideal practices of designing hierarchically composed component application, the units of functionality would be separated in specific composite components. And if the component system runtime is aware of the hierarchy and force the code to obey the rules of nesting, the runtime has full information about the applications architecture and can take the liberty of exchanging the whole composite component (including its internals – i.e. the components nested in lower levels of component hierarchy) with its new version with corrected or enhanced functionality. With the fully known architecture of the system the task is much more simpler as in a general scenario of a unconstrained application not incorporating the concepts of hierarchical component models – in the earlier case the hierarchical component system runtime has "just" to monitor the components interfaces in question and pause all incoming and outgoing communications and in this window update the component and later resume the

communication by letting the retained flow of messages (method calls) to be passed to the new version of the component. The whole process can be done on a live system without a need to stop any other components that are not participating in the update. While the process is not exactly that simple as described above, the hierarchical component models are in a unique position to support such advanced scenarios – an example our experience with a successful prototype implementation of a similar approach proving the idea is feasible in context of hierarchical component models (namely the SOFA 2 component model) can be found in [152].

Enhancing the common hierarchical component models concepts with a new concept of dynamic entities, that we have proposed in [41], [42], and later in Chapter 7, can further simplify the problem and would allow the implementation to be more general by supporting a wider range of application design approaches. The dynamic entities formalize a typical externally visible subset of components state (namely allows to identify and pass references to internally allocated resources) and allow to extend the component model's runtime knowledge about the applications structure. Revealing such knowledge to the runtime then enables to more easily and directly implement the component exchange as described above even for more complex components that do not have their state idealistically encapsulated inside, but share part of the state with other components in the system (even on higher levels of nesting).

Another challenge lay especially in emerging directions the ABB tries to apply in the context of human interfaces to the control and monitoring system it is developing. Traditionally the systems are managed both from a centralized control center and from local terminals located near the actual devices and facilities all around the plant. These local terminals are used to control any locally specific properties of the device and to provide many diagnostic and maintenance indicators and control options. However with the advent of highly computationally and graphically capable devices as smart mobile phones and smart tablets ABB is introducing an interesting paradigm shift in the area mentioned (among other reasons, this change is also backed up by demand of young employee generation, that is becoming a majority in many industrial plant world-wide, to use the systems they are used to and to control the industrial devices in a similar manner they are used to from their personal lives) – a prototype future plant employee is envisioned to have its personal smart phone and/or tablet and to be able to go thought the plant freely during his or hers shift, and control and monitor the devices remotely without need to use any specific local terminals. Furthermore he or she should not be constrained to a single plant, but he or she should be able to migrate between multiple plants of a company, even during a single shift. And the different plants (of even a same company) would most probably not be exactly the same (having different devices or different models of a same device for one functionality required, similar devices configured or deployed with a different sets of capabilities) – in context of software systems, this means the control system must be highly configurable to support different devices and different versions of the control subsystems (each plant might use a different version of a system).

Again the hierarchical component model can provide advantages in this context. The clear structuring of the application's architecture allows easy extensibility of the control system. Our positive experience on the subject is for example reflected in [142], that presents an implementation of component packaging and distribution system in context of SOFA 2 component system, which takes advantage of SOFA's

hierarchical nature. Similar approach in cooperation with the one mentioned [152] can be used to implement a highly dynamic control system for a prototype future plant as described in previous paragraph. If the potential employee would come near a device of the plant, the component system can automatically download new control component in a correct version from the device and install it into the component system instance on the employees mobile device.

ESA

The European Space Agency (ESA) is an organization uniting several of the EU member states with the goal to cooperate and bring complex space missions to life. ESA covers effort of a lot of small companies as well as large international corporations and provides coordination for successful outcome of its own project proposals. The area covered by ESA missions is much diversified from regular Earth orbiting satellites, a cargo ship serving the International Space Station to missions studying several bodies in our solar system (from Mars to Titan), to the actual on orbit delivery vehicles. A typical long term space mission incorporates a space craft of any kind (including both mentioned satellites and missions to other planets) takes currently a lot of preparation spreading several years or even a decade. An interesting observation is that in most of the missions the whole spacecraft including all core and payload hardware and software is made from scratch. And ESA is aware that this is one of the main reasons for such a long time of a mission preparation – which not acceptable in a long term view as (a) cost of such missions is becoming increasingly large, (b) if a new interesting goal for space exploration is proposed the actual science results will be delayed many years or decades (as after the spacecraft launch the mission duration itself can span several years), (c) as the selection of technologies used in the mission has to be frozen in quite early phases of the spacecraft development (this applies to both hardware and software), the spacecraft is typically very outdated at the time of the actual launch. Taking all there problems into account ESA's long term goal is to fundamentally shorten the mission preparation time from years to month (to a least one year, or in some more optimistic scenarios even to about three months).

All of these goals has been summarized and applied in an ongoing ESA initiative SAVOIR (initiated as conclusions of [12], with state current report in [68]), which has main goal of creating a common base platform for development of on-board avionics. The initiative is formulated with the specifics of space bound missions in context of ESA projects in mind. There has been a lot of discussion on many ESA organized workshops on this topic and as a result and as one of the parts of the SAVOIR is a goal to prepare component-oriented software architecture to cope with the problems described above and in SAVOIR. Several approaches were proposed, among them is the proposal of a component framework [150][84] based on typical CBSE concepts. Currently the main project established to fulfill the SAVOIR goals is the CORDET [67] project.

The advantages of the core component orientation aspects are clear and especially aim at solving the problem of software and hardware reuse, which is minimal in current approach to development of space crafts in ESA related projects (as described above). The software reuse, i.e. reusing a same piece of software – a software component – in multiple missions, is direct implication of a strict componentization of system software architecture. The hardware reuse (in a single

space craft) is an implication of not only the emergence of isolated components in the architecture, but the typical approach on designing component system's runtime for more advanced component models – i.e. if the runtime is given an exclusive control of the system's architecture evolvement and of inter-component communication, the components are bound by the component model's rules. Multiple components, that would originally each require its own on-board computer (this need for component separation typically arises from a need to separate different payloads or to separate the payload from the mission control), can be in such system allowed to run simultaneously on a single computer. This change significantly lowers the overall cost of on-board avionics by greatly reducing the amount of needed hardware (by its aforementioned reuse). Note that the hierarchical component models typically exhibit such a tight control of components and their life time.

Another specifics of space exploration missions is the typical requirement of multiple modes of operation as different on-board hardware is used during different phases of the mission – this is true especially for more complex solar system covering missions (i.e. vehicle delivery to the initial orbit, from Earth orbit to target body transition, target zone [orbit] entering, the actual science mission, optional return to Earth, etc.). Such missions often include large spacecraft's hardware reconfigurations – e.g. physically releasing/dumping some components not necessary for the rest of the mission, or separation of science modules from the mother space craft (in a list of ESA missions we can find example of the Huygens lander separation from the Cassini probe [134]). The ability of hierarchical component models to easily support smooth system architecture reconfigurations was described above and was also discussed in this context in our previous work [95]. Moreover our experience is also reflected in a specific approach to take advantage of hierarchical component models and to handle directly the different modes of operation of systems componentized into hierarchical components has been developed in [141]. The original idea is further expanded in [140] and [148].

3.1.4 Putting All Together – Formal Behavior Specification as an Advantage

Applying the CBSE concepts in regular software development unfortunately also introduces some problems. Several companies that already incorporated CBSE massively into their development process face the following problem: after several years of applications development they gathered a repository of several thousands of software components. Naturally when a new application is to be developed, they would like to reuse their existing components and at least partially develop the application just by assembling the pre-developed components together (i.e. a way of application of the COTS principle [173][53]). However, it is clear they have only the specification of the required behavior of demanded components at the initial stage of application development, and especially do not have their finalized interfaces ready. And even if they would, any component already implementing the required behavior would most probably have at least minor differences in the interface specification (not to mention, that in most cases the target component in the repository would be solving a subset or superset of the problem or be an under- or over-abstraction of the problem). This makes the process of finding the right components a quite challenging task.

It turns out that in a real scenario the size of a repository of components matters, but with opposite implications than would be naively expected – i.e. the larger the repository grows, the more useless it is. Even with hundreds of components the developers cannot browse the repository manually and standard searching mechanisms fail, as the developers are not only not able to "guess" a correct required interface declaration, but even a "guess" of a component/interface name or a reasonable subset of its informal description is impossible (the latter not only due to inherent creativity of human developers, when it comes to names and textual descriptions, but often also due to different levels of abstraction used in component description/name and the search string).

The problem sketched in previous two paragraphs is in fact an extension of the problem discussed in Section 3.1.1, i.e. a necessity to verify component composition correctness. Let's return back to the discussion presented in the section – we argued that syntactic interface compliance is not enough and to state that two components are compatible, one has to compare their behaviors on much deeper lever. However we silently assumed, the components to be composed were already found and chosen. As we leant later such an assumption is not always possible as it initially seemed. But should a developer already have a behavioral description for each of the components in a repository (to verify correctness of their composition in a potential future system), the same behavioral description can be used to locate the right component. If the developer prepares a formal description of the expected behavior for which a component needs to be localized, such description can be used during search to find a match with formal behavioral description of components existing in the repository. And should such a "intelligent" repository be implemented, the hierarchical component models would allow better search results as more abstract units of code in form of composite components can be also stored in the repository. The behavioral description of a composite component would only a subset of functionality of its internal components as constrained by the actual composition of the composed component – and as such it would be a better abstraction of the functionality provided by the composite component (as discussed in Section 3.1.1). As the behavioral description is clear of any internal behaviors not exposed by the composite component (i.e. its implementation detail), the search in the repository should be more successful, as the query can only describe the expected behavior and not an expected implementation (i.e. the developer can state in the query only what a component should do, and not how it should be done). A similar approach targeting localization of compatible components as presented above has been described in [31]

Though it was not explicitly stated before, the ability of hierarchical component models to provide suitable means of component composition correctness (i.e. absence of some types of bugs, the verification framework targets) would be also a key feature in context of ABB and ESA projects showcased above. Having the behavioral description ready for the correctness verification can serve also as a documentation value as presented in this section. Last of strengths of hierarchical component models we would like to stress here is a unique position to support software performance predictability. Since the performance prediction is out of scope of this thesis as noted in previous chapters, let's give only a few comments to this topic. The Palladio Component Model (PCM) [23] is a mature framework for performance prediction, i.e. for prediction of various QoS related attributes. The PCM shows nesting software components and creating hierarchical component architectures brings to the domain of performance prediction similar advantages as it

does to the domain of software correctness verification (i.e. structuring of the initial problem into smaller units on natural boundaries already present in the code and provision of abstractions for units of code).

The performance prediction approach can be further extended to improve solution to the component localization problem. If PCM or similar approach is used as a basic to predict component performance, the Stochastic Performance Logic (SPL) [39] then can be used to match this performance related description to needs of a developer that is looking for a right component to solve his or hers problem. A combination of behavioral description (like behavior protocols) and SPL formulas can be used both as component specification as well as a search query. Components then can be found just by specification of their functionality and their QoS attributes (without a need to exactly require any specific implementation details).

3.1.5 Summary of Hierarchical Component Models' Desired Properties

In Section 3.1.1 to Section 3.2.5 we provided a detailed analysis of advantages of hierarchical component models and shown several domains of software engineering where these advantages would be especially appreciated. They can be summarized into the following that can be viewed as the desired properties the hierarchical component models should target to fully live up to their potential:

(1) Hierarchical component architecture at runtime

(2) Software correctness assurance and verification

(3) Performance prediction

(4) Documentation

3.2 Guide to Published Results – Proposed Solution Explained

The goal of the rest of the thesis (covering the global revised goals of the thesis as introduced in Section 2.7), namely Chapter 4 to Chapter 8, is to evaluate the hierarchical component model's desired properties (1), (2) and (4) (as defined in Section 3.1.5) in context of a selected hierarchical component model: Fractal component model and its Julia implementation – a model with an explicit support for hierarchical architecture at runtime, a choice that reflects the property (1) from Section 3.1.5.

The goal of this section is to give the reader a summary of each of the following chapters (Chapter 4 to Chapter 8) and to give their content into context of remaining chapters as well as into context of the analysis provided in Chapter 1 and Chapter 2 of the thesis.

Exploring and enhancing hierarchical component models with respect of all four identified goals can lead to introduction of many very complex problems to solve and providing a solution to all of them would be out of the scope of this thesis. Instead we focus only on the problem of verification of the software design and

implementation correctness. On the other hand in the case-studies presented later in the thesis we tried to analyze the project assignments from many different angles in order to be able to deliver a complex solution that would have positive characteristics in as many software engineering aspects as possible. A more enhanced case-study solution in this sense is our CoCoME for Fractal project as described in Chapter 6, where we were able to provide an architectural model suitable for and used in both behavioral correctness verification and implementation performance predictions tasks. A complex approach to solve similar software design and development tasks is crucial to propose the best approach reasonably applicable in more than one domain. If the formal method used to provide proofs of application correctness is designed in isolation without relation to other analyses that might be required to be performed on the developed application's code or design, it can lead to a state where the different analysis methods have contradicting requirements. The same or similar task – e.g. creation of application's model – then has to be done multiple times – creating the similar input separately for each of the analysis methods for example. Such approach is of course time consuming and can lead to more errors in the models and especially to model inconsistencies.

In Section 3.1 we identified the key goals of hierarchical component models. As it seems they should be ideal to model especially the types of applications and to solve the problems described above, the following Chapters 5 to 7 present our evaluation of application modeling utilizing all the means provided by componentization into hierarchically nested components. The following sections (Section 3.2.1, Section 3.2.2, Section 3.2.3, Section 3.2.5, and Section 3.2.6) provide a more detailed explanation of published results of each respective chapter. Each section is dedicated to one of the chapters: Chapter 4 (background: behavior protocols), Chapter 5 (CRE case-study), Chapter 6 (CoCoME case-study), Chapter 7 (capturing entities in architecture), Chapter 8 (modeling Windows kernel drivers' environment).

3.2.1 Behavior Protocols and Verification of Software Model Correctness (Chapter 4)

In Chapter 4 we introduce our approach to verification of application correctness and provide introduction into its background. First we introduce the behavior protocols formalism itself – it is a specification language, where each behavior protocol is an expression that expresses all possible behaviors of a software component (behavior protocols are especially targeting hierarchical component models). Basic unit of a behavior protocol is an action expressing an incoming or outgoing method call on a component boundary (more precisely behavior protocols distinguish more fine grained events of the call itself and its return back to caller). These method call actions are then composed with several operators (like sequence, alternative, parallel execution, etc.) to form a final behavior protocol expression. More details and a formal explanation can be found in Chapter 4.

In the second half of Chapter 4 we show, how are behavior protocols used to verify correctness of component based applications. As already mentioned before, we verify the application correctness by studying the applications architecture and by verifying it for lack of composition errors. Each component in the architecture (whether primitive or composite) is assigned a single behavior protocol that describes its behavior – i.e. acceptable ordering of method calls on that component boundary,

that the component is able receive at its provided interfaces and a relationship to and promise of possibly emitted method calls to required interfaces. We introduce three methods used to apply behavior protocols in application correctness verification:

(1) Static verification: In this method we verify the applications architecture for lack of various composition errors. This process is divided into steps, where in each step a correct composition is verified for a single composite component and all components directly nested inside of it (i.e. on a minus one level of nesting – these might be primitive components [directly implemented in some programming language] or other composite components). This process verifies the inner components' composition as constrained by their enclosing composite component's behavior protocols. This proves the inner architecture of a composite component behaves only according to the composite components behavior protocol and only such behavior is exhibited to the outside of than component. In next steps this process is repeated for other composite components in the architecture, considerably on different levels of nesting. An important note is that the whole application does not have to be verified always completely, but as the composite components can be reused in a different application than created for, the same is true for their behavior protocols forming a "prove" of their functionality (i.e. if a composition of a composite component is not changes, its composition can be verified only once).

(2) Runtime verification: This method is a smarter variant of unit tests – it verifies for primitive components, they are implemented as specified in their behavior protocol.

(3) Code analysis: This is another variant of verification of primitive component correctness. Contrary to the runtime verification the code analysis method does not test the component at runtime, but does an analysis of component source code to verify the component's implementation really obeys its behavior protocols. While this method is more exhaustive and can provide a better confidence on component's correctness than runtime verification, it might not be able to finish for too complex component implementations (due to the state space explosion problem). The runtime verification then can be used as a fall back method in such situations.

Whole content of Chapter 4 is a verbatim copy of excerpts from CRE project manual [3].

3.2.2 CRE Case-study – Enhancing the Fractal Tool-chain with Correctness Verification Techniques (Chapter 5)

In Chapter 5 we present our experience from the first case-study we have devised and implemented in one of our projects – the CRE for Fractal. The CRE project mostly targeted a viable way of verifying a componentized application design and to provide basic means to verify coherence between resulting application's implementation to its original design. Contribution of the project can be divided into several key areas: design of a case-study demo, behavior protocols and their tool-chain integration into Julia Fractal implementation, implementing the demo in Fractal and modeling it in behavior protocols, extensions of behavioral protocols to

be able to describe the case-study demo, verification of behavioral correctness, ideas how to cope with complex error traces possibly resulting from the verification process. In the following paragraphs we present a summary of the project results from Chapter 5.

Applying a research concept in real life scenario is not a simple task as it might seem – as much has to be done to actually and successfully implement a viable idea, often some enhancements and/or changes are usually required (it was nicely summarized by team members of Ivana Černá from Masaryk University in Brno: "*an algorithm [sketch] is not a tool – a lot of non-trivial work is necessary to provide a feasible implementation in a target programming environment [algorithm engineering]*"). The step from an idea to its implementation is becoming more and more important and a gap between algorithms and implementation widens as the technology becomes more and more complex (a nice example of large distance of current hardware architectures from properties of they should have according to von Neuman's architecture used in theory that illustrates the problem can be found in [15]).

Applying the problem to discussed domain it mean that not only designing a formal specification language (as behavior protocols) is a challenge, but enough attention need to be paid even to the actual implementation of these concepts. As the way the ideas are implemented can be a reason allowing for a real practical usability of the whole system. This was one of the points we focused on the CRE project and our approach to integrating and extending the behavior protocol verification tool chain (i.e. the Behavior Protocol Checker or BPC for short) into Julia Fractal component model implementation tool-chain is presented in Section 5.2.

Preceding Section 5.1 presents the key contribution of Chapter 5, a case-study used to verify maturity and applicability of BPC + Fractal integration done as part of CRE project in a real-life scenario. The application presented as a case-study is an example of an enterprise system that takes advantages or hierarchical component structuring. The case study is devised in a way to incorporate many CBSE concepts and to provide a "stress" test for the tools as well as the behavior protocol formalism itself. While not directly presented in this thesis (for being quite long), the as part of the CRE project all the case-study components were implemented and also formally modeled in behavioral protocols.

The last Section 5.3 summarized our experience from the CRE project. On an example it presents a key unsolved problem of the project: a need to model dynamism of the application during its runtime, more precisely a need to model dynamically changing architectures in context of hierarchical component models. While not solved as part of CRE project, we propose a solution to it by introducing a new concept of dynamic entities to CBSE – the solution has its own dedicated part of the thesis, Chapter 7. Further in Section 5.3 we present two enhancements of our core application verification techniques: (a) a solution to problem of formally describing synchronization problems in behavior protocols – introduction of so called Atomic Actions, (b) we discuss a problem of identification of errors from error traces returned by a verification tool. We propose and evaluate several approaches to cope with very complex and long error traces we have experienced in verification of the CRE project's case study application.

Sections 5.1, 5.2, 5.3.2, 5.3.3 are verbatim copies of excerpts from CRE project manual [3], Section 5.3.1 is newly written for this thesis and Section 5.4 is a verbatim copy of an excerpt from [96] paper.

3.2.3 CoCoME Case-study – Comparing Our Approach to Others (Chapter 6)

After completion of the CRE project we participated in the CoCoME competition [151] – its main goal being to provide a comparison of different component modeling approaches and highlights of their key advantages and weaknesses. With our previous experience with Fractal component model, we were able to provide a complete solution to the problem identified above, ranging from formal behavior verification to performance evaluation and prediction.

As a common case study based on example from [105] was in detail described in introductory chapters of the CoCoME book [151], a publically available source, we do not repeat it here. In Chapter 6 we rather focus on our experience from implementing the case study in Fractal hierarchical component model (more precisely again its Julia implementation), and an evaluation of our modeling process. While we have modeled many different aspects of the example application (as mentioned at the beginning of this section), in Chapter 6 only onto the key architectural modeling itself and of formal verification of applications correctness via behavior protocol checker (BPC) integrated into Fractal (Julia).

With respect to goals of this thesis we have encountered two problems from a verification perspective in our CoCoME approach. First we ran into a problem with expressing synchronization again. While it has been solve by atomic action in the CRE project, during formal specification of CoCoME component behavior we found out, the atomic actions in fact "oversolved" the problem and that a more simple approach without atomic action could be taken. In Chapter 6 we show that modeling approach of Petri Nets [145] can be applied on behavior protocols and used to model synchronization problems. While it mitigates a need for atomic actions for expression of basic synchronization problems it is still a useful tool. As atomic action were fully implemented into BPC as part of CRE project they still can be regularly used to express complex problems in behavior protocols.

Second, while the CoCoME architecture as described in [151] is static, we believe it was rather a choice of the CoCoME organizers (so that as many component model approaches as possible can participate), than being an inherent feature of the selected type of application. In a real-life application of the scenario we see a need for dynamically modifying parts of the architecture – especially the number of stores and cash desks per store would not be static and might change during time. And approach that would support dynamic changes to the architecture without stopping the system would be very beneficial here (especially for large grocery stores that has often 24/7 business hours in Czech Republic). While we did not cope with the problem in CoCoME contest directly it forms another motivation for our proposal of dynamic architectures modeling via dynamic entities concept introduced in Chapter 7.

Whole content of Chapter 6 is a verbatim copy of excerpts from CoCoME in Fractal [38] book chapter.

3.2.4 Case-studies Experience and Open Problems

Though both CRE and CoCoME projects were successful (not only from our perspective but also from perspective of project initiators), we identified several problems during development of respective project components and their modeling and formal specification. While we have solved most of them during these projects, two problems remain still open or are not sufficiently solved in all cases: (1) support for applications with dynamic architectural changes at runtime, (2) specification of component's behavior against its potential environment. The next two sections will summarize the remaining two key contribution chapters tackling these problems, but let us give now a short summary of the motivations – motivation for the capturing dynamic entities in component architectures is twofold:

(a) As shown on concrete examples in Section 3.1.3 an explicit notion of parts of component state can be beneficial for a component model runtime to support complex reconfiguration scenarios (ranging from mode changes of components and implies architectural reconfiguration, to exchanging components with different ones),

(b) If an application uses some concepts of a specific component model runtime or an underlying programming platform to achieve some dynamic reconfigurations to reflect needs of client requests, and if such changes in applications structure are not properly captured in application's architecture, any correctness verification technique aiming at taking advantage of component nesting in hierarchical component models will not be able to correctly incorporate information about application dynamism in its program or architecture analysis as the changes in application structure happen on a different level of abstraction, out of reach of the analysis – thus results of such analysis become less reliable as more false positive or false negatives can be returned as a result of unintentional under-abstraction or over-abstraction of the problem. The following Section 3.2.5 discusses the problem further and also provides a summary of a proposed solution from Chapter 7.

In both CRE and CoCoME projects we have applied an approach to verify application correctness by recursively verify correctness of composition in hierarchy of nested components. The approach assumes a developer creates a primitive component's behavior specification that is later used to verify correctness of its composition in a superior composite component. However in order for the whole approach to be valid not only at the specification level, but also for the real application behavior, a final step was needed – to verify correctness of primitive component's implementation by verifying its code adherence to its formal behavioral specification. As described in Chapter 4, Chapter 5, Chapter 6 and also summarized above we use the Java PathFinder tool to do this final step. Unfortunately as stated above the approach requires a formal prior specification of primitive component's behavior. However there are situations where one can assume the developer of the primitive component might not be skilled enough in formal methods to write such a specification correctly. Chapter 8 provides an alternative solution to code analysis, that can be used also to cope with this problem as will discussed in Section 3.2.6.

3.2.5 Capturing Application Dynamism in Design and Runtime Architectures – A Fine-grained Entities Approach (Chapter 7)

In Chapter 7 we aim at proposing a solution to the aforementioned problem of capturing dynamic entities in application's architecture. To provide a comprehensive solution, as well as to retain all possibilities of verification of both functional and non-functional properties as done in CRE and CoCoME projects any solution should aim at: (1) extend the traditional CBSE concepts related to hierarchical component models (we constrain ourselves only to this subset of CBSE), (2) provide an implementation of the proposed concepts in a hierarchical component model runtime, and (3) design a new or extend an existing formalism to capture the new concepts in behavioral description of software components, so that applications using them can have formally verified their correctness as applications without dynamic entities. As each of these steps is a very complex one, we did not want to solve them all at once, but decided to more carefully pay attention to them one by one, so that all are designed coherently and an overall solution is successful.

In initial paragraphs of Chapter 7 and in Section 7.1 to Section 7.4 we propose a solution to point (1) – we introduce a concept of proto-binding that allows tracking references to dynamic entities as they are passed around application's architecture. While defined on a conceptual level, all new concepts presented were designed very carefully to be able to fulfill also point (2) and (3) in future and yet be general enough not to be tied to any specific hierarchical component model or formal behavioral description language. For this reason we retain all the existing CBSE concepts and the concept of proto-binding only extends them and builds on them. To be able (both for a component model runtime and any analysis tool) to keep track of dynamic changes in application's architecture we further introduce a concept of four reconfiguration actions that constrain architectural changes only to a valid subset tightly coupled to the proto-binding (i.e. only proto-bindings can participate in any changes of application's architecture, regular bindings between application's components will remain static backwards compatible with original dynamic entities unaware component model). The reconfiguration actions serve as annotations of application's architecture and denote explicit points of allowed dynamicity (runtime reconfigurations).

Building on the introduced concept of proto-bindings we also propose a new concept of proto-components capturing dynamic instantiation of components in the architecture. Proto-components again constrains dynamic reconfigurations related to component creation only to a "safe" subset we are able to guarantee to be able to apply in analyzed hierarchical component models as well as formal specification languages.

A key feature of the presented solution utilizing proto-bindings is that a client using dynamic entities does not have to know anything about providers of dynamic entities nor about their actual implementation and vice versa. Each client and provider only sees its own end of a proto-binding and is concerned only about defining reconfiguration actions at its side. Thus our solution retains the most important CBSE concept of component encapsulation, i.e. components even if exposing dynamic entities can be still viewed as a black box and any component's environment can depend only on its provided and required interfaces – the

importance of the black box feature of components is thoroughly analyzed in [30], and we target to have the all new CBSE concepts compatible with this view.

The proposed approach assumes each dynamic entity (possibly a dynamically instantiated component created via proto-component) has its owner defined at time of its creation and for its whole life time the entity resides in a context of that owner. Thus a concept of component migration is not explicitly supported yet – however no feature of proto-bindings and proto-components should deny such feature and for example an implementation of factory pattern for hierarchical component models as proposed in [85] should be just an extension of set of reconfiguration actions without changes of the basic concepts. It is definitely a direction we plan to explore more in detail in future together with an evaluation of the basic concept of proto-components.

The last Section 7.5 in Chapter 7 presents a short evaluation of presented concepts. First we provide a reference to a prototype implementation of the concepts in context of SOFA 2 component model, second we have remodeled relevant parts of the case-study demo from CRE project (as presented in Section 5.1) using the proto-bindings and reconfiguration action architectural annotations and show they are feasible in such a real-life scenario.

Content of initial paragraphs of Chapter 7 and text of Sections 7.1, 7.2, 7.3, 7.4 are verbatim copies of excerpts from [42] paper and [41] technical report, Section 7.5 contains evaluation of presented concepts and is newly written for this thesis.

3.2.6 Modeling Components' Environment – Windows Kernel Driver Developer's Perspective (Chapter 8)

As shown in Chapter 2 various component models have quite different views on what is a component and how it should be used. We have also analyzed several frameworks and their component orientation, even though the frameworks themselves do not mention component at all (e.g. the aforementioned Spring framework). It turns out that if not focusing entirely on software frameworks positioning themselves as component models or systems, a whole new spectrum of software with component-oriented aspects arises. And if concepts of component-oriented design are analyzed and their advantages are presented it is worth analyzing the broader software spectrum outside the typical component-oriented software boundaries, as it is possible the component-aware techniques will have the same advantage in the other similar component-oriented domain of software.

One of such domain is an environment of Windows kernel drivers – there are well defined units of code with what can be viewed as a set of required and provided interfaces. As the Windows kernel is structured into fairly independent subsystems (managers), each subsystem can be also viewed as a component (all functions with a same prefix would form a provided interface of that component). In Chapter 8 we analyze a problem of verifying correctness of Windows drivers' implementation, thus in CBSE concepts, correctness of composition of the Windows kernel subsystem components against the driver components (or even other drives components as well – as the Windows kernel infrastructure often utilizes a concept of base driver and its sub drivers [mini-drivers], a concept very similar to CBSE concept of hierarchically nested components). As a solution to the problem a new specification language DeSpec is introduced in Chapter 8. The language can be used

to formally describe the environment of the Windows drivers, i.e. the Windows kernel itself. However as its purpose is verify correctness of driver and not the Windows kernel, the environment's specification does not have to describe the Windows kernel implementation detail, but it rather describes only the interface (API) to the kernel drivers on a level of WDK (Windows Driver [Development] Kit) documentation.

As identified in both CRE and CoCoME case-studies, it is important to have a reasonable formal model of component's environment to be able to verify its code mostly in isolation without a need to verify the whole application. While our current approach applied to hierarchical component models expects to have a formal behavioral specification of a primitive component and the Java PathFinder model checker is then exploited to verify its actual code correctness against the specification (or more precisely the component's environment represented by automatically generated inverse behavior to that of the target component), the other way round is also feasible. Thus in scenarios where there is a rather stable implementation of an extensible component-oriented application, the DeSpec language can be used to describe the application core behavior with respect to any components it could be extended by – i.e. the allowed behavior of any additionally added components. The Zing model checker (considered in Chapter 8) then can be used as an alternative approach to verify correctness of these components with respect to their composition into the application. This approach does not require the developer of the (primitive) component to provide any specification, his or hers intentions are just given by the component's code itself. While there might be many components prepared by different developers to plug-in into the application, the application is created only once, thus a formal specification of applications public API (environment from plug-in components point of view) in DeSpec has to be prepared once by a skilled developer with good knowledge of formal methods, which provides an elegant solution for the problem outlined in Section 3.2.4.

Whole content of Chapter 8 is a verbatim copy of excerpt from [113] paper.

3.2.7 Further Focus of the Thesis

From the problems identified and discussed in Chapter 5 - Chapter 8 we further focus mainly on those listed below:

(1) Dealing with complex error traces (Section 5.4)

(2) Modeling dynamic component architectures (Section 5.3.1, and Section 3.2.3)

(3) Modeling component environment behavior (Section 4.4, Section 5.2, and Section 3.2.6)

These problems are addressed in the following parts of the thesis: (1) in Section 5.4, (2) in Chapter 7, and (3) in Chapter 8.

Chapter 4

Background: Behavioral specification

The purpose of behavior protocols is to specify the behavior of software components, so that interesting properties of their behavior can be verified. The problem of behavior verification is undecidable in general. There are two ways to face it: (1) to use behavior description languages which describe behavior of the software precisely and to put up with the fact that the tools will never stop for some inputs (behavior descriptions), (2) to use behavior description languages, which are not expressive enough to describe behavior of software precisely, but the verification of the specifications is decidable. The approach taken by the behavior protocols is the second one, due to its key advantage - possibility to implement a fully automatic method of behavior verification (as implemented in the behavior protocol checker). CREman

The rest of the chapter describes the basic concepts of behavioral protocols, as well as ways how to utilize them to verify behavioral correctness of software components.

4.1 Introduction to Behavior Protocols

The main difference between "full" description of a component behavior and a corresponding behavior protocol is that the protocol describes only sequences of method calls on the component's interfaces, abstracting from the values passed as method parameters and return values. Such a level of abstraction is very suitable for verification tasks specific to software components. CREman

On Figure 4, there is an example of a component application consisting of two simple components. The component `Logger` provides basic logging functionality, which is used by the component `Client`. Therefore, `Client`'s (required) `log` interface is bound to `Logger's` (provided) `log` interface. `Logger`'s `log` interface consists of three methods: `open`, which has to be called at the beginning of the "logging session", `log`, which can be called several times after the `open` method was called (every call of the `log` method causes writing of the string passed as the `message` parameter into a persistent store), and the `close` method, which has to be called at the end of the "logging session". In a classic software development process, description of a component's functionality (such as `Logger`) has typically the form of a plain English text, which is not suitable for automatized behavior verification. To fill this "semantic gap", we add a behavior protocol to the "classic" component interface specification.

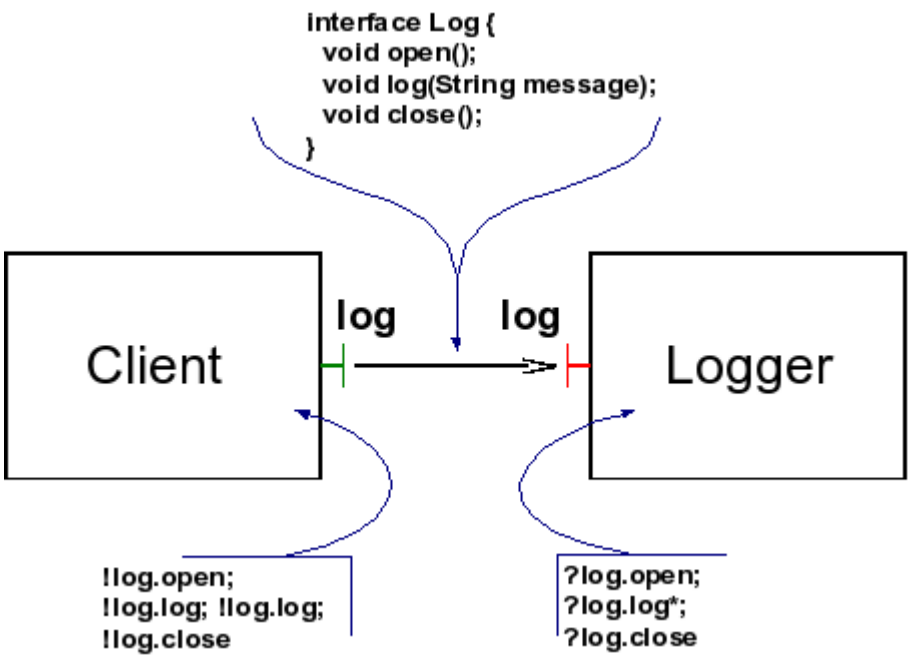

Figure 4. Example of a component application with behavior protocols

For example, the behavior protocol of `Logger`, consistent with the plain English specification above, reads as follows:

BP
```
?log.open ;
?log.log* ;
?log.close
```

This protocol consists of tokens denoting method calls (`?log.open`, `?log.log`, and `?log.close`) and operators specifying the ordering of the method calls (`;` and `*`). Every of these tokens consists of the question mark, denoting that the method call is *absorbed* by `Logger`, and the qualification of the method within the component, consisting of the interface name and the method name (separated by the dot sign). Finally, the `;` binary operator stands for *sequencing* of method calls, while the `*` postfix unary operator denotes zero or more *repetitions* of `?log.log`. Therefore, this protocol indeed specifies what was written informally above: the call of `log.open` is absorbed, then zero or more calls of `log.log` are absorbed, and finally `log.close` is absorbed. Now, let us focus on the behavior protocol of `Client`:

BP
```
!log.open ;
!log.log ;
!log.log ;
!log.close
```

It differs from `Logger` in two ways: First, the method qualifications are preceded with the exclamation mark, which stands for *emitting* a method call. Second, it specifies that `Client` calls `log.log` exactly twice. It is correct, because `Logger` is ready to accept an arbitrary number of log.log calls, if they occur after `log.open` and before `log.close` (which is the case).

4.1.1 Events and Traces

Events are the keystone of behavior protocol semantics. Every event is atomic. We define two types of events: requests and responses. Let `m` be the (fully qualified) name of a method. Then, `m^` (or `m↑`) stands for a request/call of m and `m$` (or `m↓`) stands for a response/return from `m`. Always, two components cooperate on an event: one component emits the event and another component absorbs the event. To distinguish between those two roles, we use the prefix `!` for emitting and `?` for absorbing. If `m` is a method name, the symbols `?m^`, `?m$`, `!m^`, `!m$` are called event tokens. Recall Figure 4 from the beginning of Section 0. In the protocol of Client, `!log.log^` would stand for emitting the call of `log.log`, while `?log.log$` would stand for absorbing the return from `log.log`. To specify that an event occurs as an internal event of a component `C` (i.e., it results from a communication of `C`'s subcomponents), we use the `#` prefix. To provide a way to specify a request and the corresponding response at once, we define abbreviations: if `m` is a (fully qualified) name of a method, `?m` is an abbreviation for the protocol `(?m^ ; !m$)` (the whole method call from the point of view of the callee) and `!m` stands for `(!m^ ; ?m$)` (the whole method call from the point of view of the caller). In fact, in the examples in the Section 0 introduction, only these abbreviations were used to specify the behavior, and usage of explicit requests and responses was not necessary.

We also define two more complex abbreviations: if `P` is an arbitrary protocol, `?m{P}` means that the call request of m is absorbed, and while `m` is processed, the component behaves as specified by `P`; afterwards, the call response of `m` is emitted. In a similar way, `!m{P}` means that `P` specifies the behavior of the caller between issuing the call of `m` and receiving the response of `m`. The abbreviations not only serve as syntactic sugar, allowing writing readable behavior protocols, but they also explicitly denote pairing of events (requests and corresponding responses). In certain situations, such information is essential for the behavior protocol checker. This is why for certain types of interfaces, only an abbreviation can be used to specify the method call, and the use of explicit event specification is forbidden (see Section 4.5.1).

A computation of a component application is formally described by a trace - a finite sequence of event tokens. Every protocol specifies a set of traces. Recall the protocol of Client from Figure 1.1:

BP
```
!log.open ;
!log.log ;
!log.log ;
!log.close
```

It specifies a single trace:

BP
```
<!log.open^, ?log.open$,
!log.log^, ?log.log$,
!log.log^, ?log.log$,
!log.close^, ?log.close$>
```

For Logger, the situation is more complex:

```
BP      ?log.open ;
        ?log.log* ;
        ?log.close
```

This protocol specifies an infinite number of traces, as it accepts arbitrary number of calls to `log.log`.
We show the first three shortest traces specified by the protocol:

```
BP      <?log.open^, !log.open$, ?log.close^, !log.close$>

        <?log.open^, !log.open$, ?log.log^, !log.log$,
        ?log.close^, !log.close$>

        <?log.open^, !log.open$, ?log.log^, !log.log$,
        ?log.log^, !log.log$, ?log.close^, !log.close$>

        ...
```

The set of all traces specified by a protocol `P` is denoted as L(P).

4.1.2 Behavior Protocol Basic Operators

For behavior protocols, the following basic operators are defined: sequencing (denoted by `;`), repetition (denoted by `*`), alternative (denoted by `+`), and-parallel (denoted by `|`), and or-parallel (denoted by `||`). We illustrate the meaning of the operators (except the last one) on the following protocol of the Client component from Figure 1.1:

```
BP      !log.open ;
        (
             (!log.log | !log.log)
             +
             !log.log*
        ) ;
        !log.close
```

Client, whose behavior is specified by this protocol, first calls `log.open`. Then, it either calls `log.log` twice in parallel, or it calls log.log several times sequentially (or it does not call `log.log` at all, as `*` stands for zero or more repetitions). At the end, it calls `log.close`.

Or-parallel is defined as follows: if `P` and `Q` are protocols, `(P || Q)` stands for `(P + (P | Q) + Q)`.

4.1.3 Frame and Architecture Protocols

From the point of view of behavior, every component can be divided into two parts: frame and architecture. The frame of a component C consists of all interfaces which are provided or required by C to "outside world" (the components which are external to C). The architecture of C consist of frames of C's direct subcomponents and bindings between those frames (and also bindings between interfaces of C's subcomponents and interfaces of C itself).

On Figure 5, the frame of Client consists of the (only) log interface, while its architecture is formed by the frames of A, B and the bindings <A:log1-log>, <B:log2-log>, <A:nt1-B:nt2> (as explained in Section 1.2.2, in the context of the Client component <A:log1-log> stands for the binding of the log1 interface of the A subcomponent to the log interface of Client itself; here, we introduce <A:nt1-B:nt2> - the binding between interfaces of A and B subcomponents).

An architecture is always associated with a concrete frame (we also say that the architecture implements this frame).
Following the definition of frame and architecture, we also distinguish between frame protocols and architecture protocols. Frame protocol of a component C describes requests and responses on the frame of C. The frame protocol is specified by the developer. The architecture protocol of C is automatically constructed from the frame protocols of C's direct subcomponents by the behavior protocol checker. It describes what is happening "inside" C.

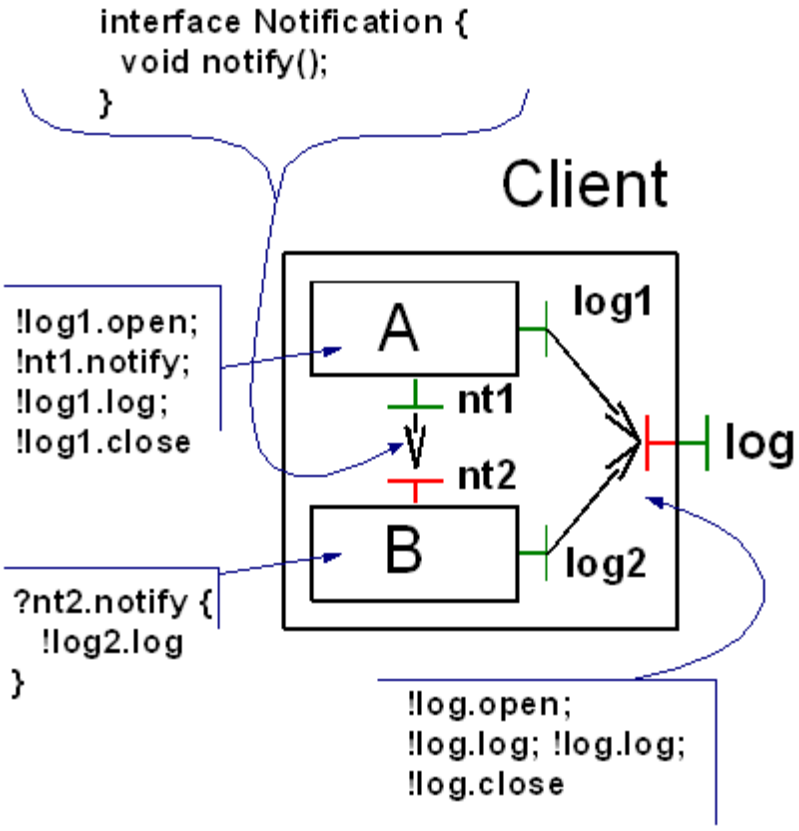

Figure 5. Example of a composite component with bindings among subcomponents

In the architecture protocol of a component C, two types of events appear: events on the frame of C, and events resulting from the communication of C's direct subcomponents (internal events). The first type of events is denoted in the same way as in frame protocols. The # prefix is used (in both event tokens and abbreviations) to denote internal events (Section 2.1).

For example, the architecture protocol of the Client component from Figure 2.1 reads as follows:

```
BP      !<A:log1-log>.open ;
        #<A:nt1-B:nt2>.notify {
             !<B:log2-log>.log
        } ;
        !<A:log1-log>.log ;
        !<A:log1-log>.close
```

Formally, the composition of subcomponent frame protocols resulting in the architecture protocol is defined by the consent operator [4]. This operator is never used by the designer specifying the frame protocols, it is only a formalization of the behavior composition which is done automatically by the behavior protocol checker.

4.2 Static Verification of Behavior Protocols

4.2.1 Protocol Compliance

One of the behavior properties, which can be statically verified with our behavior protocol checker, is compliance of an architecture protocol `PA` (of a component `C`) with the frame protocol `PF` (of `C`). Informally, there are two conditions which have to be satisfied in order for `PA` to be compliant with `PF` (let `F` be the frame of `C`): (1)`PA` specifies acceptance of any sequence of calls of the methods provided by `F` that are dictated by `PF`. (2) For such sequences, `PA` specifies only such calls of the methods required by `F` that are anticipated by `PF`. Example of an architecture protocol not compliant with the frame protocol was already described in Section 1.2.2. As a more elaborate example of compliant behavior, recall the architecture protocol of `Client` from Figure 2.1 in Section 2.3...

```
BP      !<A:log1-log>.open ;
        #<A:nt1-B:nt2>.notify {
             !<B:log2-log>.log
        } ;
        !<A:log1-log>.log ;
        !<A:log1-log>.close
```

... and the corresponding frame protocol:

```
BP      !log.open ;
        !log.log ;
        !log.log ;
        !log.close
```

The architecture protocol is compliant with the frame protocol, because if we abstract from the internal events of `Client` (which are not important from the point of view of compliance), and from different naming conventions (the architecture protocol uses binding names, the frame protocol uses interface names), both the protocols specify the same set of traces (or, in this particular case, the same trace). We have developed two different formal definitions of behavior compliance: *pragmatic compliance*, published in [146], and *consensual compliance*, which uses the consent operator [4] and is implemented in the current version of the behavior protocol checker.

4.2.2 Composition Errors

Composition errors are communication errors, which result from composition of components with incompatible behavior. If the definition of the components is enhanced by behavior protocols, those composition errors can be checked statically.

The first type of composition error is *bad activity*, which was demonstrated in Section 1.2.2. It occurs when a component `A` tries to call a method of a component `B` in such a way which in not specified in `B`'s behavior protocol.

No activity (or deadlock) occurs when computation in a component application cannot progress (none of the components is able to emit an event), and at least one of the components has not finished its computation (the application thus cannot stop correctly). To show an example of no activity, let us modify the frame protocol of `Client`'s A subcomponent from Figure 2.1 in Section 2.3:

BP

```
!log1.open ;
!log1.log ;
!log1.close
```

Here, the `B` component will be "blocked", as it expects a call of the `notify` method on its `nt2` interface - this call is never emitted by `A`. After `A` makes all the calls specified in its behavior protocol, a no activity error occurs. An *infinite activity* (divergence) occurs when computation of a component application never stops, but components are never blocked, i.e. always there is an event which can be both emitted and absorbed. An example of a component composition resulting in infinite activity can be found on Figure 2.2. Here, the `A` and `B` components call forever the `notify` method on each other's `ntp` interface in turns. More information on composition errors can be found in [4].

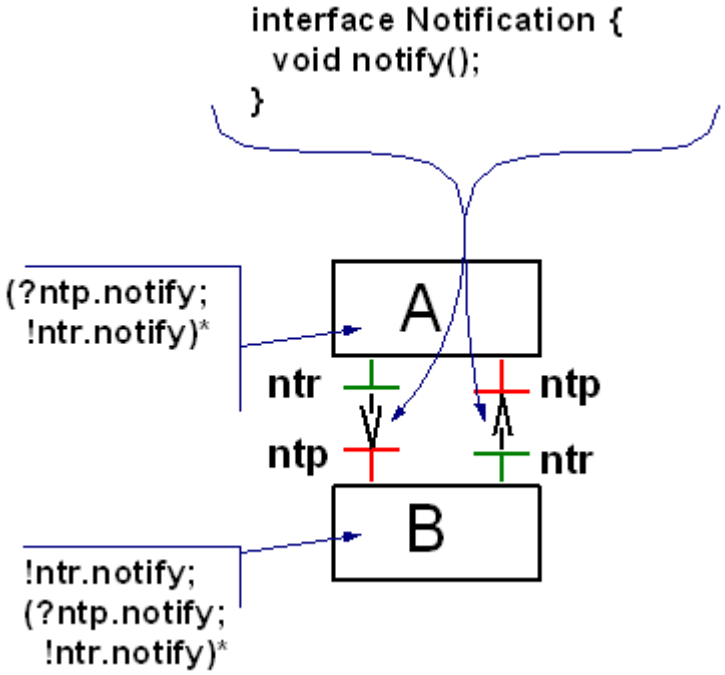

Figure 6. Example of an infinite activity

4.2.3 Incomplete Bindings

We say that a component architecture has *incomplete bindings*, if there exists an interface (either provided or required), which does not participate in any binding (we call such an interface an *unbound interface*). The existence of an unbound interface is not necessarily a design error: this typically happens when the designer reuses a component developed originally for different application and decides to utilize only a part of the component's functionality. If the behavior of the components in the architecture is specified using behavior protocols, it is possible to statically check whether the incomplete bindings cause a problem.

An unbound provided interface can cause bad activity or no activity (Section 2.4.2). On the other hand, an unbound required interface can cause a new type of composition error: *unbound requires error*. Unbound requires error occurs when a component tries to call a method on its required interface, which is unbound. An example of a component application with one unbound required interface (the `nt` interface of the `A` component) is shown on Figure 2.3. On the `ch` interface of `A`, the `a` or the `b` method can be called. If `b` is called, `A` reacts by calling `nt.notify`. As the `B` component calls only `ch.a`, the `A:nt.notify` method is never called and the fact that `A:nt` is unbound does not cause any problem. On the other hand, if the behavior protocol of `B` was `(!ch.b*)`, it would result in an unbound requires error. More information on incomplete bindings can be found in [5].

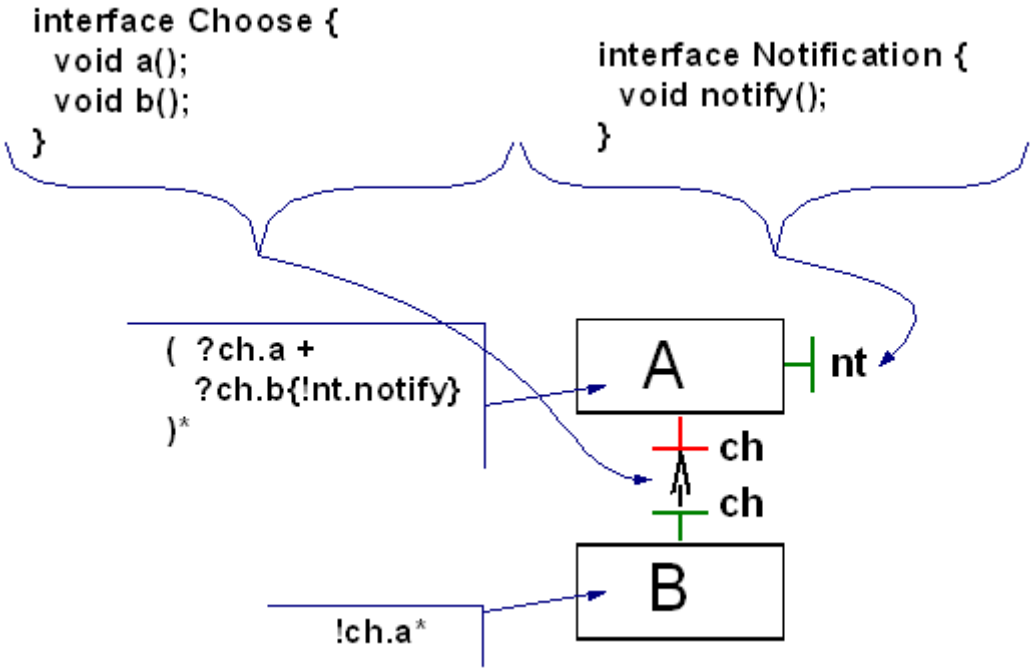

Figure 7. Example of incomplete bindings

4.3 Runtime Verification of Behavior Protocols

The run-time checker monitors the events on the external interfaces of a component (the trace) and checks whether this trace is one of those specified by the frame

protocol of the component. If not, it is considered to be an error. The main reason for using the run-time checker is verification of the composite components with dynamic architectures (which cannot be verified statically). Also, run-time checking is an alternative to static checking in the situations when the architecture of a (composite) component is so complex that the static checker cannot be used. Last but not least, run-time checker can be used to check the compliance of a primitive component behavior with the frame protocol (this cannot be done using the static protocol checker in principle, because there are no subcomponent frame protocols). We show the functionality of the run-time checker on the example from Figure 1.1 in Section 1.2.1. The frame protocol of `Client` specifies that the `log.log` method has to be called after `log.open` has been called. If `log.close` were called instead at that moment, the run-time checker would detect an error. What exactly happens when such an error is detected depends on the configuration of the run-time checker. Typically, the error is reported and logged within the runtime-checking framework. The runtime checking framework may throw an exception in the calling thread to notify the application about the erroneous call, or the application may continue without being affected. In either case, the run-time checking of the component (whose frame protocol was violated) is stopped. It is not possible to continue run-time checking of the component in this case, as the behavior protocols formal model does not support "error recovery". The run-time checker also detects the violation of the frame protocol caused by the component's environment (the "outer world"). For example, if the frame protocol of `Client` were

BP

```
!log.open;
!log.open;
!log.close
```

(i.e., to start by calling `log.open` twice) and `Client` behaved in compliance with this protocol (so that no protocol violation would be detected by the run-time checker for `Client`), error would be reported for `Logger`, as its protocol does not allow to accept a call of the `log.open` method twice.

4.4 Code Analysis

The purpose of code analysis of a primitive component is to check whether the component's behavior is *bounded* by its frame protocol, that means checking whether the component can accept and emit method calls on its frame interfaces only in sequences that are determined by its frame protocol. Main advantage of code analysis over runtime checking is that all techniques of code analysis are exhaustive, i.e. they check all the possible runs of the verified code. We decided to employ model checking, which is one of the more popular techniques of software code analysis.

Model checking [47] is a formal method of verification of finite state systems. The basic idea is that a model checker checks whether the model of a target system satisfies the property expressed in some property specification language. The checking is done by traversal of the state space that is generated from the model.

Some model checkers accept as input the model manually created by the user, while others are able to automatically extract the model from the source code. However, both approaches have severe drawbacks. Manual construction of the model is a tedious and error-prone process. On the other hand, automated extraction of the

model faces the problem that the model is an abstraction and, therefore, it may represent behavior not possible in the original program. Consequently, a model checker may then find errors that are not present in the program (i.e., false negatives). Fortunately, there exist model checkers that work directly with the implementation of a target system - Java Pathfinder is an example of such a model checker.

Properties to be checked are usually expressed via temporal logic (CTL, LTL), or in the form of assertions. Some model checkers are also able to check for a fixed set of special properties (deadlocks, uncaught exceptions, etc).

The biggest problem of model checking with respect to practical use of this technique is the size of the state space typical for software systems (the problem of *state explosion*). However, decomposition of a software system into components helps to mitigate the problem. A component usually generates smaller state space than the entire system and, therefore, can be checked with fewer requirements on space and time.

In our case, we use model checking to check whether a primitive component is bounded by its frame protocol or not. And since most implementation of the Fractal Component Model (used in our projects presented later) are Java-based (including the reference implementation Julia), we decided to use the Java PathFinder model checker (JPF) [133].

Chapter 5 CRE Case-study

The CRE case-study presented in this chapter was created as part of our CRE (Component Reliability Extensions) project [2]. The project was done in cooperation with France Telecom and the goal of the project itself can be summarized by a short citation from [2]: "*The purpose of this project is to extend the Fractal Component model and its Julia implementation with support for Behavior Protocols*". The following Section 5.1 presents a novel case study created in the CRE project to verify the new techniques implemented into Julia and Fractal. Section 5.2 describes our integration of Behavior Protocol checker into Fractal, Section 5.3 and Section 5.4 present problems identified in modeling the CRE case-study in the extended Fractal/Julia, and propose solution to mitigate them.

5.1 The Case-study

In this section we present the case-study as engineered in the CRE project. As most of the text is verbatim copied from the project's results manual, we retained its original wording – especially the case-study is referred to as "the demo" in the rest of the text. The case-study was prepared with cooperation with the France Telecom to reflect a typical application of one of its business domains. It was specially crafted in a way to employ a diverse set of architectural features, so that we would be able to stress test our modeling approaches to the edge.

The demo presents a prototype implementation of a payment system for public Internet access on airports. It is designed so that clients of several air-carriers from the same group (e.g. SkyTeam) can have access to the Internet. Clients access the system via a wireless network (e.g. WiFi); before being able to establish communication with the Internet, they have to authenticate themselves and/or pay for the service. There are currently three different ways a client can gain access to the Internet:

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All clients that have a valid fly ticket for first class or business class have full Internet access during the ticket validity period free of charge. For this access method the fly ticket identification number is used during the client login as authentication credentials in the system.

Any client that has a valid Frequent Flyer Card and has any valid fly ticket has also full Internet access during the ticket validity period free of charge. The Frequent Flyer Card identification number is used as credentials. The system checks that a valid fly ticket exists for the card.

Any client of any air-carrier can prepay Internet access by a credit card. The clients using this method will get a user name and a password that are valid for a certain amount of time (e.g. 1 week or 1 month) and in this time period the prepaid time for Internet access needs to be used up (else the remaining prepaid time will expire).

The client session (the client's ability to communicate with Internet servers) starts when the client authenticates using one of the previous methods and terminates when one of the following events occurs:

The client disconnects from the wireless network – any prepaid time not used up during the session being terminated can be used up in future sessions assuming the client's user name will not expire until then.

Client's fly ticket becomes invalid or all of the client's prepaid time is used up – the session terminates immediately and the client can start a new prepaid session.

The key part of the system behavior will be implemented in Fractal components. However, the clients will communicate with the system via JSP web pages that will then call the Fractal components with appropriate requests. The demo environment is divided into three areas/networks:

1. Airport WiFi – The public wireless network that clients connect to.

2. Airport LAN – All demo Fractal components run on computers in this network. The communication between this network and the Airport WiFi is separated by the Firewall that is controlled by the Firewall Fractal component.

3. Internet – The part representing the outer world. It hosts central servers and web services (e.g. credit card web services, air-carriers database servers) and also the client communication goes there (if not blocked by the Firewall)

On the lowest level the client connections are managed by the DhcpServer Fractal component. This component assigns IP addresses to new clients and notifies other demo Fractal components when clients disconnect, so that their sessions can be terminated. The DhcpServer component might also communicate with some sort of wireless network access point, in order to get more accurate information about client connection and disconnection events.

5.1.1 Demo Behavior

See the diagram of the whole demo in Appendix A.

Note: The numbered symbols like ②, 3a, 3b or 3E reference the appropriate numbered steps in the picture.

Initial state:

- No clients connected

- Any DHCP communication is allowed through the Firewall

- All HTTP/HTTPS requests from clients are redirected to the airport's WebServer residing in the Airport LAN. All such requests are redirected to the Login page, that all clients use to enter login credentials to open connection to the Internet.

- All other outgoing or incoming communication from/to clients is initially blocked ⓪ by the Firewall service.

Event: ***A new client connects to the Airport WiFi network***

1. The Client sends a DHCP request for an IP address ① and the DhcpServer replies ① assigning a new IP address to the Client (see section 2.1 for a detailed description of DhpcServer composite component behavior). The Client then uses this IP address for all communication with the system and during any access to the Internet. The assigned IP address also serves as a unique client identifier.

2. The Client enters the Login page (by typing any URL in the web browser) ②

3. The Client then continues in one of the three possible ways depending on the access method selected:

4. *Free access using first class or business class fly ticket ID:*

   4.1. The Client fills the fly ticket ID in the login form

   4.2. The Login page calls the Arbitrator:ILogin.LoginWithFlyTicketId(Id) method with the fly ticket Id supplied by the Client 3a

   4.3. The `Arbitrator` calls the `FlyTicketDatabase:IFlyTicketAuth.CreateToken( FlyTicketId)` method 4a to create the `Token` component representing the "logged in" state of the `Client`

   4.4. The `FlyTicketDatabase:FlyTicketClassifier` component then selects the appropriate fly ticket database component depending on the supplied fly ticket ID and calls the `IFlyTicketDb.GetTicketValidity(FlyTicketId)` method on it 5a (`CsaDbConnection` component is selected in the example).

   4.5. The database component then uses any proprietary protocol to connect to the air-carrier's database server to get the requested information 6a

   4.6. If the supplied `FlyTicketId` is valid then the associated fly ticket validity time is passed back to the `FlyTicketClassifier` component 5a

   4.7. The `FlyTicketClassifier` creates a new instance of the `Token` component 7a with the validity set to the time returned in the previous step. The `Token` component instance will be created without the `Token:CustomToken` inner component as it is not needed in this type of authentication.

   4.8. Further steps are common for all three authentication methods (to continue skip the specific steps for methods/steps 5 and 6).

5. *Free access using the Frequent Flyer Card ID:*

   5.1. The Client fills the Frequent Flyer Card ID in the login form

   5.2. The Login page calls the Arbitrator:ILogin.LoginWithFrequentFlyerId(Id) method with the Frequent Flyer Card Id supplied by the Client 3b

5.3. The Arbitrator calls the CreateToken(FrequentFlyerId) method ④ᵇ on the FrequentFlyerDatabase:IFreqFlyerAuth interface to create the Token component representing the “logged in” state of the Client

5.4. The FrequentFlyerDatabase component then connects to the central database of issued Frequent Flyer Cards ⑤ᵇ (“SkyTeam Frequent Flyer Database”) and checks the FrequentFlyerId validity

5.5. If the supplied Frequent Flyer Card ID is valid then the FlyTicketDatabase:IFlyTicketDb.GetTicketByFreqFlyerId(FrequentFlyerId) method is called ⑥ᵇ to check if there exists any valid fly ticket bought with the Frequent Flyer Card at any air-carrier’s office of the group

5.6. The FlyTicketDatabase:FlyTicketClassifier requests the same information from all of the database connection providers by calling the IFlyTicketDb:GetTicketByFreqFlyerId method on them ⑦ᵇ

5.7. Each of the database connection components then connects to its own air-carrier’s database server ⑧ᵇ to retrieve list of all valid fly tickets bought using the supplied FrequentFlyerId.

5.8. The FlyTicketClassifier gathers responses from all fly ticket databases ⑦ᵇ and the resulting list of valid fly tickets (possibly empty) is retured back from the FlyTicketDatabase:IFlyTicketDb. GetTicketByFreqFlyerId (FrequentFlyerId) call ⑥ᵇ

5.9. If the resulting list of valid fly tickets is not empty the FrequentFlyerDatabase selects one of the tickets that is currently valid and calls the FlyTicketDatabase:IFlyTicketAuth.CreateToken(FlyTicketId) method ⑨ᵇ to create a new instance of the Token component. The following steps to create the Token component are similar to the most of the steps of the a) authentication method:

5.10. The FlyTicketDatabase:FlyTicketClassifier component selects the appropriate fly ticket database component depending on the supplied fly ticket ID and calls the IFlyTicketDb.GetTicketValidity(FlyTicketId) method on it ⑩ᵇ (AfDbConnection component is selected in the example).

5.11. The database component then uses any proprietary protocol to connect to the air-carrier’s database server to get the requested information ⑪ᵇ

5.12. If the supplied FlyTicketId is valid then the associated fly ticket validity time is passed back to the FlyTicketClassifier component ⑩ᵇ

5.13. The FlyTicketClassifier creates a new instance of the Token component ⑫ᵇ with the validity set to the time returned in the previous step. The Token component instance will be created without the Token:CustomToken inner component as it is not needed in this type of authentication.

5.14. The instance of the Token component ⑫ᵇ returned from the FlyTicketDatabase:IFlyTicketAuth.CreateToken(FlyTicketId) method call ⑨ᵇ is then returned back ④ᵇ to the Arbitrator component

5.15. Further steps are common for all three authentication methods (to continue skip the specific steps for method/step 6).

6. Prepaid access

6.1. If the Client does not possess a user name and a passport to a prepaid access account then such an account needs to be created first:

6.2. The Client fills his or her credit card number and the card expiration date into the account creation form on the Login page. The Client also chooses the amount of time that will be prepaid to his or her new account.

6.3. The Client selects an AccountId or a random AccoundId can be generated by calling the AccountDatabase:IAccount. GenerateRandomAccoundId() method.

6.4. The Client selects a password or a random password is generated by the Login page

6.5. The Login page calls the AccountDatabase:IAccount.CreateAccount(AccountId, Password) method 3c to create a new prepaid account for the Client

6.6. The AccountDatabase creates a new account in the central database 4c. The account will have default validity or timeout period associated with it (e.g. 1 week or 1 month as mentioned earlier) and will have no Internet access time prepaid.

6.7. The Login page uses the AccoundId and other information supplied by the Client to call the AccountDatabase:IAccount.RechargeAccount(AccountId, CardId, CardExpirationDate, PrepaidTime) method 5c used to pay for more time to access the Internet.

6.8. The AccountDatabase calls the CardCenter:ICardCenter.Withdraw(CardId, CardExpirationTime, Amount) method 6c to withdraw the correct amount (depending on the PrepaidTime) from the Client's account.

6.9. The CardCenter component then selects the right credit card authorization center ("VISA Card Center" in the example), checks the validity of the requests and communicates with the card center 7c to process the request.

6.10. If the requested amount was successfully withdrawn from the Client's account the AccountDatabase enters the new prepaid time into the Client's account record in the central Account Database 8c and success is returned to the Login page 5c.

6.11. The Client fills his or her account used id and password into the login form on the Login page (these credentials are generated/selected during the account creation)

6.12. The Login page calls the Arbitrator:ILogin.LoginWithAccountId(AccountId, Password) method with the credentials supplied by the Client 9c

6.13. The Arbitrator calls the CreateToken(AccountId, Password) method ⟨10c⟩ on the AccountDatabase:IAccountAuth interface to create the Token component representing the "loged in" state of the Client

6.14. The AccountDatabase component gets the prepaid time of the account from the central Account Database ⟨11c⟩

6.15. The AccountDatabase creates a new instance of the Token component ⟨12c⟩ with its validity time set to the prepaid time from the previous step. The Token component instance will contain the CustomToken subcomponent. If the Client's session terminates the CustomToken component is used to communicate the amount of prepaid time already used up back to the AccountDatabase via the IAccount:AdjustAccountPrepaidTime(AccountId, SecurityCookie, TimeLeft) method ㉑. The SecurityCookie is a random string generated during creation of the Token component and it is passed by the AccountDatabase component to the CustomToken component during its construction. The CustomToken saves the SecurityCookie, so that it can use it later to prove its connection to the AccountId specified in the IAccount:AjustAccountPrepaidTime call.

The following steps are common for all three authentication methods:

7. Now the Arbitrator component already has a reference to a new instance of the Token component returned either from the FlyTicketDatabase, the FrequentFlyerDatabase or the AccountDatabase component, depending on the authentication method selected. The Arbitrator adds this reference into its internal table that maintains the bijection between Token component instances and connected Clients (Clients' IP addresses)

8. The Arbitrator calls the Firewall:IFirewall.DisablePortBlock(IpAddress) method ⑬ (8a or ⟨13b⟩ or ⟨13c⟩)

9. The Firewall component uses a proprietary communication mechanism to forward the request to the Firewall system service ⑭. The Firewall service opens all communication ports to/from the Client and stops redirecting all HTTP/HTTPS communication from the Client to the airport's WebServer (15 – Cancel port block). Until the session terminates the Client can access the Login page only using a special URL (server address that was displayed on the Login page). If the Client forgets the URL, he or she can simply disconnect from the wireless network (this action will automatically terminate the current session) and reconnect again, so that a new session is started and all Client requests are redirected back to the Login page.

10. The Client has now full access to the Internet ⑯ until its session terminates (its access Token becomes invalid or he or she disconnects from the Airport WiFi network).

Event: ***A client disconnects from the Airport WiFi network*** (17 – Client disconnects)**:**

1. If, after certain amount of time, the Client does not send the "Renew IP address" DHCP request the DhcpServer:IpAddressManager component will deduce that

the Client has disconnected and will call the Abitrator:IDhcpCallback :IpAddressInvalidated(IpAddress) method ⑱ (see section 2.1 for a more detailed description of this process). This will start the process of terminating current Client's session

2. The Arbitrator calls the IToken.InvalidateAndSave() method ⑲α on the right Token component instance (based on the IP address passed in the IpAddressInvalidated call and the IP address/Token instance mapping stored in the internal table)

3. If the Token component instance contains the CustomToken subcomponent (i.e. if the instance was created by the AccountDatabase:IAccountAuth.CreateToken calls) the following steps will occur too:

4. The Token:ValidityChecker component calls the Token:CustomToken .InvalidatingToken(TimeLeft) method ⑳ passing it the amount of time until the Token should have become invalid.

5. The CustomToken calls the AccountDatabase:IAccount .AdjustAccountPrepaidTime(AccountId, SecurityCookie, TimeLeft) method ㉑ to update the amount of prepaid time left on the Client's account.

6. The AccountDatabase updates the prepaid time in the central database ㉒.

7. The Token:ValidityChecker component calls the Arbitrator:ITokenCallback .TokenInvalidated(TokenId) method ㉓. This signals the Arbitrator component that the Token have become invalid and that the associated Client's session should be terminated.

8. The Arbitrator calls the Firewall:IFirewall.EnablePortBlock(IpAddress) ㉔

9. The Firewall component then communicates with the Firewall system service ㉕ so that all existing connections to or from the Client are closed and no new ones are allowed (except for the DHCP communication) and that all HTTP/HTTPS requests from the Client are again redirected to the Login page on the WebServer ㉖.

10. The Client's session is terminated and, from the point of view of the Client, the system is in the same state as it was in the initial state.

11. Event: Client's Token becomes invalid – i.e. Client's fly ticket becomes invalid or all of the prepaid time is used up:

12. The steps that will follow are similar to the steps following the previous event. The only difference is that the session termination is not initiated by the DhcpServer component, but by one of the Token components itself.

13. The Token:Timer component times out – i.e. Token validity has ended and it calls the ValidityChecker:ITimerCallback.Timeout() method ⑲β.

If the Token component instance contains the CustomToken subcomponent (i.e. if the instance was created by the AccountDatabase:IAccountAuth.CreateToken calls) the following steps will occur too:

14. *The Token:ValidityChecker component calls the Token:CustomToken .InvalidatingToken(TimeLeft) method ⑳ passing the amount of time until the Token should have become invalid.*

15. *The CustomToken calls the AccountDatabase:IAccount.AjustAccountPrepaidTime(AccountId, SecurityCookie, TimeLeft) method ㉑ to update the amount of prepaid time left on Client's account.*

16. *The AccountDatabase updates the prepaid time in the central database ㉒.*

17. *The Token:ValidityChecker component calls the Arbitrator:ITokenCallback .TokenInvalidated(TokenId) method ㉓. This signals the Arbitrator component that the Token have become invalid and that the associated Client's session should be terminated.*

18. *The Arbitrator calls the Firewall:IFirewall.EnablePortBlock(IpAddress) ㉔*

19. *The Firewall component then communicates with the Firewall system service ㉕ so that all existing connections to or from the Client are closed and no new ones are allowed (except for the DHCP communication) and that all HTTP/HTTPS requests from the Client are again redirected to the Login page on the WebServer ㉖.*

20. *The Client's session is terminated and, from the point of view of the Client, the system is in the same state as it was in the initial state.*

5.1.2 DhcpServer Component Description and Behavior

The DhcpServer component can behave in two different ways:

1. IP addresses for new clients are automatically generated (by a preconfigured pattern – e.g. valid IP address range) by the DhcpServer component. In this scenario the IP/MAC address mappings are stored in the TransientIpDb database component only and IpAddressManager's IIpMacPermanentDb interface is not used at all (this implies that the DhpcServer:IIpMacPermanentDb interface does not need to be bound in this scenario). This scenario is used by the demo.

2. The second option is that the IP/MAC address mappings can be permanently stored in an external database component (providing an IIpMacDb interface) and the DhcpServer assigns IP addresses to new clients according to their MAC address and the mapping stored in the database. As in the first scenario the IP address/MAC address mapping is also temporarily stored in the TransientIpDb component for the time the corresponding IP address is actually assigned to the client. Calling the DhcpServer:IManagement.UsePermanentIdDatabase method activates this behavior.

Event: ***A new client connects to the Airport WiFi network***

1. The Client sends a DHCP request ① for an IP address. This request is accepted by the DhcpServer:DhcpListener component.

2. The DhcpListener component calls the IpAddressManager.RequestNewIpAddress method ①.

3. The IpAddressManager component determines a IP address for the new client – this action is different for each of the DhcpServer usage scenarios:

4. IpAddressManager tries to generate a new IP address and checks whether it has been already assigned – by calling the IIpMacTransientDb.GetMacAddress ①.② method. If the generated IP address is already used it will generate another one and repeat the check.

5. IpAddressManager calls the IIpAddressPermanentDb.GetIpAddress method to check if a mapping for client's MAC address exists. If the mapping is not found the IpAddressManager can try to generate an automatic IP address as in the previous scenario.

6. The IP address with client's MAC address is then added by the IpAddressManager to the TransientIpDb database by calling it's IIpMacDb.Add ①.③ method.

7. The assigned IP address is returned to the client via returning the IDhcpListenerCallback.RequestNewIpAddress method call ①.① from IpAddressManager component back to the DhcpListener. The assigned IP address is then used as a unique client identifier by the rest of the system.

8. The Client can enter the Login page ② (by typing any URL in the web browser)

Event: ***A client disconnects from the Airport WiFi network*** **(17 – Client disconnects):**

The client disconnection event can occur, or be detected in one of the two ways:

1. If, after certain amount of time, the Client does not send the "Renew IP address" DHCP request to the IpAddressManager component (via DhcpListerner:IDhcpListernerCallback.RenewIpAddress method call) the present timer will expire calling the IpAddressManager:TimerCallback.Timeout method.

2. The WiFi Access Point detects client's disconnection from the WiFi network and notifies the DhcpServer:DhcpListener component of that event. The DhcpListerner will call the IpAddressManager:IDhcpListenerCallback.ReleaseIpAddress method (17.1).

    2.1. The IpAddressManager will the remove the IP address/MAC address mapping from the TransientIpDb database component by calling it's IIpMacTransientDb.Remove method (17.2).

2.2. The IpAddressManager will notify the rest of the system of client disconnection by calling the IDhcpCallback.IpAddressInvalidated (17.3) method.

2.3. That will lead into calling Abitrator:IDhcpCallback.IpAddressInvalidated method (18) that will start the process of terminating current Client's session.

5.2 BPC and Fractal Integration

One part of the CRE project was also to integrate the Behavior Protocol Checker (BPC) and the Fractal component model – namely its Julia implementation for Java platform. During the integration process we had to tackle many problems and provide solution to many issues – details can be found in the original manual – here in the following text we will present only an overview of the key problems we have faced and the ones directly related to the goals of the thesis we will provide a more detailed analysis.

To successfully finish the integration we had to introduce several assumptions about the Fractal component model and also extend some of its basic features:

The Fractal component model specification is very flexible (and structured in several conformance levels), consequently, many concrete component systems comply with it. To make the integration of behavior protocols into Fractal possible, we take the following additional assumptions: **CREman**

(1) In Fractal, every component has internal and external interfaces. We suppose that for every external interface there exists an internal interface of the same type (and vice versa). In addition, an event on an external interface immediately causes the complementary event on the corresponding internal interface, and these two events happen atomically. In a similar way, an event on an internal interface immediately causes the complementary event on the corresponding external interface (and the two events happen atomically).

(2) Interfaces in Fractal are connected by bindings. We suppose that an event occurring on an interface `I` causes immediately the complementary event on the interface `I` is bound to, and the two events happen atomically, assuming `I` is bound to exactly one interface. If `I` is bound to more interfaces, the events on those interfaces do not have to happen atomically.

Next, as we associate a frame protocol with each component of an application, and also some environment-related information with each primitive component of an application. Thus, to enable the users to use Fractal ADL for describing the architecture of Fractal applications, we had to extend the Fractal ADL syntax to accommodate the frame protocol and environment declarations.

5.2.1 Interceptors

While extending Fractal and Julia with support for runtime checking of compliance of component behavior with the specified protocol, we have encountered a number of issues, some of which have required modifications to Julia. In this section, we

describe the Fractal and Julia extensions we developed to support the runtime checking.

In principle, runtime checking is achieved by introducing an interceptor for each business interface of the component being checked; on each event (method entry or exit), this interceptor notifies the *runtimecheckcontroller* introduced into the controller part of the component. This controller creates an instance of the runtime-checker backend with the specified protocol, and notifies the checker backend of each such event. In case the checker detects that the event violates the protocol, the error is recorded; optionally, the application may be notified by throwing a `ProtocolViolationException`. The typical interaction among these parts is shown in the sequence diagram in Figure 8:

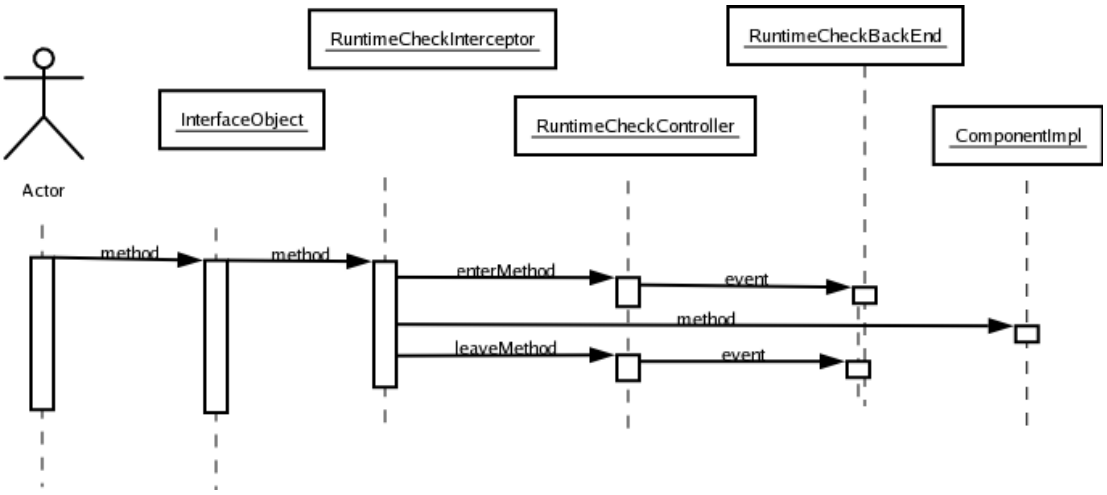


Figure 8. Interceptor architecture

More details can be found in [3].

5.2.2 Checker for Code Analysis

We use JPF for checking primitive Fractal components implemented in Java against behavior protocols. However, it is not directly possible to use JPF for checking whether a primitive component is bounded by a protocol, because JPF is, by default, able to check only properties like deadlocks and assertions. In order to solve this, we decided to use JPF in combination with the protocol checker for code analysis. In other words, we decided to let JPF and the checker cooperate on code analysis while traversing their own state spaces. Since JPF and the checker work at different levels of abstraction, we had to define a mapping from the JPF state space into the state space of the checker to make such cooperation possible. For more information on the mapping, please refer to [143].

We have modified the behavior protocol checker for static testing by adding several methods to make the cooperation with JPF possible. In particular, the checker has been enriched by a method for notification of actions performed (method called and finished) in the JPF and uses this for coordination of the state space traversal. Each time JPF moves along a transition corresponding to a method call or return from a method call, it notifies the checker of this event. Checker moves along the

corresponding transition in its own state space. Should not such a transition exist within the checker's state space, an error is reported to the user and the implementation is considered not to be bound by the protocol. To treat all the combination of implementations and protocols correctly as well as to be able to handle cycles, it is necessary to coordinate the traversal in the following way: Each time JPF would backtrack within the state space because of being in an already visited state it asks the checker for permission. Only in situations when both JPF and the checker would backtrack at this point when executed on their own (i.e., if being in an already visited state), backtracking is allowed. Hence, the bounding relation can be checked correctly.

More detailed analysis of JPF application to the CRE project can be found in [3].

5.3 Modeling the CRE Demo

When modeling and implementing the demo application proposed in Section 5.1 using behavior protocols and Fractal component model, we ran into several problems that needed to be solved. The following Section 5.3.1, 5.3.2, and Section 5.3.3, as well as Section 5.4 are dedicated to describe all the problems identified. All of the sections, with the exception of Section 5.3.1, also provide solutions to the problems that were devised as part of the CRE project. The Section 5.3.1 describes the most severe problem encountered (problem of modeling dynamic component architectures) that we were unable to solve in the CRE project without considerably changing the techniques available at that time. However later in Chapter 7 we provide a final solution to this problem and in Section 7.5 we return back to this case-study and remodel it with the newly introduced concepts and verify their ability to solve the problem described below.

5.3.1 Token Component Dynamism

One of the key challenges in the CRE project was to model, implement and verify correctness of the Token component from the case-study demo application. The basic functionality of the Token component is simple – it represents state of a client logged-in to the system, i.e. for each initiated session to the system there should exist a single Token component instance representing it – and this is the problem. The running application does not contain only a single Token instance, but multiple Token instances can be present at runtime, moreover, they are dynamically created as new clients arrive and dynamically destroyed as clients log out or disappear. Fortunately in the Fractal component model this can be implemented without problems as it supports dynamic component instantiation at runtime – the problem is that any newly created components are represented only as references to them and actually lay outside of applications architecture, and the component model runtime loses control of their further evolution in the application (a problem tackled before in Section 2.3.6). The application's architecture the Fractal component model understands is only static and represents a view on component relations at start of the application – i.e. any further changes are not captured there.

As the behavior protocols are based on similar CBSE concepts, they also do support only static architectures. In order to solve the Token problem (that leads to a dynamic architecture), we had to "cheat" a bit and prepare a simplified, idealistic architecture of the application. In the architecture the Token is represented with a single

component instance and also the behavior protocols for the static compositional verification were prepared as if only a single Token component instance existed for the whole application run time. It is obvious that by verifying correctness of composition we have provided a weaker prove than is needed to verify the actual application implementation – i.e. an abstraction of the application was used – while this approach is common, the simplification used can hide common problems with compatibility of the Arbitrator component and the Token component as it, for example, does not force the Arbitrator component to correctly handle the real multi-instance scenario (e.g. with proper synchronization).

Furthermore the behavior protocols designed for the static verification will not work with the runtime verification or code analysis methods that encounter the real components implementations that naturally exhibit behaviors not compatible with their original behavior. In order to solve the problem we had to provide another more generic variant of the protocols that would allow any method invocation traces that were originally prohibited, but could occur at runtime if the tool sees only a sequence of Arbitrator–Token method calls without the actual context (i.e. without the notion of the actual Token instance the methods are intended for). Such a protocol for a component that that would accept any method call of another component instance at any time must be naturally very generic, and thus potentially hiding many more errors from the verification tool.

Also the Token component instances can logically originate from different sources in the architecture – either from the FlyTicketClassifier component, FrequentFlyerDatabase component or from the AccountDatabase component. Each of these Token creators needs to maintain a different set of data as part of the Token's state – it is represented by the optional CustomToken component in the architecture. Unfortunately it further complicates the problem, as during the verification process based on static architectures there are two pieces of information missing: (a) the information about the Token instance identification, i.e. Token instance current state in its contract described by its behavior protocol, (b) information about the Token variant a method invocation is carried out against, thus information about a behavior protocol variant describing the correct behavior of the actual Token component instance. Again to cope with the problem the behavior protocols had to be once again generalized to incorporate a combination of all the possible behaviors of any optional extensions. While such approach does mitigate false positives (i.e. correct components will not be marked as incorrect), it potentially introduces more false negatives – i.e. a wrong variant of Arbitrator component implementation can be successfully composed together with an inappropriate implementation of Token component (one exhibiting a behavior the other does not actually support).

5.3.2 Enhancing the Behavior Protocols

In order to formally describe the synchronization needed between the DhcpListener component and clients of IManagement interface (which both inherently support parallel invocation of incoming method calls) and the IpAddressManager component (which supports only sequential invocation of methods on its interfaces – in order to limit parallelism in the Arbitrator component, the IpAddressManager sends requests to) we propose an enhancement of the behavior protocol with concept of atomic actions.

Atomic actions (AA) are a behavior protocols construct allowing cooperating components to synchronize. They have been added to behavior protocols as a consequence of component synchronization problems which arose during the work on specification of the Airport Internet Access Application components. Although in some cases the behavior of a component may be described using behavior protocols without AA, a version using AA are usually not only much easier to construct, but also more readable afterwards. Furthermore, using AA, behavior protocols correspond with component implementation in a more straightforward way. As an example of a behavior protocol containing an atomic action (enclosed in square brackets '[' and ']'), consider the following example:

BP
```
?IDhcpController.Start^ ; !IListenerController.Start^ ;
[?IListenerController.Start$, !IDhcpController.Start$]
```

An atomic action may occur in a behavior protocol at positions where a single event and an abbreviation may. Atomic action starts with '[' and ends with ']'. There is a coma-separated list of events (the use of abbreviations is not allowed as their use doesn't make sense here) between '[' and ']'.

Semantics

Basically, an atomic action is treated as a single event, i.e., it is supposed to be "executed" in a single step.

An atomic action is in one of the two states – *enabled* or *disabled*. It can be executed in the enabled state only. An atomic action is enabled in the current state if and only if for each accept event (an event starting with '?') in the atomic action there exists a component in the composition able to emit the corresponding request event in the current state. If there's not a component able to emit a request event corresponding to an accept event of the atomic action, the atomic action is disabled. The corresponding accept and request events yield, as in a common case, a tau action; consider the following protocol fragment:

BP
```
...[?ma^, !mc^]... (consent) ...!ma^... ->
    ...[#ma^, !mc^]...
```

The application of the consent operator to behavior protocols containing atomic actions may result in a protocol containing the bad activity composition error. This situation arises in the following case:

The atomic action contains no accepting event (an event starting with '?'), i.e., it contains internal and emitting events (events starting with '#' and '!', respectively) only, and there's an emit event in the atomic action that is not accepted in the current state by any component in the composition.

Notes

For each two components combined via the consent operator there may be at most one event inside of an atomic action that is also contained in the set of synchronization events for these two components. This requirement reflects the fact that a component cannot perform more than one event (a simple event or an atomic action) in a single step, which causes the consent operator not to be associative when

applying to behavior protocols containing atomic actions. In other words, the result of the composition depends on the order the components are composed together.

Atomic actions need to be handled in a special way during the runtime checking. As only one event may be executed in each step and a protocol containing an atomic action thus can't be satisfied at runtime checking, each atomic action is replaced with a protocol consisting of atomic action events combined using the and-parallel operator expressing the necessity that each of the atomic action events has to be executed, but the order doesn't matter. The transformation is done during the protocol parsing process, so it is invisible to the other parts of the system.

A formal specification of atomic actions can be found in [100].

5.3.3 Expressing Synchronization

The *virtual* synchronization components S1 to S5 presented in Appendix A won't be real Fractal components implemented as part of the demo. Their purpose is only to easily describe and easily autogenerate method call synchronization description in behavior protocols. These autogenerated components, more precisely only their behavior protocols, will be added in between real Fractal components during protocol checking.

S1 – *first synchronization component*

- provides `IDhcpListenerCallbackIn` (`IDhcpListenerCallback` interface type)
- requires `IDhcpListenerCallbackOut` (`IDhcpListenerCallback` interface type)
- requires `IS2` (`ILock` interface type)

The first synchronization component forwards the call on "`In`" interface to "`Out`" interface after it successfully locks the next synchronization component – i.e. after the `INextLock.Lock` call returns. When the call on the "`Out`" interface is finished the component unlocks the next synchronization component via `INextLock.Unlock` call.

BP
```
(
    ?IDhcpListenerCallbackIn.RequestNewIpAddress {
        !IS2.Lock;
        !IDhcpListenerCallbackOut.RequestNewIpAddress;
        !IS2.Unlock
    }
)*
```

S_i – *intermediate synchronization component* (synchronization components S2 to S5)

- provides `IDhcpListenerCallbackIn` (`IDhcpListenerCallback` interface type) (`IManagement` for components S4 and S5)
- provides IS_i (`ILock` interface type)

- requires `IDhcpListenerCallbackOut` (`IDhcpListenerCallback` interface type) (`IManagement` for components S4 and S5)

- requires IS_{i+1} (`ILock` interface type)

Each of the intermediate synchronization component processes one call from `IDhcpListernerCallback` (S2, S3) or `IManagement` (S4, S5) interfaces. If the previous component tries to lock an intermediate component (via `IPrevLock.Lock` call), it will try to lock the next component via `INextLock.Lock` method call. If the component accepts call from the "In" interface either it locks the next synchronization component and processes the call by calling the appropriate method on the "Out" interface and then unlocks the next component; or, if it has been already locked by the previous component, it will postpone the "Out" method call until it accepts the `IPrevLock.Unlock` call. Then it calls the appropriate method on the "Out" interface (note that the next synchronization component is still locked) and only after this call returns it will unlock both the next component and itself (by returning the `IPrevLock.Unlock` method call).

The following behavior protocol describes the S2 synchronization component. Behavior protocols for S3 to S5 components are similar, only the `IDhcpListenerCallbackIn.RenewIpAddress` and `IDhcpListenerCallbackOut.RenewIpAddress` method calls are replaced by a method name, that the synchronization component processes.

BP

```
(
    (
        (
            ( ( ?IDhcpListenerCallbackIn.RenewIpAddress^;
            !S3.Lock; !IDhcpListenerCallbackOut
                .RenewIpAddress
            ) | ?S2.Lock^ )
            +
            ( ( ( ?S2.Lock^; !S3.Lock) |
            ?IDhcpListenerCallbackIn.RenewIpAddress^ ) ;
            !IDhcpListenerCallbackOut.RenewIpAddress )
        ) ;
        !S2.Lock$; ?S2.Unlock^; !S3.Unlock; [!S2.Unlock$,
        !IDhcpListenerCallbackIn.RenewIpAddress$]
    )
    +
    (
        ?S2.Lock {!S3.Lock}; (
        ?IDhcpListenerCallbackIn.RenewIpAddress^ |
        ?S2.Unlock^ );
        !IDhcpListenerCallbackOut.RenewIpAddress; !S3.Unlock;
        [!S2.Unlock$, !IDhcpListenerCallbackIn
            .RenewIpAddress$]
    )
    +
    (
        ?S2.Lock {!S3.Lock}; ?S2.Unlock^; !S3.Unlock^; (
        ?IDhcpListenerCallbackIn.RenewIpAddress^ |
        ?S3.Unlock$ );
        !S3.Lock; !IDhcpListenerCallbackOut.RenewIpAddress;
        !S3.Unlock; [!S2.Unlock$,
        !IDhcpListenerCallbackIn.RenewIpAddress$]
```

```
        )
        +
        (
            ?S2.Lock {!S3.Lock}; ?S2.Unlock {!S3.Unlock}
        )
        +
        (
            ?IDhcpListenerCallbackIn.RenewIpAddress^; !S3.Lock;
            !IDhcpListenerCallbackOut.RenewIpAddress;
            !S3.Unlock^; ( ?S2.Lock^ | ?S3.Unlock$ );
            !S3.Lock; !S2.Lock$; ?S2.Unlock^; !S3.Unlock;
            [!S2.Unlock$, !IDhcpListenerCallbackIn
                .RenewIpAddress$]
        )
        +
        (
            ?IDhcpListenerCallbackIn.RenewIpAddress {!S3.Lock;
            !IDhcpListenerCallbackOut.RenewIpAddress; !S3.Unlock}
        )
    )*
```

S5 – ***last synchronization component***

- provides IManagementIn (IManagement interface type)
- provides IS5 (ILock interface type)
- requires IManagementOut (IManagement interface type)

If the last synchronization component accepts the IManagementIn .StopUsingPermanentIpAddresses method call it can immediately forward the call to the "Out" interface (if it was not locked in the past). If it accepts the IPrevLock.Lock call it will only postpone the "In" interface call until the IPrevLock.Unlock call arrives. The behavior protocol follows:

```
BP      (
            (
                ( ?S5.Lock^ | (
                ?IManagementIn.StopUsingPermanentIpDatabase^;
                !IManagementOut.StopUsingPermanentIpDatabase ) );
                !S5.Lock$; ?S5.Unlock^; [!S5.Unlock$,
                !IManagementIn.StopUsingPermanentIpDatabase$]
            )
            +
            (
                ?S5.Lock; (
                ?IManagementIn.StopUsingPermanentIpDatabase^ |
                ?S5.Unlock^ );
                !IManagementOut.StopUsingPermanentIpDatabase;
                [!S5.Unlock$,
                !IManagementIn.StopUsingPermanentIpDatabase$]
            )
            +
            (
                ?S5.Lock; ?S5.Unlock
            )
            +
            (
                ?IManagementIn.StopUsingPermanentIpDatabase
```

```
            {!IManagementOut.StopUsingPermanentIpDatabase}
        )
    )*
```

5.4 Dealing with Complex Error Traces

FACS

Behavior protocols [146] are a method of software component behavior specification. They are used for behavior specification in the SOFA [161] (also in SOFA 2 [40]) and the Fractal [34] component models. We employed behavior protocols in several non-trivial case studies of component behavior specification, comprising high number of components. This includes a non-trivial component-based test bed application in a project funded by France Telecom aiming at integration of behavior protocols into Fractal component model. One of the key lessons learned has been that the error trace length problem is severe and has to be addressed seriously. The goals of this paper are (i) to share with the reader the experience gained during specifying behavior of a non-trivial component-based application and show that the error trace length problem is really serious, and (ii) to describe the techniques we designed to address this problem.

These goals are reflected in the rest of the Section 5.4 as follows: Section 5.4.1 and 5.4.2 illustrates how to use them for component behavior specification and demonstrates the problem with the error trace length on a fragment of a non-trivial application that will be used as a running example. In Section 5.4.3, as the key contribution, the proposed techniques for addressing the error trace length and interpretation problems are described. Section 5.4.4 contains an evaluation of the proposed techniques while Section 9.1in related work summary chapter discusses related work. Section 5.4.5 concludes the paper and suggests future research direction.

5.4.1 Example: A Fragment of the Test Bed Application

In this section we describe in more detail a fragment of the demo application described above. The application is a quite complex system allowing clients of various air-carriers to access the Internet from airport lounges via local Wi-Fi networks. The whole Wireless Internet Access application is composed of about 20 Fractal components. One of the key components is the `DhcpServer` composite component (Figure 9). It communicates with system's clients at the lowest level, i.e. it is responsible for managing clients' IP addresses, monitoring overall state of the local wireless network and providing this information to the rest of the system. A simplified version is presented in this section.

DhcpServer Architecture

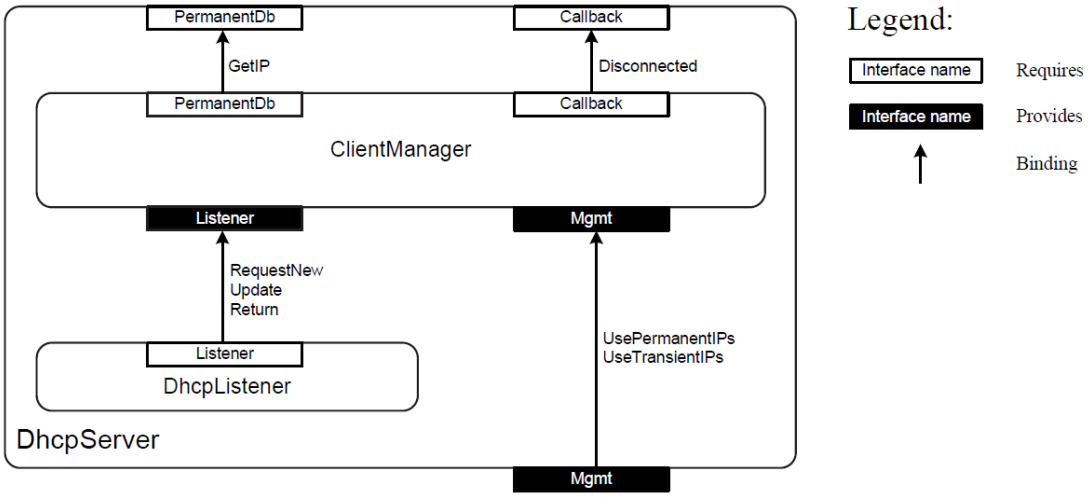


Figure 9. DhcpServer Architecture

In principle, the `DhcpServer` composite component works in two functionality modes which can be swapped via the `Mgmt` interface: (i) *DhcpServer generates IP addresses dynamically* for new clients (this is the default functionality that can be also set by calling the `UseTransientIPs` method on the `Mgmt` interface). (ii) *DhcpServer assigns IP addresses statically* based on mappings between clients' MAC and IP addresses in an external database accessible via the `PermanentDb` interface (this functionality is set by calling the `UsePermanentIPs` method on the `Mgmt` interface). When a client disconnects from the network, the DhcpServer calls the `Disconnected` method on its `Callback` interface to notify its environment about this event. As already mentioned, the DhcpServer functionality is implemented by its subcomponents: `ClientManager` and `DhcpListener`. The architecture of the DhcpServer and bindings between the subcomponents is shown on Figure 9.

BP
```
(
   !Listener.RequestNew
   ||
   !Listener.Update
   ||
   !Listener.Return
)*
```

Figure 10. Frame protocol of DhcpListener

The DhcpListener component is responsible for the "real" communication with network clients and the network infrastructure. Internally it uses existing system infrastructure to manage client nodes. Events that occur at the network level are unified by DhcpListener which converts them to method calls. As they can arrive at any time, the corresponding frame protocol has to express the inherent parallelism (Figure 10). ClientManager accepts notifications on network events from the DhcpListener and processes them either internally (`RequestNew` and `Update`) or

forwards them to DhcpServer's environment (via `Callback.Disconnected`) as part of `Return` processing. ClientManager's behavior is expressed by its frame protocol in Figure 11. The part A of the protocol represents the "*generate IP addresses dynamically*" functionality of ClientManager while the part B represents the "*assign IP addresses statically*" functionality. The parts A.1 and B.1 express the ClientManager's ability to process DhcpListener's notifications and also describe reactions to them. The parts A.2 and B.2 capture ClientManager's ability to detect client disconnections internally, resulting in a call of Disconnected. The ClientManager's functionality mode swapping mechanism is reflected in the parts A.3 and B.3: At any time, ClientManager can accept a method call requesting a mode change (`?Mgmt.UsePermanentIPs↑` or `?Mgmt .UseTransientIPs↑`), but it does not respond it immediately. Instead, it waits until the processing of all pending method calls on the Listener interface is finished and then it issues the `!Mgmt.UsePermanentIPs↓` or the `!Mgmt.UseTransientIPs↓` response. Then ClientManager is again ready to accept further calls on the `Listener` interface and respond to them according to its newly set functionality mode.

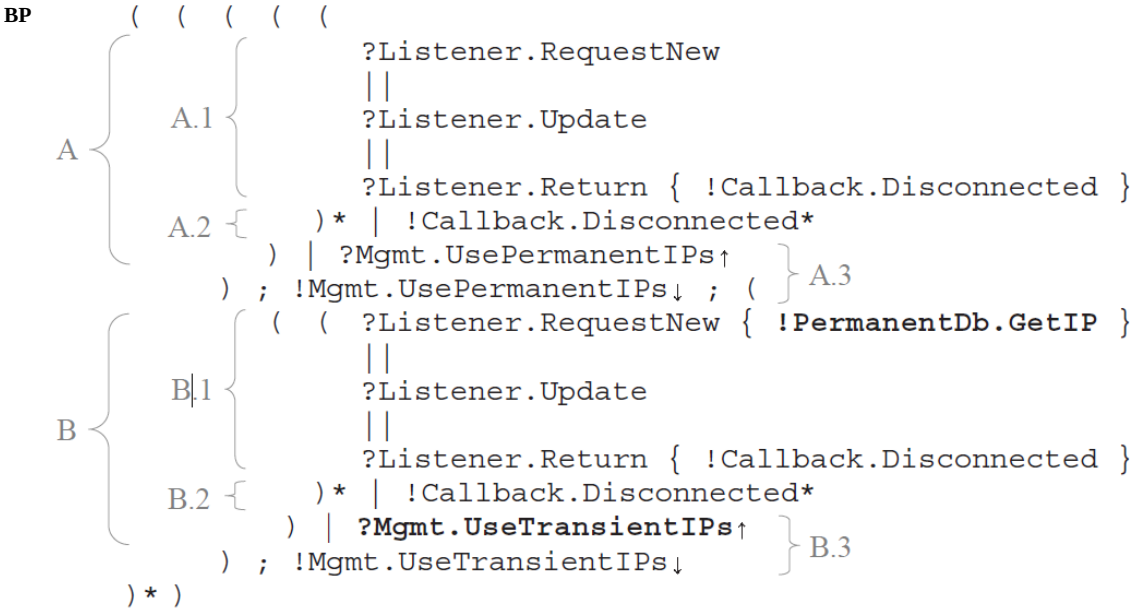


Figure 11. Frame protocol of ClientManager (The highlighted lines denote the events forming the composition error described in Sect. 2.3.3)

DhcpServer Frame Protocol

The frame protocol of DhcpServer is shown in Figure 12. The interactions between DhcpServer's subcomponents are not visible in it. However, their communication can trigger interaction with the environment of DhcpServer that is therefore visible in its frame protocol. This is illustrated by the part C of the frame protocol in Figure 12: the `!Callback.Disconnected` call can be invoked by the ClientManager subcomponent either as a reaction to an accepted `?Listener.Return` call or due to its internal detection of client disconnection; however these two causes are indistinguishable in the DhcpServer frame protocol. The part D of the protocol expresses the DhpcServer's ability to swap between its two modes.

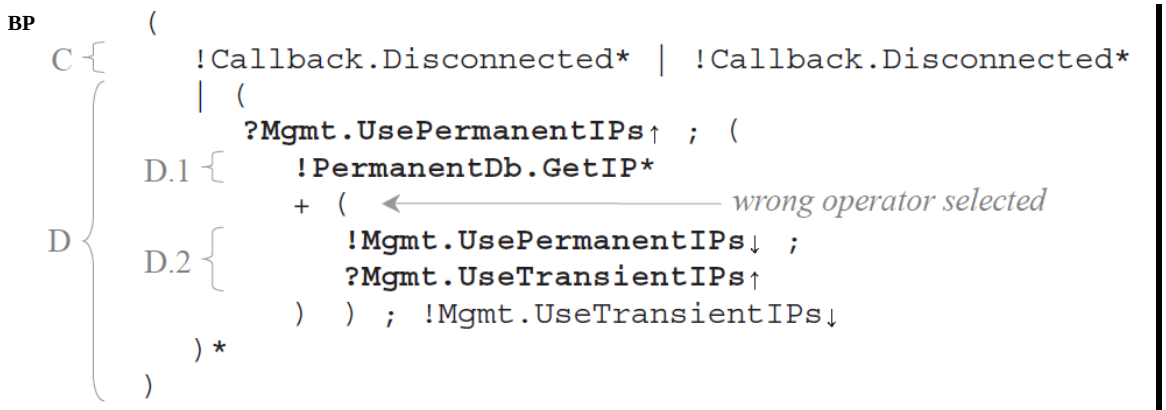


Figure 12. First version of the frame protocol of DhcpServer (Instead of +, the | operator should have been used here as demonstrated by the error trace in Sect. 2.3.3)

5.4.2 Checking for Composition Errors and Compliance

The application developer that sets up a composite component (such as Dhcp-Server) creates also its frame protocol, whereas the frame protocols of subcomponents (ClientManager and DhcpListener) are created by their respective authors. It is the developer's responsibility to check first for composition errors (horizontal compatibility) between subcomponents. The frame protocols ClientManager and DhcpListener as presented above are compatible in this sense. It should be emphasized that behavior incompatibility may occur even though the components are connected via type-compatible interfaces.

The next step in a composite component's development is to check for compliance (vertical compatibility) of its frame protocol with its architecture protocol. During the development of the first version of the DhpcServer component, the + operator was used in its frame protocol (Figure 12). However, such a protocol was not compliant with its architecture protocol. Using the behavior protocol checker, the error was found and reported by an error trace (Figure 13).

```
(S0) τListener.Return↑                (S117) τListener.RequestNew↓
(S1) τListener.Update↑                (S118) τListener.Update↑
(S2) τListener.Update↓                (S127) τListener.Update↓
(S3) τListener.RequestNew↑            (S128) τListener.Return↑
(S4) τListener.RequestNew↓            (S129) τCallback.Disconnected↑
(S5) τMgmt.UsePermanentIPs↑           (S130) τCallback.Disconnected↑
(S6) τCallback.Disconnected↑          (S171) τCallback.Disconnected↓
(S7) τCallback.Disconnected↑          (S188) τListener.Return↓
(S46) τCallback.Disconnected↓         (S189) τListener.Update↑
(S47) τListener.Return↓               (S190) τListener.Update↓
(S48) τListener.Return↑               (S191) τListener.RequestNew↑
(S49) τListener.Update↑               (S192) τListener.RequestNew↓
(S50) τListener.Update↓               (S193) τCallback.Disconnected↓
(S51) τListener.RequestNew↑           (S226) τMgmt.UsePermanentIPs↓
(S52) τListener.RequestNew↓           (S227) τListener.Return↑
(S53) τCallback.Disconnected↓         (S228) τListener.Update↑
(S54) τCallback.Disconnected↑         (S229) τListener.Update↓
(S55) τCallback.Disconnected↓         (S230) τListener.RequestNew↑
(S56) τListener.Return↓               (S231) !PermanentDb.GetIP↑
(S57) τListener.RequestNew↑
```

Figure 13. Error trace representing a compliance error

However, identifying the actual error only from such a plain error trace is not a trivial task. The key problem is that error traces of real components tend to be rather cryptic; in particular, several method calls of the frame protocol can occur in parallel. This leads to interleaving of the error-related events with other events processed in ”background”. For example, only the highlighted events on Figure 13 lead to the conclusion that the parts D.1 and D.2 of DhcpServer’s frame protocol (Figure 12) need to be processed in parallel, because the ClientManager can issue the `!PermanentDb.GetIP` call (in B.1) in parallel with accepting the `?Mgmt.UseTransientIPs↓` call (in B.3).

5.4.3 Approaches to Error Trace Analysis and Interpretation

In behavior protocols, an error trace’s end is reflected in the state space (defined by the protocol) as a state F. It is a specific feature of behavior protocols that each trace reaching F is an error trace. Hence, F is an *error state*. In consequence, an error state represents a set of error traces SF. (Note that the existence of error states is not a general feature of an LTS.) Finding all elements of SF means complete traverse of the state space. Sometimes, however, the knowledge of the whole set of error traces corresponding to an error state may be very beneficial for error cause’s identification. As the set of error traces may be huge (or even infinite), providing it as a list of traces would not be of much help. Therefore, additional forms of SF representation are needed.

Plain Error Trace

As demonstrated in Section 5.4.2, an error trace identifying a compliance or composition error may be quite long and hard to interpret. Moreover, due to the DFS tactic used, the error trace may contain states not capturing ”the essence” of the error. For example, the state subsequence S5, S226, S230, S231 of the error trace in Figure 13 also forms an error trace, but the longer one was found first. In this respect, the

other states are “not-important” ones. It is a challenge to filter out these “not-important” states (to find a canonical representation of the error trace set associated with an error state). One can imagine a filtering technique based on iterative re-searching the state space, which would take advantage of the knowledge of the depth at which the error was found.

State Space Visualization

One of the checking outputs we propose in order to make error interpretation easier is *state space visualization*. Visualization is a graphical representation of the state space associated with the protocol. For the state space related to Section 5.4.1 (DhcpServer architecture), this is illustrated on Figure 14 (only a fragment of the state space is captured here for brevity). This helps find out what the problem cause is by tracking the error trace in the state space. Apparently, state space size might be a problem here — a state space having more than 1,000 states is hard to visualize. Thus, visualizing only a part of the state space becomes a practical necessity. In this perspective, capturing only the part containing the error state and its “neighborhood” is a straightforward thought. We employed this idea with a very positive experience. Such a result still provides useful information, detailed enough to identify where the essence of an error is. Technically, our visualization outputs all the transitions leading from a state on the error trace — this helps with finding correspondence with the original protocol.

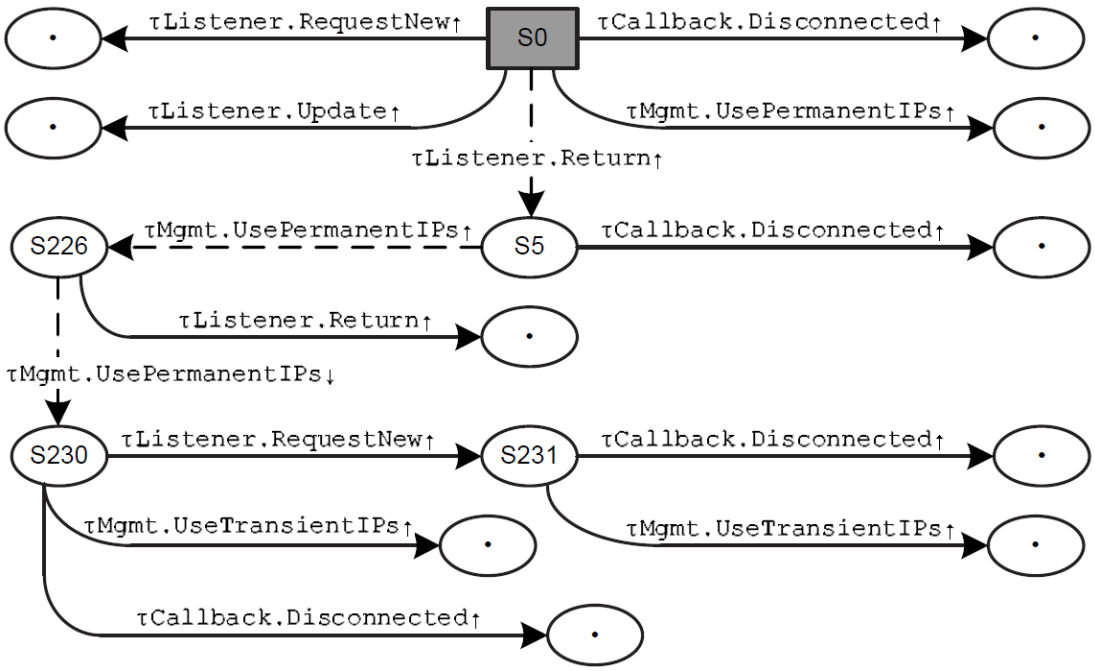


Figure 14. State space visualization — dashed lines represent longer paths omitted due to the limited space of this paper. The state S231 is the error state F.

Protocol Annotation

Another way of representing an error state are *annotated protocols*. Consider a composition of protocols P and Q via the consent operator. If the composition yields a composition error in an error state S, the state S is represented by marks <HERE>

put into P and Q, forming the annotated protocols PS and QS. For illustration consider Figure 15 where a fragment of the annotated frame protocol of DhcpServer corresponding to the error trace in Section 5.4.2 is depicted. Advantageously, there is no need to construct the entire state space, but it suffices to annotate only the protocols featuring as operands in a composition. For example, the set of error traces specified by the annotated protocol in Figure 15, together with the annotated architecture protocol of DhcpServer internals, yields the error traces:

```
BP τCallback.Disconnected↑; τCallback.Disconnected↓;
   τMgmt.UsePermanentIps↑; τMgmt.UsePermanentIps↓
   and
   τMgmt.UsePermanentIps↑; τMgmt.UsePermanentIps↓;
   τCallback.Disconnected↑; τCallback.Disconnected↓
```

There are two issues to be addressed with this technique:

(i) *Identical prefixes in alternatives.* For example, consider the following frame protocol: `(?i.m1; ?i.m2) + (?i.m1; ?i.m3)`. If an error state is to be indicated after `?i.m1`, the corresponding annotated protocol takes the form:

```
(?i.m1<HERE>; ?i.m2) + (?i.m1<HERE>; ?i.m3)
```

Even though one of the alternatives could be eliminated, we prefer keep them both to provide more context of the error.

(ii) *Transformations performed on input protocols.* In the protocol checker, the protocols are modified during the parsing process (e.g. `?i.m` is decomposed into `?i.m↑; !i.m↓` and the formatting information is lost). Therefore, exact mapping of an error state back to the source protocols may be difficult. Fortunately, the transformations typically still yield a reasonably readable behavior protocol, which, annotated, provides useful information for specification debugging.

```
BP (  (
        ?Callback.Disconnected↑; !Callback.Disconnected↓<HERE>
   )* ) | (   (
        !Mgmt.UsePermanentIps↑ ; (
           (?PermanentDb.GetIp↑; !PermanentDb.GetIp↓)*
        ) + (
           ?Mgmt.UsePermanentIps↓<HERE>;
           !Mgmt.UseTransientIps↑
        ) ; ?Mgmt.UseTransientIps↓*
   )  )
```

Figure 15. DhcpServer annotated frame protocol - simplified.

5.4.4 Evaluation

During the work on the case study mentioned in Section 5.4.1, it has turned out that combining all of the three forms of checking output is the most promising approach. Even though protocol annotation (Section 5.4.3) appears a very generic technique, in

complex cases the other checking outputs have to be also provided, since tracking all the path alternatives in an annotated complex protocol may be error-prone.

The most complex components of the case study have behavior protocols with up to 60 events; such behavior protocols generate a state space with hundreds of thousands of states. The typical errors encountered during the development of such components then generate error traces of about 100 states in length. However there were also some error states that generated error traces with several hundreds of states. It then took the developer about an hour (often even more) to identify the actual error in case only a plain error trace was available. The checking output techniques presented in Section 5.4.3 have been developed to improve debugging efficiency. During the further development of our case study application, the developers used a combination of these techniques and an average time to resolve a typical error shortened down to one third or one fourth of the original time. As for the plain error trace checking output, a problem is the existence of “local loops” in behavior of a component. Typically, with respect to the other parts of the system, the actual number of local loop traversals is of no significance in terms of error localization. These loops lengthen the error trace, making it more complex and hard to analyze. Apparently, if loops are nested, the situation is even worse. A desire is to eliminate those of “no influence” on the rest of the system. This is a challenging problem - currently, only the highest-level loops are identified and eliminated in an automated way. Annotated protocols are very similar to the approach used in Bandera Toolset [155] and PREfast [121] since they are based on emphasizing of the positions in the input protocols where a composition error has been found. Unlike in Bandera and PREfast, in behavior protocols the positions between two operations are highlighted to denote an error state.

5.4.5 Conclusion and Future Work

During the work on the project (Chapter 5) it has turned out that, besides plain error trace, additional checking outputs are needed for speeding up error detecting and debugging process. Therefore, we introduced two more approaches: (i) state space visualization, and (ii) annotated protocols. Using all the three methods in combination was found most beneficial (locating an error was then more efficient). Problems arise when checking the composition/compliance of several components described by really complex behavior protocols. The large state space generated by such a protocol causes that an error trace is typically very long and hard to interpret. Still, in our view, this is worth to pursue since we believe that the components’ compatibility problem cannot be restricted to the syntactic/type compatibility of their (bounded) interfaces [146], even though this could be checked with much smaller effort and would avoid the problems discussed in this paper; in fact, we can hardly imagine putting together a non-trivial component-based application of the size mentioned in Section 5.4.1, if the compliance checks were based only on syntactic/type compatibility of individual interfaces. Our future work is therefore focused on improving the methods currently used by the behavior protocol checker; in particular, a method for automated removing of unnecessary ”local loops” (Section 5.4.4) would further simplify the plain error trace checking output. As for state space visualization, an automated method for detecting the ”important” part of the state space (currently done by hand) is needed to simplify the resulting graphical representation of an error trace. Similar to Bandera [155] and PREfast [121], the

possibility to dynamically indicate the correspondence between a particular position in an error trace and the associated part of the protocol would perhaps further ease and speed up the debugging process.

Chapter 6 CoCoME Case-study

In this chapter we present our approach and experience of modeling the CoCoME case-study [82] in Fractal component model and its implementation in Fractal's Julia runtime and tool-chain. The CoCoME case-study was prepared for the CoCoME modeling contest [151][55] that aimed at comparison of contemporary component-oriented modeling approaches.

6.1 Modeling the CoCoME in Fractal

CoCoME

Employing Fractal in the CoCoME assignment revealed several issues that required modifications of the architecture. These modifications are presented and justified in Section 6.1.1 (Static view). Since behavior specification using Behavior Protocols is supported by Fractal, each of the components of the Trading System was annotated with its frame protocol. As CoCoME assignment does not include complete behavior specification, these protocols are created based on the CoCoME UML specification and the reference implementation and further described in Section 6.1.2 (Behavioral view). Section 6.1.4 (Deployment view) presents deployment and distribution using Fractal-specific means (FractalRMI and FractalADL). In Section 6.1.5 (Implementation view), we describe beside the basic Fractal implementation strategy also the details related to performance evaluation and estimation. Additionally, Section 6.1.3 presents behavior specification of two components featuring non-trivial behavior (CashDeskApplication and CeshDeskBus) in more detail. Behavior specification of the rest of the components can be found on the Fractal-CoCoME web page [71].

6.1.1 Static View

As the architecture of the Trading System used in Fractal differs slightly from the CoCoME assignment, this section presents the modified architecture and justifies the modifications made. In general, there are two sorts of modifications: (i) Modifications which are not directly related to Fractal and do not influence complexity of the solution, but rather contribute to the clarity of the design and the other views (in Sections 6.1.2 – 6.1.5). (ii) Modifications directly forced by specific properties of Fractal. These modifications reveal strengths and limitations of Fractal and therefore should be taken into account in the comparison between different modeling approaches.

The (i) modifications include reorganization of the component hierarchy and explicit partitioning of EventBus into two independent buses. All primitive components are left unchanged, but the composed components GUI and Application located in the Inventory component are substituted by components StoreApplication, ReportingApplication (compare Figure 16 and Figure 18). The new components more clearly encapsulate the logical units featuring orthogonal functionality, whereas the old ones merely present a general three tier architecture. The StoreApplication component encapsulates the store functionality as required by the CashDeskLine

component in UC1 (use case #1 in CoCoME assignment), whereas ReportingApplication encapsulates functionality for managing goods as used in UC3 – UC7. The Data component is left unchanged. Second modification of the component hierarchy relates to UC8, as neither the architecture in CoCoME assignment, nor its reference implementation provides a full UC8 functionality. Specifically, UC8 expects communication among EnterpriseServer and StoreServers; however no interface for the communication is present. Moreover, the reference implementation includes UC8 8 Lubomír Bulej et al. functionality as a part of UC1, which, however, should be independent. The reference implementation deeply exploits the fact that it is not distributed and accesses the shared database, which would not be the case in a real-life implementation. Therefore, the new architecture is enriched by explicitly distinguishing the EnterpriseServer component and the ProductDispatcherIf and MoveGoodsIf interfaces that encapsulate UC 8 functionality (Figure 18).

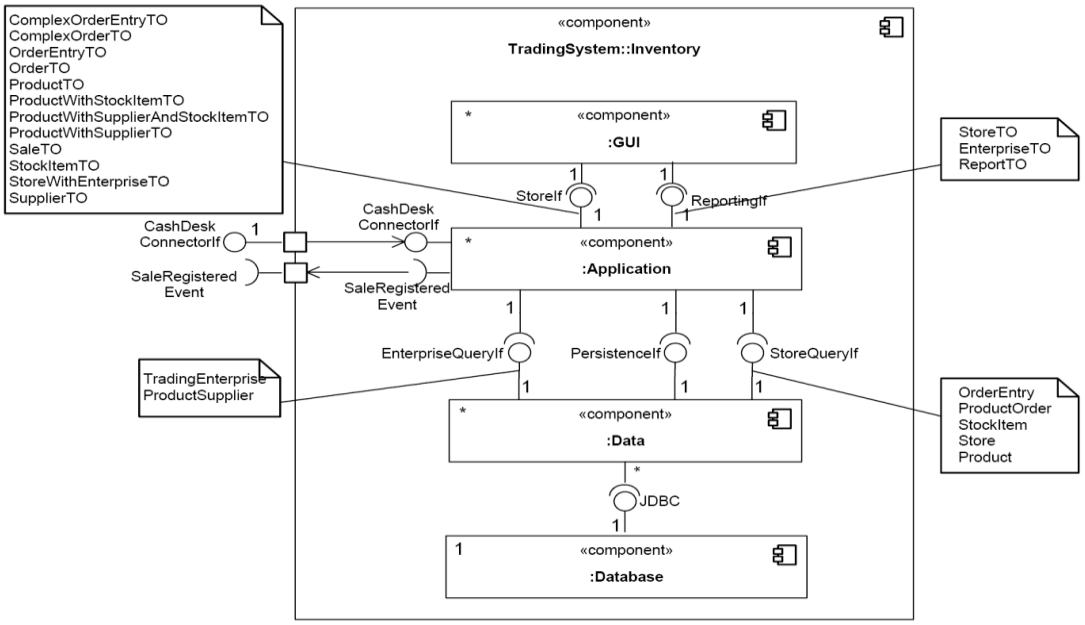


Figure 16. The original design of the Inventory component in CoCoME

EventBus from the CoCoME assignment (Figure 17) represents a composite of buses eventChannel and extCommChannel. As there is no apparent benefit of having the eventChannel outside the CashDesk component, EventBus is split into two independent buses CashDeskLineBus and CashDeskBus, which correspond to extCommChannel and eventChannel, respectively. Moreover, CashDeskBus is moved inside the CashDesk component where it more naturally belongs, since it mediates mostly the communication among the components and devices internal to CashDesk.

As to the (ii) modifications, Fractal does not support message bus as a first-class entity. Therefore, the CashDeskLineBus and CashDeskBus buses are modeled as primitive components, multiplexing the published messages to each of the subscribers (compare Figure 17 and Figure 18).

Despite the modifications made, many parts of the original design and prototype implementation are adopted even when "unrealistic", such as the CardReader component communicating with Bank through CashDeskApplication instead of directly, which presents a security threat with PIN code interception possibility. In order to share as much of the CoCoME assignment as possible, other parts of the design such as the data model and the transfer objects are left unmodified. The Fractal implementation is designed to use Hibernate and Derby database for persistency as is the case with the prototype implementation.

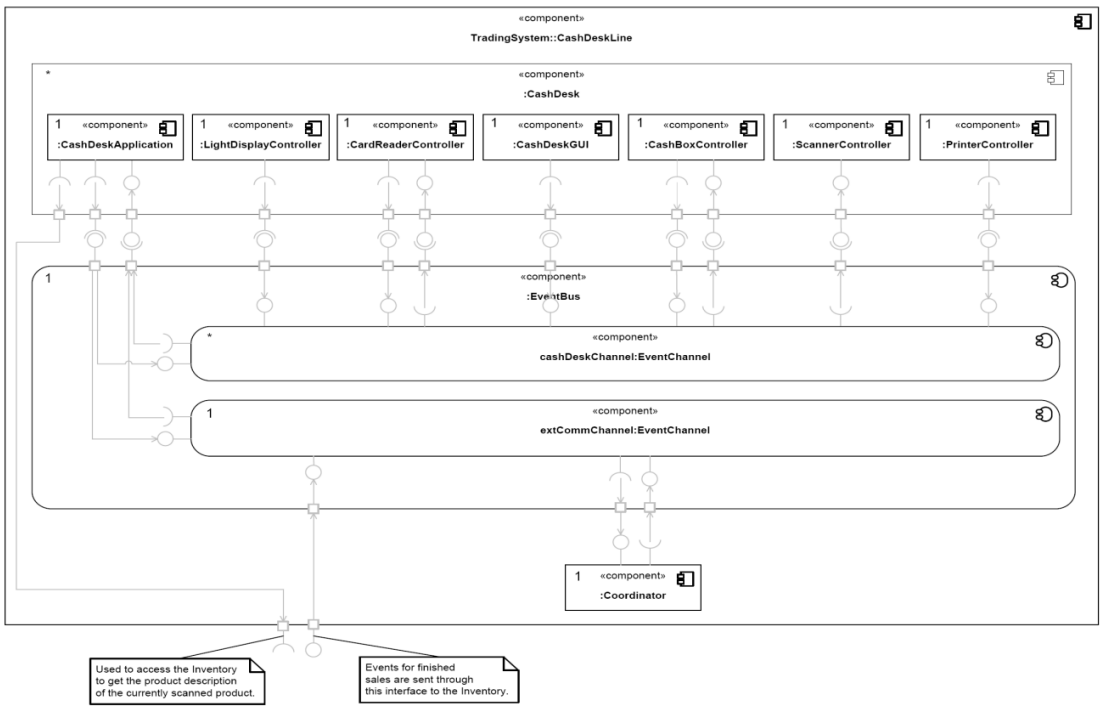


Figure 17. The original design of the CashDeskLine component in CoCoME

6.1.2 Behavioral View – Modeling CoCoME in General

The behavior protocols describing application's behavior are meant to be part of the specification of the application. Created at the application design stage, they allow developers to verify that the implementation is compliant with the design, or, in other words, that it really implements the specification. However, as the behavior protocols were not part of the specification of the CoCoME assignment, they had to be recreated from the description provided in it.

The provided specification contains only sequence diagrams and use-cases, which do not provide as precise and unambiguous specification of the application's behavior as it is required to formally verify the resulting implementation correctness (in order to be sufficient, the specification would have to include more complete UML description, like collaboration and activity diagrams or state machines). For this reason, we had to use the reference implementation provided also as a part of the specification and use both the UML descriptions and the reference implementation to create the behavior protocols for the application. A problem has however arisen during the behavior protocol development process – we found that the reference implementation is not fully compliant with the CoCoME UML specification as

provided – there are two major differences between the reference implementation and the specification: (i) missing continuation of the payment process after erroneous credit card payment – UC1, (ii) missing implementation of UC8. We solved this problem by creating two alternatives of the protocols – the first specifying the behavior imposed by the CoCoME UML specification, and the second specifying the behavior observable in the reference implementation. As our component-based implementation of the application is based on the reference implementation (we have reused as much of the reference implementation code as possible), we show later in the text that our implementation (and the reference implementation) is not exactly following the requirements imposed by the CoCoME UML specification (by formally refuting it).

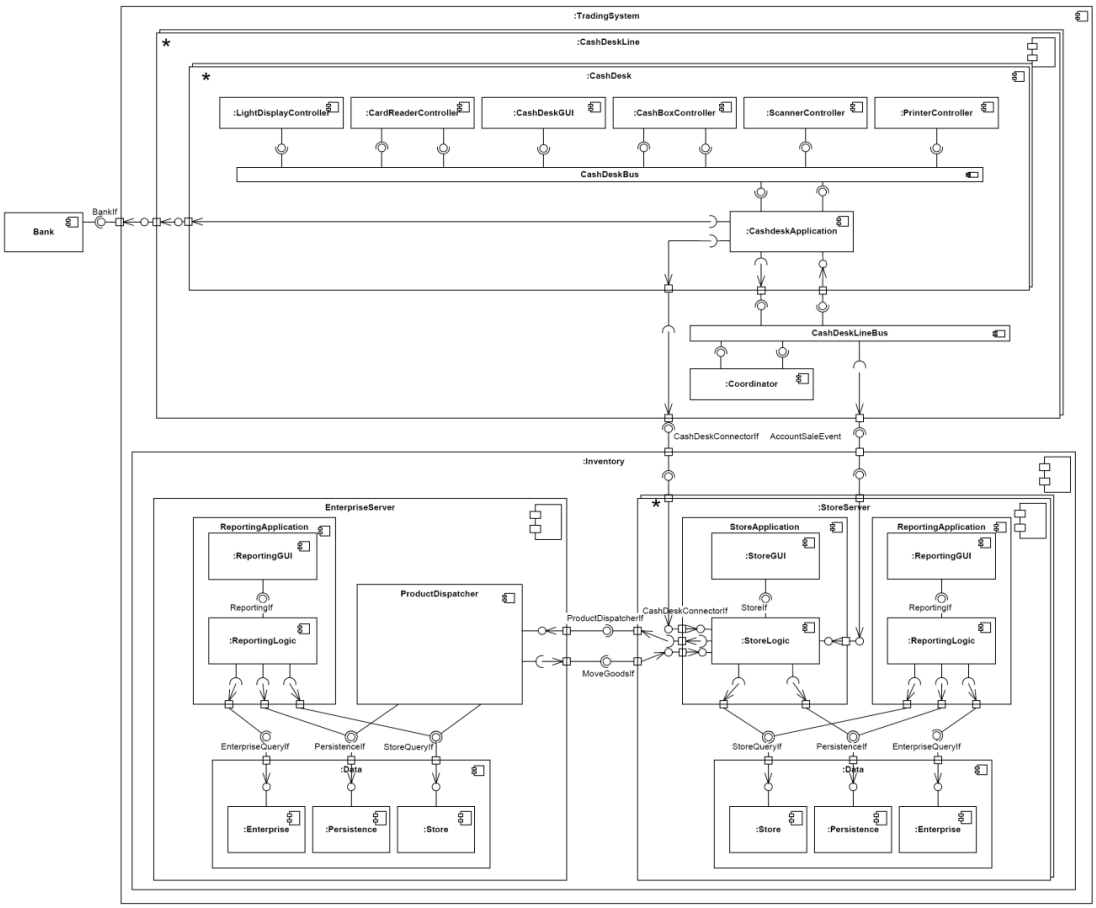


Figure 18. Final architecture, as it is used in the Fractal modeling approach

Regarding the behavior specification, it is also worth noting that we do not model the behavior of the actors (e.g. customer, cashier) specified by the UML model as we model only the software components that are part of the application's architecture. However, as the behavior of agents is observable via interfaces provided for the GUI part of the application, the behavior protocols describing the behavior of application's components also transitively impose restrictions on behavior of agents, though the actual formal verification is done against the GUI components.

We show that creating behavior protocols as part of the application specification allows precisely defining the required application's behavior early in the

development process (in the application design stage). Such specification then provides not only the global view that is required to correctly create the application's architecture, but also a per component behavioral view that can serve as a precise guide for developers of specific component implementations. Furthermore, the specification can be used to formally verify that the implementation really complies with the specification requirements and that all the application components (although each might be implemented by a different developer) are compatible and together provide the functionality (exposed by their behavior) required by the specification.

6.1.3 Behavioral View – Specification of Selected Components

This section is mostly focused on behavioral view of CoCoMe components. More specifically, it assumes that the specification of component structure, interfaces, and overall architecture is taken over from the CoCoMe assignment with the few modification mentioned in Section 6.1.1. As emphasized in Section 6.1.2, the behavior specification provided here is done in behavior protocols and stems from the CoCoMe use cases and the component behavior encoded in the Java implementation provided in the CoCoMe assignment. Since the behavior specification of the whole application is too large to fit into space reserved for this chapter, two "interesting" components (Cash-DeskApplication and CashDeskBus) were chosen to demonstrate the capabilities of behavior protocols. Interested reader may find the specification of other "interesting" components in the appendix and full specification at [71].

Demonstrating the ordinary usage of this formalism, the behavior protocol of CashDeskApplication describes the actual behavior of a cash desk. In principle, it captures the state machine corresponding to the sale process. In contrast, the behavior protocol of CashDeskBus illustrates the specific way of expressing mutual exclusion.

Since both these protocols are non-trivial, their "uninteresting" fragments are omitted in this section.

CashDeskApplication

The CashDeskApplication has application specific behavior – its frame protocol reflects the state of the current sale. It indicates what actions a cash desk allows the cashier to perform in a specific current sale state. The "interesting" parts of the protocol take the following form.

```
BP      (
        # INITIALISED
        (
             ?CashDeskApplicationHandler.onSaleStarted
        );
        # SALE_STARTED
        (
             ?CashDeskApplicationHandler.onProductBarcodeScanned{
             !CashDeskConnector.getProductWithStockItem;
             !CashDeskApplicationDispatcher.sendProductBarcodeNotValid+
             !CashDeskApplicationDispatcher.sendRunningTotalChanged
             }
```

```
)*; # <--- LOOP
?CashDeskApplicationHandler.onSaleFinished;
# SALE_FINISHED
(
     ?CashDeskApplicationHandler.onPaymentMode
);
# PAYING_BY_CASH
(
     (
     (
          ?CashDeskApplicationHandler.onCashAmountEntered
     )*;
     # On Enter
          ?CashDeskApplicationHandler.onCashAmountCompleted{
          !CashDeskApplicationDispatcher
               .sendChangeAmountCalculated
          };
          ?CashDeskApplicationHandler.onCashBoxClosed{
          !CashDeskApplicationDispatcher.sendSaleSuccess;
          !CDLEventDispatcher.sendAccountSale;
          !CDLEventDispatcher.sendSaleRegistered
          }
     )
     )
)* | (
     # Enable Express Mode
     ?CDLEventHandler.onExpressModeEnabled{
     !CashDeskApplicationDispatcher.sendExpressModeEnabled
     }
)* | (
     # Disable Express Mode
     ?CashDeskApplicationHandler.onExpressModeDisabled
)*
```

To communicate with each of the buses CashDeskBus and CashDeskLineBus, the component features a pair of interfaces (CashDeskApplicationHandler, CashDeskApplicationDispatcher and CDLEventHandler, CDLEventDispatcher). The interfaces contain a specific method for each event type that can occur on a bus. In addition, the interface, CashDeskInterface serves to get the data from Inventory.

The protocol specifies three parallel activities. The first one is the sale process itself, while the other two deal with cash desk mode switching. In the initial state, the sale process activity is waiting for SaleStartedEvent on the CashDeskBus `(?Cash-DeskApplicationHandler.onSaleStarted)`. It denotes beginning of a new sale. Then (`;` operator) BarcodeScannedEvent is accepted `(?CashDeskApplication-Handler.onProductBarcodeScanned)` for each sale item. Repetition operator (*) ensures that arbitrary finite number of events can be accepted. In reaction (the expression enclosed in {}) to each BarcodeScannedEvent, the price is obtained from Inventory. `(!CashDeskConnector.getProductWithStockItem)` . Depending on the result, the rest of the CashDesk is informed about the change of total sale price `(!Cash-DeskApplicationDispatcher.sendRunningTotalChanged)` or, alternatively (+ operator), ProductBarcodeNotValidEvent is issued `(!CashDeskApplication-Dispatcher.sendProductBarcodeNotValid)`. When SaleFinishedEvent is accepted `(?CashDeskApplicationHandler .onSaleFinished)`, the sale process reaches the payment phase which is specified in similar manner. When one sale is finished, the sale process activity returns to the

initial state to accept another sale (repetition operator *). In parallel operators (|), the cash desk performs two other activities to process cash desk mode switching events coming from either of the buses.

This simplified version of the frame protocol does not capture paying by credit card and does not cope with events not allowed in a particular sale process state.

CashDeskBus

The particular bus behavior comprises of two different aspects – events serialization and multiplexing. While the former aspect takes part in modeling "many to one" messages, the latter aspect is related to "one to many" messages. The event passing is synchronous, meaning that if an event is emitted by a publisher component, the component is blocked until all subscribers process the event. If there is another component wanting to emit a message when the bus is processing another message, the component is also blocked. Such behavior corresponds to the implementation using FractalRMI. This behavior might be prone to deadlocks, but fortunately, absence of deadlocks is one of properties we can verify using the behavior protocols.

As discussed in Section 6.1.1, the bus is implemented as a component. For every publisher and subscriber, it has an interface containing a method for every event type. As the bus component does not contain any application logic, its protocol can be generated using the information from the architecture – which components are involved in subscriber role, which components are involved in publisher role and what event types do they accept, resp. emit. This situation is not typical for behavior protocols.

The method used to model the serialization in behavior protocols follows the typical model of mutual exclusion in Petri nets [145] – borrowing a token. The protocol representing the bus is accepting events from event producers in parallel, but it does not propagate them to the subscribers immediately. Instead of it, the bus protocol is waiting for the token event which is emitted by helper protocol. As the helper protocol does not produce another event until it receives response from the previous one, the bus event propagation parts are mutually excluded. Finally, the bus protocol must have empty parallel branch accepting the spare token events. Although the helper protocol in the model produces many spare token events which are just accepted by the empty parallel branch with no other use, this is not a performance issue in the implementation. In the implementation, standard Java synchronization with passive waiting is used to achieve the mutual exclusion – important is observable behavior, the means can differ in the implementation and model.

The multiplexing is straightforward – when the bus accepts an event from a producer and the token, the event is propagated to all subscribers.

The following protocol is a fragment of the CashDeskBus protocol $P_{CashDeskBus}$.

BP

```
(?CashBoxControllerDispatcher.sendExpressModeDisabled{
    ?Helper.token{
        !CashDeskGUIHandler.onExpressModeDisabled|
        !LightDisplayControllerHandler.onExpressModeDisabled|
        !CardReaderControllerHandler.onExpressModeDisabled|
        !CashDeskApplicationHandler.onExpressModeDisabled
    }
```

```
}
)*
|
(?CashDeskApplicationDispatcher.sendExpressModeEnabled{
     ?Helper.token{
          !CashDeskGUIHandler.onExpressModeEnabled|
          !LightDisplayHandler.onExpressModeEnabled|
          !CardReaderControllerHandler.onExpressModeEnabled
     }
}
)*
     |?Helper.token*
```

The fragment captures the synchronous delivering of ExpressModeEnabled and ExpressModeDisabled events. When the CashBoxController component emits the ExpressModeDisabled event, it is accepted by the bus (`?CashBoxController-Dispatcher.sendExpressModeDisabled`). Then, after accepting the token event, the ExpressModeDisabled event is delivered in parallel to all subscribers (CashDeskGUI, LightDisplayController and CardReaderController). As the method calls are synchronous in behavior protocols, the bus waits until all subscribers acknowledge the event delivery. Then, the token is returned (the first closing curly brace) and finally, the CashBoxController is notified about successful delivery to all subscribers (the second closing curly brace). In the similar manner, the ExpressModeEnabled event is processed.

While the events from producers are accepted in parallel, which ensures that no producer can issue an event in a wrong moment, waiting for the equal token within the processing of distinct events ensures the mutual exclusion of the event deliveries, so the subscribers need not to care about parallelism. The final part of the fragment (`?Helper.token*`) accepts the unnecessary token events. As there must be a token event source, the specification must be enriched by a helper protocol P_{Helper}:`!Helper.token*`. The complete frame protocol of the Cash-DeskBus component featuring mutual exclusion is then obtained by composing the protocols $P_{CashDeskBus}$ and P_{Helper} by the consent operator - $P_{CashDeskBus} \nabla_{\{Helper.Token\}} P_{Helper}$. It synchronizes the opposite actions (`!Helper.token` and `?Helper.token`) and replaces them by single internal action.

6.1.4 Deployment View

From the deployment point of view, we introduced a few changes mainly to the middleware used in the reference architecture. These changes were motivated by the way Fractal can be distributed and by the libraries available for the distribution.

We have used FractalRMI instead of Sun RMI. FractalRMI is a library for Fractal that allows transparent distribution. The components are not aware of the fact that they communicate remotely.

In a similar fashion, we have eliminated the use of JMS, which has been used in the reference architecture for implementing buses. We have replaced each of the both busses by a component that is responsible for routing the messages. Remote communication in this case may be again transparently realized using FractalRMI.

The Fractal specification also lays out another way of solving distribution and various communication styles. It defines so called composite bindings. Each composite binding consists of a number of binding components. These components are classical components from the Fractal point of view, their responsibilities are to encapsulate or implement middleware. A significant help in implementing the composite bindings is provided by the Dream framework, which implements Fractal components that support construction of communication middleware with various communication styles, including JMS.

Our choice of FractalRMI is transparent and requires no additional implementation effort. We did not use the composite bindings and Dream also because Dream is still under development; additionally, our solution brings no restrictions to the modeled CoCoME example.

Another important aspect of deployment is the way deployment is planned and performed. In our approach, we have put the information about deployment into FractalADL. Each specified component is annotated with an element virtual-node which states the deployment node to which the component is to be deployed. The actual distribution is then realized via FractalRMI.

6.1.5 Implementation View

The Fractal implementation is based both on the Fractal architecture model of the application and the provided reference implementation. We have created a FractalADL model of the application architecture using the FractalGUI modeling tool [73], taking into account the changes mentioned in Section 6.1.4. The resulting model was then extended by hand to accommodate behavior protocol specification, because it is not supported by the modeling tool.

To speed up and simplify the development, we have used a tool to create component skeletons from the architecture model. More detailed description of the transformation can be found in Sect. 4. The functional part of the application was then adapted from the CoCoME reference implementation and integrated into the generated component skeletons.

6.1.5.1 Testing the Implementation against Use-case Scenarios

To enable the testing of functional properties specified by behavior protocols, FractalBPC allows monitoring communication on the interfaces of a component C when the application is running. The runtime checker integrated in FractalBPC automatically tests whether C communicates with other components in a way that is allowed by C's frame protocol. Any violation of the frame protocol by C or one of the components communicating with C is reported.

In addition, the reference implementation of the trading system contains a small test suite for testing the behavior of the implementation against the use case scenarios described in the CoCoME assignment. The test suite, based on the jUnit [97] framework, contains a number of tests which exercise operations prescribed by the respective use cases and verify that the system responds accordingly.

As it is, however, the test suite from the reference implementation is unsuitable for testing. The key issues are testing of crosscutting concerns, test design, and insufficient automation.

The tests attempt to verify not only that the implementation functions correctly, but also impose timing constraints on the executed operations. This makes the tests unreliable, because two orthogonal aspects are tested at the same time. Combined with rather immodest resource requirements of the application arising from the use of "heavy-duty" middleware packages for database functionality, persistence, and message-based communication, the application often fails to meet the test deadlines on common desktop hardware, even though it functions correctly.

Moreover, the tests always expect to find the trading system in a specific state, which is a very strong requirement. To accommodate it, all the applications comprising the trading system are restarted and the database is reinitialized after each test run, which adds extreme overhead to the testing process.

This is further exacerbated by insufficient automation of the testing infrastructure. The trading system consists of a number of components, such as the enterprise server and clients, store server and clients, database server, etc. Starting the trading system is a long and complicated process, which can take several minutes in the best case, and fail due to insufficient synchronization between parts of the system in the worst case. Manual starting of the trading system, combined with the need for restarting the system after each test run, makes the test suite in its present form unusable.

To enable testing in a reasonably small environment, we take the following steps to eliminate or mitigate the key issues, leading to a considerable increase in the reliability of the tests as well as reduced testing time:

- We simplify the implementation of the trading system by eliminating the GUI components, leaving just the business functionality, which allows the trading system to be operated in headless mode.
- We eliminate the validation of extra-functional properties from testing; timing properties of the trading system are gathered at runtime by a monitoring infrastructure. Validation of extra-functional system properties is independent from functional testing and is based on the data obtained during monitoring.
- We improve the testing infrastructure by automating the start of the trading system. This required identifying essential and unnecessary code paths and fixing synchronization issues between various parts of the system.

6.2 Tools and Results of Verification

Verification of an application consists of two steps. First step is checking the protocols compliance. Protocols of all components used to implement a composite component are checked against the frame protocol of the composite component. Second step is checking whether the implementation of the primitive components correspond to their protocols.

Compliance of the whole Trading System was checked using the dChecker [57] tool with positive result. The dChecker tool is based on translation of the protocols into minimized finite state machines. Then, composite state space is generated on the fly

to discover a potential bad activity error or deadlock. Moreover, in order to fight the state explosion problem, dChecker supports both parallel and distributed verification, so that the full computational power of multiprocessor and multicomputer systems is

exploited. For illustration, correctness of the whole architecture takes 192 seconds to be verified on a 2xDualCore at 2.3GHz with 4GB RAM PC. Specifically, the protocol of CashDeskApplication is translated into finite state machine consisting of 944 states. The composite state space of CashDesk features 398029 states and it takes 8 seconds to be verified (on the same PC).

Correspondence of the implementation of primitive components to their frame protocols is verified by the Java PathFinder (JPF) model checker. Since JPF, by default, checks only low level properties like deadlocks and uncaught exceptions, we use JPF in combination with the behavior protocol checker (BPC) [144]. Component environment is represented by a set of Java classes that are constructed in a semiautomated way: (i) The EnvGen tool (Environment Generator for JPF) is used to generate the classes according to the behavior specification of the environment via the component's inverted frame protocol, and (ii) the generated classes are manually modified if the environment has to respect data-flow and the component's state in order to behave correctly (original behavior protocols do not model data and component's state explicitly).

By code checking implementation of the CashDeskApplication against the frame protocol created according to the reference specification of UC1, we were able to detect the inconsistency between the reference implementation and specification of UC1 that is first mentioned in Sect 3.2. Detection of this inconsistency took 2 seconds on a 2xDualCore at 2.3GHz with 4 GB RAM PC. Code checking of the implementation of CashDeskApplication against the frame protocol created according to the reference implementation has not reported any error and took 14 seconds. Nevertheless, switching between the express and normal mode is not checked, since the environment is not able to find whether the application is in the express mode or not, and thus it does not know whether it can trigger payment by credit card (forbidden in the express mode). Moreover, we also had to introduce the CashAmountCompleted event into the frame protocol and implementation of CashDeskApplication. This change was motivated by the need to explicitly denote the moment when the cash amount is completely specified (originally, the CashAmountEntered event with a specific value of its argument was used for this purpose). Were the CashAmountCompleted event not added, the environment for CashDeskApplication would exercise the component in such a way that a spurious violation of its frame protocol would be reported by JPF.

As for run-time checking, the special version of BPC is used again. The difference is that notification is not performed by JPF, but by runtime interceptors of method calls on component's external interfaces; moreover, no backtracking in BPC is needed since only a single run of the application is checked.

When using the tools, however, the state explosion problem became an issue. Some of the behavior protocols (namely CashDeskBus and Data) originally featured prohibitively large state space. Thus, in order to fight the state explosion problem, heuristics were employed. First, CashDeskBus protocol is separated into multiple protocols (as if for multiple components), so that it can be represented by multiple

smaller finite state machines in contrast to a single unfeasibly large state machine. Second, method calls inside behavior protocol of the Data component are explicitly annotated by the thread number. This is again in order to the fight state explosion as this makes the protocol more deterministic while preserving the same level of parallelism. For these reasons, protocols on the CoCoME Fractal web page differ from the protocols described in here, as they include also the heuristics.

Chapter 7

Entities – Addressing Dynamism

Entity
EntityTR

Component-based software engineering is a methodology, which allows building software of well-defined blocks called components. A component explicitly defines its interaction points in the form of provided and required interfaces. The interaction among components is captured by so called component architecture which defines bindings (i.e., communication channels) between components required and provided interfaces. Such formalization brings important benefits in terms of documentation, analyzability, and code generation.

A component is often viewed as a black-box, which is essential for many desired features such as separation of concerns, support of product lines, etc. In the *black-box view*, all interactions of a component with its environment occur only through its well defined interfaces and any assumptions of the component regarding its admissible environment are made explicit, e.g., using a formal description of the component behavior or by specifying method contracts. This allows verifying that communicating components obey their mutual contract (in terms of method calls ordering, parameter/return value ranges, etc.).

When considering the formal behavior description of a black-box component, the behavior model must be associated with some concept in the black-box view, which is either a particular interface or a component as a whole and refer to the behavior events observable at architectural level---method calls. However, components often operate with more fine-grained concepts (e.g., instances of different objects passed as method arguments), which are not reflected on the architectural level.

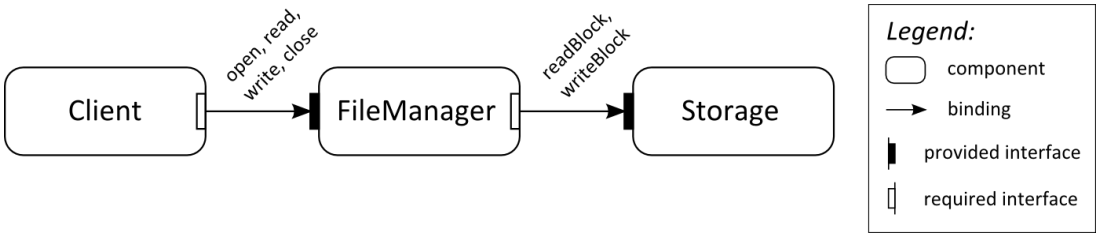


Figure 19. An example architecture featuring a FileManager component

As an example, consider the FileManager component from the architecture depicted in Figure 19. The FileManager provides a concept of a file to its environment---namely the Client component. The files can be manipulated by calling the `open`, `read`, `write`, and `close` methods on the single provided interface of the FileManager.

When modeling admissible behavior on the FileManager interfaces, it is desirable to specify that a particular file has to be first opened, then it can be read from or written toa number of times, and finally it should be closed. Standard approaches to modeling behavior of components (e.g., [4], [58], [33], [8]) consider only ordering of method calls on the component interfaces. Unfortunately, there is no support for relating method calls with the actual methods parameters. Therefore, the resulting specification cannot express the required ordering of method calls on FileManager related to the different files. Without this dependency, one can only say that all the four methods can be called in any order, which is an over-approximation of the admissible behavior and not a particularly useful one. Significant aspect of the problem is that the objects (files) are not captured at the architectural level.

Similar patterns occur very often in real applications and typically involve dynamic creation and deletion of the objects, reference passing among components and encapsulation of a number of object instances in a single component (1:N relation).At the implementation level, these objects do not necessarily have to be represented as the programing language objects. Depending on a particular component model, its underlying middleware, and design decisions, the implementation can use objects, structures, components. Therefore, to remain general enough, we will call these objects *entities*. In similar manner, references on entities may be implemented in various ways – by programming language references, pointers, handles or even string identifiers.

7.1 Goals

Our goal is to provide means for capturing entities on the architectural level. As already mentioned, such support is missing in the classical component models [35, 40, 50] with static architecture. In dynamic component models supporting architecture evolution [7, 74], the concept of entities could be represented as a dynamically created interface/component. However, formal behavior description is not as advanced in the context of dynamic component models as in the static component models. This is mainly due to the fact that the dynamic component models are too general.
Instead, we propose a conservative extension of a static component model to contain minimal set of concepts necessary to capture entities with emphasis on (i) practical implementability in a component framework, and (ii) future use of the additional information in various analysis tasks, and especially analysis of behavior compatibility among components.

However, the benefits are not tied only to the behavior modeling. In the context of the file entities example, the performance prediction analysis may estimate system performance based on the number of opened files. Documentation value of the architecture also increases by capturing the dynamic file entities, which the developers should be aware of anyway. Last but not least, capturing the entities in the architecture offers additional opportunities for code generation, e.g., the translation into handles and proxy generation might be done automatically as well as for example control of access rights to the entities.

7.2 Capturing Dynamic Entities in Architecture

In this section, different approaches to modeling entities are considered. In particular, we use means of a static component models to capture a static snapshot of a system involving entities – dynamic aspects are not modeled at this stage. The model examples serve as a basis for our proposal. Here, we first consider what existing concepts can represent entities. Later in Section 7.2, we propose extensions of these concepts to capture the inherent dynamism of entities.

For the sake of completeness, we denote the model from Figure 19 as *Solution A*. However, as already mentioned in introduction of this Chapter 7, this solution does not reflect entities at all.

7.2.1 Solution B: Entities as Separate Components

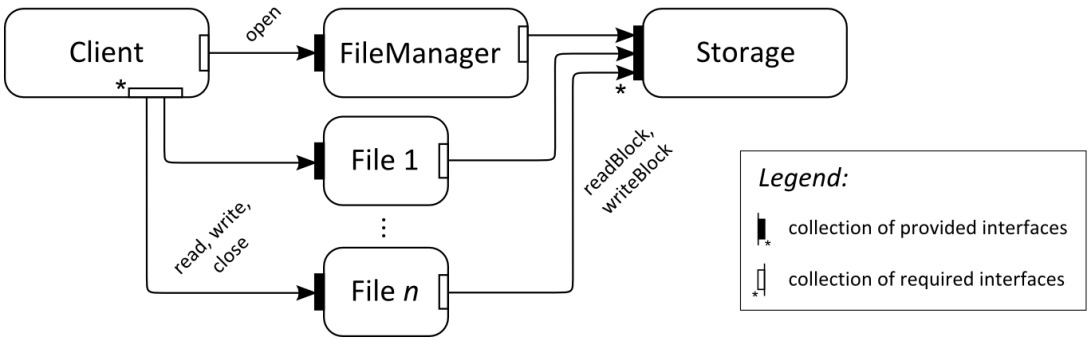


Figure 20. Entities modeled as component instances

Let us consider a case where files are modeled as separate components. Such architecture is depicted in Figure 20. In this case, the FileManager provides just the `open` method which results in instantiation of a new File component which then provides other methods related to individual files (`read`/`write`/`close`). When `close` is invoked, the particular File component instance is destroyed.In this case, individual files can be equipped with behavior description, performance information, and various quality attributes needed for different kinds of analysis. Apparently, since the application is evolving in time, the architecture in Figure 20 is just a snapshot taken in a certain moment. For instance, if the figure was capturing the structure at the beginning of the computation, there would be no File component present.

7.2.2 Solution C: Entities as Separate Interfaces

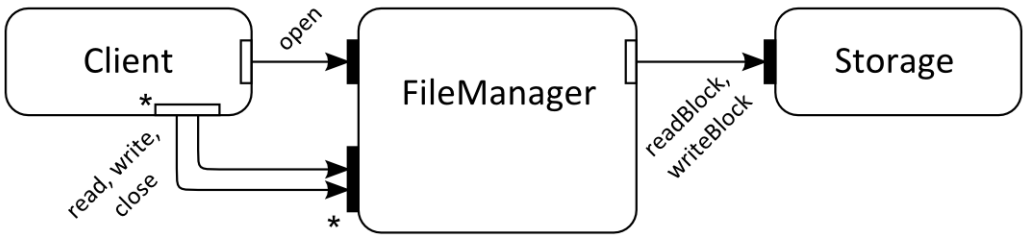


Figure 21. Entities modeled as interfaces

In some cases, using a component to model every opened file may be a too fine grained approach. The information kept for each file is not that large. In other situations, there might be also complex relations among individual entities and sub-components which should not be exposed to the rest of the architecture.

Figure 21 depicts a compromise solution where the files are modeled as separate interfaces in the architecture. The FileManager component provides an interface containing the `open` method. When it is invoked, a new interface representing the file is instantiated at the boundary of FileManager (the opened file itself will be represented by an internal component or object inside FileManager). In this case, the additional information can be associated with the interface representing the file. Notice that from the Client point of view the situation is the same as in Figure 20. Similarly to the previous solution, the architecture evolves at runtime and the figure is just a snapshot. Although the number of components remains the same (in the black-box view of the FileManager component), interfaces and bindings are being created and destroyed at runtime.

7.2.3 Requirements

The discussed approaches address entities in different ways – each with different pros and cons. When the information related to individual entities is not interesting for a developer, Solution A can be used. Since entities are not modeled at all, no additional means to capture dynamism of entities are needed.

When the developer wants to take the advantage of modeling entities, Solution B and Solution C are preferred, depending on the required granularity. From the solutions presented, it is apparent that the existing component abstractions are sufficient for capturing snapshots of the architecture involving entities. To go further and describe also the way the entities evolve, certain kind of dynamism is required. To gain as much as possible from modeling entities, the component model must provide a consistent notion of dynamic entities from all points of view – describing evolution (creation of new entities, relations among them), describing behavior of individual components referencing individual entities, and also, the entities should be identifiable in the component model runtime to allow monitoring, profiling, etc.

Before describing the proposed extension of the standard static component models by the necessary dynamism, let us first summarize a set of requirements the extension should fulfill.

> **R1**: Be strong enough to support dynamism needed in Solution B and Solution C. In particular, the extension must support dynamic component instantiation, dynamic interface creation and dynamic bindings.
>
> **R2**: Keep the architecture analyzable. The extension must be conservative in terms of number of new concepts, their complexity, and expressive power. The new concepts must be also consistent throughout the hierarchy of components to allow a compositional analysis.
>
> **R3**: Keep the documentation role of the architecture. The architecture must capture all configurations achievable by the application structure at runtime. The information should be separated from implementation details.
>
> **R4**: Preserve established concepts of component models.

7.3 Runtime vs. Design Architecture

We will use the concept of components and interfaces provided by legacy component models in two different roles: (1) to model the structure of the application as usual, i.e. to capture the application in terms of functional blocks (components) and communication among them (interfaces), (2) we will use the concept to model entities and related communication.

First, let us distinguish *design architecture* from *runtime architecture*. The runtime architecture reflects the structure of the application (including entities) in a particular instant of time during the computation. Some of components and interfaces model entities, but since it is just a snapshot no dynamism is considered and there is no need to distinguish them from other components. The information in the runtime architecture is the same as in legacy component models – static components featuring interfaces connected by static bindings and entities are formally indistinguishable from other concepts. On the other hand, the goal of the design architecture is to cover all configurations the application structure can reach in terms of number of existing entities, their location and established communication links. The design architecture can be also thought of as a template for runtime architectures.

When the dynamism of the file manager scenario is considered, certain parts of the application remain the same during the computation. Those parts are captured in the design architecture using components, interfaces, and bindings as usual. However, some components are capable to instantiate new interfaces in a collection of interfaces[2], which are bound together by new bindings (e.g., a new file was opened). Those interfaces and bindings can also disappear later (e.g., a file was closed). Nevertheless, it is always known in advance what components are able to instantiate new interfaces, what components are supposed to communicate with each other, and

[2] *Collection of interfaces* is a group of interfaces of the same type. The number is varying during the computation. Such concept is already present in some component models [35, 40].

what components represent dynamically created entities. What is not known in advance and what is being under permanent change during the computation is the number of interfaces, bindings, and components. Thus, instead of capturing the exact numbers, we propose to capture in the design architecture the information known in advance using new concepts of *proto-bindings* and *proto-components* as described below:

Proto-binding defines a location in the architecture where the bindings can be established. The proto-binding has two end-points and serves as a template of regular bindings that can be established between the end-points at runtime. The proto-binding end-point can be either a single interface or a collection of interfaces.

Proto-component represents a template of a component which may appear in the runtime architecture at the certain place. The proto-component is connected to interfaces of other components.

The concepts of proto-binding and proto-component allow enriching design architecture by information about dynamically created components and interfaces. The proposed degree of dynamism is designed with entities on mind.

Let us reconsider the Solution C (Figure 21), modeled using the proposed concepts. In Figure 22, the design architecture of Solution C is depicted. While the interface for opening files of FileManager is connected to Client by binding, interfaces for individual files and related bindings are not captured since their number varies during the computation. However, the corresponding collection interfaces are connected by the proto-binding to identify places where dynamically created bindings can be instantiated.

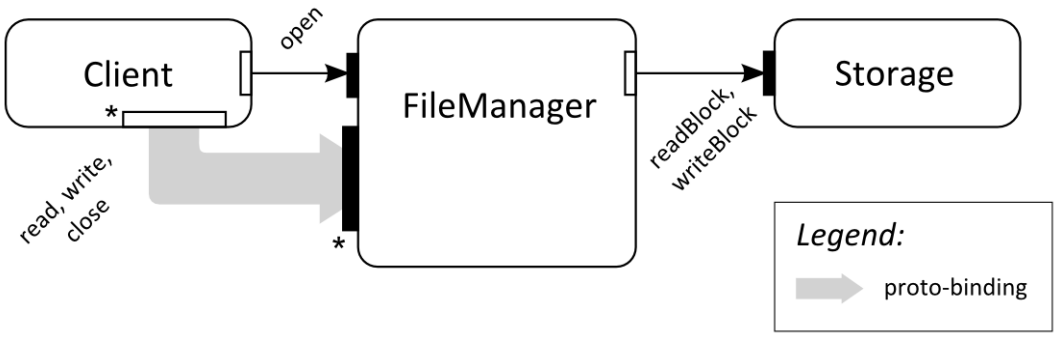


Figure 22. FileManager example - design architecture

The runtime architecture in Figure 23 captures the structure of Solution C at a certain moment at runtime. Currently, there are two files provided by FileManager to Client. Bindings between interfaces representing individual files are established with respect to the proto-binding from the design architecture.

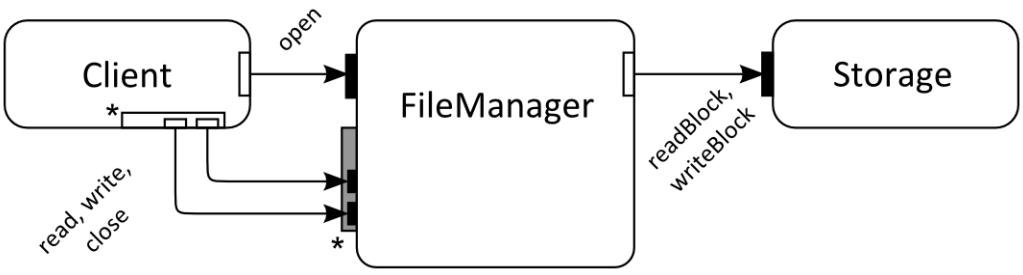


Figure 23. FileManager example - runtime architecture

The design architecture in Figure 22 does not state whether the FileManager component is primitive or composite. If the component is primitive, the implementation of the `open` method just creates a new interface instance which is consequently bound to the interface of Client (illustrated by an example in the introduction of Section 7.2.2). On the other hand, if the component is implemented by composition of other components, dynamic entities can be represented by separate components. In such case, proto-components are used (illustrated by an example in Section 7.4.4).

7.4 Entity Based Reconfiguration Actions

In Section 7.3 the concept of proto-bindings was introduced. The goal of this section is to define mechanisms controlling creation of bindings templated by proto-bindings. The proposed mechanisms are specially designed to support the concept of entities as introduced in Section 7.2 and fulfill all the requirements R1 to R4 established in Section 7.2.3. Our proposal is structured into two parts:

1) To meet the requirements R2 and R3, we propose that bindings templated by proto-bindings should not be allowed to be created or destroyed arbitrarily. Instead, these architectural changes should be triggered only by *entity references* passed among components.

2) To capture the relationship between the data flow of entity references and the supported architectural changes, we propose four basic reconfiguration actions used to annotate component interfaces -- the reconfiguration actions, defined as part of the design architecture, constrain where, when, and which architectural changes can happen at runtime.

In order to show a simple example of a design architecture using the proposed reconfiguration actions, a short overview of all four reconfiguration actions and their properties follows (more details are provided later in section 7.4.2):

To meet the requirements R2 and R4, the reconfiguration actions should be defined in a way that they can be triggered by the events visible to the component system. For a typical component system, method calls are a common observable event, therefore we allow any architectural changes defined by reconfiguration actions to be triggered only as a reaction to a method call among components. All reconfiguration actions are associated with an entity reference argument or return value of an interface method and have another target interface or collection of interfaces

specified (the target interface or collection are expected to be one end of a proto-binding). The proposed actions are:

a) *link*, creating a new binding templated by proto-binding leading from the target interface and associating it with the entity reference,

b) *unlink*, destroying the binding associated with the entity reference,

c) *create*, publishing/associating the associated entity reference via/with the target interface,

d) *destroy*, removing the association of the entity reference with the target interface, making the entity reference unavailable.

If the target of a reconfiguration action is a collection of interfaces, the *link* and *create* actions will create a new interface instance in the collection and the entity reference is associated with it, the *unlink* and *destroy* actions will remove and destroy the interface instance.

Figure 24 presents a basic example illustrating behavior of reconfiguration actions[3]. The Client component is allocating multiple entities (i.e., opening multiple files) from the FileManager server component (this follows the motivation example presented in Section 7.2). Each time the Client calls the `open` method of the IA interface it will receive a reference to a new entity (a newly opened file). The `open` call raises the following actions: (1) the *create* reconfiguration action on the return value of FileManager provided `open` method ensures a new interface is allocated in the collection of provided interfaces IB and it is associated with the returned entity reference, (2) the *link* reconfiguration action on the return value of Client required `open` method ensures a new interface is allocated in the collection of required interfaces IB and a new binding templated by the proto-binding is created. Client can then interact with the entity by calling the `use` method repeatedly via the interface IB instance associated with the acquired entity reference. When the Client decides to stop the interaction, it will call the `close` method. The associated *unlink* reconfiguration action implies the `close` is the last call on this binding and will destroy the binding and remove the instance of the required interface at the end of the `close` call. Similarly, the *destroy* reconfiguration action ensures the instance of provided interface IB is removed from the FileManager collection.

[3] In all figures the reconfiguration actions are marked by a `@` prefix to enhance readability, actions associated with an argument or return value are added before that argument or return value, actions associated with a method are added after the method declaration.

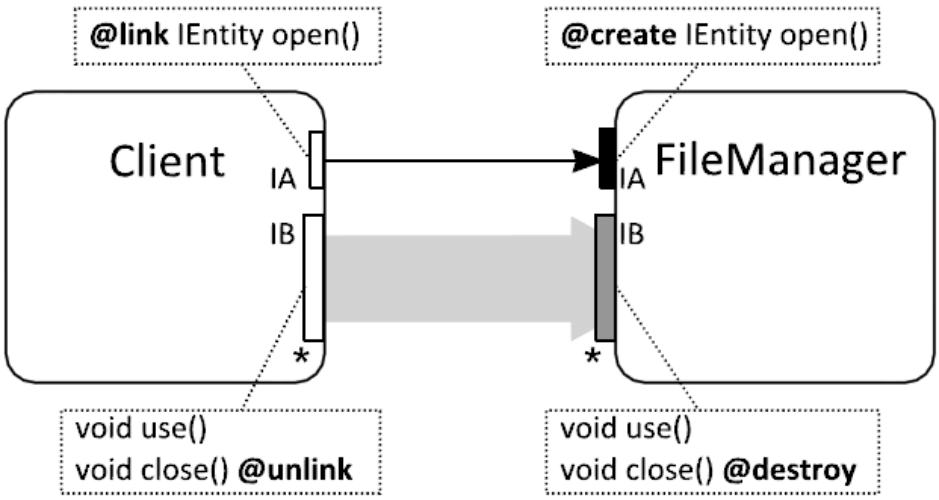


Figure 24. Example – Client/FileManager

7.4.1 Entity References

All entity references representing entities have to originate from somewhere in the component architecture. More precisely, the first component publishing the entity reference in the architecture can be defined as an *owner* of the entity reference (and the entity behind it). We aim to support two types of entity reference owners: (i) a primitive component publishing an internal data structure or object, (ii) a dynamically created component publishing references to its own interfaces -- these are defined later in Section 7.4.4. The owner of an entity reference is known in the architecture only at the exact level of nesting, where the owner resides. Everywhere else in the architecture entity references fall into two groups at a certain level of nesting:

1) *Type A*, no information about the entity reference is available to the component system, thus it can be only passed to other components, but cannot be used to establish any bindings,

2) *Type B*, the entity reference has been published via a reconfiguration action. The interface used to publish the entity reference on such a component is then defined as a *local source*; reconfiguration actions can be applied only to this type of entity references.

If the owner component of an entity reference is known at a certain level of the architecture the entity reference is supposed to be of type B and the local source is defined to be the source interface of the owner. Entity references identifying the same entity (originating from the same interface of the owner) can be of both types A and B on different levels of nesting.

To simplify the description of architecture reconfiguration actions other criteria can be used to further divide the entity references into two disjoint groups:

1) *Entering references*, i.e., entity references passed as input arguments of methods in provided interfaces, or as output arguments and return value of methods in required interfaces.

2) *Leaving references*, i.e., entity references returned as output arguments and return value of methods in provided interfaces, or input arguments of methods in required interfaces.

7.4.2 Basic Reconfiguration Actions

The goal of this section is to elaborate the four basic reconfiguration actions that were introduced in the overview at the beginning of Section 7.4. To the general properties of reconfiguration actions, the following should be added:

1) A reconfiguration action is always defined on an interface instance of a particular component and not generally on an interface type. As illustrated by examples in this section, a method of one interface type can have, and typically will have, associated different reconfiguration actions in different contexts (e.g., the difference in provided and required interface).

2) The actions can be associated not only with a direct argument of a method, but also with a method itself. Then by stating an action is associated with a method we mean the action is in fact associated with the "*this*" hidden argument of the method, i.e., it influences the reference on which the methods call occurs.

3) A reconfiguration action can be associated only with entity references that are of type B in the given context, i.e., the local source (interface) of the entity reference is known.

The section concludes with complete definitions of each of the four basic reconfiguration actions:

a) *link*, creates new binding templated by a proto-binding leading from the target interface of the action. The other end of the proto-binding has to be a local source of the entity reference the *link* action is associated with. On composite components, the *link* also makes the target interface the local source of the entity reference for the immediate lower level of nesting inside the component with the target interface, i.e., the *target component*. Thus, the *link* action defines the entity reference to be of type B at the lower level of nesting. If the *link* action is omitted in the method specification, the entity reference would be only of type A in the lower level of nesting context, i.e., subcomponents would be only able to pass or store the reference, but would not be able to create a binding using the *link* action and call methods on the reference.

   On *entering references*, the action executes when the entity reference is received – i.e., during invocation of an incoming call with input references and during return of an outgoing call with output references. Using the action on *leaving references* makes sense only in the context of a caller – then the action executes during the call invocation.

b) *unlink*, undefines the target interface as the local source of the associated entity reference at the immediate lower level of nesting and removes the binding from the target interface to the local source at the level of nesting the target component resides.

   On *entering references*, the action executes always at the end of a method call – i.e., when returning from an incoming call or when an outgoing call returns. The *unlink* action can be used in both caller and callee contexts on *leaving references* and also executes when a method call ends. The unlink action can be associated with method arguments, as well as methods themselves.

c) *create*, on primitive components, it prepares the associated entity reference (directly representing the internal state of the component, e.g., an object instance) to be sharable, plus defines the component as the owner of the entity reference, implying the create action target interface becomes the local source of the entity reference.

   On composite components (that, if not dynamically created as defined in Section 7.4.4, cannot own entity references), the *create* action creates a new internal binding templated by proto-binding leading to local source of the entity reference at the immediate lower level of nesting inside the target component. Again, the target interface becomes the local source of the entity reference at the level of nesting containing the target component.

   Similarly, as the *link* action makes the associated entity reference type B in the inner context of the target component, the *create* actions makes the entity reference type B in the outer context of the target component, i.e., at the same level of nesting the target component resides (component environment). Without the *create* action the entity reference would be only of type A to the component environment.

   The action is valid only on *leaving reference*} and always executes at the time the entity reference is being passed – i.e., in caller context, during the method invocation and in callee context, during the method return.

d) *destroy*, undefines the target interface as the local source of the associated entity reference and, on composite components, also removes the internal binding leading to the internal local source of the entity reference.

   The action, being an inverse to the *create* action, can be used only on *entering references* and again executes as the reference is being received – i.e., in caller context, during method return and, in callee context, during method invocation. The *destroy* action can be associated with method arguments, as well as methods themselves.

7.4.3 Examples of Basic Reconfiguration Actions

In this section, we present other typical examples of using different reconfiguration actions at the level of design architecture to form a description of the allowed

architectural evolution. The first example was presented in the introduction of Section 7.4.

The second example (Figure 25) shows the importance of timing of architectural change denoted by each reconfiguration action. The example represents a common pattern of passing a callback reference -- the entity reference is passed in opposite direction than in the first example. The binding to Client's entity (the callback) will be established at the beginning of the `performWith` method call, allowing the Worker to call back to Client during the call. At the end of the originating call the binding is destroyed again – so that the Worker is not allowed to call the Client out of the specific window provided by Client via the `performWith` call.

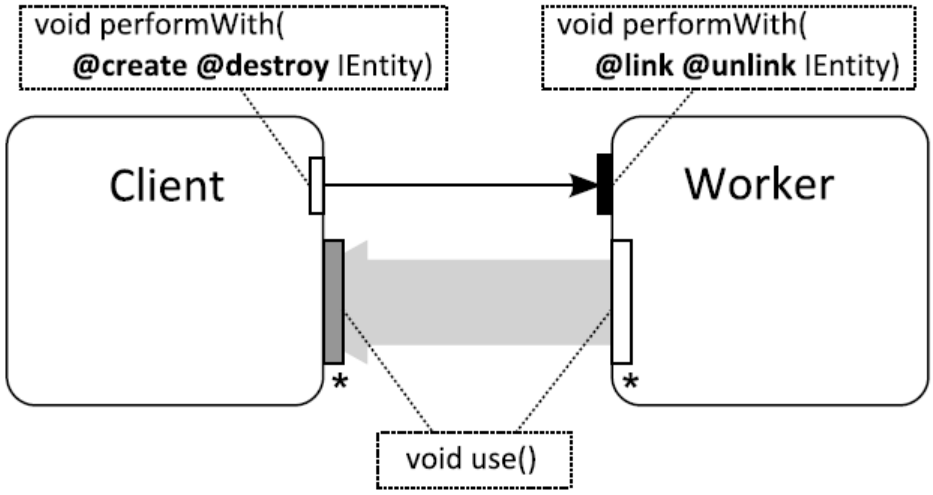


Figure 25. Example – Callback

The third example (Figure 26) shows the behavior of reconfiguration actions in a context of nested components (if we no longer look at the Client from Figure 24 as on a black box) and also illustrates component ability to just pass the received entity references without a need to create a binding to the originating component. An important note is that making the Client a composite component does not change the reconfiguration actions on its frame, but its behavior is refined by the reconfiguration actions associated with its subcomponents. The Security component opens the entities on Server, but does not use them directly (only passes them to the Worker component). This way, no reconfiguration actions are needed on any of its methods. On the other hand, the Worker component needs a binding to interact with Server entities, so the *link* action is required on the method argument where it receives the entity reference – i.e., on the `performWith` method. Similarly to the first example of the whole Client frame, the *unlink* action is required on the `close` method. Worth noting is also the inherent mechanism of partial building of bindings from Worker component back to the Server component – the first half (between Client and Server) will be created at the end of the open call, but the second half (between Worker and Client frame) won't be created until the beginning of the `performWith` call. Should the Server component be also composite, the same partial building would occur inside it as the `open` method call returns up through Server hierarchy.

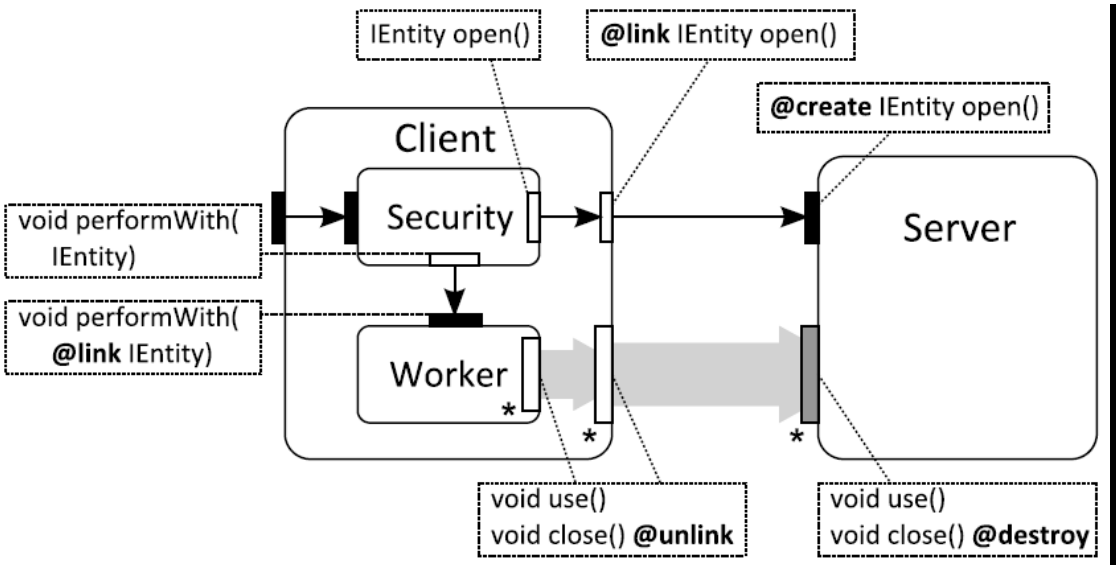


Figure 26. Example – Passing a reference through a composite component frame

7.4.4 Reconfiguration Actions for Dynamic Components

The presented concept of dynamically created bindings over proto-bindings controlled by reconfiguration actions can be naturally extended to a concept of dynamically instantiated components from proto-components. Dynamic instantiation is however a much more complex task. The most challenging issues are the location of newly created components and the related need for their initialization. As a general evaluation of all possible options in dynamic component creation is beyond the scope of this paper, we present two reconfiguration actions – *new* and *delete* specifically targeting the scenario of encapsulated entities where the dynamic components need to be created at the callee side.

An important difference from previously proposed basic reconfiguration actions is that the *new* and *delete* actions are defined at the level of the architecture and not at the level of component frames – i.e., the actions are added not by the component developers, but by the architecture designer. Another difference is they are never associated with a method argument or a reference but always with a whole method instead. Let us describe the new reconfiguration actions in more detail:

a) The *new* action can be most easily described on an example (see Figure 27). The *new* action can be associated only with methods on unbound interfaces and only methods without input arguments are allowed. The action has also one proto-component (File in Figure 27) associated with it – each time a method with *new* action is invoked a new component from that proto-component template is instantiated. All the output arguments and return value of a method with a *new* action then correspond to provided interfaces on the proto-component, i.e., also on each of the dynamically instantiated components, and is used to pass references of these interfaces to the calling component (FMLogic in Figure 27). An important feature of the *new* reconfiguration action is, that all provided interfaces of an instantiated component templated by a proto-component become local sources of the corresponding entity references returned from a *new* annotated method. From

this point on all references to instantiated component interfaces are handled in the standard way as other entity references. As illustrated on Figure 27, if FMLogic needs to call methods on IInit interface, the proper argument of `newFile` method needs to be associated with the *link* action. On the other hand, the IFile interface is directly passed as a return value of the `open` method call, so no reconfiguration actions are needed. Note that `link` action is added to the `newFile` method by the FMLogic component designer, but the *new* action is added later by the designer of the whole FileManager architecture.

A great advantage of the proposed *new* action is that it can be replaced by actual binding to another component that will provide entity references instead. This change is completely transparent and does not influence behavior or associated basic reconfiguration actions of the FMLogic component itself.

b) The *delete* action behavior is similar to the *destroy* action for interface bindings. At the end of the associated method call the dynamically instantiated component being called is destroyed – all bindings connected to it are destroyed as well. Such a component is then unreachable via standard method calls and can be stopped by the standard means of the component system.

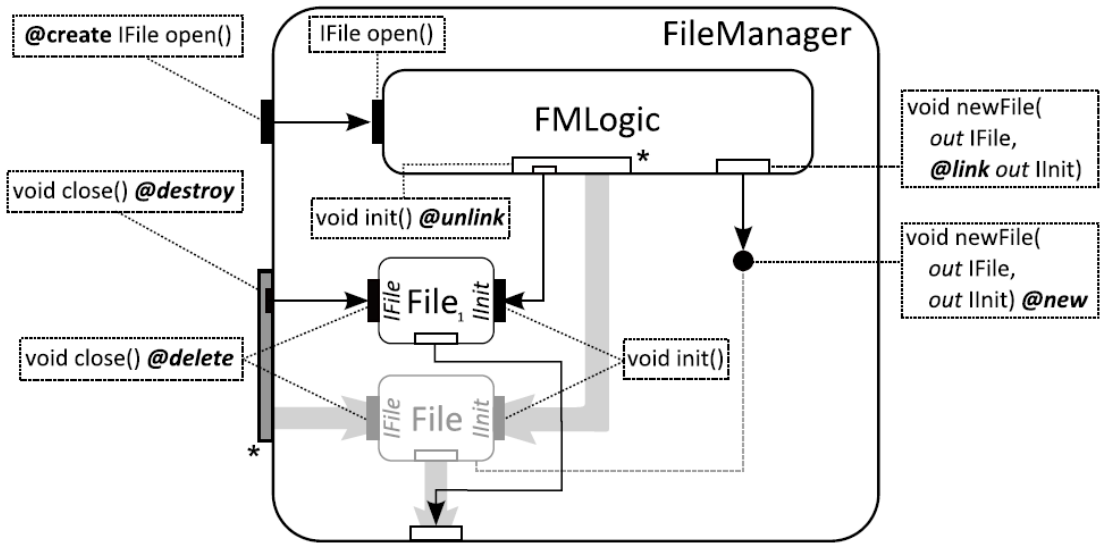


Figure 27. Example – Component instantiation from a proto-component

7.4.5 Conclusion

In this chapter, we have so far presented a way of capturing dynamic entities (e.g., files, database handles, and session objects) in a component model. Our approach allows capturing the dynamism in the initial design architecture using the proposed concepts of *proto-bindings* and *proto-components*, which explicitly document possible future bindings and component instances. Further, we have introduced six reconfiguration actions, which describe at the design level when and how the runtime architecture evolves. This way, we lay down basis for more precise modeling and

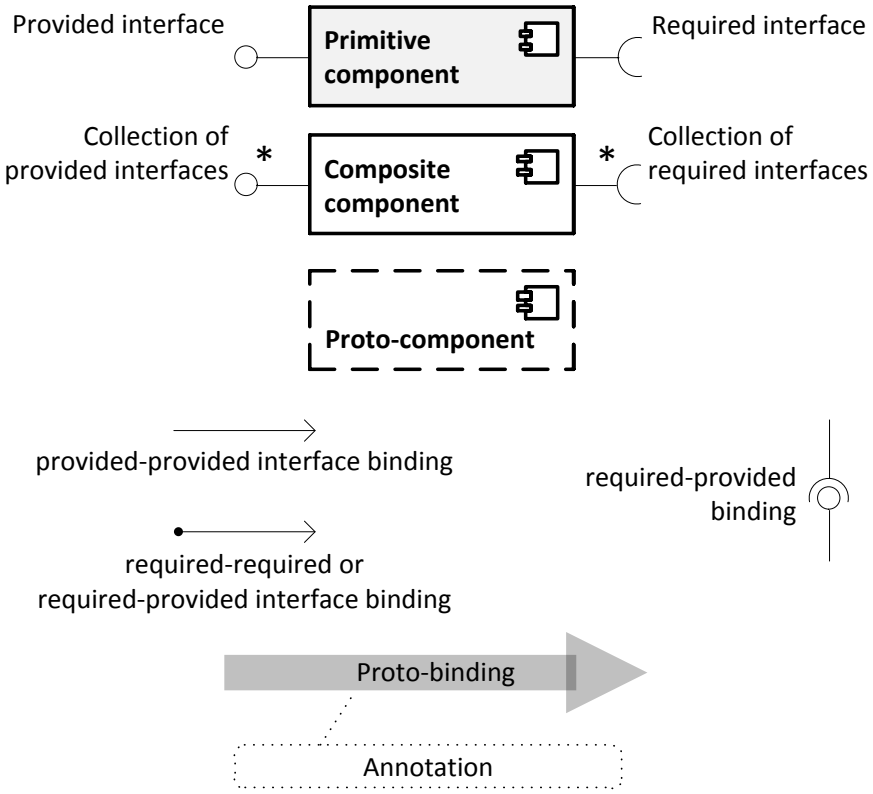
code generation, as we have also pointed out in this paper. The proposed approach works seamlessly both for flat and hierarchical component models. As for the future work, we plan to focus on adjusting our formalism for behavior modeling to reflect the proposed approach and also to focus more on a general way of component instantiation and initialization.

7.5 Evaluation – Enhancing the CRE Case-study Model

The goal of this section is to verify the concepts presented in this chapter so far and to show there are viable to model complex component architectures. Target application selected is the demo application from the CRE case-study – in Section 5.3.1 we have presented the problems in modeling the original Token component using the existing CBSE concepts. In the original architecture (which was up to now inherently static) the Token component had to be represented as a single instance, whereas in the real application it would stand for a varying number of Token instances that would be created and destroyed dynamically at runtime according to needs of clients connecting to the application. Furthermore, there were multiple points in the architecture where the Token component instances can originate from (FlyTicketDatabase component – either directly or resent via FrequentFlyerDatabase component; or AccountDatabase component) and each of the creators could provide a slightly modified version of Token component (with or without CustomToken inner component).

As the new architecture is intended to verify the dynamic entities concepts, the whole CRE case-study application has not been modeled – the irrelevant parts have been omitted from the architecture to keep it easily readable (so the figure illustrating it can fit to a single page) – these are namely: Firewall and DhcpServer component, all the services outside of the actual component architecture (remote services, clients, web application, etc.), and the CardCenter and AccountDatabase components (while these components play a similar role in the Token instantiation as the FlyTicketDatabase and FrequentFlyerDatabase components do [that are modeled], our solution with dynamic entities is designed in a consistent and generic way, and the interconnection of AccountDatabase to the Arbitrator component would be the same as for the FlyTicketDatabase and Arbitrator components, thus to further simplify the architecture the AccountDatabase has been omitted as well). Also the internal components of the FlyTicketDatabase component have been reduced to a single representative, the AfDbConnection component. The architecture of the other Connection components and their composition into the FlyTicketDatabase component would be exactly the same as is the design of the AfDbConnection component.

Furthermore the component interfaces were simplified to contain only methods relevant to dynamic architectural changes for similar reasons. The following table summarizes the symbols used in figures illustrating the architecture (note that interface instances without annotation contain only methods that have no reconfiguration actions associated with them or with any of their arguments or return value):



We in fact provide two variants of the new CRE case-study architecture: (1) one trying to match the original application as closely as possible (Figure 28, described in Section 7.5.1), (2) the other enhanced one that exposes a more advanced functionality than was needed in the CRE project, but that is a natural evolution of the original application to illustrate the dynamic entities are suitable even for more complex scenarios (Figure 29, described in Section 7.5.2).

In order to seamlessly support the dynamically instantiating Token components as well as possibility of their multiple variants, the key difference to the original architecture is made in both variants of the new architecture: the Token component is transformed into a dynamic entity and is moved outside of the Arbitrator component's scope into the scope of Token's respective creators. The Arbitrator component now only knows about `IToken` interface references bound to its `IToken` collection interface – this is a key enhancement of the original architecture, as the Arbitrator component is not bound to specific Token implementation anymore, thus the black box principle is strengthened in the architecture (that was a key goal to achieve in component-oriented architecture [30]). Now each of the three components (FlyTicketDatabase, FrequentFlyerDatabase and AccountDatabase) that can provide Arbitrator with new Token instance references can implement the Token entity in any way that is most reasonable to them. The FlyTicketToken component, that represents Token created by the FlyTicketDatabase component, is designed as a composite component and its internal subcomponent for reusability elsewhere in the architecture. This is the reason for existence of the unbound `ICustomCallback` interface of the ValidityChecker component (it would be used in AccountDatabase's implementation of Token component, which would extend the architecture by its own subcomponent of Token bound to the `ICustomCallback` interface on ValidityChecker component).

7.5.1 Basic Architecture with Entities

The basic architecture is depicted on Figure 28 – both Arbitrator and FrequentFlyerDatabase are primitive components in the architecture, only the FlyTicketDatabase is a composite component. It is designed to be generic, thus the Token component is not instantiated directly by the FlyTicketDatabase, but the task is forwarded to the AfDbConnection component. The process of creating a new Token component based on fly ticket ID submitted by application's client is initiated by the Arbitrator component, that receives the client request. The whole process can be divided into several steps:

1. The Arbitrator component creates callback object specific for the new Token component to be created, and exposes it as an entity via its `ITokenCallback` interface. The actual exposure is done by Arbitrator's call to `IFlyTicketDb.CreateToken` method on the FlyTicketDatabase component due to the *create* reconfiguration action annotation on the `ITokenCallback` argument. Note, that the Arbitator will hold one callback object for each Token component it creates in this way and uses them as a unique identifier to track request from Token components.

2. The FlyTicketClassifier (after choosing a correct component representing the specific airline – AfDbConnection for Air France in the example) will pass the request to the AfDbConnection component. The *link* annotation on the `ITokenCallback` argument of `CreateToken` method will expose the Arbitrator's callback entity (object) reference to the internals of the AfDbConnection component.

3. The requested token will be represented by a new instance of FlyTicketToken component instantiated from the proto-component by AfDbConnectionCore calling the `NewToken` method (annotations on both ends of `NewToken` method ensure correct composition of the FlyTicketToken component to its neighborhood). Before returning the `IToken` (FlyTicketToken instance reference) reference back to components at higher levels of nesting, the AfDbConnectionCore component will initialize the FlyTicketToken via its `ITokenInit` configuration interface and yield further communication with the token due to the *destroy* reconfiguration action annotation on the `SetTimeout` method.

4. As the `CreateToken` method calls are finished at each level of nesting, the FlyTicketToken instance reference (typed to `IToken` interface) will be returned and, due to correct reconfiguration annotations on the `CreateToken` return values, new binding is gradually build from the FlyTicketToken component instance through the composite component frames up to the Arbitrator's `IToken` collection interface.

Note the FlyTicketClassifier component does not have any proto-binding linked to it, as is does not need to communicate with the entity (component instance) behind `IToken` interface returned from `AfDbConnection.CreateToken` call nor with the Arbitrator's callback entity referenced by `ITokenCallback` argument of its `CreateToken` method. The FlyTicketClassifier simply passes the `ITokenCallback`

reference down to the lower levels of the architecture and the `IToken` reference up to the higher levels as well. Everything else is managed by the annotations with right reconfiguration actions.

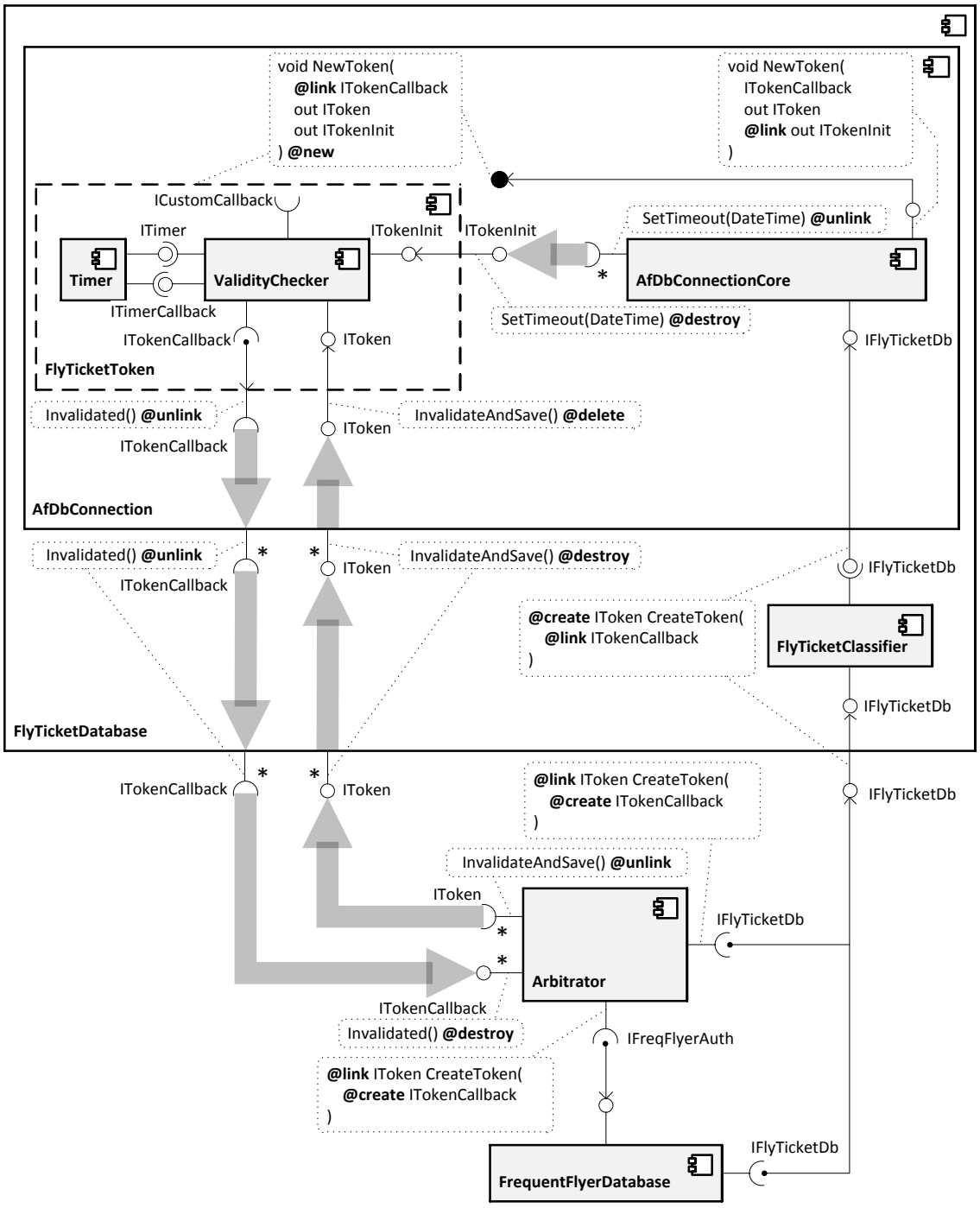


Figure 28. Basic architecture of the CRE case-study with entities.

The FrequentFlyerDatabase component in Figure 28 is implemented in a similar way the FlyTicketClassifier component is. As it only translates a frequent flyer ID into a valid fly ticket ID, which it in turn uses to query the FlyTicketDatabase for a new Token, it does not have to create its own Token instance. Thus it passes

`ITokenCallback` and `IToken` instances down and up the architecture without change similarly as the FlyTicketDatabase component does.

7.5.2 Enhanced Architecture with Entities

The Figure 29 depicts a more complex architecture based on the one shown on Figure 28. The only difference of the two architectures is that the latter one on Figure 29 implements the FrequentFlyerDatabase component in a way that would allow it to change behavior of the Token entity instances passed through it via `CreateToken` calls. The new FrequentFlyerDatabase component does not only forward the `CreateToken` method call as the original implementation from Figure 28 did, but for each Token it requests from the FlyTicketDatabase it creates a new instance of its own FreqFlyerToken wrapper component instance (primitive component, whose instantiation in the architecture is implemented by the proto-component concept), which is then returned to its callers. The FreqFlyerToken component maintains a reference for the Token entity it wraps via its `IToken` interface. The FreqFlyerToken also exposes its own `ITokenCallback` interface to be able to intercept any calls from the wrapped Token entity to its original requestor.

Note the change from architecture on Figure 28 to architecture on Figure 29 is fully transparent to the Arbitrator component – all of its bindings remained the same, as well as all the reconfiguration action annotations on all of its interfaces. The replacement of the FrequentFlyerDatabase primitive component by its more complex composite implementation from Figure 29 is local and the only changes had to be made to its bindings and interface methods annotations to reflect the new requirements of the new implementation. The ability to do so shows key strength of proposed approach to modeling dynamic entities.

The implementation of the core `IFreqFlyerAuth.CreateToken` method on the FreqFlyerCore component that drives the FreqFlyerToken component instantiation and initialization (by its method annotations) can be captured by the following pseudo code that is self-explanatory:

Pseudo code

```
IToken FreqFlyerToken.IFreqFlyerAuth.CreateToken(
     ITokenCallback outerCallback
) {
     IToken ffToken;
     ITokenCallback ffTokenCallback;
     IFFToken ffTokenSetup;

     NewToken(
          outerCallback,
          out ffToken, out ffTokenCallback, out ffTokenSetup
     );

     IToken outerToken = IFlyTicketDb.CreateToken(
          ffTokenCallback
     );

     ffTokenSetup.SetChildToken(outerToken);

     return ffToken;
}
```

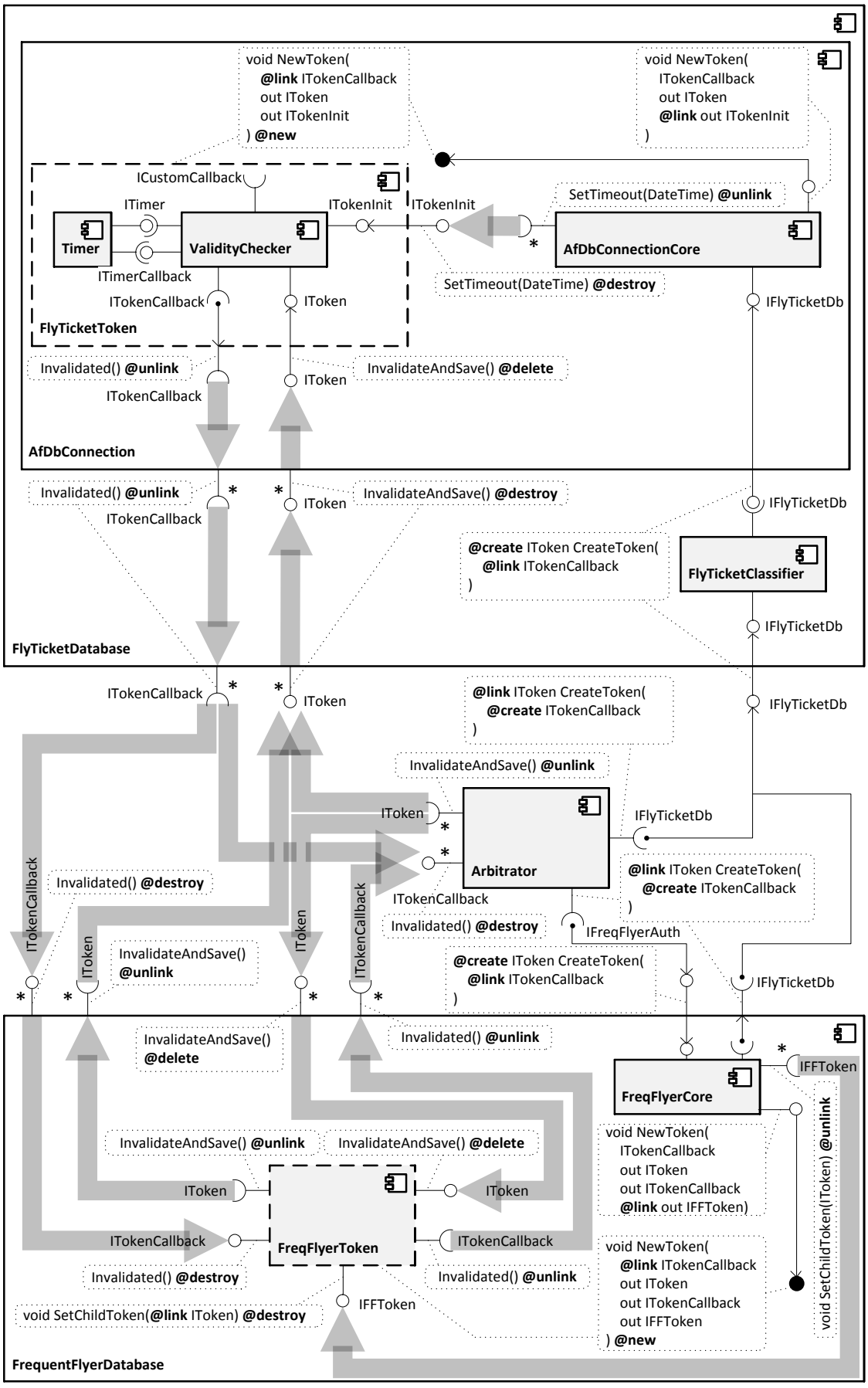


Figure 29. Architecture of CRE case-study enhanced with FreqFlyerToken

7.5.3 Summary

As shown is Section 7.5.1 and Section 7.5.2 above, our approach to capturing dynamic architectural changes by concept of dynamic entities implemented via concepts of proto-binding, proto-components and reconfiguration actions is viable and can be successfully used to describe complex architectures in a consistent way. It is a key success as to our best knowledge no previously known and implemented approach is able to model the presented dynamic architecture of the CRE case-study in a way to capture all information necessary for the reconfigurations both in the design and runtime architectures (i.e. usable both for static and runtime application analysis tools, as well as the component model runtime itself).

A final note on the subject is that the concept of dynamic entities and the four basic reconfiguration actions were already successfully implemented in a real component system. In [14] the SOFA 2 runtime has been extended with support for dynamic entities as prove of concept implementation. It shows the proposed approach is viable not only for modeling of complex applications, but also for their implementation in hierarchical component models.

Chapter 8 Modeling Environment using DeSpec

DeSpec

In recent years, efforts to verify correctness of Windows kernel drivers [124] have emerged as it is crucial for stability of the whole operating system. Microsoft itself has developed several tools for driver verification including the latest Static Driver Verifier model checker. The key to successful application of the model checking approach in this area is a reasonable choice of the environment model. However, the environment models used in current tools are too (1) non-deterministic, degrading preciseness of the model checker reports, and (2) oversimplified, losing the ability to check more specific kinds of properties of drivers. On the other hand, neither a formal or readable specification usable for documentation purposes is provided by these models. This paper targets these issues by introducing a new language for formal specification and modeling of kernel drivers and their environment.

Please note that due to space limitations the paper presents only a small excerpt of the language features. The full language specification, detailed elaboration of its features and also a large sample specification of the Windows environment can be found in [115].

8.1 Model Checking

Model checking technique is a formal verification method based on thorough examination of a program model state space. The model reflects behavior of the program related to the property being verified. It should ideally retain any part of the software that might influence the property so that the verification is sound and complete. On the other hand, the model should be as simple as possible since the model checker has to explore all its possible states. The time and space requirements for the verification are growing exponentially with respect to the number of operations, threads and variables used in the model (the *state explosion problem* [116]).

Usually, the goal is not to model check the system as a whole. Instead, the system is split into two pieces – a particular component of interest (a module, also an open system [172]) and the rest of the system (the module's environment). The environment is considered correct and its provided and required interfaces are defined by a specification. The verification tool is expected to extract a partial model from the module's source code and complete it by including the environment's behavior model according to the specification. The resulting model passed to the model checker, captures the module's interaction with the environment relevant to a set of properties being verified.

The process of model extraction from the program's source code is a difficult task as the source code language itself can induce major problems. A C language extractor needs to understand constructs like pointers, arrays, unions, reinterpreting type casts, etc. Fortunately, even though some of these constructs in general allow the extractor to build neither sound nor complete model of the program, results of the software

verification are still valuable. All the issues of the model extraction from the C source code have already been presented in paper [114].

This paper focuses on a formal description of the environment that combines the requirements on the module and modeling of the functionality provided by the environment. Temporal logics (e.g. *Linear Temporal Logic* (LTL) [104]) are often used for the former. They define how properties of the system should change in time using predicates quantified over time variable. However, specifying properties of a real application by means of plain temporal logic comes with a significant drawback. The specification is not easy to comprehend for the most of driver programmers and if a formula gets more complex neither for temporal logic experts.

Plain logic unreadability drives efforts to develop a higher-level language like Bandera *Temporal Logic Patterns* [60]. Properties expressed in this language are translated into the temporal logic formulae consumed by many existing verification tools. The patterns allow writing frequently used temporal logic formulae in very simple plain English sentences, e.g. “P is absent between Q and R” is representing the following formula:

$$\Box((Q \wedge \neg R \wedge \Diamond R) \Rightarrow [P\ U\ R])$$

Though incomplete the patterns are sufficient to specify widely used properties. Moreover, additional patterns can be added to the repertoire if needed.

Note:
$\Box$ is the universal time quantifier (always in the future), $\Diamond$ is the existential time quantifier (sometime in the future), $[\varphi\ W\ \psi]$ is the weak until operator (either ψ never holds and φ holds always, or ψ holds sometime in the future and φ holds until that moment).

In our work, we use *Zing* modeling language [10][119] as a basis for specification of the environment behavior and also as the output language of the model extractor. Zing language and Zing model checker have been developed by Microsoft Research group. The choice was made due to Zing's rich modeling functionality and the state of its current development (the preview implementation is available and works quite well). However, most ideas behind this work are not dependent on the target modeling language and can be applied to any other modeling language that provides at least classes, methods, exceptions, non-deterministic choices, and threads. Another modeling language meeting these criteria should be the new version of *Bandera Intermediate Representation* (BIR) – a modeling language of *Bogor* model checking framework [154].

8.2 Verification of Windows Drivers’ Correctness

Windows kernel drivers are relatively small libraries usually written in the C language. They run in a privileged mode that enables them to work directly with hardware. This introduces a high risk of damaging other parts of the kernel if a driver contains an error. Hence the correctness of drivers is crucial for security and stability of an operating system and drivers are common subject of software verification.

A driver can be seen as a component put into the environment comprising of the kernel and other drivers. Since drivers usually communicate with each other only via kernel function calls the inclusion of the other drivers into the environment is an

acceptable simplification. The verifier deals with the open system verification as the source code of the Windows kernel is usually not available. And even if it was, it would be virtually impossible to extract and verify the kernel model due to its inherent complexity. Besides, drivers shouldn't depend on the exact behavior of the private parts of the kernel as they can change version to version. Only the public documented functionality should be relied on.

So the model extractor should only work with the kernel specification. However, such specification is not currently available in a form that would be feasible to drive the model extractor -- the only source of official documentation is the *Driver Development Kit* (*DDK*) [123] provided by Microsoft, where the rules the drivers should comply with are described in plain English and some important details are stated vaguely or even missing entirely. It is a goal of our work to provide a language for writing the specification and to apply it on significant parts of the kernel API. Several tools that verify driver correctness have already been developed by Microsoft itself. These include the *Driver Verifier* [120] tool for run-time driver verification, the *PREfast* [121] static analysis tool based on local analysis of driver functions and finally the *Static Driver Verifier* (*SDV*) [122] (still in development) based on techniques of static analysis of the whole driver and model checking.

The Static Driver Verifier (SDV) models the kernel environment in C language enriched with special functions and macros that handle non-determinism necessary for emulating various execution paths. The rules the drivers can be verified against are written in *Specification Language for Interface Checking* (*SLIC*) [18]. Expressing a rule in the SLIC language inheres in writing pieces of C pseudo-code and defining how the environment model should be instrumented by them. The resulting instrumented code is converted to an abstract Boolean program which is passed to the model checker. The very first Boolean program extracted from the instrumented code abstracts from all local variables and replaces all conditions by non-deterministic choices. Error traces are then discovered by the model checker and confronted with the original program via symbolic execution. If an error trace describes the execution that is actually infeasible, the Boolean program is refined to be more specific with respect to the variables influencing the trace. The refined program is passed back to the model checker. This process of error search and model specialization repeats until there are no infeasible error traces found or a timeout elapses.

The environment model and the SLIC language allows safety properties to be checked with respect to operations performed sequentially on a single device object (an object representing a device in the driver). SLIC rules are limited to safety properties so it is not possible to encode all the rules defined in the DDK. The rules are specified separately from kernel environment which makes them less maintainable. Inability to model multi-threaded environment and simultaneous work on more device objects also prevents from verification of some race conditions commonly contained in faulty Windows drivers. In this work we introduce a solution that does not have these shortcomings.

Contribution

The aim of this work is to make it possible to specify and model the kernel environment in a formal yet comprehensible form, which could be used not only for

precise documentation of the kernel API but above all as an input for a model extractor that produces verifiable concurrent models of the Windows drivers. For this purpose, the paper introduces a new specification and modeling language called *Driver Environment Specification Language* (abbreviated as *DeSpec*). As shown in [115], the language is able to capture a significant subset of the rules imposed on drivers by the DDK including those that are difficult or impossible to express in the SLIC language and hence currently not verifiable by the SDV.

8.3 Windows Kernel Environment

The Windows kernel executive comprises of several components that manage various system resources – the managers [162]. The managers provide services for the other parts of the executive and for drivers. The *I/O Manager*, the *Plug & Play Manager*, and the *Power Manager* are the ones that are most interesting for driver verification as they do the majority of communication with drivers. Note, this work is limited only to drivers following the *Windows Driver Model* (*WDM*) [138]. Such drivers have to implement Plug & Play and power management features.

The I/O Manager loads and unloads drivers and issues I/O requests on them. The drivers are directly controlled by the I/O Manager, which issues I/O requests in form of *I/O Request Packets* (*IRP*s). If a driver can complete the request it fills in a place in the packet reserved for output parameters and passes the packet back to the manager. If it doesn't implement the required functionality it can pass the request to an optional lower level driver – a hierarchy is being formed by such inter-driver relationships. The other managers issue their requests and notifications to the drivers through the I/O Manager. For example, the Plug & Play Manager keeps track of the device state transitions (device removal, stopping, starting, etc.) and the Power Manager monitors the power state of the machine (whether it is going to sleep, awaking, etc.). Both managers notify the driver appropriately by sending it the respective IRPs.

Each driver has to respond correctly to an arbitrary request and content of the packet. It can return a result indicating an error, but it must never crash or damage other parts of the kernel. The driver cannot make any assumptions about drivers above or below it in the hierarchy. This requirement allows the verification tool to isolate the driver and test it on arbitrary inputs and outputs from the I/O Manager and higher/lower level drivers.

8.4 Driver Environment Specification Language

The Driver Environment Specification Language (DeSpec) is an object-oriented specification and modeling language incorporating the majority of features of the Zing modeling language [10] combined with design-by-contract elements inspired by Spec# language [20], and Bandera Temporal Logic Patterns [60]. It is designed to guide extraction of Zing models from source code of Windows kernel drivers. DeSpec language allows modeling of I/O Manager's behavior to drivers, modeling of kernel functions behavior and specifying constrains and rules that drivers should obey when calling these functions. Models and abstractions can be defined in various levels of detail, which, as one of the solutions fighting against the state space

explosion problem, enables the model extractor to infer the smallest available model sufficient for the verification of a particular rule.

DeSpec language provides means for capturing basic elements of the interaction between driver and its environment (i.e. global variables, functions and data structures). It is designed as a bridge between constructs of the C language and their models in the Zing language. In particular the models of pointers, function pointers, unions and other constructs that are not directly expressible in the Zing language are hidden behind the syntax of DeSpec language. This allows adjusting models for these features without a need to rewrite the specifications. Apparently, some constructs exploiting memory layout, such as reinterpreting casts or unions, cannot be modeled in a feasible way. Therefore they are not directly expressible in the DeSpec language. Fortunately, the driver as well as environment interface should be as platform independent as possible and thus these constructs should be used rarely.

8.4.1 Structure of Specifications

The DeSpec language is similar to the C# language in its syntactical structure. Each source file contains a list of declarations grouped to namespaces. Declarations include classes, integer enumerations, integer ranges, method delegates and method groups. A class declaration comprises of its members. Apart from fields and methods, which are common for standard object-oriented languages, DeSpec classes can also contain rules. A rule specifies constrains on fields and methods by means of temporal logic patterns. This section briefly describes DeSpec namespaces, classes and rules.

Namespaces

A namespace defines a scope for abstractions of kernel functions and structures. When the model extractor searches for an abstraction of a kernel function or a structure used in the driver's source code it looks up a single namespace only. The choice of the namespace depends on constrains to be verified. The default (global) namespace describes a minimal model for kernel functions and structures. Other namespaces usually *refine* the default model – making it more complex to enable verification of a constraint not expressible by means of default model. Constraints are embedded into the specification as method preconditions, postconditions, type constrains, rules, etc. By choosing the constraint to verify, the containing namespace is designated for being searched by the extractor. The ability to differentiate specifications by level of details is important for reducing the size of the resulting model.

Classes

Although Windows kernel is written in the C programming language its design is object oriented. Usually, a structure representing an object within the kernel (e.g. semaphore, mutex or device) is provided along with functions working with it. These functions behave like methods of the structure (object) as they all take a pointer to the structure as one of their parameters (the “this” reference). A notion of inheritance is also present on several places. Inheritance is used for sharing data among structures representing different yet related objects. The sharing technically inheres in declaring common initial fields in the related structures.

These observations justify introduction of classes as main elements of the specifications – the kernel structures provided to drivers are modeled in DeSpec as classes. The functions bound to these structures are declared as class instance methods. Functions not bound to any instance are mapped to static methods. The formal parameter referring to the instance the method is working on is specified by the *instance* keyword. The method (whether static or instance) abstracting a kernel function has to have the same name as the kernel function and no other method in the same namespace can have the same name (even though declared in another class). This rule allows the model extractor to find a specification of a function whose call has been observed in the source code. An example of a class specification follows:

DeSpec

```
class DEVICE_OBJECT {
  NTSTATUS IoAttachDevice(instance,_,out DEVICE_OBJECT attachedTo)
    requires !Driver.IsLowest;
  {
    NTSTATUS status = choose
    {
      NTSTATUS.STATUS_SUCCESS,
      NTSTATUS.STATUS_INVALID_PARAMETER,
      NTSTATUS.STATUS_OBJECT_TYPE_MISMATCH,
      NTSTATUS.STATUS_OBJECT_NAME_INVALID,
      NTSTATUS.STATUS_INSUFFICIENT_RESOURCES
    };
    attachedTo = IsSuccessful(status) ? Driver.LowerDevice : null;
    return status;
  }

  DEVICE_OBJECT IoAttachDeviceToDeviceStack(instance,_)
    requires !Driver.IsLowest;
  {
    return (choose(bool)) ? Driver.LowerDevice : null;
  }

  void IoDetachDevice(instance);

  /* more members follow */
}
```

Figure 30. DeSpec Example 1

In Example 1 (see Figure 30), the `DEVICE_OBJECT` class abstracts the structure of the same name. Instances of the structure represent devices that drivers are working with. Both *IoAttachDevice* and *IoAttachDeviceToDeviceStack* kernel functions attach the device object to the top of the device objects chain. The immediate lower device object, where the instance is attached to, is returned in the *attachedTo* output

argument and in the return value, respectively. The *IoDetachDevice* simply detaches the immediate higher level device from this device object instance[4].

The signature of a method abstracting a kernel function defines how parameters of the function are treated within the specification. The *placeholder* token (a single underscore) is used for arguments that are not important for the specification. The models of *IoAttach*- functions do not care about the second parameter. When a specification refers to the *IoAttachDevice* method, only one argument is stated in the list of actual arguments. The instance argument is picked from the argument list out before the method to denote the target instance using the dot notation. Arguments on the positions of placeholders are also omitted in the actual argument list. Methods declared in Example 1 (see Figure 30) are referred to as follows:

DeSpec

```
device.IoAttachDevice(out lower_device)
device.IoAttachDeviceToDeviceStack()
lower_device.IoDetachDevice()
```

The *out* keyword specifies that the argument is an output argument and has to be assigned within the method's body. The output argument is mapped to the C language by an additional level of indirection. The C type of the argument is thus `DEVICE_OBJECT**`. The *ref* keyword is also supported for marking arguments passed in and out by reference. A possibly empty list of preconditions and postconditions follows the signature. The syntax is similar to the one used in the Spec# language – the conditions are introduced by *requires* and *ensures* keywords, respectively. The condition is a Boolean expression with some limitations on the terms. The conditions stated in Example 1 (see Figure 30) require the lowest level driver not to call the *IoAttach*- functions. Pre- and postconditions are translated to assertions when the Zing model of the method is generated.

The body defines a model of the method's behavior using Zing syntax enriched with additional constructs that are translated to the Zing when the resulting model is generated. In Example 1, extended forms of the Zing's *choose* operator are used. Type `NTSTATUS` is an integer enumeration abstracting the kernel type of the same name. The operator *IsSuccessful* determines whether a value is a successful value of its type as recognized by the kernel.

The body can also be omitted at all if the modeled function does nothing that influences the driver at the current level of abstraction and only its calls are significant. If a kernel function returns some value to the caller (via a return value or output parameters), throws an exception or has some side-effect the specification method should have a body that models these operations.

Since a DeSpec class is usually an abstraction of a public kernel structure, it may contain fields corresponding to the fields of the structure. Additional fields that do not correspond to real fields might be necessary for storing auxiliary data used only for the sole purpose of modeling. Such fields are marked by the *synthetic* keyword. Similarly, *synthetic methods* and also *synthetic classes* can be defined in the specification. In general, DeSpec distinguishes synthetic language elements from

[4] Note the reverse roles of the device objects -- the higher level device object is attaching but the lower level device object is detaching.

non-synthetic ones. Note that all elements used in the first example are non-synthetic. Synthetic classes contain no abstractions, particularly no kernel function is mapped to a method of a synthetic class. Example of a class containing synthetic attributes follows:

DeSpec
```
static class Driver {
  synthetic DEVICE_OBJECT LowerDevice = new DEVICE_OBJECT;

  [ModelParam]
  synthetic const bool IsLowest = false;

  /* more members follow */
}
```

Figure 31. DeSpec Example 2

In Example 2 (see Figure 31), two synthetic fields are defined in the static class. The first one, *LowerDevice*, is used as a dummy device object that all devices of the current driver are attached to. The model can abstract from the precise device objects chain because the drivers shouldn't care about what drivers are layered beneath them in the chain. Similar simplifications are necessary to reduce the size of the generated model.

The second field named *IsLowest* is a literal constant field defining whether or not the driver is the lowest level driver in the driver chain. The field is annotated by the *ModelParam* attribute, which means that its initial value should be set by the user prior to the model extraction. Model parameterization is utilized when the model depends on a property that is difficult to deduce automatically from the driver's source code. It can be also used for model size tuning.

Rules

Another member that can be present in the class is a *rule*. The rule is a list of quantified temporal logic patterns [60] with pattern parameters filled with Boolean expressions.

DeSpec
```
class DEVICE_OBJECT {
  /* method declarations from Example 1 omitted */

  static rule
    forall(DEVICE_OBJECT device)
    {
       _.IoAttachDevice(out device)::succeeded ||
      (device === _.IoAttachDeviceToDeviceStack()) &&
       device!=null
    }
    corresponds to
    {
      device.IoDetachDevice()
    }
    globally;
}
```

Figure 32. DeSpec Example 3

The rule in Example 3 (see Figure 32) is a single pattern, however, in general, a rule is a list of quantified temporal logic patterns separated by commas and ending by a semicolon. The rule presented has the following meaning: "Each successfully attached device is eventually detached and each device that is detached has previously been successfully attached." Rest of the section explains the patterns in more detail. Each temporal logic pattern is formed by pattern keywords and pattern expressions. The pattern used in Example 3 (see Figure 32) can be generalized to {*P*} *corresponds to* {*Q*} *globally*, where {*P*} and {*Q*} are Boolean expressions. Each pattern can be split into two parts: the property and the scope. In this case, the property is {*P*} *corresponds to* {*Q*} and the scope is *globally*. A list of available pattern properties follows:

(i) $\{Q\}$ *is universal*

(ii) $\{Q\}$ *is absent*

(iii) $\{Q\}$ *exists*

(iv) $\{Q\}$ *precedes* $\{R\}$

(v) $\{Q\}$ *leads to* $\{R\}$

(vi) $\{R\}$ *responds to* $\{Q\}$

(vii) $\{Q\}$ *corresponds to* $\{R\}$

Properties (i) to (vi) are defined in [60]. Properties (v) and (vi) are equivalent and it depends on the situation which one is more appropriate to use. The property (vii) is equivalent to a conjunction of properties (v) and (iv), i.e. to {*Q*} *leads to* {*R*} ∧ {*Q*} *precedes* {*R*}. It has been introduced to the language since the combination is frequently used in the kernel environment and it would be inconvenient to write the two patterns separately. The available scopes are:

(i) *globally*

(ii) *before* $\{S\}$

(iii) *after* $\{P\}$

(iv) *after* $\{P\}$ *until* $\{S\}$

(v) *between* $\{P\}$ *and* $\{S\}$

The meaning of each property and scope is obvious. Detailed definitions can be found in [60] along with the equivalent LTL formulae. The LTL formula for *Q-corresponds-to-R* pattern with the global scope is:

$$\Box(Q \Rightarrow \Diamond R) \wedge [R \ W \ Q]$$

Temporal patterns can be quantified over value types or reference types. Patterns of instance rules are implicitly quantified by a variable of the declaring type. Instance rules can refer to that variable by using *this* keyword. This keyword can be omitted when referring to the instance members of the type. Unlike Bandera specification language [52], DeSpec allows quantifying over value types (i.e. integers, Boolean, enumerations). Zing symbolic value types can be used for the implementation. The reference type quantification may be implemented in the same way as in Bandera, however more scalable implementation would be possible using Zing symbolic reference types, which should be available in the next version of the Zing.

Method event operator	**Effect**
`M(args)::entered`	Returns *true* after *M* is entered with specified arguments until *M* returns. Return value is ignored.
`M(args)` `M(args)::returned`	Returns *true* after *M* is called with specified arguments and with any return value until *M* is entered again with the same arguments.
`M(args)::succeeded`	Returns *true* after *M* is called with specified arguments and with a successful return value until *M* is entered again with the same arguments.
`M(args)::failed`	Returns *true* after *M* is called with specified arguments and with an unsuccessful return value until *M* is entered again with the same arguments.
`expr === M(args)` `expr !== M(args)`	Returns *true* after *M* is called with specified arguments and with a return value (un)equal to the value of the *expr* until *M* is entered again with the same arguments.

Figure 33. Source code event operators for methods. *M* stands for non-synthetic methods, *args* stands for a list of arguments (possibly empty), and *expr* denotes an expression.

Field event operator	Effect
`F::read`	Returns *true* after *F* is read from.
`F::written`	Returns *true* after *F* is written to.
`expr === F::get` `expr !== F::get`	Returns *true* after *F* is read from and the value read is (not) equal to the value of the *expr*.
`expr === F::set` `expr !== F::set`	Returns *true* after *F* is written to and the value written is (not) equal to the value of the *expr*.

Figure 34. Source code event operators for fields. *F* stands for a non-synthetic field and *expr* denotes an expression.

Boolean expressions comprising pattern parameters should refer to so called *source code events* via *source code event operators*. A source code event refers to an execution of a particular piece of code. DeSpec allows to specify events corresponding to function calls and operations on fields (read and write) within the driver's source code. Hence, source code event operators are applicable on non-synthetic methods and fields only. Available source code event operators are listed in Figure 33 and Figure 34. In Example 3 (Figure 32), the source code event defined by the method(args)::*succeeded* operator establishes a watchdog for successful returns from the kernel function *IoAttachDevice*. It is triggered by only such function return that the third argument can be unified with the *device* quantification variable and the function return value means a successful call. The first two arguments could have been arbitrary when the function was called.

Each source code event operator is replaced by the corresponding predicate for the purpose of rule verification. The use of the source code event operator inside a pattern expression implies adding a global state variable to the resulting Zing model and instrumentation of the model with pieces of Zing code that make transitions of the state. The value of the operator state variable determines the value of the LTL formula predicate. Although Zing doesn't support LTL verification directly, it is possible to use run-time verification algorithm proposed by [76].

8.4.2 DeSpec Driven Model Extraction

Inputs to the model extraction process are the source code of the driver being verified, kernel header files, and the specifications of kernel functions and data structures written in DeSpec. At the beginning, the user should select a set of constrains that he or she wants to verify.

The user also chooses the *top-level model* to be used for the verification. This model is also written in DeSpec as a class implementing the predefined methods. Its task is to emulate the kernel's behavior to the driver including driver loading and initialization and issuing I/O requests (IRPs). Default top-level model is the most complex one. It emulates multiprocessor environment, multiple device objects, and concurrent IRPs. However, for a verification of some rules a simpler model may be sufficient. DeSpec allows to write and use such model. The choice of the simpler

model may radically reduce the size of state space and make the verification faster and sometimes even allow the verification to be completed in realistic time. However, some errors may remain undiscovered.

Once the top-level model is chosen, the model extractor generates Zing model of the driver (using its C source code and kernel headers) and combines it with the environment model. Since the resulting model is too large to be verified, the slicing [101][61] should take place retaining only those parts transitively referred to by the top-level model and the constrains being verified. As a final result, a Zing model of the driver and the related kernel functions and structures are output.

8.5 Conclusion and Future Work

This paper introduces the DeSpec language – a new specification and modeling language designed to enable writing modular, readable, and well-arranged specifications of the Windows kernel driver environment as well as formally, yet still comprehensibly, capture rules imposed on drivers by the kernel and documented in plain English in DDK.

Expressiveness and suitability of the language are demonstrated on a part of the kernel functionality in [115]. This work also shows that the available documentation of the kernel environment [123] is not sufficient for its formal specification without a deeper understanding of the Windows kernel.

As the DeSpec language is intended to be utilized by model checking tools, it addresses the main issue of this verification method – the state explosion problem. The abstractions may vary in the level of detail chosen according to the properties being verified. Complexity of the model can be further tuned by the user specified model parameters. By setting these parameters, the user can influence how complex the extracted model will be and what may it neglect. The user may also select a subset of tested driver functionality by choosing an appropriate top-level model.

The possibility of verifying LTL formulae with finite trace semantics using assertions only (see [76]) arises a question whether the use of temporal rules brings something new beyond the use of explicit assertions. Although many rules may be equivalently verified manually, i.e. by adding assertions (or method contracts) on the right places in the functions' model code, the use of rules has some advantages. Several advantages are implied by the locality. If entire “business logic” of the rule is written on a single place it is easier maintainable, more readable, and the verification of the rule can be easier (un)selected for verification. Besides, when the rule is more complex it wouldn't be easy to manually keep track of all operations in the code that influences the verified property. On the other hand, some rules are too complicated to write or comprehend that it is better to implement them manually by explicit assertions.

The ideas proposed by this paper are currently being implemented. The implementation comprises of the DeSpec language analyzer and a model extractor consuming C source code and producing a Zing model driven by DeSpec specifications.

Chapter 9

Related Work

As the initial Chapter 1 to Chapter 3 of the thesis analyze the related work quite extensively as an inherent part of the text and parts of motivations of the presented papers also position themselves relative to the related work, in this chapter we present only a rather short summary of related work not covered elsewhere in the thesis.

9.1 Error Traces

FACS

In [78], the authors address the counterexample complexity and interpretation problem by proposing a method for finding ”positives” and ”negatives” as sets of related correct traces and error traces. An interesting approach is chosen in [102], where the authors analyze the complexity of error explanation via constructing the ”closest” correct trace to a specific error trace. In [177], the authors describe an algorithm (”delta debugging”) for finding a minimal test case identifying an error in a program. This idea could be used to modify an error trace in order to find a ”close enough” correct one. An optimization of the checking process is described in [17] where multiple error traces are generated in a single checking run.

Static Driver Verifier (SDV) [122] is a tool used to verify correct behavior of WDM (Windows Driver Model) [125] drivers. The driver’s source code in C and the model written in SLIC (a part of the SLAM project [19][118]) are combined into a ”boolean” program that is maximally simplified and selected rules are checked. If a rule is violated, an error trace of the program is generated and mapped back to the driver’s C source code. Because WDM drivers are very complex, to make checking feasible, both the Windows kernel model and the rules used in the SDV have to be simplified. Thus the error traces generated by SDV are relatively short and easy to interpret. And, since they contain also the states corresponding to traversing through the kernel model, such parts are optionally hidden in the checking output. This solution might be also applicable to our plain error traces (Section 5.4.3): The events generated inside a method call could be grouped into the ”background” (Section 5.4.2). However, because it is not easy to identify the beginning and the end of a single method call in error trace (especially when the i.m*{...}* shortcuts are not used), employing this idea in the behavior protocol checker is not a trivial task.

As to the classical model checker SPIN [87][24], in case of violating of checking property specified in LTL, Spin allows traversing the trace to the error state while watching the variable values, process communication graph, and highlighted source code. Sometimes the error trace length makes this approach very hard to use and identification of the actual problem may be quite challenging. Although the approaches to ease the interpretation of an error trace in SPIN work well in most cases, its modeling language Promela [24] is not a suitable specifying software

components. Since such specification in Promela typically yields a large state space impossible to traverse in a reasonable time.

As for other tools, Java PathFinder (JPF) [133], Bogor [154][153], BLAST [28][26], SMV [159], Moped [127], and MAGIC [110] cope with counterexamples and all provide them as error traces. Specifically, JPF, Bogor, BLAST, Moped, and MAGIC print the sequence of steps leading to an error state annotated by a corresponding line of the source code, while the SMV tool provides an error trace consisting of the input file lines written in the SMV specification language. Moped is a similar to SDV in the sense that it first translates the input program (in Java) into the language of LTL in which the counterexamples are generated. They are then translated back to the input language. The MAGIC tool checks behavior of a C program against a specification described via an LTS. Besides an error trace, it can also generate control flow graphs and LTSs using the dot tool of GraphViz package [77] (also used by the behavior protocol checker). In all cases, but especially in the case of JPF, the error trace may get quite complex and not easy to interpret.

9.2 Entities

Entity
EntityTR

Since the proposed extension influences many aspects of component-based development, the related work ranges from formal verification methods through description of architecture dynamism in component models and its support at runtime to data modeling. To our best knowledge, there is no approach in the domain of component-based systems that would tackle the problem of modeling dynamic entities in a comprehensive fashion. However, there are works that solve some of the aspects, though, often with different motivation.

9.2.1 Component Models with Support for Data Modeling

Although, the concept of data and data-flow modeling is well known and accepted in different domains of software engineering, contemporary component models often neglect this part of application design and do not provide any constructs of explicit representation. Nevertheless, there are attempts to fill the gap.

In [106], the authors provide a formalization of data passing and data circulation through a component-based application. The approach considers data as a part of a component. The data can be accessed from other components, updated, and transferred among components. The basic idea is to distinguish between control and data flow. Dedicated data connectors manage access to data through a global shared data space where data are created and shared. Although, the work tries to formalize the area of component-based systems which is not deeply explored, we see the main disadvantage in the shared data space where all data has to be stored and which can cause a substantial overhead at runtime. Comparing to our approach, we preserve the place where data are created.

Scade [103], Pin [83], PECOS [75], ProCom [158] propose a data-flow modeling based on connecting components with input and output pins which represent required and provided data. Such concept is typical for embedded systems where data are produced by various sensors, processed by control components, and then they serve as inputs for actuators. Such concept differs from our proposal where data are owned by a particular component and just a data reference circulates in the application.

Providing persistency in component-based applications can be seen as a data modeling approach [50], however this concept operates with the granularity of components. However, we claim that it is not enough to represent typical application data.

9.2.2 Behavior Specification and Verification

The need for associating properties directly with dynamic entities like a file is not new. In the context of general code analysis, it has already been applied using BLAST [26], SLAM [16]. The BLAST and SLAM model checkers allow inspecting state space of a program in C for assertion violations. Moreover, there is additional specification language that allows associating an additional (shadow) state with a C structure and specifying allowed sequences of function calls using the structure. Thus, it is possible to associate such shadow state with, e.g., the `FILE` structure in the C library and restrict the correct usage patterns to those starting with a call to `open` and ending with a call to `close`. Another way to associate design information with an entity is using TraceMatches [29]. A TraceMatch is a negative specification, i.e., a set of traces (of method calls on a Java object) that are considered erroneous. Absence of such traces can be proved using either runtime checks (injected by AspectJ) or static analysis (by extension of the Soot framework).

These approaches can be used to analyze properties associated with dynamic entities. However, they expect availability of the source code and do not work compositionally, which is a basic requirement in the software component context.

There are behavior specification formalisms specific to component systems. However, majority does not consider dynamic entities at all (e.g., Interface automata [58], COIN [33], Wright [8], BP [4]). In principle, π-calculus [126] and some derived formalisms [44] have enough expressive power to describe this kind of dynamism, but the encoding is not trivial and generally unrelated with the implementation language.

9.2.3 Dynamic Reconfiguration of Architecture

Presently, dynamic architectures are quite well explored and several approaches to modeling them exist. The surveys of dynamic software architectures [32][37] present a categorization of different architecture evolution styles based on graphs [175][25], process algebras [8][108][45], UML profiles [98][13], or various logic [64].

In contrast with our proposal, all described approaches applicable in the domain of component-based systems focus on capturing general architecture reconfigurations which manipulate with coarse-grained architecture artifacts like components, bindings, interfaces, and connectors. However, we focus on describing dynamicity of more fine-grained parts of component-based applications resulting from implementation demands.

Certain contemporary component models also provide a capability of modeling architecture evolution (ArchJava [7], ACME [74], Plastik [21]) or at least have some support of architecture modification at runtime (Fractal [35]). However, they do not provide smaller granularity of modeling than a component.

9.3 DeSpec

This work incorporates or relies on ideas and approaches of model checking [47][116], model extraction [51][155], temporal logics [147][104][46], source code static analysis and slicing [101][61], and Windows kernel driver environment [162][138].

In particular, the Zing model checker [10], Bandera toolset (especially the Bogor model checking framework [154][153]), Java PathFinder [133], and SPIN model checker [87][24] are related tools devoted to the model checking. The SLAM project [118] is addressing the static analysis and verification of the C programs, especially the Windows kernel drivers. The beta version of Microsoft Static Driver Verifier (SDV) tool [122] has been recently released as a result of efforts in this area. Since this paper targets on Windows kernel drivers verification, the SDV is the closest related work. The way how rules are specified in this tool limits its verification power to safety properties. The environment model used by SDV is single-threaded, preventing verification of some race conditions, and quite non-deterministic, introducing additional false reports. It neither provides a specification of the kernel functions that might be used as documentation. On the other hand, SDV is a functional tool whose application in practice already led to discovering several errors in Microsoft's own drivers.

Finding errors in drivers is not limited to the model checking technique. Microsoft PREfast tool for drivers [121] performs static analysis of the source code and searches for common error patterns. It can, for example, find memory leaks incurred by missing function calls, dereferences of null pointers, buffer overruns, kernel functions called on incorrect IRQL level, and so on. The analysis is function scoped and hence it introduces false negatives and also restricts a set of errors it is able to detect.

The Windows operating system also enables to check how drivers work in stress conditions such as lack of memory, missing resources, lost packets, etc. In cooperation with the kernel, Driver Verifier tool [120] emulates such conditions and runs tests on the specified driver. The tool is able to detect many errors but it doesn't do any static verification so many execution paths remain unchecked.

Chapter 10

Conclusion

10.1 Summary of Contribution

All the goals of the thesis have been successfully fulfilled and the contribution of the thesis can be summarized as follows:

(a) Focusing on component models with runtime support we have introduced a new system of categorization and description of component models (with key distinction of role of component and additional categories of target platform, component definition, unit of code deployment, support for explicit provisions, support for explicit requirements and explicit support component nesting).

(b) Based our proposed categorization system we have provided a short overview of industry-supported component models and component-oriented frameworks.

(c) We have analyzed the key features of hierarchical component models and shown their key advantages for real-life software development. We have also provided several motivational examples based on industrial experience and articulated key desired properties of hierarchical component models.

(d) We have also identified a key weakness of current hierarchical CBSE approaches – inability to model dynamic changes in component architecture.

(e) We have introduced a novel case-study from our CRE project and evaluated Fractal hierarchical component model on CRE and CoCoME case-studies. We have also provided several enhancements to the Fractal model implementation as well as component composition verification techniques.

(f) We have provided the following contribution to the problems that hinder industrial use of hierarchical component models:

- Dealing with complex error traces inherent to behavior protocol compliance verification.
- Capturing dynamic architectural modification via the novel concept of entities.
- Capturing component environment behavior via introducing the novel specification language DeSpec in support of compositional verification.

Throughout the thesis we have already mentioned a number of open problems, which we recall in following Section 10.2 that also provides a summary of proposed future work.

10.2 Future Work – Key Open Problems and Research Ideas

Even though the table of component models presented in Section 2.4 provides a well-arranged overview and categorization according to the criteria proposed in Section 2.3, it is too brief to prevent any ambiguity in interpreting the evaluated CBSE concepts with respect to each component model implementation details. Thus we think a more detailed description of each of the component model and component-oriented frameworks is needed. However the description still must be prepared in context of the proposed categories – i.e. mainly the category terms and common CBSE terms should be used uniformly to analyze implementation details of each of the component models. We are currently preparing such a more detailed description as our future work.

In Section 7.5 we have shown that the entities (proposed concepts of proto-bindings and proto-components) are fully suitable to model architecture of component-based applications similar to the one created as part of the CRE project. However, we foresee that more complex requirements on the application's architecture might arise in future and the current proposal of proto-bindings would not be sufficient or well suited. As an example, one can imagine an extension of the CRE demo application in a way, the "Connection" components, that provide a mechanism to get airline specific information in a unified way, would not be local to the CRE demo application, but would be provided by the airline itself and as such be accessible remotely. Should such a change be applied to the model with entities and proto-bindings as presented in 7.5, it would imply the FlyTicketToken component will be created also on a remote computer and all communication with it will cross the computer boundary as well. However as all the required information is encapsulated inside each of FlyTicketToken component instances, it would be more beneficial if the component would be able to migrate itself closer to the actual client (the Arbitrator component) – i.e. similar feature as the core SOFA 2 provides as a nested factory pattern concept [85]. Our current implementation is SOFA 2 specific and stands on its own, thus a natural future goal is to combine the SOFA 2 factories with the general concepts of proto-bindings in future (the extension should be rather straightforward by enhancing the notion of currently static reference owner on a proto-binding context by an ability move in the architecture at runtime).

As described before the solution to dynamically evolving component architectures (Chapter 7) provides a corner-stone for foreseen behavioral correctness verification and performance prediction analysis techniques applied on applications with such complex architectural needs. While the concepts of proto-bindings and proto-components mark relevant points where the architecture can change and the reconfiguration actions defined in Chapter 7 constrain the application to a reasonable subset of reconfiguration changes possible, a general specification that would impose a contract on the application has not been provided yet. Thus our next goal is to provide a formal specification language (or an extension to an existing one, like

behavior protocols) to allow reasoning about the allowed orderings of reconfiguration actions the architecture is annotated with.

An important problem currently not solved in dynamic entities is the behavior in case of exceptions during application's runtime. As it is considered on different level of abstraction, than the key concepts of proto-bindings, proto-components and reconfiguration actions, a solution to the problem has been intentionally omitted from the core specification in Chapter 7. In fact, being an extension to a set of allowed application behaviors the problem regarding runtime exceptions should be solved together with (or as part of) the specification language for dynamic entities – the goal proposed in the previous paragraph.

In evaluation of our proposed approach to modeling dynamic entities (Section 7.5) we have shown architecture of the CRE case-study modeled using proto-bindings and proto-components and annotated with reconfiguration actions. As this approach incorporated more information than usual, the resulting architecture can become quite large and complex. Thus, in order to apply a hierarchical component model like Fractal or SOFA 2 in commercial development environment, the current development tools should be enhanced to cope with entity related concepts and to provide means to easily develop applications with complex dynamic architectures. This includes not only visualization, editing and annotating of the architecture, but also an extension to component model's runtime to allow easy debugging of proto-bindings (i.e. visualization of both design and runtime architectures).

We have also presented the problem of localization of suitable component implementation based on a query describing the required functionality – i.e. the application of the COTS principle to component-based applications in a way component models are often believed to be used in future. While in Section 3.1.4 we have shown the advantages of hierarchical component models with respect to formal specification of component behavior and its verification can be used to solve the problem mentioned, we have presented it only as an idea for future CBSE research directions. Thus a next goal is to analyze the problem in more detail and to propose a solution, ideally prepared in conjunction with a formal correctness verification technique, so that any future components can have only a single unified formal specification that can be used both for correctness verification and as a key in compatibility searches. Any proposed approach should also fit into existing performance prediction techniques in order to fit as many proposed hierarchical component models desired properties as possible.

In Chapter 8 where we have introduced the DeSpec language and we have also stated that in order to get a full working system for Windows driver verification the final step has to be finished – a full implementation of a Zing model extraction tool from component (driver) sources – one of our future goals. In the discussion in Section 3.2.6, we proposed another important goal: to use the DeSpec language and extractor tools in context of generic component systems to provide a universal tool for formal environment description usable also in regular application development.

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Appendix A

Original Architecture of the CRE Case-study Demo

As the architecture of CRE case-study does not easily fit a single A4 sized page, it has been separately printed on a single A3 sized sheet of paper that was freely inserted into each copy of this thesis.

Note the numbers in the figure mark steps in application's behavior – a detailed description can be found in Section 5.1.

The figure of the original architecture has been verbatim copied from results of our *Component Reliability Extensions for Fractal component model* project [2], only minor formatting changes have been applied.