

Chapter 5

Design and Implementation

Section 4.3 presented requirements for structures and processes for identifying and managing co-evolution. This chapter describes the way in which the requirements have been addressed. Several related structures have been implemented, using domain-specific languages, metamodeling and model management operations. Figure 5.1 summarises the contents of the chapter. To facilitate the management of non-conformant models with existing modelling frameworks, a metamodel-independent syntax was devised and implemented (Section 5.1). To address some of the challenges faced in user-driven co-evolution, an OMG specification for a textual modelling notation was implemented (Section 5.2). Finally, a model transformation language – tailored for model migration and centred around a novel approach to relating source and target model elements – was designed and implemented (Sections 5.3 and 5.4).

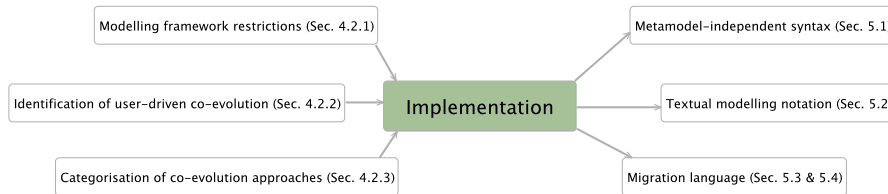


Figure 5.1: Implementation chapter overview.

The structures presented in this chapter are interoperable as shown in Figure 5.2. In particular, the modelling framework extensions provided by the metamodel-independent syntax are used to provide conformance checking for the textual modelling notation, and to enable partial migration for the model migration language. The structures were separated to facilitate re-use of the conformance checking services provided by the metamodel-independent syntax. Table 5 shows the relationship between the proposed structures and the thesis requirements (Section 4.3).

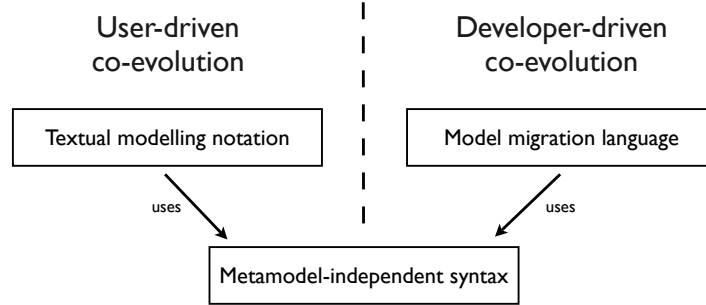


Figure 5.2: The relationships between the proposed structures

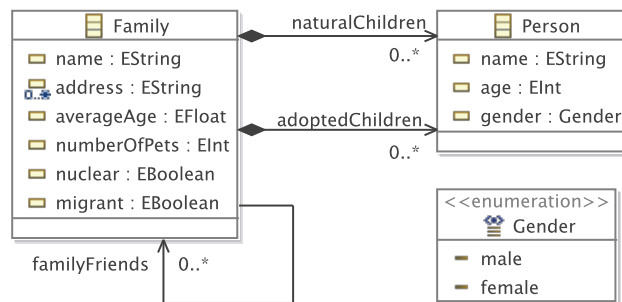
| Structure (Section) | Requirement |
|------------------------------------|---|
| Metamodel-independent syntax (5.1) | This thesis must investigate the extension of existing modelling frameworks to support the loading of non-conformant models and conformance checking of models against other metamodels. |
| Textual Modelling Notation (5.2) | This thesis must demonstrate a user-driven co-evolution process that enables the editing of non-conformant models without directly manipulating the underlying storage representation and provides a conformance report for the original model and evolved metamodel. |
| Model Migration Language (5.3) | This thesis must compare and evaluate existing languages for specifying model migration strategies. |
| Model Migration Language (5.4) | This thesis must implement and evaluate a domain-specific language for specifying and executing model migration strategies, comparing it to existing languages for specifying model migration strategies. |

Table 5.1: The relationship between the thesis requirements and the proposed structures.

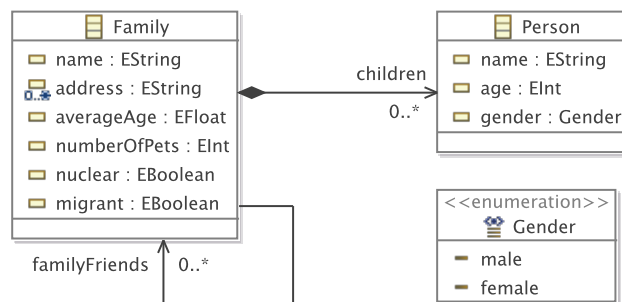
5.1 Metamodel-Independent Syntax

Section 4.2.1 discussed the way in which modelling frameworks implicitly enforce conformance, and hence prevent the loading of non-conformant models. Additionally, modelling frameworks provide little support for checking the conformance of a model with other versions of a metamodel, which is potentially useful during metamodel installation. In Section 4.3, these concerns lead to the identification of the following requirement: *This thesis must investigate the extension of existing modelling frameworks to support the loading of non-conformant models and conformance checking of models against other metamodels.*

This section describes the way in which existing modelling frameworks load and store models using metamodel-specific binding mechanisms, proposes an alternative binding mechanism using a metamodel-independent syntax, and demonstrates how this facilitates automatic consistency checking. The work presented in this section has been published in [Rose *et al.* 2009a].



(a) Original metamodel.



(b) Evolved metamodel.

Figure 5.3: Evolution of a families metamodel, based on the metamodel in [OMG 2004].

5.1.1 Metamodel Evolution Example: Families

This section uses the example of metamodel evolution in Figure 5.3. The metamodels in Figure 5.3 have been constructed in Ecore, the metamodeling language of EMF, which is based on MOF (Section 2.1.3). The metamodels use Ecore types such as EString and EFloat. The intent of most of the metamodel types and features (such as Family and numberOfPets) should be obvious from their names. The nuclear attribute on the Family type is used to indicate that the family “comprises only a father, a mother, and children.” [Merriam-Webster 2010], and not extended family members (such as cousins or grandparents).

In Figure 5.3(a), naturalChildren and adoptedChildren are modelled as separate features, and, in Figure 5.3(b), they are modelled as a single feature, children.

Models that specify values for the naturalChildren or adoptedChildren features do not conform to the evolved metamodel. For example, the model in Figure 5.4 represents a Family comprising two Persons, conforms to the original metamodel, and does not conform to the evolved metamodel. Using the families metamodel and model, the sequel explains why existing modelling frameworks cannot be used to load non-conformant models.

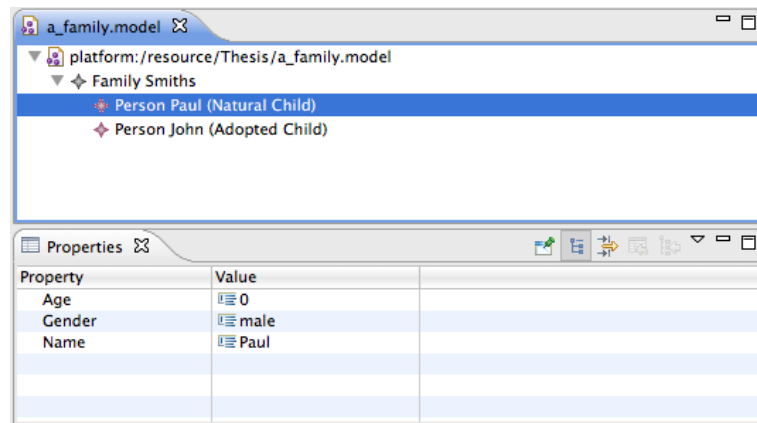


Figure 5.4: A family model, which conforms to the metamodel in Figure 5.3(a)

5.1.2 Binding to a Specific Metamodel

To load a model, existing modelling frameworks construct objects in the underlying programming language in a process termed *binding* (Section 4.2.1). The metamodel defines the way in which model elements will be bound, and binding is strongly-typed. Figure 5.5 illustrates the results of binding the family model in Figure 5.4 to the original families metamodel in Figure 5.3(a).

The objects in Figure 5.5 instantiate types that are defined in the metamodel, such as `Family` and `Person`. In other words, binding results in a *metamodel-specific* representation of the model.

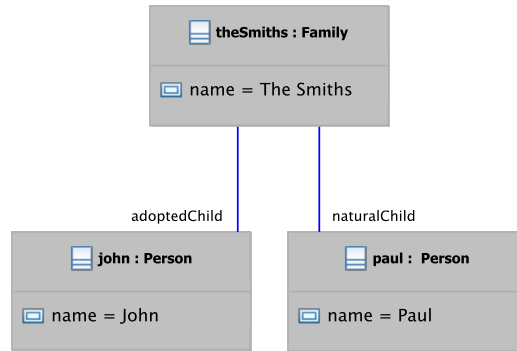


Figure 5.5: Objects resulting from the binding of a conformant model

Metamodel-specific binding fails for non-conformant models. For example, attempting to bind the family model in Figure 5.4 to the evolved families fails because the model uses `naturalChildren` and `adoptedChildren` features for the type `Family`, and these features are not defined by the metamodel in Figure 5.3(b).

Because non-conformant models cannot be loaded, model migration must be performed by editing the underlying storage representation, which can be error-prone and tedious (Section 4.2.2). The sequel discusses potential solutions for loading non-conformant models.

5.1.3 Potential Solutions for Loading Non-Conformant Models

Two potential approaches to binding (and hence loading) non-conformant models have been considered and are now discussed. The benefits and drawbacks of each approach have been compared, which resulted in the selection of the second approach, binding to a metamodel-independent syntax.

Store metamodel history

Presently, modelling frameworks are used to store only the latest version of a metamodel, and hence binding fails for models that conform to a previous version of the metamodel. If modelling frameworks could access old versions of a metamodel, models that do not conform to the current version of the metamodel could be loaded by binding to a previous version of the metamodel.

A metamodel-independent syntax

Models can always be successfully bound to a *metamodel-independent* representation, such as the one shown in Figure 5.6. Binding each model element results in the instantiation of a metamodel-independent type (`Object` in Figure 5.6) rather than of types defined in a specific metamodel, such as `Family` or `Person`. Hence, binding is independent of the types defined in metamodels, and will succeed for non-conformant models.

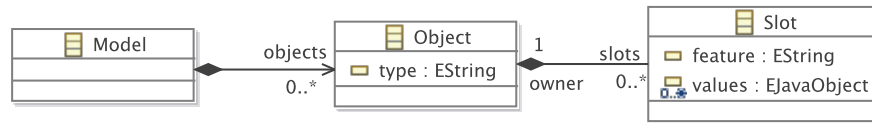


Figure 5.6: A minimal generic metamodel for MOF in Ecore, based on [OMG 2008a] and taken from [Rose *et al.* 2009a].

Benefits and drawbacks of the potential solutions

The two potential solutions for loading non-conformant models have different benefits and drawbacks, which are now discussed. Storing metamodel histories would use the binding and conformance checking services provided by existing modelling frameworks, and therefore require less implementation effort than a metamodel-independent syntax, which would require bespoke binding and conformance checking services. Furthermore, structures for managing metamodel histories might be integrated with existing approaches to managing co-evolution, such as metamodel differencing approaches (Sections 4.2.3), for switching between different versions of a MDE workflow.

Storing metamodel histories relies on the metamodel developer to enable model migration: if the metamodel developer does not provide a metamodel that contains historical data, then binding will fail for non-conformant models. Conversely, models can be bound to a metamodel-independent syntax irrespective of the actions of the metamodel developer.

A metamodel-independent syntax has been chosen because it makes fewer assumptions of the metamodel developer, and hence facilitates user-driven as well as developer-driven co-evolution.

5.1.4 Proposed Solution: A Metamodel-Independent Syntax

This section discusses the design and implementation of a metamodel-independent syntax, and of the binding and conformance checking services that are used to load non-conformant models. As discussed below, the design of the metamodel-independent syntax and conformance checking service is inspired by [OMG 2007a] and [Paige *et al.* 2007], respectively. As such, the primary contribution of this

section is the implementation and integration of the syntax and services with EMF. In addition, the syntax and services have been designed to be re-usable, and hence have been used to simplify the implementation of a textual modelling notation (Section 5.2) and a model migration language (Section 5.4).

Design

A high-level design for the way in which the metamodel-independent syntax, binding service and conformance checking service load models is shown in Figure 5.7. The **binding service** parses XMI (the canonical storage representation of models, Section 2.1.3) and produces a model that conforms to the **metamodel-independent syntax**. The **conformance checking service** is used to explicitly check the conformance of a model conforming to the metamodel-independent syntax.

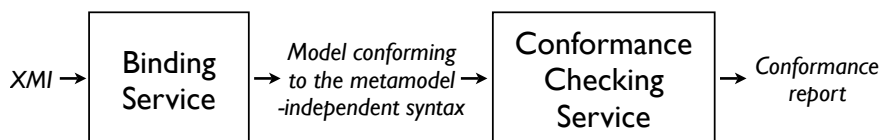


Figure 5.7: Loading models with the metamodel-independent syntax

Binding and conformance checking were split into separate services to facilitate re-use. For example, the textual modelling notation in Section 5.2 re-uses the metamodel-independent syntax and conformance checking service, in conjunction with a different binding service.

Metamodel-independent syntax The metamodel-independent syntax is used to represent a model without instantiating types defined by its metamodel. Its design was inspired by the metamodel for UML 2 [OMG 2007a] object diagrams, which describes objects in a generic, class-independent manner. UML 2 object diagrams are specified in terms of an abstract syntax (comprising, for example, `InstanceSpecification` and `Link` classes) and a concrete syntax (comprising, for example, boxes and lines). The metamodel-independent syntax proposed here is abstract. It is not used directly by metamodel developers or users and hence a concrete syntax was not required.

Abstract syntax is typically represented as a metamodel (Section 2.1.2). The metamodel in Figure 5.6 was used as an initial design for the metamodel-independent syntax, which contains a class for each type in the MOF metamodel that is instantiated in a model. In other words, `Objects` are used to represent each element of a model, and the `type` attribute is used to indicate the name of the metaclass that the `Object` intends to instantiate. Similarly, `Slots` are used to represent values in the model, and the `feature` attribute indicates the metafeature that the `Slot` intends to instantiate. The meta-

model was designed to capture the information needed to perform conformance checking (described below), and implementing the conformance checking service led to a refactored metamodel, which is presented in the sequel.

COPE (Section 4.2.3) is also built atop a metamodel-independent syntax. However, the metamodel-independent syntaxes used by COPE and proposed here were developed independently, and both were first published in 2008 (in [Rose *et al.* 2008a, Herrmannsdoerfer *et al.* 2008b]).

Metamodel-independent binding service Binding a textual representation of a model to a metamodel is a model-to-text (M2T) transformation. The metamodel-independent binding service is a M2T transformation that consumes XMI and produces a model conforming to the metamodel-independent syntax. The transformation iterates over each tag in the XMI, and creates instances of `Object` and `Slot`. For example, when encountering a tag that represent a model element, the transformation performs the steps in Figure 5.8.

Applying the metamodel-independent binding service to the families model (Figure 5.4) produces three instances of `Object`, illustrated as a UML object diagram in Figure 5.9. For clarity, instances of `Object` are shaded, and instances of `Slot` are unshaded. The first `Object` represents the `Family` model element and has three slots. Two of the slots are used to reference the `Person` model elements via the `naturalChildren` and `adoptedChildren` references.

Conformance checking service Conformance is a type of inter-model consistency, between a model and its metamodel (Section 2.1.2), and, in MDE, inter-model consistency is often validated using a set of constraints (Section 2.1.4). Furthermore, [Paige *et al.* 2007] demonstrates that conformance can be specified as a set of constraints between a model and its metamodel. As such, the conformance checking service has been designed as the set of constraints between models and metamodels in Figure 5.11.

The conformance checking service must be interoperable with the metamodel-independent syntax and, hence, the constraints are specified in terms of `Objects` and `Slots`. Clearly, to check conformance the constraints must refer to a (specific) metamodel, and the constraints are also specified in terms of concepts from the MOF metamodeling language (Section 2.1.3), such as `Class` and `Property`. Figure 5.10 shows a minimal version of the MOF metamodel.

After binding to the metamodel-independent syntax, the conformance of a model can be checked against any specific metamodel. To illustrate the value of the conformance checking service, consider again the metamodel evolution in Figure 5.3 and the bound model in Figure 5.9. For the evolved metamodel (Figure 5.3(b)), conformance checking for the model element representing the `Family` would fail. As illustrated in Figure 5.9, the `Family Object` defines slots for features named `naturalChildren` and `adoptedChildren`, which

1. Constructs an instance of `Object`, `o`.
2. For each attribute of the tag:
 - Creates an instance of `Slot`, `s`.
 - Sets `s.feature` to the name of the attribute.
 - Sets `s.value` to the value of the attribute.
 - Adds `s` to `o.slots`.
3. For each child tag:
 - Creates an instance of `Slot`, `s`.
 - Sets `s.feature` to the name of the child tag.
 - Recursively constructs an instance of `Object`, `c`.
 - Sets `s.value` to `c`.
 - Adds `s` to `o.slots`.

Figure 5.8: Pseudo code for binding XMI tags to Objects.

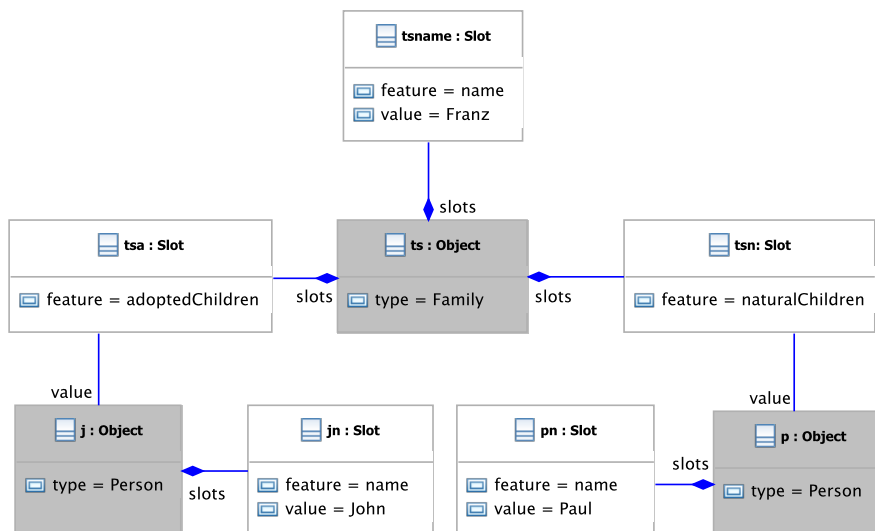


Figure 5.9: Result of binding the families model with the metamodel-independent syntax

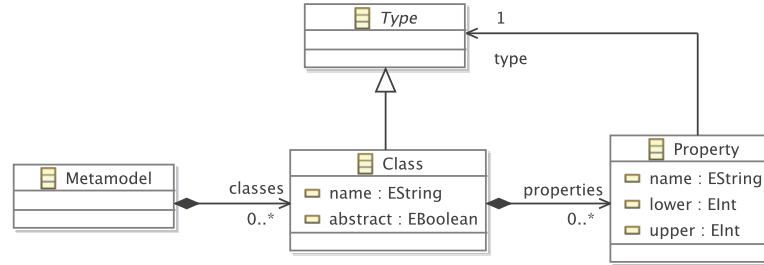


Figure 5.10: Minimal MOF metamodel, based on [OMG 2008a].

1. Each Object's type must be the name of some non-abstract metamodel Class.
2. Each Object must specify a Slot for each mandatory Property of its type.
3. Each Slot's feature must be the name of a metamodel Property. That Property must belong to the Slot's owner's type.
4. Each Slot must be multiplicity-compatible with its Property. More specifically, each Slot must contain at least as many values as its Property's lower bound, and at most as many values as its Property's upper bound.
5. Each Slot must be type-compatible with its Property. (The way in which type-compatibility is checked depends on the way in which the modelling framework is implemented).

Figure 5.11: The constraints of the conformance checking service.

are not defined the metaclass `Family` in Figure 5.3(b). Specifically, the model element representing the `Family` does not satisfy conformance constraint 3, which states: *each Slot's feature must be the name of a metamodel Property. That Property must belong to the Slot's owner's type*.

Reference implementation in Java, EMF and Epsilon

Reference implementations of the three components were constructed with Java, EMF and Epsilon (Section 2.3). The way in which each component was implemented is now discussed.

Metamodel-independent syntax Ecore, the metamodeling language of EMF, was used to implement the metamodel-independent syntax. The final metamodel is shown in Figure 5.12, which differs slightly to the initial design (Figure 5.6). Specifically, `Slot` is abstract, has a generic type (`T`), and is the superclass of `AttributeSlot`, `ReferenceSlot` and `ContainmentSlot`. These changes simplified the implementation of the (abstract) `typeCompatibleWith` method, which is used by the conformance checking service, and returns `true` if and only if every element of the `values` attribute is type compatible with the `EClassifier` parameter (a metamodel type).

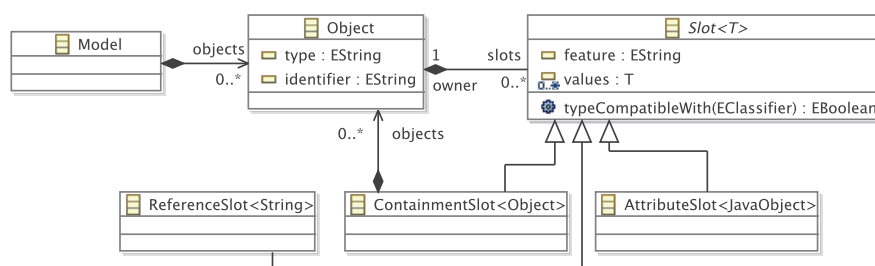


Figure 5.12: Implemented version of the metamodel-independent syntax, in Ecore

Binding service A text-to-model (T2M) transformation language (Section 2.1.4) could have been used to implement the binding service. However, in 2008 the Eclipse Modeling Project¹ did not provide a standard T2M language and using a T2M language that was not part of the Eclipse Modeling Project would have complicated installation of the service for users.

Instead, the binding service has been implemented by constructing in Java an XMI parser that emits objects conforming to the metamodel-independent syntax. Listing 5.1 illustrates the way in which XMI attributes are parsed.

¹<http://www.eclipse.org/modeling/>

The `processAttributes` method is called to generate instances of `AttributeSlot` from the metamodel-independent syntax. For each attribute in an XMI tag, the body of the loop is executed. If the attribute is not XMI metadata such as type information (line 4), the name and value of the attribute (lines 5 and 6) are extracted from the XMI, and used to add the value to an `AttributeSlot` with feature equal to the name of the attribute (line 8). Constructing Objects and Slots is the responsibility of the generator object, which is an instance variable of the parser.

```

1  private void processAttributes(Attributes atts) {
2      for (int index = 0; index < atts.getLength(); index++) {
3
4          if (!attributeIsMetadata(atts.getQName(index))) {
5              final String feature = atts.getLocalName(index);
6              final String value = atts.getValue(index);
7
8              generator.addAttributeValue(feature, value);
9          }
10     }
11 }
```

Listing 5.1: Parsing XMI attributes (in Java)

Conformance checking service The conformance constraints (Figure 5.11) were implemented with EVL (Section 2.1.4), a language tailored for (inter-)model verification and hence suitable for rapid prototyping of consistency constraints. Listing 5.2 shows the EVL constraint that checks whether each Object’s type is a non-abstract class (constraint 1 in Figure 5.11). The check part (line 3) verifies that a particular Object (referenced via the `self` keyword) refers to a metamodel type that is not abstract. When the check fails, the message (line 4) is automatically added to a set of unsatisfied constraints. The `toClass` operation (lines 8-10) is used to determine the metamodel class (an instance of `EClass`) to which the type attribute (a String) of an Object refers. The conformance checking service returns a report of unsatisfied constraints.

```

1  context Object {
2      constraint ClassMustNotBeAbstract {
3          check: not self.toClass().isAbstract()
4          message: 'Cannot instantiate the abstract class: ' + self.type
5      }
6  }
7
8  operation Object toClass() : EClass {
9      return Metamodel!EClass.all.selectOne(c|c.name == self.type);
```

```
10 }
```

Listing 5.2: A constraint (in EVL) to check that only concrete metamodel types are instantiated.

Type-compatibility has been implemented by delegating to the type-checking methods provided by EMF. The EVL constraints call the `isTypeCompatibleWith` method on the `Slot` class. Each subclass of `Slot` provides an implementation of `isTypeCompatibleWith`, which delegates to EMF to perform type-checking.

5.1.5 Structures Built atop the Metamodel-Independent Syntax

There are many potential uses for the metamodel-independent syntax described in this section. Section 5.2 describes a textual modelling notation integrated with the metamodel-independent syntax to achieve live conformance checking. The migration language presented in Section 5.4 can be used with the metamodel independent syntax to perform partial migration.

In addition to these uses, the metamodel-independent syntax is potentially useful during metamodel installation. As discussed in Section 4.2.1, metamodel developers do not have access to downstream models, and conformance is implicitly enforced by modelling frameworks. Consequently, the conformance of models may be affected by the installation of a new version of a metamodel, and the conformance of models cannot be checked during installation. Typically, installing a new version of a metamodel can result in models that no longer conform to their metamodel and cannot be used with the modelling framework. Moreover, a user discovers conformance problems only when attempting to use a model after installation has completed, and not as part of the installation process.

To enable conformance checking as part of metamodel installation in EMF, the metamodel-independent syntax has been integrated with Concordance in [Rose *et al.* 2010c]. The work was conducted outside of the scope of the thesis, and is now summarised to indicate the usefulness of the metamodel-independent syntax for supporting the automation of co-evolution activities. Concordance provides a mechanism for resolving inter-model references (such as those between models and their metamodels). Without Concordance, determining the the instances of a metamodel is possible only by checking every model in the workspace. Integrating Concordance and the metamodel-independent syntax resulted in a service, which Epsilon (Section 2.3.2) executes after the installation of a metamodel to identify the models that are affected by the metamodel changes. All models that conform to the old version of the metamodel are checked for conformance with the new metamodel. As such, conformance checking occurs automatically and immediately after

metamodel installation. Conformance problems are detected and reported immediately, rather than when an affected model is next used.

Summary

Modelling frameworks implicitly enforce conformance, which presents challenges for managing co-evolution. In particular, detecting and reconciling conformance problems involves managing non-conformant models, which cannot be loaded by modelling frameworks and hence cannot be used with model editors or model management operations. The metamodel-independent syntax proposed in this section enables modelling frameworks to load non-conformant models, and has been integrated with Concordance [Rose *et al.* 2010c] to facilitate the reporting of conformance problems during metamodel installation. The metamodel-independent syntax, binding service and conformance checking service underpin the implementation of the textual modelling notation presented in the sequel. The benefits and drawbacks of the metamodel-independent syntax in the context of user-driven co-evolution are explored in Chapter 6.

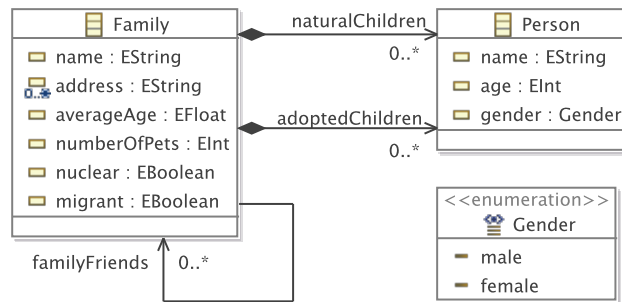
5.2 Textual Modelling Notation

The analysis of co-evolution examples in Chapter 4 highlighted two ways in which co-evolution is managed. In *developer-driven* co-evolution, migration is specified by the metamodel developer in an executable format; while in *user-driven co-evolution* migration is specified by the metamodel developer in prose or not at all. Performing user-driven co-evolution with modelling frameworks presents two key challenges that have not been explored by existing research. Firstly, user-driven co-evolution often involves editing the storage representation of the model, such as XMI. Model storage representations are typically not optimised for human use and hence user-driven co-evolution can be error-prone. Secondly, non-conformant model elements must be identified during user-driven co-evolution. When a multi-pass parser is used to load models, as is the case with EMF, not all conformance problems are reported at once, and user-driven co-evolution is an iterative process. In Section 4.3, these challenges led to the identification of the following requirement: *This thesis must demonstrate a user-driven co-evolution process that enables the editing of non-conformant models without directly manipulating the underlying storage representation and provides a sound and complete conformance report for the original model and evolved metamodel.*

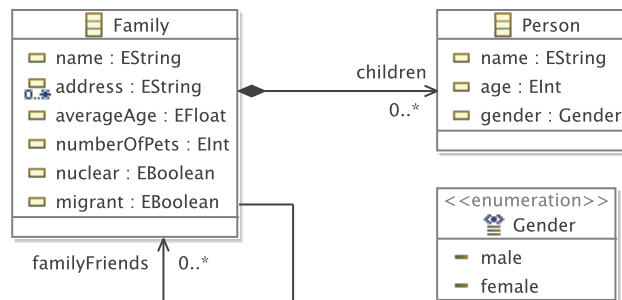
The remainder of this section describes a textual notation for models, which has been implemented for EMF, and discusses the way in which the notation has been integrated with the metamodel independent syntax described in Section 5.1 to produce conformance reports.

5.2.1 Model Migration with XMI

The co-evolution example from Section 5.1 is now used to illustrate the way in which model migration is performed by editing the underlying storage representation of a model, such as XMI (Section 2.1.3). Consider again the evolution of the families metamodel (Figure 5.13) and a model conforming to the original metamodel (Figure 5.14).



(a) Original metamodel.



(b) Evolved metamodel.

Figure 5.13: Evolution of a families metamodel, based on the metamodel in [OMG 2004].

The model in Figure 5.14 does not conform to the evolved metamodel (because it uses the `naturalChildren` and `adoptedChildren` features, which are not defined for `Person`), and hence cannot be loaded by the modelling framework. Migration might be achieved by editing the underlying storage representation directly (i.e. manually manipulating XMI). Listing 5.3 shows the XMI for the model in Figure 5.14.

```

1 <?xml version="1.0" encoding="ASCII"?>
2 <families:Family xmi:version="2.0" xmlns:xmi="http://www.omg.org/XMI"
   xmlns:families="families" xmi:id="_kE2LkAagEeC-FIOYrvUj0A" name="

```

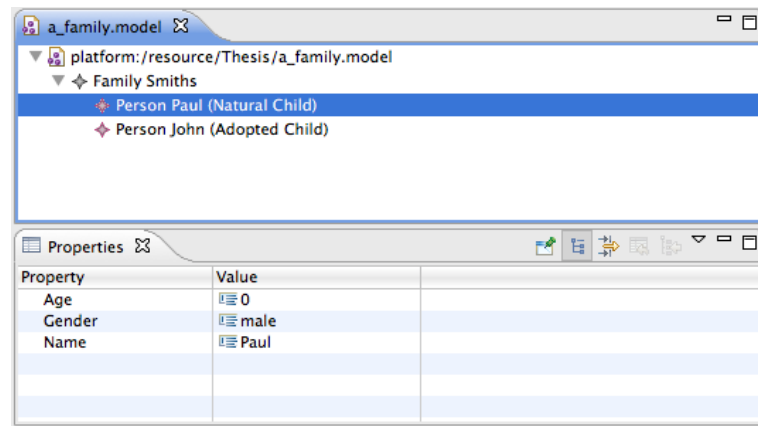



Figure 5.14: A family model, which conforms to the metamodel in Figure 5.13(a)

```

Smiths">
3  <naturalChildren xmi:id="_q8RWYAagEeC-FIOYrvUj0A" name="Paul"/>
4  <adoptedChildren xmi:id="_nj6TcAagEeC-FIOYrvUj0A" name="John"/>
5  </families:Family>

```

Listing 5.3: XMI for the family model in Figure 5.14

XMI is a concrete syntax for models, which has been optimised for use by machines and not by humans [OMG 2004]. Models often contain information that is not relevant to the domain, such as the universally unique identifiers (xmi:id attributes) on lines 2, 3 and 4 of Listing 5.3. Furthermore, information is often omitted to reduce the size of the model on disk. For example, the model elements on lines 3 and 4 of Listing 5.3 do not specify their type (Person) and this is inferred from the type of the naturalChildren and adoptedChildren features (which is accessed by the modelling framework via the XML namespace import for the families metamodel on line 2). A model references its metamodel. These issues affect the usability of XMI, and the evaluation presented in Section 6.1 further explores the suitability of XMI for user-driven co-evolution. The remainder of this section discusses the design and implementation of a syntax that provides an alternative to XMI.

5.2.2 Potential Alternatives to XMI

Two characteristics were considered when designing a notation that provides an alternative to representing models with XMI. Models can be represented textually or graphically (Section 2.1.2), and using a metamodel-specific or a metamodel-independent syntax (Section 5.1). The benefits and drawbacks of

each option have been considered particularly with respect to their implications for user-driven co-evolution, and are now discussed.

Metamodel-independent vs metamodel-specific A metamodel-specific syntax is defined in terms from the metamodel, and is often more concise than a metamodel-independent syntax. A metamodel-specific (and textual) syntax for part of the original families metamodel (Figure 5.13(a)) is shown in Listing 5.4. Using the metamodel-specific syntax, the families model in Listing 5.3 is represented as `Smiths:Paul(John)`. Notice that the syntax is defined in metamodel terms, such as `Family`, `naturalChildren`, and `adoptedChildren`. Consequently, the syntax definition can be affected by metamodel evolution, and hence cannot be used to load a model that does not conform to its metamodel. As the alternative syntax was to be used during user-driven co-evolution (to manipulate models that do not conform to their metamodel), a metamodel-independent representation was preferred to a metamodel-specific representation.

```

1 family = name ":" naturalChildren "(" adoptedChildren ")"
2 naturalChildren = name { "," name }
3 adoptedChildren = name { "," name }
4 name = "A" | ... | "z"
```

Listing 5.4: A metamodel-specific syntax for families in EBNF

Textual vs graphical For user-driven co-evolution, the usability of the notation is important because a metamodel user manipulates models with the notation to perform migration. The choice between a textual or graphical notation likely has a significant impact on usability, but it was not feasible to conduct a thorough user analysis given the time constraints of the thesis. Instead, a textual notation was selected (to reduce implementation effort). The textual notation was implemented such that the addition of an equivalent graphical notation could be added in future work.

Currently, several tools exist for representing models with textual, metamodel-specific syntaxes (such as the text-to-model transformation tools discussed in Section 2.1.4), but no tools exist for representing models in a metamodel-independent syntax other than XMI. [Steel & Raymond 2001] describe the Distributed Systems Technology Centre’s TokTok project, which provided a human-usable textual modelling notation, and is now inactive. The metamodel-independent representation described in [Muller & Hassenforder 2005] has been abandoned in favour of Sintaks², a tool for constructing metamodel-specific representations. However, the metamodel-independent representations described in [Steel & Raymond 2001, Muller & Hassenforder 2005] were both based on an OMG standard, Human-Usable Textual Notation (HUTN) [OMG 2004],

²<http://www.kermeta.org/sintaks/>

which defines a textual modelling notation that aims to conform to human-usability criteria [OMG 2004]. As a metamodel-independent, textual concrete syntax, HUTN was seen as an ideal starting point for designing a textual modelling notation for use in user-driven co-evolution.

5.2.3 OMG Human-Usable Textual Notation

The HUTN specification states its primary design goal as human-usability and “this is achieved through consideration of the successes and failures of common programming languages” [OMG 2004, Section 2.2]. The HUTN specification refers to two studies of programming language usability to justify design decisions, but, because no reference implementation exists, the OMG specification does not evaluate the human-usability of the notation. As HUTN is optimised for human-usability, using HUTN rather than XMI for user-driven co-evolution should lead to increased developer productivity. This claim is explored in Chapter 6.

Like the generic metamodel presented in Section 5.1, HUTN is a metamodel-independent syntax for MOF. However, the OMG HUTN specification focuses on concrete syntax, whereas the metamodel-independent syntax presented in Section 5.1 focuses on abstract syntax. In this section, the key features of HUTN are introduced, and the sequel presents a new reference implementation of HUTN. Throughout the remainder of this section, the original families metamodel (Figure 5.13(a)) is used to illustrate the notation.

Basic Notation

Listing 5.5 shows the construction of an *object* (an instance of a metamodel class) in OMG HUTN, here an instance of the Family class from Figure 5.13(a). Line 1 specifies the metamodel *package* containing the metamodel classes that can be instantiated by this model (FamilyPackage). A package declaration in OMG HUTN is equivalent to a namespace import at the start of an XMI document (e.g. line 2 of Listing 5.3). In Listing 5.5, line 2 names the metamodel class to be instantiated (Family) and gives an identifier for the object (The Smiths). Lines 3 to 7 define *attribute values*; in each case, the data value is assigned to the attribute with the specified name. The encoding of the value depends on its type: strings are delimited by any form of quotation mark; multi-valued attributes use comma separators, etc.

The metamodel in Figure 5.13(a) has a *simple reference* (familyFriends) and two *containment references* (adoptedChildren; naturalChildren). The OMG HUTN representation embeds a contained object directly in the parent object, as shown in Listing 5.6. A simple reference can be specified using the type and identifier of the referred object, as shown in Listing 5.7. Like attribute values, both styles of reference are preceded by the name of the meta-feature.

```

1  FamilyPackage "families" {
2      Family "The Smiths" {
3          nuclear: true
4          name: "The Smiths"
5          averageAge: 25.7
6          numberOfPets: 2
7          address: "120 Main Street", "37 University Road"
8      }
9  }

```

Listing 5.5: Specifying attributes with HUTN, taken from [Rose *et al.* 2008a]

```

1  FamilyPackage "families" {
2      Family "The Smiths" {
3          naturalChildren: Person "John" { name: "John" },
4                          Person "Jo" { gender: female }
5      }
6  }

```

Listing 5.6: Specifying a containment reference with HUTN, taken from [Rose *et al.* 2008a]

```

1  FamilyPackage "families" {
2      Family "The Smiths" {
3          familyFriends: Family "The Does"
4      }
5      Family "The Does" {}
6  }

```

Listing 5.7: Specifying a simple reference with HUTN, taken from [Rose *et al.* 2008a]

Keywords and Adjectives

In general, a metamodel-independent syntax (such as OMG HUTN) will not be as concise as a metamodel-specific concrete syntax. However, OMG HUTN does define optional syntactic shortcuts to make model specifications more compact. The OMG HUTN specification aims to make the syntactic shortcuts intuitive [OMG 2004, pg2-4].

Two of the syntactic shortcuts relate to Boolean-valued attributes and are now discussed; a complete list of syntactic shortcuts is given in [OMG 2004]. OMG HUTN permits the use of an attribute name to represent the value `true`, or the attribute name prefixed with a tilde to represent the value `false`). When used in the body of the object, this style of Boolean-valued attribute represents a *keyword*. A keyword used to prefix an object declaration is called an *adjective*. Listing 5.8 shows the use of both an attribute keyword

(~nuclear on line 6) and adjective (~migrant on line 2), and states that The Smiths are migrant and that The Does are not nuclear.

```

1  FamilyPackage "families" {
2      migrant Family "The Smiths" {}
3
4      Family "The Does" {
5          averageAge: 20.1
6          ~nuclear
7          name: "The Does"
8      }
9  }
```

Listing 5.8: Using keywords and adjectives in HUTN, taken from [Rose *et al.* 2008a]

Alternative Reference Syntax

In addition to the syntax defined in Listings 5.6 and 5.7, OMG HUTN defines two alternative syntactic constructs for specifying the value of references. For example, Listing 5.9 demonstrates the use of a reference block for defining The Does as friends with both The Smiths and The Bloggs.

```

1  FamilyPackage "families" {
2      Family "The Smiths" {}
3      Family "The Does" {}
4      Family "The Bloggs" {}
5
6      familyFriends {
7          "The Does" "The Smiths"
8          "The Does" "The Bloggs"
9      }
10 }
```

Listing 5.9: Using a reference block in HUTN, taken from [Rose *et al.* 2008a]

Listing 5.10 illustrates a further alternative syntax for references, which employs an infix notation.

```

1  FamilyPackage "families" {
2      Family "The Smiths" {}
3      Family "The Does" {}
4      Family "The Bloggs" {}
5
6      Family "The Smiths" familyFriends Family "The Does";
7      Family "The Smiths" familyFriends Family "The Bloggs";
8  }
```

Listing 5.10: Using an infix reference in HUTN, taken from [Rose *et al.* 2008a]

The reference block (Listing 5.9) and infix (Listing 5.10) notations are syntactic variations on – and have identical semantics to – the reference notation shown in Listings 5.6 and 5.7.

Customisation via Configuration

The OMG HUTN specification allows some limited, metamodel-specific customisation of the notation, using *configuration files*. Customisations include a parametric form of object instantiation; renaming of metamodel elements; specifying the default value of a feature; and providing a default identifier for classes of object.

5.2.4 Reference Implementation: Epsilon HUTN

To investigate the extent to which OMG HUTN can be used for user-driven co-evolution, an implementation, Epsilon HUTN, has been designed and implemented. This section describes the way in which Epsilon HUTN was implemented using a combination of model-management operations. From text conforming to the OMG HUTN syntax (described above), Epsilon HUTN produces an equivalent model that can be managed with EMF (Section 2.3.1). The sequel demonstrates the way in which Epsilon HUTN can be used for user-driven co-evolution.

Design of Epsilon HUTN

Implementing OMG HUTN involved building a tool for producing an EMF model (i.e. a model represented in XMI) from text conforming to the OMG HUTN syntax (described above). Essentially then, Epsilon HUTN can be regarded as a parser (that emits models), or as a text-to-model transformation. Several approaches to constructing Epsilon HUTN were considering, including: using a text-to-model (T2M) transformation tool (Section 2.1.4), using a domain-specific language (DSL) framework (Section 2.4.1), and using MDE tools and techniques such as EMF (Section 2.3.1), Epsilon (Section 2.3.2) and metamodeling.

As was the case for the design and implementation of the metamodel-independent syntax (Section 5.1), the author preferred to avoid dependencies on tools that were not part of the Eclipse Modelling Project (in order not to complicate installation of the notation for users). In 2008, the Eclipse Modeling Project³ did not provide a standard T2M language or DSL framework, and so these implementation strategies were discounted.

Instead, Epsilon HUTN was constructed using existing languages of the Epsilon platform. To parse HUTN source, a parser was generated with the ANTLR parser generator tool [Parr 2007], which had been used successfully

³<http://www.eclipse.org/modeling/>

to implement parsers for the other task-specific languages of Epsilon. A parser generated with ANTLR emits an abstract syntax tree (a set of Java objects that conform to a simple tree data structure), from which the Epsilon HUTN tool needs to produce an EMF model.

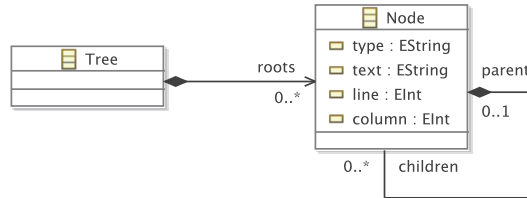


Figure 5.15: A metamodel for abstract syntax trees, in Ecore

The abstract syntax tree produced by ANTLR can be regarded as a model (conforming to the metamodel in Figure 5.15) and hence, producing an EMF model from the abstract syntax tree can be regarded as a model-to-model transformation. Epsilon HUTN, however, was designed as two separate transformations, for two reasons. Firstly, initial prototyping highlighted that the difference between a model represented in terms of the tree metamodel in Figure 5.15 and the same model represented in metamodel-specific terms is vast, and the logic required to perform a one-step transformation quickly became complicated even for simple models. In particular, each transformation rule would have required a lengthy guard statement, which would have been difficult to debug and maintain. Secondly, it became apparent that the concrete syntax defined in OMG HUTN could be transformed to the metamodel-independent syntax defined in Section 5.1, which would reduce implementation effort by re-using the metamodel and conformance checking service described in Section 5.1.

Implementation of Epsilon HUTN

For the reasons outline above, Epsilon HUTN is implemented using two model-to-model transformations. Figure 5.16 outlines the workflow through Epsilon HUTN, from HUTN source text to an EMF instantiation of the target model. The HUTN model specification is parsed to an abstract syntax tree using a HUTN parser specified in ANTLR [Parr 2007]. From this, a Java post-processor is used to construct an instance of the simple AST metamodel in Figure 5.15. Using ETL, a M2M transformation is applied to produce an intermediate model, which is an instance of the metamodel-independent syntax discussed in Section 5.1. Validation is performed on the intermediate model to ensure that the syntactic constraints specified in the OMG HUTN specifi-

cation are satisfied⁴, and that the model conforms to the target metamodel. Conformance checking is achieved by re-using the service presented in Section 5.1. Finally, a M2T transformation on the target metamodel, specified in EGL, produces a further M2M transformation, which consumes the intermediate model and produces the target model⁵.

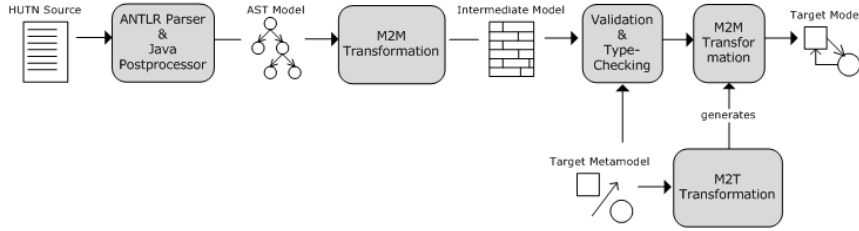


Figure 5.16: The architecture of Epsilon HUTN.

The modular architecture in Figure 5.16 facilitates the re-use of the metamodel-independent syntax and conformance checking service described in Section 5.1, and hence reduced implementation effort. A small modification was made to the metamodel-independent syntax to facilitate the implementation of Epsilon HUTN: an additional metaclass, `PackageObject`, was added to the metamodel-independent syntax. In OMG HUTN, packages are used to segregate a model such that different parts of a OMG HUTN document can refer to different metamodels. Consequently, a `PackageObject` has a type (i.e. the metamodel to which its contents refer), an optional identifier (used for inter-package references) and contains any number of `Objects`. To avoid confusion with `PackageObject`, the `Object` class in the metamodel-independent syntax was renamed to `ClassObject`. The version of the metamodel-independent syntax used with Epsilon HUTN is shown in Figure 5.17.

Each phase of the architecture in Figure 5.17 is now discussed in detail. Note that, in this section, instances of the metamodel-independent syntax producing during the execution of the HUTN workflow are termed an *intermediate model*.

Parsing the HUTN Source A parser for OMG HUTN was constructed using ANTLR [Parr 2007], a parser generator tool. ANTLR produces a parser from an annotated EBNF grammar definition. Part of the grammar definition used by Epsilon HUTN is shown in Listing 5.11 and is used to generate parser rules that process the body of `ClassObjects`. The `attr` rule on line 4, for example, matches any number of comma separated attribute values or the `null` keyword.

⁴For example, no two objects may have the same identifier.

⁵This final step involves a higher-order transformation (EGL is used to produce a transformation in ETL), and is described in more detail below.

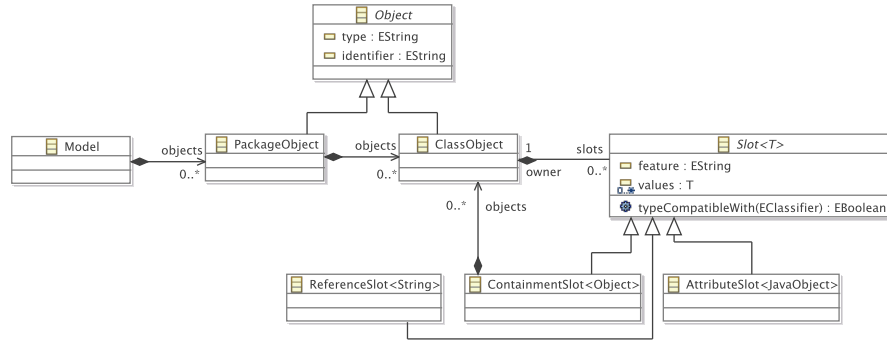


Figure 5.17: Final version of the metamodel-independent syntax, in Ecore

Epsilon HUTN uses a simple, bespoke Java post-processor to construct instances of the abstract syntax tree metamodel (Figure 5.15) from the Java objects produced by ANTLR. Specifically, the post-processor copies the Java objects produced by the parser into an EMF resource, and hence produces a model that can be managed with EMF.

```

1 cls_contents = feature | adjective
2 feature = NAME ASSIGNMENT feature_contents
3 feature_contents = attr | refs | containments
4 attr = attr_value { COMMA attr_value } | NULL

```

Listing 5.11: An extract of the Epsilon HUTN grammar definition in EBNF

AST Model to Intermediate Model Epsilon HUTN uses ETL [Kolovos *et al.* 2008b] for specifying M2M transformation. One of the transformation rules from Epsilon HUTN is shown in Listing 5.12. The rule transforms a name node in the AST model (which could represent a package or a class object) to a package object in the intermediate model. The guard (line 5) specifies that a name node will only be transformed to a package object if the node has no parent (i.e. it is a top-level node, and hence a package rather than a class). The body of the rule states that the type, line number and column number of the package are determined from the text, line and column attributes of the node object. On line 11, a containment slot is instantiated to hold the children of this package object. The children of the node object are transformed to the intermediate model (using a built-in method, `equivalent()`), and added to the containment slot.

```

1 rule NameNode2PackageObject
2   transform n : AntlrAst!Node
3   to p : Intermediate!PackageObject {
4

```

```

5    guard : n.type == 'Name' and n.parent.isUndefined()
6
7    p.type := n.text;
8    p.line := n.line;
9    p.col := n.column;
10
11   var slot := new Intermediate!ContainmentSlot;
12   for (child in n.children) {
13       slot.objects.add(child.equivalent());
14   }
15   if (slot.objects.notEmpty()) {
16       p.slots.add(slot);
17   }
18 }

```

Listing 5.12: Transforming Nodes to PackageObjects with ETL.

Intermediate Model Validation An advantage of the two-stage transformation is that contextual analysis can be specified in an abstract manner – that is, without having to express the traversal of the AST. This gives clarity and minimises the amount of code required to define syntatic constraints.

```

1 context ClassObject {
2     constraint IdentifiersMustBeUnique {
3         guard: self.id.isDefined()
4         check: ClassObject.all
5             .select(c|c.id = self.id).size() = 1;
6         message: 'Duplicate identifier: ' + self.id
7     }
8 }

```

Listing 5.13: A constraint (in EVL) to check that all identifiers are unique.

Epsilon HUTN uses EVL [Kolovos *et al.* 2009] to specify validation, resulting in highly expressive syntactic constraints. An EVL constraint comprises a guard, the logic that specifies the constraint, and a message to be displayed if the constraint is not met. For example, Listing 5.13 specifies the constraint that every HUTN class object has a unique identifier.

In addition to the syntactic constraints defined in the OMG HUTN specification, the EVL constraints for checking conformance (Section 5.1) are also executed on the model at this stage.

Intermediate Model to Target Model When the intermediate model conforms to the target metamodel, the intermediate model can be transformed to an instance of the target metamodel. In other words, the model can be represented in a metamodel-specific manner and, for example, saved to disk

using XML. In generating the target model from the intermediate model (Figure 5.16), the transformation uses information from the target metamodel, such as the names of classes and features. A typical approach to this category of problem is to use a higher-order transformation (HOT) on the target metamodel to generate the desired transformation [Tisi *et al.* 2009]. Currently, ETL cannot be used to produce a transformation from a transformation and hence Epsilon HUTN uses a slightly different approach: the transformation to the target model is produced by executing a M2T transformation on the target metamodel, using EGL [Rose *et al.* 2008b]. EGL is a template-based M2T language; [% %] tag pairs are used to denote dynamic sections, which may produce text when executed; any code not enclosed in a [% %] tag pair is included verbatim in the generated text.

Listing 5.14 shows part of the M2T transformation used by Epsilon HUTN. When executed on the target metamodel, the M2T transformation generates an ETL program (i.e. a M2M transformation). The generated ETL code transforms an intermediate model to a model that conforms to the target metamodel. The loop beginning on line 1 iterates over each meta-class in the target metamodel, producing a M2M transformation rule. The generated transformation rule consumes a `ClassObject` in the intermediate model and produces an element of the target model. The guard of the generated transformation rule (line 6) ensures that only `ClassObject` with a type equal to the current meta-class are transformed by the generated rule. To generate the body of the rule, the M2T transformation iterates over each structural feature of the current meta-class, and generates appropriate transformation code for populating the values of each structural feature from the slots on the class object in the intermediate model. The part of the M2T transformation that generates the body of M2M transformation rule is omitted in Listing 5.14 because it contains a large amount of code for interacting with EMF, which is not relevant to this discussion.

```

1  [% for (class in EClass.allInstances()) { %]
2  rule Object2[%=class.name%]
3    transform o : Intermediate!ClassObject
4    to t : Model![%=class.name%] {
5
6      guard: o.type = '[%=class.name%]'
7
8      -- body omitted
9    }
10 [% } %]
```

Listing 5.14: Part of the M2T transformation (in EGL) that takes a target metamodel and generates an intermediate model to target model transformation (in ETL).

To illustrate the way in which Epsilon HUTN generates a target model from an intermediate model, the M2T transformation in Listing 5.14 is applied to the the families metamodel in Figure 5.13(a). The M2T transformation generates the two M2M transformation rules in Listing 5.15. The rules produce instances of `Family` and `Person` from instances of `ClassObject` in the intermediate model. The body of each rule copies the values from the slots of the `ClassObject` to the `Family` or `Person` in the target model. Lines 7-9, for example, copy the value of the `name` Slot (if one is specified) to the target `Family`.

```

1  rule Object2Family
2    transform o : Intermediate!ClassObject
3    to t : Model!Family {
4
5      guard: o.type = 'Family'
6
7      if (o.hasSlot('name')) {
8        t.name := o.findSlot('name').values.first;
9      }
10
11     if (o.hasSlot('address')) {
12       for (value in o.findSlot('address').values) {
13         t.address.add(value);
14       }
15     }
16
17     -- remainder of body omitted
18   }
19
20 rule Object2Person
21   transform o : Intermediate!ClassObject
22   to t : Model!Person {
23
24     guard: o.type = 'Person'
25
26     if (o.hasSlot('name')) {
27       t.name := o.findSlot('name').values.first;
28     }
29
30     -- remainder of body omitted
31   }

```

Listing 5.15: The M2M transformation generated for the Families metamodel

Currently, Epsilon HUTN can be used only to generate EMF models. Support for other modelling languages would require different transformations between intermediate and target model. In other words, for each target modelling language, a new EGL template would be required. The transformation

| OMG HUTN | Epsilon HUTN | |
|-----------------------------|--------------|---|
| Feature | Supported? | Details of support |
| Packages | Yes | |
| Classes | Partial | Not yet supported: parametric attributes, enumeration adjectives. |
| Attributes | Yes | Corrects a mistake in the standard. |
| References | Yes | |
| Classifier-level attributes | Yes | |
| Data values | Yes | |
| Inline configuration (6.9) | No | A configuration model is used instead. |
| Configuration rules (5) | Partial | Not yet supported: parametric attributes, enumeration adjectives. |

Table 5.2: Compliance of Epsilon HUTN to OMG HUTN

from AST to intermediate model is independent of the target modelling language and would not need to change. As EMF is arguably the most widely-used modelling framework today, support for other modelling frameworks is not crucial for exploring the suitability of HUTN for user-driven co-evolution. However, one interesting example of metamodel evolution predates EMF: the changes made to UML between versions 1.5 and 2.0 of the specification. Because the UML 1 specifications use a version of MOF that is not supported by EMF, the current version of Epsilon HUTN cannot be used for migrating UML 1 models.

Compliance to OMG HUTN

Epsilon HUTN is a reference implementation of the OMG HUTN standard. There are, however, a few differences between the implementation in Epsilon and the OMG standard. The differences are now discussed and justified. The discussion is based on⁶, which provides an up-to-date report of Epsilon HUTN's compliance to the OMG HUTN standard.

Table 5.2.4 summarises the differences between Epsilon HUTN and the OMG HUTN standard. Epsilon HUTN does not support two of the syntactic shortcuts described for classes in the OMG HUTN standard: parametric attributes and enumeration adjectives. The former are used to specify attribute values in a parametric form (e.g. `Point (0,0)`), for creating a `Point` object with `x` and `y` attributes with value 0). The latter allows an enumeration value

⁶<http://www.eclipse.org/gmt/epsilon/doc/articles/hutn-compliance/>

to prefix an object definition (e.g. `female Person` for creating a `Person` with female gender). The attribute to which the parametric or enumeration values are bound is specified using OMG HUTN configuration rules (Section 5.2.3). Parametric attribute and enumeration adjectives were not implemented to reduce the amount of time required to build Epsilon HUTN. Alternative (albeit less concise) notion can be used to express models without using parametric attribute and enumeration adjectives.

Section 6.4 of the OMG HUTN standard [OMG 2004] appears to contain a mistake in the grammar definition. Grammar rule 20 implies that an attribute's name is optional when specifying a keyword attribute, and that an empty string or a tilde character are valid forms of a keyword attribute. However, the prose describing grammar rule 20 proposes no semantics for an empty string or a tilde character as a keyword attribute. Consequently, Epsilon HUTN deviates from grammar rule 20 of the OMG HUTN standard, and requires an attribute name for every keyword attribute.

Finally, the OMG HUTN standard defines syntax for specifying configuration rules *inline*, at the start of a HUTN document. Epsilon HUTN does not support inline configuration, and Epsilon HUTN documents are configured with a configuration model, which is constructed using an EMF model editor. Using a configuration model rather than inline configuration reduced the time required to implement Epsilon HUTN and facilitated re-use of configuration models between HUTN documents.

The OMG HUTN standard does not include a set of compliance tests for reference implementations. Instead, the compliance of Epsilon HUTN to OMG HUTN was checked using the many examples of HUTN documents in the OMG HUTN standard [OMG 2004]. The examples were used to create a suite of executable compliance test cases, which were run frequently during the development of Epsilon HUTN.

5.2.5 Migration with Epsilon HUTN

Used in combination with the metamodel-independent syntax presented in Section 5.1, Epsilon HUTN facilitates user-driven co-evolution using the workflow in Section 5.18, which provides an alternative to the user-driven co-evolution workflow observed in Section 4.2.2. First, the user attempts to load a model in the model editor⁷. If the model is non-conformant and cannot be loaded, the user clicks a “Generate HUTN” menu item provided by Epsilon HUTN. Epsilon HUTN then binds the model to the metamodel-independent syntax and unparses the bound model to produce HUTN source code equivalent to XMI representation of the non-conformant model.

To support the final step of the workflow in Figure 5.18, Epsilon HUTN provides an editor for HUTN documents that is integrated with the confor-

⁷The workflow in Figure 5.18 assumes a graphical model editor, such as those generated by GMF, but any editor built atop EMF will exhibit the same behaviour.

mance checking service described in Section 5.1. The user edits the HUTN document to reconcile conformance problems (i.e. perform migration), and Epsilon HUTN automatically performs conformance checking as the user edits the HUTN document. When the conformance problems are fixed, the user saves the HUTN document and Epsilon HUTN automatically generates XMI for the conformant model (using the model transformations described in Section 5.2.4). The conformant model can then be loaded in the model editor.

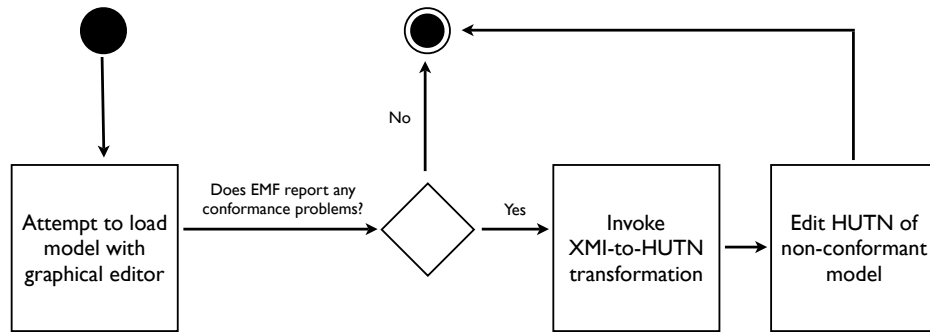


Figure 5.18: User-driven co-evolution with dedicated structures

To demonstrate the way in which HUTN can be used to perform migration, the XMI shown in Listing 5.3 is represented using OMG HUTN in Listing 5.16. Recall that the XMI describes a Family with one adopted and one natural child.

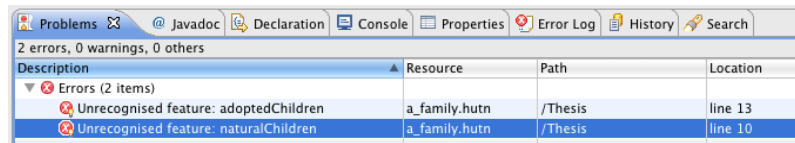
```

1 FamilyPackage "families" {
2   Family "Smiths" {
3     name: "Smiths"
4     naturalChildren: Person { name: "Paul" }
5     adoptedChildren: Person { name: "John" }
6   }
7 }
```

Listing 5.16: OMG HUTN for people with mothers and fathers.

If the Families metamodel now evolves such that children are modelled using one rather than two features (Figure 5.13(b)), Epsilon HUTN reports conformance problems on the HUTN document using the conformance checking service described in Section 5.1, as illustrated by the screenshot in Figure 5.19.

Resolving the conformance problems requires the user to merge the values for `adoptedChildren` and `naturalChildren` into a set of values for the new feature, `children`. The Epsilon HUTN development tools provide content assistance, which might be useful in this situation. Listing 5.17 shows a HUTN document that conforms to the evolved metamodel in which adopted and natural children are specified using a single feature, `children`.



| Description | Resource | Path | Location |
|---------------------------------------|---------------|---------|----------|
| Unrecognised feature: adoptedChildren | a_family.hutn | /Thesis | line 13 |
| Unrecognised feature: naturalChildren | a_family.hutn | /Thesis | line 10 |

Figure 5.19: Conformance problem reporting in Epsilon HUTN.

```

1  FamilyPackage "families" {
2      Family "Smiths" {
3          name: "Smiths"
4          children: Person { name: "Paul" },
5                      Person { name: "John" }
6      }
7  }

```

Listing 5.17: HUTN for people with parents.

When the user saves the reconciled HUTN document, Epsilon HUTN will automatically generate XMI for the (now) conformant model, and migration is complete. Compared to the user-driven co-evolution workflow observed in Section 4.2.2, the workflow presented in Figure 5.18 provides live conformance checking and a modelling notation that is optimised for humans rather than for machines. The two workflows are compared and evaluated in Chapter 6.

5.2.6 Summary

In this section, a textual modelling notation for performing model migration has been designed and implemented. The notation proposed in this section is based on the OMG HUTN standard, which was described in Section 5.2.3. The design and implementation of Epsilon HUTN, an implementation of OMG HUTN for EMF, was discussed in this section. Integration of Epsilon HUTN with the metamodel-independent syntax in Section 5.1 facilitates user-driven co-evolution with a textual modelling notation other than XMI, as demonstrated by the example above. The user-driven co-evolution workflow presented in Section 5.2.5 is evaluated in Chapter 6. The remainder of this chapter focuses on developer-driven co-evolution, in which model migration strategies are executable.

5.3 Analysis of Languages used for Migration

In contrast to the previous section, this section focuses on *developer-driven* co-evolution, in which migration is specified as a program that metamodel users execute to migrate their models. Section 4.2.3 discussed existing approaches

to model migration, highlighting variation in the languages used for specifying migration strategies. In this section, the results of comparing migration strategy languages are described, using a new example of metamodel evolution (Section 5.3.1). From the comparison, requirements for a domain-specific language for specifying and executing model migration strategies are derived (Section 5.3.3). The sequel describes an implementation of a model migration language based on the analysis presented here. The work described in this section has been published in [Rose *et al.* 2010f].

5.3.1 Co-Evolution Example

This section uses the Petri net metamodel evolution to compare model migration languages. The example is also used in co-evolution literature [Cicchetti *et al.* 2008, Garcés *et al.* 2009, Wachsmuth 2007].

In Figure 5.20(a), a Petri Net is defined to comprise Places and Transitions. A Place has any number of `src` or `dst` Transitions. Similarly, a Transition has at least one `src` and `dst` Place. The metamodel is to be evolved to support weighted connections between Places and Transitions and between Transitions and Places, as shown in Figure 5.20(b). Places are connected to Transitions via instances of `PTArc`. Likewise, Transitions are connected to Places via `TPArc`. Both `PTArc` and `TPArc` inherit from `Arc`, and therefore can be used to specify a weight.

Models that conform to the original metamodel might not conform to the evolved metamodel. The following strategy can be used to migrate models from the original to the evolved metamodel:

1. For every instance, `t`, of `Transition`:

For every `Place`, `s`, referenced by the `src` feature of `t`:

Create a new instance, `arc`, of `PTArc`.

Set `s` as the `src` of `arc`.

Set `t` as the `dst` of `arc`.

Add `arc` to the `arcs` reference of the `Net` referenced by `t`.

For every `Place`, `d`, referenced by the `dst` feature of `t`:

Create a new instance, `arc`, of `TPArc`.

Set `t` as the `src` of `arc`.

Set `d` as the `dst` of `arc`.

Add `arc` to the `arcs` reference of the `Net` referenced by `t`.

2. And nothing else changes.

5.3.2 Existing Model Migration Languages

Using the above example, the existing approaches for specifying and executing model migration strategies are now compared. From this comparison, the strengths and weakness of each approach are highlighted and requirements for a model migration language are synthesised in the sequel.

Manual Specification with M2M Transformation

Model migration can be specified using M2M transformation. For example, the Petri net migration has been specified in the Atlas Transformation Language (ATL) [Jouault & Kurtev 2005]. This is reproduced in Listing 5.18. Rules for migrating Places and TPArCs have been omitted for brevity, but are similar to the Nets and PTArcs rules.

Model transformation in ATL is specified using rules, which transform source model elements (specified using the `from` keyword) to target model elements (specified using `to` keyword). For example, the `Nets` rule on line 1 of Listing 5.18 transforms an instance of `Net` from the original (source) model to an instance of `Net` in the evolved (target) model. The source model element (the variable `o` in the `Net` rule) is used to populate the target model element (the variable `m`). ATL allows rules to be specified as *lazy* (not scheduled automatically and applied only when called by other rules).

The `Transitions` rule in Listing 5.18 codifies in ATL the migration strategy described previously. The rule is executed for each `Transition` in the original model, `o`, and constructs a `PTArc` (`TPArc`) for each reference to a `Place` in `o.src` (`o.dst`). Lazy rules must be used to produce the arcs to prevent circular dependencies with the `Transitions` and `Places` rules. Here, ATL, a typical rule-based transformation language, is considered and model migration would be similar in QVT. With Kermeta, migration would be specified in an imperative style using statements for copying `Nets`, `Places` and `Transitions`, and for creating `PTArcs` and `TPArcs`.

```

1  rule Nets {
2    from o : Before!Net
3    to m : After!Net ( places <- o.places, transitions <- o.transitions )
4  }
5
6  rule Transitions {
7    from o : Before!Transition
8    to m : After!Transition (
9      name <- o.name,
10     "in" <- o.src->collect(p | thisModule.PTArcs(p,o)),
11     out <- o.dst->collect(p | thisModule.TPArcs(o,p))
12   )
13 }
14
```

```

15 unique lazy rule PTArcs {
16   from place : Before!Place, destination : Before!Transition
17   to ptarcs : After!PTArc (
18     src <- place, dst <- destination, net <- destination.net
19   )
20 }

```

Listing 5.18: Fragment of the Petri nets model migration in ATL, taken from [Rose *et al.* 2010f]

In model transformation, [Czarnecki & Helsen 2006] identifies two common categories of relationship between source and target model, *new-target* and *existing-target*. In the former, the target model is constructed afresh by the execution of the transformation, while in the latter, the target model contains the same data as the source model before the transformation is executed. M2M transformation languages typically support new-target transformations. Some M2M transformation languages also support existing-target transformations, but typically require the source and target metamodel to be identical.

In model migration, source and target metamodels differ, and hence existing-target transformations cannot be used to specify model migration strategies. Consequently, model migration strategies are specified with new-target model-to-model transformation languages, and often contain sections for copying from original to migrated model those model elements that have not been affected by metamodel evolution. For the Petri nets example, the `Nets` rule (in Listing 5.18) and the `Places` rule (not shown) exist only for this reason.

Manual Specification with a Metamodel Mapping

Model migration can be undertaken using the model loading mechanisms of EMF [Hussey & Paternostro 2006], with a tool that is termed *Ecore2Ecore* here. The default model loading mechanism provided by EMF binds models to their metamodel (Section 4.2.1), and hence cannot be used to load models that have been affected by metamodel evolution. Therefore, *Ecore2Ecore* requires the metamodel developer to provide a mapping between the metamodeling language of EMF (*Ecore*) and the concrete syntax used to persist models (XMI). Mappings are specified using Hussey and Paternostro’s tool, which can suggest relationships between source and target metamodel elements by comparing names and types. For the Petri nets example, Figure 5.21 shows mappings between the original and evolved metamodels.

The mappings are used by the EMF XMI parser to determine the metamodel types to which pieces of the XMI will be bound. When a type or feature is not bound, the user must specify a custom migration strategy in Java. For the Petri nets metamodel, the `src` and `dst` features of `Place` and `Transition` are not bound, because migration is more complicated than a one-to-one mapping.

In Ecore2Ecore, model migration is specified on the XMI representation of the model and requires some knowledge of the XMI standard. For example, in XMI, references to other model elements are serialised as a space delimited collection of URI fragments [Steinberg *et al.* 2008]. Listing 5.19 shows a fragment of the code used to migrate Petri net models with Ecore2Ecore. The method shown converts a `String` containing URI fragments to a `Collection` of `Places`. The method is used to access the `src` and `dst` features of `Transition`, which no longer exist in the evolved metamodel and hence are not loaded automatically by EMF. To specify the migration strategy for the Petri nets example, the metamodel developer must know the way in which the `src` and `dst` features are represented in XMI. The complete listing, not shown here, exceeds 200 lines of code.

```

1  private Collection<Place> toCollectionOfPlaces
2  (String value, Resource resource) {
3
4      final String[] uriFragments = value.split("_");
5      final Collection<Place> places = new LinkedList<Place>();
6
7      for (String uriFragment : uriFragments) {
8          final EObject eObject = resource.getEObject(uriFragment);
9          final EClass place = PetriNetsPackage.eINSTANCE.getPlace();
10
11         if (eObject == null || !place.isInstance(eObject))
12             // throw an exception
13
14         places.add((Place)eObject);
15     }
16
17     return places;
18 }
```

Listing 5.19: Java method for deserialising a reference.

Operator-based Co-evolution with COPE

Operator-based approaches to managing co-evolution, such as COPE [Herrmannsdoerfer *et al.* 2009a], provide a library of *co-evolutionary operators*. Each co-evolutionary operator specifies both a metamodel evolution and a corresponding model migration strategy. For example, the “Make Reference Containment” operator from COPE [Herrmannsdoerfer *et al.* 2009a] evolves the metamodel such that a non-containment reference becomes a containment reference and migrates models such that the values of the evolved reference are replaced by copies. By

composing co-evolutionary operators, metamodel evolution can be performed and a migration strategy can be generated without writing any code.

To perform metamodel evolution using an operator-based approach, the library of co-evolutionary operators must be integrated with tools for editing metamodels. COPE provides integration with the EMF tree-based metamodel editor. Operators may be applied to an EMF metamodel, and COPE tracks their application. Once metamodel evolution is complete, a migration strategy can be generated automatically from the record of changes maintained by COPEs. The migration strategy is distributed along with the updated metamodel, and metamodel users choose when to execute the migration strategy on their models.

To be effective, operator-based approaches must provide a rich yet navigable library of co-evolutionary operators (Section 4.2.3). COPE allows model migration strategies to be specified manually when no co-evolutionary operator is appropriate. COPE employs a fundamentally different approach to M2M transformation and Ecore2Ecore, using an existing-target transformation. As discussed above, existing-target transformations cannot be used for specifying model migration strategies as the source (original) and target (evolved) metamodels differ. However, models can be structured independently of their metamodel using a metamodel-independent syntax (such as the one introduced in Section 5.1).

Listing 5.20 shows the COPE model migration strategy for the Petri net example given above⁸. Most notably, slots for features that no longer exist must be explicitly unset. In Listing 5.20, slots are unset on four occasions (on lines 2, 9, 18 and 19), once for each feature that is in the original metamodel but not in the evolved metamodel. These features are: `src` and `dst` of `Transition` and of `Place`. Failing to unset slots that do not conform with the evolved metamodel causes migration to fail with an error.

```

1  for (transition in petrinets.Transition.allInstances) {
2      for (source in transition.unset('src')) {
3          def arc = petrinets.PTArc.newInstance()
4          arc.src = source
5          arc.dst = transition
6          arc.net = transition.net
7      }
8
9      for (destination in transition.unset('dst')) {
10         def arc = petrinets.TPArc.newInstance()
11         arc.src = transition
12         arc.dst = destination
13         arc.net = transition.net
14     }

```

⁸In Listing 5.20, some of the concrete syntax has been changed in the interest of readability.

```

15  }
16
17  for (place in petrinets.Place.allInstances) {
18    place.unset('src')
19    place.unset('dst')
20  }

```

Listing 5.20: Petri nets model migration in COPE

5.3.3 Requirements Identification

Requirements for a domain-specific for model migration were identified from the review of existing languages (Section 5.3.2). The derivation of the requirements is now summarised, by considering two orthogonal concerns: the source-target relationship of the language used for specifying migration strategies and the way in which models are represented during migration.

Source-Target Relationship Requirements

When migration is specified as a new-target transformation, as in ATL (Listing 5.18), model elements that have not been affected by metamodel evolution must be explicitly copied from the original to the migrated model. When migration is specified as an existing-target transformation, as in COPE (Listing 5.20), model elements and values that no longer conform to the target metamodel must be explicitly removed from the migrated model. Ecore2Ecore does not require explicit copying or unsetting code; instead, the relationship between original and evolved metamodel elements is captured in a mapping model specified by the metamodel developer. The mapping model can be derived automatically and customised by the metamodel developer. To explore the appropriateness for model migration of an alternative to new- and existing-target transformations, the following requirement was derived:

*The migration language must **automatically** copy every model element that conforms to the evolved metamodel from original to migrated model, and must automatically not copy any model element that does not conform to the evolved metamodel from original to migrated model.*

Model Representation Requirements

With Ecore2Ecore, migration is achieved by manipulating XMI. Consequently, the metamodel developer must be familiar with XMI and must perform tasks such as dereferencing URI fragments (Listing 5.19) and type conversion. Transformation languages abstract away from the underlying storage representation of models (such as XMI) by using a modelling framework to load, store and access models. Decoupling a transformation language from the model representation facilitates interoperability with more than one modelling technology,

as demonstrated by the languages of the Epsilon platform [Kolovos 2009b]. Consequently, the following requirement was identified:

The migration language must not expose the underlying representation of original or migrated models.

To apply co-evolution operators, COPE requires the metamodel developer to use a specialised metamodel editor. The editor can manipulate only metamodels defined with EMF. Similarly, the mapping tool used in the Ecore2Ecore approach can be used only with metamodels defined with EMF. Although EMF is arguably very widely-used, other modelling frameworks exist. Adapting to interoperate with new systems is recognised as a common reason for software evolution [Sjøberg 1993], and migration between modelling frameworks is as a possible use case for a model migration language. To better support integration with modelling frameworks other than EMF, the following requirement was derived:

The migration language must be loosely coupled with modelling frameworks and must not assume that models and metamodels will be represented in EMF.

5.4 Epsilon Flock: A Model Migration Language

Driven by the analysis presented above, a domain-specific language for model migration, Epsilon Flock (subsequently referred to as Flock), has been designed and implemented. Section 5.4.1 discusses the principle tenets of Flock, which include user-defined migration rules and a novel algorithm for relating source and target model elements. In Section 5.4.2, Flock is demonstrated via application to three examples of model migration. The work described in this section has been published in [Rose *et al.* 2010f].

5.4.1 Design and Implementation

Flock has been designed to be a rule-based transformation language that mixes declarative and imperative parts. Consequently, Flock should be familiar to developers who have used hybrid-style M2M transformation languages, such as ATL and ETL [Kolovos *et al.* 2008b]. Flock has a compact syntax. The way in which Flock relates source to target elements is novel; it is neither a new- nor an existing-target relationship. Instead, elements are copied conservatively, as described below.

Like Epsilon HUTN (Section 5.2.4), Flock is built atop Epsilon. In particular, Flock uses EMC to provide interoperability with several modelling frameworks, and EOL for specifying the imperative part of user-defined migration rules.

```

1  migrate <originalType> (to <evolvedType>)?
2  (when (:<eolExpression>)|({<eolStatement>+}))? {
3    <eolStatement>*
4  }
5
6  delete <originalType>
7  (when (:<eolExpression>)|({<eolStatement>+}))?

```

Listing 5.21: Concrete syntax of migrate and delete rules.

Abstract Syntax

As illustrated by Figure 5.22, Flock migration strategies are organised into modules (`FlockModule`). Flock modules inherit from EOL modules (`EolModule`) and hence provide language constructs for specifying user-defined operations and for re-using modules. Flock modules comprise any number of rules (`Rule`). Each rule has an original metamodel type (`originalType`) and can optionally specify a guard, which is either an EOL statement or a block of EOL statements. `MigrateRules` must specify an evolved metamodel type (`evolvedType`) and/or a body comprising a block of EOL statements.

Concrete Syntax

Listing 5.21 shows the concrete syntax of migrate and delete rules. All rules begin with a keyword indicating their type (either `migrate` or `delete`), followed by the original metamodel type. Guards are specified using the `when` keywords. Migrate rules may also specify an evolved metamodel type using the `to` keyword and a body as a (possibly empty) sequence of EOL statements.

Note that Flock does not define a create rule. The creation of new model elements is instead encoded in the imperative part of a migrate rule specified on the containing type.

Execution Semantics

When executed, a Flock module consumes an original model, O , and constructs a migrated model, M . The transformation is performed in three phases: rule selection, equivalence establishment and rule execution. The behaviour of each phase is described below, and the first example in Section 5.4.2 demonstrates the way in which a Flock module is executed.

Rule Selection The rule selection phase determines an *applicable* rule for every model element, e , in O . As such, the result of the rule selection phase is a set of pairs of the form $\langle r, e \rangle$ where r is a migration rule.

A rule, r , is *applicable* for a model element, e , when the original type of r is the same type as (or is a supertype of) the type of e ; and the guard part of r is satisfied by e .

The rule selection phase has the following behaviour:

- For each original model element, e , in O :
 - Identify for e the set of all applicable rules, R . Order R by the occurrence of rules in the Flock source file.
 - If R is empty, let r be a default rule, which has the type of e as both its original and evolved type, and an empty body.
 - Otherwise, let r be the first element of R .
 - Add the pair $\langle r, e \rangle$ to the set of selected rules.

Equivalence Establishment The equivalence establishment phase creates an equivalent model element, e' , in M for every pair of rules and original model elements, $\langle r, e \rangle$. The equivalence establishment phase produces a set of triples of the form $\langle r, e, e' \rangle$, and has the following behaviour:

- For each pair $\langle r, e \rangle$ produced by the rule selection phase:
 - If r is a delete rule, do nothing.
 - If r is a migrate rule:
 - Create a model element, e' , in M . The type of e' is determined from the the `evolvedType` (or the `originalType` when no `evolvedType` has been specified) of r .
 - Copy the data contained in e to e' (using the *conservative copy* algorithm described in the sequel).
 - Add the triple $\langle r, e, e' \rangle$ to the set of equivalences.

Rule Execution The final phase executes the imperative part of the user-defined migration rules on the set of triples $\langle r, e, e' \rangle$, and has the following behaviour:

- For each triple $\langle r, e, e' \rangle$ produced by the equivalence establishment phase:
 - Bind e and e' to EOL variables named `original` and `migrated`, respectively.
 - Execute the body of r with EOL.

Conservative Copy

Flock contributes a novel algorithm, termed *conservative copy*, that copies model elements from original to migrated model only when those model elements conform to the evolved metamodel. Conservative copy is a hybrid of the new- and existing-target source-target relationships that are commonly used in M2M transformation [Czarnecki & Helsén 2006].

Conservative copy operates on an original model element, e , and its equivalent model element in the migrated model, e' , and has the following behaviour:

- For each metafeature, f for which e has specified a value:
 - Find a metafeature, f' , of e' with the same name as f .
 - If no equivalent metafeature can be found, do nothing.
 - Otherwise, copy the original value ($e.f$) to produce a migrated value ($e'.f'$) if and only if the migrated value conforms to f' .

The definition of conformance varies over modelling frameworks. Typically, conformance between a value, v , and a feature, f , specifies at least the following constraints:

- The size of v must be greater than or equal to the lowerbound of f .
- The size of v must be less than or equal to the upperbound of f .
- The type of v must be the same as or a subtype of the type of f .

EMC provides drivers for several modelling frameworks, permitting management of models defined with EMF, the Metadata Repository (MDR), Z or XML. To support migration between metamodels defined in heterogeneous modelling frameworks, EMC has been extended to include a conformance checking service; each EMC driver provides conformance checking semantics specific to its modelling framework. Specifically, EMC defines Java interfaces for specifying the way in which model values are written to a model, and an additional, conformance-checking Java method has been added to the interface. When a Flock module is executed, conformance checking responsibilities are delegated to EMC drivers by calling the new method.

In response to some types of metamodel evolution, some categories of model value must be converted before being copied from the original to the migrated model. Again, the need for and semantics of this conversion varies over modelling frameworks. For example, reference values typically require conversion before copying because, once copied, they must refer to elements of the migrated rather than the original model. In this case, the set of equivalences $\langle r, e, e' \rangle$ can be used to perform the conversion. In other cases, the target modelling framework must be used to perform the conversion, such as when EMF enumeration literals are copied.

Development and User Tools

As discussed in Section 4.2, models and metamodels are typically kept separate. Flock migration strategies can be distributed by the metamodel developer in two ways. An extension point defined by Flock provides a generic user interface for migration strategy execution. Alternatively, metamodel developers can integrate model migration with other tools by accessing `FlockModule` programmatically. The latter approach facilitates interoperability with, for example, model and source code management systems, and was used to provide a workflow architecture for the Epsilon languages in [Kolovos 2009b].

5.4.2 Examples of Flock Migration

Flock is now demonstrated using three examples of model migration. The first example demonstrates the way in which a Flock module is executed and illustrates the semantics of conservative copy. The second describes the way in which the migration of the Petri net co-evolution example (Section 5.3.1) can be specified with Flock, and is included for direct comparison with the other languages discussed in Section 5.3. The final, larger example demonstrates all of the features of Flock, and is based on changes made to UML class diagrams between versions 1.5 and 2.0 of the UML specification.

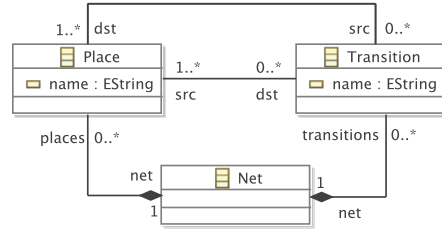
Process-Oriented Migration in Flock

The first example considers the evolution of a process-oriented metamodel, introduced in 4.1.3 and described in . The process-oriented metamodel was developed to explore the feasibility of a graphical model editor for representing programs written in process-oriented programming languages, such as *occam- π* [Welch & Barnes 2005].

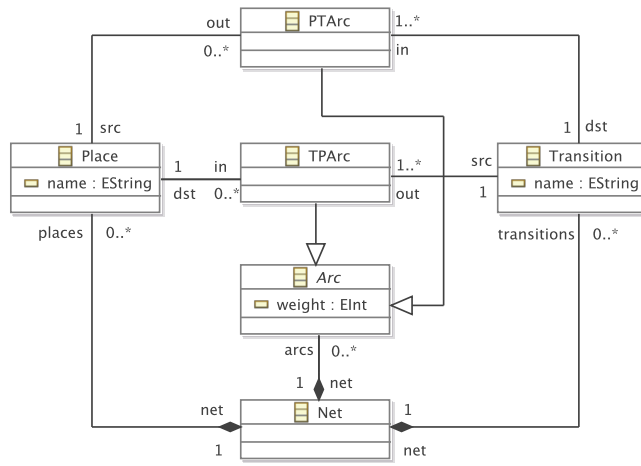
The original metamodel, shown in Figure 5.23(a), has been evolved to distinguish between `ConnectionPoints` that are a reader for a `Channel` and `ConnectionPoints` that are a writer for a `Channel` by making `ConnectionPoint` abstract and introducing two subtypes, `ReadingConnectionPoint` and `WritingConnectionPoint`, as shown in Figure 5.23(b).

The model shown in Figure 5.24 conforms to the original metamodel in Figure 5.23(a) and is to be migrated. The model comprises three `Processes` named *delta*, *prefix* and *minus*; three `Channels` named *a*, *b* and *c*; and six `ConnectionPoints` named *a?*, *a!*, *b?*, *b!*, *c?* and *c!*.

For the migration strategy shown in Listing 5.22, the Flock module will perform the following steps. Firstly, the rule selection phase produces a set of pairs $\langle r, e \rangle$. For each `ConnectionPoint`, the guard part of the user-defined rules control which rule will be selected. `ConnectionPoints` *a!*, *b!* and *c!* have outgoing `Channels` (*a*, *b* and *c* respectively) and hence the migration rule on line 1 is selected. Similarly, the `ConnectionPoints` *a?*, *b?* and *c?* have incoming `Channels` (*a*, *b* and *c* respectively) and hence



(a) Original metamodel.



(b) Evolved metamodel.

Figure 5.20: Exemplar metamodel evolution. Taken from [Rose *et al.* 2010f].

```

1 migrate ConnectionPoint to ReadingConnectionPoint when: original.
   outgoing.isDefined()
2 migrate ConnectionPoint to WritingConnectionPoint when: original.
   incoming.isDefined()

```

Listing 5.22: Redefining equivalences for the Component model migration.

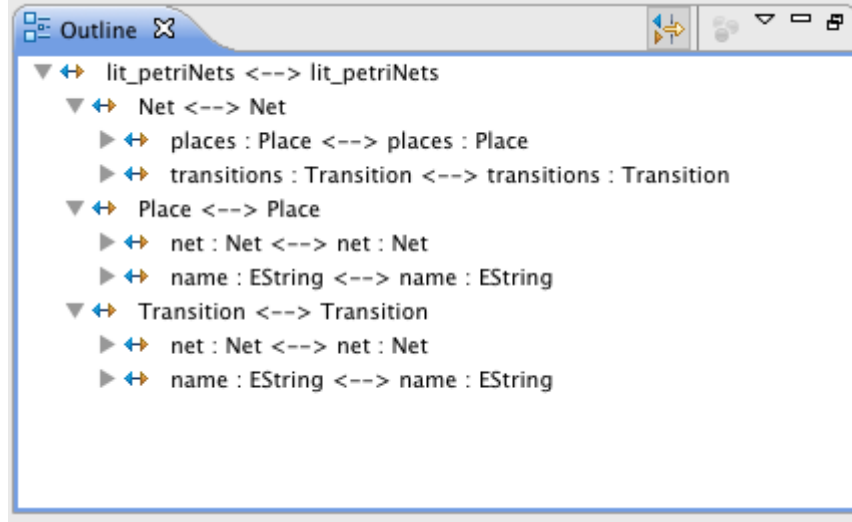


Figure 5.21: Mappings between the original and evolved Petri nets metamod-els, constructed with the tool described in [Hussey & Paternostro 2006]

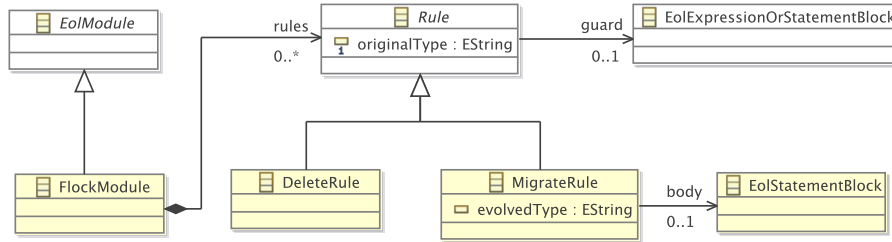
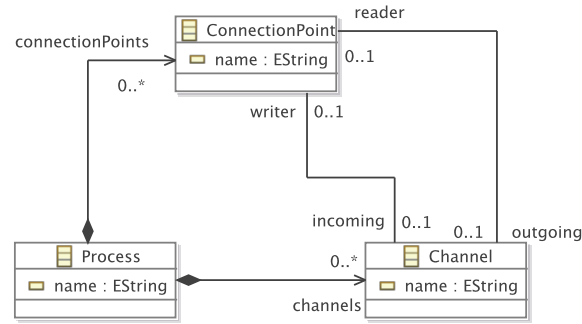


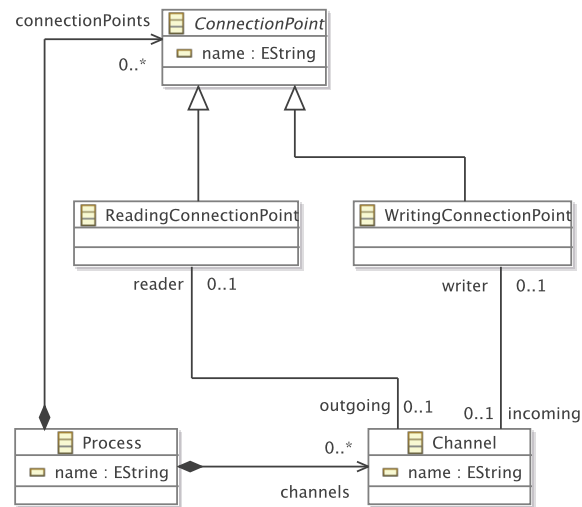
Figure 5.22: The abstract syntax of Flock.

the migration rule on line 2 is selected. There is no `ConnectionPoint` with both an outgoing and an incoming `Channel`, but if there were, the first applicable rule (i.e. the rule on line 1) would be selected. For the other model elements (the `Processes` and `Channels`) no user-defined rules are applicable, and so default rules are used instead. A default rule has an empty body and identical original and evolved types. In other words, a default rule for the `Process` type is equivalent to the user-defined rule: `migrate Process to Process {}`

Secondly, the equivalence establishment phase creates an element, e' , in the migrated model for each pair $\langle r, e \rangle$. For each `ConnectionPoint`, the evolved type of the selected rule (r) controls the type of e' . The rule on line 1 of Listing 5.22 was selected for the `ConnectionPoints` $a!$, $b!$ and $c!$ and hence an equivalent element of type `ReadingConnectionPoint` is created for $a!$, $b!$ and $c!$. Similarly, an equivalent element of type



(a) Original metamodel.



(b) Evolved metamodel.

Figure 5.23: Evolution of the Process-Oriented metamodel (Appendix A)

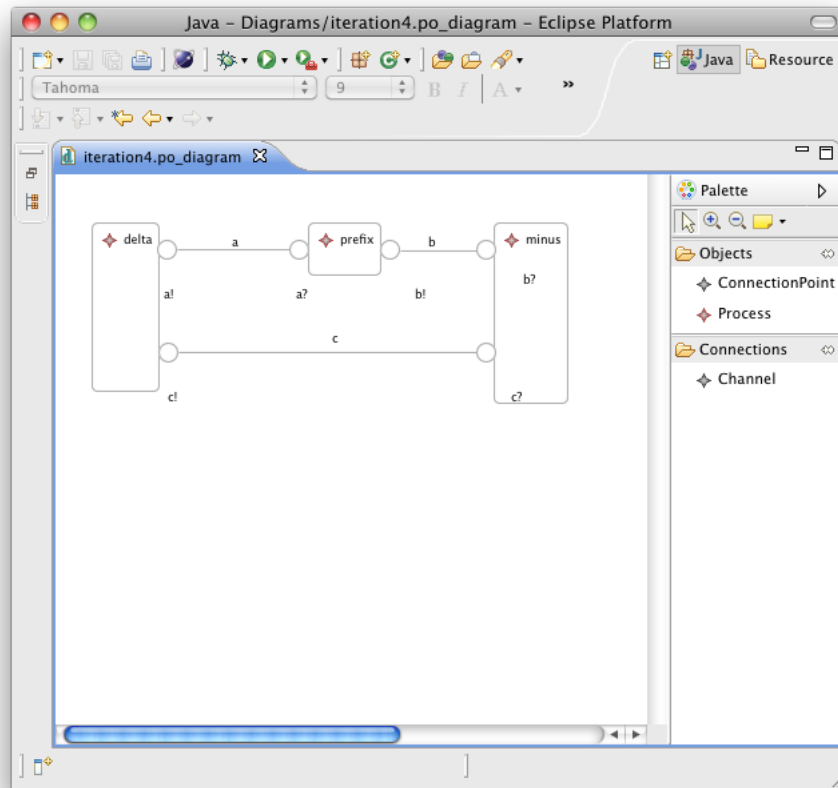


Figure 5.24: Process-Oriented model prior to migration

WritingConnectionPoint is created for $a?$, $b?$ and $c?$. For the other model elements (the Processes and Channels) a default rule was selected, and hence the equivalent model element has the same type as the original model element.

Finally, the rule execution phase performs a conservative copy for each original and equivalent model element in the set of triples $\langle r, e, e' \rangle$ produced by the equivalent establishment phase. The metamodel evolution shown in Figure 5.23 has not affected the Process type, and hence for each Process in the original model, conservative copy will create a Process in the migrated model and copy the values of all features. For each Channel in the original model, conservative copy will create an equivalent Channel in the migrated model and copy the value of the name feature from original to migrated model element. However, the values of the reader and writer features will not be copied by conservative copy because the type of these features has changed (from ConnectionPoint to ReadingConnec-

tionPoint and WritingConnectionPoint, respectively). The values of the reader and writer features in the original model will not conform to the reader and writer features in the evolved metamodel. Finally, the values of the name, incoming and outgoing features of the ConnectionPoint class have not evolved, and hence are copied directly from original to equivalent model elements.

The rule execution phase also executes the body of each rule, r , for every triple in the set $\langle r, e, e' \rangle$. The user-defined rules in Listing 5.22 have no body, and hence no further execution is performed in this case.

Petri Nets Migration in Flock

The Petri net metamodel evolution demonstrates the core functionality of Flock. In Listing 5.23, Nets and Places are migrated automatically. Unlike the ATL migration strategy (Listing 5.18), no explicit copying rules are required. Compared to the COPE migration strategy (Listing 5.20), the Flock migration strategy does not need to unset the original `src` and `dst` features of Transition.

```

1  migrate Transition {
2    for (source in original.src) {
3      var arc := new Migrated!PTArc;
4      arc.src := source.equivalent(); arc.dst := migrated;
5      arc.net := original.net.equivalent();
6    }
7
8    for (destination in original.dst) {
9      var arc := new Migrated!TPArc;
10     arc.src := migrated; arc.dst := destination.equivalent();
11     arc.net := original.net.equivalent();
12   }
13 }
```

Listing 5.23: Petri nets model migration in Flock

UML Class Diagram Migration in Flock

Figure 5.25 illustrates a subset of the changes made between UML 1.5 and UML 2.0. Only class diagrams are considered, and features that did not change are omitted. In Figure 5.25(a), association ends and attributes are specified separately. In Figure 5.25(b), the Property class is used instead. The Flock migration strategy (Listing 5.24) for Figure 5.25 is now discussed.

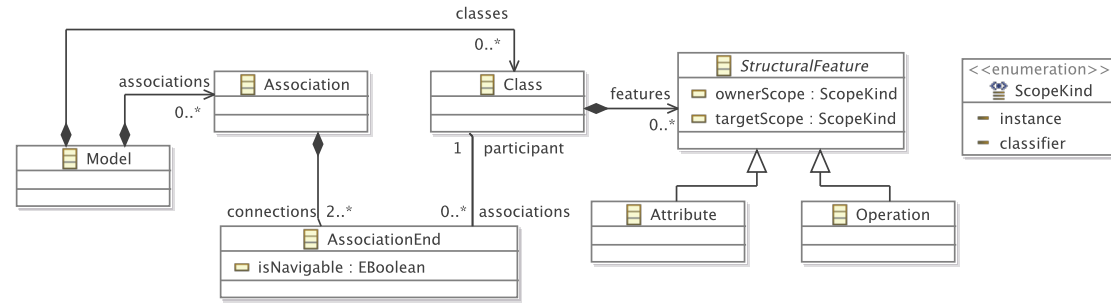
```

1  migrate Association {
2    migrated.memberEnds := original.connections.equivalent();
3  }
4
```

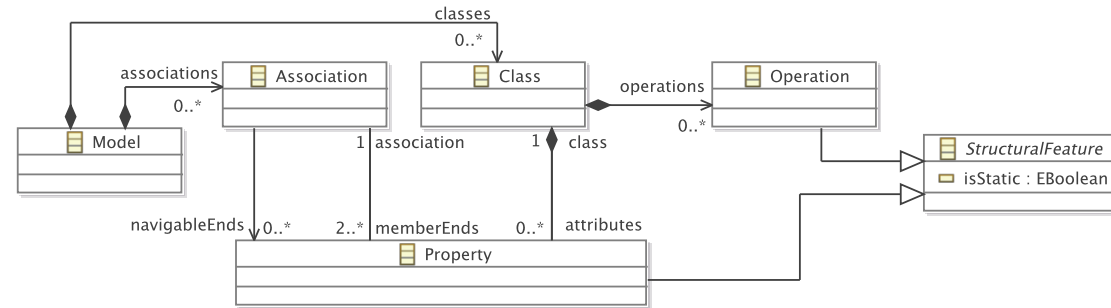


```
5 migrate Class {
6   var fs := original.features.equivalent();
7   migrated.operations := fs.select(f|f.isKindOf(Operation));
8   migrated.attributes := fs.select(f|f.isKindOf(Property));
9   migrated.attributes.addAll(original.associations.equivalent())
10 }
11
12 delete StructuralFeature when: original.targetScope <> #instance
13
14 migrate Attribute to Property {
15   if (original.ownerScope = #classifier) {
16     migrated.isStatic = true;
17   }
18 }
19 migrate Operation {
20   if (original.ownerScope = #classifier) {
21     migrated.isStatic = true;
22   }
23 }
24
25 migrate AssociationEnd to Property {
26   if (original.isNavigable) {
27     original.association.equivalent().navigableEnds.add(migrated)
28   }
29 }
```

Listing 5.24: UML model migration in Flock



(a) Original, UML 1.5 metamodel.



(b) Evolved, UML 2.0 metamodel.

Figure 5.25: UML metamodel evolution

Firstly, `Attributes` and `AssociationEnds` are migrated to be `Properties` (lines 14 to 18, and 25 to 29). In particular, the `Association#navigableEnds` reference replaces the `AssociationEnd#isNavigable` attribute; following migration, each navigable `AssociationEnd` must be referenced via the `navigableEnds` feature of its `Association` (lines 26-28).

In UML 2.0, `StructuralFeature#ownerScope` has been replaced by `#isStatic` (lines 15-17 and 20-22). The UML 2.0 specification states that the UML 1.5 values `ScopeKind#classifier` and `#instance` should be migrated to `true` and to `false`, respectively.

The UML 1.5 `StructuralFeature#targetScope` feature is no longer supported in UML 2.0, and no migration path is provided. Consequently, line 14 deletes any model element whose `targetScope` is not the default value.

Finally, `Class#features` has been split to form `Class#operations` and `#attributes`. Lines 7 and 8 partition features on the original `Class` into `Operations` and `Property`s. `Class#associations` has been removed in UML 2.0, and `AssociationEnds` are instead stored in `Class#attributes` (line 9).

Summary

Table 5.4.2 illustrates several characterising differences between *Flock* and the pre-existing languages presented in Section 5.3. Due to its conservative copying algorithm, *Flock* is the only language to provide both automatic copying and unsetting. The evaluation presented in Section 6.2 explores the extent to which automatic copying and unsetting affect the conciseness of migration strategies.

All of the approaches considered in Section 5.3 support EMF. Both *Flock* and ATL support further modelling technologies, such as MDR and XML. However, ATL does not automatically copy model elements that have not been affected by metamodel changes. Therefore, migration between models of different technologies with ATL requires extra statements in the migration strategy to ensure that the conformance constraints of the target technology are satisfied. Because it delegates conformance checking to an EMC driver, *Flock* requires no such checks.

A more thorough examination of the similarities and differences between *Flock* and other migration strategy languages is provided by the evaluation presented in Chapter 6.

5.5 Chapter Summary

Three structures for identifying and managing co-evolution have been designed and implemented to approach the thesis requirements outlined in Chapter 4. The way in which modelling frameworks implicitly enforce conformance makes

managing non-conformant models challenging, and the proposed metamodel-independent syntax (Section 5.1) extends modelling frameworks to facilitate the management of non-conformant models. The proposed textual modelling notation, Epsilon HUTN (Section 5.2), provides a human-usable notation as an alternative to XMI for performing user-driven co-evolution. Finally, Epsilon Flock (Section 5.4) contributes a domain-specific language for describing model migration.

The metamodel-independent syntax is a modelling framework extension that makes explicit the conformance relationship between models and metamodels. By binding models not to their metamodel but to a generic metamodel, the metamodel-independent syntax allows non-conformant models to be managed with modelling tools and model management operations. Furthermore, conformance checking is provided as a service, which can be scheduled at any time, and not just when models are loaded. The metamodel-independent syntax has been integrated with Concordance [Rose *et al.* 2010c] to provide a metamodel installation process that automatically reports conformance problems, and underpins the implementation of the second structure described in this chapter, a textual modelling notation.

For performing user-driven co-evolution, the textual modelling notation described in Section 5.2 provides an alternative to XMI. Unlike XMI, the notation introduced in this chapter implements the OMG standard for Human-Usable Textual Notation (HUTN) [OMG 2004] and is optimised for human usability. Epsilon HUTN, introduced here, is presently the sole reference implementation of HUTN. Constructing Epsilon HUTN atop the metamodel-independent syntax allows Epsilon HUTN to provide incremental and background conformance checking, and an XMI-to-HUTN transformation for loading non-conformant models. Section 6.1 explores the benefits and drawbacks of using the metamodel-independent syntax and Epsilon HUTN together to perform user-driven co-evolution.

The domain-specific language described in Section 5.4, Epsilon Flock, combines several concepts from existing model-to-model transformation languages to form a language tailored to model migration. In particular, Flock contributes a novel mechanism for relating source and target model elements termed conservative copy, which is a hybrid of new- and existing-target styles

| Tool | Automatic | | Modelling technologies |
|-------------|-----------|-------|------------------------|
| | Copy | Unset | |
| Ecore2Ecore | ✓ | ✗ | XMI |
| ATL | ✗ | ✓ | EMF, MDR, KM3, XML |
| COPE | ✓ | ✗ | EMF |
| Flock | ✓ | ✓ | EMF, MDR, XML, Z |

Table 5.3: Properties of model migration approaches

of model-to-model transformation. Flock is built atop Epsilon and hence interoperates transparently with several modelling technologies via the Epsilon Model Connectivity layer.

The metamodel-independent syntax, Epsilon HUTN, Epsilon Flock and Concordance have been released as part of Epsilon in the Eclipse GMT⁹ project, which is the research incubator of arguably the most widely used MDE modelling framework, EMF. By re-using parts of Epsilon, the structures were implemented more rapidly than would have been possible when developing the structures independently. In particular, re-using the Epsilon Model Connectivity layer facilitated interoperability of Flock with several MDE modelling frameworks, which was exploited to manage a practical case of model migration in Section 6.4.

⁹<http://www.eclipse.org/gmt>

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