Chapter 6

Evaluation

Chapter 5 outlined requirements for and described the implementation of a textual modelling notation and a model migration language. This chapter describes the way in which both solutions were evaluated against their requirements, and against the thesis requirements identified in Chapter 4. A further solution, the metamodel-independent syntax, was developed in Section 5.1 and is not evaluated explicitly in this chapter, as discussed below.

The textual modelling notation (Section 5.2) was developed to address the challenges faced when performing user-driven co-evolution. Using a real-world example of user-driven co-evolution, Section 6.1 demonstrates existing and novel processes for performing manual migration, and indicates the benefits of using the textual modelling notation in the novel process.

A transformation language tailored for model migration, Epsilon Flock (Section 5.4), was developed to allow the specification and execution of model migration strategies. Flock uses a novel algorithm for relating source to target model elements, termed conservative copy. Conservative copy is evaluated against two existing mechanisms for relating source and target model elements in Section 6.2 using quantitive measurements. In addition, Epsilon Flock has been evaluated by comparison with other migration tools (Section 6.3) and with transformation languages (Section 6.4). The developers of other tools have been involved in the evaluation described in Sections 6.3 and 6.4, and their contributions are highlighted. The work presented in this chapter has been published in [Rose *et al.* 2010a, Rose *et al.* 2010d, Rose *et al.* 2010c].

Evaluation of the Metamodel-Indepenent Syntax The metamodel-independent syntax was developed to address the following thesis requirement, identified in Section 4.3: *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.*

The metamodel-independent syntax was demonstrated to facilitate loading of non-conformant models and conformance checking in Section 5.1.3. Additionally, the metamodel-independent syntax was used in the implementation of the textual modelling notation, which is evaluated in Section 6.1. As such, no further evaluation of the metamodel-independent syntax is presented in this chapter. Instead, the remainder of the chapter focuses on the evaluation of the textual modelling notation and the model migration language.

6.1 Evaluating User-Driven Co-Evolution

This section evaluates the suitability of the metamodel independent syntax (Section 5.1) and the textual modelling notation (Section 5.2) for performing user-driven co-evolution, a novel process for managing co-evolution that was identified in Chapter 4. User-driven co-evolution was observed in real-world MDE projects in Chapter 4, but no tool support for user-driven co-evolution is reported in the co-evolution literature. The evaluation presented in this section seeks to demonstrate that dedicated structures for user-driven co-evolution can increase the productivity of model migration in a user-driven co-evolution process.

To explore this claim, several approaches to evaluation could have been used. The dedicated structures for user-driven co-evolution are freely available as part of Epsilon, a member of the Eclipse Modeling Project. The productivity benefits of the structures might have been explored by asking users to describe their experiences with the structures. However, the subjective nature of the feedback might have threatened the validity of this evaluation. Alternatively, evaluation might have been performed with a comprehensive user study that measured the time taken for developers to perform model migration with and without the dedicated structures for user-driven co-evolution. However, locating developers and examples of co-evolution for this study was not possible given the time available to perform the evaluation.

Instead, evaluation was conducted by comparing two approaches to user-driven co-evolution using an example of user-driven co-evolution from a real-world MDE project. The first approach uses only those tools available in EMF; while the second approach uses EMF and, in addition, two of the structures presented in Chapter 5, a metamodel-independent syntax and a textual modelling notation. The remainder of this section first recaps Section 4.2.2, which describes the challenges to productivity faced by developers while performing user-driven co-evolution with the Eclipse Modeling Framework (EMF), arguably the most widely-used MDE development environment at present. Subsequently, the two approaches to user-driven co-evolution are demonstrated. The section concludes by comparing the two approaches and highlighting ways in which two of the structures proposed in Chapter 5 might be used to increase the productivity of model migration in a user-driven co-evolution process.

6.1.1 Challenges for Performing User-Driven Co-Evolution

Chapter 4 highlighted two productivity challenges faced by developers while performing user-driven co-evolution in contemporary MDE environments. Firstly, model storage representations have not been optimised for use by humans, and hence user-driven co-evolution can be error-prone and time consuming. Secondly, the multi-pass parsers used to load models in contemporary MDE environments cause user-driven co-evolution to be an iterative process, because not all conformance errors are reported at once. The identification of these productivity challenges led to the derivation of the following research 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 conformance report for the original model and evolved metamodel.*

Two of the structures presented in Chapter 5 provide the foundation for fulfilling the above research requirement. The first, a metamodel-independent syntax, facilitates the conformance checking of a model against any metamodel. The second structure, a textual modelling notation called HUTN, allows models to be managed in a format that is reputedly easier for humans to use than XMI, the canonical model storage format [OMG 2004].

To fulfil the above research requirement, this section uses the metamodel-independent syntax and the textual modelling notation to demonstrate that user-driven co-evolution can be performed without encountering the challenges to productivity described above. To this end, an example of co-evolution is used to show the way in which user-driven co-evolution might be achieved with and without the metamodel-independent syntax and the textual modelling notation described in Chapter 5.

6.1.2 Co-Evolution Example

The remainder of this section uses a co-evolution example taken from collaborative work with Adam Sampson, then a Research Associate at the University of Kent. The purpose of the collaboration was to build a prototypical editor for graphical models of programs written in process-oriented programming languages, such as occam-π [Welch & Barnes 2005]. The graphical models would provide a standard notation for describing process-oriented programs.

The graphical model editor was developed using MDE tools and techniques. A metamodel was used to capture the abstract syntax of process-oriented programming languages, and code for a graphical model editor was automatically generated from the metamodel.

The final version of the graphical model editor is shown in Figure 6.1. The editor captures the three primary concepts used to specify process-oriented programs: processes, connection points and channels. Processes, represented as boxes in the graphical notation, are the fundamental building blocks of a process-oriented program. Channels, represented as lines in the graphical notation, are the mechanism by which processes communicate, and are unidirectional. Connection points, represented as circles in the graphical notation, define the channels on which a process can communicate. Connection points are used to specify the way in which a process can communicate, and can optionally be bound to a channel. Because channels are unidirectional, connection points are either reading (consume messages from the channel) or writing (generate messages on the channel). Reading (writing) connection points are represented as white (black) circles in the graphical notation.

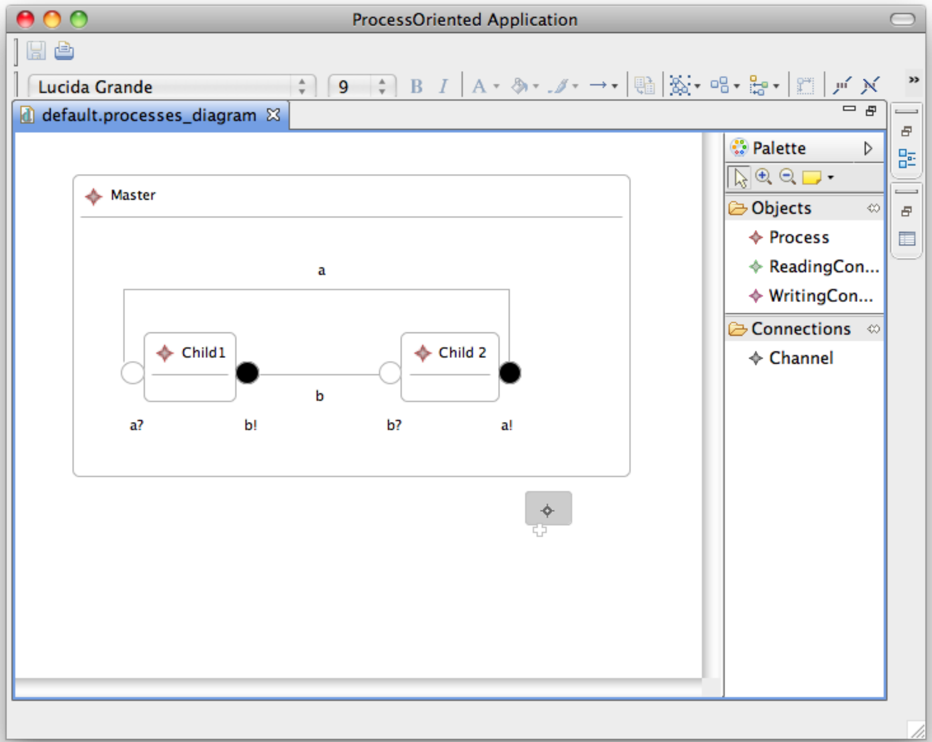


Figure 6.1: Final version of the prototypical graphical model editor.

The graphical model editor was implemented using EMF. The metamodel was specified in Ecore, the metamodelling language of EMF, and the editor was generated from the metamodel using the Graphical Modeling Framework (GMF), an extension to EMF for graphical modelling. Section 2.3 describes in more detail the way in which EMF and GMF can be used to specify metamodels and to generate graphical model editors.

The process-oriented metamodel was developed iteratively, and the six iterations are described in Appendix B. During each iteration, the metamodel was changed. The remainder of this section uses an example of metamodel changes from the fifth iteration of the project. The way in which development proceeded during that iteration is described in Section B.5 and summarised below.

Feature identification

The purpose of the iteration was to refine the way in which connection points were represented. At the start of the iteration, the graphical model editor could be used to draw processes, channels and connection points. However, no distinction was made between reading and writing connection points.

Figure 6.2 shows an exemplar model represented in the graphical model editor before the iteration began. The model contains two processes (depicted as boxes), `P1` and `P2`, one channel (depicted as a line), `a`, and two connection points (depicted as circles), `a!` and `a?`.

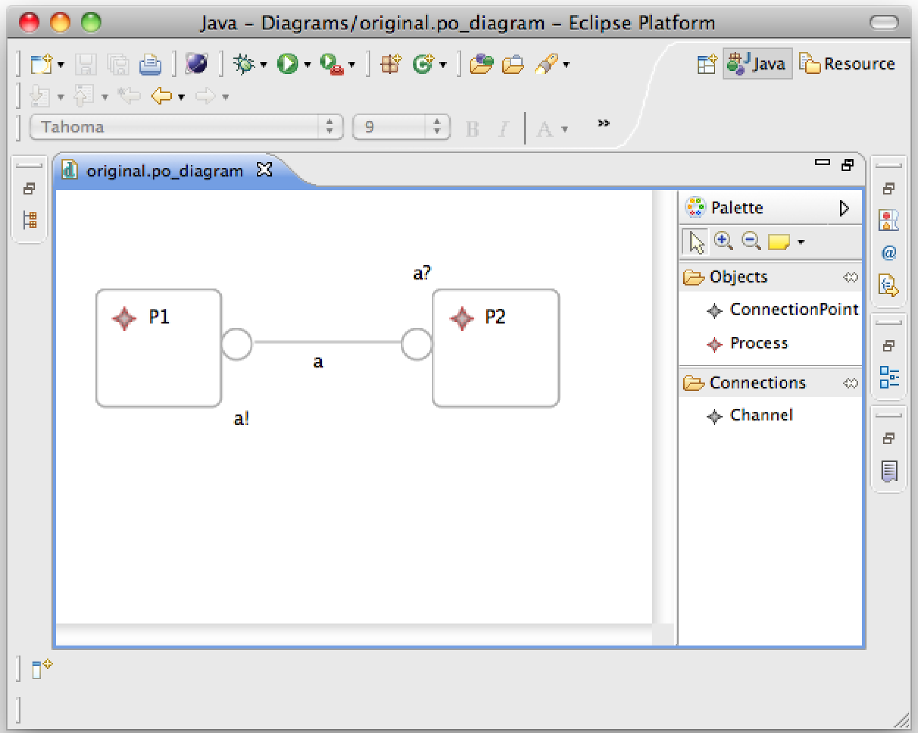


Figure 6.2: The graphical editor at the start of the iteration.

The aim of the iteration was to distinguish between *reading* and *writing* connection points in the graphical notation. The former are used to receive messages, and the latter to send messages. In Figure 6.2, `a?` is intended to represent a reading connection point, and `a!` a writing connection point. Sampson and the thesis author decided that the editor should be changed so that black circles would be used to represent writing connection points, and white circles to represent reading connection points. At the end of the iteration the model shown in Figure 6.2 would be represented as shown in Figure 6.3. Furthermore, the editor would ensure that `a?` was used only as the reader of a channel, and `a!` only as the writer of a channel. Before the iteration started, the editor did not enforce this constraint.

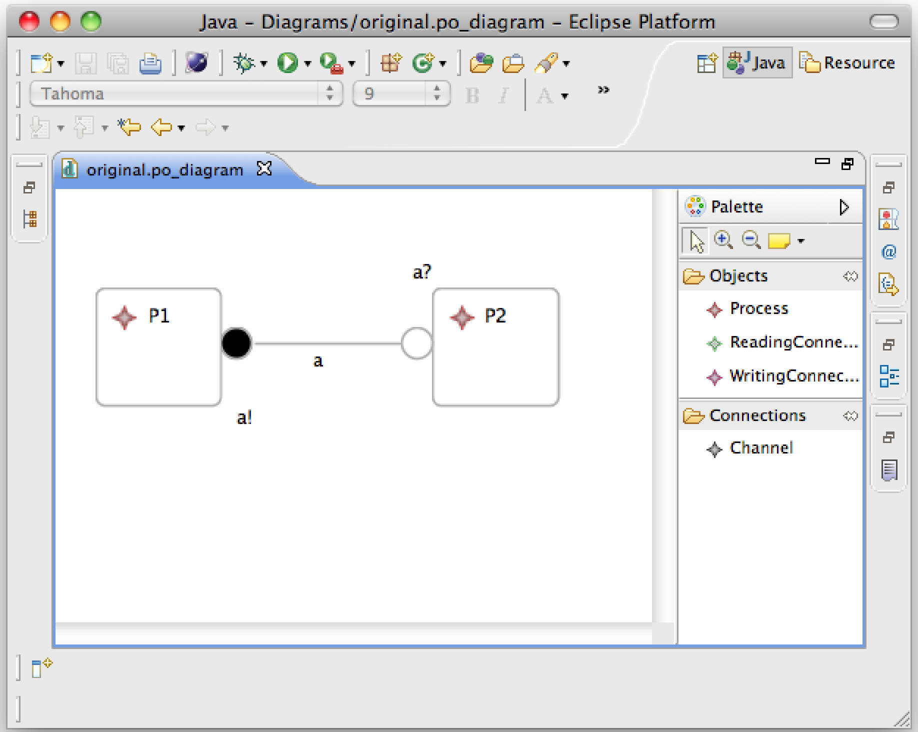
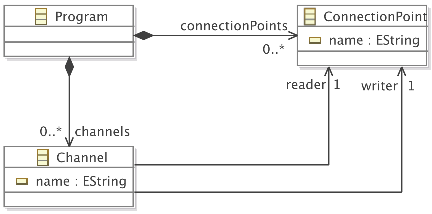


Figure 6.3: The graphical editor at the end of the iteration.

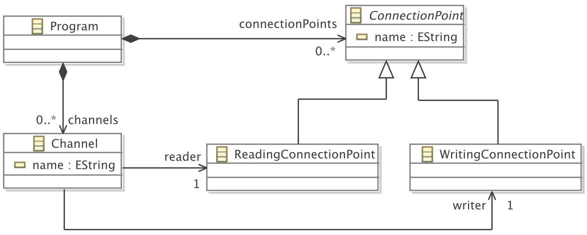
Implementation

Before the iteration began, the metamodel did not distinguish between reading and writing `ConnectionPoints`. Figure 6.4(a) shows the way in which connection points were modelled at the start of the iteration. When a `Co-nnectionPoint` was associated with a `Channel`, the `ConnectionPoint` is specified as a `reader` or a `writer` for that `Channel`, and otherwise the type of a `ConnectionPoint` is not specified.

The way in which connection points were modelled was changed, resulting in the metaclasses shown in Figure 6.4(b). `ConnectionPoint` was made abstract, and two subtypes, `ReadingConnectionPoint` and `WritingConnectionPoint`, were introduced. The `reader` and `writer` references of `Channel` were changed to refer to the new subtypes.



(a) Part of the original metamodel.



(b) Part of the evolved metamodel.

Figure 6.4: Process-oriented metamodel evolution.

Following the metamodel changes, a new version of the graphical editor was generated automatically from the metamodel using GMF. An annotation – not shown in Figure 6.4(b) – on the `WritingConnectionPoints` was used to indicate to GMF that black circles were to be used to represent writing connection points in the graphical notation.

Testing

Testing the new version of the graphical editor highlighted the need for model migration. Attempting to load existing models, such as the one shown in Figure 6.2, caused an error because `ConnectionPoint` was now an abstract class. Any model specifying at least one connection point no longer conformed to the metamodel. Model migration was performed to re-establish conformance and to allow the models to be loaded.

Several models, presented in Appendix B had been constructed when testing previous versions of the graphical editor. The models were used during each iteration to ensure that any changes had not introduced regressions. Following the metamodel changes described above, the models could no longer be loaded and required migration. A user-driven rather than a developer-driven co-evolution approach was preferred throughout the development of process-oriented editor because only a few small models required migration in each iteration.

The remainder of this section describes the way in which model migration was performed for the changes to the process-oriented metamodel outlined above. The sequel describes the way in which migration was performed during the development of the process-oriented metamodel, without dedicated structures for performing user-driven co-evolution. Section 6.1.4 describes the way in which migration could have been performed using two of the structures presented in Chapter 5. The section concludes by comparing the two approaches.

6.1.3 User-Driven Co-Evolution with EMF

During the development of the process-oriented metamodel, no structures for performing user-driven co-evolution were available. Instead, migration was performed using only those tools available in EMF, as described below.

Migration with EMF involved identifying and fixing conformance errors, using the approach shown in Figure 6.5. When a model is loaded by the graphical editor, EMF automatically reports any conformance problems. Because EMF cannot load non-conformant models, the underlying storage representation of the model, XMI, is edited by hand to reconcile conformance problems. After saving the reconciled XMI to disk, the model is loaded again in the graphical editor and, because EMF uses a multi-pass XMI parser, additional conformance problems might be reported. If further conformance problems are reported, additional changes are made to the XMI. Otherwise, migration is complete.

EMF reports conformance problems when a model is loaded. For the process-oriented metamodel, loading a model involved opening the model with the graphical model editor. For the model shown in Figure 6.2, the conformance problems shown in the bottom pane (and by the error markers in the left-hand margin of the top pane) of Figure 6.6 were reported by EMF. For example, the first conformance problem reported is shown in the tooltip in Figure 6.2, and states that a `ClassNotFoundException` was encountered because the “Class ‘ConnectionPoint’ is not found or is abstract.”

The conformance problems were fixed by editing the XMI shown in Figure 6.6, changing the type of the connection point objects to either a reading or a writing connection point. A reading (writing) connection point was used when the connection point was referenced via the `reader` (`writer`) reference of `Channel`. The reconciled XMI is shown in Figure 6.7. On lines 4 and 7, the connection point model elements have been changed to include `xmi:type`

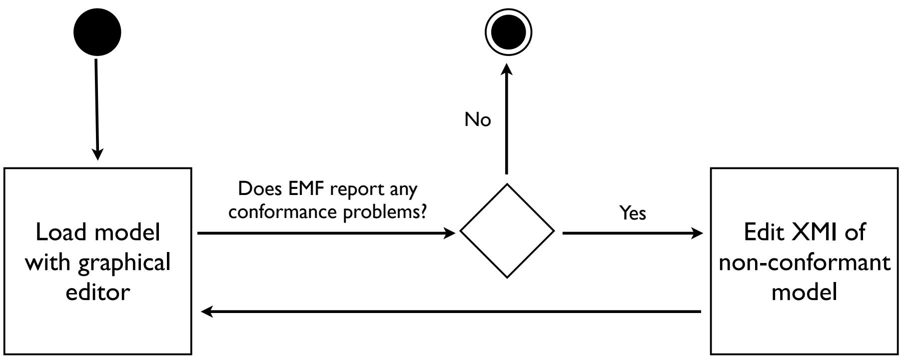


Figure 6.5: User-driven co-evolution with EMF

attributes, which specify whether the connection point should instantiate `ReadingConnectionPoint` or `WritingConnectionPoint`.

Reconciling the conformance problems by editing the XMI required considerable knowledge of the XMI specification. For example, the `xmi:type` attribute is used to specify the type of the connection point model elements. In fact, it must be included for those model elements. However, for the other model elements in Figure 6.7 the `xmi:type` attribute is not necessary, and is omitted. When and how to use the `xmi:type` attribute is discussed further in the sidebar, and is synthesised from the XMI specification [OMG 2007c] and [Steinberg *et al.* 2008]. EMF abstracts away from XMI, and typically users do not interact directly with XMI. Therefore, it may be reasonable to assume that EMF users might not be familiar with XMI, and implementation details such as the `xmi:type` attribute.

The `xmi:type` attribute

In XMI, each model element specifies a value for the `xmi:type` attribute to indicate the metaclass that the model element instantiates. For example, the model element definition on line 4 of Figure 6.7 instantiates the metaclass named `WritingConnectionPoint`. To reduce the size of models on disk, the XMI specification allows type information to be omitted when it can be inferred. For example, line 9 of Figure 6.7 defines a model element that is contained in the `channels` reference of a `Process`. Because the `channels` reference can contain only one type of model element (`Channel`), the `xmi:type` attribute can be omitted, and the type information is inferred from the metamodel.

During the development of the process-oriented editor, some mistakes were made when migrating Sampson's models. For example, the wrong subtype of `ConnectionPoint` was used as the type of several connection point

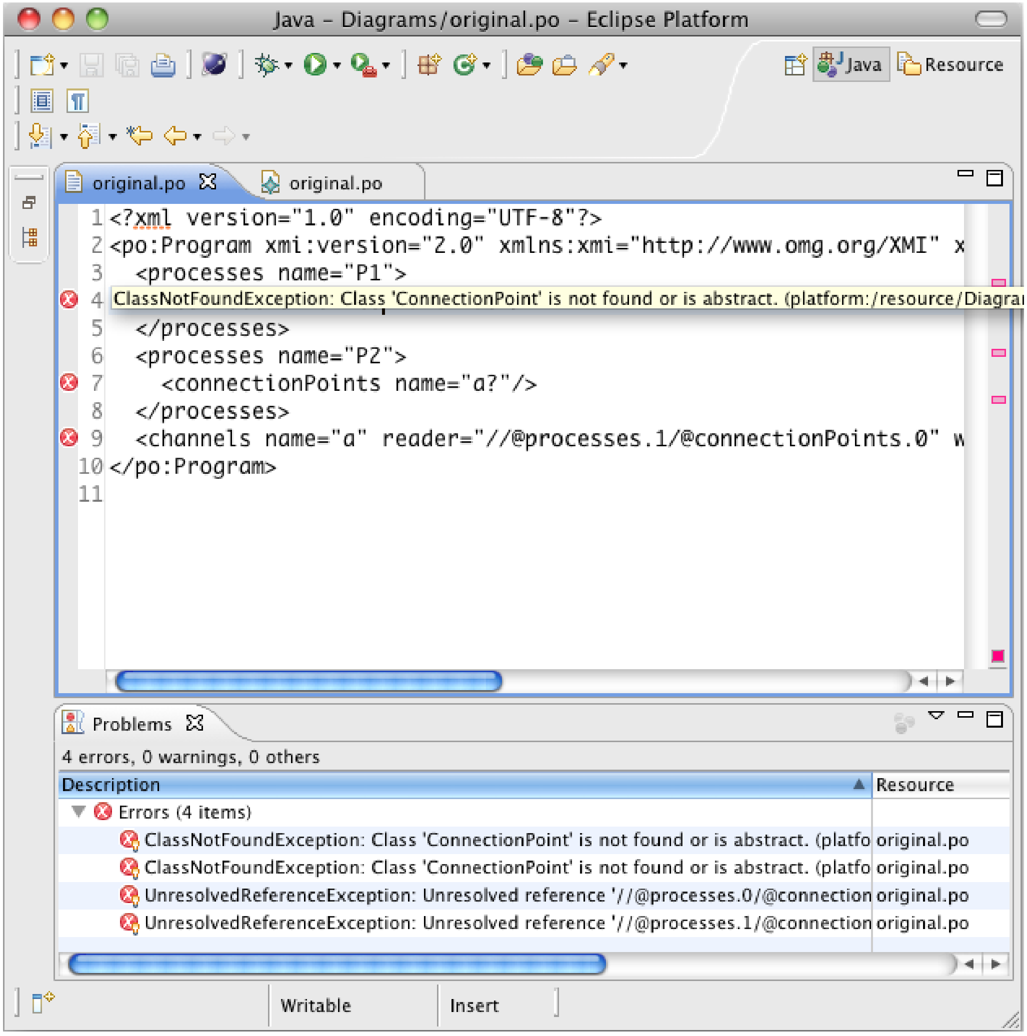


Figure 6.6: XMI prior to migration

model elements. The mistake occurred because XMI identifies model elements using an offset from the root of the document. For example, consider the XMI shown in Figure 6.7. The channel on line 9 specifies the value "//@processes.1/@connectionPoints.0" for its `reader` attribute. The value is an XMI path referencing the first connection point ("@connectionPoints.0") contained in the second process ("@processes.1") of this document ("//"); in other words the connection point on line 7. One of Sampson's models contained many channels and connection points and incorrectly counting the connection points in the model led to several mistakes during the manual editing of the XMI.

As demonstrated above, migration using only the tools provided by EMF

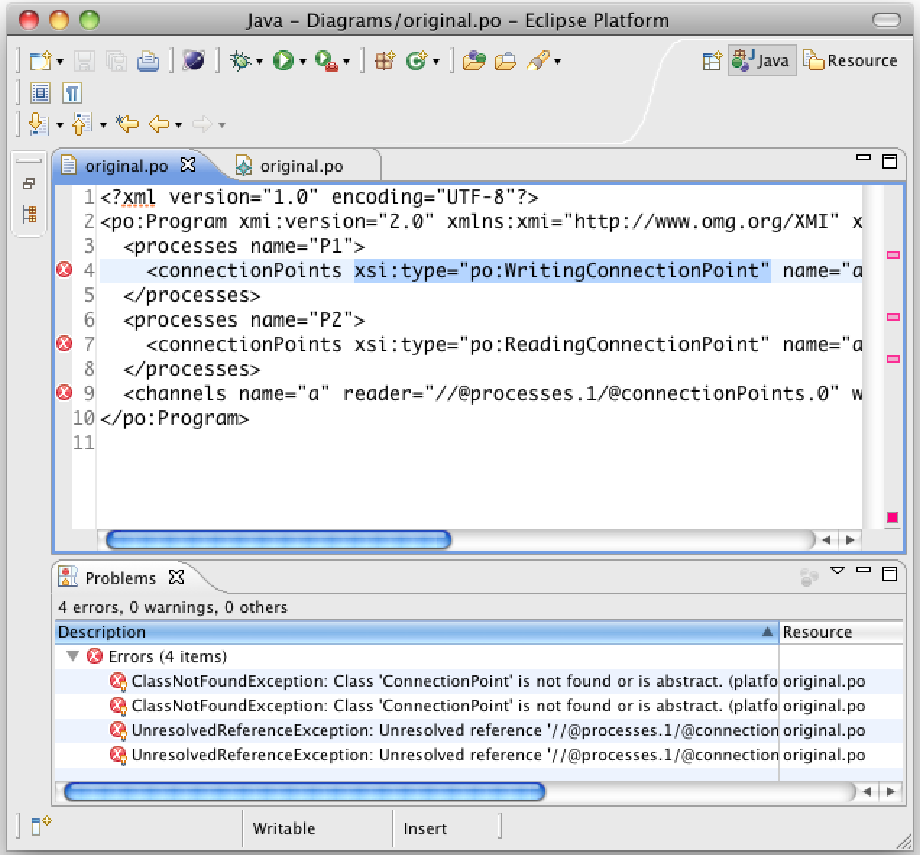


Figure 6.7: XMI after migration

was an iterative process, and mistakes were made. The sequel demonstrates that, using the dedicated structures described in Chapter 5, migration can be performed in one iteration, without requiring the developer to switch between a conformance reporting and reconciling tools. In addition, the sequel suggests how the mistake described above might be avoided by using a textual modelling notation that has been optimised for human-use.

6.1.4 User-Driven Co-Evolution with Dedicated Structures

Chapter 5 describes two structures that can be used to perform user-driven co-evolution. Here, the functionality of the two structures, a metamodel-independent syntax and a textual modelling notation, is summarised. Subsequently, an approach that uses the metamodel-independent syntax and the textual modelling notation for migrating the model from the process-oriented example is presented. The model migration example presented in this section was performed after the process-oriented editor was completed, and demonstrates how migration might have been achieved with dedicated structures for user-driven co-evolution. The sequel compares the user-driven co-evolution approach presented in this section with the approach presented above.

The metamodel-independent syntax presented in Section 5.1 allows non-conformant models to be loaded, and for the conformance of models to be checked against any metamodel. The textual modelling notation presented in Section 5.2 is built atop the metamodel-independent syntax and provides an alternative to XMI for editing models with a textual representation. Together, the two structures can be used for performing user-driven co-evolution using the approach shown in Figure 6.8. First, the user attempts to load a model. When the model cannot be loaded, the user clicks the "Generate HUTN" menu item, and the model's XMI is automatically transformed to HUTN by the implementation of HUTN described in Chapter 5. The generated HUTN source codes is presented in an editor that automatically reports conformance problems. The user edits the HUTN to reconcile conformance problems. The conformance report is automatically updated while the user edits the HUTN source. When the conformance problems are fixed, XMI for the conformant model is automatically generated, and migration is complete. The model can then be loaded in the graphical editor.

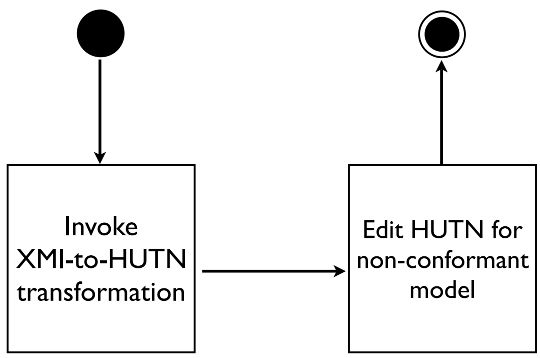


Figure 6.8: User-driven co-evolution with dedicated structures

The way in which the approach shown in Figure 6.8 might have been used for performing user-driven co-evolution for the process-oriented metamodel is now demonstrated. For the model shown in Figure 6.2, the HUTN shown in Figure 6.9 was generated by invoking the automatic XMI-to-HUTN transformation. The HUTN development tools automatically present any conformance problems, as shown in the bottom pane (and the left-hand margin of the top pane) in Figure 6.9.

Conformance problems are reconciled manually by the user, who edits the

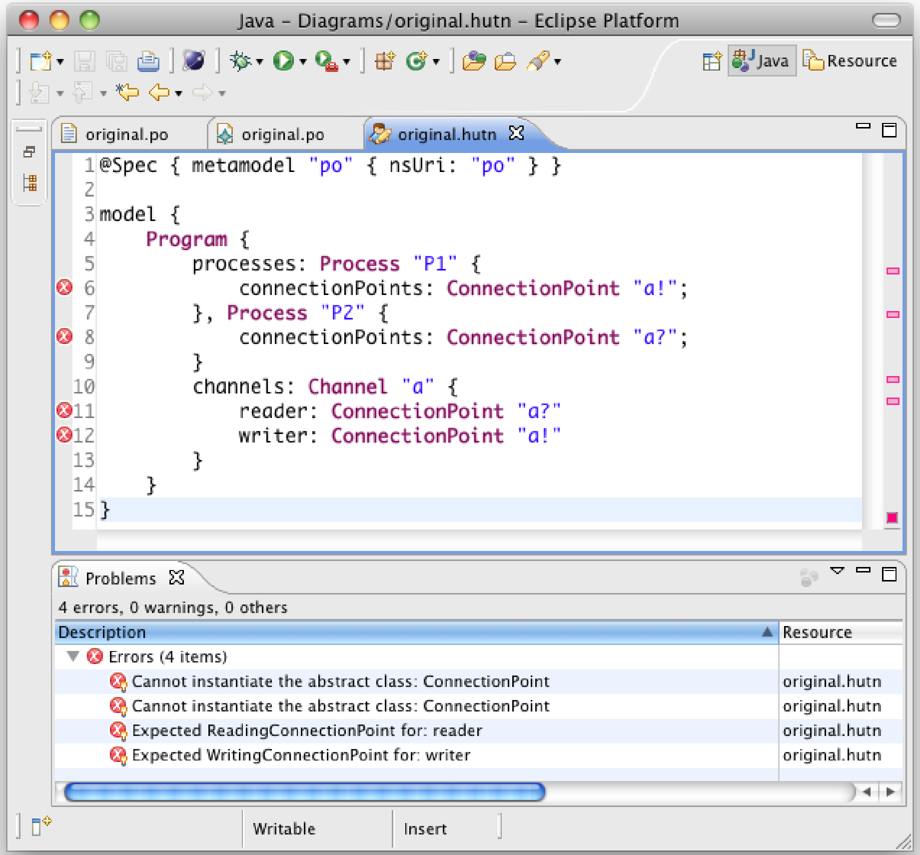


Figure 6.9: HUTN source prior to migration

HUTN source. Conformance is automatically checked whenever the HUTN is changed. For example, Figure 6.10 shows the HUTN editor when migration is partially complete. Some of the conformance problems have been reconciled, and the associated error-markers are no longer displayed in the left-hand margin.

As discussed in Section 6.1.3, mistakes were made when migrating one of Sampson's models, probably because of the way in which XMI specifies reference values. In HUTN, reference values are specified by name. The channel on lines 10-13 of Figure 6.9 refers to its reader and writer by name ("a?" and "a!" respectively), rather than using a path (such as "//@processes.1/@connectionPoints.0") as is the case with XMI.

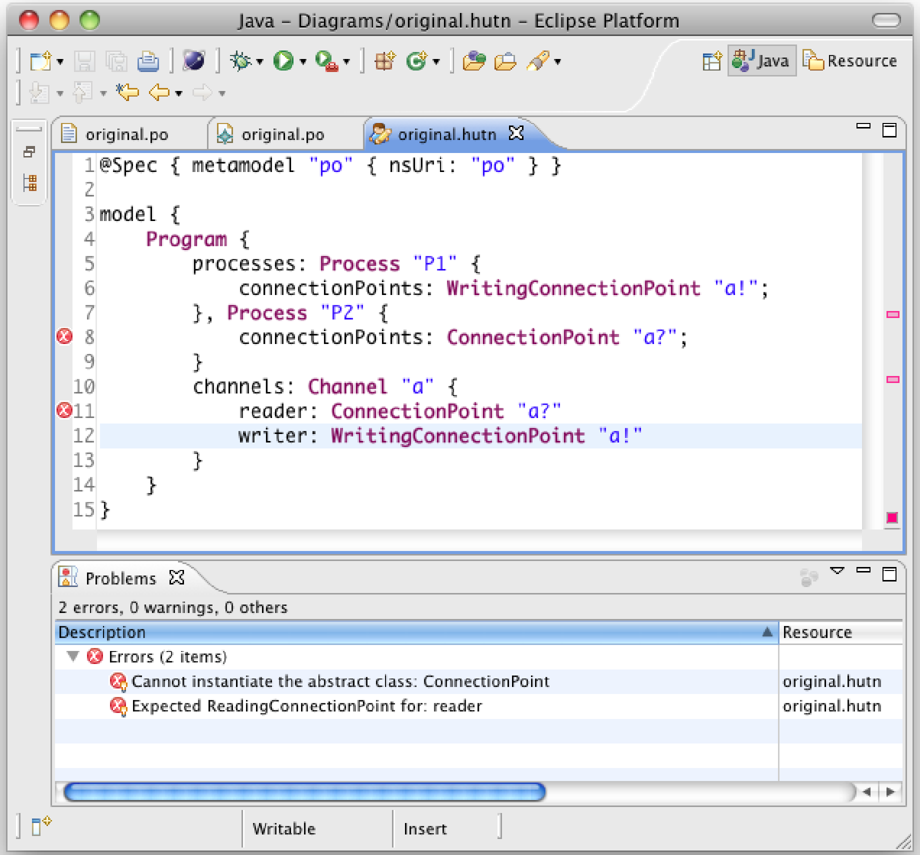


Figure 6.10: HUTN source part way through migration

6.1.5 Comparison

To suggest ways in which dedicated structures for user-driven co-evolution might increase developer productivity, the two user-driven co-evolution approaches demonstrated above are now compared. The first approach, described in Section 6.1.3, uses only those tools available in EMF for performing user-driven co-evolution, while the second approach, described in Section 6.1.4 uses two of the structures described in Chapter 5. Applying the approaches to the process-oriented example highlighted differences between the modelling notations used, and the way in which conformance problems were reported.

Differences in modelling notation

The two approaches used different modelling notations for reconciling conformance problems. The first approach used XMI, while the second used HUTN. The differences in notation that might influence developer productivity during user-driven co-evolution are now discussed. However, further work is required to more rigorously explore the extent to which developer productivity is affected by the modelling notation, as discussed in Section 6.1.6.

The way in which the type of a model element is specified varies between XMI and HUTN. In XMI, type information can be omitted in some circumstances, but must be included in others. In HUTN, type information is mandatory for every model element. Consequently, every HUTN document contains examples of how type information should be specified, whereas XMI documents may not.

Reference values are specified using paths in XMI (such as “//@processes.1/@connectionPoints.0”) and by name (such as “a?”) in HUTN. XMI paths are constructed in terms of a document’s structure and, as such, rely on implementation details. The name of a model element, on the other hand, is specified in the model, and does not rely on any implementation details. Consequently, it is conceivable that fewer mistakes will be made during user-driven co-evolution when reference values are specified by name rather than using an XMI path.

Differences in conformance reports

The two approaches varied in the way in which conformance problems were reported, and, as a consequence, the first approach was iterative and the second was not. The way in which these differences might influence developer productivity during user-driven co-evolution are now discussed. Again, further work is required to more rigorously explore the extent to which developer productivity is affected by the differences in conformance reporting, as discussed in Section 6.1.6.

With EMF, user-driven co-evolution is an iterative process. Conformance errors are fixed by the user, who then reloads the reconciled model (with, for example, a graphical editor). Each time the model is loaded, further conformance problems might be reported when, for example, the user makes a mistake when reconciling the model. By contrast, the implementation of HUTN described in Section 5.2 uses a background compiler that checks conformance while the user edits the HUTN source. When the user makes a mistake reconciling the HUTN source, the error is reported immediately, and does not require the model to be loaded in the graphical editor.

Although not demonstrated in the example considered in this section, user-driven co-evolution would, for some types of metamodel changes, remain an iterative process even if EMF performed conformance checking in the background. Because EMF uses a multi-pass parser, some types of conformance problem are reported before other types. For example, conformance problems relating to multiplicity constraints (for example, a process does not specify a name, but name is a mandatory attribute) are reported after all other types of conformance problem. When several types of conformance problem have been affected by metamodel changes, user-driven co-evolution with EMF would remain an iterative process. Single-pass, background parsing is required to display all conformance problems while the user migrates a model.

6.1.6 Towards a more thorough comparison

Although the above comparison suggests that dedicated structures for performing user-driven co-evolution might increase developer productivity, further research is required to more rigorously evaluate this claim. The ways in which this evaluation might be extended in the future are now discussed.

A comprehensive user study, involving hundreds of users, is one means for exploring the extent to which productivity varies when dedicated structures are used to perform user-driven co-evolution. Ideally, participants for the study would constitute a large and representative sample of the users of EMF. Productivity might be measured by the time taken to perform co-evolution. To remove a potential source of bias, several examples of co-evolution might be used.

Locating a reasonable number of participants and co-evolution examples for a comprehensive user study was not feasible in the context of this thesis. Nevertheless, the comparison presented in Section 6.1.5 suggests that productivity might be increased when using dedicated structures for user-driven co-evolution. By demonstrating an approach to user-driven co-evolution that uses dedicated structures, this thesis provides a foundation for further, more rigorous evaluation. For example, the HUTN specification [OMG 2004] makes claims about the human-usability of the notation, but the usability of HUTN has not been studied or compared with other modelling notations. The implementations of the co-evolution structures described in Chapter 5 enable further comparisons.

6.1.7 Summary

This section has demonstrated two approaches to user-driven co-evolution using a co-evolution example from a project in which a graphical model editor was created for process-oriented programs. The first approach used the structures available in EMF alone, while the second approach used two of the structures described in Chapter 5. Comparing the two approaches highlighted differences between the way in which conformance problems were reported and between the modelling notations used to reconcile conformance problems. The comparison described in Section 6.1.5 suggests that developer productivity might be increased by using the second approach, but, as discussed in Section 6.1.6, further work is required to more rigorously evaluate this claim.

6.2 Evaluating Conservative Copy

In contrast to the previous section, this section focuses on developer-driven migration, in which migration is specified in a programming language. As discussed in Chapter 4, the programming languages typically used to specify migration vary and, in particular, use different approaches to relating source and target model elements. This section evaluates the novel source-target relationship implemented in Flock (Section 5.4), *conservative copy*, by comparison to *new-target* and *existing-target* source-target relationships, which have been used for model migration in [Cicchetti *et al.* 2008, Garcés *et al.* 2009]) and [Herrmannsdoerfer *et al.* 2009b, Hussey & Paternostro 2006]) respectively.

The evaluation performed in this section aims to demonstrate that migration strategies are more concise when written with a migration language that uses conservative copy rather than when written with a new- or existing-target migration language. Arguably, more concise migration strategies lead to increased developer productivity (because less code is written to specify migration), and, moreover, to increased understandability of migration strategies (because less code must be read to comprehend a migration strategy).

Conciseness might be measured in many ways. For instance, [Kolovos 2009] counts lines of code to argue that more concise software components indicate a high degree of inter-component re-use. In that context, the number of lines of code is an appropriate measure because the software components were written in a single programming language. [Halstead 1977] suggests ways in which the conciseness and understandability of programs might be approximated by determining the ratio of operators (language constructs) to operands (data). Halstead's Metrics are calculated from programming language constructs and, consequently, are affected by variations in programming languages. Here, counting lines of code and Halstead's metrics are inappropriate because no single language implements the three styles of source-target relationship that are to be compared.

Instead, conciseness was measured by counting the frequency of *model operations*, program statements that are used to manipulate the target (migrated) model. Model operations were specified in a language-independent manner and then mapped onto language-specific constructs to perform the counting. Therefore, the hypothesis for the comparison was: *specifying a migration strategy with conservative copy requires no more model operations than when new-target or when existing-target are used instead.* The results presented in Section 6.2.4 corroborate the hypothesis and highlight some limitations of the implementation of conservative copy in Flock.

The remainder of this section briefly recaps the theoretical differences between the three styles of source-target relationship (Section 6.2.1), describes the co-evolution examples and languages used in the comparison (Section 6.2.2), and details the comparison method (Section 6.2.3). Finally, the results of the comparison (Section 6.2.4) are used to support the claims made above, and to highlight limitations of the conservative copy implementation provided by Flock.

6.2.1 Styles of Source-Target Relationship

Two styles of source-target relationship, new-target and existing-target, are used in existing approaches to model migration, and a third is proposed in this thesis, conservative copy. The differences between the source-target relationships were discussed in Chapter 5 and are now summarised.

With a *new-target* source-target relationship, the migrated model is created afresh by the model migration strategy. The model migration language does not automatically copy any part of the original model to the migrated model. Consequently, any model elements that are not affected by metamodel evolution must be explicitly copied from original to migrated model.

By contrast, the migrated model is initialised to be a copy of the original model in an *existing-target* source-target relationship. Prior to execution of the migration strategy, the migrated and original models are identical. Elements that no longer conform to the evolved metamodel might have been copied automatically from original to migrated model and, consequently, the migration strategy may need to delete model elements.

This thesis proposes a third style of source-target relationship termed *conservative copy*, which is a hybrid of new- and existing-target source-target relationships. Prior to the execution of the migration strategy, only those model elements that conform to the evolved metamodel are copied from original to migrated model. Conservative copy aims to reduce the amount of copying operations often required to specify migration with new-target, while also reducing the amount of delete operations used with existing-target.

6.2.2 Equipment

[1] Five examples of co-evolution taken from three projects, and three reference implementations of source-target relationships were used to perform the comparison described in this section. The co-evolution examples and the selection process for the reference implementations are now discussed.

Co-evolution Examples

To reduce contamination of the comparison, the co-evolution examples used were distinct from those identified in Chapter 4 and subsequently used in the

[1] TODO: Need a more appropriate name for this section

design of Flock in Chapter 5.

The five examples used in this section are taken from three projects. Two examples were taken from the *Newsgroup* project, which performs statistical analysis of NNTP newsgroups, developed by Dimitris Kolovos, a lecturer in this department. One example was taken from changes made to *UML* (the Unified Modeling Language) between versions 1.4 [OMG 2001] and 2.2 [OMG 2007b] of the specification. Two examples were taken from *GMF* (Graphical Modeling Framework) [Gronback 2009], an Eclipse project for generating graphical model editors.

For the newsgroup and GMF projects, the co-evolution examples were identified from source code management systems. The revision history for each project was examined, and metamodel changes were located. The intended migration strategy was determined by speaking with the developer (for the Newsgroup project) and by examining examples and documentation (for GMF). For the UML project, the co-evolution example was identified from the list of changes in the UML 2.2 specification [OMG 2007b], and by discussion with other UML users as described in Section 6.4.

For interoperability with the three reference implementations used in the comparison, the UML co-evolution was adapted. The original (UML 1.4 [OMG 2001]) metamodel is specified in XMI 1.2 [OMG 2007c], which is not supported by two of the reference implementations. The part of the UML 1.4 relating to activity graphs was reconstructed by the author in XMI 2.1 and used in place of the XMI 1.2 version. The reconstructed metamodel was checked by several UML users and was used in the expert evaluation described in Section 6.4, where the reconstructed metamodel is discussed further.

Reference Implementations Used in the Comparison

A formal semantics has not been specified for new-target, existing-target and conservative copy, and therefore the comparison reported in this section was performed using a reference implementation of each source-target relationship. Reference implementations for new- and existing-target were selected from the implementations used by existing approaches to model migration and compared to the implementation of conservative copy provided by Flock.

New-target The Atlas Transformation Language (ATL) is a model-to-model transformation language that has been used in [Cicchetti *et al.* 2008, Garcés *et al.* 2009] for model migration. ATL can be used to specify model migration with new-target, but not with existing-target as discussed in Section 5.3.2. For the comparison described in this section, ATL was selected as the new-target language because the author is not aware of any further approaches to model migration that use an alternative implementation of new-target.

Existing-target The author is aware of two approaches to migration that use existing-target transformations. In COPE [Herrmannsdoerfer *et al.* 2009b], migration strategies can be hand-written in Groovy when no co-evolutionary operator is applicable. COPE provides six Groovy functions for interacting with model elements, such as `set`, for changing the value of a feature, and `unset`, for removing all values from a feature. In the remainder of this section, the term *Groovy-for-COPE* is used to refer to the combination of the Groovy programming language and the functions provided by COPE for use in hand-written migration strategies. In Ecore2Ecore [Hussey & Paternostro 2006], migration is performed when the original model is loaded, effectively an existing-target approach. For the comparison performed in this section, Groovy-for-COPE was preferred to Ecore2Ecore because the latter is not as expressive[2] and cannot be used for migration in the co-evolution examples considered here.

In summary, the comparison described in this section uses ATL for investigating new-target, Groovy-for-COPE for existing-target, and Flock for conservative copy.

6.2.3 Method

The comparison method is now described. Following the selection of co-evolution examples and reference implementations, the author wrote a migration strategy for each co-evolution example in each of the reference implementations (ATL, Groovy-for-COPE and Flock). The intended migration strategy was determined from models available in the source code management system of the co-evolution example (Newsgroup and GMF projects), or (for the UML project) by referring to the UML specification and discussing ambiguities with other UML users, as described in Section 6.4.

Next, a set of model operations were identified in a language independent manner and then mapped onto language constructs in ATL, Groovy-for-COPE and Flock. The counting of model operations was then automated by implementing a counting program, which was tested and used to further develop the comparison technique. Finally, the counting program was executed on the evaluation examples and the results investigated (Section 6.2.4).

Because the author is more familiar with Flock than with ATL and Groovy-for-COPE, the comparison method has an obvious drawback: the migration strategies written in the latter two languages might be more concise if they were written by the developers of ATL and Groovy-for-COPE. The evolutionary operators built into COPE provide many examples of migration strategy code written by the developer of COPE and, where possible, this code was re-used.

[2]Communication with Ed Merks, Eclipse Modeling Project leader, 2009, available at `http://www.eclipse.org/forums/index.php?t=tree&goto=486690&S=b1fdb2853760c9ce6b6b48d3a01b9aac`

Language-Independent Model Operations

The way in which model operations were identified and counted is now described. Four types of model operation were considered for inclusion in the evaluation: model element creation and deletion operators, and model value assignment and unassignment operators.

Creation and deletion operators are used to create or delete model elements in the migrated model. Assignment and unassignment operators are used to set or unset data values in the migrated model. Typically, assignment operators are used for copying values from the original to the migrated model.

Deletion and unassignment operators are not necessary when specifying model migration with new-target, because the migrated model is created afresh by the model migration strategy. Any deletion or unassignment would involve removing model elements or values created explicitly elsewhere in the migration strategy. By contrast, existing-target and conservative copy will automatically create model elements and assign model values prior to the execution of the model migration strategy and hence unassignment and deletion operators are required.

Creation operators were not included in the comparison because, unlike the other operators, they are difficult to specify with regular expressions (and hence automatically count). Moreover, all of the co-evolution examples considered in the comparison assign values to model elements after they are created. Consequently, at least one assignment operator is used whenever a creation operator would have been used.

Model Operations in ATL, Groovy-for-COPE and Flock

The concrete syntax of the deletion, assignment and unassignment model operations in each language is now introduced. First however, it is important to note that the languages considered provide loop constructs and consequently a single model operation might be executed several times during the execution of a migration strategy. Here, a model operation is counted only once even if it is contained in a loop because the comparison reasons about the conciseness of migration strategies, and not about the way in which model operations are executed.

New-target in ATL For new-target in ATL, the following model operation was counted:

- **Assignment:**

```
<feature> <- <value>
```

The assignment operator is used to copy values from the original to the migrated model. Typically, the `value` on the right-hand side is a literal, the value of a feature in the original model, or derived from a combination of the two. Listing 6.1 shows these typical uses of an assignment operator in ATL: line 4 assigns to a literal value, line 5 to the value of a feature in the original model, and line 6 to a value derived from two features in the original model that are separated with a literal value. In the listings in the remainder of this section, lines on which model operations appear are highlighted.

```
1 rule Person2Employee {
2   from o : Before!Person
3   to m : After!Employee (
4       role <- "Unknown",
5       id  <- o.id,
6       name <- o.forename + " " + o.surname
7     )
8 }
```

Listing 6.1: Assignment operators in ATL

As discussed above, deletion and unassignment operators are not used for new-target model migration.

Existing-target in Groovy-for-COPE For existing-target in Groovy-for-COPE, the following model operations were counted:

- **Assignment:**

```
<element>.<feature> = <value>
<element>.<feature>.add(<value>)
<element>.<feature>.addAll(<collection_of_values>)
<element>.set(<feature>, <value>)
```

- **Unassignment:**

```
<element>.unset(<feature>)
<element>.<feature>.remove(<value>)
```

- **Deletion:**

```
delete <element>
```

Unlike ATL, Groovy-for-COPE provides distinct operators for assigning to single- and multi-valued features. The first assignment operator assigns to a single-valued feature, the second adds one value to a multi-valued feature, and the third adds multiple values to a multi-valued feature. The fourth form allows the feature name to be determined at runtime and, hence, facilitates reflective access to the model.

COPE provides two forms of unassignment. The first can be used to unassign any feature. The second form is used to remove one value from a multi-valued feature.

Conservative Copy in Epsilon Flock Epsilon Flock, a transformation language tailored for model migration, was developed in this thesis and discussed in Chapter 5. For Flock, the following model operations were counted:

- **Assignment:**

```
<element>.<feature> := <value>
<element>.<feature>.add(<value>)
<element>.<feature>.addAll(<collection_of_values>)
```

- **Unassignment:**

```
<element>.<feature> := null
<element>.<feature>.remove(<value>)
```

- **Deleting:**

```
delete <element>
```

Like Groovy-for-COPE, Flock distinguishes between assignment to single- and multi-valued features and, hence, provides three assignment operators. Unlike Groovy-for-COPE, Flock does not provide a form of assignment that allows the name of the assigned feature to be determined at runtime.

Flock does not provide a dedicated language construct for performing unassignment, which is instead achieved by assignment to `null`. One value can be removed from a multi-valued feature with the second form of unassignment.

Development and Testing of Method

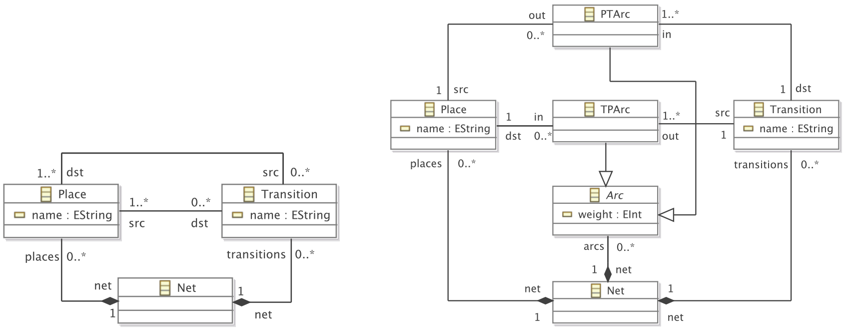
The method and a program for counting model operations were developed and tested by using the co-evolution examples described in Chapter 4, which were used to derive the thesis requirements. An example of model operation counting is given in the remainder of this section, along with the total number of model operations observed for each of the co-evolution examples described in Chapter 4.

Consider the example of metamodel-evolution shown in Figure 6.11. This is the Petri nets metamodel evolution described in Sections 5.3 and 5.4. The migration strategy replaces `Arcs` with `PTArcs` or `TPArcs`. In ATL, the migration strategy uses 12 model operations (Listing 6.2). In Groovy-for-COPE, the migration strategy uses 10 model operations (Listing 6.3) . In Flock, the migration strategy uses 6 model operations (Listing 6.4). These results are also shown in the *(Literature) PetriNets* row of Table 6.1.

Table 6.1 shows the total number of model operations needed to specify migration in ATL, Groovy-for-COPE and Flock for each of the co-evolution examples from Chapter 4. Because the examples used to produce the measurements shown in Table 6.1 were used to design Flock, they are not used to

```
rule Nets {
  from o : Before!Net
  to m : After!Net (
    places <- o.places,
    transitions <- o.transitions
  )
}

rule Places {
  from o : Before!Place
  to m : After!Place (
    name <- o.name
  )
}

rule Transitions {
  from o : Before!Transition
  to m : After!Transition (
      name <- o.name,
      "in" <- o.src->collect(p | thisModule.PTArcs(p,o)),
      out <- o.dst->collect(p | thisModule.TPArcs(o,p))
    )
}

lazy rule PTArcs {
  from place : Before!Place, destination : Before!Transition
  to ptarcs : After!PTArc (
      src <- place,
      dst <- destination,
      net <- destination.net
    )
}

lazy rule TPArcs {
  from transition : Before!Transition, destination : Before!Place
  to tparcs : After!TPArc (
      src <- transition,
      dst <- destination,
      net <- transition.net
    )
}
```

Listing 6.2: The Petri nets model migration in ATL



(a) Original metamodel.

(b) Evolved metamodel.

Figure 6.11: Exemplar metamodel evolution. Taken from [Rose *et al.* 2010e].

```
for (transition in Transition.allInstances) {
  for (source in transition.unset('src')) {
    def arc = petrinets.PTArc.newInstance()
    arc.src = source;
    arc.dst = transition;
    arc.net = transition.net
  }

  for (destination in transition.unset('dst')) {
    def arc = petrinets.TPArc.newInstance()
    arc.src = transition;
    arc.dst = destination;
    arc.net = transition.net
  }
}

for (place in Place.allInstances) {
  place.unset('src');
  place.unset('dst');
}
```

Listing 6.3: The Petri nets model migration in Groovy-for-COPE

```
migrate Transition {
  for (source in original.src) {
    var arc := new Migrated!PTArc;
    arc.src := source.equivalent();
    arc.dst := migrated;
    arc.net := original.net.equivalent();
  }

  for (destination in original.dst) {
    var arc := new Migrated!TPArc;
    arc.src := migrated;
    arc.dst := destination.equivalent();
    arc.net := original.net.equivalent();
  }
}
```

Listing 6.4: Petri nets model migration in Flock

evaluate conservative copy. Instead, they are presented here to show the way in which the evaluation method was developed, and because one of the results (*Refactor: Change Ref to Cont*) highlighted a limitation of the existing-target and conservative copy implementations in COPE and Flock, which is discussed in Section 6.2.4.

6.2.4 Results

By counting the model operations in model migration strategies, the similarities and differences between the three styles of source-target relationship were investigated. The five co-evolution examples discussed in Section 6.2.2 were measured to obtain the results shown in Table 6.2.

The comparison hypothesis stated that *specifying a migration strategy with conservative copy requires no more model operations than when new-target or when existing-target are used instead.* For four of the five examples in Table 6.2, the results support the hypothesis, but the results for the GMF Graph example do not.

The comparison hypothesis did not consider differences between new-target and existing-target, but the results show that, for the most part, a migration strategy uses fewer model operations when using existing-target rather than new-target. For all of the examples in Table 6.2 and most of the examples in Table 6.1, no migration strategy specified with existing-target contained fewer model operations when specified with new-target. However, three of the Refactor examples in Table 6.1 required more model operations when specified with existing-target than when specified with new-target.

The results are now investigated, starting by discussing the way in which

	Migration Language Source-Target Relationship		
(Project) Example	**ATL** New	**G-f-C** Existing	**Flock** Conservative
(FPTC) Connections	6	6	3
(FPTC) Fault Sets	7	5	3
(GADIN) Enum to Classes	4	1	0
(GADIN) Partition Cont	5	3	2
(Literature) PetriNets	12	10	6
(Newsgroup) Extract Person	9	6	5
(Newsgroup) Resolve Replies	8	3	2
(Process-Oriented) Split CP	8	1	1
(Refactor) Cont to Ref	4	5	3
(Refactor) Ref to Cont	3	5	3
(Refactor) Extract Class	5	4	2
(Refactor) Extract Subclass	6	0	0
(Refactor) Inline Class	4	5	2
(Refactor) Move Feature	6	2	1
(Refactor) Push Down Feature	6	0	0

Table 6.1: Model operation frequency (analysis examples).

	Migration Language Source-Target Relationship		
(Project) Example	**ATL** New	**G-f-C** Existing	**Flock** Conservative
(Newsgroup) Extract Person	9	6	5
(Newsgroup) Resolve Replies	8	3	2
(UML) Activity Diagrams	15	15	8
(GMF) Graph	101	11	14
(GMF) Gen2009	310	16	16

Table 6.2: Model operation frequency (evaluation examples).

the results support the comparison hypothesis. Subsequently, results that contradict the hypothesis are analysed in more detail. The analysis led to the discovery of two limitations of the conservative copy implementation in Flock, which are also discussed below.

Investigation of results

As discussed in Section 6.2.1, new-target, existing-target and conservative copy initialise the migrated model in a different way. New-target initialises an empty model, while existing-target initialises a complete copy of the original model. Conservative copy initialises the migrated model by copying only those model elements from the original model that conform to the migrated metamodel.

For four of the co-evolution examples, the results in Table 6.2 support the comparison hypothesis. Additionally, the results in Table 6.2 indicate that a migration strategy can be specified with fewer model operations when using existing-target rather than new-target. Three of the results for the Refactor examples in Table 6.1 contradict this contention.

In two of the co-evolution examples, a large proportion of metamodel features were not affected by evolution. These were the GMF examples shown in Table 6.2, which involved evolution of a small part of the metamodels. For the GMF examples, the ATL (new-target) migration strategies use many more model operations than Groovy-for-COPE (existing-target) and Flock (conservative copy). It is likely that the same phenomenon would have been observed, had the actual UML 1.4 metamodel been used for the UML co-evolution example, but this was not possible for the reasons given in Section 6.2.2.

New-target initialises an empty model and, hence, every element of the migrated model must be derived from the original model. For model elements that do not need to be changed in response to metamodel evolution, the migration strategy must copy those elements without change. For instance, the new-target version of the GMF Graph and Gen migration strategies contain many transformation rules such as the one shown in Listing 6.5, which exist only for copying model elements from the original to the migrated model. In Listing 6.5, 5 model operations are used (all assignments) to copy values from the original to the migrated model. The features shown in Listing 6.5 (`figures`, `nodes`, `connections`, `compartments` and `labels`) were not changed during metamodel evolution. Unlike new-target, existing-target and conservative copy do not require explicit copying of model elements from the original to migrated model due to the way in which they initialise the migrated model.

In the UML co-evolution example (Table 6.2) and the Refactor Inline Class (Table 6.1), a large proportion of metamodel features were renamed. For these examples, expressing migration with an existing-target transformation language requires more model operations than using a new-target transforma-

```
rule Canvas2Canvas {
  from o : Before!Canvas
  to m : After!Canvas (
    figures <- o.figures,
    nodes <- o.nodes,
    connections <- o.connections,
    compartments <- o.compartments,
    labels <- o.labels
  )
}
```

Listing 6.5: An extract of the GMF Graph model migration in ATL

tion language.

Existing-target requires two model operations be used when a feature is renamed, while new-target and conservative copy require only one model operation. For instance, the `transitions` feature of `ActivityGraph` was renamed to `edge` in the UML co-evolution example. The code used for migration in response to this change for new-target, existing-target and conservative copy is shown below.

New-target: `edge <- transitions`
Existing-target: `element.edge = element.unset(transitions)`
Conservative copy: `migrated.edge := original.transitions`

As shown above, migration in response to feature renaming typically requires one model operation when using new-target and conservative copy (an assignment). When using existing-target, the equivalent migration strategy requires an additional model operation (an unassignment) that removes the value from the old feature. Note that, in Groovy-for-COPE, the `unset` function unassigns a feature and returns the (unassigned) value.

The results in Table 6.2 corroborate the comparison hypothesis for four of the five examples. The five migration strategies required no more model operations when specified with conservative copy than when specified with new- and existing-target. When specified with conservative copy, the migration strategies did not contain explicit copying (which was required when using new-target for the GMF examples) and used one rather than two model operations for migration in response to feature renaming (which required two model operations when using existing-target). The GMF Graph co-evolution example does not support the hypothesis due to a limitation of the way in which conservative copy is implemented in Flock. This limitation is described below.

Two conclusions can be drawn from this discussion. Firstly, in general, fewer model operations are used when specifying a migration strategy with a conservative copy migration language than when specifying the same migration strategy with a new- or existing-target migration language. Secondly, in the examples studied here, there are often more features unaffected by metamodel evolution than affected. Consequently, specifying model migration with a new-target migration language requires more model operations than in an existing-target migration language for the examples shown in Tables 6.1 and 6.2. [Sprinkle 2003] suggests that metamodel evolution often involves changes to relatively few metamodel elements, and the results presented in this section support his contention.

Limitation 1: Duplication when migrating subtypes

For the GMF Graph example (Table 6.2), conservative copy requires more model operations than existing-target. Investigation of this result revealed a limitation of the conservative copy implementation provided by Flock, which is now described and illustrated using a simplification of the GMF Graph co-evolution example.

Figure 6.12 shows part of the GMF Graph metamodel prior to evolution. In the real metamodel, the `figure` and `accessor` features are references to other metamodel classes, rather than attributes. When the metamodel evolved, the types of the `figure` and `accessor` features were changed. Here, let us assume that their types were changed from a string to an integer. The actual metamodel changes are described in Appendix C.

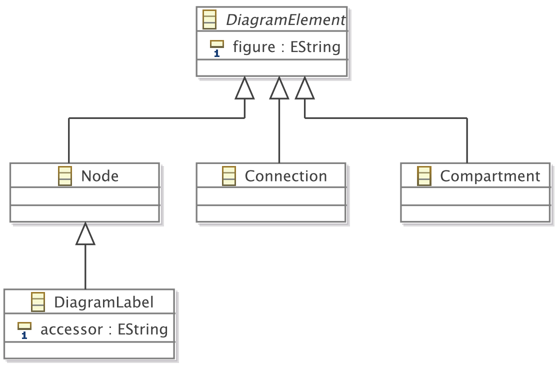


Figure 6.12: Simplified fragment of the GMF Graph metamodel.

In response to re-typing of the `figure` and `accessor` features, the migration strategy derived new values for the `figure` and `accessor` features. In the real example, a new model element was created and used to decorate [Gamma *et al.* 1995] each old value. In the simplified example presented here, the new integer value will be derived from the old string value by using its length. Appendix C includes the strategies used to perform migration for the actual metamodel changes.

As demonstrated below, ATL and Groovy-for-COPE provide mechanisms for re-using migration code between subtypes. Migration of the `figure` feature can be specified once and used for migrating all subtypes of `DiagramElement`. Currently, Flock does not provide a mechanism for re-using migration code between subtypes.

In ATL (Listing 6.6), the GMF Graph migration strategy was expressed using two model operations: the two assignment operations on lines 3 and 23. For `Nodes`, `Connections` and `Compartments`, migration of the `figure` feature is achieved by extending the `DiagramElement` transformation rule. Note the use of the `extends` keyword on lines 6, 11 and 16 for inheriting the rule on lines 1-4. For `DiagramLabels`, the values of both the `accessor` and `figure` features must be migrated. On lines 21-24, the `DiagramLabels` extends `Nodes` and hence `DiagramElements` to inherit the body of the latter for migrating figures, and, in addition, the `DiagramLabels` rule defines the migration for the value of the `accessor` feature.

In Groovy-for-COPE (Listing 6.7), the migration is similar to ATL but is specified imperatively. In Listing 6.7, a loop iterates over each instance of `DiagramElement` (line 1), migrating the value of its figure feature (line 2). The `allInstances` function is used to locate every model element with the type `DiagramElement` or one of its subtypes. If the `DiagramElement` is also a `DiagramLabel` (line 4), the value of its accessor feature is also migrated (line 5). In Groovy-for-COPE, the migration strategy uses two model operations: the assignment statements on lines 2 and 5.

In both ATL and Groovy-for-COPE, only 2 model operations are required for this migration: an assignment for each of the two features being migrated. However, the equivalent Flock migration strategy, shown in Listing 6.8, requires 5 model operations: the assignment statements on lines 2, 6, 10, 11 and 15. Note that the migration of the `figure` feature is specified four times (once for each subtype of `DiagramElement`). A single `DiagramElement` rule cannot be used to migrate the `figure` feature because, when a `migrate` rule does not specify a `to` part, Flock will create an instance of the type named after the `migrate` keyword. In other words, a `migrate DiagramElement` rule will result in Flock attempting to instantiate the abstract class `DiagramElement`. Instead migration must be specified using four migrate rules, as shown in Listing 6.8.

In the current implementation of Flock, `migrate` rules are used for specifying two concerns and the limitation described here might be avoided if those concerns were specified using two distinct language constructs. Firstly, the `to` part of a `migrate` rule is used to establish type equivalences between the original and evolved metamodel. When a metaclass is renamed, for example, migration in Flock would typically use a rule of the form `migrate OldType to NewType`. Omitting the `to` part of a rule (`migrate X`) is a

```
abstract rule DiagramElements {
 from o : Before!DiagramElement
 to  m : After!DiagramElement (
   figure <- o.figure.length()
 )
}

rule Nodes extends DiagramElements {
 from o : Before!Node
 to  m : After!Node
}

rule Connections extends DiagramElements {
 from o : Before!Connection
 to  m : After!Connection
}

rule Compartments extends DiagramElements {
 from o : Before!Compartment
 to  m : After!Compartment
}

rule DiagramLabels extends Nodes {
 from o : Before!DiagramLabel
 to  m : After!DiagramLabel (
   accessor <- o.accessor.length()
 )
}
```

Listing 6.6: Simplified GMF Graph model migration in ATL

```
for (diagramElement in DiagramElement.allInstances()) {
 diagramElement.figure = diagramElement.figure.length()

 if (DiagramLabel.allInstances.contains(diagramElement)) {
   diagramElement.accessor = diagramElement.accessor.length()
 }
}
```

Listing 6.7: Simplified GMF Graph model migration in COPE

```
migrate Compartment {
  migrated.figure := original.figure.length();
}

migrate Connection {
  migrated.figure := original.figure.length();
}

migrate DiagramLabel {
  migrated.figure := original.figure.length();
  migrated.accessor := original.accessor.length();
}

migrate Node {
  migrated.figure := original.figure.length();
}
```

Listing 6.8: Simplified GMF Graph model migration in Flock

shorthand for `migrate X to X`. Secondly, the body of each rule specifies the way in which each model element should be migrated. Separating the two concerns using distinct language constructs might facilitate the re-use of migration code between subtypes, as is the case in ATL and Groovy-for-COPE. The extent to which greater re-use and increased conciseness can be addressed with changes to the implementation of Flock, and in general, is discussed in Section 7.2. This section now considers one further limitation of existing-target and conservative copy migration languages.

Limitation 2: Side-effects during initialisation

The measurements observed for one of the examples of co-evolution from Chapter 4, Change Reference to Containment (Table 6.1), cannot be explained by the conceptual differences between source-target relationship. Instead, the way in which the source-target relationship is implemented must be considered.

When a reference feature is changed to a containment reference during metamodel evolution, constructing the migrated model by starting from the original model (as is the case with existing-target and conservative copy) can have side-effects which complicate migration.

In the Change Reference to Containment example, a `System` initially comprises `Ports` and `Signatures` (Figure 6.13). A `Signature` references any number of `ports`. The metamodel is evolved to prevent the sharing of `Ports` between `Signatures` by changing the `ports` feature to a containment rather than a reference (Figure 6.14). `Ports` are contained in `Signatures` rather than in Systems, and consequently the ports is no longer a feature of System.

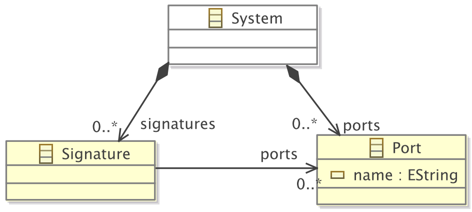


Figure 6.13: Original metamodel.

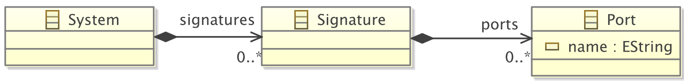


Figure 6.14: Evolved metamodel.

Listing 6.9 shows the migration strategy using new-target in ATL. Three model operations are used: the assignment statements on lines 3, 8 and 14. The rules for migrating Systems (lines 1-4) and Ports (13-15) copy values for the features unaffected by evolution (signatures and name respectively). The rule for migrating Signatures (lines 6-11) clones each member of the ports feature (using the Port rule on lines 13-15). Crucially, the Ports rule is marked as lazy and consequently is only executed when called from the Signatures rule. By contrast, the Systems and Signatures rules are executed automatically by ATL for each System and Signature in the original model, respectively.

In existing-target and conservative copy migration languages, migration is less straightforward because, during the initialisation of the the migrated model from the original model, the value of a containment reference (Signature#ports) is set. When a containment reference is set, the contained objects are removed from their previous containment reference (i.e. setting a containment reference has side-effects). Therefore, in a System where more than one Signature references the same Port, the migrated model cannot be formed by copying the contents of Signature#ports from the original model. Attempting to do so causes each Port to be contained only in the last referencing Signature that was copied.

In COPE, the containment nature of a reference is not enforced until after the migration strategy is executed. Hence, migration for the type of metamodel change considered here can be specified by unsetting the contents of the ports reference (line 4 of Listing 6.10), and creating a copy of each referenced

```
rule Systems {
 from o : Before!System
 to m : After!System (
  signatures <- o.signatures
 )
}

rule Signatures {
 from o : Before!Signature
 to m : After!Signature (
  ports <- o.ports->collect(p | thisModule.Ports(p))
 )
}

lazy rule Ports {
 from o : Before!Port
 to m : After!Port (
  name <- o.name
 )
```

Listing 6.9: Migration for Change Reference to Containment in ATL

`Port` (lines 5-7 of Listing 6.10). The migration strategy shown in Listing 6.10 uses 5 model operations: assignments on lines 8, 9 and 12; unassignment on line 10, and deletion on line 19. Note that the assignment on line 7 is to a temporary variable, and so is not counted as a model operation.

The ATL migration strategy copies ports as they are needed. By contrast, the Groovy-for-COPE migration strategy must account for the initial copy of every Port which is created prior to execution according to existing-target. The Groovy-for-COPE migration strategy must either clone only those ports that are referenced by more than one signature, or clone every referenced port, but delete all of the ports created by existing-target. The latter approach requires 1 more model operation (to delete the original ports) than the former (shown in Listing 6.10).

In Flock, the containment nature of the reference is enforced when the migrated model is initialised. Because changing the contents of a containment reference has side-effects, a `Port` that appears in the `ports` reference of a `Signature` in the original model may not have been automatically copied to the `ports` reference of the equivalent `Signature` in the migrated model during initialisation. Consequently, the migration strategy must check the `ports` reference of each migrated `Signature`, cloning only those `Ports` that have not be automatically copied during initialisation (see line 3 of Listing 6.11). The Flock migration strategy uses 3 model operations: assignments on lines 5 and 6, and a deletion on 11.

```
def contained = []

for(signature in refactorings_changeRefToCont.Signature.allInstances) {
  for(port in signature.ports)) {
    // when more than one Signature references this port
    if (contained.contains(port)) {
      def clone = Port.newInstance()
      clone.name = port.name
      signature.ports.add(clone)
      signature.ports.remove(port)
    } else {
      contained.add(port)
    }
  }
}

for(port in refactorings_changeRefToCont.Port.allInstances) {
  if (not refactorings_changeRefToCont.Signature.allInstances.any { it.
      ports.contains(port) }) {
      port.delete()
  }
}
```

Listing 6.10: Migration for Change Reference to Containment in Groovy-for-COPE

```
migrate Signature {
  for (port in original.ports) {
    if (migrated.ports.excludes(port.equivalent())) {
      var clone := new Migrated!Port;
      clone.name := port.name;
      migrated.ports.add(clone);
    }
  }
}

delete Port when:
  not Original!Signature.all.exists(s|s.ports.includes(original))
```

Listing 6.11: Migration for Change Reference to Containment in Flock

The Groovy-for-COPE and Flock migration strategies must remove any `Ports` which are not referenced by any `Signature` (lines 17-21 of Listing 6.10, and line 11 of Listing 6.11 respectively), whereas the ATL migration strategy, which initialises any empty migrated model, does not copy unreferenced `Ports`.

When a non-containment reference is changed to a containment reference, migration strategies written in Flock and Groovy-for-COPE must account for the side-effects that can occur during initialisation of the migrated model, resulting in less concise migration strategies. The existing-target and conservative copy implementations used in COPE and Flock might be changed to avoid this limitation by either automatically cloning values when a reference is changed to be a containment reference, or by allowing the user to specify features that should not be copied by the source-target relationship during initialisation. Section 7.2 discusses this issue further.

6.2.5 Summary

By counting uses of model operations, this section has compared, in the context of model migration, three approaches to relating source-target relationship: new-target, existing-target and conservative copy. The results have been analysed and the measurement method described.

The analysis of the measurements has shown that new- and existing-target migration languages are better suited to different contexts. New-target languages require fewer model operations than existing-target languages when metamodel evolution involves the renaming of features. Existing-target languages require fewer model operations than new-target languages when metamodel evolution does not affect most model elements. For the examples considered here, the latter context was more common. Conservative copy requires fewer model operations than both new- and existing-target in almost all of the examples considered here.

The comparison has highlighted two limitations of the conservative copy algorithm implemented in Epsilon Flock, and this section has shown how these limitations are problematic for specifying some types of migration strategy.

The author is not aware of any existing quantitive comparisons of migration languages, and, as such, the best practices for conducting such comparisons are not clear. The method used in obtaining these measurements has been described to provide a foundation for future comparisons.

6.3 Evaluating Co-evolution Tools

This section compares four co-evolution tools to determine their strengths and weaknesses and to provide guidance for selecting a model migration tool. As discussed in Chapter 3, several tools for managing co-evolution are described in the literature. Chapter 5 introduces a further tool, Flock. While each tool has strengths and weaknesses, little is known about how migration tools compare in practice.

The comparison and guidance presented in this section aim to simplify tool selection by recommending tools for particular situations or requirements. For example, when scalability is a concern (many large models are to be migrated), the advice presented in this section indicates that a developer should consider AML and Ecore2Ecore. Furthermore, the comparison highlighted situations in which Flock is more or less suitable than other tools, as discussed in Section 6.3.3.

The comparison reported in this section was performed using an expert evaluation. Flock and three further co-evolution tools, selected from those described in Chapter 4, were compared by MDE experts. Following the process outlined in Section 6.3.1, the tools were applied to two co-evolution examples. The remainder of this section reports the experts' experiences with each tool (Section 6.3.2), and synthesises advice and guidelines for identifying the most appropriate model migration tool in different situations (Section 6.3.3).

This section is based on joint work with Markus Herrmannsdöerfer (a research student at Technische Universität München), James Williams (a research student in this department), Dimitrios Kolovos (a lecturer in this department) and Kelly Garcés (a research student at EMN-INRIA / LINA-INRIA in Nantes), and has been published in [Rose *et al.* 2010a]. Garcés provided assistance with installing and configuration one of the migration tools, and commented on a draft of the paper. Herrmannsdöerfer, Williams and Kolovos played a larger role in the comparison. Here, the work is narrated to make clear their contributions.

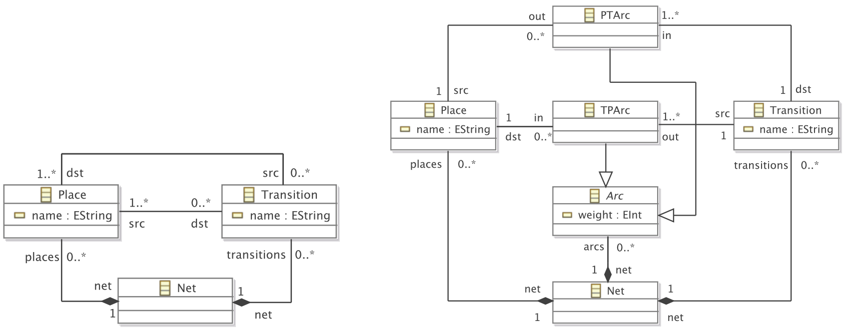
6.3.1 Comparison Method

The comparison described in this section is based on practical application of the tools to the co-evolution examples described below. This section also discusses the tool selection and comparison processes. Herrmannsdöerfer and I identified the co-evolution examples, and formulated the comparison process.

Co-Evolution Examples

To compare migration tools, two examples of co-evolution were used. The first, Petri nets, is a well-known problem in the model migration literature and was used to test the installation and configuration of the migration tools. The second, GMF, is a larger example taken from a real-world model-driven development project, and was identified as a potentially useful example for co-evolution case studies in Chapter 4 and in [Herrmannsdoerfer *et al.* 2009a].

Petri Nets. The first example is an evolution of a Petri net metamodel, previously used to describe the implementation of Epsilon Flock (Section 5.4), and in [Cicchetti *et al.* 2008, Garcés *et al.* 2009, Wachsmuth 2007] to discuss co-evolution and model migration.



(a) Original metamodel. (b) Evolved metamodel.

Figure 6.15: Petri nets metamodel evolution (taken from [Rose *et al.* 2010e]).

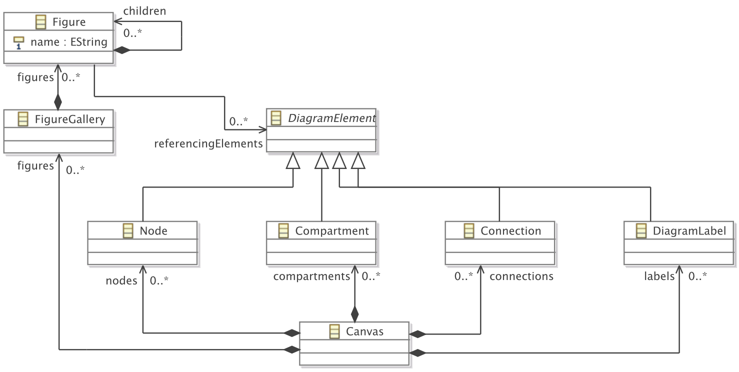
In Figure 6.15(a), a Petri `Net` comprises `Places` and `Transitions`. A `Place` has any number of `src` or `dst` `Transitions`. Similarly, a `Transition` has at least one `src` and `dst` `Place`. In this example, the metamodel in Figure 6.15(a) is evolved to support weighted connections between `Places` and `Transitions` and between `Transitions` and `Places`.

The evolved metamodel is shown in Figure 6.15(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`.

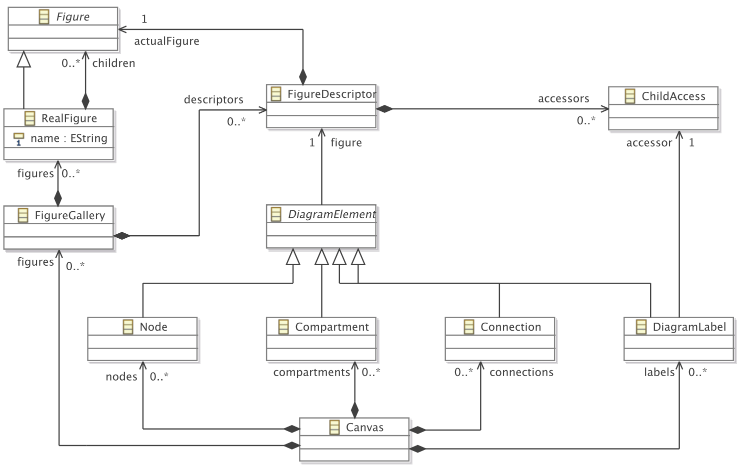
GMF. The second example is taken from GMF [Gronback 2009], an Eclipse project for generating graphical editors for models. The development of GMF is model-driven and utilises four domain-specific metamodels. Here, we consider one of those metamodels, GMF Graph, and its evolution between GMF versions 1.0 and 2.0.

The GMF Graph metamodel (Figure 6.16) describes the appearance of the generated graphical model editor. The metaclasses `Canvas`, `Figure`, `Node`, `DiagramLabel`, `Connection`, and `Compartment` are used to represent components of the graphical model editor to be generated. The evolution in the GMF Graph metamodel was driven by analysing the usage of the `Figure#referencingElements` reference, which relates `Figures` to the `DiagramElements` that use them. As described in the GMF Graph documentation[3], the `referencingElements` reference increased the effort

[3] `http://wiki.eclipse.org/GMFGraph_Hints`



(a) Original metamodel.



(b) Evolved metamodel.

Figure 6.16: GMF graph metamodel evolution

required to re-use figures, a common activity for users of GMF. Furthermore, `referencingElements` was used only by the GMF code generator to determine whether an accessor should be generated for nested `Figures`.

During the development of GMF 2.0, the Graph metamodel from GMF 1.0 was evolved – as shown in Figure 6.16(b) – to facilitate greater re-use of figures by introducing a proxy [Gamma *et al.* 1995] for `Figure`, termed `FigureDescriptor`. The original `referencingElements` reference was removed, and an extra metaclass, `ChildAccess`, was added to make more explicit the original purpose of `referencingElements` (accessing nested `Figures`).

GMF provides a migrating algorithm that produces a model conforming to the evolved Graph metamodel from a model conforming to the original Graph metamodel. In GMF, migration is implemented using Java. The GMF source code includes two example editors, for which the source code management system contains versions conforming to GMF 1.0 and GMF 2.0. For the comparison of migration tools described in this paper, the migrating algorithm and example editors provided by GMF were used to determine the correctness of the migration strategies produced by using each model migration tool.

Compared Tools

The comparison described in this section included one tool from each of the three categories identified in Chapter 4 – *manual specification*, *operator-based* and *metamodel matching* approaches. The tools selected were Epsilon Flock, COPE [Herrmannsdoerfer *et al.* 2009b] and the AtlanMod Matching Language (AML) [Garcés *et al.* 2009], respectively. A further tool from the manual specification category, Ecore2Ecore, was included because it is distributed with the Eclipse Modeling Framework (EMF), arguably the most widely used modelling framework. AML, COPE and Ecore2Ecore were discussed in Chapter 4, and Epsilon Flock in Chapter 5.

Comparison Process

The comparison of migration tools was conducted by applying each of the four tools (Ecore2Ecore, AML, COPE and Flock) to the two examples of co-evolution (Petri nets and GMF). The developers of each tool were invited to participate in the comparison. The authors of COPE and Flock were able to participate fully, while the authors of Ecore2Ecore and AML were available for guidance, advice, and to comment on preliminary results.

Each tool developer was assigned a migration tool to apply to the two co-evolution examples. Because the authors of Ecore2Ecore and AML were not able to participate fully in the comparison, two colleagues experienced in model transformation and migration, James Williams and Dimitrios Kolovos, stood in. To improve the validity of the comparison, each tool was used by someone other than its developer. Other than this restriction, the tools were allocated arbitrarily.

The comparison was conducted in three phases. In the first phase, criteria against which the tools would be compared were identified by discussion between the tool developers. In the second phase, the first example of co-evolution (Petri nets) was used for familiarisation with the migration tools and to assess the suitability of the comparison criteria. In the third phase, the tools were applied to the larger example of co-evolution (GMF) and results were drawn from the experiences of the tool developers. Table 6.3 summarises the comparison criteria used, which provide a foundation for future comparisons. The next section presents, for each criterion, observations from applying the migration tools to the co-evolution examples.

Table 6.3: Summary of comparison criteria.

Name	Description
Construction	Ways in which tool supports the development of migration strategies
Change	Ways in which tool supports change to migration strategies
Extensibility	Extent to which user-defined extensions are supported
Re-use	Mechanisms for re-using migration patterns and logic
Conciseness	Size of migration strategies produced with tool
Clarity	Understandability of migration strategies produced with tool
Expressiveness	Extent to which migration problems can be codified with tool
Interoperability	Technical dependencies and procedural assumptions of tool
Performance	Time taken to execute migration

6.3.2 Comparison Results

This section reports the similarities and differences of each tool, using the nine criteria described above. The migration strategies formulated with each tool are available online[4].

Each subsection below considers one criterion. This section reports the experiences of the developer to which each tool was allocated. As such, this section contains the work of others. Specifically, Herrmannsdöerfer wrote about Epsilon Flock, Williams wrote about COPE and Kolovos wrote about Ecore2Ecore. (I wrote about AML, and the introductions to each criterion).

Constructing the migration strategy

Facilitating the specification and execution of migration strategies is the primary function of model migration tools. This section reports the process for and challenges faced in constructing migration strategies with each tool.

AML. An AML user specifies a combination of match heuristics from which AML infers a migrating transformation by comparing original and evolved metamodels. Matching strategies are written in a textual syntax, which AML compiles to produce an executable workflow. The workflow is invoked to generate the migrating transformation, codified in the Atlas Transformation Language (ATL) [Jouault & Kurtev 2005]. Devising correct matching strategies was difficult, as AML lacks documentation that describes the input, output and effects of each heuristic. Papers describing AML (such as [Garcés *et al.* 2009]) discuss each heuristic, but mostly in a high-level manner. A semantically invalid combination of heuristics can cause a runtime error, while an incorrect combination results in the generation of an incorrect migration transformation. However, once a matching strategy is specified,

[4] `http://github.com/louismrose/migration_comparison`

it can be re-used for similar cases of metamodel evolution. To devise the matching strategies used in this paper, AML's author provided considerable guidance.

COPE. A COPE user applies *coupled operations* to the original metamodel to form the evolved metamodel. Each coupled operation specifies a metamodel evolution along with a corresponding fragment of the model migration strategy. A history of applied operations is later used to generate a complete migration strategy. As COPE is meant for co-evolution of models and metamodels, reverse engineering a large metamodel can be difficult. Determining which sequence of operations will produce a correct migration is not always straightforward. To aid the user, COPE allows operations to be undone. To help with the migration process, COPE offers the *Convergence View* which utilises EMF Compare to display the differences between two metamodels. While this was useful, it can, understandably, only provide a list of explicit differences and not the semantics of a metamodel change. Consequently, reverse-engineering a large and unfamiliar metamodel is challenging, and migration for the GMF Graph example could only be completed with considerable guidance from the author of COPE.

Ecore2Ecore. In Ecore2Ecore model migration is specified in two steps. In the first step, a graphical mapping editor is used to construct a model that declares basic migrations. In this step only very simple migrations such as class and feature renaming can be declared. In the next step, the developer needs to use Java to specify a customised parser (resource handler, in EMF terminology) that can parse models that conform to the original metamodel and migrate them so that they conform to the new metamodel. This customised parser exploits the basic migration information specified in the first step and delegates any changes that it cannot recognise to a particular Java method in the parser for the developer to handle. Handling such changes is tedious as the developer is only provided with the string contents of the unrecognised features and then needs to use low-level techniques – such as data-type checking and conversion, string splitting and concatenation – to address them. Here it is worth mentioning that Ecore2Ecore cannot handle all migration scenarios and is limited to cases where only a certain degree of structural change has been introduced between the original and the evolved metamodel. For cases which Ecore2Ecore cannot handle, developers need to specify a custom parser without any support for automated element copying.

Flock. In Flock, model migration is specified manually. Flock automatically copies only those model elements which still conform to the evolved metamodel. Hence, the user specifies migration only for model elements which no longer conform to the evolved metamodel. Due to the automatic copying algorithm, an empty Flock migration strategy always yields a model conforming to the evolved metamodel. Consequently, a user typically starts with an empty migration strategy and iteratively refines it to migrate non-conforming elements. However, there is no support to ensure that all non-conforming elements are migrated. In the GMF Graph example, completeness could only be ensured by testing with numerous models. Using this method, a migration strategy can be easily encoded for the Petri net example. For the GMF Graph example whose metamodels are larger, it was more difficult, since there is no tool support for analysing the changes between original and evolved metamodel.

Changing the migration strategy

Migration strategies can change in at least two ways. Firstly, as a migration strategy is developed, testing might reveal errors which need to be corrected. Secondly, further metamodel changes might require changes to an existing migration strategy.

AML. Because AML automatically generates migrating transformations, changing the transformation, for example after discovering an error in the matching strategy, is trivial. To migrate models over several versions of a metamodel at once, the migrating transformations generated by AML can be composed by the user. AML provides no tool support for composing transformations.

COPE. As mentioned previously, COPE provides an undo feature, meaning that any incorrect migrations can be easily fixed. COPE stores a history of *releases* – a set of operations that has been applied between versions of the metamodel. Because the migration code generated from the release history can migrate models conforming to any previous metamodel release, COPE provides a comprehensive means for chaining migration strategies.

Ecore2Ecore. Migrations specified using Ecore2Ecore can be modified via the graphical mapping editor and the Java code in the custom model parser. Therefore, developers can use the features of the Eclipse Java IDE to modify and debug migrations. Ecore2Ecore provides no tool support for composing migrations, but composition can be achieved by modifying the resource handler.

Flock. There is comprehensive support for fixing errors. A migration strategy can easily be re-executed using a launch configuration, and migration errors are linked to the line in the migration strategy that caused the error to occur. If the metamodel is further evolved, the original migration strategy has to be extended, since there is no explicit support to chain migration strategies. The full migration strategy may need to be read to know where to extend it.

Extensibility

The fundamental constructs used for specifying migration in COPE and AML (operators and match heuristics, respectively) are extensible. Flock and Ecore2Ecore use a more imperative (rather than declarative) approach, and as such do not provide extensible constructs.

AML. An AML user can specify additional matching heuristics. This requires understanding of AML's domain-specific language for manipulating the data structures from which migrating transformations are generated.

COPE provides the user with a large number of operations. If there is no applicable operation, a COPE user can write their own operations using an in-place transformation language embedded into Groovy[5].

Re-use

Each migration tool capture patterns that commonly occur in model migration. This section considers the extent to which the patterns captured by each tool facilitate re-use between migration strategies.

AML. Once a matching strategy is specified, it can potentially be re-used for further cases of metamodel evolution. Match heuristics provide a re-usable and extensible mechanism for capturing metamodel change and model migration patterns.

COPE. An operation in COPE represents a commonly occurring pattern in metamodel migration. Each operation captures the metamodel evolution and model migration steps. Custom operations can be written and re-used.

Ecore2Ecore. Mapping models cannot be reused or extended in Ecore2Ecore but as the custom model parser is specified in Java, developers can decompose it into reusable parts some of which can potentially be reused in other migrations.

Flock. A migration strategy encoded in Flock is modularised according to the classes whose instances need migration. There is support to reuse code within a strategy by means of operations with parameters and across strategies by means of imports. Re-use in Flock captures only migration patterns, and not the higher level co-evolution patterns captured in COPE or AML.

[5] `http://groovy.codehaus.org/`

Conciseness

A concise migration strategy is arguably more readable and requires less effort to write than a verbose migration strategy. This section comments on the conciseness of migration strategies produced with each tool, and reports the lines of code (without comments and blank lines) used.

AML. 117 lines were automatically generated for the Petri nets example. 563 lines were automatically generated for the GMF Graph example, and a further 63 lines of code were added by hand to complete the transformation. Approximately 10 lines of the user-defined code could be removed by restructuring the generated transformation.

COPE requires the user to apply operations. Each operation application generates one line of code. The user may also write additional migration code. For the Petri net example, 11 operations were required to create the migrator and no additional code. The author of COPE migrated the GMF Graph example using 76 operations and 73 lines of additional code.

Ecore2Ecore. As discussed above, handling changes that cannot be declared in the mapping model is a tedious task and involves a significant amount of low level code. For the PetriNets example, the Ecore2Ecore solution involved a mapping model containing 57 lines of (automatically generated) XMI and a custom hand-written resource handler containing 78 lines of Java code.

Flock. 16 lines of code were necessary to encode the Petri nets example, and 140 lines of code were necessary to encode the GMF Graph example. In the GMF Graph example, approximately 60 lines of code implement missing built-in support for rule inheritance, even after duplication was removed by extracting and re-using a subroutine.

Clarity

Because migration strategies can change and might serve as documentation for the history of a metamodel, their clarity is important. This section reports on aspects of each tool that might affect the clarity of migration strategies.

AML. The AML code generator takes a conservative approach to naming variables, to minimise the chances of duplicate variable names. Hence, some of the generated code can be difficult to read and hard to re-use if the generated transformation has to be completed by hand. When a complete transformation can be generated by AML, clarity is not as important.

COPE. Migration strategies in COPE are defined as a sequence of operations. The release history stores the set of operations that have been applied, so the user is clearly able to see the changes they have made, and find where any issues may have been introduced.

Ecore2Ecore. The graphical mapping editor provided by Ecore2Ecore allows developers to have a high-level visual overview of the simple mappings involved in the migration. However, migrations expressed in the Java part of the solution can be far more obscure and difficult to understand as they mix high-level intention with low-level string management operations.

Flock clearly states the migration strategy from the source to the target metamodel. However, the boilerplate code necessary to implement rule inheritance slightly obfuscates the real migration code.

Expressiveness

Migration strategies are easier to infer for some categories of metamodel change than others [Gruschko *et al.* 2007]. This section reports on the ability of each tool to migrate the examples considered in this comparison.

AML. A complete migrating transformation could be generated for the Petri nets example, but not for the GMF Graph example. The latter contains examples of two complex changes that AML does not currently support[6]. Successfully expressing the GMF Graph example in AML would require changes to at least one of AML's heuristics. However, AML provided an initial migration transformation that was completed by hand.

In general, AML cannot be used to generate complete migration strategies for co-evolution examples that contain *breaking and non-resolvable changes*, according to the categorisation proposed in [Gruschko *et al.* 2007].

COPE. The expressiveness of COPE is defined by the set of operations available. The Petri net example was migrated using only built-in operations. The GMF Graph example was migrated using 76 built-in operations and 2 user-defined migration actions. Custom migration actions allow users to specify any migration strategy.

Ecore2Ecore. A complete migration strategy could be generated for the Petri nets example, but not for the GMF Graph example. The developers of Ecore2Ecore have advised that the latter involves significant structural

[6] http://www.eclipse.org/forums/index.php?t=rview&goto=526894#msg_526894If

changes between the two versions and recommended implementing a custom model parser from scratch.

Flock. Since Flock extends EOL, it is expressive enough to encode both examples. However, Flock does not provide an explicit construct to copy model elements and thus it was necessary to call Java code from within Flock for the GMF Graph example.

Interoperability

Migration occurs in a variety of settings with differing requirements. This section considers the technical dependencies and procedural assumptions of each tool, and seeks to answer questions such as: "Which modelling technologies can be used?" and "What assumptions does the tool make on the migration process?"

AML depends only on ATL, while its development tools also require Eclipse. AML assumes that the original and target metamodels are available for comparison, and does not require a record of metamodel changes. AML can be used with either Ecore (EMF) or KM3 metamodels.

COPE depends on EMF and Groovy, while its development tools also require Eclipse and EMF Compare. COPE does not require both the original and target metamodels to be available. When COPE is used to create a migration strategy after metamodel evolution has already occurred, the metamodel changes must be reverse-engineered. To facilitate this, the target metamodel can be used with the Convergence View, as discussed in Section 6.3.2. COPE targets EMF, and does not support other modelling technologies.

Ecore2Ecore depends only on EMF. Both the original and the evolved versions of the metamodel are required to specify the mapping model with the Ecore2Ecore development tools. Alternatively, the Ecore2Ecore mapping model can be constructed programmatically and without using the original metamodel[7]. Unlike the other tools considered, Ecore2Ecore does not require the original metamodel to be available in the workspace of the metamodel user.

Flock depends on Epsilon and its development tools also require Eclipse. Flock assumes that the original and target metamodels are available for encoding the migration strategy, and does not require a record of metamodel changes. Flock can be be used to migrate models represented in EMF, MDR,

[7]Private communication with Marcelo Paternostro, an Ecore2Ecore developers.

XML and Z (CZT), although we only encoded a migration strategy for EMF metamodels in the presented examples.

Performance

The time taken to execute model migration is important, particularly once a migration strategy has been distributed to metamodel users. Ideally, migration tools will produce migration strategies whose execution time is quick and scales well with large models.

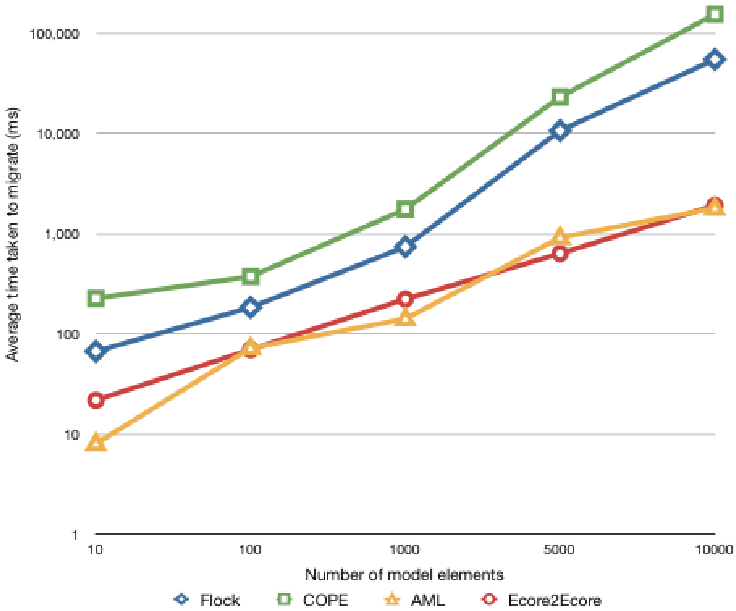


Figure 6.17: Migration tool performance comparison.

To measure performance, five sets of Petri net models were generated at random. Models in each set contained 10, 100, 1000, 5,000, and 10,000 model elements. Figure 6.17 shows the average time taken by each tool to execute migration across 10 repetitions for models of different sizes. Note that the Y axis has a logarithmic scale. The results indicate that, for the Petri nets co-evolution example, AML and Ecore2Ecore execute migration significantly more quickly than COPE and Flock, particularly when the model to be migrated contains more than 1,000 model elements. Figure 6.17 indicates that, for the Petri nets co-evolution example, Flock executes migration between two and three times faster than COPE, although the author of COPE reports that turning off validation causes COPE to perform similarly to Flock.

6.3.3 Discussion

The comparison described above highlights similarities and differences between a representative sample of model migration approaches. From this comparison, guidance for selecting between tools was synthesised. The guidance is presented below, and was produced by all four participants in the comparison (Herrmannsdöerfer, Williams, Kolovos and myself).

COPE captures co-evolution patterns (which apply to both model and metamodel), while Ecore2Ecore, AML and Flock capture only model migration patterns (which apply just to models). Because of this, COPE facilitates a greater degree of re-use in model migration than other approaches. However, the order in which the user applies patterns with COPE impacts on both metamodel evolution and model migration, which can complicate pattern selection particularly when a large amount of evolution occurs at once. The re-usable co-evolution patterns in COPE make it well suited to migration problems in which metamodel evolution is frequent and in small steps.

Flock, AML and Ecore2Ecore are preferable to COPE when metamodel evolution has occurred before the selection of a migration approach. Because of its use of co-evolution patterns, we conclude that COPE is better suited to forward- rather than reverse-engineering.

Through its Convergence View and integration with the EMF metamodel editor, COPE facilitates metamodel analysis that is not possible with the other approaches considered in this paper. COPE is well-suited to situations in which measuring and reasoning about co-evolution is important.

In situations where migration involves modelling technologies other than EMF, AML and Flock are preferable to COPE and Ecore2Ecore. AML can be used with models represented in KM3, while Flock can be used with models represented in MDR, XML and CZT. Via the connectivity layer of Epsilon, Flock can be extended to support further modelling technologies.

There are situations in which Ecore2Ecore or AML might be preferable to Flock and COPE. For large models, Ecore2Ecore and AML might execute migration significantly more quickly than Flock and COPE. Ecore2Ecore is the only tool that has no technical dependencies (other than a modelling framework). In situations where migration must be embedded in another tool, Ecore2Ecore offers a smaller footprint than other migration approaches. Compared to the other approaches considered in this paper, AML automatically generates migration strategies with the least guidance from the user.

Despite these advantages, Ecore2Ecore and AML are unsuitable for some types of migration problem, because they are less expressive than Flock and COPE. Specifically, changes to the containment of model elements typically cannot be expressed with Ecore2Ecore and changes that are classified by [Herrmannsdoerfer *et al.* 2008] as *metamodel-specific* cannot be expressed with AML. Because of this, it is important to investigate metamodel changes before selecting a migration tool. Furthermore, it might be necessary to anticipate which types of metamodel change are likely to arise before selecting a migration tool. Investing in one tool to discover later that it is no longer suitable causes wasted effort.

Table 6.4: Summary of tool selection advice. (Tools are ordered alphabetically).

Requirement	**Recommended Tools**
Frequent, incremental co-evolution	COPE
Reverse-engineering	AML, Ecore2Ecore, Flock
Modelling technology diversity	Flock
Quicker migration for larger models	AML, Ecore2 Ecore
Minimal dependencies	Ecore2Ecore
Minimal hand-written code	AML, COPE
Minimal guidance from user	AML
Support for metamodel-specific migrations	COPE, Flock

Strengths and Weaknesses of Flock

The comparison and guidance highlight strengths and weaknesses of AML, COPE, Ecore2Ecore and Flock. The findings for Flock are now summarised.

Strengths Flock was the only co-evolution tool suitable for performing model migration when the original and evolved metamodels are specified in different modelling technologies. For the examples of metamodel evolution explored here, Flock is more expressive than AML, but requires more guidance from the user. This is consistent with the trade-off between flexibility and level of automation of co-evolution approaches identified in Chapter 4.

Weaknesses The results presented here indicate that model migration with Flock takes longer to execute than with AML and Ecore2Ecore. This is likely because Flock migration strategies are interpreted, while AML and Ecore2Ecore migration strategies are compiled. Compared to COPE and AML, Flock lacks re-use of model migration patterns across varying metamodels. In Flock, model migration is specified in terms of concrete metamodel types and cannot be re-used for different metamodels. By contrast, COPE and AML capture model migration in a metamodel-independent manner.

6.3.4 Summary

The work presented in this section compared a representative sample of approaches to automating developer-driven co-evolution using an expert evaluation. The comparison was performed by following a methodical process and using an example from a real-world MDE project. Some preliminary recommendations and guidelines in choosing a co-evolution tool were synthesised from the presented results and are summarised in Table 6.4. The comparison was carried out by the tool developers (or stand-ins where the developers were unable to participate fully). Each developer used a tool other than their own so that the comparison could more closely emulate the level of expertise of a typical user.

Some criteria were excluded from the comparison because of the method employed. For instance, the learnability of a tool affects the productivity of users, and, as such, affects tool selection. However, drawing conclusions about learnability (and also productivity and usability) is challenging with the comparison method employed because of the subjective nature of these characteristics. A comprehensive user study (with hundreds of users) would be more suitable for assessing these types of criteria.

6.4 Transformation Tools Contest

In contrast to the previous section, which compared Flock to three co-evolution tools, the evaluation performed in this section compares Flock with model-to-model transformation tools. As discussed in Chapter 4, model migration can be regarded as a specialisation of model-to-model transformation. Chapter 5 introduces Flock, a language tailored for model migration. This section assess the suitability of Flock for specifying model migration and for specifying model-to-model transformation by comparison to other model-to-model transformation languages.

To this end, the author participated in the 2010 edition of the Transformation Tools Contest (TTC), a workshop series that seeks to compare and contrast tools for performing model and graph transformation. At TTC 2010[8], two rounds of submissions were invited: cases (transformation problems, three of which are selected by the workshop organisers) and solutions to the selected cases. Nine transformation tools, including Flock, were assessed for a model migration problem based on a real-world example of metamodel evolution from the UML [OMG 2007b]. In addition, TTC 2010 included a *live contest* in which a further transformation problem was announced and solutions submitted during the workshop. Fourteen transformation tools, including Flock, were compared in the live contest.

Compared to the evaluation described in Section 6.3, the evaluation in this section compares Flock to a wider range of tools (model and graph transformation tools, and not just model migration tools), and investigates the suitability of Flock for specifying model transformation (and not just model migration). The remainder of this section describes the model migration prob-

[8] `http://www.planet-research20.org/ttc2010/index.php?Itemid=132`

lem (Section 6.4.1) and Flock solution (Section 6.4.2), and the use of Flock for specifying a model transformation in the live contest (Section 6.4.3).

6.4.1 Model Migration Case

To compare Flock with other transformation tools for specifying model migration, the author submitted a case to TTC based on the evolution of the UML. The way in which activity diagrams are modelled in the UML changed significantly between versions 1.4 and 2.1 of the specification. In the former, activities were defined as a special case of state machines, while in the latter they are defined atop a more general semantic base[9] [Selic 2005].

The remainder of this section briefly introduces UML activity diagrams, describes their evolution, and discusses the way in which solutions were assessed. The work presented in this section is based on the case submitted to TTC 2010 [Rose *et al.* 2010d].

Activity Diagrams in UML

Activity diagrams are used for modelling lower-level behaviours, emphasising sequencing and co-ordination conditions. They are used to model business processes and logic [OMG 2007b]. Figure 6.18 shows an activity diagram for filling orders. The diagrams is partitioned into three *swimlanes*, representing different organisational units. *Activities* are represented with rounded rectangles and *transitions* with directed arrows. *Fork* and *join* nodes are specified using a solid black rectangle. *Decision* nodes are represented with a diamond. Guards on transitions are specified using square brackets. For example, in Figure 6.18 the transition to the restock activity is guarded by the condition `[not in stock]`. Text on transitions that is not enclosed in square brackets represents a trigger event. In Figure 6.18, the transition from the restock activity occurs on receipt of the asynchronous signal called `receive stock`. Finally, the transitions between activities might involve interaction with objects. In Figure 6.18, the Fill Order activity leads to an interaction with an object called `Filled Object`.

Between versions 1.4 and 2.2 of the UML specification, the metamodel for activity diagrams has changed significantly. The sequel summarises most of the changes, and details can be found in [OMG 2001] and [OMG 2007b].

Evolution of Activity Diagrams

Figures 6.19 and 6.20 are simplifications of the activity diagram metamodels from versions 1.4 and 2.2 of the UML specification, respectively. In the interest of clarity, some features and abstract classes have been removed from Figures 6.19 and 6.20.

[9] A variant of generalised coloured Petri nets.

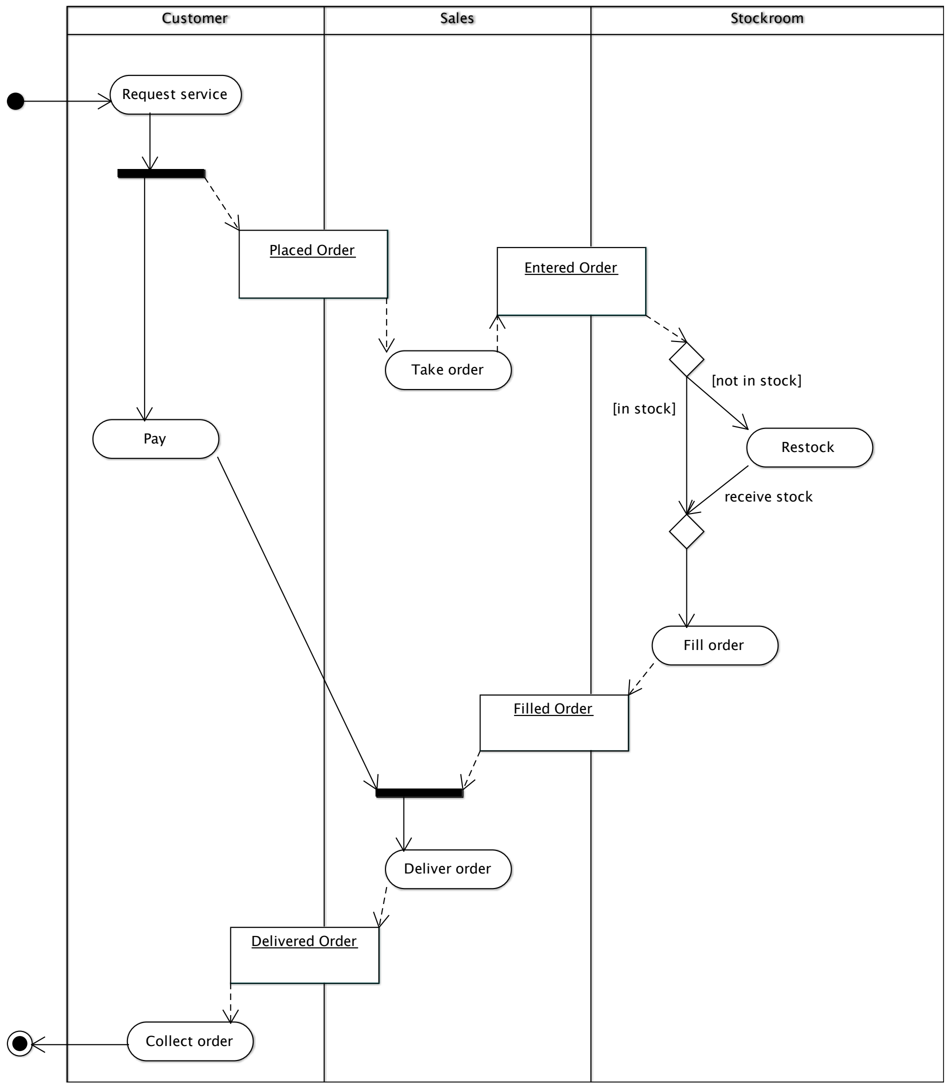


Figure 6.18: Exemplar activity model.

Some differences between Figures 6.19 and 6.20 are: activities have been changed such that they comprise nodes and edges, actions replace states in UML 2.2, and the subtypes of control node replace pseudostates.

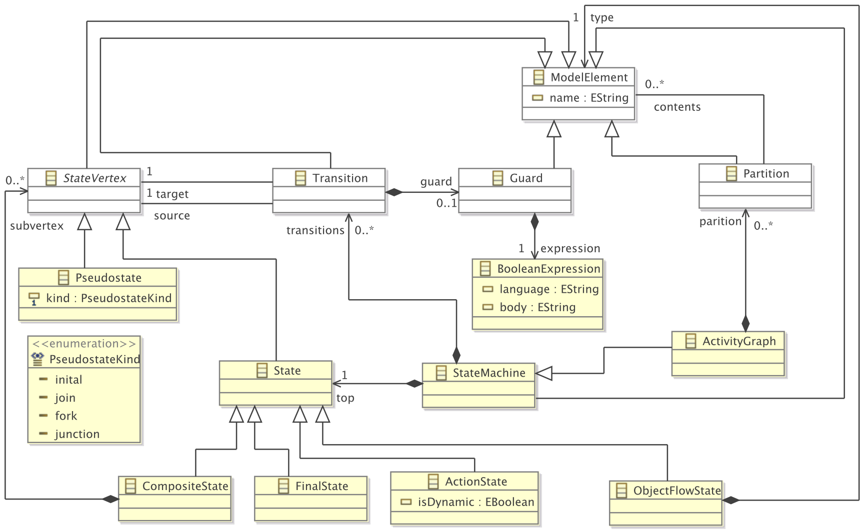


Figure 6.19: UML 1.4 Activity Graphs (based on [OMG 2001]).

To facilitate the comparison of solutions, the model shown in Figure 6.18 was used. Figure 6.18 is based on [OMG 2001, pg3-165]. Solutions migrated the activity diagram shown in Figure 6.18 – which conforms to UML 1.4 – to conform to UML 2.2. The UML 1.4 model, the migrated UML 2.2 model, and the UML 1.4 and 2.2 metamodels are available from[10].

Submissions were evaluated using the following four criteria, which were decided in advance by the author and the workshop organisers:

- **Correctness**: Does the transformation produce a model equivalent to the migrated UML 2.2. model included in the case resources?
- **Conciseness**: How much code is required to specify the transformation? (In [Sprinkle & Karsai 2004] et al. propose that the amount of effort required to codify migration should be directly proportional to the number of changes between original and evolved metamodel).
- **Clarity**: How easy is it to read and understand the used transformation? (For example, is a well-known or standardised language?)
- **Extensions**: Which of the case extensions (described below) were implemented in the solution?

[10] `http://www.cs.york.ac.uk/~louis/ttc/`

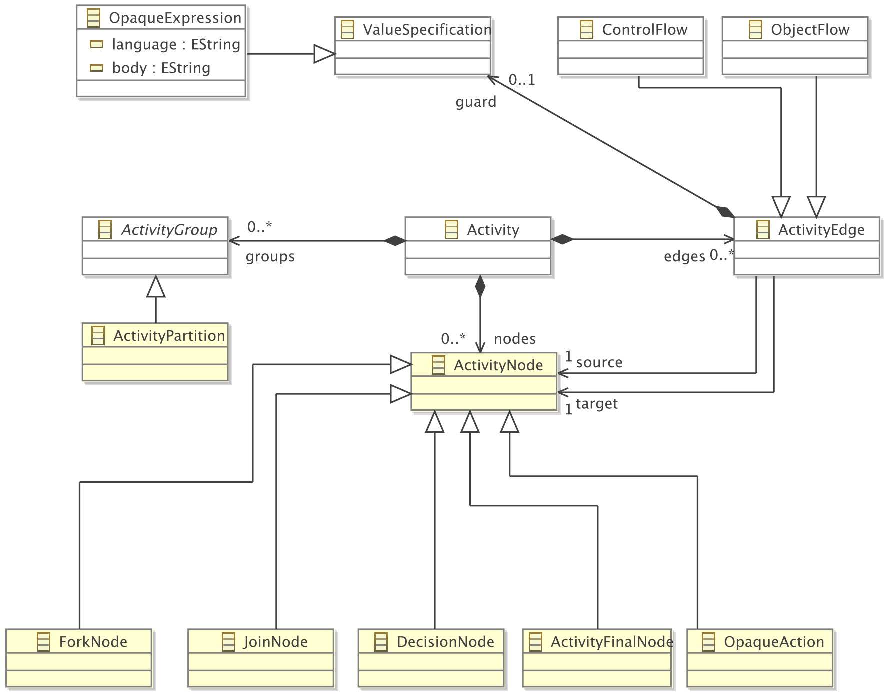


Figure 6.20: UML 2.2 Activity Diagrams (based on [OMG 2007b]).

To further distinguish between solutions, three extensions to the core task were proposed. The first extension was added after the case was submitted, and was proposed by the workshop organisers and the solution authors. The second and third extension were included in the case by the author.

Extension 1: Alternative Object Flow State Migration Semantics

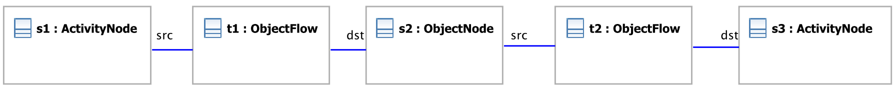
Following the submission of the case, discussion on the TTC forums[11] revealed an ambiguity in the UML 2.2 specification indicating that the migration semantics for the ObjectFlowState UML 1.4 concept are not clear from the UML 2.2 specification. The case was revised to incorporate both the original semantics (suggested by the author and described above) and an alternative semantics (suggested by a workshop participant via the TTC forums) for migrating ObjectFlowStates. The alternative semantics are now described.

In the core task described above, instances of `ObjectFlowState` were migrated to instances of `ObjectNode`. Any instances of `Transition` that had an `ObjectFlowState` as their source or target were migrated to in-

[11] `http://planet-research20.org/ttc2010/index.php?option=com_community&view=groups&task=viewgroup&groupid=4&Itemid=150` (registration required)

stances of `ObjectFlow`. Figure 6.21 shows an example application of this migration semantics. Structures such as the one shown in Figure 6.21(a) are migrated to an equivalent structure shown in Figure 6.21(b). The `Transitions`, `t1` and `t2`, are migrated to instances of `ObjectFlow`. Likewise, the instance of `ObjectFlowState`, `s2`, is migrated to an instance of `ObjectNode`.

(a) ObjectFlowState structure in UML 1.4



(b) Equivalent ObjectNode structure in UML 2.2

Figure 6.21: Migrating Actions for the Core Task

This extension considered an alternative migration semantics for ObjectFlowState. For this extension, instances of `ObjectFlowState` (and any connected `Transitions`) were migrated to instances of `ObjectFlow`, as shown in Figure 6.22 in which the UML 2.2 `ObjectFlow`, `f1`, replaces `t1`, `t2` and `s2`.

The alternative semantics were proposed on the TTC 2010 forums, and agreed as an extension to the core task by consensus between the solution authors and the workshop organisers.

Extension 2: Concrete Syntax

The second extension relates to the appearance of activity diagrams. The UML specifications provide no formally defined metamodel for the concrete syntax of UML diagrams. However, some UML tools store diagrammatic information in a structured manner using XML or a modelling tool. For example, the Eclipse UML 2 tools [Eclipse 2009b] store diagrams as GMF [Gronback 2009] diagram models.

Submissions were invited to explore the feasibility of migrating the concrete syntax of the activity diagram shown in Figure 6.18 to the concrete syntax in their chosen UML 2 tool. To facilitate this, the case resources included an

(a) ObjectFlowState structure in UML 1.4

(b) Equivalent ObjectFlow structure in UML 2.2

Figure 6.22: Migrating Actions for Extension 1

ArgoUML project[12] containing the activity diagram shown in Figure 6.18.

Extension 3: XMI

The UML specifications [OMG 2001, OMG 2007b] indicate that UML models should be stored using XMI. However, because XMI has evolved at the same time as UML, UML 1.4 tools most likely produce XMI of a different version to UML 2.2 tools. For instance, ArgoUML produces XMI 1.2 for UML 1.4 models, while the Eclipse UML2 tools produce XMI 2.1 for UML 2.2.

As an extension to the core task, submissions were invited to consider how to migrate a UML 1.4 model represented in XMI 1.x to a UML 2.1 model represented in XMI 2.x. To facilitate this, the UML 1.4 model shown in Figure 6.18 was made available in XMI 1.2 as part of the case resources.

Following the submission of the case, Tom Morris, the project leader for ArgoEclipse and a committer on ArgoUML, encouraged solutions to consider the extension described above. ArgoUML cannot, at present, migrate models from UML 1 to UML 2. On the TTC forums, Morris stated that “We have nothing available to fill this hole currently, so any contributions would be hugely valuable. Not only would achieve academic fame and glory from the contest, but you’d get to see your code benefit users of one of the oldest (10+ yrs) open source UML modeling tools.” [13]

[12] `http://argouml.tigris.org/`

[13] `http://www.planet-research20.org/ttc2010/index.php?option=com_community&view=groups&task=viewdiscussion&groupid=4&topicid=20&Itemid=150` (registration required)

6.4.2 Model Migration Solution in Epsilon Flock

This section describes a Flock solution for migrating UML activity diagrams in response to the evolution described above. The solution was developed by the author, and, at the workshop, compared with migration strategies written in other languages. The workshop participants and organisers rated each tool.

The Flock migration strategy was developed in an iterative and incremental manner, using the following process, starting with an empty migration strategy:

1. Execute Flock on the original model, producing a migrated model.
2. Compare the migrated model with the reference model provided in the case resources.
3. Change the Flock migration strategy.
4. Repeat until the migrated and reference models were the same.

The remainder of this section presents the Flock solution in an incremental manner. The code listings in this section show only those rules relevant to the iteration being discussed.

Actions, Transitions and Final States

Development of the migration strategy began by executing an empty Flock migration strategy on the original model. Because Flock automatically copies model elements that have not been affected by evolution, the resulting model contained `Pseudostatess` and `Transitions`, but none of the `ActionStates` from the original model. In UML 2.2 activities, `OpaqueActions` replace `ActionStates`. Listing 6.14 shows the Flock code for changing `ActionStates` to corresponding `OpaqueActions`.

```
migrate ActionState to OpaqueAction
```

Listing 6.12: Migrating Actions

Next, similar rules were added to migrate instances of `FinalState` to instances of `ActivityFinalNode` and to migrate instances of `Transition` to `ControlFlow`, as shown in Listing 6.15.

```
migrate FinalState to ActivityFinalNode
migrate Transition to ControlFlow
```

Listing 6.13: Migrating FinalStates and Transitions

Pseudostates

Development continued by selected further types of state that were not present in the migrated model, such as `Pseudostatess`, which are not used in UML 2.2 activities. Instead, UML 2.2 activities use specialised `Nodes`, such as `InitialNode`. Listing 6.16 shows the Flock code used to change `Pseudostates` to corresponding `Nodes`.

```
migrate Pseudostate to InitialNode when: original.kind = Original!
    PseudostateKind#initial
migrate Pseudostate to DecisionNode when: original.kind = Original!
    PseudostateKind#junction
migrate Pseudostate to ForkNode when: original.kind = Original!
    PseudostateKind#fork
migrate Pseudostate to JoinNode when: original.kind = Original!
    PseudostateKind#join
```

Listing 6.14: Migrating Pseudostates

Activities

In UML 2.2, `Activitys` no longer inherit from state machines. As such, some of the features defined by `Activity` have been renamed. Specifically, `transitions` has become `edges` and `paritions` has become `group`. Furthermore, the states (or nodes in UML 2.2 parlance) of an `Activity` are now contained in a feature called `nodes`, rather than in the `subvertex` feature of a composite state accessed via the `top` feature of `Activity`. The Flock migration rule shown in Listing 6.17 captured these changes.

```
migrate ActivityGraph to Activity {
  migrated.edge = original.transitions.equivalent();
  migrated.group = original.partition.equivalent();
  migrated.node = original.top.subvertex.equivalent();
}
```

Listing 6.15: Migrating ActivityGraphs

Note that the rule in Listing 6.17 used the built-in `equivalent` operation to find migrated model elements from original model elements. As discussed in Section 5.4, the `equivalent` operation invokes other migration rules where necessary and caches results to improve performance.

Next, a similar rule for migrating `Guards` was added. In UML 1.4, the the `guard` feature of `Transition` references a `Guard`, which in turn references an `Expression` via its `expression` feature. In UML 2.2, the `guard` feature of `Transition` references an `OpaqueExpression` directly. Listing 6.18 captures this in Flock.

```
migrate Guard to OpaqueExpression {
```

```
  migrated.body.add(original.expression.body);
}
```

Listing 6.16: Migrating Guards

Partitions

In UML 1.4 activity diagrams, `Partition` specifies a single containment reference for its `contents`. In UML 2.2 activity diagrams, partitions have been renamed to `ActivityPartitions` and specify two containment features for their contents, `edges` and `nodes`. Listing 6.19 shows the rule used to migrate `Partitions` to `ActivityPartitions` in Flock. The body of the rule shown in Listing 6.19 uses the *collect* operation to segregate the `contents` feature of the original model element into two parts.

```
migrate Partition to ActivityPartition {
  migrated.edges = original.contents.collect(e:Transition | e.equivalent());
  migrated.nodes = original.contents.collect(n:StateVertex | n.equivalent());
}
```

Listing 6.17: Migrating Partitions

ObjectFlows

Finally, two rules were written for migrating model elements relating to object flows. In UML 1.4 activity diagrams, object flows are specified using `ObjectFlowState`, a subtype of `StateVertex`. In UML 2.2 activity diagrams, object flows are modelled using a subtype of `ObjectNode`. In UML 2.2 flows that connect to and from `ObjectNodes` must be represented with `ObjectFlows` rather than `ControlFlows`.

Listing 6.20 shows the Flock rule used to migrate `Transitons` to `ObjectFlows`. The rule applies for `Transitions` whose source or target `StateVertex` is of type `ObjectFlowState`.

```
migrate ObjectFlowState to ActivityParameterNode

migrate Transition to ObjectFlow when: original.source.isTypeOf(ObjectFlowState) or original.target.isTypeOf(ObjectFlowState)
```

Listing 6.18: Migrating ObjectFlows

In addition to the core task, the Flock solution also approached two of the three extensions described in the case (Section 6.4.1). The solutions to the extensions are now discussed.

Alternative ObjectFlowState Migration Semantics

The first extension required submissions to consider an alternative migration semantics for `ObjectFlowState`, in which a single `ObjectFlow` replaces each `ObjectFlowState` and any connected `Transitions`.

Listing 6.21 shows the Flock source code used to migrate `ObjectFlowStates` (and connecting `Transitions`) to a single `ObjectFlow`. This rule was used instead of the two rules defined in Listing 6.20. In the body of the rule shown in Listing 6.21, the `source` of the `Transition` is copied directly to the `source` of the `ObjectFlow`. The `target` of the `ObjectFlow` is set to the target of the first outgoing `Transition` from the `ObjectFlowState`.

```
1 migrate Transition to ObjectFlow when: original.target.isTypeOf(
     ObjectFlowState) {
2  migrated.source = original.source.equivalent();
3  migrated.target = original.target.outgoing.first.target.equivalent();
4 }
```

Listing 6.19: Migrating ObjectFlowStates to a single ObjectFlow

Because, in this alternative semantics, `ObjectFlowStates` are represented as edges rather than nodes, the partition migration rule was changed such that `ObjectFlowStates` were not copied to the `nodes` feature of `Partitions`. To filter out the `ObjectFlowStates`, line 3 of Listing 6.19 was changed to include a reject statement, as shown on line 3 of Listing 6.22.

```
1 migrate Partition to ActivityPartition {
2  migrated.edges = original.contents.collect(e:Transition | e.equivalent
      ());
3  migrated.nodes = original.contents.reject(ofs:ObjectFlowState | true).
      collect(n:Original!StateVertex | n.equivalent());
4 }
```

Listing 6.20: Migrating Partitions without ObjectFlowStates

XMI

The second extension required submissions to migrate an activity graph conforming to UML 1.4 and encoded in XMI 1.2 to an equivalent activity graph conforming to UML 2.2 and encoded in XMI 2.1. The core task did not require submissions to consider changes to XMI (the model storage representation), but, in practice, this is a challenge to migration, as noted by Tom Morris on the TTC forums[14].

[14] `http://www.planet-research20.org/ttc2010/index.php?option=com_community&view=groups&task=viewdiscussion&groupid=4&topicid=20&Itemid=150` (registration required)

As discussed in Section 5.4, Flock is built atop Epsilon, which includes a model connectivity layer (EMC). EMC provides a common interface for accessing and persisting models. Currently, EMC supports EMF (XMI 2.x), MDR (XMI 1.x), and plain XML models. To support migration between metamodels defined in heterogenous modelling frameworks, EMC was extended during the development of Flock to provide a conformance checking service.

Consequently, the migration strategy developed for the core task works for all of the types of model supported by EMC. To migrate a model encoded in XMI 1.2 rather than in XMI 2.1, the user must select a different option when executing the Flock migration strategy. Otherwise, no other changes are required.

Comparison with other solutions

At the workshop, solutions to the migration case described in Section 6.4.1 were presented. Each solution was allocated two opponents who highlighted weaknesses of each approach. Following the solution presentations and opposition statements, each solution was scored using the four criteria described above, correctness, clarity, conciseness and number of extensions solved. Every workshop participants scored each solution on clarity and conciseness. The workshop organisers scored each solution on correctness and number of extensions solved, as these criteria could be measured objectively. Epsilon Flock was awarded first position for the migration case.

The opposition statements highlighted two weaknesses of Flock. Firstly, there is some duplicated code in Listing 6.16: the `migrate Pseudostate to X` statement appears several times. The duplication exists because Flock only allows one-to-one mappings between original and evolved metamodel types. The conservative copy algorithm would need to be extended to allow one-to-many mappings to remove this kind of duplication.

Secondly, the body of Flock rules are specified in an imperative manner. Consequently, reasoning about the correctness of the a migration strategy is arguably more difficult than in languages that use a purely declarative syntax. This point is discussed further in Section 6.5, which considers the limitations of the thesis.

6.4.3 Epsilon Flock in the Live Contest

TTC 2010 also invited the workshop participants to take part in a live contest. A problem was announced at the start of the workshop, and participants developed their solutions during the first day. The solutions were presented in the workshop and assessed in four categories. Flock was awarded first position for the *exogenous transformation* category. The remainder of this section discusses the parts of the problem that relate to the exogenous transformation category and the Flock solution.

The live contest problem required several model management operations be combined to perform beta-reduction of a simplified lambda calculus. Flock was used to specify one of the model management operations: model transformation between two similar (but not identical) metamodels. Flock was chosen rather than a new-target transformation language because the metamodels shared several classes and features. Using Flock allowed automatic copying of the model elements conforming to the classes common to both source and target metamodel. In other words, transformation rules were specified only for those parts of the metamodels that differed.

Flock was awarded first position by the workshop participants and organisers for the category in which it was entered. Participation in the live contest highlighted that, in addition to model migration, Flock can be used for specifying model transformation. In particular, Flock was appropriate because the source and target metamodels were similar (having several classes and features in common) and the conservative copy strategy reduced the number of rules required to specify the transformation.

6.4.4 Summary

This section has discussed the way in which Flock was evaluated by participating in the 2010 edition of the Transformation Tools Contest (TTC). Flock was assessed by application to an example of migration from the UML and comparison with eight other model and graph transformation tools. Flock was awarded first prize by the workshop participants and organisers. Additionally, Flock was used as part of a solution to a live contest developed during the workshop. The live contest highlighted that Flock is suitable for specifying some types of model transformation (in particular, those in which the source and target metamodel have common classes and features), as Flock was awarded first prize in the exogenous transformation category.

In addition to evaluating Flock, the work described in this section provides three further contributions. Firstly, the migration case submitted to TTC 2010, described in Section 6.4.1 provides a real-world example of co-evolution for use in future comparisons of model migration tools. The case is based on the evolution of UML, between versions 1.4 and 2.2. The migration strategy was devised by analysis of the UML specification, and by discussion between workshop participants.

Secondly, the Flock solution to the migration case (Section 6.4.2) demonstrates the way in which a migration strategy can be constructed using Flock. In particular, Section 6.4.2 describes an iterative and incremental development process and indicates that an empty Flock migration strategy can provide a useful starting point for development.

Finally, Section 5.4 claims that Flock support several modelling technologies. The solution described in Section 6.4.2 demonstrates the way in which Flock can be used to migrate models over two modelling technologies: MDR

(XMI 1.x) and EMF (XMI 2.x), and hence supports the claim made in Section 5.4.

6.5 Limitations

The limitations of the thesis research are now discussed. Some of the shortcomings identified here are elaborated on in Section 7.2, which highlights areas of future work.

Generality The thesis research focuses on model-metamodel co-evolution, but, as discussed in Chapter 4, metamodel changes can affect artefacts other than models. Model management operations and model editors are specified using metamodel concepts and, consequently, are affected when a metamodel changes. The work presented in Chapter 5 focuses on migrating models in response to metamodel changes, and does not consider integration with tools for migrating model management operations and model editors. To reduce the effort required to manage the effects of metamodel changes, it seems reasonable to envisage a unified approach that migrates models, model management operations, model editors, and other affected artefacts.

Reproducibility The analysis and evaluation presented in Chapters 4 and 6 respectively involved using migration tools to understand and assess their functionality. With the exceptions noted below, the work presented in these chapters is difficult to reproduce and therefore the results drawn are somewhat subjective. On the other hand, multiple approaches to analysis and evaluation have been taken, and the work has been published and subjected to peer review.

Not all of the work in Chapter 4 and 6 is difficult to reproduce. In particular, Section 4.2 describes limitations of existing migration tools and was derived from the experiments discussed in Appendix A. To aid reproducibility, evaluation methods are described in detail in Sections 6.2 and 6.3. In general, the lack of real-world examples of co-evolution restricts the extent to which any work in this area can be considered reproducible.

Formal semantics No formal semantics for the conservative copy algorithm (Section 5.4) have been provided. Instead, a reference implementation, Epsilon Flock, was developed, which facilitated comparison with other migration and transformation tools. Without a reference implementation, the evaluation described in Sections 6.2, 6.3 and 6.4 would have been impossible. For Epsilon as a whole, [Kolovos 2009] makes a similar case for choosing a reference implementation over a formal semantics. For domains where completeness and correctness are a primary concern, a formal semantics would be required before Flock could be applied to manage model-metamodel co-evolution.

6.6 Summary

To be completed, but will include a paragraph similar to the following:

In addition to the evaluation described in this chapter, the work presented in this thesis has been subjected to peer review by the academic and Eclipse communities. The thesis research has been published in papers at XX workshops, YY European conferences and ZZ international conferences. HUTN, Flock and Concordance (Chapter 5) are part of the Epsilon project, a member of the research incubator for the Eclipse Modeling Project (EMP), which is arguably the most active MDE community at present. EMP's research incubator hosts a limited number of participants, selected through a rigorous process and contributions made to the incubator undergo regular technical review.

Appendix C

Migration Strategies used for Evaluation

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