mel - Model Extraction Language and Interpreter

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

This thesis includes material from one published work [22] that was written under the supervision of Dr. Joanne Atlee, who contributed with ideas, discussion, and editing. Exceptions to sole authorship of material are as follows:

Chapter 1 primarily consists of material published in [22], which I co-authored with Dr. Joanne Atlee, Alistair Finn Hackett, and Dr. Mike Godfrey. Most of the paper was written collaboratively.

Chapter 2 in part consists of material published from the same paper [22]. Sections 2.2 and 2.3 were heavily modified and extended from the material presented in the paper by myself for the purposes of inclusion in this thesis.

Abstract

There is a large body of research on extracting models from code-related artifacts to enable model-based analyses of large software systems. However, engineers do not always have access to the entire code base of a system: some components may be procured from third-party suppliers based on a model specification or their code may be generated automatically from models. Additionally, the development of software systems does not produce only source code as its output. Modern large software system have various artifacts relevant to them, such as software models, build scripts, test scripts, version control history data, and more. In order to produce a more complete view of a modern software system *heterogeneous fact extraction* of various artifacts is necessary - not just of source code.

This thesis introduces `mel`— a model extraction language and interpreter for extracting "facts" from models represented in XMI; these facts can be combined with facts extracted from other system components to form a lightweight model of an entire software system. We provide preliminary evidence that `mel` is sufficient to specify fact extraction from models that have very different XMI representations. We also show that it can be easier to use `mel` to create a fact extractor for a particular model representation than to develop a specialized fact extractor for the model from scratch.

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There are many people without whom this thesis would likely never have come to completion.

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Dedication

This thesis is dedicated to those whom I have missed more than you may ever know these past years:

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Chapter 1

Introduction

As software systems grow increasingly large and complex, they are becoming harder to analyze. Many program-analyses simply do not scale to the sizes of industrial software systems. One strategy to combat this problem is to create a lightweight model of the software system and then analyze the model. For example, compiler technologies and static analyzers can be employed as *model extractors* (e.g., LSME [53], Doop [9], Rigi [52], Frappé [16], eKNOWS Code Model Service [59], Rex [54]) that extract software models (e.g., call graphs, data-flow graphs, dependency graphs) from software artifacts. More generally, extracted models comprise collections of *"facts"* about a system's software components — *entities* (e.g., functions, classes, variables), *relationships* (function calls, variable assignments), and *attributes* (e.g., a function is a callback) — that are amenable to analyses expressed as algebraic manipulations [28], graph queries [16, 59], Datalog programs [9], and so on.

The above techniques all assume that the system under analysis comprises various kinds of software entities: source code, object code, build code, configuration files, and other code-related artifacts. However, engineers do not always have access to all of the system's source artifacts. Some components, libraries, or subsystems may be procured from third parties (e.g., based on a specification Model). Hereafter, we distinguish between *prescriptive and descriptive models* (denoted as capitalized *Models*) that are artifacts produced by engineers as part of the software-development process versus *extracted models* (denoted as lowercase *models*) that are generated from software, Models, and other artifacts. Other components may be generated automatically from Models that are more descriptive and semantically informative than the generated code. Moreover, software developers use software models as an additional artifact when developing and comprehending software systems, ranging from the deep end of Model-driven engineering (MDE) to simply using

Models for communication between engineers or as documentation [30]. While Models may not be completely ubiquitous they certainly are a common artifact of software engineering products and are seemingly here to stay. As such, to create a single coherent model of the entire system, we would need a means to extract facts from Models.

The construction of fact extractors for Models poses a major challenge. There is a wide variety of Model representations: multiple types of Models may be employed, and different types of Models may be expressed in different notations and representations. Even when Models are expressed in eXtensible Markup Language (XML) [10] and Model editors for the same Model types (e.g., UML Model editors) use the XML Metadata Interchange (XMI) [18] standard for expressing metamodels and metadata, the Models' XMI schema vary considerably. A specialized extractor may need to be created for every pair of Model editor and supported Model type.

This thesis introduces a model extractor language (`mel`) and *mel* interpreter (called `mint`) to support rapid development of fact extractors for Models that are represented in the XML Metadata Interchange (XMI) up to and including the version 2.5.1 standard [18]. `mel` is a domain-specific language (DSL) for succinctly expressing which facts (e.g., Model elements, relationships, attributes) are to be extracted from a Model. The `mel` language is designed to allow the user to concentrate on the *essential* complexity of deciding what information to extract from a Model and leave to `mel` and `mint` the *accidental* complexity of how to pluck that information from an XML/XMI representation.

1.1 Thesis Contributions

The contributions proposed by this thesis are:

- The development and presentation of a domain-specific language `mel`, and corresponding interpreter `mint`, for specifying and extracting model-based information from a Model represented in XML.
- An evaluation of the extent to which `mel` is expressive enough to apply to different Model types, including UML class and state machine diagrams [19], Arcadia Logical Architecture diagrams, [67], Feature Models [43], Simulink Block Diagrams [49].
- An evaluation of whether it is easier to write a `mel` program to create a fact extractor for a particular Model representation than it is to develop the fact extractor from scratch using existing XML querying tools.

1.2 Thesis Organization

The rest of this thesis is organized as follows:

Chapter 2 starts with a background on fact extraction, XMI and XML as model representations, and works and tools related prior to the process of XML analysis and transformation.

Chapter 3 introduces `mel`, specifies its input language, and describes its implementation.

Chapter 4 reports the results of studies that evaluate the effectiveness of `mel` in easing the creation of new model extractors for Models and the extent of `mel`'s ability to generalize to a variety of XML/XMI-based Models.

Lastly, Chapter 5 discusses conclusions drawn from the evaluation of `mel`.

Chapter 2

Background

This chapter discusses the context necessary for understanding `mel` and its purpose. Mainly, this chapter presents information on fact extraction, XML as a language, and existing tools seeking to aid the transformation or distillation of XML data.

2.1 Fact Extraction

A fact extractor is a program built to analyze a structured software artifact and produce a specific customized set of desired information about that artifact. The data set produced by a fact extractor can be called a *factbase* - as it is a database of facts about the particular software artifact. A produced factbase also represents a particular *model* of the software artifact, defined by the software details that the extractor is designed to extract from the artifact.

Most commonly, fact extractors are built to extract facts from source code or even directly from a compiled binary file. Given that a fact extractor is a program built to extract desired information from a software artifact, many commercial static-analysis tools can be considered to contain within them a fact extractor that pulls from the source code the information it requires for its analysis. For example, SciTools Understand [62], a popular IDE that provides static-analysis features, includes an extractor.

As a factbase is just a collection of data about a software artifact, it can have any form. In this thesis, a factbase is a collection of *entities* and *relationships* between entities, both of which can be annotated with *attributes* without any particular formatting.

2.1.1 Extraction of Lightweight Models

We will consider a lightweight model to be a model that abstracts a software system at a high level, including only as much information as is exactly necessary for the desired analyses. The purpose of extracting only exactly as much information as is necessary is to both avoid information overload on the user, as well as to facilitate efficient analysis of very large software systems. There is a rich history of extracting lightweight models from source-code artifacts for a variety of purposes, including the construction of high-level architectural views [8, 51] and the validation of developers' mental models of a system's design against the code [53]. At their most basic, the models produced by such tools are based on facts extracted from the source code; the models can be augmented with facts drawn from other development information such as version control meta-data, process metrics, and data from the dynamic instrumentation of the running system. Each extractor understands what information to collect from its respective target, and there is a central model of the system into which this extracted information is integrated. Extracting information from diverse artifacts is important because it improves one's existing knowledge about the system and permits new kinds of analyses to be performed. In this thesis, we propose a tool to aid in extracting information from *software Models*, such as UML Class and StateMachine diagrams, Arcadia Logical Architecture diagrams, and Feature Models. The information extracted from such Models can then be included with information extracted from source code to provide a more holistic view of the software. To the best of our knowledge, this has not been done before.

An architecture for a fact extraction tool pipeline might look like Fig. 2.1. To perform extraction at scale, extractors typically first process individual development artifacts producing a set of factbases, one for each source artifact. After the individual artifacts have been processed, the results are typically merged together into a single factbase, where references within one artifact to model elements in other artifacts are resolved. The structuring of the facts — which come from a diverse set of artifacts — into a coherent system model creates a common vocabulary that aids the end-user in phrasing queries and performing analyses over the augmented system model.

Our factbases model information about *program entities* — such as global variables, function, and files/classes — and the *relationships* between them, such as containment/ownership, function calls, and global variable accesses. Additionally, both entities and relationships can have *attributes*, such as function parameter types, the line number within a file where the entity/relationship is located, and if a variable access by a function is `read` or `write`.

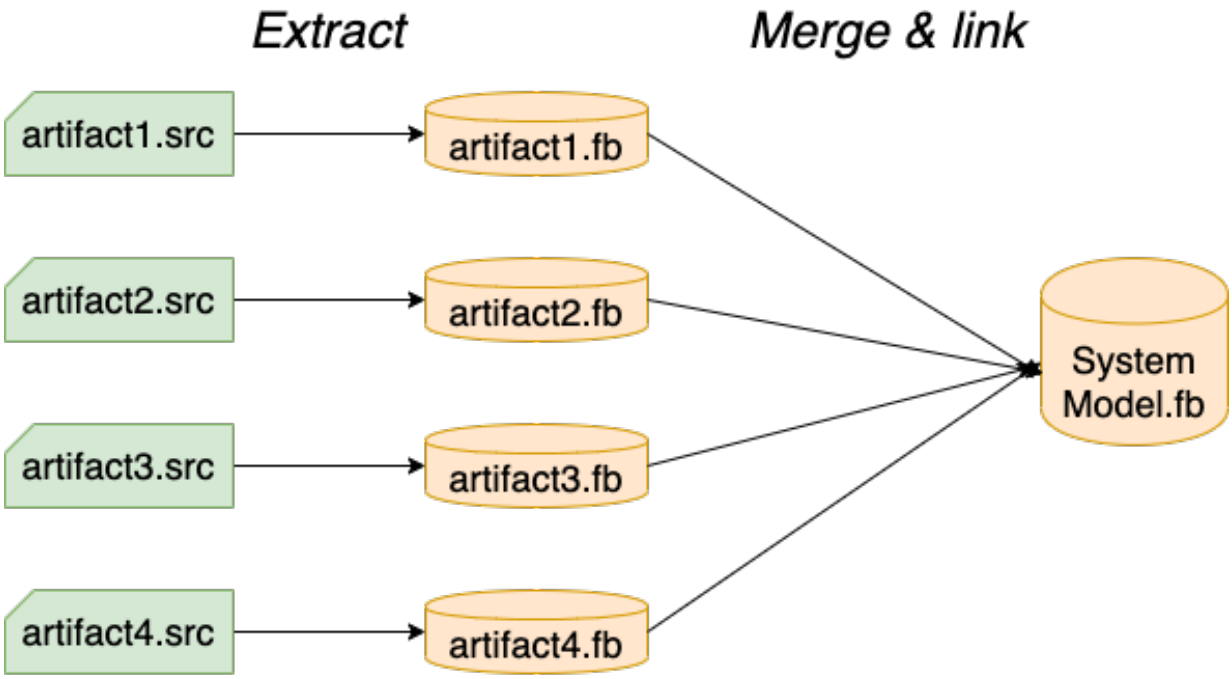


Figure 2.1: Architecture of a fact-extraction tool pipeline

2.1.2 Heterogeneous Fact Extraction

Source code is not the only relevant artifact produced during software development. Software artifacts can include source code, object code, build code, configuration files, various system Models, version-control log data, and other code-related artifacts. It is not uncommon for extractors of artifacts other than source code to be created in order to build a fuller picture of a piece of software.

Heterogeneous fact extraction is the act of extracting facts from more than one type of software artifact. The goal of heterogeneous fact extraction is to provide a more holistic and complete view of a piece of software. For example Passos and Czarnecki [56] developed an extractor to scrape the Linux kernel Git repository in order to extract data about feature additions and removals [56]. This extractor was built specifically to extract information that could not have been gleaned from source code alone and was used to form a fuller understanding of the evolution of the Linux kernel from a feature-oriented perspective [57].

Creating an extractor requires the developer to both (1) identify the relevant information from the artifact, and (2) write software to find and pluck that information from out

of the artifact. One issue that arises is that the developer of an extractor may not know all the information users of the extractor may desire from the artifact. The technical challenge of locating and plucking information from the artifact depends on the type of artifact itself. If the artifact is source code then the process likely involves walking the abstract syntax tree of the source code to locate relevant pieces of information. In the case of Passos and Czarnecki's work, their extractor needed to execute API requests to obtain the relevant git log information and then scrape those files for the information they were interested in. In the case of Software Models represented in an XML format, the effort required is the traversing of the XML tree to find relevant tags and relationships between them - often traversing the tree multiple time to resolve references between entities.

This thesis supports heterogeneous fact extraction by providing a language and tool for the rapid development of Model extractors. `mel` eases the task of extractor creation by allowing the developer to focus only on identifying the information they are interested in and not on the minutiae of how to find and pluck that information from the XML.

2.2 XML and XMI

Many Modelling languages have a graphical representation, but Modelling tools represent this as a textual representation to ease the storing and sharing of Models. The most common textual representation for Models is the eXtensible Markup Language (XML) [10]. A further specialization of XML for representing Models has been created by the Object Management Group (OMG): the XML Metadata Interchange (XMI) standard [18]. The XMI standard is sufficiently expressive to represent Models belonging to any Model standard published by the OMG, including UML and SysML diagrams. The purpose of XMI is to standardize the representation of OMG specified Models allowing for the exporting and importing of models across compliant tools. Because XMI is a specialization of XML they share many features/rules. The term XM* will be used when referring to both XML and XMI.

An XM* representation is a tree of nested tagged *nodes*, with a single root node. Each node comprises an *opening tag*, *content*, and matching *closing tag*:

```
<tagname> content </tagname>
```

A node's content can contain text, nested nodes, or both. It is common for attribute values to also be stored as attributes of a node which must be written in the node's opening tag, for example:

```
<tagname attr1="Value1" attr2="Value2"> content </tagname>
```

When a node conveys all of its information as attributes, it is useful to express it as an *empty node* that is simply a self-closing tag with attributes and no content. A node is marked as self-closing by prepending its closing > with a forward slash to become />, for example:

```
<tagname attr1="Value1" attr2="Value2"/>
```

Seen in Figure 2.2 is a tiny XMI Model that declares a UML Class named "C1", which has a feature represented as a child node.

```
<xmi:XMI version="2.0" ...>
  <UML:Class name="C1" xmi:type="uml:Class" xmi:id="_1">
      <feature xmi:type="UML:Attribute" xmi:id="_2" name="a1" />
  </UML:Class>
</xmi:XMI>
```

Figure 2.2: A simple Model expressed in XMI.

Relational information in XM* documents is often encoded in one of two ways. The first common encoding is through an ancestor/descendant relationship as seen between the feature and class nodes in Figure 2.2. The second common method is to encode relational data through unique identifier attributes and through references to an identifier attribute of another node. Figure 2.3 demonstrates this alternative method of using unique identifiers to encode the same ancestor/descendant relationship between nodes class and feature that appears in Figure 2.2.

```
<xmi:XMI version="2.0" ...>
  <UML:Class name="C1" xmi:type="uml:Class" xmi:id="_1">
  <feature xmi:type="UML:Attribute" xmi:id="_2"
           name="a1" parentClass="_1"/>
</xmi:XMI>
```

Figure 2.3: A simple Model expressed in XMI representing relational data using unique identifiers.

2.2.1 Differences between XML and XMI

As XMI is a specialization of XML, any valid XMI document is also a valid XML document whereas the converse is not always true. An XML document is an XMI document only if it conforms to the specifications laid out in the XMI specification [18].

Since XMI is meant to standardize model representations, the primary difference between XMI and arbitrary XML are the restrictions on the tags that may be used. The XMI standard also specifies how tags and their attributes must be used, and what they represent. Effectively XMI is a smaller more controlled subset.

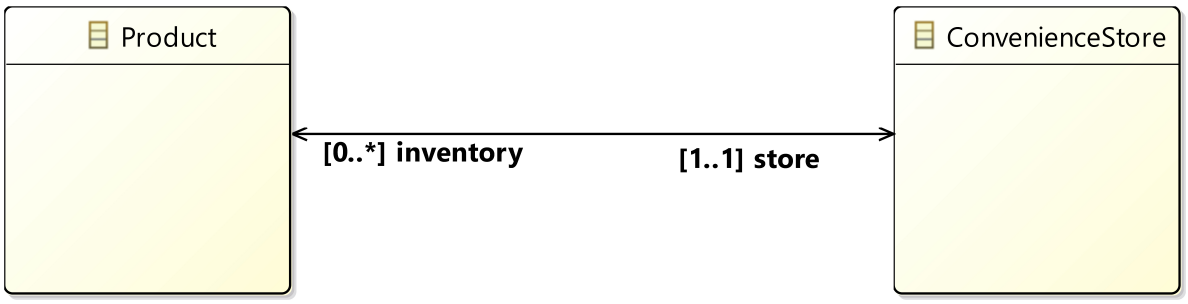
2.2.2 EMF Core (ECore)

The Eclipse Modelling Framework (EMF) is a framework built by the Eclipse Foundation for the modelling of software and generation of code from Models. EMF Core (ECore) [63] is the meta model for describing Models and serializing them to XMI. Many of the Models that are publicly available through the Model database compiled by Hebig, Ho-Quang, Chaudron, Robles, and Fernandez and [25] were created using one of the many Eclipse-based modelling tools, and thus are represented in EMF ECore.

While ECore representation *is* XMI, ECore differs from most other common XMI representations in one major way: References to existing tags, or declarations that would involve a reference to an existing tag, are written in ECore as an absolute or relative path to the node. Figure 2.4 illustrates this, showing how a bi-directional relationship with labels `inventory` and `store` is encoded in the ECore XMI representation. The relationship that class `Product` has with class `ConvenienceStore` is stored as an `eStructuralFeatures` tag. The `eType` and `eOpposite` attributes of this `eStructuralFeatures` tag illustrate ECore's form of encoding references as paths. That is,

- The `store` relationship of class `Product` encodes its target as an `eType` Attribute, which has value `#//ConvenienceStore`. The `#//` refers to the root of a document. If a path to a Document appears on the left of the `#`, then it refers to the root of that specified Document; if nothing appears on the left, then it the path starts at the root of the current Document. So this particular `eType` attribute resolves to the `ConvenienceStore` type defined in this document.

- Secondly, the `eOpposite` attribute encodes the corresponding relationship in a bi-directional relationship. Here, the `eOpposite` attribute has the value




```
<eClassifiers xsi:type="ecore:EClass" name="Product">
  <eStructuralFeatures xsi:type="ecore:EReference" name="store"

      lowerBound="1" eType="#//ConvenienceStore"
      eOpposite="#//ConvenienceStore/inventory"/>
</eClassifiers>
<eClassifiers xsi:type="ecore:EClass" name="ConvenienceStore">
  <eStructuralFeatures xsi:type="ecore:EReference"
      name="inventory" upperBound="-1"
      eType="#//Product" eOpposite="#//Product/store"/>
</eClassifiers>
```

Figure 2.4: A simple UML class diagram created with the EMF Core Diagram Editor and a Snippet of the corresponding ECore representation. This shows the entirety of the representation of the two classes and their relationships. The `eType` and `eOpposite` attributes demonstrate how ECore encodes references to other data in the Model. (Produced with Eclipse Modeling Tools version 4.19.0).

`#//ConvenienceStore/inventory`, which refers to the `inventory` relationship within the `ConvenienceStore` class.

- The opposing relationship `inventory` has similar references to the `Product` class and its `store` relationship.

2.3 XML Analysis & Transformation Tools

A wide variety of tools exist to interpret and translate XML documents. Because XMI is a specialization of the XML, these tools implicitly function on XMI documents as well. The World Wide Web Consortium (W3C) defines the XML specification and it has also produced a number of tools for working with XML documents.

This section discusses the W3C tools *XQuery* [61] and *XPath* [13] as well as several academic tools for working with XML documents.

2.3.1 XPath and XQuery

XPath and XQuery are tools for querying and working with the contents of an XML file. Because W3C defines the XML and its specification, XPath and XQuery belong to the W3C recommended tool set for working with XML documents.

XPath

XPath is a query language in which the user can write queries to specify matching nodes and attributes in an XML file based on expressions of paths in the XML tree. Simple relationships can be represented in XPath through the use of XPath Axes which allow the user to refer to nodes via their relationship to a current node.

Figure 2.5 provides a simple XML fragment with relational data between vegetables. The figure shows two groups of vegetable types (Greens and Roots) each of which comprises three individual "veggie" child nodes and an additional non-grouped vegetable "Tomato". Figure 2.6 demonstrates several XPath queries that could be applied to the XML fragment in Figure 2.5 to extract particular pieces of information. The queries' purposes and behaviours are as follows:

Line 1 This query selects all `<veggie>` nodes in the XML document. The `//` syntax specifies a descendant relationship. A query that starts with a `//` specifies any descendant of the root of the document thereby effectively matching any node in the document. If this query is applied to the XML fragment in Figure 2.5 the result set contains all seven `<veggie>` nodes in the document.

Line 2 This query selects all `<veggie>` nodes that are direct children of a `<vegetables>` node. The `/` syntax indicates a direct parent-child relationship. Thus the `//vegetables`

```
<root>
  <vegetables label="Greens">
      <veggie id="1" label="Asparagus"/>
      <veggie id="2" label="Broccoli"/>
      <veggie id="3" label="Kale"/>
  </vegetables>
  <vegetables label="Roots">
      <veggie id="4" label="Carrot"/>
      <veggie id="5" label="Onion"/>
      <veggie id="6" label="Turnip"/>
  </vegetables>
  <veggie id="7" label="Tomato"/>
</root>
```

Figure 2.5: An XML model with groups of siblings

```
//veggie
//vegetables/veggie
//vegetables/@label
//vegetables[@label="Greens"]/child::veggie
//vegetables[@label="Roots"]/child::veggie
```

Figure 2.6: Five simple XPath queries, one per line

portion of the query selects all `<vegetables>` nodes in the document, and subsequent `/veggie` portion of the query selects all `<veggie>` nodes that are direct children of the previously selected `<vegetables>` nodes. If this query is applied to the XML fragment in Figure 2.5, the result set contains all `<veggie>` nodes in the document except for the one with label "Tomato".

Line 3 This query selects all the values of the `label` attributes of all `<vegetables>` nodes in the document. If this query is applied to the XML fragment in Figure 2.5 the result set contains the two strings "Greens" and "Roots".

Line 4 This query selects all `<veggie>` nodes that are direct children of any `<vegetables>` nodes that have a `label` attribute whose value is "Greens". If this query is applied to the XML fragment in Figure 2.5, the result set contains the three `<veggie>` nodes

found under the first <vegetables> node — that is those with labels “Asparagus”, “Broccoli”, and “Kale”.

Line 5 This query behaves similarly to the query on Line 4 with the exception being that the <vegetables> nodes selected in the first portion of the query have a label attribute value of “Roots” instead of “Greens”. If this query is applied to the XML fragment in Figure 2.5, the result set contains the three <veggie> nodes found under the second <vegetables> nodes — that is those with labels “Carrot”, “Onion”, and “Turnip”.

Such queries are useful and effective for selecting elements in a factbase but not for deriving new facts to include in the factbase. For example, one would not be able to write an XPath query to generate a “sibling” relationship between <veggie> nodes in the XML fragment shown in Figure 2.5. However using an XPath processor in conjunction with a general purpose programming language, a programmer could combine query results to generate such a sibling relationship for their factbase.

In conclusion, although XPath is a useful query language for extracting specific nodes or groups of nodes from an XML document, it lacks the innate ability to generate relational data between nodes. The more powerful XQuery can aid a developer in this regard.

XQuery

XQuery is a mature general-purpose XML query and transformation language that is designed to transform XML into either other hierarchical representations or user-formatted reports. XQuery was developed after and built on top of XPath. As such XQuery is a superset of XPath and almost any valid XPath query is valid in XQuery as well[1].

As a more general-purpose language, XQuery allows for much more complex data to be produced than XPath allows and queries can be more complex. For example, the sibling relationship between <veggie> nodes in Figure 2.5 can be derived with the XQuery program shown in Figure 2.7. The constructs used in this example are a mix of XPath selectors and common imperative programming concepts; their behaviour is as follows:

Line 1 defines a variable $veggies and assigns its value to the collection of tags returned by the subsequent for loop.

[1] With small exceptions for old version compatibility modes and expansion of character entity references (e.g. ’&’ is & in XQuery and remains & in XPath).

```
1  let $veggies :=
2    for $veggie in //veggie
3    return <veg id="{ $veggie/@id }" name="{ $veggie/@label }" />
4
5  let $siblings :=
6    for $vegetable in //vegetables
7      for $veggie in $vegetable//veggie
8        for $v2 in $veggie/following-sibling::veggie
9          return <sibling s1="{ $veggie/@label }" s2="{ $v2/@label }" />
10 return <data>
11  { $veggies }
12  { $siblings }
13 </data>
```

Figure 2.7: XQuery program for generating a sibling relationship

Line 2 is a for loop where an iterator variable `$veggie` is used to iterate through the nodes produced by the XPath selector `//vegetables`. That is, this for loop iterates over each `veggie` node in the original document.

Line 3 has a return statement which constructs a new fact with the tag `veg`, whose `id` attribute has the value of the `veggie` node's `id` Attribute and `name` attribute has the value of the `veggie` node's `label` Attribute. As this return statement is within a for loop it constructs one fact for each node iterated by the for loop.

Line 5 defines a variable `siblings` and assigns its value to the collection of tags returned by the subsequent for loop.

Line 6 is a for loop that iterates over every `vegetables` node in the original document, binding each to the iterator variable `$vegetable`.

Line 7 is a nested for loop that iterates over every `veggie` node that is underneath the `vegetables` node currently selected by the enclosing for loop in Line 6.

Line 8 is another nested for loop that applies the `following-sibling` XPath axis to the `veggie` node currently selected by the enclosing for loop in Line 7. The axis application `$veggie/following-sibling::veggie` produces all of the subsequent `veggie` node siblings of the selected node `$veggie`, and the collection is iterated over by `$v2`.

```
<data>
   <veg name="Asparagus" id="1"/>
   <veg name="Broccoli" id="2"/>
   <veg name="Kale" id="3"/>
   <veg name="Carrot" id="4"/>
   <veg name="Onion" id="5"/>
   <veg name="Turnip" id="6"/>
   <veg name="Tomato" id="7"/>
   <sibling s1="Asparagus" s2="Broccoli"/>
   <sibling s1="Asparagus" s2="Kale"/>
   <sibling s1="Broccoli" s2="Kale"/>
   <sibling s1="Carrot" s2="Onion"/>
   <sibling s1="Carrot" s2="Turnip"/>
   <sibling s1="Onion" s2="Turnip"/>
</data>
```

Figure 2.8: The result of applying the XQuery program in Figure 2.7 to the XML fragment in Figure 2.5.

Line 9 is a return statement constructs a new fact node with a `sibling` tag whose `s1` attribute is the `label` of the `veggie` node currently selected in the for-loop on Line 7 and the `s2` attribute is the `label` of the `veggie` node currently selected in the for-loop on Line 8.

Lines 10-13 specify the ultimate return value of this XQuery program. As XQuery produces hierarchical data, the produced value is a single `data` node that encloses the produced `veg` nodes stored in the variable `$veggies` and the `sibling` nodes stored in the variable `$siblings`. The produced results can be seen in Figure 2.8.

Although XQuery is sufficient as a query language for XM* documents, and any `mel` program can be approximated in XQuery, `mel` seeks to abstract the process of fact extraction to a higher level than XQuery does. Particularly, XQuery is not focused on the resolution of relational data. Rather, XQuery allows users to refer to collections of XM* nodes, but also requires that the processing of those nodes be explicitly done by the user. Commonly, this takes the form of writing multiple loops to resolve relationships the user is interested in. The procedure of looping through potential nodes of interest and processing the ones actually relevant to the user's interests is exactly the type of accidental complexity that `mel` seeks to relieve the programmer of. Where `mel` allows the user to state the

relationship they are interested, XQuery requires the user defines programatically how that relationship be resolved.

2.3.2 Academic Developed XML Tools

In addition to the W3C tools, there has been academic interest in developing tools for processing XML documents. In this section several of these relevant works are discussed.

XTQ

XML Tree Query (XTQ) [45] is a declarative XML query language presented by Li, Liu, Zhu, and Ghafoor. XTQ's syntax is heavily influenced by both XQuery and SQL. XTQ provides a powerful and expressive query language that expands on existing XML query languages at the time of its writing, primarily:

1. XTQ allows one to write expressive patterns to explicitly specify conjunctive, disjunctive, and hierarchical relationships between matching data elements.
2. XTQ's data filtering mechanism allows for easy filtering on composite data structures (made of many elements from the XML). The claim is that such queries could not be easily written in other languages without the use of multiple sub-queries.

In areas where XTQ succeeds, so too does `mel`. Additionally, `mel` seeks to further support extraction of relational data and is more focused on the production of user-defined relationships than XTQ is.

XPathLog

XPathLog, presented by May [50], is a declarative language meant to be used as an extension to XPath. XPathLog focuses on querying and modifying an existing XML document, whereas `mel` focuses on reasoning about XML in a relational context. Also, mel focuses on operating on and outputting sets of tuples (that is, factbases) from an XML artifact, rather than producing hierarchically structured XML.

Model Transformation

Bhatti and Malik [6] propose a tool for bi-directional transformation between the XML for one Model and the XML for another Model. This work relates to `mel` in that both seek to transform an XML representation of a Model into a different representation. The tools differ, however, in that `mel` seeks to extract from an existing Model only the facts the user desires based on expressive queries the user can write, whereas the bi-directional transformation tool translates an entire model from one XML schema to another. The proposed bi-directional framework is preliminary, has been applied only to small examples, and is limited to cases where the tool is provided with the metamodels for both the source and target XML representations.

XML Translation to Databases

Somewhat analogous to `mel` is the work on translating an XML document into a database. One example is the work on s-XML by Subramaniam, Haw, and Hoong [65], which is a technique of mapping an XML document into a relational database. Although `mel` also produces a database, `mel` seeks to produce a database comprising only the information the user is interested in. This distinction is an important difference between `mel` and tools that produce databases from XML documents. Firstly, these tools offer no actual user-defined processing of the XML data, rather they produce a relational database and the user must then write queries to that database to resolve the facts they are interested in. `mel` itself functions as both a relational query language and a tool for translating XML documents into databases. Furthermore, the language features of `mel` are specifically designed to aid in the querying and specifying of relationships of interest as they appear in XML documents. This is not true of general purpose relational databases, and once a translation tool has produced a database for querying the user must write queries about their XML document in a traditional query language with no concept of how data was structured in the XML document. Additionally, the work on s-XML notes a common failure of XML mapping methods to store all relationships between nodes of importance. This problem does not exist in `mel`, as the important relationships are explicated in the program the user writes. Additionally, the effort expended to write a `mel` program is not saved by using a tool like s-XML, because the `mel` program reflects the relational queries the user will write once a mapping tool produces a database for them.

Chapter 3

Model Extractor Language (`mel`)

In this chapter we introduce `mel`, which is a small declarative language for specifying fact extraction from Model artifacts, and the `mel` interpreter called `mint`. `mel` is a domain-specific language that allows the user to specify the facts that they want to extract from a Model. Such a specification will vary not only according to the type of Model under study (e.g., class facts from Class diagrams versus state facts from StateMachine diagrams) but also the representation of the Model (i.e., how classes or states are represented textually in a Model) and the user's needs (not all extractable facts will be relevant to the user's purpose). The intended scope of applicability of `mel` is any Model represented in XM*.

One of the challenges is that, although there exists a standard for rendering textual representations of Models, different Modelling tools may employ radically different XMI schema, even for the same notation.

This chapter is organized as follows: Section 3.1 defines the core required features `mel` must provide in order to satisfy extracting facts from various XM* documents, Section 3.2 introduces the general structure of a `mel` program and major language features, Section 3.3 displays the full `mel` grammar and discusses the specific organization of a `mel` program, and Section 3.4 introduces the `mel` interpreter `mint` and explains its usage.

3.1 Requirements of `mel`

`mel` was developed using the research methodology of design science [27]. As part of the design science methodology, the required features were identified as part of an iterative development process in which `mel` programs were developed to extract information from a

variety of Model types. This iterative process led to the identification of several ways that essential information is encoded in the XML representation of Models. These identified encoding methods dictate the requirements of `mel`, as the language must allow the user to specify the extraction of facts encoded in those ways. Each of these requirements corresponds to a relationship between the XM* document and some desired facts that the developer of a Model extractor would need to identify. Nine requirements for `mel` are listed in Table 3.1. The satisfaction of these nine requirements is sufficient for `mel` to extract all the Model information identified in the Models considered in this thesis.

Table 3.1: A summary of the language requirements for `mel`.

No.	Name	**Description**
1	Refer to XM* nodes by tag	The language must provide a method of referring to nodes in the XM* document by tag type. A reference to an XM* tag type should resolve to all the nodes in the XM* document that have that tag.
2	Extract values of Attributes of XM* nodes	The language must provide a method to specify which Attributes of an XM* node should represent identifiers or attributes in the factbase.
3	Refer to pairs of XM* nodes that are related by Attribute values	The language must provide a method to relate two XM* nodes when their specified Attributes have matching values. The reference should resolve to all pairs of such nodes in the XM* document whose Attribute values are equal.
4	Refer to pairs of XM* nodes that are related by a parent/child relationship	The language must provide a method to relate two XM* nodes (with specified tags) when one node is a child of the other. The reference should resolve to one pair of nodes for each node in the XM* document of (with the specified child tag) that has a parent node (with the specified parent tag).
5	Refer to pairs of XM* nodes that are related by an ancestor/descendant relationship	The language must provide a method to relate two XM* nodes when one node is a descendant of the other. The reference should resolve to one pair of nodes for each node in the XM* document (with the specified descendant tag) that has an ancestor node (with the specified ancestor tag)

Table 3.1: A summary of the language requirements for `mel`.

No.	Name	**Description**
6	Constrain results based on the values of Attributes/attributes	The language must provide a method to write constraints on the allowed values for Attributes of referenced XM* nodes or attributes of extracted facts. Specifically, it must allow constraints on the equality/inequality of string values.
7	Refer to tuples of XM* nodes that are children/descendants of the same XM* node	The language must provide a method to refer to a collection of XM* nodes (with specified tags) that are all children of the same parent node (with a specified tag); or are all descendants (with specified tags) of the same ancestor node (with a specified ancestor tag).
8	Refer to hierarchies of XM* nodes in the XM* document	The language must provide a method to refer to a series of XM* nodes (with specified tags) that appear in a specified structural hierarchy in the XM* document.
9	Refer to substrings of XM* Attributes	The language must provide a method to refer to a specified substring of an XM* Attribute value.

It is also worth noting that while the design science methodology used focused on XM* representations of Models, these requirements mean that `mel` is capable of extracting information from a wide range of XM* documents - not just those that represent software Models. However, `mel` has been specialized to focus on the types of XM* documents that represent Models, as these were the documents considered in the iterative development process of the language.

3.2 Usage of `mel`

A `mel` program is a sequence of declarations of fact types: each declaration starts with the name of a fact type to be extracted and the name(s) of its parameter(s) followed by the clauses that specify how facts of that type are constructed from information in the Model. The left-hand side and right-hand side of a declaration are separated by the token "`|-`".

Consider the declarations provided in Figure 3.2. A fact type with one parameter is an

```
<SWModel>
  <compFeatNode id="F1" userName="Feature 1" component="CompA"/>
  <compFeatNode id="F2" component="CompB"/>
  <compFeatNode id="F3" userName="Feature 3" component="CompA"/>
</SWModel>
```

Figure 3.1: A simple Model expressed in XML.

```
component(C) |- compFeatNode{component:C};
feature(X) |- compFeatNode{id:X, userName:label};
featParent(C,F) |- compFeatNode{component:C, id:F};
^sibling(F,G) |- featParent(C,F), featParent(C,G), F!=G;
```

Figure 3.2: A sample `mel` program.

entity fact; its parameter is the unique identifier for an extracted entity of that type. A fact type with two parameters is a *relationship* fact; its parameters refer to the two entities that are being related. On the right-hand side, each clause is one of the following types:

XM* reference clause: a reference to XM* nodes in the input Model, as in the first three rules in Figure 3.2.

Declaration reference clause: a reference to a declaration previously made in the `mel` program, as in the fourth rule in Figure 3.2 (discussed further in Section 3.2.1).

XM* path reference clause: a reference to specified patterns of XM* nodes that appear in the input Model (discussed further in Section 3.2.10).

Constraint: a restriction on the value of of bound identifiers (discussed further in Section 3.2.2).

An XM* reference clause starts with the name of an XM* tag followed by a *property list*. A property list is a comma-separated list of *properties* enclosed in curly braces, where each property is an *attribute binding* or a *requirement*[1]. An attribute binding is the binding of some value to a named identifier in the resultant fact. Specifically, the binding operator, ":", is a binary operator that binds the value of its left-hand operand to the name provided

[1]Requirements and their syntax are discussed fully in Section 3.2.8

Table 3.2: Results of applying the `mel` Program in Figure 3.2 to the XML fragment in Figure 3.1

Row No.	Fact Type	First Param	Second Param	Attributes
1	**component**	CompA		
2	**component**	CompB		
3	**component**	CompC		
4	**feature**	F1		{ label="Feature 1" }
5	**feature**	F2		
6	**feature**	F3		{ label="Feature 3" }
7	**featParent**	CompA	F1	
8	**featParent**	CompB	F2	
9	**featParent**	CompA	F3	
10	**sibling**	F1	F2	{ C="CompA" }

as the right-hand operand. Thus, a binding takes the form `X:Y`, where `X` is most commonly the name of an XM* Attribute[2] inside of an XM* node in the Model, and Y is the name of one of a fact type's parameters or is a declaration/reference to an attribute of the fact type.

To understand how `mel` declarations extract facts from a Model, consider the small pedagogical Model given in Figure 3.1, in which component `CompA` contains features `F1` and `F3`, and component `CompB` contains feature `F2`. Suppose that the `mel` user would like to extract from the Model (1) the set of *components*, (2) the set of *features*, (3) information about which components the features belong to, and (4) information about which features reside in the same component. The `mel` program in Figure 3.2 comprises four definitions that correspond to the four types of facts to be extracted.

Line 1 is one of the most simple declarations that can be written in a `mel` program.

component(C) declares that the factbase should have entity facts of type `component`. The identifier of each entity is bound to the parameter `C`, so that the identifier can be referred to by name in the clauses of this declaration.

compFeatNode{component:C} matches instances of the XM* tag `compFeatNode`. The value of the XM* Attribute `component` of each such node is bound to parameter `C` (i.e., the identifier of the extracted entity fact). This declaration

[2]As with Model vs. model, we distinguish between XM* Attributes in the input Model from attributes in the extracted model by capitalizing all references to the former.

requires an identifier so if the Model contained a `compFeatNode` node without a `component` Attribute, it would not be extracted.

The results of applying this declaration to the Model shown in Figure 3.1 are shown in the first three rows of Table 3.2.

Line 2 is similar to the declaration in Line 1, but it includes an additional binding that extracts an attribute associated with `feature`.

feature(X) declares that the factbase should have entity facts of type `feature`. The identifier of each entity is bound to the parameter `X`.

compFeatNode{id:X, userName:label} matches instances of the XM* tag `compFeatNode`. The value of the XM* Attribute named `id` of each such node is bound to parameter `X` (i.e., the identity of the extracted entity). Additionally, the value of the nodes XM* Attribute `userName` is bound to the attribute `label` associated with the extracted entity. By default, declared attributes are optional. Thus, although a `compFeatNode` node requires an `id` Attribute in order to be matched by this clause, it does *not* require a `userName` Attribute. It is also possible to require that node possess an XM* Attribute in order to satisfy a clause, as shown in Section 3.2.8.

The results of applying this declaration to the Model shown in Figure 3.1 are shown in the fourth to sixth and last two rows of Table 3.2. It should be noted that all `feature` entities `F1`, `F2`, and `F3` are extracted, but only `F1` and `F3` have `label` attributes (because the XML node for `F2` does not have a `userName` Attribute); thus entity `F2` is still extracted despite not having a `userName` Attribute.

Line 3 declares a relationship as opposed to an entity.

featParent(C, F) declares that the factbase should have relationship facts of type `featParent`. The first entity in each relationship is bound to the parameter `C` and the second entity is bound to the parameter `F`.

compFeatNode{component:C, id:F} matches instances of the XM* tag `compFeatNode`, as before. The `component` and `id` Attributes of each node are bound respectively to the parameters `C` and `F` for each extracted relationship. Because `C` and `F` are parameters of the relationship, only `compFeatNode` nodes that have both `component` and `id` Attributes are matched.

The results of applying this declaration to the Model shown in Figure 3.1 are shown in rows 7-9 of Table 3.2.

Line 4 declares another relationship and is the first declaration to use a declaration modifier, refer to previously extracted facts, include a constraint clause, and have multiple clauses. The exact semantics of declarations with multiple clauses (called compound clauses) will be discussed in Section 3.2.3.

^sibling(F, G) declares that the factbase should have relationship facts of type `sibling`. The first entity in each relationship is bound to the parameter `F` and the second entity is bound to the parameter `F`. The prefix `^` is a declaration modifier that specifies that this declaration should not be commutative. That is, facts of the form `sibling A B` and `sibling B A` should not both appear in the factbase. The commutative nature of the relationship may be undesirable by the user, as the cycle formed by it may have negative effects on future analyses depending on the analysis method. As such the `^` modifier is provided to allow users to specify extraction of only one edge in an otherwise commutative relationship. The prefix `^` should be used whenever a relationship is non-directed but the clauses do not disallow both facts to be produced; `mel` will extract whichever relationship it sees first while scanning the XM* document and will ignore the second relationship.

featParent(C, F) matches instances of the previously extracted relationship `featParent` and binds the first entity in the relationship to attribute `C` and the second entity to parameter `F`.

featParent(C, G) matches instances of the previously extracted relationship `featParent` and binds the first entity in the relationship to attribute `C` and the second entity to parameter `G`. If an identifier is used multiple times in the same declaration, it refers to the same value in all instances. Thus, the `C` in the first `featParent(C,F)` clause must match the `C` in this `featParent(C,G)` clause, generates a relationship between entities F and G.

F!=G is a constraint clause which restricts this declaration to only facts where the parameter `F` is not the same as the parameter `G`. That is, the `sibling` relationship should be non-reflexive and include any relationship instances between a `feature` and itself. The exact semantics of constraint clauses is discussed further in Section 3.2.2.

The result of applying this declaration to the Model shown in Figure 3.1 is row 10 of Table 3.2.

This example illustrates the basic usage of `mel`. At its core, `mel` is meant to facilitate the rapid development of queries to extract data from Models, so that the user can concentrate

on the *essential* complexity of deciding what information to extract from a Model and leave to `mel` and `mint` the *accidental* complexity of how to pluck that information from the XM* representation.

When extracting facts from a textual representation of a Model, the important questions for the user to answer are: *"What parts of the model do I care about?"* and *"What relationships in the model are important?"*. Each declaration of a `mel` program is an answer to one of these two questions and nothing more. A `mel` user need not write any cumbersome code to parse a model's textual representation, pluck out the information they care about, and constrain the result set to facts that satisfy certain conditions. Instead the `mel` user declares facts they are interested in and the clauses necessary for deriving those facts from the Model.

This concludes our introduction to basic `mel`. Many additional features and intricacies to the language are discussed in the following subsections.

3.2.1 Declaration Reference Clauses

A declaration reference clause is a clause that refers to fact type previously defined in the `mel` program. The two `featParent` clauses that appear in the `sibling` declaration (line 4 in Figure 3.2) are examples of declaration reference clauses (referring to the fact type defined in line 3).

```
1 featParent(C, F) |- compFeatNode{component:C, id:F,
2                                  userName:fLabel};
3 feature(X) |- featParent(owningComponent, X){fLabel:label};
```

Figure 3.3: A `mel` program that demonstrates the use and semantics of declaration reference clauses.

Specifically, a declaration reference clause binds its parameters to the parameters of the referenced definition.

To exemplify the concept of declaration reference clauses, consider the `mel` program shown in Figure 3.3, which provides an alternative definition of the `feature` entity shown in Figure 3.2. In this program, a `feature` entity is produced for each extracted instance of the `featParent` relationship, rather than being based on instances of the `compFeatNode` XM* nodes in the Model. The results of applying this program to the XML fragment

Table 3.3: Results of applying the `mel` Program in Figure 3.3 to the XML fragment in Figure 3.1

Fact Type	First Param	Second Param	Attributes
featParent	CompA	F1	{ fLabel="Feature 1" }
featParent	CompB	F2	
featParent	CompA	F3	{ fLabel="Feature 3" }
feature	F1		{ label="Feature 1" owningComponent="CompA" }
feature	F2		{ owningComponent="CompB" }
feature	F3		{ label="Feature 3" owningComponent="CompA" }

shown in Figure 3.1 are shown in Table 3.3. This table demonstrates how the binding of parameters of declaration reference clauses works.

In this example the `featParent` relationship is declared with the parameter names "`C`" and "`F`" and the clause that references this declaration names the parameters "`owningComponent`" and "`X`".

Each produced `feature` fact has its identifier, named `X`, bound to the value of the second parameter of the corresponding `featParent` fact, as shown in Table 3.3. Additionally, because the first parameter in the declaration reference clause is named `owningComponent`, each produced `feature` fact has an attribute named `owningComponent` whose value matches the value of the first parameter of the corresponding `featParent` fact that was used to produce it.

Lastly, the `feature` facts generated by the original program (in Figure 3.2) had a `label` attribute which corresponds to the `userName` Attribute of the corresponding XM* node. Because the `feature` facts in this program are generated by references to extracted `featParent` relationships (rather than from references to XM* data), the `featParent` relationship must extract this label information if we want to include it in our `feature` facts. This is why the `featParent` relationship definition extracts the `userName` Attribute of `compFeatNode` nodes and binds it to an attribute `fLabel` of the relation. Then, the declaration of `feature` facts needs a means to access the attributes of referenced facts.

To this end, declaration reference clauses can have property lists; the snytax is identical to that of property lists in XM* reference clauses, except that the properties refer to attributes of the referenced fact rather than to XM* Attributes. Consider, for example, the property list `{fLabel:label}` in the `featParent` declaration reference clause in

the `feature` declaration. Because this property list belongs to a `featParent` declaration reference clause, the identifier `fLabel` on the left-hand side of the binding operator refers to attributes of previously declared `featParent` facts. Thus, this property list specifies that the `fLabel` attribute of each `featParent` fact, if present, should be used as the `label` attribute of the corresponding `feature` fact.

In the subsequent subsections, any newly discussed feature that applies to a property list of XM* reference clauses also applies similarly to a property list of declaration reference clauses. For the sake of brevity, each feature is discussed only with respect to XM* reference clauses, but the reader should recognize that the same feature applies also to the property list of a declaration reference clause (where references to XM* Attributes are replaced with references to attributes of the corresponding facts).

3.2.2 Constraint Clauses

A constraint clause restricts the value of a bound identifier, using one of three operators: equality (=), inequality (! =), or the like operator (∼=). At least one operand is the name of an attribute of a produced fact, and the other operand is either another attribute of a produced fact or a string literal. String literals are discussed in more detail in Section 3.2.5.

The detailed behaviour of the three operators is as follows.

= An equality constraint evaluates to true if and only if its two operands have exactly the same value; it evaluates to false otherwise.

! = An inequality constraint evaluates to true if and only if its two operands have different values; it evaluates to false otherwise.

∼= A like constraint evaluates to true if and only if its right-hand operand is a string literal that expresses a regular expression pattern and that pattern matches the constraint's left hand operand.

When a constraint clause is included in a `mel` declaration, the constraint is applied to each potential fact that could be produced as part of the declaration; if the constraint evaluates to true, then that fact remains in the result set, whereas if the constraint evaluates to false then that fact is removed from the result set. Figure 3.4 demonstrates a Model of a library's contents. The `mel` program shown in Figure 3.5 demonstrates use of each of the three constraint operators. The declaration of entities of type `SKing` includes a constraint

```
<library>
    <book title="Spin" author="Robert Charles Wilson" genre="Sci-Fi"/>
    <book title="It" author="Stephen King" genre="Horror"/>
    <book title="GEB" author="Douglas Hofstadter" genre="Non-Fiction"/>
    <book title="Misery" author="Stephen King" genre="Horror"/>
    <book title="Great Expectations" author="Charles Dickens"/>
</library>
```

Figure 3.4: A Model of a library of books with a variety of authors and genres.

```
SKing(X) |- book{title:X, author:A, genre:G}, A="Stephen King";
GNovels(X) |- book{title:X, author:A, genre:G}, X~="[gG].*";
NotHorror(X) |- book{title:X, author:A, genre:G}, G!="Horror";
```

Figure 3.5: A `mel` program demonstrating the use of constraint clauses.

clause specifying that the `A` attribute of each result (ie.e. the `author` Attribute) must be equal to the string "`Stephen King`". The `GNovels` fact declaration includes the constraint clause specifying that the `X` parameter (the `title` Attribute of the book) must be like the string "`[gG].*`". That is the `GNovels` fact set should only include books whose `title` matches at least one string specified by the regular expression pattern "`[gG].*`". Lastly, the `NotHorror` declaration includes a constraint clause specifying that the `G` attribute of each result (i.e. the `genre` Attribute) does not equal the string "`Horror`".

3.2.3 Compound Productive Clauses

Each `mel` declaration is defined after the turnstile symbol '`|-`' by one ore more clauses separated by commas. Each clause is either a *productive* clause (that adds facts to the result set) or a *reductive* clause (that removes facts from the result sets). Constraints are the most common type of reductive clause. As they are discussed above, in Section 3.2.2, this section focuses on the compounding of productive clauses. There are two well-formedness conditions that must be met by productive clauses in rules that have compound productive clauses:

1. Each productive clause must have at least one bound identifier (parameter or attribute) in common with another productive clause in the declaration.

```
<nodes>
    <Entity id="ABC" mayExist="GAR"  name="Hello"/>
    <Entity id="GAR" mustExist="HET"/>
    <Entity id="XYZ" mustExist="GAR" mayExist="ABC"/>
    <Entity id="TAB" mustExist="XYZ" mayExist="GAR"/>
    <Entity id="BOO" mustExist="ABC"/>
    <Entity id="KEL" mustExist="ABC" mayExist="HET"/>
</nodes>
```

Figure 3.6: An XML fragment with several `Entity` tags that do not each contain all the attributes other `Entity` tags do.

```
Decl(X) |- Entity{id:X, mustExist:necessary, mayExist:optional},
           Entity{id:necessary};
```

Figure 3.7: A `mel` program that demonstrates the behaviour of compound clauses.

2. It must be possible to form a connected graph, whose vertices represent the productive clauses of the declaration and whose edges join vertices whose corresponding productive clauses share bound identifiers.

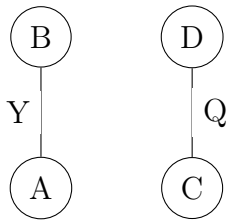


Figure 3.8: The disconnected graph formed by the productive clauses `A{id:X, att:Y}`, `B{id:Y}`, `C{id:P, att:Q}`, `D{id:Q}`, where each clause is given a vertex, and edges are drawn between vertices whose productive clauses share a bound identifier. The vertices have been labeled with the XM* tag of their corresponding clause, and the edges have been labeled with the bound identifier shared between the productive clauses.

Each productive clause in a `mel` generates potential facts; but in order to match the full declaration (1) the value of any attribute which occurs more than once in the set of clauses must match the value of all other occurrences of that attribute in the other clauses, and (2) the connectivity between productive clauses (through common attributes) must cover all of

Table 3.4: Results of applying the first clause of the declaration in Figure 3.7 to the XML fragment shown in Figure 3.6. Each row represents one fact that would be extracted and the columns are the values the identifiers would be bound to.

X	**optional**	**necessary**
ABC	GAR	
GAR		HET
XYZ	ABC	GAR
TAB	GAR	XYZ
BOO		ABC
KEL	HET	ABC

Table 3.5: Results of applying the second clause of the declaration in Figure 3.7 to the XML fragment shown in Figure 3.6. Each row represents one fact that would be extracted. As only one attribute, `necessary`, is extracted, there is only that value associated with each fact.

necessary
ABC
GAR
XYZ
TAB
BOO
KEL

the productive clauses in the declaration. As a negative example the set of clauses `A{id:X, att:Y}`, `B{id:Y}`, `C{id:P, att:Q}`, `D{id:Q}` is invalid because the clauses referring to XML tags `A` and `B` have no connection to the other two clauses; the clauses referring to XML tags `C` and `D` are similarly disconnected from the other two clauses. That is, the graph that would be formed by these productive clauses is disconnected, as shown in Figure 3.8. The facts generated by compound clauses are effectively the result of computing the intersection over the matching attributes of the facts that would be generated by each productive clause individually if it were the lone clause of a declaration, and then filtering this fact set as per the reductive clauses. Each fact generated has attributes for all the attributes that were bound in any of the productive clauses of the definition.

Consider the result of applying the `mel` program in Figure 3.7 to the XML fragment shown in Figure 3.6. The resultant facts should be one `Decl` fact for each `Entity` XML

Table 3.6: Results of applying the `mel` program in Figure 3.7 to the XML fragment shown in Figure 3.6. This is the result of joining the two potential-fact sets shown in Tables 3.4 and 3.5.

Fact Type	Entity	necessary	optional
Decl	XYZ	ABC	GAR
Decl	TAB	GAR	XYZ
Decl	BOO	ABC	
Decl	KEL	ABC	HET

node that has a `mustExist` Attribute whose value is the same as an `id` Attribute of any `Entity` XML node in the Model.

To understand the behaviour of compound clauses, it helps to consider the *potential facts* that each clause would extract if it were the sole clause in the declaration. The potential facts that would be extracted by the first clause are shown in Table 3.4: there is one fact for each `Entity` node in the XML fragment, however not all entries have values for the attributes named `optional` and `necessary`.

The potential facts extracted by the second clause are shown in Table 3.5: again there is one fact for each `Entity` node in the XML fragment. However, the second clause binds the `id` Attribute to the `mustExist` attribute in its result, as opposed to the first clause which binds the `mustExist` Attribute to the attribute `necessary` in the result.

The resulting set is produced by computing the equivalent of an inner join of the two collections of potential facts, using the shared attribute's name as the key to join on. Because the shared attribute is `necessary`, and because `necessary` is bound in the first and second clause to the XM* Attributes `mustExist` and `id` respectively, it follows that the program generates only facts from `Entity` nodes in the XM* whose `mustExist` Attribute corresponds to the `id` of any arbitrary `Entity` node in the XML. As a result there is no fact for the `Entity` nodes with `id` values of `ABC` or `GAR`. The `Entity` with the `id` value `ABC` has no `mustExist` Attribute and thus cannot be joined with any potential facts generated by the second clause. The `Entity` with the `id` value of `GAR` does have a `mustExist` Attribute, however the value of the attribute is `HET` which does not correspond to the `id` Attribute of any `Entity` node in the XML fragment, and thus cannot be joined with any of the potential results generated by the second clause. This generalizes to compound clauses with more two productive clauses by applying this process across all productive clauses computing the inner join on each of the shared attributes.

3.2.4 Optional Clauses

As discussed in Section 3.2.3, if a `mel` declaration contains multiple clauses then only facts that satisfy all of the clauses will be produced. *Optional* clauses allow for extracting specified information only when it is available. An optional clause in `mel` is a clause that is prefixed with a `@` symbol. Optional clauses are particularly useful when trying to extract information about optional attributes related to entities or relationships introduced in another XM* node.

Consider the XML snippet in Figure 3.9, in which some component nodes have an associated `owningTeam` node that specifies the software team responsible for the component. In this example, the `CompA` node has an associated `owningTeam` node while the `CompB` node does not. Suppose that the user desires to extract all `component` nodes including the owning team as an attribute when available.

```
<SWModel>
  <component id="CompA"/>
  <component id="CompB"/>
  <owningTeam name="DevGroup1" ownedComponent="CompA"/>
</SWModel>
```

Figure 3.9: A Model expressed in XML where Attributes are *sometimes* present. An `owningTeam` tag may exist associated with any given `component` tag, but is not required.

```
component(C) |- component{id:C},
                @owningTeam{name:team, ownedComponent:C};
```

Figure 3.10: A `mel` program using an optional clause, specified by a prefixed `@` symbol.

The sample `mel` program in Figure 3.10 includes both a normal clause (the first clause) and an optional clause (the second rule prefaced by '`@`'). The program extracts all entities and attribute bindings that match all the constraints in all normal clauses (in this case `component` nodes with Attribute `id`). The program's optional rules specify additional `component` attributes to be extracted from `owningTeam` nodes whose `ownedComponent` Attribute value matches the `component` fact's `id` value. The results of apply the `mel` program in Figure 3.10 to the Model in Figure 3.9 are shown in Table 3.7.

Table 3.7: Results of applying the `mel` Program in Figure 3.10 to the XML fragment in Figure 3.9.

Fact Type	Entity	Attributes
entity1	CompA	{ team="DevGroup1" }
entity1	CompB	

3.2.5 XM* Non-Basic Identifiers and String Literals

In some cases, an XM* Attribute might have a name containing non-alphanumeric characters which violates the grammar for `mel` identifiers, which are strictly alphanumeric strings. One common example seen in many Models is for an XM* Attribute name to include colon characters, which also happens to be the `mel` binding operator. In order to extract Attributes with such names, `mel` allows the left-hand side of a binding operator to be a string. However, `mel` prescribes different meanings to double-quote and single-quote enclosed strings, which is important to note. A double-quote enclosed string in `mel` is a string that represents either an identifier or a string literal, depending on the context. A single-quote enclosed string in `mel` always represents a string literal and never represents the value of an Attribute or attribute. A double-quote string has the following rules for its usage:

- If a double-quoted string appears as the left-hand operand of a binding operator, it refers to an XM* Attribute with the given name.
- If a double-quoted string appears as the right-hand operand of a binding operator, it refers to the name of an attribute of each produced fact.
- If a double-quoted string appears as either operand in a constraint, then it refers to the name of an attribute of each produced fact if an attribute with the given name exists, otherwise it is the string literal.

The results shown in Table 3.8 illustrate the difference between single-quote and double-quote strings, as well as the semantics of double-quote strings. To clarify, the results we consider each declaration in Figure 3.12 and the corresponding results it produces when applied to the XML fragment shown in Figure 3.11:

Line 1 In this declaration, the double-quoted string `"e:type"`, which is used as the left-hand operand of a binding operator, is a reference to the XM* Attribute with the

```
<nodes>
    <entity id="X1" e:type="string" />
    <entity id="x2" e:type="int" />
</nodes>
```

Figure 3.11: A simple XML fragment with `entity` tags with complex Attribute names (e.g., `e:type`) in XML.

```
entity1(X) |- entity{id:X, "e:type":type};
entity2(X) |- entity{id:X, 'e:type':type};
entity3(X) |- entity{id:X, "e:type":type}, "type"!="int";
entity4(X) |- entity{id:X, "e:type":type}, 'type'!="int";
entity5(X) |- entity{id:X, "e:type":type}, "int"!="int";
entity6(X) |- entity{id:X, "e:type":"Fun Type"};
```

Figure 3.12: A toy `mel` program illustrating the behaviour of double-quote and single-quote enclosed strings.

same name. As such, this usage binds the value of the XM* Attribute `e:type` to the attribute `type` of each produced entity. The result of this is shown in the first two rows of Table 3.8, where both `entity1` facts `X1` and `X2` were extracted with their corresponding type.

Line 2 Because a single-quoted string always resolves to a literal value, the string `'e:type'` binds the literal value `e:type` as the value of the `type` attribute in the result set. The result of this is shown in the third and fourth rows of Table 3.8, where both `entity2` facts `X1` and `X2` have `type` attributes with value `e:type`.

Line 3 This declaration is similar to the one on Line 1, except it includes the constraint `"type"!="int"`. In this scenario double-quoted strings are used as the operands to a constraint. As per the semantics of double-quoted strings in a constraint, the string `"type"` refers to the `type` attribute of the extracted entity because that attribute exists, and the string `"int"` refers to the literal string value `"int"` because no such attribute exists in the extracted entity. Note that this constraint could have equivalently been written as `type!='int'`, which more explicitly specifies that `type` is an attribute in the result and `'int'` is a literal value. This constraint disallows any results where the `type` attribute has the value `"int"`. The result of this is shown in the fifth row of Table 3.8, where only one `entity3` fact is extracted: that of `X1`

Table 3.8: Results of applying the `mel` Program in Figure 3.12 to the XML fragment in Figure 3.11

Fact Type	Entity	Attributes
entity1	X1	{ type="string" }
entity1	X2	{ type="int" }
entity2	X1	{ type="e:type" }
entity2	X2	{ type="e:type" }
entity3	X1	{ type="string" }
entity4	X1	{ type="string" }
entity4	X2	{ type="int" }
entity6	X1	{ Fun Type="string" }
entity6	X2	{ Fun Type="int" }

whose `type` attribute has the value `"string"` not `"int"`.

Line 4 This declaration is similar to the one on Line 1, except it includes a constraint `'type'!="int"`. A single-quoted string always refers to a string literal. Moreover, the double-quoted string `"int"` resolves to the literal string value because no attribute in each produced entity is bound to the name `int`. Thus, this constraint is trivially true constraint, stating that the string `'type'` must not equal the string `'int'`. Because the constraint evaluates to this declaration is equivalent to the one on Line 1. The result of this is shown in the sixth and seventh rows of Table 3.8, where both `X1` and `X2` are extracted as `entity4` facts, despite what one might confuse for a constraint on the `type` attribute.

Line 5 This declaration is similar to the one on Line 1, except it includes a constraint `"int"!="int"`. In this case, both double-quoted strings refer to their literal string values because there is no attribute with the name `int` in each produced entity. Thus, this constraint is trivially false, stating that the string `'int'` must not equal the string `'int'`. Because the constraint is false, no `entity5` facts may be extracted as they all violate the clause. The result of this is shown in Table 3.8 through the absence of any `entity5` facts.

Line 6 This declaration is similar to the one on Line 1, except instead of binding the `e:type` Attribute to the attribute `"type"` it binds it to the attribute `"Fun Type"`. The result of this is shown in rows eight and nine of Table 3.8, where the attribute of each `entity6` fact has the name `Fun Type`.

Table 3.9: Results of applying the `mel` Program in Figure 3.14 to the XML fragment in Figure 3.13

Fact Type	Entity	Attributes
function	foo	{ retType="int" prototype="int foo(int, int);" }

The dual roles that double-quoted strings can play lead to the seemingly unintuitive semantics described above. As such, the suggested best practice is that double-quoted strings be used only as the left-hand operand of a binding operator when made necessary by the XM* document that the program is applied to. Any other time strings are used, they should be restricted to mean literal values and thus be delimited by single quotes. However, if a `mel` programmer desires that an attribute in the factbase have a name that is not a valid `mel` identifier (i.e. any identifier that is not strictly alphanumeric), then they can use a double-quoted string in as the right-hand operand of a binding operator (e.g., as in line 6 of Figure 3.12 to bind an attribute to name `"Fun Type"` which includes a space). If an attribute's name is non-alphanumeric, then it must be referred to in constraints using strings delimited with double quotes.

Additionally, one may question the benefit of having the ability to bind attributes to string literals as is done in line 2 of Figure 3.12. While the ability to bind attributes to string literals may not appear very useful on its own, it has some limited uses and in Section 3.2.9 we discuss an additional feature of `mel` that makes effective use of this ability.

3.2.6 Contents of an XM* Node

An XM* node can have content that comprises either nested XM* nodes or string data. Because an XM* node's content can be string data, which may be pertinent to a user's needs, `mel` provides a feature `mel.contents` that refers to the string-data contents of an XM* node. `mel.contents` is used as the left-hand operand of a binding operator (as shown in Figure 3.14) to bind the value of the string contents of the given XM* node to the attribute being bound. Effectively `mel.contents` can be considered the pseudo-Attribute name of the contents of an XM* node. Table 3.9 shows that the extracted `prototype` attribute of the extract `Func` has the value of the string contents of the `function` node shown in Figure 3.13.

3.2.7 Extracting a Substring of an XM* Attribute

```
<function id="foo" return="int">
int foo(int, int);
</function>
```

Figure 3.13: A sample XML node that contains string data.

```
Func(X) |- function{id:X, return:retType, mel.contents:prototype};
```

Figure 3.14: A simple `mel` program that makes use of the `mel.contents` pseudo-Attribute for accessing the string contents of an XM* node.

```
<SWModel>
  <component id="CompA"/>
  <component id="CompB"/>
  <component id="CompC"/>
  <compFeatNode id="F1" userName="Feature 1"
                component="#CompA"/>
  <compFeatNode id="F2" userName="Feature 2"
                component="#CompB"/>
  <compFeatNode id="F3" userName="Feature 3"
                component="#CompA"/>
</SWModel>
```

Figure 3.15: A sample XML fragment that shows reference Attributes that have the referenced identifier prefixed with a # character.

```
featParent(C,F) |- compFeatNode{id:F, component["#(.*)"]:C};
```

Figure 3.16: A `mel` program that makes use of Attribute modifiers to specify a substring of an XM* Attribute to extract.

Table 3.10: Results of applying the `mel` Program in Figure 3.16 to the XML fragment in Figure 3.15

Fact Type	First Param	Second Param
featParent	CompA	F1
featParent	CompB	F2
featParent	CompA	F3

Sometimes the value of an XM* Attribute contains extraneous characters. A common example are Attributes prefixed with additional characters. Figure 3.15 shows an XML fragment where `compFeatNode` nodes reference their owning component through the Attribute `component`, however the values of the Attributes are prefixed with a character `#`. Ideally, the values of extracted identifiers strip away these extra characters. `mel` provides a feature called an *Attribute modifier* which is a regular expression pattern with at least one *capturing group*. A capturing group in a regular expression pattern is any portion of the string enclosed in parentheses. The value the first capturing group produces when the regular expression is applied to a string is the value that is bound to the attribute. An Attribute modifier is applied to an Attribute by suffixing the Attribute name with an Attribute modifier, in which the regular expression pattern is specified as a string enclosed in square brackets on the left-hand side of a binding operator: `X[Regex]:Y`. The string `Regex` represents a regular expression pattern with at least one capturing group. For example, if a binding is `X["abc([123]*)(.*)"]:Y` and the Attribute `X` has a value of `"12abc323671xyz"`, then the attribute `Y` will be bound to the value `"323"`, because the first capturing group used in the Attribute modifier matches any string that comprises only the digits 1, 2, and 3 that immediately follows the string `abc`.

The syntax and meta-characters of regular expressions that `mel` supports are those as defined by the ISO C++ 2017 standard [34] and implemented by the the compiler `g++` as part of the GNU compiler collection [21].

The `featParent` declaration in Figure 3.16 includes a `compFeatNode` clause that modifies the `component` Attribute with the Attribute modifier `"#(.*)"` and binds the result to the parameter `C`. The regular expression pattern `"#(.*)"` matches a string that begins with the character `#` and is then followed by any string, denoted by `".*"`, which is enclosed in a capturing group. As such, it is the value of the arbitrary string that follows the charcter `#` in the Attribute string that is bound to the parameter `C`.

```
SKing(X) |- book{title:X, author="Stephen King"};
GNovels(X) |- book{title:X, title~="[gG].*"};
NotHorror(X) |- book{title:X, genre!="Horror"};
```

Figure 3.17: A transformation of the `mel` program shown in Figure 3.5 which includes the same restrictions on result sets without extracting the author and genre as attributes in the result set.

3.2.8 Constraints on XM* Attributes.

A user may want to extract a subset of the matching XM* nodes in a Model. Constraints on result attributes are discussed in Section 3.2.2, however these constraints are written on extracted attributes. It is possible a user may instead want to constrain matching XM* node instances based on their Attribute values without necessarily binding those values to attributes in the result. `mel` supports this concept via *Attribute requirements*, which specify constraints on an XM* tags's Attribute values that must be met in order for an instance of the tag to match the fact type declaration. To differentiate between constraint clauses and constraints placed on XM* Attributes, the term *constraint* is used for constraint clauses and the term *requirement* is used for requirements placed on XM* Attributes included within an XM* reference clause. For example, the declarations in the program shown in Figure 3.5 can be modified so as not to extract the author and genre of books while still extracting facts related to only the desired subset of XM* nodes.

Requirements can make use of any of the constraint operators introduced in Section 3.2.2. However, when these operators are used within a requirement, the left-hand operand always represents the name of an Attribute in the XM* node and the right-hand operand must always be a string literal. Thus, the semantics of each operator needs to account for the possibility that its left-hand operand refers to an Attribute that does not exist in the XML node:

= Used in a requirement, an equality operation evaluates to true if and only if the value its left-hand operand is exactly equal to the value of its right-hand operand. If the XM* Attribute referred to by the left-hand operand does not exist in the node, the operation evaluates to false, as no string (even the empty string) is equal to a non-existent string.

! = Used in a requirement, an inequality operation evaluates to true if and only if the value its left-hand operand is not exactly equal to the value of its right-hand operand. If

the XM* Attribute referred to by the left-hand operand does not exist in the node, then the operation evaluates to true, as a non-existent string is trivially not equal to any existing string.

~= Used in a requirement, a "like" operation evaluates to true if and only if the value of its left-hand operand matches the regular expression pattern of its right-hand operand. If the XM* Attribute referred to by the left-hand operand does not exist in the node, then the operation evaluates to false, as no string (even the empty string) exists within a non-existent string.

In addition to the equality, inequality, and like operators, requirements may also specify Attributes that *must* or *must not* appear in the given XM* node in order for it to be a valid fact. These requirements are written using the two unary `mel` functions named `mel.exists` and `mel.nexists`. Such a requirement takes the form of `mel.exists(attrName)` or `mel.nexists(attrName)`, where the former evaluates to true if and only if the XM* Attribute named `attrName` exists in the XM* node, whereas the latter has the inverse semantics.

```
component(C) |- compFeatNode{component:C};
feature(X) |- compFeatNode{id:X, mel.exists(userName),
                           userName:label};
featParent(C,F) |- compFeatNode{component:C, id:F}, feature(F);
^sibling(F,G) |- featParent(C,F), featParent(C,G), F!=G;
```

Figure 3.18: An alternative to the `mel` program shown in Figure 3.2 that uses a requirement in the `feature` declaration to specify that matching `compFeatNode` XM* nodes *must* have a `userName` Attribute.

As an example, the program shown in Figure 3.18 uses the `mel.exists` function. This program behaves very similarly to the `mel` program presented in Figure 3.2, with the exception that it extracts `feature` facts only from `compFeatNode` nodes that have a `userName` Attribute. That is, if this program were applied to the XML fragment shown in Figure 3.1 it would not extract the `feature` fact `F2` because the `compFeatNode` node that defines it does not have a `userName` Attribute. Additionally, the clause `feature(F)` is added to the `featParent` declaration to ensure that `featParent` relationships are extracted only between `feature` and `component` facts that already exist in the produced factbase.

An alternative solution, to ensure that `featParent` relationships are formed only with `feature` facts that exist would be to include the `mel.exists(userName)` requirement within `compFeatNode` clause of the `featParent` declaration.

3.2.9 The Ternary Operator

The beginning of Section 3.2 specified that property lists may contain attribute bindings or requirements. So far. the attribute bindings shown have only been of the form `X:Y` where `X` is either a reference to an Attribute or a string literal. It has not been discussed yet how a user may conditionally bind an attribute to different values.

```
<animals>
    <animal id="Cat" sound="meow"/>
    <animal id="Fox"/>
    <animal id="Dog" sound="bark"/>
</animals>
```

Figure 3.19: A Model representing animals, optionally containing the sound that animal makes as an Attribute.

Consider the Model shown in Figure 3.19. Suppose that the user desires to extract from this Model an entity for each `animal` that includes as an attribute the sound the animal makes. If there is not a `sound` Attribute in the XM* for a given `animal` XM* node, the user would like the `sound` attribute of the corresponding produced fact to have the value "Who knows?".

`mel` provides a *ternary* operator with the following form

```
requirement ?  valIfTrue > valIfFalse
```

where `requirement` is any valid requirement as described in Section 3.2.8, and `valIfTrue` and `valIfFalse` must each be one of:

- A string literal, in single quotes, which evaluates to the exact value of the string literal.
- An identifier corresponding to an XM* Attribute, evaluating to the value of that Attribute. We will see that a ternary always appears as a left-hand operand of a binding operator; thus double-quoted strings appearing in a ternary operator are always interpreted as the name of an Attribute, as discussed in Section 3.2.5.

- A nested ternary, which evaluates as per the semantics defined below.

A ternary expression may appear only as the left-hand operand of a binding operator, or nested within another ternary operation. The value of a ternary operation is the value of its `valIfTrue` expression if the given requirement is true and is the value of its `valIfFalse` expression otherwise.

```
1 Animal(X) |- animal{id:X,
2                     mel.exists(sound) ? sound > 'Who knows?':noise};
```

Figure 3.20: A `mel` program that demonstrates the use of the ternary operator.

The `mel` program shown in Figure 3.20 shows the use of a ternary operator to conditionally bind the `noise` attribute of each `Animal` fact to either the string literal `'Who knows?'` or to the value of the `sound` Attribute of the corresponding `animal` XM* node. The result set of applying this program to the XML fragment shown in Figure 3.19 is three `Animal` facts each with a `noise` attribute. The `Cat` fact has a `noise` attribute of `"meow"`, the `Dog` fact has a `noise` attribute of `"bark"`, and the `Fox` fact has a `noise` attribute of `"Who knows?"`. The value of the `noise` attribute of the `Fox` fact is a result of the ternary operator producing the string `"Who Knows?"` because the XML node for `Fox` has no `sound` Attribute, making the requirement `mel.exists(sound)` evalaute to false.

```
1 Animal(X) |- animal{id:X, mel.exists(sound) ?
2                             sound='bark' ? 'ruff' > sound
3                         > 'Who knows?':noise};
```

Figure 3.21: A `mel` program that demonstrates the use of nested ternary operators.

An example of nested ternary operators is shown in Figure 3.21. In this program, the `noise` attribute of each extracted `Animal` fact depends not only on whether the `sound` Attribute exists, but also on its value if it does exist. If the `sound` Attribute exists, then it is then compared to the string literal `"bark"`; if the values are equal then the expression produces value `"ruff"`; if the values are not equal then the expression produces the value of the Attribute. Alternatively, if the `sound` Attribute does not exist at all, then the expression produces value `"Who knows?"`. Thus, the difference in the values produced by the programs shown in Figures 3.20 and 3.21 when applied to the XML fragment shown in Figure 3.19 is that the former extracts the `noise` attribute of the `Dog` fact as `"bark"`, whereas the latter extracts the same attribute as `"ruff"`.

3.2.10 XM* Trees of Elements

So far, the clauses specifying what information to extract from the XM* input document have been limited to XM* reference clauses, which match all corresponding nodes regardless of their locations in the XM* input. However, the tree structure of an XM* document is commonly used to encode meaningful information about the Model it represents Thus, it is necessary to be able to specify not only individual nodes but patterns of nodes to consider for extraction. `mel` provides operators for specifying parental (`->`) or ancestral (`=>`) relationships between XM* nodes. These operators define paths through the XM* node structure, thus they are collectively referred to as path operators. The path operators can be used to write clauses to specify hierarchical patterns of nodes which must appear in the XM* for a fact to be generated.

Parent Operator

The most common relationship among XM* nodes is the *parent* relationship, in which a child XM* node is nested within a parent node. Figure 3.22 shows an XML fragment for a Model that comprises features, components, and an ownership relationship between components and features. A feature's owning component is represented in the XML fragment by containing each `feature` node within its owning `component` node. Thus, this XML fragment represents a Model in which features `F1` and `F3` belong to component `CompA`, and feature `F2` that belongs to component `CompB`.

```
<SWModel>
  <component id="CompA">
    <feature id="F1" userName="Feature 1"/>
    <feature id="F3" userName="Feature 3"/>
  </component>
  <component id="CompB">
    <feature id="F2" userName="Feature 2"/>
  </component>
</SWModel>
```

Figure 3.22: An XML fragment that encodes relevant Model information as parental relationships between nodes.

Given the XML fragment in Figure 3.22, a `mel` declaration to extract a parental relationship `featParent` between components and their owned features could be written as:

```
featParent(C,F) |- component{id:C}->compFeatNode{id:F};
```

This declaration matches only instances of XM* `component` tags that have an XM* Attribute `id` and have a child tag `compFeatNode` with its own XM* Attribute `id`. The right-hand operand of a path operator may also be a collection of descendants that each must exist, rather than a single descendant.

```
sibling(F,G) |- component{}->[compFeatNode{id:F},
                              compFeatNode{id:G}], F!=G;
```

Figure 3.23: Example use of the `mel` parent operator.

The `sibling` relationship between `feature` facts could be written using path operators as shown in Figure 3.23. The right-hand operand of the parent operator in this example demonstrates how square brackets can be used specify a collection of descendants that each must exist underneath the left-hand operand of the operator. Thus, the XM* path clause in the above declaration specifies to look for `component` tags that have multiple distinct `compFeatNode` tags as child nodes. When this clause is applied to the XML fragment in Figure 3.22, only combinations of features F1 and F3 are considered because feature F2 does not reside underneath the same `component` node as F1 and F3 and the constraint `F!=G` disallows reflexive results that relate features F1, F2, or F3 to themselves. Thus, the only produced relationships are shown in Table 3.11.

Table 3.11: Results of applying the `mel` Program in Figure 3.23 to the XML fragment in Figure 3.22

Relationship Type	First Parameter	Secdon Parameter
sibling	F1	F3
sibling	F3	F1

An important observation of this sibling declaration is that the reference to tags of type `component` has an empty property list. This example demonstrates how the `sibling`

```
<component id="CompA">
  <compFeatNode id="F1" userName="Feature 1"/>
  <ownedFeatureSet>
    <featureCollection label="Display Features">
      <compFeatNode id="F2" userName="Feature 2"/>
    </featureCollection>
    <compFeatNode id="F3" userName="Feature 3"/>
  </ownedFeatureSet>
</component>
```

Figure 3.24: An XML fragment that acts as an exemplar for nested relationships.

relationship could be extracted even if the `component` tags have no unique identifier Attributes.

Ancestor Operator

Sometimes a relationship of interest may not be a direct parental relationship but rather an ancestral relationship. The *ancestor* operator specifies descendent nodes that are nested arbitrarily deep. Consider the XML snippet of nested nodes shown in Figure 3.24.

In this example, we have three features all contained within component `CompA` but at different levels of nesting in the XML structure:

- `Feature 1` is a directly child of `CompA`.
- `Feature 2` is nested in a `featureCollection` tag, which itself is nested underneath an `ownedFeatureSet` tag, which is finally a child of the component `CompA`.
- `Feature 3` is nested only underneath a `featureSet` tag.

Because the ancestor operator matches XM* nodes of arbitrary depth of nesting, the relationship between `components` and their respective `features` can be extracted with a single `mel` declaration:

```
featureOf(C,F) |- component{id:C}=>compFeatNode{id:F};
```

Specifying Paths

The path operators are so-named because they can be combined to specify more complicated paths in the XM* structure, than just parent-child or ancestor-descendent relationships.

Given the XML snippet shown in Figure 3.24, consider the case that one wants to extract only features that are contained within an `ownedFeatureSet` node that itself is a child of a `component` node:

```
1 featureOf(C,F) |- component{id:C}
2                     ->ownedFeatureSet{}
3                        =>compFeatNode{id:F};
```

The above declaration of `featureOf` combines the use of a parent operator with an ancestor operator to specify a path expression. Specifically the clause looks for `component` nodes that have a child node with an `ownedFeatureSet` tag, then searches for any `compFeatNode` nodes that are descendants (at any depth) of that `ownedFeatureSet` node.

3.2.11 Elide Results of Intermediate Rules.

The `mel` user may want to declare and extract facts that are not output to the result set. For example, some facts may be extracted for the sole purpose of easing the definition of more complicated facts. `mel` supports *intermediate declarations*, which are distinguished with the prefix ".", whose results are elided from the result set. As an example, suppose that the `mel` user would like to extract information about `sibling` features that lie in the same `component`, but not have intermediate facts about `features` and their `parent` relations appear in the final result set. If the `featParent` declaration in Figure 3.2 were replaced by the following declaration

```
1 .featParent(C,F) |- compFeatNode{component:C, id:F};
```

then the results of applying this modified `mel` program to the XML Model from Figure 3.1 would be the results in Table 3.2, but without the contents of rows 7-9.

program ::= *decl*+
decl ::= [*mods*] *name* '('*params*')' '|-' *clauses* ';'
mods ::= ('.' | '^' | '$')*
params ::= *name* [',' *name*]
clauses ::= *clause* (',' *clause*)*
clause ::= ['@'] *xmlRef* | ['@'] *declRef* | ['@'] *path* | *constraint* | ['@'] *fnCall*
xmlRef ::= *id* '{' *propList* '}'
declRef ::= *name* '('*params*')' '{'*propList*'}'
path ::= ['@'] *xmlRef* ('->' | '=>') *paths*
constraint ::= (*id* [*strMod*] | *literal*) *op* (*id* [*strMod*] | *literal*)
fnCall ::= ('mel.parent'|'mel.ancestor') '(' *xmlRef* ',' *xmlRef* ')'
propList ::= *binding* | *attreq* | *propList* ',' (*binding* | *attreq*)
attreq ::= *lvalue* [*strMod*] *op* *literal* | *eReq* '(' *lvalue* ')'
eReq ::= 'mel.exists' | 'mel.nexists'
binding ::= *lvalue* [*strMod*] ':' *id* | *ternary* ':' *id*
ternary ::= *attreq* '?' *ternOption* '>' *ternOption*
ternOption ::= *ternary* | *lvalue* [*strMod*] | *literalStr*
op ::= '=' | '!=' | '~ ='
paths ::= ['@'] *xmlRef* | *path* | '[' *listofPaths* ']'
listofPaths ::= (['@'] *xmlRef* | *path*) (',' ['@'] *xmlRef* | *path*)*
lvalue ::= *id* | 'mel.contents'
strMod ::= '[' *literal* ']'
id ::= *name* | *string*
name ::= ALPHA (ALPHA | DIGIT | '_')*
literal ::= *string* | *literalStr*
string ::= '"' CHAR* '"'
literalStr ::= '/' CHAR* '/'

Figure 3.25: Grammar for `mel` programs: *Non-terminal* symbols are italicized and TERMINAL symbols are in uppercase. Literals are enclosed in single quotes. "|" denotes alternation, "["..."]" encloses optional symbols, and "("...")" encloses a grouping of symbols. "*" denotes zero or more repetitions of the previous symbol or grouping, and "+" denotes one or more repetitions of the previous symbol or grouping.

3.3 Grammar of `mel`

The full grammar for `mel` is provided in Figure 3.25. A *program* is a sequence of *decl*arations. Each *decl*aration defines either an entity type (with one *param*eter) or a relationship type (with two *param*eters). *Decl*arations can be prefaced with *mod*ifiers which modify their behaviour. A *decl*aration prefaced with *mod*ifier '.' denotes an elided fact type whose instances will not be part of the output; but the instances can be used to identify other extracted facts that are part of the output. Prefacing a *decl*aration with the *mod*ifier '^' declares that the relationship type cannot be commutative (i.e., cannot relate an entity X to entity Y as well as relate Y to X). In such cases, `mel` removes the second of the commutative instances from the result set. Lastly, prefacing a *decl*araton with the *mod*ifier '$' specifies that duplicate facts (i.e. facts with the same values for their parameters) should not be extracted, in this case `mel` selects the first such found fact.

Each *decl*aration is followed by a series of *clauses* that correspond to the four types of clauses discussed earlier in Section 3.2.

3.4 `mint` the `mel` Interpreter

As with any programming language there needs to be a method of executing programs written in the language. The solution to executing `mel` programs is the `mel` interpreter `mint`. `mint` is implemented in C++ using *GNU Bison* [44] for parsing, Fast Lexical Analyzer Generator (*Flex*) [44] for tokenizing, and the RapidXML library [36] for parsing XML text. C++ was chosen for its highly efficient code, access to the aforementioned parsing libraries, and because it is more architecture-independent than assembly.

3.4.1 Usage of `mint`

`mel` programs are executed by providing them as input to the `mel` interpreter (`mint`) along with the additional input(s) of the XM* file(s) to process. A `mel` program and the XM* file are respectively analogous to the intensional database (IDB) and extensional database (EDB) of a Datalog program. *mint* is used as a simple command-line interface tool whose usage is of the form

```
$ mint <melProgram> <XM*File> [XM*Files]... [-n] [-o output]
```

where the first argument is the `mel` program the user has written, the second argument is an XM* file to be extracted from, and the user can optionally provide additional XM* files if the Model they are extracting from comprises several files. The optional flag (`-n`) denotes that the output format is comma-separated value (CSV) files, one for all the nodes and one for all the relationships, by default `nodes.csv` and `edges.csv` in the current working directory respectively. The other optional (`-o`) argument specifies the name of the file to which the resultant factbase is output. If `-n` and `-o fileName` are used in conjunction then the two output CSV files corresponding to edges and nodes respectively will be `fileNameEdges.csv` and `fileNameNodes.csv`. If neither of the flags are used then `mint` outputs the resultant factbase to the standard output stream.

Chapter 4

Evaluation of `mel`

In this chapter, we discuss the evaluations performed on `mel` and the methods of the experiments performed. The evaluation of `mel` focuses on two criteria:

1. The extent to which `mel` generalizes to XM*-based representations of Models and to desired extractions
2. The effectiveness of `mel` in easing the creation of new fact extractors for Models

In order to test `mel` against a wide variety of Model types, we looked for publicly available Models that exercise complex features in their respective Modelling languages; that were generated by Modelling tools commonly used in education, research, or industry [1, 31, 37, 42]; and whose XM* representations varied from each other. Finding suitable Models for the study was a challenge because of the dearth of publicly available sophisticated Models for a majority of the Model types. Researchers Hebig, Ho-Quang, Chaudron, Robles and Fernandez [25] provide a solid database for UML diagrams, although the vast majority of the Models available from, the database are UML Class Diagrams. In the end, we sourced Models from sample Models provided with Modelling tools and from public GitHub repositories.

The Model types considered in this evaluation are UML StateMachine and Class diagrams [19], Simulink Block diagrams [49], Arcadia Logical Architecture diagrams [67], and Feature Models [43]. With the exception of a particularly structured feature constraints in Feature Models, we found that `mel` was sufficiently expressive to generalize to all five Model types. The data sets used for these studies are available in the repository `https://github.com/Roshack/ModelsUsedWithmel` which includes for each Model

an image of at least one diagram from the Model, the XM* representation of the Model, and the factbase produced when the corresponding `mel`-generated extractor was applied to it. Additionally, our studies on the effectiveness of `mel` in easing the creation of new fact extractors produced generally favourable results in terms of development time and succinctness of the programs developed.

4.1 Scope of Applicability of `mel`

Our first study evaluated whether `mel` is expressive enough to extract facts of interest from different Model types with varying XM* representations. For each Model type we discuss the types of facts extracted, the different editors and representations that were considered, and the correctness tests of the extractors written in `mel` when applied to the Models of that type.

In order to test the correctness of both the `mel`-generated extractors, and the interpreter `mint` itself, we sampled facts for each Model considered:

1. Twenty facts (or all facts, if there were fewer than twenty in the Model) were randomly selected from the visual depiction of each Model of the Model type being assessed. These 20 facts were then confirmed to exist in the factbase produced by applying the `mel`-generated extractor to the XM* representation of the Model.

2. Twenty facts were randomly selected from the factbase produced by applying the `mel`-generated extractor to the XM* representation of a Model. These facts were then confirmed to exist in the XM* of the Model and in the visual depiction of the Model.

The above process was applied to all the Models of each type considered. The remainder of this subsection will discuss the different Model types considered. For each Model type, we discuss (1) the information that must be extracted from the Model to produce a factbase that represents a complete model of a Model of that type; (2) the number of Models considered, the editors we used to produce them and an overview of the differences in the textual representations between the editors; (3) the `mel`-generated extractors written for each Model/editor pair; and lastly (4) the results of applying the `mel`-generated extractors to the Models.

Table 4.1: Necessary facts for extraction from UML StateMachine diagrams.

Entities	**attributes**
State Machines	name
States	name; entry, exit, and internal actions/guards
Regions types	name

Relationships	**attributes**
Sub state	
Containment of state by region	
Containment of region by state	
Concurrent regions	
Transitions	triggers, guards, and actions

4.1.1 UML StateMachine Diagrams & Statechart Diagrams

UML StateMachine diagrams are adaptations of the statechart formalism proposed in 1987 by Harel [23]. Statecharts extend traditional state machines with hierarchical states, typed variables, concurrent submachines, and the communication of events between concurrent submachines. We differentiate between the mathematical concept of a state machine and the class of UML StateMachine diagrams through the capitalization of the latter. StateMachine diagrams were selected for this study because (1) the data they model is distinct from other Model types considered, and (2) they feature prominently in academic works across a wide variety of applications [14, 39, 66].

Information to be Extracted

For this study, we identified several key pieces of information to extract as facts from UML StateMachine diagrams, shown in Table 4.1 This set of facts is our attempt at extracting a comprehensive model of a UML StateMachine diagram without omitting any details. Thus, an extractor would need to be able to extract all of the information listed in Table 4.1 to be considered successful.

Models & Tools Considered

As subject StateMachine diagrams, we considered Models generated by either IBM Rhapsody (version 8.4) [32] or YAKINDU Statechart Tools (SCT) [35]. Rhapsody was selected

because it is used in industry and studied in research on Model-driven engineering [37]. YAKINDU was selected because it serializes its Model representations quite differently from how Rhapsody serializes Models; also Yakindu provides a plethora of thirty sample Models.

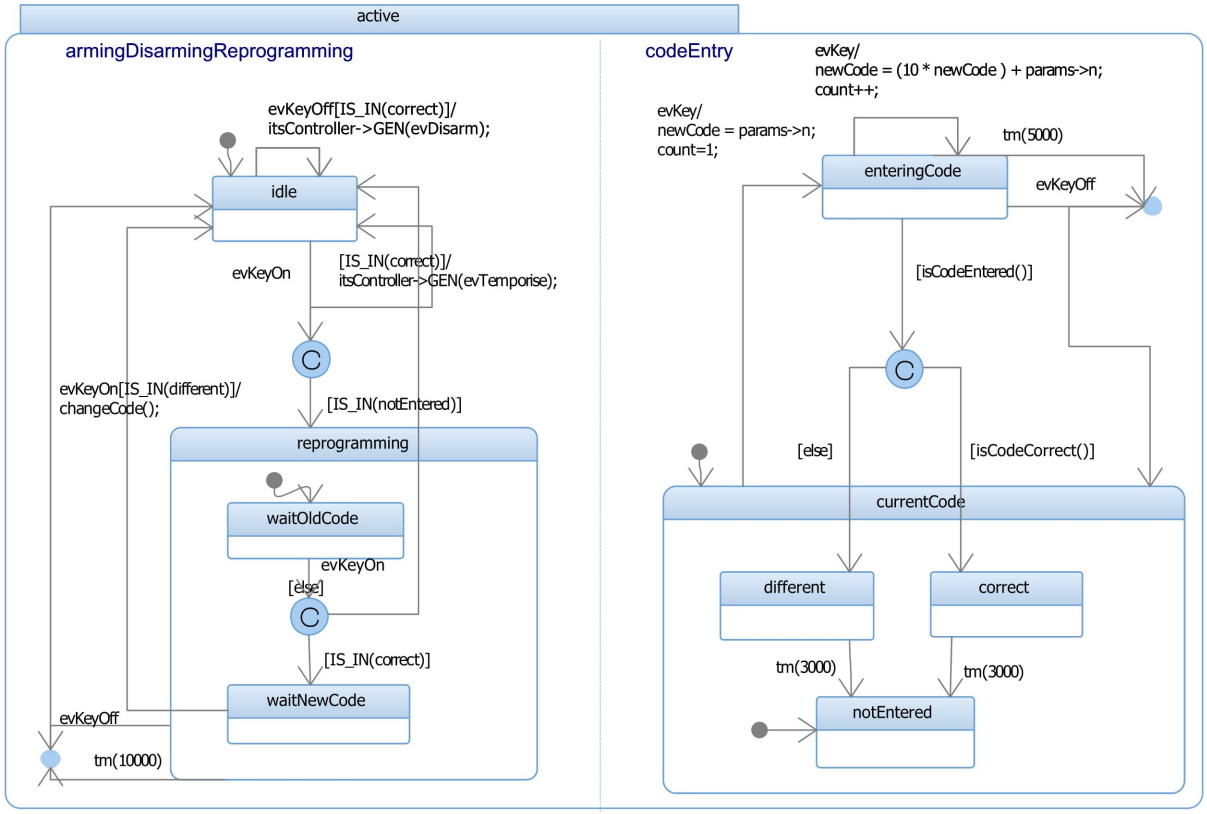


Figure 4.1: UML StateMachine diagram of an embedded home alarm system (Rhapsody).

The UML StateMachine shown in Figure 4.1 is for a component of a hypothetical home alarm system written in C++. It comes from a sample Rhapsody project provided as part of the IBM Rhapsody version 8.4. A YAKINDU produced model is also shown in Figure 4.2 which includes much more detail. For example, the YAKINDU Model includes examples of actions that occur while residing in, entering, or exiting a state.

Snippets of XML from these two Models are shown in Figures 4.3 and 4.4 respectively. While the two Model representations share similarities, as do most representations of the same Model type, they also have some important differences. One major difference is in

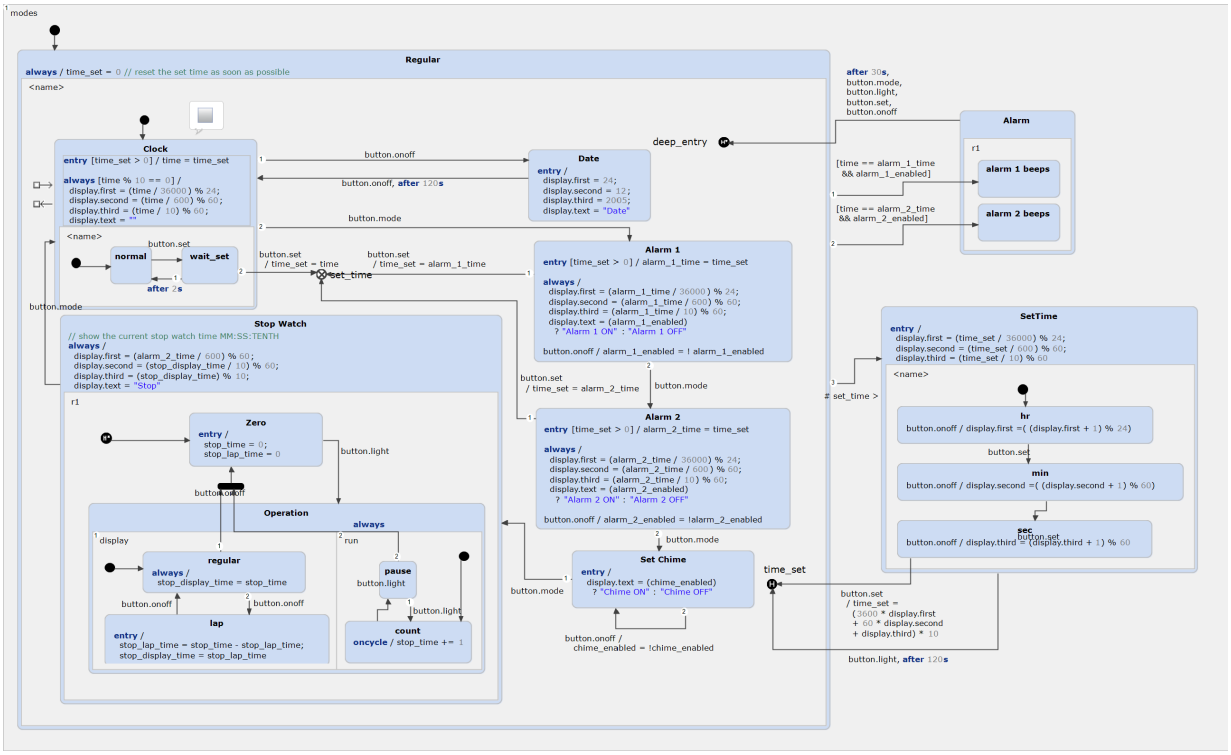


Figure 4.2: UML StateMachine diagram of Harel's statechart for a digital watch [23], produced using YAKINDU SCT.

how the two editors serialize data about transition triggers, guards, and actions as well as state actions and their corresponding guards. Figure 4.3 shows how Rhapsody encodes the transition's triggers, guards, and actions through a particular set of relationships:

Triggers are represented by a `trigger` node that is nested underneath its corresponding `transition` node. The `trigger` node contains the identifier of a `packagedElement` node. The corresponding `packagedElement` node has an `xsi:type` of `uml:SignalEvent` that isfound elsewhere in the XML hierarchy. The `uml:SignalEvent` has a `signal` Attribute whose value corresponds to the identifier of a *different* `packagedElement` whose `xsi:type` is `uml:Signal`. Within that second `packagedElement`, the value of the trigger is stored within the `name` Attribute.

Guards are represented as the `value` Attribute of a `specification` node, which resides underneath a `ownedRule` node, which in turn resides underneath the node for the `transition` in question.

```
<region xmi:id="_mapNhJ" name="armingDisarmingReprogramming">
  . . .
  <subvertex xmi:id="161" name="idle"/>
  . . .
  <transition xmi:id="170" target="161" guard="175" source="161">
    <ownedRule xmi:id="175" context="OLDID+1424988+170">
      <specification xmi:id="_mapNqp" value="IS_IN(correct)"/>
    </ownedRule>
    <effect xmi:id="_mapNq5">
      <body>&#xD;\nitsController->GEN(evDisarm);</body>
    </effect>
    <trigger xmi:id="174" event="1d0f6"/>
  </transition>
        . . .
</region>
. . .
<packagedElement xmi:type="uml:SignalEvent" xmi:id="1d0f6" signal="_marCdp"/>
<packagedElement xmi:type="uml:Signal" xmi:id="_marCdp" name="evKeyOff"/>
```

Figure 4.3: Snippet of the XMI representation of the Rhapsody StateMachine Model shown in Figure 4.1. Identifiers have been abbreviated and non-referenced Attributes have been omitted.

Effects are represented as the contents of a `body` node, which resides underneath an `effect` node, which in turn resides underneath the node for the `transition` in question.

As shown in Figure 4.4, YAKINDU instead chooses to represent a transition's trigger, guard, and action all together as a single string. Each transition is stored as a `outgoingTransition` node whose `specification` Attribute contains all the information about that transition other than its source and target states. The `specification` Attribute takes the form of the literal value displayed in the Model including line feed characters. This XML snippet also shows how all of a state's actions are also encoded as one large string.

Rhapsody's and YAKINDU's representations place different requirements on the respective extractors that can analyze them. An extractor for Rhapsody diagrams must be able to sufficiently specify and resolve relational connections to pluck out a transition's trigger, guard, and action. Conversely, an extractor for YAKINDU Models need not resolve any relation to find a trigger's information, but be able to parse relevant substrings from a string Attribute.

```
<sgraph:Statechart xmi:id="YX1">
 . . .
  <vertices xsi:type="sgraph:State" xmi:id="q1B" name="Alarm 1"
    specification='entry [time_set > 0] / alarm_1_time = time_set
                   always /
                     display.first = (alarm_1_time / 36000) \% 24;
                     display.second = (alarm_1_time / 600) \% 60;
                     display.third = (alarm_1_time / 10) \% 60;
                     display.text = (alarm_1_enabled)
                      ? "Alarm 1" : "Alarm 1 OFF"
                   button.onoff / alarm_1_enabled = ! alarm_1_enabled'>
    <outgoingTransitions xmi:id="eZW" target="fW1"
                         specification="button.set
                                        / time_set = alarm_1_time"/>
    <outgoingTransitions xmi:id="S5V" specification="button.mode" target="BTI"/>
  </vertices>
 . . .
  <vertices xsi:type="sgraph:State" xmi:id="BTI" name="Alarm 2"
    specification='entry [time_set > 0] / alarm_2_time = time_set
                   always /
                     display.first = (alarm_2_time / 36000) \% 24;
                     display.second = (alarm_2_time / 600) \% 60;
                     display.third = (alarm_2_time / 10) \% 60;
                     display.text = (alarm_2_enabled)
                       ? "Alarm 2 ON" : "Alarm 2 OFF"
                   button.onoff / alarm_2_enabled = !alarm_2_enabled'>
        . . .
  </vertices>
 . . .
  <vertices xsi:type="sgraph:Exit" xmi:id="fW1" name="set_time"/>
 . . .
</sgraph:Statechart>
```

Figure 4.4: Snippet of the XMI representation of the YAKINDU StateMachine Model shown in Figure 4.2. Identifiers have been abbreviated, non-referenced Attributes have been omitted, and white space has been adjusted to improve readability. YAKINDU stores all of a transition or state's triggers, guards, and actions as one contiguous string.

Overall, a total of eleven StateMachine diagrams were used in evaluating `mel`. Ten of these were generated using YAKINDU and the remaining one was generated using Rhapsody.

`mel` Extractors for Rhapsody and YAKINDU Models

The `mel` extractors written for StateMachine diagrams produced by Rhapsody and YAKINDU can be seen in Figures 4.5 and 4.6, respectively. The structures of these two programs further illustrates the differences in how Rhapsody and YAKINDU encode their Models. Examining the `Transition` declaration in Figure 4.5 reveals that extracting all the relevant information takes eight compound clauses, five of which involve parent operators - meaning that at least **thirteen** nodes need to be resolved and connected to generate each `Transition` fact. The `Transition` declaration of Figure 4.6 represents the other extreme: it is defined using a single clause involving a parent operator, meaning that only two nodes need to be resolved and connected to generate each `Transition` fact. However, this `Transition` declaration makes use of several non-trivial regular expressions to resolve the attributes it would like to produce for each fact.

The two extremes of Rhapsody and YAKINDU Model representations demonstrate that the expressiveness of `mel` is sufficient both to resolve complex interconnected relationships as well as resolve complex mappings of XML Attributes to fact attributes.

```
StateMachine(X) |- ownedBehavior{"xmi:type"="uml:StateMachine",
                                 "xmi:id":X, name:name};

Region(R) |- region{"xmi:id":R, name:name};

State(X) |- subvertex{"xmi:id":X, name:label, "xmi:type"[":(.*)"]:type};

SubState(P, C) |- subvertex{"xmi:id":parent}->region{}->
                                              subvertex{"xmi:id":child};

^Concurrent(R1, R2) |- subvertex{}->[region{"xmi:id":R1},
                                    region{"xmi:id":R2}],
                       R1 != R2;

RegionOf(S, R) |- subvertex{"xmi:id":S}->region{"xmi:id":R};

Transition(source, target) |-
        transition{"xmi:type"="uml:Transition", "xmi:id":transitionId,
                   source:source, target:target},
        # trigger
        @transition{"xmi:id":transitionId}->trigger{event:eventId},
        @packagedElement{"xmi:type"="uml:SignalEvent",
                         "xmi:id":eventId, signal:signalId},
        @packagedElement{"xmi:type"="uml:Signal", "xmi:id":signalId, name:trigger},
        # guard
        @transition{"xmi:id":transitionId}->@ownedRule{"xmi:id":ownedRuleId},
        @ownedRule{"xmi:id":ownedRuleId}->@specification {value:guard},
        # effect
        @transition{"xmi:id":transitionId}->effect{"xmi:id":effectId},
        @effect{"xmi:id":effectId}->body{mel.contents["[ \\t\\r\\n]*([^]*)"]:effect};
```

Figure 4.5: `mel` program for extracting facts from a UML StateMachine diagram created with Rhapsody.

```
StateMachine(X) |- "sgraph:Statechart"{"xmi:id":X, name:name};

Region(R) |- vertices{}=>regions{"xmi:id":R, name:label};

State(X) |-
    vertices{"xmi:id":X, name:label,
             "xsi:type"='sgraph:State' ? 'State'
               > "xsi:type"='sgraph:Entry' ? 'Entry'
                > "xsi:type"='sgraph:Exit' ? 'Exit'
                 > "xsi:type"='sgraph:Synchronization' ? 'Sync'
                  > '':type,
    specification["entry[^/]*/[ \\t\\r\\n]*([^]*?)[ \\t\\r\\n]*(always|exit|$)"]
        :entryEvent,
    specification["entry[^/]*\\[([^\\]]*)\\][^]*"]
        :entryGuard,
    specification["always[^/]*/[ \\t\\r\\n]*([^]*?)[ \\t\\r\\n]*(exit|$)"]
        :alwaysEvent,
    specification["always[^/]*\\[([^\\]]*)\\][^]*"]
        :alwaysGuard,
    specification["exit[^/]*/[ \\t\\r\\n]*([^]*?)[ \\t\\r\\n]*$"]
        :exitEvent,
    specification["exit[^/]*\\[([^\\]]*)\\][^]*"]
        :exitGuard};

SubState(P, C) |- vertices{"xsi:type"="sgraph:State", "xmi:id":P}
                    ->regions{}->vertices{"xsi:type"="sgraph:State", "xmi:id":C};

^Concurrent(R1, R2) |-
    vertices{}->[regions{"xmi:id":R1, name:L1},
                 regions{"xmi:id":R2, name:L2}], R1!=R2;

RegionOf(S, R) |-
    vertices{"xsi:type"="sgraph:State", "xmi:id":S, name:sLabel}
        ->regions{"xmi:id":R, name:"rLabel"};

Transition(Src,Targ) |-
    vertices{"xmi:id":Src}
        ->outgoingTransitions{target:Targ,
                              specification[".*\\[([^\\[\\]]*)\\].*"]:guard,
                              specification["([^/\\[\\]]*)(\\[.*\\])?/?.*"]:trigger,
                              specification[".*/([^]*)"]:event};
```

Figure 4.6: `mel` program for extracting facts from a UML StateMachine diagram created with YAKINDU.

Modelling Tool	Name	# States	# Transitions	# Entities	# Relationships
YAKINDU SCT	Arduino HMI	26	34	33	55
	Arduino Polling	4	4	5	4
	Arduino Blinky LED	4	4	5	4
	Coffee Machine	21	22	26	35
	Motion Detection Camera	12	14	16	23
	Music Player	81	119	102	163
	Smart Home	49	71	59	103
	Traffic Light Control	21	22	27	39
	Digital Watch	39	42	47	69
	Arduino Zowi	16	17	20	28
Rational Rhapsody	Home Alarm With Ports	52	56	76	75

Table 4.2: Summary of the StateMachine Models considered in this study, including the number of states and transitions in each Model and the total number of entity and relationship facts extracted in the factbase.

Results of StateMachine Diagram Extraction

Table 4.2 summarizes the Rhapsody-generated StateMachine Model and the ten YAKINDU-generated StateMachine Models that we considered. For each of the eleven StateMachine Models used in this study Graphical representations of diagrams from the Models and their XMI representations can be found in the online repository[1]. Additionally, the graphical representations of the diagrams are included in Appendix B.

Using the process described at the beginning of Section 4.1, we applied our two `mel`-generated extractors to the eleven StateMachine Models in our evaluation set produced result sets without error. We manually examined the generated facts and found that there were no sampled Model facts that did not exist in the generated factbase, plus the facts' attributes all had appropriate values. Similarly, none of the extracted facts sampled were found to be extraneous to the Model.

[1] https://github.com/Roshack/ModelsUsedWithmel

4.1.2 UML Class Diagrams

UML Class diagrams are perhaps the most well-known type of software Model and have found to be the diagram most commonly reported to be used in industry [31]. It is for this reason that `mel's` applicability to UML Class diagrams is considered. Additionally, due to the popularity of UML Class diagrams, there exists an incredibly large number of distinct tools for generating them, each supporting different Modelling constructs and employing their own XM* representations. Thus, UML Class diagrams and tools provide good evidence of the potential need for specialized extractors for every distinct tool.

Information to be Extracted

The full set of information to be extracted from UML Class diagrams is reported in Table 4.3. It is important to note that each tool may support only a subset of the facts and attributes listed in Table 4.3. For example, UML Class diagrams created with the Eclipse Modelling Tools cannot denote a class as being `final`, meaning that no such attribute can be extracted. For each of the facts and attributes listed, if it is supported by the Modelling tool, then it should be extracted from the Model.

Models & Tools Considered

UML Class diagrams are the most easily available Model type and we consider diagrams from each of several tools:

Tool	Number of Models
UMLDesigner [55]	3
MagicDraw [33]	4
Eclipse Modelling Tools [63]	6
ArgoUML [60]	2

UMLDesigner, MagicDraw, and ArgoUML all store their diagrams in a representation approximating a OMG UML 2.X standard [19], thus their representations are all fairly similar to one another. Consider the UMLDesigner and Eclipse Modelling Tools diagrams shown in Figures 4.7 and 4.8, respectively. The UMLDesigner Model is for a fictional Travel Agency system, which is a sample UML Class diagram project provided with the UMLDesigner version 9.0 [55]. The Model generated with the Eclipse Modelling Tools is sourced from the UML model database [25] and is a recreation of a pedagogical example from Warmer

Table 4.3: Necessary facts for extraction from UML Class diagrams.

Entities	**attributes**
Classes	name, abstract, final, and interface[a]
Interfaces	
Enumeration types	name
Enumeration values	
Fields	name, visibility, constness, type, multiplicities, and concreteness
Methods	name, visibility, return type, and concreteness
Parameters	name and type

Relationships	**attributes**
Ownership of enumeration values	
Ownership of fields	
Ownership of methods	
Ownership of parameters	
Associations between classes	role names and multiplicities
Composition of classes	role names and multiplicities
Aggregation of classes	role names and multiplicities
Specialization of classes	

[a]Depending on the language interfaces may be their own entity, or a class may define an interface

and Kleppe's book on the Object Constraint Language [68]. The two Models have different XMI representations: UMLDesigner serializes its Models according to the OMG UML standard version 2.1, and the Eclipse Modelling Tools serialize Models according to the EMF ECore specification and file format.

The most notable difference between the OMG XMI and the ECore representations of UML Class diagrams is in their methods of referencing other nodes. Documents adhering to the OMG XMI specification refer to other nodes through unique identifier Attributes. ECore documents, as discussed earlier in Section 2.2.2, refer to other nodes through strings that represent *paths* in the XMI structure.

Figures 4.9 and 4.10 demonstrate the two distinct methods of resolving references. The association relationship in OMG representation is determined by considering the `type` Attribute of the two `ownedEnd` nodes that are children of the `packagedElement` whose

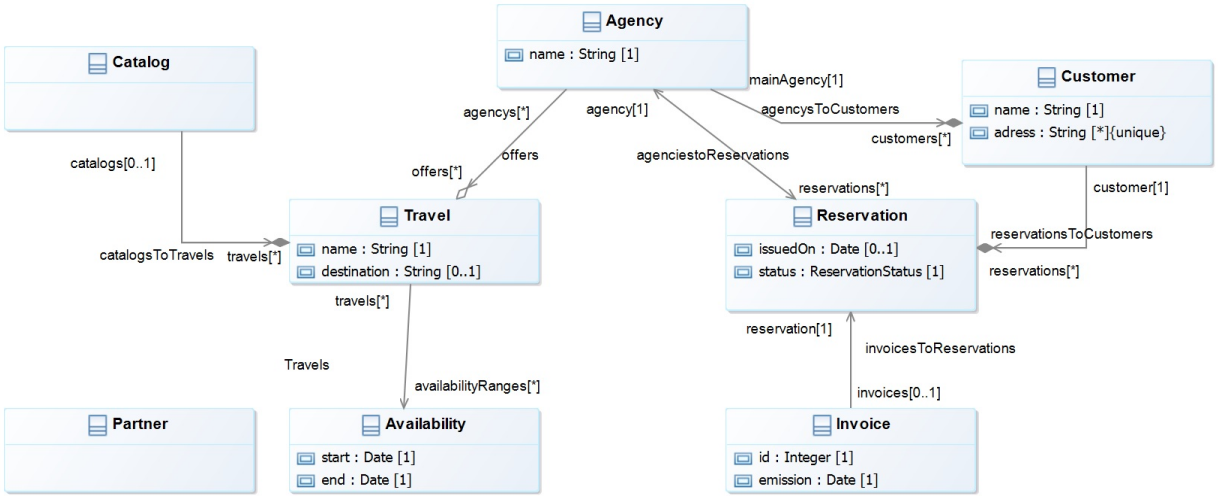


Figure 4.7: UML Class Model of a travel agency (UMLDesigner).

`xmi:type` is `uml:Association`. In ECore representation, the association relationship is perhaps more intuitive to read, because the two-way relationship is defined as an embedded XML node in both of the two `eStructuralFeatures` nodes. The first node defines the relationship from class `ServiceLevel` to the class `Membership` (resolved by the value of the `eType` Attribute). The opposing relationship is both mentioned by path in the first `eStructuralFeatures` node, but also defined itself as an `eStructuralFeatures` child node of the `Membership` class node.

`mel` Extractors for UML Class Diagrams

The `mel` extractors for UMLDesigner class diagrams and Eclipse Modelling Tools class diagrams comprise mostly simple `mel` declarations, so we do not discuss them in detail. The full programs for each are located in the Appendix in Figures A.3 and A.4 respectively.

Instead we will consider just the extraction of `Association` facts expressed as two `mel` declarations, shown in Figures 4.11 and 4.12. The interesting detail about these two declarations is that the bindings of the `target` attribute of each association are not all that different despite the distinct methods of referencing entities. One might expect that the extractor for ECore Models would need to resolve the entire path to determine the `target` of an association, however it can be resolved with a single attribute binding. This is because the regular expression selectors that `mel` supplies allow the user to easily extract

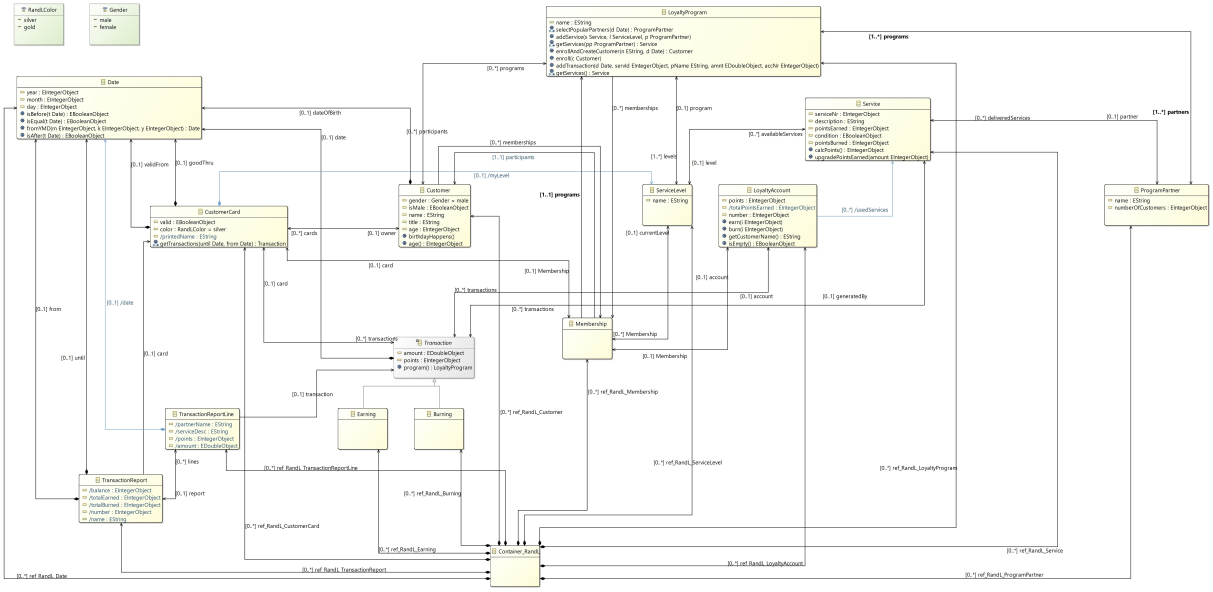


Figure 4.8: UML Class Model of a loyalty program of a fictional company. The Model is a recreation, using the Eclipse Modelling Tools, of the Royal and Loyal example from Warmer and Kleppe's book on the Object Constraint Language [68].

the `identifier`, which is needed to find the target class (the `targ` binding in Line 4 of Figure 4.12). Thus, we do not need to use the path operators to extract the `target` and are able to resolve it with a single binding similar to the resolution of the `target` for UMLDesigner Models. The similarity to the declaration for extraction associations from UMLDesigner Models can be seen in Figure 4.11, in which `type` Attributes in the `ownedEnd` nodes are used to resolve the bindings of `S` and `E` (Lines 6 and 8 of Figure 4.11).

Results of UML Class Diagram Extraction

Each `mel`-generated extractor was able to extract all the relevant facts from each UML Class diagram that we produced using each of the four tools: UMLDesigner, MagicDraw, Eclipse Modelling Tools, and ArgoUML. It is also worth noting the differences between the `mel` programs for UMLDesigner, MagicDraw, and ArgoUML are relatively small leading to very rapid development for the second-, third-, and fourth-developed extractors because we were being able to reuse most of the facts already defined.

Using the process described at the beginning of Section 4.1, we applied our `mel`-generated extractors to fifteen subject models, summarized in Table 4.4. For each of

```
. . .
<packagedElement xmi:type="uml:Class" xmi:id="F8K" name="Travel">
 . . .
</packagedElement>
. . .
<packagedElement xmi:type="uml:Class" xmi:id="2k8" name="Agency">
 . . .
</packagedElement>
. . .
<packagedElement xmi:type="uml:Association" xmi:id="C4M"
                 name="offers" memberEnd="NYM 4PO" navigableOwnedEnd="4PO">
  <ownedEnd xmi:id="NYM" name="agencys" type="2K8" association="C4M">
    <lowerValue xmi:type="uml:LiteralInteger" xmi:id="C4O"/>
    <upperValue xmi:type="uml:LiteralUnlimitedNatural" xmi:id="KMF" value="*"/>
  </ownedEnd>
  <ownedEnd xmi:id="4PO" name="offers" type="F8k" association="C4M">
    <lowerValue xmi:type="uml:LiteralInteger" xmi:id="CWM"/>
    <upperValue xmi:type="uml:LiteralUnlimitedNatural" xmi:id="EeC" value="*"/>
  </ownedEnd>
</packagedElement>
. . .
```

Figure 4.9: Snippet of the XMI representation of the UMLDesigner Class diagram shown in Figure 4.7, representing an `association` relationship. Identifiers have been abbreviated and non-referenced Attributes have been omitted.

```
. . .
  <eClassifiers xsi:type="ecore:EClass" name="ServiceLevel">
   . . .
    <eStructuralFeatures xsi:type="ecore:EReference" name="Membership"
        ordered="false" upperBound="-1" eType="#//Membership"
        eOpposite="#//Membership/currentLevel"/>
  </eClassifiers>
 . . .
  <eClassifiers xsi:type="ecore:EClass" name="Membership">
   . . .
    <eStructuralFeatures xsi:type="ecore:EReference" name="currentLevel"
        eType="#//ServiceLevel" eOpposite="#//ServiceLevel/Membership"/>
  </eClassifiers>
. . .
```

Figure 4.10: Snippet of the ECore representation of the Eclipse Modelling Tools Class diagram shown in Figure 4.8. Identifiers have been abbreviated and non-referenced Attributes have been omitted.

```
^Association(S,E) |-
    Class(S), Class(E),
    packagedElement{"xmi:id"["_(.*)"]:associationID,
                    "xmi:type"="uml:Association", name:label}
      ->[ownedEnd{type["_(.*)"]:S, aggregation!="composite"}
          ->[@lowerValue{mel.nexists(value) ? '0' > value:ownerLowerMult},
             @upperValue{mel.nexists(value) ? '*' > value:ownerUpperMult}],
         ownedEnd{type["_(.*)"]:E, aggregation!="composite"}
          ->[@lowerValue{mel.nexists(value) ? '0' > value:owneeLowerMult},
             @upperValue{mel.nexists(value) ? '*' > value:owneeUpperMult}]];
```

Figure 4.11: `mel` declaration for extracting `association` facts from a UML Class diagram generated with UMLDesigner.

```
Association(src, targ) |-
    eClassifiers{"xsi:type"="ecore:EClass", name:src}
        ->eStructuralFeatures{"xsi:type"="ecore:EReference",
                              containment!="true", name:srcLabel, eType[".*/(.*)"]:targ,
                              eOpposite[".*/(.*)"]:destLabel,
                              mel.nexists(lowerBound) ? '0' > lowerBound:lowerBound,
                              mel.nexists(upperBound) ? '1' >
                                  upperBound = "-1" ? '*' > upperBound:upperBound };
```

Figure 4.12: The `mel` declaration for extracting `association` facts from a UML Class diagram generated with the Eclipse Modelling Tools.

Modelling Tool	Name	# Classes	# Associations	# Entities	# Relationships
ArgoUML	Advent	45	42	177	218
	Zork	10	90	52	163
Eclipse Modelling Tools	Coffee Machine	11	7	14	35
	Java Language	9	25	10	63
	MakeItHappen	3	4	6	31
	Royal and Loyal	15	54	38	139
	Store	55	73	65	305
	XUml Compiler	61	118	70	214
MagicDraw	Alarmas	6	3	124	111
	MediaTeka	4	4	50	60
	Parking Lot	14	10	41	72
	Library	5	6	32	43
UMLDesigner	CLAY Engine	27	26	32	102
	Rennspur	17	17	94	123
	Travel Agency	8	16	43	55

Table 4.4: Summary of the UML Class diagrams considered in this study, showing the number of classes and associations (general associations, aggregations, and compositions) in each Model and the total number of entity and relationship facts extracted in the factbase.

the 15 Class diagrams used in this study Graphical representations of diagrams from the Models and their XMI representations can be found in the online repository[2]. Additionally, the graphical representations of the diagrams are included in the Appendix B.

We manually examined 20 Model elements randomly selected from each subject Model and verified that each element was correctly extracted in the factbase with the proper details and that none of the facts randomly selected from each extracted factbase were determined to be extraneous or incorrect in their details.

4.1.3 Simulink Block Diagrams

Simulink was considered due to its popularity as a modelling and code-generation tool that sees wide use in industry particularly in safety-critical systems and industries requiring strict adherence to specified standards [29]. Additionally, the inclusion of Simulink Block diagrams in the study improves its analysis of scope of applicability, because Simulink Models have the most distinct textual representation in that XML tags typically have no Attributes for referencing related nodes, instead referencing related nodes by its location in the XML tree structure.

Information to be Extracted

The information to be extracted from Simulink Block diagrams is shown in Table 4.5. We extract blocks which have many different types for example gain, signal generator, or subsystem blocks which contain nested diagrams. The two relationships we are interested in extracting are the flow of signals between blocks and the containment hierarchy of blocks that occurs when subsystem blocks comprise nested blocks.

Models Considered

The only tool considered for these diagrams is the MATLAB Simulink tool [48], as Simulink modelling notation is proprietary. Ten Simulink Models were used in the experiment. A single system of one of the Models considered is shown in Figure 4.13.

Analgous to how state chart diagrams allow for nested state machines, Simulink Block diagrams allow for nested *subsystem* blocks. An example of a subsystem block is the block labeled "Aircraft Dynamics Model" in Figure 4.13; the details of this subsystem block are

[2] https://github.com/Roshack/ModelsUsedWithmel

Table 4.5: Necessary facts for extraction from Simulink Block diagrams.

Entities	**attributes**
Blocks	name and type
Relationships	**attributes**
Block/port ownership	port name
Signal flow	signal label
Subsystem block/block ownership	

depicted in a separate Block diagram. A sample of the XML representation of the diagram shown in Figure 4.13 is shown in Figure 4.14. This XML snippet shows the signal flow from the `q, rad/sec` port in the `Aircraft Dynamics Model` subsystem to the `Controller` subsystem. To detect such signal flows `mel` must be able to refer to two children of a parent node that has no Attributes with which refer to it.

`mel` Extractor for Simulink Block diagram

The `mel` extractor for Simulink Block diagrams shown in Figure 4.15 demonstrates how the `mel path` operators can be used to denote relationships through a parent node with no Attributes. This is simply a result of the inherent meaning of the `path` when the right hand operand is a list, which denotes a collection of XML nodes that are all underneath the *same* ancestor/parent node. For example, the `signal` relationship on Line 6 of Figure 4.15 specifies that a `signal` relationship's parameters are bound to the string contents of two `P` nodes which have `Name` Attributes of `Src` and `Dest`. There exist many such tags in the XML document, so it is important that the parent operator can be used to specify that these two tags are underneath the same `Line` node. If applied to the XML fragment shown in Figure 4.14 this would extract the relationship between block `3` and `33`, but would not combine the values extracted from these `P` nodes with those extracted from other `P` nodes in the document, as they do not reside under the same (Attribute-free) `Line` tag.

Results of Simulink Block Diagram Extraction

A summary of the Simulink Models that we considered in this study can be seen in Table 4.6. For each of the 10 Block diagrams used in this study Graphical representations of diagrams from the Models and their XMI representations can be found in the online

Name	# Blocks	# Signal Flow	# Entities	# Relationships
ADC Quantization Algorithm	7	4	7	7
Air-Fuel Intake Dynamics	8	7	8	8
Aircraft Longitudinal Flight Control	64	54	64	69
Anti-Windup PID Control Example	9	6	9	12
Bouncing Ball Model	8	6	8	9
Component Based Modelling	14	8	14	14
Fault-Tolerant Fuel Control System	21	20	21	29
Intake Airflow Estimation and Closed-Loop Correction	24	25	24	32
Modeling an Anti-Lock Braking System (ABS)	14	14	14	24
PID Controller Tuning	41	33	41	67

Table 4.6: Summary of the Simulink block diagrams considered in this study, showsing the number of blocks and signals in each Model and the total number of entity and relationship facts extracted in the factbase.

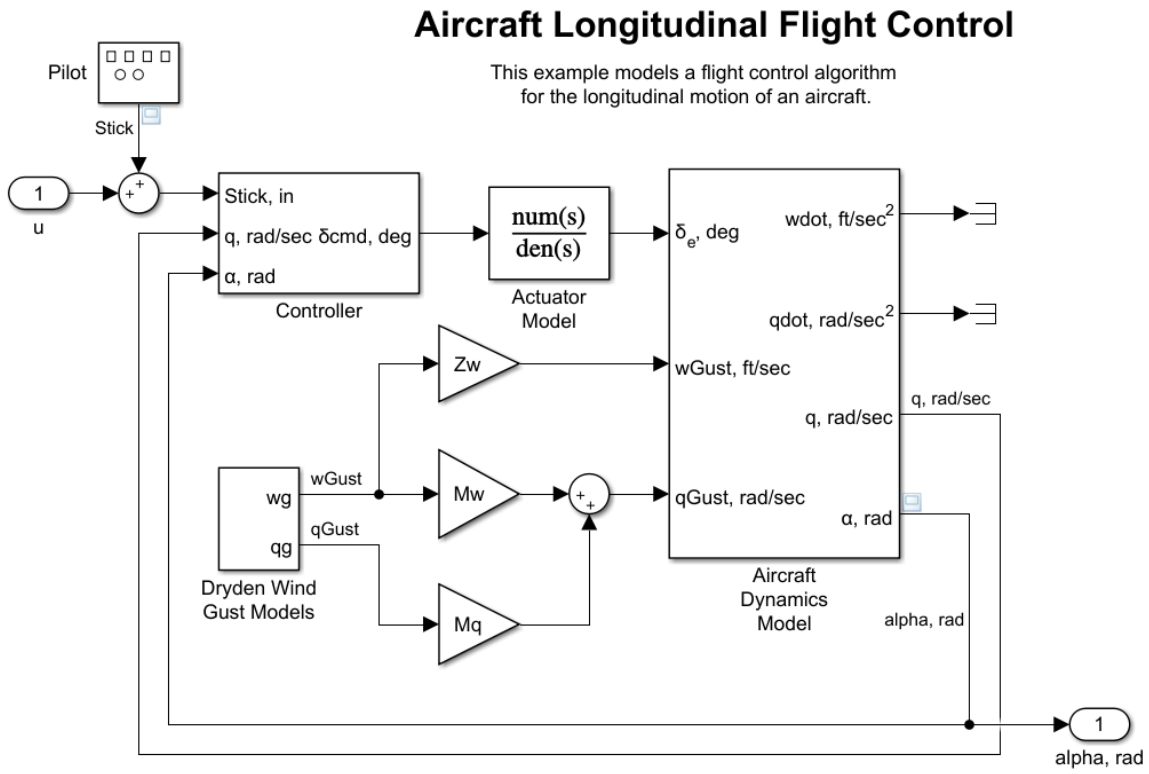


Figure 4.13: A system of a Simulink Model for a longitudinal flight control algorithm. The blocks with titles beneath them are subsystems for which an entire sub-Model is defined.

repository[3]. Additionally, the graphical representations of the diagrams are included in the Appendix B. Using the process described at the beginning of Section 4.1, we applied our `mel`-generated extractor to each Simulink Model and produced result sets without error. No facts considered from the Models were missing in the generated factbases, and the generated factbases did not include extraneous facts.

4.1.4 Arcadia Logical Architecture Diagrams

Arcadia Logical Architectures diagrams from Thales' Capella modelling tool were chosen for another distinct textual representation. Capella saves its Models in an XMI file that

[3] https://github.com/Roshack/ModelsUsedWithmel

```
. . .
 <Block BlockType="SubSystem" Name="Controller" SID="33">
   . . .
 </Block
 . . .
 <Block BlockType="SubSystem" Name="Aircraft Dynamics Model" SID="3">
 . . .
 </Block>
 . . .
 <Line>
  <P Name="Name">q, rad/sec</P>
  <P Name="Src">3#out:3</P>
  <P Name="Dst">33#in:2</P>
    . . .
 </Line>
. . .
```

Figure 4.14: Snippet of the XML representation of the Simulink Block diagram shown in Figure 4.13. Non-referenced Attributes have been omitted.

```
block(X) |- Block{BlockType:type, Name:name, SID:X}
             ->P{Name="Gain", mel.contents:gainLabel};
parent(P,C) |- Block{SID:P}->System{}->Block{SID:C};
port(B,P) |- Block{SID:B}->Port{}->[P{Name="Name", mel.contents:name},
                                    P{Name="PortNumber", mel.contents:P}];
signal(Src,Targ) |- Line{}->[P{Name="Src", mel.contents["(.*)#"]:Src},
                             P{Name="Dst", mel.contents["(.*)#"]:Targ},
                             @P{Name="Name", mel.contents:label}];
signal(Src,Targ) |- Line{}->[P{Name="Src", mel.contents["(.*)#"]:Src},
                             Branch{}->P{Name="Dst", mel.contents["(.*)#"]:Targ},
                             @P{Name="Name", mel.contents:label}];
```

Figure 4.15: `mel` extractor for Simulink Block diagrams.

Table 4.7: Necessary facts for extraction from Arcadia Logical Architecture diagrams.

Entities	**attributes**
Functions	name
Components	name, is actor, is human
Relationships	**attributes**
Data flow between functions	data label
Data flow between components	data label
Functions containing functions	
Components containing functions	

adheres to the OMG XMI standard 2.0 but is written using a custom metamodel defined for the tool.

Information to be Extracted

Arcadia Logical Architecture diagrams specify abstract components, functions, and data they communicate between them. As the Logical Architecture diagrams create an entire view of the logical behaviour of a system, they include actors in the system as components. Because of this, `Component` facts include attributes to specify whether or not they are an actor and if they are human, as shown in Table 4.7.

Models Considered

Four Arcadia Logical Architecture diagrams were considered for this part of the evaluation. One of the subject Models used is shown in Figure 4.16. In Arcadia Models, the entity types are mostly denoted by colour:

- The darker blue boxes are components
- The lighter blue boxes represent actors
  - If an actor has a stick figure symbol then it is also represents a human
- The green boxes represent functions
  - Function ownership is shown in other diagrams of the Architecture

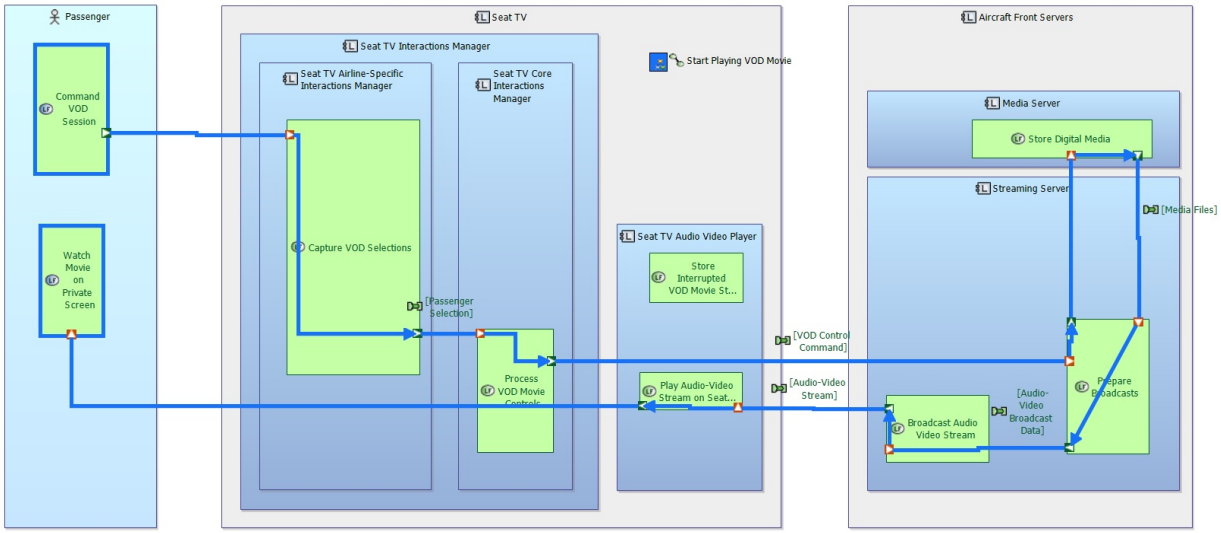


Figure 4.16: Arcadia Logical Architecture diagram for an in-flight entertainment system (Capella).

- The lines between functions and functions, and components and components, represents the flow of data
  - The green text beside a line is the data being sent

A sample of the XML representation of Arcadia diagrams can be found in Figure 4.17

`mel` Extractor for Arcadia Logical Architecture diagram

The `mel`-generated extractor for Arcadia Logical Architecture diagrams is shown in Figure 4.18 This program contains relatively short and small declarations, because Arcadia Models have a simple XMI representation and noes have identifying tag Attributes — calling for the type of identifier references and relational reference that `mel` excels at.

Results of Arcadia Logical Architecture Diagram Extraction

Due to the smaller number of subject Models for evaluating `mel` on Arcadia Logical Architecture diagrams, the correctness-testing process described at the beginning of Section 4.1

```
. . .
<ownedLogicalComponents
    xsi:type="capella.core.data.la:LogicalComponent"
    id="_JNwHUJY7Ed6rH5SGn-UjSg" name="Media Server">
  <ownedFunctionalAllocation
      id="9744f85d-326f-43fd-8b47-6a63de1d52c6"
      targetElement="#be9b5663-23ea-4413-abeb-3d5df84c93b8"
      sourceElement="#_JNwHUJY7Ed6rH5SGn-UjSg"/>
  . . .
</ownedLogicalComponents>
. . .
<ownedFunctions
    xsi:type="capella.core.data.la:LogicalFunction"
    id="be9b5663-23ea-4413-abeb-3d5df84c93b8"
    name="Store Digital Media">
  . . .
</ownedFunctions>
. . .
```

Figure 4.17: XML Fragment of the Model shown in Figure 4.16. Type Attributes have had their values truncated to fit the page.

Name	# Components	# Functions	# Dataflows	# Entities	# Relationships
Level Crossing Traffic Control	18	274	323	615	391
OCP Security Project	1	92	92	175	92
In-Flight Entertainment System	23	219	262	504	310
Zorro	1	41	29	71	29

Table 4.8: Summary of the Arcadia diagrams considered in this study, showing the number of components, functions, and data flows in each Model and the total number of entity and relationship facts extracted in the factbase.

```
absFunction(X) |- ownedFunctions{id:X, name:label};

absComponent(X) |- ownedLogicalComponents{id:X, name:label, actor:isActor,
                                          human:isHuman};

dataFlow(Out,In) |- ownedFunctionalExchanges{mel.nexists(exchangedItems) ? name
                                               > exchangedItems["#(.*)"]:dID,
                                            source["#(.*)"]:Out, target["#(.*)"]:In},
                    @ownedExchangeItems{id:dID, name:data};

dataFlow(Out,In) |- ownedLogicalComponents{id:Out}
                        ->ownedFeatures{id:ox, orientation="OUT"},
                    ownedLogicalComponents{id:In}
                        ->ownedFeatures{id:ix, orientation="IN"},
                    ownedComponentExchanges{name:data, source["#(.*)"]:ox,
                                            target["#(.*)"]:ix};

subFunction(P,C) |- ownedFunctions{id:P}->ownedFunctions{id:C};
compFunction(C,F) |- ownedFunctionalAllocation{sourceElement["#(.*)"]:C,
                                               targetElement["#(.*)"]:F};
```

Figure 4.18: `mel` program for extracting facts from an Arcadia Logical Architecture diagram.

was modified to select forty, instead of twenty, Model elements or facts for assessing correctness. This means that we randomly selected 40 elements (or all, if fewer than 40 were present) from each Model and checked for their existence in the factbase. We also then selected 40 random facts from the factbase and verified they were present in the Model with the appropriate Attributes. This process found the elements sampled from each Model were present in their corresponding factbases, and the facts sampled from each factbase were present in their corresponding Model. For each of the 4 Arcadia diagrams used in this study Graphical representations of diagrams from the Models and their XMI representations can be found in the online repository[4]. Additionally, the graphical representations of the diagrams are included in the Appendix B.

4.1.5 Feature Models

Feature Models were included in our assessment of `mel` because they are considerably different from the types of Models considered so far. The tool FeatureIDE version 3.6.2 [43, 40] is a well supported tool produced by FOSD researchers. FeatureIDE serializes Models according to its own XML format that does not adhere to any XMI standard, offering another unique XML representation for our assessments.

Information to be Extracted

The information to be extracted was the information about the features and the relationships between them. As such, the only entities extracted were features themselves, as shown in Table 4.9. Relationships between facts are either implicit in the Model (e.g., two features being alternative sub-features of the same parent feature are implicitly mutually exclusive) or explicit in the Model (e.g., a declared global constraint involving features that are not siblings).

Models Considered

Ten Feature Models were considered, one of which is shown in Figure 4.19. It is important to note the distinction between an `Or` group and an `Alternative` of group, where the former is an inclusive or and the latter is exclusive or of the parent node's child nodes. As

[4] https://github.com/Roshack/ModelsUsedWithmel

Table 4.9: Necessary facts for extraction from Feature Models.

Entities	**attributes**
Feature	is abstract, is mandatory, name
Relationships	**attributes**
Feature containment	
Mutual exclusion of features	
Mutual inclusion of features	
Implication	
Disjunction	
Conjunction	

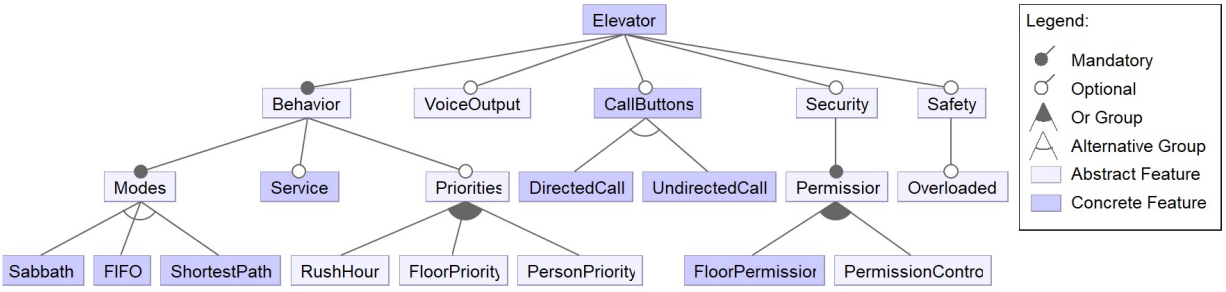


Figure 4.19: Feature Model diagram for an elevator system (FeatureIDE).

such, when extracting facts from a Feature Model, any features that are underneath the same `Alternative` must be considered to be mutually exclusive. Similarly, any features that are mandatory children of a group must be considered to be required together.

The XML representation that FeatureIDE uses mimics the tree-structure of the Feature Model exactly. This can be seen in Figure 4.20, which shows the top level `Elevator` feature and its five children. Because children nodes can be any of `feature`, `or` `and`, or `alt`, `mel` extractors can be verbose. However, the real cause for concern is the implementation of the cross-tree constraints.

Figure 4.21 demonstrates how cross-tree constraints are encoded in FeatureIDE's textual representation. This XML snippet represents two logical expressions:

$$\begin{aligned} DirectedCall &\implies ShortestPath \\ Behaviour &\implies (CallButtons \wedge DirectedCall) \vee (Elevator \wedge FIFO) \end{aligned}$$

```
. . .
  <and abstract="true" mandatory="true" name="Elevator">
    <and abstract="true" mandatory="true" name="Behavior">
      . . .
    </>
    <feature abstract="true" name="VoiceOutput"/>
    <alt name="CallButtons">
      . . .
    </alt>
    <and abstract="true" name="Security">
      . . .
    </and>
    <and abstract="true" name="Safety">
      . . .
    </and>
  . . .
```

Figure 4.20: Snippet of the XML representation of the Feature Model diagram shown in Figure 4.19. Non-referenced Attributes have been omitted.

The way these expressions are represented poses a problem for `mel`. Although `mel` can handle expressions with a finite depth of nesting, it is unable to effectively handle arbitrarily nested expressions. In order to handle expressions of this type, which effectively define the grammar for logical expressions, a `mel` program would need to implement a logical expression parser - of which `mel` is not capable as it is not intended to be a Turing-complete language. Because `mel` seeks to abstract the accidental complexity of Model extraction, it is just meant to be a language that allows the user to declare the relevant relationships between an XM* document and a corresponding desired factbase; `mel` is not meant to be a language for arbitrary computation. However, as all of the Models considered had no degree of nesting deeper than three we were able to write a `mel` extractor which could extract all of the constraints in the sample Models.

`mel` Extractor for Feature Model diagrams

The extractor that was written for Feature Models is quite long, due to requiring many alternative rules for resolving children features. As such the program is displayed in the Appendix as Figure A.5. The set of declarations that defines the relationship between `and` nodes and their children is shown in Figure 4.22. This declaration demonstrates how the presence of many alternative XML tag types to denote the same abstract meaning can potentially lead to a combinatorial explosion of declarations.

```
<rule>
  <imp>
    <var>DirectedCall</var>
    <var>ShortestPath</var>
  </imp>
</rule>
<rule>
  <imp>
    <var>Behavior</var>
    <disj>
      <conj>
        <var>CallButtons</var>
        <var>DirectedCall</var>
      </conj>
      <conj>
        <var>Elevator</var>
        <var>FIFO</var>
      </conj>
    </disj>
  </imp>
</rule>
```

Figure 4.21: Snippet of the XML representation of cross-tree constraints written in FeatureIDE.

Results of Feature Model Extracton

We applied `mel` to the ten Feature Models summarized in Table 4.10. While our `mel`-generated extractor was fully capable of extracting information from the Feature Tree, the extractor could only extract nested constraint expressions of finite depth. As our sampled Models had no constraints nested deeper than three levels, our `mel`-generated extractor that extracts constraints up to three levels deep was able to extract all of the facts from the sampled Models. Additionally, each of the facts randomly selected from each extracted factbase were present in the Model itself.

```
FeatureOf(A,B) |- and{name:A}->and{name:B};
FeatureOf(A,B) |- and{name:A}->alt{name:B};
FeatureOf(A,B) |- and{name:A}->or{name:B};
FeatureOf(A,B) |- and{name:A}->feature{name:B};
```

Figure 4.22: `mel` declarations for extracting children of `and` nodes in a FeatureModel.

Name	# Features	# Group	# Entities	# Relationships
Bike Configurator	54	12	55	154
Car	16	6	16	30
Desktop Searcher	16	8	22	32
EPL-AHEAD	12	4	23	43
Elevator	8	8	21	30
Hello World	4	2	6	8
Landing Gear	7	6	8	8
Poker	10	4	11	16
TankWar	31	11	37	62
Variable Characters	9	7	15	19

Table 4.10: Summary of the Feature Model diagrams considered in this study, showing the number of features and groups (`alternative`, `or`, or `general` groups) in each Mode, and the total number of entity and relationship facts extracted in the factbase.

4.2 Ease of Using `mel`

The second criterion of our evaluation of `mel` involved assessing our hypothesis that it is easier to create a fact extractor for a Model using `mel` than using other technologies. Our assessment comprises two studies. The first study compares a `mel`-generated extractor to an existing specialized extractor for Arcadia Logical Architecture Models built using Python, which was created previously for a separate project; the comparison criterion is succinctness of the code (as a proxy for ease of programming)[5]. The second study compares the time it takes for a user to create a fact extractor using `mel` versus the time it takes using the XQuery programming language [61]; the comparison criteria are succinctness of the code and the development time (both as proxies for ease of programming). The execution times of the programs was not considered as a criterion because it is in the order of milliseconds on all examples, and is not relevant to how a language eases the programmers task. In each case, the outputs of both programs were compared against each other to verify that they extracted the same facts. Additionally, we examined the output of the extractors developed by the subjects against their target Models to verify the correctness of their extractors. We sampled twenty random facts from each target Model and verified that they existed in the extracted factbase. We also examined twenty random facts in each extracted factbase and compared them to the corresponding Model to verify their existence and the values of their attributes.

4.2.1 `mel` Comparison to Custom Extractor.

This study assessed the brevity of a `mel` program compared to that of an existing special-purpose fact extractor for Capella Models that was developed for a previous project. We use the brevity of a programming language as a proxy for measuring a language's support for a programming task and the effort of programming. The latter extractor was developed using Python, which was chosen for the previous project because of its built-in library for parsing XML and its strong support for string processing. Both extractors were developed by the author of `mel` and this thesis. While times were not recorded, the development time of the `mel` extractor was considerably shorter; however, this comparison is entirely facile as the initial design of `mel` was built around generalizing the writing of this particular extractor - so by the time that `mel` was defined the extractor had already been conceived.

[5] We could not use development time as a comparison criterion because the Python extractor was pre-existing and the time taken to develop it had not been recorded.

Both extractors take as input an Arcadia Logical Architecture diagram generated by Capella [20] and output the set of facts detailed in Table 4.7.

The sizes of the resulting programs are provided in Table 4.12. The size of the `mel` program is an order of magnitude smaller than the Python program, even when we control for `mel's` automatic formatting of results by removing from the Python program the code responsible for formatting the output. This result is unsurprising: brevity is a natural side effect of most domain-specific languages. Still, the result is reported because a negative result was possible and would imply a failure in the design of the language.

4.2.2 Testing the Development Time of `mel` Programs.

This study evaluated `mel` with respect to the time it takes to create a fact extractor. Two user subjects were used, both of whom are experts in programming language theory. The user subjects shall henceforth be referred to as Subject A and Subject B. Neither subject was involved with the development of `mel`. We chose XQuery [61] to be the competing technology in this study because of its facilities for parsing XML and manipulating extracted values and its ease of use. Prior to the writing of this thesis, a conference paper on `mel` was published [22] which includes some evaluation by Subject A on two prior versions of `mel`. The three versions of `mel` (and corresponding `mint`) are version 1.0, version 1.1, and version 1.2 (which is the current version). We summarize the additions made by versions 1.1 and 1.2 in Table 4.11. The development of new versions of `mel` based on the results of prior studies is indicative of the design science research methodology [27] which was employed as part of this thesis.

Each evaluation was a set of tasks given to the subject. Each task was to create an extractor in both `mel` and XQuery for a specified Model. The subjects were given instructions to time their development of both extractors, as well as steps to follow to minimize favourable bias for either language. There were three steps to each experiment:

1. Examine the specified Model to determine the tags, relationships, and Attributes in the XML that were relevant to the facts they were asked to extract for the task.
2. Write their first extractor, timing their development time.
3. Write their second extractor, timing their development time.

In order to mitigate the likely bias that the second extractor for each Model type would be easier to write, the subjects were primarily asked to write their `mel`-generated extractor

first. Of the five tasks assigned to Subject A they were asked to write the XQuery extractor first in only one task. Similarly, of the four tasks given to Subject B they were asked to write the XQuery extractor first in only one task. This was so that if a favourable bias did exist it would be in XQuery's favour.

We first discuss the experimental setup and then discuss the results of the experiments in Sections 4.2.3 and 4.2.4.

Experiment Set One (`mel` 1.0)

The first set of experiments was performed by Subject A for the inclusion in a conference paper [22]. The subject was asked to create `mel` and XQuery fact extractors for relevant facts from two Model representations:

Task1: Arcadia Logical Architecture diagram (Capella) - Figure 4.16

- **Entities:** functions, components, data entities
- **Relationships:** data flows between functions

Task2: UML Class diagram (UMLDesigner) Figure 4.7

- **Entities:** classes, attributes
- **Relationships:** classes' attributes, associations, compositions
- **Attributes:** attributes' type, visibility, constness, multiplicity

For each Task, the subject first analyzed the XML to determine which tags were relevant to the extraction. Additionally for each of these tasks, the subject wrote the `mel` program first and the XQuery program second. It is possible, for any Task, creating and debugging the first program helped the subject gain a better understanding of the XML, easing the development of the second program.

Experiment Set Two (`mel` 1.1)

In the second set of experiments, Subject A was provided with a third Model and a new version of `mel` (version 1.1) to test.

Task3: UML StateMachine diagram (Rhapsody) Figure 4.1:

- **Entities:** state machines, regions, states
- **Relationships:** state hierarchy, transitions between states
- **Attributes:** transitions' trigger, guard condition, effects

In this task Subject, A was asked to write their XQuery program first and `mel` program second.

Experiment Set Three (`mel` 1.2)

In the third set of experiments Subject A wrote extractors for two additional Models and a second subject, Subject B, wrote extractors for those same two Models, as well as for the Models originally provided to Subject A in Tasks 1 and 3.

The two new models were a UML Class diagram in ECore format, produced with the Eclipse Modelling Tools, and a Simulink Block diagram. Due to the length of time that had passed since Subject A had used `mel` or XQuery, and the fact that Subject B had not used either language, both subjects were given a set of facts to first extract from a UML Class diagram as a warm-up for both languages. Once they had completed that task, they were given an additional Model that included more details and were asked to time how long it took them to modify their extractors to extract the two additional facts. The reasons for the warm-up and subsequent followup task were two-fold: first to help the Subjects to familiarize themselves with each language, and secondly to provide some cursory insight into how extensible programs of each language were. The Simulink Block diagram test was completed the same as the tests from the first three experiments with Subject A.

Warm-up: UML Class diagram (ECore) Figure B.14

- **Entities:** classes, attributes
- **Relationships:** classes' attributes, associations, compositions
- **Attributes:** attributes' type, visibility, constness, multiplicity, classes' being abstract or final

Task4: UML Class diagram (ECore) Figure 4.8

- **Entities:** methods

- **Relationships:** classes' methods
- **Attributes:** isDerived attribute for methods and isDerived attribute for fields

Task5: Simulink Block diagram Figure 4.13

- **Entities:** blocks, ports
- **Relationships:** signal flow between blocks
- **Attributes:** names of signals

Both subjects performed their warm-up task followed by Task 4 and then Task 5, at which point Subject A was finished. Subject B then completed a task with the same setup as Task 1 (Arcadia) above, and finished by completing Task 3 (StateMachine) from above. In each of these tasks, both subjects properly separated XML analysis time from extractor development. All tasks were performed with the creation of the `mel` program first, except for when Subject B completed Task 3 in which they wrote their XQuery extractor first as Subject A was originally asked to write their XQuery extractor first for the same Model in the second experiment.

4.2.3 Succinctness of `mel`

In general, `mel` saw favourable performance over XQuery with respect to succinctness. The results shown in Table 4.12 demonstrate this.

Table 4.12: Program Sizes of Extractors, where numbers with a single underline are sizes of `mel` 1.1 programs and numbers with a double underline are sizes of `mel` 1.0 programs. All other numbers are sizes of `mel` 1.2 programs.

			Arcadia	UMLDesigner	ECore	StateChart	Simulink	Total
Subject A	Lines	`mel`	6	38	36	31	52	172
		XQuery	33	47	36	39	38	193
	Words	`mel`	58	143	208	204	223	836
		XQuery	115	207	277	178	312	1089
	Chars	`mel`	434	1482	1709	1630	1618	6873
		XQuery	1122	2016	2515	1763	2623	10039
Subject B	Lines	`mel`	9	N/A	23	26	11	69
		XQuery	38	N/A	83	77	45	243
	Words	`mel`	22	N/A	70	60	35	187
		XQuery	97	N/A	282	208	119	706
	Chars	`mel`	493	N/A	1358	1348	616	3815
		XQuery	1175	N/A	3061	2547	1056	7839

For each program written by Subject B, the `mel`-generated extractor was considerably shorter than the XQuery program in terms of numbers of lines, words, and characters. The results for Subject A are slightly more mixed in terms of numbers of lines and words; but in total character count (including whitespace characters), Subject A's `mel` programs are each more succinct than their XQuery counterparts.

Inspection of Subject A's programs suggests that the main reason their `mel` programs had similar or even larger number of lines and words is due to stylistic spacing choices taken by Subject A. For their own reasons of readability, Subject A chose to separate most tokens by spaces, increasing total word and character count. Additionally, Subject A chose to place most clauses on their own line and also placed closing square brackets on their own line when they closed a collection of tags that served as the right-hand operand to a path operator. These stylistic choices are important considerations in evaluating the succinctness of `mel` as the Subject was not instructed to do this, suggesting that they did it to improve readability for themselves. Because readability directly affects the usability of a programming language, the increased length due to Subject A's style choices should

not be ignored as inconsequential to program length, as without them the programs may have been harder to write for the Subject.

Even with the stylistic choices made by Subject A, each `mel` program still has fewer total lines than their XQuery counterparts other than Subject A's ECore programs, which have equal number of lines, and Subject A's Simulink programs, in which the `mel` program is larger than the XQuery program. Totalling the line counts for each Subject shows that Subject A's `mel` programs were an average of 11% lines fewer than their XQuery counterparts, while Subject B's `mel` programs were an average of 71% lines fewer than their XQuery counterparts.

The word counts of the Subjects' programs show similar results, with each `mel` program having fewer total words than its corresponding XQuery program, except for Subject A's StateChart programs. Totalling the word counts for each Subject shows that Subject A's `mel` programs were an average of 23% words fewer than their XQuery counterparts, while Subject B's `mel` programs were an average of 73% words fewer than their XQuery counterparts.

Lastly, the character counts weigh heavily in favour of `mel`, with not a single XQuery program taking fewer characters than its `mel` counterpart. Totalling the character counts for each Subject shows that Subject A's `mel` programs were an average of 31% characters fewer than their XQuery counterparts, while Subject B's `mel` programs were an average of 51% characters fewer than their XQuery counterparts.

There are a few potential reasons for the differences in program sizes. The most likely reason is that there are several cases where `mel` hides the accidental complexity of searching and retrieving data from the XM* document that matches relational declarations, where XQuery does not. One example of this, seen repeatedly in both Subjects' programs, is in the resolutions of hierarchical structures of nodes. Processing relationships between specified nodes in a hierarchical structure typically required at least one for loop, if not nested for loops in the corresponding XQuery program. This repetitive search and retrieval of desired nodes from the XM* document is the type of accidental complexity that `mel` seeks to hide from the user. In a `mel` program, the user need not worry about *how* to resolve the relationships they are interested in, but simply state what those relationships are. In fact, resolving any relationship between two nodes in XQuery demonstrates this accidental complexity. In order to search for pairs of nodes that share common Attribute values the user must again write explicit for loops that iterate over the possible nodes and produce results for those that match the desired relationship. Once again, `mel` resolves these relationships implicitly for the user, who needs only state the relationship itself.

4.2.4 Development Time of `mel` Extractors

Table 4.13: Development Time of Extractors. Time in bold denotes the extractor which was written first by the given subject for the Model type.

Model	Subject A		Subject B	
	`mel` Time	XQuery Time	`mel` Time	XQuery Time
Arcadia	**46m**	75m	**22m**	12m
UMLDesigner Class Diagram†	**53m**	43m	N/A	N/A
ECore Class Diagram‡	**6m 15s**	8m 3s	**7m**	11m
StateChart	30m	**54m**	22m	**58m**
Simulink	**29m 33s**	30m 54s	**45m**	41m
Total	164m 48s	210m 57s	96m	122m

† For this task Subject A forgot to analyze the XML before writing extractors, as such the `mel` time is conflated with the XML deduction time.
‡ The task involving ECore Class diagrams was not the development of the entire extractor, but rather the addition of two fact declarations to the extractors that the Subjects had previously developed.

Table 4.13 shows the development time taken by each Subject to create each extractor. Subject A spent less time writing their extractors in `mel` than in XQuery for four of the five tasks given to them. Of the four tasks that Subject B completed, they spent less time on their `mel` programs than their XQuery programs in two tasks, and vice versa on the other two. However, there are some details of note about the tasks in which Subjects took longer to write their `mel` programs than their XQuery programs.

Subject A forgot to spend time analyzing the XML structure before beginning development for their `mel`-generated extractor for UML Class diagrams produced with UMLDesigner. Given that Subject A recorded their XML deduction time for Arcadia Logical Architecture diagrams and StateChart diagrams as 26 minutes and 33 minutes respectively, it is reasonable to assume that the fact that it took 10 minutes longer for them to develop their `mel` extractor for UMLDesigner Models than their XQuery program was at least partly due to time spent interpreting the XML.

Subject B provided their thoughts on why their `mel` program for Arcadia Logical Architecture diagrams took much longer to develop than their XQuery program: (1) they forgot the semantics of compound clauses and had to go review the documentation they

were provided, and (2) they misspelled an XML reference in their program. Two possible causes of Subject B's first suggested slowdown could be due to the learning curve with a new language or it could indicate that the behaviour of compound clauses in `mel` are unintuitive or difficult to work with. In the case of Subject B's second suggested slowdown, `mint` actually includes a feature to help debug misspelled XML references, however the Subject was unaware of this feature and missed it entirely. The feature in question produces a colourful warning when an XML reference clause produces zero results, suggesting that the programmer may have misspelled something. The warnings `mint` produce are printed to the standard error stream, but are printed before the program output is printed to standard output. Because the warnings were printed before the output of the program Subject B never noticed them. Had Subject B been aware of `mint's` warning features, they could have deliberately checked for any warnings, which they believe would have saved them time.

Overall, both subjects spent less total time developing their `mel` programs than their XQuery programs. Subject A spent just under 165 minutes developing all of their `mel` programs and just under 211 minutes developing all of their XQuery programs. Thus, on average Subject A spent roughly 21% less time on developing their `mel` programs. Similarly, Subject B spent 96 minutes developing their `mel` programs and 122 minutes developing their XQuery programs for an average of 21% less time spent developing their `mel` programs. Also, it is not insignificant that users spent less time on average developing `mel` programs than time on developing XQuery programs, despite the fact that the majority of the tasks were biased in favour of XQuery because the Subjects wrote their `mel` programs first. However, we must also consider the possibility that the learning effort exerted in the first task left each Subject with less energy to expend on the second task, potentially leading to slower development of the second extractor.

There are a few potential reasons for the differences in development times. Once again, we believe that efficiencies in development time offered by `mel` are primarily the result of the way `mel` hides accidental complexities from the user. Additionally, both of our Subjects described particular issues in debugging mistakes in XQuery programs in contrast to `mel`. Subject A specifically mentioned that the optional-clauses feature of `mel` were particularly useful in debugging, as they could toggle clauses on/off easily to find the mistake that was causing their declaration to produce incorrect results. In contrast, while debugging XQuery programs Subject A had a more difficult time factoring out their for loops into let bindings to isolate errors. Subject A also mentioned that `mel` excels over XQuery at resolving relationships between cross-tree nodes: that is, resolving relationships between nodes with matching Attribute values regardless of their location in the XM* document — due to how `mel` hides the accidental complexity of walking the tree from the user. Subject

B also expressed the same belief, however they characterized this as `mel` being easier at expressing joins. Again, a join in XQuery would take the form of a for loop wherein the programmer resolves the join's relationships themselves, an explicit resolution of the accidental complexity of extracting relational data from an XM* document.

Table 4.11: A summary of the features added in versions 1.1 and 1.2 (current) of `mel` (and `mint`).

Version Number	Features Added
Version 1.1	Added warning messages to `mint` when: 1. a declaration reference refers to an undeclared name 2. no instances of an Attribute name referenced in an XML reference are found in the corresponding XML document 3. a declaration produced zero facts.
Version 1.2	• Introduced the path operators, deprecating the `mel.parent` and `mel.ancestor` functions† • Introduced constraint clauses • Introduced regular-expressions for use with Attribute modifiers, which previously matched only strings between a user-defined prefix and suffix • Introduced the like operator (∼=) • Introduced single-quote string literals and the ability to bind attributes to string literals • Introduced the ternary operator

† — These functions are still present in the `mel` grammar shown in Figure 3.25, but not discussed in Chapter 3. This is because these functions are deprecated in favour of the path operators. An application of `mel.parent` or `mel.ancestor` behave the same as a single use of the `parent` or `ancestor` operators respectively.

Chapter 5

Conclusions

This chapter discusses the contributions made in this thesis, as well as the limitations of the work, and finally the possibilities of future work.

5.1 Contributions

This thesis provides as its primary contributions the development of the Model Extraction Language `mel` and its corresponding interpreter `mint`. As a language `mel` has been used to extract facts from UML Class and StateMachine diagrams, Arcadia Logical Architecture diagrams, Simulink Block diagrams, and Feature Models. Additionally, the Models analyzed came from a wide variety of tools with varying XM* schemata which demonstrates a wider applicability of `mel`. Evaluations show promising results with respect to the applicability of `mel` to Models represented in XM*; and to `mel`'s ability to ease the development of fact extractors. Experimental results found that `mel` was at least as effective as a language for extracting information from XML documents as the W3C recommended tool XQuery. Additionally, on average, the written `mel` programs were shorter and took less development time than their XQuery counterparts.

5.2 Threats and Limitations

Although evaluations of `mel` produced generally positive results, there are some limitations to the language worth noting and threats to the validity of the experimental results to discuss.

The one notable limitation of `mel` as a language was found when writing an extractor for Feature Models. While the facts represented within the feature tree did not pose a problem to `mel`, the arbitrary cross-tree constraints did. Due to the fact that the cross-tree constraints took the form of arbitrarily nested logical expressions, `mel` was unable to resolve any constraint to a fact. The `mel` extractor written was able to resolve constraints so long as they were limited to a depth of one. Although this is a limitation of `mel`, it is outside of the scope of the language. The arbitrarily nested constraints are written in a way that would require the extractor to simulate a recursive parser for logical expressions. Since `mel`, much like Datalog which it is influenced by, is not a Turing-complete language it cannot achieve such behaviour.

The most notable threat to the evaluation is that the evaluation of `mel's` ability to ease extractor development time was performed by only two subjects on a combined total of Five Models. This small sample size could mean that `mel's` performance can be explained by statistical noise rather than by the features of the language. Additionally, both subjects are personal acquaintances of the author of this thesis which may have subconsciously biased their evaluation. It is worth noting, however, that both subjects are academics and would not intentionally bias the results of the experiment.

5.3 Future Work

Future work extending this thesis could include, but is not limited to, (1) extending the features of `mel` to support more Model representations: more XML representations, as in the constraints of Feature Models, or generalizing the back-end of `mel` so that XML reference and path reference clauses can be dispatched to other representations as well. (2) Extending the evaluations of `mel` through applying it to additional Model types, Model examples, industrial case studies, and the performing of a full user study.

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Appendix A

Extra `mel` Programs

A.1 `mel`-Generated Extractors for UML Class diagrams

```
Class(X) |- packagedElement{"xmi:type"="uml:Class", name:label, "xmi:id":X,
                            mel.nexists(ID)};

Enum(X) |- packagedElement{"xmi:type"="uml:Enumeration", name:label, "xmi:id":X,
                          mel.nexists(ID)};

EnumValues(E,V) |- packagedElement{"xmi:type"="uml:Enumeration", name:enum, "xmi:id":E}
                    ->ownedLiteral{"xmi:id":V, name:enumValue, value:value};

InheritsFrom(Parent,Child) |- packagedElement{"xmi:id":Child}
                              ->generalization{general:Parent};

Interface(X) |- packagedElement{"xmi:type"="uml:Interface", name:name, "xmi:id":X,
                              mel.nexists(ID)};

Field(X) |- packagedElement{"xmi:type"="uml:Class"}
             ->ownedAttribute{"xmi:type"="uml:Property", "xmi:id":X, name:label,
                       visibility:visiblity, isReadOnly:const, isStatic:static,
                       type:typeID, mel.exists(type), mel.nexists(association),
                       mel.nexists(ID)},
               @packagedElement{"xmi:id":typeID, name:type};

Field(X) |- packagedElement{"xmi:type"="uml:Class"}
             ->ownedAttribute{"xmi:type"="uml:Property", "xmi:id":X, name:label,
                       visibility:visiblity,  isReadOnly:const,
```

```
                        mel.nexists(type), mel.nexists(association),
                        mel.nexists(ID)}
                  ->type{href["#%"]:typeID},
                packagedElement{"xsi:type"="uml:DataType", "xmi:id":typeID, name:type};

Field(X) |- packagedElement{"xmi:type"="uml:Class"}
              ->ownedAttribute{"xmi:type"="uml:Property", "xmi:id":X, name:label,
                        visibility:visiblity, isReadOnly:const,
                        mel.nexists(type), mel.nexists(association),
                        mel.nexists(ID)}
                ->type{}=>referenceExtension{referentPath[".*::([^:]*)$"]:type};

FieldOf(C,A) |- packagedElement{"xmi:type"="uml:Class", "xmi:id":C, mel.nexists(ID)}
                        ->ownedAttribute{"xmi:id":A, mel.nexists(association)};

Method(X) |- ownedOperation{"xmi:id":X, name:name, visibility:visibility,
                            mel.nexists(ID)}
                ->@ownedParameter{"xmi:type"="uml:Parameter", direction="return",
                                  name:returnName, type:TID},
            @packagedElement{"xmi:type"="uml:Class", name:returnType, "xmi:id":TID};

MethodOf(Class, Method) |- packagedElement{"xmi:id":Class, mel.nexists(ID)}
                                ->ownedOperation{"xmi:id":Method},
                          Class(Class), Method(Method);


Parameter(X) |- ownedParameter{"xmi:type"="uml:Parameter", "xmi:id":X, name:name,
                                type:TID, direction!="return", mel.nexists(ID)},
                @packagedElement{"xmi:type"="uml:Class", name:type, "xmi:id":TID};

ParameterOf(Fn,P) |- ownedOperation{"xmi:id":Fn}->ownedParameter{"xmi:id":P},
                     Method(Fn), Parameter(P);

Composition(Owner,Ownee) |-
  packagedElement{"xmi:id":Owner}
    ->ownedAttribute{"xmi:id":ownerRelID, "xmi:type"="uml:Property", name:ownerLabel,
                     association:AID, aggregation="composite"}
      =>[@lowerValue{value:ownerLowerMult}, @upperValue{value:ownerUpperMult}],
  packagedElement{"xmi:id":Ownee}
    ->ownedAttribute{"xmi:id":owneeRelID, "xmi:type"="uml:Property",
                     name:owneeLabel, association:AID}
      =>[@lowerValue{value:owneeLowerMult}, @upperValue{value:owneeUpperMult}],
  packagedElement{"xmi:type"="uml:Association", "xmi:id":AID, name:compLabel},
  ownerRelID!=owneeRelID;

```

```
71
72  ^Composition(Owner,Ownee) |-
73    Class(Owner){label:ownerClass},
74    Class(Ownee){label:owneeClass},
75    packagedElement{"xmi:type"="uml:Class", "xmi:id":Owner}
76      ->ownedAttribute{"xmi:type"="uml:Property", name:owneeLabel, type:Ownee,
77                       aggregation="composite", association:AID}
78        =>[@lowerValue{value:owneeLowerMult}, @upperValue{value:owneeUpperMult}],
79    packagedElement{"xmi:type"="uml:Association", "xmi:id":AID}
80      =>[@lowerValue{value:ownerLowerMult}, @upperValue{value:ownerUpperMult}];
81
82  ^Association(Owner,Ownee) |-
83    packagedElement{"xmi:id":Owner}
84      ->ownedAttribute{"xmi:id":ownerRelID, "xmi:type"="uml:Property", name:ownerLabel,
85                       association:AID, aggregation!="composite"}
86        =>[@lowerValue{value:ownerLowerMult}, @upperValue{value:ownerUpperMult}],
87    packagedElement{"xmi:id":Ownee}
88      ->ownedAttribute{"xmi:id":owneeRelID, "xmi:type"="uml:Property",
89                       name:owneeLabel, association:AID}
90        =>[@lowerValue{value:owneeLowerMult}, @upperValue{value:owneeUpperMult}],
91    Class(Owner), Class(Ownee),
92    packagedElement{"xmi:type"="uml:Association", "xmi:id":AID, name:assocLabel},
93    ownerRelID!=owneeRelID;
94
95
96  ^Association(Owner,Ownee) |-
97    packagedElement{"xmi:type"="uml:Class", "xmi:id":Owner}
98      ->ownedAttribute{"xmi:type"="uml:Property", name:owneeLabel, type:Ownee,
99                       aggregation!="composite", association:AID}
100       =>[@lowerValue{value:owneeLowerMult}, @upperValue{value:owneeUpperMult}],
101   packagedElement{"xmi:type"="uml:Association", "xmi:id":AID}
102     =>[@lowerValue{value:ownerLowerMult}, @upperValue{value:ownerUpperMult}];
```

Figure A.1: `mel` program for extracting facts from UML Class diagrams generated with the MagicDraw tool.

```
Class(X) |- "UML:Class"{"xmi.id":X, name:label, visibility:vis, isAbstract:abstract};

Field(X) |- "UML:Attribute"{"xmi.id":X, name:label, visibility:vis}
                =>@"UML:MultiplicityRange"{lower:lowerMultr, upper:upperMult};

FieldOf(C,F) |- "UML:Class"{"xmi.id":C}=>"UML:Attribute"{"xmi.id":F};

Method(X) |- "UML:Operation"{"xmi.id":X, name:label, visibility:vis,
                             isAbstract:abstract};

MethodOf(C,M) |- "UML:Class"{"xmi.id":C}=>"UML:Operation"{"xmi.id":M};

Param(X) |- "UML:Parameter"{"xmi.id":X, name:label, kind!="return"}
                ->"UML:Parameter.type"{}
                    ->"UML:Class"{"xmi.idref":classType},
            Class(classType){label:type};

ParamOf(M,P) |- "UML:Operation"{"xmi.id":M}=>"UML:Parameter"{"xmi.id":P};

SuperClass(Parent,Child) |-
    "UML:Generalization"{}
        ->["UML:Generalization.child"{}->"UML:Class"{"xmi.idref":Child},
          "UML:Generalization.parent"{}->"UML:Class"{"xmi.idref":Parent}];


Association(A,B) |-
  "UML:Association"{name:label}
    =>["UML:AssociationEnd"{"xmi.id":aEndID, name:aMult, aggregation!="composite"}
        =>"UML:Class"{"xmi.idref":A},
      "UML:AssociationEnd"{"xmi.id":bEndID, name:bMult, aggregation!="composite"}
        =>"UML:Class"{"xmi.idref":B}],
  aEndID!=bEndID;

$Composition(Owner,Ownee) |-
    "UML:Association"{name:label}
        =>["UML:AssociationEnd"{name:ownerMult, aggregation="composite"}
              =>"UML:Class"{"xmi.idref":Owner},
           "UML:AssociationEnd"{name:owneeMult, aggregation!="composite"}
              =>"UML:Class"{"xmi.idref":Ownee}];
```

Figure A.2: `mel` program for extracting facts from UML Class diagrams generated with the ArgoUML tool.

```
Class(X) |- packagedElement{"xmi:type"="uml:Class", name:label, "xmi:id"["_(.*)"]:X};

Field(X) |- ownedAttribute{name:label,"xmi:id"["_(.*)"]:X}
                ->[lowerValue{mel.nexists(value) ? '0' > value:multLower},
                   upperValue{value:multUpper},
                   type{href["#(.*)"]:type}];

enum(X) |- packagedElement{"xmi:type"="uml:Enumeration", "xmi:id":X, name:name};

enumValues(E,V) |-  packagedElement{"xmi:type"="uml:Enumeration", "xmi:id":E}
                        ->ownedLiteral{"xmi:id":V, name:label}
                            ->specification{"xmi:type"[".*:(.*)"]:type, value:value};

.typeOf(A,B) |- ownedAttribute{type:conn, name:label,"xmi:id"["_(.*)"]:B},
                packagedElement{"xmi:id":conn, name:A};

Field(X) |- ownedAttribute{name:label,"xmi:id"["_(.*)"]:X}
                ->[lowerValue{value:multLower}, upperValue{value:multUpper}],
            typeOf(type,X);

FieldOf(C,A) |- packagedElement{"xmi:type"="uml:Class", "xmi:id"["_(.*)"]:C}
                    ->ownedAttribute{"xmi:id"["_(.*)"]:A};

^Association(S,E) |- Class(S), Class(E),
        packagedElement{"xmi:id"["_(.*)"]:associationID,
                        "xmi:type"="uml:Association", name:label}
          ->[ownedEnd{type["_(.*)"]:S, aggregation!="composite"}
          ->[@lowerValue{mel.nexists(value) ? '0' > value:ownerLowerMult},
             @upperValue{mel.nexists(value) ? '*' > value:ownerUpperMult}],
             ownedEnd{type["_(.*)"]:E, aggregation!="composite"}
                ->[@lowerValue{mel.nexists(value) ? '0' > value:owneeLowerMult},
                   @upperValue{mel.nexists(value) ? '*' > value:owneeUpperMult}]];

^Composition(S,E) |- Class(S), Class(E),
        ownedEnd{"xmi:id":SID, type["_(.*)"]:S, name:ownerRoleName},
        ownedEnd{"xmi:id":EID, type["_(.*)"]:E, name:owneeRoleName,
                 aggregation="composite"},
        packagedElement{"xmi:id"["_(.*)"]:compositionID,
                        "xmi:type"="uml:Association", name:label}
          ->[ownedEnd{type["_(.*)"]:S}, ownedEnd{type["_(.*)"]:E,
                      aggregation="composite"}],
        @ownedEnd{"xmi:ID":SID}
            ->[lowerValue{value:ownerLowerMult}, upperValue{value:ownerUpperMult},
               lowerValue{value:owneeLowerMult}, upperValue{value:owneeUpperMult}];
```

Figure A.3: `mel` program for extracting facts from UML Class diagrams generated with UMLDesigner.

```
class(X) |-
    eClassifiers{"xsi:type"="ecore:EClass", name:X,
                 mel.exists(abstract) ? abstract > 'false':isAbstract,
                 mel.exists(interface) ? abstract > 'false':isInterface};

memberOf(C,A) |- eClassifiers{"xsi:type"="ecore:EClass", name:C}->
                    eStructuralFeatures{"xsi:type"="ecore:EAttribute",
                                        name:A, eType[".*/(.*)"]:type};

method(M) |- eOperations{name:M, eType[".*/(.*)"]:type};

enum(X) |- eClassifiers{"xsi:type"="ecore:EEnum", name:X};

enumValues(E,V) |-  eClassifiers{"xsi:type"="ecore:EEnum", name:E}
                      ->eLiterals{name:V, mel.exists(value) ? value > '0':value};

parameterOf(M,P) |- eOperations{name:M}->
                     eParameters{name:P, eType[".*/(.*)"]:paramType};

methodOf(C,M) |- eClassifiers{"xsi:type"="ecore:EClass", name:C}->
                    eOperations{name:M, eType[".*/(.*)"]:type};

superClass(Parent,Child) |- eClassifiers{"xsi:type"="ecore:EClass", name:Child,
                                         eSuperTypes[".*/(.*)"]:Parent},
                            class(Parent);

association(src, targ) |-
    eClassifiers{"xsi:type"="ecore:EClass", name:src}
        ->eStructuralFeatures{"xsi:type"="ecore:EReference",
                              containment!="true", name:srcLabel,
                              eType[".*/(.*)"]:targ, eOpposite[".*/(.*)"]:destLabel,
                              mel.nexists(lowerBound) ? '0' > lowerBound:lowerBound,
                              mel.nexists(upperBound) ? '1' >
                                upperBound = "-1" ? '*' > upperBound:upperBound };

composition(src, targ) |-
    eClassifiers{"xsi:type"="ecore:EClass", name:src}
        ->eStructuralFeatures{"xsi:type"="ecore:EReference",
                              containment="true", name:srcLabel,
                              eOpposite[".*/(.*)"]:destLabel, eType[".*/(.*)"]:targ,
                              mel.nexists(lowerBound) ? '0' > lowerBound:lowerBound,
                              mel.nexists(upperBound) ? '1'
                                > upperBound = "-1" ? '*' > upperBound:upperBound };
```

Figure A.4: `mel` program for extracting facts from UML Class diagrams generated with the Eclipse Modelling Tools.

A.2 `mel`-Generated Extractor for Feature Models

```
Feature(X) |- struct{}=>feature{abstract:isAbstract, mandatory:isMandatory, name:X};
Feature(X) |- and{abstract:isAbstract, mandatory:isMandatory, name:X};
Feature(X) |- or{abstract:isAbstract, mandatory:isMandatory, name:X};
Feature(X) |- alt{abstract:isAbstract, mandatory:isMandatory, name:X};

FeatureOf(A,B) |- and{name:A}->and{name:B};
FeatureOf(A,B) |- and{name:A}->alt{name:B};
FeatureOf(A,B) |- and{name:A}->or{name:B};
FeatureOf(A,B) |- and{name:A}->feature{name:B};

FeatureOf(A,B) |- alt{name:A}->and{name:B};
FeatureOf(A,B) |- alt{name:A}->alt{name:B};
FeatureOf(A,B) |- alt{name:A}->or{name:B};
FeatureOf(A,B) |- alt{name:A}->feature{name:B};

FeatureOf(A,B) |- or{name:A}->and{name:B};
FeatureOf(A,B) |- or{name:A}->alt{name:B};
FeatureOf(A,B) |- or{name:A}->or{name:B};
FeatureOf(A,B) |- or{name:A}->feature{name:B};

^MutuallyExclusive(A,B) |- Feature(A), Feature(B), A!=B,
                           alt{name:parent},
                           FeatureOf(parent,A), FeatureOf(parent,B);

^RequiredTogether(A,B) |- Feature(A){isMandatory:M}, Feature(B){isMandatory:M},
                          M='true', A!=B, and{name:parent},
                          FeatureOf(parent,A), FeatureOf(parent,B);

Implies(A,B) |- imp{}->[var{mel.contents:A}, var{mel.contents:B}], A!=B;
Disjoint(A,B) |- disj{}->[var{mel.contents:A}, var{mel.contents:B}], A!=B;
Conjoint(A,B) |- conj{}->[var{mel.contents:A}, var{mel.contents:B}], A!=B;
```

Figure A.5: `mel` program for extracting facts from Feature Model diagram generated with FeatureIDE.

A.3 `mel` and XQuery programs written by Subject A

```
function(id) |- ownedFunctions { id: id, name: name };
component(id) |- ownedSystemComponents { id: id, name: name };
dataFlow(from, to) |-
    ownedFunctionalExchanges { source["#%"]: source, target["#%"]: target,
                               name: name },
    parent(inputs { id: target, name: inputName },
           ownedFunctions { id: from, name: inputFunction }),
    parent(outputs { id: source, name: outputName },
           ownedFunctions { id: to, name: outputFunction });
```

Figure A.6: `mel` program written by Subject A for completion of Task 1 as described in Section 4.2.2. Some additional line breaks have been added to allow the program to fit on the page.

```
xquery version "3.1";

for $doc in doc("db/inflight.melodymodeller")
let $functions :=
    for $fn in $doc//ownedFunctions
    return <function id="{ $fn/@id }" name="{ $fn/@name }" />
let $components :=
    for $component in $doc//ownedSystemComponents
    return <component id="{ $component/@id }" name="{ $component/@name }" />
let $functionDataflow :=
    for $xchg in $doc//ownedFunctionalExchanges
    let $targetId := substring($xchg/@target, 2)
    let $sourceId := substring($xchg/@source, 2)
    for $fromOwner in $doc//ownedFunctions
    where $fromOwner/inputs/@id = $targetId
    order by $fromOwner/@id
    for $toOwner in $doc//ownedFunctions
    where $toOwner/outputs/@id = $sourceId
    order by $toOwner/@id
    for $result in (<functionDataflow
        id="{ $xchg/@id }"
        name="{ $xchg/@name }"
        from="{ $fromOwner/@id }"
        fromName="{ $fromOwner/@name }"
        to="{ $toOwner/@id }"
        toName="{ $toOwner/@name }" />)
    return $result[not(.=preceding-sibling::functionDataflow)]

return <data>
    { $functions }
    { $components }
    { $functionDataflow }
    </data>
```

Figure A.7: XQuery program written by Subject A for completion of Task 1 as described in Section 4.2.2.

```
class(id) |- packagedElement { "xmi:id": id, name: name, "xmi:type" = "uml:Class" };

classContains(class, attr) |-
    class(class),
    mel.parent(packagedElement { "xmi:id": class }, ownedAttribute { "xmi:id": attr });

attribute(id) |-
    mel.parent(ownedAttribute { "xmi:id": id, name: label },
    type { href ["pathmap://UML_LIBRARIES/UMLPrimitiveTypes.library.uml#%"]: type }),
    mel.parent(ownedAttribute { "xmi:id": id }, lowerValue { value: lowerBound }),
    mel.parent(ownedAttribute { "xmi:id": id }, upperValue { value: upperBound });

association(from, to) |-
    mel.parent(
        packagedElement { "xmi:id": associationId },
        ownedEnd { type: from, name: fromName, aggregation != "composite" }),
    mel.parent(
        packagedElement {
            "xmi:type" = "uml:Association",
            "xmi:id": associationId,
            name: associationName,
            navigableOwnedEnd: navigableOwnedEnd
        },
        ownedEnd { type: to, name: toName, "xmi:id": navigableOwnedEnd });

composition(from, to) |-
    mel.parent(
        packagedElement { "xmi:id": associationId },
        ownedEnd { type: from, name: fromName, aggregation = "composite" }),
    mel.parent(
        packagedElement {
            "xmi:type" = "uml:Association",
            "xmi:id": associationId,
            name: associationName,
            navigableOwnedEnd: navigableOwnedEnd
        },
        ownedEnd { type: to, name: toName, "xmi:id": navigableOwnedEnd });
```

Figure A.8: `mel` program written by Subject A for completion of Task 2 as described in Section 4.2.2. Some additional line breaks have been added to allow the program to fit on the page.

```
xquery version "3.1";

declare namespace xmi = "http://schema.omg.org/spec/XMI/2.1";

for $doc in doc("db/agency.uml")
let $classes :=
    for $class in $doc//packagedElement[@xmi:type = "uml:Class"]
    return <class id="{ $class/@xmi:id }" name="{ $class/@name }" />
let $attributes :=
    for $attr in $doc//ownedAttribute
    let $type := replace($attr/type/@href, "^.*#", "")
    let $lowerBound := $attr/lowerValue/@value
    let $upperBound := $attr/upperValue/@value
    return <attribute id="{ $attr/@xmi:id }" name="{ $attr/@name }" type="{ $type }"
                      lowerBound="{ $lowerBound }" upperBound="{ $upperBound }" />
let $classAttrs :=
    for $class in $doc//packagedElement[@xmi:type = "uml:Class"]
    for $attr in $class/ownedAttribute
    return <classAttr classId="{ $class/@xmi:id }" attrId="{ $attr/@xmi:id }" />
let $associations :=
    for $assoc in $doc//packagedElement[@xmi:type = "uml:Association"]
    let $fromEnd := $assoc/ownedEnd[@xmi:id = tokenize($assoc/@memberEnd, "\s")[1]]
    let $toEnd := $assoc/ownedEnd[@xmi:id =
                    tokenize($assoc/@navigableOwnedEnd, "\s")[last()]]
    where not(exists($fromEnd/@aggregation)) or $fromEnd/@aggregation != "composite"
    return <association
        id="{ $assoc/@xmi:id }"
        name="{ $assoc/@name }"
        from="{ $fromEnd/@type }"
        to="{$toEnd/@type }" />

let $compositions :=
    for $assoc in $doc//packagedElement[@xmi:type = "uml:Association"]
    let $fromEnd := $assoc/ownedEnd[@xmi:id = tokenize($assoc/@memberEnd, "\s")[1]]
    let $toEnd := $assoc/ownedEnd[@xmi:id =
                    tokenize($assoc/@navigableOwnedEnd, "\s")[last()]]
    where $fromEnd/@aggregation = "composite"
    return <composition id="{ $assoc/@xmi:id }" name="{ $assoc/@name }"
        from="{ $fromEnd/@type }" to="{$toEnd/@type }" />

return <data> { $classes } { $attributes } { $classAttrs }
    { $associations }{ $compositions }
    </data>
```

Figure A.9: XQuery program written by Subject A for completion of Task 2 as described in Section 4.2.2. Line breaks have been removed in some places and added in others to accommodate formatting for this thesis.

```
stateMachine(id) |-
        ownedBehavior { "xmi:type" = "uml:StateMachine", name: name, "xmi:id": id };

region(id) |-
        region { "xmi:type"= "uml:Region", "xmi:id": id, name: name },
        mel.ancestor(region {"xmi:type" = "uml:Region",
                      stateMachine: stateMachine }, region { "xmi:id": id });
region(id) |-
        region { "xmi:type" = "uml:Region", "xmi:id": id, name: name,
                 stateMachine: stateMachine };

state(id) |-
        subvertex { "xmi:type" = "uml:State", "xmi:id": id, name: name },
        mel.parent(region { "xmi:type" = "uml:Region", "xmi:id": region },
                   subvertex { "xmi:id": id });

stateContains(parent, child) |-
        subvertex { "xmi:type" = "uml:State", "xmi:id": parent },
        mel.parent(subvertex { "xmi:id": parent },
                   region { "xmi:type" = "uml:Region", "xmi:id": regionBetween }),
        mel.parent(region { "xmi:id": regionBetween },
                   subvertex { "xmi:type" = "uml:State", "xmi:id": child });

transition(source, target) |-
        transition { "xmi:type" = "uml:Transition", "xmi:id": transitionId,
                     source: source, target: target },
        # trigger
        @mel.parent(transition { "xmi:id": transitionId },
                    trigger { event: eventId }),
        @packagedElement { "xmi:type" = "uml:SignalEvent",
                           "xmi:id": eventId, signal: signalId },
        @packagedElement { "xmi:type" = "uml:Signal", "xmi:id":
                           signalId, name: trigger },
        # guard
        @mel.parent(transition { "xmi:id": transitionId },
                    ownedRule { "xmi:id": ownedRuleId }),
        @mel.parent(ownedRule { "xmi:id": ownedRuleId },
                    specification { value: guard }),
        # effect
        @mel.parent(transition { "xmi:id": transitionId },
                    effect { "xmi:id": effectId }),
        @mel.parent(effect { "xmi:id": effectId },
                    body { mel.contents: effect });
```

Figure A.10: `mel` program written by Subject A for completion of Task 3 as described in Section 4.2.2. Some additional line breaks have been added to allow the program to fit on the page.

```
xquery version "3.1";

declare namespace xmi = "http://schema.omg.org/spec/XMI/2.1";

for $doc in doc("homealarm.xmi")
let $stateMachines :=
    for $stm in $doc//ownedBehavior[@xmi:type = "uml:StateMachine"]
    return <statemachine id="{ $stm/@xmi:id }" name="{ $stm/@name }" />
let $regions :=
    for $region in $doc//region[@xmi:type = "uml:Region"]
    let $stateMachine := if( exists($region/@stateMachine) )
                         then $region/@stateMachine else
                         $region/ancestor::region[exists(./@stateMachine)]
                                                 /@stateMachine
    return <region id="{ $region/@xmi:id }" name="{ $region/@name }"
            stateMachine="{ $stateMachine }" />
let $states :=
    for $state in $doc//subvertex[@xmi:type = "uml:State"]
    return <state id="{ $state/@xmi:id }" name="{ $state/@name }"
            region="{ $state/parent::region/@xmi:id }" />
let $stateContainss :=
    for $state in $doc//subvertex[@xmi:type = "uml:State"]
    for $child in $state/region/subvertex[@xmi:type = "uml:State"]
    return <stateContains outer="{ $state/@xmi:id }" inner="{ $child/@xmi:id }" />
let $transitions :=
    for $trans in $doc//transition[@xmi:type = "uml:Transition"]
    let $eventId := $trans/trigger/@event
    let $signalEvent := $doc//packagedElement[@xmi:type = "uml:SignalEvent"
                                              and @xmi:id = $eventId]
    let $signal := $doc//packagedElement[@xmi:type = "uml:Signal"
                                         and @xmi:id = $signalEvent/@signal]
    return <transition id="{ $trans/@xmi:id }" source="{ $trans/@source }"
        target="{ $trans/@target }" trigger="{ $signal/@name }"
        guard="{ $trans/ownedRule/specification/@value }"
        effect="{ $trans/effect/body/text() }" />
return <data>
    { $stateMachines } { $regions }
    { $states } { $stateContainss } { $transitions }
    </data>
```

Figure A.11: XQuery program written by Subject A for completion of Task 3 as described in Section 4.2.2. Line breaks have been removed in some places and added in others to accommodate formatting for this thesis.

```
class(name) |-
    eClassifiers { name: name, "xsi:type" = "ecore:EClass",
                   abstract: abstract };

member(className, member) |-
    eClassifiers { name: className, "xsi:type" = "ecore:EClass" }
        -> [eStructuralFeatures { "xsi:type" = "ecore:EAttribute",
                                  name: member, eType: type }];

method(className, method) |-
    eClassifiers { name: className, "xsi:type" = "ecore:EClass" }
        -> [eOperations { name: method, eType["#//(\\w+)"]: returnType }];

methodParam(method, param) |-
    eClassifiers { } -> eOperations { name: method } -> [
        eParameters { name: param, eType["#//(\\w+)"]: type }
    ];

superClass(class, super) |-
    eClassifiers { name: class, "xsi:type" = "ecore:EClass",
                   eSuperTypes["#//(\\w+)"]: super };

association(classA, classB) |-
    class(classA), class(classB),
    eClassifiers { name: classA, "xsi:type" = "ecore:EClass" } -> [
        eStructuralFeatures { "xsi:type" = "ecore:EReference",
                              name: label, eType["#//(\\w+)"]: classB,
            upperBound = '-1' ? '*' > upperBound : upperMult,
                          mel.exists(lowerBound) ? lowerBound > '0' : lowerMult,
            containment != "true", mel.exists(derived) ?
                          derived = 'true' ? 'true' >
                              'false' > 'false' : derived }];
composition(classA, classB) |-
    class(classA), class(classB),
    eClassifiers { name: classA, "xsi:type" = "ecore:EClass" } -> [
        eStructuralFeatures { "xsi:type" = "ecore:EReference", name: label,
                  eType["#//(\\w+)"]: classB,
                  upperBound = '-1' ? '*' > upperBound : upperMult,
                  mel.exists(lowerBound) ? lowerBound > '0' : lowerMult,
            containment = "true", mel.exists(derived) ?
                derived = 'true' ? 'true' > 'false' > 'false' : derived }];
```

Figure A.12: `mel` program written by Subject A for completion of Task 4 as described in Section 4.2.2. Some additional line breaks have been added to allow the program to fit on the page.

```
xquery version "3.1";
let $doc := doc("royal.xml")
let $class :=
    for $class in $doc // eClassifiers [ @xsi:type = "ecore:EClass" ]
    return <class name="{$class/@name}" abstract="{if($class/@abstract = "true")
            then "true" else "false"}" />
let $memberOf :=
    for $class in $doc // eClassifiers [ @xsi:type = "ecore:EClass" ]
    for $member in $class / eStructuralFeatures [ @xsi:type = "ecore:EAttribute" ]
    return <memberOf className="{$class/@name}" name="{$member/@name}"
            type="{$member/@eType}" />
let $superClassOf :=
    for $class in $doc // eClassifiers [ @xsi:type = "ecore:EClass" and @eSuperTypes ]
    let $superClassName := analyze-string($class/@eSuperTypes, "#//(\w+)") /
                                        fn:match / fn:group [@nr = "1"] / text()
    return <superClassOf className="{$class/@name}"
            superClassName="{$superClassName}" />
let $associationOrComposition :=
    for $class in $doc // eClassifiers [ @xsi:type = "ecore:EClass" ]
    for $assoc in $class / eStructuralFeatures [ @xsi:type = "ecore:EReference" ]
    let $targetName := analyze-string($assoc/@eType, "#//(\w+)") / fn:match /
                                    fn:group [@nr = "1"] / text()
    let $lowerMult := if(exists($assoc/@lowerBound)) then $assoc/@lowerBound else "0"
    let $upperMult := if($assoc/@upperBound = "-1") then "*" else $assoc/@upperBound
    let $derived := if($assoc/@derived = "true") then "true" else "false"
    return
        if($assoc/@containment = "true")
        then <composition from="{$class/@name}" to="{$targetName}"
        label="{$assoc/@name}" lowerMult="{$lowerMult}"
        upperMult="{$upperMult}" derived="{$derived}" />
        else <association from="{$class/@name}" to="{$targetName}"
        label="{$assoc/@name}" lowerMult="{$lowerMult}"
        upperMult="{$upperMult}" derived="{$derived}" />
let $methodOf :=
    for $class in $doc // eClassifiers [ @xsi:type = "ecore:EClass" ]
    for $method in $class / eOperations
    let $returnType := analyze-string($method/@eType, "#//(\w+)") / fn:match /
                                    fn:group [@nr = "1"] / text()
    return <methodOf class="{$class/@name}" name="{$method/@name}"
            returnType="{$returnType}" />
let $paramOf :=
    for $method in $doc // eClassifiers [ @xsi:type = "ecore:EClass" ] / eOperations
    for $param in $method / eParameters
    let $type := analyze-string($param/@eType, "#//(\w+)") / fn:match /
                                fn:group [@nr = "1"] / text()
    return <paramOf method="{$method/@name}" name="{$param/@name}" type="{$type}" />
return <results> {$class} {$memberOf} {$superClassOf}
        {$associationOrComposition} {$methodOf} </results>
```

Figure A.13: XQuery program written by Subject A for completion of Task 4 as described in Section 4.2.2. Some line breaks have been added to allow for formatting of this thesis.

```
signalGenerator(id) |-
    Block { BlockType = "SignalGenerator", SID: id, Name: name };

sum(id) |- Block { BlockType = "Sum", SID: id, Name: name };

gain(id) |- Block { BlockType = "Gain", SID: id, Name: name };

subSystem(id) |- Block { BlockType = "SubSystem", SID: id, Name: name };

.block(id) |- signalGenerator(id);
.block(id) |- sum(id);
.block(id) |- gain(id);
.block(id) |- subSystem(id);

port(blockId, portIdx) |-
    Block { SID: blockId } -> [
        Port { } -> [
            P { Name = "PortNumber", mel.contents: portIdx },
            P { Name = "Name", mel.contents: name }]
        ];

portRel(from, to) |-
    Block { SID: fromBlockId } -> [
        Port { } -> [
            P { Name = "PortNumber", mel.contents: fromIdx },
            P { Name = "Name", mel.contents: from }]
    ],
    Block { SID: toBlockId } -> [
        Port { } -> [
            P { Name = "PortNumber", mel.contents: toIdx },
            P { Name = "Name", mel.contents: to }]
    ],
    port(fromBlockId, fromIdx), port(toBlockID, toIdx),
    from != to,
    Line { } -> [
        P { Name = "Src", mel.contents["(\\d+)#.*"]:
            fromBlockID, mel.contents[".*:(\\d+)"]: fromIdx },
        P { Name = "Dst", mel.contents["(\\d+)#.*"]:
            toBlockID, mel.contents[".*:(\\d+)"]: toIdx }];

blockRel(fromId, toId) |-
    block(fromId), block(toId),
    fromId != toId,
    Line { } -> [
        P { Name = "Src", mel.contents["(\\d+)#.*"]: fromId,
            mel.contents[".*:(\\d+)"]: fromPort },
        P { Name = "Dst", mel.contents["(\\d+)#.*"]: toId,
            mel.contents[".*:(\\d+)"]: toPort }];
```

Figure A.14: `mel` program written by Subject A for completion of Task 5 as described in Section 4.2.2. Line breaks have been removed in some places and added in others to accommodate formatting for this thesis.

```
xquery version "3.1";

let $doc := doc("simulink.xml")
let $signalGenerator :=
    for $block in $doc // Block [ @BlockType = "SignalGenerator" ]
    return <signalGenerator id="{$block/@SID}" name="{$block/@Name}" />
let $sum :=
    for $block in $doc // Block [ @BlockType = "Sum" ]
    return <sum id="{$block/@SID}" name="{$block/@Name}" />
let $gain :=
    for $block in $doc // Block [ @BlockType = "Gain" ]
    return <gain id="{$block/@SID}" name="{$block/@Name}" />
let $subSystem :=
    for $block in $doc // Block [ @BlockType = "SubSystem" ]
    return <subSystem id="{$block/@SID}" name="{$block/@Name}" />
let $block := ($signalGenerator,$sum,$gain,$subSystem)
let $port :=
    for $block in $doc // Block
    for $port in $block / Port
    return <port blockId="{$block/@SID}" name="{$port/P[@Name="Name"]/text()}"
            number="{$port/P[@Name="PortNumber"]/text()}" />
let $portRel :=
    for $line in $doc // Line
    let $fromBlockId := analyze-string($line/P[@Name="Src"]/text(), "(\d+)#")
                                        / fn:match / fn:group [@nr = "1"] / text()
    let $toBlockId := analyze-string($line/P[@Name="Dst"]/text(), "(\d+)#")
                                        / fn:match / fn:group [@nr = "1"] / text()
    let $fromPortIdx := analyze-string($line/P[@Name="Src"]/text(), ".*:(\d+)")
                                        / fn:match / fn:group [@nr = "1"] / text()
    let $toPortIdx := analyze-string($line/P[@Name="Dst"]/text(), ".*:(\d+)")
                                        / fn:match / fn:group [@nr = "1"] / text()
    for $p1 in $port[@blockId = $fromBlockId and @number = $fromPortIdx]
    for $p2 in $port[@blockId = $toBlockId and @number = $toPortIdx]
    return <portRel fromBlockId="{$fromBlockId}" toBlockId="{$toBlockId}"
                            fromPortIdx="{$fromPortIdx}" toPortIdx="{$toPortIdx}" />
let $blockRel :=
    for $line in $doc // Line
    let $fromBlockId := analyze-string($line/P[@Name="Src"]/text(), "(\d+)#")
                                    / fn:match / fn:group [@nr = "1"] / text()
    let $toBlockId := analyze-string($line/P[@Name="Dst"]/text(), "(\d+)#")
                                    / fn:match / fn:group [@nr = "1"] / text()
    let $fromPortIdx := analyze-string($line/P[@Name="Src"]/text(), ".*:(\d+)")
                                    / fn:match / fn:group [@nr = "1"] / text()
    let $toPortIdx := analyze-string($line/P[@Name="Dst"]/text(), ".*:(\d+)")
                                    / fn:match / fn:group [@nr = "1"] / text()
    for $b1 in $block[@id = $fromBlockId], $b2 in $block[@id = $toBlockId]
    return <blockRel fromBlockId="{$fromBlockId}" toBlockId="{$toBlockId}"
            fromPort="{$fromPortIdx}" toPort="{$toPortIdx}" />
return <results> {$signalGenerator} {$sum} {$gain} {$subSystem}
                  {$port} {$portRel} {$blockRel} </results>
```

Figure A.15: XQuery program written by Subject A for completion of Task 5 as described in Section 4.2.2. Some additional line breaks have been added to allow the program to fit on the page.

A.4 `mel` and XQuery programs written by Subject B

```
Function(X) |- ownedArchitectures{name="Logical Architecture"}
              =>ownedFunctions{"xsi:type"[".*:(.*)"]="LogicalFunction", name:X};

Component(X) |- ownedArchitectures{name="Logical Architecture"}
              =>ownedLogicalComponents{"xsi:type"[".*:(.*)"]="LogicalComponent",
                                       name:X};

Flow(X, Y) |- ownedFunctionalExchanges{source["#(.*)"]:SOURCE, target["#(.*)"]:TARGET,
                                        name:name},
              ownedFunctions{id:SOURCE, name:X},
              ownedFunctions{id:TARGET, name:Y};
```

Figure A.16: `mel` program written by Subject B for completion of Task 1 as described in Section 4.2.2. Some additional line breaks have been added to allow the program to fit on the page.

```
let $part1 :=
<part1>{
    for $x in doc("in-flight-ent-system")//ownedArchitectures
    where $x/@name="Logical Architecture"
    for $y in $x//ownedFunctions
    where analyze-string($y/@xsi:type, "[-a-zA-Z0-9_]+$")/fn:match = "LogicalFunction"
    return <function name="{$y/@name}"/>
}
</part1>

let $part2 :=
<part2>{
    for $x in doc("in-flight-ent-system")//ownedArchitectures
    where $x/@name="Logical Architecture"
    for $y in $x//ownedLogicalComponents
    where analyze-string($y/@xsi:type, "[-a-zA-Z0-9_]+$")/fn:match = "LogicalComponent"
    return <component name="{$y/@name}"/>

}
    </part2>

let $part3 :=
<part3>{
    for $x in doc("in-flight-ent-system")//ownedFunctionalExchanges
    let $src := analyze-string($x/@source, "[-a-zA-Z0-9_]+$")/fn:match
    let $tgt := analyze-string($x/@target, "[-a-zA-Z0-9_]+$")/fn:match
    for $y in doc("in-flight-ent-system")//ownedFunctions
    where $y/@id = $src
    for $z in doc("in-flight-ent-system")//ownedFunctions
    where $z/@id = $tgt
    return <flow source="{$y/@name}" target="{$z/@name}" name="{$x/@name}"/>
}
    </part3>
return <ans>
    {$part1}
    {$part2}
    {$part3}
    </ans>
```

Figure A.17: XQuery program written by Subject B for completion of Task 1 as described in Section 4.2.2.

```
StateMachine(X) |- ownedBehavior{"xmi:type"="uml:StateMachine", name:X};

Region(X, Y) |- ownedBehavior{"xmi:type"="uml:StateMachine", name:X}
                =>region{"xmi:type"="uml:Region", name:Y};

Owns(X, Y) |- ownedBehavior{"xmi:type"="uml:StateMachine", name:X}
              =>region{"xmi:type"="uml:Region", name:Y};
Owns(X, Y) |- subvertex{name:X}
              =>region{"xmi:type"="uml:Region", name:Y};
State(X, Y) |- ownedBehavior{"xmi:type"="uml:StateMachine", name:X}
              =>subvertex{"xmi:type"="uml:State", name:Y};
Contains(X, Y) |- ownedBehavior{"xmi:type"="uml:StateMachine"}
              =>subvertex{"xmi:type"="uml:State", name:X}
              =>subvertex{"xmi:type"="uml:State", name:Y};

Transition(X) |- transition{"xmi:type"="uml:Transition", name:X, target:TARGET,
                            source:SOURCE}
                 ->[
                   @trigger{event:EVENT},
                   @ownedRule{}->specification{value:guard},
                   @effect{}->body{mel.contents:effect}
                 ],
                 @packagedElement{"xmi:type"="uml:SignalEvent", "xmi:id":EVENT,
                        signal:SIGNAL},
                 @packagedElement{"xmi:type"="uml:Signal", "xmi:id":SIGNAL,
                                  name:trigger},
               subvertex{"xmi:type"="uml:State", "xmi:id":SOURCE},
               subvertex{"xmi:type"="uml:State", "xmi:id":TARGET};
```

Figure A.18: `mel` program written by Subject B for completion of Task 3 as described in Section 4.2.2. Some additional line breaks have been added to allow the program to fit on the page.

```
xquery version "3.1";
declare namespace xmi="http://schema.omg.org/spec/XMI/2.1";
let $part1 :=
<part1>{
   for $x in doc("HomeAlarmWithPorts.xmi")//ownedBehavior
   where $x/@xmi:type="uml:StateMachine"
   return <StateMachine name = "{$x/@name}"/>
}</part1>

let $part2 :=
<part2>{
    for $x in doc("HomeAlarmWithPorts.xmi")//ownedBehavior
   where $x/@xmi:type="uml:StateMachine"
   for $y in $x//region
   return <Region machine ="{$x/@name}" name="{$y/@name}"/>
}
    </part2>

let $part3 :=
<part3>{
    for $x in doc("HomeAlarmWithPorts.xmi")//(ownedBehavior | subvertex)
    for $y in $x/region
    return <Owns state="{$x/@name}" region="{$y/@name}"/>
}
    </part3>

    let $part4 :=
    <part4> {
    for $x in doc("HomeAlarmWithPorts.xmi")//ownedBehavior
    where $x/@xmi:type="uml:StateMachine"
    for $y in $x//subvertex
    where $y/@xmi:type="uml:State"
    return <State machine="{$x/@name}" name="{$y/@name}"/>
    }
    </part4>

    let $part5 :=
    <part5>{
    for $x in doc("HomeAlarmWithPorts.xmi")//ownedBehavior
    where $x/@xmi:type="uml:StateMachine"
    for $y in $x//subvertex
    where $y/@xmi:type="uml:State"
    for $z in $y//subvertex
```

```
    where $z/@xmi:type="uml:State"
    return <Contains outer="{$y/@name}" inner="{$z/@name}"/>
    }
        </part5>

        let $part6 :=
        <part6> {
            for $x in doc("HomeAlarmWithPorts.xmi")//transition
            where $x/@xmi:type="uml:Transition"
            for $u in doc("HomeAlarmWithPorts.xmi")//subvertex
            where $u/@xmi:type="uml:State" and $u/@xmi:id = $x/@source
            for $w in doc("HomeAlarmWithPorts.xmi")//subvertex
            where $w/@xmi:type="uml:State" and $w/@xmi:id = $x/@target
            let $guard := $x/ownedRule/specification/@value
            let $effect := data($x/effect/body)
            let $trigger := if (exists ($x/trigger/@event)) then
            let $event := $x/trigger/@event
            for $y in doc("HomeAlarmWithPorts.xmi")//packagedElement
            where $y/@xmi:type="uml:SignalEvent" and $y/@xmi:id = $event
            let $signal := $y/@signal
            for $z in doc("HomeAlarmWithPorts.xmi")//packagedElement
            where $z/@xmi:type="uml:Signal" and $z/@xmi:id = $signal
            return $z/@name
            else ""
            return <Transition name="{$x/@name}" trigger="{$trigger}" guard="{$guard}"
                    effect="{$effect}"/>
        }</part6>
return <ans>
    {$part1}
    {$part2}
    {$part3}
    {$part4}
    {$part5}
    {$part6}
    </ans>
```

Figure A.19: XQuery program written by Subject B for completion of Task 3 as described in Section 4.2.2. Some additional line breaks have been added to allow the program to fit on the page.

```
Class(X) |- eClassifiers{"xsi:type"="ecore:EClass", name:X, abstract:abstract,
                          interface:interface};
hasMember(X, Y) |- eClassifiers{"xsi:type"="ecore:EClass", name:X}
                ->eStructuralFeatures{"xsi:type"="ecore:EAttribute", name:Y,
                  eType[".*\#//(.*)"]:type,
                  mel.exists(derived)?derived>'false':derived};
hasSuper(X, Y) |- eClassifiers{"xsi:type"="ecore:EClass", name:X,
                                mel.exists(eSuperTypes), eSuperTypes["\#//(.*)"]:Y};
Associated(X, Y) |-
  eClassifiers{"xsi:type"="ecore:EClass", name:X}->
  eStructuralFeatures{"xsi:type"="ecore:EReference", name:Y,
       mel.nexists(containment),
       mel.exists(lowerBound)?lowerBound>'0':lowerBound,
       mel.exists(upperBound)?upperBound = '-1' ? '*' > upperBound > '1':upperBound};
Composed(X, Y) |-
  eClassifiers{"xsi:type"="ecore:EClass", name:X}->
  eStructuralFeatures{"xsi:type"="ecore:EReference", name:Y,
       containment='true',
       mel.exists(lowerBound)?lowerBound>'0':lowerBound,
       mel.exists(upperBound)?upperBound = '-1' ? '*' > upperBound > '1':upperBound,
                  mel.exists(derived)?derived>'false':derived};
Method(X) |- eOperations{name:X, eType[".*\#//(.*)"]:returnType};
HasParam(X, Y) |- eOperations{name:X}->
  eParameters{name:Y, eType[".*\#//(.*)"]:type,
                  mel.exists(derived)?derived>'false':derived};
```

Figure A.20: `mel` program written by Subject B for completion of Task 4 as described in Section 4.2.2. Some additional line breaks have been added to allow the program to fit on the page.

```
xquery version "3.1";
let $part1 :=
<part1>
    {
for $x in doc("royalandloyal")//eClassifiers
where $x/@xsi:type = "ecore:EClass"
let $abstract := if (exists($x/@abstract)) then data($x/@abstract) else "false"
let $interface := if (exists($x/@interface)) then data($x/@interface) else "false"
return <class name="{data($x/@name)}" abstract="{$abstract}" interface="{$interface}"/>
}
</part1>
let $part2 :=
<part2>
    {
for $x in doc("royalandloyal")//eClassifiers
where $x/@xsi:type="ecore:EClass"
for $y in $x/eStructuralFeatures
where $y/@xsi:type="ecore:EAttribute"
let $type := analyze-string(data($y/@eType), "[-a-zA-Z0-9_]+$")
let $derived := if (exists($y/@derived)) then data($y/@derived) else "false"
return <membership class="{data($x/@name)}" member="{data($y/@name)}"
        type="{data($type/fn:match)}" derived="{$derived}"/>
}
</part2>
let $part3 :=
<part3>{
    for $x in doc("royalandloyal")//eClassifiers
where $x/@xsi:type="ecore:EClass"
let $st := analyze-string(data($x/@eSuperTypes), "[-a-zA-Z0-9_]+$")
return if (exists($x/@eSuperTypes)) then<superclass sub="{data($x/@name)}"
            super="{data($st/fn:match)}"/> else ()
}
</part3>

let $part4 :=
<part4>{
for $x in doc("royalandloyal")//eClassifiers
where $x/@xsi:type="ecore:EClass"
    for $y in $x/eStructuralFeatures
where $y/@xsi:type="ecore:EReference"
where not(exists($y/@containment))
let $upper := if (exists($y/@upperBound)) then if (data($y/@upperBound) = "-1")
              then "*" else data($y/@upperBound) else "1"
```

```
let $lower := if (exists($y/@lowerBound)) then data($y/@lowerBound) else "0"
let $derived := if (exists($y/@derived)) then data($y/@derived) else "false"
return <association class="{data($x/@name)}" other="{data($y/@name)}" lower="{$lower}"
        upper="{$upper}" derived="{$derived}"/>
}

    </part4>
    let $part5 :=
<part5>{
for $x in doc("royalandloyal")//eClassifiers
where $x/@xsi:type="ecore:EClass"
    for $y in $x/eStructuralFeatures
where $y/@xsi:type="ecore:EReference"
where $y/@containment = "true"
let $upper := if (exists($y/@upperBound)) then if (data($y/@upperBound) = "-1")
              then "*" else data($y/@upperBound) else "1"
let $lower := if (exists($y/@lowerBound)) then data($y/@lowerBound) else "0"
let $derived := if (exists($y/@derived)) then data($y/@derived) else "false"
return <containment class="{data($x/@name)}" other="{data($y/@name)}" lower="{$lower}"
        upper="{$upper}" derived="{$derived}"/>
}

    </part5>
    let $part6 :=
    <part6>{
        for $x in doc("royalandloyal")//eOperations
        let $type := analyze-string(data($x/@eType), "[-a-zA-Z0-9_]+$")
        return <method name="{$x/@name}" returnType="{$type/fn:match}"/>
    }
        </part6>
let $part7 :=
  <part7> {
      for $x in doc("royalandloyal")//eOperations
      for $y in $x/eParameters
      let $type := analyze-string(data($y/@eType), "[-a-zA-Z0-9_]+$")
      return <hasParam methodName="{$x/@name}" paramName="{$y/@name}"
              type="{$type/fn:match}"/>
  }
  </part7>
    return <ans>{$part1}
    {$part2}
    {$part3}
    {$part4}
    {$part5}
    {$part6}
```

```
89      {$part7}
90  </ans>
```

Figure A.21: XQuery program written by Subject B for completion of Task 4 as described in Section 4.2.2. Some additional line breaks have been added to allow the program to fit on the page.

```
BlockType(X) |- Block{BlockType:X, Name:Name};
Port(X) |- Block{}->Port{}->P{Name='Name', mel.contents:X};
Owns(X, Y) |- Block{Name:X}->Port{}->P{Name='Name', mel.contents:Y};
Flow(X, Y) |- Block{Name:X, SID:XSID},
              Line{}->[P{Name='Src', mel.contents["(.*)#.*"]:XSID},
                       P{Name='Dst', mel.contents["(.*)#.*"]:YSID}],
              Block{Name:Y, SID:YSID};
Flow(X, Y) |- Block{Name:X, SID:XSID},
              Line{}->[P{Name='Src', mel.contents["(.*)#.*"]:XSID},
                       Branch{}->P{Name='Dst', mel.contents["(.*)#.*"]:YSID}],
              Block{Name:Y, SID:YSID};
```

Figure A.22: `mel` program written by Subject B for completion of Task 5 as described in Section 4.2.2. Some additional line breaks have been added to allow the program to fit on the page.

```
let $part1 :=
<part1>
    {
        for $x in doc("system_root")//Block
        return <Block type="{$x/@BlockType}" name="{$x/@Name}"/>
    }
    </part1>

let $part2 :=
<part2>{
    for $x in doc("system_root")//Block//Port/P
    where $x/@Name = "Name"
    return <Port name="{data($x)}"/>
}
    </part2>

let $part3 :=
<part3> {
    for $x in doc("system_root")//Block
    for $y in $x//Port/P
    where $y/@Name = "Name"
    return <Owns Block="{$x/@Name}" Port="{data($y)}"/>
}
</part3>

let $part4 :=
<part4>{
    for $x in doc("system_root")//Block
    for $y in doc("system_root")//Line
    for $z in $y/P
    where $z/@Name = "Src" and analyze-string(data($z),"^[0-9]+")/fn:match = $x/@SID
    for $w in $y/(if (Branch) then Branch/P else P)
    (:for $w in $y/P:)
    where $w/@Name = "Dst"
    for $u in doc("system_root")//Block
    where analyze-string(data($w),"^[0-9]+")/fn:match = $u/@SID
    return <Flow Src = "{$x/@Name}" Dst="{$u/@Name}"/>
}
    </part4>
return <ans>
    {$part1}
    {$part2}
    {$part3}
```

```
44      {$part4}
45      </ans>
```

Figure A.23: XQuery program written by Subject B for completion of Task 5 as described in Section 4.2.2. Some additional line breaks have been added to allow the program to fit on the page.

Appendix B

Diagrams of Models Used in Studies

B.1 UML StateMachine Diagrams

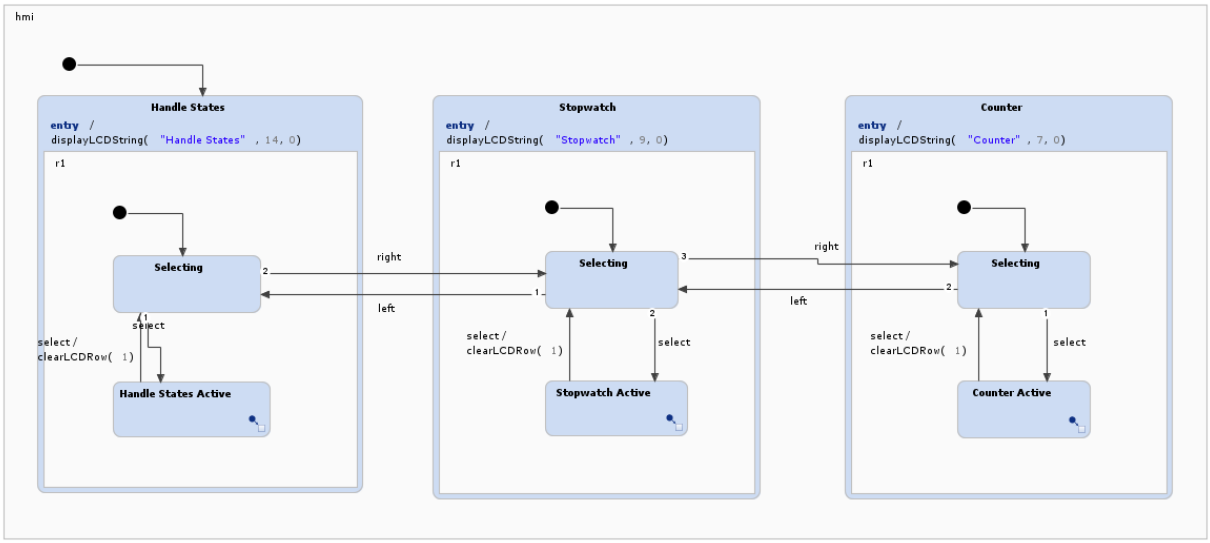


Figure B.1: StateMachine diagram for an Arduino stopwatch system (YAKINDU).

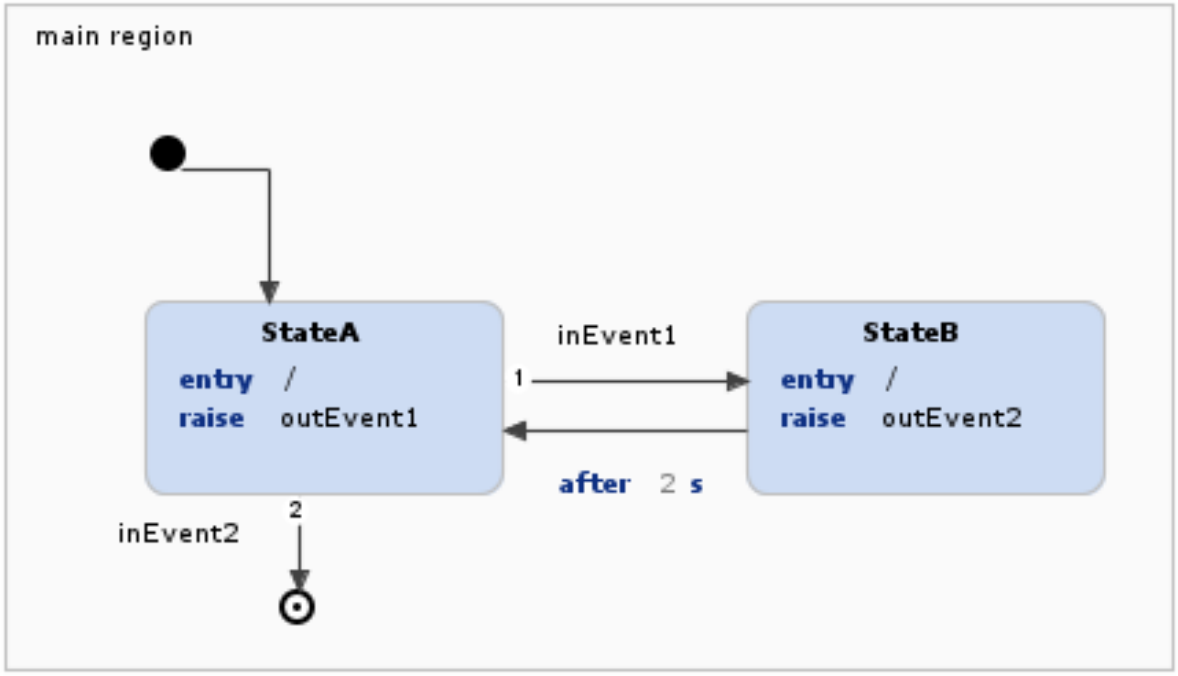


Figure B.2: StateMachine diagram for a polling system meant to be implemented directly on hardware (YAKINDU).

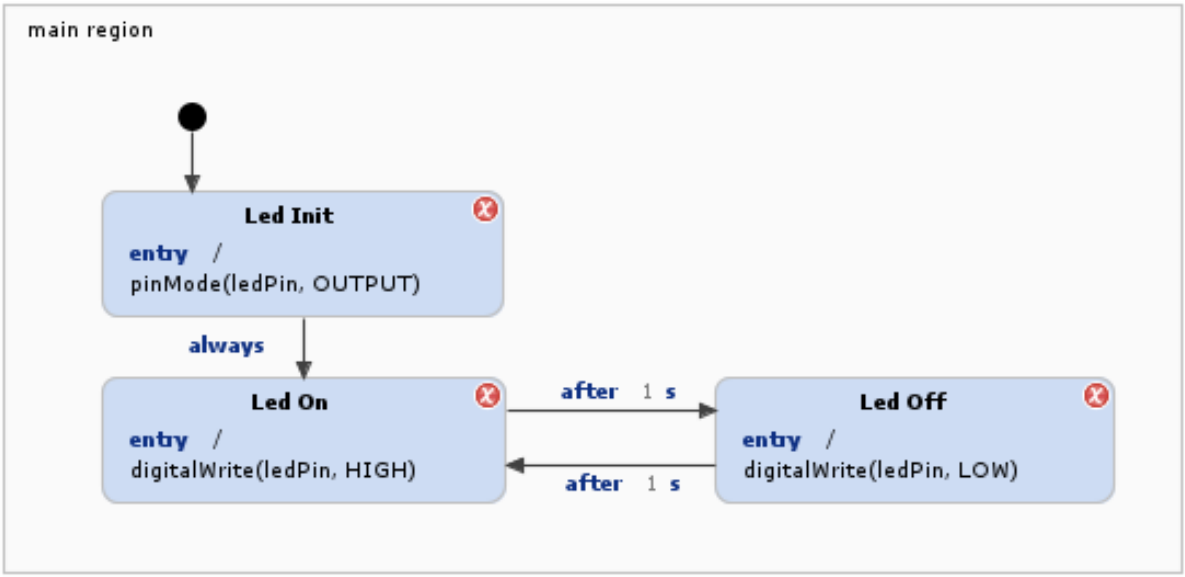


Figure B.3: StateMachine diagram for a blinking LED (YAKINDU).

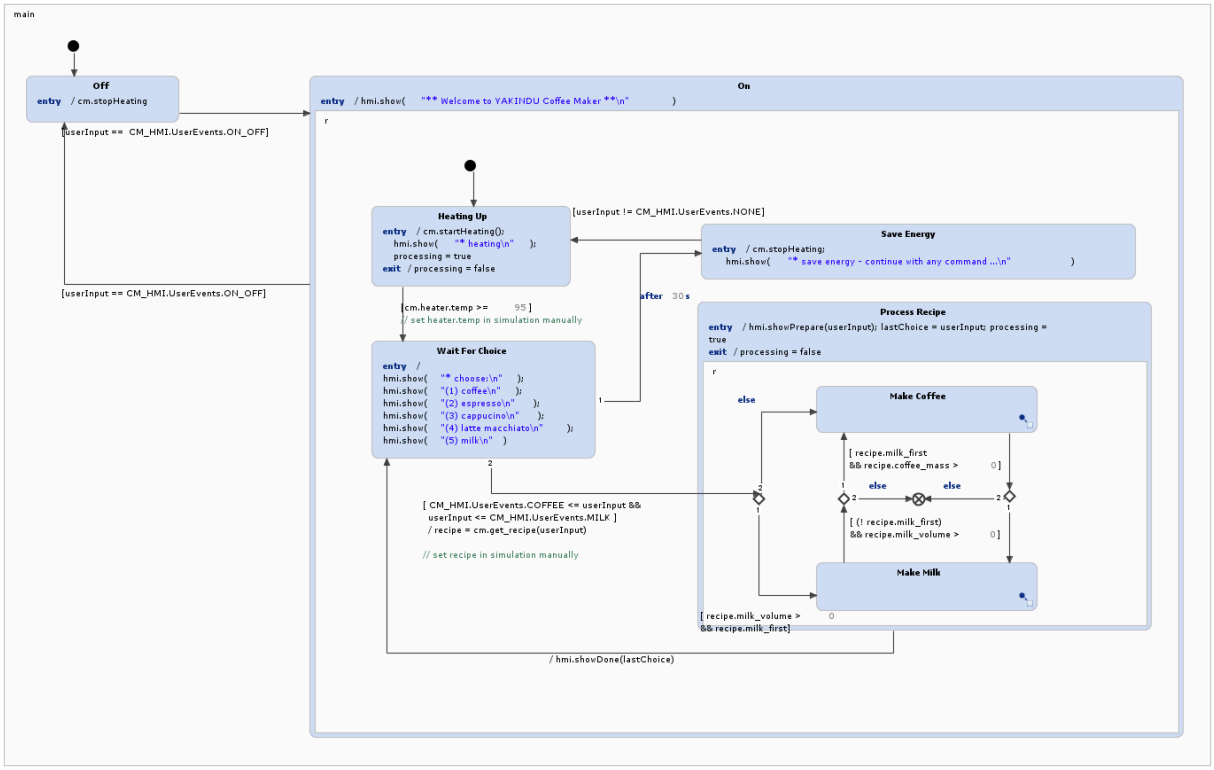


Figure B.4: StateMachine diagram for a Coffee Machine (YAKINDU).

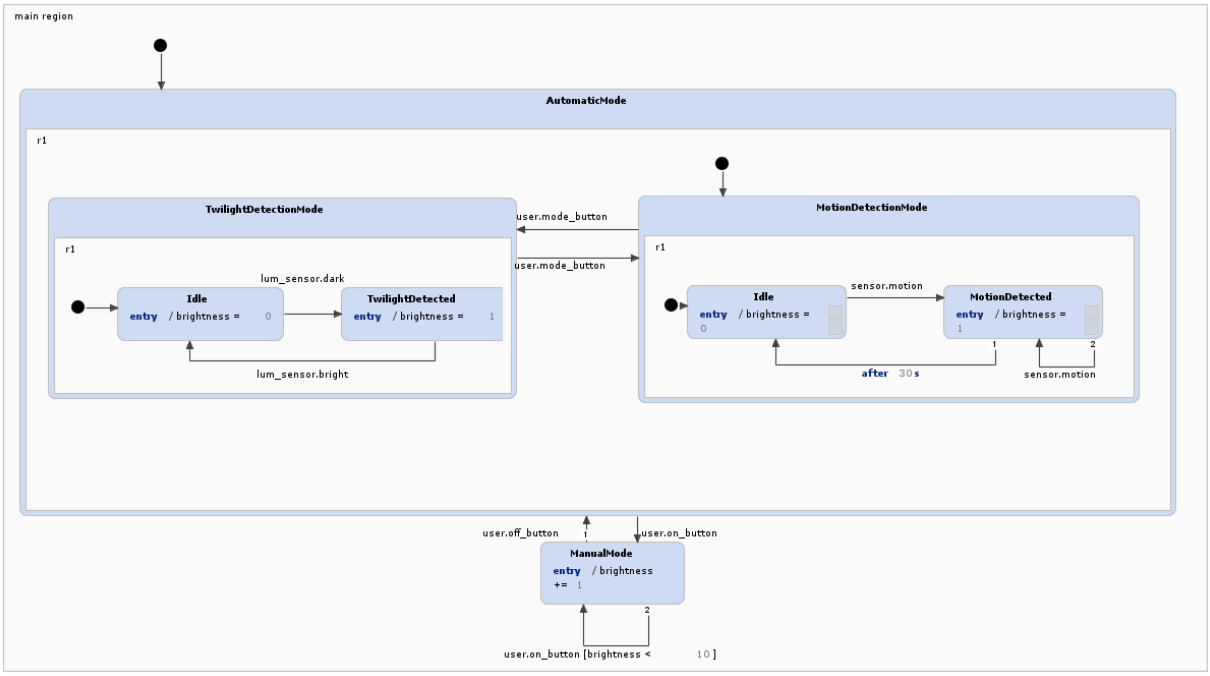


Figure B.5: StateMachine diagram for a motion detector (YAKINDU).

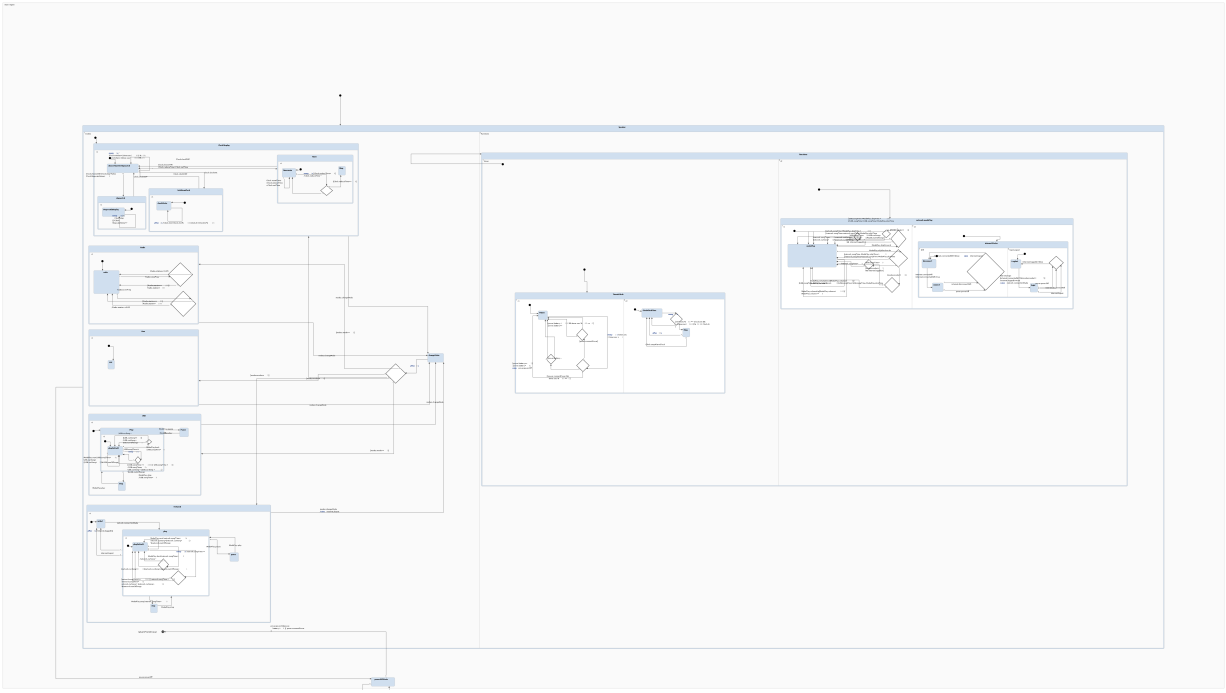


Figure B.6: StateMachine diagram for a music player (YAKINDU).

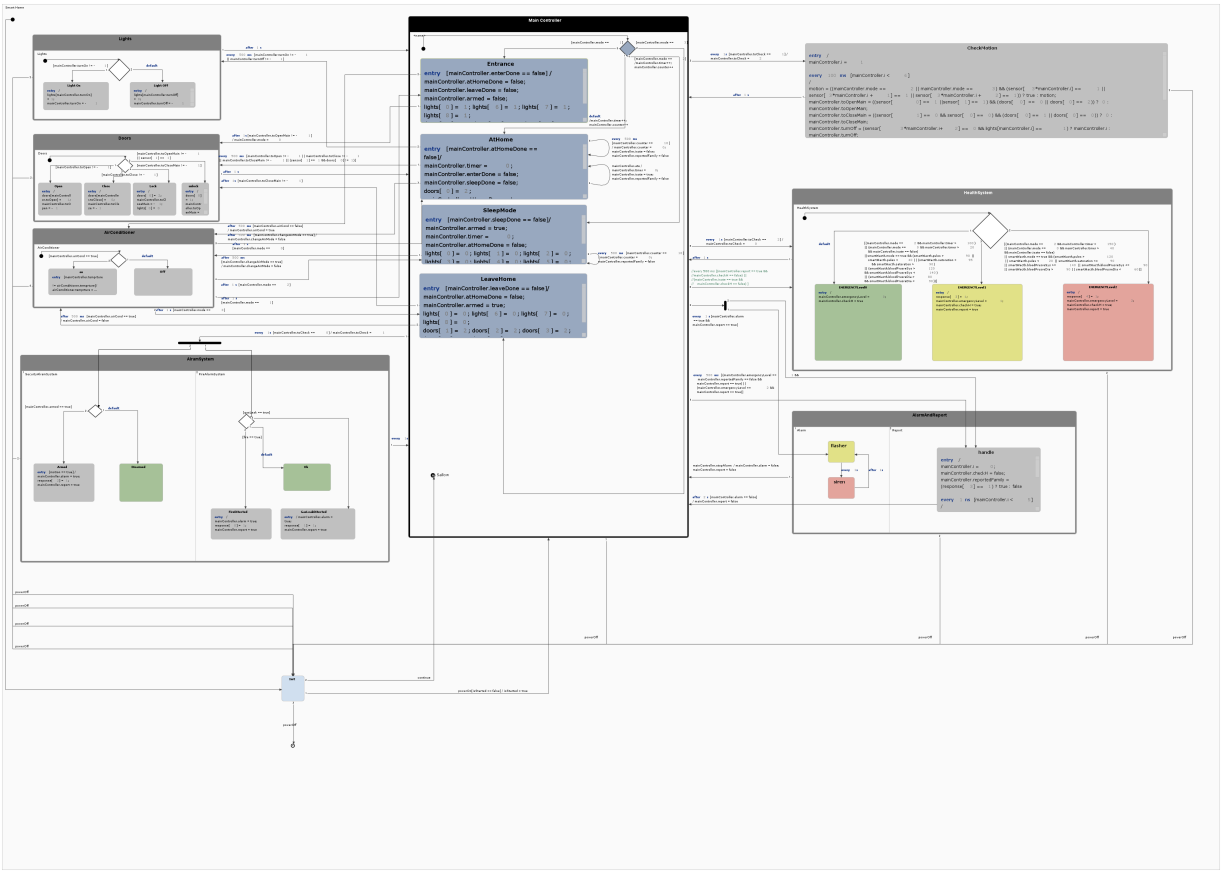


Figure B.7: StateMachine diagram for a smart home system (YAKINDU).

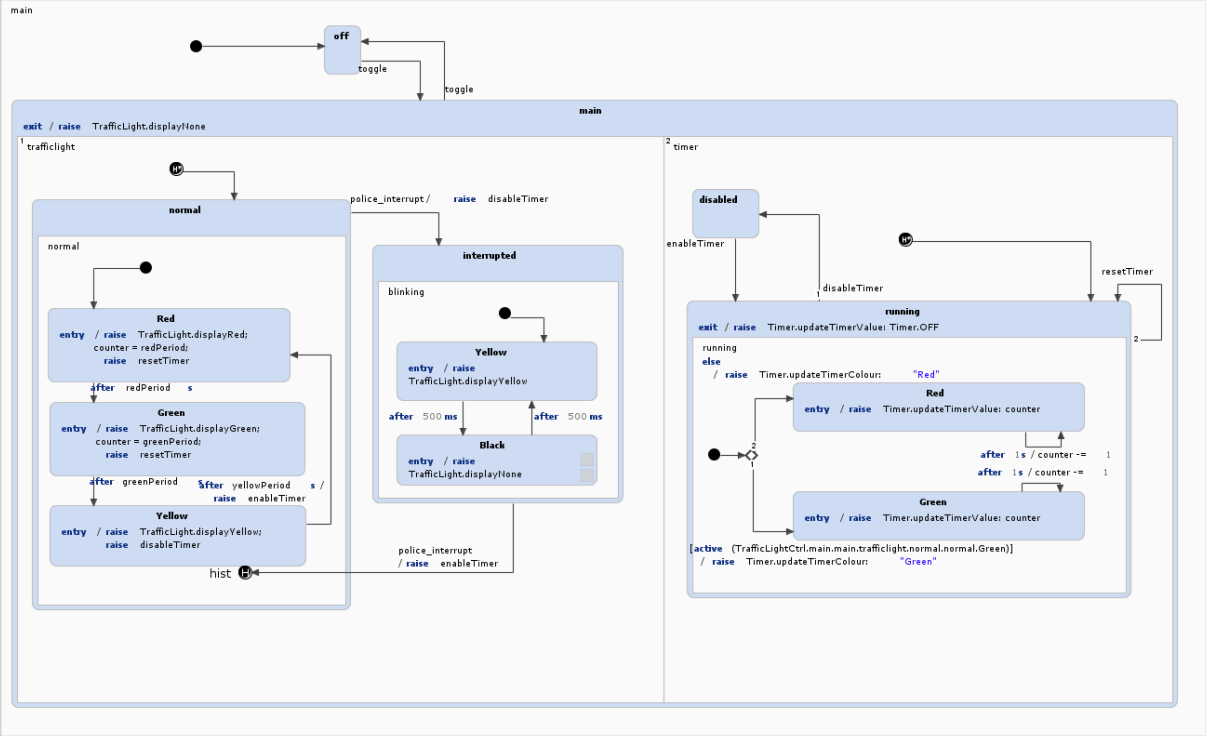


Figure B.8: StateMachine diagram for a traffic light controller (YAKINDU).

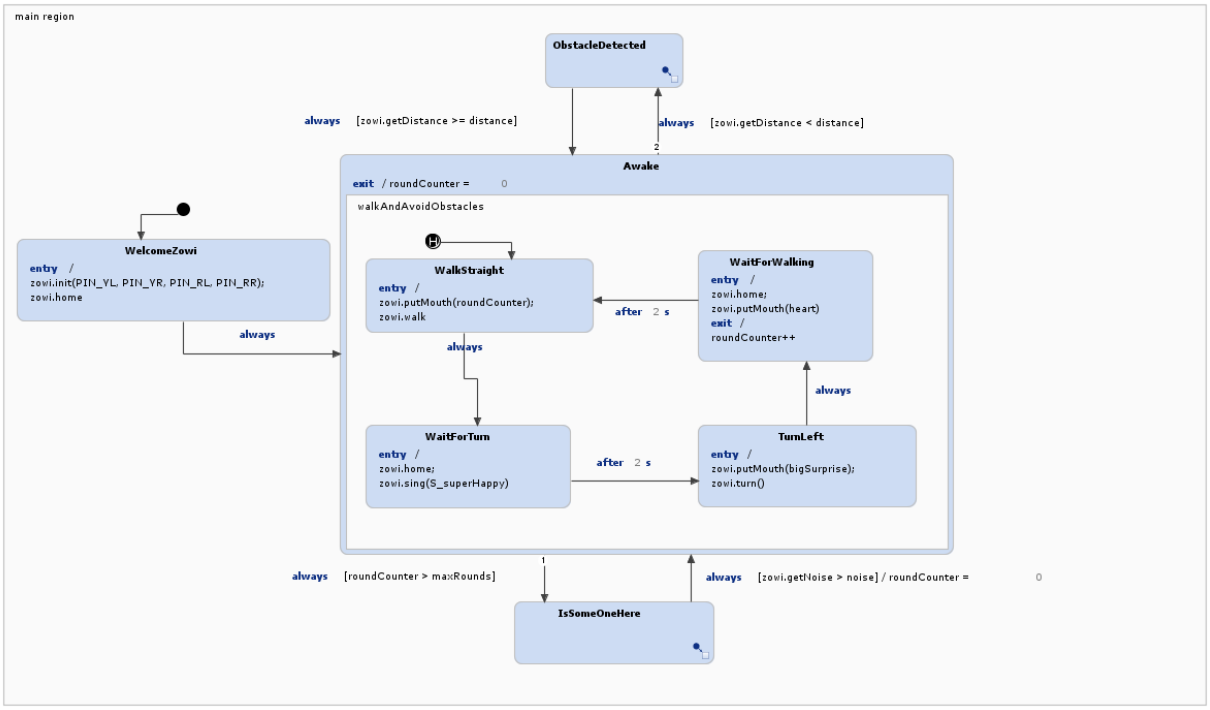


Figure B.9: StateMachine diagram for an autonomous robot (YAKINDU).

B.2 UML Class Diagrams

B.2.1 ArgoUML Class Diagrams

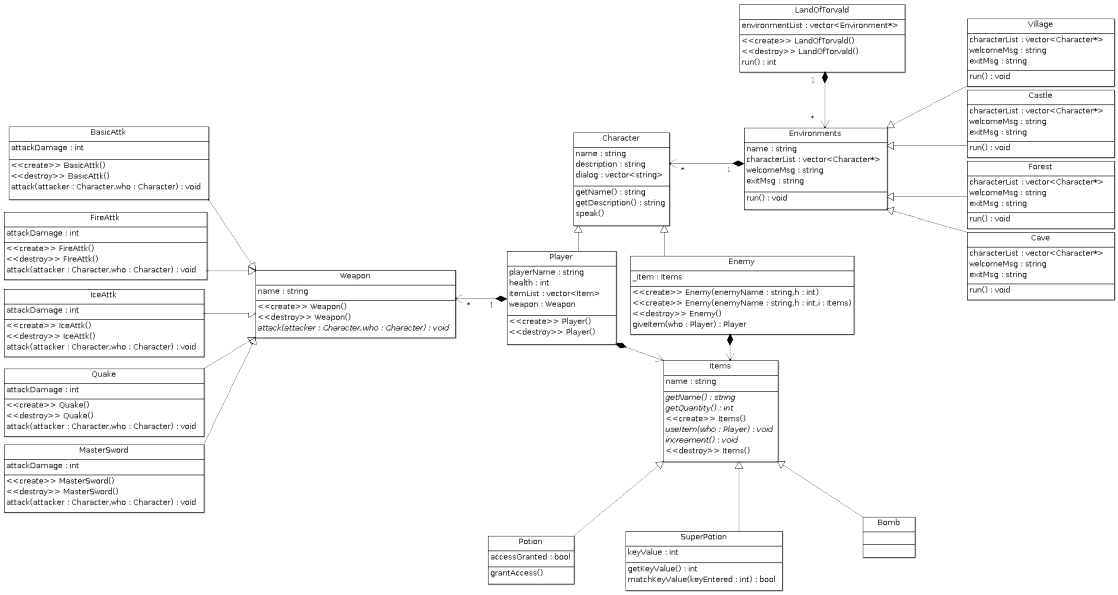


Figure B.10: UML Class diagram for a video game named Advent (ArgoUML).

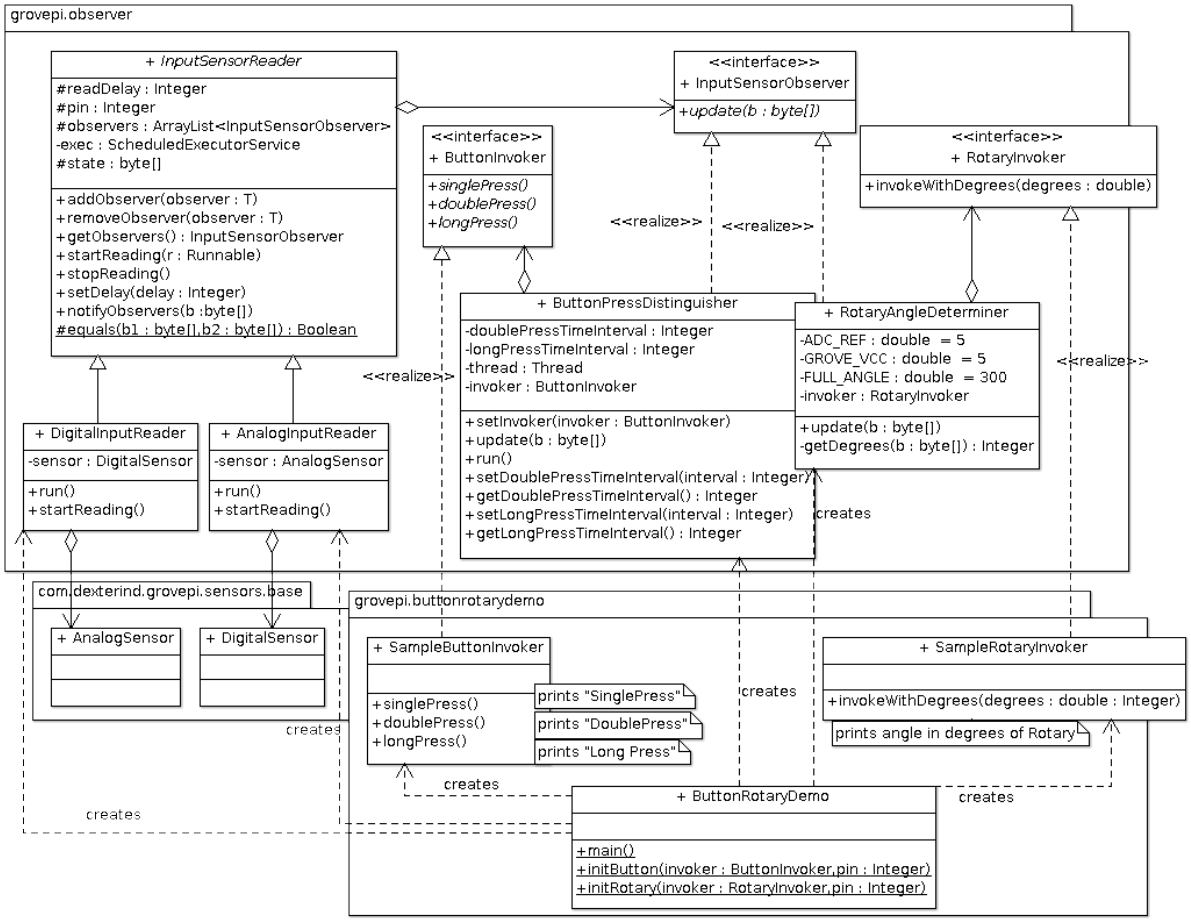


Figure B.11: UML Class diagram for a rotary button system (ArgoUML).

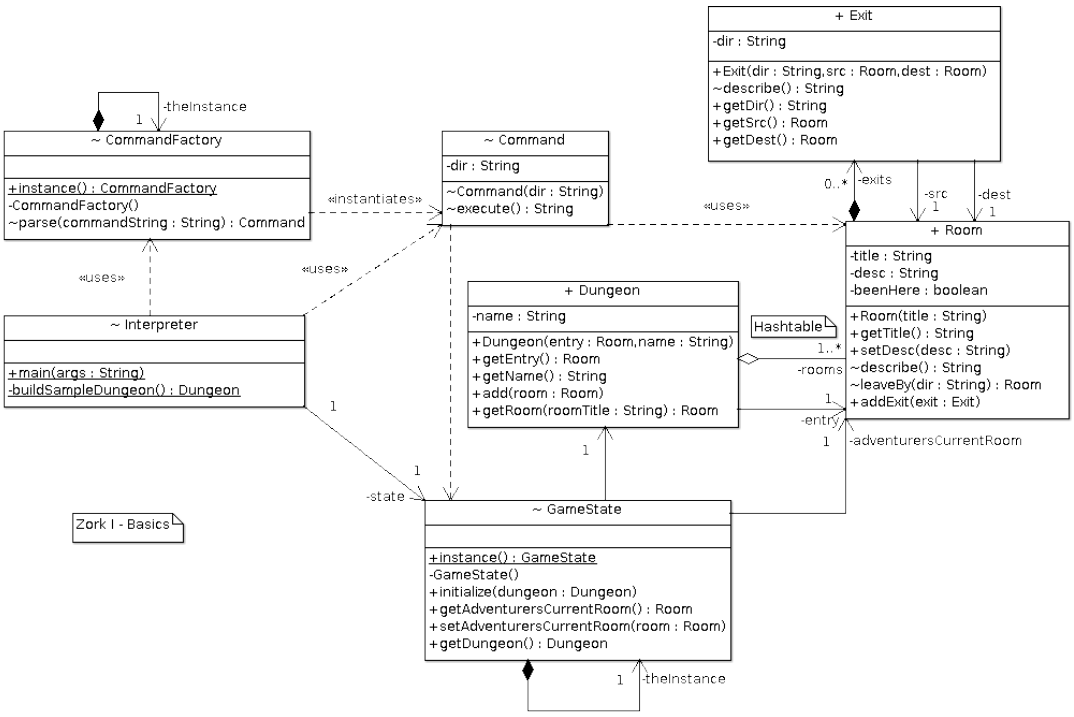


Figure B.12: UML Class diagram for a dungeon crawler video game (ArgoUML).

B.2.2 Eclispe Modelling Tools UML Class Diagrams

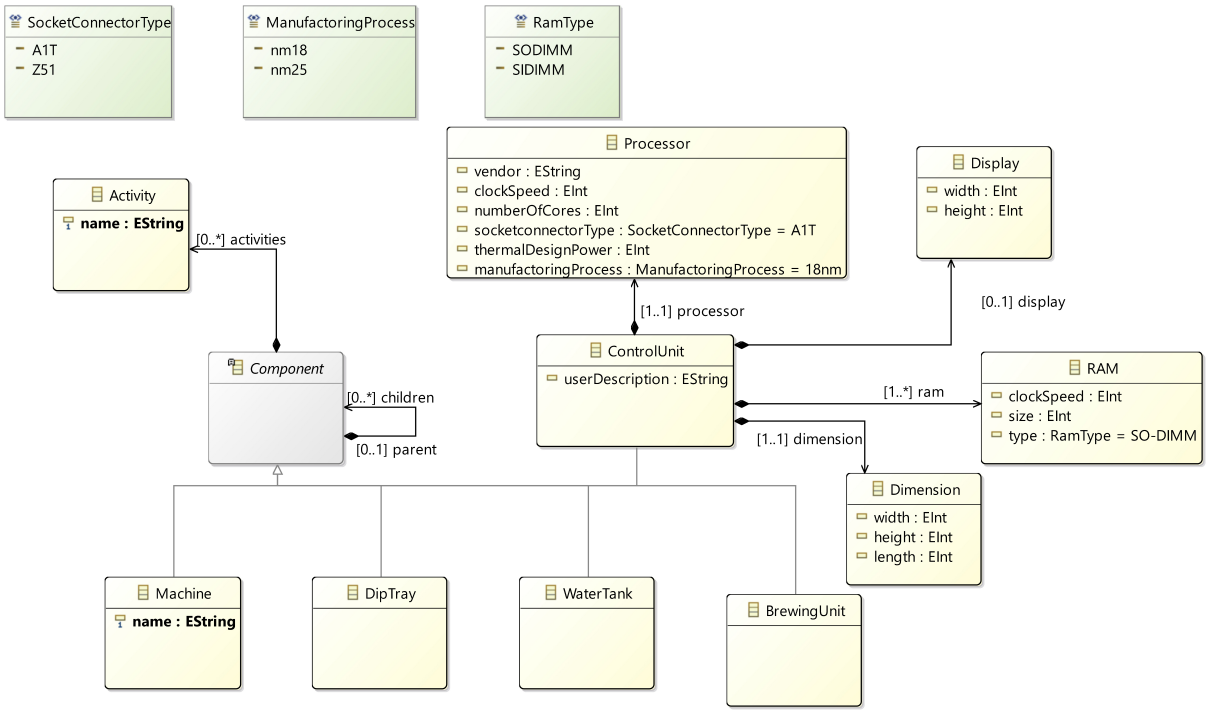


Figure B.13: UML Class diagram for a coffee brewing system (Eclipse Modelling Tools).

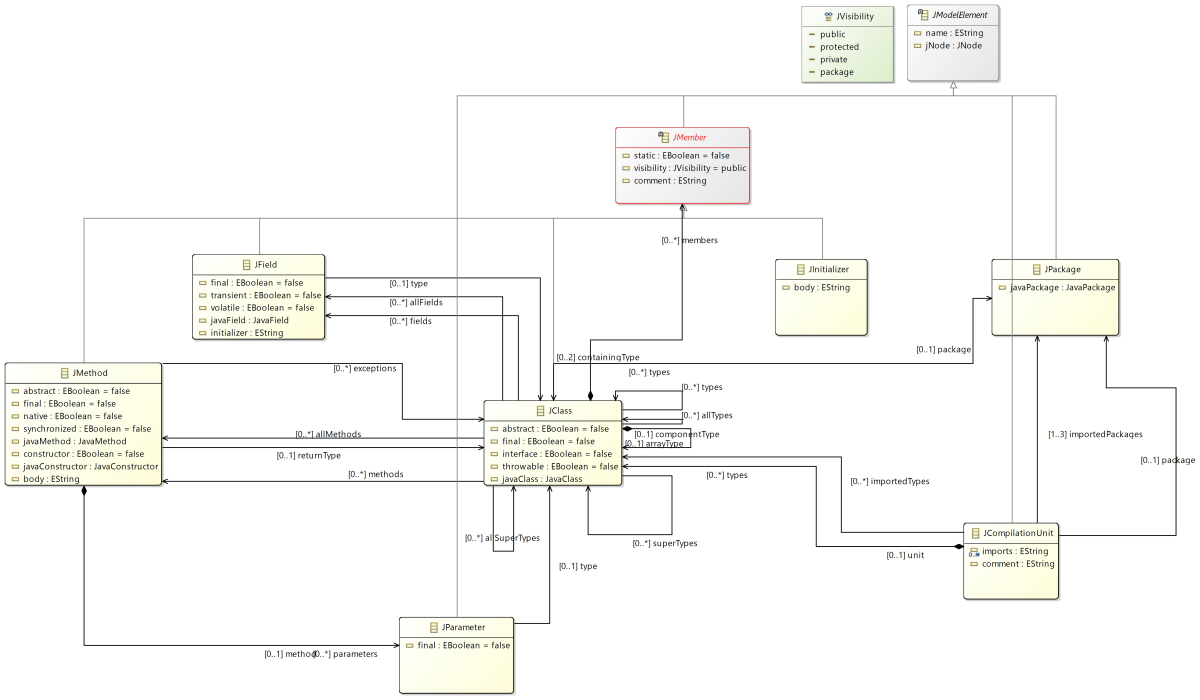


Figure B.14: UML Class diagram for a Java compiler (Eclipse Modelling Tools).

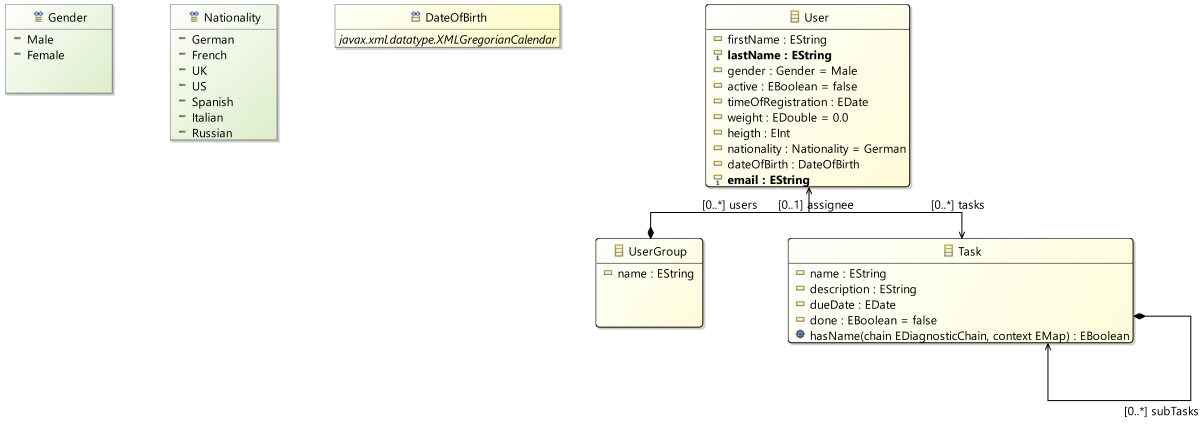


Figure B.15: UML Class diagram for a task management system (Eclipse Modelling Tools).

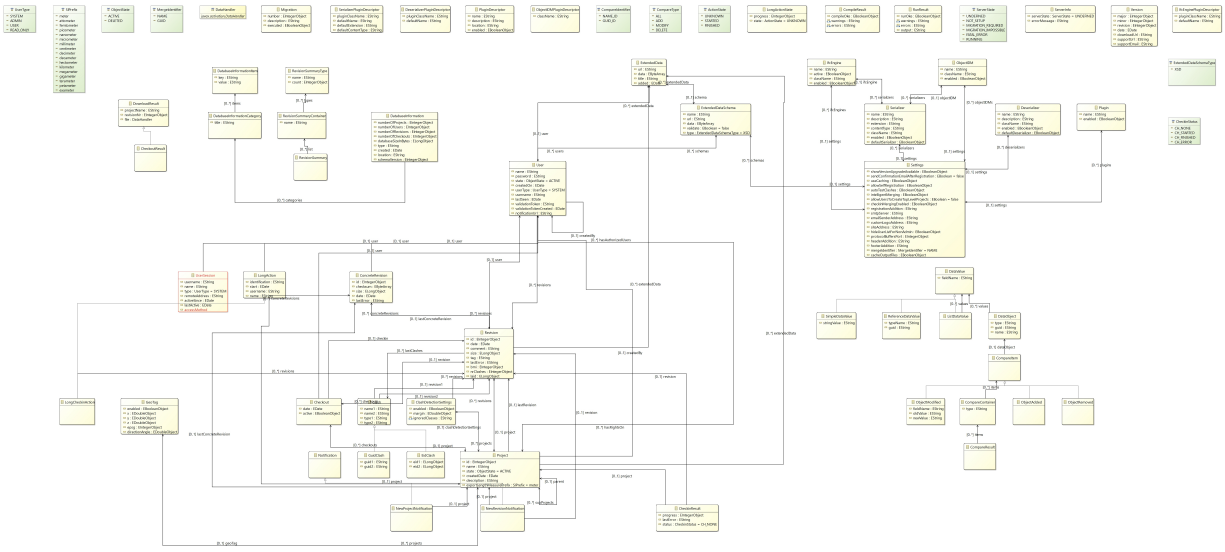


Figure B.16: UML Class diagram for a retail store system (Eclipse Modelling Tools).

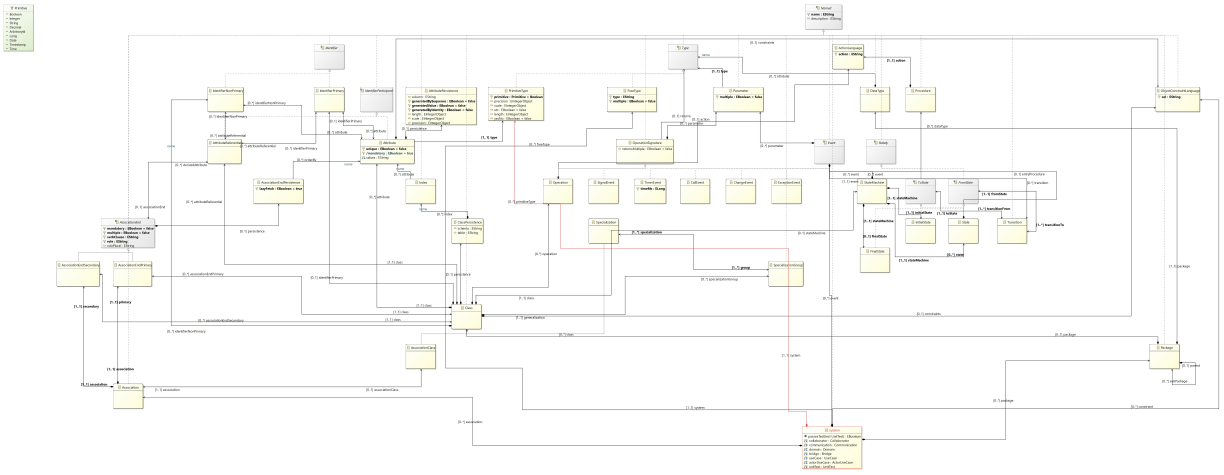


Figure B.17: UML Class diagram for Model to code compilation software (Eclipse Modelling Tools).

B.2.3 MagicDraw UML Class Diagrams

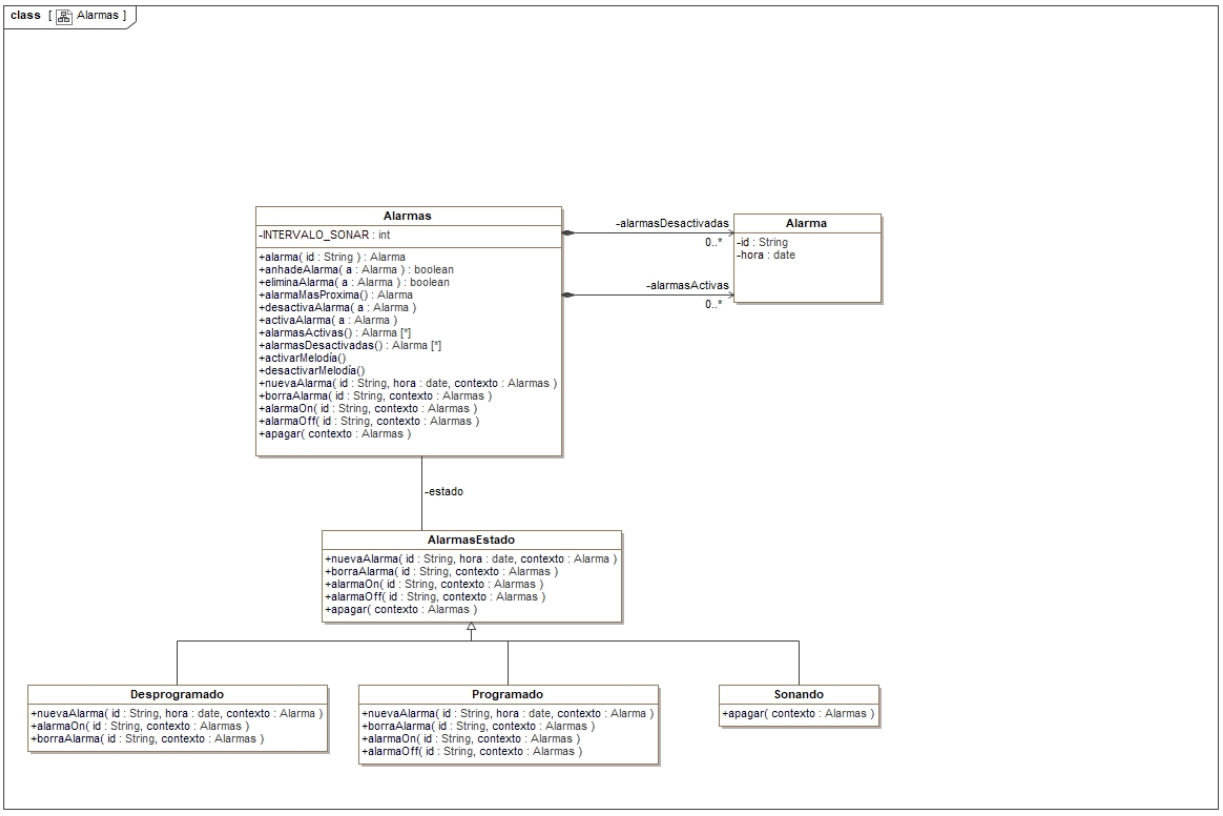


Figure B.18: UML Class diagram for an alarm system (MagicDraw).

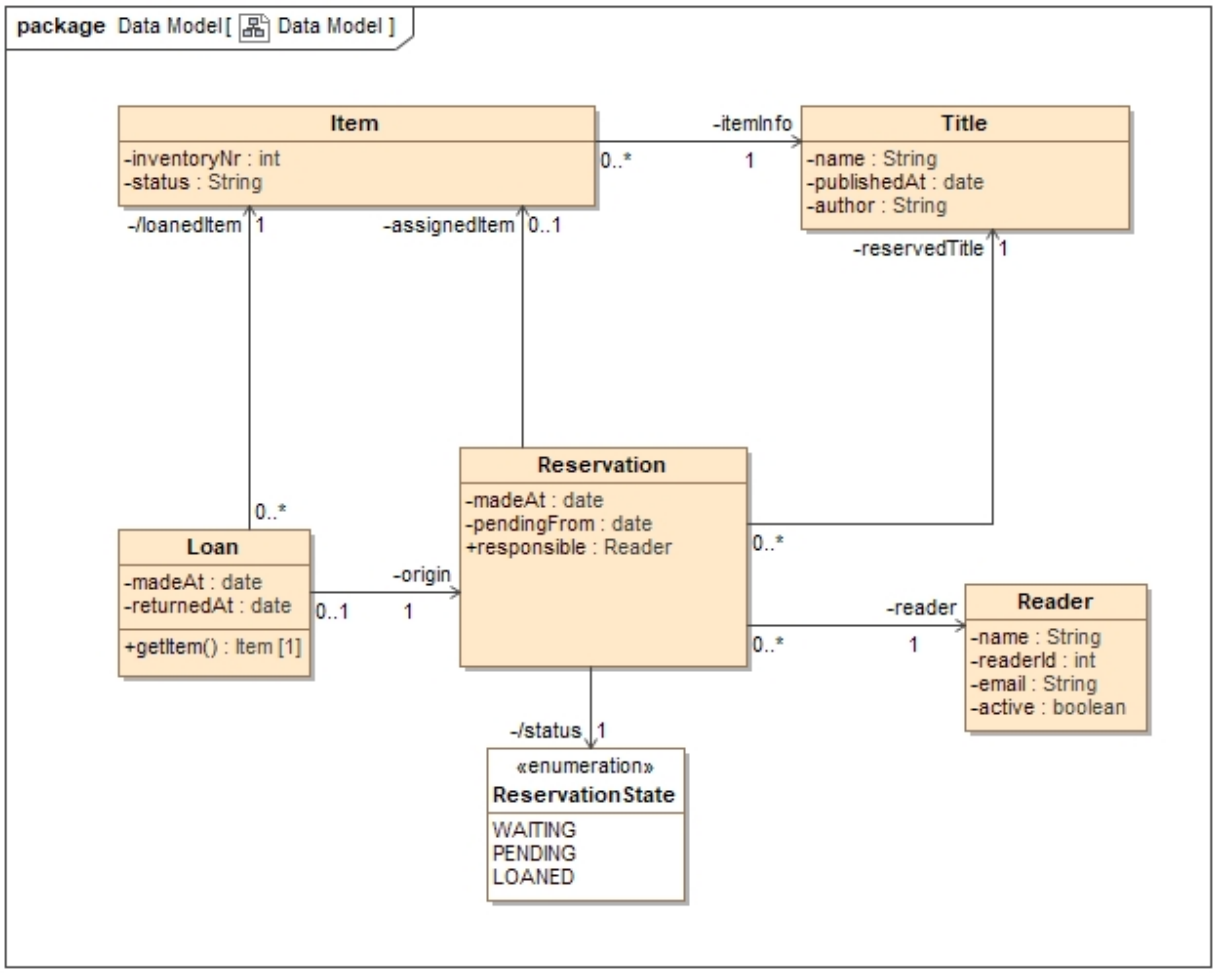


Figure B.19: UML Class diagram for a library booking system (MagicDraw).

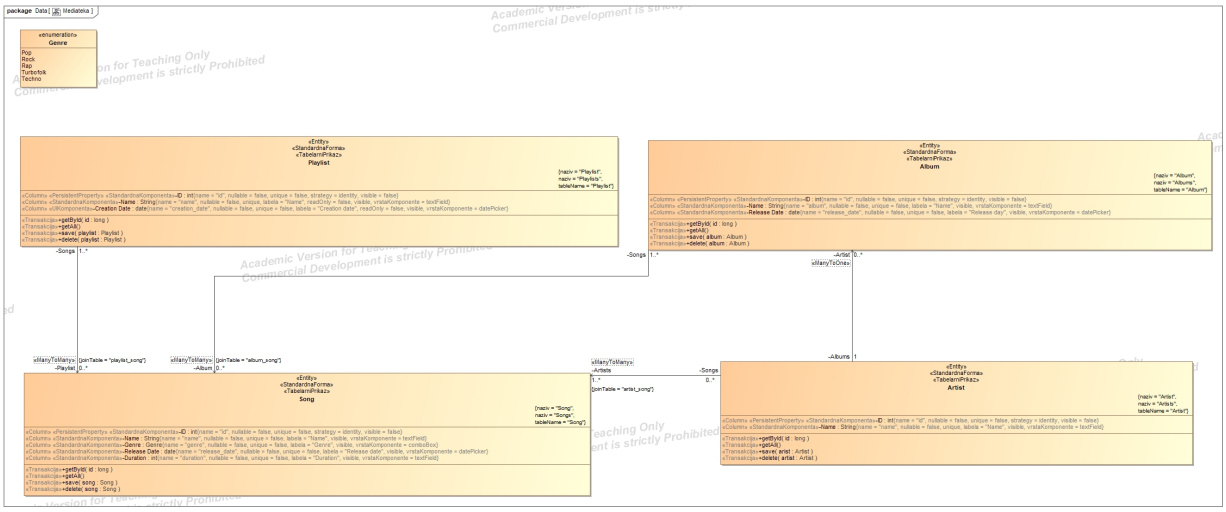


Figure B.20: UML Class diagram for a music management system (MagicDraw).

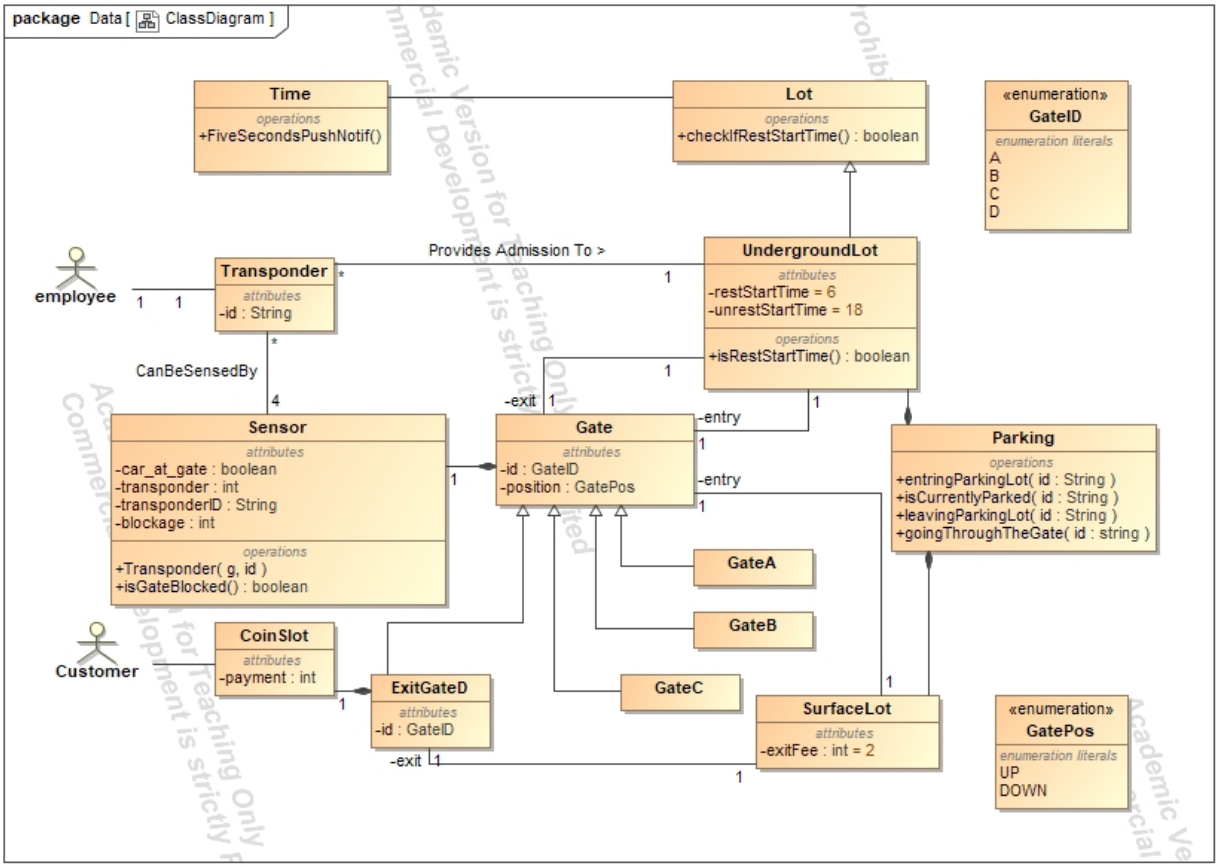


Figure B.21: UML Class diagram for a parking lot gate system (MagicDraw).

B.2.4 UMLDesigner UML Class Diagrams

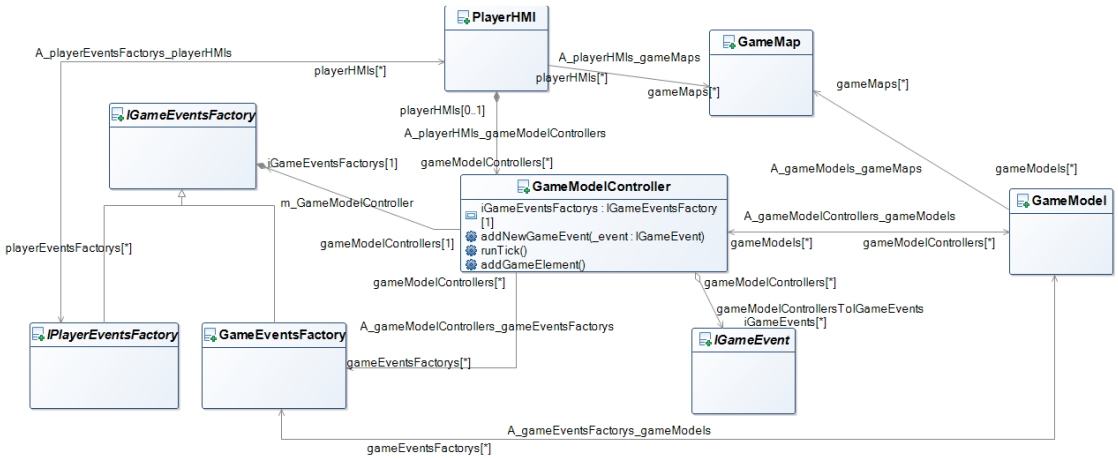


Figure B.22: UML Class diagram for a custom video game engine (UMLDesigner).

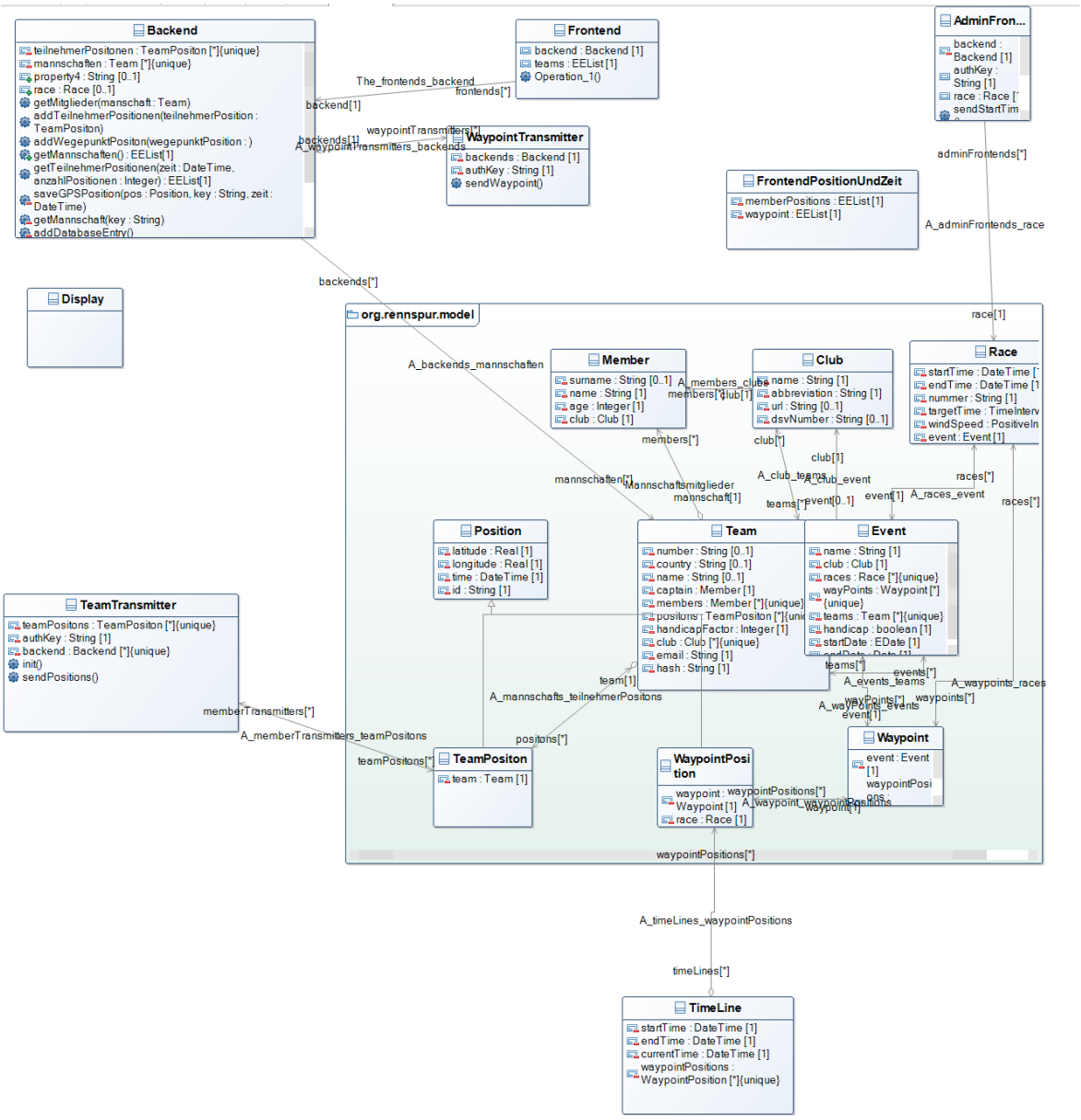


Figure B.23: UML Class diagram for a race management system (UMLDesigner).

B.3 Simulink Block Diagrams

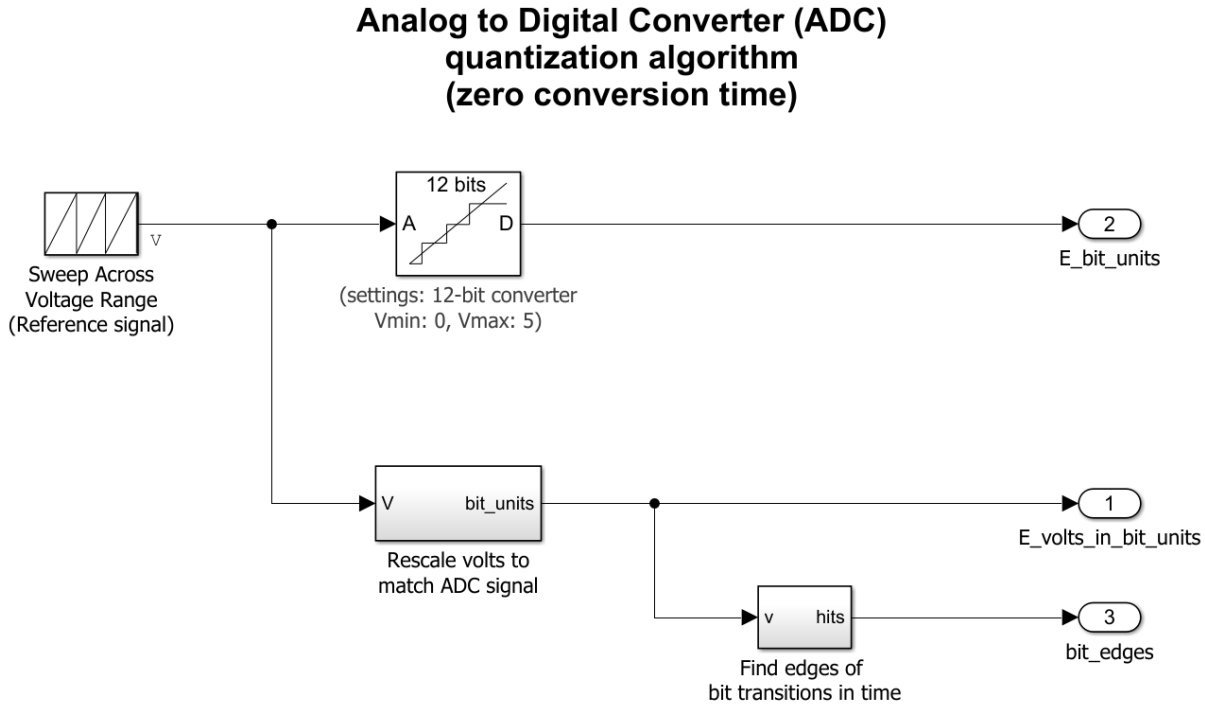
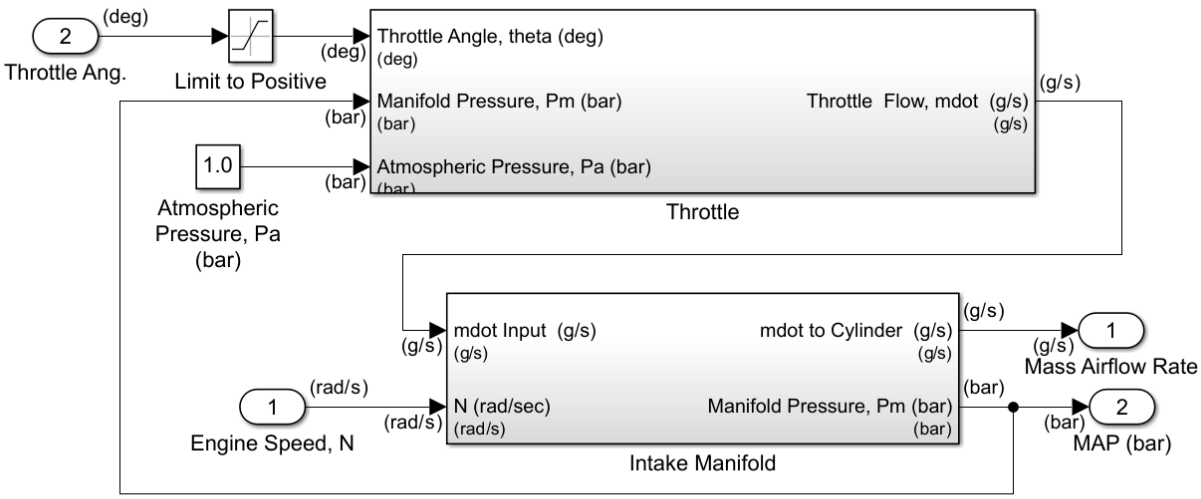


Figure B.24: Simulink Block diagram for an analog to digital converter quantization algorithm (Simulink).



Air-Fuel Intake Dynamics

Figure B.25: Simulink Block diagram for the dynamics of air-fuel intake (Simulink).

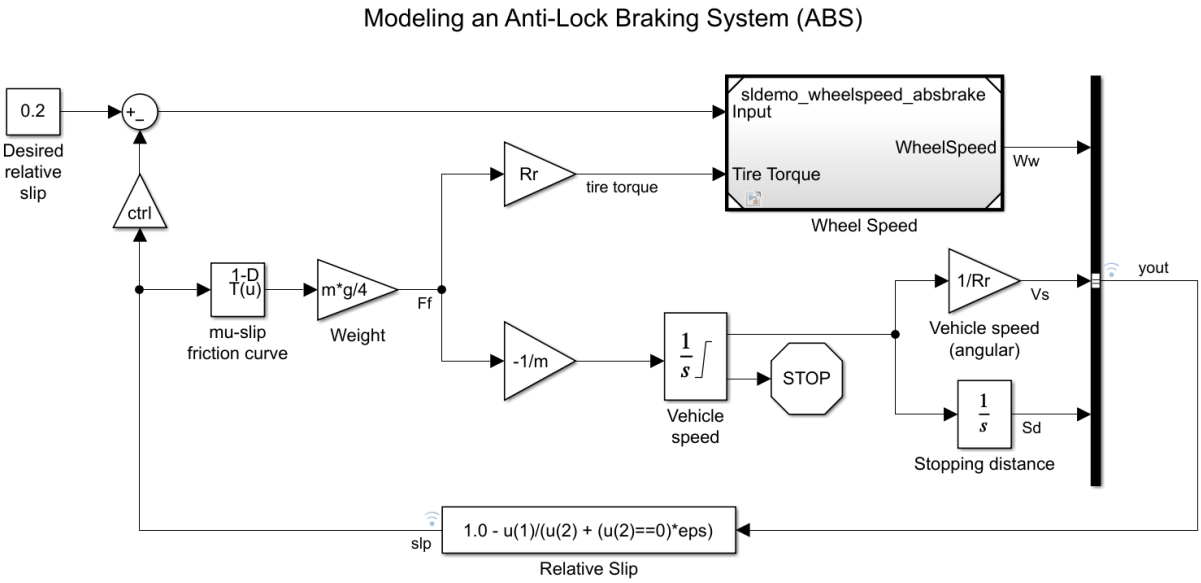


Figure B.26: Simulink Block diagram for an anti-lock brake system (Simulink).

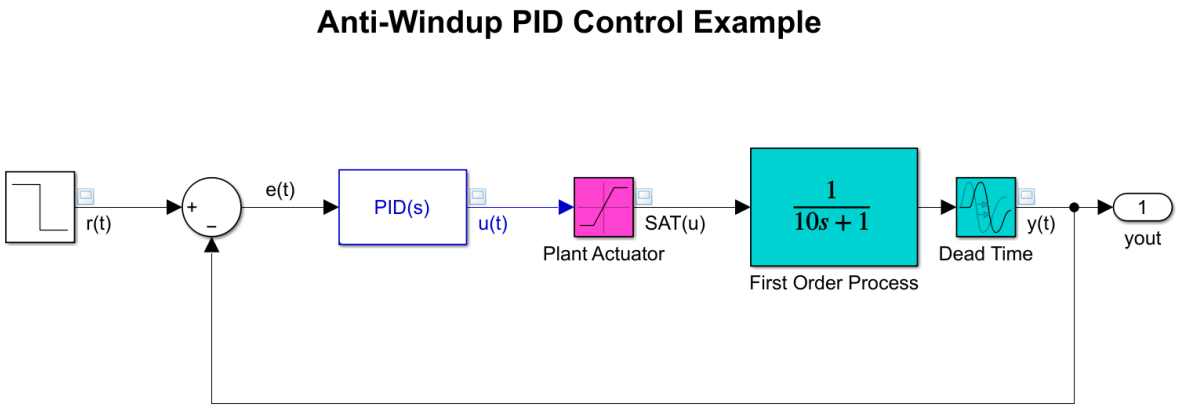


Figure B.27: Simulink Block diagram for a sample anti-windup PID control system (Simulink).

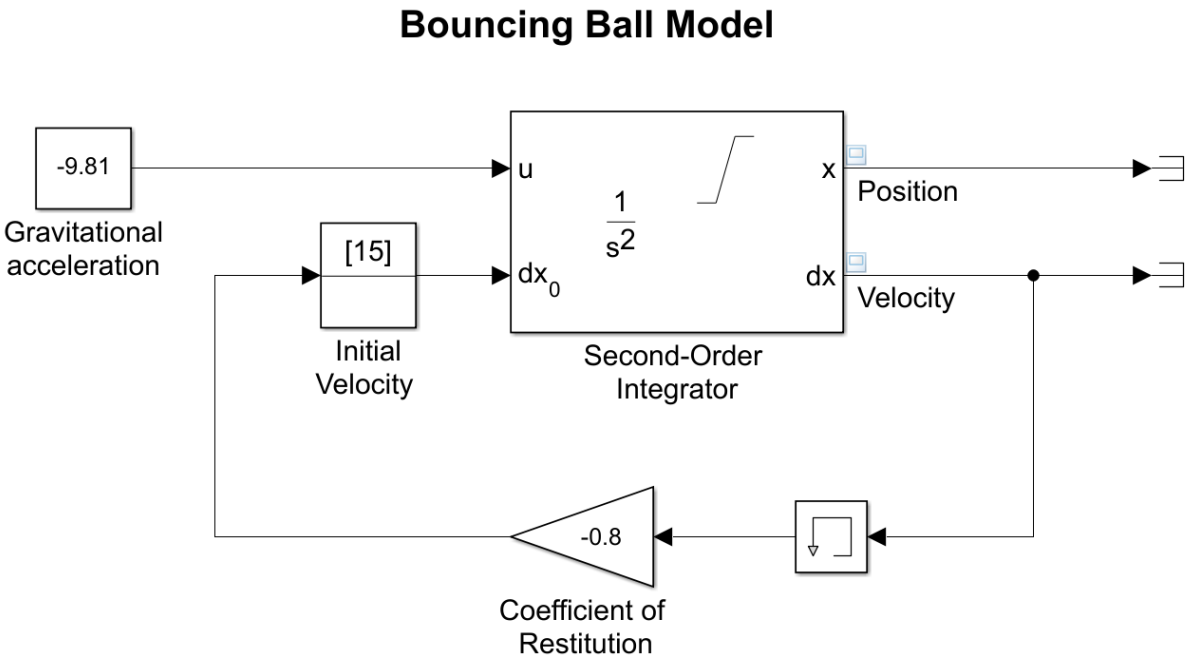


Figure B.28: Simulink Block diagram for a bouncing ball (Simulink).

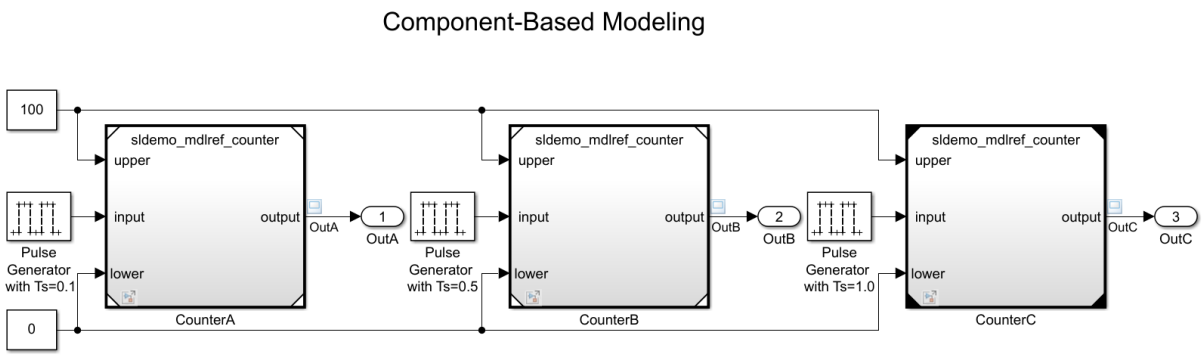


Figure B.29: Simulink Block sample diagram for component-based Modelling (Simulink).

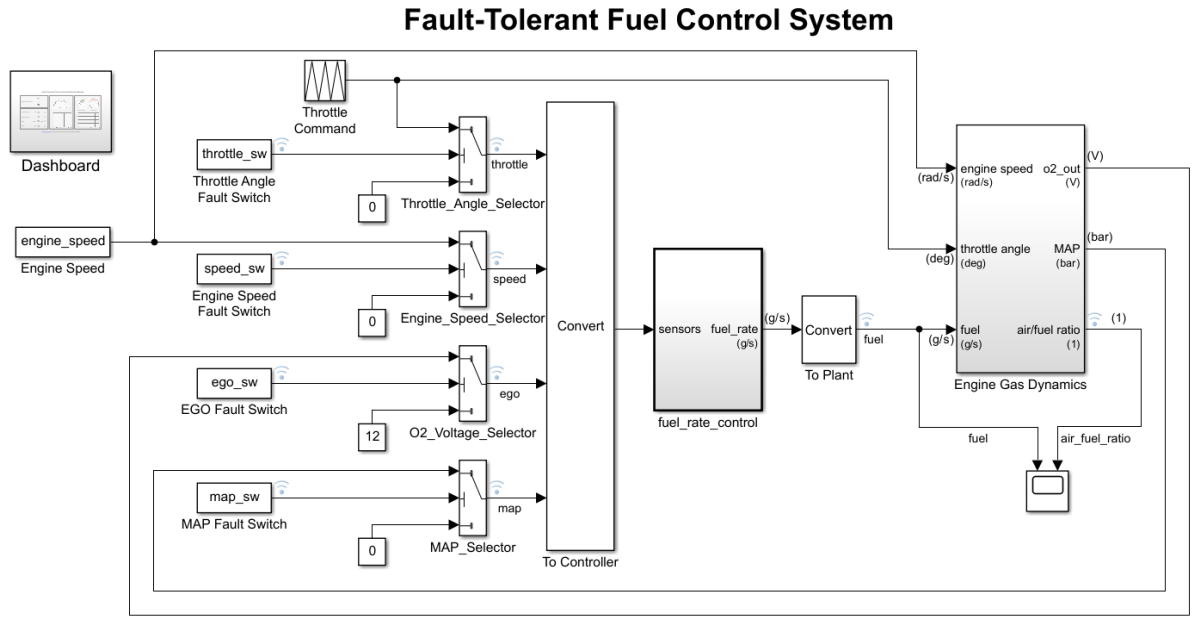


Figure B.30: Simulink Block diagram for a fault-tolerant fuel control system (Simulink).

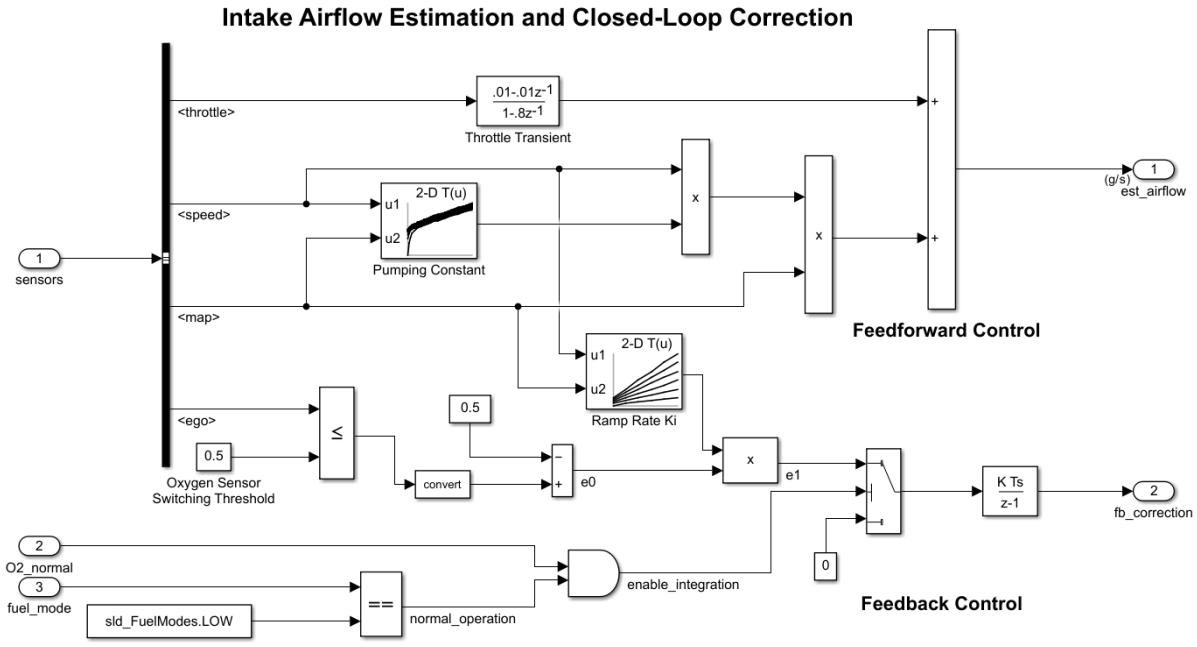


Figure B.31: Simulink Block diagram for intake airflow estimation and closed loop correction (Simulink).

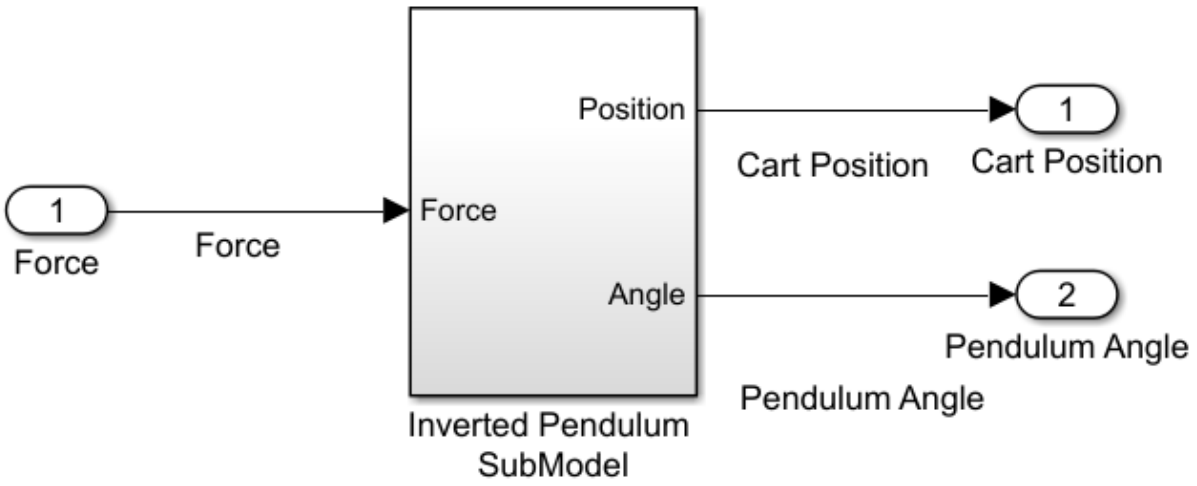


Figure B.32: Simulink Block diagram for a PID tuning system, with Figures B.33 and B.34 (Simulink).

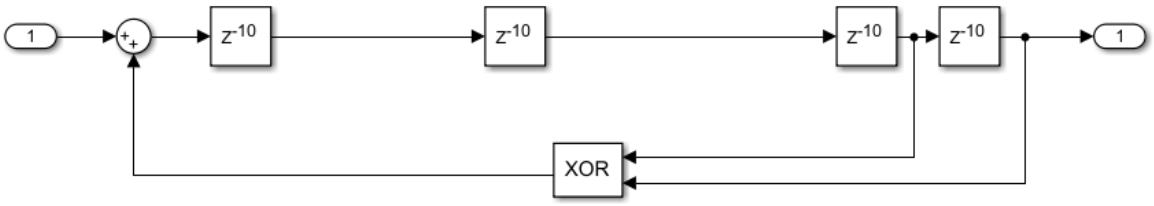


Figure B.33: Simulink Block diagram for a PID tuning system, with Figures B.32 and B.34 (Simulink).

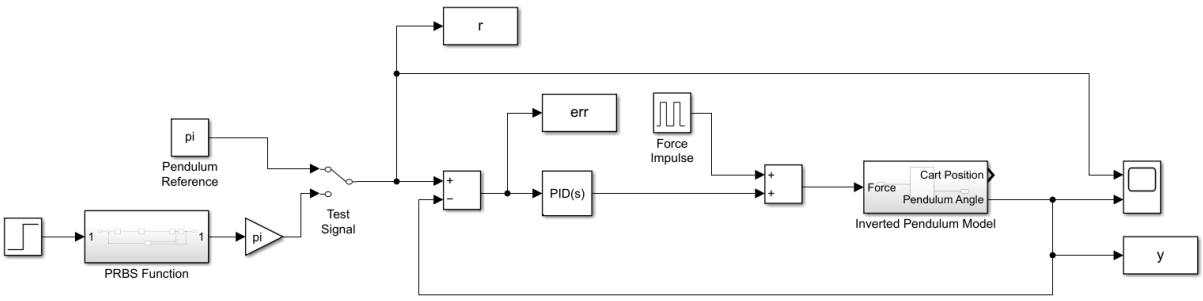


Figure B.34: Simulink Block diagram for a PID tuning system, with Figures B.33 and B.32 (Simulink).

B.4 Arcadia Diagrams

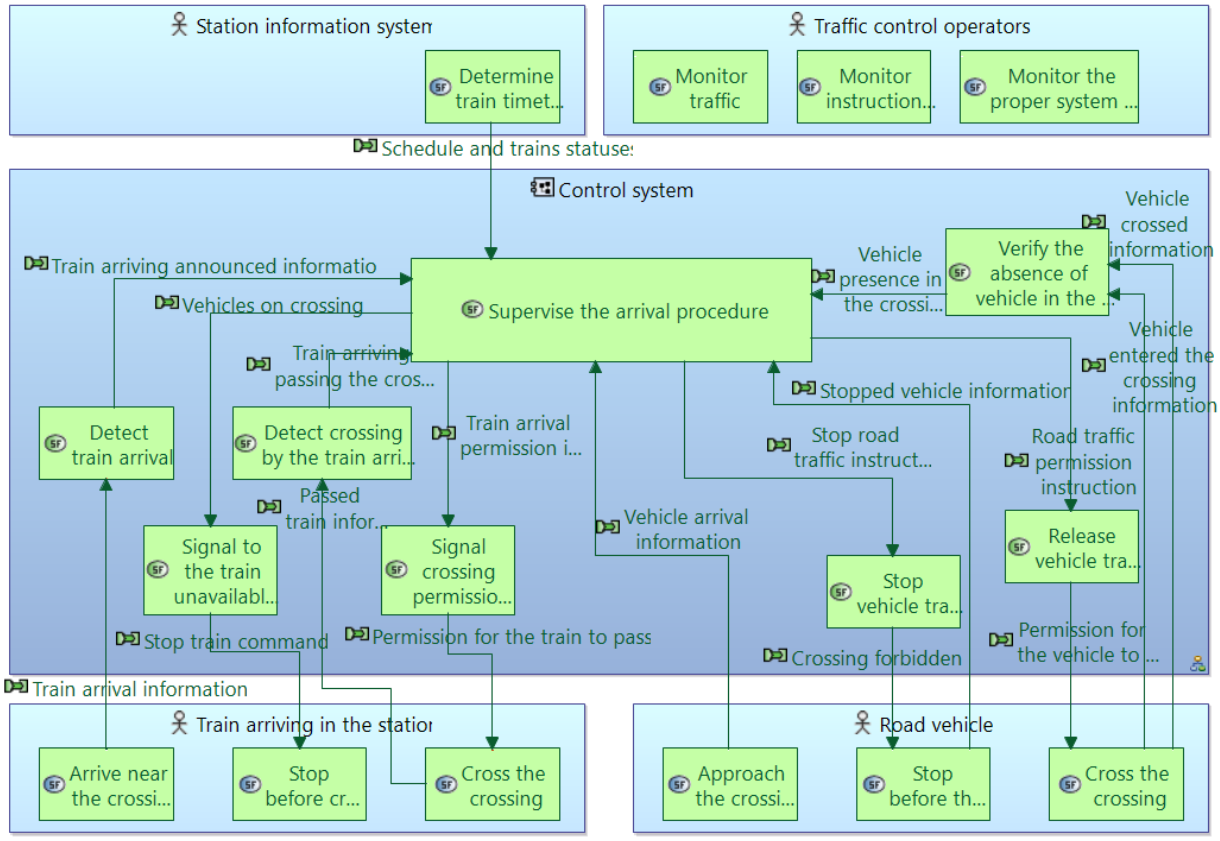


Figure B.35: Arcadia diagram for a train crossing system.

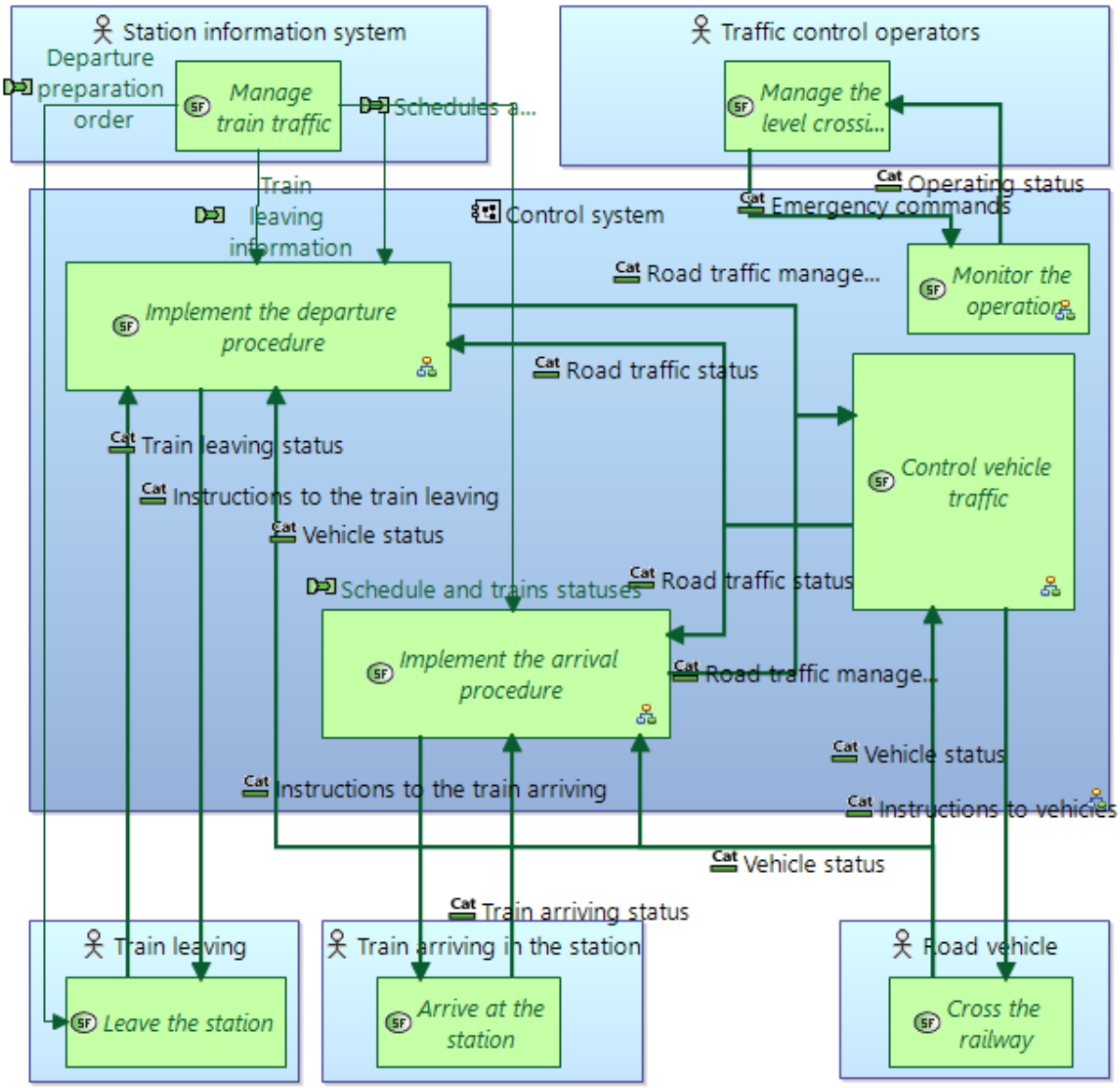


Figure B.36: A second Arcadia diagram from a train crossing system.

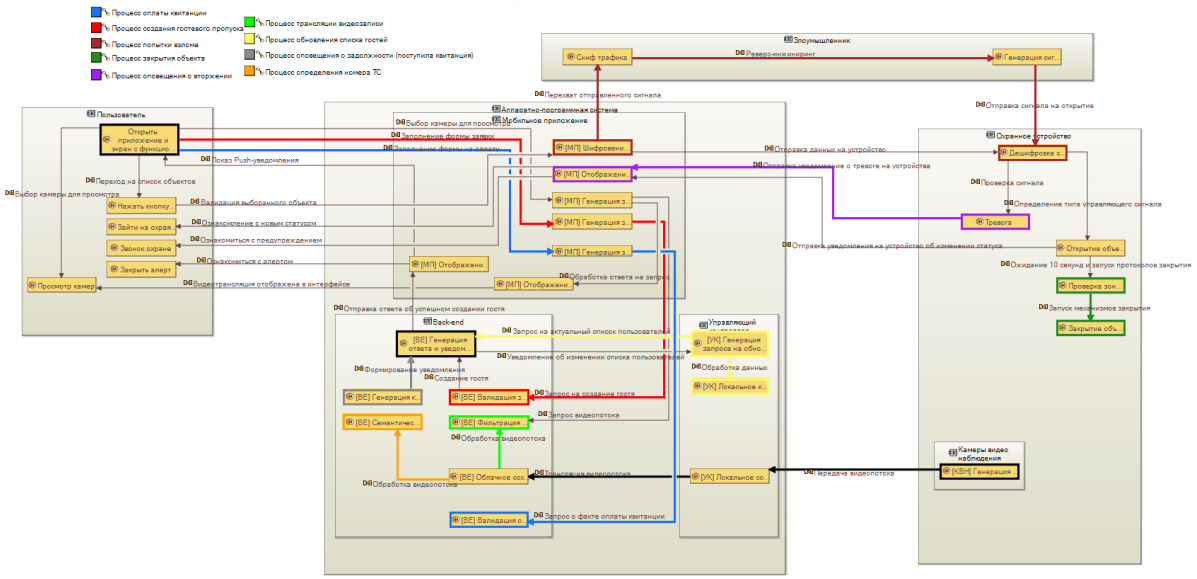


Figure B.37: Arcadia diagram for a security system.

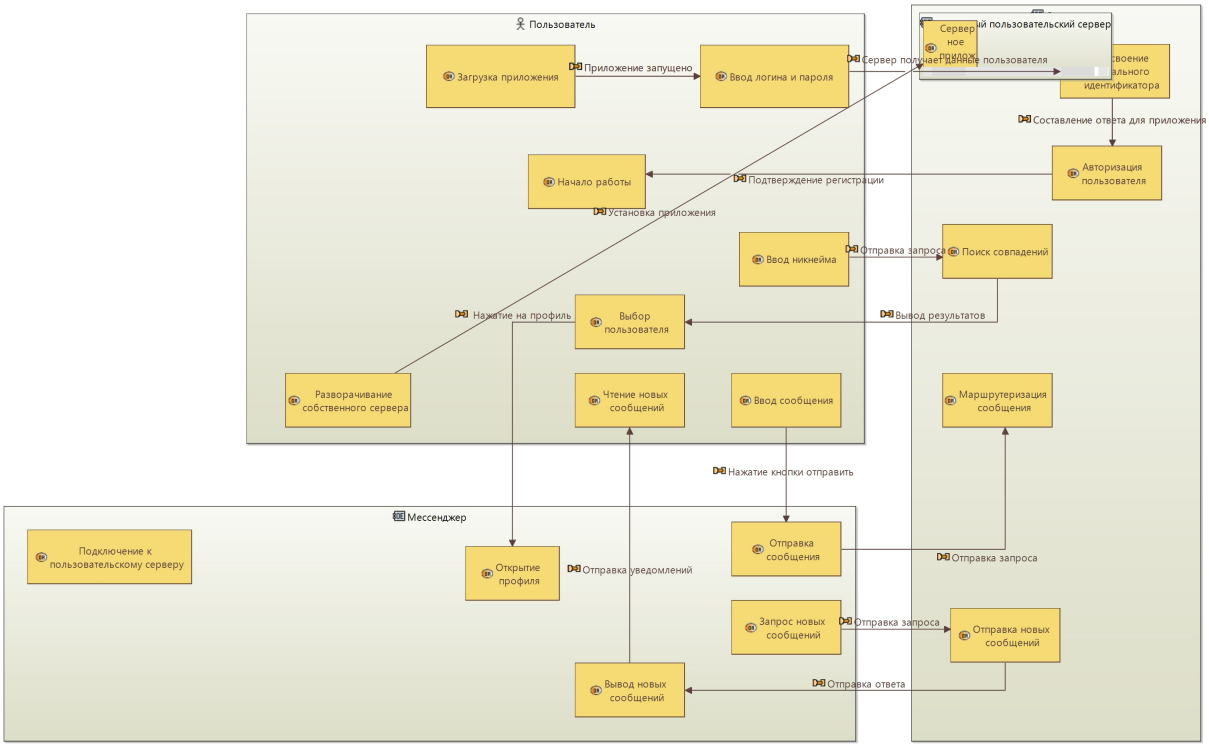


Figure B.38: Arcadia diagram for an unknown system.

B.5 Feature Models

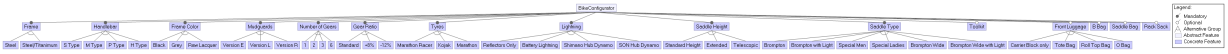


Figure B.39: Feature Model diagram for a bicycle configurator system (FeatureIDE).

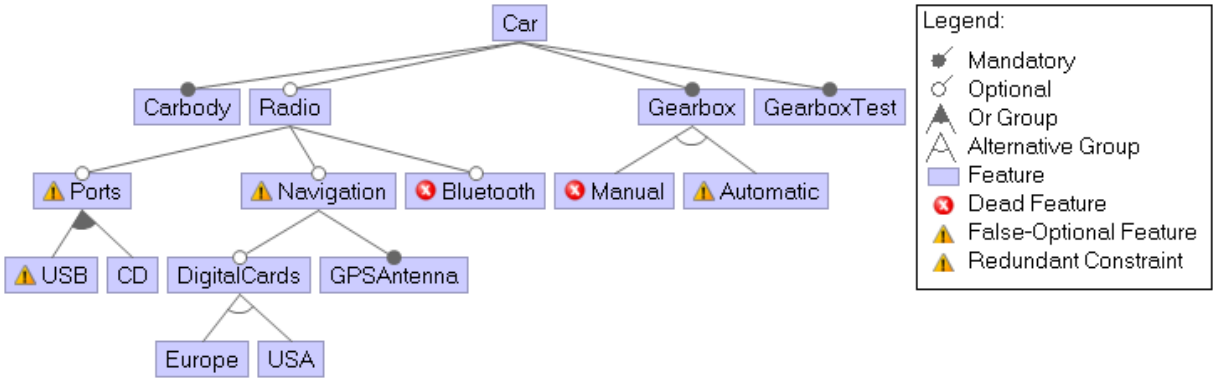


Figure B.40: Feature Model diagram for a simple car Model (FeatureIDE).

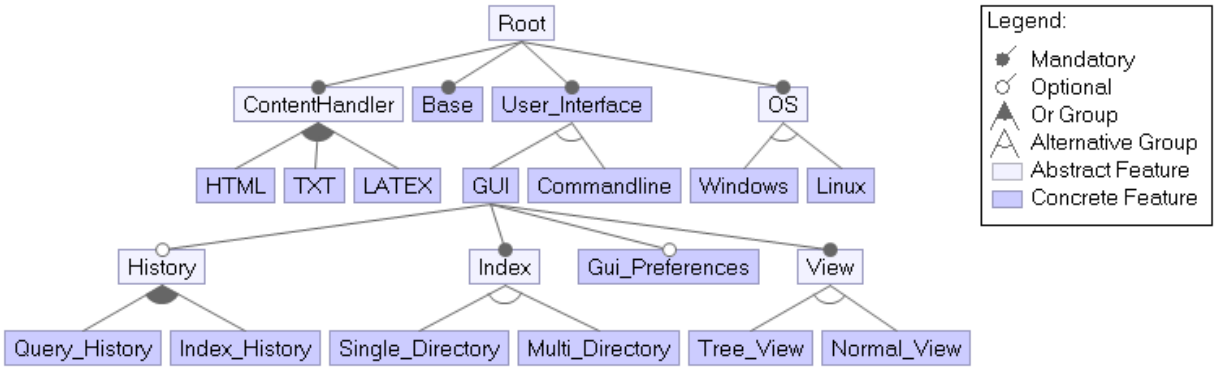


Figure B.41: Feature Model diagram for a desktop searching system (FeatureIDE).

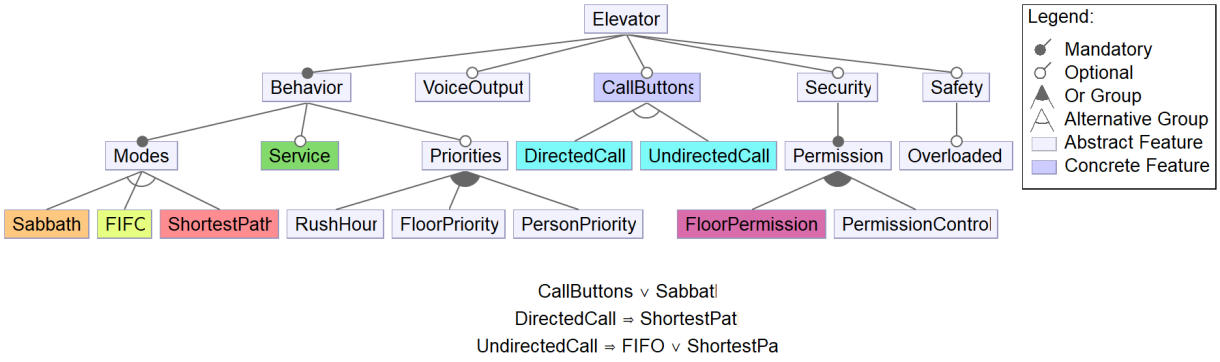


Figure B.42: Feature Model diagram for an elevator system (FeatureIDE).

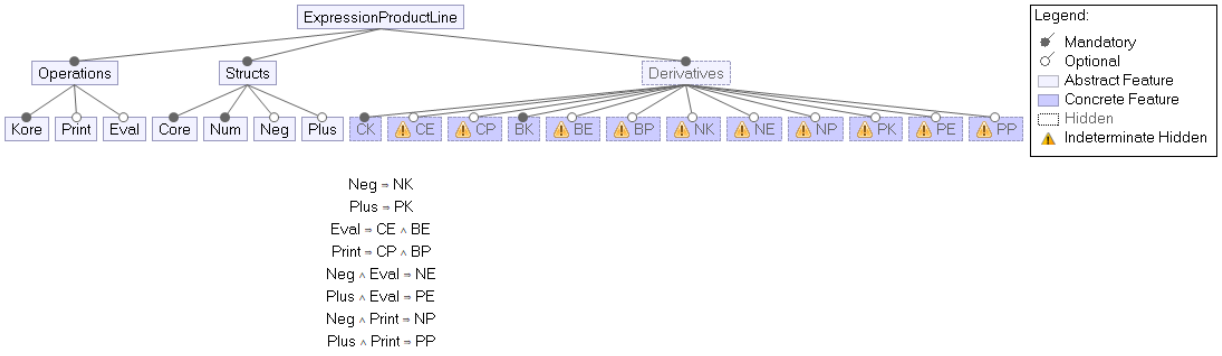


Figure B.43: Feature Model diagram for programming expressions expressed as a product line (FeatureIDE).

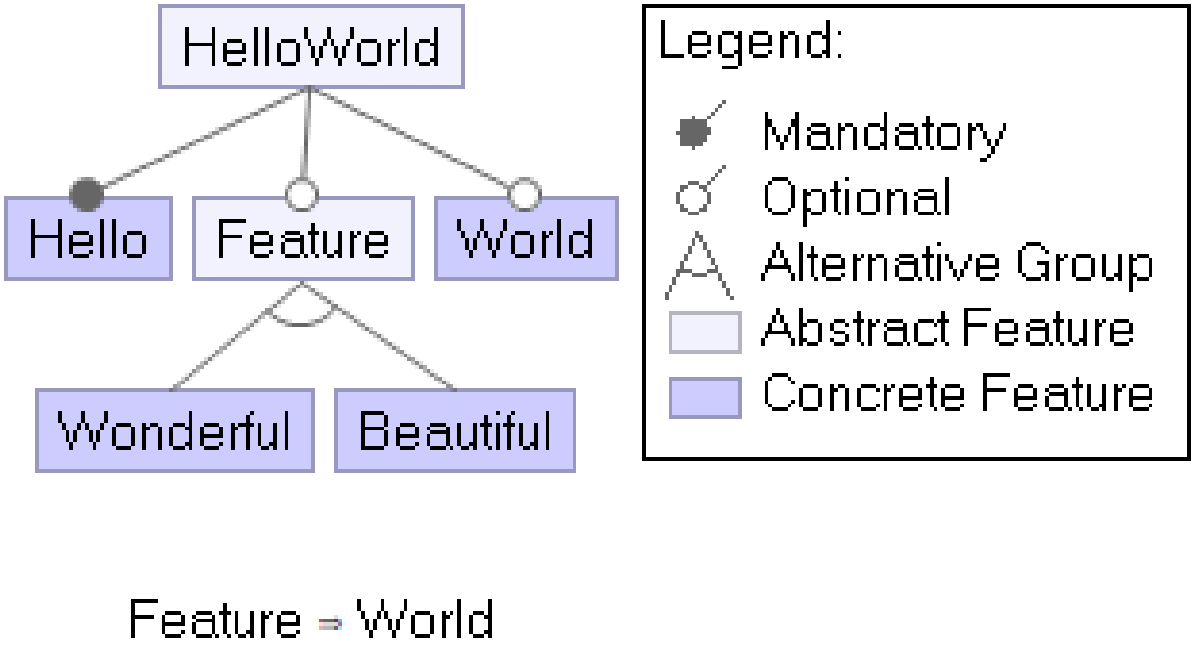


Figure B.44: Feature Model diagram for a simple Hello World program (FeatureIDE).

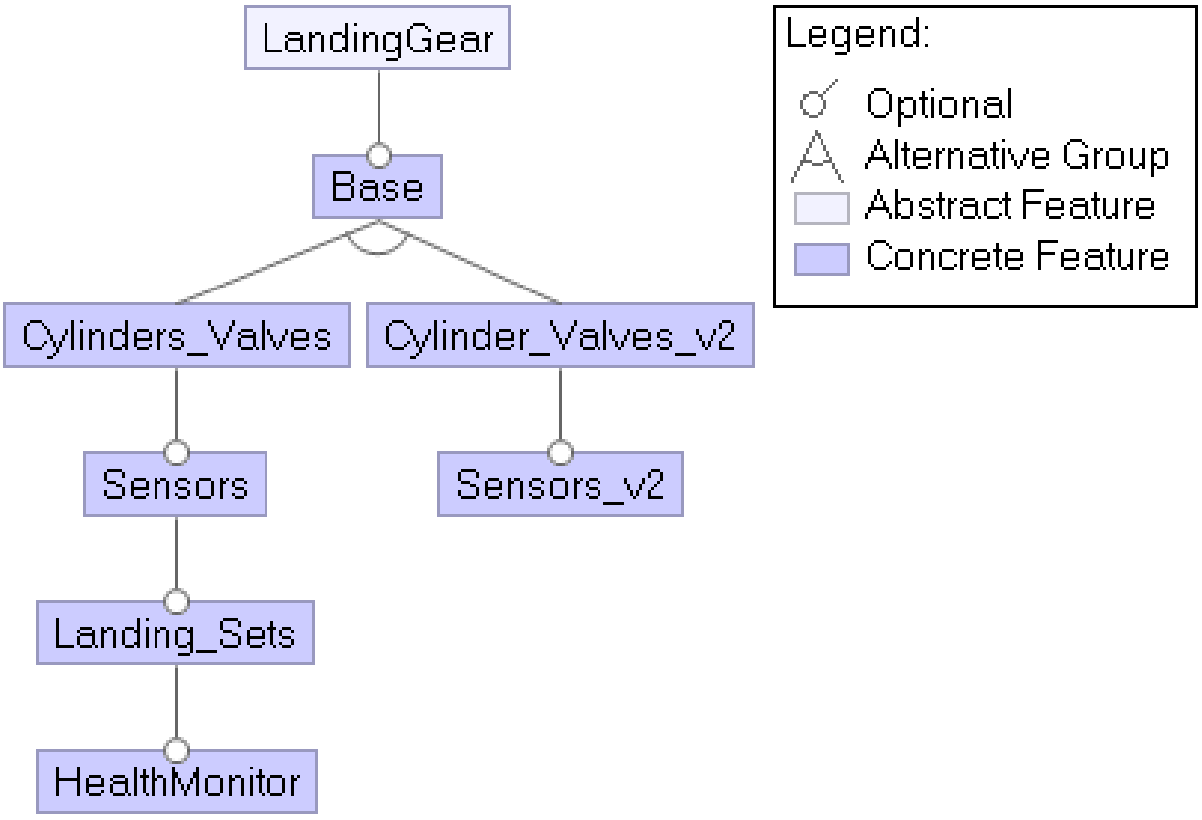


Figure B.45: Feature Model diagram for the landing gear of a plane (FeatureIDE).

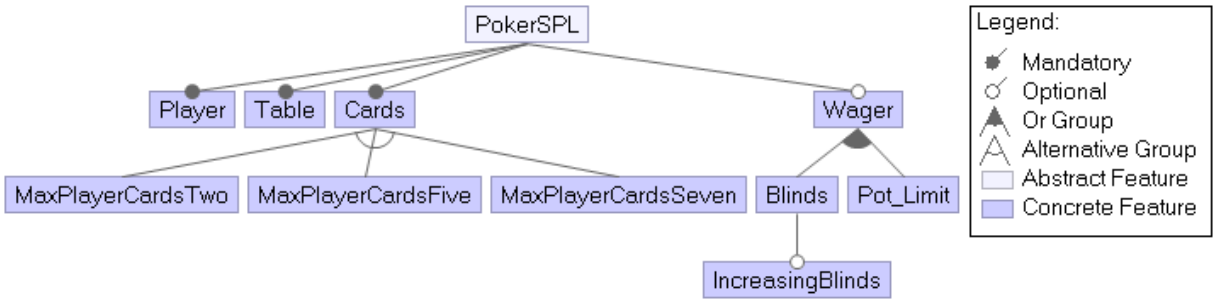


Figure B.46: Feature Model diagram for a game of Poker (FeatureIDE).

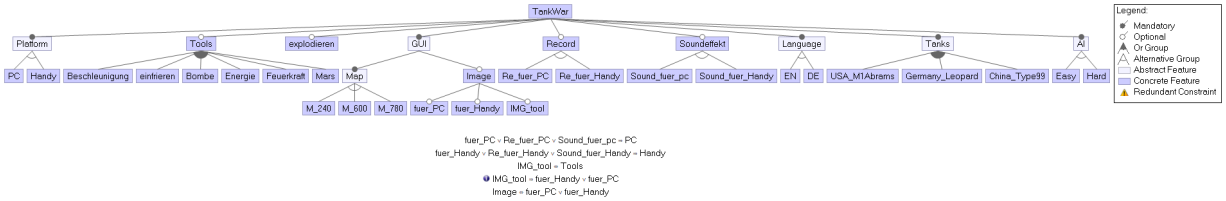


Figure B.47: Feature Model diagram for a game called TankWar (FeatureIDE).

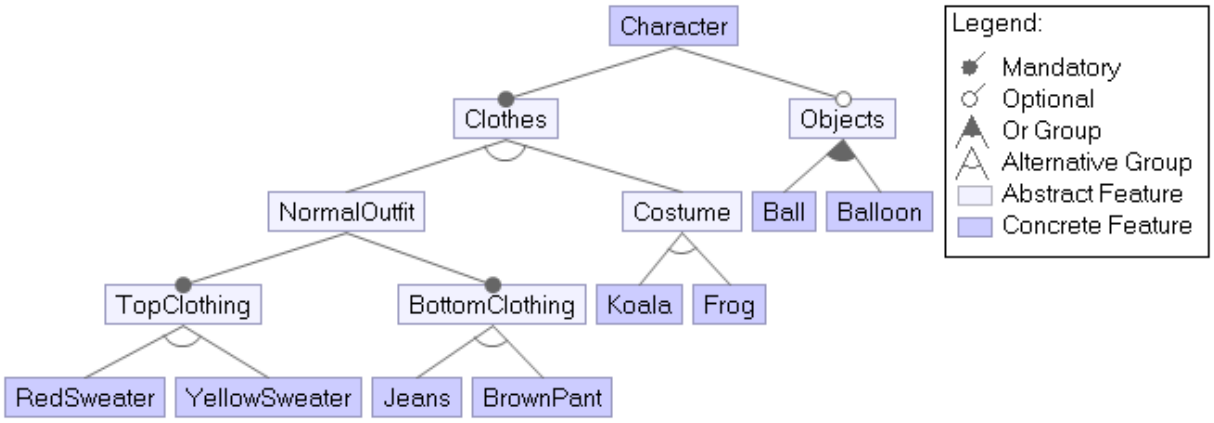


Figure B.48: Feature Model diagram for fictional characters (FeatureIDE).