Evolution in Model-Driven Engineering

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Contents

Chapter 2

Background

Before reviewing software evolution research, it is first necessary to survey literature from model-driven engineering (MDE), which is the context in which the thesis research was conducted. Section 2.1 introduces the terminology and fundamental principles used in MDE. Section 2.2 reviews guidance and three methods for performing MDE. Section 2.3 describes contemporary MDE environments. The related areas of domain-specific languages and language-oriented programming are discussed in Section 2.4. Finally, the benefits of and current challenges for MDE are described in Section 2.5.

2.1 MDE Terminology and Principles

Software engineers using MDE construct and manipulate artefacts familiar from traditional approaches to software engineering (such as code and documentation) and, in addition, work with different types of artefact, such as *models*, *metamodels* and *model transformations*. Furthermore, MDE involves new development activities, such as *model management*. This section describes the artefacts and activities typically involved in a model-driven engineering process.

2.1.1 Models

Models are fundamental to MDE. [Kurtev 2004] identifies many definitions of the term model, such as: "any subject using a system A that is neither directly nor indirectly interacting with a system B to obtain information about the system B, is using A as a model for B." [apo], "a model is a representation of a concept. The representation is purposeful and used to abstract from reality the irrelevant details." [Starfield *et al.* 1990], and "a model is a simplification of a system written in a well-defined language." [Bézivin & Gerbé 2001].

While there are many definitions of the term model, a common notion is that a model is a representation of the real-world [Kurtev 2004, pg12]. The part of the real-world represented by a model is termed the *domain*, the *object system* or, simply the *system*. A further commonality is noted by [Kolovos *et al.* 2006c]: a model may have either a textual or graphical representation.

[Ackoff 1962] distinguishes three kinds of model. *Iconic* models have a likeness to their object system. *Analogous* models share characteristics of their object system. *Analytic* models present a description of their object system. For example, a toy in the shape of an aeroplane is *iconic*, a toy that can fly is *analogous* to an aeroplane, and a set of differential equations describing the way in which the propellors of an aeroplane propellor function is *analytic*.

In this thesis, the models discussed are *analogous*. The lending service of a library might be modelled by described books, people and loans, which share characteristics of their real-world counterparts: for example, a person loans a book.

In computer science, models analogous to an object system can be used to construct a computer system. The model of the real-world might be used to determine the way in which data is stored on disk, or the way in which a computer program is to be structured. In this sense, a model is analogous both the object system in the real world and to a further object system: the computer system. Terms in the model can be used to think about both the real system and the computer system.

[Jackson 1995] proposes that, in the context of computer science, Figure 2.1 illustrates what it means to be a model. According to [Jackson 1995], a model is the description of the domain (object system) and the machine (computer system). Computer scientists switch between *designations* when using a model to think about the object system or to think about the software system.

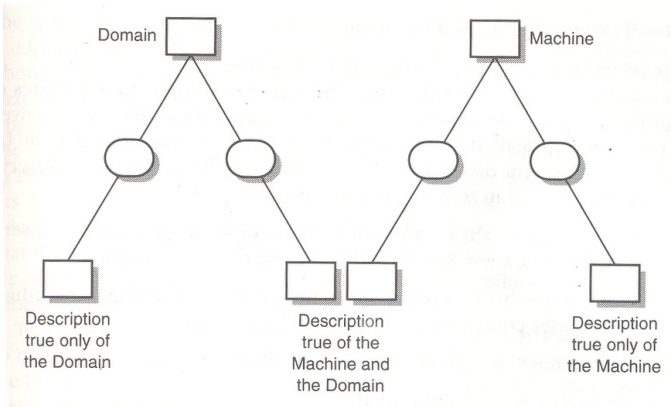

Figure 2.1: Jackson's definition of a model, taken from [Jackson 1995, pg.125].

In summary, this thesis considers models that are analogous, rather than iconic or analytical. Furthermore, models are analogous to both a (real-world) system and a computer system.

2.1.2 Modelling in Computer Science

Analogous models are used widely in software engineering. To explore this statement, this section considers two approaches to developing computer systems, each seemingly with radically different views of models. [Evans 2004] advocates modelling throughout software development to better understand the real-world

system and to structure the computer system. [Martin & Martin 2006] advocates that code should be regarded as the model of both the real-world system and the computer system.

In Favour of Models over Code

[Evans 2004] proposes the use of models throughout the development process to capture and communicate knowledge of the object system and to shape the structure of the resulting software system. Wherever possible, the way in which code is structured is driven by the model. Throughout, [Evans 2004] emphasises the importance of modelling and a process, which he terms *refactoring to deeper insight*, that seeks incremental improvements to models.

> Distillation is the process of separating the components of a mixture to extract the essence in a form that makes it more valuable and useful. A model is a distillation of knowledge. With every refactoring to deeper insight, we abstract some crucial aspect of domain knowledge and priorities. [Evans 2004, pg397]

After each refactoring to deeper insight, the model should more closely represent the object system, and the computer system is changed to reflect the newfound knowledge.

In Favour of Code over Models

By contrast, [Martin & Martin 2006, ch14] prescribes modelling only for communicating and reasoning about a design, and not "as a long-term replacement for real, working software". Rather [Martin & Martin 2006] advocates using models to quickly compare different ways in which a system might be modelled and then to disregard those models in favour of working code.

[Martin & Martin 2006] seeks to justify this position by noting that, in some engineering disciplines, models are used to reduce risk. Structural engineers build models of bridges. Aerospace engineers build models of aircraft. In these disciplines, a model is used to determine the efficacy of the real thing and, moreover, is cheaper to build and test than the real thing, often by a huge factor. The produce of many engineering disciplines is physical and the manufacturing process costly. By contrast, software models are often not much cheaper to build and test than the software they represent. Consequently, [Martin & Martin 2006] argues that working code is to be favoured over models.

In this justification, it is clear that [Martin & Martin 2006] often favours code over *models of computer systems*, but makes no argument for favouring code over *models of object systems*. In fact, the case study (Chapter XX) used to demonstrate the principles and practices prescribed in [Martin & Martin 2006], describes a model of a payroll system, according to Jackson's definition of a model [Jackson 1995]. The model of the payroll system is used to make decisions about the way in which the corresponding computer system is structured. Here then, the code is both the model of the computer system and the model of the object system.

Models in MDE

As the discussion above demonstrates, the way in which models are used and regarded varies in software engineering. In [Evans 2004], models are key – they are used to shape the solution's design, to define a common vocabulary for communication between team members, and to distinguish interesting and uninteresting elements of the object system. In [Martin & Martin 2006], code is the primary artefact used to describe the object system and the computer system, and can be regarded as a model.

MDE recognises that models – albeit in different forms – are used throughout software engineering. Furthermore, MDE seeks to capture the way in which models can be used to develop software, as discussed in Section 2.1.4. To facilitate this, models are structured such that they are amenable to manipulation. The sequel describes metamodelling, a process for describing the structure of models.

2.1.3 Metamodelling

In model-driven engineering, models are structured (satisfy a well-defined set of syntactic and semantic constraints) rather than unstructured [Kolovos 2009]. A *modelling language* is the set of syntactic and semantic constraints used to define the structure of a group of related models. In model-driven engineering, a modelling language is often specified as a model and, hence the term *metamodel* is used in place of *modelling language*.

Conformance is a relationship between a metamodel and a model. A model *conforms to* a metamodel when the metamodel specifies every concept used in the model definition, and the model uses the metamodel concepts according to the rules specified by the metamodel. Conformance can be described by a set of constraints between models and metamodels [Paige *et al.* 2007]. When all constraints are satisfied, a model conforms to a metamodel. For example, a conformance constraint might state that every object in the model has a corresponding non-abstract class in the metamodel.

Metamodels facilitate model interchange and, therefore, interoperability between modelling tools. For this reason, Evans recommends that software engineers "use a well-documented shared language that can express the necessary domain information as a common medium of communication." [Evans 2004, pg377]. To support this recommendation, Evans discusses Chemical Markup Language (CML), a standardised language, which has facilitated the interoperability of tools (such as JUMBO Browser, which creates graphical views of chemical structures) developed by various institutions.

A metamodel typically comprises three categories of constraint:

- **The concrete syntax** provides a notation for constructing models that conform to the language. For example, a model may be represented as a collection of boxes connected by lines. A standardised concrete syntax enables communication. Concrete syntax may be optimised for consumption by machines (e.g. XML Metadata Interchange (XMI) [OMG 2007c]) or by humans (e.g. the concrete syntax of the Unified Modelling Language (UML) [OMG 2007a]).

- **The abstract syntax** defines the concepts described by the language, such as classes, packages, datatypes. The representation for these concepts is independent of the concrete syntax. For example, compilers may elect to use an abstract syntax tree to encode the abstract syntax of a program (whereas the concrete syntax for the same language may be textual or diagrammatic).

- **The semantics** identifies the meaning of the modelling concepts in the particular domain of language. For example, consider a modelling language defined to describe genealogy, and another to describe flora. Although both languages may define a tree construct, the semantics of a tree in one is likely to be different from the semantics of a tree in the other. The semantics of a modelling language may be specified rigorously, by defining a reference semantics in a formal language such as Z [ISO/IEC 2002], or in a semi-formal manner by employing natural language.

Concrete syntax, abstract syntax and semantics are used together to specify modelling languages. There are many other ways of defining languages, but this approach (first formalised in [Álvarez *et al.* 2001]) is common in model-driven engineering: a metamodel is often used to define abstract syntax, a grammar or text-to-model transformation to specify concrete syntax, and code generators, annotated grammars or behavioural models to effect semantics.

MOF

Software engineers using model-driven engineering can use existing and define new metamodels. To facilitate interoperability between model-driven engineering tools, the OMG has standardised a language for specifying metamodels, the meta-object facility (MOF). Metamodels specified in MOF can be interchanged between model-driven engineering environments. Furthermore, modelling language tools are interoperable because MOF also standardises the way in which metamodels and their models are persisted to and from disk. For model and metamodel persistence MOF prescribes XML Metadata Interchange (XMI), a dialect of XML optimised and standardised by the OMG for loading, storing and exchanging models.

Because MOF is a modelling language for describing modelling languages, it is sometimes termed a metamodelling language. A simplified fragment of the UML defined in MOF, is shown in Figure 2.2. The concrete syntax of MOF is similar to the concrete syntax of UML class diagrams. Specifically:

- Modelling constructs are drawn as boxes. The name of each modelling construct is emboldened. The name of abstract (uninstantiable) constructs are italicised.

- Attributes are contained within the box of their modelling construct. Each attribute has a name, a type (prefixed with a colon) and may define a default value (prefixed with an equals sign).

- Generalisation is represented using a line with an open arrow-head.

- References are specified using a line. An arrow illustrates the direction in which the reference may be traversed (no arrow indicates bi-directionality). Labels are used to name and define the multiplicity of references.
- Containment references are specified by including a solid diamond on the containing end.

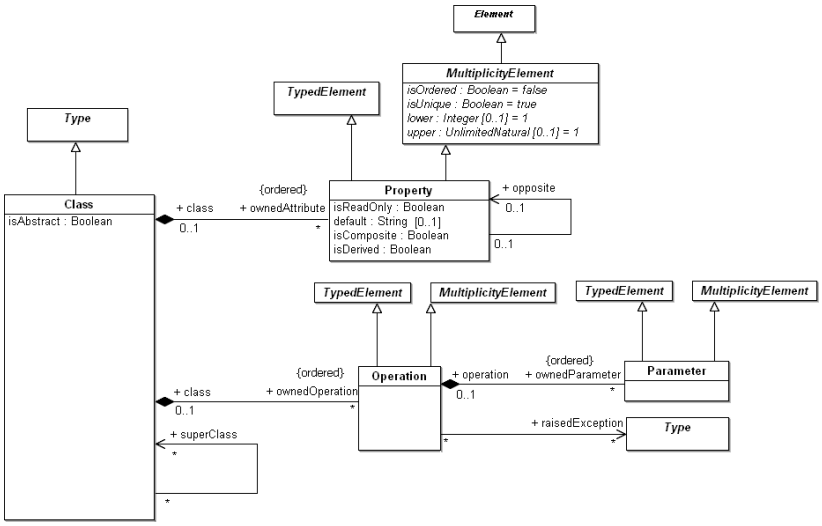

Figure 2.2: A fragment of the UML metamodel defined in MOF, from [OMG 2007a].

Prior to the formulation of MOF, the means for describing modelling constructs has been inconsistent between modelling languages. For example, both entity-relationship (ER) diagrams and UML class diagrams can be used to specify models of structured data but, as [Frankel 2002, pg97] notes, similar constructs from ER diagrams and UML class diagrams have different concrete syntax. MOF standardises the way in which modelling languages are defined.

A standardised metamodelling language has facilitated the construction of MDE tools that can be used with a range of modelling languages. Without a standardised metamodelling language, modelling tools were specific to one modelling language, such as UML. In contemporary MDE environments, any number of modelling languages can be used together and manipulated in a uniform manner. The sequel discusses the way in which models and metamodels are used to construct systems in MDE.

2.1.4 Model Management

Model-driven engineering (MDE) is a principled approach to software engineering in which models are produced throughout the engineering process. Models are *managed* to produce software. This thesis uses the term *model management*, defined in [Kolovos 2009], to refer to development activities that manipulate models for the purpose of producing software. Typical model management

activities, such as model transformation and validation, are discussed in this section. Section 2.2 discusses MDE guidelines and methods, and describes the way in which model management activities are used together to produce software.

Model Transformation

Model transformation is a development activity in which software artefacts are derived from others, according to some well-defined specification. Three different types of model transformation are described in [Kleppe *et al.* 2003, Kolovos 2009]. Model transformations are specified between modelling languages (model-to-model transformation), between modelling languages and textual artefacts (model-to-text-transformation) and between textual artefacts and modelling languages (text-to-model transformation). Each type of transformation has unique characteristics and tools, but share some common characteristics. The remainder of this section first introduces the commonalities and then discusses each type of transformation individually.

Common characteristics of model transformations The input to a transformation is termed its *source*, and the output its *target*. In theory, a transformation can have more than one source and more than one target, but not all transformation languages support multiple sources and targets. Consequently, much of the model transformation literature considers single source and target transformations.

[Czarnecki & Helsen 2006] describes a feature model for distinguishing and categorising model transformation approaches. Two of the features are relevant to the research presented in this thesis, and are now discussed.

Source-target relationship A *new-target* transformation creates target models afresh on each invocation. An *existing-target* transformation is executed on existing target models. Existing target transformations are used for partial (incremental) transformation and for preserving parts of the target that are not derived from the source.

Domain language Transformations specified between a source and a target model that conform to the same metamodel are termed *endogenous* or *rephrasings*, while transformations specified between a source and a target model that conform to different metamodels are termed *exogenous* or *translations*.

Endogenous, existing-target transformations are a special case of transformation and are termed *refactorings*. Refactorings have been studied in the context of software evolution and are discussed more thoroughly in Chapter 3.

Model-to-Model (M2M) Transformation M2M transformation is used to derive models from others. By automating the derivation of models from others, M2M transformation has the potential to reduce the cost of engineering large and complex systems that can be represented as a set of interdependent models [Sendall & Kozaczynski 2003].

M2M transformations are often specified as a set of *rules* [Czarnecki & Helsen 2006]. Each rule specifies the way in which a specific set of elements in the source

model is transformed to an equivalent set of elements in the target model [Kolovos 2009, pg.44].

Many M2M transformation languages have been proposed, such as the Atlas Transformation Language (ATL) [Jouault & Kurtev 2005], the Epsilon Transformation Language (ETL) [Kolovos *et al.* 2008a] and VIATRA [Varró & Balogh 2007]. The OMG [OMG 2008c] provide a standardised M2M transformation language, Queries/Views/Transformations (QVT) [OMG 2005]. M2M transformation languages can be categorised according to their *style*, which is either declarative, imperative or hybrid.

Declarative M2M transformation languages only provide constructs for mapping source to target model elements and, as such, are not computationally complete. Consequently, the scheduling of rules can be *implicit* (determined by the execution engine of the transformation language). By contrast, imperative M2M transformation languages are computationally complete, but often require rule scheduling to be *explicit* (specified by the user). Hybrid M2M transformation languages combine declarative and imperative parts, are computationally complete, and provide a mixture of implicit and explicit rule scheduling.

Because declarative M2M transformation languages cannot be used to solve some categories of transformation problem [Patrascoiu & Rodgers 2004], and imperative M2M transformation languages are difficult to write and maintain [Kolovos 2009, pg.45], [Kolovos *et al.* 2008a] notes that the current consensus is that hybrid languages, such as ATL are more suitable for specifying model transformation than pure imperative or declarative languages.

An exemplar M2M transformation, written in the hybrid M2M transformation language ETL, is shown in Listing 2.1. The source of the transformation is a state machine model, conforming to the metamodel shown in Figure 2.3. The target of the transformation an object-oriented model, conforming to the metamodel shown in Figure 2.4. The transformation in Listing 2.1 comprises two rules.

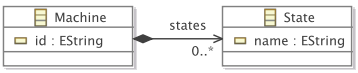

Figure 2.3: Exemplar State Machine metamodel.

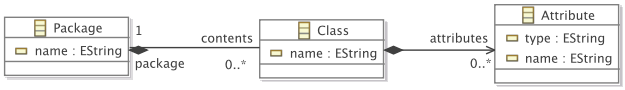

Figure 2.4: Exemplar Object-Oriented metamodel.

```
1  rule Machine2Package
2    transform m : StateMachine!Machine
3    to      p : ObjectOriented!Package {
4
5    p.name   := 'uk.ac.york.cs.' + m.id;
6    p.contents := m.states.equivalent();
```

```
7  }
8
9  rule State2Class
10   transform s : StateMachine!State
11   to      c : ObjectOriented!Class
12
13   guard: not s.isFinal {
14
15   c.name := s.name + 'State';
16 }
```

Listing 2.1: Exemplar M2M transformation in the Epsilon Transformation Language

The first rule (lines 1-7) is named `Machine2Package` (line 1) and transforms *Machine*s (line 2) into *Package*s (line 3). The body of the first rule (lines 5-6) specifies the way in which a `Package`, `p`, can be derived from a `Machine`, `m`. Specifically, the `name` of `p` is derived from the `id` of `m` (line 5), and the `contents` of `p` are derived from the `states` of `m` (line 6).

The second rule (lines 9-16) transforms `States` (line 10) to `Classes` (line 11). Additionally, line 13 contains a *guard* to specify that the rule is only to be applied to `States` whose `isFinal` property is `false`.

When executed, the transformation rules will be scheduled **implicitly** by the execution engine, and invoked once for each `Machine` and `State` in the source. On line 6 of Listing 2.1, the built-in `equivalent()` operation is used to produce a set of `Classes` from a set of `States` by invoking the relevant transformation rule. This is an example of **explicit** rule scheduling, in which the user defines when a rule will be called.

Model-to-Text (M2T) Transformation M2T transformation is used for model serialisation (enabling model interchange), code and documentation generation, and model visualisation and exploration. In 2005, the OMG [OMG 2008c] recognised the lack of a standardised M2T transformation with its M2T Language Request for Proposals [1]. In response, various M2T languages have been developed, including JET[2], XPand[3], MOFScript [Oldevik *et al.* 2005] and the Epsilon Generation Language (EGL) [Rose *et al.* 2008].

Because M2T transformation is used to produce unstructured rather than structured artefacts, M2T transformation has different requirements to M2M transformation. For instance, M2T transformation languages often provide mechanisms for specifying sections of text that will be completed manually and must not be overwritten by the transformation engine.

*Template*s are commonly used in M2T languages. Templates comprise *static* and *dynamic* sections. When the transformation is invoked, the contents of static sections are emitted verbatim, while dynamic sections contain logic and are executed.

An exemplar M2T transformation, written in EGL, is shown in Listing 2.2. The source of the transformation is an object-oriented model conforming to the metamodel shown in Figure 2.4, and the target is Java source code. The template assumes that an instance of `Class` is stored in the `class` variable.

```
1  package [%=class.package.name];
2
```

[1] http://www.omg.org/docs/ad/04-04-07.pdf
[2] http://www.eclipse.org/modeling/m2t/?project=jet#jet
[3] http://www.eclipse.org/modeling/m2t/?project=xpand

```
3  public class [%=class.name] {
4    [% for(attribute in class.attributes) { %]
5     private [%=attribute.type%] [%=attribute.name];
6    [% } %]
7  }
```

Listing 2.2: Exemplar M2T transformation in the Epsilon Generation Language

In EGL, dynamic sections are contained within `[%` and `%]`. *Dynamic output* sections are a specialisation of dynamic sections contained within `[%=` and `%]`. The result of evaluating a dynamic output section is included in the generated text. Line 1 of Listing 2.2 contains two static sections (`package'` and `;`) and a dynamic output section (`[%=class.package.name]`), and will generate a package declaration when executed. Similarly, line 3 will generate a class declaration. Lines 4 to 6 iterate over every `attribute` of the `class`, outputting a field declaration for each `attribute`.

Text-to-Model (T2M) Transformation T2M transformation is most often implemented as a parser that generates a model rather than object code. Parser generators such as ANTLR [Parr 2007] can be used to produce a structured artefact (such as an abstract syntax tree) from text. T2M tools are built atop parser generators and post-process the structured artefacts such that they conform to a metamodel specified by the user.

Xtext [4] and EMFtext [Heidenreich *et al.* 2009] are contemporary examples of T2M tools that, given a grammar and a target metamodel, will automatically generate a parser that transforms text to a model.

An exemplar T2M transformation, written in EMFtext, is shown in Listing 2.3. From the transformation shown in Listing 2.3, EMFtext can be used to generate a parser that, when executed, will produce state machine models. For the input, `lift[stationary up down stopping emergency]`, the parser will produce a model containing one `Machine` with `lift` as its `id`, and five `States` with the `names`, `stationary`, `up`, `down`, `stopping`, and `emergency`.

```
1  SYNTAXDEF statemachine
2  FOR <statemachine>
3  START Machine
4
5  TOKENS {
6    DEFINE IDENTIFIER $('a'..'z'|'A'..'Z')*$;
7    DEFINE LBRACKET $'['$;
8    DEFINE RBRACKET $']'$;
9  }
10
11 RULES {
12   Machine ::= id[IDENTIFIER] LBRACKET states* RBRACKET ;
13   State ::= name[IDENTIFIER] ;
14 }
```

Listing 2.3: Exemplar T2M transformation in EMFtext

Lines 1-2 of Listing 2.3 define the name of the parser and target metamodel. Line 3 indicates that parser should first seek to construct a `Machine` from the source text. Lines 5-9 define rules for the lexer, including a rule for recognising `IDENTIFIER`s (represented as alphabetic characters).

Lines 11-14 of Listing 2.3 are key to the transformation. Line 11 specifies that a `Machine` is constructed whenever an `IDENTIFIER` is followed by a

[4] `http://www.eclipse.org/Xtext/`

LBRACKET and eventually a RBRACKET. When constructing a Machine, the first time an IDENTIFIER is encountered, it is stored in the id attribute of the Machine. The states* statement on line 12 indicates that, before matching a RBRACKET, the parser is permitted to transform subsequent text to a State (according to the rule on line 13) and store the resulting State in the states reference of the Machine. The asterisks in states* indicates that any number of States can be constructed and stored in the states reference.

Model Validation

Model validation provides a mechanism for managing the integrity of the software developed using MDE. A model that omits information is said to be *incomplete*, while related models that suggest differences in the underlying phenomena are said to be *contradicting* [Kolovos 2009]. Incompleteness and contradiction are two examples of *inconsistency*. In MDE, inconsistency is detrimental, because, when artefacts are automatically derived from each other, the inconsistency of one artefact might be propagated to others. Model validation is used to detect, report and reconcile inconsistency throughout a MDE process.

[Kolovos 2009] observes that inconsistency detection is inherently pattern-based and, hence, higher-order languages are more suitable for model validation than so-called "third-generation" programming languages (such as Java). The Object Constraint Language (OCL) [OMG 2006] is an OMG standard that can be used to specify consistency constraints on UML and MOF models. OCL cannot be used to specify inter-model constraints, unlike the xlinkit toolkit [Nentwich *et al.* 2003] and the Epsilon Validation Language (EVL) [Kolovos *et al.* 2008b].

An exemplar model validation constraint, written in EVL, is shown in Listing 2.4. The constraint validates state machine models that conform to the metamodel shown in Figure 2.3. The constraint shown in Listing 2.4 is defined for States (line 1), and checks that there exists some transition whose source or target is the current state (line 4). When the check part (line 4) is not satisfied, the message part (line 6) is displayed. When executed, the EVL constraint will be invoked once for every State in the model. The keyword self is used to refer to the particular State on which the constraint is currently being invoked.

```
1  context State {
2    constraint NoStateIsAnIsland {
3      check:
4        Transition.all.exists(t | t.source == self or t.target == self)
5      message:
6        'The state ' + self.name + ' has no transitions.'
7    }
8  }
```

Listing 2.4: Exemplar model validation in the Epsilon Validation Language

Further model management activities

In addition to model transformation and validation, further examples of model management activities include model comparison (e.g. [Kolovos *et al.* 2006b]), in which a *trace* of similar and different elements is produced from two or more models, and model merging or weaving (e.g. [Kolovos *et al.* 2006a]), in which two or more models are combined to produce a unified model.

Further activities, such as model versioning and tracing, might be regarded as model management but, in the context of this thesis, are considered as evolutionary activities and as such are discussed in Chapter 3.

2.1.5 Summary

This section has introduced the terminology and principles necessary for discussing MDE in this thesis. Models provide abstraction, capturing necessary and disregarding irrelevant details. Metamodels provide a structured mechanism for describing the syntactic and semantic rules to which a model most conform. Metamodels facilitate interoperability between modelling tools and MOF, the OMG standard metamodelling language, enables the development of tools that can be used with a range of metamodels, such as model management tools. Throughout model-driven engineering, models are manipulated to produce other development artefacts using model management activities such as model transformation and validation. Using the terms and principles described in this section, the ways in which model-driven engineering is performed in practice are now discussed.

2.2 MDE Guidelines and Methods

For performing model-driven engineering, new practices and processes have been proposed. Proponents of MDE have produced guidance and methods for model-driven engineering. This section discusses the guidance for MDE set out in the Model-Driven Architecture [OMG 2008b] and the methods described by [Stahl *et al.* 2006, Kelly & Tolvanen 2008, Greenfield *et al.* 2004].

2.2.1 Model-Driven Architecture (MDA)

Model-Driven Architecture (MDA) is a software engineering framework defined by the OMG. MDA provides a set of guidelines for model-driven engineering. MDA prescribes the use of a Platform Independent Model (PIM) and one or more Platform Specific Models (PSMs).

A PIM provides an abstract, implementation-agnostic view of the solution. Successive PSMs provide increasingly more implementation detail. Inter-model mappings are used to forward- and reverse-engineer these models, as depicted in Figure 2.5.

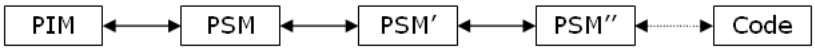

Figure 2.5: Interactions between a PIM and several PSMs.

The crucial difference between MDA and related approaches, such as round-trip engineering (in which models and code are co-evolved to develop a system), is that traditional round-trip engineering uses some manual transformations, whereas MDA prescribes automated transformations between PIM and PSMs.

McNeile [McNeile 2003] identifies two ways in which engineers are utilising MDA. Both interpretations begin with a PIM and vary in the way they are used to produce executable code:

- **Translationist**: The PIM is used to generate code directly using a sophisticated code generator. Any intermediate PSMs are internal to the code generator. No generated artefacts are edited manually.

- **Elaborationist**: Any generated artefacts (such as PSMs, code and documentation) can be augmented with further details of the application. To ensure that all models and code are synchronised, tools must allow bi-directional transformations.

Translationists must encode behaviour in their PIMs [Mellor & Balcer 2002], whereas elaborationists have a choice, frequently electing to specify behaviour in PSMs or in code [Kleppe *et al.* 2003].

The MDA prescribes a set of standards for MDE. The MDA allocates standards to one of four tiers, representing different levels of model abstraction. Members of each tier are instances of the members of parent tiers. These tiers can be seen in Figure 2.6, and a short discussion based on [Kleppe *et al.* 2003, Section 8.2] follows.

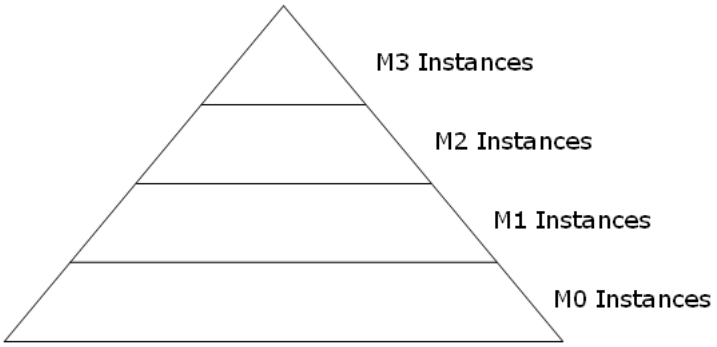

Figure 2.6: The tiers of standards used as part of MDA.

The base of the pyramid, tier M0, describes the domain (real-world). When modelling a business, this tier is used to describe items of the business itself, such as a real customer or an invoice. When modelling software, M0 instances describe the software representation of such items. M1 contains a model of the concepts in M0, for example a customer may be represented as a class with attributes. The M2 tier describes the model of the modelling language used to describe elements of M1. For example, if UML [OMG 2007a] were used to describe concepts as classes in the M1 tier, M2 would contain the UML metamodel. Finally, M3 is the meta-metamodel layer, which provides a description of the metamodel used in M2. M3 is necessary to permit reasoning about metamodels (such as the UML), and to enable tool standardisation. The OMG defines the Meta-Object Facility (MOF) [OMG 2008a] as the sole inhabitant of the M3 tier.

2.2.2 Methods for MDE

Several methods to MDE are prevalent today. In this section, three of the most established are discussed: Architecture-Centric Model-Driven Software Development [Stahl *et al.* 2006], Domain-Specific Modelling [Kelly & Tolvanen 2008] and Microsoft's Software Factories [Greenfield *et al.* 2004]. All three methods have been defined from a pragmatic standpoint, and have been used repeatedly to solve problems in industry. The methods vary in the extent to which they follow the guidelines set out by MDA.

Architecture-Centric Model-Driven Software Development

Model-Driven Software Development is the term given to MDE by in [Stahl *et al.* 2006]. The style of MDE that Stahl et al. describe, *architecture-centric model-driven software development* (AC-MDSD), focuses on generating the infrastructure of large-scale applications. For example, a typical J2EE application contains concepts (such as EJBs, descriptors, home and remote interfaces) that "admittedly contain domain-related information such as method signatures, but which also exhibit a high degree of redundancy" [Stahl *et al.* 2006]. It is this redundancy that AC-MDSD seeks to remove by using code generators, requiring only the domain-related information to be specified.

AC-MDSD applies more of the MDA guidelines than the other methods discussed below. For instance, AC-MDSD supports the use of a general-purpose modelling language for specifying models. [Stahl *et al.* 2006] utilise UML in many of their examples, which demonstrate how AC-MDSD may be used to enhance the productivity, efficiency and understandability of software development. In these examples, models are annotated using UML profiles to describe domain-specific concepts.

Domain-Specific Modelling

[Kelly & Tolvanen 2008] present a method for MDE termed Domain-Specific Modelling (DSM). DSM is based on the translationist interpretation of MDA; DSM seeks to translate models containing concepts from the problem domain to full code. In motivating the need for DSM, Kelly and Tolvanen state that large productivity gains were made when third-generation programming languages were used in place of assembler, and that no paradigm shift has since been able to replicate this degree of improvement. Tolvanen[5] notes that DSM focuses on increasing the productivity of software engineering by allowing developers to specify solutions by using models that describe the application domain.

To perform DSM, expert developers define:

- **A domain-specific modelling language**: allowing domain experts to encode solutions to their problems.
- **A code generator**: that translates the domain-specific models to executable code in an existing programming language.
- **Framework code**: that encapsulates the common areas of all applications in this domain.

[5] Tutorial on Domain Specific Modelling for Full Code Generation at the Fourth European Conference on Model Driven Architecture (ECMDA), June 2008, Berlin, Germany.

As the development of these three artefacts requires significant effort from expert developers, Tolvanen[5] states that DSM should only be applied if more than three problems specific to the same domain are to be solved.

Tools for defining domain-specific modelling languages, editors and code generators enable DSM [Kelly & Tolvanen 2008]. Reducing the effort required to specify these artefacts is key to the success of DSM. In this respect, DSM resembles a programming paradigm popular in the *domain-specific language* (DSL) community, termed *language-oriented programming* (LOP), which also requires tools to simplify the specification of new languages. DSLs and LOP are discussed further in Section 2.4.

Throughout [Kelly & Tolvanen 2008], examples from industrial partners are used to illustrate that DSM can greatly improve developer productivity. Unlike MDA, DSM seems to be optimised for increasing productivity, and less concerned with portability or maintainability. Therefore, DSM is less suitable for engineering applications that frequently interoperate with – and are underpinned by – changing technologies.

Microsoft Software Factories

Greenfield [Greenfield *et al.* 2004, pg159] states that industrialisation of the automobile industry has addressed problems with economies of scale (mass production) and scope (product variation). Software Factories, a software engineering method developed at Microsoft, seek to address problems with economies of scope in software engineering by borrowing concepts from product-line engineering. Greenfield [Greenfield *et al.* 2004] argues that, unlike many other engineering disciplines, software development requires considerably more development effort than production effort in that scaling software development to account for scope is significantly more complicated then mass production of the same software system.

The Software Factories method [Greenfield *et al.* 2004] prescribes a bottom-up approach to abstraction and re-use. Development begins by producing prototypical applications. The common elements of these applications are identified and abstracted into a product-line. When instantiating a product, models are used to specify product variance (e.g. by selecting particular product features). To generate these models, tools for use with Software Factories provide mechanisms for defining wizards and feature-based configuration selection dialogues. By contrast, DSM relies upon the use of concrete syntax for producing models that describe product variance. By providing explanations that assist in making decisions, the wizards used in Software Factories guide users towards best practices. Greenfield et al. state that "moving from totally-open ended hand-coding to more constrained forms of specification [such as wizard-based feature selection] are the key to accelerating software development" [Greenfield *et al.* 2004, pg179].

The Software Factories method better addresses problems of portability compared to DSM: the former provides *viewpoints* into the product-line (essentially different views of development artefacts), which allow decoupling of concerns (e.g. between logical, conceptual and physical layers). Viewpoints provide a mechanism for abstracting over different layers of platform independence, adhering more closely than DSM to the guidelines provided in MDA. Unlike the guidelines provided in MDA, the Software Factories method does not insist that

development artefacts be derived automatically where possible.

Finally, Software Factories prescribes the use of domain-specific languages (discussed in Section 2.4.1) for describing models in conjunction with Software Factories, rather than a general-purpose modelling language, as the authors of Software Factories believe that the latter often have imprecise semantics [Greenfield *et al.* 2004].

2.2.3 Summary

This section has discussed the ways in which process and practices for MDE have been captured. Guidance for MDE has been set out in the MDA standard, which seeks to use MDE to produce adaptable software in a productive and maintainable manner. Three methods for performing model-driven engineering have been discussed.

The methods discussed share some characteristics. They all require a set of exemplar applications, which are examined by MDE experts. Analysis of the exemplar applications identifies the way in which software development may be decomposed. A modelling language for the problem domain is constructed, and instances are used to generate future applications. Code common to all applications in the problem domain is encapsulated into a framework.

Each method has a different focus. AC-MDSD seeks to reduce the amount of boilerplate code being generated, particularly in enterprise applications. Software Factories concentrate on providing different viewpoints into the system, allowing different domain experts to collaborate when specifying a system. DSM aims to decrease the time taken to develop software solutions to instances of the problem domain.

Perhaps unsurprisingly, the proponents of each method for MDE recommend one or more tools, each optimised for that method (such as MetaCase for DSM). Alternative tools are available from open-source modelling communities, including the Eclipse Modelling Project, which provides – among other tools for MDE – arguably the most widely used MDE modelling framework today. Some of the tools used for MDE are reviewed in the sequel.

2.3 MDE Tools

For MDE to be applicable in the large, and to complex systems, mature and powerful tools and languages must be available. Such tools and languages are beginning to emerge, and this section discusses the state of arguably the most widely used MDE development environment, and a platform for constructing model management languages.

This section provides a brief overview of the Eclipse Modelling Framework [Eclipse 2008a], which implements MOF and underpins many contemporary MDE tools and languages, facilitating their interoperability. Subsequently, a discussion of Epsilon [Eclipse 2008c], an extensible platform for the specification of model management languages, is presented. The highly extensible nature of Epsilon (which is described below) makes it an ideal host for the rapid prototyping of languages and exploring research hypotheses.

There are many other MDE tools and environments, which this section does not discuss as they are not as relevant to the research conducted in this the-

sis. Further examples of MDE tools include ATL [ATLAS 2007] and VIATRA [Varró & Balogh 2007] for M2M transformation, oAW [openArchitectureWare 2007a] for model transformation and validation, and MOFScript [Oldevik *et al.* 2005] and XPand [openArchitectureWare 2007b] for M2T transformation.

2.3.1 Eclipse Modelling Framework

[Eclipse 2008b] is an open-source community seeking to build an extensible development platform. The Eclipse Modelling Framework (EMF) project [Eclipse 2008a] enables MDE within Eclipse. EMF provides a modelling framework with code generation facilities, and a meta-modelling language, Ecore, that implements the MOF 2.0 specification [OMG 2008a]. EMF is arguably the most widely-used contemporary MDE modelling framework.

EMF is used to generate metamodel-specific editors for loading, storing and constructing models. EMF model editors comprise a navigation view that depicts the model as a structure and a properties view that is used to specify the values of model element features. By default, EMF editors represent models on disk as XMI 2.1 [OMG 2007c] documents. Figure 2.7 shows an EMF model editor for a simplistic state machine language.

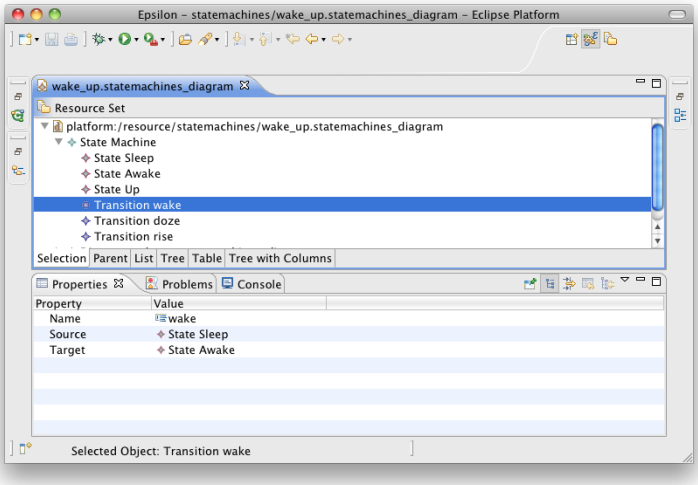

Figure 2.7: EMF state machine model editor.

Users of EMF can define their own metamodels in Ecore and generate a corresponding model editor. EMF provides both a tree-based editor (Figure 2.8) and a diagrammatic editor (Figure 2.9) for constructing metamodels. The latter uses syntax taken from UML class diagrams. An extension to EMF provides a textual editor for metamodels (Figure 2.10).

The range of concrete syntaxes used for describing metamodels presents a challenge for tools that wish to augment the way in which metamodels are defined (e.g. for specifying semantics). Extensions made to one type of metamodel editor (e.g. tree-based) will not be automatically be available in others (e.g. visual and textual). However, EMF does facilitate the programmatic monitoring

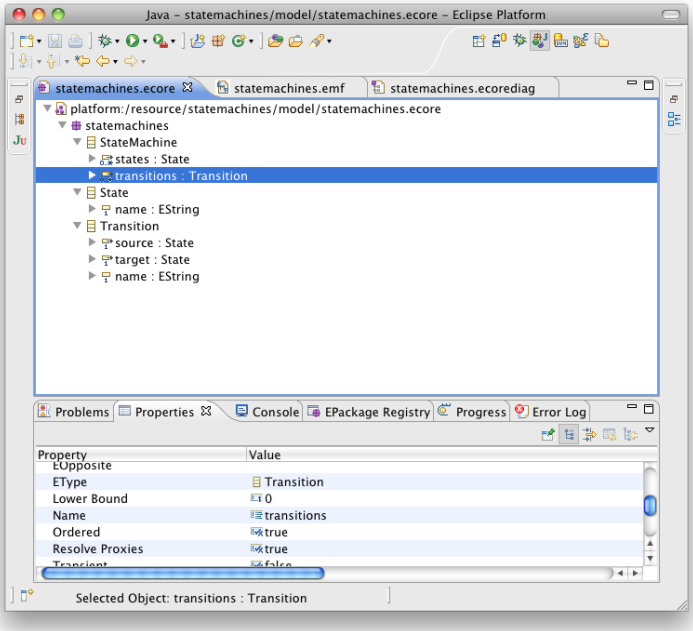

Figure 2.8: EMF tree-based metamodel editor.

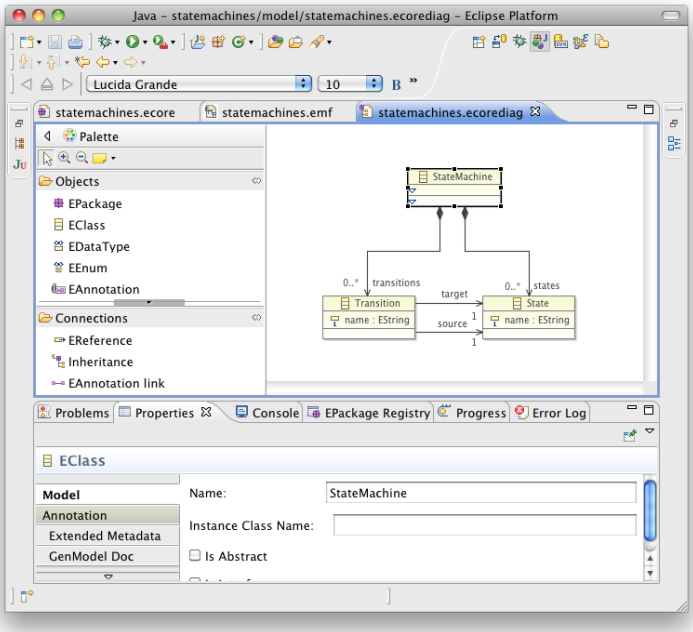

Figure 2.9: EMF diagrammatic metamodel editor.

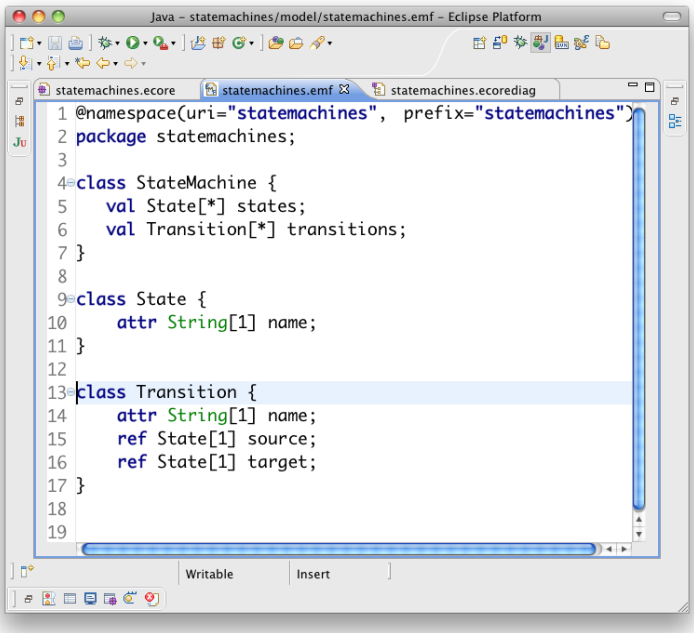

Figure 2.10: EMF textual metamodel editor.

of model changes, which can be used for implementing metamodel extensions, as discussed in Chapter 5.

From a metamodel, EMF can generate a metamodel-specific model editor. The metamodel specified in Figures 2.8, 2.9 and 2.10 was used to generate the Java code for the model editor shown in Figure 2.7. Because model editors are generated from metamodels, models and metamodels are kept separate in EMF.

The Graphical Modeling Framework (GMF) [Gronback 2009] is used to specify graphical concrete syntax for metamodels defined in EMF. GMF itself uses a model-driven approach: users specify several models, which are combined, transformed and then used to generate code for the resulting graphical editor. Figure 2.11 shows a model editor produced with GMF for the simplistic state machine language described above.

Many MDE tools are interoperable with EMF, enriching its functionality. The remainder of this section discusses one tool that is interoperable with EMF, Epsilon, which is a suitable platform for rapid prototyping of model management languages and, hence, is useful for performing MDE research.

2.3.2 Epsilon

The Extensible Platform for Specification of Integrated Languages for mOdel maNagement (Epsilon) [Eclipse 2008c] is a suite of tools and domain-specific languages for MDE. Epsilon comprises several integrated model management languages – built atop a common infrastructure – for performing tasks such as model merging, model transformation and inter-model consistency checking

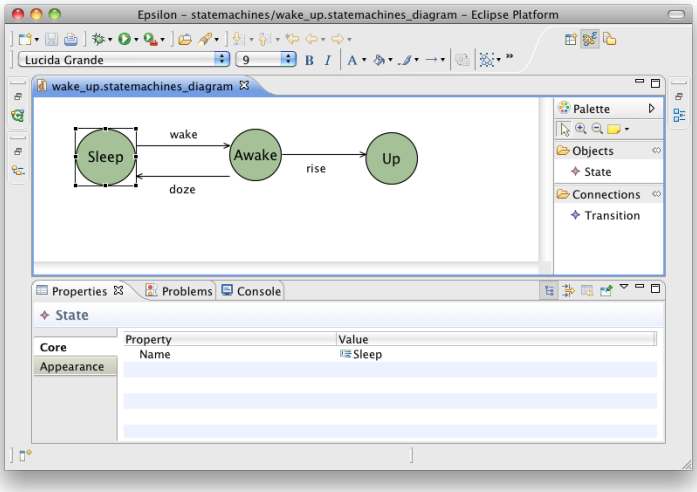

Figure 2.11: GMF state machine model editor.

[Kolovos 2009]. Figure 2.12 illustrates the various components of Epsilon.

Whilst many model management languages are bound to a particular subset of modelling technologies, limiting their applicability, Epsilon is metamodel-agnostic – models written in any modelling language can be manipulated by Epsilon's model management languages [Kolovos *et al.* 2006c]. Currently, Epsilon supports models implemented using EMF, MOF 1.4, XML, or Community Z Tools (CZT) [6]. Interoperability with further modelling technologies can be achieved via extensions of the Epsilon Model Connectivity (EMC) layer.

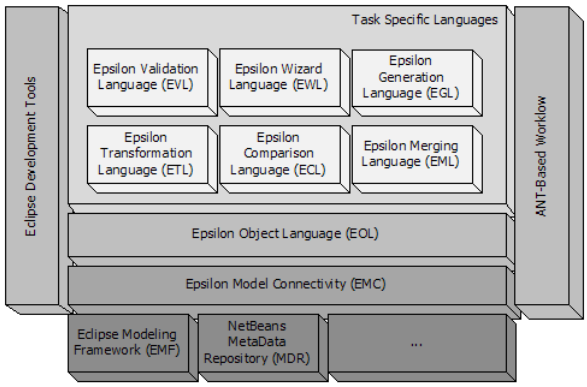

Figure 2.12: The architecture of Epsilon, taken from [Rose *et al.* 2008].

The architecture of Epsilon promotes reuse when building task-specific model management languages and tools. Each Epsilon language can be reused whole-

[6] http://czt.sourceforge.net/

sale in the production of new languages. Ideally, the developer of a new language only has to design language concepts and logic that do not already exist in Epsilon languages. As such, new task-specific languages can be implemented in a minimalistic fashion. This claim has been demonstrated in [Rose *et al.* 2008], which describes the Epsilon Generation Language (EGL) for specifying model-to-text transformation. Epsilon has been used extensively for the implementation of tools described in Chapter 5.

The Epsilon Object Language (EOL) [Kolovos *et al.* 2006c] is the core of the platform and provides functionality similar to that of OCL [OMG 2006]. However, EOL provides an extended feature set, which includes the ability to update models, access to multiple models, conditional and loop statements, statement sequencing, and provision of standard output and error streams.

As shown in Figure 2.12, every Epsilon language re-uses EOL, so improvements to this language enhance the entire platform. EOL also allows developers to delegate computationally intensive tasks to extension points, where the task can be authored in Java.

Epsilon is a member of the Eclipse GMT [Eclipse 2008d] project, a research incubator for the top-level modelling technology project. Epsilon provides a lightweight means for defining new experimental languages for MDE. For these reasons, Epsilon is uniquely positioned as an ideal host for the rapid prototyping of languages for model management.

2.3.3 Summary

This section has introduced the MDE tools used throughout the remainder of the thesis. The Eclipse Modeling Framework (EMF) implements MOF and provides tools for defining metamodels, generating metamodel-specific editors, and persisting models to disk. EMF is arguably the most widely used contemporary MDE modelling framework and its functionality is enhanced by numerous tools, such as the Graphical Modeling Framework (GMF) and Epsilon. GMF allows metamodel developers to specify a graphical concrete syntax fortheir metamodels, and can be used to generate graphical model editors. Epsilon is an extensible platform for defining and executing model management languages, provides a high degree of re-use for defining new model management languages and can be used with a range of modelling frameworks, including EMF.

2.4 Research Relating to MDE

MDE is closely related to several other engineering and software development fields. This section discusses two of those fields, Domain-Specific Languages (DSLs) and Language-Oriented Programming (LOP). A further related area, Grammarware, is discussed in the context of software evolution in Section 3.2.3. Each area is closely related to the research central to this thesis. Other areas relating to MDE but less relevant to this thesis, such as formal methods, are not considered here.

2.4.1 Domain-Specific Languages

For a set of closely-related problems, a specific, tailored approach is likely to provide better results than instantiating a generic approach for each problem [Deursen *et al.* 2000]. The set of problems for which the specific approach outperforms the generic approach is termed the problem domain. A *domain-specific programming language* (often called a *domain-specific language* (DSL)) enables solutions in a particular problem domain to be encoded.

Like modelling languages, DSLs describe abstract syntax. Furthermore, a common language can be used to define DSLs (e.g. EBNF [ISO/IEC 1996]), like the use of MOF for defining modelling languages. In addition to abstract syntax, DSLs typically define a textual concrete syntax but, like modelling languages, can utilise a graphical concrete syntax.

Cobol, Fortran and Lisp first existed as DSLs for solving problems in the domains of business processing, numeric computation and symbolic processing respectively, and evolved to become general-purpose programming languages [Deursen *et al.* 2000]. DSLs are often designed to be very simple, especially at inception, but they can grow to become complicated (e.g. SQL). However, a DSL cannot be used to program an entire application. Within their domain, simple DSLs are easy to read, understand and edit [Fowler 2005].

A typical approach to constructing a DSL involves describing the domain using constructs from a general-purpose language (the *host*), such as classes, interfaces and message passing in an object-oriented language [Dmitriev 2004]. DSLs created using this approach are termed *internal* by [Fowler 2010]. Examples of internal DSLs include the frameworks for working with collections that are included in some programming languages (e.g. STL for C++, the Collections API for Java). Some languages are better than others for hosting internal DSLs. For example, Fowler [Fowler 2005] proposes Ruby as a suitable host due to its "unintrusive syntax and flexible runtime evaluation." Graham [Graham 1993] describes a related style of development in Lisp, where macros are used to translate domain-specific concepts to Lisp abstractions.

However, [Dmitriev 2004] reports that embedding a DSL is often unsatisfactory, as the problem domain must be constructed by using the concepts specified in the host, which is a general-purpose language. This leads to a mismatch between domain and programming abstractions, which must be bridged by skilled developers. [Dmitriev 2004] suggests that a DSL should not be bound to programming language abstractions. Developing a translation for programs written in a DSL to programs written in a general-purpose language is an alternative to embedding. DSLs constructed using this approach are termed *external* DSLs by [Fowler 2010]. Programs written in simple DSLs are often easy to translate to programs in an existing general-purpose language. Approaches to translation include preprocessing; building or generating an interpreter or compiler; or extending an existing compiler or interpreter [Dmitriev 2004].

The construction of an external DSL can be achieved using many of the principles, practices and tools used in MDE. Parsers can be generated using text-to-model transformation; syntactic constraints can be specified with model validation; and translation can be specified using model-to-model and model-to-text transformation. The use of MDE tools for constructing an external DSL is demonstrated in the implementation of a textual modelling notation in Chapter 5.

DSLs have been successfully used as part of application development in many domains, as described in [Deursen *et al.* 2000]. They have been used in conjunction with general-purpose languages to build systems rapidly and to improve productivity in the development process (e.g. DSLs for the automation of system deployment and configuration). More recently, some developers are building complete applications by combining DSLs, in a style of development called Language-Oriented Programming.

2.4.2 Language-Oriented Programming

[Ward 1994] coins the term Language-Oriented Programming (LOP) to describe a style of development in which a very high-level language is used to encode the problem domain. Simultaneously, a compiler is developed to translate programs written in the high-level language to an existing programming language. Ward describes how this approach to programming can enhance the productivity of development and the understandability of a system. Additionally, Ward mentions the way in which multiple very high-level languages could be layered to separate domains.

The high-level languages that Ward discusses are domain-specific. [Fowler 2005] notes that combining DSLs to solve a problem is not a new technique. Traditionally, UNIX has encouraged developers to use small (domain-specific) languages (such as awk, make, sed, lex, yac) together to solve problems. Lisp (and, more recently, Ruby) programmers often construct domain-specific languages when developing programs [Graham 1993]. Smalltalk also has a strong tradition of this style of development [Fowler 2005].

To fully realise the benefits of LOP, the development effort required to construct DSLs must be minimised. Two approaches seem to be prevalent. The first advocates using a highly dynamic, reflexive and extensible programming language. Clark terms this category of language a *superlanguage* [Clark *et al.* 2008]. The superlanguage permits new DSLs to re-use constructs from existing DSLs, which simplifies development.

A *language workbench* [Fowler 2005] is an alternative means for simplifying DSL development. Language workbenches provide tools, wizards and DSLs for defining abstract and concrete syntax, for constructing editors and for specifying code generators.

For defining DSLs, the main difference between using a language workbench or a superlanguage is the way in which semantics of language concepts are encoded. In a language workbench, a typical approach is to write a generator for each DSL (e.g. MPS [JetBrains 2008]), whereas a superlanguage often requires that semantics be encoded in the definition of language constructs (e.g. XMF [Ceteva 2008]).

[Clark *et al.* 2008] acknowledges that a modern development environment for a superlanguage is an important concern. Therefore, the success of both LOP approaches depends, to some extent, upon the quality of their development environment (or workbench). Dependency on language workbenches is a key difference between LOP and MDE for two reasons:

1. The emphasis for LOP is in defining (textual) concrete syntaxes. Tools for MDE often provide an editor for manipulating abstract syntax directly,

and constructing models using a concrete syntax is optional. Graphical (diagrammatic) concrete syntaxes are also popular when modelling.

2. MDE tools frequently support many types of model-management operation (such as model-to-model transformation and model merging), while language workbenches concentrate solely on translating DSL programs to code using generators. (Superlanguages do not need to provide any facilities for manipulating the abstract syntax directly).

Some of the key concerns for MDE tools are also important to the success of language workbenches. For example, tools for performing LOP and MDE need to be as usable as those available for traditional development, which often include support for code-completion, automated refactoring and debugging. Presently, these features are often lacking in tools that support LOP or MDE.

In summary, LOP addresses many of the same issues with traditional development as MDE, but requires a different style of tool. LOP tools focus more on the integration of distinct DSLs, and providing editors and code generators for them; while MDE tools concentrate more on model management operations, such as model-to-model transformation.

2.4.3 Summary

2.5 Benefits of and Current Challenges for MDE

Compared to traditional software engineering approaches and to domain-specific languages and language-oriented programming, MDE has several benefits and weaknesses. This section identifies benefits of and challenges to MDE, synthesised from the literature reviewed in this chapter.

2.5.1 Benefits

Three benefits of MDE are now identified, and used to describe the advantages of the MDE principles and practices discussed in this chapter.

Tool interoperability MOF, the standard metamodelling language for MDE, facilitates interoperability between tools via model interchange. With Ecore, EMF provides a reference implementation of MOF atop which many contemporary MDE tools are built. Interoperability between modelling tools allows model management to be performed across a range of tools, and developers are not tied to one vendor. Furthermore, models represented in a range of modelling languages can be used together in a single environment. Prior to the formulation of MOF, developers would use different tools for each modelling language. Each tool would have different storage formats, complicating the interchange of models between tools.

Managing complexity For software systems that must incorporate large-scale complexity, such as those that support large businesses, managing stochastic interaction in the large is a key concern. With MDE it is possible to sacrifice total reliability or validity of a system to achieve a working solution. Sacrificing

reliability or validity is not always possible when other engineering approaches are used to construct software (such as formal methods).

Maintainability in the large The guidelines set out for MDE in MDA [OMG 2008b] highlight principles and patterns for modelling to increase the adaptability of software systems by, for example, separating platform-specific and platform-independent detail. When the target platform changes (for example a new technological architecture is required), only part of the system needs to be changed. The platform-independent detail can be re-used wholesale.

Related to this, MDE facilitates automation of the error-prone or tedious elements of software engineering. For example, code generation can be used to automatically produce so-called "boilerplate" code, which is repetitive code that cannot be restructured to remove duplication (typically for technological reasons).

While MDE can be used to reduce the extent to which a system is changed in some circumstances, MDE also introduces additional challenges for managing changing systems [Mens & Demeyer 2007]. For example, mixing generated and hand-written code typically requires a more elaborate software architecture than would be used when code is only hand-written. Further examples of the challenges that MDE presents for maintainability are discussed in Section 2.5.2.

2.5.2 Challenges

Three challenges for MDE are now identified, and used to motivate areas of potential research for improving MDE. The remainder of the thesis focuses on the final challenge, maintainability in the small.

Learnability MDE involves new terminology, development activities and principles for software engineering. For the novice, producing a simple system with MDE is arguably challenging. For example, [Kolovos *et al.* 2009] explores the steps required to generate a graphical model editor with the Graphical Modeling Framework (GMF), concludes that GMF is difficult for new users to understand, and presents a mechanism for simplifying GMF for new users. It seems reasonable to assume that the extent to which MDE tools and principles can be learnt will eventually determine the adoption rate of MDE.

Scalability As discussed in [Rose *et al.* 2010b], in traditional approaches to software engineering a model is considered of comparable value to any other documentation artefact, such as a word processor document or a spreadsheet. As a result, the convenience of maintaining self-contained model files which can be easily shared outweighs other desirable attributes. [Kolovos *et al.* 2008c] notes that this perception has led to the situation where single-file models of the order of tens (if not hundreds) of megabytes, containing hundreds of thousands of model elements, are the norm for real-world software projects.

MDE languages and tools must scale such that they can be used with with large and complex models. [Hearnden *et al.* 2006, Ráth *et al.* 2008, Tratt 2008] explore ways in which the scalability of model management tasks, such as model transformation, can be improved. [Kolovos *et al.* 2008c] takes a prescribes a

different approach, suggesting that MDE research should aim for greater modularity in models, which, as a by-product, will result in greater scalability in MDE.

Maintainability in the small Notwithstanding the benefits that MDE promises for maintaining systems, the introduction of additional development artefacts, activities and tools presents additional challenges for maintainability at the low level [Mens & Demeyer 2007].

In traditional approaches to engineering, maintainability is primarily achieved by restructuring code, updating documentation and running regression tests [Feathers 2004]. It is not yet clear the extent to which existing maintenance activities can be applied to he additional development artefacts introduced by MDE. (For example, should models be tested and, if so, how?)

As demonstrated in Chapter 4, the way in which some model-driven engineering tools are structured limits the extent to which some maintenance activities can be performed. Understanding, improving and assessing the way in which evolution is managed in the context of MDE is an open research topic to which this thesis contributes.

2.5.3 Summary

This section has identified some of the benefits of and challenges for contemporary MDE. The interoperability of tools and modelling languages in MDE allows developers greater flexibility in their choice of tools and facilitates interchange between heterogenous tools and modelling frameworks. MDE is more flexible than other, more formal approaches to software engineering, which can be beneficial for constructing complex systems. The principles and practices of MDE can be used to achieve greater maintainability of systems by, for example, separating platform-independent and platform-specific details.

As MDE tools approach maturity, non-functional requirements, such as learnability, scalability and maintainability, become increasingly desirable for practitioners. This section has identified weaknesses in the way in which existing MDE approaches and tools approach non-functional requirements. The remainder of this thesis focuses on one of those non-functional requirements, maintainability.

2.6 Chapter Summary

To be completed.

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