

Taming Aspects with Managed Data

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Abstract

Chapter 1

Introduction

Cross Cutting Concerns (CCC) is a problem the classic programming techniques can not tackle with sufficiently. This results in scattered and tangled code, which affects the system's modularity and it's ease of maintenance and evolution. Since Object Oriented Programming (OOP) and Procedural Programming (PP) techniques can not solve this problem, Aspect Oriented Programming (AOP) was introduced [KLM⁺97] in order to provide a solution to the problem, by presenting the notion of *aspects*.

AOP results in a modular and *single-responsibility* based design, whose properties must be implemented as *components* (cleanly encapsulated procedure) and *aspects* (not clearly encapsulated procedure), both separate concepts that are combined for the result through an automated process called *weaving*. However, relying on AOP, paradoxically, does not improve the evolution of a project even with the modularity that it provides. The reason is that it introduces tight coupling between the aspects and the application. As a result, the way to address this problem is to consider of a new sophisticated and expressing crosscut language. CCC could be handled on a higher level of the language such as the data structuring and management mechanisms.

Managed data [LvdSC12] allows the developers to take control of important aspects of data as reusable modules. Using managed data a developer can build *data managers* that handle the fundamental data manipulation primitives that are usually hard-coded in the programming language, by introducing custom data manipulation mechanisms. Managed data have been researched and implemented under the Enso project¹, which is developed in Ruby² (a dynamic programming language) using the meta-programming framework of Ruby. Furthermore, it is considered [LvdSC12] that managed data cannot be fully supported in static languages directly, which makes it more challenging for this thesis since it is implemented in Java. In this thesis we use the Java reflection API in order to implement managed data and focus on specific aspects and design patterns implementations using the data managers concept.

Finally, in order to evaluate the implementation of aspects and how we deal with CCC in managed data, we have reimplemented a part of a well-known use case, the JHotDraw, and evaluated the results on a number of explicit criteria.

1.1 Initial Study

In their study on managed data, Cook et al. [LvdSC12] present the main idea of managed data, while using a show case of it in an implementation in Ruby. As a use case they present the Enso project in order to reuse database management and access control mechanisms across different data definitions.

This thesis is an extension of their work; we implement managed data in Java (a static programming language) using the Java reflection API³ and dynamic proxies⁴. Although proxies in static programming languages can not implement the full range of managed data [LvdSC12]. Java provides a strong

¹<http://enso-lang.org/>

²<https://www.ruby-lang.org/en/>

³<https://docs.oracle.com/javase/tutorial/reflect/>

⁴<https://docs.oracle.com/javase/8/docs/api/java/lang/reflect/Proxy.html>

implementation of the [Meta-Object Protocol \(MPO\)](#) [KDRB91], which can be used through the Java Reflection API [FFI04]. Additionally, our work focuses on the aspects perspective and it provides a solution to the [CCC](#) problem by using managed data and their data managers.

The most famous implementation of [AOP](#) is the one provided by Kiczales et al. called AspectJ [KHH⁺01]. Although AspectJ has been used by a number of projects, some of them with significant research results [HK02] [MM], it includes all the trade-offs of [AOP](#), which are presented in detail in Section 1.2. In this thesis we show how we use managed data in order to tame aspects and compare the results with an AspectJ show case, the AJHotDraw.

1.2 Problem statement

1.2.1 Problem Analysis

Predefined data structuring mechanisms

One of the most important characteristics of programming languages is the data structures definition. Different types of data structures can be found on different languages and paradigms including *structures*, *objects*, *predefined data structures*, *abstract data types* and more. The common characteristic of these definitions is that they are all predefined. Thus, they do not allow the developers to take control on the data structuring and management mechanisms, but only to create data of these types [LvdSC12].

The problem with this approach is that the predefined data structuring mechanisms can not implement [Cross Cutting Concerns](#) and other “common requirements” for data management. In particular, those requirements are not properties that belong to a data structure definition, since, although it is easy to define them individually for every data type, that introduces a significant amount of duplicated and scattered code through the program.

Consequently, in this thesis we implement managed data, which gives the programmers control over the data structuring mechanisms.

Crosscutting concerns

As it has been seen [HMK05] there are a number of concerns during software implementation, that a developer has to work with. For good software modularity, these concerns have to be implemented on different modules, each of these modules implement only one concern. However, some of these concerns can not fit to separate modules but their implementation cuts across the system’s modules. Those concerns are called [Cross Cutting Concerns](#) and result to the problem of *scattered* and *tangled* code.

The problem we study focuses on the [CCC](#) that are scattered around the application, resulting in a hard to maintain system by tangling implementation logic and concerns code together. In order to deal with this problem a refactoring of those concerns has to take place, in which the tangled and scattered implementation has to be replaced with an equivalent *aspect* [HMK05].

In this thesis we focus on the modularization of such [CCC](#) in aspects, using managed data. We refactor those concerns in modular data structures each of which implement only one concern by lifting the data management up to the application level and allowing the developers to define the concerns in their own data structures.

Aspect Oriented Programming problems

Even though, [AOP](#) provides new modularization mechanisms, which should result in easier evolving software, it delivers solutions that are as hard and sometimes even harder to evolve than before [TBG03]. The problem lays on the aspects, which have to include a crosscut description of all places in the application where this code yields an influence. Thus, the aspects are tightly coupled to the application and this greatly affects the evolvability of the overall system.

Additionally, Steimann [Ste05] argues that modeling languages are not aspect ready. The problem that arises is located at the level of software modeling. More specifically, whereas in [OOP](#) roles are

tied to the collaborations, in *roles modeling* collaborations rely on interactions of objects and aspects are typically defined independently of one another.

Furthermore, in terms of order, it has been observed that aspects are not elements of the domain, they rather describe the order than the domain. Finally, aspects invariably express non-functional requirements, but if the non-functional requirements are not elements of domain models then neither are aspects.

1.2.2 Research Questions

Managed data has not been practically implemented in a static language before, therefore our first research questions states “*Can managed data be implemented in a static language?*”. Based on the previous argumentation about the relevance of [AOP](#) and the solutions that managed data can provide in [Cross Cutting Concerns](#), our second research question is “*Can managed data solve the problem of crosscutting concerns?*”. Finally by using a software showcase, the JHotDraw framework, as well as its [AOP](#) implementation AJHotDraw [MM], we evaluate the implementation of managed data on an inventory of aspects and design patterns. As a result the third research question states “*To what extent can managed data tame an inventory of aspects and design patterns in the JHotDraw framework, compared to the original and the [AOP](#) implementation?*”.

1.2.3 Solution Outline

Our solution consists of an implementation of managed data in Java. In particular, we have implemented a framework that can be used in order to create managed data in Java. This framework provides all the mechanisms of managed data using Java reflection and dynamic proxies. Additionally, one can use the framework in order to refactor the [CCC](#) of an application.

As it has been already mentioned, to validate our hypotheses we have implemented managed data in Java using the Java Reflection API and Dynamic Proxies. More specifically we define *schemas* using Java interfaces and dynamic proxies for the *data managers*. Furthermore, we provide a proof of concept the examples given in [LvdSC12] but this time developed in Java using our framework. To stack data managers [LvdSC12], we use the *Decorator Pattern* [Gam95].

In order to see if managed data solves the problems that [AOP](#) introduces, we have implemented an inventory of the following aspects and design patterns from JHotDraw using data managers:

The Observer Pattern, which as presented in literature [TBG03] [HMK05] [MMvD05a], is by nature not modularized and the scatters pattern code through the classes. This pattern is considered as a difficult case because it is used a lot in the original JHotDraw source code but with multiple variations, thus it is difficult to extract an abstract version.

The Undo aspect, which is analyzed extensively [Mar04] and a solution is provided by AJHotDraw. More specifically, this aspect consists of aspect-oriented refactoring of the *Command* pattern with *Undo* actions.

This inventory is implemented using data managers that have modularity as a main characteristic and is evaluated in a new JHotDraw implementation. We compared those aspects with the original version of JHotDraw, and the aspect version, AJHotDraw. Since our solution is a refactoring of the JHotDraw framework we needed a way to ensure the behavioral equivalence between the original and the refactored solution [Fow09]. To archive that, we used the original JHotDraw test suite that consists of 1218 executable tests in total.

1.2.4 Research Method

In order to answer our research questions we studied the theoretical background, we examined our managed data implementation in Java and we evaluated our implementation in an existing use case system, the JHotDraw.

Managed data implementation in a static programming language. In order to answer the question if managed data could be implemented in a static language, we’ve implemented man-

aged data in Java using Java’s reflection capabilities⁵, Java interfaces for schemas definition and dynamic proxies⁶ for the data managers. An extensive presentation of the implementation is given in Chapter 4.

Use case implementation. In order to argue about the contribution of our implementation and managed data for aspects handling in general, we’ve used a use case application (JHotDraw) which is considered as a good design use case for **OOP**, along with its **AOP** implementation (AJHotDraw). Thus, we have built our version of the JHotDraw application using our managed data framework to refactor the **CCC**.

Use case evaluation. In order to show if our managed data solved the issues of **AOP** in terms of modularity, we have gathered a number of metrics for each of the three implementations the results are presented extensively in Chapter 6.

1.3 Contributions

Contribution 1: Managed data implementation in Java. Our first contribution is the implementation of managed data in a static language, in our case we chose Java. The reason we chose Java as the programming language is because Java is a very popular, static, object oriented programming language, with meta-programming (reflective) capabilities which we took advantage of. Managed data implemented as an internal **Domain Specific Language (DSL)** in Java, using interfaces for schema definitions and dynamic proxies for the data managers.

Contribution 2: Managed data Java framework. The final deliverable is a Java library, which the developer can use to define managed data and data managers for them. Additionally, the developer can define and implement aspects as reusable modules and introduce them in an application without mixing the business logic with the concern logic. More specifically, the schemas and the data managers have to be defined by the developer, as well as any additional functionality that needs to be integrated to the patterns or roles of the application.

Contribution 3: Managed data Evaluation in JHotDraw. We implemented a new version of the JHotDraw application using our framework in order to evaluate our refactoring of **CCC**. More specifically, we focused on the *Undo* concern, which is a *Command Pattern* and it is scattered around the modules of the JHotDraw, as well as the *Observer Pattern* which has been used in multiple parts of JHotDraw and cuts “pattern code” on different modules.

Contribution 4: JHotDraw implementation results assessment and comparison with AJHotDraw. Finally, we present the results of our evaluation and we compare them with AJHotDraw which implements **AOP** using the AspectJ language, again in Java.

1.4 Related Work

In this section we discuss the related work of research that inspired this thesis. In particular, we discuss points that we followed and points that we’ve tried to improve as well as the reason of doing it.

Meta-Object Protocol

Managed data can be implemented using reflection and the **MPO**. The authors of Enso [LvdSC12] implemented it in Ruby using the meta-programming framework and in particular, the **method_missing** mechanism. In other languages (such as Java, JavaScript or C#) that support dynamic proxies, they can be used for the managed data implementation, which is the way we’ve implemented it. The **MPO** [KDRB91] was first implemented for simple **OOP** capabilities of the Lisp language in order to satisfy some developer demands including compatibility, extensibility and developers

⁵<https://docs.oracle.com/javase/tutorial/reflect/>

⁶<https://docs.oracle.com/javase/8/docs/api/java/lang/reflect/Proxy.html>

experimentation. The idea was that the languages have been designed to be viewed as black box abstractions without giving the programmers the control over semantics or the implementation of those abstractions. **MPO** opens up those abstractions to the programmer so he can adjust aspects of the implementation strategy. Providing an open implementation can be advantageous in a wide range of high-level languages and thus **MPO** technology is a powerful tool for providing that power to the programmer [KDRB91]. Furthermore, **MPO** provides flexibility to the programmer because as a language becomes more and more high level and its expressive power becomes more and more focused, the ability to cleanly integrate something outside the language's scope becomes more and more difficult. Thus, both **MPO** and managed data allow the programmer to be able to control the interpretation of structure and behavior in a program. However, **MPO** focuses on behavior of the objects and classes, while in managed data the focus rests solely on the data management. One could conclude that managed data is a subset of the **MPO** approach since managed data have a more narrow scope.

Adaptive Object Model

Managed data [LvdSC12] is closely related to the **Adaptive Object Model (AOM)**. **AOM** [YJ02] is an architectural style that emphasizes flexibility and runtime dynamic configuration. Architectures that are designed to adapt at runtime to new user requirements by retrieving descriptive information that can be interpreted at runtime, are sometimes called a “reflective architecture” or a “meta architecture”. An **AOM** system, is a system that represents classes, attributes, relationships, and behavior as metadata, something that is closely related to the managed data. However, on one hand **AOM** style is more general than the managed data since it is described at a very high level as a pattern language and it covers business rules and user interfaces, in addition to data management. On the other hand, **AOM** does not discuss issues of integration with programming languages, the representation of data schemas, or bootstrapping, which are central characteristics of managed data. **AOM** is also presented as a technique for implementing business systems, not as a general programming or data abstraction technique [LvdSC12].

Model Driven Software Development

Model Driven Software Development (MDSD) refers to a software development method which generates code from defined models. The models represent abstract data that consist of the structure and properties definition of an entity. The idea of the model in **MDSD** is closely related to the *schemas* in managed data. Similarly to the model definition, schemas define the structure, the properties and any metadata that describe an entity, followed by code generation that adds any extra functionality and manipulation mechanisms to that entity.

The Enso Language

Enso project⁷ is the first implementation of managed data, it is open source⁸ and is used for EnsoWeb, a web framework written with managed data. Although Enso is implemented in Ruby, which is a dynamic language, the source code was a very helpful resource for our static implementation in Java. The design of Enso was an inspiration for our implementation even though some parts have changed completely in order to conform to our needs and support Java's static type system. Additionally, examples presented in Enso, are also implemented in our case and are presented in Chapter 3.

Aspect Oriented Programming

Although **AOP** is not directly connected to managed data, it is a mechanism that is relatively easy to be supported in managed data. This mechanism consists of the *weaving* of aspect code in specific join points. The way to support this in managed data is through data managers. How to tame aspects in managed data is the main topic of this thesis and is going to be presented extensively in the following chapters.

⁷<http://enso-lang.org/>

⁸<https://github.com/enso-lang/enso>

1.5 Document Outline

In this section we outline the structure of this thesis. In Chapter 2 we introduce the background, focusing on the concepts, which the reader must be familiar with in order to follow the next chapters. In Chapter 3 we demonstrate an example to show the capabilities of our implementation. In Chapter 4 the implementation of managed data in Java is presented and discussed, providing detailed explanation of our issues and implementation details. Next, in Chapter 5 a showcase is presented, by applying our implementation to refactor aspects in JHotDraw. In Chapter 6 an evaluation of the aspect refactoring is illustrated. Additionally, some metrics, claims and results are presented. Finally, a conclusion is given in Chapter 7 followed by further work in Chapter 8.

Chapter 2

Background

2.1 Cross Cutting Concerns

There is significant research in software engineering that focuses on the importance of software modularity. The most significant, among the many, advantage of modular systems is the extensibility and evolution of a system [Par72].

However, during the development of a system there is a number of concerns that have to be considered and implemented into the system. In order to follow the modularity principles, those concerns have to be implemented in separate modules, this way the program will be extensible and its evolution will be easier. Nonetheless, many of those concerns can not fit into the existing modular mechanisms in any of the existing programming paradigms including both [Object Oriented Programming](#) and [Procedural Programming](#). In those cases, the concerns are scattered through the modules of the system, resulting to scattered and tangled code. Those concerns are called [Cross Cutting Concerns](#) [HMK05]. CCC are considered a serious issue for the evolution of a system and their effects of tangled and scattered code can be disastrous for a system's extensibility.

The reason is that the code which is related to a concern is scattered in multiple modules, while the concern code is tangled with the each module's logic resulting in a system, which does not follow the *Single Responsibility Principle* and consequently is hard to maintain.

Among many examples of those CCC are persistence, caching, logging, error handling [LL00] and access control. Additionally, some design patterns scatter "design pattern code" through the application, for instance the *Observer Pattern*, *Template Pattern*, *Command Pattern* etc. [HK02] [Mar04].

In order to solve this problem we need a way to refactor and transform the non-modularized CCC into a modular *aspect*. In other words, refactorings of CCC should replace all the scattered and tangled code of a concern with an equivalent module [HMK05], which in AOP terminology is called *aspect* [KLM⁺97].

2.2 Aspect Oriented Programming

Kiczales et al. present AOP [KLM⁺97] by using an example of a very simple image processing application. In that system, as in every system, whenever two properties which are being programmed must compose different tasks and yet be coordinated (in the example filters and loop-fusion), they **crosscut** each other. Because general purposes languages provide only one composition mechanism, which leads to complexity and tangling, the programmer must do the co-composition manually. According to their theory, a system's property can be either a *component*, if it can be clearly encapsulated in a generalized procedure, otherwise it is an *aspect*. AOP supports the programmer in separating components and aspects from each other by providing mechanisms that make it possible to abstract and compose them together when producing the whole system (*aspect weaving*). Alternatively to the common programming paradigms, OOP and PP that allow programmers to only separate the *components* from each other but crosscut the concerns.

However, implementing AOP programs is not that easy since several tools are needed in order to

succeed. More specifically, a general purpose language needs only a language, a *compiler* and a *program* written in the language that implements the application. In the case of an AOP based implementation, a program consists of a *component language*, in which the components are programmed, one or more *aspect languages*, in which the aspects are programmed, an *aspect weaver* for the combined languages, a *component program* that implements the components using the component language and finally, one or more *aspect programs* that implement the aspects using the aspect languages. Additionally, an essential function of the aspect weaver is the concept of *join points*, namely the elements of the component language semantics that the aspect programs coordinate with.

2.2.1 AspectJ

There is significant work in the area of aspect oriented languages but one the most important contribution is the AspectJ¹ project, which is a simple and practical aspect-oriented extension to Java and it has been introduced by Kiczales et al. [KHH⁺01]. The authors of AspectJ provide examples of programs developed in AspectJ and show that by using it, CCC can be implemented in clear form, which in other general purpose languages would lead to tangled and scattered code. AspectJ was developed as a compatible extension to Java so that it would facilitate adoption by current Java programmers. The compatibility lays on upward compatibility, platform compatibility, tool compatibility and programmer compatibility. One of the most important characteristics of AspectJ is that it is not a DSL but a general purpose language that uses Java’s static type system. Our goal is to apply those properties for our managed data implementation.

2.2.2 Design Patterns in Aspect Oriented Programming

Hannemann et al. present a showcase of AOP [HK02] in which they conduct an aspect-oriented implementation of the Gang of Four design patterns [Gam95] in AspectJ, in which 17 out of 23 cases show modularity improvements. Even though design patterns offer flexible solutions to common software problems, those patterns involve crosscutting structures between roles and classes / objects. There are several problems that the OOP design patterns introduce in respect to CCC, specifically in cases when one object plays multiple roles, many objects play one role, or an object play roles in multiple patterns [Sul02] (design pattern composition).

The problem lays on the way a design pattern influences the structure of the system and its implementation. Pattern implementations are often binded to the instance of use resulting in their scattering into the code and losing their modularity [HK02].

Even worse, in case of multiple patterns used in a system (pattern overlay and pattern composition), it can become difficult to trace particular instances of a design pattern. Composition creates large clusters of mutually dependent classes [Sul02] and some design patterns explicitly use other patterns in their solution.

Observer pattern in Aspect Oriented Programming

Hannemann et al. [HK02] provide some example implementations of several design patterns, including the *Observer Pattern* in which they focus on a detailed implementation. As they mention, in an observer pattern implementation, both the *Subject* and the *Observer* have to know about their roles and have “pattern related code” in them. As a result, adding or removing code from a class requires changes of code in that class.

In their implementation [HK02] of the observer pattern in AspectJ, they separate abstract aspects for:

- The *Subject* and *Observer* roles in classes.
- Maintenance of a mapping from *Subjects* to *Observers*.
- The trigger of *Subjects* that update *Observers*.

¹<https://eclipse.org/aspectj/>

And concrete aspects for each instance of the pattern fills in the specific parts:

- Which classes can be *Subjects* and which *Observers*.
- A set of changes on the *Subjects* that triggers the *Observers*.
- The specific means of updating each kind of *Observer* when the update logic requires it.

Modularity Properties

The modularity properties implemented in this thesis are[\[HK02\]](#):

Locality: All the code that implements the observer pattern is in the abstract and concrete observer aspects, none of it is in the participant classes. The participant classes are entirely free of the pattern context and as a consequence there is no coupling between the participants.

Reusability: The core pattern code is abstracted and reusable. The abstract aspect can be reused and shared across multiple observer pattern instances.

Composition transparency: Because a pattern participants implementation is not coupled to the pattern, if a *Subject* or *Observer* takes part in multiple observing relationships their code does not become more complicated and the pattern instances are not confused.

(Un)pluggability: Because *Subjects* and *Observers* don't need to be aware of their role in any pattern instance, it is possible to switch between using a pattern and not using it in the system.

In general an object or a class that is not coupled to its role in a pattern can be used in different contexts without modifications and the reusability of participants can be increased. The locality also means that existing classes can be incorporated into a pattern instance without the need to adapt them with extra effort. All the changes are made in the pattern instance. This makes the pattern implementations themselves relatively (un)pluggable. If we can reuse generalized pattern code and localize the code for a particular pattern instance, this can result in multiple instances of the same pattern in one application, making it easy to understand (composition transparency). This solves the common problem of having multiple instances of a design pattern in one application.

2.2.3 Evolvability issues

Since modularization and separation of concerns make the evolution of an application a lot easier and [AOP](#) provides mechanisms for modularization and system decomposition, aspect-oriented programs should be easier to be evolved and maintained. Paradoxically, this is not the case [\[TBG03\]](#) since [AOP](#) technologies deliver applications that are as hard, and sometimes even harder, as non-[AOP](#).

According to Tourwe et al. [\[TBG03\]](#) the problem is that aspects have to include a crosscut description of all places in the application. Thus, it is much harder to make such crosscuts oblivious to the application and most importantly to the rest of the modules. Additionally, current means for specifying concerns rely heavily in the existing structure of the application, therefore the aspects are tightly coupled to the application (and its structure) and of course this affects negatively the evolvability of a system since it makes it hard to change it's structural. As Tourwe [\[TBG03\]](#) proposes, a solution for this problem would be the creation of a new, more sophisticated crosscut language. A language that enables the developer to discriminate between methods based on what they actually do instead of what they look like, in a more intentional way. This new language that implements [CCC](#) in a modular way is something try to realize in our thesis.

2.3 Managed Data

Managed data [\[LvdSC12\]](#) is a data abstraction mechanism that allows the programmer to control the definition of the data and their manipulation mechanisms. Additionally it provides a modular way to control aspects of data. Managed data helps the programmer by giving them control over

the structuring mechanisms, which until now were predefined by the programming languages. The developers could not take control of them, they could only create data of those types. Managed data provides significant flexibility since it lifts data management up to the application level, by allowing the programmer to build data managers that handle the fundamental data manipulation primitives, normally hard-coded into the programming language.

Managed data has three essential components:

Data description language, that describes the desired structure and properties of data.

Data managers, that enable creation and manipulation of instances of data.

Integration, with a programming language to allow data to be created and manipulated.

In the traditional approach, the programming language includes data definition mechanisms and their processes, which are both predefined. However, with managed data, the data structuring mechanisms are defined by the programmer by interpretation of data definitions. Of course, since a data definition model is also data, it requires a meta-definition mechanism.

2.3.1 Schemas

The schemas are the way to describe the structure of the data to be managed. They can be just a simple data description language which programmers can use to describe simple kind of data. For example Cook et al. [LvdSC12] used Ruby hash for the data description on a simple example where the hash was an object that represented a mapping from values to values. However, a simple schema format like this can not be used to describe itself because it is not a record.

A self-describing schema would allow schemas to be managed data themselves. We therefore need a self-describing schema that can be used to describe schemas, namely the “Schema-Schema”. A Schema-Schema is also managed data with its own data manager. This process is called *Bootstrapping* and it is needed in order to “jumpstart” the process. This extends the benefits of programmable data structuring to their own implementation. Schemas can be interpreted in many different ways to create different kinds of records based on the manipulation provided by the data managers.

2.3.2 Data Managers

Data managers are the mechanisms that interpret *schemas* with defined manipulation strategies set by the programmers. The input to a data manager is a schema, which describes the structure of the data to be managed. Since the schema is only known dynamically, the data managers must be able to determine the fields and methods of the managed data object dynamically as well. In order to implement such an operation we need a meta-programming mechanism that dynamically analyses the structure of a schema and applies to it the functionality of the data managers. In their implementation Cook et al. [LvdSC12] used the “missing_method” implementation in order to succeed that. In our case we will use Java’s reflection API and dynamic proxies.

2.4 Java Reflection and Dynamic Proxies

The Java programming language provides the programmer with a Reflection API² that offers the ability to examine or modify the runtime behavior of applications running in the [Java Virtual Machine \(JVM\)](#). Additionally, Java comes with an implementation of Dynamic Proxies³ which is a class that implements a list of interfaces specified at runtime.

2.4.1 Reflection

Reflection is the ability of a running program to examine itself and its environment and to change what it does depending on what it finds [FFI04].

²<https://docs.oracle.com/javase/tutorial/reflect/>

³<https://docs.oracle.com/javase/8/docs/api/java/lang/reflect/Proxy.html>

In order for this self-examination to be successful, the program needs to have a representation of itself, which is called *metadata*. In a [OOP](#) language this metadata is organized into objects, hence they are called *metaobjects*. Finally, the process of the runtime self-examination of these metaobjects is called *introspection*.

Java supports reflection with its reflection API since the version 1.1. Java provides many operations for using metaobjects performing intercession. Using Java reflection a running program can learn a lot about itself. This information may derive from classes (the `Class` metaobject), class name, class methods, a class super and sub classes, methods (the `Method` metaobject), method name, method parameters, method type, variables, variables handlers and more. Querying information from these metaobjects is called introspection. Additionally to the examining of the these metaobjects, a developer has the ability to dynamically call a method that is discovered at runtime. This process is called *dynamic invocation*. Using dynamic invocation, a `Method` metaobject can be instructed to invoke the method that it represents during the program's runtime.

Although reflection is considered helpful for developing flexible software, it has some known pitfalls:

Security. Since metaobjects give a developer the ability to invoke and change underlined data of the program, it also gives access them to places that are supposed to be secure (e.g. `private` variables).

Code complexity. Consider a program that uses both normal objects and metaobjects. That introduces an extra level of complexity since now a developer has to deal with different kinds of objects on different levels, meta and normal level.

Runtime performance. Of course the runtime dynamic examination and introspection introduce significant overhead on most language implementations. In the case of Java's dynamic proxies a 6.5x overhead observed [\[MSD15\]](#). However, this is not something that we take into consideration in our implementation.

2.4.2 Dynamic Proxies

Since 1.3 version Java supports the concept of *Dynamic Proxies*. A *proxy* is an object that supports the interface of another object (*target*), so that the proxy can substitute for the target for all practical purposes[\[FFI04\]](#). A proxy has to have the same interface as the *target* so that it can be used in exactly the same way. Additionally it *delegates* some or all of the calls that it receives to its target and thus acts as either an intermediary or a substitute object. As a result, a programmer has the capability to add behavior to objects dynamically. The Java reflection API contains a dynamic proxy-creation facility, in `java.lang.reflect.Proxy`.

There are several examples of dynamic proxies implementation in Java including implicit conformance, future invocations [\[PSH04\]](#), dynamic multi dispatch, design by contract or [AOP](#) [\[Eug06\]](#).

Proxy Objects

A proxy is an object which conforms to a set of interfaces, for which that proxy was created for. The corresponding proxy class extends the class `Proxy` and implements all its interfaces. Thus, conforming to all those interfaces, a proxy can be casted to any of them and any method defined in those interfaces can be invoked on the proxy object [\[Eug06\]](#).

Invocation Handlers

All the proxy objects have an associated object of type `InvocationHandler`, which handles the method invocations performed on the proxy, and its interface is shown in Listing [2.1](#).

The arguments of the `invoke` method include the object on which the method was originally invoked (i.e., the proxy), the method itself that was invoked on the proxy, and the arguments of that method, if any. Therefore, the `invoke` method is capable of handling any method invocation.


```

1 public interface InvocationHandler {
2     public Object invoke(Object proxy, Method method, Object[] args) throws Throwable;
3 }

```

Listing 2.1: The Invocation Handler Interface

Issues

A proxy instance is an object and it responds to the methods declared by `java.lang.Object`. Thus, when these methods should be invoked and from which object is an issue that arises [FFI04].

The methods `equals`, `hashCode`, and `toString` are inherited by all classes from the `Object` class and they are handled just like custom methods. If they are proxied then they are also overridden by the proxy classes and invocations to them are forwarded to the invocation handler of the proxy. Other methods defined in `Object` are not overridden by proxy classes, as they are `final` [Eug06].

Logging Example

Previously we mentioned the *logging CCC 2.1*. Imagine that every method invocation of an object has to be logged into the console, in that case we would need to write logging code on each of the methods of that class. This would lead to scattered logging code through the methods. This is problem can be solved with dynamic proxies and a simple solution is presented in Listing 2.2.

```

1 public class TracingIH implements InvocationHandler {
2     public static Object createProxy(Object obj, PrintWriter out) {
3         return Proxy.newProxyInstance(
4             obj.getClass().getClassLoader(),
5             obj.getClass().getInterfaces(), new TracingIH( obj, out));
6     }
7
8     private Object target;
9     private PrintWriter out;
10
11     private TracingIH(Object obj, PrintWriter out) {
12         target = obj;
13         this.out = out;
14     }
15
16     public Object invoke(Object proxy, Method method, Object[] args) throws Throwable {
17         Object result = null;
18
19         try {
20             out.println(method.getName() + "(...) called" );
21             result = method.invoke( target, args );
22         } catch (InvocationTargetException e) {
23             out.println(method.getName() + " throws " + e.getCause());
24             throw e.getCause();
25         }
26         out.println(method.getName() + " returns" );
27         return result;
28     }
29 }

```

Listing 2.2: An invocation handler for a proxy that traces calls [FFI04]

2.5 JHotDraw And AJHotDraw

JHotDraw⁴ is a Java GUI framework for technical and structured graphics. It is an open-source, well-designed and flexible drawing framework of around 18,000 non-comment lines of Java code. JHotDraw’s design relies heavily on some well-known design patterns[Gam95] and it is considered as a showcase for software quality techniques provided to the OOP community.

The fact that JHotDraw is praised for its design makes it an ideal candidate as a showcase for an aspect oriented migration. Marin and Moonen [MM] use this showcase for adoption of aspect-oriented techniques in existing systems. In particular, they present AJHotDraw⁵, which is an aspect-oriented version of JHotDraw developed in Java and AspectJ. The goal of AJHotDraw is to take JHotDraw and migrate it to a functionally equivalent aspect-oriented version.

The authors presented a fan-in analysis of JHotDraw [MVDM04] and implemented an idiom-driven approach to aspect-mining. This way they could extract a number of aspects in JHotDraw. Next, they performed a concern exploration in order to expand their mining results, leading to concern sorts. Concern sorts is a consistent way to address crosscutting concerns in source code. This led to the identification and documentation of crosscutting concerns in JHotDraw, which helps the developers to identify CCC in JHotDraw. In order to tame the aspects in a more consistent and formal way, Marin et al. provided a list of *template aspect* solutions for their concern sorts. Finally, they performed aspect refactoring of JHotDraw by presenting the AJHotDraw, which according to them, was the largest migration to aspects available to date. Their refactoring aimed at maintaining the conceptual integrity of the original design.

In order to refactor the existing framework, the first thing that AJHotDraw developers needed to do was to create a test subproject for the JHotDraw, called TestJHotDraw⁶, which ensures behavioral equivalence between the original and the refactored solution. Refactoring implies preserving the observable behavior of an application[Fow09] and since the developers of AJHotDraw ought to test their functionality, TestJHotDraw was created. There are several contributions of the aspect-oriented implementation approach[MM]. The authors suggest that the project contributes to a gradual and safe adoption of aspect-oriented techniques in existing applications and allows for a better assessment of aspect orientation.

In this thesis we have used JHotDraw and AJHotDraw in order to evaluate our CCC refactoring in managed data. TestJHotDraw is written in AspectJ, a language we did not want include in our project, and therefore it is not used. Instead, we used the JHotDraw original test suite which consists of 1218 test cases, included in our refactoring. The detailed evaluation is described in Chapter 6.

2.5.1 Refactoring of Crosscutting Concerns

The refactoring of legacy code to aspect oriented code is also known as *Aspect Refactoring* [MMvD05a]. During this process it is important to identify which elements are going to be refactored and which *aspect* solutions will replace them. To evaluate the refactored elements [Fow09], a testing component is needed in order to ensure behavior conservation, hence some coherent criteria to organize CCC are needed. Marin, Moonen and Deursen [MMvD05a] organize the CCC into types, which are descriptions of similar concerns that share the following properties:

- A generic behavioral, design or policy requirement to describe the concern within a formalized, consistent context (e.g., role superimposition to modular units (classes), enforced consistent behavior, etc.),
- An associated legacy implementation idiom in a given (non-aspect oriented) language (e.g., interface implementations, method calls, etc.)
- An associated (desired) aspect language mechanism to support the modularization of the type’s concerns (e.g., *pointcut* and *advice*, introduction, composition models).

⁴<http://www.jhotdraw.org/>

⁵<http://swierl.tudelft.nl/bin/view/AMR/AJHotDraw>

⁶<http://swierl.tudelft.nl/bin/view/AMR/TestJHotDraw>

2.5.2 The Observer Pattern

Design patterns introduce CCC by scattering “pattern code” through an application. Hannemann et al. [HMK05] discuss this with an example of CCC refactoring of the observer pattern. The observer pattern is by nature not-modularized. The pattern crosscuts a large number of modules, tangling the scattered concern implementation with the component code and complicating changes.

Role-based Refactoring

The authors present a *role-based* refactoring, which consists of classifying the roles of the pattern in different aspects. The role-based refactoring approach helps the developer to transform a scattered implementation of CCC into an equivalent but modular AOP implementation. Both CCC and refactoring are described in terms of roles.

According to the authors[HMK05], the steps of role-based refactoring are the following:

Selecting a CCC refactoring: The refactoring includes an abstract description of the CCC it targets and a set of instructions to produce a modular AOP implementation of the refactoring (e.g. the Observer pattern CCC refactoring).

Stating a mapping: Map role elements comprising the CCC description to the program elements of the scattered code (e.g. the Subject and the Observer role to concrete classes)

Planning the refactoring: make the right choices for specific cases since a CCC refactoring involves modifying several parts of a codebase (e.g. naming).

Execution: transform the code according to the refactoring instructions (e.g. modularizes Observer pattern as a result).

Thus, to refactor CCC it is required a mapping from the abstract CCC description to programming components that explicitly describe the CCC implementation. This mapping for the case of the observer pattern is presented by Hannemann et al. [HMK05] in Figure 2.1.

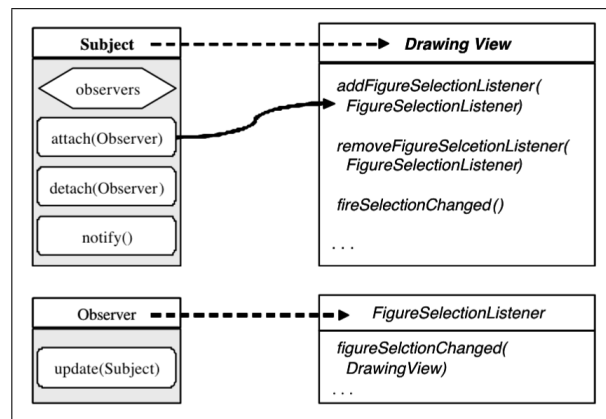


Figure 2.1: Observer pattern: Role Mapping [HMK05]

This figure describes the roles mapping in a specific case on JHotDraw, the *Figure Selection Listener*. However the authors have shown an abstract and reusable way of describing those roles.

2.5.3 The Figure Selection Observer of JHotDraw

As mentioned above, Hannemann et al. [HMK05] presented a refactoring of the *Observer* design pattern in JHotDraw. Likewise, during the AJHotDraw implementation[MMvD05a] [HMK05], the authors proposed a type-based refactoring on the same *Observer* instance, the *FigureSelectionListener*.

The concern sorts identified in this case are: the *Role Superimposition*, which is similar to the role-based refactoring described previously and the *Consistent Behavior*, which describes a set of methods consistently invoking a specific action as a step in their execution.

The legacy code architecture of JHotDraw is displayed in Figure 2.2.

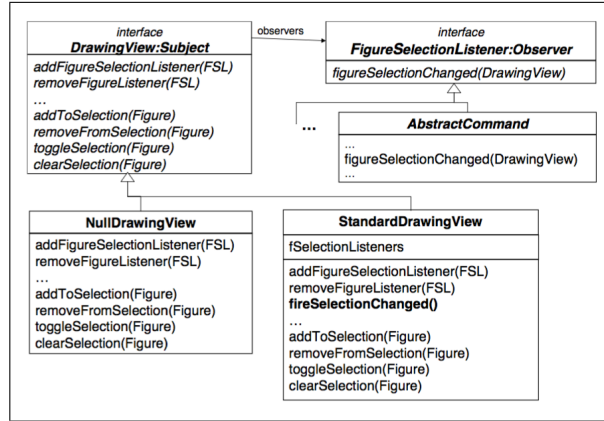


Figure 2.2: Observer pattern: Selection Listener [MMvD05a]

The `FigureSelectionListener` has the *Observer* role in the pattern implementation. Any class that is subject to changes of the selection of figures in a `DrawingView`, implements this interface. The `DrawingView` interface partially defines the *Subject* role by including two methods `addViewChangeListener` and `removeViewChangeListener`. From the classes that implement this interface only one, the `StandardDrawingView`, contains a non-empty implementation of the *Subject* role in the `fireSelectionChanged` method. Note that this method is only defined in the concrete class, which deviates from the standard Observer pattern implementation.

In their aspect refactoring, they described an aspect that is constructed comprising both the *Subject* and *Observer* roles definition and maintaining a list of associations between each *Subject* and its *Observer* objects. Their type-based refactoring[MMvD05a] distinguishes several crosscutting elements in JHotDraw's *Observer* pattern. First, the role superimposition, applied twice, for each of the two roles. Second, consistent behavior to notify the observers of the changes in the *Subject* object. Where superimposition is defined as the aspect implementation of a specific role and consistent behavior as the aspect implementation of a *consistent behavior* for a number of method elements that can be captured by a natural pointcut. The `GenericRole` (empty) interface documents the crosscutting type of role superimposition. Specific roles, like *Observer* and *Subject* (`SelectionSubject`) extend the interface. These elements are shown in Figure 2.3.

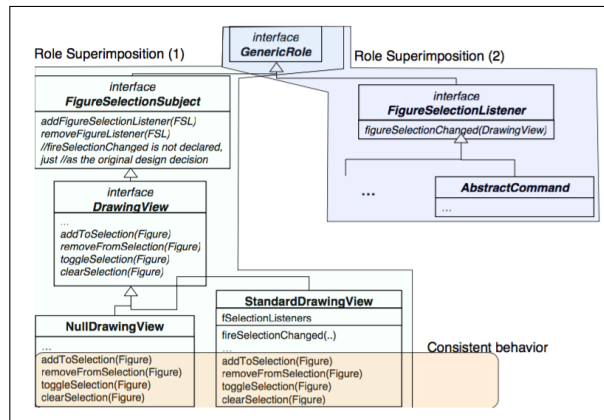


Figure 2.3: The concern types in Selection Listener [MMvD05a]

2.5.4 The “Undo” Concern of JHotDraw

After a fan-in analysis of JHotDraw [MVD04], Marin identified the “Undo” concern in JHotDraw and he presents an approach to its aspect-oriented refactoring [Mar04]. He uses the *(un)pluggability* property of a concern as an estimate of its refactoring cost. The author proposes the refactoring of the “Undo” concern in JHotDraw using AspectJ with the implementation of AJHotDraw. During the fan-in analysis [MVD04], the results have shown about 30 undo activities defined for various elements of JHotDraw. A representation of the elements in the JHotDraw implementation of the “Undo” concern can be seen in Figure 2.4.

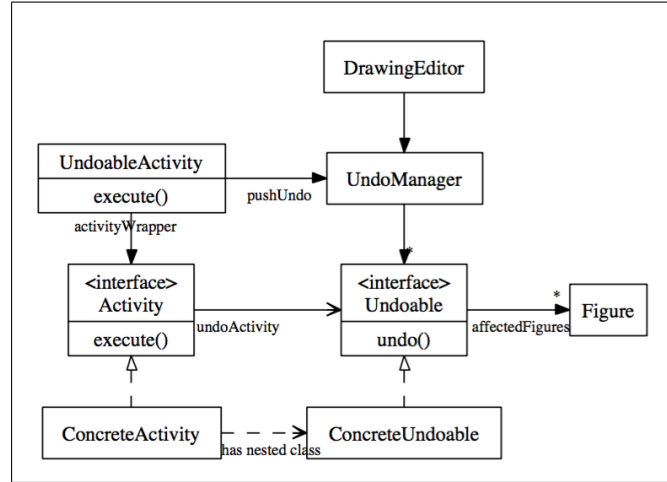


Figure 2.4: Participants for undo in JHotDraw [Mar04]

The **Activity** component participates in the implementation of the *Command* design pattern [Gam95]. Many of these activities have support for undo functionality, which in JHotDraw is implemented by means of nested (undo) classes. The nested class knows how to undo the given activity which maintains a list of affected figures whose state is also affected if the activity would be “undone”. Whenever the activity modifies its state it also updates fields in its associated undo activity to actually perform the undo. The **Undoable Command** object serves three roles:

- it consumes the request to execute the command
- then, it delegates the command’s execution to the wrapped command
- and last, acquires a reference to the undo activity associated with the wrapped command and it pushes it into a stack managed by an **UndoManager**. When executing an **Undo Command**, the top undo activity in the stack is extracted and, after the execution of its **undo()** method, is pushed into a redo stack managed by the same **UndoManager**.

Given this implementation, it is obvious that the primary decomposition of *Command* is crosscut by a number of elements as follows:

- The field by **AbstractCommand** for storing the reference to the associated **Undo Activity**.
- The accessors for this field implemented by the same class.
- The **UndoActivity** nested classes implemented by most of the concrete commands that support undo.
- The factory methods for the undo activities declared by each concrete command that can be undone.
- The references to the before enumerated elements from non-undo related members.

The implementation of AJHotDraw succeeded in refactoring this concern in JHotDraw through the following steps [Mar04]:

1. An undo-dedicated aspect is associated to each of undo-able command. The aspect will implement the entire undo functionality for the given command, while the undo code is removed from the command class.
2. Each aspect will consistently be named by appending `UndoActivity` to the name of its associated command class to enforce the relation between the two.
3. Next, the command's nested `UndoActivity` class moves to the aspect. The factory methods for the undo activities also move to the the aspect, from where are introduced back, into the associated command classes, using inter-type declarations.
4. Finally, the undo setup is attached to those methods from which was previously removed, namely `execute()` method, by means of an AspectJ `advice`.

This proposition [Mar04] provides an easy migration to an aspect-based solution. The CCC has been identified, then removed from the system, and finally re-added in an aspect-specific manner.

(Un)pluggability of the Undo concern

In order to evaluate the CCC refactoring of “Undo” Marin [Mar04] used the (Un)pluggability property. The author groups the complexity of the commands based two criteria. First, on the degree of *tangling* of the undo setup in the command's logic, particularly the activity's `execute()` method. Second, on the impact of removing the undo-related part from its original site, which can be estimated by the number of references to the factory method and to the methods of the nested undo activity. Thus, the (un)pluggability property gives a measure of how clearly the concern is distinguished in the original code and is a good estimate of the refactoring costs.

AspectJ Drawbacks and Limitations

By executing aspect-refactoring the two concerns are separated, modularized and the secondary concern of undo is no longer tangled into the implementation of the primary one.

However, there are certain drawbacks to this approach. For instance, AspectJ's mechanisms do not allow introduction of nested classes, the post-refactoring association will only be an indirect one, based on naming conventions (“`UndoActivity`”). This is a weaker connection than the one provided by the original solution. Another drawback that is observed is the change of the visibility of the methods introduced from the aspects, for example the inter-type declarations. The visibility declared in the aspect refers to the aspect and not to the target class. Such drawbacks could be overcome by a better aspect language support, which will be further discussed in this thesis.

Chapter 3

Example Application: State Machine Monitoring

In this chapter in order to show how our managed data implementation works in practice, and in particular in terms of aspect refactoring, we present a showcase. The showcase consists of a very simple state machine application. A similar example is presented in Enso paper as a showcase for its Object Grammar capabilities [SCL⁺12].

Consider the requirements of the state machine as the following:

- A state **Machine** consists of a number of named **State** declarations.
- Each **State** contains **Transitions** to other states, which are identified by a **name**, when a certain event happens.
- A **Transition** is identified by a certain **event**.

For reasons of simplicity, this example will be a very basic *door state machine*, which includes three states **Open**, **Close** and **Locked**, accompanied by their transitions: **open_door**, **close_door**, **lock_door** and **unlock_door** respectively. Figure 3.1 illustrates the door state machine.

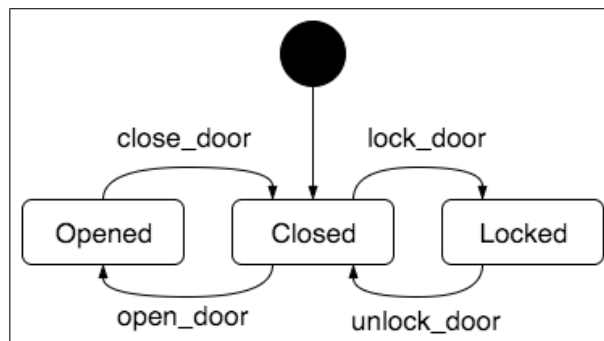


Figure 3.1: Basic door state machine

To implement this we need to define the models, interpret the definition given a list of events and finally add any additional functionality (*concern*) needed, for instance monitor the state of the door.

3.1 Schemas definition

As a first step, all the models of the state machine program need to be defined. An object diagram is illustrated in Figure 3.2.

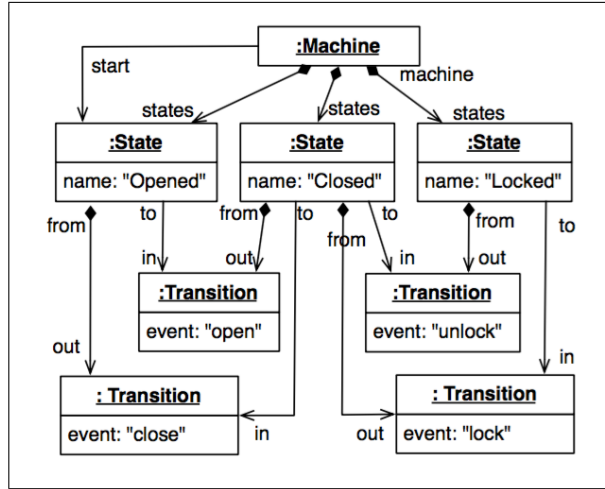


Figure 3.2: Basic door state machine object diagram

In our implementation we define schemas using Java interfaces with a set of meta-data described with Java annotations. Therefore, as extracted from the requirements we need Machine (Listing 3.3), State (Listing 3.4) and Transition (Listing 3.5) schemas.

```

1 public interface Machine extends M {
2     State start(State... startingState);
3
4     State current(State... currentState);
5
6     @Contain
7     Set<State> states(State... states);
8 }

```

Listing 3.3: The Machine Schema

As it can be seen in Listing 3.3, the Machine schema definition requires a **starting** state, the **current** state of the machine and a set of **states** that the machine can be into at each time. Note that the @Contain annotation suggests that the **states** field is part of the spine tree and it is not a cross-reference. This will be further explained in Chapter 4.

```

1 public interface State extends M {
2     @Key
3     String name(String... name);
4
5     @Inverse(other = Machine.class, field = "states")
6     Machine machine(Machine... machine);
7
8     @Contain
9     Set<Transition> out(Transition... transition);
10
11     @Contain
12     Set<Transition> in(Transition... transition);
13 }

```

Listing 3.4: The State Schema

For the `State` definition, Listing 3.4, we need a `name` field, which represents the name of the state. This `name` field has been annotated with the `@Key` annotation, which indicates uniqueness. The `states` field of `Machine` can be indexed by name. Moreover, the schema includes a set of `in` and `out` `Transitions`. Since those two fields are of type `Set`, one field of the `Transition` schema has to be marked as *key*. In this case, it is the `name` field (Line 2 Listing 3.5). Finally, the field `machine` represents the state machine that the state is part of. As it can be seen in the schema definition, Listing 3.4, the `machine` field has been annotated with `@Inverse`, which indicates that this field is a reference to a field of another schema. In this case, the `machine` field of `State` schema is a reference to `states` field of `Machine` schema.

```
1 public interface Transition extends M {
2     @Key
3     String event(String... event);
4
5     @Inverse(other = State.class, field = "out")
6     State from(State... from);
7
8     @Inverse(other = State.class, field = "in")
9     State to(State... to);
10 }
```

Listing 3.5: The Transition Schema

Finally, in the `Transition` schema definition, Listing 3.5, we need an `event` that corresponds to the event of the transition and is the **key** of that schema. The `from` and `to` fields represent the state that the machine changes from and to respectively. However, these are just references to the `State` schema (Listing 3.4).

3.2 Factory definition

Now that we have our schemas, we need a way to build instances of managed objects that these schemas describe. In Java to create these three schemas as managed data we need to define a factory, which creates managed data instances (managed objects) for each of these schemas 3.6. Note that the method definitions work as **Constructors** of managed objects.

```
1 public interface StateMachineFactory {
2     Machine Machine(); // constructor for Machine managed objects
3     State State();     // constructor for State managed objects
4     Transition Transition(); // constructor for Transition managed objects
5 }
```

Listing 3.6: The StateMachine Factory

3.3 Basic Data Manager

As mentioned above, in order to interpret and manage the defined data we need data managers. Our implementation includes the definition of a **Basic data manager** that is responsible of interpreting a schema definition to instances of *managed objects*. Conclusively, in order to make a *managed object*, the data manager needs its schema definition (the interfaces that define the schemas) and the schema factory (the interface that defines the constructors of the schemas).

3.3.1 A simple program

In the case of a simple program without any concerns, we have to use our managed data to define the state machine and then interpret it. The definition of the door state machine is given in Listing 3.7 in Java.

In practice, the basic data manager needs to provide us with mechanisms that interpret the managed object that based on `stateMachineSchema`, shown in Line 6. The basic data manager also supports the field accessors of those data, namely, the setters and getters of their values. An basic interpreter for the state machine is shown in Line 42. As it can be seen, the schema factory is used to create managed objects. The *setup* of the fields is done automatically by the data manager who is responsible for the managed object interpretation.

3.4 Monitoring and notification concerns

Consider a case in which we want to add concerns at the previous door state machine implementation. A simple concern could be *monitoring*, which would log every change in the current state of the state machine. Another concern could be *notification*, which would fire an action when a specific state is set.

Imagine that the system has to notify someone in case the door is opened. If the door opens, then the **Open** state will be set as the current state of the machine. In that case, a notification has to be sent by e-mail. This looks similar to the *monitoring* concern; however, in this case the notification is a specific action: send an e-mail in case the door opens.

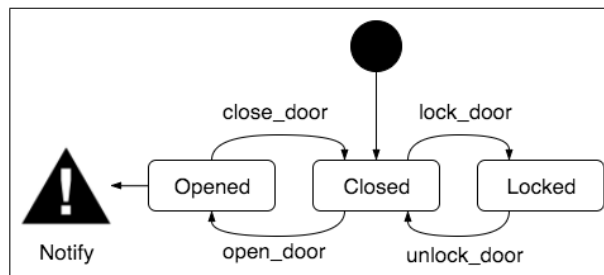


Figure 3.3: Simple door state machine: notify closed door

In order to implement those concerns we need a mechanism that continuously monitors the changes (transitions) of the machine's **current** state and reacts accordingly. Usually, this would lead to scattered *monitoring* and *notification* code in the interpretation method or the models themselves (the machine model). This is where data managers come to the rescue. A data manager can implement concerns as modular aspects without crosscutting code to the components. The programmer can define a manipulation mechanism of his/her data that includes an aspect of preference. Therefore, by implementing our concerns with data managers we can keep the component and aspect code separate.

3.4.1 Observable Data Manager

Regarding the *observation* of changes in the current state of our door state machine, we need a data manager that observes those changes in the managed object. In particular, the **Machine**'s **State** field. This data manager creates concrete managed objects, namely *observable managed objects*, where observers can be attached in order to be notified of changes. It is important to mention that this new data manager has to inherit the basic one in order to include the basic functionality of schema interpretation and field access. This leads to a **stack** of two data managers, each one adding a new aspect of data in a modular way.

```

1 public class StateMachineExample {
2     public static void main(String[] args) {
3         Schema schemaSchema = ...;
4         Schema stateMachineSchema = ....;
5         BasicDataManager basicDataManager =
6             new BasicDataManager(StateMachineFactory.class, stateMachineSchema);
7         StateMachineFactory stateMachineFactory = basicDataManager.make();
8
9         Machine doorStateMachine = stateMachineFactory.Machine();
10
11         State openState = stateMachineFactory.State(OPEN_STATE);
12         openState.machine(doorStateMachine);
13
14         State closedState = stateMachineFactory.State(CLOSED_STATE);
15         closedState.machine(doorStateMachine);
16
17         State lockedState = stateMachineFactory.State(LOCKED_STATE);
18         lockedState.machine(doorStateMachine);
19
20         Transition closeTransition = stateMachineFactory.Transition(CLOSE_TRANSITION);
21         closeTransition.from(openState); closeTransition.to(closedState);
22
23         Transition openTransition = stateMachineFactory.Transition(OPEN_TRANSITION);
24         openTransition.from(closedState); openTransition.to(openState);
25
26         Transition lockTransition = stateMachineFactory.Transition(LOCK_TRANSITION);
27         lockTransition.from(closedState); lockTransition.to(lockedState);
28
29         Transition unlockTransition = stateMachineFactory.Transition(UNLOCK_TRANSITION);
30         unlockTransition.from(lockedState); unlockTransition.to(closedState);
31
32         doorStateMachine.start(closedState);
33         interpretStateMachine(doorStateMachine, new LinkedList<>(Arrays.asList(
34             LOCK_TRANSITION,
35             UNLOCK_TRANSITION,
36             OPEN_TRANSITION)));
37     }
38 }
39
40 private static void interpretStateMachine(
41     Machine stateMachine, List<String> commands)
42 {
43     stateMachine.current(stateMachine.start());
44     for (String event : commands) {
45         for (Transition trans : stateMachine.current().out()) {
46             if (trans.event().equals(event)) {
47                 stateMachine.current(trans.to());
48                 break;
49             }
50         }
51     }
52 }

```

Listing 3.7: Door state machine

3.4.2 Monitor and notify concerns

In the example the *observers* are the concerns: *monitoring* and *notification*. Accordingly, the *current* state of the state machine is the *subject* that informs the observers of its change. The definition of the concerns is given in Listing 3.8.

```
1 public class StateMachineMonitoring {
2     public static void monitor(Object obj, String field, Object value) {
3         if (field.equals("current")) {
4             logger.log(" > Current state changed to " + ((State) value).name());
5         }
6     }
7
8     public static void notify(Object obj, String field, Object value) {
9         if (field.equals("current") && ((State) value).name().equals(OPEN_STATE)) {
10             if (EmailSender.send("Danger!", "Someone just opened the door!")) {
11                 logger.notify(" > Danger e-mail sent!.");
12             }
13         }
14     }
15 }
```

Listing 3.8: Door state machine concerns definition

Since there is an observable data manager and the concerns are implemented in a separate and reusable module, completely unrelated to our logic code, we still need to integrate them in the original code. The integration code is presented in Listing 3.9. The only part that changes is Line 9 of the original code, where the data manager of the *Machine* managed object has changed to the new observable data manager. Additionally, the concerns are attached to the machine object very easily, as can be seen in Lines 12 and 13 of Listing 3.9.

```
1 ...
2 // State Machine monitoring
3 ObservableDataManager observableDataManager =
4     new ObservableDataManager(StateMachineFactory.class, stateMachineSchema);
5
6 StateMachineFactory observableStateMachineFactory = observableDataManager.make();
7
8 // Door State Machine definition, with observable data manager
9 Machine doorStateMachine = observableStateMachineFactory.Machine();
10
11 // Add monitoring and notification concerns
12 ((Observable) doorStateMachine).observe(StateMachineMonitoring::monitor);
13 ((Observable) doorStateMachine).observe(StateMachineMonitoring::notify);
14 ...
```

Listing 3.9: Door state machine with concerns

By running the program with the commands `LOCK_TRANSITION`, `UNLOCK_TRANSITION` and `OPEN_TRANSITION`, the output is presented in Listing 3.10.

```
> Current state changed to Closed  
> Current state changed to Locked  
> Current state changed to Open  
> Danger e-mail sent!
```

Listing 3.10: Door state machine with concerns: output

The basic data manager allows to solely build managed objects, but the observable data manager also provides the functionality of attaching concerns in the managed objects after a specified event. Concluding, the example presented a modular solution of CCC without scattering and tangling code in the components.

Chapter 4

Managed data in Java

As it has already been mentioned, the programming languages include data definition mechanisms that are predefined. This makes them unable to define CCC without repeating and scattering code through the components [LvdSC12]. Notably, the problem is that CCC are not considered features of the data types, but instead features of data management. As a result, we implement managed data to allow the developer to define the mechanisms of data manipulation. This chapter describes our managed data implementation in Java, testing our first research question, which states “*Can managed data be implemented in a static language?*”. It is important to mention that our implementation is inspired by Enso¹, which is written in Ruby. Although Ruby is a dynamic language, Enso significantly contributed to our implementation’s design. In this chapter we present the implementation of managed data in Java, which is available also online as an open-source project called JavaMD (Java Managed Data)².

4.1 Managed Data Implementation

Managed data allows the programmer to handle the fundamental data manipulation mechanisms using *Data Managers*, one of its distinguishing features being modularity. Using a data description language the programmer defines *Schemas*. *Schemas* are the input of *Data Managers*. A *Data Manager* in turn interprets the data description language that is used to define the structure and the behavior of the data to be managed. *Schemas* and *Data Managers* are essential components of managed data, along with *Integration* in the programming language, in our case being Java.

4.1.1 Data description with Schemas

To create instances of data, we first need to define their structure. *Schemas* describe the outline structure of our data. In order to define *Schemas* in managed data we need a data description language that allows to define records as collections of fields. This language can be anything, e.g. XML, JSON or a different formalism like the one used in Enso. For our implementation we chose to use **Java Interfaces** as a data description language to define records of managed data. By using Java interfaces we use Java’s syntax for our definitions. Moreover, Java interfaces use several conventions to encode semantics, for instance Java annotations, which are very useful for meta data definition on *Schemas*.

As a result, to define a *Schema* we first need to define a set of classes that describe that schema. A schema **Klass**³ is described by a name and a set of **Fields**, each of which has a name and a **Type**. Since Java interfaces are used to define a **schemaKlass** we need a way to define **Fields** for that **schemaKlass**. A **Field** in our data description language can be defined by using **Java’s Method** definition.

¹<https://github.com/enso-lang/enso>

²<https://github.com/Theo1Zacharopoulos/JavaMD>

³ We use the “Klass” instead of “Class” convention in order to avoid any kind of ambiguities between Java’s Class type and our type system. Klass is used to describe our own class type while Class describes Java’s native class type.

Additionally, there are several attributes, considered meta data, that help define the structure of a **Schema**. In order to define the meta data in our data description language (interfaces), we use *Java Annotations*. Annotations are very declarative in the way they express meta data in interfaces and they are consistent with the system (Java).

Thus, to provide a field with meta data, we define annotations in a *Method* target level since a **Field** is defined by a *Method* declaration Java interfaces.

Note that by using Java interfaces and annotations for our schemas definition, we gain a first level of type checking from **JVM**. The reason is that before we run our runtime interpretation of schemas, **JVM** performs type checking in the definitions and in case of wrong types it notifies the programmer. Additionally, this is beneficial when a programmer uses IDE's that perform real time type inspection⁴. In those cases errors on the definitions will be spotted immediately.

The list of the available structure concepts that are supported in our language is presented below [LvdSC12]:

@Key When a method (field definition) is annotated with the **@Key** annotation that forces its value to be unique within collections of this field's **Klass**. The key should be used on a single field of a **Type** and its value represents the uniqueness of its **Klass**'s instance. Another way to look at this is as a counterpart of the **hashCode** in traditional Java programs. This way when many values of a **Klass** are in a **Set**, the key field ensures uniqueness in its context.

@Inverse This annotation includes two *annotation element definitions*⁵. When a method is annotated with the **@Inverse(Class other, String field)** annotation, then the inverse **field** element must be a **Field**'s name in the **Class** interface, given by the **type** element. This meta data is used as a reference declaration in schemas, meaning that when a programmer updates the value of a field that is annotated with inverse, then the value of the field that refers to will be also updated. This mechanism is interpreted by the managed object and is used for automated *wiring* of the field across a schema.

@Contain When a field is annotated with the **@Contain** annotation, then this field is considered as *traversal*. In general, traversals describe a minimum spanning tree that is called *spine* and ensures reachability of values. The spine is used in implementations that need a depth-first search by distinguishing between the actual information and the cross-references of the spanning tree. If a spanning tree is defined, then all nodes in a model must be uniquely reachable by following just the spine fields [SCL⁺12]. An example of such functionality is the equivalence between managed objects that is presented in Section 4.4.1. Sometimes traversal fields describe composition, or “is a part of”, relationships [LvdSC12].

@Optional When the **@Optional** annotation is on a field's definition this field can include **null** values. **Inverse** fields are **Optional**.

Java Inheritance In addition to the Java annotations, our language uses more Java mechanisms for schemas definition. Java inheritance is one of them. A **schemaKlass** can extend another **Klass** (super), which works as the traditional Java inheritance, supporting sub typing mechanisms. Implementing this we introduce a *Type Hierarchy* model that includes super and sub classes on managed objects. Note that since we use interfaces for **schemaKlass**, we implicitly support multiple inheritance because a Java interface can extend more than one interfaces.

Java Collections Finally, another Java mechanism that we use is the definition of a field that includes many values. To define such a field, a programmer has to declare a field's **Type** as a **java.util.List** or a **java.util.Set** of this **Type**.

Using all the aforementioned constructs of our data definition language, a programmer can define any kind of schema, even itself (see Section 4.2). Schema definition examples are presented in Chapter 3 Listings 3.3, 3.4 and 3.5. In those definitions the above concepts can be recognized and their meaning can be revealed in context.

⁴<https://www.jetbrains.com/help/idea/15.0/code-analysis.html>

⁵<https://docs.oracle.com/javase/tutorial/java/annotations/declaring.html>

4.1.2 Schema Factories

However, even if we have the definitions of schemas, we still need a way to create instances of managed data described by them. We can not use Java's mechanisms⁶ for this functionality since we need them to be managed data and not ordinary objects. Thus, we use Java interfaces to define *Schema Factories*. A *Schema Factory* is a list of constructor definitions for specific schema *Klasses*.

The methods in this interface are used similarly to the constructors in a Java class, while their implementation is handled by the data managers. Since those methods are constructors, we can define a constructor with or without initial values. Unfortunately, we have encountered a limitation regarding constructors with initialization values, making them inappropriate to use in complicated schemas.

Methods Ordering Issue

The problem lays on Java's reflection mechanisms in terms of methods ordering. More specifically, when the methods of a `java.lang.Class` are requested by using the `public Method[] getMethods()` method⁷, the returned values are not ordered the way as defined in the source code. Consequently, since the schema definition is reflectively analyzed in the data managers and is dependent on that order, those methods can not be used in the initialization of values.

However, we overcame this difficulty and were able to support this feature in an alternative manner. In our implementation both the defined methods and the fields are **alphabetically ordered** by name before being initialized.

That feature can be used by the programmer although it can be confusing. Therefore, as an advice, we suggest to either provide constructors without initialization values or to write constructors with only **primitive** initialization values in **alphabetical order**. Otherwise we risk getting values in a random order leading to an error or a wrong value assignment.

4.1.3 Data Managers Implementation

However, the schemas are not a complete managed data specification without a corresponding **Data Manager**. A data manager is responsible for interpreting the schema and building virtual objects (managed objects). The managed object's fields are defined by the given schema and acts according to the specifications given by the data manager. Additionally, the data manager ensures that the data given are valid with respect to the schema. More specifically, the data managers describe how a schema definition is handled from the outside world and what its specifications are. These properties may include **CCC** that can be described separately by special data managers, separating schema and concern definitions. Thus, a managed object can have multiple interpretations based on the data manager that is used to interpret it.

A data manager is initialized with a **Schema** and provides a new **Managed Object** instance whose properties are defined by that data manager. Additional to the **Schema** that includes a Set of **Types** (**Primitives** or **Klasses**), it also needs a **Schema Factory** that declares the constructors of the given schema *Klass*. After the initialization of a data manager and the interpretation of the schemas, a data manager provides the mechanism of building new **Schema Factories**, which in turn create **Managed Objects** with the specifications of the data manager.

In the example presented in listing 4.11, Line 3 defines a basic data manager that gets the schema factory and the schema of a state machine as input. Next, Line 7 shows a new schema factory being created, which builds managed objects with the specifications attached from the basic data manager. Finally, Line 10 illustrates how the managed object instances with those specifications can be built.

⁶new keyword

⁷ As it is mentioned in <https://docs.oracle.com/javase/8/docs/api/java/lang/Class.html#getMethods-->, the elements in the returned array are not sorted and are not in any particular order.


```

1 // Create a basic data manager for state machines
2 BasicDataManager basicDataManagerForStateMachines =
3     new BasicDataManager(StateMachineFactory.class, stateMachineSchema);
4
5 // Create a schema factory that makes managed objects
6 // with the specifications of the basic data manager.
7 StateMachineFactory stateMachineFactory = basicDataManagerForStateMachines.make();
8
9 // Build an instance of managed object with those specifications.
10 Machine stateMachineInstance = stateMachineFactory.Machine();

```

Listing 4.11: Basic data Manager Example

Basic Data Manager

As described above, we use Java interfaces to define schema Classes that include fields. Those fields are dynamically discovered by the data manager who has the ability to determine the fields and methods of the managed data object during runtime. In addition, when the data manager adds functionality on a managed object then it first delegates the calls to its specifications and then to the fields of an instance. In order to dynamically interpret a schema inside a data manager and delegate functionality, we used Java Reflection and Dynamic Proxies.

In our implementation we have separated the Proxy factory (**DataManager**) from the Invocation Handler (**MObject**). This way, the **DataManager** class is responsible for creating proxied instances of managed data, while the **MObject** instances are responsible for interpreting the schema and delegating actions with their invocation handling mechanisms. Figure 4.1 illustrates this structure. As it can be seen the data manager is a *factory* that has only one exposed method, `make()`, that is used to build a **SchemaFactory**, which in turn builds **MObject** instances.

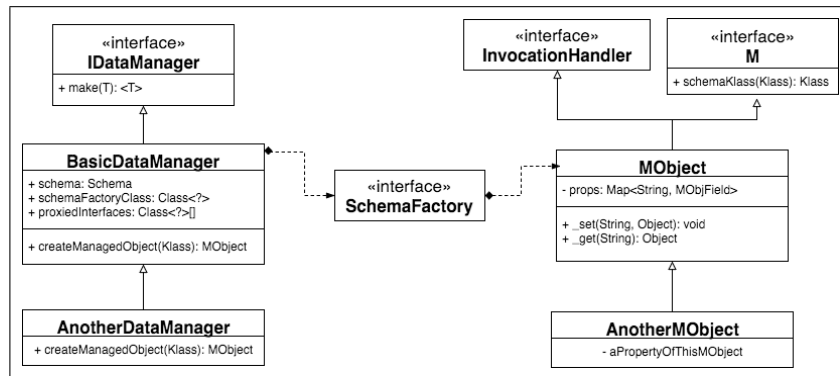


Figure 4.1: Data Manager and MObject

Stacking Data Managers

In order to create a stack of data managers that combine behavior and specifications, we can use inheritance. Figure 4.1 shows how this works. In detail, **AnotherDataManager** extends **BasicDataManager** and only overrides the `createManagedObject()` method. This method is responsible for creating a new instance of an **MObject**. In this case, the `createManagedObject()` method will create a new **AnotherMObject** instance. Additionally, the constructor of data managers needs to accept a dictionary of initialization parameters for overriding data managers that require different inputs. Note that it is important that the data managers inherit from a base data manager, leading to the modular aspect of the data managers. As it can be seen, for stacking data managers we used the *Decorator Pattern* [Gam95] which is mentioned also in Cook et al. [LvdSC12] as a strategy for static OOP languages.

4.1.4 Managed Objects

The `MObject`, is an implementation of the `InvocationHandler` interface. Thus, the `MObject`'s `invoke()` method is called in every field access of the managed object's instance. To manipulate its fields' values this object has two methods, `_set()` and `_get()`. In the implementation of these methods additional checks are performed to ensure the correctness of types and structure of the values. Those methods can be overridden from derived `MObjects` in order to *Decorate* the basic `MObject` with their functionality. Of course they require to call their `supers` for running all the checks.

The `MObject` is the *backing object* that stores a reference to the `schemaKlass` and its implementation represents an instance of that `schemaKlass`. That `schemaKlass` is a meta class that describes the layout of the `MObject` and keeps the `Fields` and their `Types`. During construction, the fields of the `MObject` are specified by its `schemaKlass`. When a field check has to be performed, the `MObject` uses its `schemaKlass`. The usage of the `schemaKlass` for setting up the fields is shown in Listing 4.12.

The `schemaKlass` is given to the `MObject` by the `DataManager` that is responsible for creating it. Using this `schemaKlass` the `MObject` setups the `Fields` of the `Klass`, Line 3. Inside the `setupField` method the interpretation of the schema is performed. In particular, in Line 10 we check if that field is a multi-value field, and if not, we just set it up as a `Primitive` or a `Klass` accordingly. Consider that the `field.type().schemaKlass().name()` is used like a common `instanceof` in Line 14. In case the field has many values, we first check if it is `Primitive`, since we do not support Set of `Primitives`. Following that, we check if a `Key` field exists on that field's type and in that case this field is a `Set`, otherwise it is a `List`.

4.1.5 Implementing a Data Manager

The implementation and the integration of a new data manager is straight forward in our framework. As it can be seen in Figure 4.1, the basic components of a new data manager implementation are the `Data Manager` class (proxy) and the `MObject` class (invocation handler).

First, to follow the modularity aspect and the ability to stack data managers together combining their specifications, we need to inherit from, at least, the `BasicDataManager` and `MObject` respectively. A simple data manager that could be useful is a data manager that introduces immutability to its managed objects. A `Lockable` data manager should first inherit the `BasicDataManager` to get its field access specification. The implementation of the `LockableDataManager` is illustrated in 4.13.

```
1 public class LockableDataManager extends BasicDataManager {
2
3     public LockableDataManager(Class<?> moSchemaFactoryClass, Schema schema) {
4         // Add the Lockable class in order to use it in the managed object.
5         super(moSchemaFactoryClass, schema, Lockable.class);
6     }
7
8     @Override
9     protected MObject createManagedObject(Klass klass, Object... _inits) {
10         return new LockableMObject(klass, _inits);
11     }
12 }
```

Listing 4.13: Lockable Data Manager

Additionally it should add some *locking* mechanism to ensure immutability of its objects. This is defined in the `Lockable` interface which is responsible of ensuring the implementation of the specifications. Figure 4.14 shows the specifications of the interface.

```

1 public MObject(Klass schemaKlass, Object... initializers) {
2     this.schemaKlass = schemaKlass;
3     this.schemaKlass.fields().forEach(this::safeSetupField);
4     if (initializers != null) {
5         this.safeInitializeProps(initializers);
6     }
7 }
8
9 protected void setupField(Field field) {
10     if (!field.many()) {
11
12         // if it is a primitive make it a Primitive field,
13         // otherwise a reference (managed object)
14         if (field.type().schemaKlass().name().equals("Primitive")) {
15             this.props.put(field.name(), new MObjectFieldSinglePrimitive(this, field));
16         } else {
17             this.props.put(field.name(), new MObjectFieldSingleMObj(this, field));
18         }
19     } else {
20
21         // in case it is a Primitive, then is always a List
22         // Sets of Primitives are not supported (yet)
23         if (field.type().schemaKlass().name().equals("Primitive")) {
24             this.props.put(field.name(), new MObjectFieldManyList(this, field));
25         } else {
26
27             Klass klassType = (Klass) field.type();
28             if (klassType.key() != null) {
29                 this.props.put(field.name(), new MObjectFieldManySet(this, field));
30             } else {
31                 this.props.put(field.name(), new MObjectFieldManyList(this, field));
32             }
33         }
34     }
35 }

```

Listing 4.12: MObject: setup fields

```

1 public interface Lockable {
2     void lock();
3 }

```

Listing 4.14: Lockable Interface

Since we have the specifications and the data manager that creates the *Lockable* managed object, we still need the implementation. The implementation is located in the *MObject* and in this case the *LockableMObject*, Figure 4.15.

```

1 public class LockableMObject extends MObject implements Lockable {
2     private boolean isLocked = false;
3
4     public LockableMObject(Klass schemaKlass, Object... initializers) {
5         super(schemaKlass, initializers);
6     }
7
8     public void lock() {
9         isLocked = true;
10    }
11
12    @Override
13    public void _set(String name, Object value)
14        throws NoSuchFieldError, InvalidFieldValueException, NoKeyFieldException {
15        if (isLocked) {
16            throw new IllegalAccessError(
17                "Cannot change " + name + " of locked object " + schemaKlass.name() + ".");
18        }
19        super._set(name, value);
20    }
21 }

```

Listing 4.15: Lockable Managed Object

The *LockableMObject*, by extending the *MObject* and implementing the *Lockable* interface, inherits the basic functionality of a managed object and gets a specification description respectively. Its role is to implement the logic of the immutability, which is as simple as it looks. In order to use this functionality, one needs to create managed objects using this data manager. An example is shown in Figure 4.16.

```

1 final PointFactory lockablePointFactory = lockableFactory.make();
2 final Point2D lockablePoint = lockablePointFactory.Point2D(1, 2);
3
4 // It was mutable until now, now it is locked (immutable).
5 ((Lockable)lockablePoint).lock();
6
7 try {
8     lockablePoint.x(2); // Should throw here since its immutable.
9 } catch (IllegalAccessError e) {
10     System.out.println("IllegalAccessError: " + e.getMessage());
11 }

```

Listing 4.16: Immutability Example

4.2 Self-Describing Schemas

As explained by Cook et al. [LvdSC12], a self-describing schema is a schema that can be used to define schemas, including itself. Our framework is fully self-described, the schemas are also described by schemas which are both models [KBJV06]. To allow schemas to be managed data we need a “self-describing schema mechanism” or *SchemaSchema*. Through the *SchemaSchema* the approach of managed data can be applied at the meta level as well.

The reason that a self-describing schema is important is because schema schemas can be used from schema factories to create schemas. The schema of schemas is just a schema that allows the creation of schemas, including its own schema [SCL⁺12]. Additionally, by presenting the schema as the first-class model [KBJV06], they can be extended in the same way just like ordinary models.

4.2.1 SchemaSchema

By using Java interfaces the *Schema* classes are tightly coupled structurally to the Java interfaces used to define them. Since we want to decouple from Java interfaces and reflection we need our own *Klass* system. In order to be self-describing we want this *Klass* system to be also represented as managed data. To model the structure of a *Schema* itself we need to be able to describe a class as a collection of *Fields*, each of which has a *name* and a *Type* [LvdSC12]. Thus, for our *SchemaSchema* definition we need a *Type*, a *Field* and a *Schema* as a collection of *Types*. A *Type* could be both a *Primitive*, without *Fields*, and a *Klass*, with a set of *Fields*. Additionally, those *Fields* may have some extra meta data attributes that are explained in Section 4.1.1.

A schema like this can describe itself since every concept used in the explanation is de facto included in the definition. For a self-describing implementation we need to describe our own *SchemaSchema*.

Figure 4.2 illustrates the modeling of this definition.

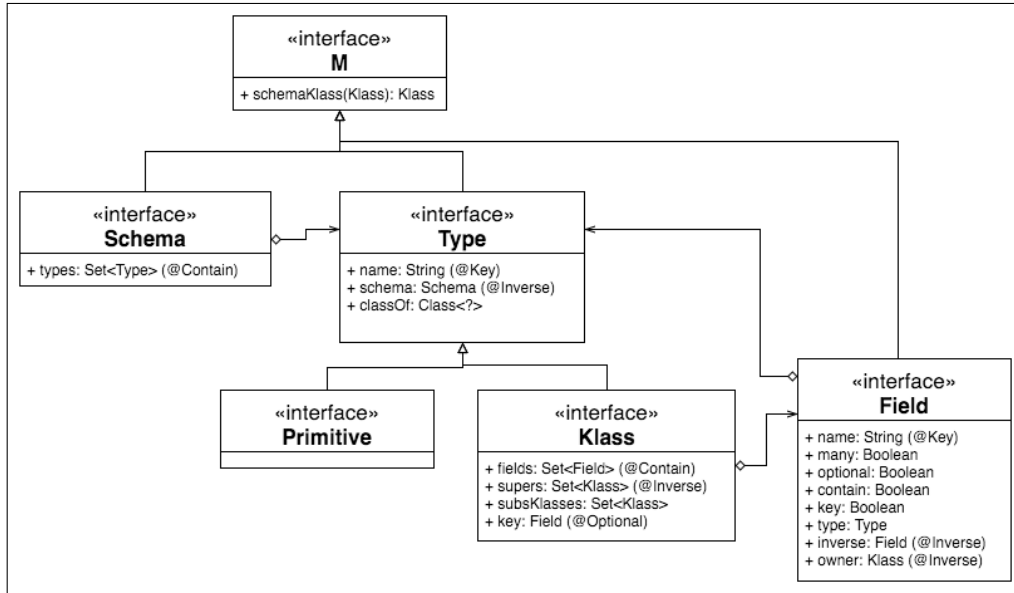


Figure 4.2: The schema of schemas

4.2.2 SchemaFactory

Considering that we have the schema of our schema (*SchemaSchema*) we need a way to create instances of those *schemaSchemaKlasses*. In this case, as we do with the normal schemas, we use a schema factory. However, this time it is a *schemaSchemaFactory* that defines constructors of all the schema classes that are needed to describe our *SchemaSchema*. Listing 4.17 shows its definition.

```

1 public interface SchemaFactory {
2     Schema Schema();
3     Primitive Primitive();
4     Klass Klass();
5     Field Field();
6     Field Field(
7         Boolean contain, Boolean key, Boolean many, String name, Boolean optional);
8 }

```

Listing 4.17: Schema SchemaFactory

4.2.3 Schema Loading

To construct the Klass system we need to analyze the Java interfaces using reflection and then build actual instances of the Schema, Klass, Field etc. using the appropriate factory. The `SchemaLoader` is responsible of this process.

`SchemaLoader`'s `load` static method takes as input a Set of interfaces, which are the schema definitions, a `SchemaSchemaFactory` that includes constructor definitions of the `SchemaSchema` and an instance of the `SchemaSchema`. During the reflective analysis of the input interfaces the `SchemaLoader` builds the corresponding `Types` and `Fields` of those interfaces using the `SchemaSchemaFactory`. A `Schema` consists of the Set of these `Types`. An example taken from Chapter 3, is shown in Listing 4.18.

```

1 final Schema schemaSchema = ...;
2 final SchemaFactory schemaFactory = ...;
3
4 final Schema stateMachineSchema = SchemaLoader.load(
5     schemaFactory,
6     schemaSchema,
7     Machine.class,
8     State.class,
9     Transition.class);

```

Listing 4.18: SchemaLoader Example

In the code, the `SchemaLoader` gets as input a `SchemaSchemaFactory` and a `SchemaSchema`, which will be explained further in Section 4.3. Moreover, it gets a set of interfaces that describe the state machine schema. This schema consists of a set of schema `Klasses` that are described by interfaces, namely `Machine.class`, `State.class` and `Transition.class`. Next, the `SchemaLoader` analyzes the definition of those schemas using reflection and then makes a `Schema` by using the `SchemaFactory` that it has been given. A simple description of that process is shown in Listing⁸ 4.19. As illustrated we first implement the instances and following that we use setters to wire them up. The reason for this is that not everything exists at the time that it needs to be set.

⁸ Most of the implementation has been excluded for brevity.

```

1 public static Schema load(
2     SchemaFactory factory, Schema schemaSchema, Class<?>... schemaClassesDef)
3 {
4     // create an empty schema using the factory, will wire it later
5     final Schema schema = factory.Schema();
6
7     // build the types from the schema classes definition
8     final Set<Type> types = new LinkedHashMap<>();
9     for (Class<?> schemaClassDefinition : schemaClassesDefinition) {
10         final String className = schemaClassDefinition.getSimpleName();
11
12         // build the fields from method definitions
13         final Set<Field> fieldsForClass = new LinkedHashMap<>();
14         for (Method schemaClassField : schemaClassDefinition.getMethods()) {
15
16             // field the field metadata though annotations
17             // ...
18             // add its fields, the owner Klass will be added later
19             final Field field = factory.Field();
20             field.name(fieldName);
21             field.contain(contain);
22             field.key(key);
23             field.many(many);
24             field.optional(optional);
25
26             fieldsForClass.add(field);
27         }
28
29         // create a new class
30         final Klass klass = factory.Klass();
31         klass.name(className);
32         klass.schema(schema);
33         // wire the owner class in fields,
34         fieldsForClass.values().forEach(field -> field.owner(klass));
35     }
36
37     // wire the types on schema,
38     // it is inverse so it will refer to schema.types() immediately
39     types.forEach(type -> type.schema(schema));
40
41     return schema;
42 }

```

Listing 4.19: SchemaLoader

Listing 4.19 shows the usage of Java reflection in our implementation. However, because Java reflection capabilities are limited, this restricted our implementation.

4.3 Bootstrapping

Considering that SchemaSchema is managed data itself, we can use the SchemaLoader to build a new SchemaSchema. Nonetheless, we need a description of that SchemaSchema, which will be used during the loading process to build the schema Classes. As a result, we need a *Bootstrap Schema* to jumpstart this process. The *Bootstrap Schema* is exclusively self-describing, as it must manage itself

[LvdSC12], and hardcoded in its own class, `BootSchema`.

4.3.1 Cutting the umbilical cord

Having a `BootSchema` in place we can now create “real” `SchemaSchemas`⁹. For consistency, we use those “real” `SchemaSchemas` in order to build other schemas, this way everything is managed data. After building a real `SchemaSchema` we no longer need the `BootSchema`, which leads to a process that we call “Cutting the umbilical cord”. An example of “Cutting the umbilical cord” is shown in Listing 4.3.1, where we use the `BootSchema` to build the `realSchemaSchema` and then we use this `realSchemaSchema` to build another `realSchemaSchema` (`realSchemaSchema2`).

```
1 final Schema bootstrapSchema = new BootSchema();
2 BasicDataManager basicFactory =
3     new BasicDataManager(SchemaFactory.class, bootstrapSchema);
4
5 // Create a schema Factory which creates Schema instances.
6 final SchemaFactory schemaFactory = basicFactory.make();
7
8 // The schemas are described by the SchemaSchema,
9 // this schemaSchema is also self-describing.
10 final Schema realSchemaSchema =
11     SchemaLoader.load(
12         schemaFactory,
13         bootstrapSchema,
14         Schema.class,
15         Type.class,
16         Primitive.class,
17         Klass.class,
18         Field.class,
19         Primitives.class);
20
21 BasicDataManager basicFactory2 =
22     new BasicDataManager(SchemaFactory.class, realSchemaSchema);
23 final SchemaFactory schemaFactory2 = basicFactory2.make();
24 final Schema realSchemaSchema2 =
25     SchemaLoader.load(
26         schemaFactory2,
27         realSchemaSchema,
28         Schema.class,
29         Type.class,
30         Primitive.class,
31         Klass.class,
32         Field.class);
```

Listing 4.20: Cutting the umbilical cord

Figure 4.3 illustrates the models during a bootstrapping process. As it can be seen, the `BootSchema` is used in order to describe the `Schema Schema`, making the `Schema Schema` independent and managed data itself. Thus, it can be used to create other schemas like the `Machine schema` or even itself.

⁹ We call them real because they are managed data and not hard-coded.

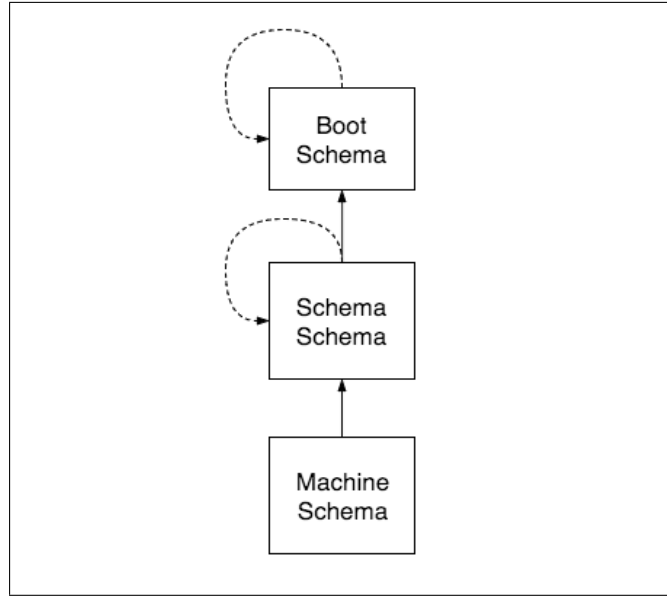


Figure 4.3: Boot Schema models

4.3.2 Primitives Definition

Since the Bootstrap Schema defines the primitive types for its description, the real schema schema needs a way to include them as well. These initial Java primitives supported in our implementation are shown in Table 4.1.

	Class<?>	Name	Default Value
Integer	Integer.class	"Integer"	0
int	int.class	"int"	0
Boolean	Boolean.class	"Boolean"	false
boolean	boolean.class	"boolean"	false
String	String.class	"String"	"
Double	Double.class	"Double"	0.
Float	Float.class	"Float"	0.f
Class	Class.class	"Class"	null

Table 4.1: Primitives Table

To define those primitives we use an interface called *Primitives*, introduced during the loading of the real schema, as seen in Line 19 of Listing 4.20. The definition of this interface is shown in Listing 4.3.2 which is a simple **Class/Name** mapping ¹⁰.

¹⁰We use the “_” prefix convention in order to define names of primitives that are reserved words in Java.

```

1 public interface Primitives {
2     Integer Integer();
3     int _int();
4
5     Boolean Boolean();
6     boolean _boolean();
7
8     String String();
9     Class Class();
10    Float Float();
11    Double Double();
12 }

```

Listing 4.21: Primitives Definition

The benefits of such a definition is that the `Primitives` interface is extensible. By extending it one can add more primitives in the schema as long as it is introduced during the schema loading.

4.4 Implementation Issues

The fact that we use Java reflection and dynamic proxies, along with the fact that everything is managed data, even the `schemaSchema`, introduces some issues, including the methods ordering problem described in Section 4.1.2.

4.4.1 Equivalence

The `bootstrapSchema`, `realSchemaSchema` and `realSchemaSchema2` managed objects from the Listing 4.3.1 should be equal because they ultimately describe the same *Schema*.

However, since, apart from the `bootstrapSchema`, they are managed data and not normal Java objects, we need a way to check for equality on managed objects. We have implemented the equivalence functionality for managed objects, using the *Equality Checking for Trees and Graphs algorithm* by Michael D. Adams and R. Kent Dybvig [AD08].

4.4.2 The `classOf` field

As it has been presented in Section 2.4.2, for a proxy object to conform with interfaces and be casted to any of them, it needs these interfaces during its initialization. To support that, we have added the `classOf` field in the `Type` schema `Klass`, which is of type `java.lang.Class` and is a reference of the Java class that this schema `Klass` is described to.

4.4.3 Hash-code of Managed Objects

To avoid any unpredictable activities that a `hashCode` invocation would bring in managed objects, we have omitted it. We do not depend on the ordinary `hashCode` for managed objects, we do not call it and therefore we have not implemented it. If it is a collection field type, then the field has to have a `Key` field. In this case, we obtain the value of the key field and index it into a `HashMap`.

Using the `Key` field as the key of the hashmap works whether it is a primitive or not since we get the `Object.hashCode()` of that key. However, that suggests that the key is not of our schema `Klass` system but a Java type. Finally, the `MObject` invocation handler delegates the call of the `hashCode` method to the real object so that it would never fail, although this is not suggested because it may lead to unpredictable results.

4.4.4 Java 8 Default Methods

Java 8 supports the definition of default methods in interfaces. According to the specification¹¹, default methods enable the programmer to add new functionalities to the interfaces and can be used as method implementation in abstract classes. We use Java 8 default methods in order to add functionality to our schema definitions. In particular, methods that are defined as *default* are ignored during the interpretation and no fields are created for them. We consider this as a helpful mechanism for defining functionality inside the schemas. A notable feature is that the default method invocation in the MObject is **protected**, which makes it possible for the derived data managers to “monitor” when a default method is invoked.

4.5 Benefits and Limitations

One of the advantages of this language is the simplicity of its usage. A programmer simply needs to define the schemas, followed by the data managers, and can easily write a program using them. The language takes care of the dependencies, references and any other underline mechanisms. Moreover, it uses Java concepts, which makes it safer in terms of type checking and definitions making it easier for Java developers to adapt. Furthermore, by being a self-describing language it is no longer bounded to the Java constructs transforming everything into managed data. Finally, the effortless mechanism of stacking data managers makes it significantly modular on every level, meta or not.

However, in addition to the implementation issues described in the previous section, there are significant performance implications since we use Java reflection and dynamic proxies to dynamically interpret the schemas. This makes it unfavorable for applications that focus on performance and are based on JVM optimizations.

Another issue that arises is that integration in existing systems is complicated considering every model has to be redefined as a schema and every functionality has to be reimplemented in data managers. However, an existing system integration is presented in Chapter 5.

4.6 Claims

We claim that managed data leads to a powerful data abstraction that gives the programmer control over fundamental mechanisms of data creation and manipulation [LvdSC12]. Those mechanisms are traditionally predefined by the programming languages. Managed data gives control over them by using data managers. Moreover, we claim that managed data introduces a modular way to define data and aspects of data. In Chapter 5 we present how to *aspect refactor* an existing application using managed data.

¹¹<https://docs.oracle.com/javase/tutorial/java/IandI/defaultmethods.html>

Chapter 5

Taming Aspects of JHotDraw with managed data

5.1 Crosscutting Concerns Identification

Our managed data framework can address the problem of CCC by capturing them in modular data managers. But solving the problem of CCC requires to identify them first in the source code. *Aspect mining* is a reverse engineering process that aims at finding CCC in existing systems [MVDM04]. The aspect mining topic has been addressed from several research contribution including methods like machine learning [SGP04], clone detection [BVDVET05], IDE tools [RM02] and more. Marin et al. [MVDM04] introduced a technique based on spotting methods that are invoked from many different places (high fan-in) in order to identify candidate aspects in open-source Java systems. One of these projects included the JHotDraw. Consequently, we chose their findings as our main focus in CCC of JHotDraw. In particular, we focused on two main concerns, the *FigureSelection*, which is an observer pattern implementation and the *Undo* concern that is part of the command pattern.

5.2 Aspect Refactoring in Managed Data

In order to evaluate the ability of managed data to tame aspects, we have refactored aforementioned concerns of JHotDraw. More specifically, in this chapter is present the refactoring of the *FigureSelectionListener* observer pattern as well as the *Undo* concerns. For their refactoring we used our implementation of managed data in Java that presented in the previous chapter. The choice of those concerns has been made on purpose since those are the concerns that AJHotDraw refactors using AspectJ and AOP techniques. Therefore, having three versions of the same application (JHotDraw) solving the same concerns, will provide us with better assessment methods on their comparison. The three systems that participate our assessment are: **JHotDraw**¹, the original OOP version, **AJHotDraw**², the AOP refactored version and our **ManagedDataJHotDraw**³, the managed data aspect refactored version. We focus on those concerns because those are the ones identified, solved, analyzed and presented in AJHotDraw. Note that, for reasons of reliable comparison and compatibility, we used the version *JHotDraw v.5.4b1* because AJHotDraw is also based on the same version.

However, to refactor JHotDraw, we first had to migrate in managed data. The result of this migration is available to an open-source project the ManagedDataJHotDraw. We claim that this is the first aspect refactoring of an application using managed data to date since this project aims on showing how managed data can deal with CCC.

¹<http://www.jhotdraw.org/>

²<https://sourceforge.net/projects/ajhotdraw/>

³<https://github.com/Theo1Zacharopoulos/ManagedDataJHotDraw>

5.3 Migration Process

The refactoring of an application with the size of JHotDraw required a significant amount of time to study and familiarizing with, yet, its well-designed OOP code, made it easy to grasp. In particular, we tried to focus only on the parts that we were going to refactor since we wanted to assess the same refactorings that AJHotDraw developers [MM] did. Thanks to their fan-in analysis [MVDM04] that identified a number of aspects in the legacy system, we emphasize on them in order to make a fair comparison. Furthermore, while the AJHotDraw focused on a completely new version of JHotDraw written using AspectJ, we implemented ManagedDataJHotDraw maintaining the coherence and the original design.

5.3.1 DrawingView

One of main components of the JHotDraw architecture is the *DrawingView* interface. As Figure 5.1 illustrates, the drawing *DrawingView* is responsible of rendering *Drawings* and listens to its changes. It is also responsible of receiving the user input and delegate it to the current tool.

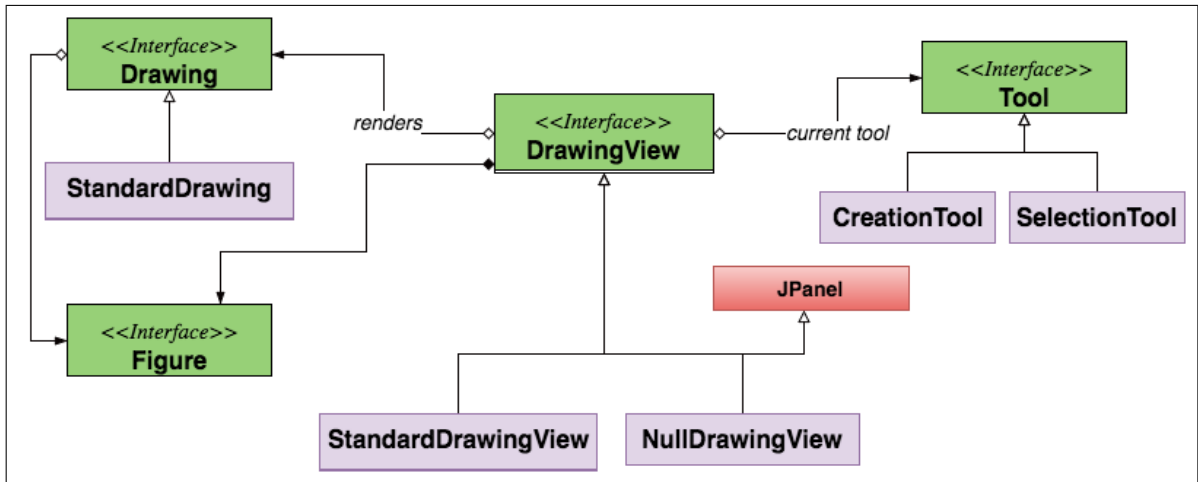


Figure 5.1: DrawingView of JHotDraw

The fact that **DrawingView** plays such a significant role along with the subject / observer properties, makes it a good candidate for manage data migration. The reason is that the specifications of that class can be implemented as data managers and added dynamically to it.

5.3.2 Managed Data DrawingView

To support the type reference capabilities of the **DrawingView** interface, we first implemented an **MDDrawingView**, namely Managed Data DrawingView, which is used for substituting the **DrawingView** in whole JHotDraw. Having this super interface for type reference, we needed the actual managed data schemas. As Figure 5.1 shows, there are two implementations of the **DrawingView**, particularly the **StandardDrawingView**, which is the implementation that is used when a new drawing view is created in the application, and the **NullDrawingView**, which represents a null drawing view of the *null-object* pattern.

Following their original design, we have implemented two schemas, one for the **StandardDrawingView** and one for the **NullDrawingView**, namely, **MDStandardDrawingView** and **MDNullDrawingView** respectively. The instances of those schemas has been used in the same way their normal counterparts used in JHotDraw. A snippet of the **MDStandardDrawingView** is shown in Listing 5.22. Most of the implementation has been omitted for brevity.

```

1 public interface MDStandardDrawingView extends M, MDDrawingView {
2     ...
3     // Composition over inheritance, the original inherits the JPanel
4     JPanel panel(JPanel... panel);
5
6     default JPanel getPanel() {
7         return panel();
8     }
9
10    default void setPanel(JPanel _panel) {
11        panel(_panel);
12    }
13    ...
14    Rectangle damage(Rectangle... damage);
15    Drawing drawing(Drawing... drawing);
16    ...
17    default FigureEnumeration selectionZOrdered() {
18        List result = CollectionsFactory.current().createList(selectionCount());
19        FigureEnumeration figures = drawing().figures();
20
21        while (figures.hasNextFigure()) {
22            Figure f= figures.nextFigure();
23            if (isFigureSelected(f)) {
24                result.add(f);
25            }
26        }
27        return new ReverseFigureEnumerator(result);
28    }
29    ...
30    default void repairDamage() {
31        if (getDamage() != null) {
32            panel().repaint(damage().x, damage().y, damage().width, damage().height);
33            setDamage(null);
34        }
35    }
36    ...
37 }

```

Listing 5.22: MDStandardDrawingView schema

From Listing 5.22 it can be seen that the MDStandardDrawingView interface extends both M, defining that this is a schema definition, and MDDrawingView for sub-type support. Additionally, all the functionality implemented in methods in the original DrawingView, now is implemented default methods in the schema interface. As state for these methods is used the fields of this schema. As Lines 17 and 30 show, the fields of the schema can be used to query their values inside the default methods. Note that the code in those defaults methods is identical to the original DrawingView. Furthermore, for consistency with the legacy code, we have implemented setters and getters, Lines 10 and 6, for the field values accessors. This way we kept consistent the way the other classes access values of this class.

An notably issue is that the original StandardDrawingView extends the javax.swing.jpanel class as Figure 5.1 shows. However, such a structure is not supported in managed data. One can not extend classes for schema definitions in managed data. To overcome this issue we favored *composition over inheritance* in this case, making the JPanel a field, named *panel* of the schema. To support the JPanel as a type of a field though, it needs also to be defined as managed data. The same holds for

the rest of the fields such as `Rectangle` and `Drawing`.

As explained in Section 4.3.2 our framework allow us to define primitives externally by inheriting the `Primitives` interface. The JHotDraw primitives definition is showed in Listing 5.23.

```
1 public interface JHotDrawPrimitives extends Primitives {
2     javax.swing.JPanel JPanel();
3
4     java.awt.Color Color();
5     java.awt.Cursor Cursor();
6     java.awt.Point Point();
7     java.awt.Dimension Dimension();
8     java.awt.Rectangle Rectangle();
9
10    CH.ifa.draw.framework.DrawingEditor DrawingEditor();
11    CH.ifa.draw.framework.Drawing Drawing();
12    CH.ifa.draw.framework.Painter Painter();
13    CH.ifa.draw.framework.PointConstrainer PointConstrainer();
14
15    CH.ifa.draw.framework.Handle Handle();
16    CH.ifa.draw.framework.Figure Figure();
17 }
```

Listing 5.23: JHotDraw Primitives Definition

This proved very helpful since we do not need to reimplement everything as managed data during refactoring of big application. Especially classes that are provided by libraries such as `javax.swing` and `java.awt`.

Limitations

However, extending our framework's primitives with the `JHotDrawPrimitives` we lose the “pureness” of managed data. That led to an application that is part of it managed data part of it not. But this is something that can happen in cases of refactoring of bug applications like JHotDraw.

Another limitation that arises from the previous implementation is that some keywords like “Transient” or “Synchronized” can not be supported on default methods. Instead, we could use annotations that add these properties to the methods as future work. Moreover, privacy is also an issue. All default methods are `public`, which means that the encapsulation is violated. Finally, private classes definition is not possible in schemas, although this is not the point of them since they can be defined outside as managed data.

5.3.3 MDDrawingView Schema Factories

Having the `MDStandardDrawingView` and `MDNullDrawingView` schemas in place we still needed their factories as to create instances of them. Besides the schema factories, which is as simple as Listing 5.24 shows, we still needed a way to give initialization values to the schema instances the same way that the original `DrawingView` does. Additionally, this factory should be used exactly like the `new` Java keyword inside the source code. This factory just replicates the original `DrawingView` constructor and is used from the program to create new instances of the schemas. The code of the `MDStandardDrawingView` instances factory is illustrated in Listing 5.3.3, in comparison with the original constructor illustrated in Listing 5.3.3.

```

1 public interface DrawingViewSchemaFactory {
2     MDStandardDrawingView DrawingView();
3     MDNullDrawingView NullDrawingView();
4 }

```

Listing 5.24: DrawingView Schema Factory

```

1 public StandardDrawingView(DrawingEditor editor, int width, int height) {
2     setAutoscrolls(true);
3     fEditor = editor;
4     fViewSize = new Dimension(width,height);
5     setSize(width, height);
6     fSelectionListeners = CollectionsFactory.current().createList();
7     addFigureSelectionListener(editor());
8     setLastClick(new Point(0, 0));
9     fConstrainer = null;
10    fSelection = CollectionsFactory.current().createList();
11
12    setDisplayUpdate(createDisplayUpdate());
13    setBackground(Color.lightGray);
14
15    addMouseListener(createMouseListener());
16    addMouseMotionListener(createMouseMotionListener());
17    addKeyListener(createKeyListener());
18 }

```

Listing 5.25: StandardDrawingView Constructor

```

1 public static MDDrawingView newDrawingView(
2     DrawingEditor editor, int width, int height) {
3     final MDStandardDrawingView drawingView = drawingViewSchemaFactory.DrawingView();
4     MyJPanel jPanel = new MyJPanel();
5     jPanel.setAutoscrolls(true);
6     jPanel.setSize(width, height);
7     jPanel.setBackground(Color.lightGray);
8     drawingView.panel(jPanel);
9     jPanel.setDrawingView(drawingView);
10    drawingView.editor(editor);
11    drawingView.size(new Dimension(width, height));
12    jPanel.setSize(width, height);
13    drawingView.lastClick(new Point(0, 0));
14    drawingView.constrainer(null);
15    drawingView.setDisplayUpdate(new SimpleUpdateStrategy());
16    drawingView.setBackground(Color.lightGray);
17    drawingView.drawing(new StandardDrawing());
18    jPanel.addMouseListener(...);
19    jPanel.addMouseMotionListener(...);
20    jPanel.addKeyListener(...);
21    return drawingView;
22 }

```

Listing 5.26: MDStandardDrawingView Instances Factory

5.3.4 MDDrawingView Integration

Finally, to integrate the MDDrawingView managed objects in the existing system we had first to replace every instance of `DrawingView` with `MDDrawingView`, every `StandardDrawingView` with `MDStandardDrawingView` and every `NullDrawingView` with `MDNullDrawingView` accordingly. In addition in each place that a new instance of these is created we placed it with our instances factory, like the once presented in Listing 5.3.3.

5.4 Aspect Refactoring of JHotDraw

Aspect refactoring usually refers to the refactoring of legacy in aspect oriented code (AOP). However, in this section we present an aspect refactoring of legacy code in managed data.

5.4.1 FigureSelectionListener

The `FigureSelectionListener` observer pattern of JHotDraw is a case that first presented by Hannemann et al. [HMK05] in their role-based refactoring of design patterns in AspectJ. Later Marin et al. used the same aspect and migrated it to their AJHotDraw implementation. Likewise, we have also implemented the same aspect for our refactoring in order to assess our concern solution with the existing one.

5.4.2 FigureSelectionListener in JHotDraw

The original observer pattern of the `FigureSelectionListener` functionality in JHotDraw is illustrated in Figure 5.2.

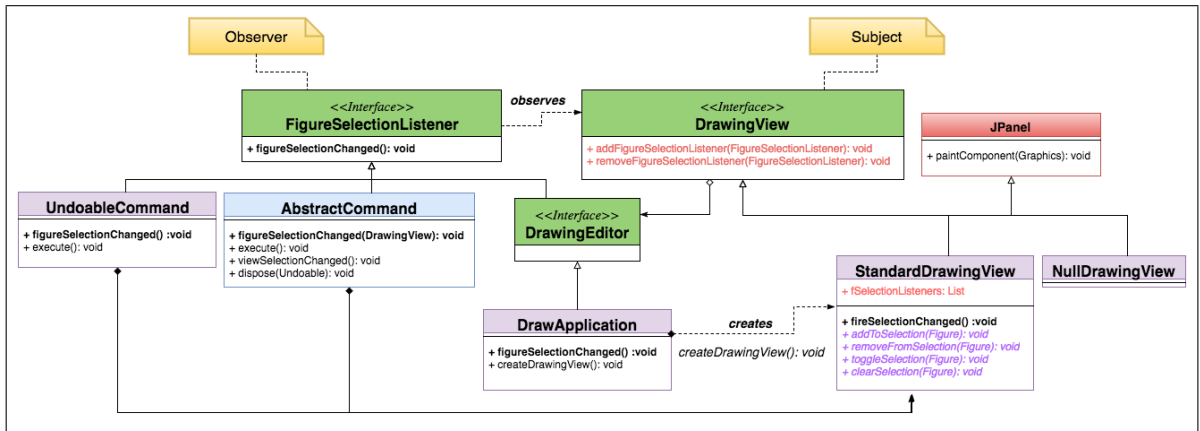


Figure 5.2: FigureSelectionListener in JHotDraw

As the figure illustrates, the `FigureSelectionListener` interface defined the *Observer* role. The classes that are interested in the changes of selection of figures in a `DrawingView` implement this interface. Accordingly, the `DrawingView` defines the *Subject* role providing methods for adding and removing figure selection listeners. The only class that implements this is the `StandardDrawingView` which the `NullDrawingView` has an empty implementation.

The `StandardDrawingView` keeps the selection listeners in a list, the `fSelectionListeners`, and notifies the listeners by calling the method `fireSelectionChanged`. This method is invoked after the call of the methods: `addToSelection`, `removeFromSelection`, `toggleSelection` and `clearSelection`, which indicate the change of figure selection. On the observers side, the figure selection listeners implement the `figureSelectionChanged` method that is executed in the case of notification from the subject.

5.4.3 Refactoring FigureSelectionListener in AJHotDraw

Marin et al. present a refactoring of this concern in AJHotDraw [MMvD05a]. Their refactoring can be seen in Figure 5.3.

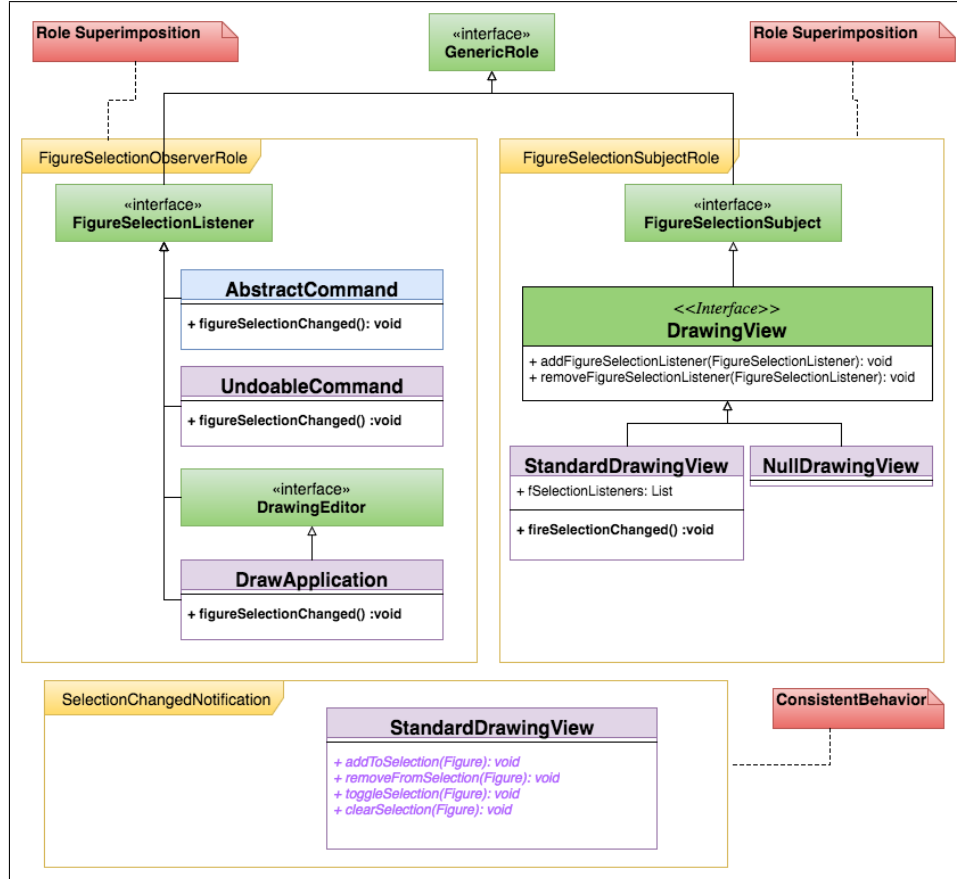


Figure 5.3: FigureSelectionListener in AJHotDraw

The type-based refactoring they proposed they have used two crosscut sorts, namely *role superimposition* and *consistent behavior*.

Role Superimposition

As defined by the authors [MMVD05b], the role superimposition refers to the implementation of a specific secondary role or responsibility. In the **FigureSelectionListener** case, they used it twice, one for each of the roles. More specifically, they abstract the role in a **GenericRole** interface and specific roles, observer and subject extend this interface.

Consistent Behavior

According to the authors [MMVD05b], the consistent behavior sort implements a consistent behavior for a number of method elements that can be captured by a natural pointcut. In this case it is used to notify the observers of the changes in the subject object. More specifically, the methods **addToSelection**, **removeFromSelection**, **toggleSelection** and **clearSelection** are consisted behavior. The definition of the pointcuts that describes the consisted behavior is illustrated in Listing 5.27.

```

1 public aspect SelectionChangedNotification {
2     pointcut invalidateSelFigure(StandardDrawingView sdw) :
3         ( withincode(boolean StandardDrawingView.addToSelectionImpl(Figure))
4           withincode(void StandardDrawingView.removeFromSelection(Figure)))
5         && call(void Figure.invalidate())
6         && this(sdw);
7
8     pointcut clear_toggleSelection(StandardDrawingView sdw):
9         (execution(void StandardDrawingView.clearSelection())
10          execution(void StandardDrawingView.toggleSelection(Figure)))
11         && this(sdw);
12
13     after(StandardDrawingView sdw): invalidateSelFigure(sdw) {
14         sdw.fireSelectionChanged();
15     }
16
17     after(StandardDrawingView sdw): clear_toggleSelection(sdw) {
18         sdw.fireSelectionChanged();
19     }
20 }

```

Listing 5.27: AJHotDraw: Consistent Behavior in FigureSelectionListener

Benefits and Consistent Behavior

According to the authors [MMvD05a], such refactoring has the benefit that the crosscutting elements are addressed individually, which leads to a modular solution and any deviations from the pattern implementation can be addressed separately.

However, as they also mention [MMvD05a], the definition of pointcuts to capture the calls to the notifier, as for many consistent behavior instances, is difficult. As Listing 5.28 shows, the original `clearSelection` method in JHotDraw calls `fireSelectionChanged` under conditions. However, considering the AOP solution of AJHotDraw, Listing 5.27, this is not the case. Their pointcut definition, the pattern refactoring solution notifies the observers independently of the condition in the caller. This implementation deviates from the behavior conservation of the original JHotDraw leading to a harmful for the functionality implementation. Although, according to Marin et al. it is potentially harmless in this case. Finally, the problem of the unconditional call of the a method in a pointcut is clearly a problem of the language, AOP current mechanisms of AspectJ does not support such functionality.

```

1 public void clearSelection() {
2     if (selectionCount() == 0) {
3         // avoid unnecessary selection changed event when nothing has to be cleared
4         return;
5     }
6     FigureEnumeration fe = selection();
7     while (fe.hasNextFigure()) {
8         fe.nextFigure().invalidate();
9     }
10    ...
11    fireSelectionChanged();
12 }

```

Listing 5.28: StandardDrawingView clearSelection Method

5.4.4 Refactoring FigureSelectionListener in ManagedDataJHotDraw

That leads us to our managed data refactoring of the `FigureSelectionListener` concern.

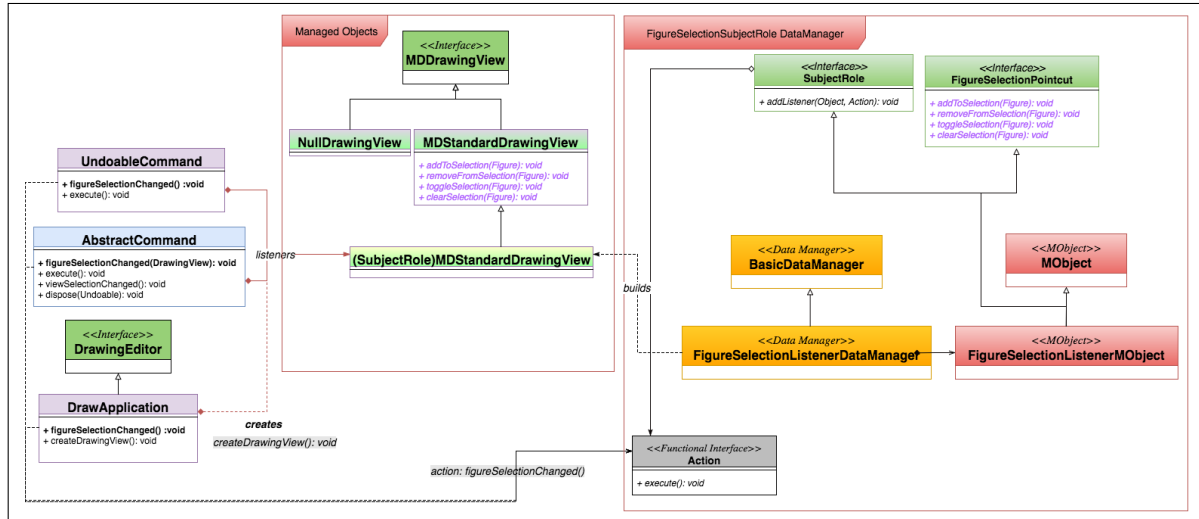


Figure 5.4: FigureSelectionListener in ManagedDataJHotDraw

5.4.5 SubjectRole Data Manager

Data manager

MObject

Predicate

Action

5.4.6 SubjectRole Integration

Consistent Behavior Pointcut

```

1 public interface FigureSelectionPointcut {
2     void addToSelection(Figure figure);
3     void removeFromSelection(Figure figure);
4     void toggleSelection(Figure figure);
5     void clearSelection();
6 }

```

Listing 5.29: FigureSelectionPointcut interface

```

1 public class FigureSelectionListenerSubjectRoleMObject extends MObject
2     implements FigureSelectionPointcut, SubjectRole {
3     ...
4     private void executeListenerActions() {
5         listeners.values().forEach(Action::execute);
6     }
7
8     @Override
9     public void addToSelection(Figure figure) {
10         executeListenerActions();
11     }
12
13     @Override
14     public void removeFromSelection(Figure figure) {
15         executeListenerActions();
16     }
17
18     @Override
19     public void toggleSelection(Figure figure) {
20         executeListenerActions();
21     }
22
23     @Override
24     public void clearSelection() {
25         if (((MDStandardDrawingView) this.getProxy()).selectionCount() > 0) {
26             executeListenerActions();
27         }
28     }
29 }

```

Listing 5.30: FigureSelectionListenerSubjectRoleMObject

FigureSelectionChanged Action

5.5 Claims

5.6 Threads to Validity

Chapter 6

Evaluation

6.1 Research Questions and Answers

6.2 Evidence

6.3 Results

6.3.1 Locality

6.3.2 Reusability

6.3.3 Composition transparency

6.3.4 (Un)pluggability

6.4 Claims

6.5 Discussion

6.5.1 In Practice

6.5.2 Benefits and Pitfalls

6.5.3 Modularity

6.6 Remarks

Chapter 7

Conclusion

Chapter 8

Further Work

Acknowledgments

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